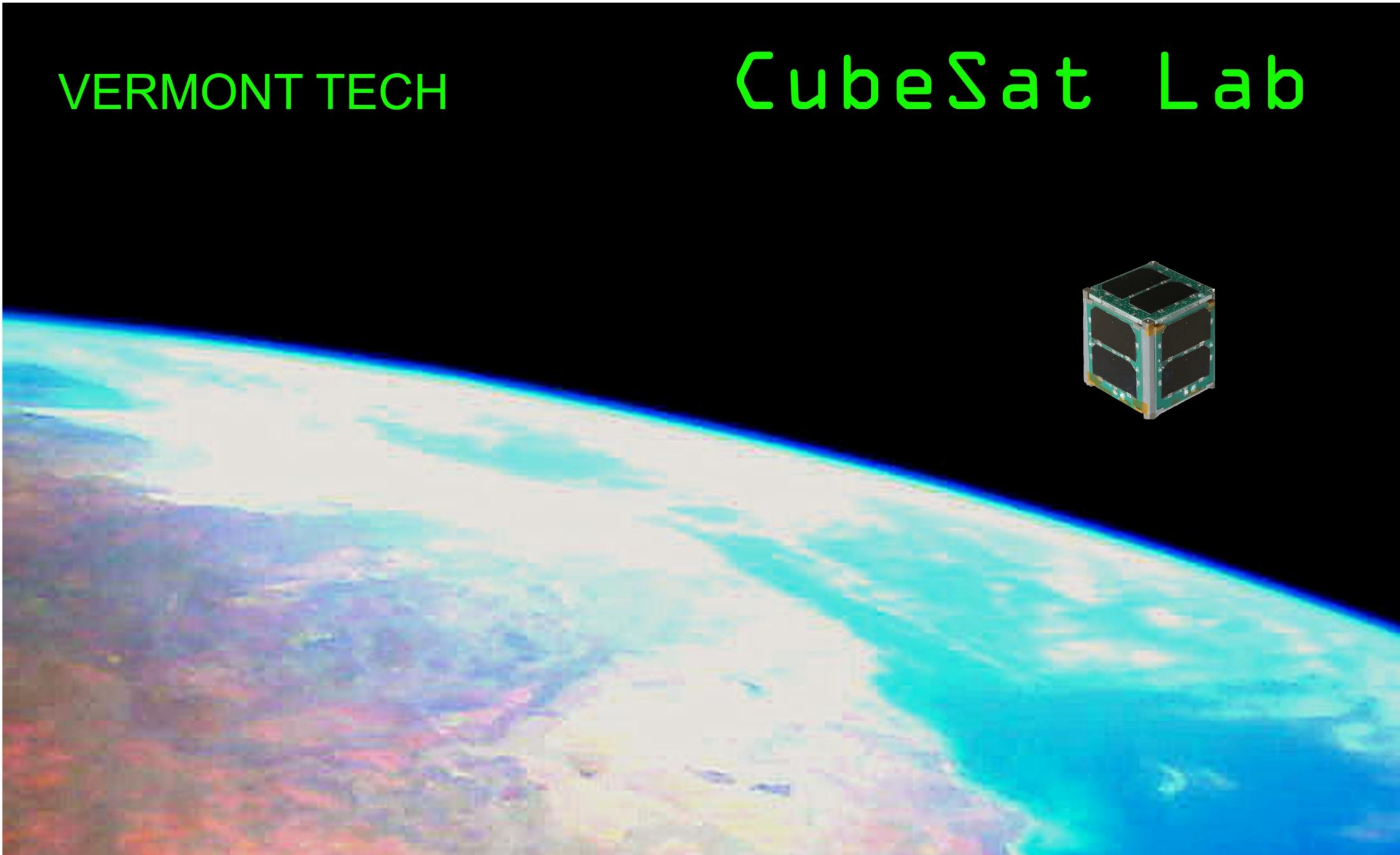
CubedOS: A SPARK Message Passing Framework for CubeSat Flight Software

SPARK/Frama-C Conference - Copyright 2017 Carl Brandon & Peter Chapin

Dr. Carl Brandon & Dr. Peter Chapin carl.brandon@vtc.edu peter.chapin@vtc.edu
Vermont Technical College +1-802-356-2822 (Brandon), +1-802-522-6763 (Chapin)



VERMONT TECH

Why We Use SPARK/Ada

ELaNa IV lessons for CubeSat software:

- NASA’s 2010 CubeSat Launch Initiative (ELaNa)
- Our project was in the first group selected for launch
- Our single-unit CubeSat was launched as part of NASA’s ELaNa IV on an Air Force ORS-3 Minotaur 1 flight November 19, 2013 to a 500 km altitude, 40.5^o inclination orbit and remained in orbit until reentry over the central Pacific Ocean, November 21, 2016. **Eight others were never heard from, two had partial contact for less than a week, and one worked for 4 months.**
- The Vermont Lunar CubeSat tested components of a Lunar navigation system in Low Earth Orbit

VERMONT TECH

Vermont Lunar CubeSat

It worked until our reentry on November 21, 2015:

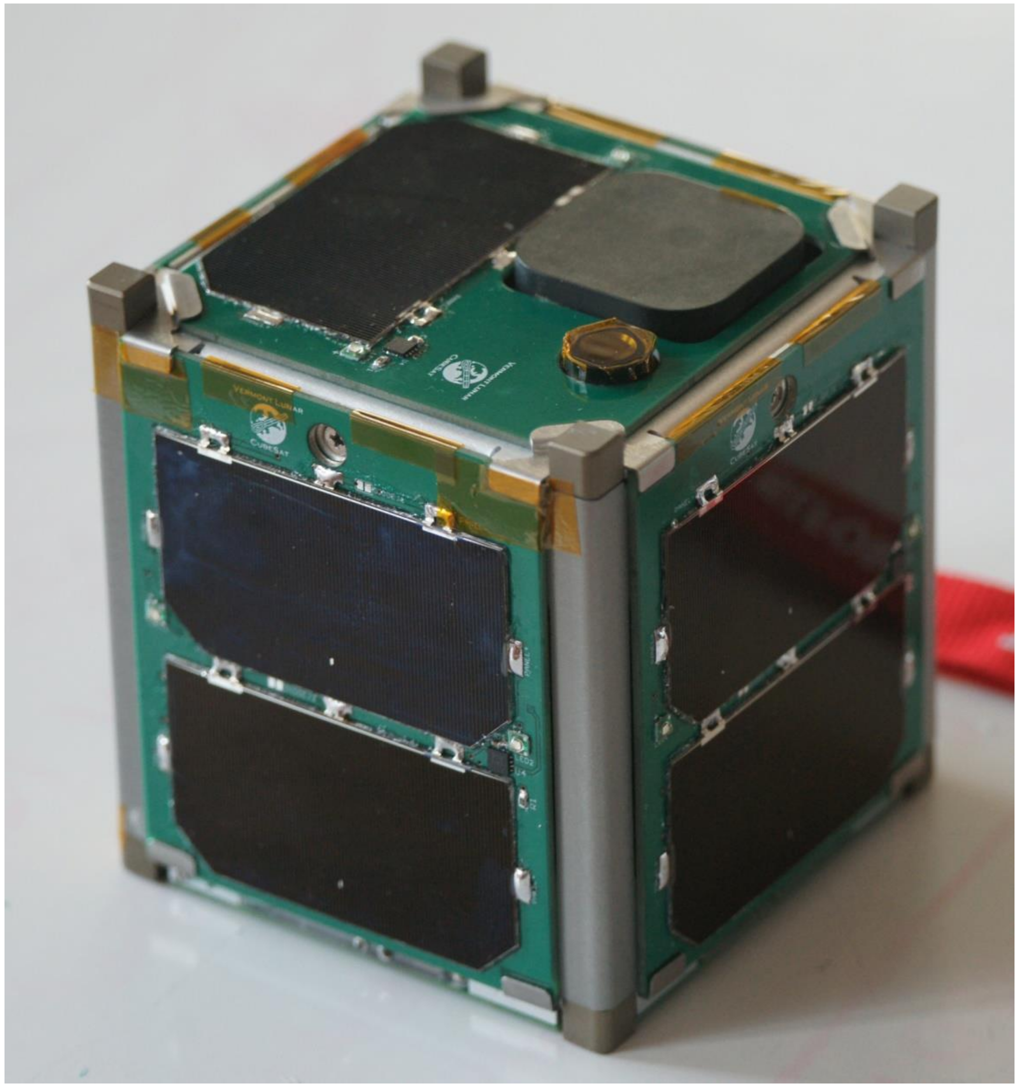
- We completed 11,071 orbits.
- We travelled about 293,000,000 miles, equivalent to over 3/4 the distance to Jupiter.
- Our single-unit CubeSat was launched as part of NASA's ELaNa IV on an Air Force ORS-3 Minotaur 1 flight November 19, 2013 to a 500 km altitude, 40.5^o inclination orbit and remained in orbit until November 21, 2016. **It is the only one of the 12 ELaNa IV university CubeSats that operated until reentry, the last one quit 19 months earlier.**
- We communicated with it the day before reentry
- We are the only successful university satellite on the east coast
- **Follow our project at cubesatlab.org**

Vermont Lunar CubeSat *SPARK 2005* software

- 5991 lines of code
- 4095 lines of comments (2843 are SPARK annotations)
- A total of 10,086 lines (not including blank lines)
- The Examiner generated 4542 verification conditions
- All but 102 were proved automatically (98%)
- We attempted to prove the program free of runtime errors
- Which allowed us to suppress all checks
- The C portion consisted of 2239 lines (including blank lines)
- Additional provers in SPARK 2014 would improve this

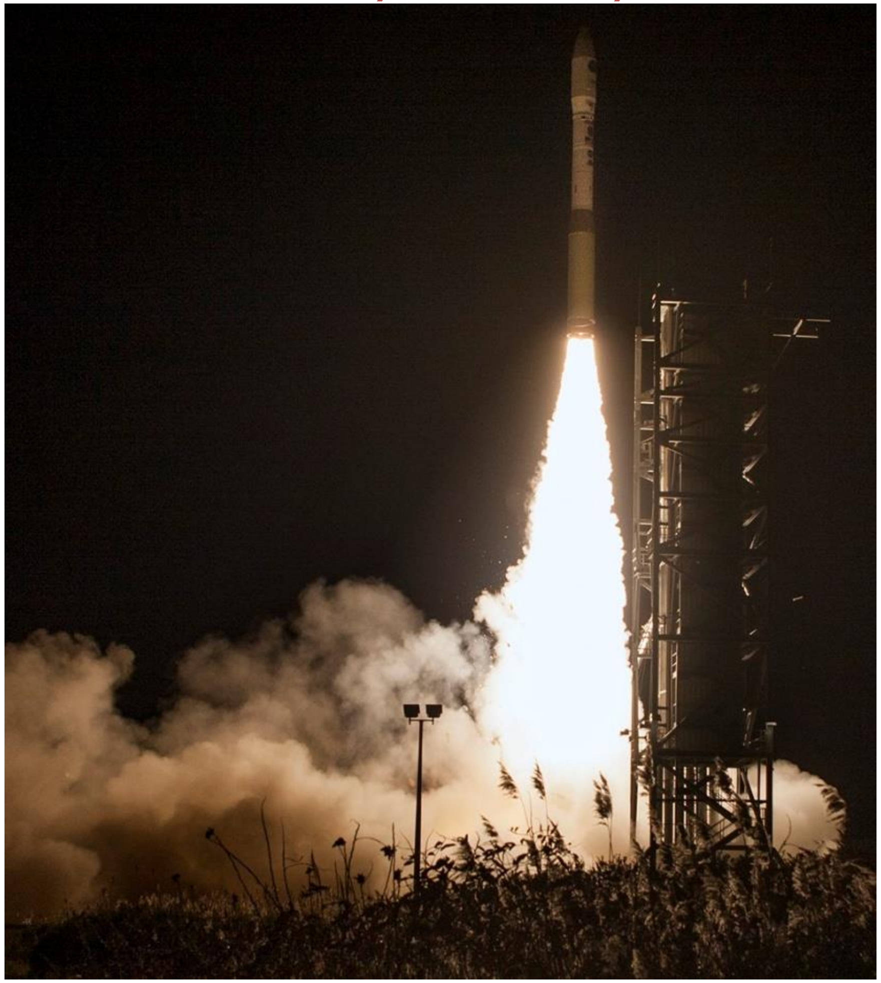
Vermont Lunar CubeSat

VERMONT TECH



Vermont Lunar CubeSat (10 cm cube, 1 kg)

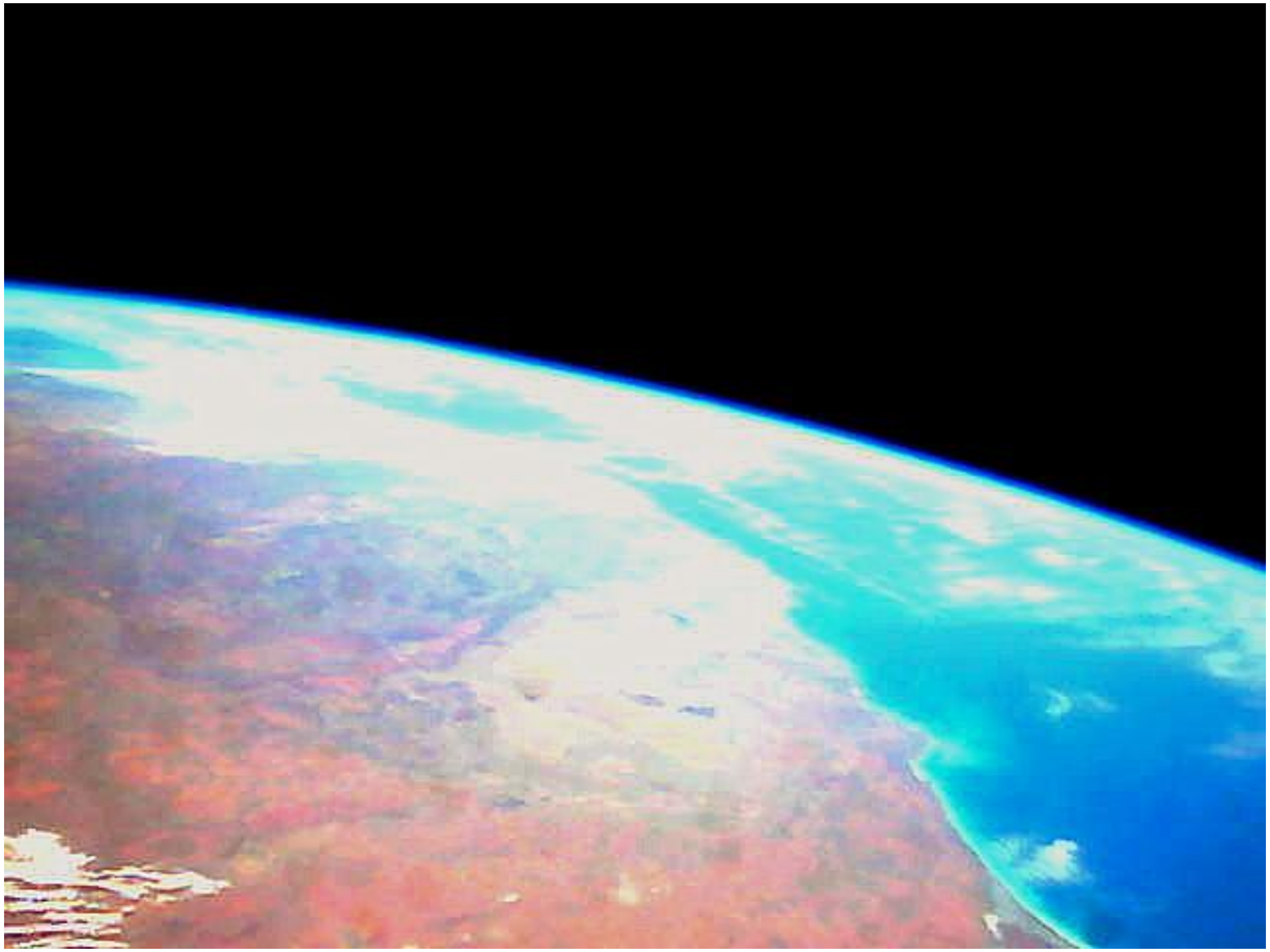
ELaNa IV Launch Minotaur 1 – Wallops Island November 19, 2013, 8:15 PM



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

VERMONT TECH

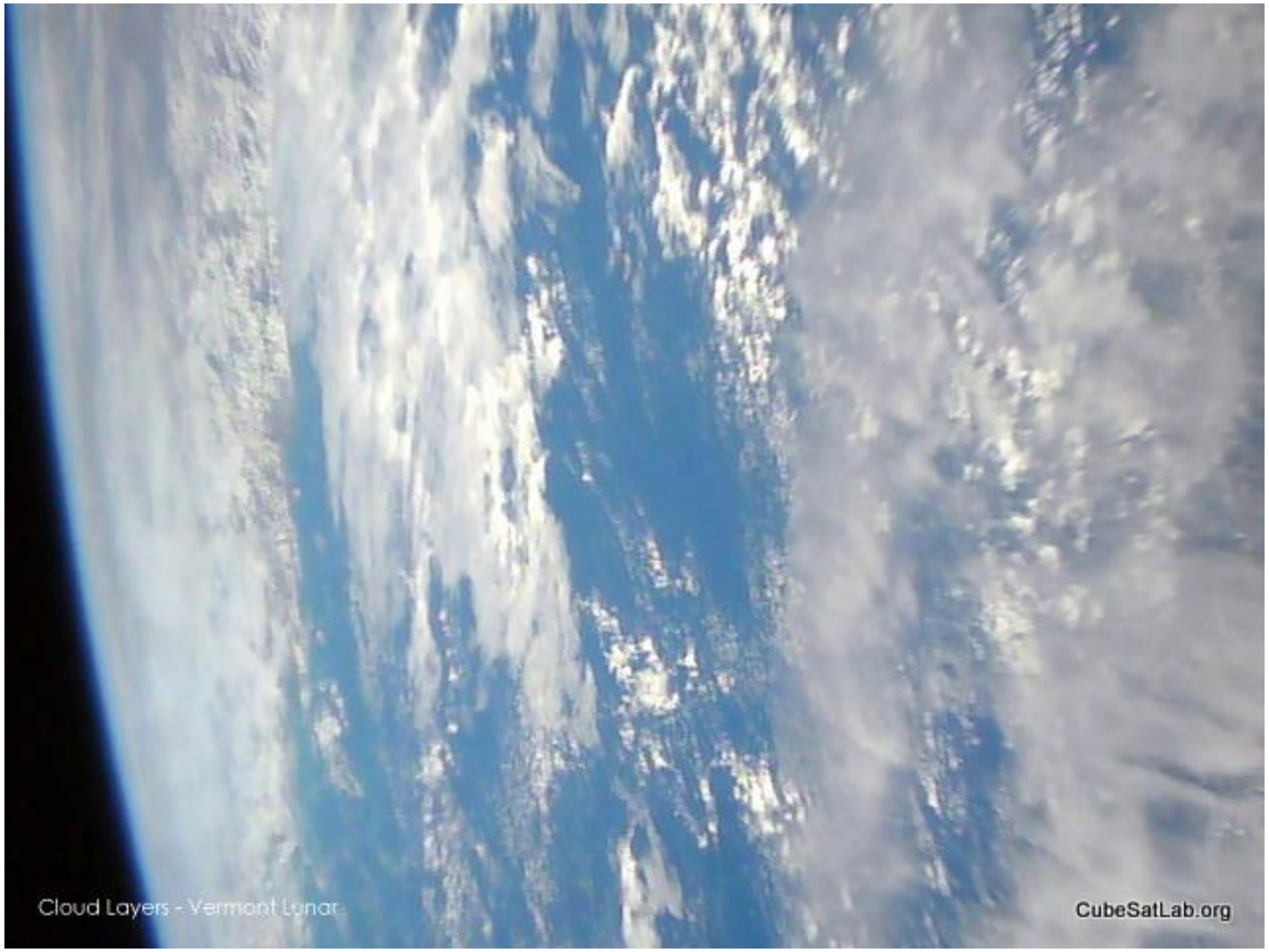
Vermont Lunar CubeSat



Our first picture of Earth, The North coast of Western Australia

VERMONT TECH

Vermont Lunar CubeSat



Clouds over the ocean, June 2015, 19 months after launch.

VERMONT TECH

Software Development Comments for our first CubeSat

- 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

- Although the CubeSat is limited to 1.3kg, the paperwork is unlimited 😉

VERMONT TECH

Four aerospace software failures that would have been prevented with SPARK/Ada:

- Mars Science Laboratory Sol-200 Memory Anomaly
- Ariane 5 initial flight failure
- Boeing 787 generator control computer shutdown
- Boeing 787 avionics reset

Mars Science Laboratory

Sol-200 Memory Anomaly

- Six months after landing on Mars, uncorrectable errors in the NAND flash memory led to an inability of the Mars Science Laboratory (MSL) prime computer to turn off for its normal recharge session.

- This potentially fatal error was apparently due to two pieces of its C software having pointers which pointed to the same memory. Curiosity has about 3.5 MLOC written in C. (One would expect about 35,000 errors.)

- SPARK/Ada would have prevented this almost fatal error in a 2.5 billion dollar spacecraft.

Ariane 5 initial flight failure:

Good

Bad, 37 seconds later

Ariane 5 initial flight failure:

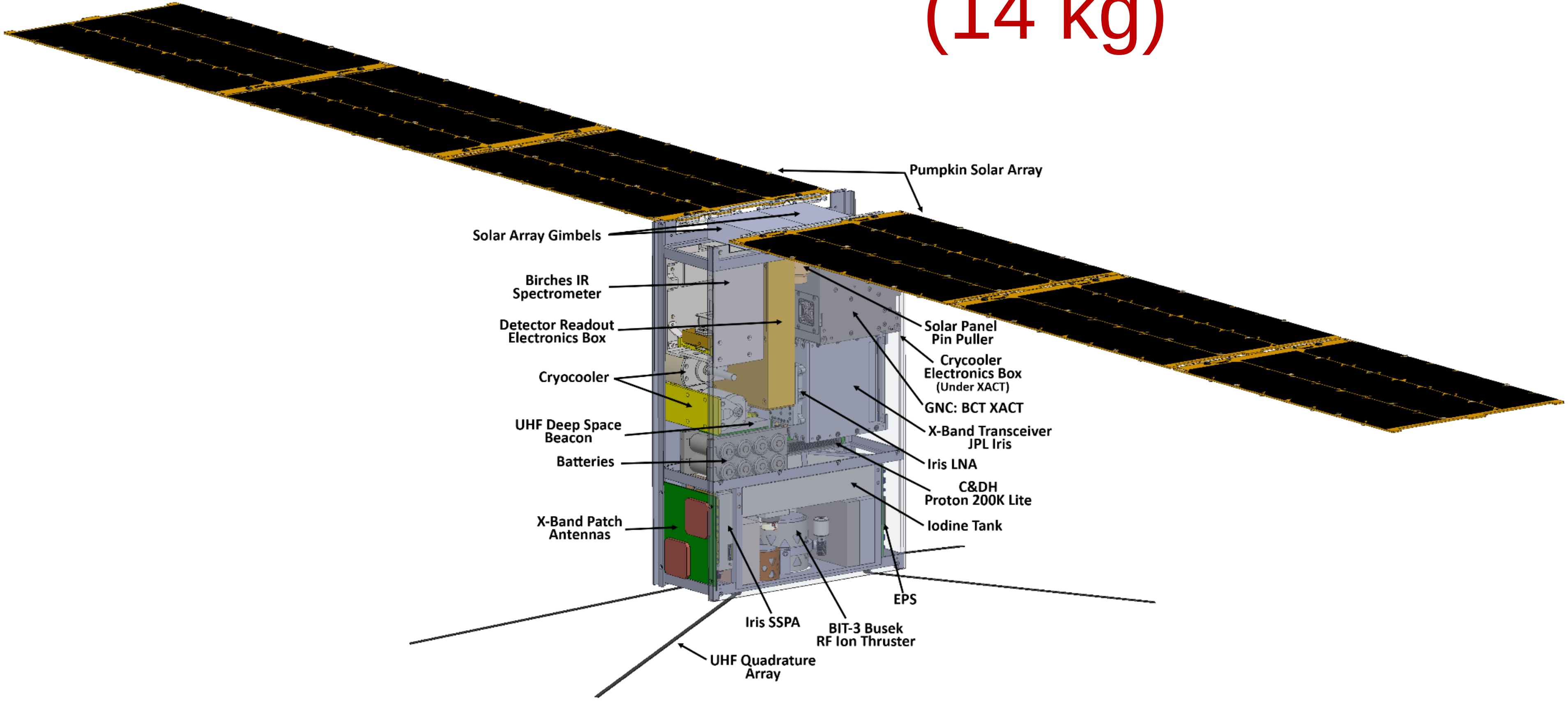
- Software reused from Ariane 4, written in Ada
- The greater horizontal acceleration caused a data conversion from a 64-bit floating point number to a 16-bit signed integer value to overflow and cause a hardware exception.
- “Efficiency” considerations had omitted range checks for this particular variable, though conversions of other variables in the code were protected.
- The exception halted the reference platforms, resulting in the destruction of the flight.
- Financial loss over $500,000,000.
- SPARK/Ada would have prevented this failure

Boeing 787 generator control computer:

- There are two generators for each of two engines, each with its own control computer programmed in Ada
- The computer keeps count of power on time in **centiseconds** in a 32 bit register
- Just after 8 months elapses, the register overflows
- Each computer goes into "**safe**" mode shutting down its generator resulting in a complete power failure, causing loss of control of the aircraft
- The FAA Airworthiness Directive says to shut off the power before 8 months as the solution
- There is now a second 787 reset problem
- SPARK/Ada would have prevented this

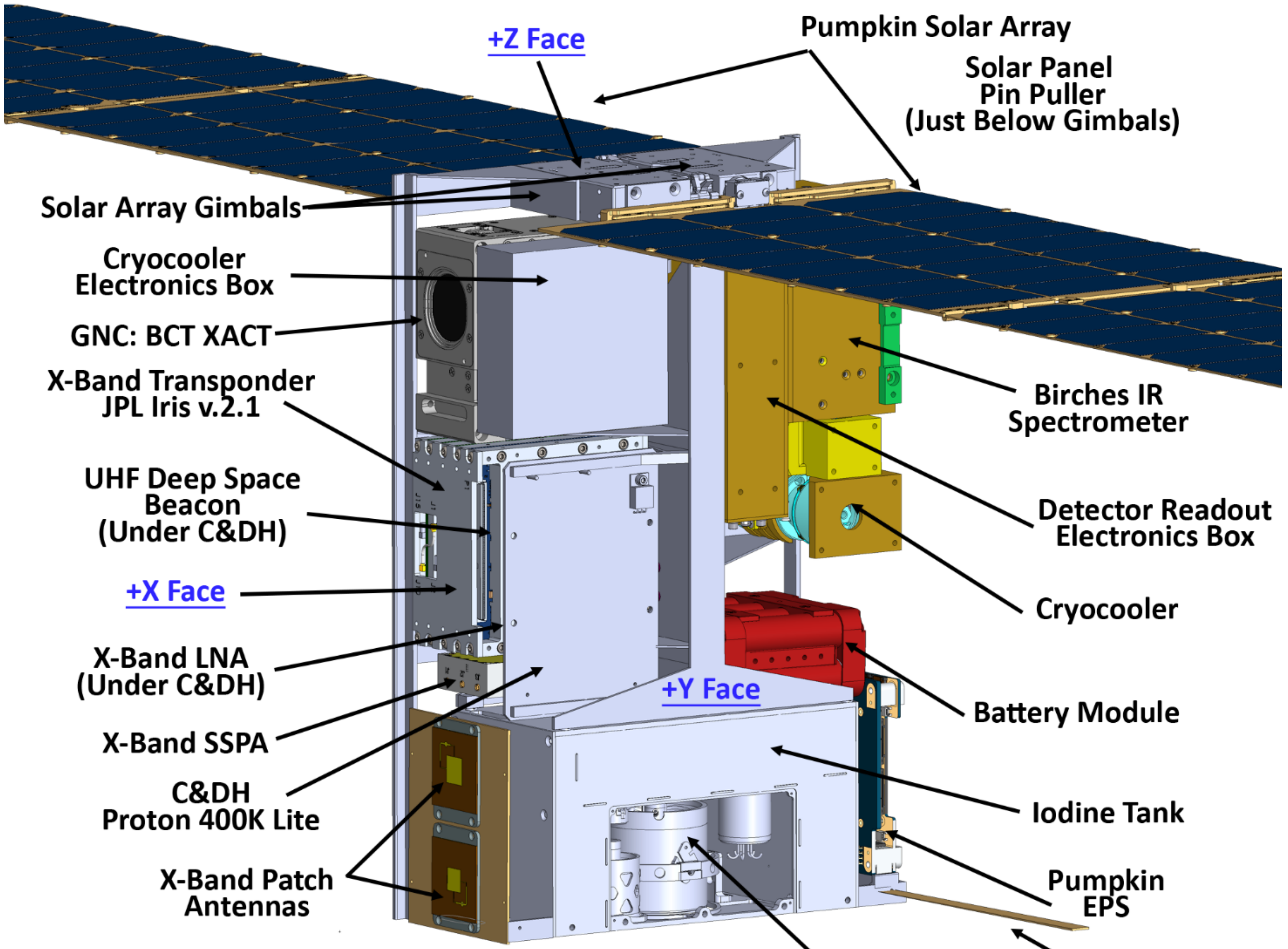
VERMONT TECH

Lunar IceCube (10cm x 20cm x 30cm) (14 kg)



Lunar IceCube 6U CubeSat, Morehead State University, PI., Goddard (BIRCHES IR Spectrometer), JPL (Iris 2 data & nav radio) & Vermont Tech (Flight software). Busek ion drive with 1.5 kg Iodine propellant, Pumpkin photovoltaic array (120 W).

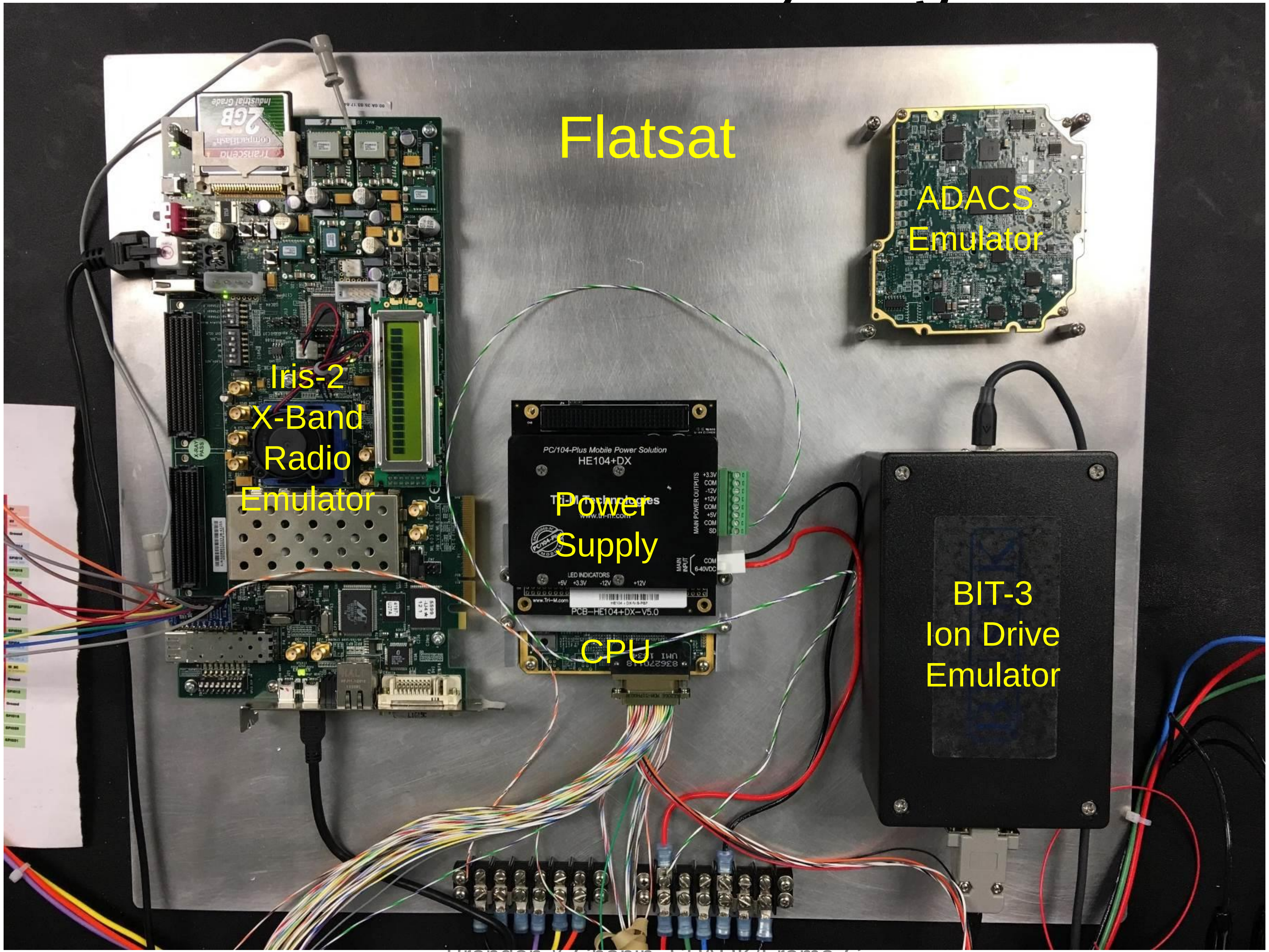
VERMONT TECH



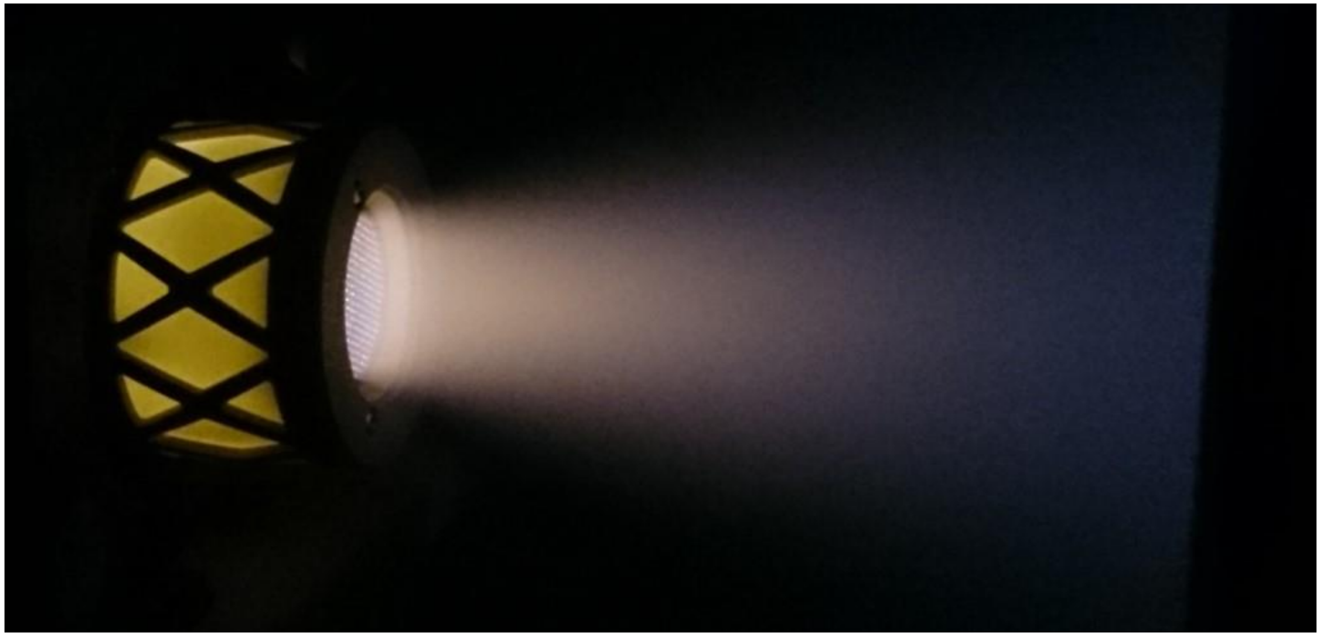
Hardware Controlled by Flight Software

- A photovoltaic (PV) panel orientation drive for aiming the panels
- Broadband Infrared Compact High Resolution Exploration Spectrometer (BIRCHES), Goddard Space Flight Center
- Blue Canyon XACT attitude determination and control system (ADACS): star tracker camera, CPU, and 3 momentum wheels
- Iris-2 X-band data & nav radio by NASA's Jet Propulsion Lab
- Busek BIT-3 iodine propellant ion drive (first use in space), controlling thrust and gimbals
- Spiral Thrusting (developed at JPL) for 3-axis momentum wheel desaturating
- Flight software will run on a Space Micro Proton-400 dual core PowerPC, radiation hardened CPU board

Hardware Controlled by Flight Software

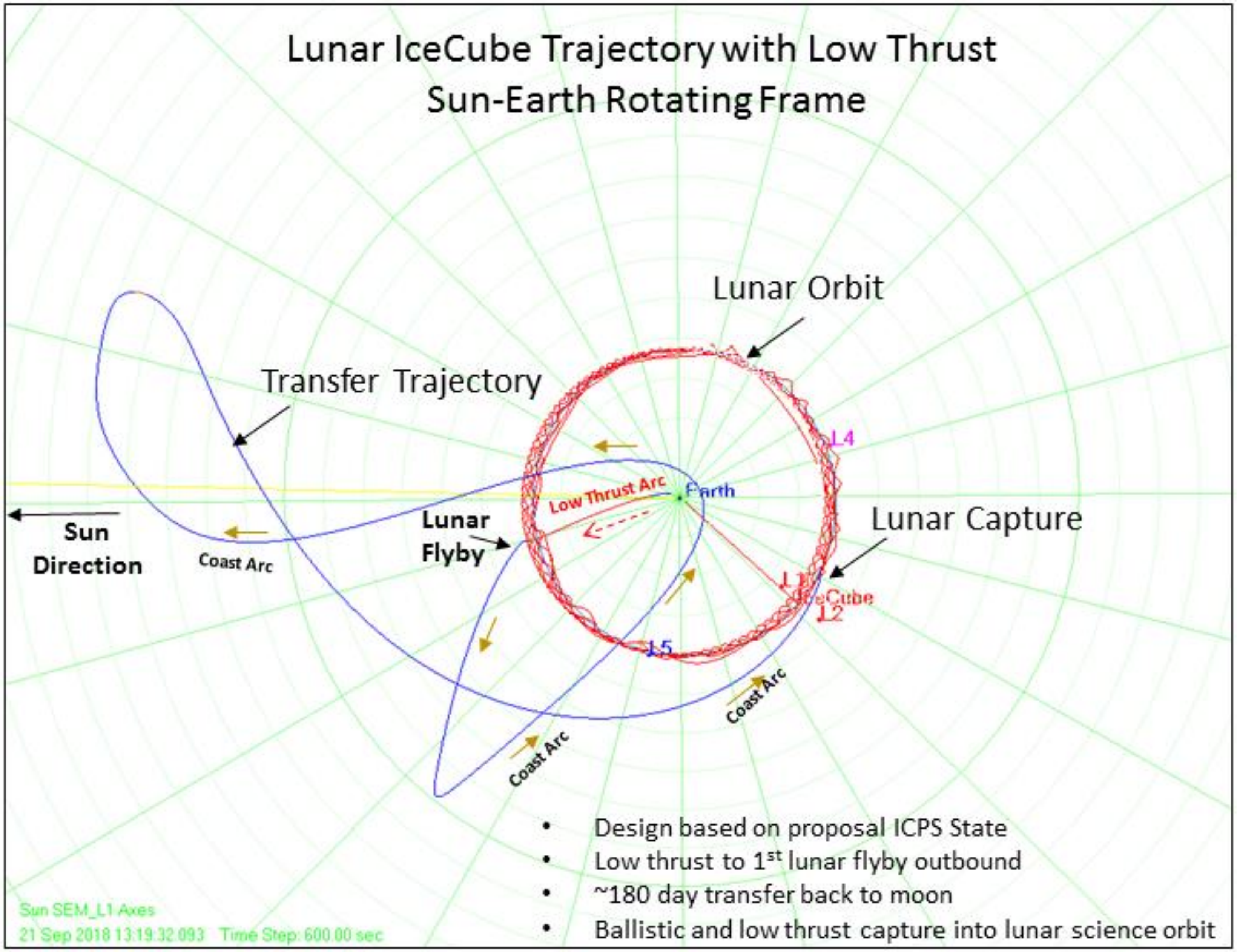


Busek Ion Thruster



BIT-3 Iodine Propellant

75W, 1.15 mN, 2.5 cm beam width, I_{SP} = 2,000



Lunar IceCube Trajectory with Low Thrust
Sun-Earth Rotating Frame

- Design based on proposal ICPS State
- Low thrust to 1st lunar flyby outbound
- ~180 day transfer back to moon
- Ballistic and low thrust capture into lunar science orbit

Lunar IceCube Flight Software based on *CubedOS*

- *Intended to be a general purpose framework for CubeSat flight software*
- Written **in SPARK**; proven free from runtime errors
- Provides inter-module message passing framework
- Provides services of interest to flight software
- Can integrate existing Ada or C runtime libraries
- Uses a Low Level Abstraction Layer (LLAL) to abstract OS/hardware
- *Conceptually similar to NASA's cFE/CFS except written in SPARK (not C).*

Lunar IceCube Software Environment

- VxWorks 6.9 on PowerPC
- SPARK 2014 with Ravenscar runtime

Current Development Team

- VTC: 2 faculty, 5 students (2 MS, 3 BS)
- Morehead State University: 1 faculty, 1 student

CubedOS/IceCube Verification Goals

- No flow errors
- Show freedom from runtime error
- Other correctness properties as time allows

CubedOS/IceCube Testing

- Unit tests with AUnit (x86)
- Some additional test programs (x86)
- Hardware development system (PowerPC)
- Hardware “FlatSat” (PowerPC)

Continuous Integration

- We use Jenkins-CI (https://jenkins.io/)
- Every night…
  - … builds & executes unit test programs
  - … does SPARK flow analysis
  - … does SPARK proofs
- Build considered to have failed if unit tests fail
  - Requiring successful proofs for “successful” build too high a bar

Software Architecture

- Collection of “modules” that pass messages
  - Each module reads messages from exactly one mailbox
  - Each module contains a message processing task
  - Modules all execute concurrently
- Collection of libraries
  - Passively called from multiple modules

Software Architecture

- CubedOS comes out-of-the-box with:
  - A set of standard server modules
    - Timing services
    - Publish/Subscribe services
    - File system interface
    - Communication protocols (e. g., CFDP)
    - … etc
  - A set of library facilities
    - CRC, Packet encoding/decoding, data compression

Lunar IceCube Flight Software

- A CubedOS application
  - Application modules for:
    - Device drivers for subsystem hardware
    - Spacecraft state manager (“main” module that initiates and coordinates other activity)
    - Command scheduler
    - Implementation of CubedOS standard file system interface

CubedOS Mailboxes

```
generic
   Module_Count : Positive;
   Mailbox_Size : Positive;
   Maximum_Message_Size : Positive;
package CubedOS.Generic_Message_Manager is
 type Message_Record is
      record
         Sender      : Module_ID_Type;
         Receiver    : Module_ID_Type;
         Message_ID  : Message_ID_Type;
         Priority    : System.Priority;
         Size        : XDR_Size_Type;
         Payload     : XDR_Array;
      end record;
 type Message_Array is array(Message_Index_Type) of Message_Record;
 protected type Mailbox is … end Mailbox;
 Mailboxes : array(Module_ID_Type) of Mailbox;
end CubedOS.Generic_Message_Manager;
```

Mostly for future expansion

XDR encoded message parameters

CubedOS Mailboxes

- Each instantiation of the message manager creates a “communication domain”
- Multiple communication domains possible
- Each module has unique ID within its domain
- Each module has a single task that reads its mailbox and handles/dispatches messages
- Message parameters are encoded/decoded *at runtime* into octet streams and installed into the receiver’s mailbox

CubedOS Modules

- Each module is a hierarchy of packages
    - Complex modules might have multiple private child packages to support implementation
- Some_Module.API
    - Contains subprograms for encoding/decoding messages
    - ***Generated automatically by the XDR2OS3 tool*** (under development) from a high level message specification
- Some_Module.Messages
    - Contains the message loop and message handling

CubedOS Modules

- Module communication is point-to-point
  - Sender names receiver explicitly
  - Receiver learns sender ID from message header
  - Replies returned via (dynamically specified) ID
- Server modules
  - Can be written without knowledge of clients
  - Provided by third party libraries

Advantages

- Lots of behavior deferred to runtime
  - Flexible and dynamic communication patterns
  - Easily extensible via module libraries
  - OOP-like behavior
    - Many different implementations of the same module API are possible; clients need not know which implementation they are using

Disadvantages

- *Lots of behavior deferred to runtime!*
  - Message encoding/decoding overhead (space and time)
  - Loss of type safety (compare with well-typed protected object entry calls)
- *Not the SPARK way!*
  - But… type safety issue mitigated somewhat by XDR2OS3

Modified XDR Message Specification

```
typedef unsigned int Channel_ID_Type range 1 .. 16;
typedef enum { Success, Failure } Status_Type;
constant Max_Data_Size = 1024;

message struct {
  Channel_ID_Type Channel;
} Subscribe_Request;

message struct {
  Channel_ID_Type Channel;
  Status_Type Status;
} Subscribe_Reply;

message struct {
  Channel_ID_Type Channel;
  opaque Data<Max_Data_Size>;
} Publish_Request;
```

XDR2OS3 Specification Output

```
package CubedOS.Publish_Subscribe.API is
  type Channel_ID_Type is range 1 .. 16
  type Status_Type is (Success, Failure);
  Max_Data_Size : constant := 1024;

  type Message_Type is
    (Subscribe_Request,
     Subscribe_Reply,
     Publish_Request);

  function Subscribe_Request_Encode
    (Sender : Module_ID_Type;
     Channel : Channel_ID_Type;
     Priority : System.Priority) return Message_Record
    with Global => null;
     ...
end CubedOS.Publish_Subscribe.API;
```

XDR2OS3 Specification Output

```
package CubedOS.Publish_Subscribe.API is
   ...
 procedure Subscribe_Request_Decode
      (Message : in  Message_Record;
       Channel : out Channel_ID_Type;
       Status  : out Status_Type)
   with
     Global => null,
     Pre => Is_Subscribe_Request(Message),
     Depends => ((Channel, Status) => Message);

end CubedOS.Publish_Subscribe.API;
```

XDR2OS3 Body Output

```
package body CubedOS.Publish_Subscribe.API is
  function Subscribe_Request_Encode
     (Sender : Module_ID_Type;
      Channel : Channel_ID_Type;
      Priority : System.Priority) return Message_Record
  is
      Message : Message_Record :=
        Make_Empty_Message
          (Sender, ID, Message_Type'Pos(Subscribe_Request), Priority);
      Position : XDR_Index_Type;
      Last : XDR_Index_Type;
  begin
      Position := 0;
      XDR.Encode
        (XDR.XDR_Unsigned(Channel), Message.Payload, Position, Last);
      Message.Size := Last + 1;
      return Message;
  end Subscribe_Request_Encode;
```

Problem with Mailboxes

- SPARK won’t track information flow through arrays
  - *“high: multiple tasks might queue on protected entry "message_manager.mailboxes.receive”*
- We suppress this message!
- Can’t track flow between modules
  - We must take responsibility for initialization, etc.
  - But… this allows flexible communication
- Full strength of SPARK within modules
- NOTE: *Must ensure modules have unique IDs!*

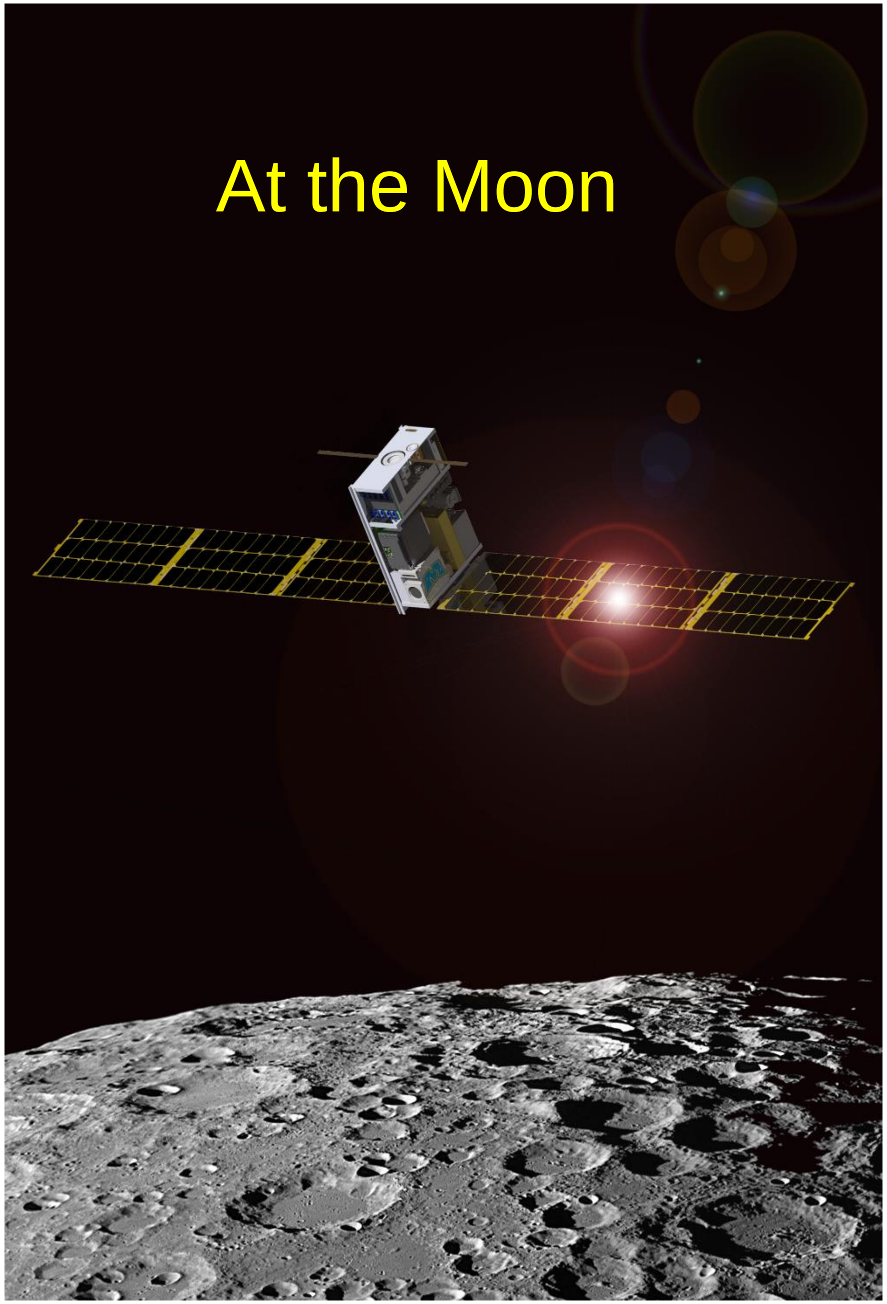
Why not NASA's cFE/CFS?

- "cFE/CFS" = "Core Flight Executive / Core Flight System"
- Similar architecture
  - Uses publish/subscribe (not point-to-point)
  - Uses CCSDS space packets for messages
- cFE written in C. Not verified
- We hope to eventually offer CubedOS as a competing SPARK platform for spacecraft software

VERMONT TECH

Lunar IceCube Launch Vehicle

NASA's Space Launch System 2018


At the Moon

VERMONT TECH

One of Our Ground Stations

The 70m Dish at Goldstone, California

VERMONT TECH

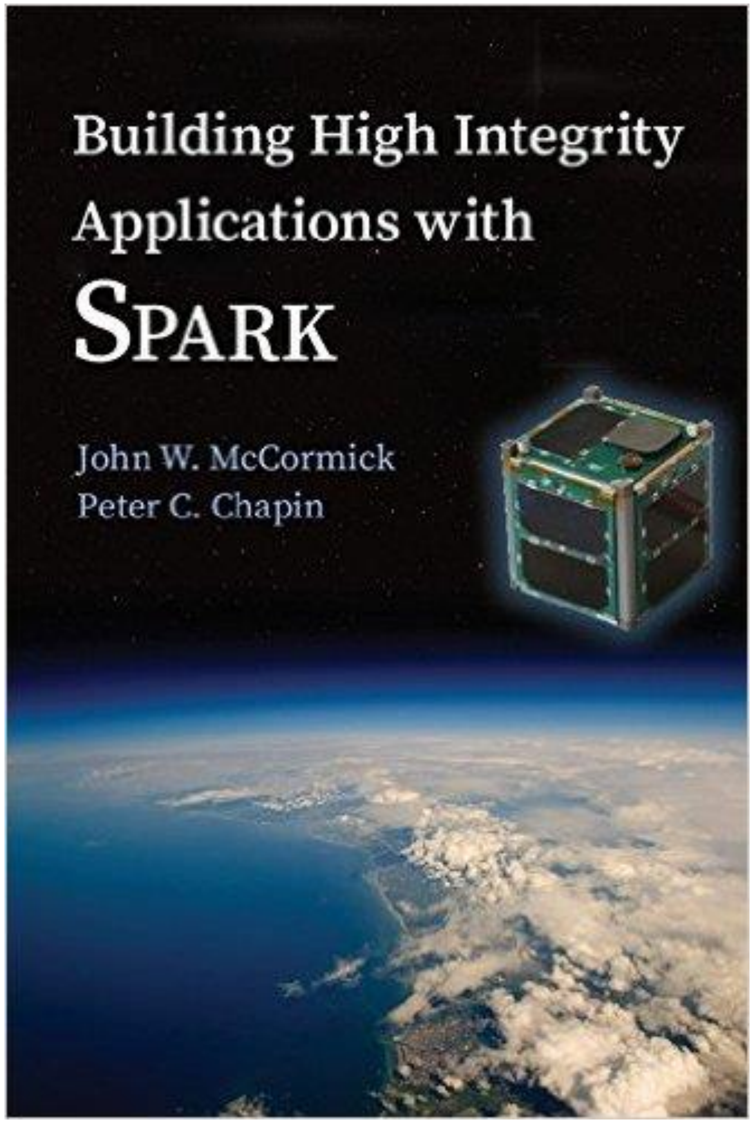
21m Dish at Morehead State University

VERMONT TECH

Acknowledgements

- NASA Vermont Space Grant Consortium
- Vermont Technical College
- AdaCore, Inc. (GNAT Pro, SPARK Pro)
- Morehead State University (Spacecraft)
- Applied Graphics, Inc. (STK)
- Busek (BIT-3 Iodine ion drive)
- Pumpkin, Inc. (PV-panels, gimbals, battery, EPS)
- NASA Jet Propulsion Lab (Iris-2 Radio)
- NASA Goddard Space Flight Center (BIRCHES)

A SPARK 2014 Book is Available



CubedOS: A SPARK Message Passing Framework for CubeSat Flight Software

Dr. Carl Brandon & Dr. Peter Chapin carl.brandon@vtc.edu peter.chapin@vtc.edu
Vermont Technical College +1-802-356-2822 (Brandon), +1-802-522-6763 (Chapin)