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CE2: A CUBESAT ELECTRON COLLECTOR EXPERIMENT

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The Naval Research Laboratory developed an experiment to measure the effectiveness of an electron collection device in space. Electron collection from the plasma surrounding the earth is a key element of an emerging concept for spacecraft propulsion that makes use of the physics principles of electrodynamics. Electrodynamic propulsion offers the prospects of enabling spacecraft to maneuver without the expenditure of conventional fuel, that is the possibility of propellant-less maneuvers. This experiment will measure the effectiveness of narrow metal tapes for collecting electrons from the earth's plasma.

INTRODUCTION

Electrodynamic propulsion is a technology that may lead to a very efficient means for maneuvering spacecraft. Although its maneuver force is small compared to chemical propulsion, its value derives from its potential for changing altitude, changing planes or making up for drag without expending fuel. This paper describes a space experiment to explore one component of electrodynamic propulsion: the collection of electrons from the earth's plasma.

Electrodynamic propulsion is based on the basic properties of electricity and magnetism: electrons moving across magnetic field lines have a force exerted on them. If they are in a plasma, their paths spiral around the field lines; if in a wire, they exert a side-force on the wire, normal to both the wire and the field. This is analogous to the force on the armature of an electric motor as it revolves inside the magnetic field of the motor's outer windings. One concept proposed for electrodynamic propulsion is to use a tether between two spacecraft as the current

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conducting wire. The tether can also provide other functions, like distributing spacecraft functions and mass between the two endmasses, and passively keeping the two end-masses together.

Figure 1 illustrates the principle behind electrodynamic thrusting. The force vector is the cross product of the local magnetic field vector and a vector whose magnitude is equal to the current and whose direction is in the direction of the current. For thrust in a particular desired direction to change an orbit parameter, one must pulse the electrical current at the time when the cross product produces a vector in the desired direction. These details are for future missions where all hardware components, collector, emitter and current carrying tether are available in one system. The purpose of this experiment is only to measure the performance of an electron collector.

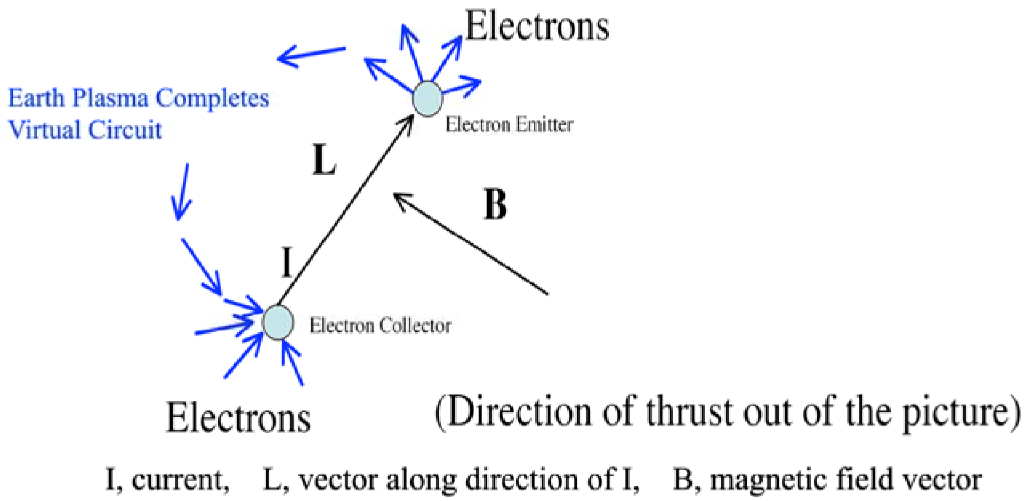

Figure 1: Physics Principle Behind Electrodynamic Thrusting

PLASMA CONTACT ISSUES

To induce useful thrust, current must flow in one direction through the tether, and in the other direction through the surrounding plasma. This requires some sort of tether-to-plasma electrical contact at each end. Electron emission has been used by spacecraft for many years to neutralize spacecraft charging by high-energy electrons. Hollow cathode emitters are one device that has been perfected for this purpose. Efficient electron ***collection*** has generally not been a goal, so has been tested only a few times: at orbital velocity by PMG and TSS-1R, and at lower speed by the CHARGE sounding rockets. (See refs [1, 2] for details.)

Electron collection by large objects is limited by electron thermal velocity, and by the spiraling of electrons around field-lines, which limits cross-field collection. Current increases with voltage, but tends to saturate at high voltage. But for narrow enough wires or tapes, the collectable current is not expected to saturate, but rather to scale with the square root of the bias voltage. This collection regime is referred to as “orbit motion limited” (OML), since it depends on the electron gyro or “orbit motion” to bring electrons close enough to the tape to respond to the collector bias. Collection in the OML regime allows much smaller collectors for a given current. This can reduce collector mass and drag. Short wide tapes have practical advantages over long thin equal-area wires or tapes, so it is useful to establish the width limits of OML collection.

Unfortunately, ground tests cannot establish the width limit for OML collection, because representative tests require the collector to move through a large volume of plasma at approximately five times the mean ion speed. Analyses and simulations are also inconclusive, because the calculations are not tractable unless many simplifying assumptions are made[3, 4, 5].

The analyses by Sanmartin[6,7] suggest OML collection for tapes up to a few cm wide, depending on plasma density and magnetic field strength. Analyses also suggest that the convex circumference of the collector should be more important than the exact cross-section.

The above factors plus an unexpected flight opportunity drove us to develop this experiment. Our goal is to measure electron collection in low earth orbit, using bare metal tapes 15mm and 30mm wide and >1m long. We plan do this over collector bias voltages of 0 to >200V, in a variety of tape orientations relative to the magnetic field and velocity vector, over a ~5:1 day/night plasma density range and a ~2:1 range of magnetic field strengths. The wide range of parameters available around the orbit should allow us to characterize OML limits fairly well, despite CubeSat packaging constraints that limit us to only 2 collectors, varying by only a factor of 2 in width.

We would prefer to focus entirely on electron collection, but electron emission turns out to also be an issue. For large "operational-scale" systems, a hollow cathode emitter generally seems like the best emitter. Hollow cathodes generate and emit a small amount of ionized xenon, through which a much larger electron current can flow out into the ionosphere, without significant space charge limitations on emitted current. But hollow cathodes do not scale down well, and the emitted plasma may also perturb nearby collection. After studying alternatives[8, 9, 10, 11, 12], we have settled on resistance-heated tungsten wires. To reduce "local short-circuiting" of emitted electrons back to the collectors, the hot wires are at the far end of a 1.1m long insulated tape. The voltages needed to overcome space-charge effects cause near-radial "hot electron" expansion from the hot emitter into the plasma, with <1% likely to re-impact collectors >1m away.

The emitter space-charge voltages are comparable to the electron collection voltages, so we also need a "floating probe" to determine collector bias relative to the local plasma. Our strategy is to connect a high-voltage capacitor between the hot-wire emitter and one collector, to drive the current loop. We use the other collector as a nearly-isolated plasma voltage-reference probe.

THE EXPERIMENT OPPORTUNITY

The opportunity for this experiment came about when it was learned that California Polytechnic State University (Cal Poly) had ~25mm of unused height available inside a CubeSat they were constructing. We learned of the availability of this space for our experiment in January of 2008, and delivered the experiment to Cal Poly on August 20, 2008.

Cal Poly's CubeSat provided the structure, electrical power, on board processor and the command and data handling capability. Cal Poly also performed the final spacecraft vibration and environmental testing. The Naval Research Laboratory constructed the experiment to fit in the very confined space, performed environmental testing, and delivered the experiment to Cal Poly, where NRL and Cal Poly staff worked together to integrate the experiment into the CubeSat.

The CubeSat is slated for launch mid 2009 as part of the launch of TacSat-3. The Cal Poly experiment will undergo operations for 3-6 months before CE2 will start its operations. Because of the launch schedule, space experimental data will not be available at the time this paper is presented. Thus we will concentrate in this paper on the engineering behind the development of the experiment.

CP6 began as the second of two flight candidates built for the CP3 mission. After the April 2007 DNEPR launch successfully deployed CP2 and CP3 into Low Earth Orbit, it was apparent that the communication uplink margin was very small due to low receive sensitivity. Looking forward to CP6, Cal Poly's development team focused on the communication uplink issue and general bus software stability. The primary mission for CP3 and CP6 is to evaluate a suite of COTS sensors with applications in attitude determination. CP6 will also beacon every two minutes with sensor readings that provide general satellite health information.

CE2 EXPERIMENT

The CE2 experiment was designed to fit in a small area approximately 2.5 cm x 10 cm x 10 cm on one end of the standard 1U Cal Poly 10 cm CubeSat. Figure 2, shows the CubeSat with the CE2 experiment mounted on the. Here the aluminum structure is on the top and the tapes are to the right extend down into the CubeSat.

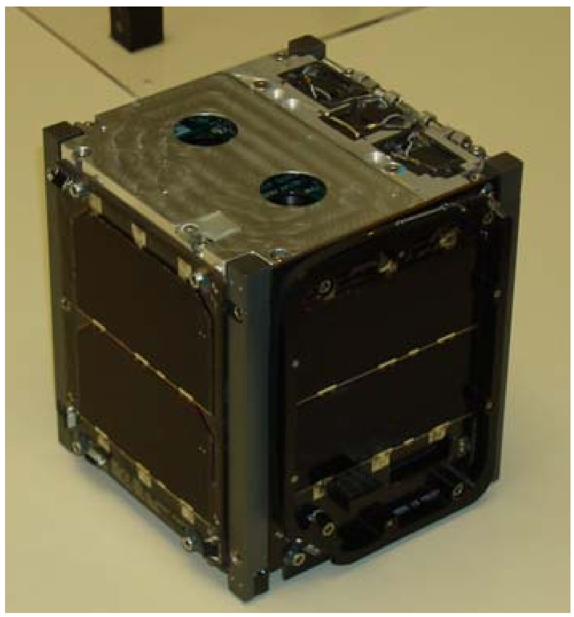

Figure 2: CE2 experiment integrated to Cal Poly CubeSat

The two sides of the CE2 experiment are shown in Figure 3. Here we identify several important components which will be discussed in more detail later in the paper. Two printed-circuit boards, shown on the left in Figure 3, mount on an aluminum plate, which in turn mounts on the top of the CubeSat. This covers some instruments inside the CubeSat. The three cylindrical objects in the picture on the left are rolls of thin Elgiloy tape that form the heart of the experiment.

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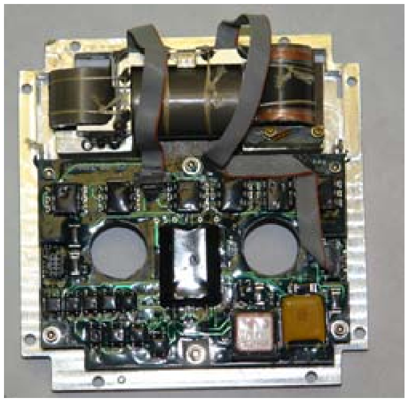
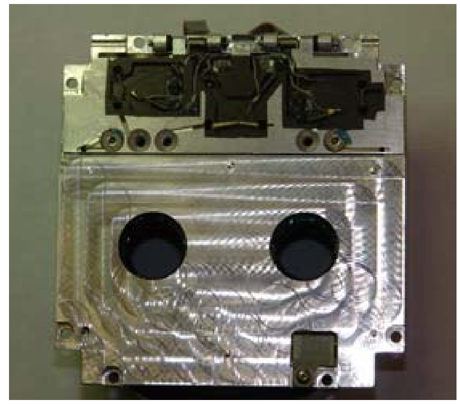
<tr><td></td><td></td></tr>
<tr><td>Tapes and electronics boards attached to cover plate</td><td>Reverse side of experiment showing structure to which electronics and tapes are attached</td></tr>
</table>

Figure 3: Both Sides of the CE2 Experiment

The primary payload developed by Cal Poly allotted a small amount of space on one end of the CubeSat for the CE2 experiment. There were several constraints on the integration. It had to fit in the volume allotted, roughly 2.5 cm x 10 cm x 10 cm. As a secondary experiment CE2 could not inhibit the primary Cal Poly payload. The Cal Poly payload included instruments that required access to space at all times. Thus the CE2 experiment was designed with ports in the electronics boards through which the Cal Poly instruments will have an uninterrupted field of view. CE2 was provided 100mW of continuous power from the solar arrays on the CubeSat.

The electron collection and emission system consists of 3 strips of coiled thin metal resembling carpenter tape measures. These strips will deploy prior to the experiment operations. These tapes are restrained from deployment by thin Vectran cords that maintain the tension on the tapes. The cords ensure the tapes will not deploy prematurely before the start of the experiment.

<u>Experiment Engineering Description</u>

The heart of the electrodynamic experiment consists of 3 tapes used to collect and emit electrons. Two of the tapes are the electron collectors and the third supports emission of electrons. The two collection tapes are made of Elgiloy, while the third tape consists of blued spring steel, with narrow copper foil return-conductors along each edge. The tapes are thin and rounded like a carpenters tape measure to provide rigidity. Figure 4 depicts the deployment arrangement of the three tapes. The tape to the right is the emitter tape while the other two are collector tapes. Either or both collector tapes can be electrically connected to the emitter tape through a high-voltage capacitor, to draw electrons from the plasma to replace those emitted by tungsten filaments. Having two different width collectors will provide data about the dependence of collection efficiency on width of the tapes.

The emitter tape is 1.1 meters long and is composed of a 12 mm wide by 76 micron thick piece of blued spring steel. On each side of the spring steel is a small 1 mm space and then a 2 mm wide by 76 micron thick piece of copper foil and then a 0.5 mm space. The entire length of the emitter tape is covered in Mylar OL13 laminate which acts as an insulator for the high voltages running between the spring steel and copper foil. The wider collector tape is made of a piece of Elgiloy which is 1.4 m long by 30 mm wide by 100 micron thick. The inner 20 cm of the Elgiloy are laminated in Mylar OL13 to prevent any high voltage discharges back to the grounded frame. The remainder of the tape is bare Elgiloy.

The thinner collector tape is also a single piece of Elgiloy which is 1.7 m long by 15 mm wide by 100 micron thick. Again the inner 20 cm are laminated to prevent any high voltage discharges back to the grounded frame and the remainder of the tape is bare Elgiloy. The three tapes are shown in Figure 4. in their deployed configuration.

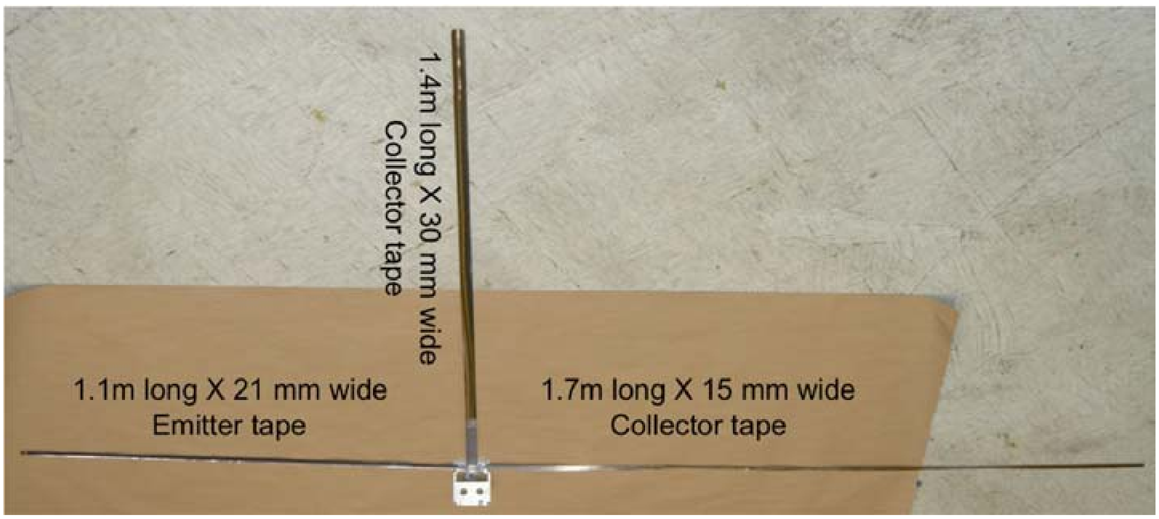


Figure 4: Deployed tapes for CE2.

The end of the emitter tape consists of a structural support for the two redundant thoriated tungsten wire filaments which actually emit the electrons. Figure 5 provides pictures of the filaments. The thoriated tungsten filaments run between the outer bolt joints and are attached so that the filaments have some slack. The emitter tape design uses the spring steel plus one of the two copper strips to provide heater current to each of the two hot-wire electron emitters at the end of the tape. This allows either wire to be heated separately. (Both are biased to a common high voltage by their common connection to the spring steel, but only the heated wire emits electrons.) To provide current to the filaments two thin strips of copper were laminated to the Elgiloy emitter tape, which can be seen in the picture on the left of Figure 5. The two emitters will be super heated in space, which will cause them to emit electrons thermionically. One of the two filaments is shown in its lighted state in the picture on the right of Figure 5

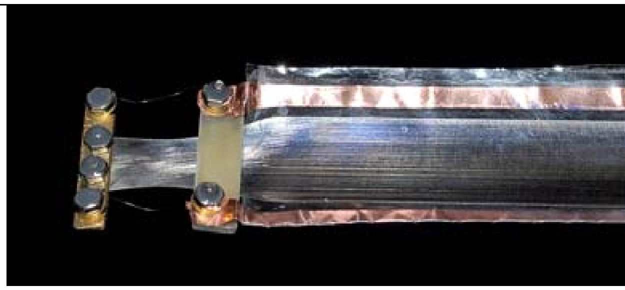
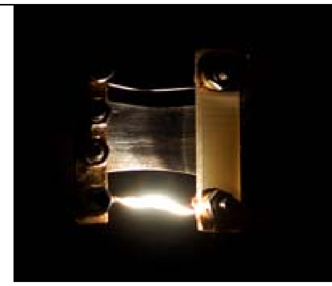
	
End of emitter tape with two tungsten filaments	End of emitter tape with one of the tungsten filaments illuminated

Figure 5: Filaments At End of Emitter Tape

Mechanical System

The mechanical system has to provide for two deployment events. The first will be the opening of a hinged door on which the three tapes are attached. The door and the three tapes can be seen in the undeployed state in Figure 6.

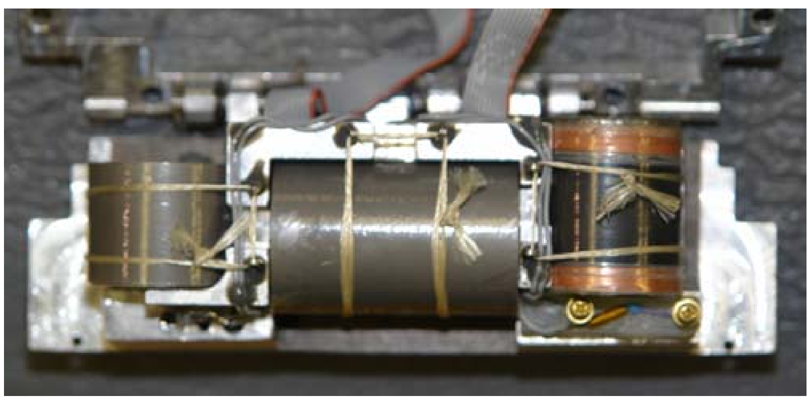


Figure 6: The Three Tapes Secured To The Door By The Vectran Cord.

The door is held to the upper cover by hinges that are spring loaded. Braided Vectran cord is used to secure the door. The deployment of the door occurs when a nickel chromium wire mechanism is heated and burns through the Vectran cord. The nickel chromium wire is attached to a grounded fastener on one end and then loops around the Vectran cord and is attached to a positive wire and an extension spring on the opposite end. The spring, the electric wire, and the nickel chromium wire are attached via the use of a crimped pin barrel. The extension spring is used in order to provide a cutting stroke motion of the nickel chromium wire through the Vectran. The current is passed through the nickel chromium wire which heats up and burns through the Vectran. Two release mechanisms were used for the door in order to prevent premature deployment while stowed in the P-POD (redundancy against premature deployment rather than redundancy to deploy). The door will deploy to approximately 145°. Figure 7 shows one of the nickel chromium release mechanisms (inside red box) used to deploy the door.

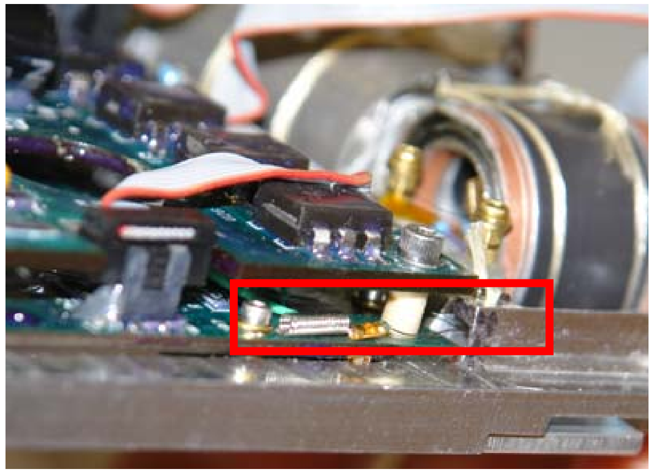


Figure 7: Release mechanism used to deploy the door

The tapes were rolled up by hand and held in place by Vectran cords. The Vectran cords are weaved through a number of holes in the CE2 door to the back side of the door where it comes in contact with their own respective nickel chromium release mechanisms. The release mechanisms used for the deployment of the tapes is similar to those used for the door. Figure 8 shows the top of the CE2 door and the three release mechanisms for the deployment of the tapes.

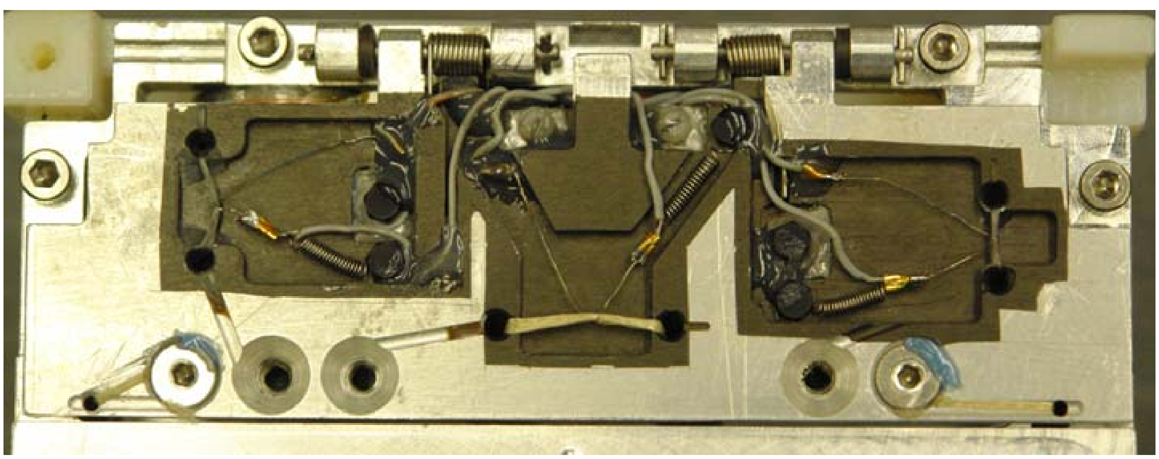


Figure 8: Outside Of The CE2 Door With The 3 Tape Release Mechanisms.

The door was machined from a piece of 6061 aluminum on a precision mill. The inside of the door has a "retaining wall" in order to assist with the stowing of the tapes as well as to act as a guide during the initial stages of the tape deployments. Certain areas of the door were hard anodized (black) in order to provide electrical isolation as necessary. The hinge for the door utilizes custom Delrin bushings with a stainless steel dowel pin and two separate torsion springs for deployment. The torsion springs were sized for high torque margin under worst-case cold harness resistance.

The remainder of the CE2 payload is a 6061 aluminum support frame, which was also machined on a precision mill. The support frame connects to the door via the hinge. The support frame allows for the CE2 payload to be stowed and then integrated as a complete system to the CubeSat provided by Cal Poly. The entire CE2 payload fits onto one of the sides of the CubeSat and is fitted over the payload already on the CubeSat. There are two holes in the CE2 support frame which allow a clear view of space for the CP6 instruments. The two circuit boards are attached to the support frame and fit around the instruments as well.

QUALIFICATION TESTING

The schedule for the experiment was extremely short, only eight months from concept to delivery, with very limited funding. For these reasons a thorough, formal qualification test program was not conducted as the schedule and budget did not allow for it. Instead, we did an abbreviated series of "high value / targeted tests."

The abbreviated CE2 payload test program consisted of a qualification (MPE +6dB) random vibration test of the payload integrated on a CP6 spare CubeSat structure, which in turn was integrated into a fixture that represented the environment of the Poly-Picosatellite Orbital Deployer (P-POD). This qualification random vibration test was performed at Cal Poly prior to flight CubeSat integration. This was followed by CE2 payload level thermal vacuum testing with deployment of the three tapes and lighting of the emitter filaments at NRL prior to integration at Cal Poly. Component level tests were also performed at NRL on the nichrome wire / Vectran cord cutter release devices to characterize their performance. However a fully qualified release design with robust margins for deployment was not achievable within the budget and timeframe of this program. There is a shortage of qualified release devices appropriate for the CubeSat community and NRL is trying to start a program to foster the creation of a base of qualified release devices for the community, as there is rarely adequate schedule or budget to qualify new release devices for each CubeSat mission.

Once the flight CE2 experiment was delivered to Cal Poly it was integrated into the flight CP6 satellite in the PolySat/CubeSat class 100,000 clean room. The complete CP6 satellite was vibration tested to protoflight levels of MPE+3dB with the same procedure used for CE2 vibration qualification. The complete CP6 CubeSat also underwent bake-out in the PolySat/CubeSat thermal vacuum chamber, including two cycles from -20C to 70C at $2x10^{-5}$ torr.

Finally, CP6 was integrated into the flight P-POD with two other CubeSats and underwent an acceptance vibration test. The acceptance vibration test of the P-POD was performed by Cal Poly students at the Wallops Island launch site.

ELECTRONICS

Two electronics boards are employed by the experiment: a low voltage board and a high voltage board. They are closely stacked to minimize the experiment's total volume. A small stacking connector provides the interface between them. Each has two holes to allow the Cal Poly instruments to have a clear view of space. These ports can be seen in Figure 3.

Control of the experiment is provided by a PIC microcontroller (the PIC18LF8722) on the low voltage (LV) board. This was programmed in C. Its main tasks were to: interface to the main CubeSat processor via an I2C communications bus, control door and tape deployments, actuate switches to control the experiment, and collect experiment data. The software allows for flexibility in the parameters of the experiment runs and the associated data collection.

The PIC microcontroller was selected because of its uncommonly low power consumption. Initially, a field programmable gate array (FPGA) had been considered, but it was deemed that the PIC microcontroller would be more power efficient. The PIC was also attractive because of its integrated analog to digital converter and I2C interface, which simplified data collection and communication with the CubeSat processor respectively. A small access port provides for in-circuit programming of the PIC. The low voltage board also houses the solid-state switches that actuate the door and tape release deployments.

The experiment requires high voltage to drive current collection and emission, and an impulse of current to heat the thoriated tungsten enough for it to emit electrons. Providing charging and high voltage/ground isolation required use of 21 solid-state relays with optically isolated control signals. These resided on the high voltage (HV) board, as did the high voltage power supply, current and voltage measurement amplifiers, and associated circuitry. Some relays are used to switch resistors that change the measurement range of collected data.

We provide a current-collection voltage sweep by first charging a high-voltage capacitor using a tiny EMCO isolated DC/DC convertor, and then collecting data as it discharges through the external current loop and a switchable parallel load resistor. To heat one of the two emitter wires, we charge a 5V supercapacitor using the bus voltage, isolate it from the bus, and discharge it through one of the two heater current loops, using the blued steel as one leg, and one of the two copper strips as a return conductor.

All components used on the LV and HV boards were procured from commercially available sources and do not have any specific space-qualified pedigree. This was driven by schedule and budget constraints, as were many design decisions. The electronics successfully completed temperature cycle testing in air at -45C and +75C prior to integration with the CubeSat.

SOFTWARE

For CE2 communications, the Cal Poly Bus served as a messenger between CE2 and the ground station. Communication between CE2 and the bus used a simple protocol built on top of I2C. For the safety of the primary payload, high voltage activities were enabled and disabled via the bus. The bus monitors the commands received from the ground and decides if the satellite has the resources (i.e. power) for CE2 to execute the command safely. If so, the satellite enables what resource the CE2 payload needs and passes the command over the I2C.

Software for the CubeSat Electron Collector Experiment was written in C for Microchip’s PIC microcontroller. The microcontroller included hardware support for many of our experiment functions, including two I2C ports, 10-bit analog to digital conversion channels, high-current sinking and sourcing on digital outputs, hardware counters, and hardware timers. Source code was compiled using Microchip’s MPLAB C18 C compiler and assembled with Microchip’s MPASM Assembler. The microcontroller was programmed with Microchip’s PICkit 2, which provided in-circuit debugging integrated with Microchip’s MPLAB IDE. The use of a high-level language such as C, the in-circuit debugging provided by the PICkit, and the code project management provided by MPLAB were critical to meeting the aggressive timeline of this project.

The software used a simple state machine framework. The default state was to sit idle and wait for ground station commands received from Cal Poly’s CDH board over the I2C interface. Once a command was received and decoded, the software would change state and execute the supplied command. During this time the payload is unresponsive to further commands. The software does not support command queuing. When the current command completes execution, the software returns to the idle state and waits for the next uplink command. The software supports four primary commands, <cut cord>, <run exp>, <get data>, and <get status> as well as several auxiliary commands.

Data collected by the software is stored in an off chip eeprom using a second I2C bus to minimize traffic on the satellite's primary communication bus. The eeprom hardware had a natural page size, which conveniently corresponded to an appropriate size for downlink. Therefore, operations data was made to conform to this page size and structured so that a header at the beginning of each page completely described when the page was acquired, what data is contained in the page, some limited status information about the payload, and the data itself. This ensured all pages could be successfully interpreted even if received out of order or if a subset of pages were lost during downlink.

The payload collection tapes and emitters must be deployed before any experiments can be preformed. This is accomplished with the <cut cord> command, which heats a resistive wire to cut the cords restraining the deployment mechanisms. During execution the software collects some status data, energizes the specified cutter, logs the status of the payload during the specified cut time, and finally turns off the cutter. Cords can only be cut one at a time. Due to the substantial power load, the CubeSat requires considerable recharge time between cuts.

The main function of the software is to execute the <run exp> command. This command contains 27 bytes of uplink parameters to expand the flexibility of the payload by allowing ground station operators to control numerous experiment timings, charging levels, discharge rates, and sensor input ranges. Once this command is initiated, the experiment is repeated, at the specified intervals, until enough data has been collected to fill the data storage. This command eventually overwrites all previously acquired data.

The software also supports the <get status> command, which downlinks the current status of the payload, including the states of all input and output pins, and numerous internal registers, including timers and counters. This was an important aid in understanding the current state of the payload, and diagnosing unexpected behavior, as well as verifying normal operation of the payload systems and communication links.

Data is retrieved from the payload with the <get data> command. This command initiates downlink of a subset of the data stored in the external eeprom, up to and including the entire contents of the data storage. Operators have considerable flexibility specifying which pages to downlink, allowing them to select the best datasets and maximize the effectiveness of limited downlink bandwidth. Once the request is received, the CubeSat will transmit data down whether or not a receiver is listening. This command does not alter the contents of the data storage, so it may be resent as many times as needed if downlink communications are not reliable.

The software also supports several auxiliary commands that are not intended for use during orbit, but proved valuable during the debugging stages of development. These commands can change firmware parameters and sensor calibrations, read the values of individual input pins, and control the state of individual output pins. Even though they are not intended for use during normal operations they were included in the flight software because their low level nature potentially allows them to solve unforeseen problems or exploit unforeseen opportunities.

PHYSICS EXPERIMENT

Individual aspects of the electron emitter and Elgiloy collector operation were tested under vacuum and a variety of simulated space plasma conditions in the Naval Research Laboratory's

Space Physics Simulation Chamber. The Space Chamber is a large-volume device in which steady-state magnetized plasmas with parameters appropriately scaled to ionospheric or magnetospheric conditions are created. In this environment, the characteristics expected to be encountered on orbit could be realistically assessed.

The operational principle of the NRL CubeSat experiment is relatively simple. Current is made to flow between a hot emissive filament and a current-collecting tape, which is biased relative to the emitter. The scientific requirements for meaningful data collection from such a system are: (i) reliable operation of the electron-emitting filaments at emission levels high enough that current is limited only by the plasma electron collection, (ii) accurate measurement of collected current, and (iii) determination of background plasma density and temperature in the region of the collection experiment. Laboratory tests were performed in order to investigate each of these experimental requirements.

The reliability of the filaments for adequate emission was tested under both vacuum and scaled ionospheric conditions. One design criterion was an emission current of at least 10 mA when biased approximately -400 V with respect to the collecting tape. This corresponds to emission current exceeding the maximum current collected by the large area Elgiloy collector in the highest density ionospheric plasma conditions anticipated. Due to realistic expectations of power available for capacitor charging and expected levels of filament heater current, an 11-mm long, 0.0635-mm diameter 1% thoriated tungsten wire was chosen as the emitter filament.

The robustness of these filaments directly controls the operational lifetime of the collection experiment. To characterize the expected lifetime, filaments were pulsed on for repeated 1 second intervals, either at a constant current of 0.8 A or at a constant voltage of 4 V to 4.5 V. These values correspond to the predicted filament current required for the necessary emission and the expected bus voltage level for capacitor charging. The filaments were held in place by securing the end of the thoriated tungsten between the rounded faces of two #6 stainless steel washers, analogous to the method used on the CubeSat emitter tape (see Figure 5). Repeated testing demonstrated that the tension on the filament was the largest contributing factor determining filament lifetime. We found that filaments pulled taut between connecting posts failed quickly, but those with slack can be expected to survive for more than 5,000 successive pulses. Additional testing indicated that thermal stress from pulsing the filament, vibrations during launch, and mechanical stress during emitter tape deployment did not significantly impact filament lifetime.

The emission characteristics of the thoriated tungsten filaments were tested with the emitter and a 148.5-cm^2 Elgiloy collector connected in series, as they would be in flight. In the space experiment, a bias of up to -400 V will be applied to the emitter with respect to the collecter. For the laboratory testing, operation was restricted to the more conservative value of -200 V to ensure that adequate emission could be obtained if the experiment were forced to operate at a reduced voltage. At a bias of -200 V, 24 mA of emitted/collected current were measured, well in excess of the 10 mA experimental requirement.

In order to accurately compare data obtained on orbit with various electron collection models, the background plasma electron temperature and density must be determined. Methods were explored to use the emitters and collectors as plasma diagnostics to conserve the limited space and resources available on the CubeSat. It was determined that two different types of plasma probes could be fashioned from the available electrodes, utilizing the existing current and voltage measurement circuitry and high and low voltage capacitors as voltage sources.

One background plasma diagnostic is an asymmetric double probe, which uses the two Elgiloy collectors as the probe surfaces. This setup differs from the traditional plasma double probe[13] since there is a difference in the collecting area of the two surfaces. However, estimates of the plasma density and electron temperature can be recovered by accounting for the difference in collection areas in the derivation of the theoretical current-voltage characteristic curve for the probe. These data will be acquired immediately before initiation of an iteration of the tether electron collection experiment.

An independent measurement of electron temperature and plasma density will be made by a unique triple probe technique immediately following the tether data collection. In this method, both collectors will be used along with the unheated filaments to form a variation of a plasma triple probe system. A traditional triple probe plasma diagnostic consists of three identical probe tips immersed in a plasma[14]. By measuring the current flowing between a biased pair of the electrodes, and measuring the potential of the third, electrically isolated electrode with respect to the positively biased probe tip, the electron temperature and plasma density can be determined. The model of current collection by a plasma triple probe depends on the assumptions that the plasma electrons are Maxwellian, the mean free path of the electrons is large compared to the sheath and to the probe dimensions, the sheath dimensions are small compared to the separation between probes, and that the ion saturation current varies weakly with voltage. These conditions should be satisfied for the CubeSat.

The onboard electronics and the combination of emitter and collectors on the CubeSat experiment can be configured to use this technique for rapid determination of electron temperature and density, despite the unequal electrode surface areas. The emitter will be electrically isolated and used to measure the potential difference to the smaller Elgiloy collector. That collector will be biased positive with respect to the larger Elgiloy collector, forming the current monitoring portion of the triple-probe circuit. Laboratory testing of this unorthodox triple probe arrangement showed reasonable agreement of plasma parameter measurements with standard laboratory Langmuir probe measurements.

CE2 EXPERIMENT OPERATIONS

As noted earlier, CE2 experiment operations will not begin until 3-6 months after the CubeSat is launched and deployed. But there will be an opportunity to downlink basic housekeeping data early. This will provide verification that the PIC controller and comm interface are ok. This is feasible without causing deployment or high-voltage charging, because the CubeSat can enable power to the PIC, while disabling power to our high-voltage and high-current components.

Once we know that the CubeSat and our PIC are functioning properly, we can spend the next few months developing analysis tools to let us evaluate the flight data quickly. These tools will come in handy once we start our experiment.

The experiment will begin with by cutting the two Vectran cords that keep the door closed. Successful door opening can be inferred from several sensors, including a photodiode mounted on the door. Then we will deploy our 3 tapes, probably one on each orbit. As noted earlier, the door release and tape deployments all involve heating a 6-mil nichrome wire to cut through braided Vectran cord. We need to separate these events to limit our energy draw from the CubeSat batteries, and also to study and respond to any anomalies seen in the flight data.

Once the tapes are deployed, we can check out and start using our experiment. Our experiment involves high voltages, and our PIC microcontroller directly controls the circuit topology through 21 relays. It would clearly be easy to get into unforeseen and damaging states.

To prevent this while limiting development and test cost and time, our philosophy was to program and test a single fixed sequence. But we tried to allow "safe flexibility" by allowing daily uplink of a new 27-byte list of parameters as part of each <run exp> command. These parameters select the collector and emitter, A/D ranges, intervals between voltage sweep "shots," and intervals between successive events in each shot.

Each <run exp> command causes the PIC to fill up our eeprom memory, stop, and wait for another command. The CubeSat can request an abort at any time. An abort ends a whole day's run (after a shot, if one is already in progress). In addition, our PIC checks the bus voltage before each shot, and cancels that shot if Vbus<4.0V. This minimizes power consumption in power-poor situations.

Our intent during each shot is to sense voltage and current over a wide range of bias voltages as the HV capacitor voltage decays. For flexibility, we allow changes in A/D range and sample interval between successive pages of data collected for each shot. The selections and intervals are all fixed for a given day, but can be changed as desired from one day to the next.

The HV cap charging time drives the peak HV capacitor voltage and hence the likelihood of damage due to arcing. To minimize the chance of early failure, we plan to use short charging times the first few days, and gradually increase the charging time after that. Similarly, the supercap charge time affects the peak supercap voltage. This drives the hot-wire temperature and thermionic emission capability. Stepping this up gradually can show us when electron emission transitions from temperature-limited to space-charge-limited. This lets us heat the wires enough, without shortening their life by overheating them.

We plan to uplink <run exp> commands during the last of several consecutive passes with good comm links. The timing of the shots is controlled by 3 parameters: a start delay of 0-65535 seconds, a shot group delay of 0-5400 seconds, and a between-shot delay of 0-400 seconds. A multi-orbit start delay lets us focus our experiment on the orbits with the most interesting magnetic field variations, while the other two parameters let us focus on specific times within an orbit (all day or night, etc.). By setting the group delay to 0, we can take data at uniform intervals of up to 400 seconds, until the eeprom memory is full. This may be a useful option if there is a significant solar flare during the experiment.

As tight as our mass and power budgets are, our tightest limitation is actually downlink data. In addition, the CubeSat attitude is measured but not controlled, so we may not know which shots are the most useful until we study the CubeSat attitude data. These factors drove us to a strategy of selective download. We plan to download summary experiment data plus CubeSat attitude data on the first good downlink pass each day, and analyze that data well enough within 90 minutes after the pass to identify which shots best fill in gaps in our flight data. The main discriminator will probably be CubeSat attitude (and hence tape orientation in the magnetic field), but plasma density and other parameters may also be important. On later passes we will uplink <get data> commands that specify which pages of detailed data to send for which shots. To limit problems caused by downlink dropouts, each page includes enough header data to make it interpretable on its own. (In addition, selective download lets us re-send pages not received intact on previous passes.) We can keep downlinking stored data for several days if needed—until we uplink a new <run exp> command and start overwriting the old data.

Preliminary calculations suggest that the deployed tapes may tend to stabilize CubeSat attitude with the two narrow tapes up and down (due to gravity gradients), and the wide tape facing aft (due to drag). After we collect as much data as we want in this attitude, we will want to vary the CubeSat attitude. The CubeSat has air-core magnetorquer coils and attitude sensors, but it does not have sophisticated enough software to allow active feedback control of its attitude. Hence we can only ask Cal Poly to use the torquers to perturb the CubeSat attitude. This will result in weakly damped oscillations for some time, allowing a wider range of experiment data points.

Perturbing the attitude should also result in somewhat higher average drag. This might also be useful for active collision avoidance, once we learn how much we can affect the orbit decay rate by perturbing the attitude. In addition, the timing of our tape deployment will also affect drag and decay rates. Hence we may want to adjust deployment time for collision-avoidance reasons.

The CE2 experiment is currently awaiting launch with TacSat-3. Assuming a launch in mid 2009, CE2 operations are expected to commence before the end of the calendar year. Figure 9 shows a rendering of CE2 deployed, as it might appear in space.

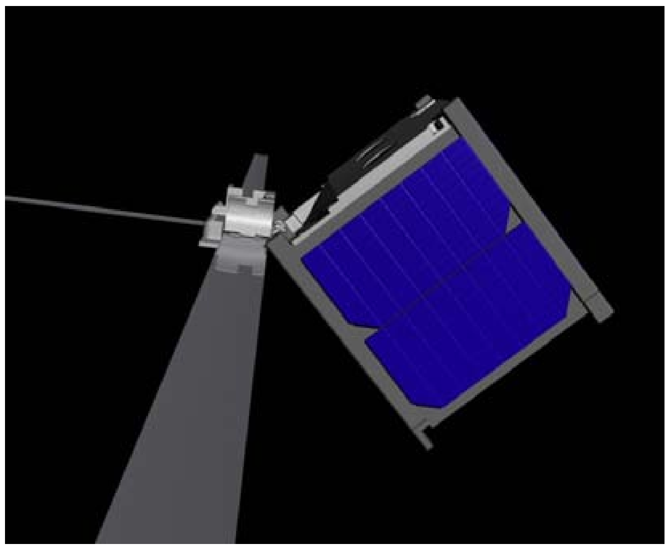


Figure 9: Rendered Picture of CE2 Experiment on Cal Poly CubeSat

CONCLUSION

CE2 is an experiment to test the physics of collecting and emitting electrons using a spacecraft immersed in the earth's ionospheric plasma. This experiment is a pathfinder for a later experiment that will have a long tether between the collector and emitter devices. A compact experiment designed to fit in a CubeSat has been developed. This experiment will provide valuable experience in collecting and emitting electrons in the earth's plasma. This is one of a long line of electrodynamics experiments designed around the use of CubeSats, which provides inexpensive access to space.

REFERENCES

Overviews of Electrodynamic Tethers

[1]Cosmo, M.L. and Lorenzini, E.C., “Tethers in Space Handbook”, Third Edition, Smithsonian Astrophysical Observatory, Dec. 1997.

[2]McCoy, J., et al., “Plasma Motor-Generator (PMG) Flight Experiment Results,” Proceedings of the Fourth International Conference on Tethers in Space, pp. 57-82, Smithsonian Institution, Washington, DC, April 1995.

Electron Collection by Wires or Tapes

[3]Sanmartin, J., M. Martinez-Sanchez, and E. Ahedo, “Bare Wire Anodes for Electrodynamic Tethers,” *Journal of Propulsion and Power*, Vol. 9, No. 3, pp. 353–360, 1993.

[4]Onishi, T., and M. Martinez-Sanchez, “Computation of Current to a Moving Bare Tether,” 6th Spacecraft Charging Technology Conference, AFRL-VS-TR-2000-1578, 1 September 2000.

[5]Van Noord, J. L., B. West, and B. Gilchrist, “Electrodynamic Tape Tether Performance with Varying Tether Widths at Low Earth Altitudes,” AIAA-2001-1141, 39th Aerospace Sciences Meeting & Exhibit, Reno, NV, 8-11 January 2001.

[6] J.R. Sanmartin and R.D. Estes, "Validity of the orbital-motion-limited regime of cylindrical probes," pp 399-417 in NASA/CP-1998-206900, Proceedings of the Tether Technology Interchange Meeting, Huntsville, 1997.

[7] Juan R. Sanmartin, "Collection Effects on Close Parallel Bare Tethers,"paper AIAA2000-1073 at the 38th Aerospace Sciences Meeting & Exhibit, Reno, January 2000.

Electron Emitters

[8]Aston, G., Aston, M.B., and Williams, J.D. (2001) Miniature Plasma Activated Systems for Tether Current Generation. STAIF 2001 Proc., pp. 452-460.

[9]Binh, V. T. et al (2000) Solid-State Field Controlled Electron Emission: an alternative to therm-ionic and field-emission. Mat. Res. Soc. Symp. Proc. Vol. 621, pp. R4.3.1-R4.3.6.

[10]Friz, W. et al., Ambient Temperature Electron Emitter Device “COEED,” IEEE International Vacuum Electronics Conference, 2 p., 2000.

[11]Komoda, T. et al (2001) Ballistic Electron Surface-Emitting Cold Cathode by Porous Polycrystalline Silicon Film Formed on Glass Substrate. Mat. Res. Soc. Symp. Proc. V. 630, pp. F4.1.1-F4.1.12.

[12]Marrese, C.M. (1999), A Review of Field Emission Cathode Technologies for Electric Propulsion Systems and Instruments, http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/18637/1/99-2020.pdf.

Plasma Diagnostic Probes

[13]E. O. Johnson and L. Malter, *Phys. Rev.*, **80**, 58 (1950).

[14]S. L. Chen and T. Sekiguchi, *J. Appl. Phys.*, **36**, 2363-2375 (1965).