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C. Team Definition

We propose Science Program Around Communication Engineering with High Achieving Undergraduate Cadres (SPACE HAUC) to demonstrate X-band beam steering from a CubeSat platform. To make these ambitious goals a reality, we have built a strong team consisting of developers and technologists who have direct experience with student-focused space missions. Professor Supriya Chakrabarti, the Principal Investigator (PI), was the PI on NASA's Student Launch Program's (SLP) mission called Student-run Program for Exoatmospheric Collecting Technologies and Rocket Experiment (SPECTRE - http://www.bu.edu/csp/uv/spectre/spectre_index.html). The proposal for SPECTRE grew out of a class and was implemented using the Senior Design Program with faculty, research staff, and graduate students as mentors to the undergraduate student teams. Professor Timothy Cook was the Project Manager (PM) on Tomographic Experiment Using Radiative Recombinative EUV and Radio Sources (TERRIERS), the predecessor to NASA's University Explorer (UNEX) program. Both Chakrabarti and Cook have been PIs on a large number of past and on-going suborbital missions each with students in significant and meaningful roles. This culture of hands-on learning is how the proposing team has conducted these previous missions, which are aligned with the key goals of the Undergraduate Student Instrument Project (USIP-2015) program.

Several undergraduate students have participated in discussions that led to the development of this proposal. The SPACE HAUC team consists of faculty, research staff, and graduate students, who will mentor and support the undergraduate student teams (Table 1). In addition, the undergraduate implementation team will be supported by members of two industry partners who will serve as mentors to the students. Mr. Adam Greenbaum of Charles Stark Draper Laboratory will mentor the Systems Engineering team. Similarly, Dr. Kevin Maschhoff, Dr. Martin Ryba and Mr. John Polizotti of BAE Systems will mentor the optics, flight processor, and the communication teams. BAE System will also contribute the use of their environmental facilities. The availability of these industry mentors will expose the students to state-of-the-art industry practices in relevant disciplines and, of course, opportunities for post-college employment.

To meet the resource constraints of the USIP-2015 program, we will offer a mix of academic credits (including a specially designed class), Capstone projects, student activity projects, and summer internships to deliver a successful spaceflight program. SPACE HAUC also enjoys strong support from the University of Massachusetts, Lowell (UMass Lowell) administration, who will support this effort through its Co-op scholars program (http://www.uml.edu/BeyondU/coops/Co-op-Scholars/co-op-scholars.aspx), the highly successful DifferenceMaker program (http://www.uml.edu/Innovation-Entrepreneurship/DifferenceMaker/default.aspx), and provide course relief for participating faculty.

Team Personnel

The undergraduate members of the SPACE HAUC team were drawn from the UMass Lowell Rocketry Club, the Society of Physics Students (SPS), and the American Institute of Aeronautics and Astronautics (AIAA). Professor Cook, a current NASA PI, is a key member of the team. In addition, Professor Christopher Hansen, also a current NASA PI, whose expertise includes additive manufacturing, is also a mentor. His experience will be invaluable to the team, since the array of patch antennas and phase shifters, the two key technologies that will be validated aboard the SPACE HAUC mission, will be 2-D printed at UMass Lowell's Printed Electronics Research Collaborative (PERC), of which he is a key member. Other faculty mentors include Professor Michael Darish, who supervises the Capstone projects for our Electrical Engineering students and Professor Juan Pablo Trelles, an expert in thermal modeling and design. Each will mentor the student teams in their respective fields.

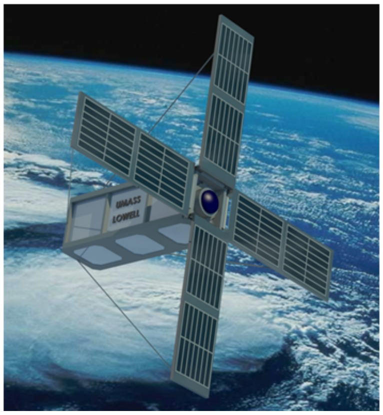


Figure 1: A conceptual rendering of SPACE HAUC in orbit showing its four solar panels deployed. The patch antenna array will be placed behind the deployed paddles thereby yielding approximately a 70-cm baseline. The body mounted solar panels are not shown.

In addition, Dr. Susanna Finn, an astrophysicist who was responsible for the calibration of LITES (Limb-Imaging Ionospheric and Thermospheric Extreme-Ultraviolet Spectrograph), which will fly aboard the International Space Station (ISS) in 2016, will serve as another professional mentor to the team. Dr. Finn will lead the mission operations and data analysis for LITES at UMass Lowell. She will be available to the team as the Deputy PI and will mentor the mission operations student team on SPACE HAUC. Two UMass Lowell graduate students, who are currently engaged in suborbital flights for their Ph.D. dissertations, will also be available to the SPACE HAUC undergraduate student teams as mentors.

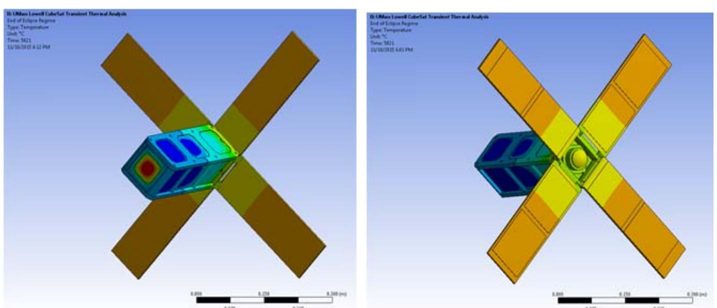


Figure 2: The students involved in the proposal development participated at a more sophisticated level than typical undergraduate students. As an example, we have included the results of a simplified transient thermal model developed entirely by the student team using ANSYS. The team made some basic assumptions about the spacecraft subsystems and mission design.

We have already identified several undergraduate students with responsibilities for key areas (Table 1). The students in leadership roles have been chosen for their experience – they have participated in engineering co-ops at Draper Laboratory, are involved in on-going spaceflight programs and have demonstrated leadership qualities. The undergraduate team consists of seniors and juniors majoring in sciences and in engineering.

The core engineering student team is highly motivated. They have met with the PI and the faculty mentors as a team and in smaller groups and have been instrumental in developing this proposal. During this proposal development, they were given specific tasks without any deadlines. The team understands the importance of timeliness and provided progress reports and produced results with very little guidance from the mentors. For example, they have already created the conceptual design for 3U SPACE HAUC (Figure 1).

In addition, the core student team undertook the challenge of performing a simple finite element analysis of the basic system. While it is understood that the experiment details are far from being complete, this exercise (Figure 2) shows that the framework of a thermal model is in place. Furthermore, the reviewers can feel assured that with guidance from the mentors, a more realistic model can be developed in a timely fashion.

Team Member Roles and Responsibilities

Role	**Name: students are shown in color** Blue**: Sophomore;** Green**: Junior;** Red**: Senior;** **Bold: Physics;** Highlighted**: EE/CS;** Rest**: ME.**	**Mentor (grad. students shown in red)**
Principal Investigator	S. Chakrabarti	
Deputy PI	S. Finn	
Project Manager (PM)	Dat Le	K. Maschhoff, BAE
Systems Engineer (SE)	Jacob Hulme	A. Greenbaum, Draper
Payload	Kristofer Tite	J. Polizotti, BAE
Processor(s?)	Student X	M. Ryba, BAE
Mechanical system	Dat Le, Team leader	C. Hansen
Antenna	Eric Carey	
Solar panel	Jacob Hulme	
Power System	**Benjamin Redman**	M. Darish
Thermal System	Dat Le	J.P. Trelles
Attitude Control and Determination	Charles Barbon, Team leader	T. Cook
Algorithm, software	William Kammerer	
Sun sensors	**Forest Mathieu**	
Communication	James Benedict, Team leader	M. Ryba, BAE
Downlink	James Benedict	
Ground station/Uplink	Student X	
Integration and test activities	Student X	G. Howe
Ground Support Equipment	Tim Barrett	K. Hewawasam
Mission operations and data processing	**Michael Mirakian**	S. Finn
Web page/team communication	Student X	S. Chakrabarti

Table 1: SPACE HAUC team members include undergraduate students in key roles with faculty, staff, and graduate student mentors. The team also includes members from aerospace industry, which provides the team members with rich experiential learning opportunity.

The roles and responsibilities of the team members are shown in Table 1. As we have indicated, some of the undergraduate students listed here are seniors (shown in the middle column in red). As a result, they may not be around to see SPACE HAUC reach orbit. However, their legacy will be continued by junior classmen, who are listed in Table 1 (shown in green and blue), and others that we will recruit.

The culture of designing, building, and conducting spaceflight missions at UMass Lowell is relatively new. However, in the past three years, we have accomplished quite important feats. We have flown a sounding rocket mission (IMAGER), are readying another (PICTURE), we will fly two high altitude balloons in 2017 and 2019, and will fly LITES aboard the ISS in 2016. Each of these missions supported or plans to support Ph.D. dissertations. In addition, each of these experiments benefitted from the participation of undergraduate students in supporting roles in all areas. SPACE HAUC will swap these roles by putting undergraduate student projects in space with graduate students in supporting roles.

New Student Recruitment

We already have a core group of undergraduate students committed to SPACE HAUC. Nevertheless, we will need to recruit several other students to complete the team. Some of these students will be from the Kennedy College of Sciences (KCOS) while others will come from the Francis College of Engineering (FCOE). It may be possible that students from our Manning School of Business (MSB) or our School of Fine Arts Humanities and Social Sciences (FAHSS) might want to join the project team. We plan to integrate them based on their background whether in technical areas such as mission operations and data processing, or for project management, communication, and publicity.

We expect that the senior students will graduate during the execution of SPACE HAUC, so we will recruit new students in two ways. First, we will offer a course on space science mission design in our Honors College (http://www.uml.edu/Honors/default.aspx) in Fall 2016 (Table 2). This one-semester, 3-credit course intended for junior level students will be centered on the conceptual design of a spaceflight mission. It will be conducted in a round-table discussion format using the results of students' research – much like a research group meeting. The instructor will act as the facilitator and expect the students to lead most of the discussions. In this project-based and team-based class, the students will apply their science and technical knowledge to develop SPACE HAUC. The students will perform quantitative trade studies consistent with real-life constraints such as cost, schedule, manufacturability, team-expertise, operational environment, mission lifetime, etc. Students will 1) learn the fundamentals of key subsystems involved in a spaceflight mission and 2) apply their skills of inquiry, research, and critical thinking to design a complete space science mission to solve a real-world problem while working within a multidisciplinary team.

The second way we will recruit new students will be to encourage the students to participate in SPACE HAUC-focused Capstone projects that are offered both in KCOS and FCOE. In departments that do not offer the Capstone option, the students will conduct Directed studies under the guidance of faculty mentors involved in SPACE HAUC.

In addition, we will recruit highly meritorious and motivated students through well-established programs such as the Co-op scholars and the DifferenceMaker programs. In addition, we will provide summer support to a small group of SPACE HAUC participants through this proposed effort to ensure continuous and forward progress.

Team Communications

The SPACE HAUC team will use electronic communications for daily coordination and data exchange. Such use of computer technology is commonplace in the industry and will expose the student team to it early in their career. Since some of our mentors will not be present on campus regularly, the use of Skype, WebEx, or some other electronic means will enable the participation of all members in most of the key meetings, such as Design Reviews, Readiness Reviews, etc. In fact, the PI and the PICTURE team have participated in a Mission Readiness Review with the NASA

Sounding Rockets Program Office as recently as November 9, 2015, where he and some team members participated remotely.

The PI, Deputy PI, PM, and the Systems Engineer (SE) will meet with the team weekly. We will establish a SPACE HAUC web site accessible to all that will also carry all current project information and technical data and documents. We will invite the NASA Mission Manager to all our key meetings. Of course, NASA will have full access to the web site. Since participation in SPACE HAUC will require coursework (see Table 2), the students and faculty advisor(s) will have more frequent interactions. The hardware development plan was organized with the academic career of the students in mind.

Training

This project will provide students with the knowledge of critical design process essentials where they will begin with designing a patch antenna array for ground-satellite communications which must adhere to many design parameters including beamwidth, efficiency, and polarization, and to design constraints including size and weight. Moreover, the students will fabricate the antennas with the 2-D printers. After the fabrication, the students will test the antennas and validate their performance. The students will return to the design process to fix any problems they might find during the validation stage.

Table 2: The overall development plan for SPACE HAUC hardware is carefully meshed with existing curricula which will provide the undergraduate team members with the necessary background. The Space Science Mission Design class (highlighted in yellow) will be introduced through the Honors College in Fall 2016 to provide additional background. Specific hardware development activities and milestones for SPACE HAUC that will be incorporated within the students' academic program are shown in red.

	Spring 2016		Summer 2016	Fall 2016		Spring 2017		Summer 2017
	KCOS	FCOE	**Subsystem design Engineering Reviews Preliminary Design Review (PDR)**	KCOS	FCOE	KCOS	FCOE	**Systems Integration and functional tests Environmental tests Mission Readiness Review Launch Mission Operations and Data Analysis**
Existing Curricula available to the SPACE HAUC student team	Expl. the Universe	Intro. To Eng.		Expl. the Universe	Intro. To Eng.	Expl. the Universe	Intro. To Eng.	
	Directed Study	Directed Study		Directed Study	Directed Study	Directed Study	Directed Study	
	Capstone Design	Capstone Design		Capstone Design	Capstone Design	Capstone Design	Capstone Design	
	Special Electives	Special Electives		Special Electives	Special Electives	Special Electives	Special Electives	
Honors College				**Space Science Mission Design**				
These extracurricular and informal programs will be available for SPACE HAUC development	Society for Phys. Students	AIAA Rocketry Club		Society for Phys. Students	AIAA Rocketry Club	Society for Phys. Students	AIAA Rocketry Club	
	Team Recruitment Mission and System Designs			**Critical Design Review (CDR) Manufacturing Subsystem functional tests**				

The integrated SPACE HAUC core team will comprise science and engineering students mentored by an experienced, interdepartmental faculty team and colleagues from our two industry partners –Draper Laboratory and BAE Systems. Both have named the mentor(s) and are committed to participate in mentoring the team in a meaningful ways (see their letters of commitment in Appendix I). Detailed analysis, design, and testing will be performed through directed studies/Capstone courses. A team of 5 faculty advisors from the KCOS and FCOE will advise the student team (Table 1). Furthermore, the specially designed Honors College class (Table 2) will also allow students from MSB and FAHSS to be involved in SPACE HAUC in addition to those from the KCOS and FCOE.

Institutional Support

SPACE HAUC enjoys tremendous institutional support at UMass Lowell, where Space Science and Technology is a strategic priority. Drs. Chakrabarti and Cook brought their programs and the team to UMass Lowell in 2012. The university provided generous start-up support, which enabled on-going projects to be conducted with minimal impact. For these reasons, we consider the Deans of KCOS and FCOE and all others from UMass Lowell who wrote letters of support (see Appendix I), to be members of the SPACE HAUC team. Each of them has made a strong commitment to this program, which will be invaluable to the success of this project.

Last year, the Lowell Center for Space Science and Technology (LoCSST - www.uml.edu/Research/LoCSST/default.aspx), a new research center, was formed with the following mission:

- Provide a home for space science (which includes science from space such as remote sensing as well as science about space such as characteristics of Earth, planets, stars, galaxies and regions in between) and technology (such as instrumentation, systems, control, communication, operations, and data analysis) research activities on the UMass Lowell campus
- Involve industry partners in curriculum, research, projects and proposals/business development
- Train the next generation of space scientists, technologists, teachers, business leaders, and policy makers

The SPACE HAUC program embodies each and every one of these goals in letter and in spirit.

Dr. Christopher Mendillo, an astrophysicist and Mr. Jason Martel, a mechanical engineer, both veterans of several suborbital spaceflight missions, have generously agreed to serve as back up mentors to the undergraduate teams. In their present work, they have involved undergraduate students.

Finally, we are fortunate that the state-of-the-art electronics printing facilities of the Raytheon – UMass Lowell Research Institute (RURI) and the Printed Electronics Research Collaborative (PERC) will be available to the members of the SPACE HAUC team (see the letter of support from Dr. Craig Armiento, the Director or RURI and PERC). Another facility that will be very useful to SPACE HAUC is the Antenna Characterization Laboratory.

External Support

In addition to our two industry partners, we are fortunate to receive support from a group of our peers. UMass Lowell has been a member of the Massachusetts Space Grant Consortium (MASGC) since 2013. The PI has been a member of its steering committee for almost two decades. SPACE HAUC will be conducted under the sponsorship of MASGC (see the letter of support from Dr. Jeffrey Hoffman, the Director in Appendix I).

D. Technology Investigation

While this project is intended primarily as a hands-on student training mission, it has a significant technology demonstration component. This project will demonstrate X-band beam steering from a 3U CubeSat. A number of factors combine to make this demonstration timely. While some CubeSats have high precision pointing capability, most have more modest attitude control. As a result, as seen from the spacecraft, the ground station appears to move as the pointing of the CubeSat changes. Furthermore, since a gimbaled antenna is well beyond the mass and complexity available to a typical CubeSat, a conventional, pointed, high gain antenna is impractical. Deployable systems have been discussed (Cheung et al., 2015) but pointing a body mounted high gain antenna to a fixed ground location from low earth orbit (LEO) also involves significant risk in the spacecraft agility and sensor and software sophistication. At the same time, CubeSats are often limited by the available telemetry bandwidth. Payloads including high definition cameras, high speed imaging systems, and other similar high data rate devices are now rugged enough to survive a CubeSat environment and are seeing application on small satellites. These payloads generate large data volumes and are quickly limited by the available telemetry bandpass.

Furthermore, CubeSats have been discussed for high earth orbit (HEO) or even interplanetary applications (Shin et al., 2015; Shao et al., 2015). The high data rates and challenging link budgets of these systems demand higher efficiency telemetry systems. At the same time, the small size of a CubeSat necessarily results in significant power limitations. Omni-directional, or near omni-directional, antennas are technically simple but require significantly more power than a higher gain antenna. Because of the complexity and licensing of a higher frequency system CubeSats frequently resort to lower frequency communications. While this project cannot avoid the difficulties of X-band licensing, it can, and will, demonstrate that high rate, high frequency communication is practical in a CubeSat.

This demonstration is enabled by a number of new technologies. The first is the extensive adoption of software-controlled radio. While these systems were once only implemented on high end military and space systems, computer technology has advanced to the point where software-controlled systems are regularly used by many amateur radio developers and operators. It should be noted that we are not suggesting that the X-band signal will be generated by software control. We will use the software-controlled radio system to generate an intermediate frequency (IF) signal and will then use a conventional X-band local oscillator, mixer, filters, and power amplifier to generate the broadcast signal. This will make the system both practical and ensure that we are able to comply with the licensing requirements.

The software control system will also alter the phase to a series of patch antennas on the spacecraft. By altering the delays of this phased array of antennas we will be able to shape and steer the beam, resulting in higher antenna gain than an unphased array of antennas. Since the spacecraft body rates will be slow compared to both the processing time required to alter the phasing and the delay times for those alterations to take effect, we will be able to dynamically steer and shape the beam in order to maximize the antenna gain for any ground station look angle and thus to track the ground station as the spacecraft orientation and orbital position change.

SPACE-HAUC will demonstrate a high rate communications system. The system will use an X-band phased array antenna and will thus incorporate no moving parts. The phased array will enable rapid beam steering making it a useful high gain antenna on CubeSats with limited pointing capability.

Technology Implementation

The telemetry will be implemented by using a software-controlled radio to create an intermediate frequency (IF) modulated signal. The IF will be mixed with a local oscillator and amplified to produce the broadcast signal. Filters will be used to ensure that the out-of-band signal stays below the levels required by our broadcast license. Furthermore, the transmitter will only be active if a correctly coded incoming signal is received from the SPACE HAUC ground station.

The receiver will take the signal from the antenna array via a diplexor. The signal will be down converted and sent to the receiver where the bit synchronization and demodulation will be implemented in software. When the system is not locked on an incoming signal, the antennas will be unphased and the beam pattern will be as large as possible. When an incoming signal is detected, the antenna phases with be altered in order to maximize the antenna gain, and thus the incoming signal strength. The use of a diplexor, rather than separate antenna arrays for the transmitted and received signals, allows us to monitor and correct the phasing of the received signal and to apply that correction to the transmitted signal as well. Since the transmitted and received signal are at similar frequencies, the phasing of the incoming signal will also provide a near optimum antenna gain for the transmitted signal.

We will consider altering the data rate as the signal strength changes in order to maximize the data throughput. Since the system is software-controlled, much (but not all) of the telemetry development will be a software development effort. We will implement this as a phased development effort on a "most important first" basis. First we will achieve basic system functionality and we will then proceed to implement and improve beam steering and optimization algorithms as time and testability permit.

The SPACE HAUC system is Sun-pointed and operates only during the day. The ground station therefore will appear only on the sunlit hemisphere of Earth (i.e., antisunward as seen from the spacecraft). The antenna patches will be mounted to the +Z side of the deployed solar panels. The -Z side is sunward in nominal operations. By first unphasing the antennas we can create a low gain hemispheric antenna pattern. When contact is established we can adjust the antenna phases to improve the antenna gain in the direction of the ground station. As the spacecraft both spins and moves along the orbital track, the control system will continually adjust the phasing to maximize the gain in the instantaneous direction of the ground station. This will allow us to use the phased array as an "electronic gimbal" and achieve high antenna gain from a moving, rotating platform without complicated body pointing or moving parts.

The transmitter will send all data, both camera and housekeeping, in real time. When the system is in contact with the ground station, the transmitter will query the camera and the avionics system for science and housekeeping data packets, respectively, and immediately transmit them. There will be no on-board long term storage. The overall system will provide high speed, high resolution images of the Sun while the spacecraft is in contact with the ground. No data will be available from times when the spacecraft is not in contact with the ground station.

We will implement the system using CCSDS packets. This will mean that the students constructing the system will be familiar with this industry standard protocol and that any other ground station will also be able to contact the spacecraft.

Antenna Design

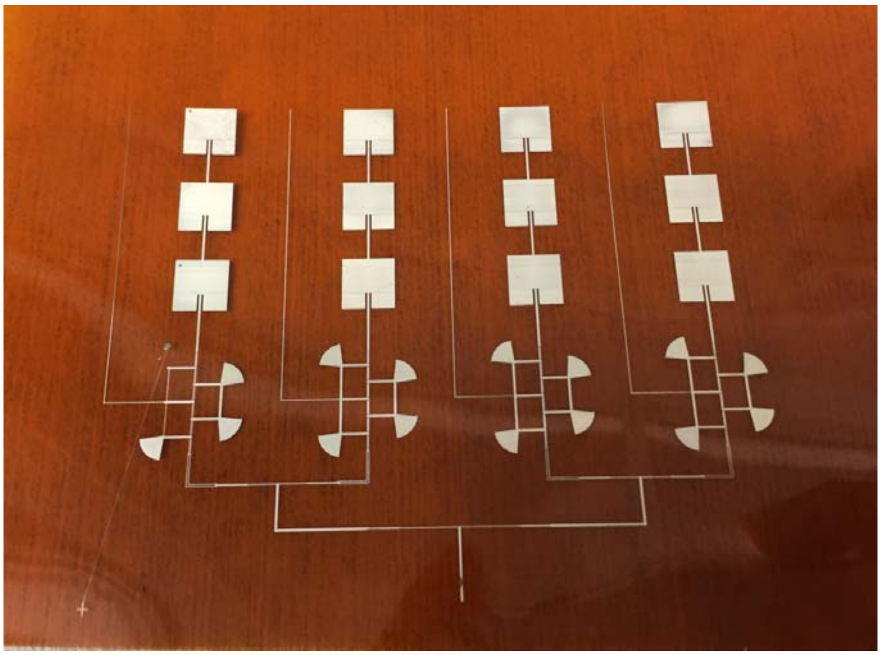


Figure 3: UMass Lowell has developed methods of 2-D and 3-D printing which will enable rapid production of the antenna arrays and phase shifters used in this effort. This photo depicts an X-band patch (top squares) with its associated phase shifting component (bottom pattern).

The system antennas will be a patch antenna array design similar to that described in Osorio and Ramirez, 2015. In that work, the antenna array is fabricated on the side of the CubeSat and the phase shifters are fabricated on the other side of the actual patches. In SPACE HAUC the antenna array will be mounted on four deployable paddles with the phase shifters between the antenna and the paddle substrate. The UMass Lowell team has extensive modeling, design, and fabrication experience in conformal antenna design and fabrication (Bhowmik et al., 2013 and Haghzadeh et al., 2015). We will use printed (using the Optomec aerosol jet printer) patch antenna arrays (one per deployable paddle) with radial stubs which act as a virtual ground (and allow for the design without using vias) with novel phase shifters. These phase shifters are composed of a left-handed transmission line composed of interdigitated capacitors (which are filled with a ferroelectric ink developed at UMass Lowell) and shunt inductors. When a bias is applied to the phase shifter, the permittivity of the ink changes and hence the capacitance changes and different values of the phase can be obtained. These phase shifters allow for a fast and efficient means of phase shifting and for an easy implementation of the phased array design for the CubeSat.

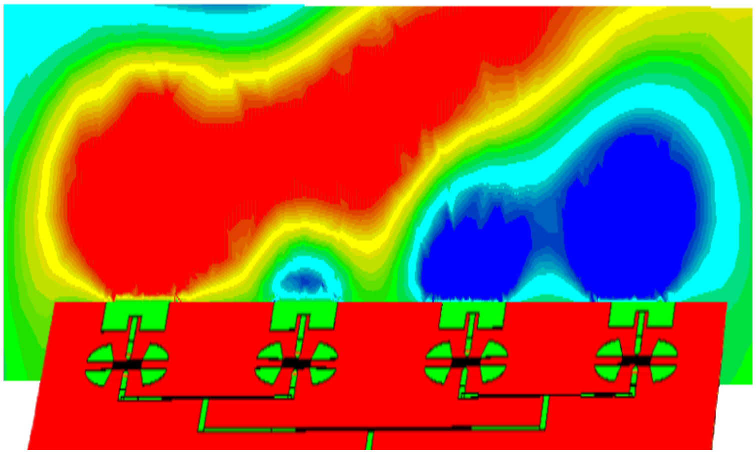


Figure 4: UMass Lowell has developed the phase shifters needed to carry out this investigation and simulated their performance. This is a simulation of a phased array antenna with radial stubs and the novel phase shifter. The electric fields are displayed to demonstrate the beam steering.

RURI and PERC share a facility dedicated to developing printed electronics. The facility occupies the entire 4th floor of the Saab Emerging Technologies and Innovation Center (ETIC), a modern building that includes the manufacturing and test facilities to be used by the SPACE HAUC team. The RURI/PERC facility was initiated in January 2015.

The core mission of RURI and PERC is to develop new devices and subsystems that provide electromagnetic, electronic, and photonic functionality using Additive Manufacturing approaches. Applications include flexible phased array antennas (such as those proposed here), Radio Frequency Identification Devices (RFIDs), health monitoring, and Frequency Selective Surfaces (FSS). Printed electronics projects will employ several approaches to printing both active and passive devices onto nonstandard substrates such as plastic films. This work builds on significant material exploration and uses a variety of functional inks (conductive, dielectric, semiconducting, etc). The RURI/PERC facility consists of four laboratories relevant to SPACE HAUC work and are described below.

The **Printing Laboratory** has three different types of CAD-driven printing approaches: a capillary-based dispensing system (Sonoplot), an aerosol jet system (Optomec), and an nScrypt micropen dispenser. The SonoPlot® GIX Microplotter II is a precision picoliter fluid dispensing system. The printing process relies on a glass capillary dispenser that uses an ultrasonic transducer to dispense fluid in near contact with the substrate. This technology can produce picoliter droplets that form features on a surface as small as 10 μm wide. A wide range of fluids can be used, including aqueous solutions and many organic solvent-based mixtures.

The laboratory is also equipped with an Optomec AJ-200 system that utilizes an aerosol jet technique that enables printing feature sizes as small as 10 μm wide using inks with viscosities from 1-1000 cP. The Aerosol Jet process begins with a mist generator that atomizes a source material and creates a material stream that is aerodynamically focused. The system can create a collimated material beam from a nozzle that can be positioned as much as 7 mm above the substrate surface thus enabling fine patterning on nonplanar substrates (e.g., over existing structures and into channels). Our system has both pneumatic and ultrasonic atomizers as well as fixturing for angled deposition which allows printing on vertical surfaces.

The facility recently acquired an nScrypt micropen dispenser that will allow patterning of a wider range of ink viscosities than possible with the Optomec and Sonoplot printers. The system will also enable the dispensing of adhesives and pastes that will be needed for chip integration and packaging.

The Printing Laboratory is also equipped with processing and material characterization equipment including a vacuum bake oven, a Keyence digital microscope, a 4-point probe resistivity measurement system, and a KLA-Tencor profilometer. RURI and PERC researchers also have access to UMass Lowell's nanofabrication clean room that is equipped with tools such as atomic layer deposition, CNT and graphene deposition, and e-beam lithography, as well as other standard clean room equipment.

The Electrical Characterization Laboratory has a wide variety of equipment for microwave characterization of printed components and subsystems. This lab is used for characterization of Frequency Selective Surfaces and CNT printed transistors. Major pieces of equipment include: HP8510 Network Analyzer (HP 8510 50GHz and 20GHz, WR-90, Agilent 8753E, Rhode & Schwartz ZVB8), Spectrum Analyzer (Rhode & Schwartz FSQ8, FSEM FSEB), and HP - Agilent X11644A Mechanical Calibration Kit, 8.2 to 12.4 GHz.

The **Antenna Characterization Laboratory** is equipped with an ETS-Lindgren RF Shielded Enclosure. The enclosure will be modified to serve as an anechoic chamber to characterize antennas in the 5 – 15 GHz range and will be available to characterize the antennas used in this effort.

The **Modeling Laboratory** is equipped with a Dell Workstation for running simulations. Our design suite is the ANSYS Multiphysics Design suite with includes solid modeling, electromagnetic modeling (HFSS), and thermal modeling.

Ground Station

The SPACE HAUC space system will be controlled by a single, dedicated ground system at UMass Lowell. The system will share a high degree of commonality with the flight system. A dedicated ground station will allow extensive testing of the space/ground link throughout development at the cost of some additional licensing difficulty. The lost cost of this system virtually precludes the use of commercial space communications assets. Nonetheless, the system will be CCSDS based and will thus be capable of communicating with commercial assets should the opportunity arise.

The ground station will use the same phased array system developed for the flight system. NORAD orbital elements will be used for the initial array phasing and the transmitter will be activated when the spacecraft clears the local horizon. Like the space system, contact with the spacecraft will allow us to further refine the phase solution to improve the antenna gain and data throughput.

Licensing

Licensing an X-band system will be a significant schedule driver for this project. Starting at the inception of this program we will work with NASA to obtain the necessary broadcast licenses.

E. Mission Implementation

In order to meet the goals set out above, this mission will use a spin-stabilized, Sun-pointing spacecraft. The spacecraft will be in a 3U configuration with four deployable solar panels stowed along the long sides of the satellite for launch. The panels will deploy into a cross configuration as the spacecraft is released (Figure 1). The spacecraft will also include body mounted solar panels for use during initial attitude acquisition (not shown in Figure 1). Each panel will have solar panels on the forward side and the phased array of patch antennas on the back. The system will operate in daylight only and will have minimal battery capacity (only for stay-alive heaters and similar functionality). It will power down at each dusk terminator crossing and re-boot at each dawn terminator crossing. Data will be generated by a small camera imaging the Sun in either Balmer alpha (656.2 nm) or Lyman alpha (121.6 nm) and the data will be down linked as it is collected. There will be no data storage of the image data beyond the buffering needed to feed the images into the telemetry stream.

Mechanical Design

The spacecraft will use a 3U configuration with four deployable solar arrays along the long sides of the package. Each panel will be mounted to the spacecraft by an axle and torsion spring and will be held in place by the launcher. As the spacecraft is deployed the torsion springs will unfold the panels to hard limited provided by wire stays between the spacecraft body and the tips of the panels (Figure 1). Trim weights will be added to the tips of the panels to control the direction of the principle axis.

The long body axis on the spacecraft will be the Z-axis with the axles and torsion springs at the -Z end and the solar panels extending along the +/- X and Y axes. The spacecraft will be inserted into the launcher (such as the P-POD) with the -Z end toward the push-plate launch mechanism so that the panel deployment also assists the deployment of the spacecraft. In order to avoid shadowing of the solar arrays the solar panels will be mounted on the -Z side of the panels. The fine Sun sensor will be mounted on the -Z end of the body and the magnetometers will be mounted on the +Z end on the body to minimize the exposure to magnetic fields generated by the solar panels. The antenna arrays will be mounted on the +Z side of the panels. As a result the ground plane generated by the spacecraft body and panel stays will affect the beam pattern.

Attitude Control

The spacecraft will have attitude determination and control capabilities. The attitude sensors will consist of coarse Sun sensors, fine Sun sensors (approximately 1 degree resolution), and 3-axis magnetometers. The control actuators will be a set of three magnetic torque coils. The spacecraft will spin about its largest principle axis – the Z axis. The magnetic torque coils will be pulse width modulated. This will allow "nulls" in the control field pulses during which the magnetometers can sense the external magnetic fields without serious self-induced interference.

The attitude control system will be based on the attitude control system developed for the TERRIERS satellite – with the bugs in that system repaired. After each spacecraft boot the ACS will automatically sequence through a number of modes. At boot it will enter Mode 0, which disables the torque coils and monitors the magnetometers until stable measurements are obtained. This allows the filters on the sensors to stabilize, and avoids reacting to spurious start up transients. Once the sensors are returning stable readings, the spacecraft will enter Mode 1. In Mode 1 the magnetometers and torque coils are active. The coils are used to damp nutation about the Z axis in response to the Z axis magnetometer. Once the Z axis magnetometer shows that nutation has been controlled the system will enter Mode 2. Mode 2, like Mode 1, senses the ambient field with the magnetometers and controls with the torque coils. In Mode 2, torques will be applied in order to spin the spacecraft about the Z axis. Once the desired spin rate has been achieved the system will enter Mode 3. Mode 3 uses the coarse Sun sensors, the magnetometers, and the torque coils. In Mode 3 torque will be applied to maintain the spin rate and to precess the -Z axis toward the Sun. Once the Sun is within the field of view of the fine Sun sensor, the system will enter Mode 4. In Mode 4 the fine Sun sensor, the magnetometers, and the torque coils will be active. Mode 4 will continue to precess the Sun to the -Z axis. This will be the spacecraft operational mode.

It is a simple fact of magnetic control systems that torque can only be applied perpendicular to the instantaneous local ambient magnetic field. As a result, the control system cannot correct the component of the spacecraft's angular momentum parallel to the field. Fortunately in all but the lowest inclination orbits, the direction of the local field changes along the orbital track. In LEO the spacecraft motion results in reasonably rapid changes in the direction of the ambient field and over time all components of the spacecraft's angular momentum can be controlled. This results in a fairly slow moving system, but one that meets the overall system requirements with minimal components and no moving parts. This also requires an orbit with ≥40° inclination.

Power

The power system will consist of solar cells, a peak power tracker, a watchdog control board, DC-DC power converts, and, if needed, a small battery and battery charge regulator. Power will be provided by primary solar cells mounted on four deployed solar panels each slightly smaller than 10 × 30 cm. In order to allow for initial operations, these will be supplemented by several auxiliary body mounted panels each approximately 10 × 10 cm which will provide power while the satellite pointing is off nominal.

In normal operations the spacecraft will spin about the Z axis and the solar panels will be fully continuously illuminated. This will provide ≥100 watts of power. During initial operations, the auxiliary panels will be limited to ~10 watts. Also during initial operations, while the -Z axis is not yet pointed toward the Sun, power will be provided by panels located on the +/- X and Y sides of the body. In nominal operation these will be pointed perpendicular to the Sun direction and will produce very little power. Given that we have minimal power storage, it is likely that the speed of the initial acquisition will be limited by the power produced by the body mounted solar panels.

The panels, both the main deployed panels and the auxiliary body mounted panels, will be laid out so as to minimize the net current loops. This is important both to minimize the disturbance torques on the system as the power levels change and to avoid contaminating the magnetometer measurement.

The primary power loads are the attitude control system and the telemetry system. The peak power tracker will use a buck regulator to match the impedance of the spacecraft to the solar panels as the spacecraft power loads vary. The system power will be used directly with excess power being left on the panels. In the event that more power is being drawn than is available, the transmitter power will be throttled and the torque coils will be "browned out" as required.

Thermal

Thermal control will be achieved by passive control of radiator surfaces and blanketing. Since the thermal mass of this system is small and the thermal control is not reconfigurable, the thermal model is particularly important. We have assembled the first student team in order to address our thermal considerations. Their preliminary model is shown in Figure 2. This model will be refined as the system design proceeds and will allow us to select appropriate emissivity surfaces and thermal conduction paths to control the thermal environment. Should the model show that it is necessary we will supplement the control system with heaters to maintain the temperature of critical components.

Telemetry, Data Collection, and Data Management

The primary mission of this CubeSat is the demonstration of an X-band phased array antenna and resulting high data rate telemetry. The particulars of the spacecraft and ground station telemetry systems are discussed above.

Mission Traceability

Being a student-centered CubeSat mission, our goals are modest. Table 3 shows our Mission Traceability Matrix while Table 4 shows the mission parameters.

Table 3: The SPACE HAUC's traceability matrix demonstrates that its mission requirements are straightforward, well-understood, and can be implemented within the USIP-2015 constraints.

Technology Goals	Technology Objective	Measurement requirements	Spacecraft performance	Instrument requirements	Projected performance
Demonstrate high bandwidth communications which can be accommodated in a student CubeSat environment.	Demonstrate beam steering with a phased array X-band antenna from a CubeSat.	Achieve a high data rate satellite to ground data link...	Low risk/low cost ACS. Sun-pointing.	Beam steering.	Beam steering to ~ 5 degrees.
			Low risk/no moving parts. Spinning spacecraft.		
		...with a high gain antenna.	CubeSat form factor. ≥ 40° inclination orbit.	X-band array on deployed panels to achieve sufficient aperture.	70 cm ×10 cm panels in cross configuration (see Figure 1).

Table 4: SPACE HAUC mission parameters are modest and can be accommodated by many missions.

CubeSat Mission Parameters								
Mission Name	Mass	Cube Size	Desired Orbit		Acceptable Orbit Range	400 km @51.6° incl. Acceptable – Yes or No	Readiness date	Desired Mission Life
SPACE HAUC	3kg ± 0.8 kg	3U	Altitude	400 km	350–550 km	Yes	August 31, 2017	> 3 Mo.
			Inclination	51.6°	≥ 40°			

F. Schedule

The schedule, shown in Table 5, lays out the estimated timeline for design, development, testing and integration, and delivery of the SPACE HAUC payload based on the senior team members' experience. The SPACE HAUC schedule is roughly broken up by the university semesters over the course of the project, and additionally utilizes valuable time during the summer when the undergraduates will not be involved with coursework. The payload design, manufacturing, and testing, including all subsystems, has substantial reserve built into the schedule.

In the Spring semester 2016 (beginning in January 2016), the students will take course credits to work on SPACE HAUC mission design for their Capstone projects. In April, toward the end of the semester, the mission design will undergo a Concept Review (CR). This will give the students a few weeks after the review and before the semester ends to modify design and plans. Early in the project the team will also begin the important process of acquiring licensing for the X-band transmitter.

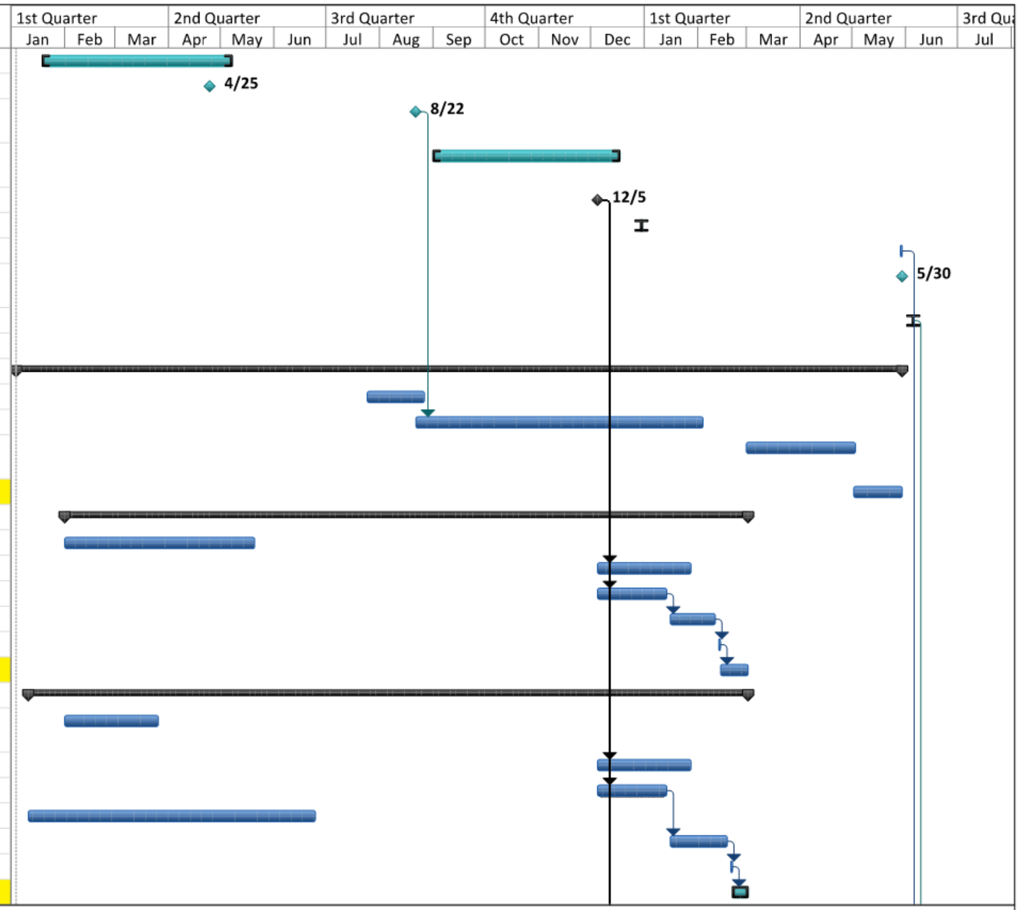
Over the summer 2016 from June through August, the students will finalize the mission design as well as begin design of all subsystems including the processor, mechanical system, power and thermal systems, attitude control system, and the communication/ground station. The Preliminary Design Review (PDR) will take place in August 2016, once again allowing for a few weeks of post-review modification and assessment before the semester begins. At this point some students might leave the project after graduating.

In the Fall semester 2016, the Space Science Mission Design course has been created to continue training the students and to facilitate their efforts as the subsystem student teams work toward finalizing designs (including all thermal, electrical, and mechanical models) leading up to the Critical Design Review (CDR). SPACE HAUC will have its CDR in December 2016. The annual report will be submitted at the end of 2016 summarizing the progress on the SPACE HAUC mission made in Year 1.

The students will be able to utilize the time between semesters to procure and manufacture parts. The Spring 2017 semester will be used to test the subsystems, and integrate and test the full payload. The payload will have its final Mission Readiness Review in late May 2017 and will be launch-ready within 18 months of the project initiation.

Table 5: The SPACE HAUC schedule includes generous and phased reserved to ensure mission success.

ID	Task Name	Duration	Start	Finish
1	Capstone Design Courses	80 days	Tue 1/19/16	Sat 5/7/16
2	Concept Review (CR)	0 days	Mon 4/25/16	Mon 4/25/16
3	Preliminary Design Review (PDR)	0 days	Mon 8/22/16	Mon 8/22/16
4	Space Science Mission Design Course	78 days	Thu 9/1/16	Sat 12/17/16
5	Critical Design Review (CDR)	0 days	Mon 12/5/16	Mon 12/5/16
6	Annual Report	1 day	Fri 12/30/16	Fri 12/30/16
7	Payload delivery	1 day?	Mon 5/29/17	Mon 5/29/17
8	Mission Readiness Review (MRR)	0 days	Tue 5/30/17	Tue 5/30/17
9	Launch	1 day	Mon 6/5/17	Mon 6/5/17
10				
11	**Instrument**	**366 days?**	**Mon 1/4/16**	**Mon 5/29/17**
12	Mission/System Design	1.25 mons	Mon 7/25/16	Fri 8/26/16
13	Procure long-lead items	6 mons	Mon 8/22/16	Fri 2/3/17
14	Instrument-level integration and test	45 days	Wed 3/1/17	Tue 5/2/17
15	Reserve	20 days	Tue 5/2/17	Mon 5/29/17
16	**Processor**	**283 days?**	**Mon 2/1/16**	**Wed 3/1/17**
17	Design	4 mons	Mon 2/1/16	Fri 5/20/16
18	Procurement	2 mons	Mon 12/5/16	Fri 1/27/17
19	Development	1.5 mons	Mon 12/5/16	Fri 1/13/17
20	Testing	1 mon	Mon 1/16/17	Fri 2/10/17
21	Delivery	1 day?	Mon 2/13/17	Mon 2/13/17
22	Reserve	12 days	Tue 2/14/17	Wed 3/1/17
23	**Mechanical System**	**298 days?**	**Mon 1/11/16**	**Wed 3/1/17**
24	Antenna/Solar Panel Design	2 mons	Mon 2/1/16	Fri 3/25/16
25	Procurement	2 mons	Mon 12/5/16	Fri 1/27/17
26	Development	1.5 mons	Mon 12/5/16	Fri 1/13/17
27	Structure Design	6 mons	Mon 1/11/16	Fri 6/24/16
28	Testing	25 days	Mon 1/16/17	Fri 2/17/17
29	Delivery	1 day?	Mon 2/20/17	Mon 2/20/17
30	Reserve	7 days	Tue 2/21/17	Wed 3/1/17



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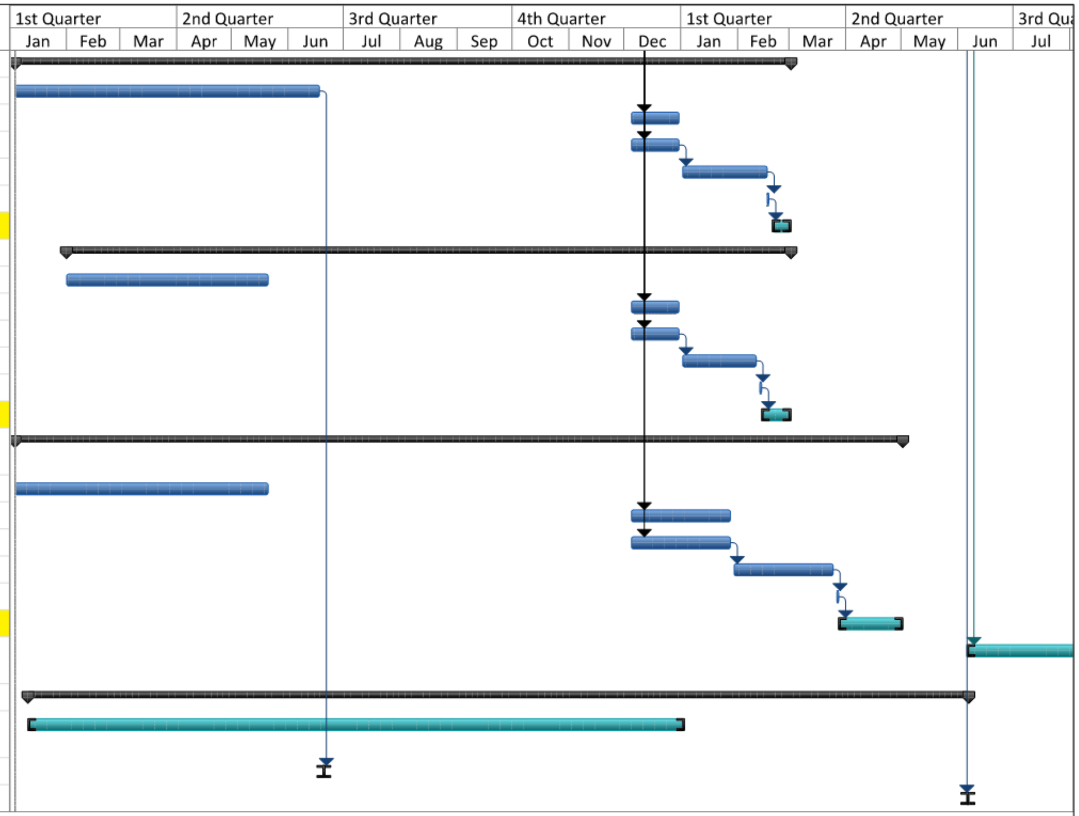
ID	Task Name	Duration	Start	Finish
31	**Power/Thermal Systems**	**303 days?**	**Mon 1/4/16**	**Wed 3/1/17**
32	Design/Modeling	6 mons	Mon 1/4/16	Fri 6/17/16
33	Procurement	1 mon	Mon 12/5/16	Fri 12/30/16
34	Development	1 mon	Mon 12/5/16	Fri 12/30/16
35	Testing	34 days	Mon 1/2/17	Thu 2/16/17
36	Delivery	1 day?	Fri 2/17/17	Fri 2/17/17
37	Reserve	8 days	Mon 2/20/17	Wed 3/1/17
38	**Attitude Control System**	**283 days?**	**Mon 2/1/16**	**Wed 3/1/17**
39	Design	4 mons	Mon 2/1/16	Fri 5/20/16
40	Procurement	1 mon	Mon 12/5/16	Fri 12/30/16
41	Development	1 mon	Mon 12/5/16	Fri 12/30/16
42	Testing	1.5 mons	Mon 1/2/17	Fri 2/10/17
43	Delivery	1 day?	Mon 2/13/17	Mon 2/13/17
44	Reserve	12 days	Tue 2/14/17	Wed 3/1/17
45	**Communication/Ground Station**	**346 days?**	**Mon 1/4/16**	**Mon 5/1/17**
46	Design	5 mons	Mon 1/4/16	Fri 5/20/16
47	Procurement	2 mons	Mon 12/5/16	Fri 1/27/17
48	Development	2 mons	Mon 12/5/16	Fri 1/27/17
49	Testing	2 mons	Mon 1/30/17	Fri 3/24/17
50	Delivery	1 day?	Mon 3/27/17	Mon 3/27/17
51	Reserve	25 days	Tue 3/28/17	Mon 5/1/17
52	Mission Ops and Data Analysis	261 days	Tue 6/6/17	Tue 6/5/18
53	**Major Deliverables**	**367 days?**	**Mon 1/11/16**	**Tue 6/6/17**
54	X-band Transmitter Licensing	256 days	Mon 1/11/16	Mon 1/2/17
55	Thermal models	1 day?	Mon 6/20/16	Mon 6/20/16
56	Payload delivery	1 day?	Tue 6/6/17	Tue 6/6/17



G. Management

The SPACE HAUC Program will utilize the PI mode of management with clear lines of authority, program controls, roles, and responsibilities. The organizational structure is shown in Figure 5. Development of flight hardware and the ground calibration and testing will be done at UMass Lowell with close participation of mentors from the university and industry partners.

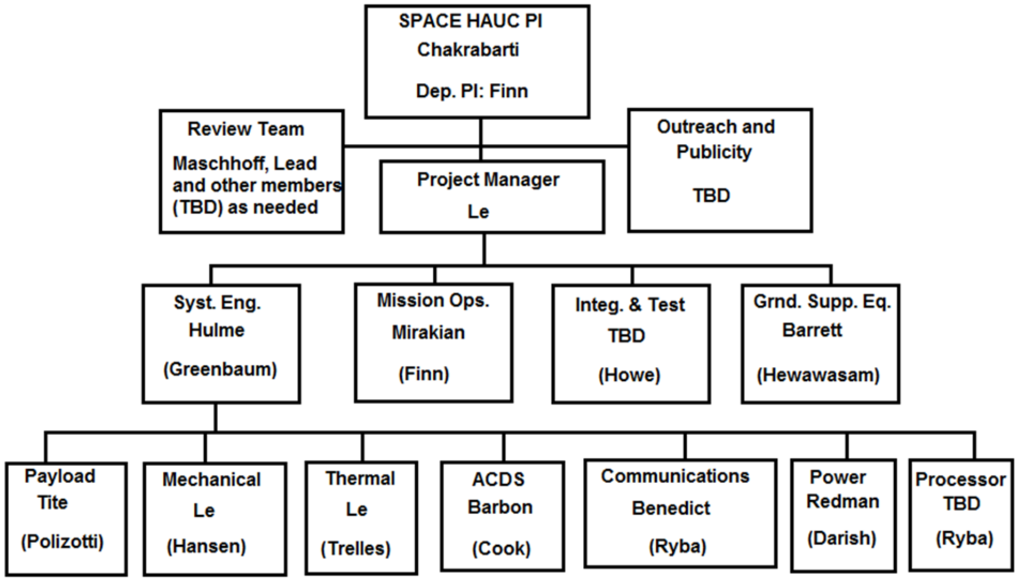


Figure 5: The SPACE HAUC management structure balances the education needs of the students and the goals of project success by pairing undergraduate students with experienced mentors, shown in parentheses, for each key subsystem.

Management Approach

The SPACE HAUC management team is led by Dr. Supriya Chakrabarti, the PI and an experienced investigator, who will solely be responsible to NASA for the successful execution of the program and represents the entire team in its NASA dealings. Dat Le, an undergraduate student, will be the PM and will manage the project so that it meets its mission goals within cost and schedule baselines. The sections below describe how our decision process is streamlined to execute the project with maximum efficiency and performance while reducing risk and shortening the management learning curve.

Student Roles and Responsibilities

The team recognizes the challenges in executing a project of this magnitude with students across multiple disciplines. Accordingly, we have sharpened our collaboration skills throughout the proposal activity using a fully integrated project team that is ready to successfully execute the SPACE HAUC mission. The student roles and responsibilities are summarized in Figure 5 and Table 1. We have incorporated a review team consisting of key experienced space scientists led by Dr. Kevin Maschhoff of BAE Systems. He will select members to help the program resolve major issues, if/as necessary.

Decision Making Process

The SPACE HAUC investigation is the direct responsibility of the PI. The day-to-day management of the technical baseline, project schedule, and mission budget is the responsibility of the PM. However, since the PM is not experienced and the PI will have academic responsibility, Dr. Susanna Finn, the Deputy PI, will provide day-to-day continuity and experienced oversight for the team. The PI will rely heavily on the PM and the Deputy PI for cost and schedule decisions.

Project decisions will be made and documented online at a site that will be accessible to all. The PI has used such a system (Redmine) successfully for an on-going sounding rocket mission to execute and document all changes to the technical, cost, and schedule baselines at the project level. Technical, cost, and schedule issues will be discussed at the weekly status meetings. If appropriate, decisions are made and documented in real-time. If not, an action item is generated and tracked to closure within a common action item database. While input for decisions may come from a variety of sources, the leader for the affected element has decision responsibility.

Risk and Margin Management (RMM)

Given the nature of this project, a higher level of risk than most spaceflight missions is acceptable. The two highest risks to this project involve schedule risks, with the availability of the X-band communication license being highest. To minimize this risk, we will start the process of securing a broadcast license at the start of the project. Students' schedules are somewhat unpredictable due to many demands on their time. We will have at least three students in each team to decrease the effects of the students' individual schedules. The third risk is the performance of the antenna. To mitigate this risk, we plan to implement a proven design and start early manufacturing so the system undergoes a thorough and rigorous testing.

The SPACE HAUC implementation plans contain adequate cost, technical, and schedule margins where the major risks are known and manageable. We will use continuous risk management for project planning, management, and control. The development schedule reserve is phased to provide additional schedule confidence. We have included a total of about 3-month schedule margin. Such high margin is appropriate since this is our highest risk. Given that several components are commercial-off-the-shelf (COTS) items a mass margin of 20%, added to 10% contingency, should be adequate.

For tracking and control, the SE will maintain the technical allocations. Cost control approach is described in Section H. We will use the integrated schedule to keep the focus on schedule. The current schedule has serial operations, and can be adjusted and compressed to show additional schedule flexibility if needed during Systems Integration and Test. SPACE HAUC project has healthy reserves, and has a proven process to maintain those reserves sufficiently to develop and fly this mission.

Total Project Costs

The total cost of this project is estimated to be approximately $269,927. The total funding requested from NASA is $199,997 (See Table 6).

H. Cost

The estimated SPACE HAUC mission cost encompasses all proposed activities. Costs are developed using a Level 1Work Breakdown Structure (WBS) element. Our request of $199,997 (FY15 dollars) is within the total program cap. In addition, the university has committed a cost share of $69,930. The cost share consists of support for two undergraduate students per year ($16,000), student stipends ($14,500) and faculty salary release of $39,430.

All SPACE HAUC co-investigator funding is included in the mission costs but they are not shown in the budget. These faculty salaries will be covered by academic course release offered by the deans of KCOS and FCOE, and Vice Provost for Research (see Appendix I). Our estimate for these costs is $39,430. There is no international participations. Cooperative contributions from BAE Systems alone is estimated to be $25,000 - $35,000 (see the letter from Ms. Lisa Aucoin). This cost sharing from BAE is not accounted for in Table 6. SPACE HAUC includes some NASA-funded items or services that would be considered contributed costs; most important in this category is the launch cost.

Cost control will be enforced by using the existing cost control systems at UMass Lowell, which will provide cost-performance measurements against plans for all partners. Cost will be compiled and measured against the budget plan. Cost performance will be reported to the PM on a monthly basis.

Cost Estimating Methodology

The total grass-roots, bottom-up cost estimate is provided in Table 6. The techniques employed to estimate resource requirements depend on the cost element (e.g., labor, materials, subcontracts, other direct costs (ODC), travel) being estimated. Direct labor estimates are calculated using two approaches: 1) schedule based planning and 2) comparison to previous work. Planning estimates were developed for process effort, such as management, systems engineering, mission assurance, and level-of-effort (LOE) engineering. Comparison to previous work involved a review of the task performed on our current sounding rocket experiment, which is analogous to SPACE HAUC.

For tasks directly analogous in all comparable aspects, the labor history is considered directly representative of the labor required for the proposed task. Adjustments are made by factoring in the tasks that could be performed as a part of the students' academic work such as an independent study or a Capstone project. These efforts were compared against previous project efforts and were used to validate the bottoms up number.

To ensure cost realism and completeness, resources were estimated wherever possible based on the engineering judgment of the actual performers and planners for the task. Since many of the tasks are similar to those performed by our team on other programs, SPACE HAUC was able to leverage this heritage to produce high confidence level cost estimate.

To mitigate cost and risk, COTS hardware is used wherever possible. These hardware costs were obtained from a variety of sources, such as established catalogs and recent orders for the same or similar items, as well as expert knowledge of the typical costs of the various types of parts to be acquired. This method was used to cost parts, tools, and test equipment, as well as major hardware components. Computer purchase costs have been included for Mission Operations and Data Analysis activities. The use of existing software licenses (specialized software such as SolidWorks, IDL, and ZeMAX programs and MS Office productivity software) resulted in significant savings.

Cost estimates include travel projected for SPACE HAUC and are based on destinations, number of trips, duration, and purpose of travel. Budgeted hotel and per diem rates follow government guidelines, and no relocation costs are included. Examples of cost estimating methods used for some of the specific WBS elements are listed below.

PM and SE. These were estimated by comparing required responsibilities and tasks to programs with similar analysis, execution, tracking, and documentation of the applicable PM and SE tasks.

Spacecraft and Payload. A grass-roots bottoms-up cost based on the knowledge of the SPACE HAUC. They were costed by labor, procurement, services and travel. The resulting payload efforts were compared against other space projects undertaken by UMass Lowell over the past 10 years to validate the bottoms-up estimate.

Mission Operations. Costs include labor, facilities, software, and hardware costs, and support for on-orbit check-out, anomaly support and resolution, critical events coverage, and contingencies, as well as rehearsal and training. These costs draw on the UMass Lowell team’s experience developing and participating in Mission Operations Centers (for EUVE and TERRIERS/STEDI missions), SOC, and data archives.

Reserve. The management reserve includes 10% for execution of unforeseen tasks and other risk mitigation plans. Our costs include redesign, rework/retest, contingency for lot re-buys and funded schedule reserve/unfunded schedule slack.

Table 6: SPACE HAUC budget includes risk-weighted cost reserve (not shown) for successful outcome.

WBS	WBS Element	Req. funding	Univ. Contr.	Total Yr 1	Req. funding	Univ. Contr.	Total Yr 2		Total
1	**Project Team**	38,000	14,000	52,000	47,300	16,500	63,800		146,300
	Student Salaries (10-12 undergrads)	32,000	8,000		40,000	8,000			
	Grad. Student Stipends (1+)	6,000			7,300				
	Other Stipends (supported by LoCSST)		6,000			8,500			
2	**Support Eqipment**	5,000	0	5,000	3,060	0	3,060		8,060
	Lab, Shop, 3-D print, Anal. instrum.	5,000			3,060				
3	**Payload**	30,000	19,715	49,715	0	19,715	19,715		108,860
	Antenna	0							
	Electronics, structures, cameras,batteries	30,000	0			0			
4	**Integration and Testing**	0	0	0		0	0		0
	On Campus								
	Off-Campus				4,500				
	Test facilities								
5	**Mission Operations**				5,000				
6	**Travel and Shipping**	2,750		2,750	10,000		10,000		12,750
7	**All Direct Costs**	45,750	14,000	59,750	65,360	16,500	81,860		172,110
8	**Indirect Costs (53.0%)**	24,248		24,248	34,641		34,641		58,888
9	**Total Requested funding**	99,998	33,715		100,000				**199,997**
10	**University Contributions**		33,715	33,715		36,215	36,215		69,930
11	**Total Project Costs**	133,713		133,713	136,215		136,215		**269,927**

I. Appendices

Letters of Commitment

Massachusetts Space Grant Consortium

Professor Jeffrey A. Hoffman
Director
MIT 33-312
77 Massachusetts Avenue
Cambridge, MA 02139
(617) 452-2353

12 November, 2015

Professor Supriya Chakrabarti
Associate Dean for Research & Graduate Studies
College of Sciences
Olney Science Center
One University Avenue
Lowell, MA 01854

Dear Professor Chakrabarti,

This letter confirms that the Massachusetts Space Grant Consortium has selected UMass Lowell's spacecraft design project to support for NASA's USIP competition. Your project fulfills the goal of involving students in the design, construction, testing and operation of real space hardware, and MASGC believes the project is worthy of support. We wish you success with your proposal.

Regards,