Dellingr: NASA GSFC's first 6U CubeSat

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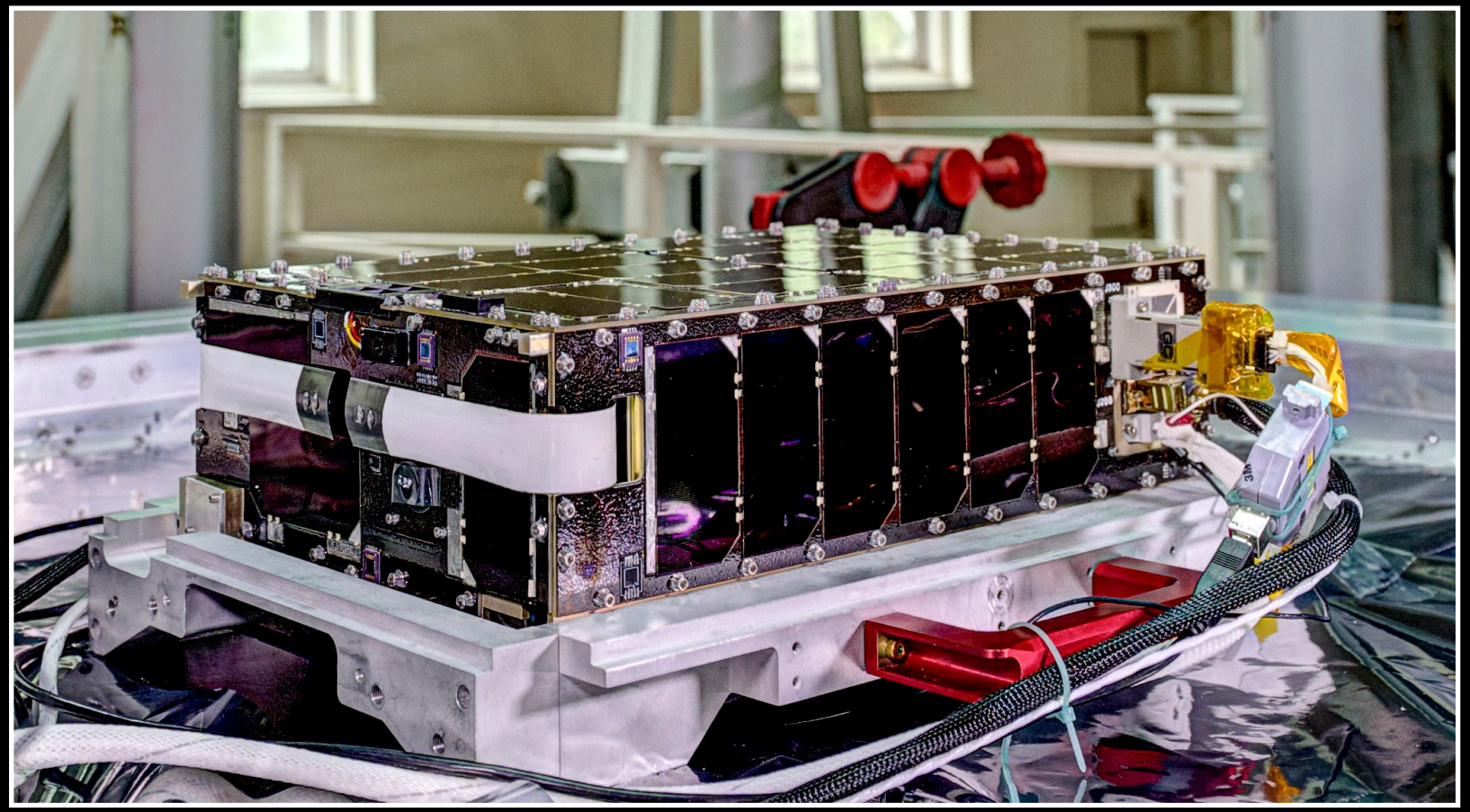
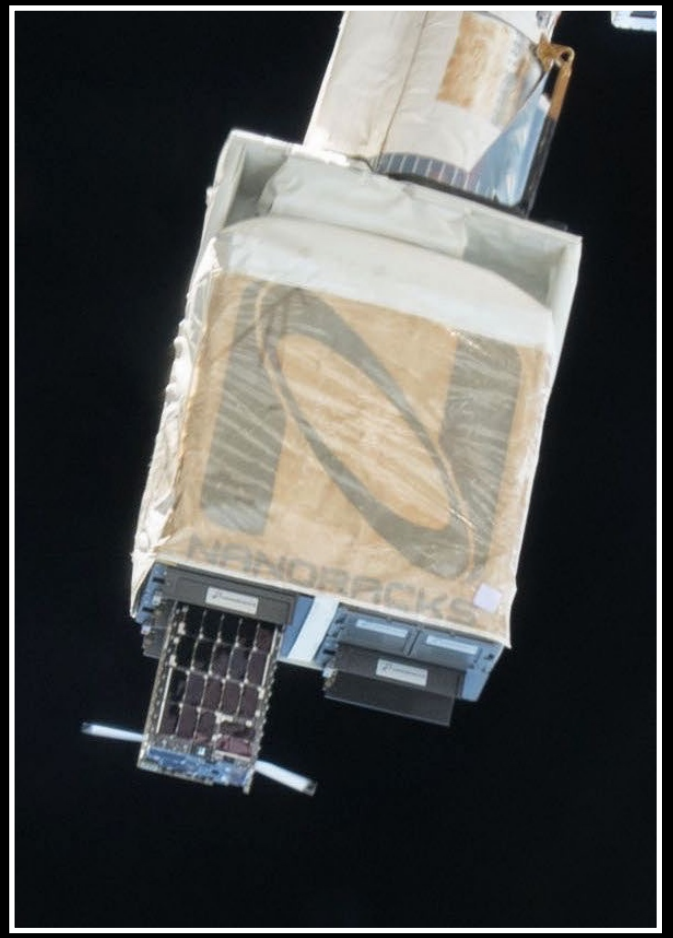
+ many, many others



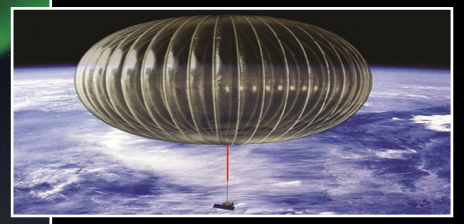


SmallSats are at the ***interface*** between "suborbital" and flight missions

a focal point for tension

"Do no harm"

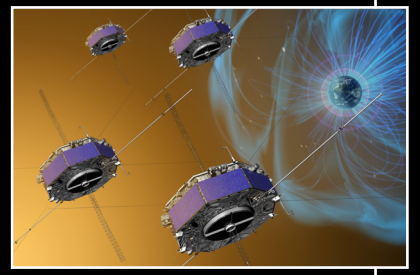
7120.8

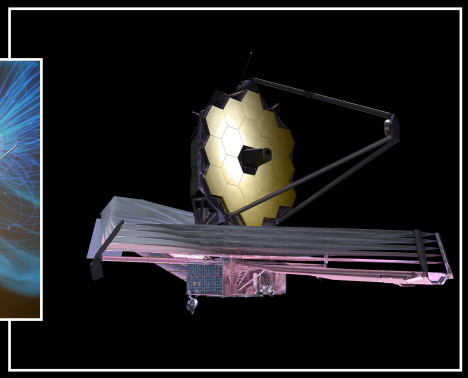


Traditional WFF

Class C, B, A

7120.5





Traditional Greenbelt

Less ← Capability, cost, management, oversight, HQ insight → More

Struggle is to balance reliability and/or resiliency against cost & schedule

SmallSats stress every point on the implementation chain

(in unique ways*)

Formulation

↓

Implementation

↓

Launch & operations

Uncertainties: orbits, rideshare process for AOs, COTS, propulsion, TMC (programmatic vs. technical risk acceptance?), tailoring during proposals. Also margins (mass, power)

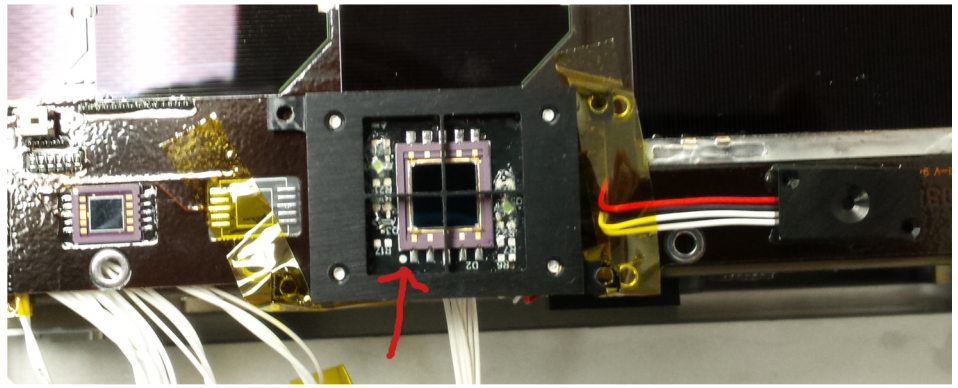
Burdens: Reporting requirements, KDP gates, launch manifesting, de-orbit requirements, spectrum licensing, management (.5, .8), SMA (C/D/DNH), tailoring down rather than up. Also vendor issues

Issues: Rideshare process, operations/comm, comm band for smallsats (S/X/Ka) and SCaN, 'finding' the spacecraft, constellation management

To facilitate science investigations at low cost, we need to identify and then ease the stress points

*Either with stresses unique to cubesats, or with standard stress points that, because cubesats have short development cycles and are resource constrained, burden development.

See our 2017 & 2018 SmallSat papers



Separation Switches

UHF Radio

Reaction Wheels Assembly

Cards Stack:
Dagr Instrument
C&DH - ACS
Batteries
Power System
GPS
Special Services

UHF Antenna and GPS Splitter Board

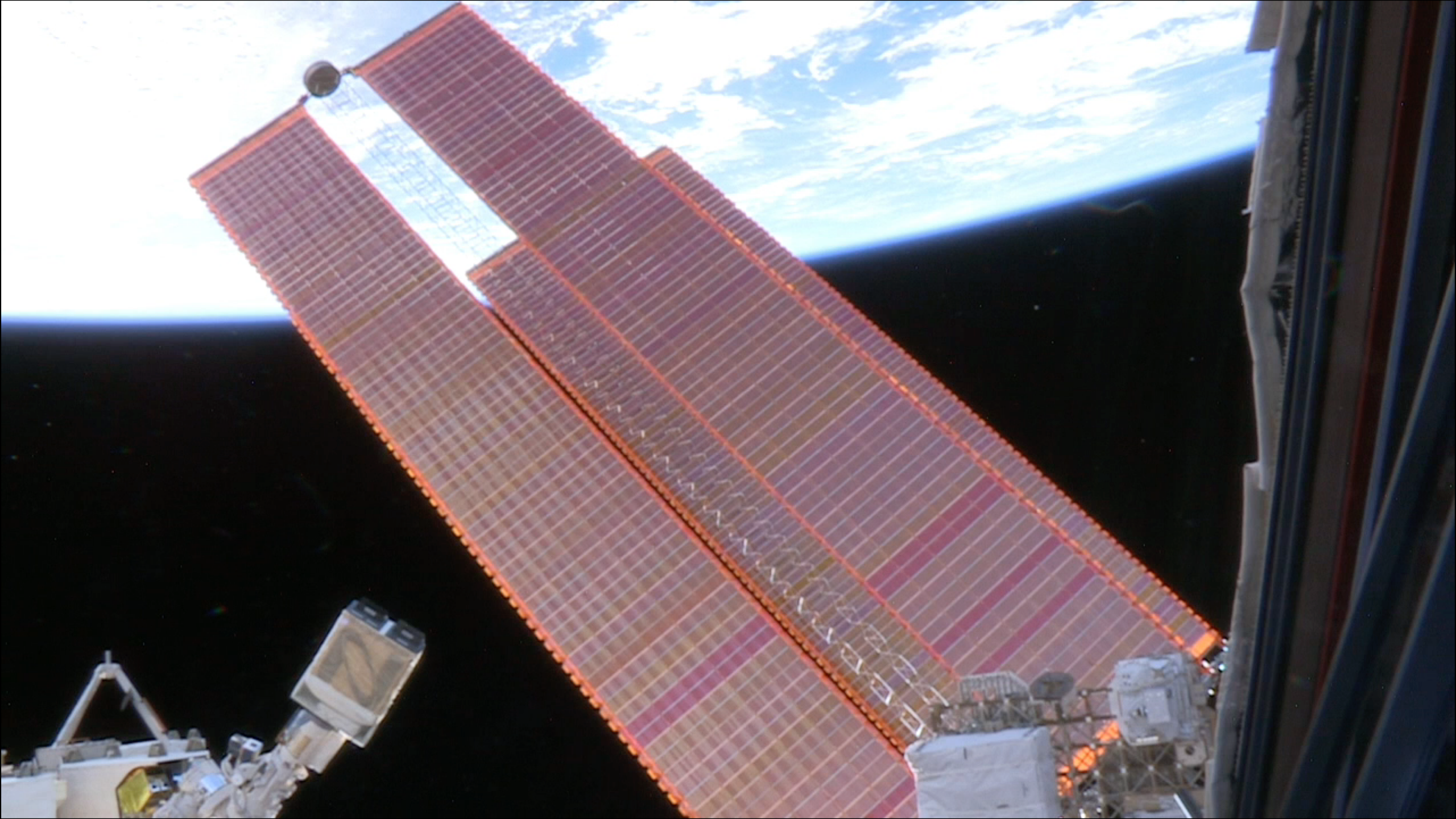
Thermal Louvers Experiment

Dagr Magnetometer 1

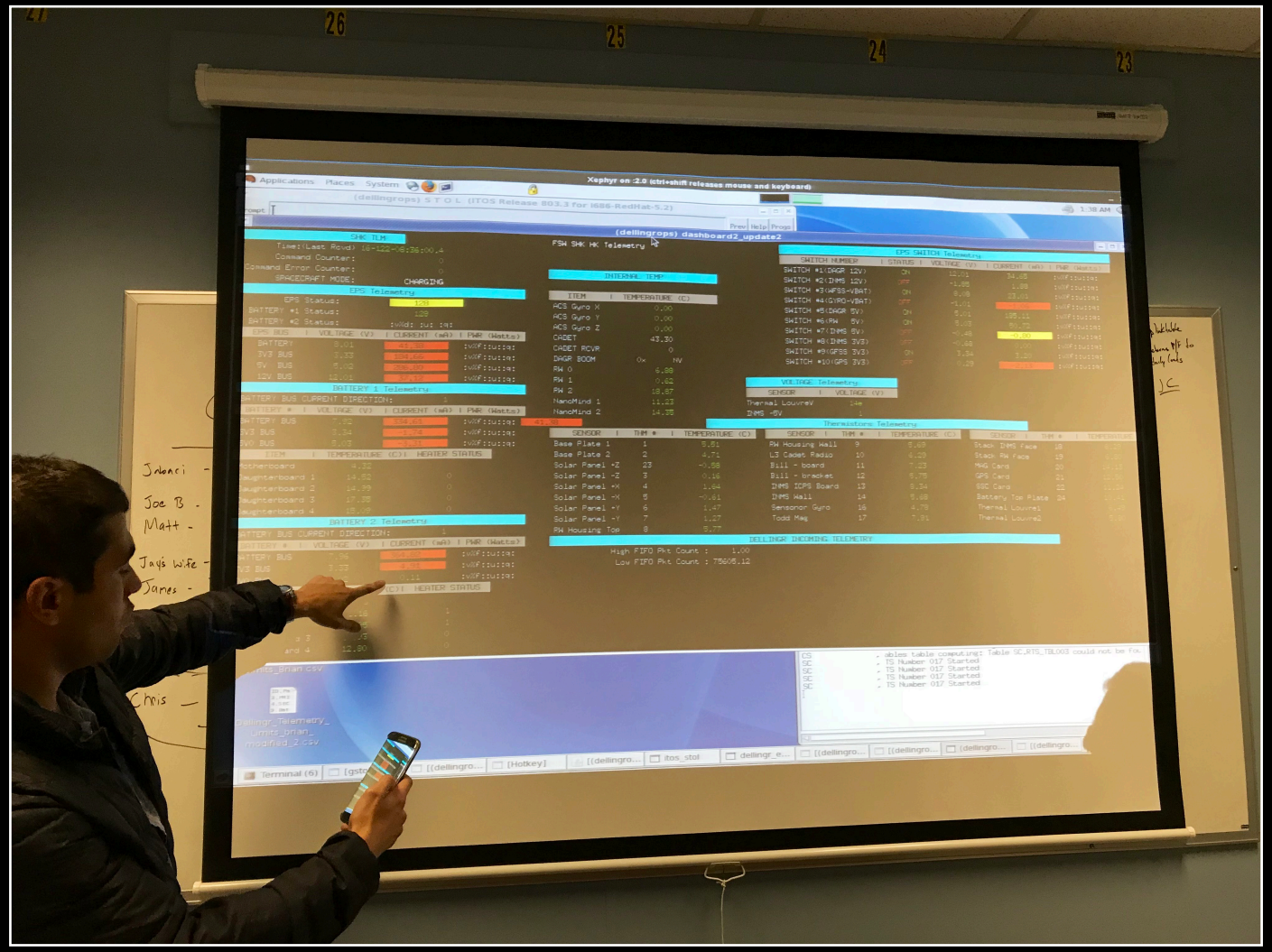
Higher Sensitivity Gyroscope

Dagr Magnetometer 2

Ion-Neutral Mass Spectrometer

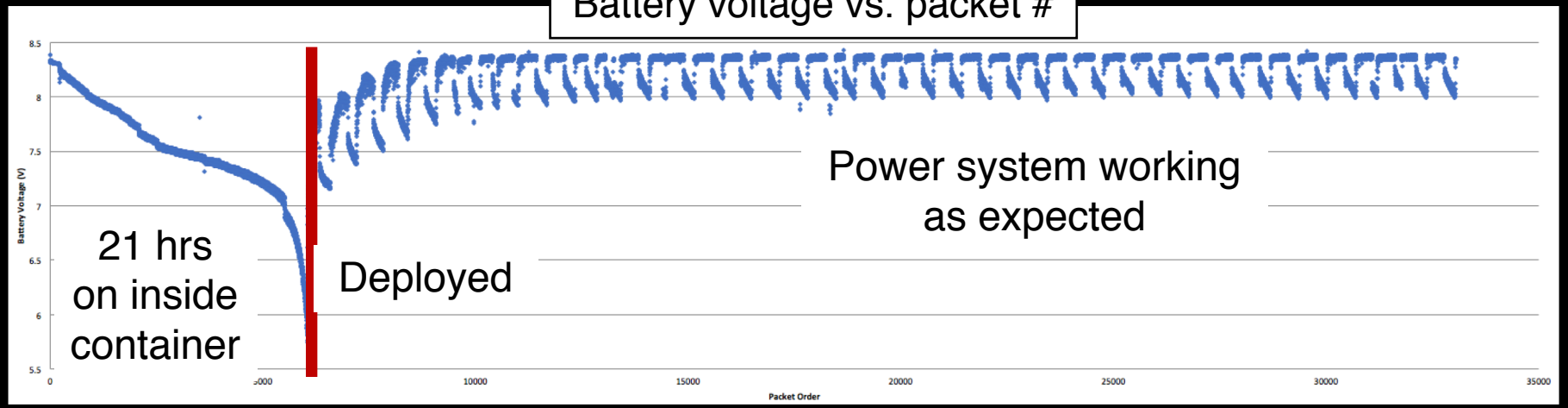


Ejected on November 20, 2017
Contact on first pass that evening

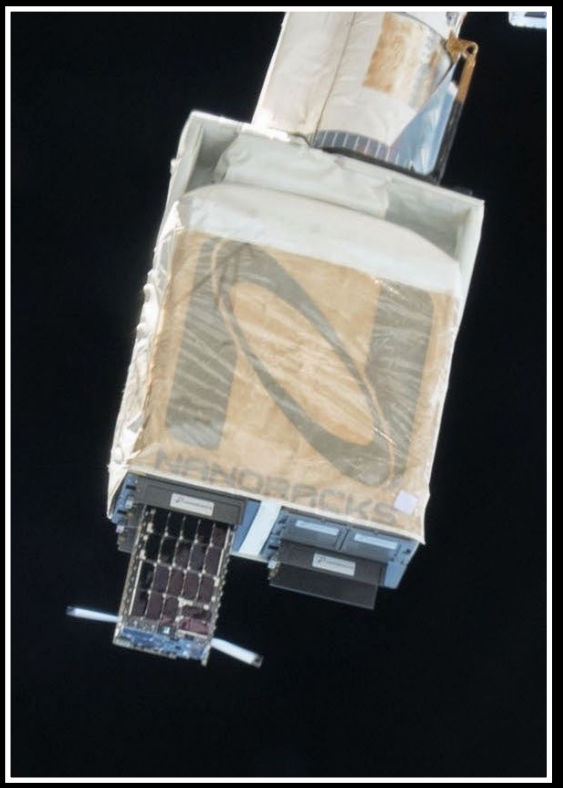


Deployment and initial checkout

Battery voltage vs. packet #

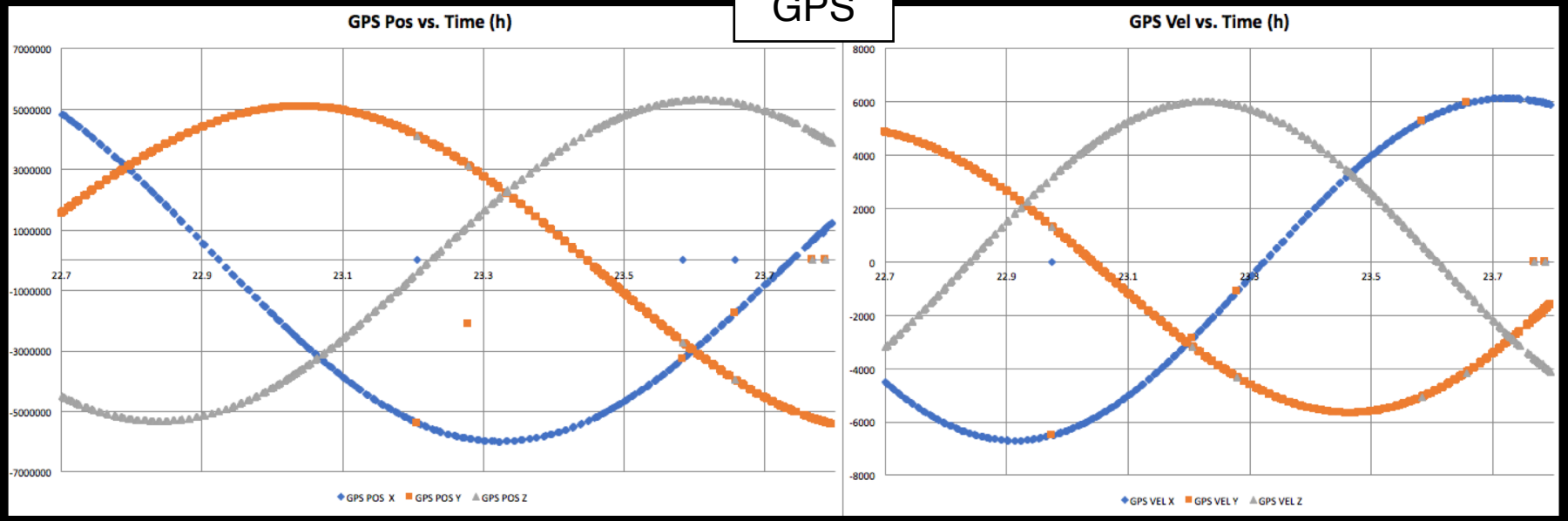


First 74 Hours (battery voltage). Satellite turned on inside deployer at unknown time for 21 hours. Dellingr restored nicely upon ejection.



We observed antenna and boom deploy in real-time

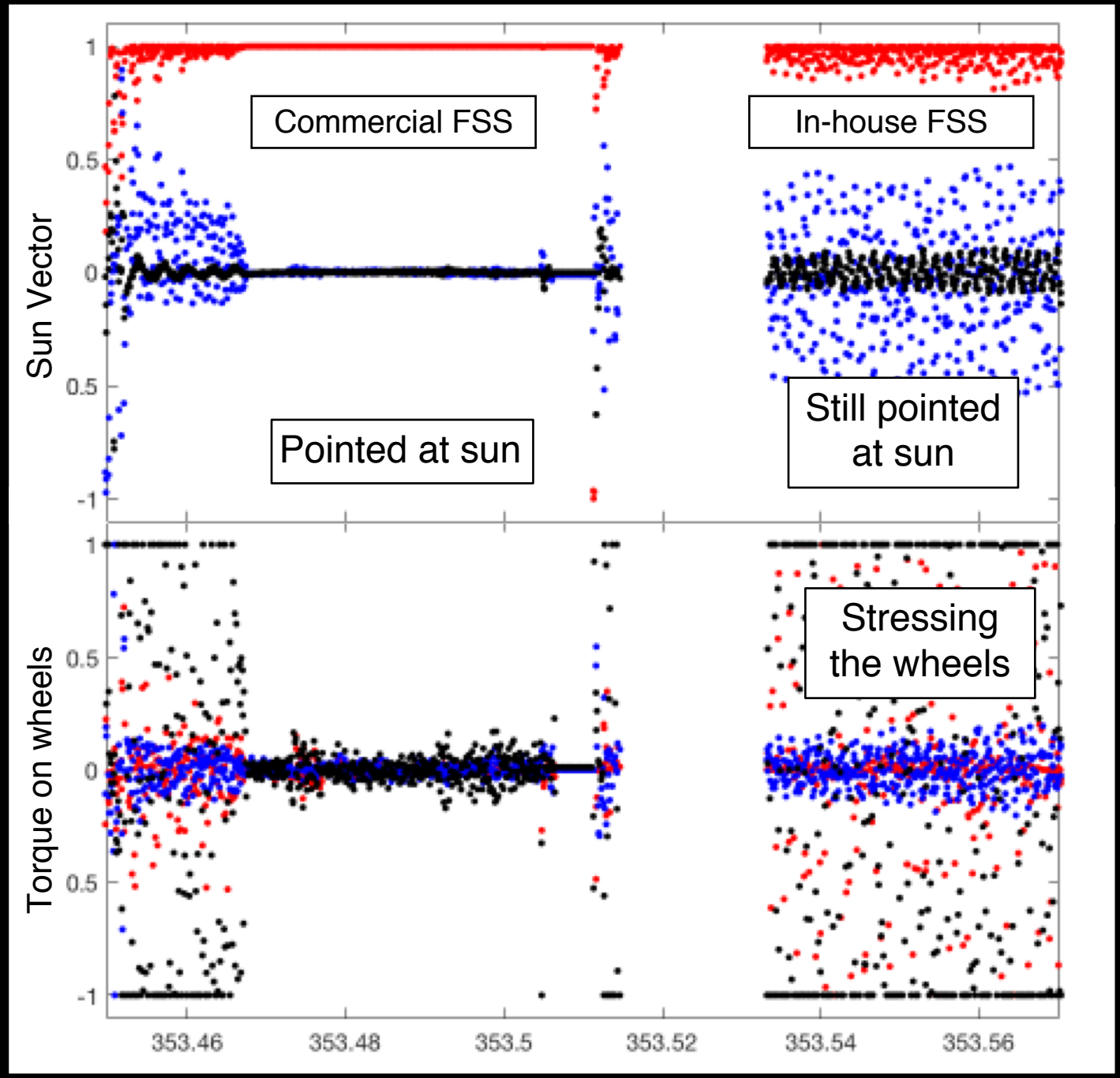
GPS



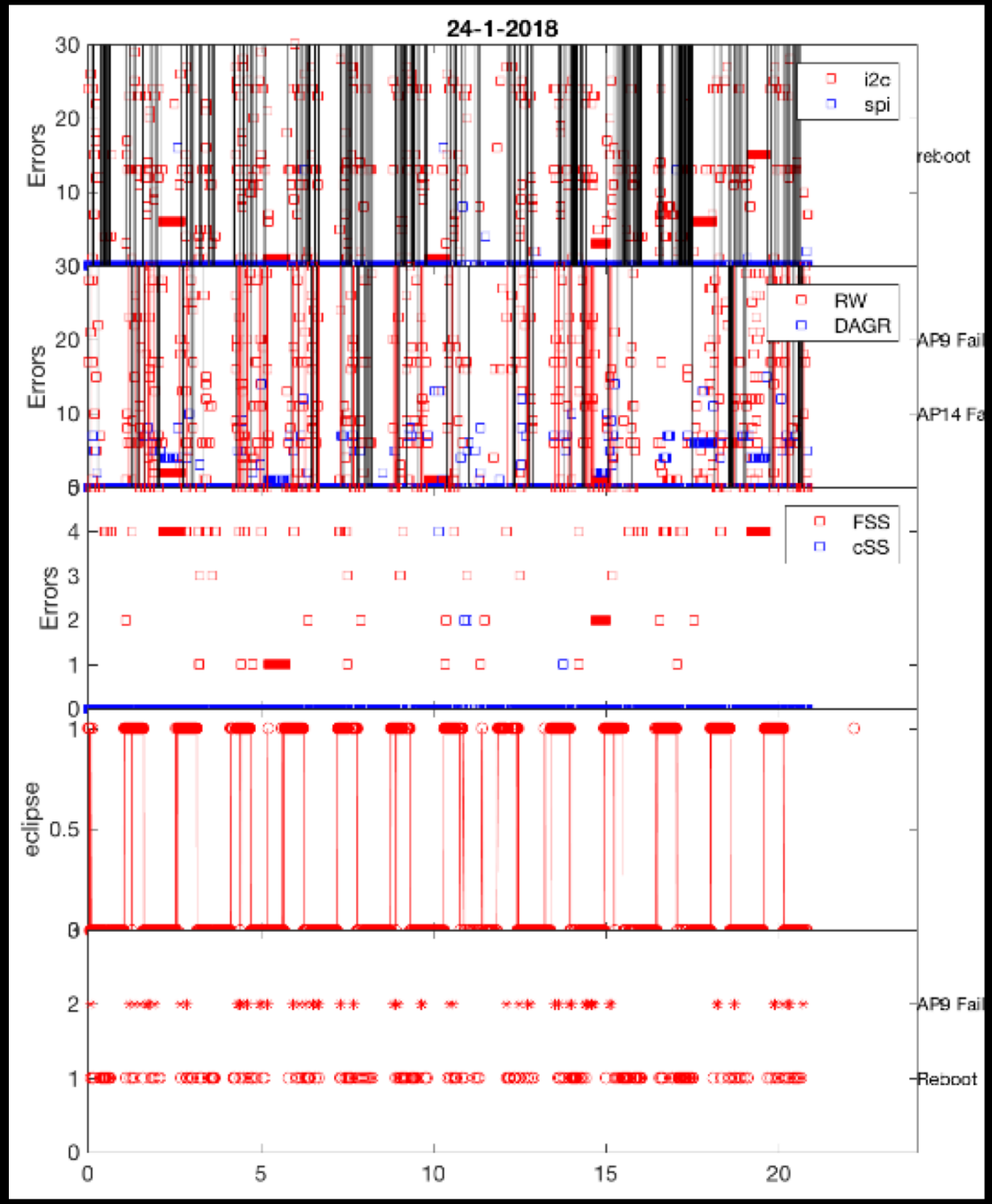
Attitude Control System starts misbehaving

Nov. 20, 2017	- Eject from ISS. All good!
Nov. 30, 2017	- Observed anomalous gyro data - Observed sun pointing inaccuracy
Dec. 19, 2017	- **GPS unresponsive**
Dec. 21, 2017	- In-house FSS noisy

We enter January bruised but not beaten, and had a plan to recover INMS mode



CPU having difficulty talking to subsystems



Early January, we started to see a lot of errors on the I2C bus (how the flight computer talks to various subsystems).

By late January, the reset situation had significantly worsened

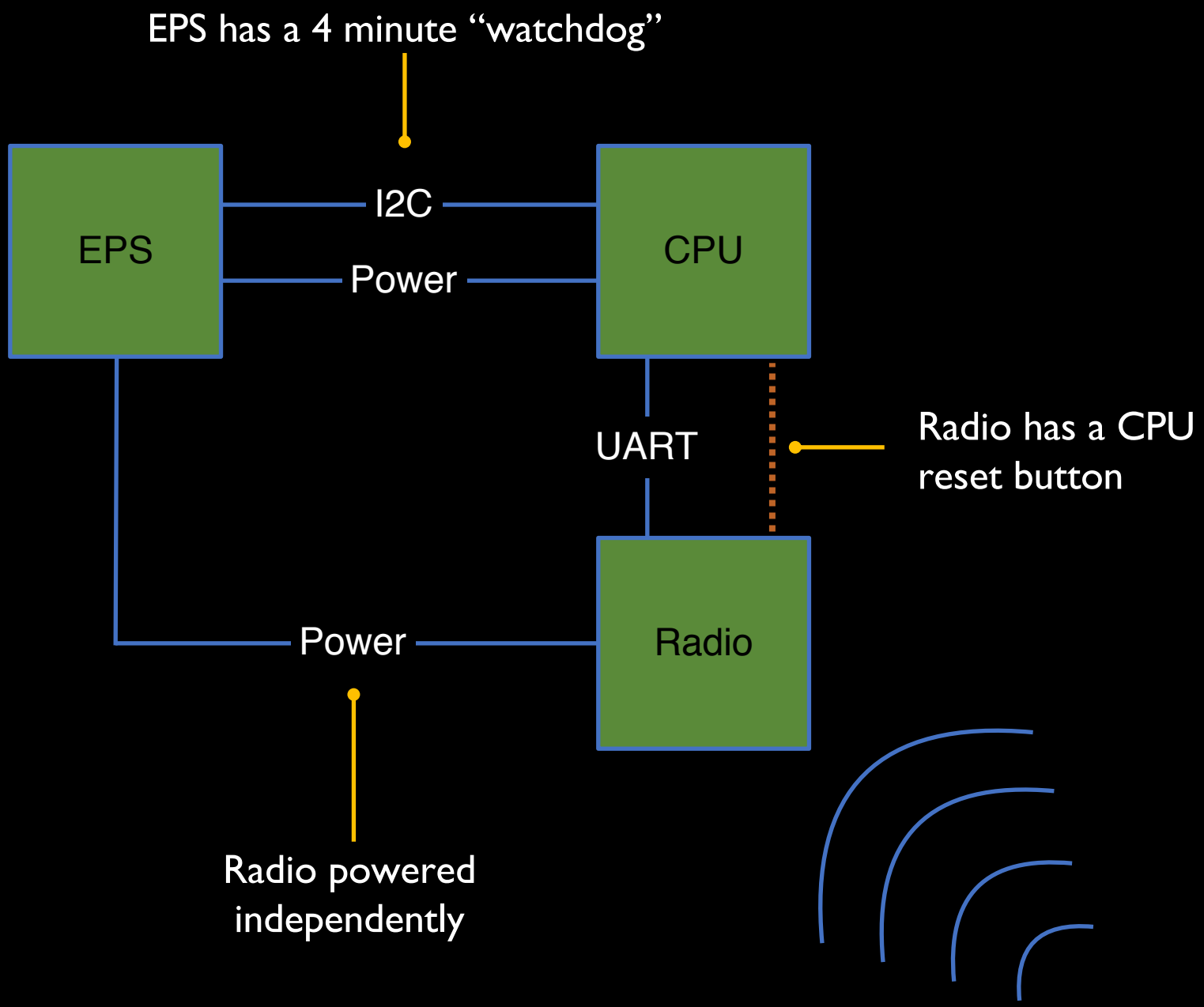
January 26-February 5

```
18-031-20:23:04.000000 (2       ) (SC      ) ( 73) (RTS Number 001 Started                                                    )
18-031-20:23:10.000000 (3       ) (CFE_SB  ) ( 17) (Msg Limit Err,MsgId 0x18c2,pipe ACS_CMD_PIPE,sender SCH                   )
16-122-00:00:12.000000 (2       ) (FM      ) (104) (Free Space Table verify results: good entries = 2, bad = 0, unused = 6    )
16-122-00:00:12.000000 (2       ) (FM      ) (  1) (Initialization complete: version 2.3.1.0                                  )
16-122-00:00:12.000000 (2       ) (FM      ) (100) (Child Task initialization complete                                        )
16-122-00:00:12.000000 (3       ) (SC      ) (123) (Unbundle RTS OK: /boot/rtsb01.bin, Dest: /ram, RTS Size: 416, RTS Num: 4  )
16-122-00:00:12.000000 (3       ) (SC      ) (123) (Unbundle RTS OK: /boot/rtsb02.bin, Dest: /ram, RTS Size: 416, RTS Num: 14 )
16-122-00:00:12.000000 (3       ) (SC      ) (123) (Unbundle RTS OK: /boot/rtsb03.bin, Dest: /ram, RTS Size: 416, RTS Num: 16 )
16-122-00:00:13.000000 (3       ) (SC      ) (123) (Unbundle RTS OK: /boot/rtsb04.bin, Dest: /ram, RTS Size: 416, RTS Num: 24 )
16-122-00:00:13.000000 (3       ) (SC      ) (123) (Unbundle RTS OK: /boot/rtsb05.bin, Dest: /ram, RTS Size: 416, RTS Num: 31 )
16-122-00:00:13.000000 (2       ) (SC      ) ( 21) (RTS table file load count = 32                                            )
16-122-00:00:13.000000 (2       ) (SC      ) (  9) (SC Initialized. Version 2.3.0.0                                           )
16-122-00:00:13.000000 (2       ) (LC      ) ( 56) (WDT verify results: good = 15, bad = 0, unused = 49                       )
16-122-00:00:14.000000 (2       ) (LC      ) ( 66) (ADT verify results: good = 14, bad = 0, unused = 50                       )
16-122-00:00:14.000000 (2       ) (LC      ) (  2) (LC Initialized. Version 0.0.0.0                                           )
16-122-00:00:16.000000 (2       ) (SEC     ) (  4) (SEC: RESET command                                                        )
16-122-00:00:16.000000 (2       ) (SEC     ) (  1) (SEC Initialized. Version 1.0.0.0                                          )
16-122-00:00:16.000000 (2       ) (FUL     ) (  1) (FUL App Initialized. Version 1.0.0.0                                      )
16-122-00:00:16.000000 (2       ) (FDL     ) (  1) (FDL App Initialized. Version 1.0.0.0                                      )
16-122-00:00:16.000000 (2       ) (MM      ) (  1) (MM Initialized. Version 0.0.0.0                                           )
16-122-00:00:16.000000 (2       ) (CS      ) (144) (CS Eeprom Table verification results: good = 8, bad = 0, unused = 8      )
16-122-00:00:16.000000 (2       ) (CS      ) (143) (CS Memory Table verification results: good = 0, bad = 0, unused = 16     )
16-122-00:00:16.000000 (2       ) (CS      ) (107) (CS Memory Table: No valid entries in the table                            )
16-122-00:00:16.000000 (2       ) (CS      ) (142) (CS Apps Table verification results: good = 0, bad = 0, unused = 24        )
16-122-00:00:17.000000 (2       ) (CS      ) (108) (CS Apps Table: No valid entries in the table                              )
16-122-00:00:17.000000 (2       ) (CS      ) (139) (CS Tables Table verification results: good = 46, bad = 0, unused = 26     )
16-122-00:00:17.000000 (2       ) (CS      ) (  1) (CS Initialized. Version 0.0.0.0                                           )
16-122-00:00:17.000000 (2       ) (MD      ) (  7) (Dwell Tables Recovered: 0, Dwell Tables Initialized: 4                    )
18-031-20:24:08.000000 (2       ) (SC      ) ( 73) (RTS Number 001 Started                                                    )
18-031-20:24:14.000000 (3       ) (CFE_SB  ) ( 17) (Msg Limit Err,MsgId 0x18c2,pipe ACS_CMD_PIPE,sender SCH                   )
16-122-00:00:07.000000 (2       ) (CADET   ) (  1) (L386 CADET: App Initialized using DEFAULTS. Version 1.0.0.0               )
```

January 26, Friday. Last contact with flight computer.
January 29, Monday, windy.
January 30, Tuesday, windy.
January 31st contact through radio, but couldn't talk to spacecraft.

From January 26 - February 5, >13,000 resets. Reboot every 64 seconds, continuously, for 10 days.

“We just confirm Dellingr is back to business”



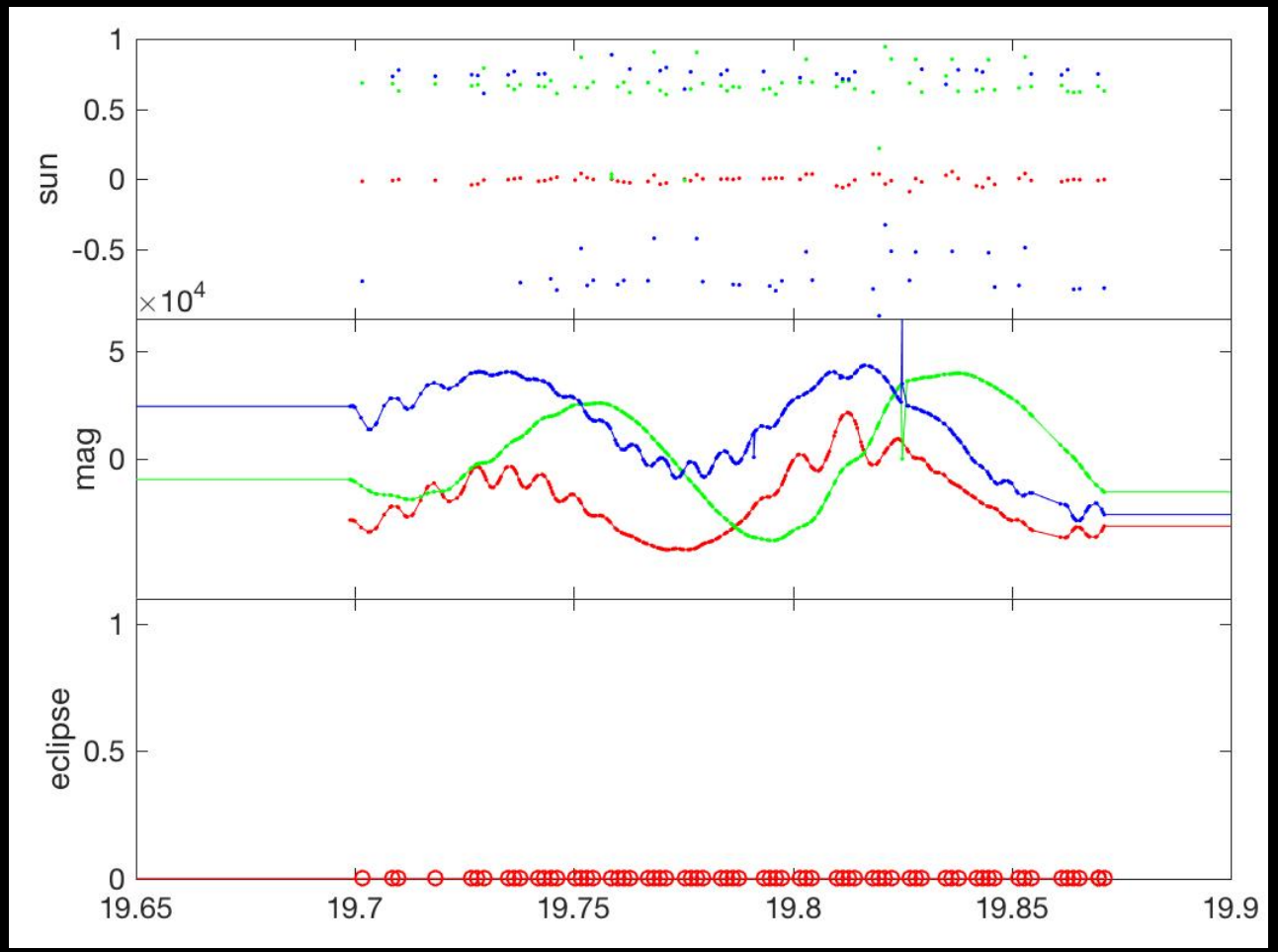
Team sent a CPU reset command for the entire duration of the pass - ~7 minutes.

Lack of I2C activity triggered an EPS reset

Contact next pass. Turned off the wheels.

Next pass confirmed no resets.

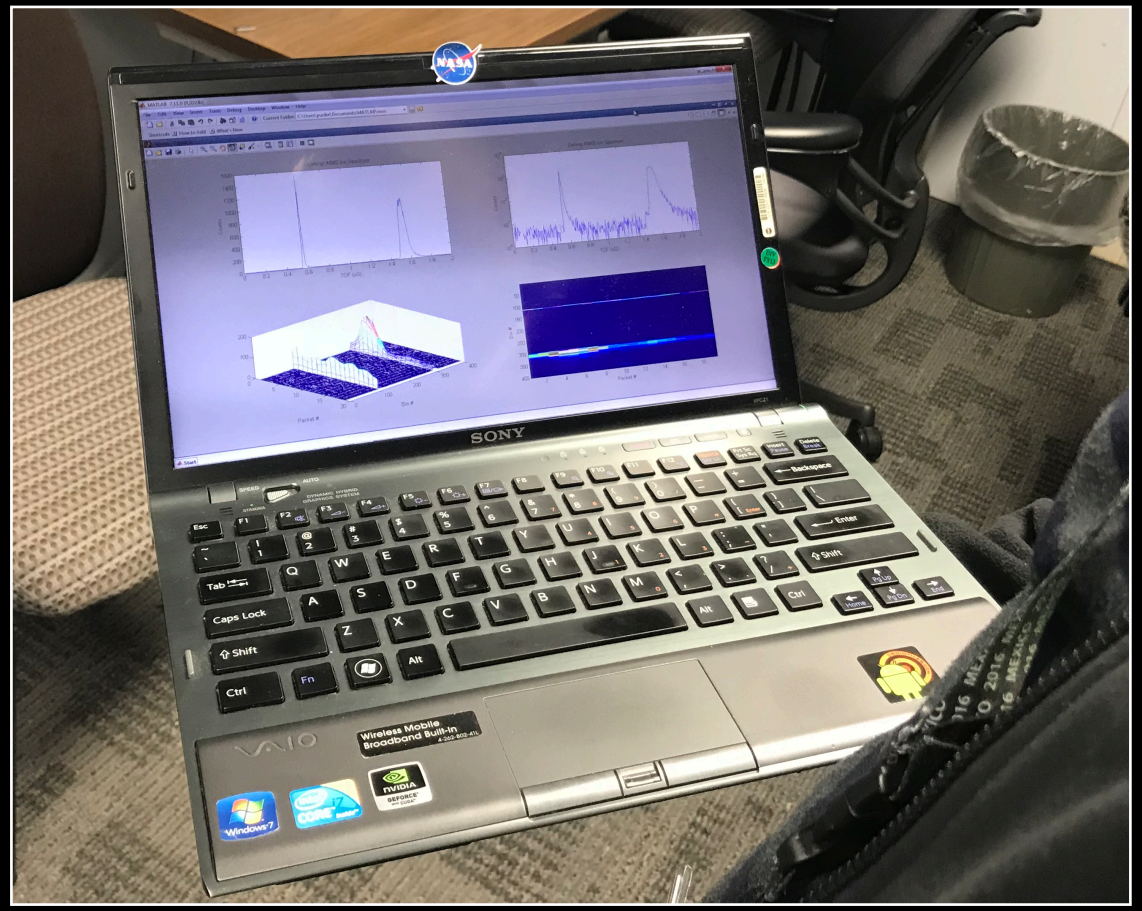
9 minutes of data during the Feb 6 pass after recovery

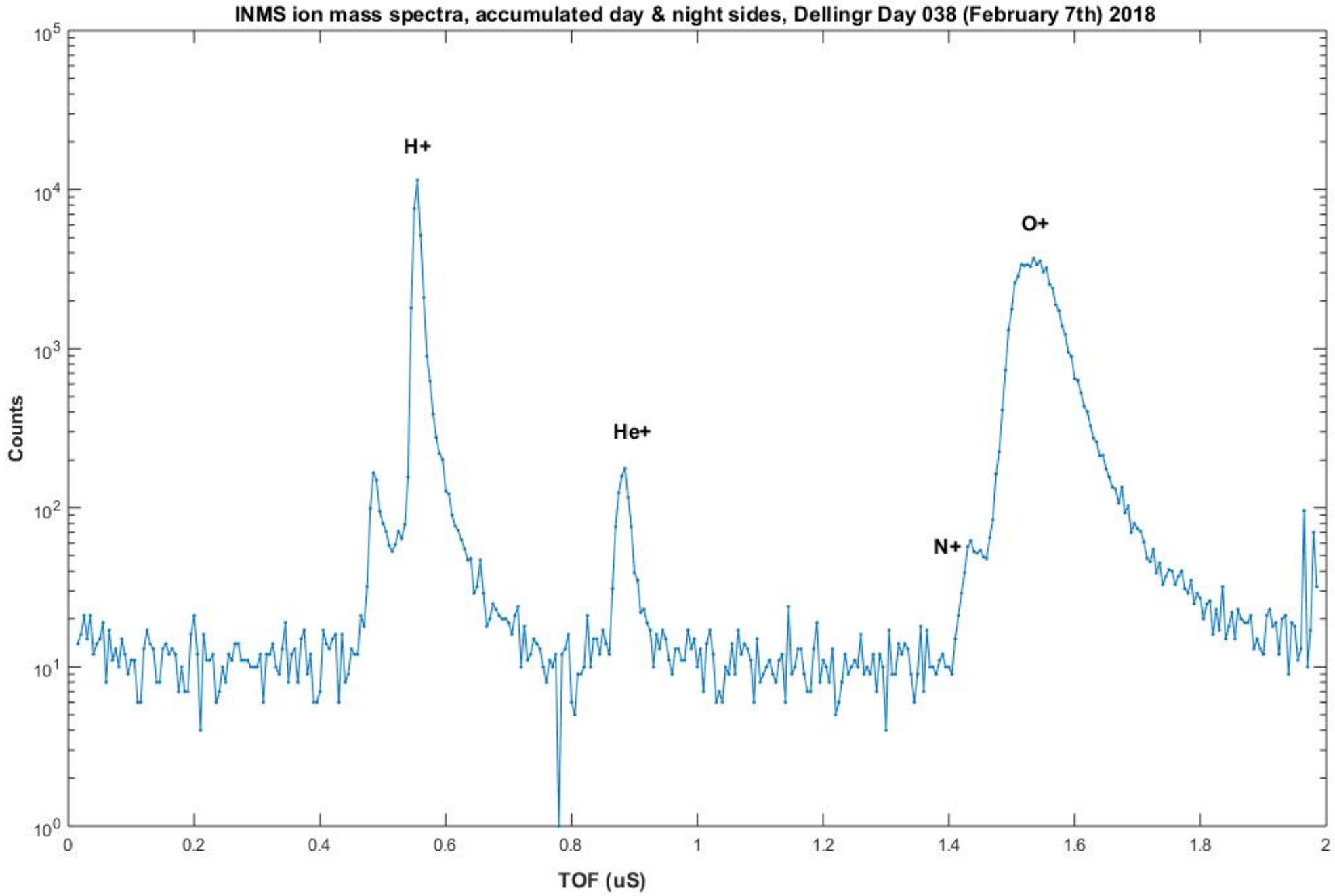


917 pm February 6:

"Victory. Behnam was able to turn on INMS in the ION mode. We had no resets between the last pass and this one."

February 9. Data!

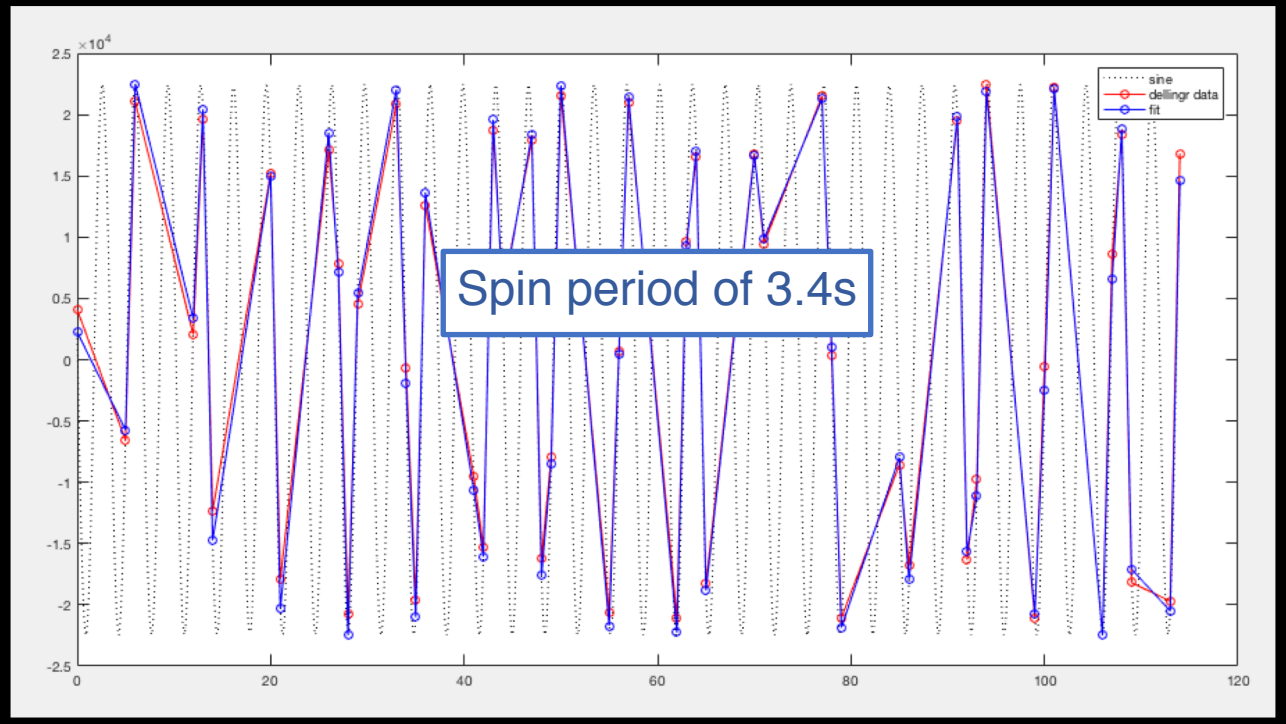



INMS ion mass spectra, accumulated day & night sides, Dellingr Day 038 (February 7th) 2018
H+
He+
N+
O+
Counts
TOF (uS)
10^5
10^4
10^3
10^2
10^1
10^0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

The best laid plans, and all that

We were able to upload some software patches to keep the RW off/on. We turned on INMS neutral mode (could not download). Had plans for larger updates. But …

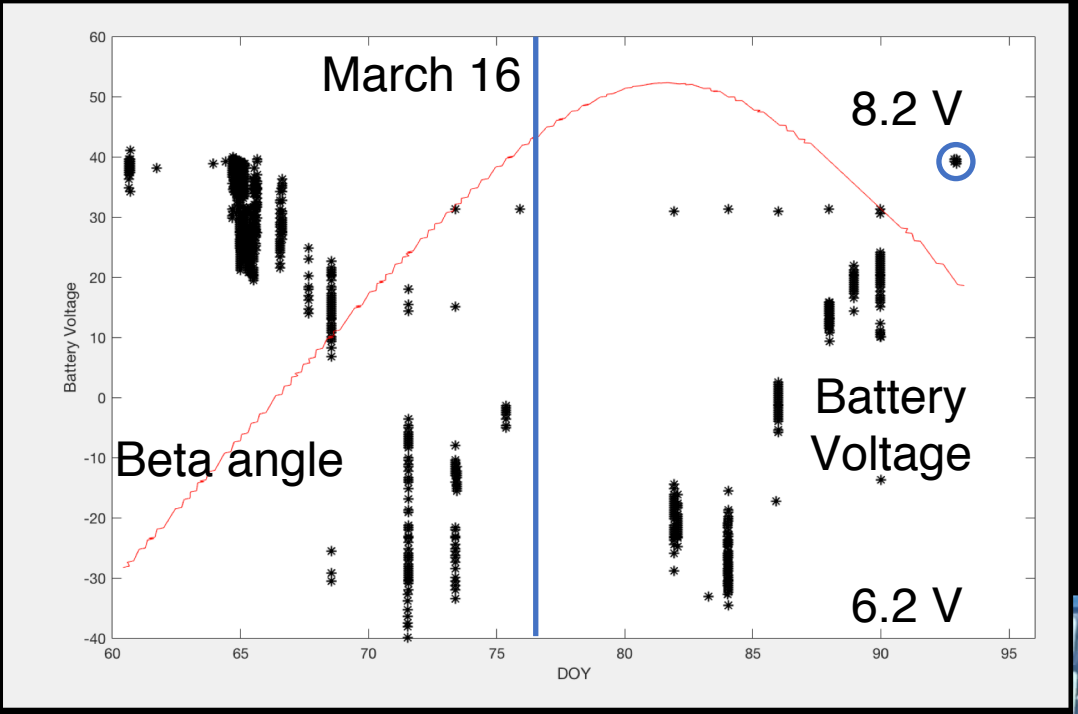
ACS system designed for 40°/s. Dellingr is spinning at 120°/s



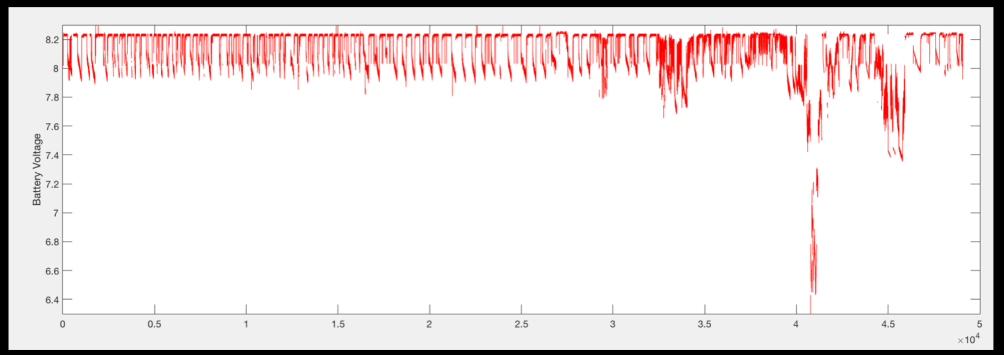
2 minutes of data from March 16th

As of 7:18 am March 16th:

Dellingr is spinning too fast… is not power positive… communication is weak… we have 1 pass/day… and the resets are starting again… for a different reason…

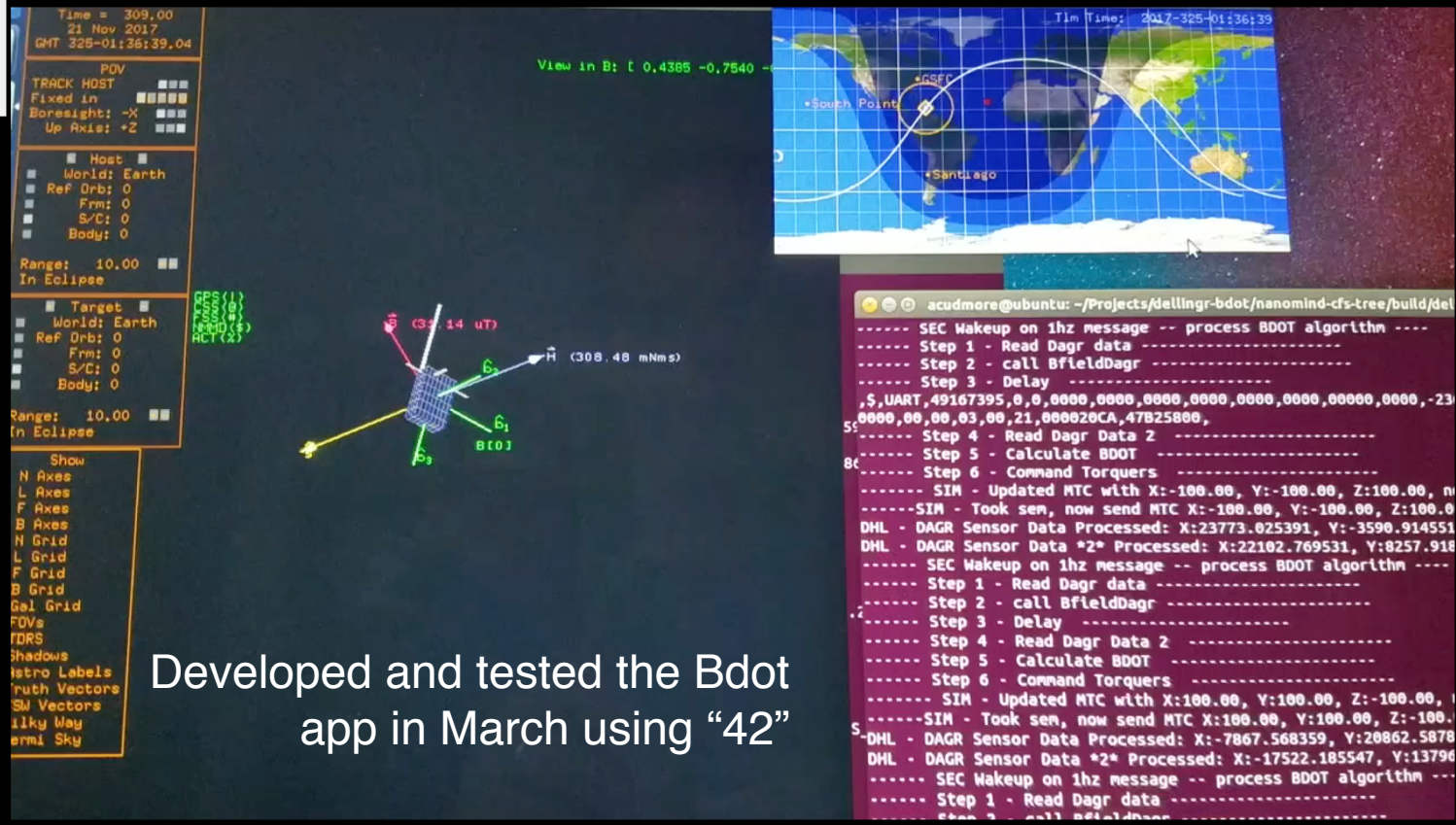


- Passes started to occur in early evening
- Power improved past week (beta angle)
- Resets likely EPS



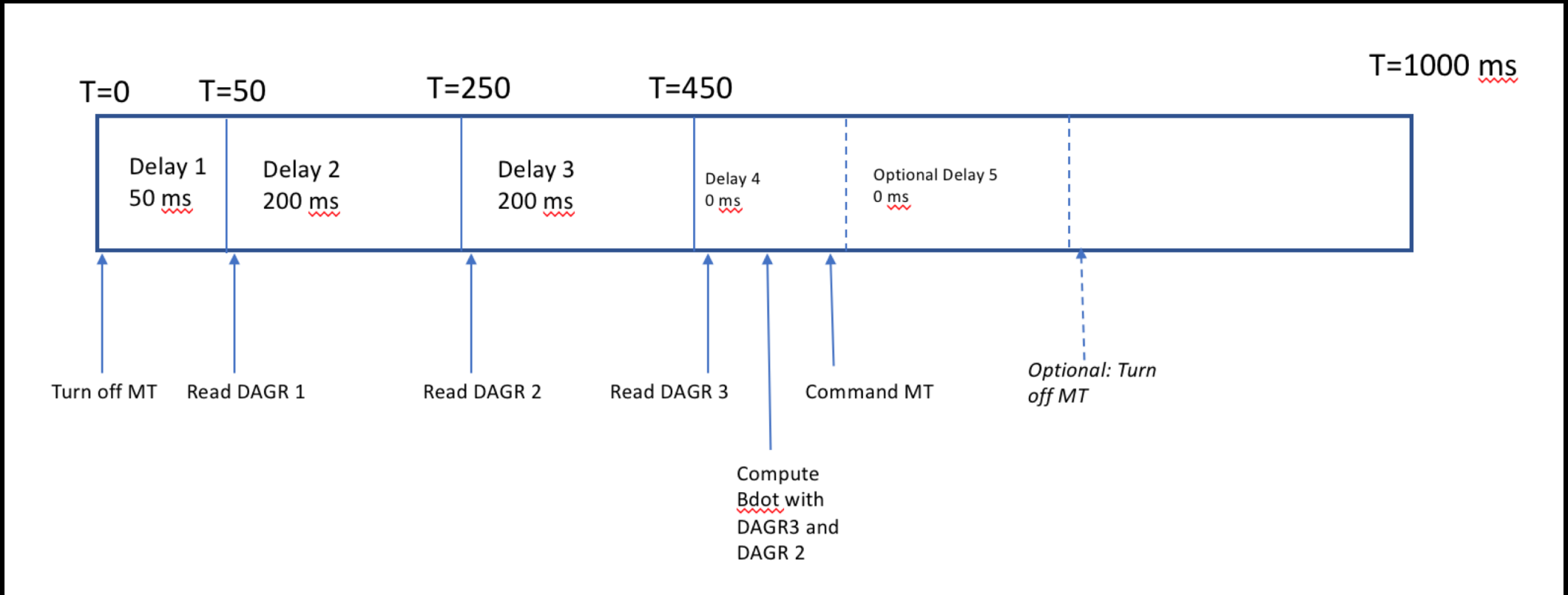
App split into 8 pieces, 181 bytes each
(4 commands + 1 to move)

3/29 - 1 pass, successful
3/30 - 1 pass, successful
4/2 - 3 passes, successful
4/3 - WFF UHF dish breaks



Despin via bdot

V1 uploaded from 3/29-4/5, didn't work
V2 uploaded from 4/12-4/17, partial success
V3 uploaded from 5/1-ongoing.



Issues:
WFF developed FSS is very noisy, despite ground testing
GSP failed after 4 weeks, despite ground testing
Cannot run onboard ephemeris due to underpowered CPU
ACS not designed for >~20°/second spin rate
IMU not providing clean data since launch (likely software bug)
Extensive I2c errors for much of January related to reaction wheels
Faced vendor and technical issues with EPS, batteries, and radio

Things that increased reliability and/or resiliency:
Multiple FSS
In-house ACS
Core Flight Software
Flatsat during operations — didn't have it during development
Experienced engineers
25 hour reset
Ability to talk directly to radio

Things that would be nice:
Power reset capability (a backdoor)
Better uplink & full duplex radio
Ability to turn off and isolate subsystems (we mostly have this)
A full time team & trending

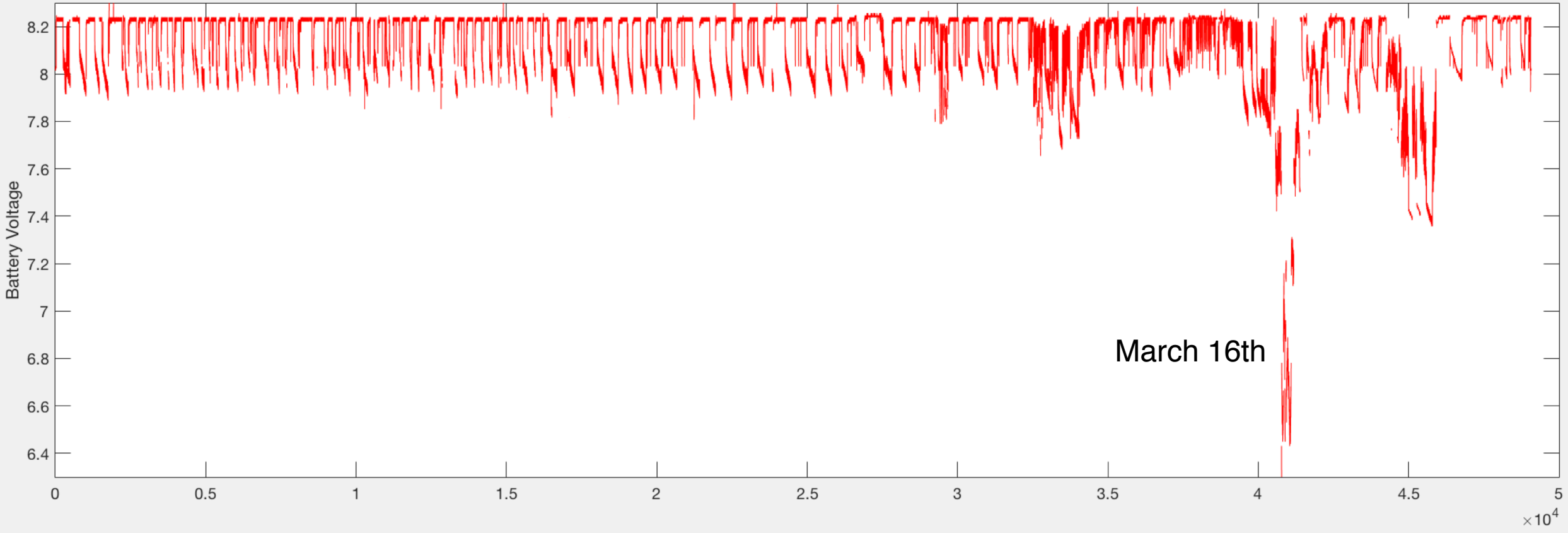
Other things that happened:
Cadet radio data deleted. Twice
Cadet radio froze. 25 hour reset cleared it.

Conclusions
Dellingr relied on "Build, test, fix". That provided level of confidence s/c would work on orbit.

GSP failure and I2C issues were not observed during testing.

Given price point and risk posture, Dellingr landed in the right place. A small change of luck and we'd have a fully successful *science* mission (we still might!).

Battery voltage from January 1, 2018 to today



Since then, things have improved:
Power is healthy.
Resets were EPS shutting off at 6.2 V
Spin period is another story….

Take-aways

Proudly flying the Dellingr flag

Lessons Learned

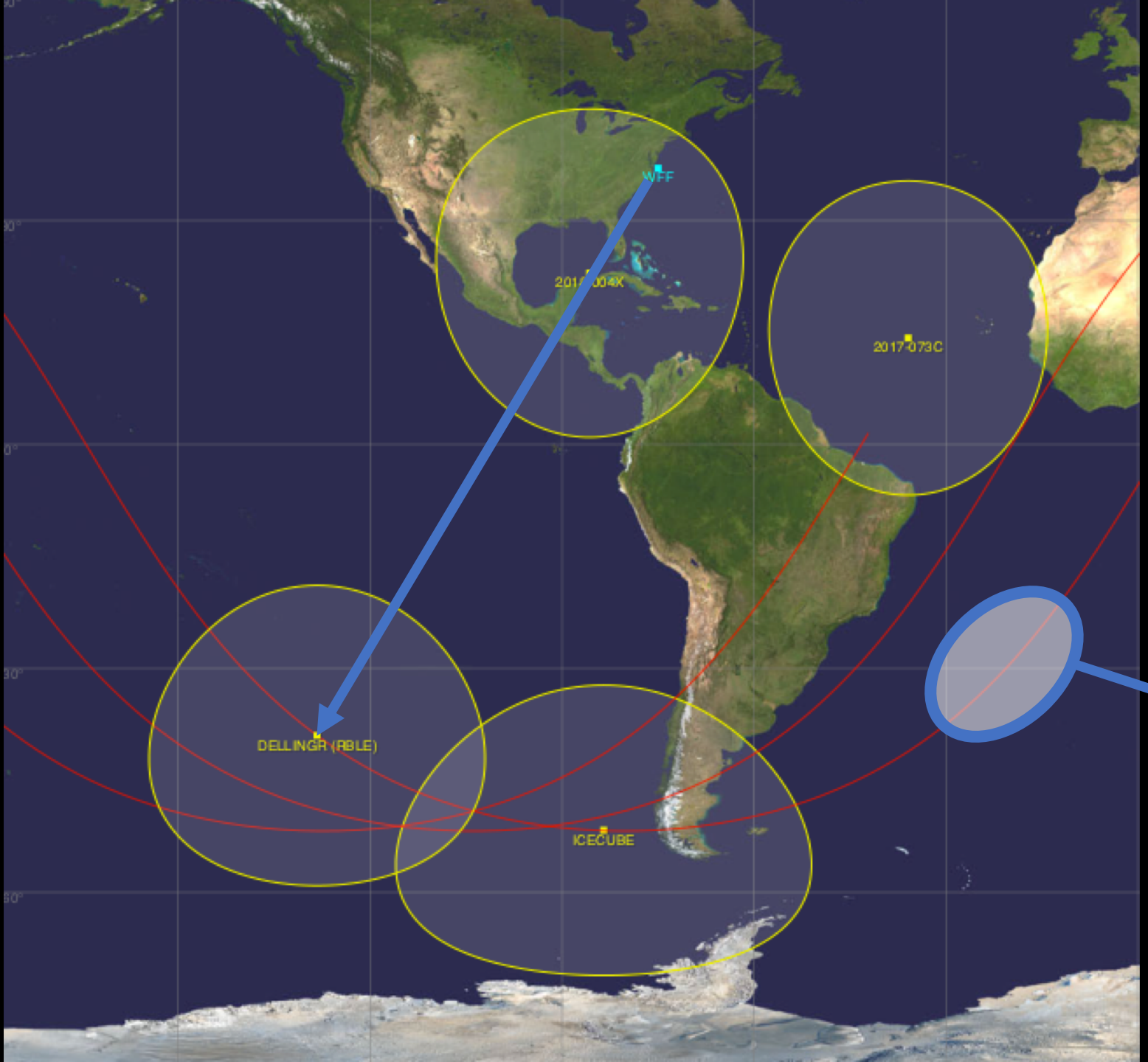
- FSW reuse and core-flight are key to keeping costs down, and need a flatsat for software development work
- We tested, but still suffered a critical failure (GPS)
- Harness Mockup – A 3D printed or similar physical model is needed for wire harness development
- Dellingr invested in detailed I&T procedures and documentation as part of the pathfinder ("build, test, fix") approach
- Component level performance tests should be completed before integration, as cubesat hardware is less mature
- Dellingr wasn't "reliable", but is "resilient"

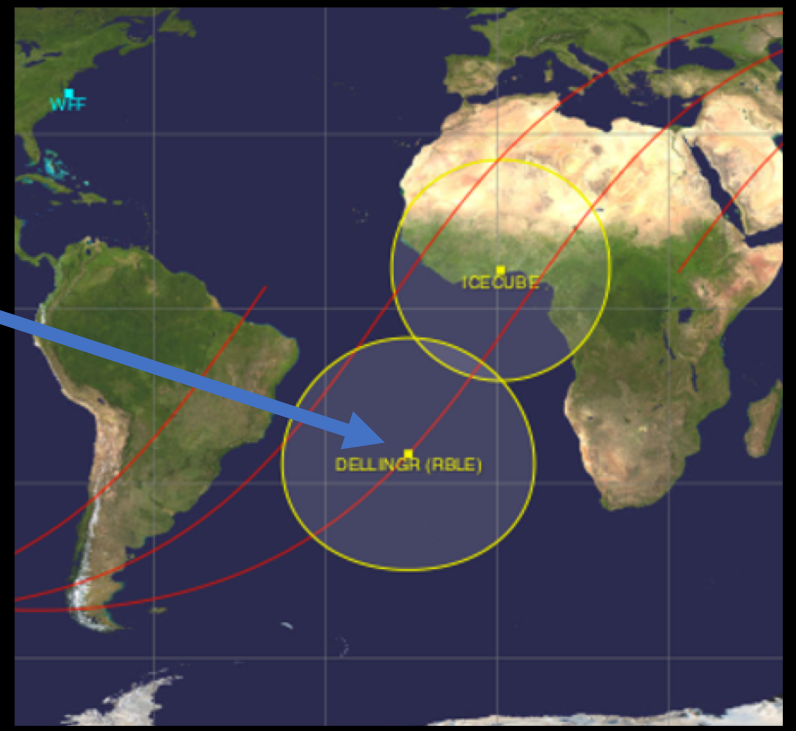
The future for GSFC

- Future focus is on rad-hard, high performance SmallSats for Decadal Survey science (GTOSat is pathfinder).
- Dellingr experience and capabilities leveraged for GSFC SmallSat science missions - changing the culture.

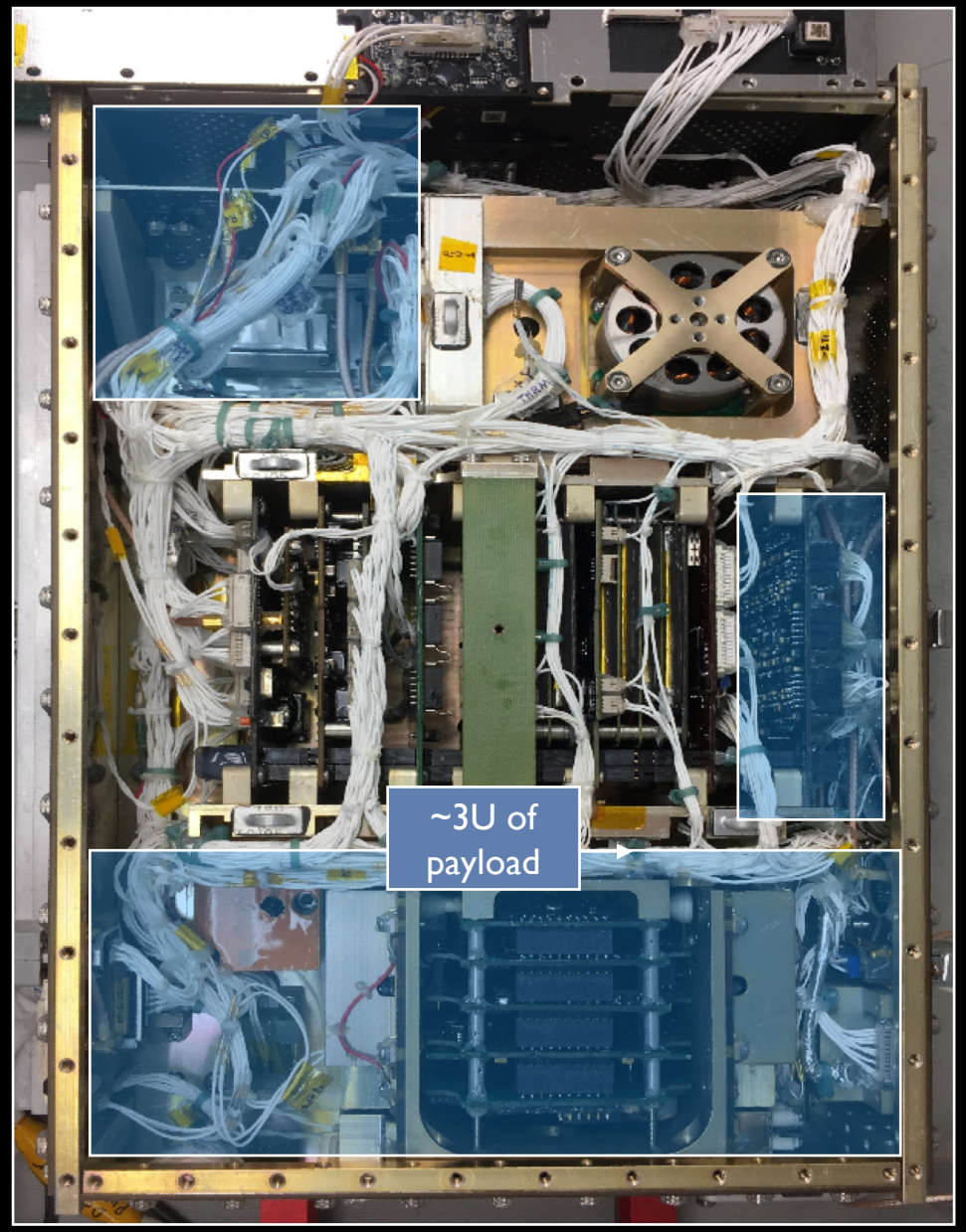
January 25

"Due to some unknown reason all LO-FIFO data deleted around 8 hours ago."



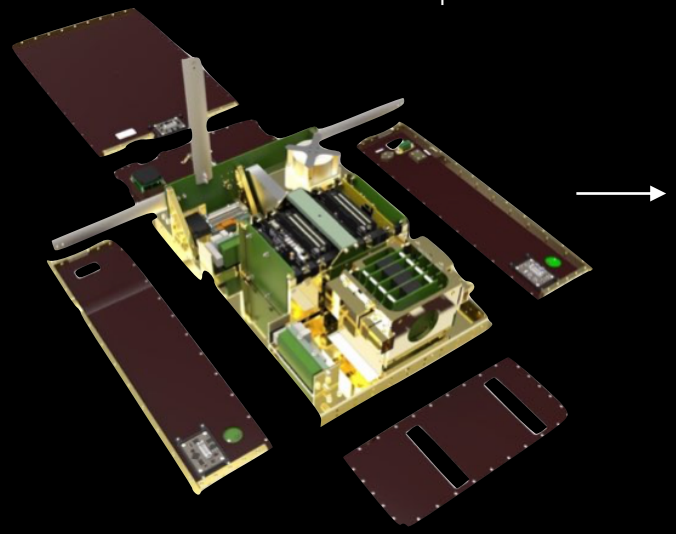


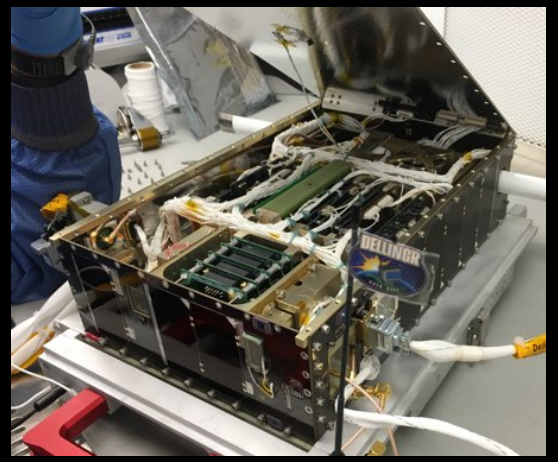
Dellingr overview



- **COTS:**
  - Flight computer, EPS, batteries, UHF radio, reaction wheels, GPS, IMU, FSS, camera, CSS
- **In-house**
  - Special Services Card, solar panels, UHF antenna, FSS, release mechanisms, magnetometer boom, GPS splitter & antenna, flight software, instruments

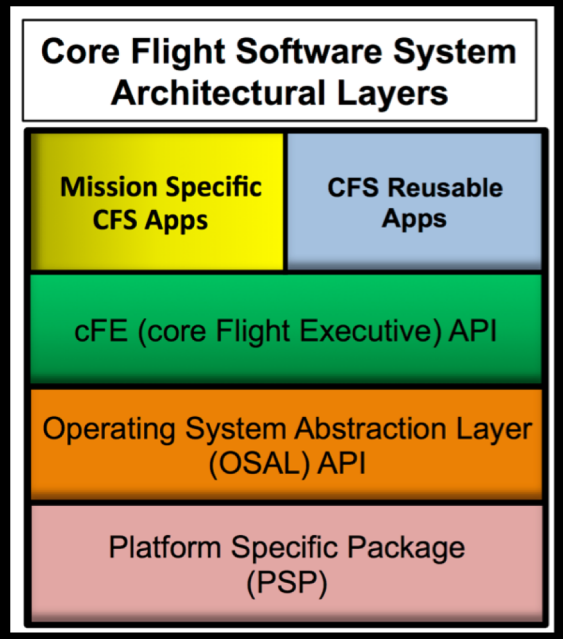
baseplate facilitated integration





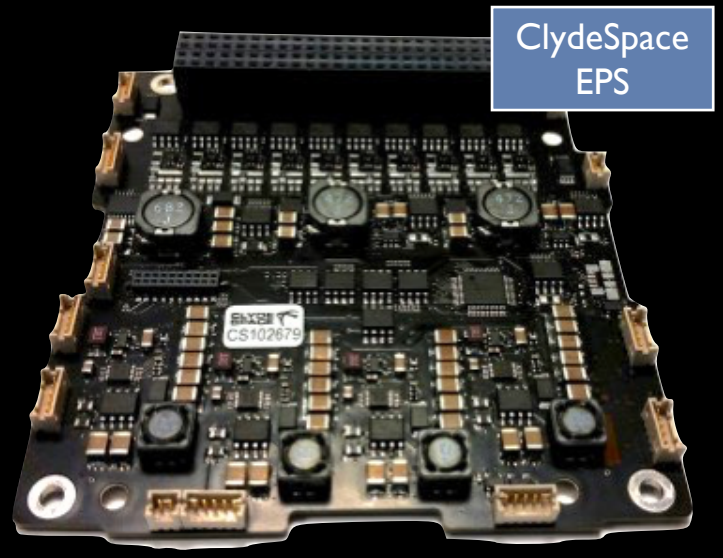
Flight Software, C&DH, electrical bus

Gomspace C&DH

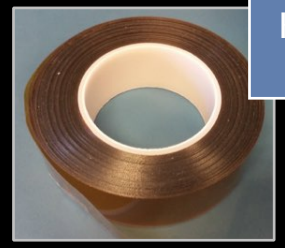


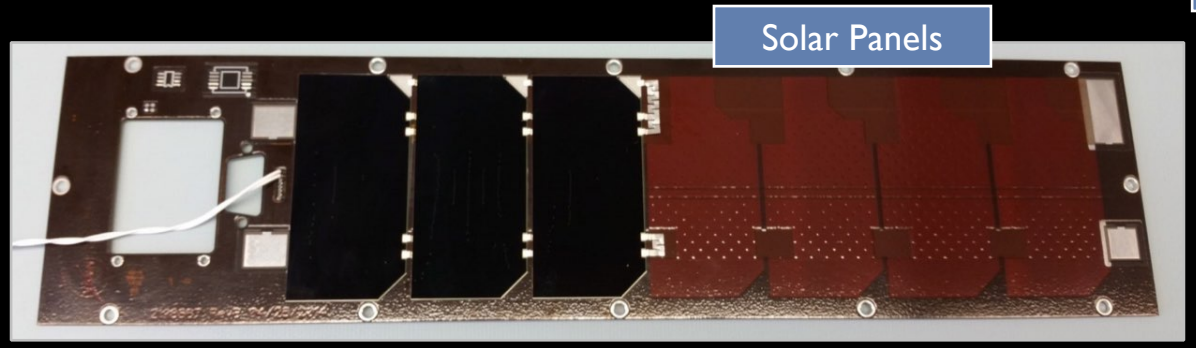
- **Gomspace Nanomind for flight computer**
  - 40 MHz Amtel ARM, 2 MB SRAM, 8 MB flash
  - FreeRTOS
- **Core Flight Software**
  - Open source framework, available via SourceForge
  - Used on LRO, GPM, MMS, etc.
  - Abstracts software architecture from hardware
  - Publish/subscribe messaging framework, event reporting, FDC, scheduling
- **Mission specific applications**
  - ACS, spacecraft housekeeping, instrument interface, and radio control
- **NanoMind included I2C, SPI and 3 UARTS**
  - Supplemented on SSC with A2D, general purpose I/O pins, and additional UARTS

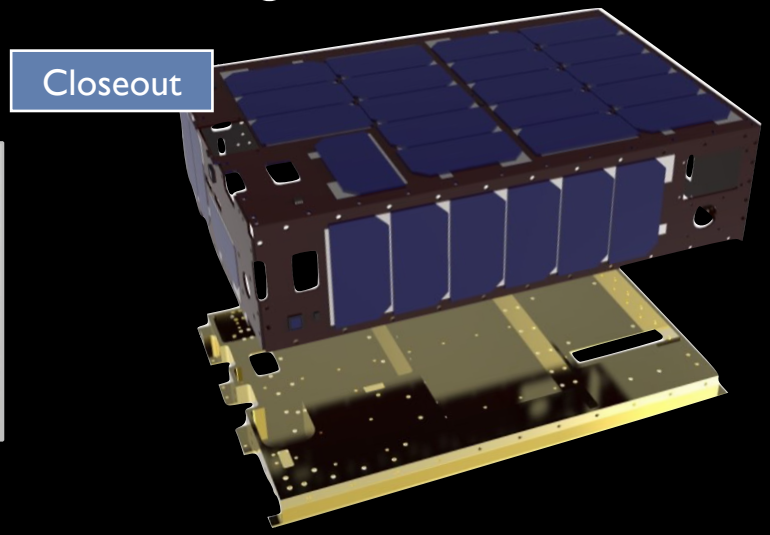
Power



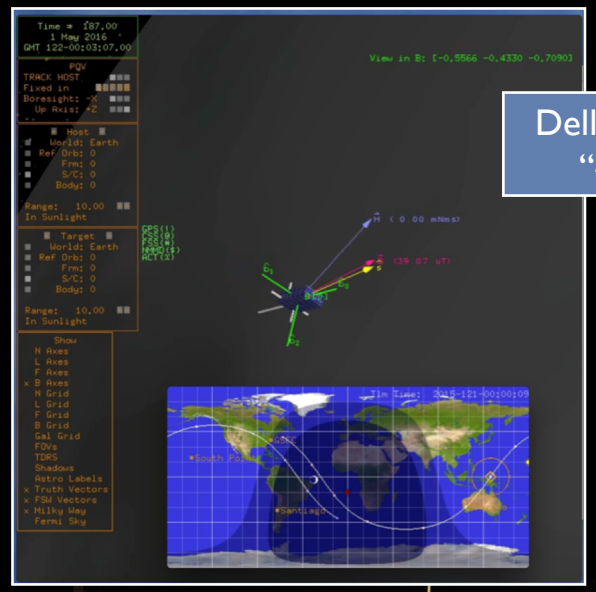
- ClydeSpace 3rd generation EPS
- Two ClydeSpace 40 Wh ISS approved batteries
  - Originally three 30 Wh; did not meet ISS requirements
- In-house solar panels
  - SolAero ZTJ Triple Junction CIC cells (GPM spares)
  - Mounted to PCB substrate with double-sided kapton tape (thanks Aerospace!)
  - Embedded torquers for momentum dumping
  - Formed closeout panels
- SSC added fuses, switches and current regulation for release mechanisms



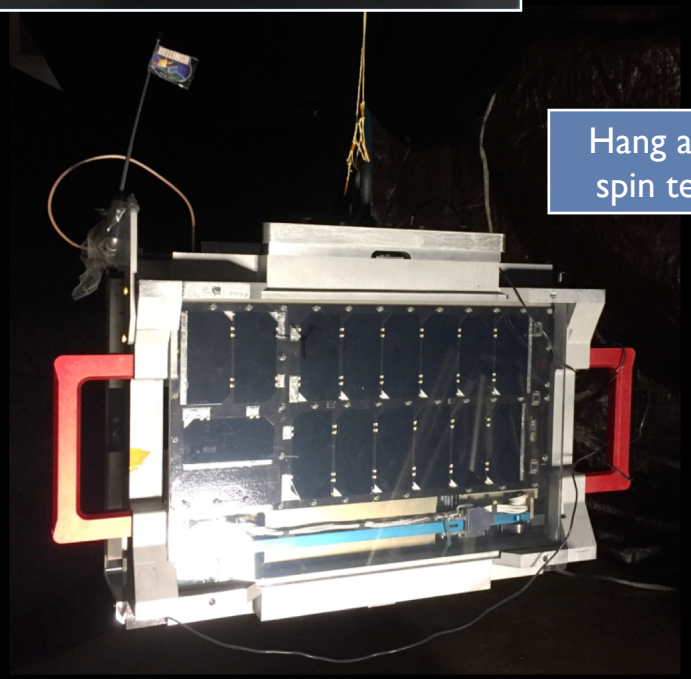




Attitude Determination and Control System

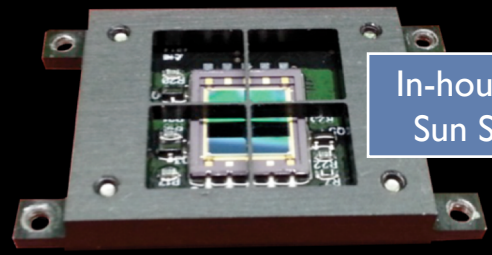


Dellingr in "42"



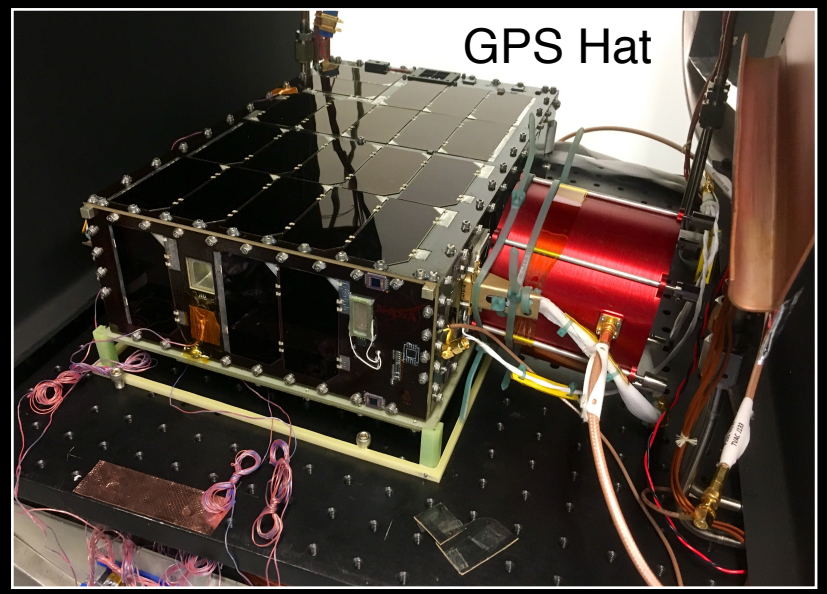
Hang and spin test

- Sensors - Combination of magnetometer, sun sensors (fine and coarse), and IMU
- Actuators - Reaction wheels and torquers for momentum control
- ACS software developed in-house, based off Solar Dynamics Observatory (SDO)
  - Software written as cFS apps
- **Verified in 42 and with hang and spin test**
  - 42 simulates all 6 DoF, all sensors and and actuators, including the reaction wheels and the torquers



In-house Fine Sun Sensor

Testing



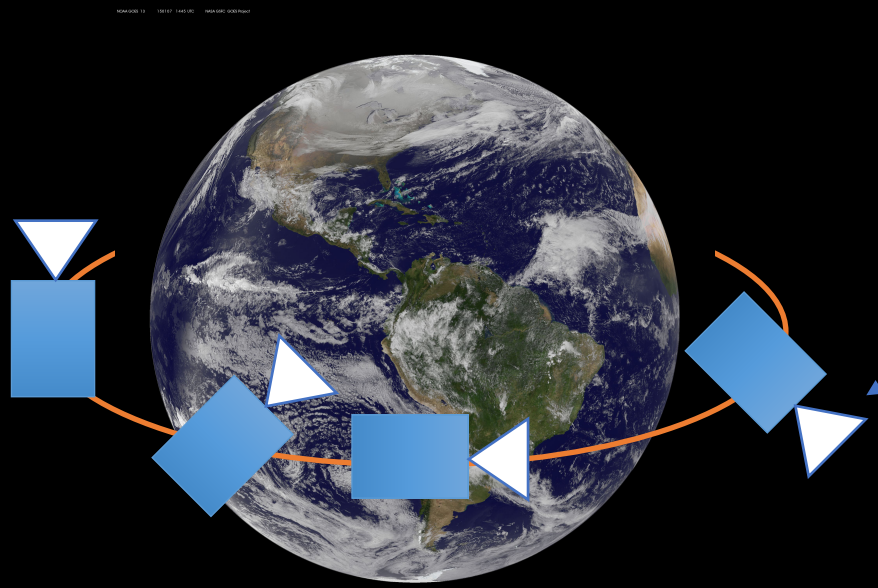
- **Initial environmental**
  - TVAC bakeout, 8 TVAC cycles, thermal balance, day in life, random vibe (9.47 GRMS) & sine-burst (14.5g)
- **Magnetics**
  - Calibrated magnetometers and characterized spacecraft interference; validated phasing
- **End-to-end comm at WFF**
  - L3 Cadet, half-duplex up to 3 Mbps downlink
  - SDL TITAN ground software
- **ITOS (I&T and MOC)**
  - Enables "Test as you fly"
  - Developed for original SMEX program
  - Commands initiated at MOC (Greenbelt), sent to WFF
- **Final NR vibe, 2 cycle TVac, regression testing, final mag cal. delivery May 31**


August 14, 2017
STAGE 1 TELEMETRY
SPEED
ALTITUDE
00097
km/h
00.1
km
UPCOMING
MAX-Q
RELEASED FALCON 9 AND WE HAVE
BEGUN OUR FLIGHT TO THE
INTERNATIONAL SPACE STATION
LAUNCH: CRS-12
STARTUP
LIFTOFF
MAX-Q
MAIN ENGINE CUTOFF
STAGE 1 BOOSTBACK
STAGE 1 ENTRY BURN
STAGE 1 LANDING
SECOND STAGE ENGINE CUTOFF
DRAGON DEPLOY
ARRAY DEPLOY
SPACEX

Ion Neutral Mass Spectrometer

- A key instrument for GDC, and *highest priority for Dellingr operations*
- Required several weeks of outgassing before turning on high voltage (could not turn on in early mission)
- Jan 10, 2018 turned on and verified nominal voltages and currents
- Loss of GPS requires software patch to recover INMS science mode

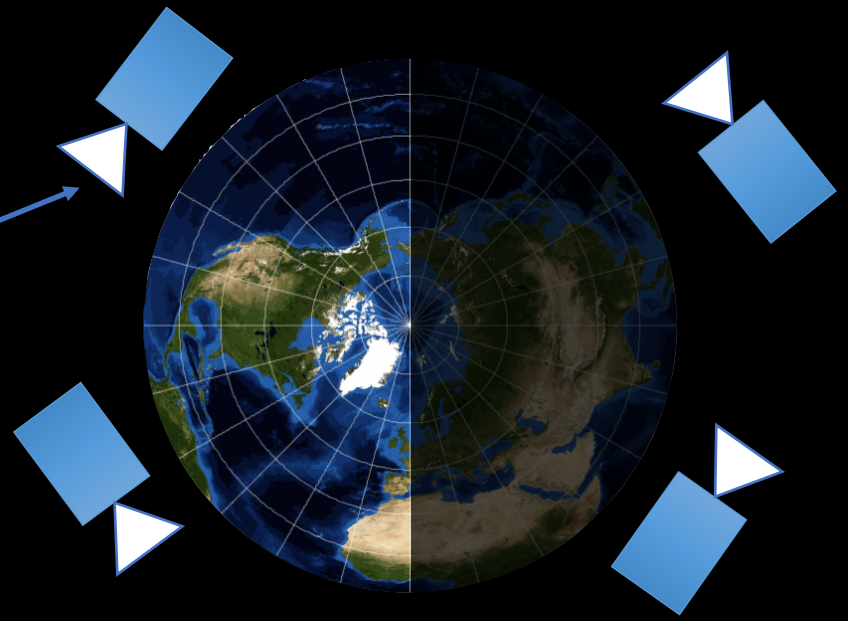
Short term solution



Use INMS in sun-point mode and spin through ram on dayside (requires several uploads)

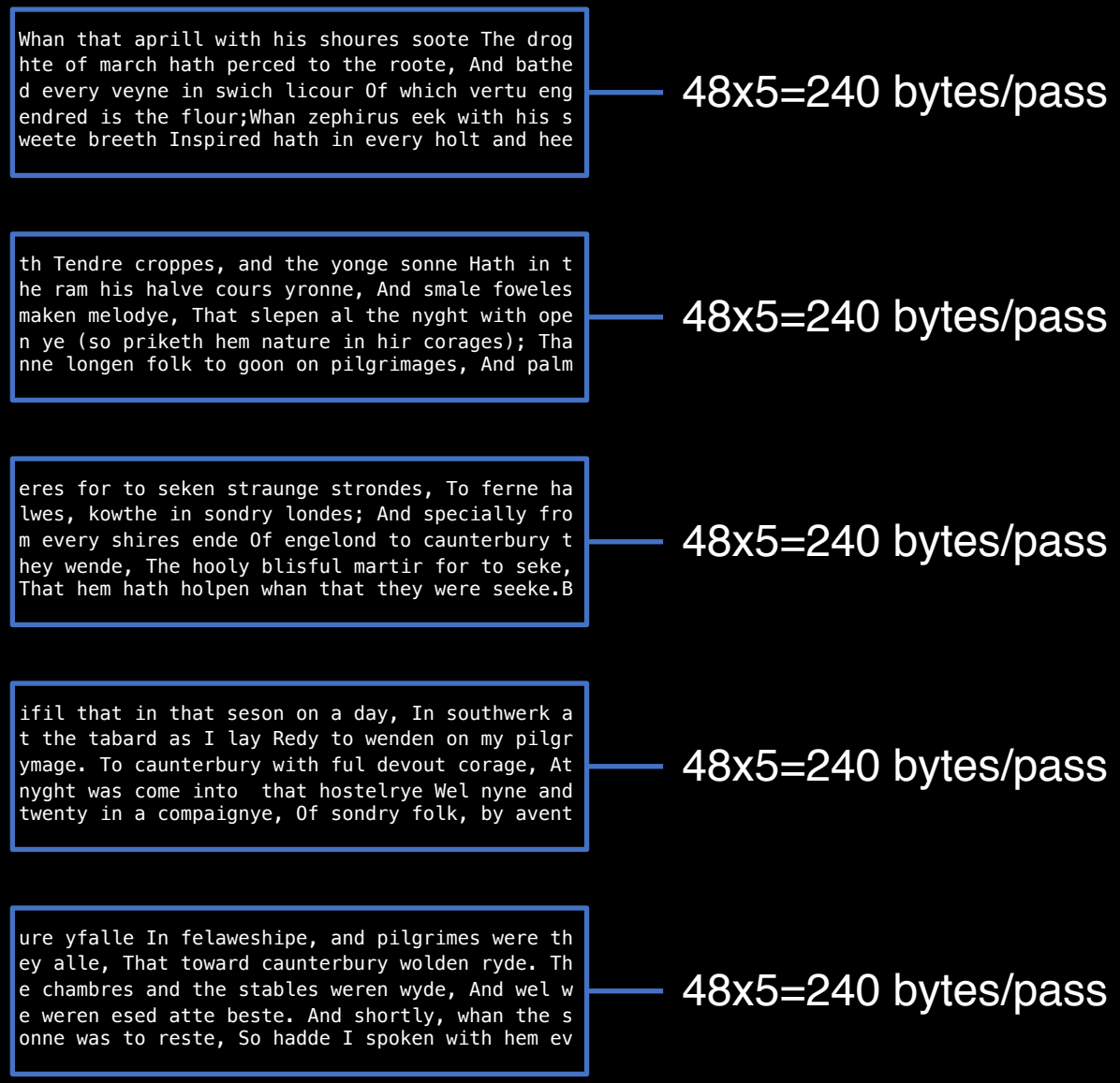
INMS entrance aperture

Long term solution



Use INMS as ram-sensor or run ephemeris propagator on orbit


```
Whan that aprill with his shoures soote The drog
hte of march hath perced to the roote, And bathe
d every veyne in swich licour Of which vertu eng
endred is the flour;Whan zephirus eek with his s
weete breeth Inspired hath in every holt and hee
```



We need ***at least*** 5 perfect passes to get 1000 bytes uploaded

Need additional commands to put the fragments together