# Designing a Science-Based CubeSat Mission

Tyler Sholes[1], Jared Fuchs, [2], Samantha Johnson[3], Alay Shah[4], and Ian Hines[5]
*University of Alabama in Huntsville, Huntsville, Alabama, 35899*

**The University of Alabama in Huntsville Space Hardware Club CubeSat POLARIS team is designing a 3U science driven CubeSat. CubeSats offer a launch opportunity for small low-cost payloads with condensed development timelines and specialized, short duration, science and technology objectives. POLARIS will provide unique observational data on polarized high energy astrophysical sources. This science mission provides unique challenges to what is already present for the highly constrained mass and size requirements in CubeSat bus development. Because of this the science and engineering teams must work iteratively and in parallel. The POLARIS instrument team sets the mission goals and engineering requirements for the Bus, while the engineering team analyzes these goals and reports back on the feasibility and trades necessary in designing to meet that goal. POLARIS is being developed and executed by a multidisciplinary team of science and engineering students. We will present on the CubeSat POLARIS mission design, goals, and the strategic reasoning for using CubeSats as science platforms.**

## I. Mission Goals and Design

### A. Overview, History, Goals

CubeSats are small satellites often launched as secondary payloads. They are cheaper to build, and can be designed and built in a much shorter timeframe than other satellites. They are made in multiples of 10x10x11 cm units, called Us. Because of their small sizes, CubeSats have a number of limitations: CubeSats have a very small power output, they have reduced space for instrumentation, and they have very short lifespans.

At the end of the Fall 2016 semester, the University of Alabama in Huntsville (UAH) Space Hardware Club (SHC) began development on a 3U CubeSat and a science instrument, POLARIS. The engineering and science goals first arose independently. The UAH SHC had some experience in CubeSat development from a 1U CubeSat launched in 2012, but members wanted to expand the project. A science mission offered an opportunity to bring in a larger more diverse group of people to expand the CubeSat mission. UAH specializes in high energy astrophysics as an area of research, and nearby Marshall Space Flight Center (MSFC) has x-ray and gamma ray groups within its Science Research Office. High energy astrophysics and space missions are a natural combination, since high energy light is attenuated within Earth's atmosphere and cannot be observed with ground telescopes. The CubeSat project provides the best vehicle for students to explore high energy astrophysics with their own instrumentation.

The POLARIS instrument is an astrophysical polarization detector designed to operate in the hard x-ray and soft gamma-ray regime. This science mission aims to provide unique observational data on polarized high energy astrophysical sources. The mechanisms that generate polarized light allow us to probe the nature of magnetic field morphology, accretion disk structures, and the fundamental physics around neutron stars and black holes.

POLARIS will be paired with the Bus architecture, which is being designed by the engineering team to allow it to achieve its goals in orbit and to be able to change rapidly as the goals of the science team change and evolve. The science and engineering teams now work together to produce a strong and feasible science mission.

Additionally, a student education mission is integrated into the science and engineering missions. Students have the opportunity to hone their current skills and develop new ones within the multidisciplinary project. Team members are encouraged, and frequently required, to participate in areas outside their discipline or knowledge base to learn more and also to help foster clearer communication between the different subteams.

[1]Program Manager CSP, Undergraduate, Mechanical and Aerospace Engineering Department, AIAA Student Member
[2]Science Lead CSP, Undergraduate, Physics Department, AIAA Student Member
[3]Science Team CSP, Graduate, Physics Department, AIAA Student Member
[4]Systems Engineer CSP, Undergraduate, Industrial and Systems Engineering Department, AIAA Student Member
[5]Engineering Team CSP, Undergraduate, Computer Science Department, AIAA Student Member

### B. Mission Design

The POLARIS instrument operates by inducing a compton scatter inside a low Z material and recording the azimuthal angle from the scatter event. Compton scattering is a type of inelastic scattering of a photon in which it loses some of its energy to the scattering material, usually a charged particle[1]. In the POLARIS instrument, the astrophysical source radiation interacts with the low Z material, scatters, and then interacts with a high Z material and is absorbed. The scatterer and the absorber materials are scintillators, which luminesce in the visible spectrum when hit by high energy radiation. The visible light emitted from scintillator material can then be recorded by a photomultiplier as a signal.

Size poses an issue for the sensitivity of the instrument. In the high energy regime, astrophysical sources have a low flux rate, or photons per unit time per unit area, which the instrument will compensate for with longer observation times. The instrument is designed to fit within a 1U volume at the top of the spacecraft bus, utilizing an unfolding baffle to narrow the field of view. Position and energy deposition information of each scatter event will be processed to reconstruct the event and determine the polarization percentage. The data processing will also account for orientation effects in the distribution and sorting between multiscatter events in the detector. This will take take place on the ground to reduce on orbit processing, reducing power, processing, and data storage requirements on the Bus.

The scintillator light output will be readout by silicon photomultipliers (SiPMs). Coincidence between the scattering material and absorbers and energy triggers will be used to reduce the background counts. Basic energy detection will be present on both the scatterer and absorber to determine polarization and flux in target energy ranges.

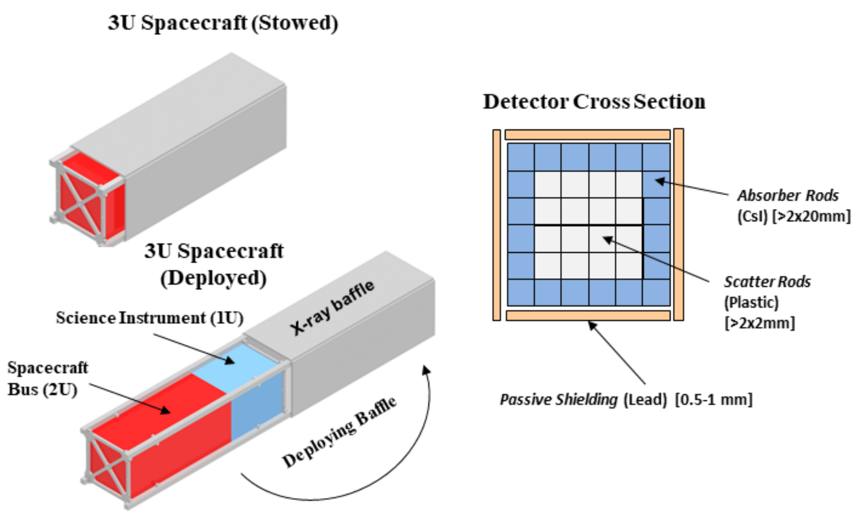


**Fig. 1 Overview of Instrument Configuration.**

The CubeSat POLARIS (CSP) Bus architecture is being derived from the science requirements and general CubeSat ground rules and assumptions. The Bus will occupy the 2U volume under the science instrument and the area around the science instrument. The largest single system in the bus will be the Attitude Determination and Control System (ADCS). The ADCS will incorporate a combination of custom built reaction control wheels and magnetic torque rods to be able to point the science instrument at different astrophysical sources. The magnetic torque rods will be incorporated into the exterior solar panel printed circuit boards (PCBs) as a center layer to reduce the volume that they occupy. The team plans to use two seperate half-duplex radios for ground communication. This radio and electrical power systems will use commercially available parts with flight heritage for reliability.

Currently, the subsystems are being developed within their separate subteams. The mission critical systems design, development, and testing are the highest priority. Communication between teams is open and regular. After each of the subsystems have finished being designed, built, and tested, they will be integrated and undergo full system testing.

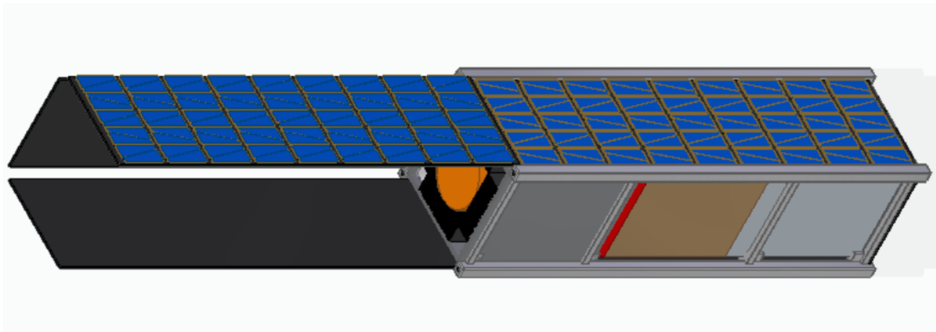

**Fig. 2 Overview of the spacecraft (external view, one side of baffle is removed for clarity).**

## II. Strategic Capabilities of CubeSat Science Platforms

CubeSats offer several strategic advantages for developing new technologies and science. Due to their small size and relatively frequent launch opportunities, CubeSats allow for emerging science and technology pathways to be explored quickly and cost-effectively. CubeSats can serve as a pathfinder for future large missions; they can highlight potential design problems or determine if a larger mission is even viable. For example, POLARIS will be collecting data within a wavelength of light that has rarely been measured with regards to polarization. NASA's Science Mission Directorate considers CubeSats "scalable platforms" and is highly supportive of using CubeSats for science [1]. Alternatively, if the science can be done with a CubeSat, a larger more expensive mission may be unnecessary. Larger missions can take decades to build, calibrate and launch, but CubeSats have a much shorter timescale for launch and data collection. In the event that a large mission fails, whether it be a technical failure or a cancellation of resources, the availability of time and resources to relaunch or redesign a mission are questionable. In the event that CubeSat mission fails, it can be rebuilt with relatively low cost and little time. CubeSats also have the unique ability to become low cost multi-point measurement platforms. Swarms can be easily deployed that can take specialized instruments and distribute several measurements in both position and time, unlike expensive single observation platforms.

NASA has determined CubeSats to be worthwhile endeavors, as demonstrated by the CubeSat Launch Initiative, or CSLI [2] [3], non-profit organizations, and NASA centers opportunities to fly secondary payloads aboard already-planned missions. The missions must align with an aspect of NASA's strategic goals, which are delineated in NASA's strategic plan. From NASA's Launch Service Provider [4], CubeSats are aligned with NASA's Strategic Plan through:

Strategic Goal 1: Expand the frontiers of knowledge, capability, and opportunity in space.

- Objective 1.7: Transform NASA missions and advance the Nation's capabilities by maturing crosscutting innovative space technologies.

Strategic Goal 2: Advance understanding of Earth and develop technologies to improve the quality of life on our home planet.

- Objective 2.3: Optimize Agency technology investments, foster open innovation, and facilitate technology infusion, ensuring the greatest national benefit.
- Objective 2.4: Advance the Nation's STEM education and workforce pipeline by working collaboratively with other agencies to engage students, teachers, and faculty in NASA's missions and unique assets.

The strategic plan discusses NASA expanding their CubeSat program due to their cost-effectiveness. On a center level, CSP addresses MSFC's Strategic Goal 1 of "expand[ing] human knowledge through new scientific discoveries"[5].

Student education is both a mission and strategic feature of the CubeSats; allowing students to contribute to cutting-edge science and technology helps train the future STEM workforce. Students experienced in CubeSat missions can later apply those skills to larger missions and projects. Student CubeSats can help test new technologies and science cheaply. Collaboration between students and professional engineers and scientists on CubeSat missions can be beneficial to all parties. Because of its location in Huntsville, the UAH SHC has the opportunity to collaborate with researchers from NASA's MSFC, industry members in the local area, and also research centers on the UAH campus itself. This type of student education can benefit students personally, but it also helps provide the city with a higher caliber of graduate.

CubeSats have a strategic capability as a science platform in that they are actual space hardware. Astrophysics in the high energy regime is difficult to perform even on high altitude balloons and rockets because high energy light is attenuated by the Earth's upper atmosphere and information from the astrophysical source is lost. Additionally, the space environment allows for scientific experiments that cannot be performed on Earth, for example: precise astrophysics or biological effects from space radiation.

Historically, CubeSats were launched as a way to provide productive ballast to payloads. They are usually launched as secondary or hosted payloads. Due to different teams working on different payloads on the same launch, connections are formed between the different organizations. Because of this, CubeSats can help promote partnerships and collaboration between organizations.

CubeSats offer an opportunity to perform scientific experiments and collect data quickly, cost-effectively, and collaboratively. CubeSats are an excellent platform for students to train in STEM fields, and for NASA to achieve its goals and objectives.

## III. CubeSat Challenges

Despite their many promising capabilities, CubeSats present a unique set of challenges. The same small size, small mass, and placement as secondary or hosted payloads that enable CubeSats to be developed and launched quickly and cost effectively can also be obstacles to the scientists, engineers, and program managers that develop CubeSats.

Programmatic challenges may appear in CubeSat projects. CubeSat launches are dependant on the schedules of primary payloads. If primary payloads become delayed or cancelled, CubeSats may be reassigned to a different payload with different requirements for the CubeSat. Development can be dependant on student academic schedules. Because of a CubeSat's uneven schedule, its work can become stalled, losing momentum and team members. CubeSats are often launched together, and larger CubeSats have more difficulty finding launch opportunities.

CubeSats present a unique set of challenges from both an engineering and science perspective. CubeSats have very strict mass, volume, and testing requirements. These restrictive requirements flow down into all subsystems and are amplified in their impact when incorporating all of the functionality and redundancy required for any system in space. The sheer amount of systems and objects that any satellite must have, from batteries and solar panels to radios and data storage, quickly add up in volume and mass. Additionally a change in any system quickly propagates into other systems. These challenges are very well documented in CubeSats, but when adding a science mission the challenges on the Bus and system as a whole compound. As an example, in CSP the science instrument requires the ability to point at different astrophysical sources leading to the necessity of an extensive ADCS, a system that is usually minimal if exists at all on a CubeSat. The ADCS will increase the levels of power, computing, and volume necessary to complete the mission. Additionally, CubeSats often suffer from deployment issues. Deployment from the main payload can be unstable and violent, potentially damaging the CubeSat or rendering it unable to perform the planned experiments. CubeSats, like all satellites, experience thermal problems while in orbit. In CubeSats there is not much room for heating or cooling systems to mitigate these problems, so they are specifically designed to redistribute heat inside of the CubeSat, and to only heat what is most impacted by thermal fluctuations.

Science functionality can also be limited by CubeSat size, mass, power, and lifetime. Limited size and mass means that instruments must be smaller. In astrophysics, this can translate to smaller collecting area which means increased observation time. CubeSats have much shorter lifespans than other satellites, and increased observation time can greatly reduce the number of observable targets. Limited mass can also reduce instrument size or efficiency. For example, the POLARIS instrument requires a baffle to reduce its field of view to increase detection accuracy. However, the baffle must be a highly dense material such as lead or another heavy metal, which adds extra mass. Increasing the baffle thickness and length would result in better scientific data, but the CubeSat can only support a limited amount of mass per U. Reduced power on the CubeSat translates to reduced data rates and available science data. Reduced power may also mean that more data processing must be done on ground instead of in flight.

While CubeSats can present limitations to achieving certain scientific and engineering goals, a strong and organized systems engineering approach can address these potential problems and further enable CubeSat development teams to meet their requirements and achieve their goals.

## IV. Addressing Design Challenges

To overcome the issues that are incurred when trying to balance the optimal design for the science instrument and the physical limitations encountered when building CubeSats, an iterative design approach is useful to find the point of best performance from the science instrument while accounting for the environment and limitations of the CubeSat. The science mission is the primary driver, but the engineering impact is weighted into the studies. The iterative approach is used in considering all possibilities available and their effect on the science mission. From these trades the engineering team considers its impact and feasibility. This process is iterated as both the science and engineering teams approach the best solution and refine the design towards the final solution.

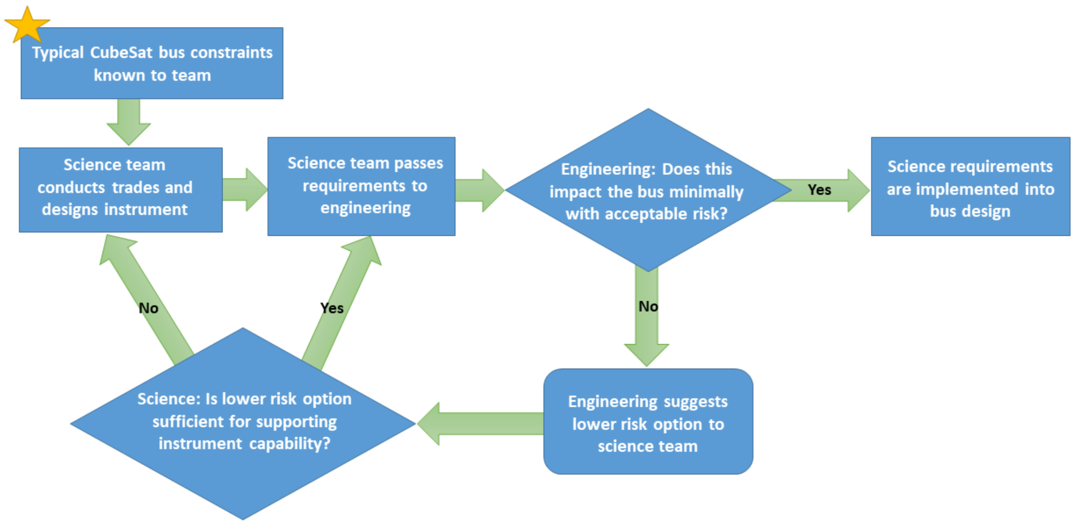


**Fig. 3 Risk Determination/Mitigation Flowchart.**

The science mission requirements for CSP drive the CubeSat Bus development. The Bus system development has been affected by the iterative design process necessary to accommodate the science instrument. As the science instrument develops and goes through iterations, the Bus has to adapt quickly. The engineering team first analyses the risk of implementing new goals as shown in Figure 3. After the risk has been determined to be minimal, the engineering team has to turn new goals into system requirements and return the results of trades to the science team to be considered. Because of the constantly evolving goals of the science instrument the Bus changes designs often, and often has comprehensive design changes. These design changes have led to the Bus being mostly made up of two different groups of systems: the systems that do not change iteration to iteration, and the ones that do.

After several iterations it was found that it was best for the systems that have to change often to have a modular design. The systems that have seen the most iterative changes are Command and Data Handling (CDH) and Electrical Power Systems (EPS). The CDH systems developed into a series of different microprocessor units, or MCUs, so that each MCU could change, varying the amount of data processing power, without affecting most of the rest of the CDH systems. For the EPS system the biggest portion that had to change is the amount of power storage that CSP has to have. This led to us developing a system where all of the CubeSat batteries are contained in small plug and play units that have the entire battery protection circuitry, regulators, and battery connections. As the power storage requirements change, these small boards can either be added or removed to accommodate the new requirement. By making the changing systems more modular, it has allowed for a more rapid and accurate list of trades to be sent to the science team from each design change because the entire system does not have to be changed each time. Making some systems modular has also lead to easier ways to experiment and test each subsystem by making it possible to only build one or two modules and put them through a multitude of tests. By having only a module or two in each test, when problems are identified it is faster and cheaper to fix the problem and get back to testing.

Some systems do not change each iteration. The two biggest systems that have not changed are the Communications and ADCS. These systems do not change for very different reasons. The Communications system does not change because during the first few iterations it was found that the system was already optimized for CSP and changing it each iteration would not be beneficial. The ADCS was a different story. It did not change due to the massive time required to develop the controls and control systems required to point CSP at the accuracy levels dictated by the science mission. Because these systems do not change, many other systems across CSP have been designed around the ADCS and Communications systems. Testing of the non-changing subsystems has been difficult due to large number of changes that are required when a flaw in the system is found.

Using a combination of systems that change and key ones that don't for each iteration of the Bus has allowed for a more expedient and accurate list of trades for each new set of goals provided by the science team in addition to allowing for a faster way to test and refine subsystems that have to change each time.

## V. Conclusion

A CubeSat is the best option for the POLARIS instrument and the CSP team. Currently, CSP is designing the instrument and CubeSat bus, with an emphasis on designing mission-critical components. The team's approach to developing the science instrument and CubeSat bus iteratively and in parallel has allowed the mission development to be more collaborative and cohesive while progressing the science, engineering, and student education missions. CubeSats are a valuable platform for performing scientific research, developing technologies, and furthering student education. They can add constraints to missions, but CubeSat teams can confront these issues by using a strong and organized systems engineering approach to their design.

## Acknowledgments

The SHC CSP team would like to thank the Alabama Space Grant Consortium and Dr. Dale Thomas for their financial support. The team would also like to thank the project mentors and advisors for their advice and support: Space Hardware Club Advisor Dr. Francis Wessling, Dr. Wayne Baumgartner, and Dr. Richard Tantaris.

## References

[1] *X-Rays: Another Form of Light*, Harvard-Smithsonian Center for Astrophysics, 2012. URL http://chandra.harvard.edu/xray_astro/xrays.html.

[2] Pierce, D., Seablom, M., Petro, A., Sweet, A., Crusan, J., and Horne, W., "NASA perspectives on Cubesats and Highlighted Activities," Tech. rep., June 22 2015. URL http://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_166651.pdf, Briefing to Committee on Achieving Science Goals with CubeSats.

[3] NASA, "Announcement of CubeSat Launch Initiative," , August 3 2017. URL https://www.nasa.gov/sites/default/files/atoms/files/cubesat_launch_initiative_announcement_2017.pdf, NRC/Space Studies Board.

[4] Higginbotham, S., "CubeSat Launch Initiative," , 2016. URL https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120015542.pdf, Launch Services Program.

[5] "NASA Strategic Plan," , 2018. URL https://www.nasa.gov/sites/default/files/atoms/files/nasa_2018_strategic_plan.pdf.