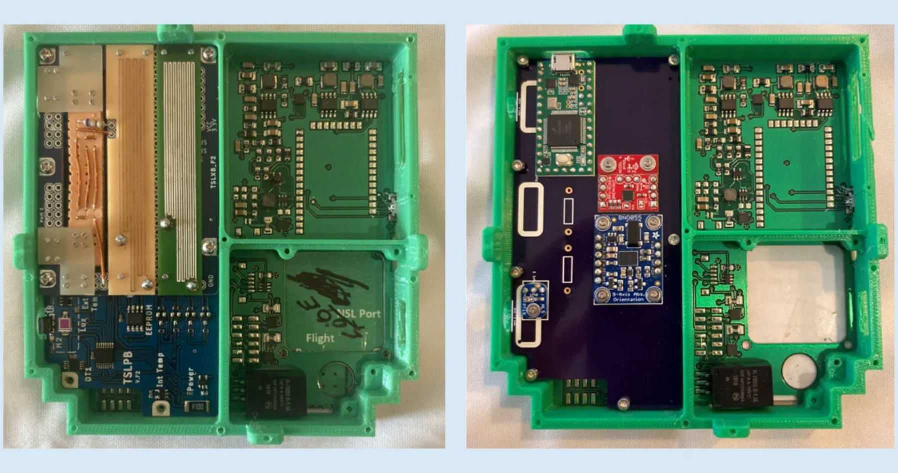
CUBESAT DEVELOPERS WORKSHOP

HOME

ProtoSat & MEMSat:

Princeton University's First ThinSats



POSTER BOARD AUTHORS

Kyle Ikuma

MEMSAT DESIGNER

Kyle is a sophomore (class of '23) in Mechanical and Aerospace Engineering from Norwood, New Jersey. He developed, designed, and assembled MEMSat during the summer of 2020, along with other innovations to make Princeton's ThinSat program accessible to more students. He will be pursuing a robotics and controls research internship at Princeton during the summer of 2021.

Shannen Prindle

PROTOSAT PCB PRINTING LEAD

Shannen is a Mechanical and Aerospace Engineering major in the class of 2023 from Herndon, Virginia. She designed and fabricated the ProtoSat Voltera V-One PCB. Next year, she'll be working on Princeton's first cubesat project. She will be a Production Intern at SpaceX during the upcoming summer 2021.

Shalaka Madge

PROTOSAT SOFTWARE LEAD

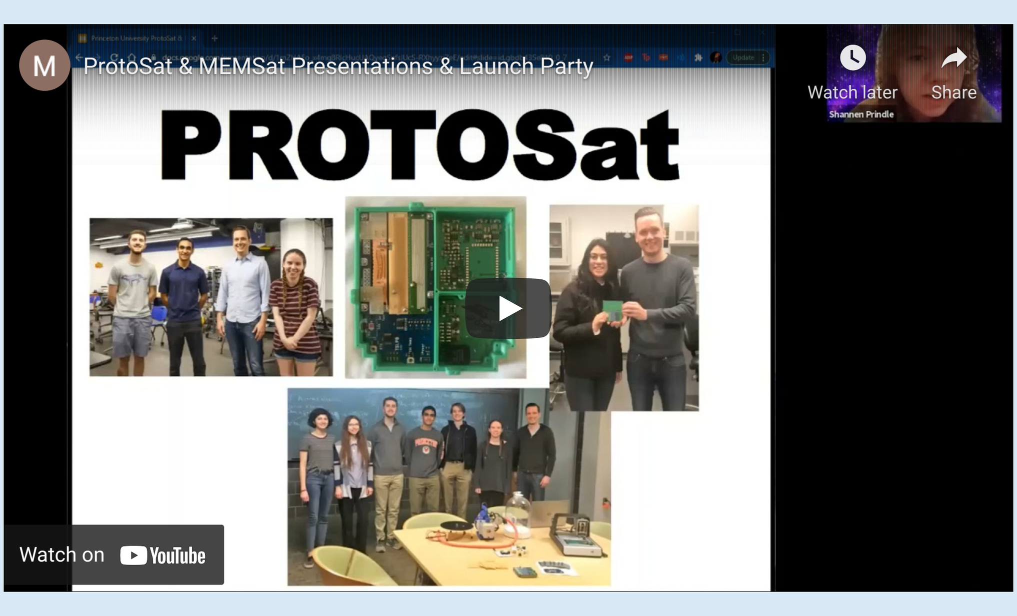
Shalaka is a Mechanical and Aerospace Engineering senior from Roxbury, NJ. She worked on sensor readout test cases and data packet timing & parsing. Next year, she'll be using her ThinSat skills at BAE Systems, as part of their Engineering Leadership Development Program.

Mike Galvin

PRINCETON NANOSAT PROGRAM ADVISOR

Mike is the Principal Investigator of Princeton's undergrad Nanosat Lab. His background was in spacecraft mechanical design & systems engineering at Lockheed Martin. On the research side, he currently works on the mechanical design of several ground & flight instruments for upcoming NASA missions.

Student Presentations & Launch Party



ProtoSat & MEMSat: Princeton University's First ThinSats

ProtoSat

Motivation

ProtoSat's scientific objective is to launch- and space-qualify (i.e., increase the TRL of) three different types of rapid-prototyped circuit boards, all believed to have never been subjected to the space environment before. The three prototyping methods are all very inexpensive and student-friendly, so proving their space-worthiness would further lower the bar to entry to space for academic CubeSat and ThinSat programs everywhere.

Tools and Design

Circuit Prototyping Tools

- Roland MDX-40A CNC Mill *[Figure 1]*
  - CNC milling is the most common student-level PCB prototyping method
  - Allows for robust, cheap circuit boards to be made in-house
  - Avoid cost, lead times, and (oft-surprising) administrative overhead of outsourced procurements by students
  - Milled subtrate is copper-clad FR1, perhaps never flown before (unlike the standard FR4). FR1 is reinforced by cellulose pulp rather than the usual FR4 glass fibers (an inhalation hazard), for more student-safe milling/drilling. Interesting questions about outgassing and TVAC/radiation susceptibility?
- Voltera V-One *[Figure 2]*
  - Desktop PCB printer, which prints conductive ink and solder paste onto (also) nonstandard FR1 *[Figure 4]*
  - Easier, faster, safer, and even more student-friendly than CNC milling
  - Already of active interest to NASA for in-space circuit manufacturing by astronauts in climate-controlled environments like the ISS, but Voltera PCBs themselves have never before been exposed to a full launch & space environment
  - Interesting questions about ink outgassing and durability (cracking?) under launch loads/TVAC/radiation?
- Biscuit Board
  - COTS ultra-thin plastic solderless breadboard, cut-to-size to fit into the TSLXB *[Figure 5]*
  - Stronger spring clips grip jumper wires more tightly than standard breadboard under launch loads
  - Still certainly not REALLY a spaceworthy circuit prototyping method, but included to demonstrate the true limits of more aggressive workmanship standards enabled by low-cost, short-duration academic picosat missions like ThinSat

Payload Design

- All 3 circuit boards were embedded onto a reworked (cutout) Twiggs Space Lab Expansion Board (TSLXB) for easy circuit continuity readout
  - Waterjet-cut to fit the BiscuitBoard *[Figure 6]*
- Circuits were intetionally designed to be dense and fragile
  - Labryinthine traces for Voltera and CNC boards
  - Compact wire placements for Biscuit Board
- If damaged during launch or orbit, analog voltage read-outs from TSLXB would report circuit as "open". Otherwise, any interesting on-orbit changes to resistance will also be reported.
- Additionally, the "host" TSL Payload Board (TSLPB) provides a suite of its own interesting sensor readouts (IMU internal/external/IR temps, solar intensity) for enriching student data analyses after-the-fact!

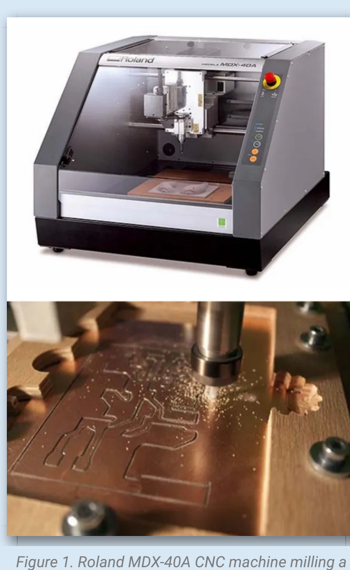


Figure 1. Roland MDX-40A CNC machine milling a PCB..

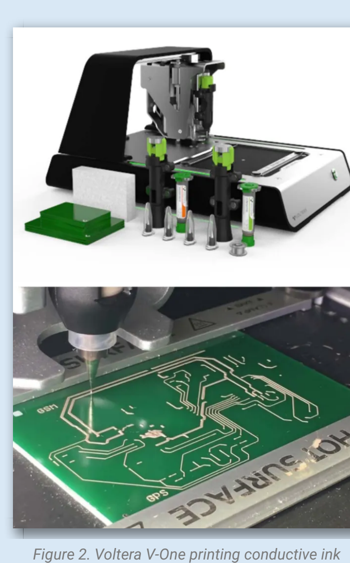


Figure 2. Voltera V-One printing conductive ink traces.

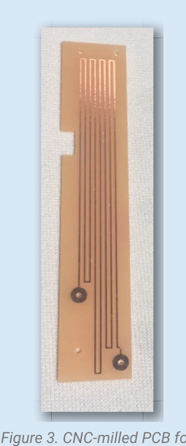


Figure 3. CNC-milled PCB for payload.

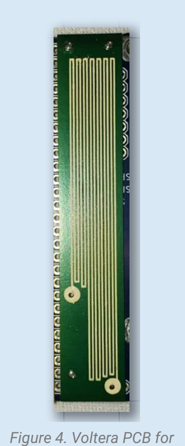


Figure 4. Voltera PCB for payload.

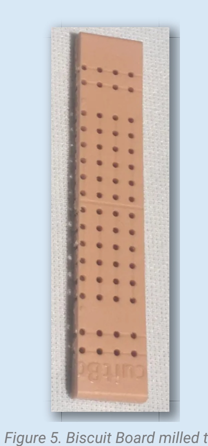


Figure 5. Biscuit Board trimmed to size for payload.

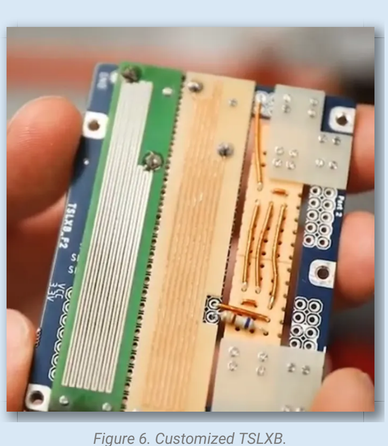


Figure 6. Customized TSLXB.

Figure 7. DIY student-safe TVAC chamber.

Environmental Qualification

- **Thermal cycling**
  - Performed using standard toaster oven and lab freezer, great options for student labs! *[Figure 8]*
  - Followed GSFC-STD-7000A NASA spec, compensating for nonvacuum conditions with longer hot/cold dwell times (according to §2.2.5)
  - Performance results
    - All circuit survived
    - Saw minimal (negligible) resistance variance of CNC & Voltera circuits before/after thermal cycling
    - Saw dramatic resistance variance (15 to 130 Ω) at temp extremes, likely due to CTE-induced change of spring clip preload/contact
- **Sustained vacuum (outgassing) and TVAC tests**
  - Used COTS classroom bell jar (PN 1003166 from a3bs.com) for sustained (24hr) vacuum/outgassing/TML test (roughly according to ASTM E595). Great option for student nanosats, just the right size!
    - At a sustained 0.05 atm, the total mass loss (TML) for the payload was only 0.1% (surprisingly low with some of the plastics and polymers included).
    - No dominant contributor to TML identified
  - Next, upgraded the bell jar for use as one of the first-ever DIY, ultra-cheap, compact, student-safe (zero-cryogen) thermoelectric TVAC chambers! *[Figure 7]*. Minimal use thus far for flight programs (still fine-tuning the achievable temp limits), but promising initial performance.
- **Vibration testing**
  - Local shaker table facility enlisted to subject payload to Antares random vibe environment *[Figure 9]*
    - Applied along all 3 axes separately
  - All circuits survived, no cracking or jumper wire loosening

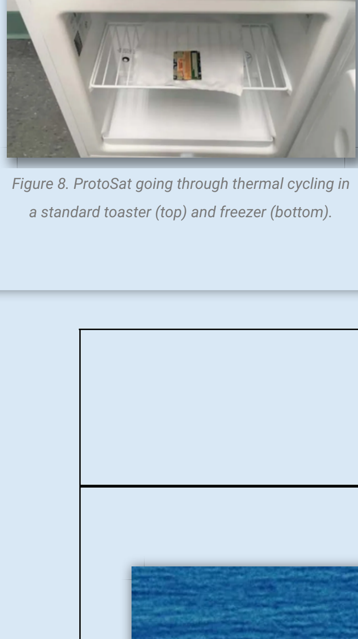


Figure 8. ProtoSat going through thermal cycling in a standard toaster (top) and freezer (bottom).

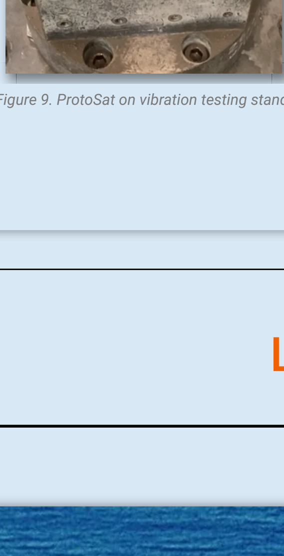


Figure 9. ProtoSat on vibration testing stand.

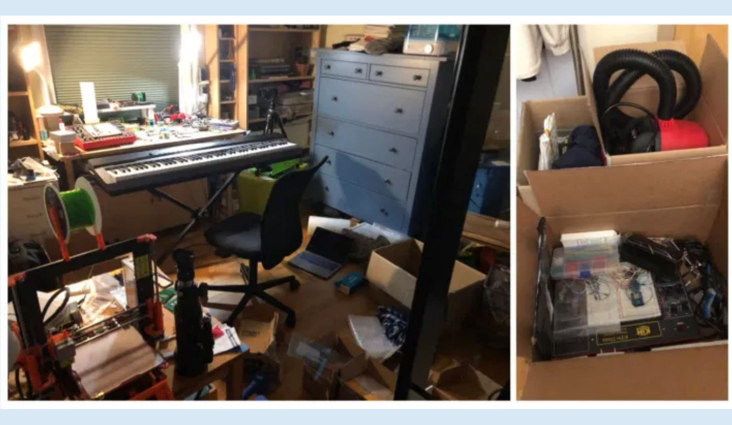
MEMSat

Motivation

MEMSat hosts three different colocated micro-electromechanical (MEMS) Inertial Measurement Unit (IMU) models (all popular models in the nanosat community) for the first-ever comparative test of their relative performance in a zero-G orbital environment.

Additionally, a secondary research objective was to determine whether the MEMSat PCB could be reliably student-manufactured on the same Voltera PCB printer used for ProtoSat (see left). This PCB was significantly more complex than the ProtoSat board, and this design proved to test the limits of the Voltera for spaceflight circuit boards.

Work Environment



Due to COVID-19, MEMSat was designed, tested, and assembled by Kyle in his own bedroom! (conveniently aided by Virginia Space/NSL's 3D-printed ThinSat Engineering Model, their Space Data Dashboard, and the Voltera)

Development and Design

- MEMSat Circuit Board Design
  - Designed a circuit that integrated three different popular MEMS inertial measurement units (IMUs):
    - Adafruit BNO055
    - SparkFun MPU-9250
    - The ThinSat bus's own onboard IMU (unpublished here, but also compared as one popular in the nanosat community)
  - Wrote Arduino code to process and transmit dual IMU data to a ground station
  - Calculated placement of both IMU boards such that the IMU chips were as close to the ThinSat's center of mass as possible (for comparable rotational readings) [Figure A]
  - Added a light sensor to one of the ThinSat viewports, to try to infer the ThinSat's orientation (i.e., infer intermittent pointing towards the Sun or Earth)
  - Manually routed traces on a single side of the board, to enable printing this single-sided PCB on the Voltera V-One PCB printer. Could not rely on auto-routing, so manually routing the traces was tedious and a challenging puzzle! [Figure B]

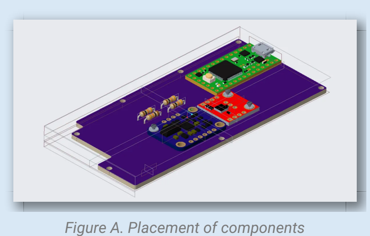


Figure A. Placement of components

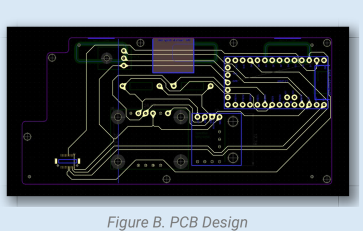


Figure B. PCB Design

Manufacturing and Assembly

- Voltera V-One print attempt [Figure C]
  - Large number of intricate traces, so a high chance of error
    - Conductive ink over-extruded and shorted out some traces
    - Alternatively, under-extrusion left a gap in the trace [Figure D]
    - Occasional misalignment of pre-drilled holes and printed circuit
  - Difficulty soldering pins to the printed traces- the soldering iron often melted the low-melting-point ink traces, despite using special low-temp solder and soldering iron [Figure E]
- This particular circuit design deemed too complex for reliable Voltera printing, especially for flight hardware. Ordered flight board from OSH Park (professional PCB etching service), and soldered the components on using NASA-recommended solder and copper wires [Figure F]
- Ensured solder joints and hardware were under the 1mm clearance on the back side of the board [Figure G]

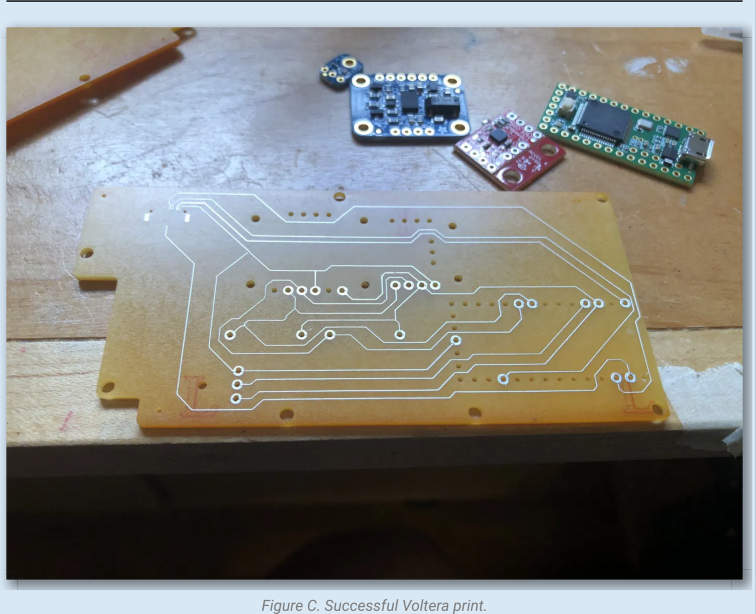


Figure C. Successful Voltera print.

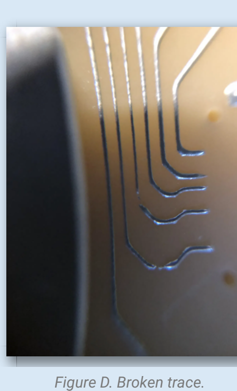


Figure D. Broken trace.

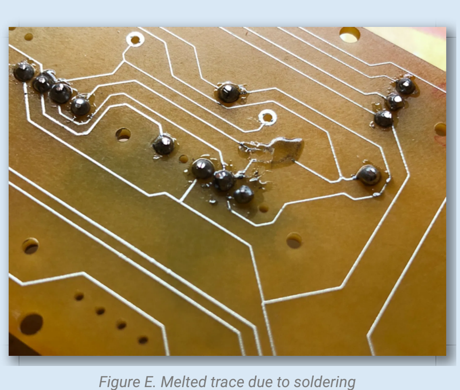


Figure E. Melted trace due to soldering

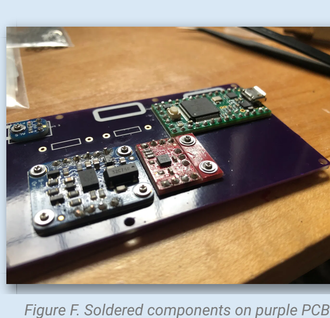


Figure F. Soldered components on purple PCB from OSH Park.

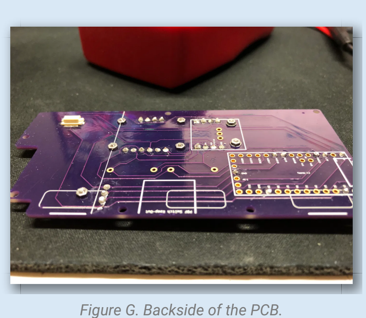


Figure G. Backside of the PCB.

Ground Testing and Validation

- Prior to PCB fabrication, the circuit was tested on a breadboard [Figure H, I]
- Using first the breadboard, and then the final payload (in its ThinSat engineering model), various tests were performed to compare and validate the ground performance of the IMUs and code:
  - Accelerometer: tested the payload in different orientations, with the gravity vector as a reference. Consistent, expected performance across both IMUs (BNO055 & MPU-9250).
  - Gyroscopes: rotated the circuit on a swivel chair by hand (roughly followed the speed of a seconds hand of a clock for an expected reading of 1RPM). Noisy readout from both IMUs, but both confirmed capable of reading out 1RPM acceptably above their noise floors (typically approx 0.01 rad/s=0.1 RPM).
  - Magnetometers (more difficult to test)
    - Wrote code to implement both IMUs as rudimentary compasses. Both IMUs functioned acceptably as compasses, but the BNO055 showed more expected, smooth, consistent, repeatable and less discontinuous readout.
    - Compared readouts of both IMUs to expected triaxial magnetic field magnitudes (gauss levels) at sea level in Princeton. Both IMUs acceptably reported expected lateral components of the field, but the BNO055 occasionally underreported the expected vertical component. Unclear if this was due to some rough handling by us.
    - It should be noted that the smoother performance of the BNO055 may be partially attributed to onboard processing by an its integral ARM Cortex-M0 based processor. This processor is included for turnkey Kalman filtering of ALL sensor data, to yield especially convenient and accurate absolute orientation, but we learned that this advanced functionality would unfortunately prove unavailable on-orbit due to indeterminate gravity vector (the unit can still be used in unfiltered "basic mode", comparable to the MPU-9250). But note also that this same onboard processor (and its advanced functionality) render this IMU potentially more susceptible to space radiation, and harder for students to code (with a 118-page datasheet and a GREAT but sometimes overwhelming variety of modes available…).

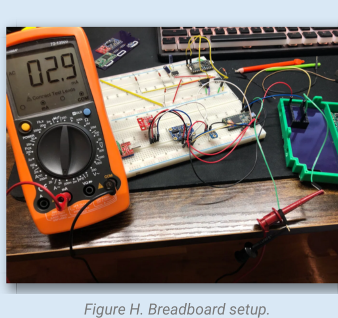


Figure H. Breadboard setup.

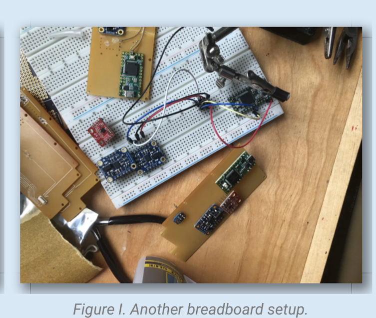
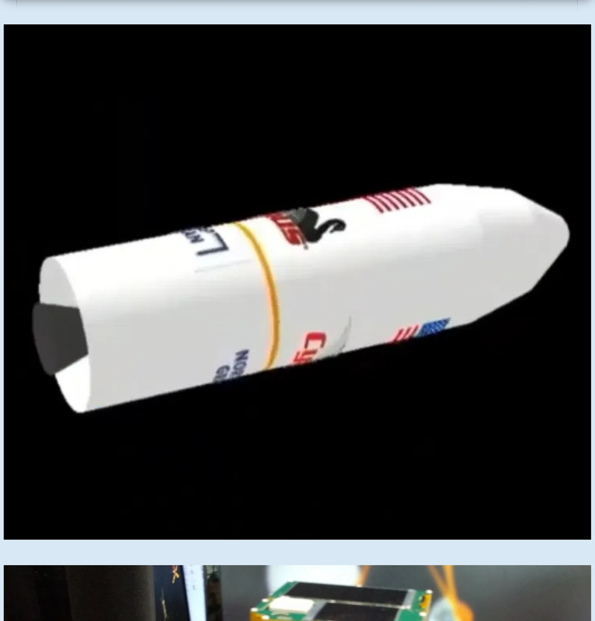
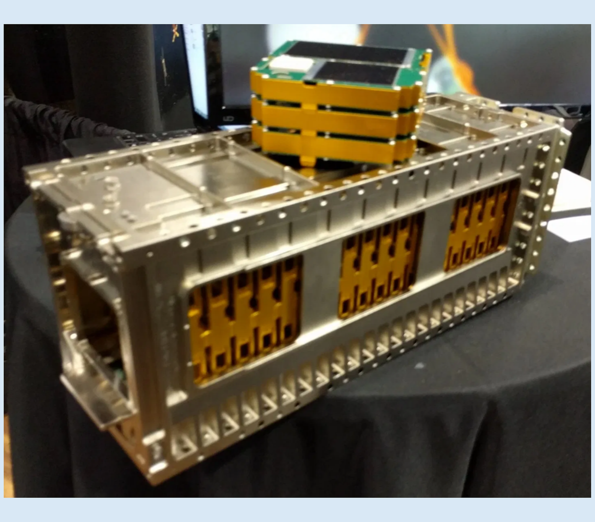


Figure I. Another breadboard setup.

Launch!





ProtoSat and MEMSat launched into orbit on Feb 20, on the Antares/Cygnus NG-15 resupply mission to the ISS. They were both ejected from the CSD dispenser (mounted on the Antares upper stage) into a ~200km Extreme Low Earth Orbit. Unfortunately, due to a systemic (fleetwide) ThinSat bus anomaly, no data was downlinked. But we had a great learning experience throughout the whole ThinSat program, we put our first-ever Princeton student hardware into orbit, and look forward to an opportunity to launch rebuilds of both ProtoSat and MEMSat soon!

We'd like to acknowledge gracious support from Virginia Space's ThinSat Program, the New Jersey Space Grant, Princeton's Mechanical & Aerospace Engineering Department (MAE), its School of Engineering & Applied Sciences (SEAS), its Council on Science & Technology (CST), Voltera, Xinabox, Twiggs Space Lab (TSL), NearSpace Launch (NSL), and Northrop Grumman for the NG-15 Antares launch!