A SPARK/Ada CubeSat Control Program

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2009 NASA Consortium Development Grant

- Analyze and prototype a self propelled CubeSat to the Moon

- Students did the majority of the work at each institution

- Vermont Technical College: Carl Brandon, Science P. I. (structure, thrusters, communication, navigation, electronics) and Peter Chapin (software)

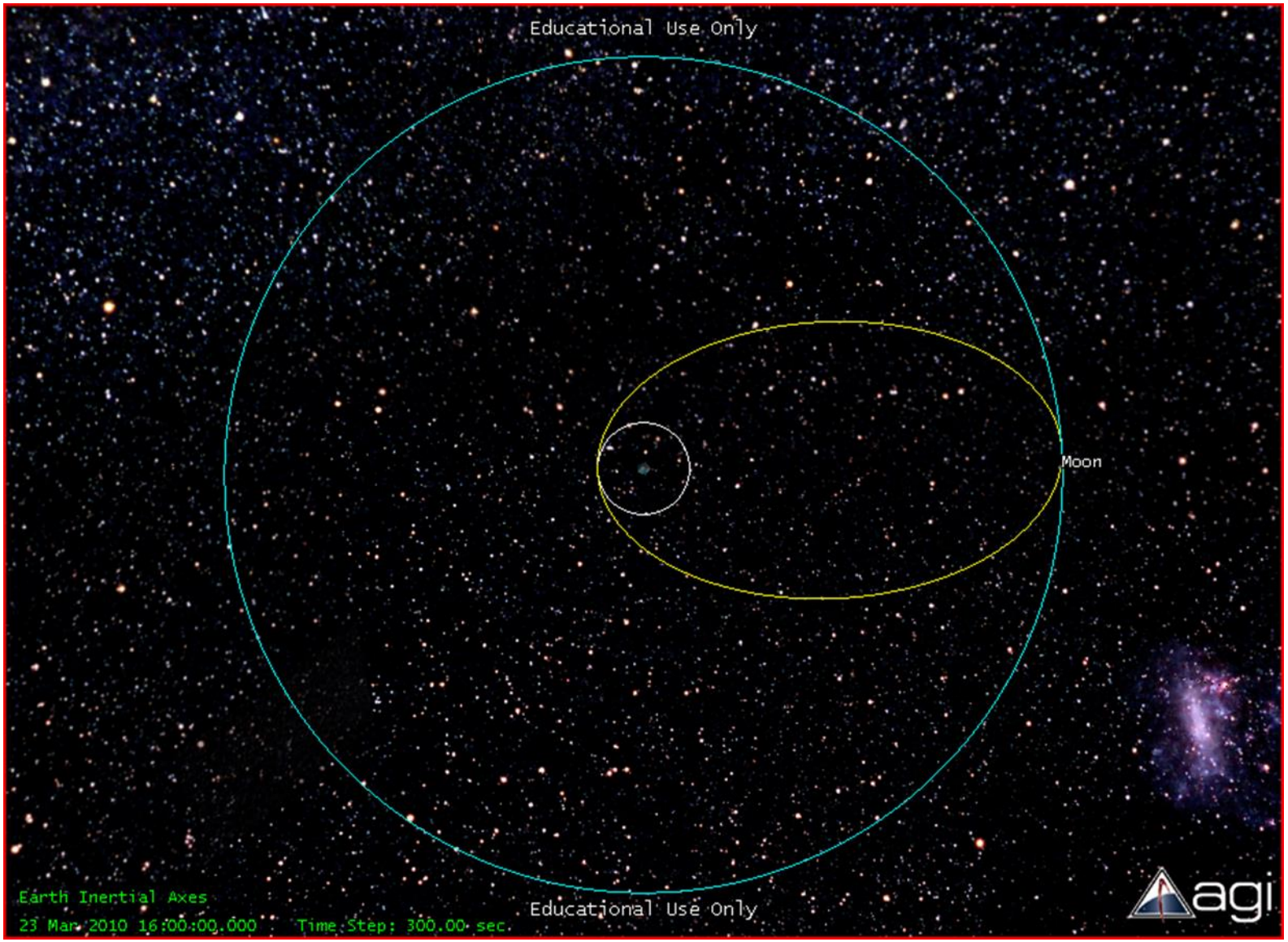
2009 NASA Consortium Development Grant

• University of Vermont: Jun Yu (low energy transfer and radiation environment modeling with St. Michael's College math students) and Jeff Frolik (spacecraft coordination, landing)

• Norwich University: Danner Friend & Jacques Beneat (star tracker & near body analysis)

•Assistance from NASA Goddard Spaceflight Center and NASA Jet Propulsion Laboratory personnel

Mono-Propellant Flight Path



Chemical Propulsion System

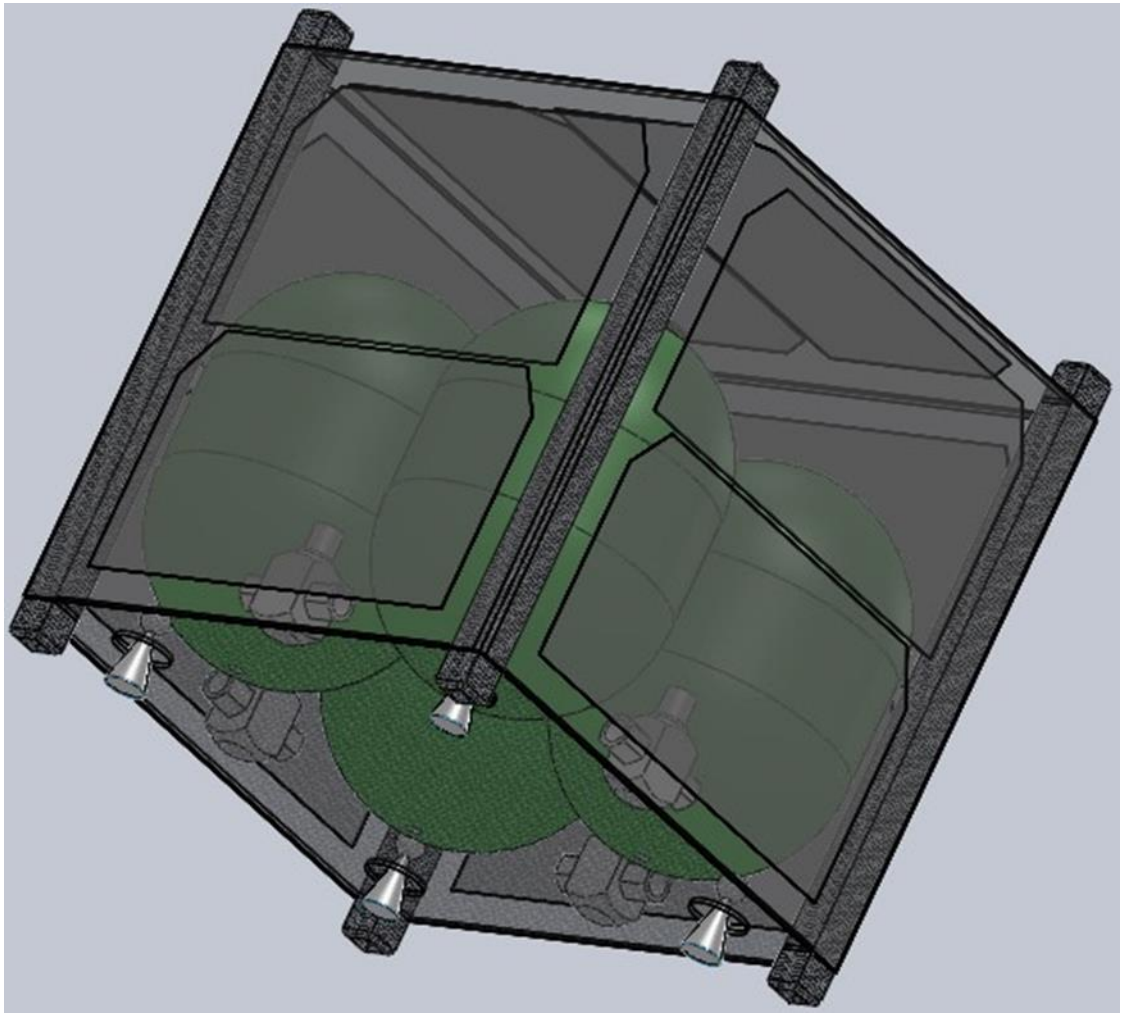
- Initial decision to use bi-propellants changed to mono-propellant for safety reasons on the advice of NASA Goddard

- Lander and Booster will each have four 1 N thrusters

- Monopropellant: Hydroxyl Ammonium Nitrate and Methanol (88%:12% by mass) mixed

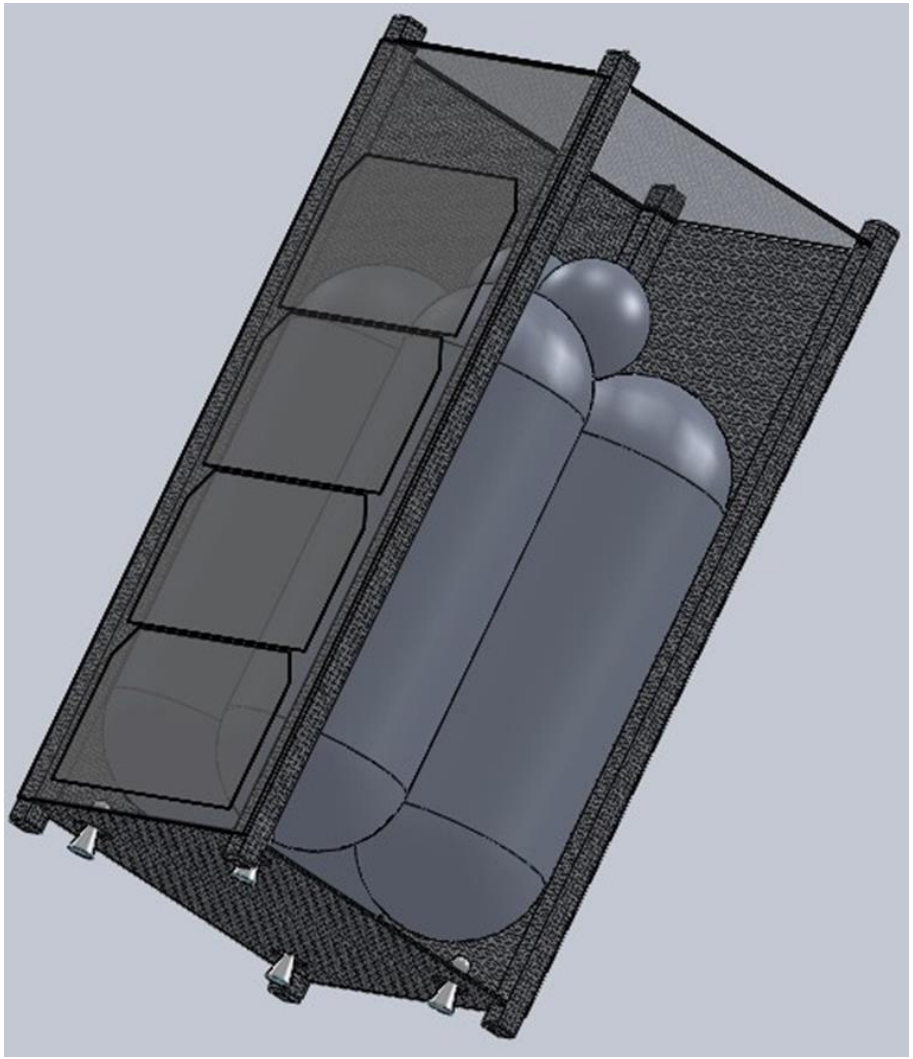
- Specific Impulse about 270 seconds

Chemical Propulsion System



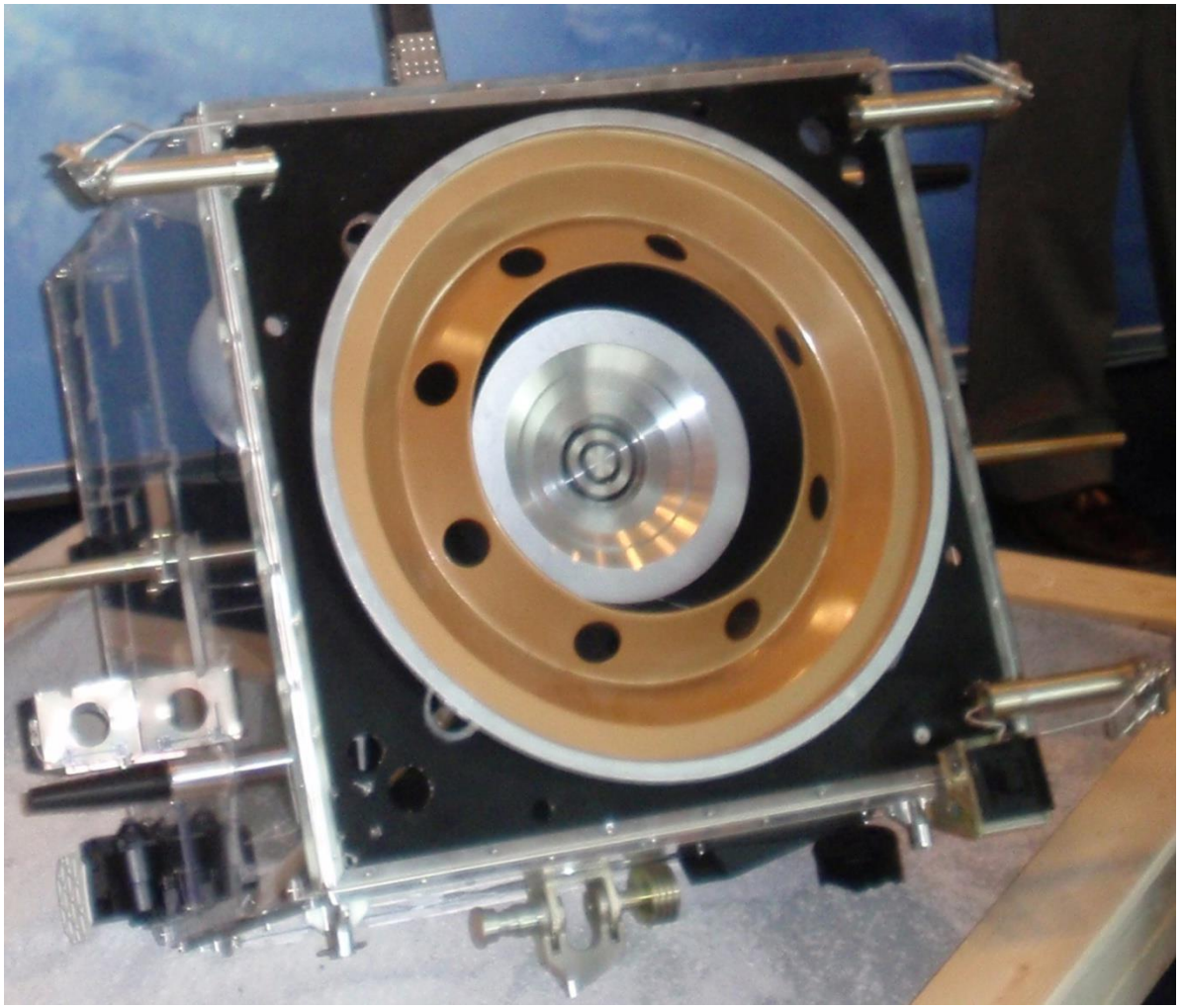
Lunar Lander

Chemical Propulsion System



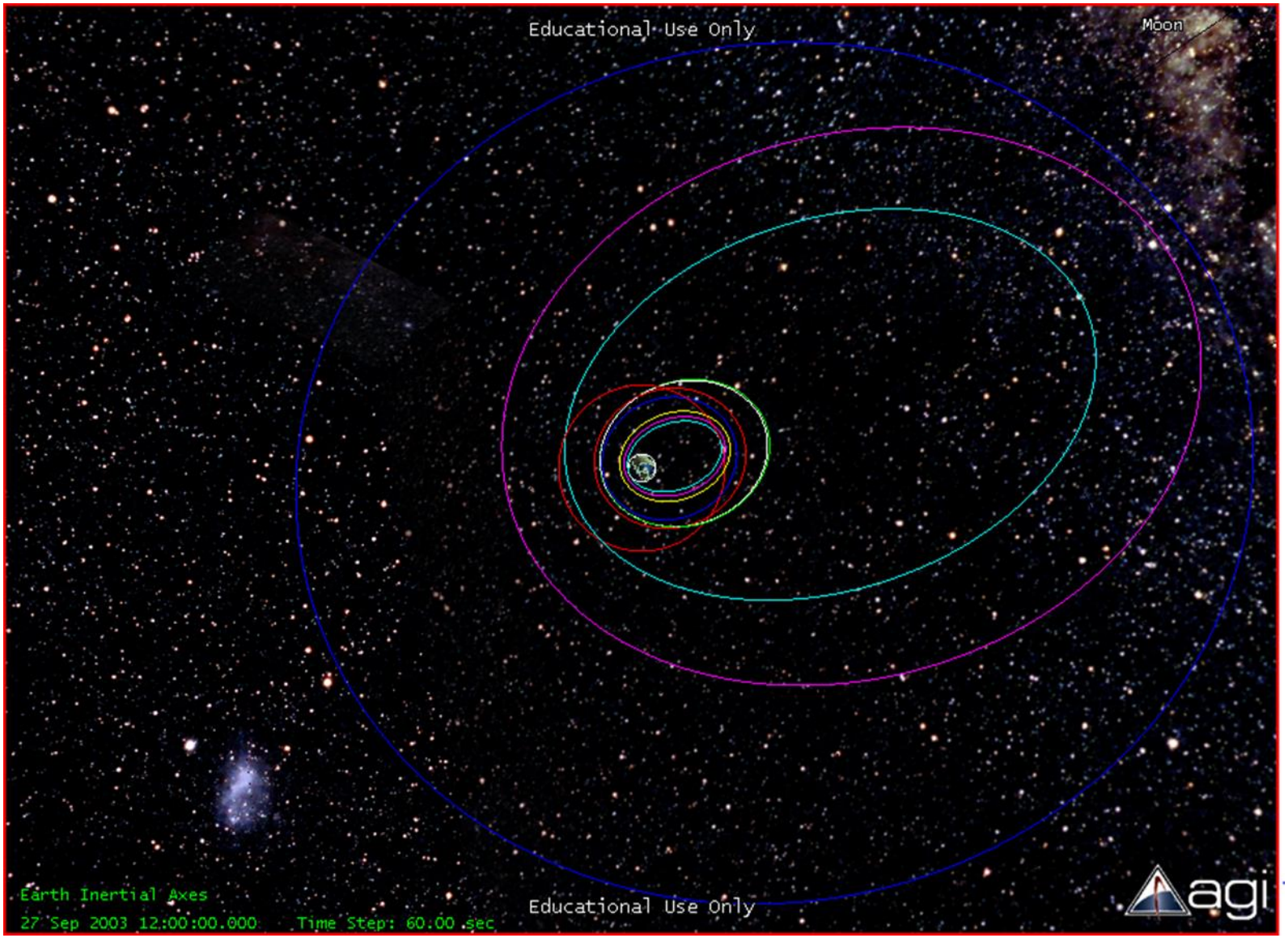
Booster

1 m Wide, 367kg ESA SMART-1

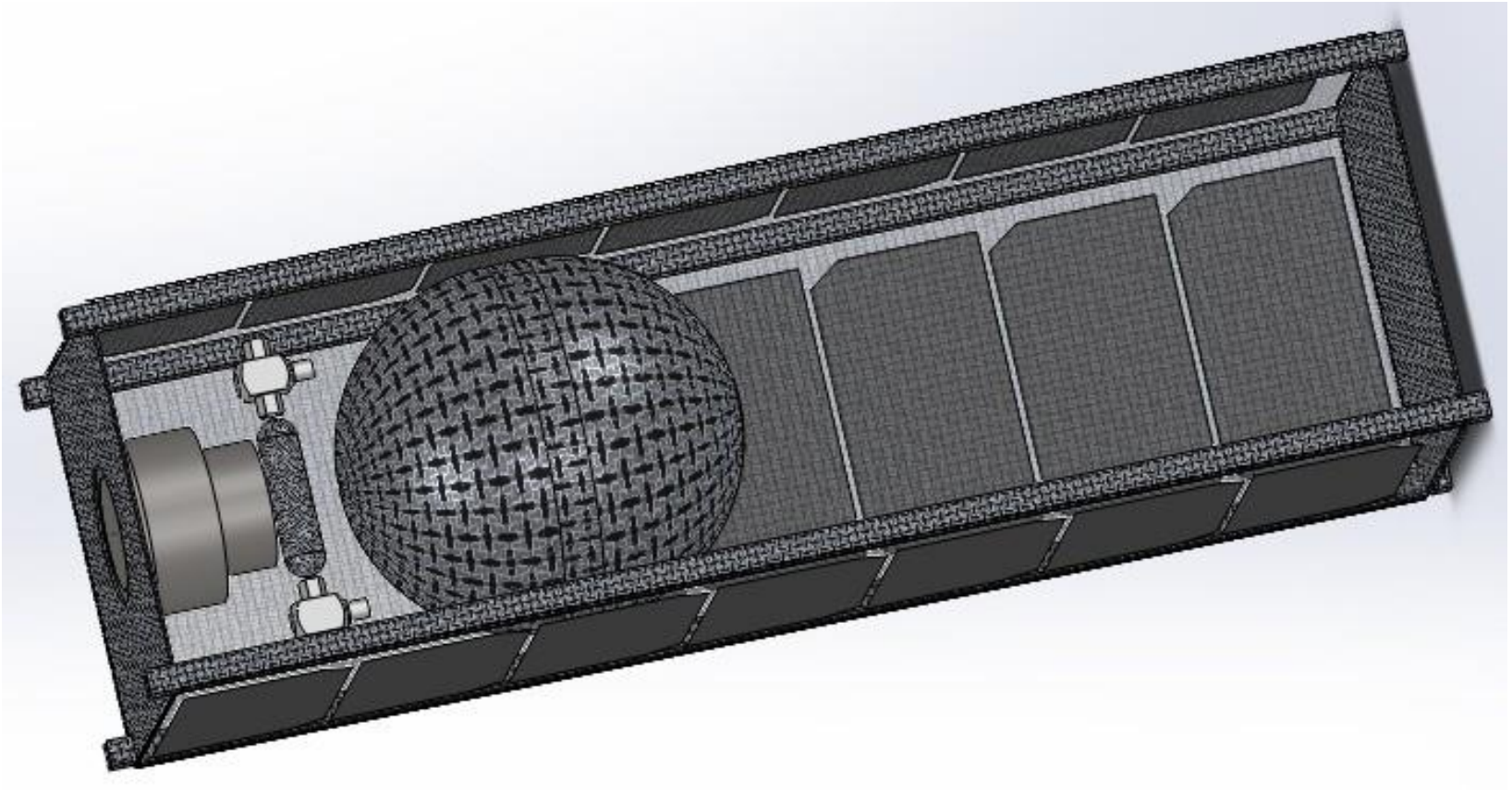


82 kg xenon @ 150 atmospheres, 1,200W

Ion Drive Orbits ala SMART-1

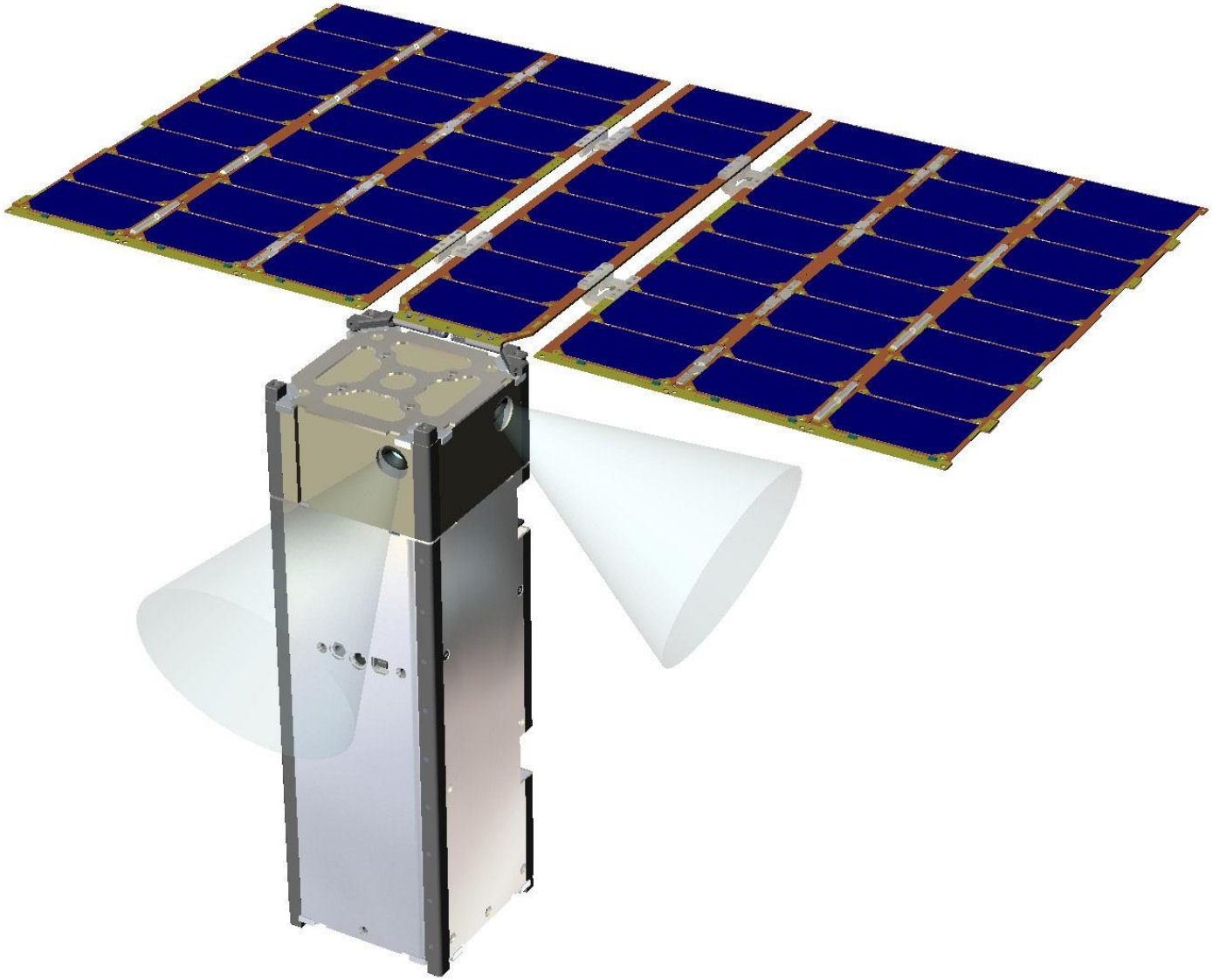


5kg Follow on Ion Drive CubeSat



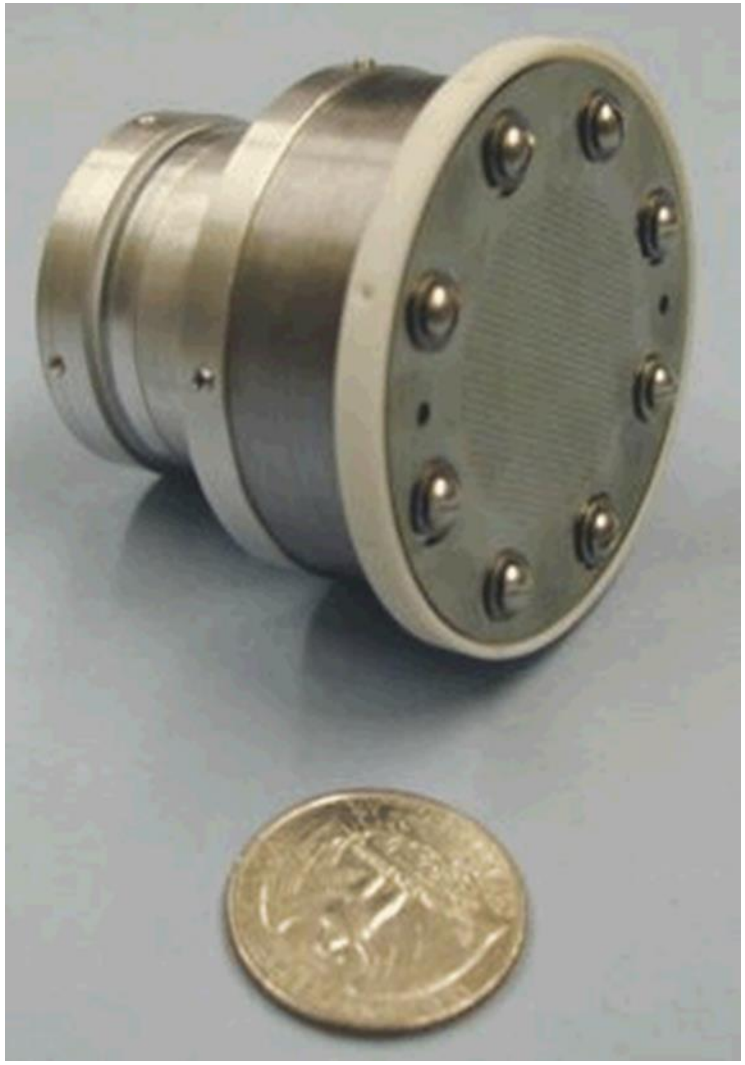
Triple CubeSat Ion Drive Propulsion system, Lunar or Interplanetary without fold out PV pane (10cm x 10cm x 30cm)l

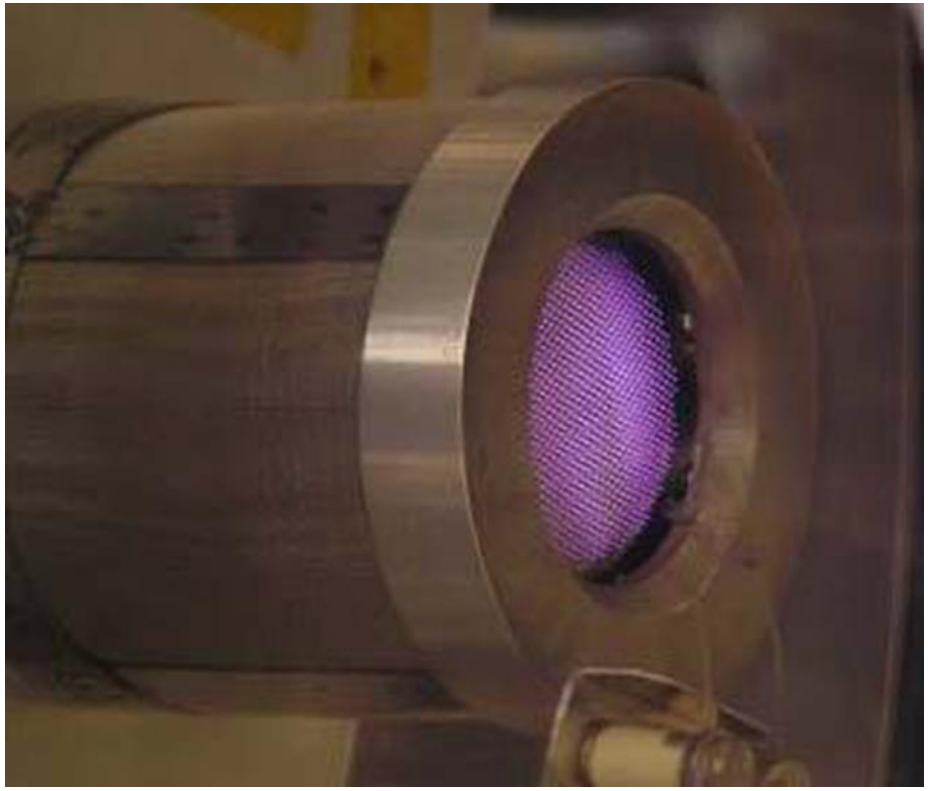
Follow on Ion Drive CubeSat



Triple CubeSat with CubeSat Kit 56 W fold out PV panel

Follow on Ion Drive CubeSat





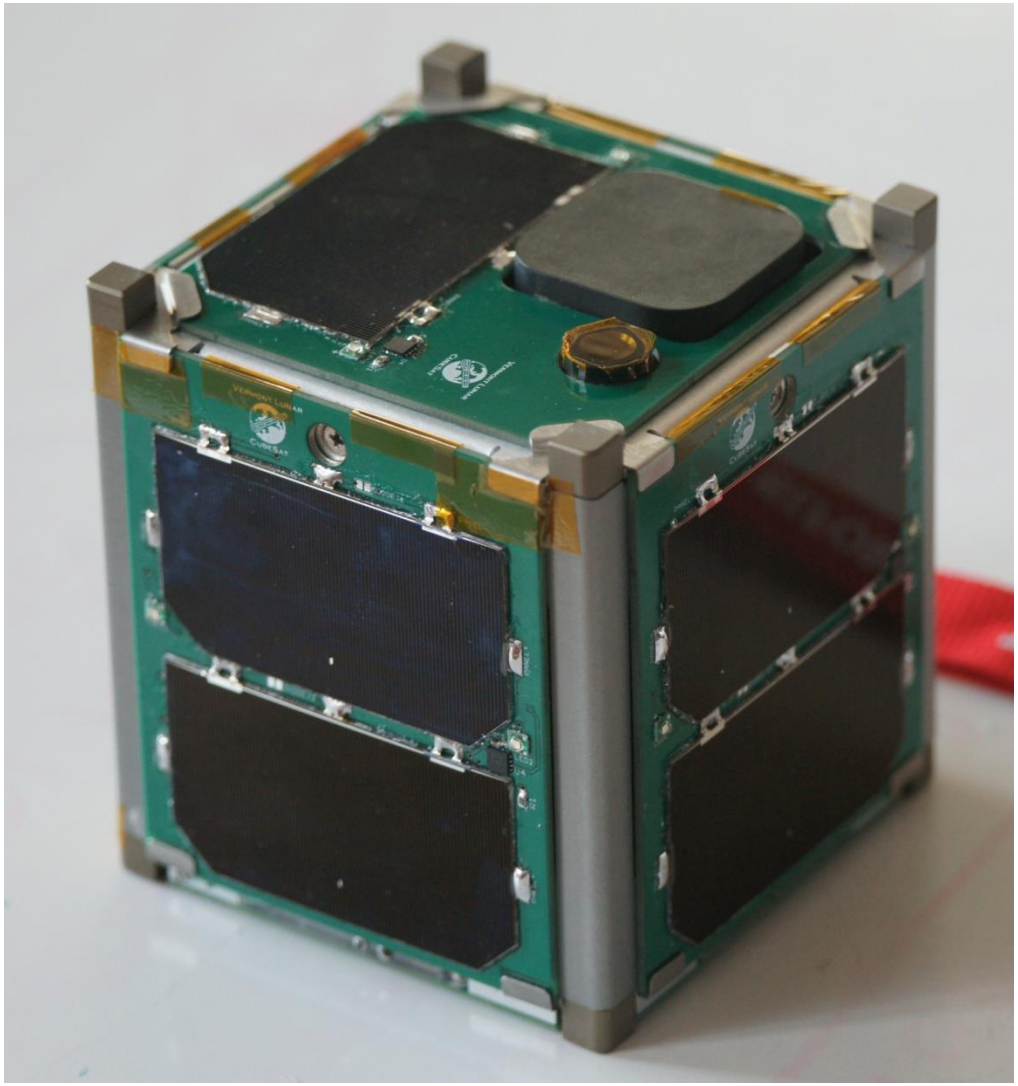
JPL Miniature Xenon Ion (MiXI) Thruster

NASA Launch Opportunity

- NASA's 2010 CubeSat Launch Initiative (ELaNa)
- Our project was in the first group selected for launch
- Our single-unit CubeSat will be launched as part of NASA's ELaNa IV on an Air Force ORS-3 Minotaur 1 flight October 30, 2013 to a 500 km altitude, 40.5^{o} inclination orbit and will remain in orbit about 3 years
- It will test the Lunar navigation system in Low Earth Orbit
- Follow our project at www.cubesatlab.org

Our ELaNa IV CubeSat

VERMONT TECH



Vermont Lunar CubeSat

Our ELaNa IV CubeSat

VERMONT TECH

Motherboard and Pluggable Processor

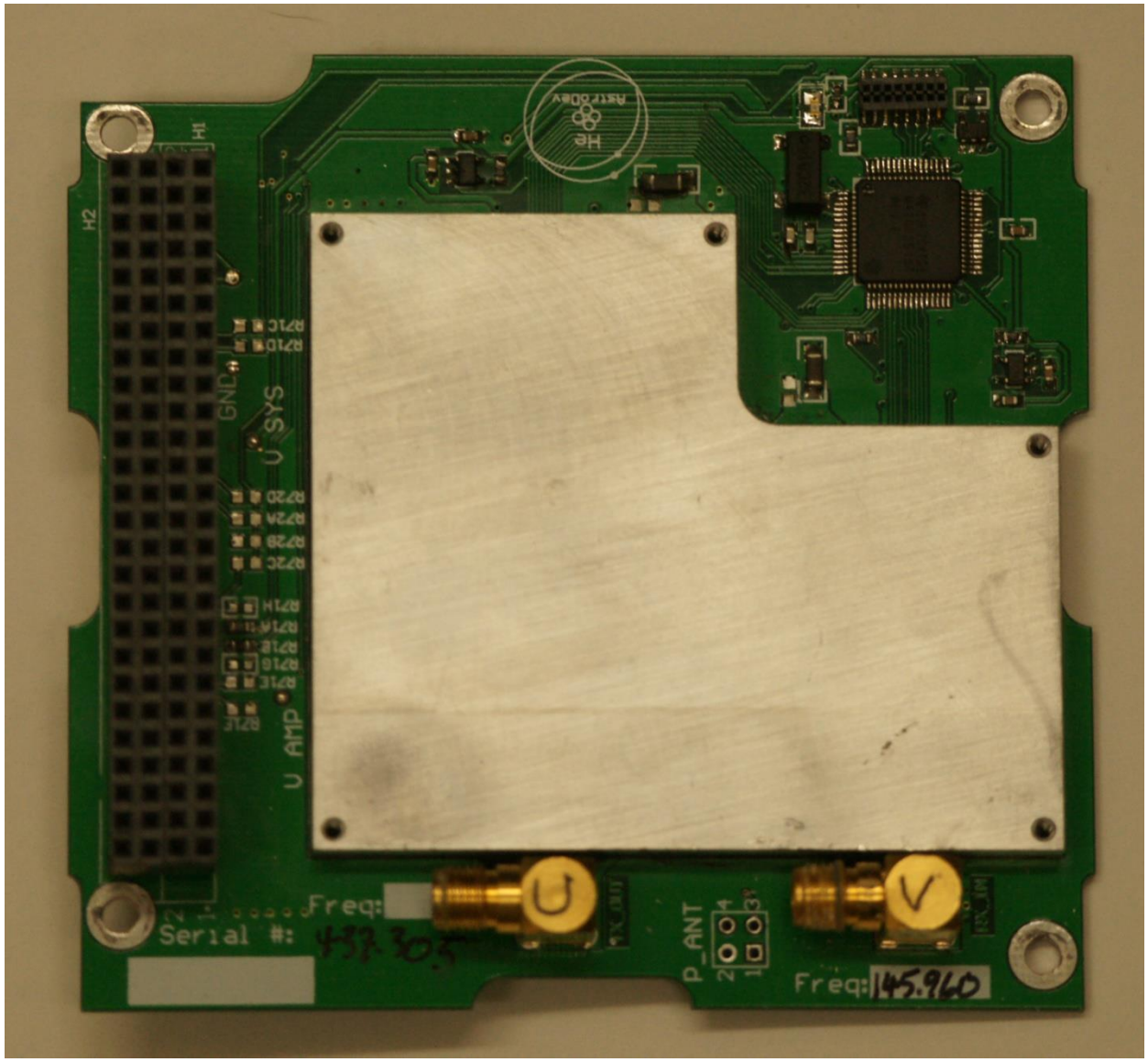
CPU

- Texas Instruments MSP430F2618 16-bit micro-controller
- 116KB program memory, 8KB on-chip SRAM
- 2 USCI, 8-channel 12-bit ADC, 2-channel 12-bit DAC, 16-bit Timer, 3-channel DMA and on-chip comparator
- Motherboard also contains a 2GB SD card

Software Controlled Hardware

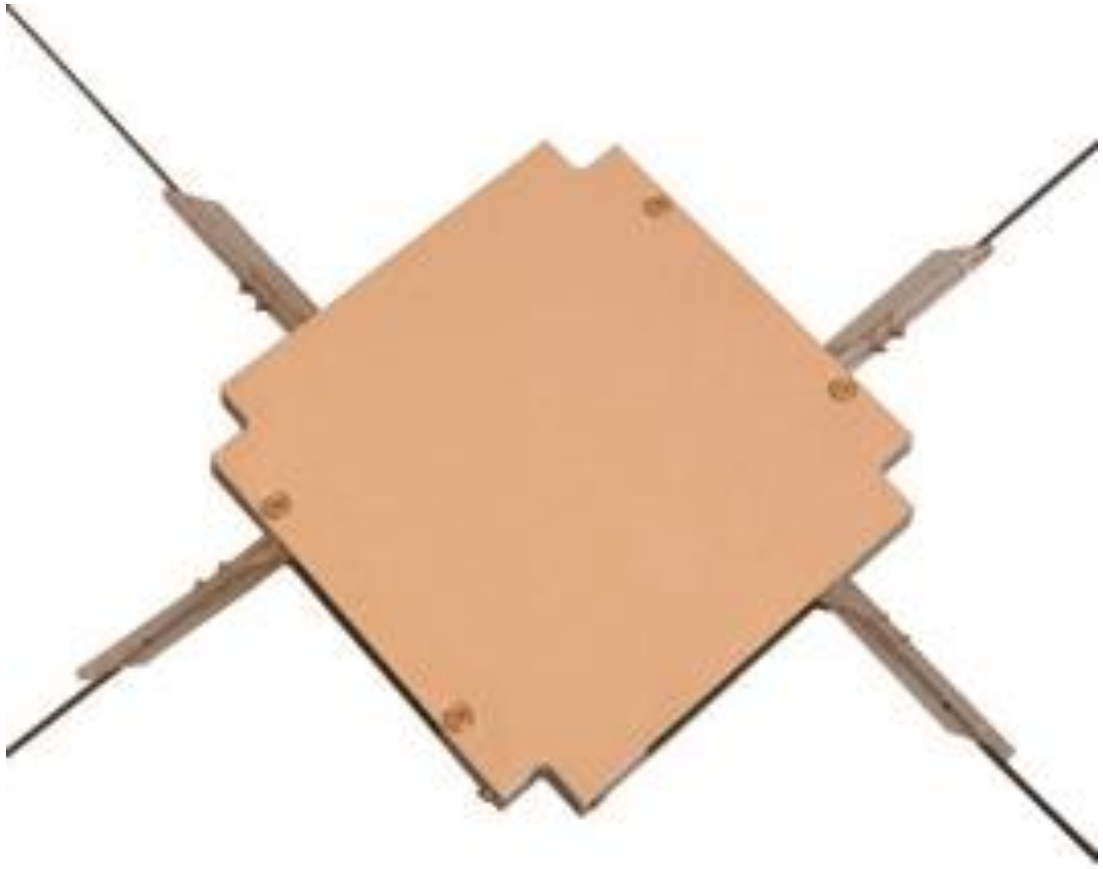
Clyde Space Electrical Power System

Software Controlled Hardware



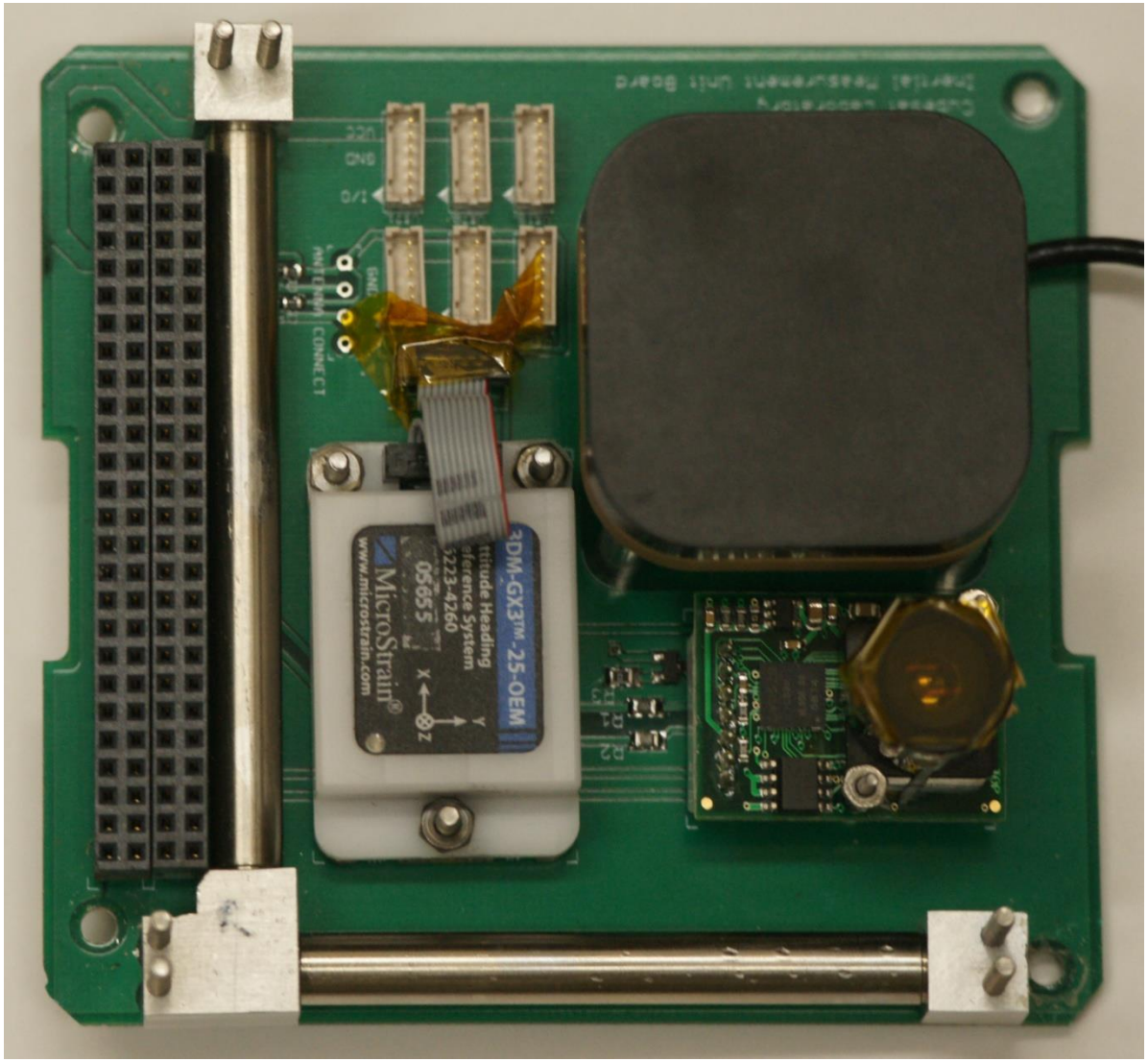
Astrodev Helium-100 2m receiver, 70cm transmitter

Software Controlled Hardware



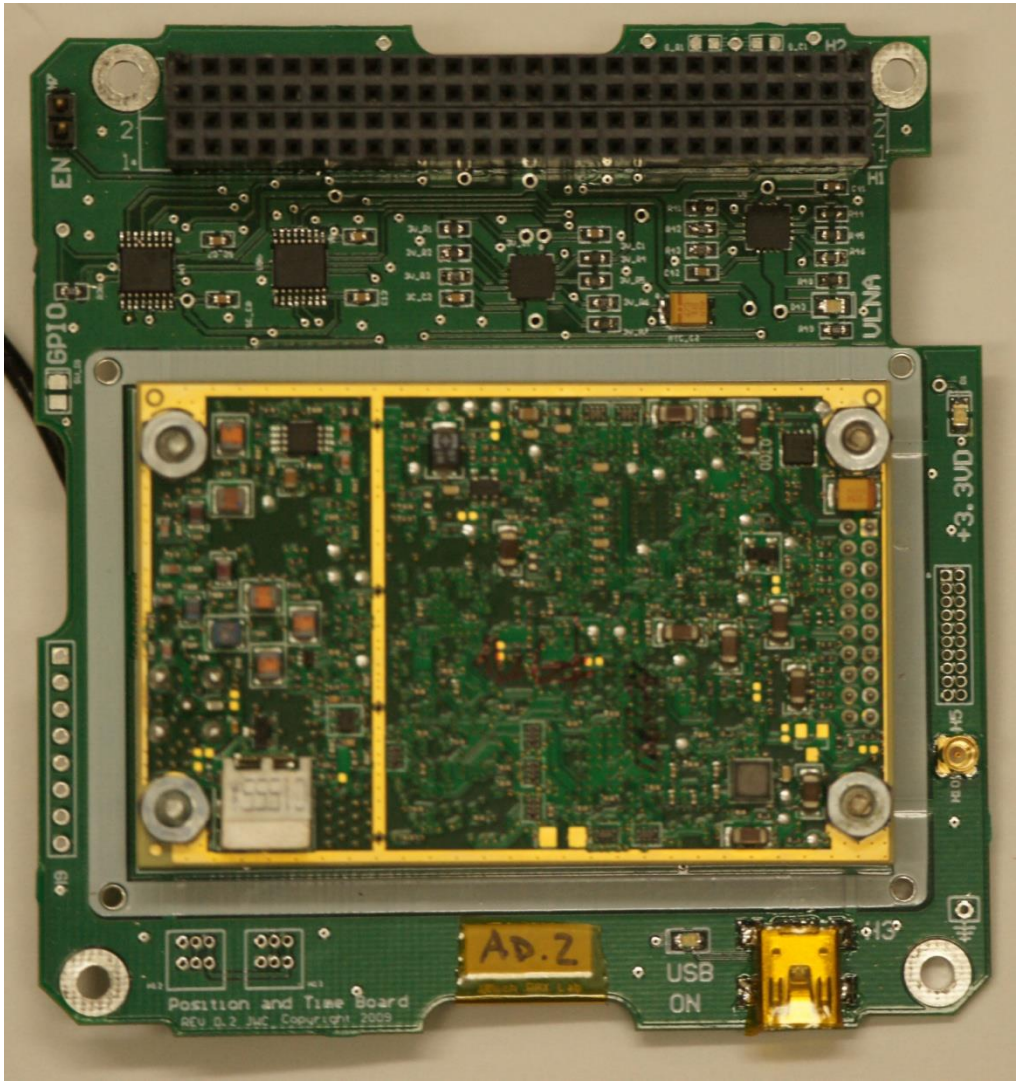
ISIS AntS crossed dipole antenna

Software Controlled Hardware

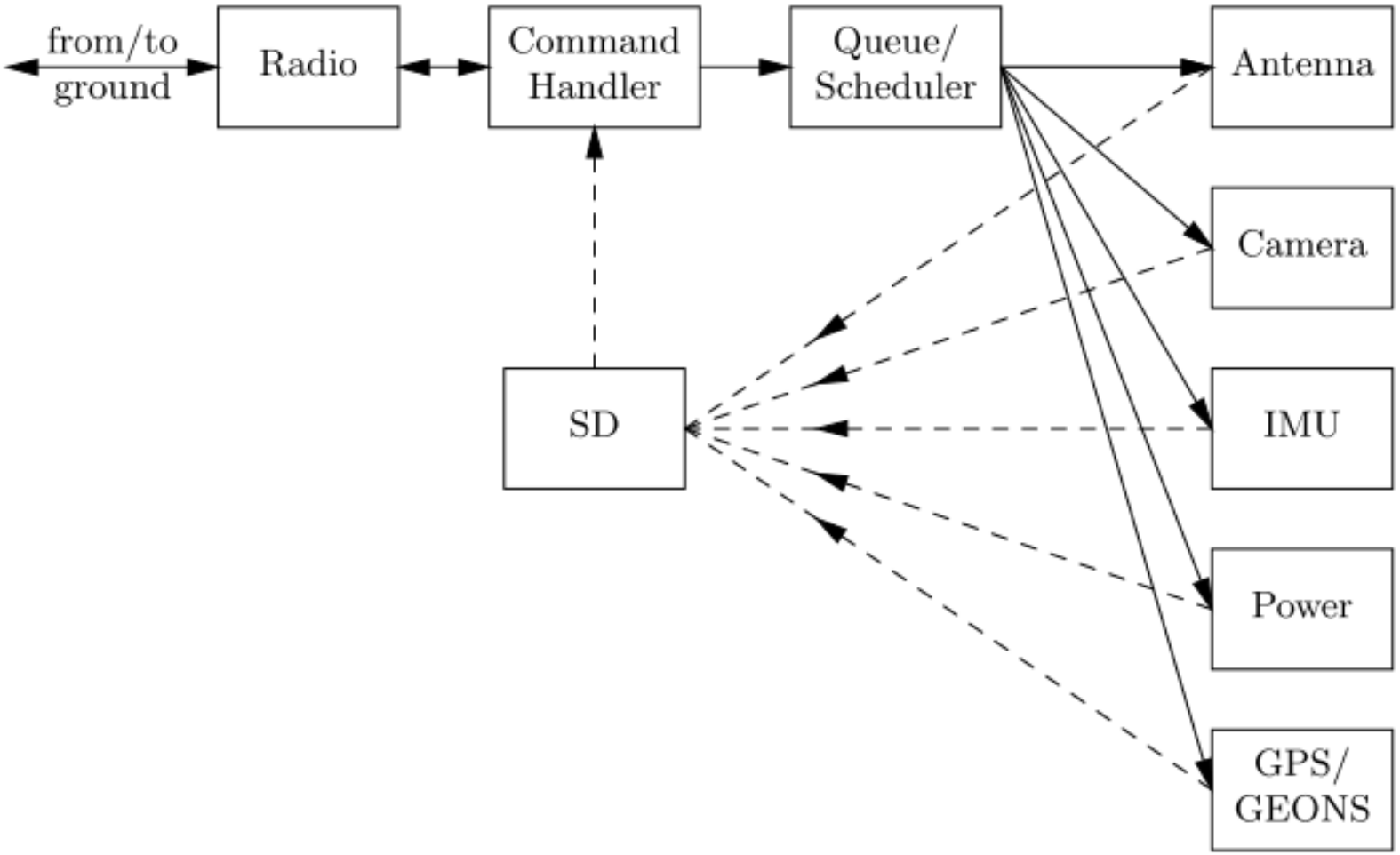


IMU, GPS patch, camera & hysteresis board

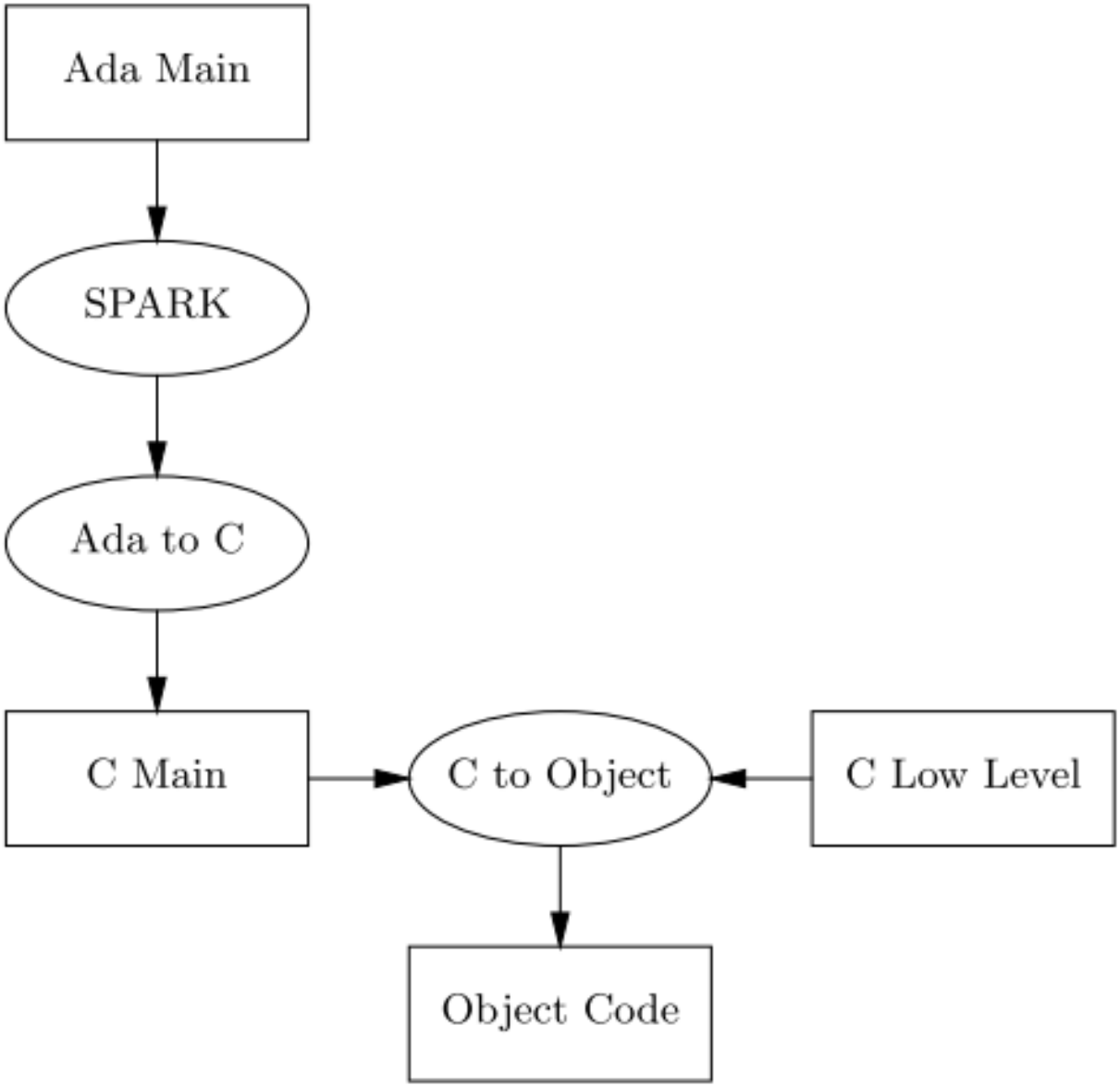
NovAtel OEMV-1 GPS Board Mounted on University of Michigan Position and Time Board



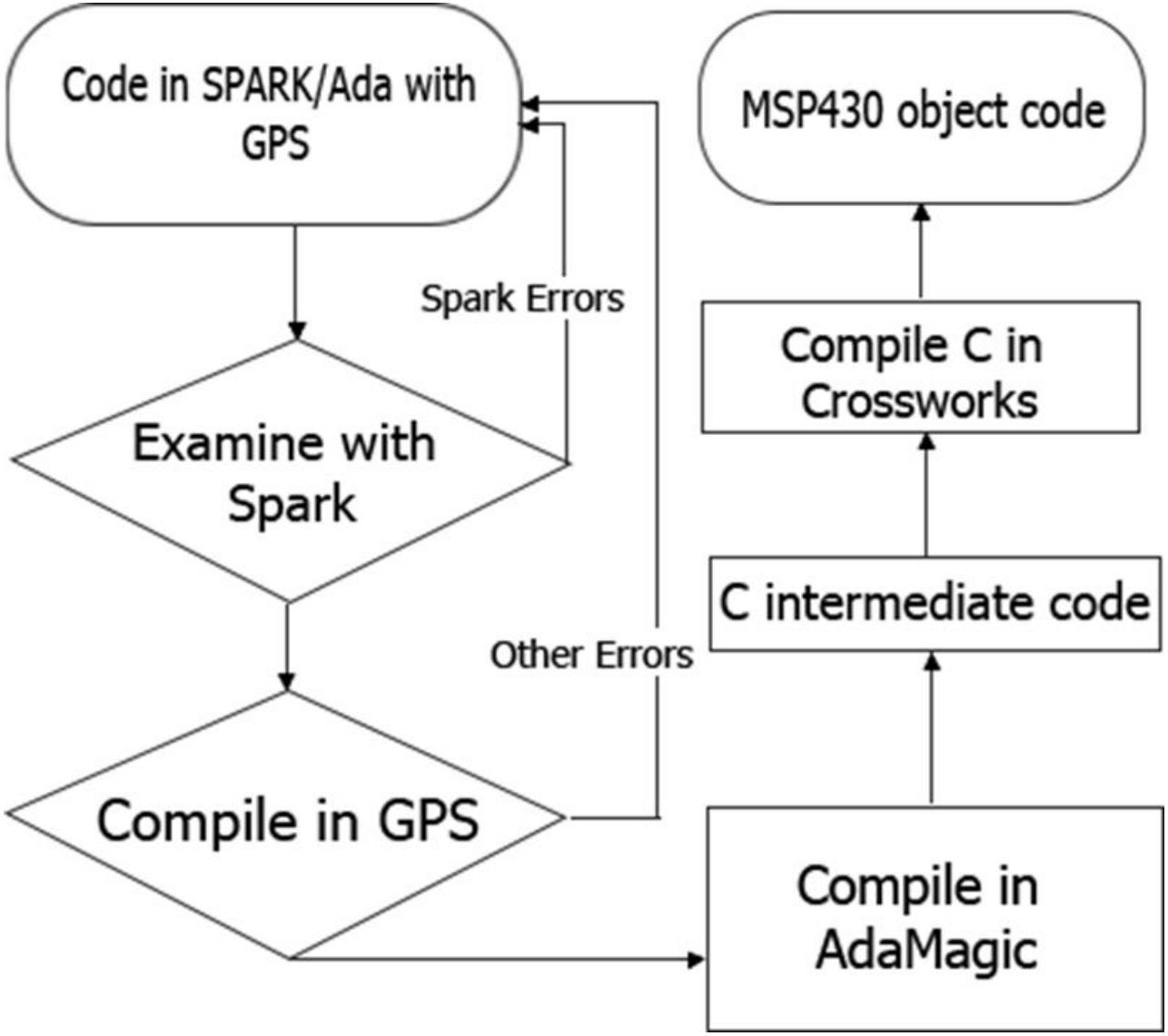
Control Program Architecture



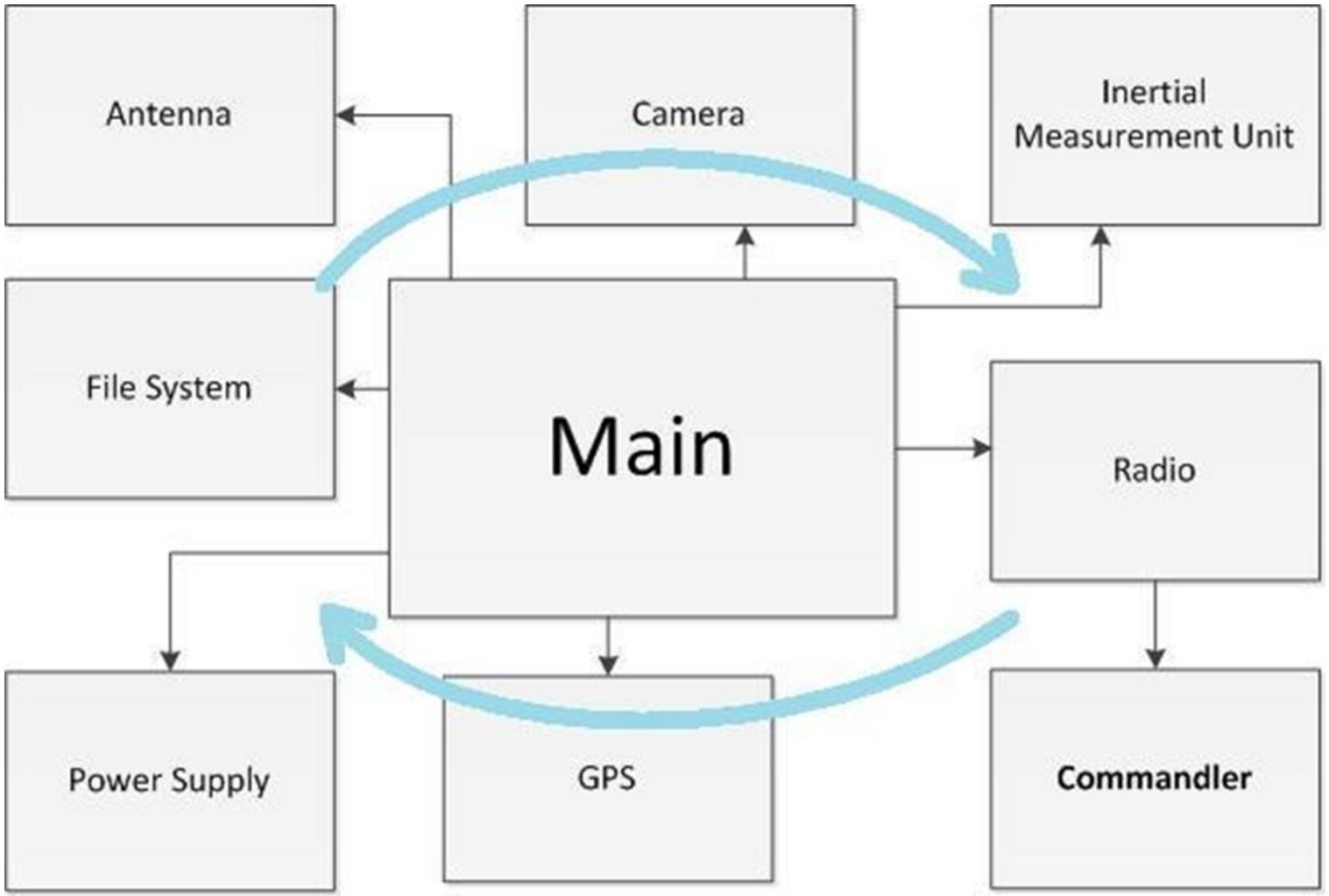
Software Tool Chain



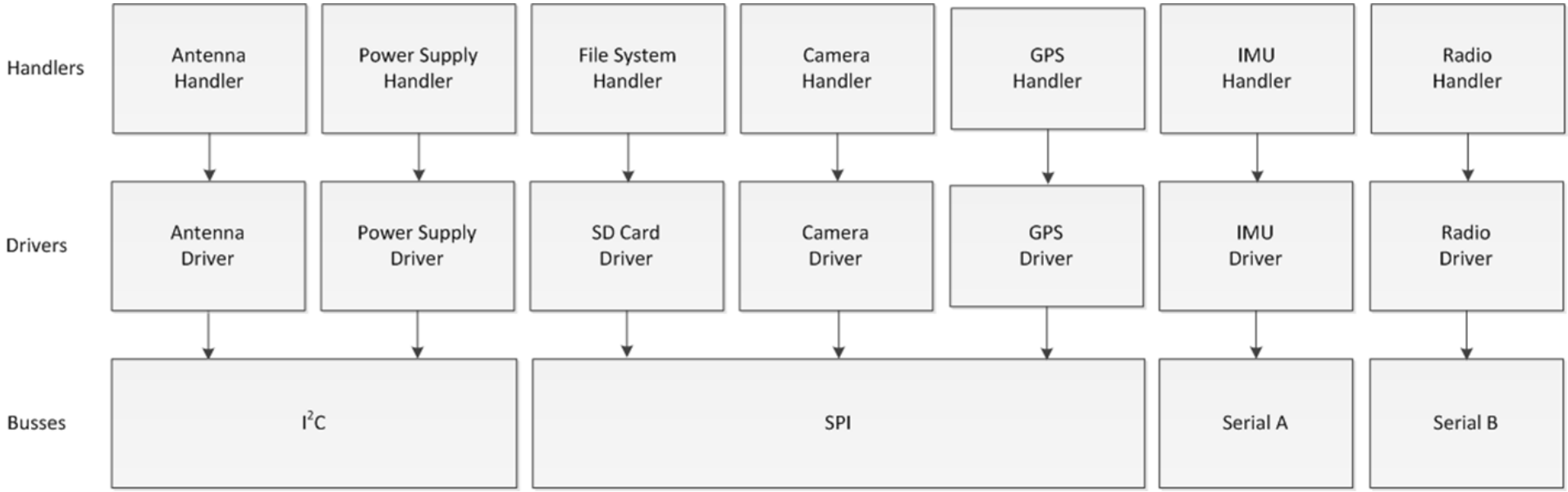
Software Development Process



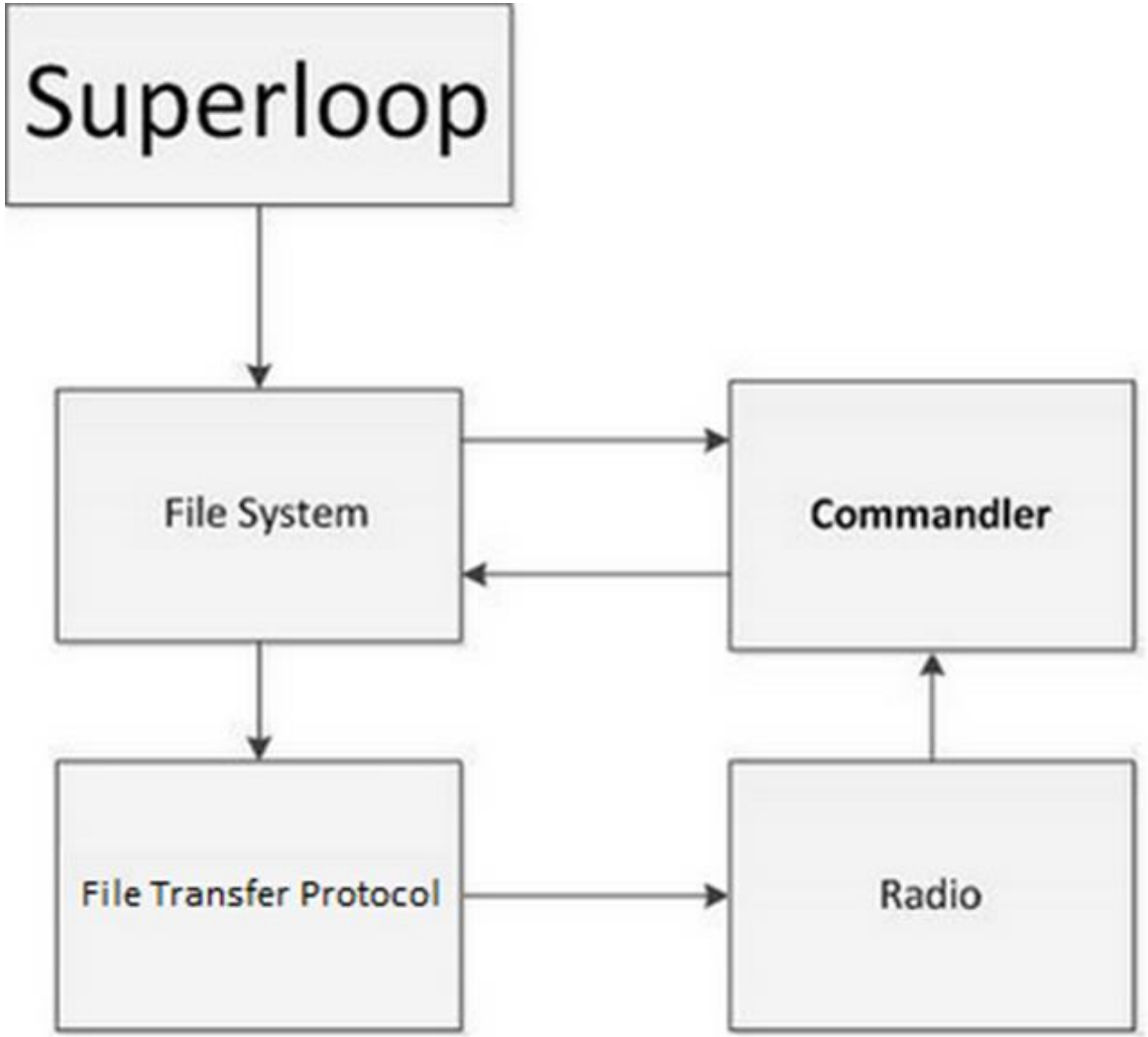
System Design



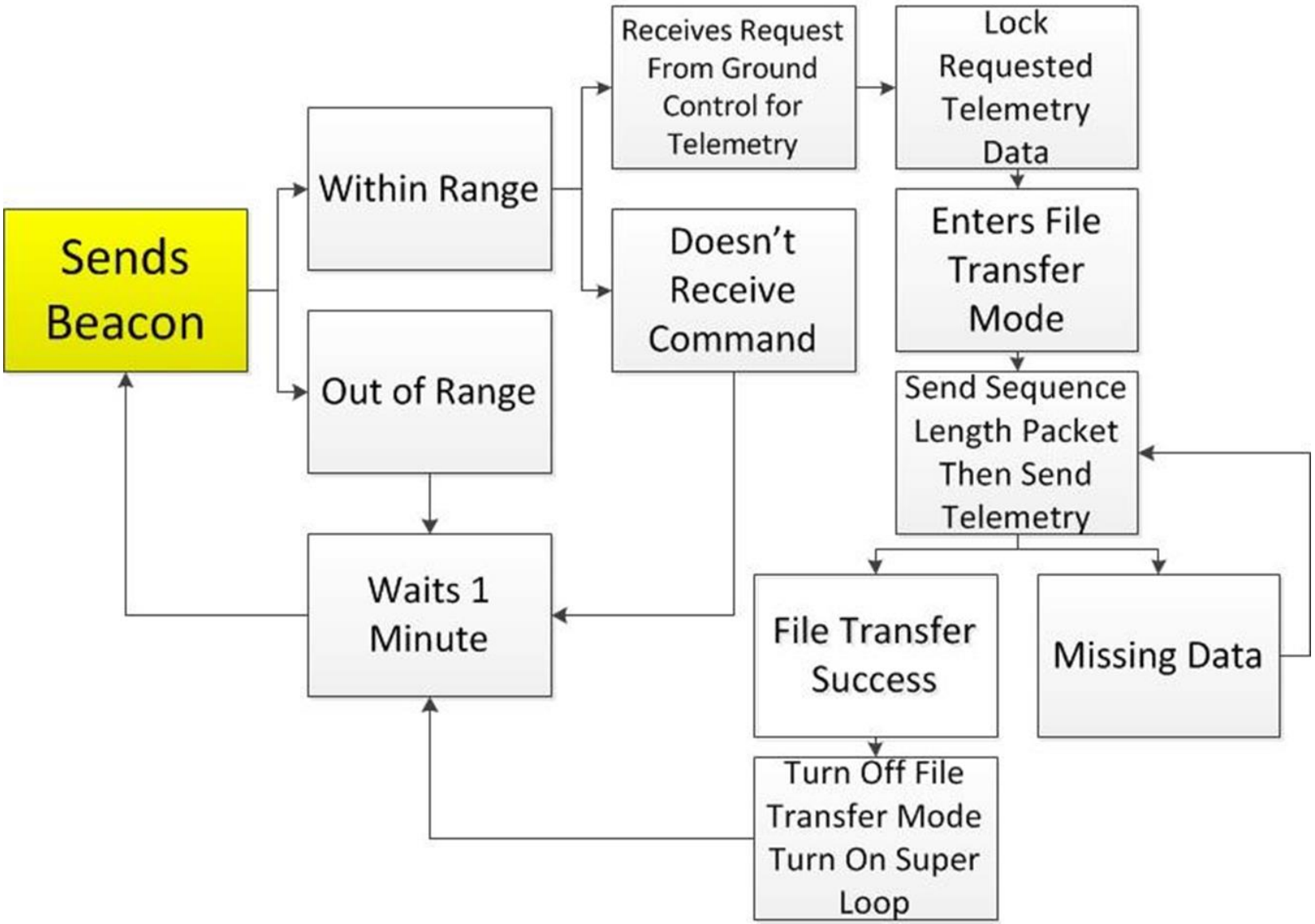
Subsystems


Handlers
Antenna Handler
Power Supply Handler
File System Handler
Camera Handler
GPS Handler
IMU Handler
Radio Handler
Drivers
Antenna Driver
Power Supply Driver
SD Card Driver
Camera Driver
GPS Driver
IMU Driver
Radio Driver
Busses
I²C
SPI
Serial A
Serial B

Subsystems


Superloop
File System
Commandler
File Transfer Protocol
Radio

Data Communication



Subsystems Interfacing

Subsystem	*Interfacing*
Antenna	I^2C
Radio	RS-232
Camera	SPI
EPS (Power Supply)	I^2C
Inertial Measurement Unit (IMU)	RS-232
GPS & GEONS	SPI

Student Participation

- 2011 (Summer) – Jeremy Audet & Matt Ward started the flight control software
- 2012 (Summer) – Dan Turner picked up where Matt and Jeremy left off with the flight control software
- 2012 (Fall) – Michael Collins and Colin Myers started working on the flight control software

Student Participation

- 2013 (Spring) – India Beauregard helped develop the IMU board, Michael Collins continued with flight software and hardware, Colin Myers worked on ground station software
- 2013 (Summer) – Dan Turner continued with radio and GPS software

Control Software

- Control Software written in SPARK/Ada using Adacore's GNAT Programming Studio & GNAT Pro compiler
- Praxis' SPARK Toolset used to prove the absence of run time errors
- Sofcheck's AdaMagic compiles it to produce ANSI C intermediate code
- C code compiled to object code
- Software runs on CubeSat Kit MSP430 CPU

SPARK/Ada Example

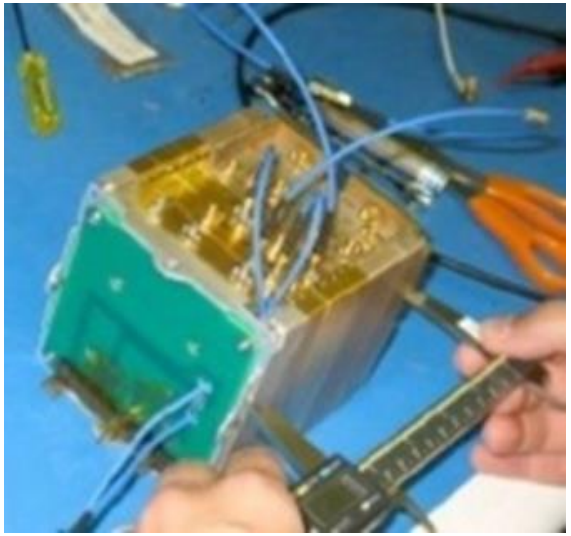

```
procedure Get_From_Radio(Ch : out Character; Rx_Success : out Boolean)
  --# global in out USCI_A1.State, Utility.Hardware; in Utility.Timer_Done;
  --# derives          USCI_A1.State        from USCI_A1.State &
  --#                   Ch                   from USCI_A1.State &
  --#                   Rx_Success           from USCI_A1.State &
  --#                    Utility.Hardware    from Utility.Hardware &
  --#                   null                 from Utility.Timer_Done;
  is
    Finished : Boolean;
  begin
    Utility.Start_B(Utility.Millisecond_Count_Type(20));
....   ....   ....   ....
    if USCI_A1.Get_Rx_Buffer_Used > 0 then
      USCI_A1.Eat_Char(Ch);
      Rx_Success := True;
    else
      Ch := ' ';
      Rx_Success := False;
    end if;
  end Get_From_Radio;
```

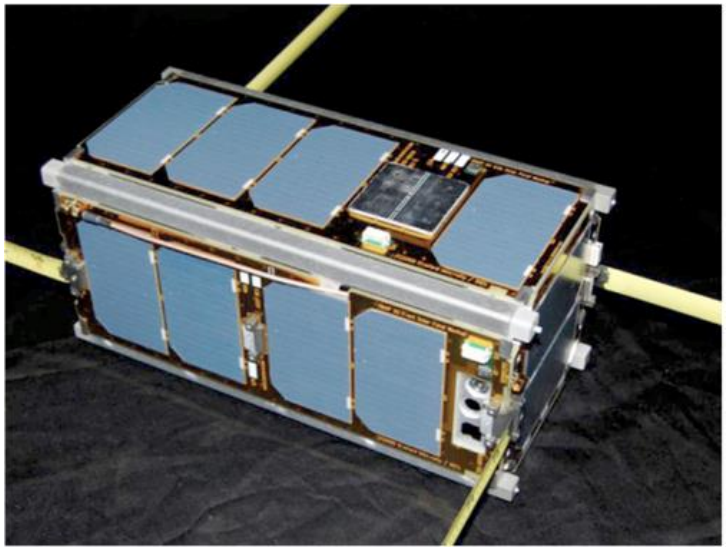
Navigation Components

- Converting the NASA Goddard GEONS navigation system to SPARK/Ada should yield about 1% of the error rate of C software (an avionics study)
- This process has already found a number of anomolies in the NASA GEONS software
- The GEONS software runs on the GPS board ARM processor
- Celestial navigation camera
- Novatel GPS on University of Michigan Position and Time Board
- Passive magnetic attitude control
- Inertial measurement unit (3 axis magnetometer, gyro and accelerometer)
- Ground based transponder (see LMST, next slide)

Low Mass Radio Science Transponder

- Developed at NASA's Jet Propulsion Lab
- X band transponder
- Currently 1U size, to be reduced to ½ U
- Will fly on the ELaNa selected LMRST-Sat
- A great addition for an interplanetary flight





Software Development Comments

- No formal method used, it was “agile” like in practice
- Students worked on two campuses, some hardware was only available in Randolph (GPS, Radio)
- Human created configuration file describing the C compiler for AdaMagic could have errors
- AdaMagic, GNAT or Crossworks could have errors
- Runtime checks disabled
- No runtime system used

Software Development Comments

- Some lowest level functions, i.e. interrupts were written in C, which was kept to a minimum and trivial in nature to be easily verified by hand
- Driver packages in SPARK were general in nature to enable reuse
- No time critical issues allowed the use of a simple super loop, and RavenSPARK was not used
- Our follow on Lunar flight with navigation and control timing issues will require RavenSPARK

Software Development Comments

- Message queue package allows inter process communication
- A command handler deals with ground station commands
- A scheduler handles tasks when not in contract with the ground station
- A mock system to simulate the hardware was used for testing
- A CubeSat Kit development board was used for hardware testing

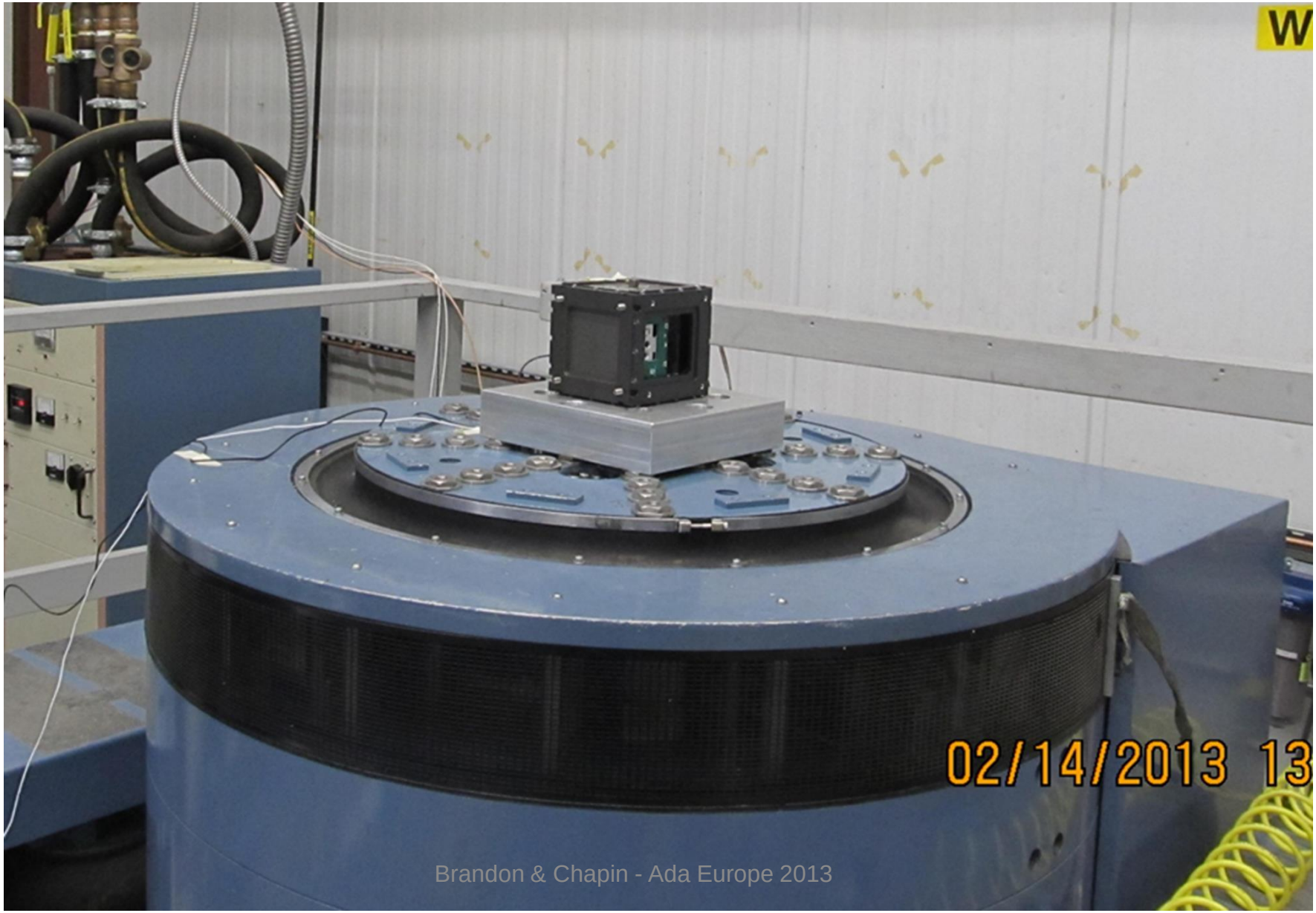
Software Development Comments

- SPARK caught errors as we refactored the software as we developed greater understanding of the hardware
- SPARK helped the discipline of the software during turnover as some students graduated and were replaced
- Although we did not have a formal development process, without SPARK we probably would not have completed the project with the limited personnel resources and tight time constraint
- A huge amount of time was used by the P. I. to prepare dozens of documents for NASA and the Air Force
- Although the CubeSat is limited to 1.3kg, the paperwork is not.

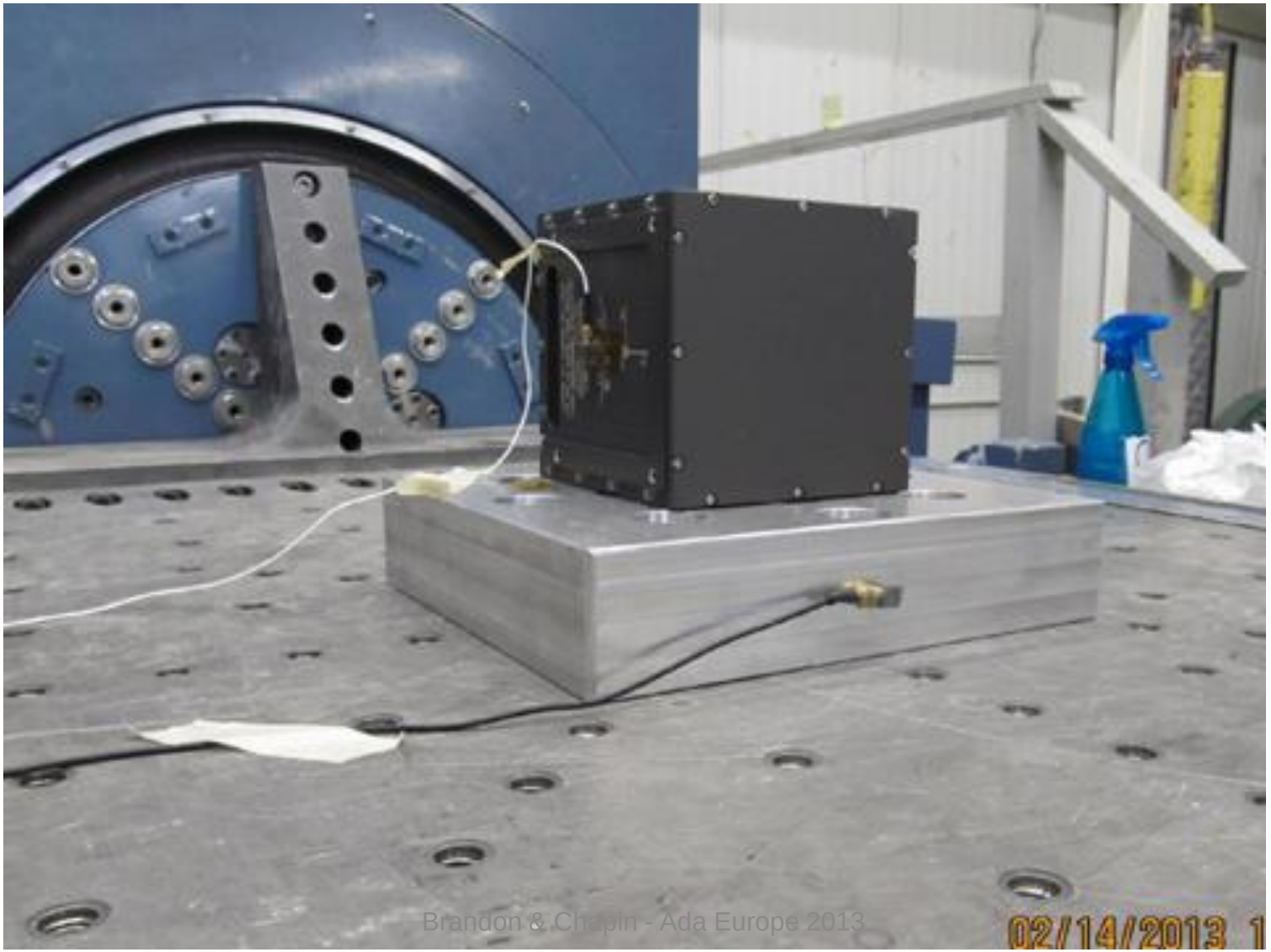
Software Development Comments

- Students who took the High Integrity Programming course were more comfortable with SPARK
- One student, self taught in SPARK, was remarkably productive
- Students were completely accepting of the rigors of SPARK
- Students adding SPARK after the design, found this much more difficult than starting with it
- Design changes mid project were greatly helped by SPARK

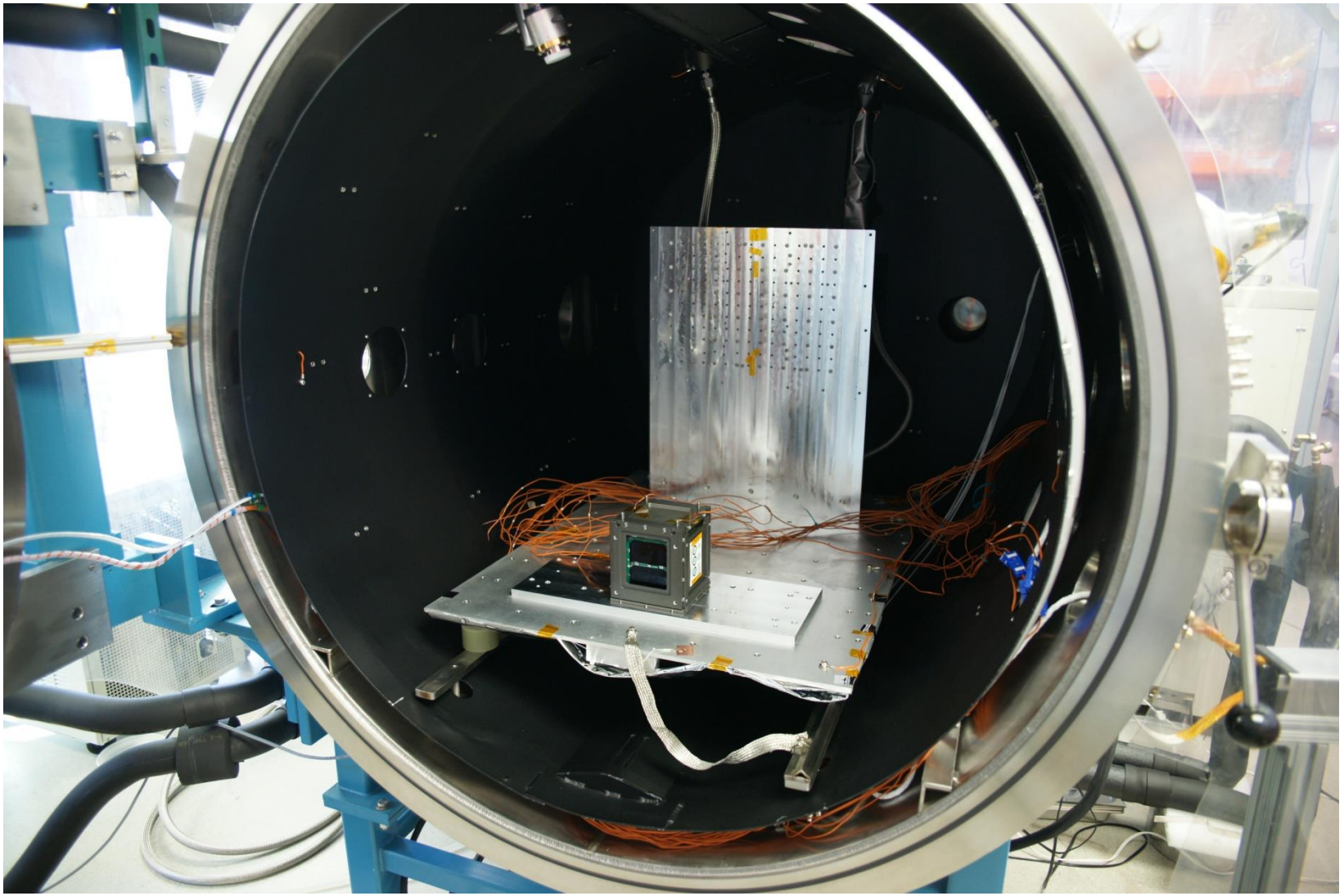
X and Y axis Vibration Test



Z-axis Vibration Test



Vacuum Thermal Bakeout



NASA Launch Opportunity
Minotaur 1 – Wallops Island

First two stages are Minuteman II first two stages, third and fourth stages are Pegasus second and third stages

Acknowledgements

- NASA Vermont Space Grant Consortium
- NASA
- Vermont Technical College
- AdaCore, Inc. (GNAT Pro)
- Altran Praxis (SPARK)
- SofCheck (AdaMagic)
- Applied Graphics, Inc. (STK)
- LED Dynamics (PV boards)
- Microstrain (IMU)

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