CubeSat Information and Lessons Learned

Thank you for your interest in the CubeSat Launch Initiative (CSLI). Below is some information that will help with the development of your CubeSat and includes lessons learned from other entities as they were designing, building, and operating their CubeSat.

The CubeSat 101: Basic Concepts and Processes for First-Time CubeSat Developers document provides guidance and recommendations to assist in the development of your CubeSat. This document contains invaluable information that should be reviewed. The document walks you through the development process, requirement sources for launch, licensing procedures and more. There have been some advancements since it was originally published and will be reposted once the document has been updated.

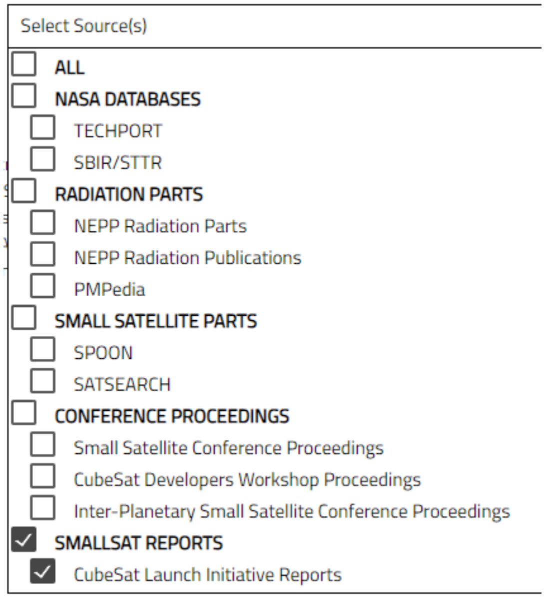
Additional documentation to review that may be helpful in organizing and managing your project are the NASA Systems Engineering Handbook, NASA Risk Management Plan, and the NASA Work Breakdown Structure (WBS) Handbook. These tools, concepts, and methodologies can be tailored for your specific project.

The Small Spacecraft Virtual Institute has several resources including the Small Satellite Reliability Initiative (SSRI) Knowledge Base Tool with a mission to share resources, best practices, and lessons learned. The Small Spacecraft Body of Knowledge has a link to Small Satellite Conference Proceedings that has presentations and papers on a variety of topics. The Small Spacecraft Community of Practice Webinar Series contains presentations from past missions and topics such as conjunction risk analysis, cost estimation, and systems engineering.

Middle schools and high schools face many challenges and Thomas Jefferson High School for Science and Technology prepared a paper, "Identifying and Overcoming Challenges in High School CubeSat Program" that is the result of a case study they performed of various high school CubeSat organizations across the United States. The challenges facing these teams and possible solutions are provided so it worthwhile to review.

A couple of approaches that schools undertook included collaborating with multiple schools within their school district, and another worked with educators, district curriculum development leaders and community mentors to design and implement lesson plans and problem-based learning experiences for the STEM classrooms. They reached out to local industry, national laboratories, and parent volunteers to achieve their mission. Where possible they utilized commercially available and flight-tested components for all subsystems. There were technical mentors throughout the process to provide guidance to help reduce technical system failure risk and maintain mission feasibility. The students performed the testing and integration of all flight hardware under the supervision of instructors and mentors.

The Small Satellite Information Search is a tool to search various sources of data including the Final Reports from past CSLI missions in addition to presentations from conferences and workshops. To search for lessons learned for CSLI only, click on the down arrow for Selected Source(s) and click on All to deselect, then click on SmallSat Reports and click on Search. These reports include valuable lessons learned that the teams have experienced related to the development of their CubeSat, project management, testing, etc. and may prevent similar situations from occurring and ensure mission success. In addition, if you are looking to collaborate with another university you can see who has previously participated and what their mission entailed.



In addition to the resources identified above, below are some bulletized items that were identified by previous CubeSat developers based on their experience and are items to consider when formulating, designing, and developing your CubeSat project.

Project Team and Documentation:

- For Educational missions it is important that the Principal Investigator and Co-Principal Investigators manage expectations as to what is truly possible for a student educational mission with limited budget and schedule. Trying to do too much, defeats the primary purpose of an educational mission.
- Technical and Project leadership should be carried out as two distinct roles to prevent the conflation of technical issues and project issues such as budget and schedule. Systems Engineering students can help to bridge the gap between various sub teams, technical requirements, budgets, and schedules.
- Team organization and continuity is vital. Long-running programs face substantial risks due to student and staff workforce transitions. Proper documentation of all satellite systems and assembly/test procedures is essential to allow rotating staff/student workforce to successfully continue and complete project work. Have good documentation of the final flight system as it is helpful when troubleshooting during mission operations. To gain valuable information, have resources available for a robust investigation of on-orbit anomalies.
- As students graduate or team members transition in/out, may experience loss of expertise, failure to maintain previously rigorous standards of mission assurance and an unwillingness to admit problems which could lead to poor decisions. The earlier issues are brought forward, the more successful the project will be.
- Document all project activities, decisions, methods used, formats, code, lessons learned etc. Insufficient documentation contributes to the loss of experience and knowledge, and difficulty

in troubleshooting especially with software. Consider turnover and the need for knowledge capture/mentoring. Configuration Management is essential; maintain your documentation so you don't have to reverse engineer if key personnel leave the team; prevent scope creep. Someone who is not part of the project should be able to read and understand it.

- Strong management of the project schedule and mitigation plans for anticipated and unanticipated delays. Ensure experienced mentoring to provide guidance and support to meet program objectives (i.e., hardware development will be challenging, and science investigations will be difficult to achieve). When creating a schedule, set goals for larger milestones which can drive the schedule, and define smaller, achievable milestones up to two-weeks out.
- Allocate time and budget after flight to analyze the data and document the results. Writing technical/engineering papers is a good way to share lessons learned and is good exposure for students and junior personnel.

Design and Development:

- Approach the project as a set of systems to make it more manageable. Reviewing the NASA Systems Engineering Guidebook may be helpful.
- Be mindful of any light pollution generated by the CubeSat and state clearly the impact on ground based astronomical observations. Reach out to the American Astronomical Society (AAS) Committee on Light Pollution for advice on what is acceptable and methods to minimize the impact. Another resource is the International Astronomical Union Center for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference Payload website https://cps.iau.org/.
- CubeSats with drag devices for de-orbit will face greater scrutiny from the regulatory community and may not be approved; design for demise and minimize the use of high melting point materials (titanium, tungsten, ceramics, glasses, tantalum, etc.).
- CubeSats with propulsion should include GPS as well as the ability to share predicted ephemeris data with the 18 SPCs and all other satellite operators. In short, know where you are in space and where you will be at all times to minimize conjunctions with other spacecraft or crewed vehicles.
- If you have any propulsion or any other means of modifying your orbit, consider encryption for your spacecraft, preventing the ability of 'bad' actors controlling your spacecraft and ramming it into another object.
- There are International Space Station (ISS) unique technical considerations/restrictions (battery testing, toxic materials, propulsion, lasers, inhibits, additive manufacturing, etc.). For the most comprehensive series of requirements that you will have to consider, please review the following page on the Nanoracks website Technical Resources - Download Nanoracks IDD & ICD Documents. Please pay close attention to the Lithium-ion battery test requirements.
- If possible, design your spacecraft to accommodate the broadest range of orbits possible. Orbit flexibility maximizes your launch opportunities while restrictive orbit requirements can limit launch opportunities, thereby potentially leading to later than desired launch dates. In short, if the bus is going to Pittsburgh, it can't take you to Seattle.
- Implement back-up plans for subsystems much earlier in the design process and have clearly defined gates for making those decisions. Establish parallel path for critical item suppliers if there is evidence of an impending delay or of reduced performance.
- Gain a clear understanding of your mission objective(s) and the minimum functionality necessary to allow you to achieve them. Eliminate unnecessary complexity, design in easy

assembly/disassembly to account for human factors and incorporate more commercial components in the design to reduce the need to design from the ground up.

- Deployment altitudes should be in line with planned mission duration and de-orbit capability. For example, designing a spacecraft without deorbit capability that will only last a couple of weeks or requesting a 550 km deploy when the mission will end in six months resulting in the spacecraft being a hazard to navigation for years to come.
- If you are a 3U or larger and are planning for an altitude of 540 km or higher ensure that you have considered how you will passivate your batteries and reaction wheels. Also consider the probability of explosion for all propulsion systems and reaction wheels above this altitude, ensuring that the risk is small in all instances.
- Consider how far along the CubeSat development is prior to accepting a launch assignment to avoid multiple schedule delays.
- In general, use an agile model for development so that you can get something working early and then refine it as your knowledge increases. This will reduce risks of big failures on large milestones late in the process.
- Having a team member and/or external reviewer with prior experience related to CubeSat development can be beneficial when considering options at key decision points.

Components:

- For imagery, consider installation of higher-resolution cameras and higher bandwidth downlink to enhance the ability to capture and download quality images.
- Have a clear understanding of vendor capabilities and look at their heritage and past performance. Smaller vendors may underestimate the costs and scope of the required work.
- COTS components may not be as developed as advertised.
- Purchase multiple copies of the flight radio system, test the fundamentals of the radio system, and have a beacon so you can observe some data. A reliable radio is essential.

Integration and Testing:

- Start hardware integration as early as possible to avoid the pitfalls of development delays and last-minute integration issues. Develop strong validation and verification standards early in the project. Understanding your spacecraft and managing anomalies are effort well worth considerable time investment.
- Integration of components from different suppliers could cause compatibility issues so may want to consider sourcing them from the same manufacturer.
- Thermistor wires are prone to fatigue and breaking so covering them with epoxy and heat shrink tubing can help however it may cause problems with fit. Start fit checking early and do this often as it will reveal design issues.
- No matter how often you've checked your CAD, always dry-fit your components to make sure the physical part matches with what you've designed.
- Plan to test early and often to reveal any design issues to prevent inoperability on orbit. Test as you fly and fly as you test so you are prepared for what you will encounter on orbit. For the aspects of the mission that cannot be "tested as you fly" should receive extra scrutiny and design margin. Simulate and test every condition the CubeSat can experience during on-orbit

operations. Do as much testing as possible. Test the flight system early and often, to make sure it is reliable and can recover from faults.

- Consider having the battery manufacturer to perform the vacuum testing for you.

Operations and Communications:

- Mission operations and planned duration needed to achieve mission success must account for the aggregate probability that all required aspects of the mission are functioning properly simultaneously.
- Close coordination with the integrator/CSLI team is crucial and don't be afraid to bring up issues early. Build an engineering unit in addition to the flight unit if possible. This would be beneficial in the event of having to perform a failure review.
- Have a robust two-way communications design and add a redundant downlink if possible. Do no rely on a single ground station for comms and ensure licenses account for multiple ground stations. Ensure there is adequate power as well to detect the beacon. Consider commercial off-the-shelf components vs in-house build. Test the communications workflow thoroughly. Once on orbit, a break in communications can be difficult to recover from.
- A great resource is the SatNOGS community. They operate a network of amateur radio ground stations with community software tools to track, receive from, and decode telemetry and other data from satellites using amateur radio frequencies. The Radio Amateur Satellite Corporation (AMSAT) is a worldwide group of Amateur Radio Operators (Hams). Another community is the American Radio Relay League (ARRL). Coordination with the amateur community can be extremely helpful.