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Getting Started: Using a Global Circumnavigation Balloon Flight to Explore Picosatellite (CubeSat) Technology

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Abstract

Washington University's Project Aria is currently involved in the CubeSat program. Project Aria is a student-led engineering education, research, and K-12 outreach program. The project's CubeSat goal is the development of a spherical imaging spacecraft, the "Palantir", ready for launch in late 2002. Recently, the Palantir team was offered the opportunity to fly a small payload on a global circumnavigation balloon flight in mid-2001. The payload would collect atmospheric data such as temperature, pressure, and humidity. The student team decided to use this opportunity to explore various technologies they plan for Palantir. This resulting in a fast, challenging engineering project that developed the skills needed for a successful picosatellite project.

The technologies to be explored include a self-contained power system with solar cells, on-board computers, on-board cameras, various sensors, satellite communications, and mission operations. One specific test involves mounting temperature sensors throughout the probe. The students will then compare actual thermal reading to predicted thermal readings. Other specific tests will involve the use of several different types of solar cells to judge performance. Finally, students will remotely operate the payload as they would the satellite to explore operating concepts and tools. This balloon opportunity allows students the chance to explore various technologies and operating concepts needed for a successful satellite program without the high cost of a launch.

This paper briefly describes the Palantir CubeSat program, the Palantir Technology Demonstration balloon program, and the results of the flight. Particular attention is paid to goals of the balloon flight and a review of the successes and failures. Lessons learned from the test flight can be applied to other universities seeking to develop CubeSats and other project-based programs.

Introduction

"If, by chance, you happen to be in the southern hemisphere this summer (to us Northerners) and spot what appears to be a giant light bulb floating in the sky, don't panic. It is definitely flying and at the same time an object, but it is most assuredly identified. What you probably are looking at is Steve Fossett's hot air balloon, which will carry him in his fifth attempt to circumnavigate the world. Attached to his balloon will be a small engineering test payload, the Palantir Technology Demonstration. The tech demo or, simply known as the "payload", was designed and constructed by Washington University students to demonstrate various engineering concepts and collect scientific data relevant to upcoming space missions. The payload will also take pictures and collect atmospheric data throughout Fossett's flight."[1]

At least this was the original plan. In the summer of 2001, the undergraduate engineering team of Washington University's Project Aria was given the opportunity to fly a payload on Steve Fossett's round-the-world balloon flight. The plan was to fly a technology demonstration of various systems that would be needed for the upcoming Palantir spherical imaging cubesat.

The payload was to be mounted on the outside of Fossett's balloon and use a combination of solar cells and batteries for power. The payload was to collect temperature, pressure, altitude, humidity, and location data. This information would be gathered by the computer system on board and sent back to St. Louis via the amateur radio and satellite network. In addition to the mission control staff at Washington University, schools in Australia were going to be tracking Fossett's flight and the data received by the tech-demo. Perhaps the most interesting sensor on board was a small camera that will be able to take pictures of Fossett's flight as he travels around the world, which will serve as a prelude to the final goal of the Palantir Project.

Although the goal of this project was to build and fly a prototype, the real purpose was educational. Our long-term goal with this student team is to build a series of picosatellites based on the Cubesat concept – the Palantir. The Palantir is a very challenging project, particularly with undergraduate engineers. The technology demonstration would allow the student engineering team a chance to design, build, test, and operate a completely self-contained "satellite" without the associated launch-costs. The project was a great opportunity to expand our student's knowledge through a real project. As an educational project, it was a great success. As a payload, it fell short of its goal.

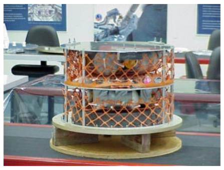
Project Aria

Both the Palantir Technology Demonstration and the Palantir Cubesat project are part of a larger educational, outreach, and research program in the School of Engineering and Applied Science at Washington University in St. Louis. Project Aria is an education and outreach program designed to aid both engineering undergraduates and St. Louis regional elementary and secondary students. Project Aria is a hands-on space engineering/science program that allows students to gain engineering and science experience through the analysis, design, manufacture, launch, and operations of various space-related projects including spacecraft and space technology projects. It allows them to work with multi-disciplinary teams on a project beyond the scope of any one person or one discipline. The purpose for including elementary and secondary students is to encourage them to go into a science, engineering, or technology field by exposing them to exciting work prior to their academic and career choices.

Currently Project Aria is focused on several different space engineering projects. One of these, the Aria-1, is a Space Shuttle-based project that flew on STS-106 in September 2000. This project carried forty-five experiments from over three hundred K-12th grade students from eight local area schools. A second shuttle-base project flew

[1] Jared Macke (Sophomore – Computer Science)

in March of 2001 and carried 124 experiments



from 22 schools. A third shuttle-based project, the Aria-3, is schedule for flight in November of 2001. This is a joint US/Australian outreach program carrying 22 experiments from eight Australian and seven US K-12 schools.

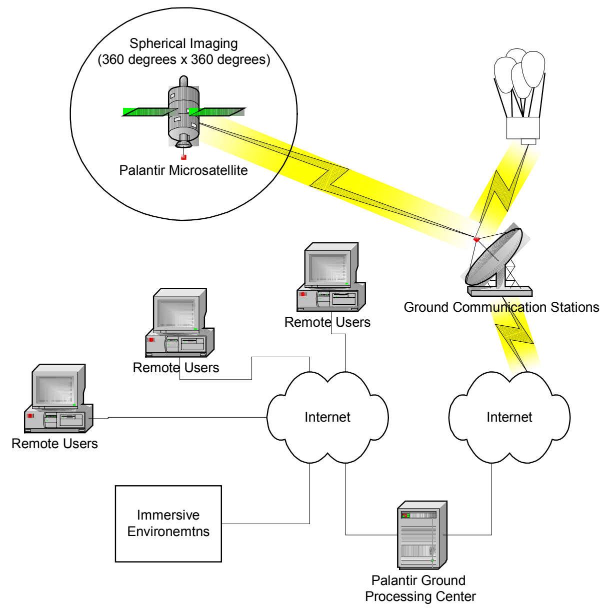
Palantir Program

The Palantir program is one of the newest programs of Project Aria. Currently, Palantir is restricted to university students although there are plans to involve K-12th grade students during operations.

The Palantir program is a student-lead research project aimed at improving humankind's ability to understand space through unmanned satellites and robotic probes. Consisting of a series of picosatellites combined with advanced ground systems, the project Palantir will allow individuals to experience space from the point of view of the Palantir satellites.

The Palantir program includes an on-board imaging system capable of capturing wide-angle imagery. Accordingly, the satellites will receive, record, and repeat image data from the space environment and then transmit that data through a ground station network to both remote desktop computer users and advanced immersive visualization systems.

The Palantir is based on the CubeSat concept developed by 10-cm3 cube designed to use a common launch system.



Palantir Development

Obviously, the Palantir program is a very ambitious and technically challenging program. It has yet to be demonstrated that it is even technically feasible. Adding to this complication is the inherent lack of experience that is associated with an undergraduate student project.

The development team is student-lead with mentoring by various faculty members (including the authors). The team consists of students from all collegiate levels working on the project over the course of several years. During that time, both student project managers and team members will change as students graduate, go on to other activities, and join the project. This leads to a very challenging management situation. To help, we are always on the lookout for shorter-term activities that will encourage both student education and team development.

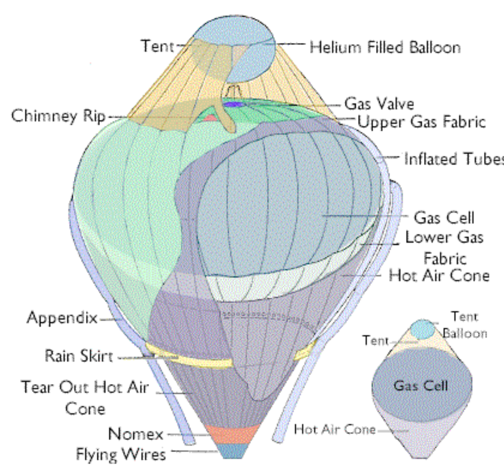
Solo Spirit opportunity

In early 2001, the Palantir student engineering team was offered a chance to fly a payload on Steve Fossett's next solo circumnavigation balloon flight attempt. Steve Fossett is one of a handful of global ballooning adventurers. Fossett's goal is to be the first person to fly a balloon around the world solo. The project, Solo Spirit 2001, involved launching his balloon from Kalgoorlie, Australia, fly across the South Pacific, across South America, across the South Atlantic and the Indian Ocean back to Australia.

The Solo Spirit balloon uses a combination of helium and hot air to fly, a design known as a Roziere balloon. The balloon envelope is 140 feet tall and 60 feet wide. It contains 550,000 cubic feet of helium plus 100,000 cubic feet of hot air. It was designed by Donald Cameron and built by Cameron Balloons Ltd, Bristol, England. The balloon contains no engine; powered solely by the wind. Forty tanks of fuel, a mixture of propane and ethane, hang from the outside of the capsule. This fuel is burned to heat the helium in the balloon to cause it to rise. The pilot steers the balloon by ascending or descending to catch winds blowing in the desired direction. The balloon carries the Comstock Autopilot, which can maintain the balloon at a constant altitude by using a computer to control the burners. This allows the pilot to get some sleep!

Cameron Balloons also built the gondola, an unpressurized capsule 7' long, 5' 6" wide, and 5' high. It is a lightweight composite of Kevlar and carbon, fitted with a plastic bubble hatch on top. Lithium batteries power the electronic components inside the capsule. A pair of heaters keeps the capsule interior temperature between 40 and 70 degrees Fahrenheit.

A Global Positioning System (GPS) relies on satellites to determine the balloon's precise latitude and longitude for navigation. The Inmarsat C satellite communication system is the primary means of communication between Solo Spirit and Mission Control, with the Inmarsat Mini M satellite telephone as a backup. High-Frequency (HF) radio is used for communication with Air Traffic Control. Very-high-frequency (VHF) radio provides air-to-air and air-to-ground communication up to 100 miles. The Solo Spirit Mission Team is not giving making the radio frequencies used available. Finally, the balloon is equipped with an Emergency Position Identifier Rescue Beacon (EPIRB) which can be activated by the pilot to initiate an international search and rescue.



Pros and Cons of the Solo Spirit Opportunity

The first step for the student team was to decide on whether to accept this opportunity. The flight would allow the team to fly some form of prototype or technology test-bed. The flight would allow:

- Global operations
- Global satellite communications
- Challenging environmental conditions

Although the flight shared some of the characteristics of a satellite, it did not share all. Unlike a satellite, the payload would be subjected to varying pressure and humidity. Like space, the payload would be subjected to temperature extremes (although not to the same degree as space). This lead to the question of how valuable such an effort would be for future satellite development. After consideration, it was decided that the knowledge gained would greatly benefit the student team.

Technology Demonstration

Once the decision was made to proceed, a list of features was developed. The payload was:

- To be self-contained, i.e. draw no power or support from the Solo Spirit.
- Generate power via solar cells.
- Collect external temperature, pressure, and humidity data.
- Collect internal temperature, pressure, and humidity data. Particularly collect temperature date throughout the payload in order to validate the students thermal predictions.
- Collect power data from solar cells and batteries.
- Take external images.
- Communicate this data via Amateur Radio links.

Technology Demonstration Design

The design of the payload consists of multiple subsystems. During the design and development stages, the payload team was split up along the lines of these subsystems. Along with a group specified to keep an overview of everything, there were weekly meetings (daily meetings as we approached integration) where all the subgroups would update the team on their ideas and plans, thus keeping everyone aware of everything. This helped to guarantee that all the subsystems would work together. The subgroups were divided into

- Power
- Camera
- Sensors
- Communications
- Computer
- Structure

There were some general specifications that needed to be met with regard to all of the components that would fly. Basing our data off of Mr. Fossett's previous flight, we needed components to work in a ½ atmospheric pressure environment with an average temperature of –20°C.

Power

In order to allow the payload to operate, power was essential. Two sources of power were chosen. First a set of batteries was to be used. It was chosen that the 12 volts needed would be comprised of two battery packs, each consisting of 100 1.2 volt, size C, NiCd batteries. Each pack would have 20 tubes of 5 batteries in series. The 20 tubes were placed in parallel and the two battery packs were placed in series. Originally Lithium batteries were examined due to their extremely light weight, however they were not rechargeable, therefore NiCd batteries were chosen. The batteries had to be rechargeable in order to work with the 2nd source of power, 36 solar cells. Solar cells were used in order to test

them on their efficiency and whether or not they would be a viable option for the CubeSat. The solar cells were set up on all sides of the payload and were wired so they would either power the load or recharge the batteries. Diodes, voltage and current sensors were added to accumulate data on their performance.

Camera

One of the main acquisition components of the Payload (being a prototype of the CubeSat design) was that of a video camera. A CCD camera would transmit a video stream into a frame grabber which would snap a picture and save it to the computer's hard drive and allow for it to be downloaded at a future time.

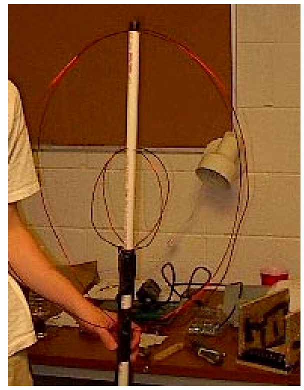
Sensors

The other main acquisition components were the sensors. The payload had both internal and external sensors. A humidity and pressure sensor was placed both inside and outside the container. Two accelerometers were placed inside the container, measuring vertical acceleration and rotational acceleration of either the container or of the balloon, depending upon the final mounting.

A collection of 25 temperature sensors was also implemented. These were strung on a single CAT5 cable and would measure temperatures of different components and also the change of temperature (delta T) across the container's sides, along with one sensor that would hang a few feet below the payload to gather the atmospheric temperature. A GPS (Global Positioning Satellite) was also onboard to track the flight during the 15 days.

Communication

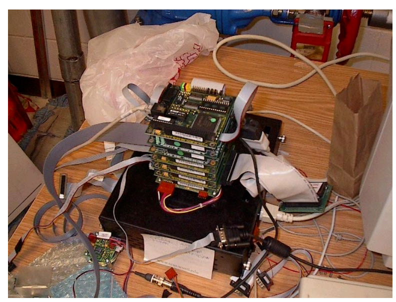
In order to send the saved data to volunteer ground stations across Australia, South America, and South Africa, a communication system had to be developed. The project used a Kenwood HAM hand radio with a built in TNC (Terminal Node Controller) connected to the computer. The antenna used was a self-built eggbeater with both 70 cm and 2 m band capabilities on the same antenna. The antenna was connected to a duplexer (allowing both bands to be connected to one radio), which in return was connected to a coaxial cable of approximately 12 feet in length. This



allowed the antenna to hang down from the payload, around the Solo Spirit fuel tanks and below the capsule, thus allowing a full 360° communications range. The software was designed to encode the data/images in UUencoding and transmit it to ground stations who would use ProComm (a shareware software program) to download the text. The ground stations would then log the text in a file and e-mail it back to control in St. Louis where the UUencoding would be decoded.

Computer

Computer control was a fundamental part of the Technology Demonstration. The flight



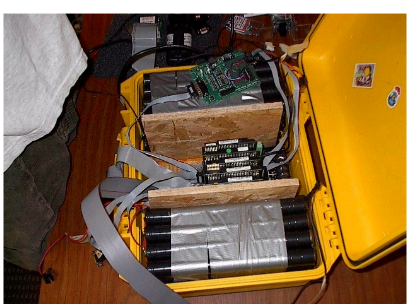
computer was based on the PC/104 architecture. This architecture allows a PC compliant computer to be constructed in a minimal amount of space. Each board plugs into each other forming a vertical stack that shares a single bus. On the base of this stack sat a WinSystems 133 MHz CPU card with 32 megabytes of memory. ATD (Analog to Digital) cards were added to gather the analog data from the humidity, pressure, and electrical sensors. This data could then by digitized and stored. A frame grabber board was used to capture images and a DC/DC converter board was used to supply the 12-volt input to the specific components, with 12V or 5V, depending upon the need. A 160-Mb solid-state flashcard was used to house all the software and acquired data.

The Linux Operating System was chosen to run the computer. Linux is renowned for its stability and its ability to run on minimal systems with minute hard drive usage, a plus for a system which more hard drive space meant more pictures. Linux also allowed relatively quick software development thanks to its open source nature. However the operating system did prove to be troublesome due to its lack of "user friendliness," and many of the students' unfamiliarity with the operating system. This did make troubleshooting difficult when problems arose in Australia.

The computer was designed to cycle through a series of states and then shut itself down. It would boot up, obtain temperature readings, sensor readings, GPS readings (GPS was acquired last so ample time was given to get a lock on the GPS satellites) and then the computer would take a picture. Once this was done, the radio would be initialized and a beacon would be sent out every 30 seconds, for 10 minutes. The beacon would appear on the ground station's computer with the given call sign to log into. Once connection was accomplished, the PC/104 would automatically transmit the UUencoded files.

After 10 minutes, the computer would set a microcontroller with timer to restart the computer in 50 minutes and then would shut itself off. Through this process we would accumulate data every hour on the hour, where zero is when the PC/104 was manually started the first time, and this would be given to the ground stations so they would have an accurate clock to work by.

Structure



The structure to house all of this was relatively simple. A Pelican travel case was used as the main container and was approximately 15 x 10 x 6 inches in dimension. Inside, the case was partitioned into three sections, where the two sides would be used for battery placement, leaving the middle partition for the electronics. An internal structure was built from plywood, creating a floor and two walls. This was used to house the PC/104 and the majority of the sensors and radio. The camera was placed at the end of the internal structure and held in place by RTV Silicon adhesive. On the outside, a structure of metal struts and L-brackets were used to create an exoskeleton. The exoskeleton was used to allow the solar cells, which were RTVed onto acrylic sheets, be attached by bolting on the acrylic sheets.

Integration

Status upon arrival

Integration of the Payload was performed in Kalgoorlie, WA (Western Australia) in the airport workshop. The last bits of software needed to be uploaded and all the wiring done. When the Payload arrived in Kalgoorlie, It was found that the PC/104 would not respond on the serial terminal, a fault that originated in the operating system caused by multiple and quick power cycles. Due to the 13-hour time difference, communication with the support team back in St. Louis was limited to a few hours a day. Therefore, it took a few days to fix the PC/104.

Upon completion, the wiring was worked on and the software was uploaded. Multiple versions of the communication software had to be tested until all the bugs were resolved. This took a few days, once again due to the time differences.

Anomalies

After a few weeks of work (at all hours to accommodate the time difference) the payload was 100% working. Further testing was performed in order to determine anomalies that could happen or that we could force to happen, so that directions could be written to bypass them. Everything else was then installed into the structure. Once the computer was installed a test was run, resulting in a computer hang. It was determined that the IDE cable connecting the computer and flashcard wasn't working correctly. A replacement was found and installed. During this process, an error occurred and the PC/104 was taken back out to be worked on.

While this error was being examined, a very unique and unknown anomaly occurred which caused massive power drain and strange reactions by the hardware. The reason for this is unknown, as this anomaly was never reproducible. However, during the anomaly, the flashcard was fried. Unfortunately, without a computer to drive the processes, the payload was disabled.

Recovery Effort

A new flashcard was rush delivered, but due to the short time given and that Kalgoorlie is a great distance from any major metropolis, the replacements arrived on the last day. The Australian and St. Louis teams worked endlessly to try and get the payload up and running, but time was against the team and nothing could be done to save the payload.

In the Students' Words –

"Lessons Learned"

Although, as fate stepped in, we did not have a payload fly aboard the Solo Spirit, the Payload project was a success. The team was faced with a fast learning curve and to their credit they stepped up to the challenge and took control. Many lessons have been learned throughout the payload process, either organizational or technical. This project was the first faced by many of the team members and it was at first a confidential project. For many months the students had to work under the secrecy of confidentiality, as Mr. Fossett had not gone public with his new RTW plans. This made the project more challenging, as it was very hard to research information from people without letting them know the uses.

Another challenge faced by the team members was that of being students. Time and many other obligations kept the team from working on the project fulltime. Classes and schoolwork were top priority so adhering to our schedule was difficult.

One valuable lesson that we will always remember is that of testing everything. As previously mentioned, time was not on the project's side, but future projects must and will go through extensive testing. One of the big flaws of our system was that occasionally the flight computer acted strangely. Had we had another few weeks, it would have been able to truly understand how the system worked when it left for Kalgoorlie, WA.

Redundancy is yet another lesson we will take to heart. Had the team been given the right opportunity (and for future projects), having a fully functional second hard drive would have been invaluable.

Not all lessons learned were negative, as the team acquired valuable technical knowledge for the future. The understanding of power systems, computer programs, and radio transmissions grew enormously over the few months, as the students started with little to no knowledge.

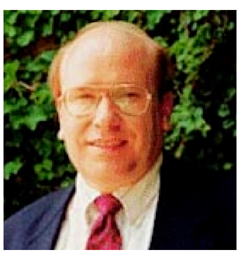
It is a tremendous disappointment that the physical project failed, but the knowledge acquired during the last 6 months is invaluable to future projects, both in school and when we enter the real world of careers. Everyone in the team benefited by being a part, and for that, the payload was a success.

The team members will continue to aid the Solo Spirit team by joining them in mission control to offer any help needed, as well as learn from the experience.

Conclusions

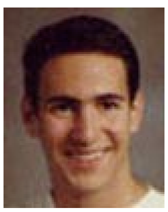
In the end the Palantir Technology Demonstration may have ended in a "non-success" but the experience proved it self worthwhile. The construction of the Technology Demonstration that required a power subsystem that could both provide power, but also charge the batteries; a computer which could handle images, data, and amateur radio communications; and an advanced understanding of the intricacies of amateur packet radio, taught the engineering team countless lessons. Each phase of the project, design, construction, and integration were each full of challenges and difficulties, which the team had to overcome. These challenges provided valuable experience for the team. This Technology Demonstration was a necessary step in achieving the Palantir picosatellite goal.

With the experience gained from the Technology Demonstration, the Palantir engineering team continues onward toward the goal of a wide angle imaging satellite.



Keith Bennett *is an affiliate assistant professor of computer science at Washington University in St. Louis. His principal teaching responsibility is the capstone design sequence, and he is the founding director of Project Aria at Washington University. Before coming to Washington University, he worked as a software manager and systems engineering at McDonnell Douglas on projects such as the National Aerospace Plane and various mission planning and tactical surveillance systems. He has an M.S. in Computer Science from Washington University and a B.S. in Computer Science & European History from Vanderbilt University.*

Michael Swartwout *is an assistant professor of mechanical engineering at Washington University in St. Louis. His principal teaching responsibility is undergraduate design; his primary research is the design of robotic vehicles for improved operability, and his primary hope is to combine those two into one program. He served as project manager for the Sapphire microsatellite at Stanford University and now is co-director of Project Aria at Washington University. He has an B.S. and an M.S. from the University of Illinois in Urbana-Champaign, and earned his Ph.D. in Aeronautics & Astronautics from Stanford University in 1999.*



Barry Tobias *is entering his senior year at Washington University studying Mechanical Engineering. Born in Cape Town, South Africa, he grew up in Birmingham, Alabama. He was the project manager of ARIA-1, a GAS canister containing multiple passive experiments that flew aboard STS-106 in September of 2000. Currently Barry is the Student Coordinator of the ARIA projects. In May of 2001, Barry spent a month in Kalgoorlie, Western Australia, as part of the integration team to place a payload on adventurist Steve Fossett's round-the-world balloon flight. Along with his activities in the ARIA space systems lab, he has been the Chair of Washington University's AIAA chapter and been Co-President of the university's Ultimate Frisbee team for two years.*

Patrick McNally *is a sophomore computer science student at Washington University. He is currently the Computer Systems Manager for the Palantir project.*

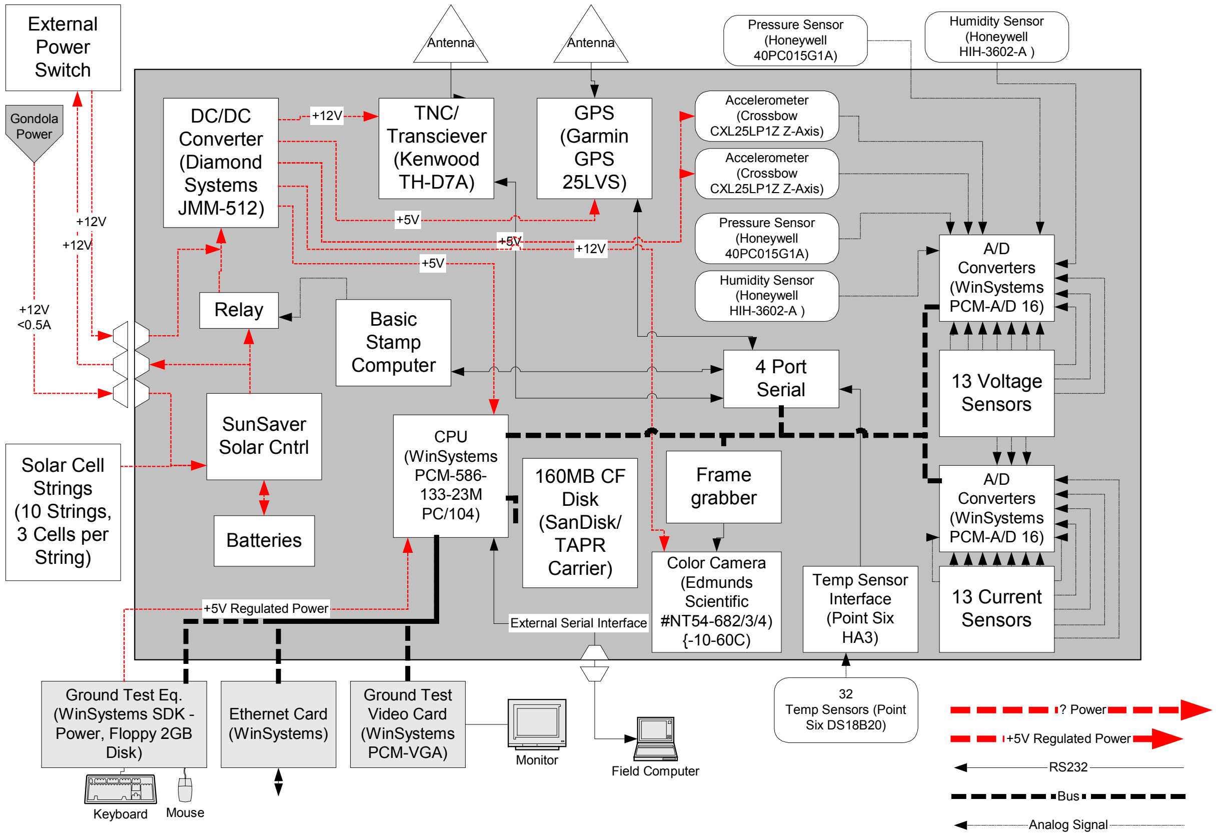


Figure 1 - Payload Schematic