CubeSat Design for LEO-Based Earth Science Missions[1][2]

Stephen Waydo, Daniel Henry, Mark Campbell
University of Washington
Department of Aeronautics & Astronautics, Box 352400
Guggenheim Hall
Seattle, WA 98195-2400
waydo@aa.washington.edu/(206)290-4015
dvhenry@u.washington.edu/(310)545-1577
mc288@cornell.edu/(607)255-4268

Abstract—The 2001 University of Washington Space Design class designed and developed a CubeSat platform to accomplish science objectives related to ionospheric modeling. Small satellites (between 1 and 15 kg) show great promise as a low-cost option to perform limited LEO science missions. This paper describes a CubeSat bus that supports two mission architectures based on two instrument packages. Both architectures involve multiple CubeSats separated from each other to gather spatially and temporally distributed data. The first is a combined Plasma Impedance Probe/DC Probe system on two satellites, separated by a tether. The second is two separate CubeSats that perform GPS scintillation measurements. In addition to the common bus structure, unique design traits (such as tethered gravity gradient control) and extensive hardware and software prototyping are discussed in the paper.

TABLE OF CONTENTS

1. INTRODUCTION

Variations in ionospheric plasma density can create large amplitude and phase fluctuations in radio waves passing through this region. For this reason, the creation of models of ionosphere density is of critical interest to scientists working in the field of satellite communications [1]. Multiple measurements of plasma density over a region are of particular value when creating these models. The 2001 University of Washington Space Design class designed and developed a CubeSat platform to take such distributed measurements. The prime objective of the class was to develop a common CubeSat platform for low cost, LEO-based science missions. The spacecraft bus was designed to be versatile enough to accommodate different payloads that meet the mass, volume, and power constraints. Two missions were used to focus the design effort, based on two mission architectures and two instrument packages. The first is a combined Plasma Impedance Probe (PIP)/DC Probe system [2] on two satellites, separated by a tether. The second is two separate CubeSats that perform GPS scintillation measurements [3]. The science objective of both missions is to take distributed measurements within the ionospheric plasma to aid the understanding of ionospheric density structures and contribute to the creation of accurate models. A second, equally important, objective is to explore CubeSats for senior-level capstone design courses.

Although the two instrument packages place sightly different requirements on satellite subsystems, many subsystem designs could be shared between the two missions. In particular, the Structures, Power, and Communications subsystems as well as the hardware portion of the Command & Data Handling (C&DH) subsystem are identical between the two missions. The Attitude Control System (ACS) was different for each mission, but gravity-gradient stabilization approach was used in both cases.

This paper first details the systems design of the CubeSat, along with the major science requirements that motivated and guided the design. Each subsystem is then discussed in varying level of detail, with the gravity gradient control approach a focus point. Finally, prototyping of the satellite is shown as a verification of the design methodology and concept.

2. SYSTEMS DESIGN

The CubeSat program, created at Stanford University's Space Systems Development Laboratory, provides logistics and launch services for 1-kg cube-shaped satellites measuring 10-cm on a side [4]. CubeSats are deployed in groups of three from the Poly Picosatellite Orbital Deployer (P-POD), designed at CalPoly-San Louis Obispo [5]. Launch is aboard a Russian Dnepr launch vehicle (converted from the SS-18 ballistic missile) from Baikonur Cosmodrome.

A generic CubeSat-based platform capable of satisfying the basic requirements of LEO-based science missions was

---

0-7803-7231-X/01/$10.00/© 2002 IEEE

[2] IEEEAC paper #248

developed. This platform consists of all subsystems needed to support and power a small science instrument as well as communicate data to a ground station. Additionally, two separate science and attitude control subsystems were developed to accommodate the two science missions.

Mission Plan

The current baseline for the first CubeSat launch is to release the CubeSats from the P-POD at 300-km altitude and 60 degrees inclination. These are the orbit parameters that were used in developing the mission plan.

The following is the mission outline for both CubeSat missions:

Day 0: Deployment from P-POD launcher, separation of CubeSats
Day 1-10: Passive attitude stabilization into data-taking formation
Day 11-30: Science data collection and downlink
Day 31-44: Mission margin, additional data collecting
Day 45: De-orbit and end-of-life

Separation Procedure

The two CubeSats will separate upon deployment by means of a spring compressed in between each satellite as specified by the CubeSat Design Specifications Document [4]. This spring will provide a relative separation velocity of 5 mm/s in a random orientation.

In the case of the DC/PIP mission, a controlled-friction device will be used to bring the CubeSats to zero relative velocity as they reach full deployment of the 10-meter tether. For the GPS mission, the separation velocity will be used to impart a slow drift on the two satellites. This drift rate will gradually separate the satellites to the required 100 meters and beyond. Both of these procedures will be discussed in more detail in section 5, Attitude Control, below.

Mission Modes

Table 1 defines the modes of operation of the CubeSat system.

Table 1. Mission Modes

Mission Mode	Task
1	Deployment/power on
2	Stabilization
3	Magnetometer calibration
4	Science data collection
5	Ground communication
6	Conserve power/recharge
7	Stanby

Modes 1 and 2 apply only to the initial deployment and stabilization portions of the mission. Mode 3, magnetometer calibration, consists of monitoring the magnetometer signal to determine peak amplitude and will be performed periodically. Mode 4, science data collection, is the primary mode of operation, with the CubeSat switching to mode 5, ground communication, as communication opportunities occur. Mode 6, conserve power and recharge, is only used in the event that normal operations cannot be supported by the power subsystem. Mode 7, standby mode, is the default mode of operation when no other modes apply.

Internal and External Configuration

Figure 1 depicts the internal configuration of the CubeSat. The large toroid on the bottom face is the gravity gradient damper discussed in the Attitude Control section below. The damper surrounds the tether deployer in this figure; the boom mechanism used by the GPS mission also fits in this space. The communications, C&DH, and science cards used by the CubeSat are arranged in a stack parallel to the bottom face, and the batteries are enclosed in a separate box on the right side of the figure.

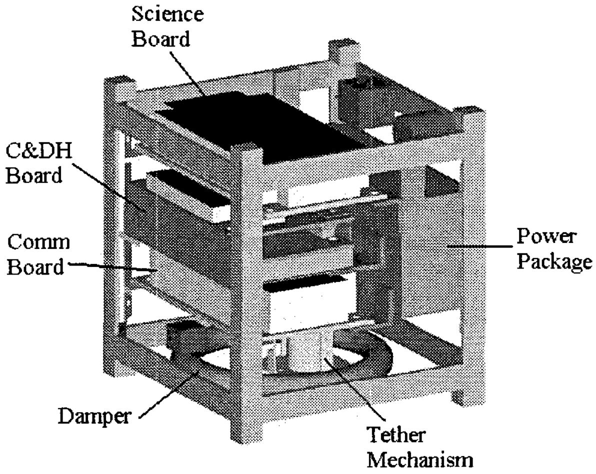


Figure 1. Internal Configuration

Figure 2 is a series of diagrams outlining the spacecraft's external configuration. The two missions have slightly different external configuration needs. Common external components include solar cells and a communications antenna, and both configurations provide access to an RJ45 Ethernet port and a kill switch as specified by the CubeSat program [4]. The DC/PIP mission also incorporates two patch antennae for the science experiment, and the GPS mission includes a pair of redundant GPS antennae. Both missions have equal solar cell coverage.

All components, with exception to the science packages, are off the shelf components and/or designed by the students. The primary qualification of these components will be through thermal vacuum and vibration testing on both the component and spacecraft level.

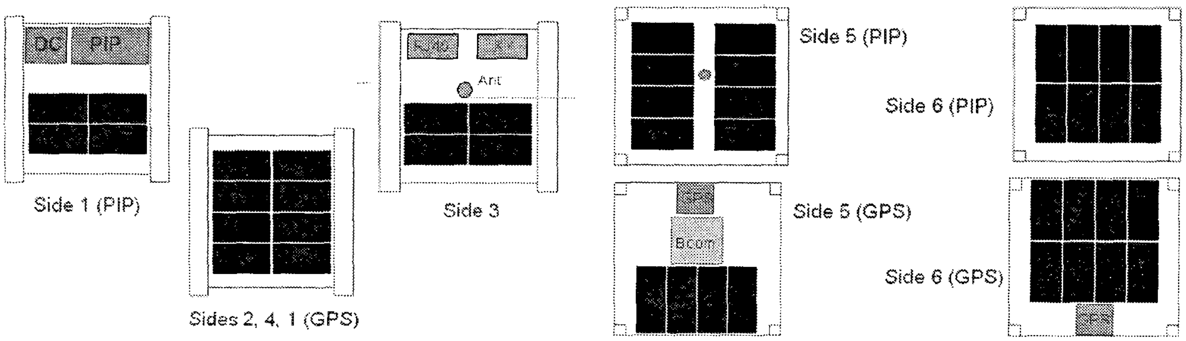


Figure 2. External Configuration

Table 2. Mass Budget

	Budgeted				Actual			
	Percentage of Total		Allocated Mass (g)		Mass Estimate (g)		Variance (g)	
Subsytem	**DC/PIP**	**GPS**	**DC/PIP**	**GPS**	**DC/PIP**	**GPS**	**DC/PIP**	**GPS**
Structure	20%	20%	200	200	170	170	30	30
Thermal	2%	2%	20	20	13	13	7	7
Attitude Dynamics	4%	11%	40	110	32	72	8	38
C&DH	12%	12%	120	120	111	111	9	9
Communications	16%	16%	160	160	145	145	15	15
Power	18%	18%	180	180	163	163	17	17
Science	23%	16%	230	160	208	102	22	58
Total Allocated	95%	95%	950	950	842	776	108	174
System Contingency	5%	5%	50	50	50	50		
Total Mass	100%	100%	1000	1000	892	826	108	174

Mass Budget

Table 2 is the mass budget for both CubeSat missions. Of the 1-kg maximum launch mass, 950 grams are allocated to the subsystems and a 50 gram system contingency is reserved. In addition, each subsystem's mass estimate includes a 5-10% subsystem contingency depending on the fidelity of the subsystem's mass list. With this contingency both missions weigh in at less than 900 grams, so there is some additional breathing room in the budget.

3. SCIENCE MISSION

As stated above, the science objective of both missions is to take distributed plasma density measurements within the ionospheric plasma. The two mission architectures meet this objective using two different science packages. This section will describe each of these science packages, as well as the magnetometer used by both missions to determine when to take data.

DC/Plasma Impedance Probe

The first mission concept under development makes use of two science instruments to measure plasma density directly. The primary instrument is a Plasma Impedance Probe (PIP), which measures the plasma frequency. The science package also includes a DC probe, which measures the electric current in the plasma and will serve as a backup of the more accurate PIP. Both instruments make use of small patch antennae that must be placed in the velocity direction (leading face) such that they measure plasma that is undisturbed by the satellite body. The distributed ionospheric science places a requirement that two simultaneous measurements must be spaced at least three meters apart. The most useful data for the DC/PIP mission is near the equator.

The DC/PIP mission will utilize two CubeSats, each with a DC/PIP science instrument. The DC probe patch antenna measures 2.54x2.54x0.64 cm, and the PIP patch antenna measures 5.02x2.54x0.64 cm, so both instruments can be mounted on one face of the CubeSat. Each instrument is connected to a single science board using coaxial cable. The science board then transmits the data to the on-board computer, where it is stored until it can be downlinked to earth. The science board and instruments consume 1.5W of power when active.

Preliminary analysis of the communications subsystem indicates that the CubeSat is capable of downlinking a minimum of about 1 megabyte per day of science data (based on one ground station, at 9600 baud). A data taking region consisting of +/-10° of latitude, corresponding to about 11 minutes of data-taking time per orbit, was chosen to fit within the downlink capability.

GPS Scintillation

The second mission concept under development is to measure fluctuations in Global Positioning System (GPS) signal strength to infer information about the plasma density between the science satellites and the GPS satellites. This technique, known as GPS scintillation [5], is useful to measure larger structures in the ionosphere, and requires a satellite separation of at least 100 meters. The GPS antennae must also be provided a clear view to the GPS satellites orbiting far above the CubeSats in half-geosynchronous orbit.

The GPS antenna is a small patch antenna measuring 2x2 cm. Two antennae are used on opposite sides because it is unpredictable which of two sides will be zenith-pointing (this is discussed more fully in the Attitude Control section). The antennae are connected to a GPS board specially designed by Cornell University [6], which samples GPS data at 79 Hz, corresponding to about 100-meter data resolution at a 300-km orbit.

The greater separation of the GPS CubeSats as compared to the DC/PIP satellites enables them both to transmit simultaneously without encountering interference problems for some portion of the mission. This doubles the maximum amount of data that can be downlinked, expanding the data-taking region to +/- 20° latitude.

Magnetometer

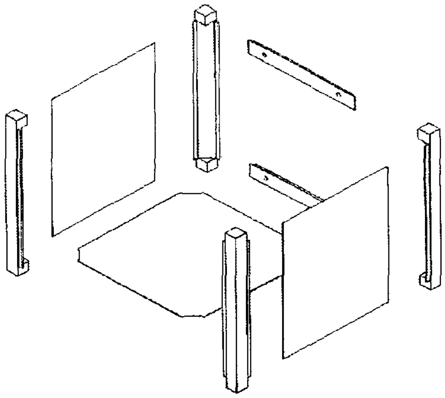
Both science missions utilize a magnetometer to determine when the satellite is within the desired data-taking region. The chosen magnetometer is a Honeywell 3-axis solid-state magnetometer. Fluctuations in the total magnitude of the Earth's magnetic field are used in combination with an assumed satellite attitude to estimate the satellite's position. The magnetometer will be periodically calibrated on-orbit to ensure that science data are taken within the proper region.

4. COMMON SUBSYSTEM DESCRIPTION

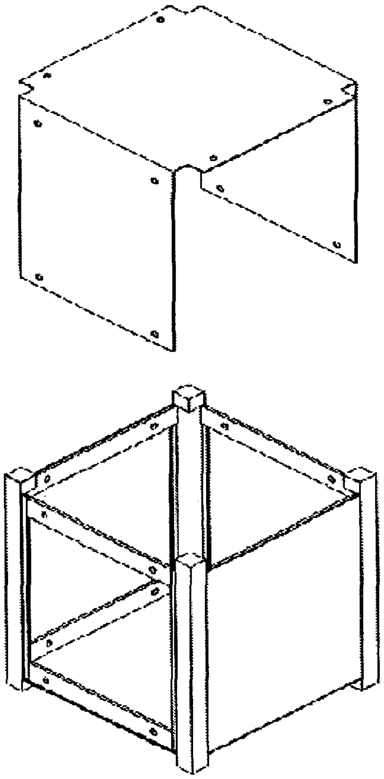
Structures

The primary requirements on the Structures subsystem are to satisfy the external requirements placed on the design by the CubeSat launch interface, as well as provide adequate interfaces to each subsystem to ensure safe passage through all phases of the mission. In additional, an ability to accommodate multiple science and ACS payloads with little or no modification of the design is a strong driver. A further requirement is ease of fabrication and assembly of both the satellite structure and the satellite as a whole.

The Structures subsystem design consists of three types of parts: rails, beams, and panels, all of which are made of 7075 Aluminum. The rails make up four parallel edges of the CubeSat and their dimensions are defined by the CubeSat launch interface. The beams are epoxied to the rails to create the other eight edges of the CubeSat. Three side panels are epoxied to the beams and rails in a U-shape to form half of the external surface of the satellite. The final three sides are formed by a single U-shaped panel that can be fastened in place following integration of internal components. Figure 3 depicts the structural components.



a. Exploded view



b. Assembly

Figure 3. Structural components

Internal components are fastened to the structure as a single package using brackets and fasteners. Those subsystems which are different for the two missions, ADCS and science, use identical interfaces so that the same hardware and assembly procedure can be used.

Power

The Power subsystem uses Tecstar triple junction 26.5% efficiency solar cells to provide system power as well as to charge lithium polymer batteries that are used when sunlight is unavailable. The unregulated bus for the solar cells and the batteries ranges from 7V to 12V, and the power system provides a regulated voltage of 5V +/- 1% at up to 600 mA current.

Table 3 is the power budget for each of the CubeSat missions. Approximately 1.3W orbital average power (OAP) is estimated to be available after taking system efficiency into account, 1.1W is allocated to the subsystems in the power budget, allowing for a 0.2W (15%) system contingency. Actual OAP estimates taking into account duty cycling of instruments and communications are 0.67W for the DC/PIP mission and 0.95W for the GPS mission. The higher power usage for the GPS mission is due to two factors: the higher peak power consumption of the GPS board and the larger percentage of the orbit over which good science data can be obtained.

Communications

An amateur-band communications system was chosen for the CubeSat for three reasons. First, there is a lack of regulatory constraints in attaining the frequency bands. Second, commercial off the shelf parts can be used for the flight system. Third, other schools can be coordinated such that there is more ground station access.

Transceiver—The chosen transceiver is a Tekk KS 960 commercially available amateur-band transceiver modified to conform to the CubeSat design limitations as well as to operate in space. The primary modifications are as follows:

- Remove the board from the enclosure
- Remove the power regulation components
- Reduce the transmission power
- Replace all electrolytic capacitors

Table 3. Power Budgets

a. DC/PIP

DC/PIP mission	**Budgeted**		**Estimate**				
Subsystem	**Percentage of Total**	**Allocated Power (W)**	**Standby Power (W)**	**Peak Power (W)**	**Peak On Time (%)**	**Average Power (W)**	**Variance (W)**
Thermal	11%	0.14	0.002	2.01	7%	0.14	0.000
C&DH	11%	0.14	0.05	0.30	30%	0.13	0.02
Communications	16%	0.21	0.10	1.00	5%	0.15	0.06
Science - Board	42%	0.55	0.00	1.50	17%	0.26	0.29
Science - Magnetometer	5%	0.07	0.00	0.025	100%	0.03	0.04
Total Allocated	85%	1.11	0.15			0.67	0.44
Contingency	15%	0.20				0.20	
Total Power	100%	1.30				0.87	0.43

b. GPS

GPS mission	**Budgeted**		**Estimate**				
Subsystem	**Percentage of Total**	**Allocated Power (W)**	**Standby Power (W)**	**Peak Power (W)**	**Peak On Time (%)**	**Average Power (W)**	**Variance (W)**
Thermal	11%	0.14	0.002	2.01	7%	0.14	0.000
C&DH	11%	0.14	0.05	0.30	30%	0.13	0.02
Communications	16%	0.21	0.10	1.00	5%	0.15	0.06
Science - Board	42%	0.55	0.00	2.00	27%	0.54	0.01
Science - Magnetometer	5%	0.07	0.00	0.025	100%	0.03	0.04
Total Allocated	85%	1.11	0.15			0.95	0.15
Contingency	15%	0.20				0.20	
Total Power	100%	1.30				1.15	0.15

The first modification is simply to reduce mass and allow the board to fit within the CubeSat envelope. The transceiver in its enclosure weighs 145g, which is much more than is reasonable to accommodate in a 1kg system.

The second modification, removing the power regulation components, reduces the mass of the transceiver and is made possible by the existence of a regulated power bus on the CubeSat itself. This modification will also reduce the power required by the subsystem, as there will no longer be an efficiency loss on the board due to power regulation.

The transmission power of the transceiver must be reduced to fit within the spacecraft power budget. The commercial specification for the transceiver is 2W transmit, while the power budget only allows for 1W transmission power based on the downlink budget.

The final modification, replacing the electrolytic capacitors, is necessary to make the board space worthy. Equivalent Tantalum capacitors will be used in their place.

Antenna—The antenna is a single half-wave dipole antenna tuned to the downlink frequency of 437.49MHz. A dipole antenna was chosen because it has a larger beam width than a monopole antenna, allowing for longer communication windows (more science data) and easier attitude control requirements. These results were determined to be more important than the resulting loss in gain.

The antenna is fabricated from steel tape measure. The primary reason for this is that a tape measure can be rolled up to a very small volume and restrained indefinitely, then will unroll and lock very reliably upon removal of the restraint. Each half of the dipole antenna is rolled up separately and both are restrained using a single nylon wire which is then run through a resistor. After the CubeSat has been deployed into orbit, current will be run through the resistor, severing the wire and allowing the antenna to unfurl.

Ground Stations—The primary ground station to be used to communicate with the CubeSat will be located at Stanford University in Palo Alto, California, but almost any Orbiting Satellites Carrying Amateur Radio (OSCAR) ground station could be used. Multiple ground stations could be used if one ground station proves to be inadequate to downlink all science data.

Command & Data Handling

The Command & Data Handling (C&DH) subsystem consists of the on-board flight computer with memory for science storage, as well as data interfaces for science, telemetry, and communications.

On-board Computer—The Tattletale 8v2 processor board was chosen to provide on-board computing for several reasons. This board, available off the shelf [7], contains 9 analog lines as well as two RS-232 ports needed to transfer data to and from the science and communications subsystems, minimizing the amount of electrical integration work required. Low cost (~$500) and availability were also significant factors in the selection.

Another significant feature of the Tattletale is its ability to regulate the clock speed of the processor and therefore the power input to the subsystem. This will allow the CubeSat to minimize C&DH system power consumption depending on the operating mode.

Single event upsets are addressed by monitoring each board's current; if it consistently draws a large current outside its normal range, the power is cycled to that board. Bit flips and other errors are addressed with simple error correction techniques and ground evaluation.

Software—The software architecture of the C&DH subsystem accommodates either science mission. Because of the small number of operating modes and simplicity of the mission, a simple loop architecture rather than an operating system architecture is used. This loop , written in TxBASIC, continuously monitors telemetry, communications state, and satellite location (as determined by the magnetometer), and calls appropriate sub-functions as necessary. The three major sub-functions are science, communications, and fault response.

The science function is called when the magnetometer indicates that the satellite is within the appropriate data-taking region. This function collects and records science data for a length of time determined by the mission's region of interest. The science function also periodically monitors the health sensors and can call the fault response function if necessary.

The communications function is called when the transceiver indicates that it has received a beacon signal from a ground station. The function sends science data to the ground until all of the stored data have been sent or the function determines that the beacon signal has been lost, indicating that the satellite has passed out of communication range. As with the science function, the communications function monitors satellite health and can call the fault response function if needed.

The fault response function is activated if any other function detects abnormal health readings. The fault function examines the abnormal reading and calls an appropriate health function, for example a "too hot" function or a "too cold" function.

5. ATTITUDE CONTROL

The two science missions place very different requirements on the attitude control subsystem. Two different attitude control systems were designed to meet these requirements, with common interfaces defined to minimize impacts to the other satellite subsystems. Both missions incorporate gravity-gradient stabilization techniques, although the implementation is different. Both ACS systems also use viscous liquid vibration dampers.

DC/PIP

The DC/PIP science mission requires the two instrument pairs to be separated by three to ten meters. The instruments themselves must also face into undisturbed plasma, i.e. they must be on the leading face of the CubeSat, which must be maintained within 45° of the direction of travel. These requirements are met by a combination of gravity-gradient stabilization and careful control of disturbance torques.

Tether—Pitch and roll control as well as separation distance of the two spacecraft are maintained by a ten-meter aramid fiber tether. Gravity-gradient forces tend to stabilize the tethered system in an upper-lower formation, and the tension in the tether stabilizes the individual satellites in pitch and roll.

Satellite separation is induced by a spring compressed between the two satellites which forces them apart upon deployment. The tether is coiled around a cylinder within one of the CubeSats, then wrapped around a post to introduce friction into the system. This friction slows the rate of separation of the CubeSats to prevent them from hitting the end of the tether and bouncing back, which would prevent them from stabilizing in formation. Figure 4 is a solid model of the tether deployer.

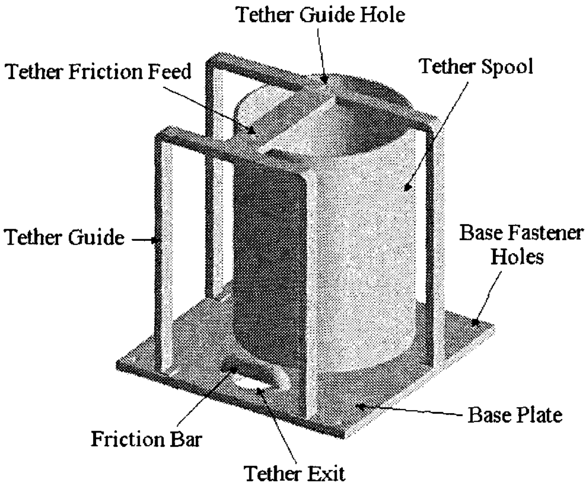


Figure 4. Tether deployer

CP-GP offset—Yaw control is required on the DC/PIP mission to keep the antennae pointed into undisturbed plasma. This is achieved by taking advantage of the minute amount of atmosphere remaining at LEO. An offset of the CG of the satellite toward the antenna side relative to the geometric center (also the center of pressure) stabilizes the satellite with the antennae face leading. A CG offset of 12.5-mm is sufficient to meet the pointing requirement and is within the 20-mm maximum offset allowed by the launch and deployment system [4].

GPS

Much larger separations of at least 100 meters are required for the GPS scintillation mission. Additionally, the desired separation is along the orbit track rather than in altitude. For these reasons, a two CubeSat tethered approach is not feasible. Instead, the spring force separation of the CubeSats upon deployment induces a slow drift out to 100 meters and beyond. The GPS antenna pointing requirement is that the antenna must have a clear view to the GPS satellites, which orbit far above LEO in half-geosynchronous orbit. The normal of the GPS antenna must point within 30° of zenith to satisfy this requirement. A deployable gravity-gradient boom is used to stabilize the satellite in pitch and roll so that one of two sides will point towards the GPS satellites. Redundant GPS antennae are used so that there is no orientation requirement. Yaw control is not required for the GPS mission.

Drift separation—The GPS mission relies on the drift rate between the two CubeSats induced at satellite deployment to achieve the required 100-km separation for science collection. The separation rate can be approximated using the Hill-Clohessy-Wiltshire (HCW) linearized orbit equations. The HCW equations utilize a coordinate system defined such that x is measured radially outward from the reference satellite (assumed to be in a circular orbit), y is measured along the orbit track, and z is measured out of the orbit plane, pictured in figure 5 below.

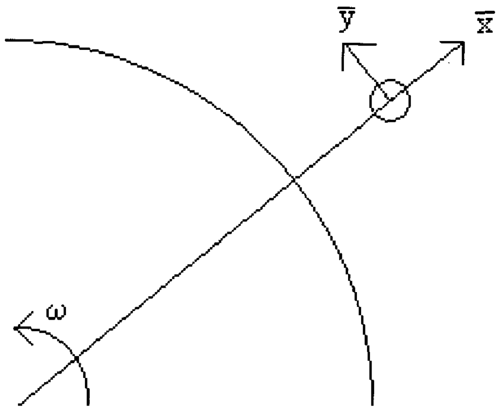


Figure 5. Coordinate system for HCW equations

For satellites starting at the same location with an initial relative velocity, the HCW equations give:

$$x(t) = \frac{\dot{x}_0}{n}\sin(nt) + \frac{2\dot{y}_0}{n}[1-\cos(nt)] \qquad (1)$$

$$y(t) = \frac{2\dot{x}_0}{n}[\cos(nt) - 1] + \frac{4\dot{y}_0}{n}\sin(nt) - 3\dot{y}_0 t \tag{2}$$

$$z(t) = \frac{\dot{z}_0}{n}\sin(nt) \tag{3}$$

where n is the mean motion of the reference orbit.

Equation 2 describes the along-track separation of the satellites, and is the only equation that includes a component that is directly proportional to time t. From the last term in equation 2, the satellites separate along the orbit track at three times their initial along-track separation velocity. For the planned initial separation velocity of 5 mm/s and assuming a purely random orientation of this velocity, there is an approximately 99% probability that the satellites will reach the required 100-meter separation within the desired 10 days. If the initial velocity is exactly along the orbit track, the satellites will reach a maximum of 39-km separation at the end of the 30-day primary mission. Data taken at this separation will still be useful to the scientific community.

Gravity-gradient boom—The gravity-gradient boom consists of two portions, the boom and the tip mass. The boom is a steel measuring tape identical to the type used as the communications antenna. The tip mass is a 10-gram block of solid steel affixed to the end of the boom to increase the moment of inertia perpendicular to the boom and thus increase the gravity-gradient torque. During integration and launch, the boom is rolled up with the tip mass in the center and restrained using nylon wire. As with the communications antenna, deployment is initiated by running current through a resistor to sever the restraint.

Gravity Gradient Damping

In addition to the stabilization techniques described above, both satellites require damping to attenuate the transients induced by deployment. A viscous liquid filled toroid containing a ball bearing is used in both cases. As the ball travels through the liquid due to satellite oscillations, vibrational energy is dissipated by viscous friction. The damper is sized to reduce all oscillations to within the pointing requirements within 10 days of deployment.

6. PROTOTYPING

Extensive hardware and software prototyping of spacecraft subsystems was conducted. The sections below highlight some of these prototyping activities.

Structures

A complete structural prototype was fabricated and assembled to verify both the design and the assembly procedures. Figure 6 is a picture of the primary structural components.

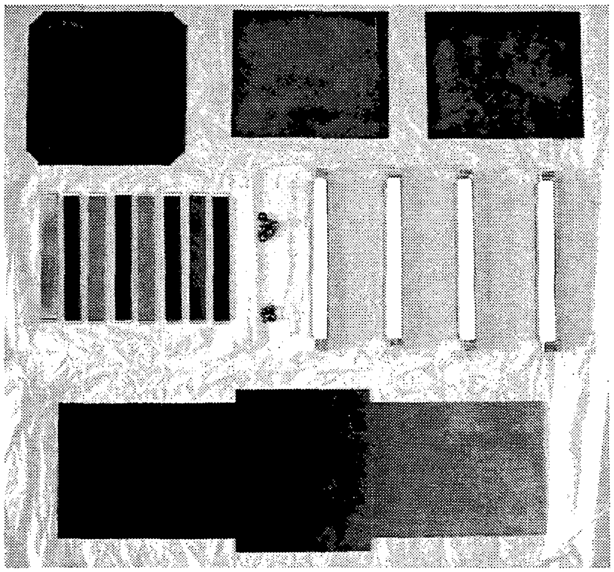


Figure 6. Structural components

Epoxy assembly of the spacecraft structures took place within a specially fabricated jig to ensure that the necessary alignments were preserved. Figure 7 is a picture of the spacecraft structures in the jig during assembly.

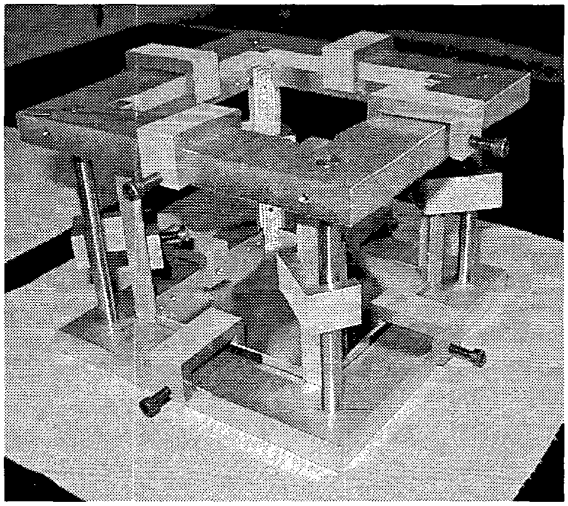


Figure 7. Structural assembly

After the epoxy had cured, the clamshell panel was affixed using #2 fasteners. This panel is fastened rather than epoxied to facilitate access to interior components after assembly on the eventual flight model. Figure 8 is a picture of the final completed structural assembly.

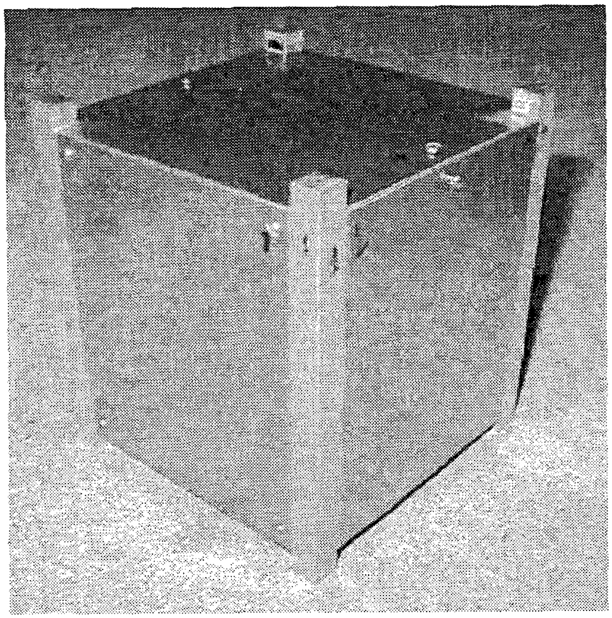
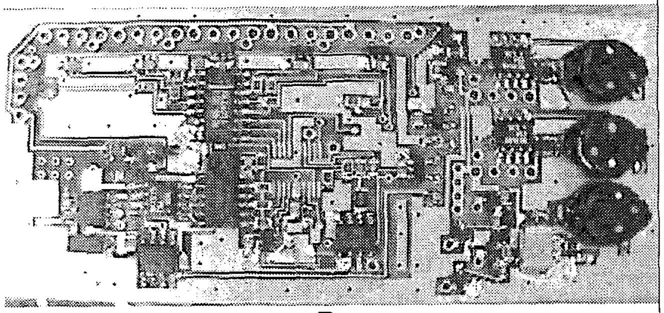


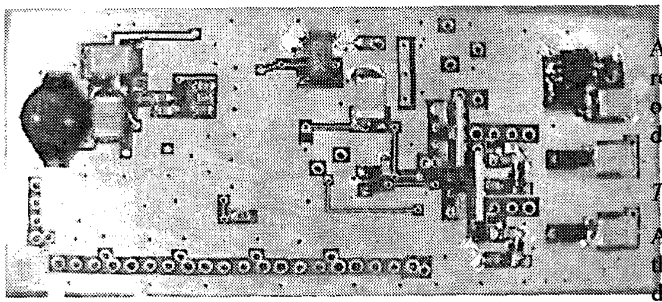
Figure 8. Completed structure

Power distribution board

A prototype power distribution board was fabricated and populated with components. Figure 9 is a picture of the completed board.



a. Top



b. Bottom

Figure 9. Power Board

Communications antenna testbed

A prototype antenna and simulated CubeSat were constructed for the purpose of evaluating the antenna design. Figure 10 is a picture of the antenna testbed.

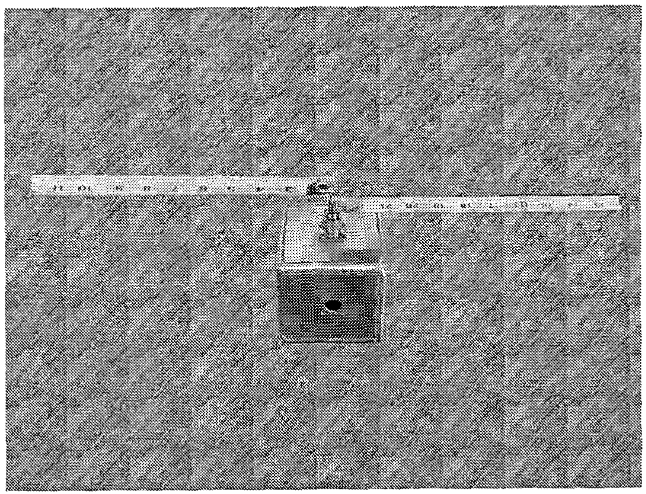


Figure 10. Antenna testbed

The antenna's performance was tested using a Standing Wave Ratio (SWR) meter to examine resonance at the downlink frequency. Figure 11 is a graph of the measured SWR at various frequencies.

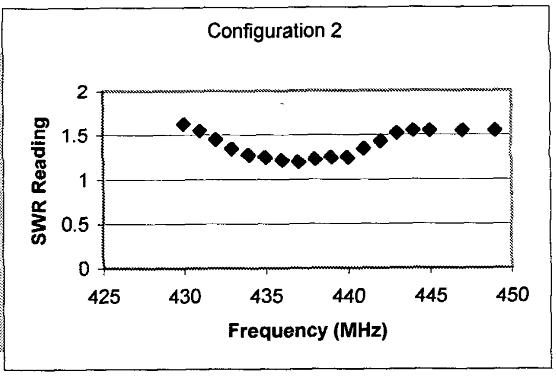


Figure 11. Antenna performance

A fairly broad SWR curve was observed, indicating good resonance over a wide range of frequencies. These observations verified the feasibility of the half-wave dipole design.

Tether deployer

A prototype tether deployer was designed and built to test the deployment concept. Figure 12 is a picture of the deployer prototype.

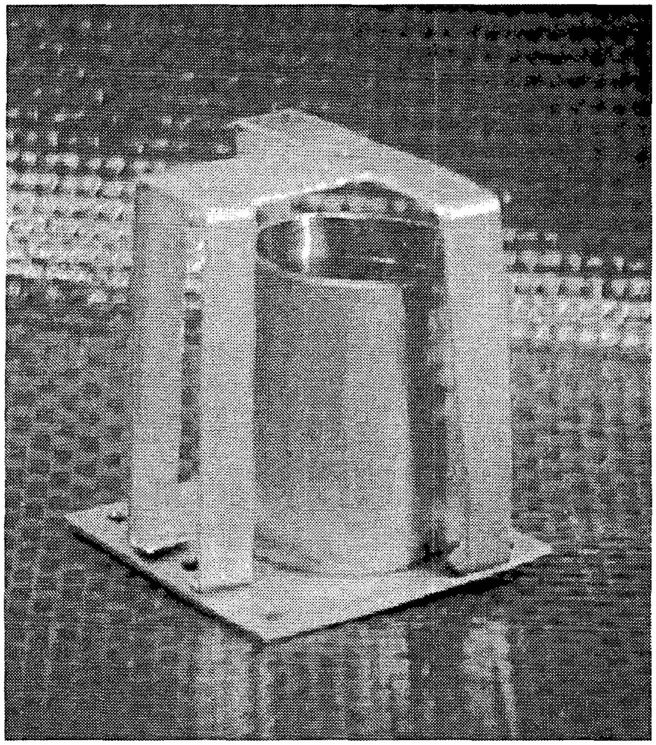


Figure 12. Tether deployer prototype

The tether is stowed wrapped around the large central cylinder. The tether passes through the two holes drilled in the frame around the cylinder, then through the hole in the base plate and out to the other spacecraft. The tether can be wrapped around the bar spanning the exit hole to increase deployment friction if necessary.

The prototype was used to test the friction developed within the system during tether deployment. Three meters of Dupont Aracon Metal-Clad Aramid fiber were used as the prototype tether. A mass was attached to the free end of the tether and was allowed to drop freely with only the friction in the deployer retarding the motion. Tests were conducted both with and without the tether being wound once around the friction bar to assess the effects of adding this additional component. The drop was recorded on video equipment and digitized images were used to analyze the motion. Friction force repeatability within 20% was observed in testing.

Gravity-gradient boom

A gravity-gradient boom, tip mass, and deployer were constructed to test the deployment concept. Figure 13 is a picture of the stowed boom with tip mass.

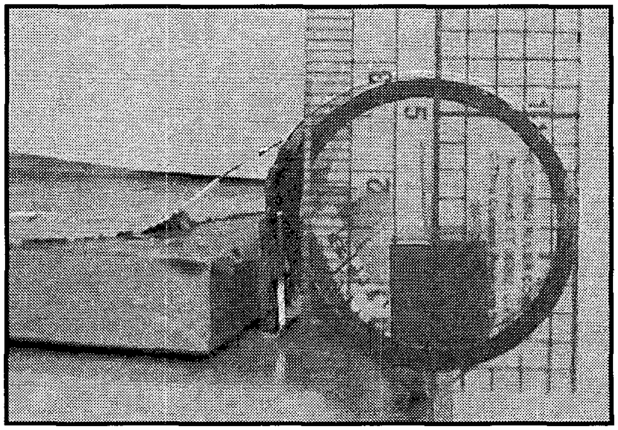


Figure 13. Stowed boom prototype

7. SUMMARY AND CONCLUSION

This study verified picosatellites to be an excellent platform from which to gather useful LEO-based science data. Enough design work was performed to confirm that these CubeSat concepts are viable and will result in very significant science return at very low cost. Either mission has the capability to collect useful science data over a period of at least 20-30 days.

This project did extend beyond the simple goal of examining CubeSats as a science platform, however. A detailed design was developed for a modular, versatile CubeSat bus which could be used for many future LEO-based science missions. Two attitude control options were developed to accommodate two major types of pointing and separation requirements that science missions other than those examined may entail.

It should also be noted that all of the design work described in this paper, as well as a great deal of more detailed work not discussed here, was performed by a group of 23 senior-level undergraduate Aeronautics & Astronautics students. The scope of the project enabled every student to contribute significantly to the design, and the large number of students involved allowed the project to take on a very "industry-like" flavor. Students worked on small subsystem teams within the larger group primarily under the direction of two student systems engineers, with support and guidance given by a professor, a teaching assistant, and an industry representative. Systems engineering, requirements, flowdown, teamwork, and interdisciplinary work were all primary components of the study. The fact that this mission was treated as a real flight project, and will be developed further and eventually fly, added immeasurably to the educational experience. Working on a project that was more than a paper study greatly enhanced student motivation and gave the students valuable real engineering experience.

REFERENCES

[1] Kelley, Michael C. *The Earth's Ionosphere, Plasma Physics and Electrodynamics,* Academic Press, San Diego, 1989.

[2] Fish, Chad, *ION-F Science Mission Instrumentation, Plasma Impedance Probe.* Available online at http://www.aa.washington.edu/research/dawgstar/docs/main_docs/AA-22713-DOC001.doc

[3] Groves, K.M. et. al. *Equitorial scintillation and system support.* Radio Science Vol. 32, #5, pp 2047-2064, Sep-Oct 1997.

[4] Stanford University and California Polytechnic Institute at San Louis Obispo. *CubeSat Design Specifications Document, Revision 3,* March 2001. Available online at http://ssdl.stanford.edu/cubesat/

[5] Connolly, Ryan, *The P-POD Payload Planner's Guide, Revision C,* June 5, 2000. Available online at http://www.calpoly.edu/~aero/polysat/planners_guide.pdf

[6] Beach, TL et. al. *Total electron content variations due to nonclassical traveling ionospheric disturbances: Theory and Global Positioning System observations.* Journal of Geophysical Research Vol. 102, #A4, pp7279-7292, April 1997.

[7] Onset Computer Corporation. *TattleTale 8v2 Specification.* Available online at http://www.onsetcomp.com/Products/Product_Pages/Tattletale_pages/TT8.html

ACKNOWLEDGEMENTS

The 2001 University of Washington Space Design class:

Teaching staff:	Ben Diedrich, Dr. Mark Campbell, Dr. Charles Vaughan
Systems:	Dan Henry, Stephen Waydo
Science:	Jeremy Chan, Chris Kachel
ACS-DC/PIP:	Judy Fahoum, Lia Matthews
ACS-GPS:	Brad Lewis, Elizabeth Meredith
Structures:	Bobak Ferdowsi, Yoh Kawanami, David Padineant, Joshua Lanman
Thermal:	Greg Cameron, Francis Louie
Communications:	Michelle Judy, Kerylyn Lay
C&DH:	Dion Davoud, Steven Fleiger-Holmes, Ray Hansen
Power:	Sam Andreason, Mike Paulsene, Daren Welsh, Allen Yoo

Steve Waydo *was a senior student in the Department of Aeronautics and Astronautics at the University of Washington at the time of this project, and with Dan Henry served as one of two systems engineers on the project. He received his BSAA degree in 2001 and has since joined the Control and Dynamical Systems group at Caltech, where his research is primarily focused on control of multi-vehicle systems. He has also spent two tours as a co-op student at NASA's Jet Propulsion Laboratory, first as a mechanical engineer working on the conceptual design of the 2003 Mars Exploration Rovers, then as the propulsion analyst for the 2007 Mars Smart Lander. He is currently a graduate student at Caltech majoring in Control Systems.*

Dan Henry*, a student systems engineer on this project, was also a senior student in the Department of Aeronautics and Astronautics of the University of Washington. Dan now works for the Electro-Optical Systems Engineering Center at Raytheon Electronic Systems in El Segundo, CA. He has performed work on systems engineering processes as well as spacecraft instrument testing, but primarily works on development of spacecraft instruments for surveillance and reconnaissance.*

Mark Campbell *is an Assistant Professor in the Mechanical and Aerospace Engineering Department at Cornell University, and was on the faculty at the University of Washington at the time of this study. He received his Ph.D. from MIT in 1996, and continued at MIT as a Research Associate/ Lecturer. While at MIT, Dr. Campbell developed space based model uncertainties, and designed 250 robust controllers implemented on-orbit for MACE, a dynamics and control laboratory flown on Space Shuttle Endeavor in 1995. Dr. Campbell's research interests are in multiple satellites and autonomous systems such as aircraft and spacecraft, and actively controlled structures. Dr. Campbell has over 40 publications in the areas of dynamics, smart materials, and control, including the book "High Performance Structures: Dynamics and Control."*