Enabling Technologies for Deep Space CubeSats

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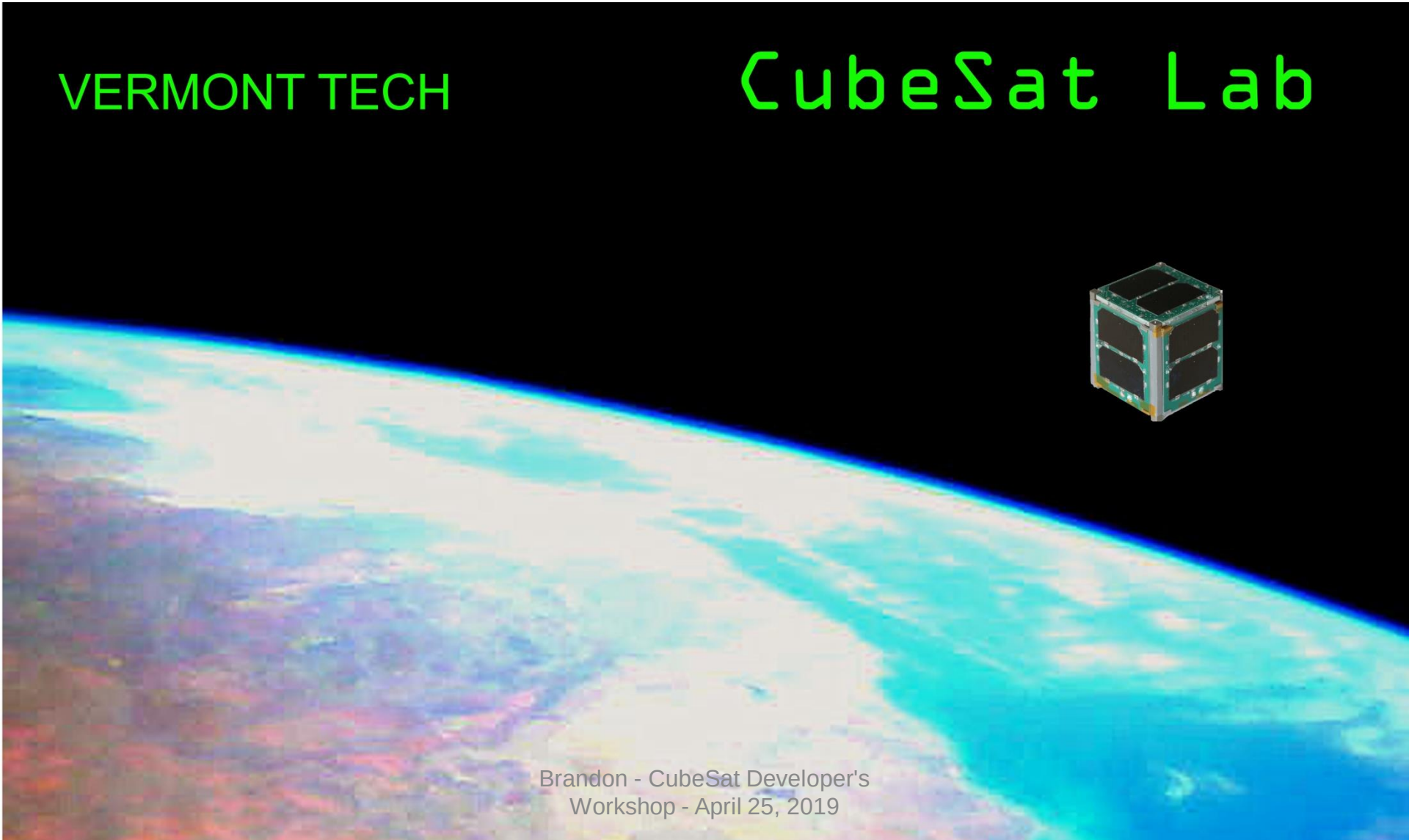
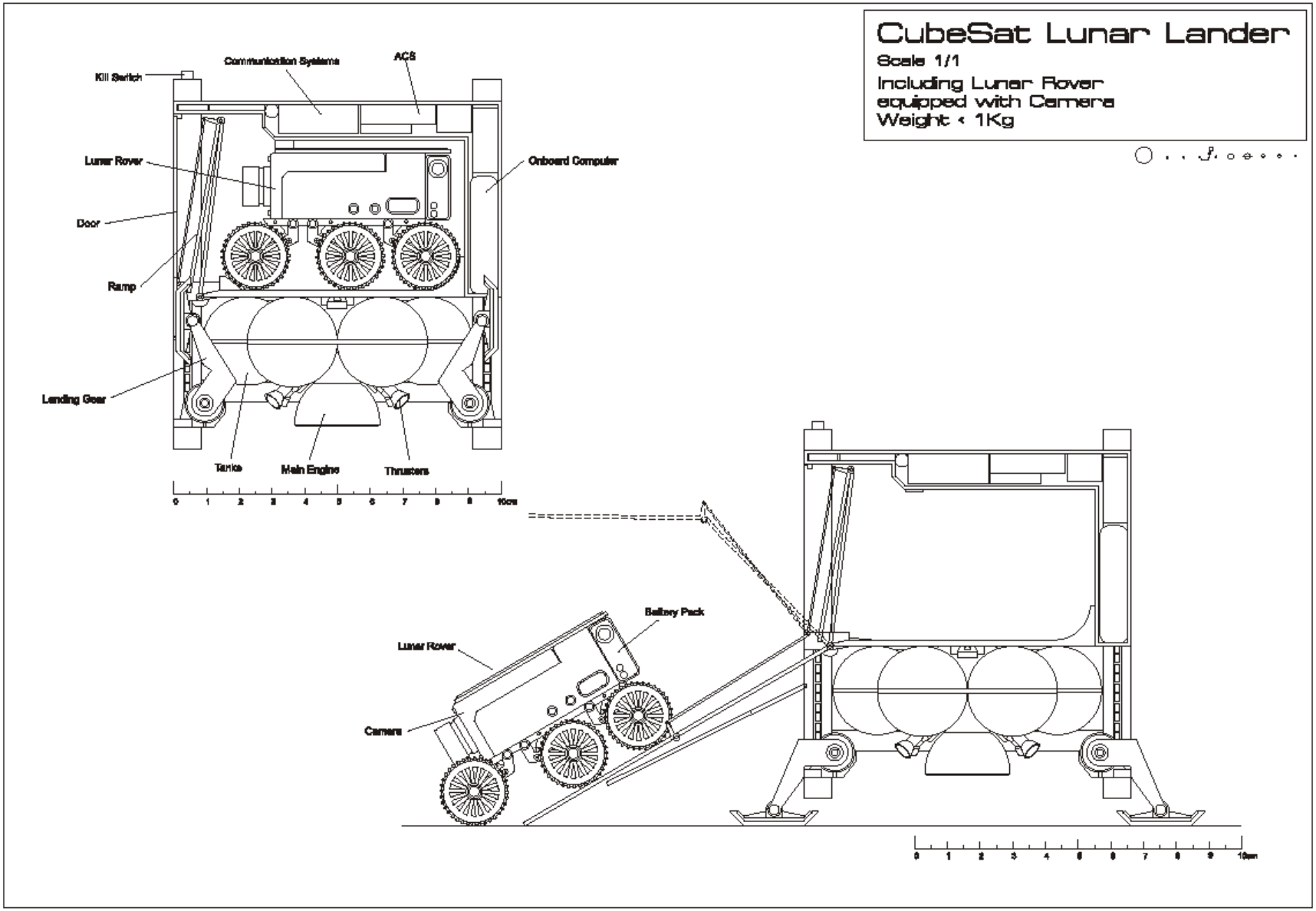
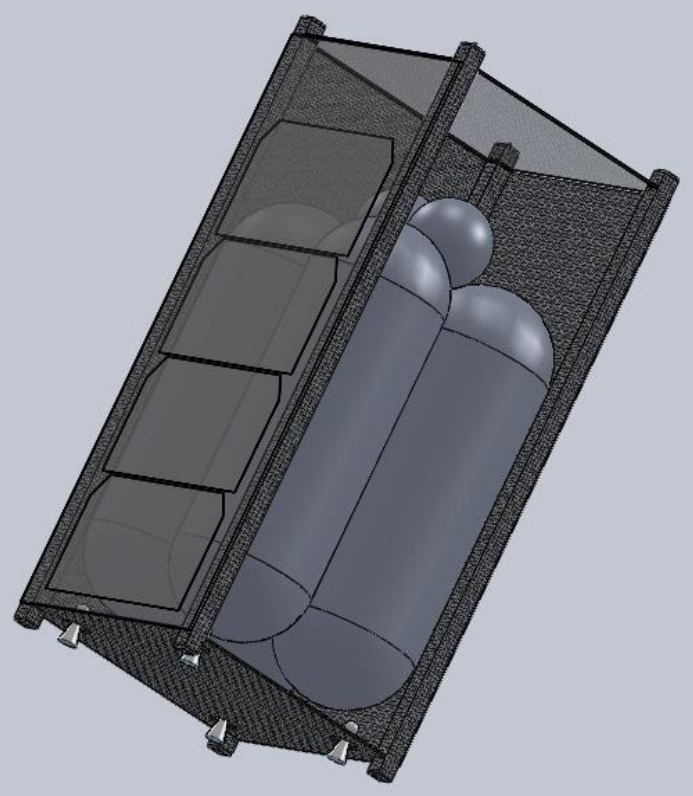


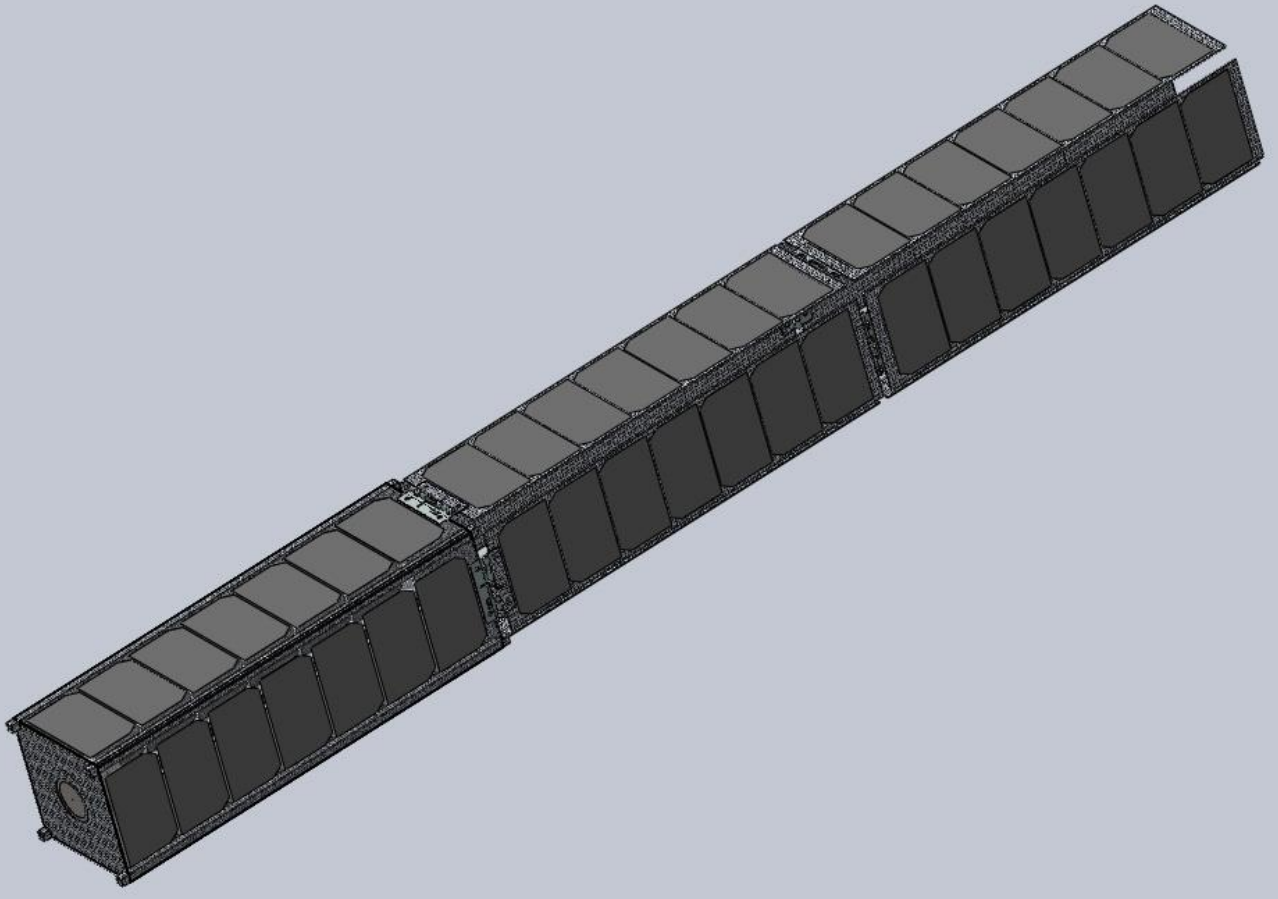

CubeSat Lunar Lander
Scale 1/1
Including Lunar Rover
equipped with Camera
Weight < 1Kg
Kill Switch
Communication Systems
ACS
Lunar Rover
Onboard Computer
Door
Ramp
Landing Gear
Tanks
Main Engine
Thrusters
Battery Pack
Lunar Rover
Camera

I was an invited speaker (of the Moon Society) to the Space Development Conference, along with Scott Carpenter, John Glenn and Buzz Aldrin. I spoke about sending CubeSats to the Moon.

Monopropellant 2U Booster CubeSat



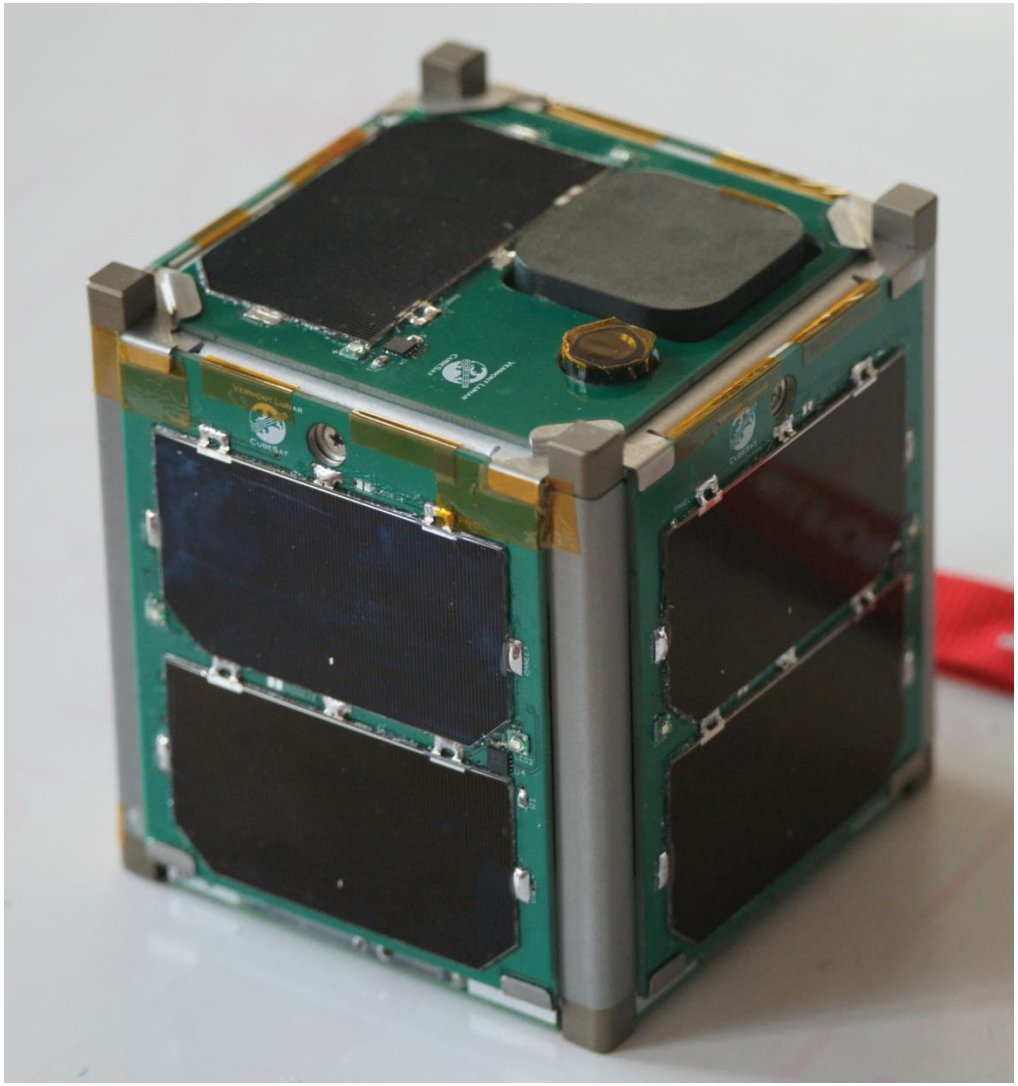
3U Ion Drive CubeSat with PV panels



Monopropellant hydroxyl-ammonium nitrate Thruster, Busek BGT-X5, 0.5N, 225s ISP

Vermont Lunar CubeSat

VERMONT TECH



Vermont Lunar CubeSat (10 cm cube, 1 kg)

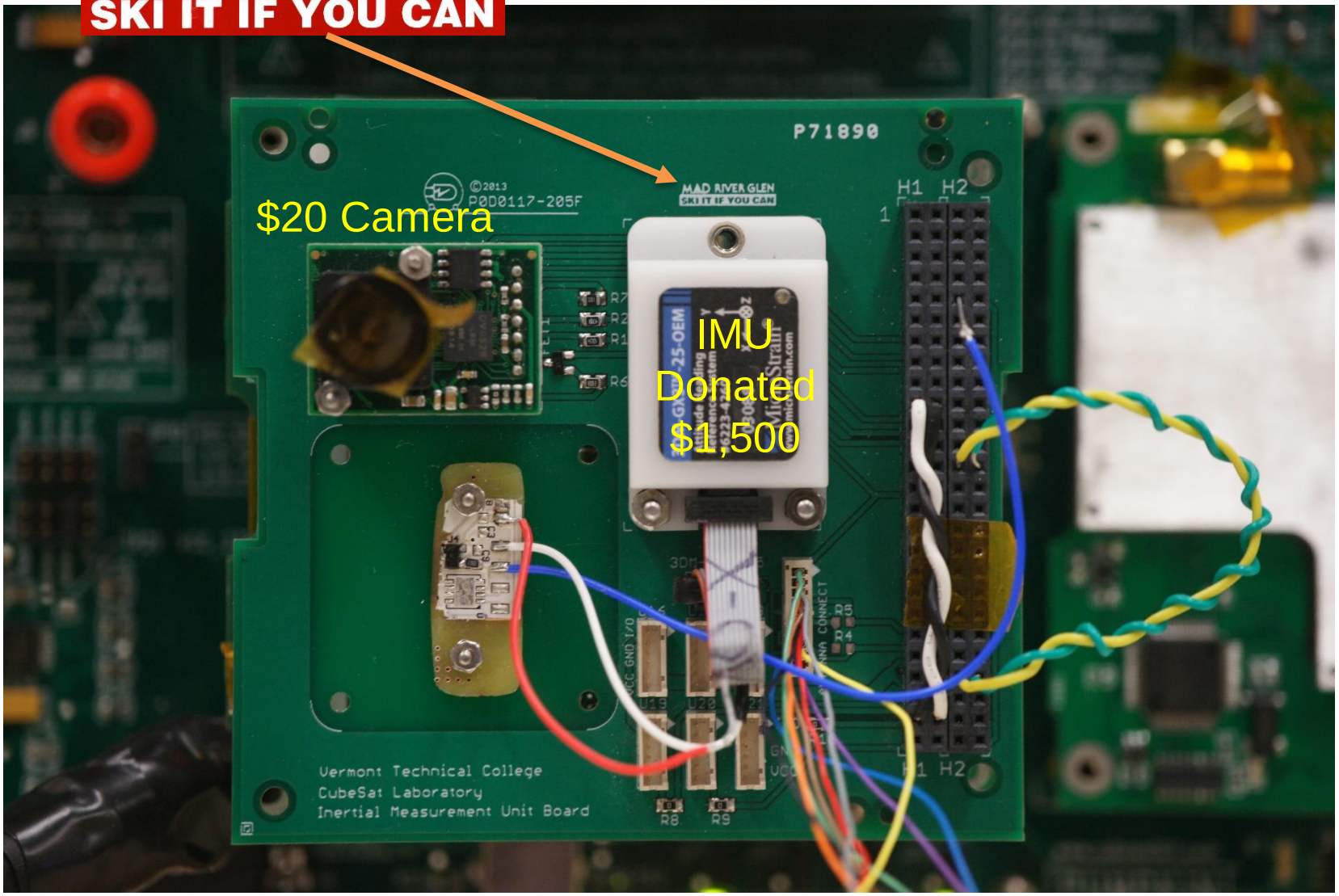
Vermont Lunar CubeSat

VERMONT TECH

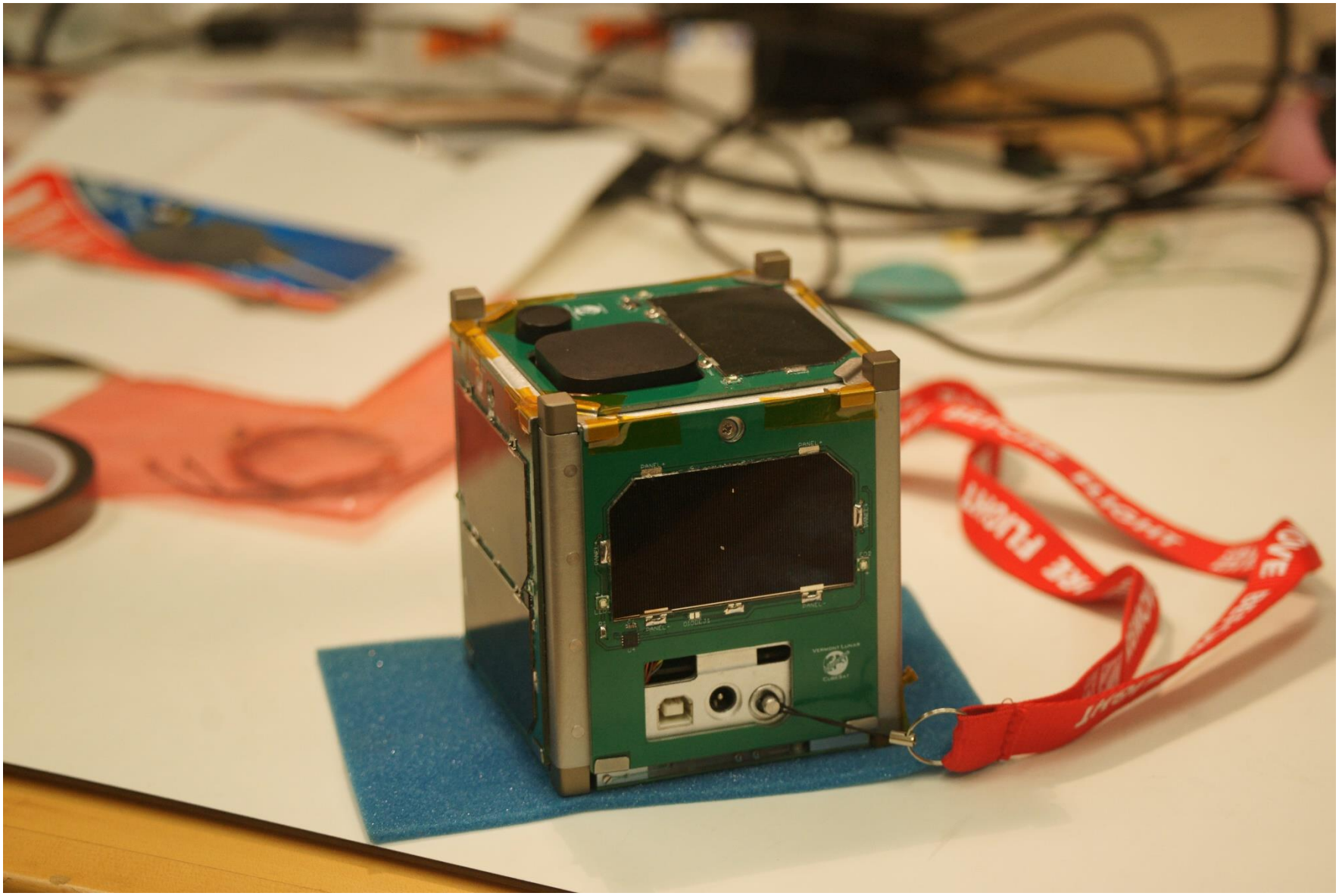
It worked until our reentry on November 21, 2015:

- 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 were the first university satellite from New England
- We were the only successful university satellite on the east coast until this year
- **Follow our project at cubesatlab.org**

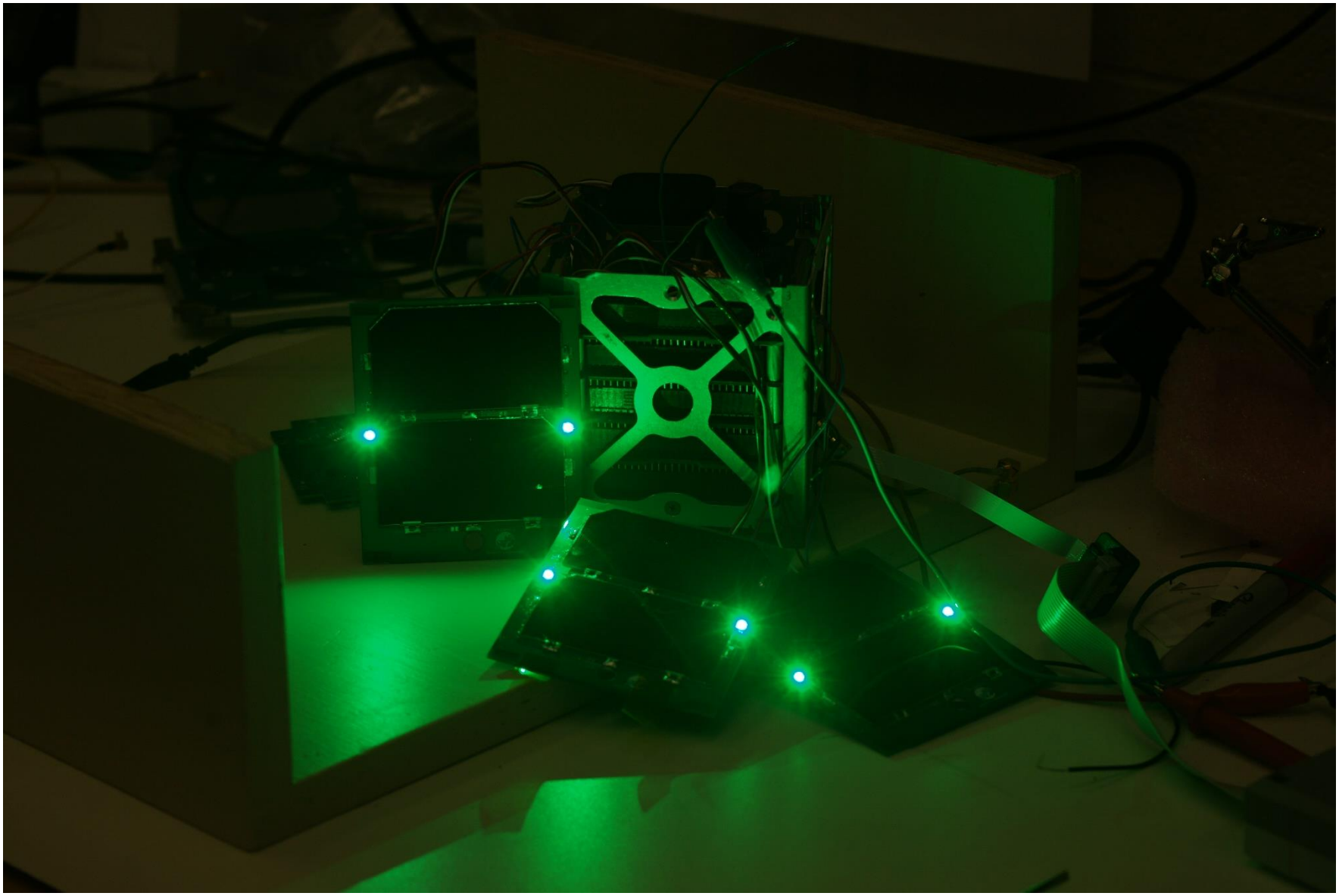
Camera, inertial measurement unit.



Assembled Vermont Lunar CubeSat

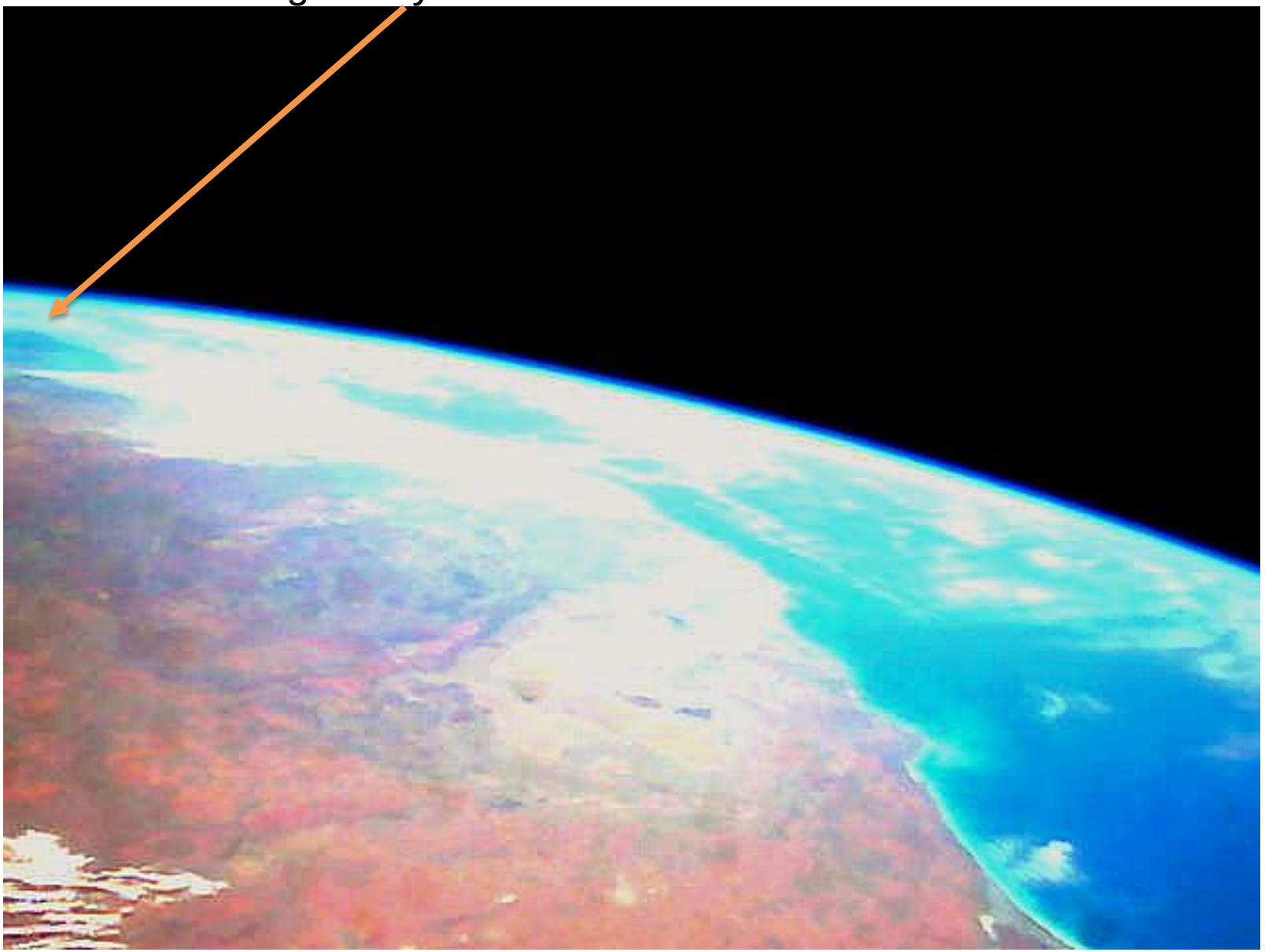


Testing the LEDs

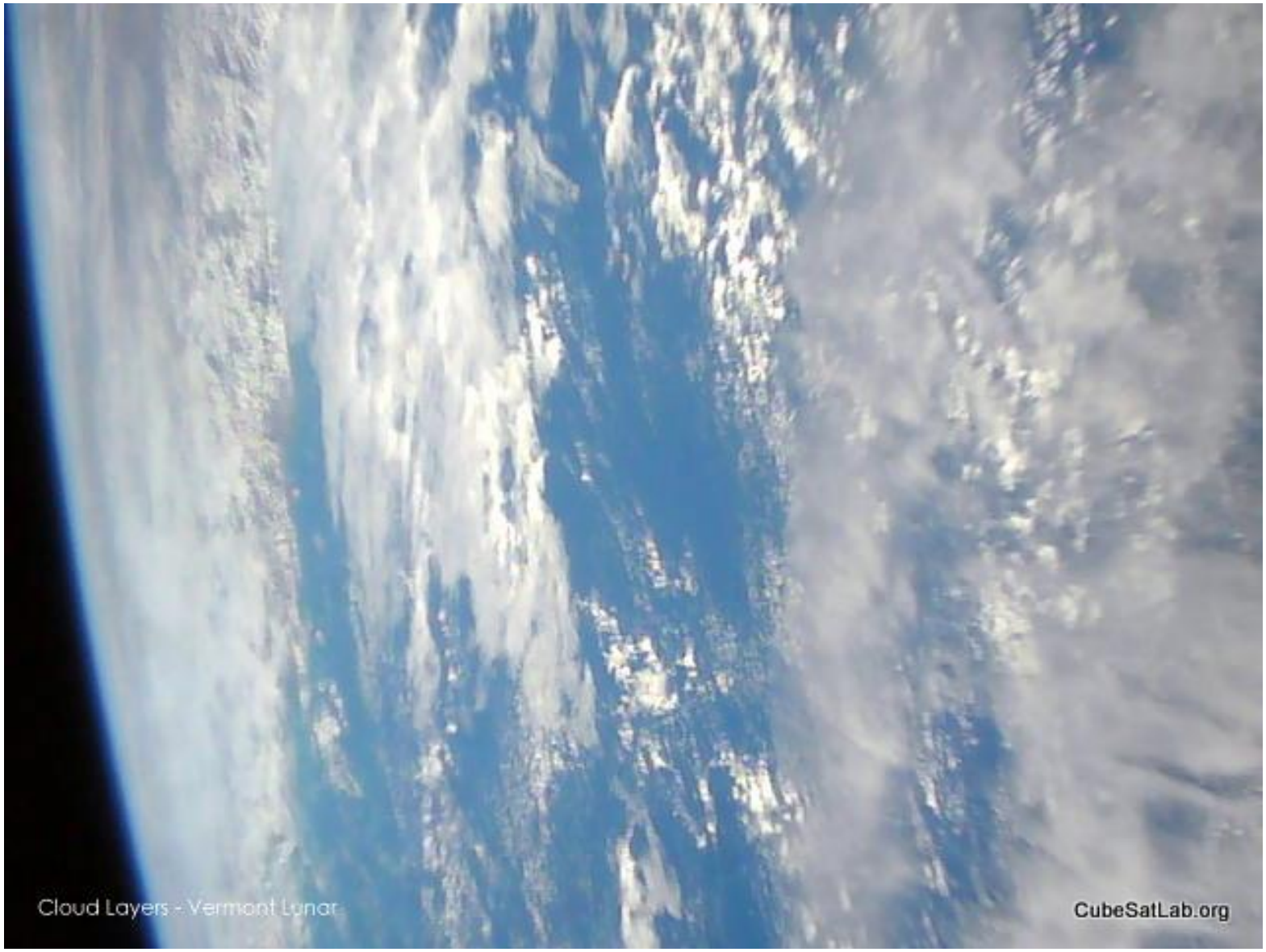


ELaNa IV Launch Minotaur 1 – Wallops Island November 19, 2013, 8:15 PM

I am with my two software students, Dan and India, and my son, Jack. First two stages are Minuteman II, third and fourth stages are Pegasus second and third stages

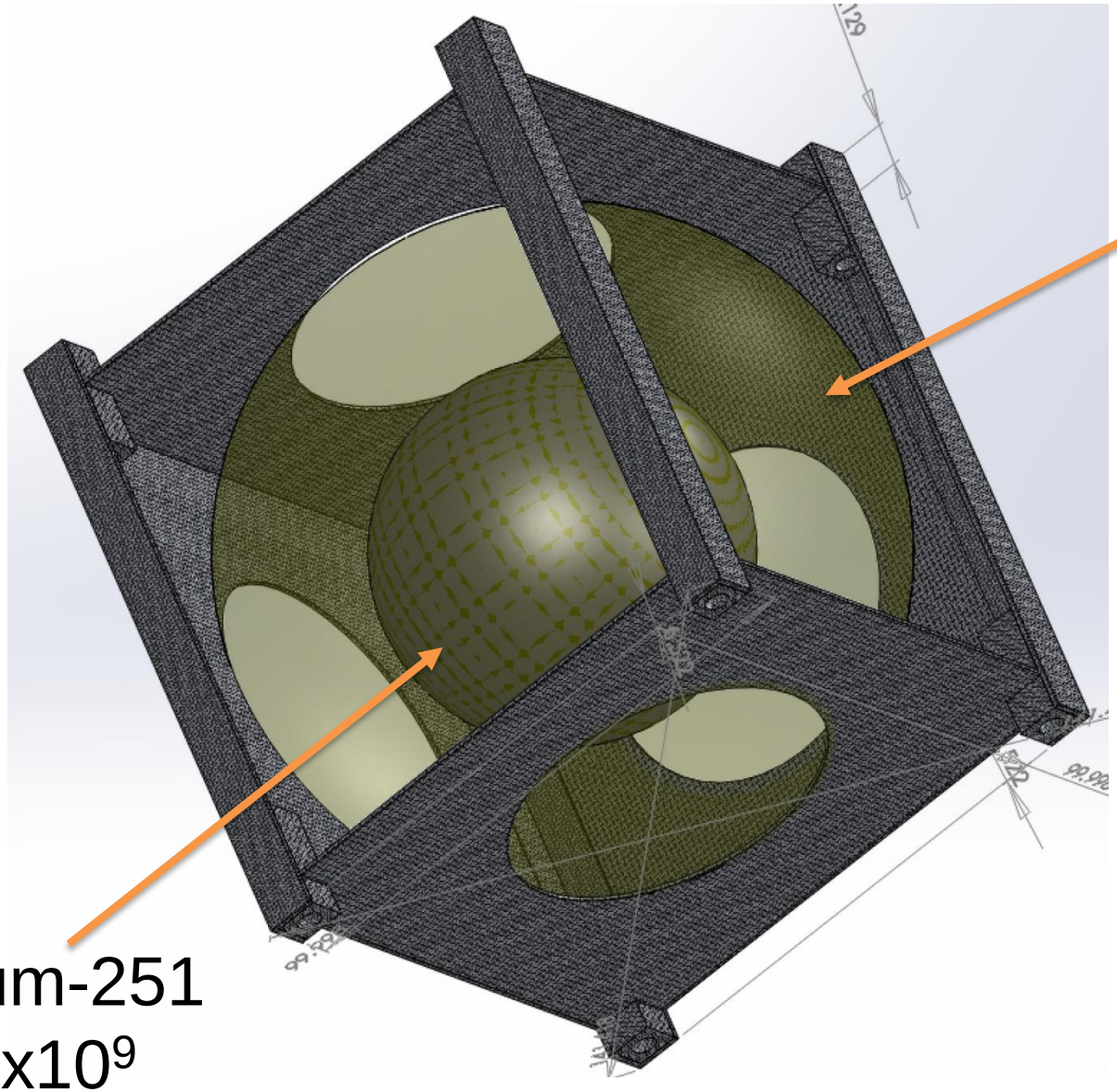


Our first picture of Earth, The North coast of Western Australia



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

Large Area Orbital Debris Mitigation



Californium-251
5 kg, $50x10^{9}

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, **after two years and two days. Eight others were never heard from, two had partial contact for a few days, and one worked for 4 months.**
- The Vermont Lunar CubeSat tested components of a Lunar navigation system in Low Earth Orbit

Deep Space Enabling Technologies

- Spiral Thrusting for 3-axis angular momentum control with a two axis thruster
- JT-65 Weak Signal Radio Protocol for deep space communication without the DSN
- Extremely high reliability software, CubedOS, SPARK/Ada

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), mostly SD card driver we purchased
- Additional provers in SPARK 2014 would improve this

Language Comparison

UK Ministry of Defense C-130J software study:
The anomalies per 1,000 lines of code (average):

- **for C was 97**
- **for Ada 95 was 25**
- **for SPARK/Ada 95 was 4**

Newer Tokeneer project (for NSA)

- **For SPARK/Ada 2005 was 0.4**

Productivity of 38 lines of code per programmer day (about what our student achieved, also), compared with 10 to 12 lines of code when using C.

We are now using the even newer SPARK/Ada 2014

Language Comparison
Real world data

- If your student programmers do not know SPARK/Ada, it takes about two weeks to become productive
- SPARK/Ada productivity of 38 lines of code per programmer day, compared with 10 to 12 lines of code when using C
- After three weeks, the new SPARK/Ada programmer has caught up with the C programmer
- For a 10,000 line program, the SPARK/Ada programmer would finish in 1.09 years (4 errors)
- For a 10,000 line program, the C programmer would finish in 3.33 years (970 errors)

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, they have corrected about 1,500 so far)
- 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

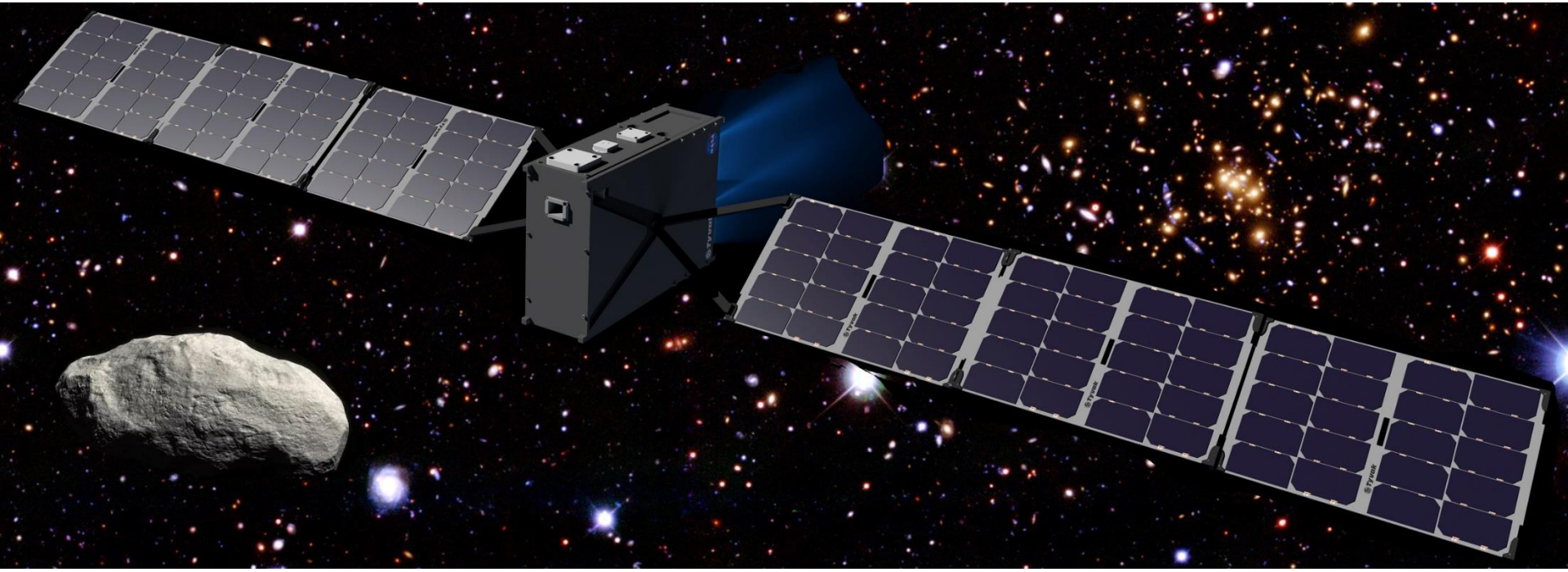
Ariane 5 initial flight failure:

- 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:

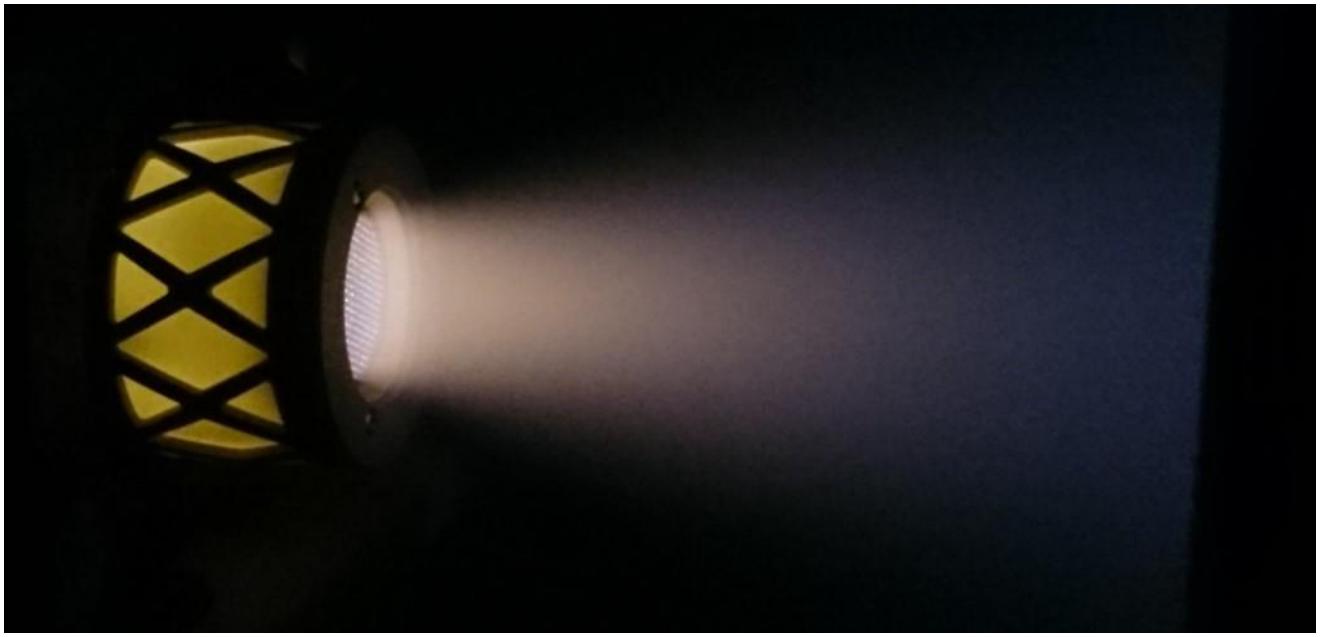
- There are two generators for each of two engines, each with its own control computer programmed in Ada (Airbus Rolls Royce controllers are in SPARK)
- The computer keeps count of power on time in **centiseconds** (used by stopwatches) in a 32 bit register
- Just after 8 months elapses, the register 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 both

Deep Space Application



6U CubeSat with ion thruster
Deep space mission

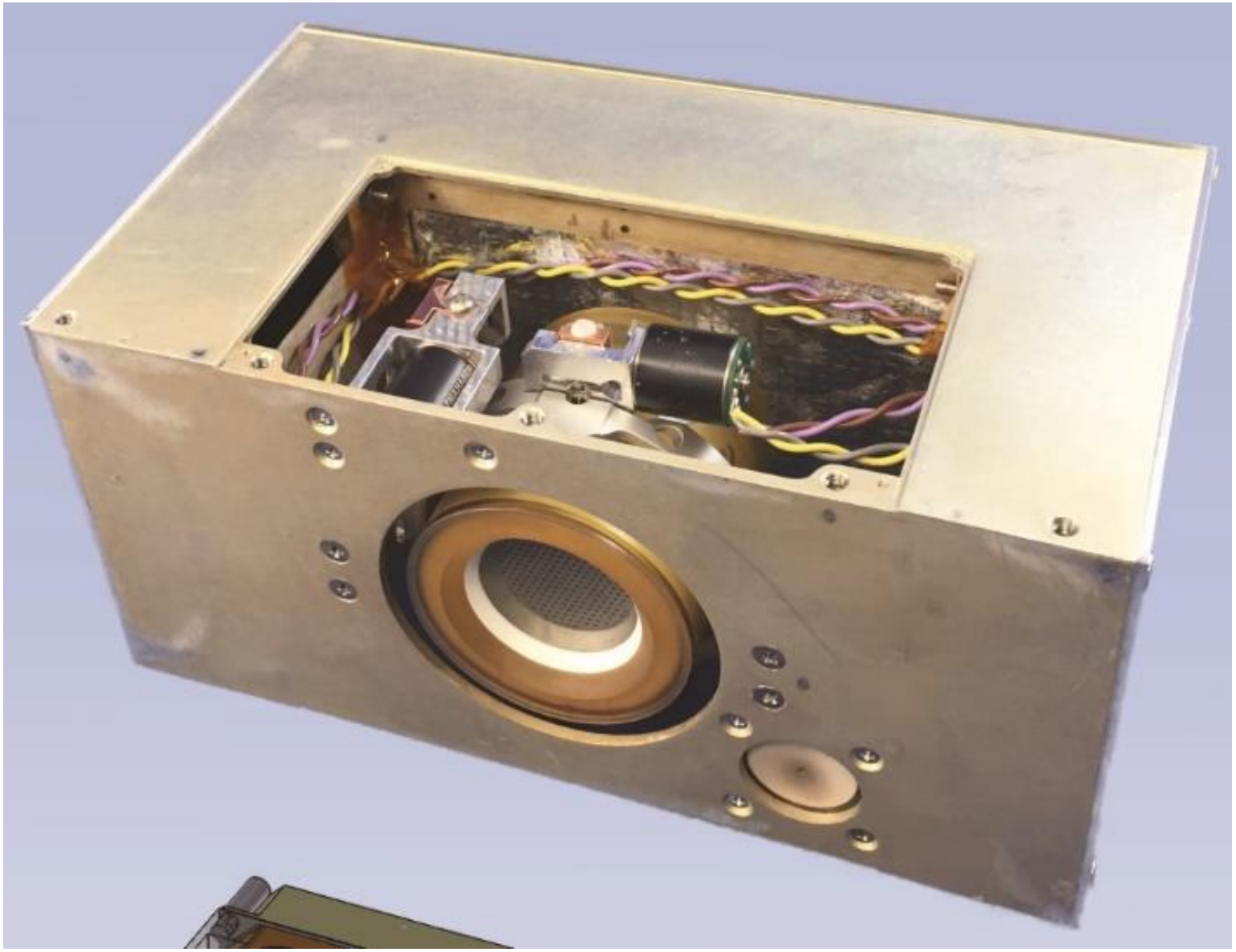
Busek Ion Thruster



BIT-3 Iodine Propellant

75W, 1.24 mN, 2.5 cm beam width, I_{SP} = 2,640
For a 6U, 14 kg spacecraft with 1.5 kg iodine:
Delta-V = 2,900 m/s

Busek Bit-3 Ion Thruster

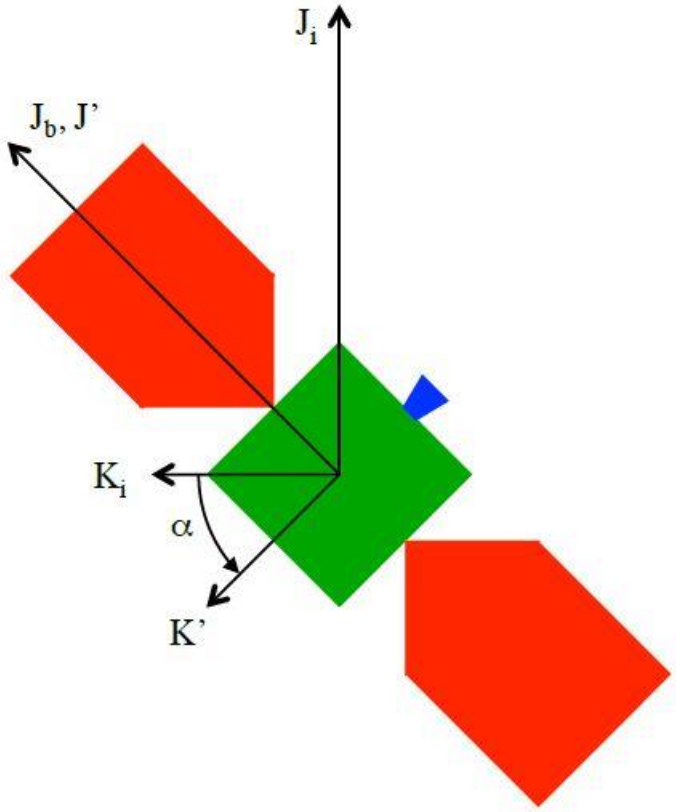


Isp = 2,300 s, Iodine mass = 1.5kg, Δv = 2,500 m/s, 8,600 hours of thrust

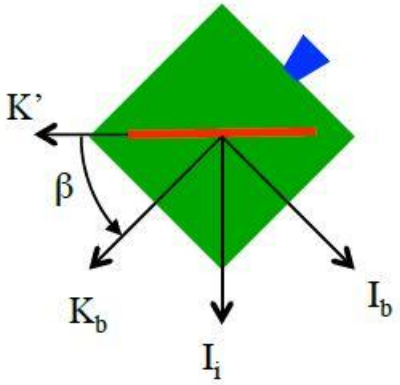
Busek BIT-3 Ion Thruster

Spiral Thrusting for 3 axis control with a 2 axis thruster

Software by Chris Farnsworth, M.S.S.E. student at Vermont Technical College



First Rotation (about I_i)



Second Rotation (about J')

Algorithm by Thomas M. Randolph, Timothy P McElrath, Steven M. Collins, David Y. Oh NASA Jet Propulsion Lab

Spiral Thrusting for 3 axis control with a 2 axis thruster

$$\begin{vmatrix} X' \\ Y' \\ Z' \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{vmatrix} \begin{vmatrix} X_i \\ Y_i \\ Z_i \end{vmatrix}$$

Rotation around I

$$\begin{vmatrix} X_b \\ Y_b \\ Z_b \end{vmatrix} = \begin{vmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{vmatrix} \begin{vmatrix} X' \\ Y' \\ Z' \end{vmatrix}$$

Rotation around J

$$\begin{vmatrix} X_b \\ Y_b \\ Z_b \end{vmatrix} = \begin{vmatrix} \cos\beta & \sin\alpha\cos\beta & -\cos\alpha\sin\beta \\ 0 & \cos\alpha & \sin\alpha \\ \sin\beta & -\sin\alpha\cos\beta & \cos\alpha\sin\beta \end{vmatrix} \begin{vmatrix} X_i \\ Y_i \\ Z_i \end{vmatrix}$$

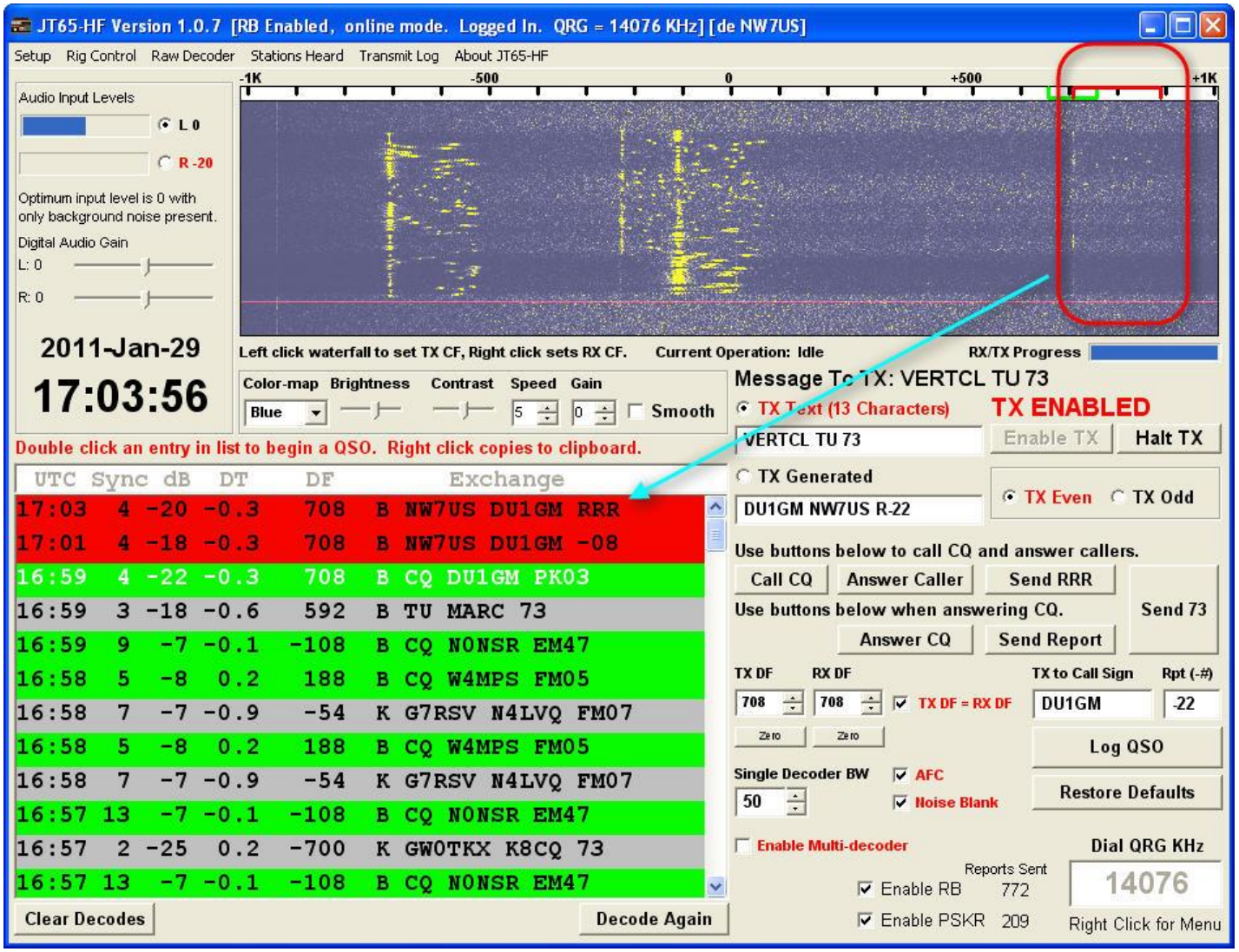
Matrix product gives the result of both rotations

Deep Space Network Ground Stations

The 70m Dish at Goldstone, California, X-band, 74 dB gain, normally needed for deep space communication

JT65 Weak Signal Protocol

Joe Taylor (my physics prof, 1993 physics Nobel Prize)



JT65 Weak Signal Protocol

Joe Taylor (my physics prof, 1993 Nobel Prize)

Each message contains 72 (378 with FEC) bits over 48 seconds

With a 3m dish, @ 9 GHz, you can reach Jupiter (4.45 AU)

Calculated Performance

SNR (dB)	Channel symbols	Bits	
−18	46.9	281	10.1
−20	39.6	237	8.4
−22	31.9	191	6.9
−24	23.1	139	4.9
−26	15.5	93	3.3
−28	9.6	58	2.1

Actual Performance

Frequency (MHz)	432
Lossless antenna gain (dBi)	22.40
Solar Flux at 432 MHz (SFU)	44.0
Tx power at antenna (W)	100
EME path loss (dB)	261.6
G/Ta (dB/K)	5.5
G/Ts (dB/K)	1.6
Y Sun (dB)	9.9
EME S/N in B=2500 Hz (dB)	-23.0
EME S/N in B=50 Hz (dB)	-6.0

JT65 Weak Signal Protocol

MarCO (6U, 10cm x 20cm x 30cm, 14kg) with 4 W Iris-2 X-Band (9 GHz) Radio, relay for InSight, 60 cm × 34 cm antenna, >28 dB gain (1m dish is 37 dB)

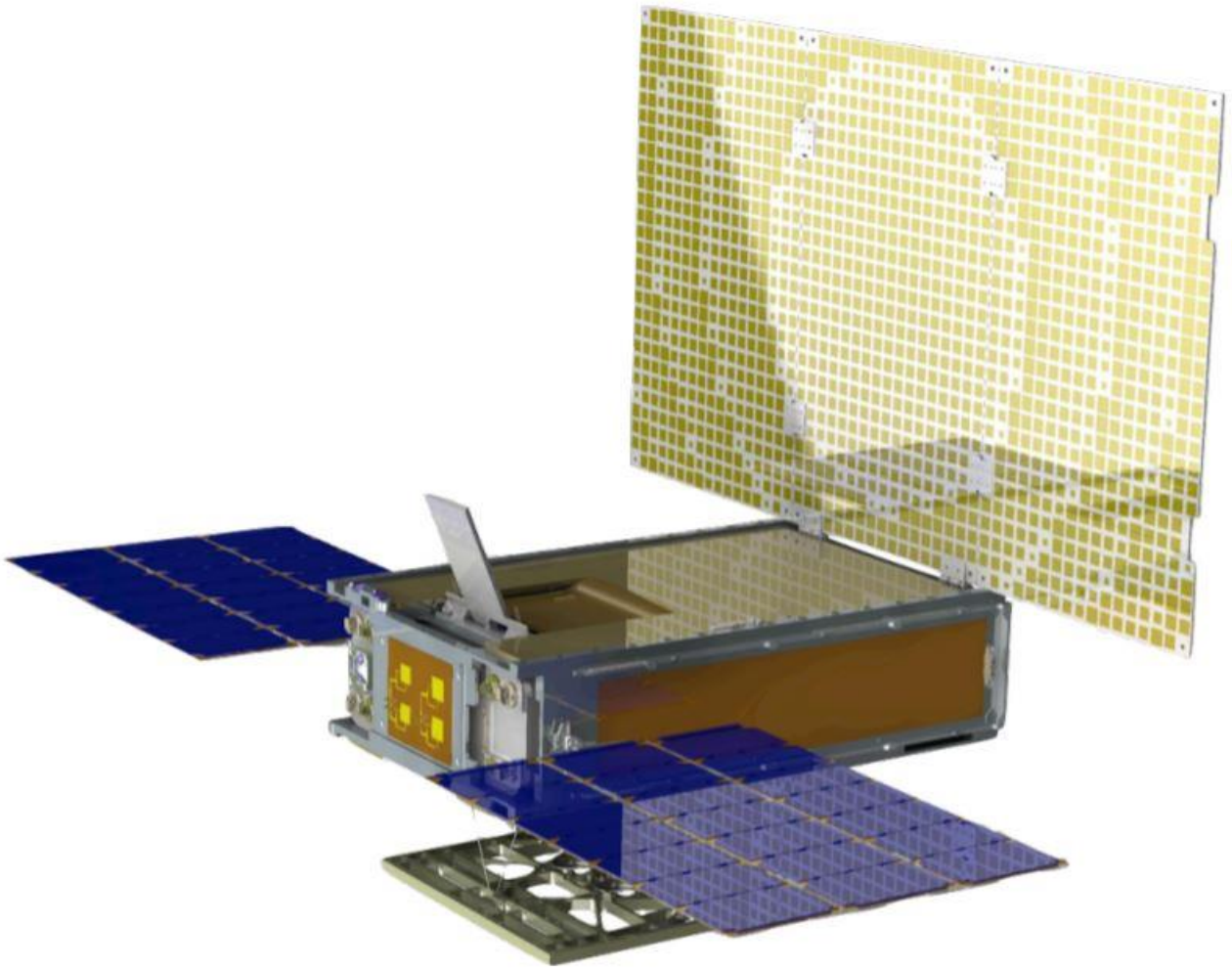
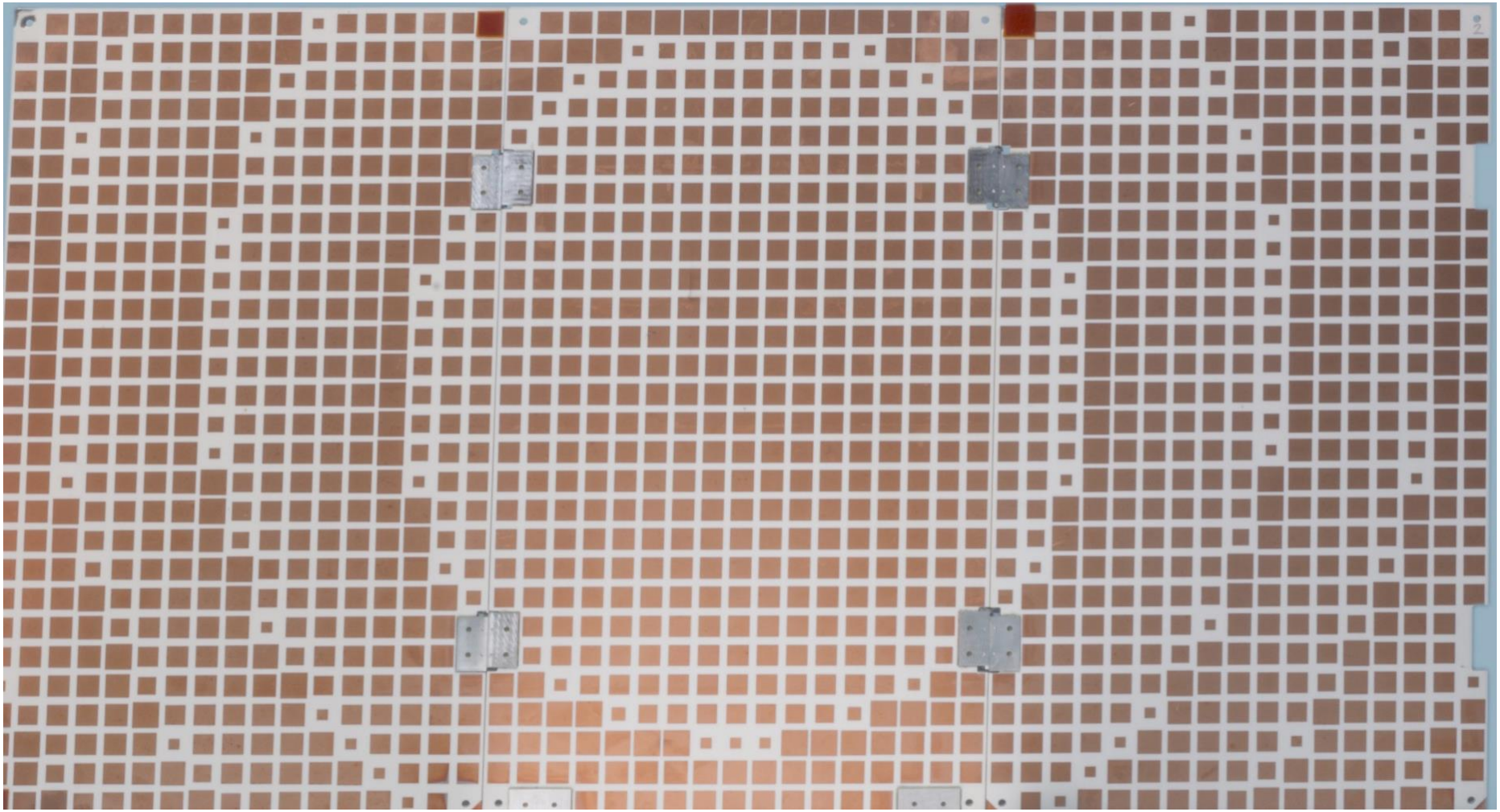


Figure 1 – CAD model rendering of a MarCO CubeSat. The large vertical panel is the high-gain reflectarray, capable of transmitting 8 kbps from Mars to the Deep Space Network's 70m dish in Madrid, Spain.

JT65 Weak Signal Protocol

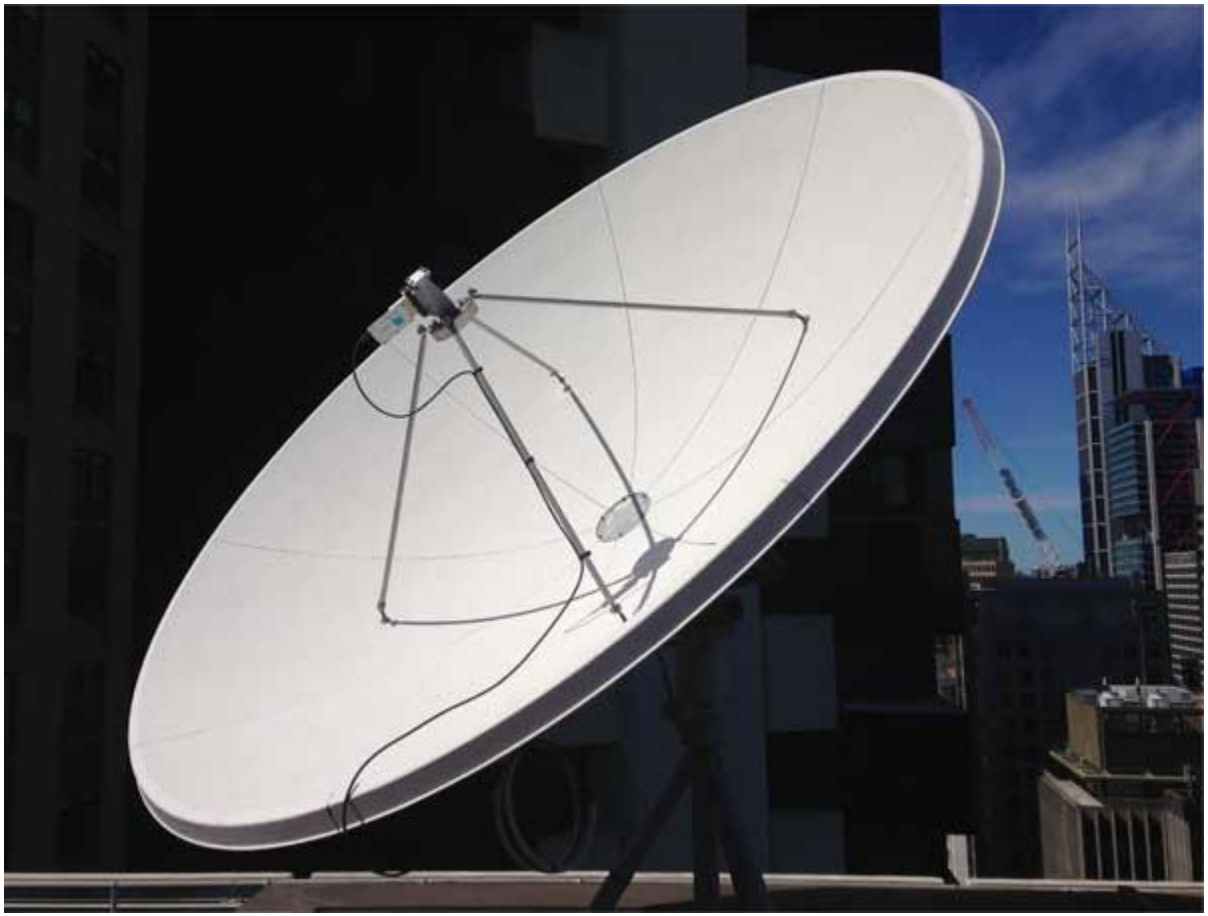
The Mars Cube One deployable high gain reflectarray antenna, https://ieeexplore.ieee.org/document/7696473

60 cm × 34 cm antenna, >28 dB gain (1m dish is 37 dB) 2,040 cm2



JT65 Weak Signal Protocol

Allows the use of a 3m dish university ground station instead of the 70m DSN



JT65 Weak Signal Protocol

- We received a grant last week to test JT-65 for deep space CubeSat use
- 70 cm band will be used as X-band transceivers cost 10x as much
- Moon bounce will be used for testing
- Moon bounce path loss, 262 dB
- Straight line to Jupiter path loss, 262 dB
- Although data rate is slow, 24 hour use would allow 50.6 kB per day

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
- *Conceptually similar to NASA's cFE/CFS except written in SPARK (not C).*
- Non ITAR parts on GitHub, https://github.com/cubesatlab/cubedos & merc
- ITAR parts from us

CubedOS Verification Goals

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

CubedOS Testing

- Unit tests
- Some additional test programs (x86)
- Hardware development system (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

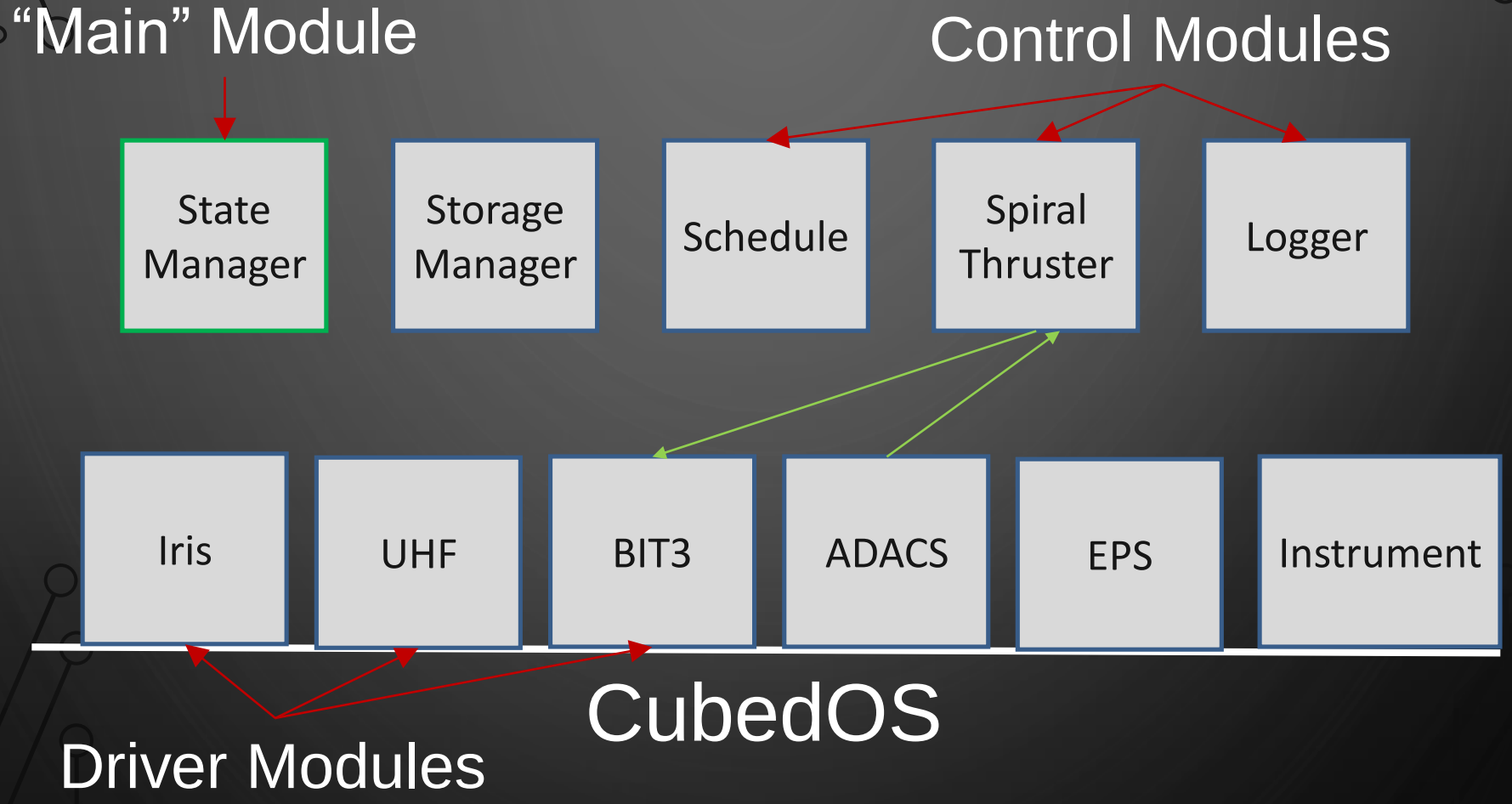
Software Architecture

- 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

Small Spacecraft 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

Software Stack (Spacecraft Modules)



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 merc tool*** 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
- Future work
  - supporting CubeSat swarms using distributed message passing between CubedOS domains on different spacecraft

merc

File server mxdr file

Sean Klink, M.S.S.E. graduate at Vermont Technical College

```
message struct -> Read_Request{
    File_Handle_Type       Handle;
    Read_Size_Type          Amount;
};

message struct <- Read_Reply {
    Valid_File_Handle_Type      Handle;
    Read_Result_Size_Type       Amount;
     opaque Message_Data[1024] Message_Data;
} with message_invariant =>
Amount <= Message_Data'Length;
```

Generated spec file

```
 function Read_Request_Encode
     (Sender_Domain : Domain_ID_Type;
      Sender   : Module_ID_Type;
      Handle   : Valid_File_Handle_Type;
      Amount   : Read_Size_Type;
      Priority : System.Priority := System.Default_Priority)
return Message_Record
     with Global => null;

function Read_Reply_Encode
     (Receiver_Domain : Domain_ID_Type;
      Receiver : Module_ID_Type;
      Handle   : Valid_File_Handle_Type;
      Amount   : Read_Result_Size_Type;
      Message_Data     : CubedOS.Lib.Octet_Array;
      Priority : System.Priority := System.Default_Priority)
return Message_Record
     with
       Global => null,
       Pre => Amount <= Message_Data'Length;
```

Generated body file

```
function Open_Request_Encode
   (Sender_Domain : Domain_ID_Type;
    Sender     : Module_ID_Type;
    Mode       : Mode_Type;
    Name       : String;
    Request_ID : Request_ID_Type;
    Priority   : System.Priority := System.Default_Priority) return Message_Record
  is
    Message : Message_Record := Make_Empty_Message
     (Sender_Domain => Sender_Domain,
      Receiver_Domain => Domain_ID,
      Sender     => Sender,
      Receiver   => ID,
      Message_ID => Message_Type'Pos(Open_Request),
      Priority   => Priority);

    Position : XDR_Index_Type;
    Last : XDR_Index_Type;
  begin
    Position := 0;
    XDR.Encode(XDR.XDR_Unsigned(Mode_Type'Pos(Mode)), Message.Payload, Position,
Last);
    Position := Last + 1;
    XDR.Encode(XDR.XDR_Unsigned(Name'Length), Message.Payload, Position, Last);
    Position := Last + 1;
    XDR.Encode(Name, Message.Payload, Position, Last);
    Position := Last + 1;
    XDR.Encode(XDR.XDR_Unsigned(Request_ID), Message.Payload, Position, Last);
    Message.Size := Last + 1;
    return Message;
  end Open_Request_Encode;
```

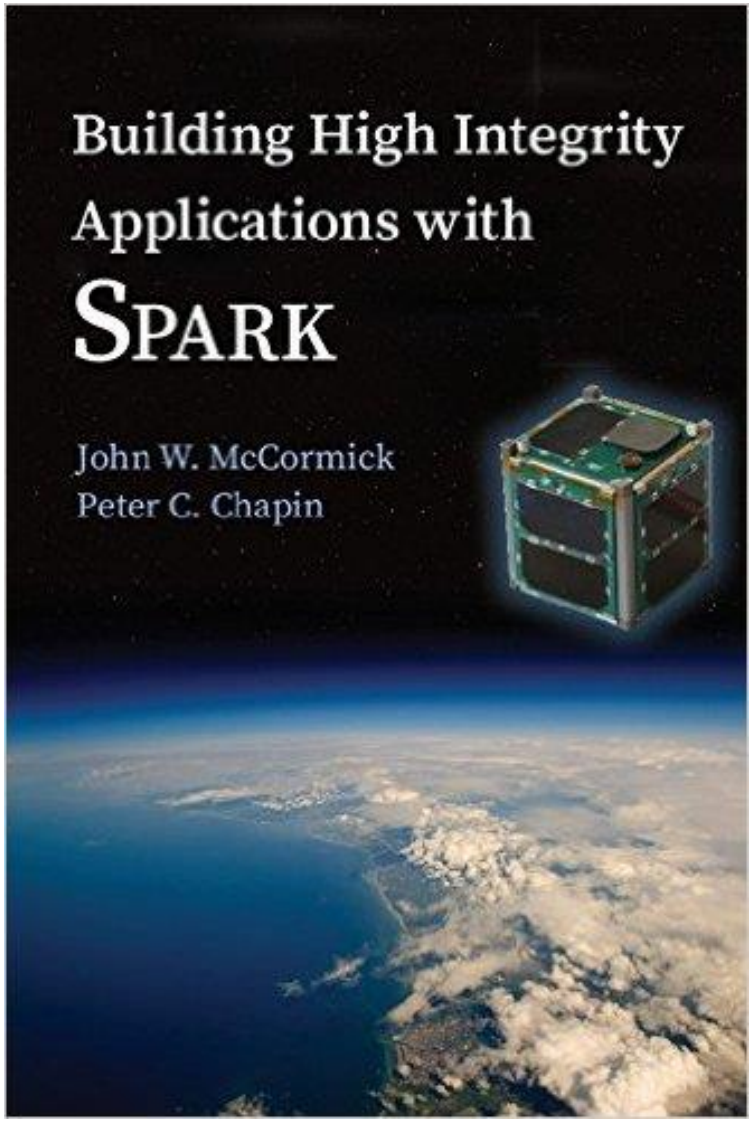
```
procedure Open_Request_Decode
   (Message : in  Message_Record;
    Mode : out Mode_Type;
    Name : out String;
    Name_Size : out Natural;
    Request_ID : out Request_ID_Type;
    Decode_Status : out Message_Status_Type)
is
   Position : XDR_Index_Type;
   Raw_Mode : XDR.XDR_Unsigned;
   Raw_Name_Size : XDR.XDR_Unsigned;
   Raw_Request_ID   : XDR.XDR_Unsigned;
   Last : XDR_Index_Type;
begin
   Decode_Status := Success;
   Name := (others => ' ');
   Request_ID := Request_ID_Type'First;
   Position := 0;
   if Decode_Status = Success then
      XDR.Decode(Message.Payload, Position, Raw_Mode, Last);
      Position := Last + 1;
      if Raw_Mode in Mode_Type'Pos(Mode_Type'First) ..
Mode_Type'Pos(Mode_Type'Last) then
         Mode := Mode_Type'Val(Raw_Mode);
      else
         Decode_Status := Malformed;
         Mode := Mode_Type'First;
      end if;
   end if;
```

```
 if Decode_Status = Success then
      XDR.Decode(Message.Payload, Position, Raw_Name_Size, Last);
      Position := Last + 1;
      if Raw_Name_Size in XDR.XDR_Unsigned(Natural'First) ..
XDR.XDR_Unsigned(Natural'Last) then
         Name_Size := Natural(Raw_Name_Size);
     else
        Name_Size := 0;
     end if;
     if Name_Size < 1 then
        XDR.Decode(Message.Payload, Position, Name(Name'First .. Name'First +
(Name_Size - 1)), Last);
     end if;
   end if;
   if Decode_Status = Success then
       XDR.Decode(Message.Payload, Position, Raw_Request_ID, Last);
       Position := Last + 1;
       if Raw_Request_ID in XDR.XDR_Unsigned(Request_ID_Type'First) ..
XDR.XDR_Unsigned(Request_ID_Type'Last) then
          Request_ID := Request_ID_Type(Raw_Request_ID);
          Decode_Status := Success;
       else
           Decode_Status := Malformed;
       end if;
    end if;
end Open_Request_Decode;
```

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
- possible CubedOS/CFS bridge that will translate messages between the systems

A SPARK 2014 Book is Available



Vermont's First Astronaut

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Enabling Technologies for Deep Space CubeSats

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