The Newcomers Guide to CubeSats

by Jorge Rodriguez and Sandy Antunes

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CAPITOL Technology University

CACTUS-1

Specific citations and history are given for each component as follows:
Cactus-1 proposals and mission overviews
A. Antunes, R. Schrenk, R. P. Smith, A. Walters, R. Maharaja, M. Horvath
Hermes payload (on Cactus only-- for Hermes sounding rockets, see Maharaja) by C. Murray, E. Schroen (power Board design), Carlos Del Cid, R. Maharaja, P. Smith, IP rights retained by R. Maharaja
Trapsat payload by R. Schrenk, K. Moore, Z. Richards, M. Strittmatter, A. Walters, R. P. Smith, IP rights retained by R. Schrenk
3U++ Tabbed Frame: by R. P. Smith, R. Schrenk, provided under an open hardware license
Pi-CPU/Health & Safety Boards: by R. P. Smith, A. Antunes, provided under an open hardware license
Power bus: by R. P. Smith, G. Auvray, C. Odigwe, A. Antunes, R. Schrenk
Solar: (Added this because power and solar have different aspects (i.e. licensing to use))
by R. P. Smith with assembly help from George Gieomekis, Marcus Bailey, Sam Lawson, Nick Keller, Sarah Sharpe, Alex English, Nick Aniello, Chris Finch
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Comms: by M. Horvath, A. Johnson, A. Antunes
Burn wire, foot switches, inhibits, ports, and subsystems not mentioned: considered either part of the above, part of the general Cactus mission, or not sufficiently novel to merit publication or separate enumeration.
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Introduction

by Jorge Rodriguez

Why do you want to build a CubeSat? To photograph space and the earth; to experiment unproven technology and techniques; to create an art project that'll be out of this world? Whatever it is, this book will provide any reader with a baseline platform and information they will need to build a fully functional CubeSat, without jumping through endless hoops to launch the darn thing. This means the designs and instructions are all open source, meant to be accessible and free to anyone, especially DIYers and Students. The years of work have already been done and tested, and we want to release our version to facilitate and shorten the build process for anyone who needs it. Of course, not every project is perfect, and many go through development hell for several years with no end in sight; learning bits and pieces from every key member of the project, CACTUS-1 experienced several hiccups that could have crippled the end product, but the students and professors persevered.

However, the original designeers left room you to play around with; add or remove components, that’s your call. We want this to be as easy as possible, plug and play, however, every build will inevitably have their issues. But the main purpose of the CubeSat Cookbook is to shorten the overall build time, and lesson the headaches that come with designing, coding and assembling a CubeSat. The Capitol Technology University Cactus-1 Team has spent many gruesome years working on Cactus-1, and this book will show the fruits of their labor by contributing their efforts to the small CubeSat community, and help it grow.

CACTUS-1 Mission

The purpose of CACTUS-1 was to launch two separate payloads in a 10x10x30 cm form factor for about $20k in materials and testing. These two payloads, TrapSat and HERMES, were built by separate teams for different purposes over the course of two years by Capitol students. TrapSat’s main mission was to experiment with a unique material called Aerogel, a low density synthetic porous material in which the liquid component of the material has been replaced by air. While ‘gel’ is in the name, Aerogel is actually a fragile, glass-like material that works wonders as a thermal insulator and particle capturing device. The latter is CACTUS-1's intent with Aerogel: to capture space debris and investigate what has been captured using a camera connected to a Raspberry Pi microcomputer that periodically turns on the LED hovering above the Aerogel containment bed and snaps a time-stamped picture of the bed. When radio contact is available, the TrapSat comms team can send a message to the TrapSat to send that data back to earth for the TrapSat team to evaluate the materials flying in LEO. With TrapSat's mission to capture as much debris as possible, the chosen orbit was a polar orbit (passing above the poles).

CACTUS-1 holds another payload, HERMES: A small attachment to the CACTUS-1 satellite that is completely independent from TrapSat. HERMES is an experimental communications payload using the Iridium Satellite Constellation for uplink and downlink communications. HERMES shares no components with TrapSat other than the chassis they are riding on.

While the build and pending launch of CACTUS-1 is completed, it wasn't without its problems. Design disagreements, budgeting issues and poor team management were only a handful of key issues throughout the CACTUS-1 campaign as evident by the fact that the original goal for CACTUS-1 was to be ready for deployment in a single year (2016-2017). Of course with such a large project for a small body of students with an even smaller body of volunteers, a viable CubeSat would need the perfect underdog story. We were fortunately to receive an extra 8 months due to launch pushback, long enough for students to gain their bearings, and get to work on a steadier basis, leaving adequate room for learning experiences

Recognize the Spacecraft Subsystems you will need, and consider having a separate team for each. By defining interfaces to meet specifications (such as power and data handling), a large project can be broken into asynchronous small teams, which works well in a university setting.

1. Data processing and handling (CPU and Storage)
2. Communications
3. Attitude control systems
4. Power generation, cleaning and distribution
5. Mechanical
6. Science (Purpose of the satellite)

Power!

Specifically, battery power! Batteries are everywhere! They power your remotes, smartphones, laptops, and your dusty old gameboy! But as we've all come to learn, not all batteries are created equal; Some may remember that joyous feeling when mom came home from The Store and said she got you a brand new box of batteries for you little nintendo. She pulled the unfamiliar box from her bag, and you snatched those suckers out of excitement. You rip out your dying Energizer batteries from the week prior, pop in mom's shiny new pack of - Dullacell? Of course, you can barely read, but you knew something was off. They didn't look like the typical Duracell, or the Energizer's mom usually gets from The Store. But, maybe they're just alike; after all they're almost spelled the same. Similar name, same juice you suppose, but heck it all you need to play! You've already gotten the weekly rhythm for battery replacement; use your nails for leverage against the positive notch, and - pop! Out with the old, in with the new.

Your daily 8 hour session of Kirby and Motocross Maniacs continues another day! However, you notice that only two hours into your daily grind, the game shuts off and you lose your progress. You sit there angry and confused, and think to yourself "I have new batteries, so what happened?" At the time, none of it made sense, but with foresight, you've pointed out the quality. You just had your first experience with poor quality and a lack of heritage, two quintessential properties needed when considering what will power your next CubeSat.

In most picosatellites (small satellites), such as CubeSats, a pack of batteries will power everything from your Pi/Arduino, transceiver, cameras, lights and anything else you throw in your space box. Having a reliable, rechargeable, not-interfering battery is critical to any mission, as this will be the life source of your CubeSat during its flight. Searching for a power source that ticks every box can be daunting, even downright impossible if you don't know where to start. But that's what this book is for! At the time of publication (2019), lithium-ion batteries are simply the best, safest option for any amateur space team. Specifically, a good set of 18650 Lithium Ion batteries are well rounded batteries, that has earned its reputation as a reliable source of power for multiple space flights. Knowing the batteries you've purchased have successfully not failed in space is one less thing to worry about.

Made from the same stuff as your smartphone and laptop battery, the 18650 Lithium ion battery is a rechargeable battery with space capabilities. From the right manufacturer, these bad boys can survive both extremes in space, while being recharged by the sun with solar panels . Because of their recharging abilities, 18650 batteries are the go-to choice for many CubeSat enthusiasts. In addition, they are a very dry battery, meaning when they are exposed to extremely high, or low temperatures, the 18650 won't explode in their case, leaking battery juice in the satellite.

Extreme durability is crucial for flight approval; Your satellite must follow a strict "Do no harm" requirement. Meaning, a CubeSat cannot interfere or damage its neighbors on the launch rocket. This, and many more rules will be elaborated on in the "Requirements and Policies" section. When it comes down to it, there's nothing stopping your team from using anything else, but to save you time and money, 18650's would strip the search for power down to brands and your specific power needs.

Finding Batteries

Now, you've decided to want to use a pack of lithium ion batteries to power your satellite. Great! If you're the person of loves a shortage of supplies and hundreds of counterfeits, even better! Unfortunately the 18650 battery market is plagued with liars and lack of batteries themselves. Unfortunately, the search for quality 18650 batteries will require you to be patient and have insider knowledge to get a good deal and avoid fake chinese sellers. This shortage of batteries can be linked to two devices that also use them: Teslas and Vapes. The all electric automotive underdog Tesla packs over 7,000 18650 batteries to power their 85 kWh (Killowatt hour) battery pack for the Tesla Model S. While Tesla has never been on the same production scale as Chevy or Ford, the Tesla lineup has begun to sell like hot cakes in the past few years. Their popularity has caused a significant scarcity of dependable batteries. Trends shape the market, and the surge of vaporizers and quadcopters contribute to the 18650 gold rush as well, meaning manufacturers simply cannot keep up with the demand.

To add insult to injury, many counterfeit sellers take to Ebay to fool any enthusiast looking for their power fix. Fake sellers will take empty shells of a 18650 battery, drop in El Cheapo AA batteries and call it a day, leaving any uninformed customer duped. So when you think you've found a great deal from *totalllegitseller18298* on Ebay, it's probably best to shy away. For the best shopping experience, keep to big name brands like Panasonic to supply your battery needs. It's very unlikely an reputable brand will damage their reputation by selling you a fake product. Online prices may range from $5 to $17, depending on the vendor. This does not take into account for shipping costs, taxes, and time to ship, so shop wisely!

The number '18650' is simply the dimension of the battery. '18' standing for the diameter of the battery in millimeters, and '650' means the battery is approximately 65 mm long. 18650 batteries are lithium-ion batteries whose charge capacity, charge, discharge characteristics will vary from manufacturer. Held in the spec sheet, is the battery capacity in milliAmp hours (mAh), voltage output, weight, charging specs. In addition, the safe charge, discharge, and storage temperatures in Celsius are given. The graphs show a more detailed look at the numerical values in the above specification. Starting with the charging graph, shows the charging rate at different voltages stopping around 180 minutes. The Life Cycle Characteristics displays the decrease in charging capacity over several hundred cycles. Lastly, discharge characteristics are given by differing temperatures and the rate of discharge.

Battery Box

When you have your pack of batteries, you will need a battery box to neatly use your new batteries. 18650 battery holders are widely available online, varying in quality and purposes. Because most are made with plastic and thin metal connections, getting a hold a holder is relatively easy and cheap. Being straightforward, your main concern will be if you need a series or parallel connection, and the number of batteries held in the box. Quick recap: a holder set in series will increase the output voltage, while a holder connected in parallel will increase the charge capacity (mA). For example, we can use a box that holds four 18650 batteries with a rating of 3.7 V, 3400mAh. If the box comes in parallel, the charge capacity has increased to 13,600 mAh, while a series box will increase the output voltage to 14.8 V. There’s plenty of room to play with in the early stages of your CubeSat, however, your power budget is largely dependant on your weight, purpose, and the components that are using power. Batteries are just a part of the bigger picture, as most CubeSats will rely mostly on solar energy for power, and to charge the batteries during sun exposure.

CACTUS-1 Power board schematic

Presented here is the full schematic of the CACTUS - 1 power board, which proudly displays the battery, voltage regulators, and plugs for the solar panels. Before sending the pcb files to have this board manufactured, study the schematic to get a full understanding of how current will flow through the board, and where voltage needs to be restricted. On the left hand side of the schematic is a line of solar panel plugs for each panel on the CubeSat. Pierce has also left additional plugs (P5 and P6), in case your satellite may need to attach additional devices. If you are unfamiliar with the busy streets of schematics, please visit https://learn.sparkfun.com/tutorials/how-to-read-a-schematic/overview to get started.

CACTUS-1 PCBS - Sensor, Pi, Solar Autodesk Eagle

The zip file will open with a folder labelled 'PCBs' and an Eagle. epf file, indicating PCB data must be opened with the Eagle program. As the name suggests, PCBs will contain multiple folders and files on the PCB boards for the CACTUS - 1 picosatellite. Opening any labelled folder will reveal a plethora of file versions with a .sch and .brd file extension. Most of these are not human-readable, but assume you are using a PCB editor (like Eagle) or viewer program. A .brd file will show how the PCB board will appear after it has been manufactured. Think of it like the blueprint for a PCB board, which will detail the measurements and how the board schematic is translated to a working PCB. Schematic files end with a .sch extension, and simply show the schematic of the PCB. The other files (.cam, .libr, etc) are support files generated by the program and used by the PCB fabricator.

Structural Components

Vibration Test Clamp Fixture and Blueprint

Each CubeSat (or any satellite for that matter) must undergo some form of abusive testing to ensure the satellite can survive the trip to space. One form of testing is the vibration test, in which the satellite is put into a chamber, bolted down using a custom clamp fixture made for the satellite, and shaken around to simulate the intense forces felt from a rocket setting out to space. Think of it like the one scene from Finding Nemo where Darla (Braces Girl) shakes Nemo's water bag to high hell; If your dinky space box can survive the frustrated wrath of the metal faced god, you've earned the right to fly.

Bear in the mind the actual vibration motion is much smaller in distance moved-- more like a vibration sander or electric toothbrush-- but a lot faster than Darla can manage, at tens to thousands of vibrations per second. The vibration is run over low and high frequencies based on a spectrum or range, usually using a profile called GEVS (General Environmental Verification Standard, https://standards.nasa.gov/standard/gsfc/gsfc-std-7000) that NASA/GSFC makes available as a default good profile to test with.

Knowing the forces your satellite must survive, it is critical to design and forge a clamp that can secure your CubeSat in place. Provided in our repository is the blueprint used by CACTUS-1 for the CubeSat Vibe (vibration) testing rig. It is based off a design provided by Planetary Systems, modified by Capitol for 3U++ use, and has been provided to Morehead State University so they can test other 'tabbed' designs. A parts list with the part name, size/type, material and vendor is provided, as well assembled and exploded views of the clamp for a better understanding of the product. Additionally, the exact measurements of each component is openly laid out to facilitate the manufacturing process of the test clamp fixture.

CACTUS - 1 3U Tabbed Frame

Pierce Smith designed and drew the metal components for the CACTUS - 1 CubeSat. He designed the blueprint to feature the full dimensions and materials, making it easy for you and your metal manufacturer to replicate the design. Because the CACTUS -1 satellite is technically two payloads, the blueprint presents the framework for both TRAPsat and Hermes. The metal frames for the Bus, TrapSat and Hermes are presented in all their glory in a 1 to 1 scale. Additionally, the design for metal components used to hold the comms board, Aerogel, and batteries are presented.

Mission Readiness Review (MRR)

From an outsider looking in, the world of space policies, licenses and politics can feel overly complicated (And it is!). Designing and building a satellite can be brutal, even downright heartbreaking when so many things go wrong, or can’t be avoided. But there was a strong dedication I felt stepping into the Mission Readiness Review (MRR) with the Cactus - 1 team. A devotion to their craft that I have never seen in person, all resonating in one room. Members of TrapSat and Hermes (many couldn't come due to scheduling) all glowed with confidence and excitement for what they had made. I wasn't sure what to expect from the review, but I knew I was about to take in much more than I could chew.

MRR and pre-ship are only two of many rviews. Generally you run a PDR (Preliminary Design Review) before you get approval for going ahead with a mission design, and a CDR (Critical Design Review) before they approve going with the final flight build. At Capitol, these are informal, our CubeSat incorporates technology developed in part via our High Altitude Balloon (HAB) launches or in courses. In this context, our PDR is basically 'did a prof look it over and okay it' and CDR is 'are you set up enough that we're willing to buy parts to build it for real', especially with our high altitude balloons. But we did work PDR and CDR into the new Senior Design course, and schedule regular team progress reviews to ensure we were compying with our design docs, goals, and test plans. MRR was the only external review, to both NASA and the launch provider.

What I thought

While reading the NASA MRR checklist, I was left quite anxious and terrified of the events that were about to unfold. I still didn't know every nook and cranny of CACTUS-1, not the specs, how it was made, or who did what. Yet, here we were in a brightly lit modernist office kitchen, drinking NASA's coffee, waiting to be reviewed. I had no part in the inception of CACTUS, but the wall of a review still made me incredibly nervous.

Letting my imagination run amok, I expected a grandiose presentation, with the CACTUS team at the forefront. A stage for the satellite team, men in lab coats probing both man and machine for all its worth. Malicious engineers anxious to pick apart every piece of the team and their slideshow. "Why should we let YOU fools fly?" they would say, seeking to murder a mission. However, what I witnessed was far from my overdramatic daydream; In its place was a friendly hand, nudging and bugging the team towards a successful launch.

What happened

My poor misconception of the MRR ended swiftly, as there was no stage, no lab coats and no maniacal plan for failure. A welcoming breeze from the air conditioned room conjugated with the friendly faces of the reviewer and launch provider, revealing a professionally positive atmosphere for which missions are meant to fly. The room was set in a business-like manner; Professor Sandy Antunes introduced himself as the lead engineer and PI, Pierce Smith and George Giakoumakis represented TrapSat, Mark Horvath from Hermes, and Jorge the writing intern (twas I). Once everyone was formally introduced, the presentation began with Virgin Orbit's representative (launch provider) giving his power point, detailing the ins and outs of his company's rocket. Virgin's presentation primarily detailed their schedule until launch, launch location (California), launch time, actions the payload providers are allowed to do to before departure, and how their payload will be handled before launch. Pressure is put on by both the payload provider (CACTUS-1) and NASA on Virgin Orbit to ensure a safe flight for all payloads; Informing both parties that trained professionals will carefully handle all payloads in a secure location, once the payloads have been received. The launch provider's MRR is quite short, perhaps 30 minutes of capsulation and integration information. After the launch service presentation is over, the room is open to any questions and concerns.

After all question and concerns were settled, it was our turn to present the CACTUS-1 picosatellite. As the lead engineer, PI, and mentor, Professor Antunes took the lead in the presentation. Beginning the powerpoint with the main mission of both TrapSat and Hermes, he openly stated each payload had separate missions and worked independently, however, shared the same body. Essentially two payloads on one satellite; This lead to rather interesting engineering to work within each space. While discussing the purpose of each payload, the time frame of operation was established for each. Trapsat aimed to achieve their mission within 3 months in orbit. If the spacecraft hasn't burned up like my late night nuggets, the mission may continue for an additional 9 months. When the 12 months have passed, the satellite must enter a suicide state, manually turning on all LEDs to drain the battery of all charge. Hermes, however, was descoped by our team to operate for a week in orbit, then shut itself down. A licensing issue left the Hermes mission in a rather complicated position, only allowing the use of a specific frequency for 1 week, afterwards the payload must shutdown. Antunes chose to explain the main mission, time frame, any complications or oddities, and how the satellite will terminate itself.

Getting the room up to date with current events on the satellite was next on the priority list. Luckily for CACTUS, Vibe and thermal vacuum testing was completed just one week prior to the MRR, giving the team a chance to focus on the final build. A majority of the MRR was discussing the many quirks and features of the satellite, such as preliminary actions to prevent the antennas from deploying early or powering on during launch. In the case for TrapSat, a burn wire is set in place to deploy the antennas once in orbit; Hermes uses a timer prior to launch to prevent accidental power and voiding their license.

Overarcing issues such as Environmental Requirements that must be met with a CubeSat to be Environmentally Compliant are mostly handled prior to the review in the ODAR (Orbital Debris and Re-entry) filing we had to make with the launch brokers. Basically, we list all our materials in case any might be a problem. Other than that, we don't have much because we're not firing rockets. The rocket company has a lot of this paperwork to do for their rocket, though.

“Deployables verification” simply mean to explain that the satellite has deployable equipment attached, and that its purpose and that it conforms to any size/weight/safety requirements set in place. The other verification is providing evidence you tested it. We have 1 deployable on Cactus-1-- the antenna. A burn wire burns and the tape-measure antenna springs out from where it's tied to the side of the satellite. So we have to state that yes, we've tested the burn wire system and it works, and also that (safety requirement) we are confident that it won't deploy early or accidentally and thus cause a risk to the rocket.

The main discussions answer many general concerns, like potentially hazardous materials that flying aboard. “How will they be shielded within the CubeSat to prevent exposure to the rocket and surrounding payloads?” “Will your team need to apply for any waivers to approve the fit your size budget?” “What about any major problems and concerns you encountered during your build time or brought up in Vibe?” These are only a fraction of the questions you will encounter during the MRR to ensure a safe flight, not only for your team, but for every payload sharing the same launch rocket.

When discussing “Mission Assurance Issues” to the board of reviewers, common topics are there to discuss regarding the team’s confidence in their mission. Our MRR team covered this when we went, a lot of that meeting/MRR was them bringing up questions to make sure we are set. One required item is “System Verification update and non-compliances”, which is a catch-all to bring the review board up to date on any compliance concerns so it can be evaluated and either given a timescale to bring into compliance, or lead to a waiver being filed.

However, it cannot be emphasized enough to read through the PRP (Preferred Reliability Practices) MRR packet to double, triple check each bullet to make sure your mission fits within their specs. The MRR isn't a scary test meant to scare the weak. NASA wants you to pass just as much as you want to see yourself pass. In end, it's meant to see what your build and mission may be lacking, and how your team can improve before the launch date. Whether it's to finish the build, get tested, or trivial glitches, get it done after this progress review, and good luck.

How to improve team management and keep team members

gathered by Jorge Rodriguez from interviews with the Cactus-1 team

Cactus-1 was a student-led student-run mission where professors played a minimal role in oversight, primarily providing mentoring support and procurement support. As such, we noticed some general rules and tips from our build, that involved 30 students over a 3-year span.

TrapSat Mission

- *"TrapSat is a debris collection, imaging, and profiling subsystem with the goal to map out debris clouds in orbit."*

Hermes Mission

- *"Hermes is an experimental payload communication payload using the Iridium constellation for uplink and downlink communications."*

Why they use their orbit?

- *"The chosen orbit was a polar oribit (Altitude disclosed driven maily by TrapSat's desire to collide with debris which is common at the poles."*

Planned Lifetime

- *"About 3 months, with extended missions possible as far as the space craft survives."*

Budget

- *Goal: budget of about $20k, while the end cost of the satellite was under $10k*

Working as a student and teacher relationship

- A relationship is still a relationship as both parties getting back what their putting in?
- Keeping and organized system of notes of the project is essential so information isnt lost to the void **(Pierce solved most of this with his senior project)**

The management

- Prepare for the meetings/ establish a fixed time for weekly meetings
    - Bring results, questions and an agenda to your weekly meetings
- Make weekly progress
    - Keep everyone posted to keep communication across the team

Working with others

- Be clairvoyant with your team
    - Detail what has/ hasn't been done
    - What you need help with
    - What you don't understand

Pick a topic of mutual interest

- Begin with something in common for the beginning of the relationship
    - (Personal Note) For me it was the interest in cubesats and space physics/ satellites/ NASA
    - Have students build an emotional time for the project? (Not easy or forced but inspiration for students not to quit?)

Be explicit about what you need from your advisor

- Advisor will always be a compromise between their personality, your personality, his advising philosophy and the realities of limited time
    - Ask for more guidance of a different way of guidance
- Your value to the project lies in how much you get done it doesn't matter whether you invented it all yourself

Be a team player

- If there are other people in the project, find out what they're doing
    - Ask questions
    - Get a broader sense of the project beyond your part of the project

Share what you do

- Back up your work

- Comment your code
- Log experiments
- Keep everything valuable in a shared repository for yourself, your advisor and other teammates to look back on and study
    - Use github, google drive, dropbox
        - BUT KEEP IT CONSISTENTLY IN ONE PLACE

Avoid diffusion

- Do not spread out work over many different repositories, cloud services, emails , making it hard for anyone to look back and create reports for simple checking
- Keep track of what you've done as simple notes

Why do team members leave?

- frustration began from starting from scratch
- Short time and small budget was a restraint
- Began as a large collaborative effort from several departments of capitol
- Not enough consistent hands on board

Pierce Interview Notes

- Pierce noted that there was a disconnect between people in the subsystem level and whole level
    - Real world there's going to be a disconnect
        - You get paid and you're done
    - This isn't the real world, so there should have been more communication in the team
- A lot of frustration with heritage
- Originally had a powerbarod research team

    - The team wanted a powerboard build by another team that had been used and worked
        - Good example of heritage (According to Pierce)
    - Could not find information on the board from the team that built it
- Powerboard team could't find reliable information on a powerboard that had been previously used
    - They insisted on creating a new board but was shut down because higher ups insisted on boards with heritage to appease MRR.
    - Powerboard team quit because they weren't allowed to build anything
    - This point was made even more clear because the powerboard chosen, was then redesigned had barely been questioned during the MRR, and because it had been overlooked, it goes to show that heritage is not the end all be all of a project
- Quite a bit of advice and concerns from other professors and students were ignored when reviewing certain boards
- A lot of time was used to soldering and wiring high efficient solar panels, essentially wasting valuable time and manpower for minimal gains
    - Time could have been saved with bigger, less efficient boards
- Comms board team could not figure out how to fully utilized the comms board because of how undocumented it was.
    - When choosing outside built equipment, make sure it's fully documented or built in house so that it does not take months to understand an essential piece of equipment

Pierce Tips

- Ease of assembly
- Documentation
- Has it been flown before? / heritage
- Price
- PC 104 electrical and physical standard boards (only used physical)

Beginning People

- Started out with about 50-60 people (According to Pierce)
- Many of whom were just lurkers
- Many people stayed to simply help, like hold wires, assemble boards and generally being a helping hand
    - Spreading out the workforce to simply helpers, developers and designers could alleviate the stressful development of CubeSat
        - Designated helpers

Lessons Learned

Here we go through many of the lessons learned after our 3 year build. In Appendix A and Appendix B, we reference our Cactus-1 build explicitly, while in this section we cover general design and team management choices that would be of benefit to any team starting on a CubeSat project.

Successful 'Final Push efforts' by hard working students to complete milestone

- Final few dedicated students performed excellent work when approaching internal deadlines
- Final push efforts happen a lot because students are very busy while school, work and life
- Find reliable and hardworking students that want to stick around to make a successful mission

  Adaptation of designs and future-proofing work helped keep the program and keep schedule slip to a minimum
- Implement future proofing to designs

    - When two configurations are considered but unsure, implement bot so that future teams may choose either config in their designs
- Future proofing saves time and money for future development
- CubeSats are difficult for waterfall style work because new discovery of work tends to happen and future proofing may alleviate the unknown problems early on

- Design Choices involving heritage were not properly analyzed
- CubeSats meant to be experimental, not many CubeSats will have heritage
- It is important that a team challenges a heritage idea that the same way it would challenge any other idea
- A good idea, decent design, decent testing and documents to back t up will be more than enough to fly

Fixation on heritage

- Choosing to rely so heavily on the heritage power board was thought to be a good idea for legitimacy, and ease of use.
    - But new or old, the design didn't matter and there was so many mods done to the board that in retrospect a new board would have been better.
- Using the knowledge from the mission Pierce suggests to create a new powerboard for the next capitol mission.
    - Or create specific criteria for an existing board to minimize modification.
        - Want to create a One-size-fits-all design for CubeSats
- Cookbook Vol 1, Pages 29, advice and assumptions, are very important to your next design
- The assumptions about budget and size only apply if your design is similar to Pierce's
- It was no repeated many time sbut heritage is not the end all be all

Designing

- When designing in house, it can be an excellent learning experience for students to learn the ins and outs of a system
    - These rules don't really apply to processors and comms equipment as it would costs too much time and money to develop
    - Keep an eye on the power budget of the systems
        - Systems/ Comms ops Page 30
- Systems Synthesis = System Design
    - Translate the system functional architecture into a physical architecture.
        - It creates a "how" for every "what" and how well.
            - This design can be seen by how you would want to move while in space
                - Completely passive
                - Minimal pointing with magnets PMAC
                - 3 point axis controls with React Wheels
- PC /104 PCB Standard suggested many times

Appendix A: A Short List of Cactus-1 Considerations

This is a list of Cactus-1 subsystems and operations needed. Cactus-1's detailed engineering specification are provided in "Cookbook Vol. 1". We provide this list here to provide new teams a look at the number of potential subsystems so as to help you with forming appropriate teams to tackle the project.

- **Comms**
    - Comm board
    - Antenna
  - CPU (Pi)
  - Health and Safety Sensors
    - Temperature
    - Accelerometer
    - Magnetic Field
    - Battery/power levels
    - etc
-
- **Structure**
  - 3U metal frame
  - footswitches and inhibits
  - pointing/attitude
    - Passive magnets + hysterisis rods
  - Burn wire for antenna deployment
  - Thermal ets/mylar
-

- **Integration and Testing (I&T)**
    - Integration
        - anti-static
        - wiring
        - mounting stuff
        - software
    - Testing
        - component testing
        - Shake & Bake (vibe test, thermal vacuum test)
-
- **Payloads**
    - TrapSat
        - chunk of aerogel
        - 2 cameras + LEDs for lighting
        - triggered by CPU, sends back images
    - Hermes
        - COTS Iridium satellite modem
        - stand-alone; has own power etc
-
- **Licensing and Policy stuff**
    - MRR-- Mission Readiness Review (must-pass 2-hour review by rocket people)
    - FCC paperwork (and IARU/ITU stuff)
    - NOAA (approval for cameras)
    - Policies
- **"Do No Harm"**
        - Heritage
        - OS and COTS vs Custom design
        - Limits: 1.2kg/U, each U is 10cm x 10cm x 10cm, we're a 3U

- Requirements?
-
- **Ground Station**
- Antenna
- Radio
- Software
- ConOps (Concept of Operations)

We also provide our candid look at our initial plan and schedule, what constraints drove that, and how this matched the actual build process as it unfolded.

Cactus-1 Constraints

- Many risks and constraints
    - small school with small budget
    - schedule, cost and scope
    - To be built under $20,000 and in 2 years
- Because of the small cubesat community, pre-built subsystems were very expensive ($5,000-10,000 average) and finding subsystems that fit specific needs also difficult
    - Because of this, subsystems had to be developed in house to satisfy their needs and fit with the budget
- Outcomes
    - Succeeded in budget goals
    - figure 3 shows $9,300 on just CubeSat
    - Figure 4 shows $17,150 for whole program (out of $20k)

Time and Schedule

- Development started in August 2016 with goal to complete in August 2017
    - Much of the project was rushed and nowhere near completion by following year
    - Many risks that come with amateur CubeSat increase R&D time

        - Lack of knowledge
        - Need for flexible time schedules
        - Decrease in class participation
- Lack of knowledge
    - Led by sophomores
    - Students had some experience with other sounding rockets, but wasn’t enough to prepare the CubeSat workload
    - Many students first project
    - Large hassle as students needed to teach other students, rather than work on the project
    - Subsystems had many mistakes
- Need for flexible time schedules
    - Many mistakes meant for schedules must compensate for amateur mistakes
    - No Subsystems defined from beginning so development was in series, not parallel ideally
- Decrease in class participation
    - Lost interest, felt unneeded or stopped by school work
    - Development on several subsystems halted and need to be picked up sequentially by remaining students

Scope

- Two goals for cactus-1 made it rushed
    - Built in one year and under $20k
- Already a big project, then added difficulty of 2 goals
- Cactus-1 would have been unachievable from the start if it weren't for launch schedule slips
- Capitol has a reputation for building well built systems on a very low budget

- Niche commercially available parts were too expensive for initials goal, thus 'buy or build' was relegated to 'build' while delivering a fully functional system

Design Choices

Attitude control system

- Basic requirement is to keep in line with velocity vector and enable communications when needed
    - Low cost, low complexity, SWaP properties
- Chose subsystem called Passive Magnetic Attitude Control (PMAC)
    - No input power
    - Low space + low mass
    - No commanding (passive)
    - Simple to operate, hard to implement
- Uses hysteresis rods
    - Must use simulators to know right amount of hysteresis for how strong magnet should be
- System should be accepted but would flip 180° when going over poles
    - Cheap enough to work but now the TrapSat Payload needs to be mounted on both sides for access

Power systems

- Power subsystems was open ended
- Needs to provide power to Raspberry Pi and comms system
- Follow PC 104 standard
    - Physical required
    - Electrical preferred (Discussed later in doc)
- Could buy, buy from University, or build in-house

  - Buy too expensive
  - University parts were sadly undocumented so very unhelpful
  - Logical choice was to build in-house
- Original powerboard came from Interorbital CubeSat for free
  - Comms system from same company so integration theoretically easier
  - Not used because lack of sufficient voltage and lack of documentation
  - Power board drastically modified to make it reliable
- Powered by 18650 batteries
  - Cheap logical choice

Mechanical and Physical

- Biggest constraints for system, for deployment, and launch provider
  - Vibrational, physical size, and surface characteristics
- Structure big priority because most expensive and longest turnaround time
- Used commercially available frames as reference and inspiration for custom design to avoid buying
  - If cost of buying vs building were similar, it would have been more logical to simply buy a frame
- Planetary Systems inspired the single part to meet the mating requirements of tabbed sked interface between launcher and CubeSat
  - Vibrational and physical requirements go to rest of structure and allow for tolerances
- TrapSat payload need to be facing velocity vector during orbit to trap debris
  - Payload on front and back of CubeSat
  - HERMES on the bottom end
  - Have to find a right balance in payloads and components to balance center of gravity

Hermes Physical Segment

- Card Stack
- Batteries
- Shell
- Solar Panels
    - What is a helix antenna?
- Look at Cad files of Hermes to have understand its components

Thermals

- Thermals (Something to generate heat) not considered because temperature fluctuates between -10 Celsius and 10 Celsius
    - Mylar eting and hybrid aerogel insulation to insulate the CubeSat
- eting used inside and out to reflect sunlight, insulate the cubesat and because it is conductive

Solar Design

- Need to know basic electronics
    - Voltages
    - amps
    - whiskering
    - types of solder
    - silicon sealant
    - circuitry mitagation
    - diodes
    - etc.

- Learning basic electronics is key to designing efficient solar panel integration and placement

Manufacturing

- Decide on who makes PCBs
    - Make PCB files yourself in Eagle
        - Free software good enough for the job
    - Have a professional create the PCB
- Can learn how to read and design PCBs by following Pierce
- Pierce provides a short tutorial on how to recreate his solar panels in this final doc

Noted Efficiencies

- Packing efficiency
    - How much you can mathematically stuff on a surface
- Solar power efficiency
    - High efficient solar panels offset the low packing efficiency meaning they cannot reach peak potential
- Lessons learned
    - Learned from the geometry of the solar cells and solar panels to improve the rigidity of each cells in its uncut form
    - A lot of wasted space between the cells
    - Reduced work and time by opting for larger solar cells/panels
    - Efficiency loss using larger cells (50% eff) offset by larger area (2x area) plus adds ease of assembly.

Power Design

- Power comes in, cleaned and goes to charge or goes directly to power the system

- Students need to study how powerboard PCBs function
    - Parallel and series circuits
- Students need to learn about voltage regulators
- Voltages for your needs and reliable voltage
    - Voltage regulator does all the work

Power Distribution

- Charged from the original design
    - This was changed because original board was very unreliable and provided weird voltage
        - Removed boost circuit to DC DC converter
            - Need to know what these are.
- What are trim resistors in a circuit?
- Need to know when to quit with certain equipment to avoid frustration and no progress
- What is lockout voltage?
    - Lowest voltage something can function at, when below this voltage deville will turn off
- What is a Linear regulator?
    - Incoming voltage from the solar panel will be converted to lower bus voltage
- Deciding trade offs with efficiencies
    - read page 26
- Do you know how to add filters to a circuit?
- Protection diodes are useful

Appendix B: Markup and Comments on Capitol CubeSat Cookbook Vol 1. (the Engineering Guide)

We provide 2 sections here. First, a rating/review of our CubeSat Cookbook Vol 1.: The Engineering Guide, indicating the technical level of each section. That is followed by specific design insight and lessons learned to accompany that book. Note the table below also acts as a preview for the Vol. 1 Table of Contents, and we recommend you download this book as well!

Cookbook Vol. 1. Engineering Document Technical Difficulty Rating

CACTUS-I Overview .	5	(Easy)
CACTUS-I System Design	6	(Easy - Intermediate)
Constraints	6	(Easy)
Time and Schedule	7	(Easy)
Scope	8	(Easy)
Design Choices	8	(Intermediate)
Attitude control system	8	(Intermediate)
Power systems	9	(Intermediate)
Mechanical and Physical	9	(Intermediate)
Lessons Learned	11	(Intermediate)
What Went Well	11	(Easy)
What Did Not go Well	12	(Easy)
CACTUS-I Structure Design	13	(Easy - Difficult)
Major Design Features	13	(Intermediate)
Overview of Interfaces with Launch Provider	14	(Intermediate)
Material Choices	15	(Difficult)
BUS Segment	15	(Intermediate)
TRAPSat Segment	16	(Easy)
HERMES Segment	16	(Easy)
Thermal	16	(Easy)
Vacuum	17	(Easy)
Lessons Learned	17	(Intermediate)
CACTUS-I Solar Design	18	(Easy - Difficult)
Interfaces and Connections between Segments	42	(Difficult)
Solar	45	(Intermediate)
Larger Solar Cells	45	(Intermediate)
Larger Solar PCBs	49	(Intermediate)
The Fallback, using the Same Cells	50	(Intermediate)
Electrical	50	(Easy - Difficult)
Interfaces and Connections between Segments	42	(Difficult)
Solar	45	(Intermediate)
Larger Solar Cells	45	(Intermediate)
Larger Solar PCBs	49	(Intermediate)
The Fallback, using the Same Cells	50	(Intermediate)
Electrical	50	(Easy - Difficult)
Special note	50	(Easy)

PC/104 ISA	51	(Difficult)
Power Conversion Methods and Applications	53	(Difficult)
Bus Voltage	60	(Difficult)
Special note	50	(Easy)
Interfaces and Connections between Segments	42	(Difficult)
Solar	45	(Intermediate)
Larger Solar Cells	45	(Intermediate)
Larger Solar PCBs	49	(Intermediate)
The Fallback, using the Same Cells	50	(Intermediate)
Electrical	50	(Easy - Difficult)
Special note	50	(Easy)
PC/104 ISA	51	(Difficult)
Power Conversion Methods and Applications	53	(Difficult)
Bus Voltage	60	(Difficult)
PC/104 ISA	51	(Difficult)
Power Conversion Methods and Applications	53	(Difficult)
Bus Voltage	60	(Difficult)
Materials	18	(Intermediate)
Direction on Manufacturing	19	(Difficult)
Efficiencies	21	(Intermediate)
Lessons Learned	21	(Easy)
CACTUS-I Power Design	22	(Easy - Difficult)
Design Overview	22	(Easy)
Power Input and Cleaning	24	(Intermediate)
Charging	25	(Intermediate)
Power Distribution	25	(Intermediate)
Lessons Learned	26	(Intermediate)
Future Guidance	28	(Easy - Difficult)
Assumptions .	28	(Easy)
Advice	29	(Easy)
Recommendations for Design	29	(Easy)
Systems	30	(Easy - Difficult)
Con ops	30	(Easy)
General design constraints	30	(Intermediate)
Systems Synthesis	30	(Difficult)
Interfaces	33	(Difficult)
Power budgeting	37	(Intermediate)
Mechanical	38	(Easy - Difficult)
End Mount Improvements	38	(Easy)
Card Stack Improvements	38	(Difficult)
Tabbed Sled and Shell Improvement	42	(Difficult)
Interfaces and Connections between Segments	42	(Difficult)
Solar	45	(Intermediate)
Larger Solar Cells	45	(Intermediate)
Larger Solar PCBs	49	(Intermediate)
The Fallback, using the Same Cells	50	(Intermediate)
Electrical	50	(Easy - Difficult)
Special note	50	(Easy)
PC/104 ISA	51	(Difficult)
Power Conversion Methods and Applications	53	(Difficult)
Bus Voltage	60	(Difficult)

Cactus-1 Specific Engineering Design Lessons Learned

1. Making a new CPU would be too risky and costly for a small school, but using an existing CPU like an arduino or Raspberry Pi
    1. Check Page 33 for questions for each subsystem

- Look through Texas Instruments tech files for circuit board power supplies because Texas Instruments provides very detailed information on creating your own power supply. As stated by Pierce TC provides detailed information on how integrated circuits work, common circuits created with IC and the math behind it all.
- Because the mechanicals for Cactus-1 worked well, Pierce recommends to use the mechanical as a base for new systems
- Akins 15th law of Spacecraft design
- Design structure matrix (DSM) called N^2, is a matrix used to examine the interferees of a proposed system design
- Make a simplified design interface to avoid complication as the build itself will be heavily complex
- Understanding DSMS can be hard for the uninitiated
- Cubesats are meant to be looser paths to success than high scale, expensive satellites as much of the design comes from new experiences and exploration from students
- It is still recommended to use ISA PC 104 physical standard,
    - while the electrical standard could have been used, the board required would add unnecessary complexity to the board
    - The board was specialized for this mission

Power Budgeting

- A power budget is the balance between power coming in and power going out

Mechanicals (Cookbook Vol 1, page 38)

- The sled launching design worked well so this design should be used again for CACTUS -II or the CubeSat you make
  - Other launch designs considered but this works well

- (Cookbook Vol 1, page 38 and 39)
  - Card stack improvements are very technical
    - Leave to students to figure out

Interface 1

- Technical heavy to improve stack design

Interface 2

- Improvements or adjustments to the card stack design that may function for your design
  - Omitting some components for others etc.
  - Technical heavy

Solar (Cookbook Vol 1, page 45)

- High packing efficiency > low packing efficiency out balances low efficiency large cells
- if these powers balance out then that would mean a reduction in time and money for the same power output.
- When comparing solar panels, consider its length, width, max voltage, max current, power output per unit, wattage per area, price, price break and price per milliwatt
- Attempting to improve packing efficiencies
  - By using the same boards and cells, packing efficiencies could be improved in software by packing the cells in s a geometrically efficient way without thinking about human error. But real world examples would be very difficult task for students as they cannot recreate perfect computer designed boards.

- Compares various solar cells from IXYS which are 22% efficient and packing efficiency tends to be 70%
    - Smallest size available from IXYS that generates .5 Volts and 44.6 mA. These need to be connected in series to have a useable voltage
    - IXYS also offers multicell devices such as this 9 cell device which connects the small cells in series for convenience
- A comparison list is very handy for comparing size, power and power between solar cell units to determine the best cell for your needs and budget
    - Such as the Trisol X single cell vs IXYS single cell: $2 vs $1.4; 2.3V vs .5V; 14.6 ma vs 44.6 mA; etc.
- Pierce discusses the values of efficiency (lower = better)
    - Trisol X 28% while IXYS only 22%
    - Connection methods, time to build, quantity available, and ease of implementation should be considered
- Pierce compares the large SLMP121Ho9L 9 cell IXYS to the existing Trisol X had built solar panel design
    - Mid range wattage per one and price per wattage
    - Larger panel = shorter time to build
    - As of now (2019) plenty of parts available for CubeSat build
    - Based on previous experience, this board could be easier to work with since it uses the edge solder method
    - not large, implementation easier into PCB
    - Max voltage output is 4.5 volts, which is ideal for low voltage bus using 18650's

(Cookbook, page 48)

- Pierce redesigned the original solar panel to use the 9 cell IXYS cell and found that even from an individual power cell efficiency may drop from 28% to 22%, the packing efficiency has doubled, bringing an additional 20% over power: 510 mW (Trisol X) to 602 mW (IXYS)

Larger Solar PCB's (Cookbook Vol 1, page 49)

- Pierce noted that the way Cactus is built means that segments of the build could be taken and used as its own thing for other projects, however, because each satellite is unique, this perceived benefits is actually not useful. Because the modular feature is not needed the solar panels attached to the shells can be bigger based on pierces original design to span across multiple shells. This theoretical design could still work with the tabbed sled and solar panels.
- Pierce showcases the small and large solar panels he designed in EAGLE.
    - Because of the limitations of the free version, he could not create a merged board because of the area limitations
    - This can be remedied by paying the monthly/ yearly subscription
    - If given access to the paid version, Pierce could have merged 3 boards together for an increase from 55% to 58% in solar area, without creating 2 separate boards with wasted space in between
    - A 9.25% increase in performance would be seen as a merged board would allow for 5 extra cells

<u>The Fallback, using the same cells </u>Page 50

- Pierce desperately wants new cells to be used, however, if the Trisol X cells must be used, the packing efficiency has to be improved in the next generation to add new cells
- Tips for new board
    - Corner of cells re added to fall into position easier
    - less soldier paste used for each cell
    - packing efficiency increased by placing solar panels closer together
- To determine how close, students must learn to build a board and begin to plan the layout by their experience
    - Pierce provides a software example (Figure 43) to show what a new board could look like if assembled perfectly to improve efficiency and add additional cells. though tight, it can be done with steady mind and steadier hands.

<u>Electrical</u>

- Pierce highly suggests the power subsystem be build in-house for better integration and because it is the easier of the subsystems to create from scratch.
  - Wants to new subsystem to be PC/ 104 compliant for easier wiring
  - 3 Sections
    - Solar input and cleaning
    - power storage, charging and discharging
    - Power distribution and conditioning

Special Note

- Pierce leaves power board design to Erik Schroen. He has more experience with power board designs -- see his work in our Cookbook Vol. 3!

<u>Power System Block diagrams and controls</u> Intermediate Difficulty Technical

PC/ 104 ISA

- Board stacking design to PC 104 board
  - Female boards on top .1” spaced apart and male pins on bottom to stack boards with pins indefinitely
  - Pins available from SAMTEC
    - Can be purchased from Maser Electronics
    - 32 x 2 pin and 20 x 2 pin header
      - ESQ-132-14-G-D
      - ESQ-120-14-G-D
- To save space, remove the break away spacers on the header, which measures about .435”
  - Or order headers without spacers

- The benefit of standardizing the boards evident as Pierce demonstrates that the interconnected board layout constructs power pins that can provide power to every device connected to the pin.
- Total pins available 104 (2 x 32 + 2 x 20)
    - If needed, J2 (2 x 20) can be larger to provide additional pin, but would break ISA interface standard
    - ISA interference can only provide 1 amp per pin
    - If more amps are needed, use 2 pins and a 10 Ohm resistor to balance current
    - A wiring chart will be necessary to manage any connections with wires
    - Create pin chart of the ISA pin layout

<u>Power conversion methods and applications</u> Page 53

- Linear Regulators
- Boost Converters
- Buck Converters
- DC DC COTS
- Power storage with batteries

Linear Regulators

- Brings high voltages down to low voltages
- Done by shunting excess current to ground through another component link
- Efficiency varies depending on voltage difference from source to target voltage
    - Greater the difference, more voltage sent to ground, the hotter they get
- Does not use switching frequency to raise or lower voltage
    - DC voltage is fairly consistent
- Can react quickly to a charge in source voltage

    - output voltage not interrupted by change in voltage
    - not useful for capitol grade CubeSat but it is nice to have
- Power wasted from linear regulator
    - P = (V in - V out) * I Load
- Efficiency dependent on voltage difference
    - Efficiency = ((V in - V out)/(V in)) * 100

Pros and Cons

- Not efficient
- Cheap
- Very low noise input
- wasteful for power-starving CubeSats

Boost Converters

- Called a **Switch Mode Power Supply**
- Generate high voltage outputs from low voltage inputs
- Uses high frequency switching in combination with inductors, capacitors and diodes to create hight, steady voltage
- See figure 47 for Boost Converters explanation
- Active switch will turn on and off at high frequencies
- two stages to consider for the boost circuit
- Assume two things
    - In Continuous Conduction Mode (CCM)
    - Already reached Steady State (SS)
        - CCM means current in conductor will never reach zero

- Indicates circuit already providing expected power board

<u>Good applications for these devices </u>(Assuming voltage bus 3.6v to 4.2 volts)

- Communications high voltage source
  - DC DC converter followed by LDO linear regulator for high voltage, low noise
- **General 5 V power source**
  - boost converters for efficient 5V power source
- Solar Input
  - Because each case is different, you may find that a buck converter, linear regulator or a circuit is necessary for the voltage needed by the Bus.

<u>Bus Voltage </u>Page 60

- Central voltage that power distribution will run from
- (Solar) input voltage converted to bus voltage; converted to acceptable voltage for power distribution
- Part selection and cost may revolve around bus voltage
- Pierce mentions that an unregulated bus voltage is just a raw power source whose voltage may vary
  - this can be seen if the battery were connected directly in the CubeSat, meaning the battery was the bus voltage
- Solar power is similar
  - battery charging occurs during sunlight - **regulated**
  - When not charging battery sends power directly and is the bus voltage - **unregulated**
  - Because of the variability of voltgages, the circuitry needs to be able to handle the expected voltage ins
- Pierce clearly designed a circuit board that would try to provide a steady voltage between 3.4 and 4.2 volts

    - Battery voltage varies from 3.4 to 4.2 volts depending on charge
    - Solar input of 4.2 volts to allow charging at any point
    - When detects battery below 4.2 volts, will provide solar current to battery
    - Because of the varying voltage, all power distribution outputs must be able to take in 3.6 - 4.2 v and convert it to the necessary voltage for each subsystem

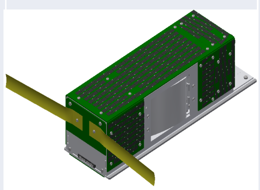
- Pierce’s power system is dynamic enough to distribute power to multiple subsystems with a clean voltage, and can be slightly modified with additional batteries in series to provide a higher voltage; A higher Bus voltage provides a wider range of potential voltages and alleviates stress on the components by lowering necessary current flow. Because of its background, the power bus may dynamically send power to any component at any time, dark or shine.
- Pierce showcase another example of an interconnected voltage bus for your next CubeSat, in which the bus is now regulated to a strict 5 V power supply. All activity (Power in and out) happens through the power bus, while switches are directly linked from the bus to the component for regulated power. An I2C chip can be added to the circuitry to monitor charging levels and switch subsystems on or off. Because of the added complexity, the I2C chip can communicate to the PI 0 over the newly implemented PC/104 ISA interface on the powerboard. The figure below demonstrates the detailed bus design with the major components connected, their power usage and how each component interacts with each other.

Appendix C: QUAD CHARTS

Quad Charts were an item teams were required to submit monthly to the NASA CubeSat Launch Initiative (CSLI), who were providing our free launch opportunity. We provide one such quad charts to show the format and general 'at a glance' utility of these reports.

CACTUS-1

Capitol Technology University



Mission Description

Cactus-1 (Unified Capitol U CubeSat-1) will demonstrate the use of Silica Aerogel for the use of capturing and profiling micro space debris and micrometeorites utilizing the TRAPSat subsystem as well as testing the performance of high bandwidth IP based communications (CiV) against conventional amateur radio access.

Major Milestones

07/16 PDR
07/16 PCaM prototype RockSat-X test
09/16 CDR
12/16 component testing begin
01/17 FSW testing (delayed to 4/17)
07/31 Final integration & test
09/17 Flight Unit Shake & Bake complete
10/17 FRR
12/17 Delivery

Size	Mass	RF Power	Configuration
3U++	2.8 kg+/- 15%	0.5, 0.9 W	Tabs

Deliverables Status

RF License: FCC License submitted, working on SpaceCap
ODAR: Will submit update
NOAA: approved (n/a)
MSPSP: Submitted

Issues/Concerns

Waiting for frame to ship.
Also trying to figure out how to attain a tab dispenser.

<MONTH> 2016

Appendix D: CACTUS-1 Original Proposal

[This is the initial technical description of our Cactus-1 mission. Notice that, as our proposal evolved, we change the name of our mission from "CapUSat" to "Cactus-1" (Combined Advanced Capitol Technology University Satellite-1). T his writeup below is provided for inspection purposes to other teams and is not the final draft of our proposal-as-awarded. We also include R. Schrenk's technical description as a support document.]

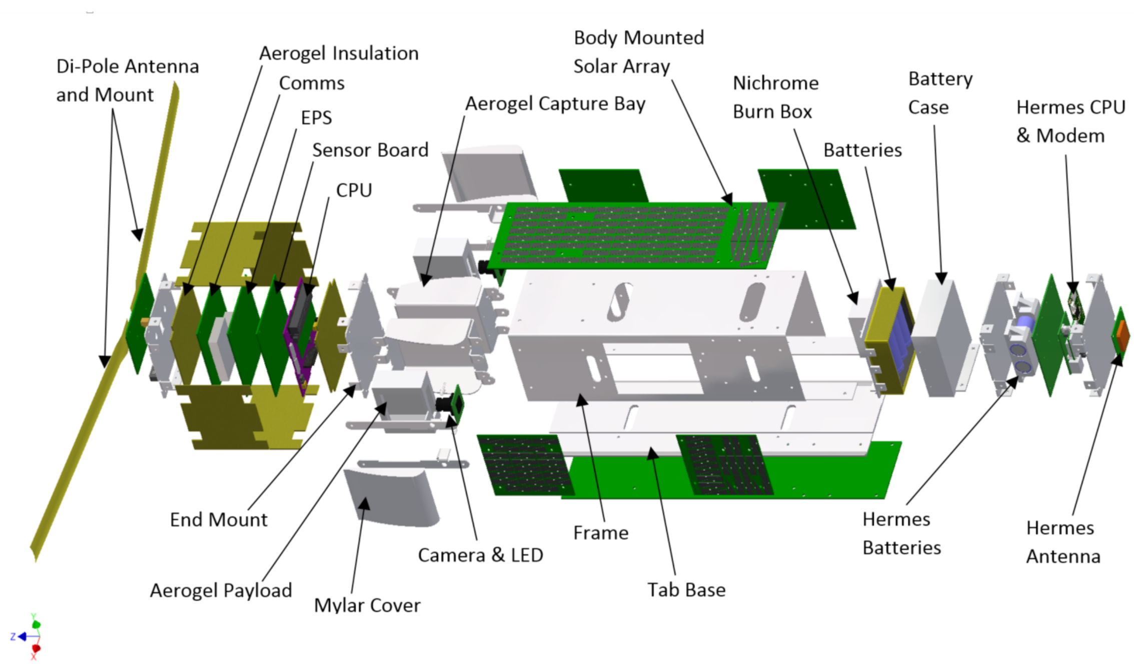
Our "CapUSat" (Unified 'Capitol U' CubeSat) mission is the capstone following our lab and high altitude balloon development programs, where our tested student-initiated projects can be deployed in their target orbital environment to demonstrate crosscutting and innovative technologies (Objective 1.7) and proving our detector technology is suitable for future use in profiling the content of the interplanetary medium (Objective 1.5). Our payload has 2 primary technical goals:

* Operate the Particle Capture and Measurement (PCaM) aerogel payload in orbit with sufficient cadence to yield debris and particle measurements of the near-Earth environment, and

* Use our CubeSat-via-Internet (CVI) commanding system to reduce the ground commanding 'footprint' by using ordinary internet utilities via a satellite internet provider (Iridium and/or GlobalStar) to increase bandwidth and reduce the need for custom commanding software.

Our tertiary technological goal is the use of aerogel et insulation as an effective lightweight thermal shield for CubeSats.

Our current work has a Technology Readiness Level (TRL) of 4, "Subsystem validation in laboratory environment" and we are moving to TRL 5, "Subsystem component validation in relevant environment", through our multiple high altitude balloon missions and upcoming summer ballistic flight. Preparing then flying in low Earth orbit will enable us to reach TRL 7, "System prototyping demonstrated in operational environment- space", a stage that can only be reached by an actual orbital flight. We intend to support this development at Capitol Technology University through our existing program incorporating classroom work, senior projects, and both internally and Maryland Space Grant Consortium funded internships.



TECHNICAL DESCRIPTION

CACTUS-1

December 2016

Capitol Technology University

Ryan M Schrenk

rmschrenk@captechu.edu

The overall goal of the CACTUS-1 mission is to profile and capture micrometeorites and micro-debris using aerogel in an effort to initiate the cleanup of LEO as well as provide a platform for a technology demonstration for an experimental communication and command subsystem, and verify our bus design (which itself is based strongly on open hardware designs).

The satellite will be launched as a secondary payload aboard Launcher 1, December 2017. It will be inserted into a Polar orbit at at nearly circular roughly 500 km semi major axis, on an inclination from the equator of or near 90 degrees. Cactus-I will deploy unpowered and be able to receive communications after a charging orbit. Transmission of health and safety telemetry and payload data occur when commanded by the ground and are capped by the flight system at no more than 10 minutes in duration (or when a turn-off is received, whichever comes first). The satellite is also capable of short periodic health-and-safety packet transmissions. The satellite will have a toggleable capacity to respond to amateur user 'pings' with a short return telemetry packet to encourage educational use.

Our minimum mission success criteria is two weeks of working operations; our nominal mission duration for scientific results is 3 months; our extended optional mission duration is 2 years. Atmospheric friction will slow the satellite and reduce the altitude of the orbit, along with negligible mass increase and energy from likely impacts, will help to slowly de-orbit the satellite. De-orbiting timescales will be assessed as per the ODAR (Orbital Debris Assessment Report).

The spacecraft is a single 3U unit with the dimensions of approximately 36.6cm x 10.3cm x 11.0cm, based from our launch provider IDD (Dec 2016). We using the cannister tab design (rather than the older rails style). The total mass is roughly 2.75 kg.

SUBSYSTEM DESCRIPTIONS:

Guidance, Navigation and Control (GNC) Subsystem:

The CACTUS-1 spacecraft will be utilising Passive Magnetic Attitude Control or PMAC to accomplish GNC. PMAC is comprised of a pointing magnet and hysteresis rods for angular momentum dampening. Since this system is passive we have no true GNC subsystem and no orbit corrections can be made.

Command and Data Handling (C&DH) Subsystem:

The C&DH for CACTUS-1 utilizes a main frequency 433.050-434.790Mhz. This is accomplished through using a Radiometrix TR2M-433-5 multi-channel transceiver with AFS2-433 RF power amplifier. The Antenna is a full wave dipole tape antenna. The system is controlled by a PiSat board running NASA's open source Core Flight Software (CFS).

The second or experimental Hermes comms system is comprised of an Iridium modem 9603 N transceiver and a helicoil 48mm antenna.

Electrical Power Subsystem (EPS):

The primary EPS is a direct energy transfer system using the solar array to produce 3.08W average. This is composed of (6) 1U and (2) 0.5U solar panels using Trisol 28% efficient GaAs triple junction solar cells, it utilizes (4) COTS LG 18650 3.7V 28090 mAhr Lithium ION battery cells. The EPS drives the primary PiSat board, which acts as the distribution hub for the sensors and payloads. Nominal power usage is 1.77W with an additional +1.1W when transmitting.

The Hermes secondary payload experimental EPS consists of (4) 0.5U solar panels using Trisol GaAs 28% efficiency solar cells, and (2) COTS LG 18650 battery cells. Hermes will utilize the smart technology within a power bank to distribute power evenly throughout the system. Hermes will use a fractional duty cycle for use and spend the majority of its time powered off and charging, with short experimental use of the Iridium modem.

To turn on the entire CubeSat, there are two powered inhibit switches and 1 SW timer to ensure that the spacecraft is triggered on when launched from the launcher.

Thermal Control Subsystem (TCS):

The TCS insulates the card stack of the CubeSat with Aerogel eting insulation. The CubeSat will have embedded sensors within all systems to monitor thermal anomalies through the PiSat boards and transmit the temperature data. If any temperatures reach a certain threshold that is considered unsafe, there will be a set of RTS commands and procedures to maintain the temperature such as; deciding which sections to turn on or off, or speed up or slow down the processor or hibernate until temperatures reach a safe and nominal threshold.

Structure Subsystem:

This structure is a 3U++ canisterized payload (based on 12/2016 IDD). The structure is fabricated with 7075 Aluminum for the outside structure. (Details on the significant layouts and designs)

Propulsion Subsystem:

There is no propulsion subsystem integrated within the spacecraft.

<u>Pressure Vessels:</u>

There are no pressure vessels. The possible hazardous or exotic material is that we are using silica aerogel as an orbital debris capture mechanism, as a two 51mm x 51mm x 13mm pieces. We are also using aerogel eting encased in kapton tape as insulation in our thermal et.

<u>Payload Subsystems:</u>

TRAPSat (TRapping with Aerogel Prototype Satellite) will be used to capture micro-meteorites and other various types of space debris. This system will include Silica Aerogel monolith as the main instrument for the capture and a camera to take a picture of the Aerogel. The Aerogel will be placed within a 3D printed RASC (Raised Aerogel Support Container) for secure placement. The data collection will be stored through the PiSat compute module. The second payload, Hermes, will use COTS Iridium 9603 Modem to serve as an experimental communications payload while utilizing the orbiting Iridium Constellation of satellites. This system will use a Raspberry Pi Zero as the compute module. By incorporating these payload in this 3U CubeSat mission, this will be one of the few CubeSats that has two integrated payloads on one mission.

CubeSat material/construction description. The primary CubeSat structure is made of Aluminum 7075. It contains all standard commercial off the shelf (COTS) materials, electrical components, PCBs and solar cells.

Appendix E: Day in the Life test

Cactus-1
Day in the Life Report
July 9 2018
Alex Antunes, PI, aantunes@captechu.edu

A. Scope and Overview

The purpose of this document is to provide verification of the Cactus-1 day-in-the-life for ELaNa XX. This provides verification of the operations of the primary Cactus-1 bus and the TrapSat payload module. We performed the below set of operations prior to and after our vibe testing and thermal vacuum.

We note that the remove-before-flight pin and Day in the Life test of the Hermes Iridium modem payload cannot be performed due to licensing; once the Hermes system is active, it operates for 7 days then shuts down and deletes all software to ensure full compliance with the FCC shut-down and terms of the 7-day Iridium license. As the Hermes module is a stand-alone bolt-on secondary payload, it is not within the needs nor scope of thsi test.

B. Test Overview

This functional test covers two scenarios. The first is Initial Deployment and Power-up of the Satellite, testing the footswitch power inhibits, the boot-up procedure, and the autonomous release of the antenna via a burn wire circuit. We then include a 'standard orbit' test of the spacecraft being contacted and performing its data sequence and downlink, in order to test payload system functionality.

For these tests, for the initial burn wire to release the antenna, we substituted an LED for the burn wire to avoid having to open the satellite to replace the burn apparatus. The burn release test of the wire and the antenna were carried out earlier at a component level in a small vacuum tank, and also tested in a high altitude balloon flight.

The full sequence is below. Items in italic are test procdures that would not occur in actual flight, but that we do as monitoring during lab tests to provide additional analysis data.

1. The footswitches are depressed.

2. The remove-before-flight pin is removed from the main satellite.

3. The footswitches are released.

4. After waiting an estimated minute for boot-up, we use a network connection to verify the satellite has powered up.

5. The automatic antenna deployment command is seen (via #4) to occur at time + 15 minutes. (We keep the burn wire inhibit; no actual burn occurs during testing)

6. An initial camera data image pair is taken autonomously by the TrapSat payload.

7. After a wait of 5 minutes, representing a period of satellite operations, we initiated a data gather:

    a. a 'transmit data' command is sent

    b. automatically, all health-and-safety systems are polled

    c. then, comms tranmission is initiated to transfer this health-and-safety packet

    d. then, comms transmission ceases and the comms device is powered down to save power

    e. automatically, a new pair of TrapSat camera images are taken (for downlinking at the next contact)

8. The satellite returns to its sleep/wait state until another 'transmit data' command is received.

C. Test Results and Conclusion

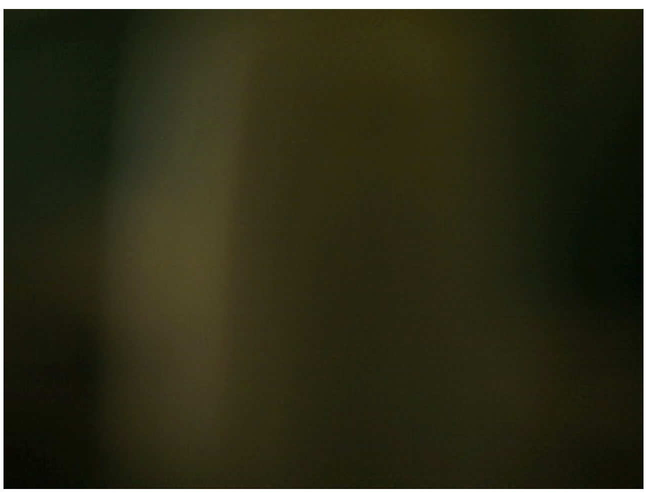
The most recent test was carried out on July 6, 2018 (immediately following oru therma-vacum tests). The sample health-and-safety packets from ground are shown below. The sample image files were generated and are attached; they are dark (as expected) because there was obviously not the sunlight illumination that we expect in orbit (the payload expects passive solar illumination to get clear images).

The initial boot sequence and data sequences both function. No transmissions occurred other than at the commanded times. The health and safety data is appropriate and matches ground tests. No anomalies were found.

Sample health-and-safety packet:

WJ2XBN Cactus-1:04-Jul-2018 01:34:54UT:GPU/CPUtemp=32.6C,32.552C:Temp=24.60C,Pre=99428.00Pa,Alt=158.30m:ADC =3344,3168,3120,4256:Mag=-360,-1721,-684.

Cam 0 test data:



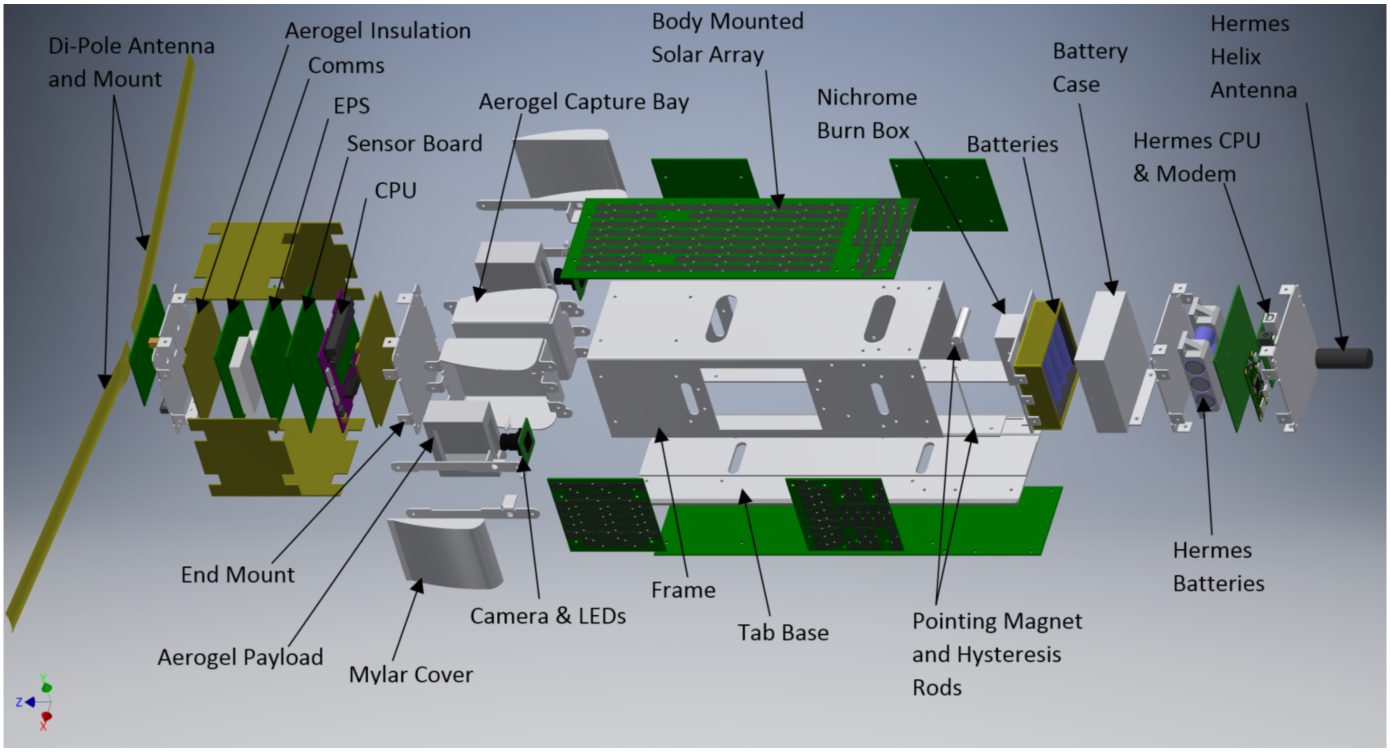


Figure 1: CACTUS - 1 Expanded View

Appendix F: Additional Resources

In addition to our Capitol CubeSat Cookbook Vol. 1: Engineering Guide, this document (Vol 2.: Newcomer's Guide), and Vol. 3: Designing a Common Electrical Powersystem), the links below are additional CubeSat references.

List of NASA Preferred Reliability Practices

https://oce.jpl.nasa.gov/preferred_practices.html

Environmental Compliance Definition

https://www.rmagreen.com/rma-blog/what-is-environmental-compliance

AeroSpace Failure Review Board Guidance Document

http://aerospace.wpengine.netdna-cdn.com/wp-content/uploads/2015/04/TOR-20118591-19-Failure-Review-Board-Guidance-Document.pdf Pg 18 & 22 for UVF

NASA CubeSat 101

https://www.nasa.gov/content/cubesat-launch-initiative-resources

CubeSat 101: Basic Concepts and Processes for First-Time CubeSat Developers (pdf)

How to do research with a professor

https://www.cs.jhu.edu/~jason/advice/how-to-work-with-a-professor.html

Student Team Projects: Tips to Complete a Successful Remote Project

https://collegepuzzle.stanford.edu/student-team-projects-tips-to-complete-a-successful-remote-project/