MICHIGAN EXPLORATION LABORATORY

NEC TEMERE, NEC TIMIDE.

Science and CubeSats – the NSF Experiment

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(1) University of Michigan Ann Arbor, MI
(2) SRI International Menlo Park, Ca

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In 1996, I wanted to build something, and there was a chance to build a satellite.

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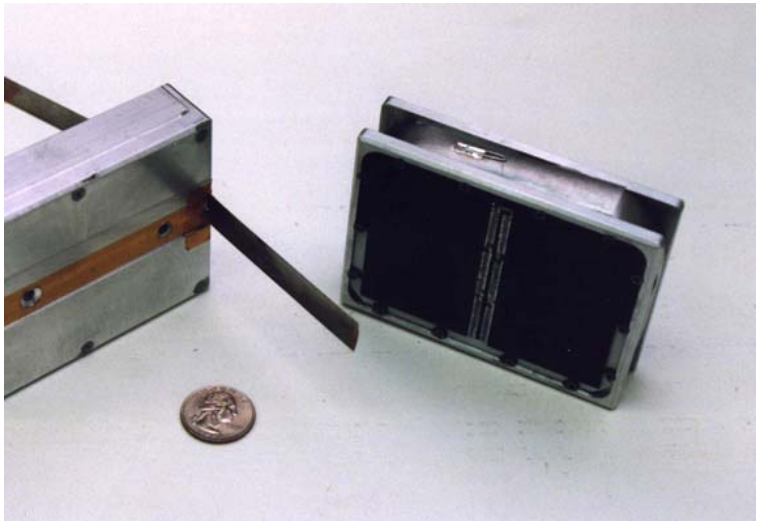
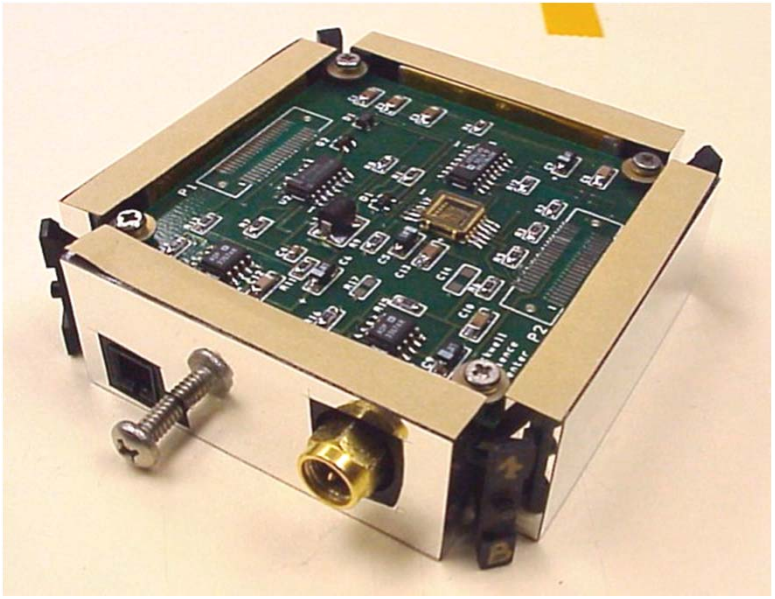
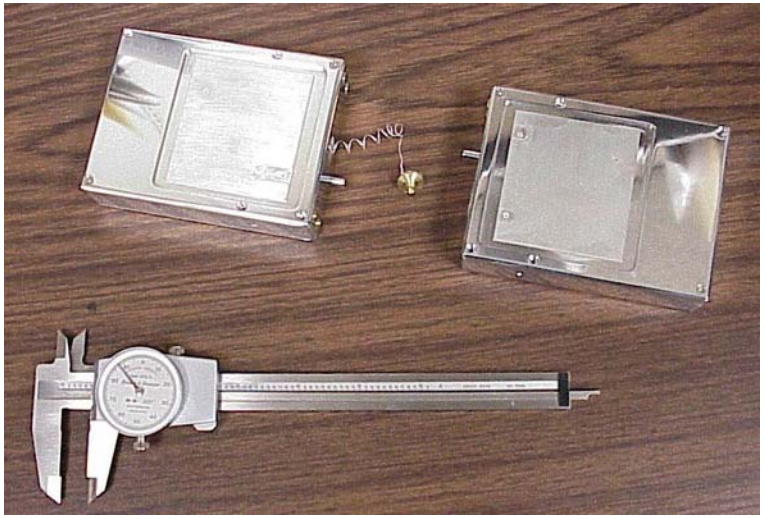
OPAL's original mission was to deploy free flying magnetometers, but we lost our $$.







We built our satellite in a garage…more or less.

OPAL was launched 1/26/2000 on a Minotaur-1.

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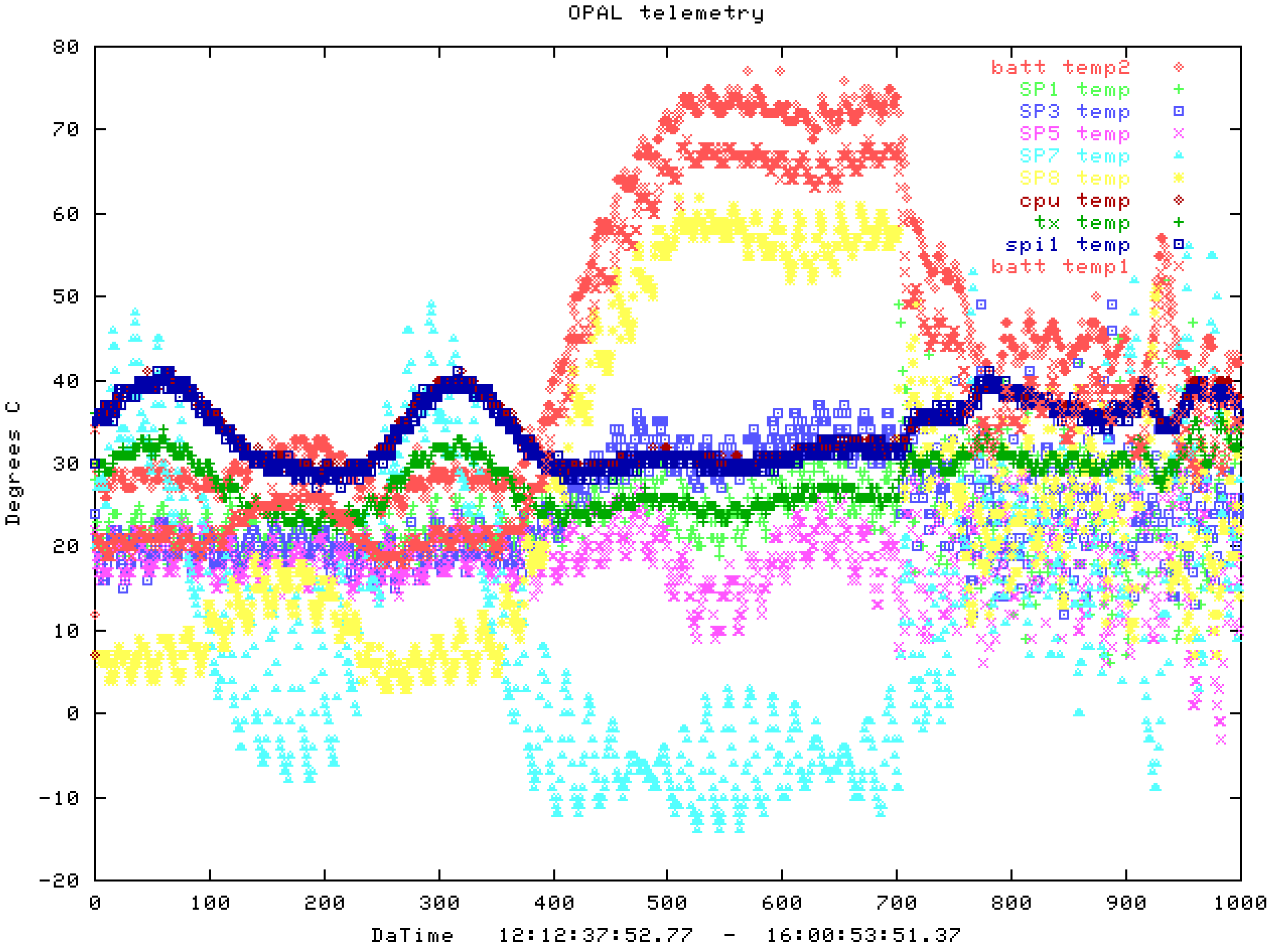
OPAL telemetry
batt temp2
SP1 temp
SP3 temp
SP5 temp
SP7 temp
SP8 temp
cpu temp
tx temp
spi1 temp
batt temp1
Degrees C
80
70
60
50
40
30
20
10
0
-10
-20
0
100
200
300
400
500
600
700
800
900
1000
DaTime 12:12:37:52.77 - 16:00:53:51.37

In 2007, NSF asked, “Can science be done with CubeSats?”

- Space-based measurements from small satellites have ***great potential*** to advance discovery and understanding of space weather.

- Equally important, such missions play a crucial role in ***training the next generation*** of experimental space scientists and aerospace engineers.

- Regular access to space, provided by small satellites, will ***maintain creativity and innovation*** in space science and aerospace engineering and keep a general widespread interest in space.

Moretto, T. and R. M. Robinson (2008),
Small Satellites for Space Weather Research,
Space Weather, 6, S05007, doi:10.1029/2008SW000392.

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Initial *constraints* on the RAX mission **– September 2008**

Cubesat form factor

Launch: STP –S26 December 2009

650 km, 72^{o} inclination

Delivery in less than 12 months

Deorbit within 25 years of mission end

Low mass…less than 3kg

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RAX is a *university-class* mission.

Co-investigators:

Dr. Hasan Bahcivan

Prof. James Cutler

45 students on core Michigan team
+12 students in Michigan project courses
+2 engineers from SPRL
+3 SRI engineers
+1 faculty member
+1 scientist

63+ students and professionals working on RAX (no full time)

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RAX addresses the fundamental nature of ionospheric plasma irregularities.

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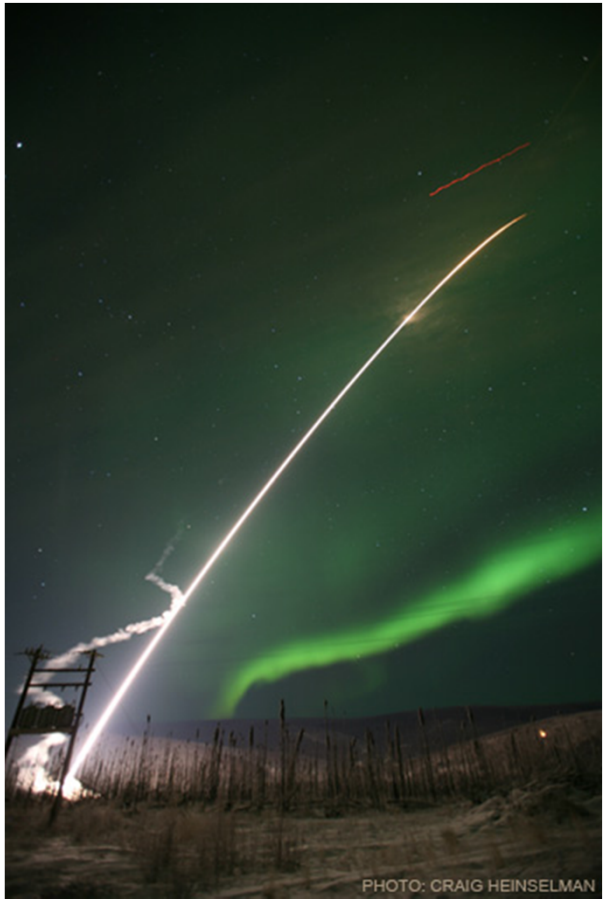
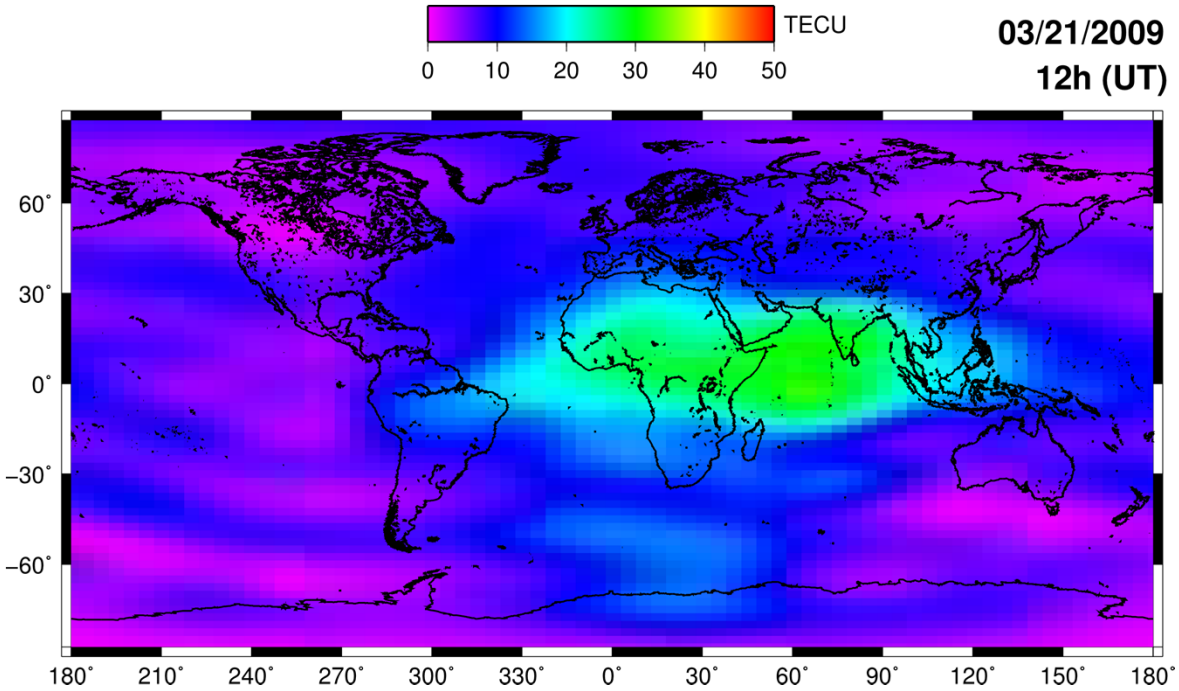
Fredrick Church, Magnetic Storm of 1859

These irregularities can compromise the operation of communication and navigation satellites





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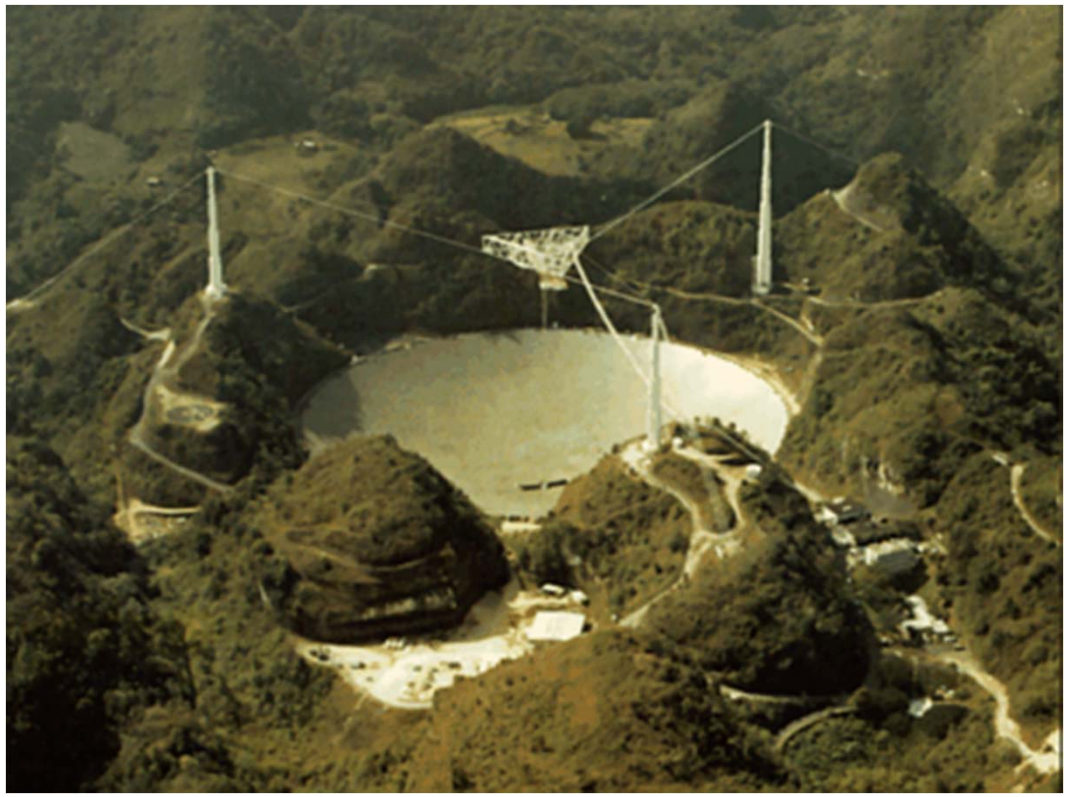
The RAX mission is a bistatic radar.



+

Transmitter

Incoherent Scatter Radar
(Arecibo, PFISR, ESR, Millstone)

Receiver

RAX Cubesat

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Bistatic radar concept…more to scale.

+

Transmitter

Receiver

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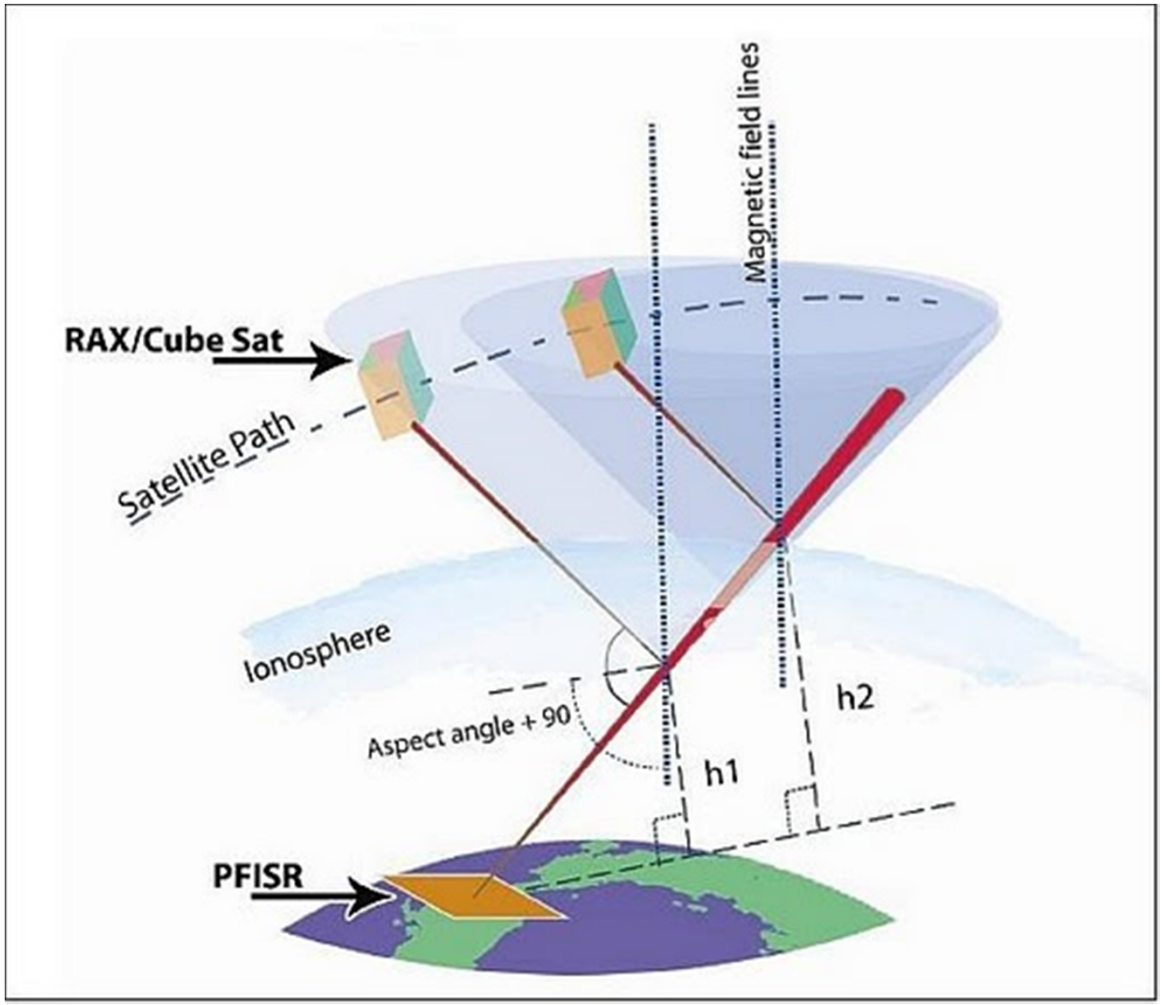
Radar echoes scatter in cones and towards space.



ISR	Freq. MHz	Power MW	BW	Inv. Lat.
PFISR	449.0	2.0	1.0	78
RISR	443.0	2.0	1.0	81
ESR	500.0	1.0	0.6	75
Millstone	440.0	2.5	0.6	53
Arecibo	430.0	2.5	0.2	34

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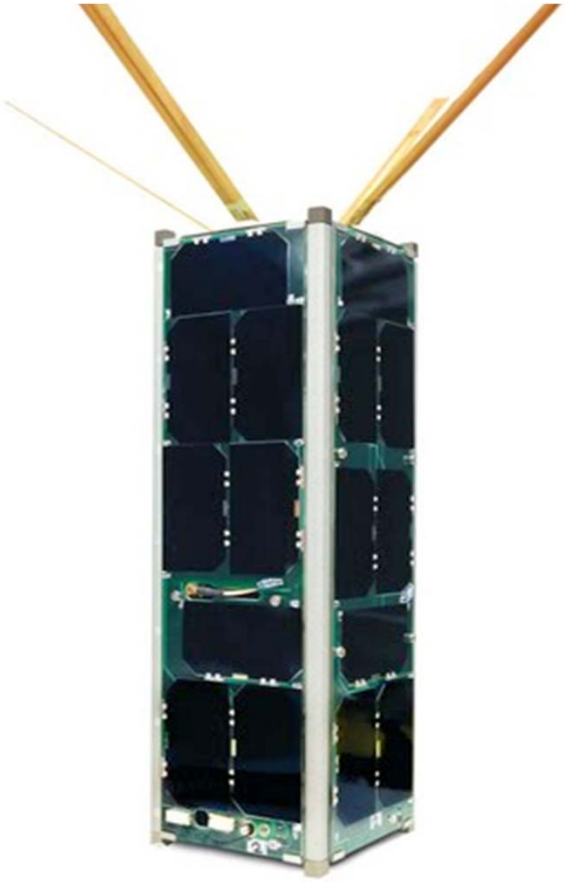
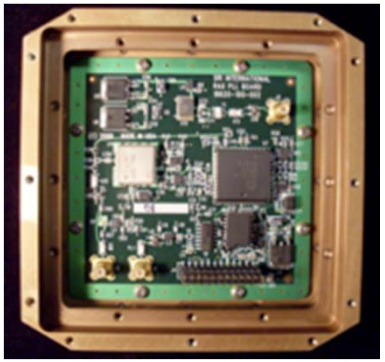
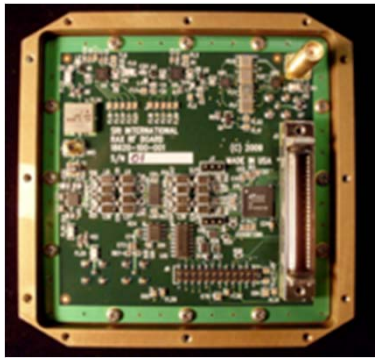
The SRI-developed radar receiver was integrated into the UMich-developed satellite bus.

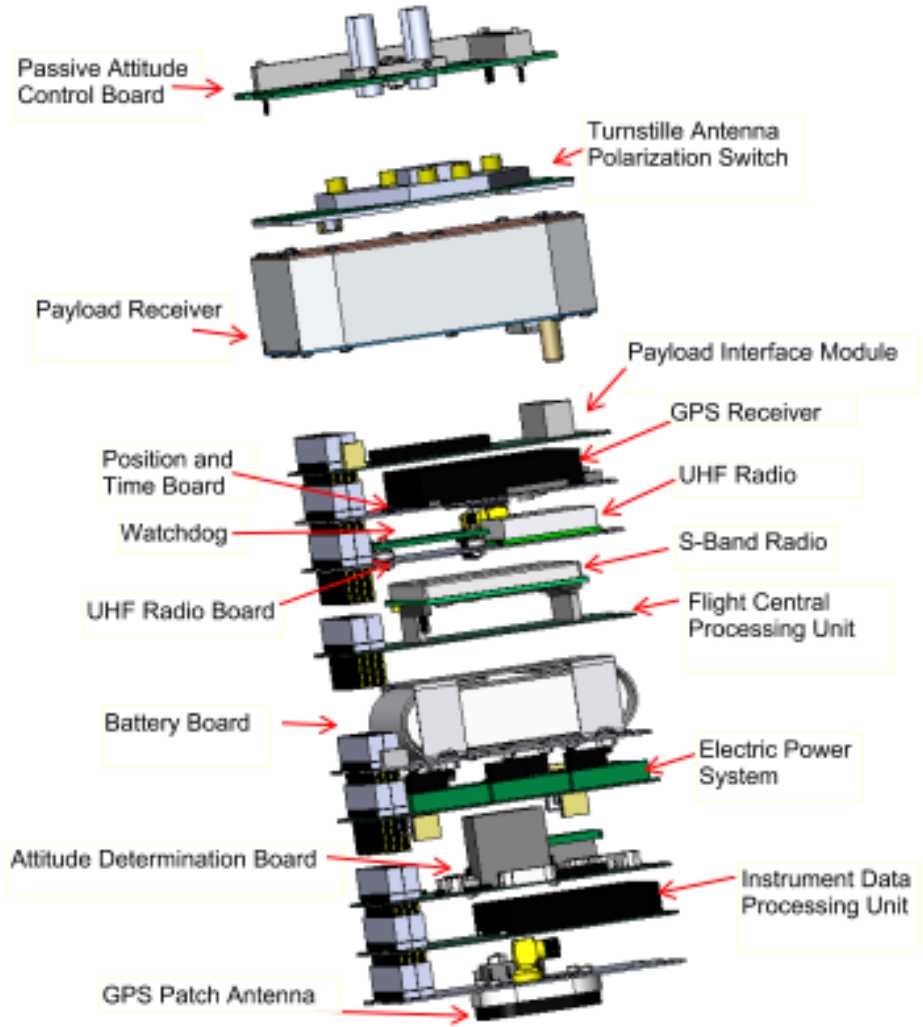


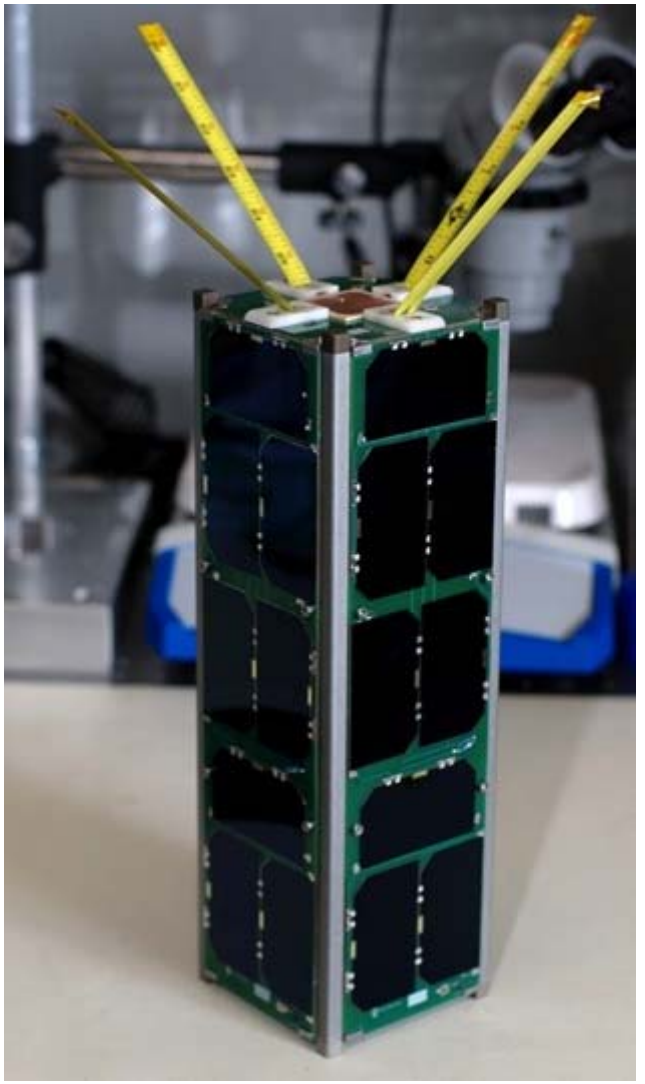
Radar receiver



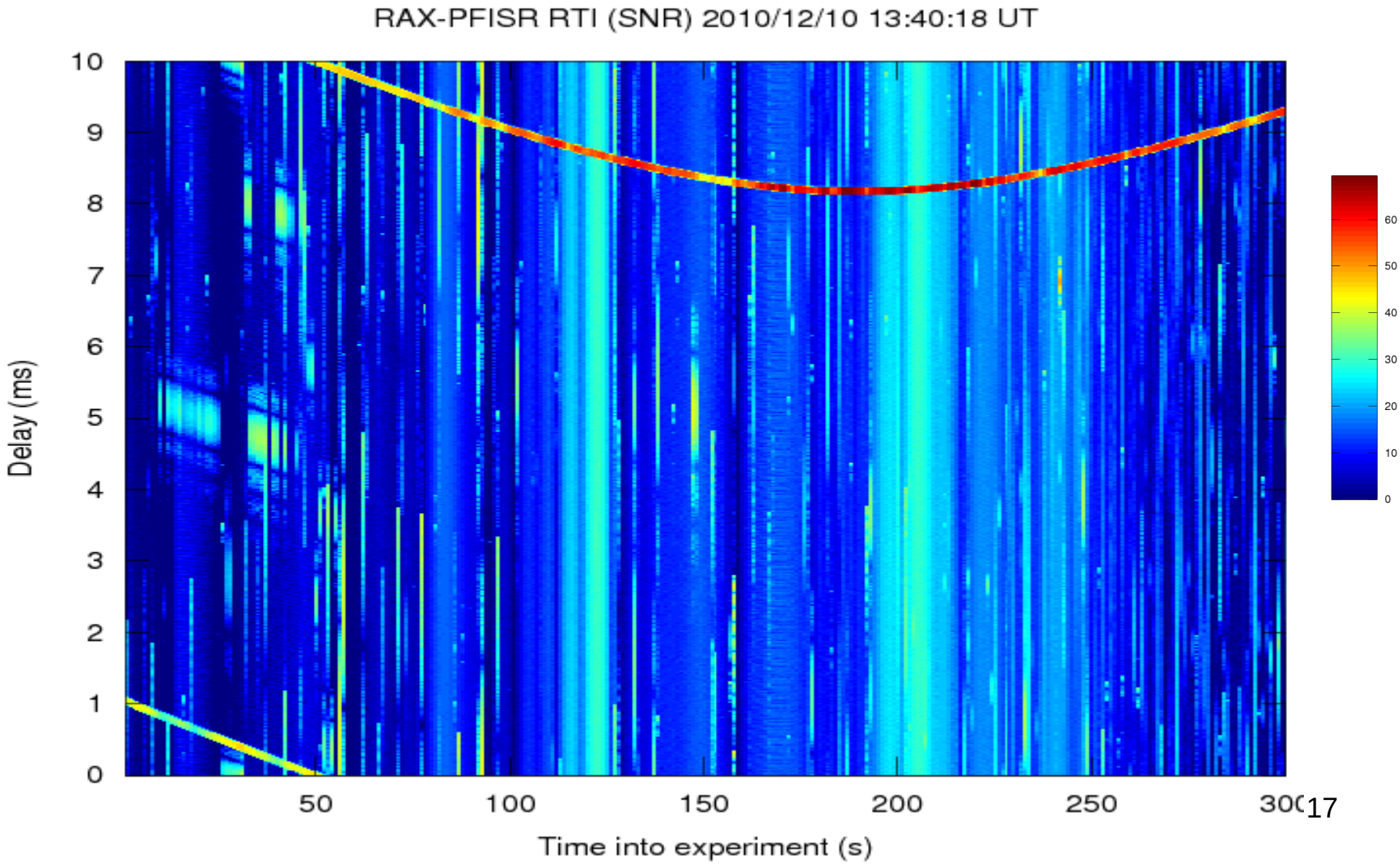


The satellite was composed of many COTS and custom subsystems, more custom than initially expected.

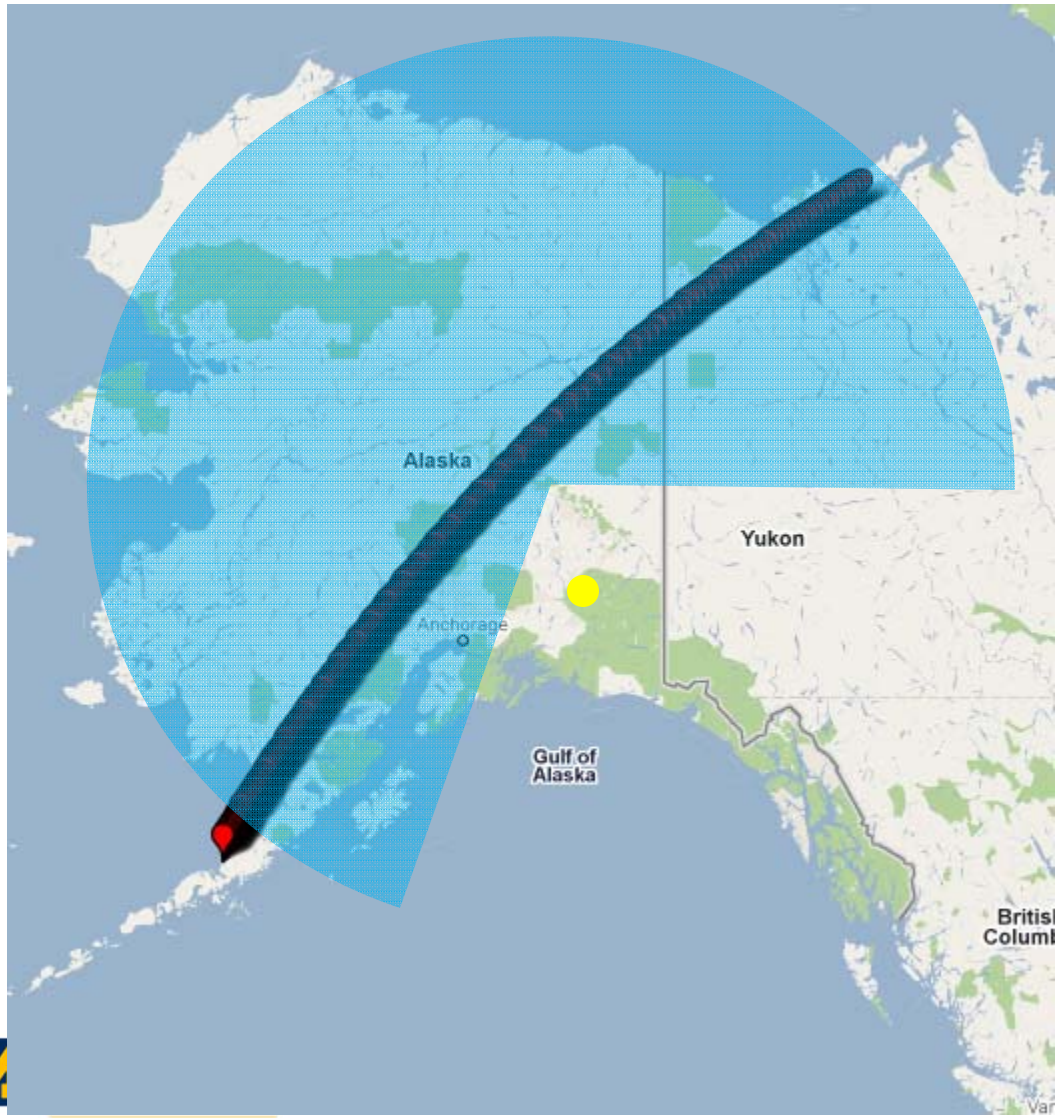




RAX-1 Experiment: The receiver and radar worked as expected—an end to end system test.



RAX-1 Experiment: Pave Paws radar painted the entire path of the experiment.



From Wikimedia Commons

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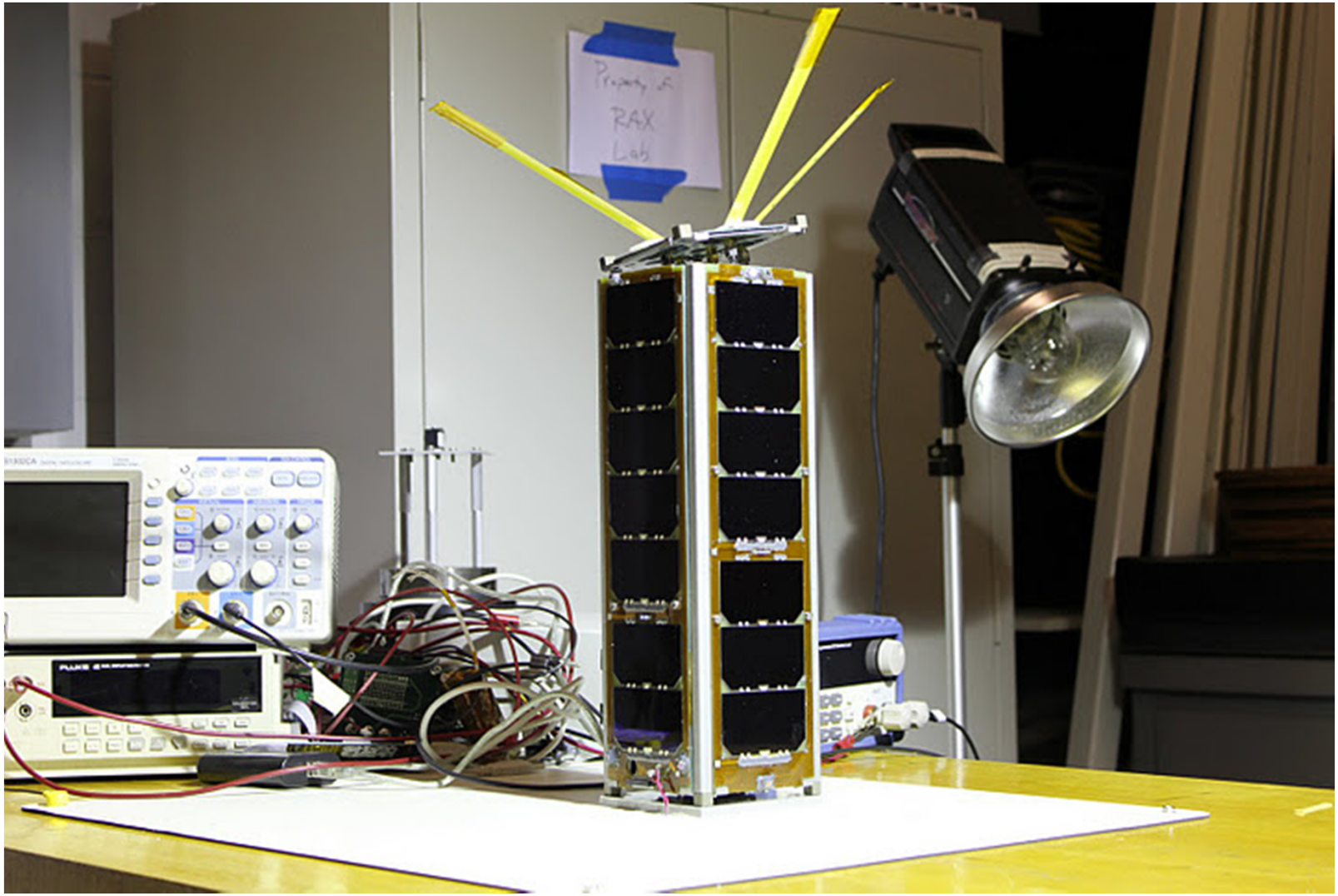
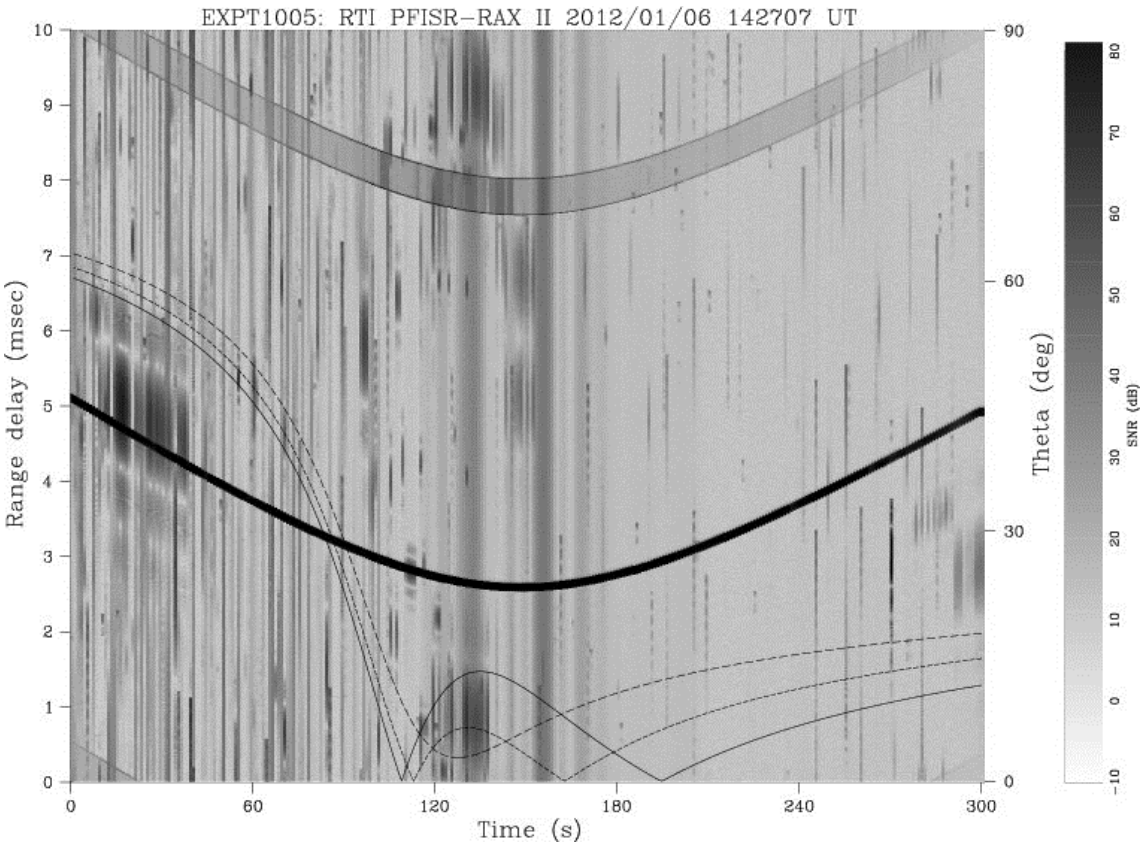
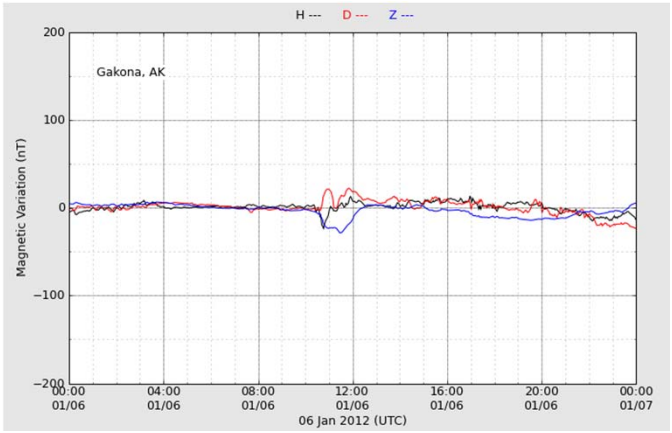
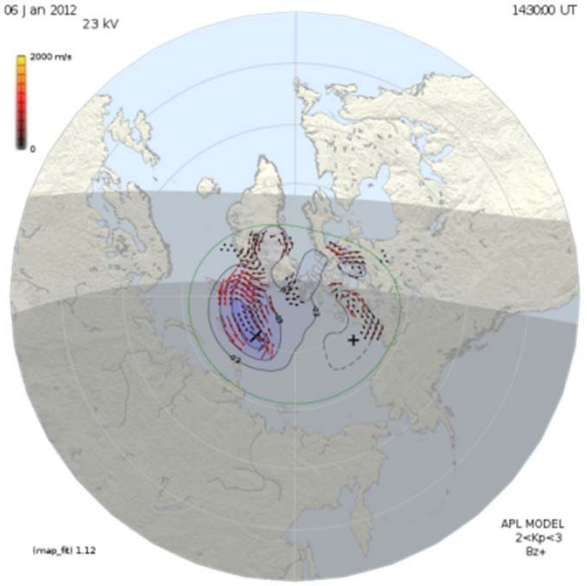
RAX-1 had a solar panel failure, RAX-2 built in 6 months. It's working. Quite well.



An early mission experiment showed additional noise sources.







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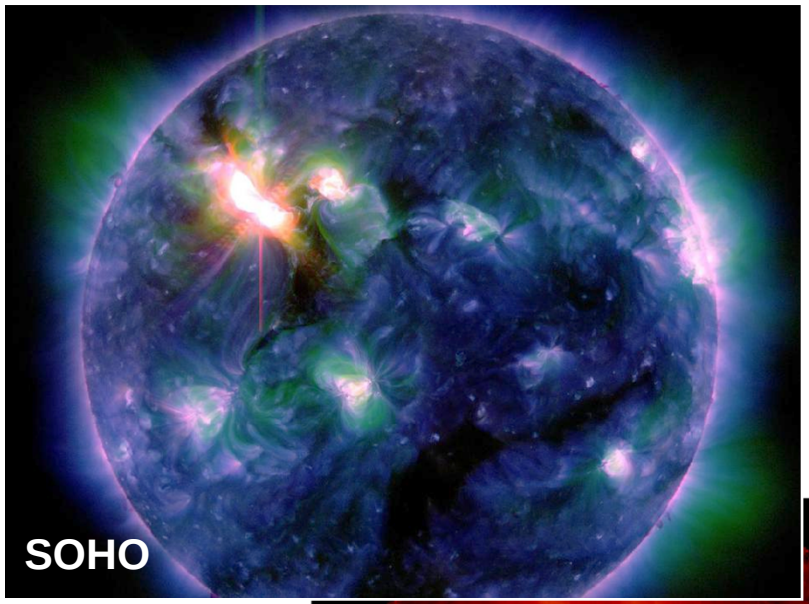
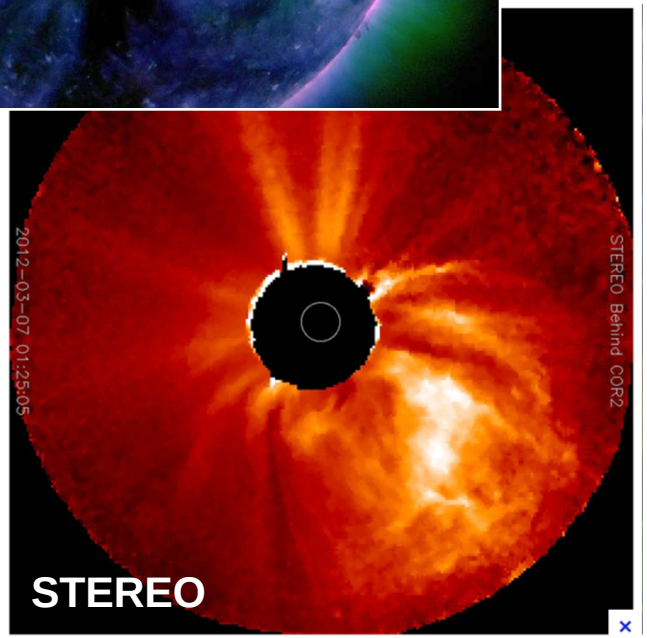
There was a strong CME in March of 2012.



X5.4 Flare
6 March



Earth-Directed CME
7 March

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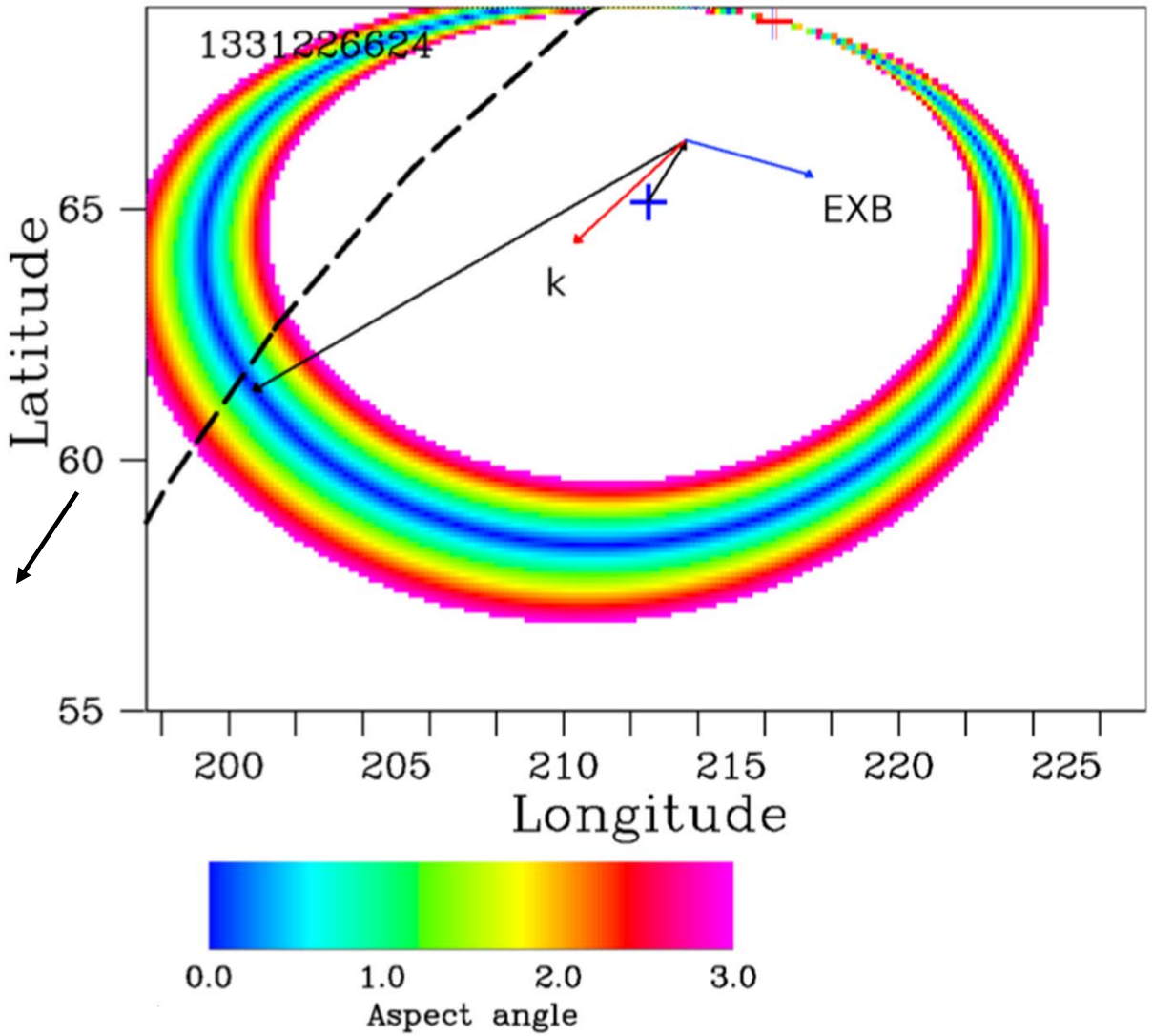
RAX ran consecutive daily experiments on March 6, 7, *8* 2012 over PFISR.



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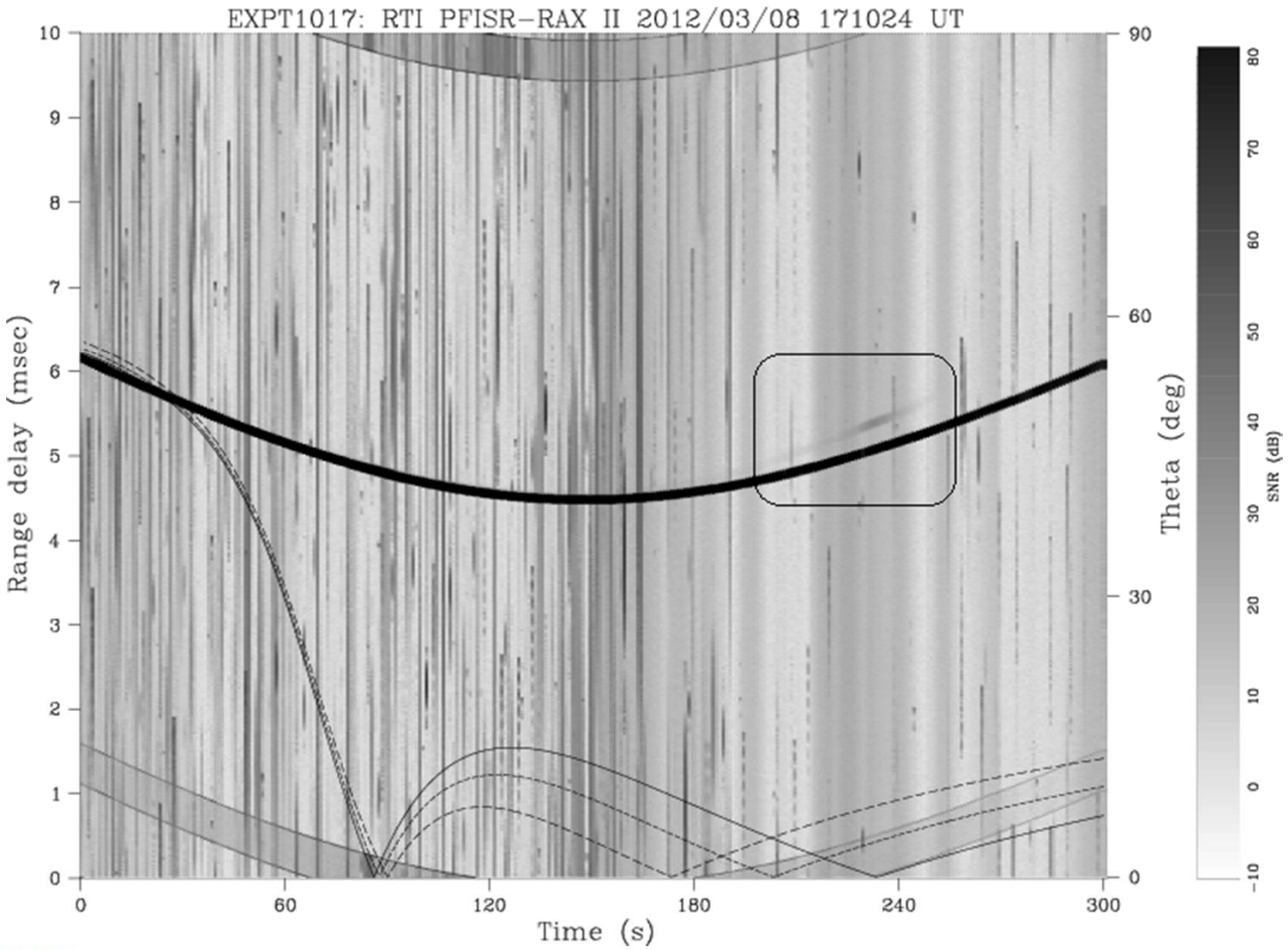
RAX received its first echoes on 8 March, 2012 over PFISR.



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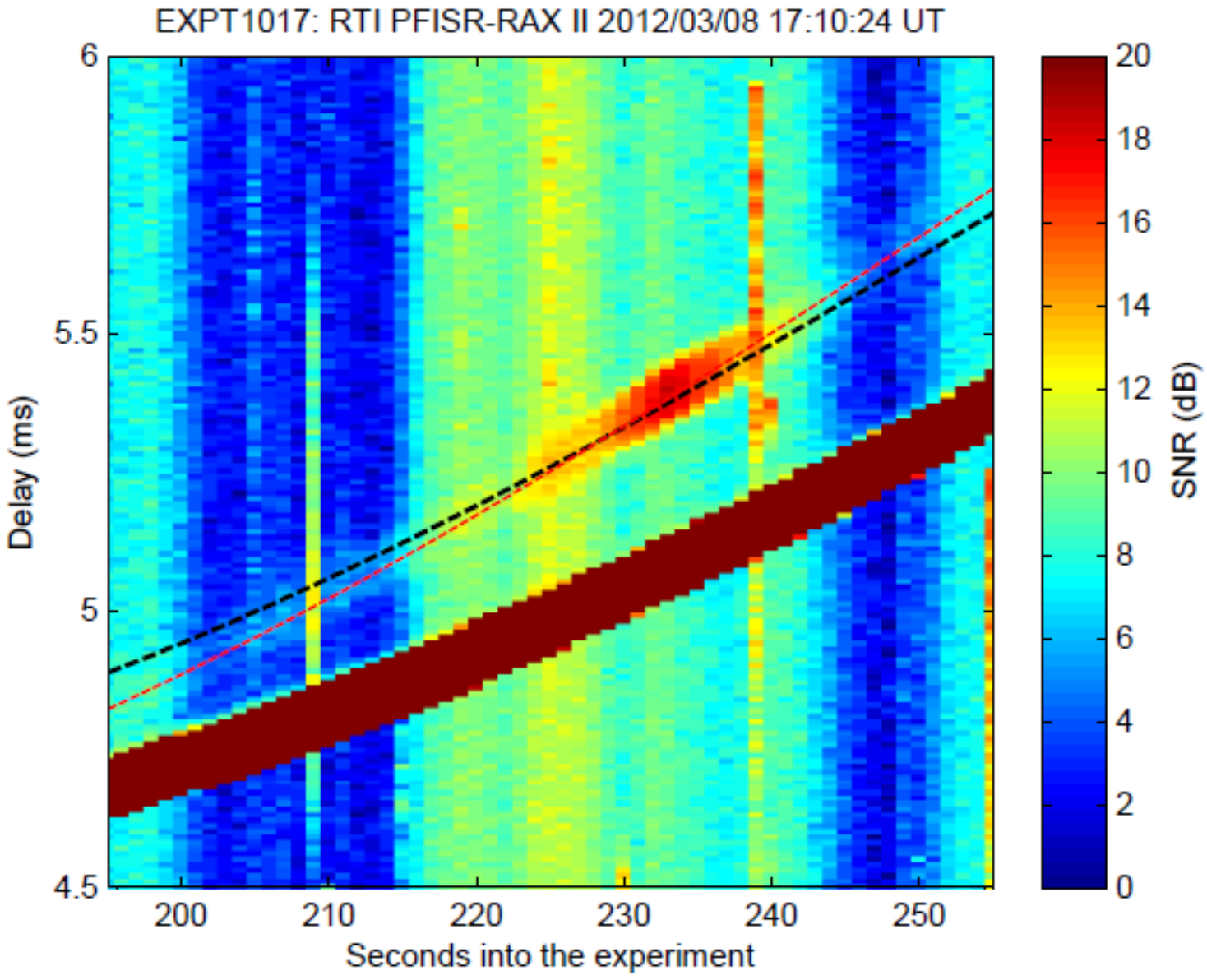
Zoomed in echoes at an altitude of approximately 100km as marked by the black-dashed line.



The peak in SNR corresponds to an aspect angle of 90's.

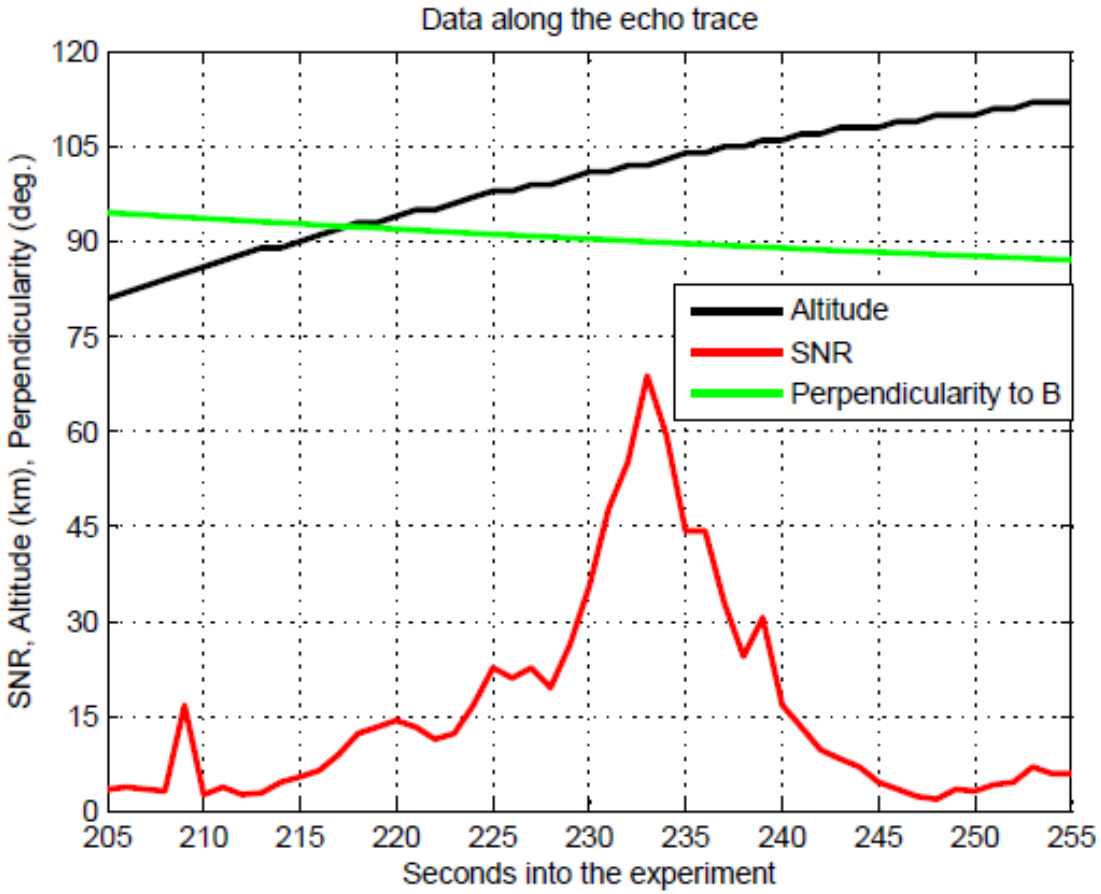
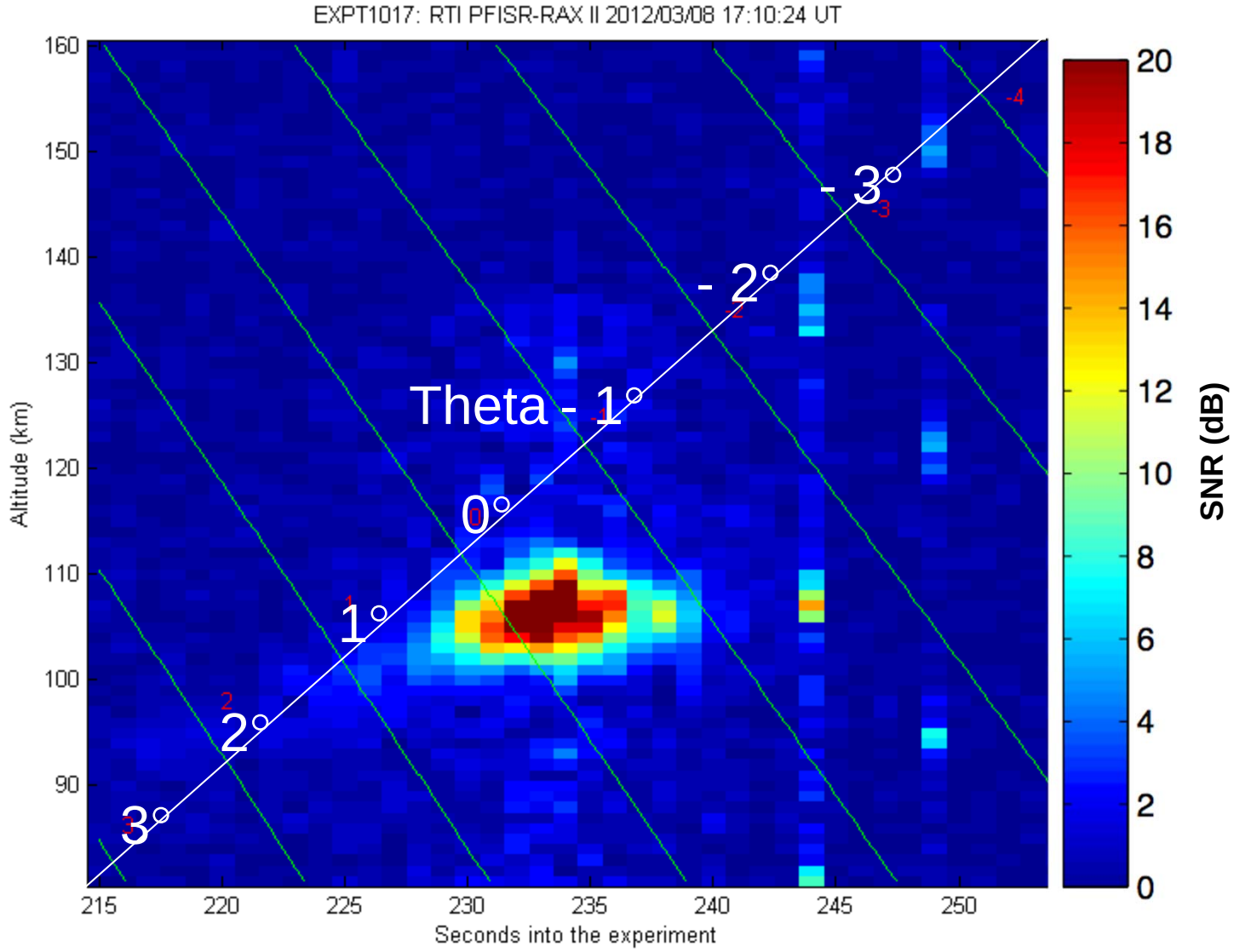


Figure 4. SNR (red line), aspect angle (green line), and altitude (black line) along the red trace shown in Figure 3.

Unprecedented views of the irregularity alignment and distribution.



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Raw data provides additional analysis of doppler and altitude.

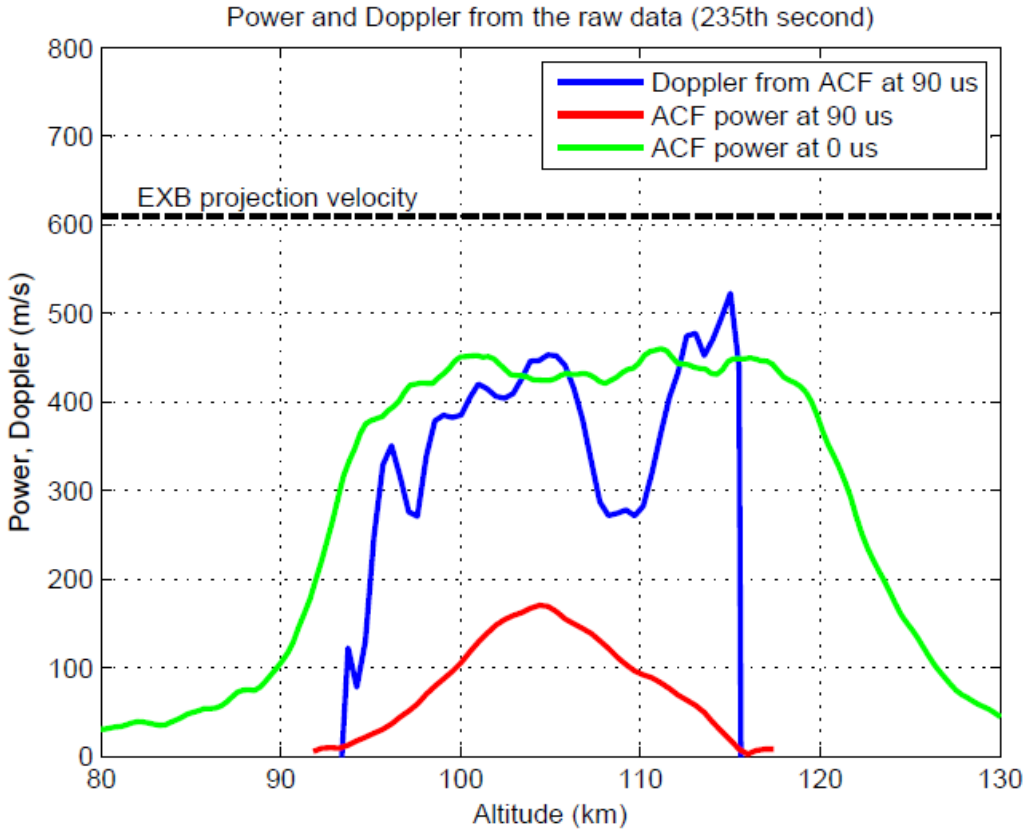
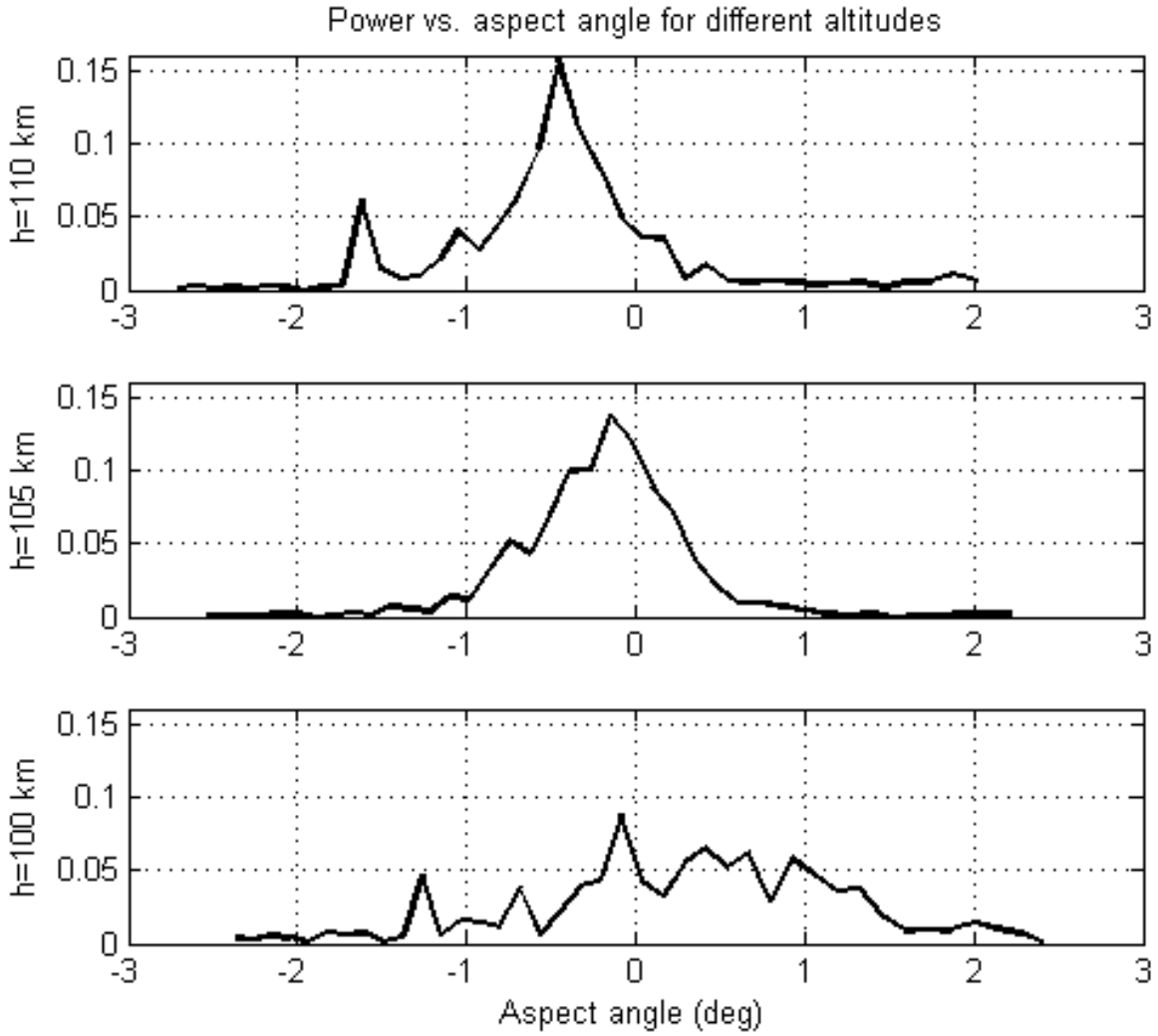


Figure 5. Raw echo intensity (green line), altitude-resolve intensity (red line) and Doppler velocity (blue line) as a function of altitude for the 235th second into the experiment (a vertical cut through the peak intensity in Figure 3).

Raw data provides additional analysis of doppler and altitude.



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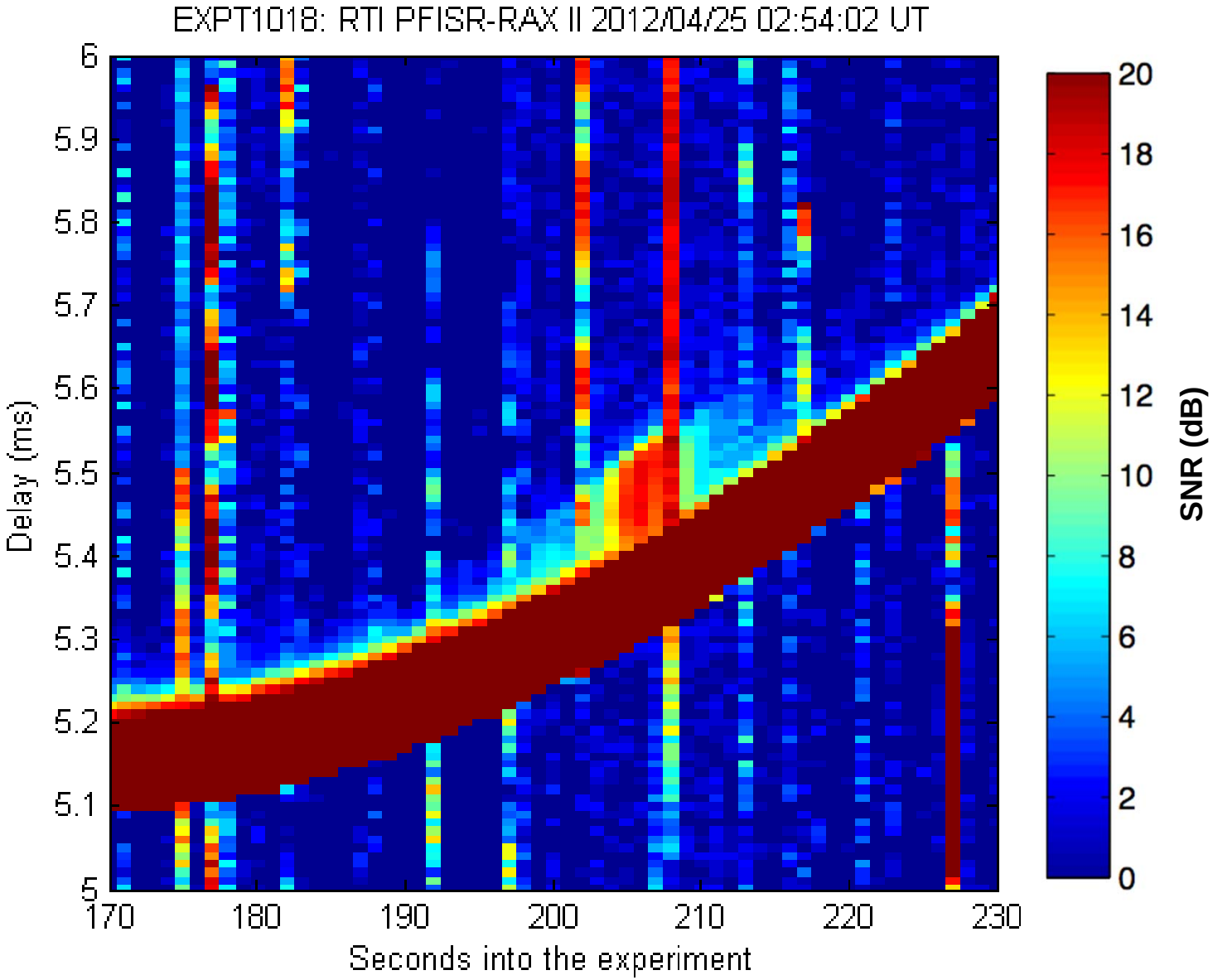
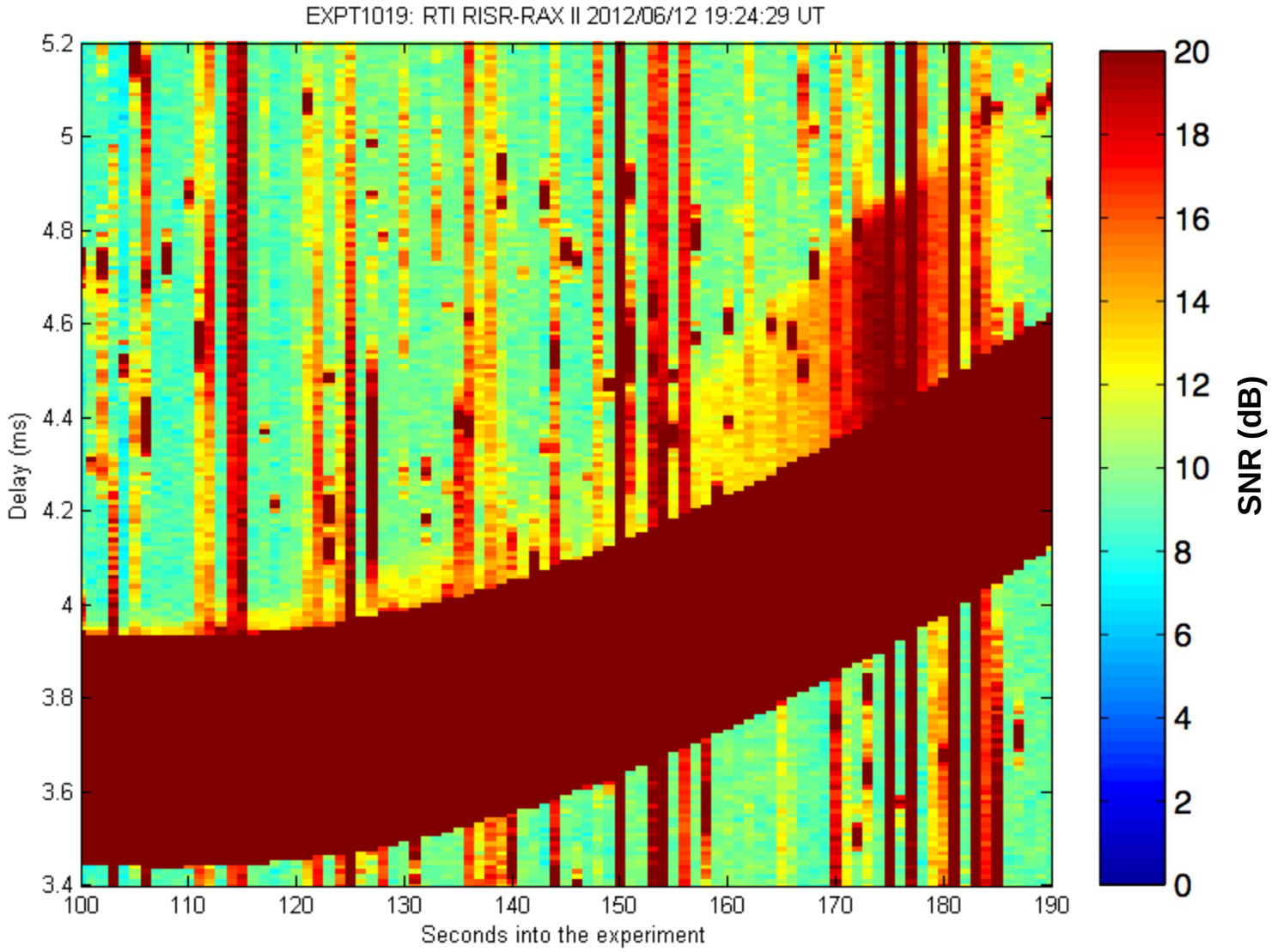
RAX measured echoes over PFISR on 25 April 2012.



RAX measured echoes over RISR in Canada on 12 June 2012.



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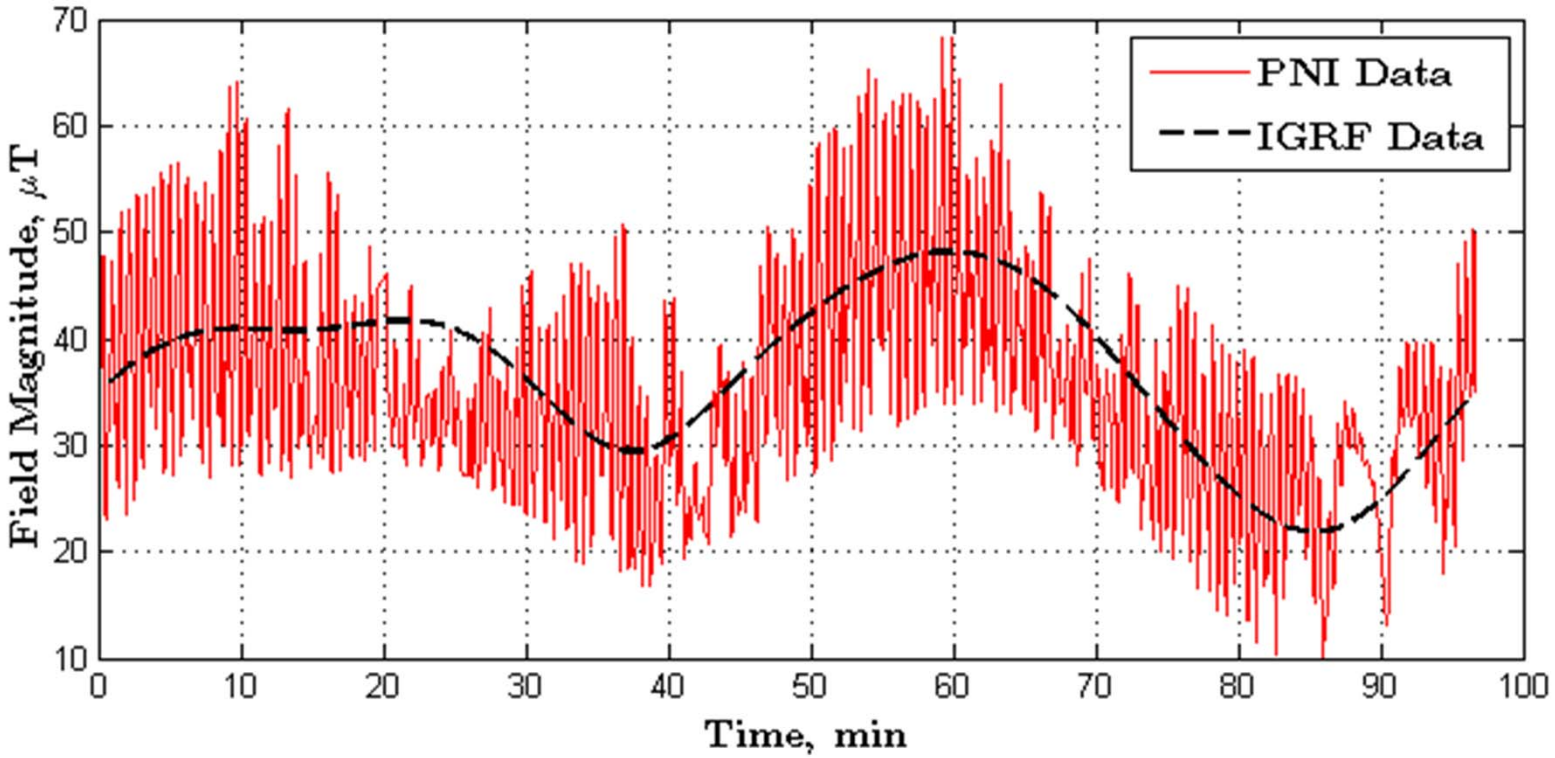
The initial experimental data is extremely interesting and detailed analysis is underway.

- Highest resolution every obtained.
- Irregularities are very mirror like (~0.1 degree at 110) and somewhat less field aligned at 100-105 km.
- Irregularities detected at both crossings of the cone.
- No clear detections from F region, no indication of Post-Rosenbluth instability or any other sub-meter scale instability
- It is also possible that the structures are extremely mirror like, reducing visibility by an ISR.
- Also analyzing the direct pulse data for total electron content and scintillations
- Detailed timing analysis underway of RAX system.

RAX: more with less, better sensing with coarse, distributed sensors.



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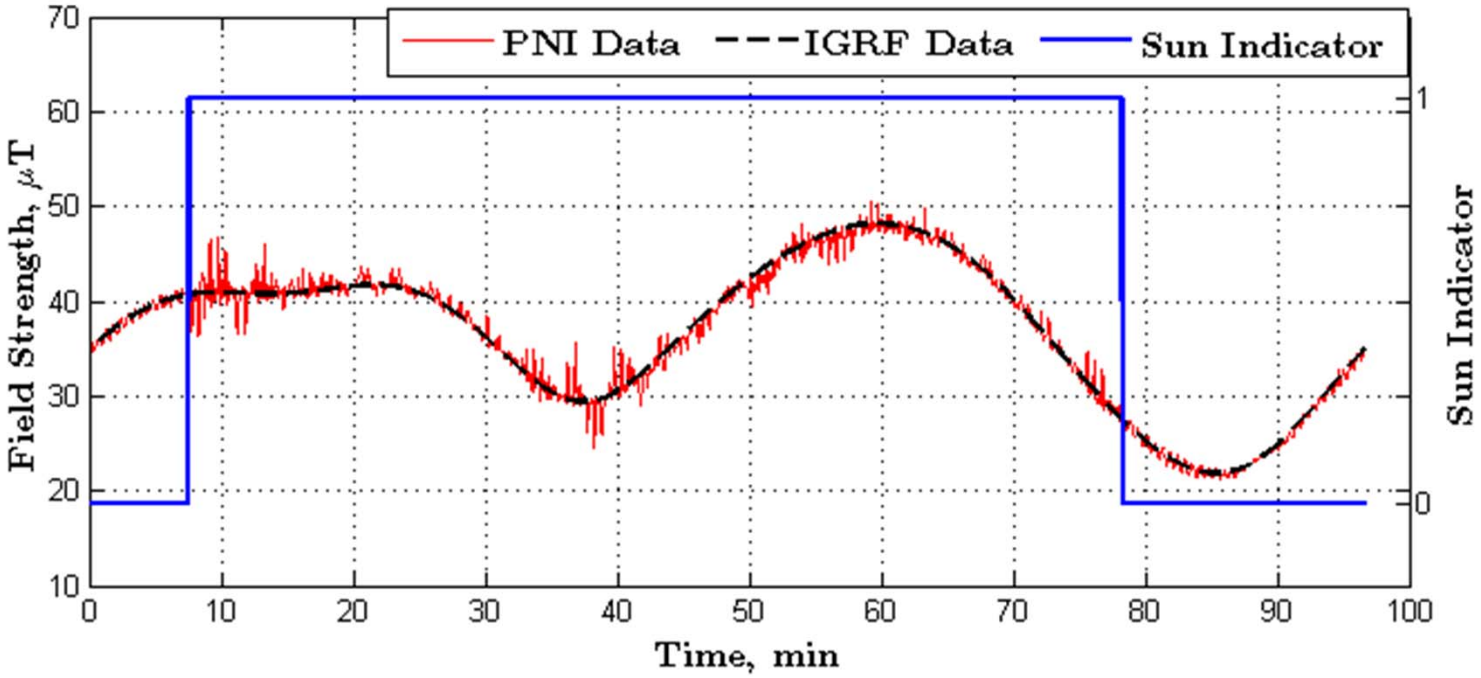

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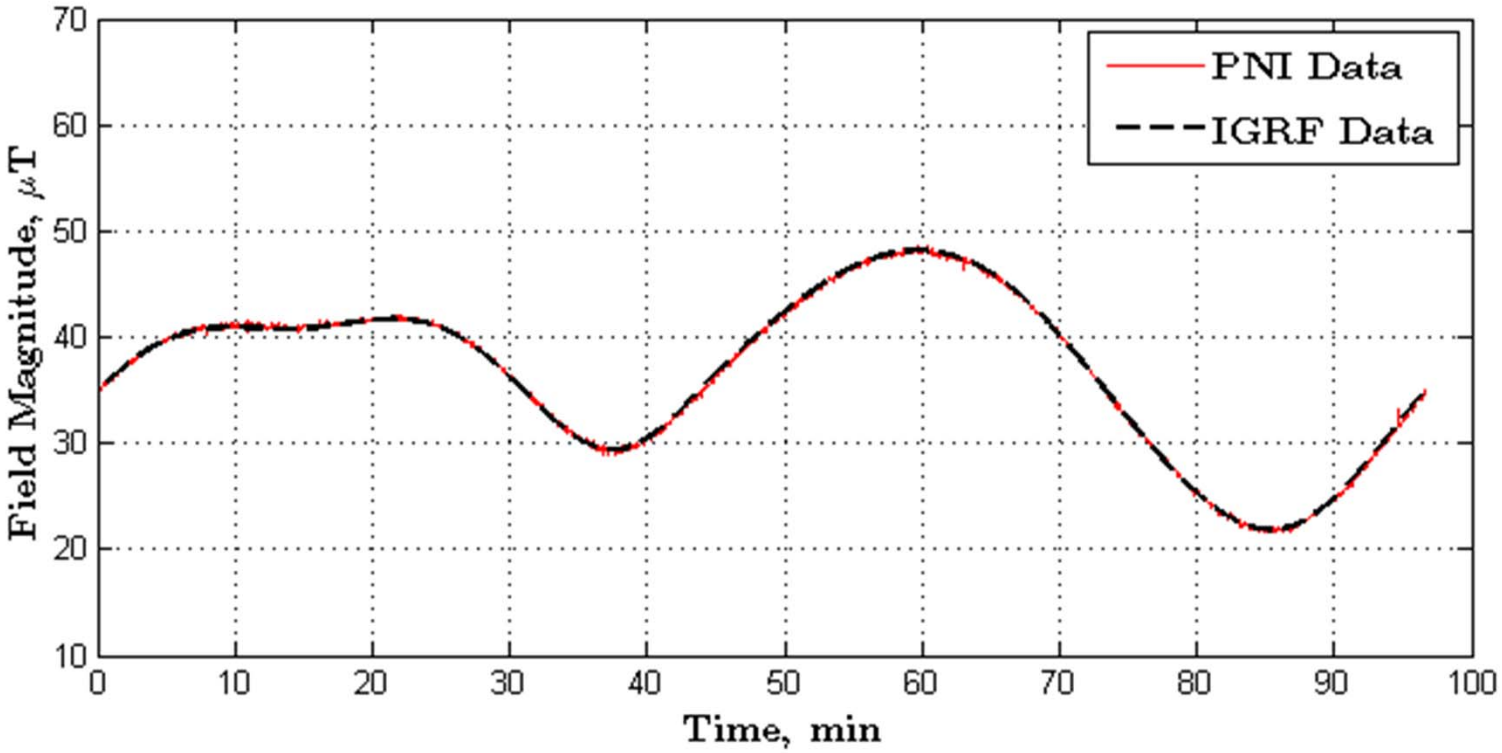

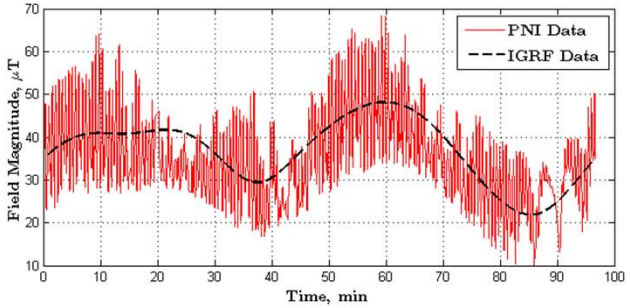

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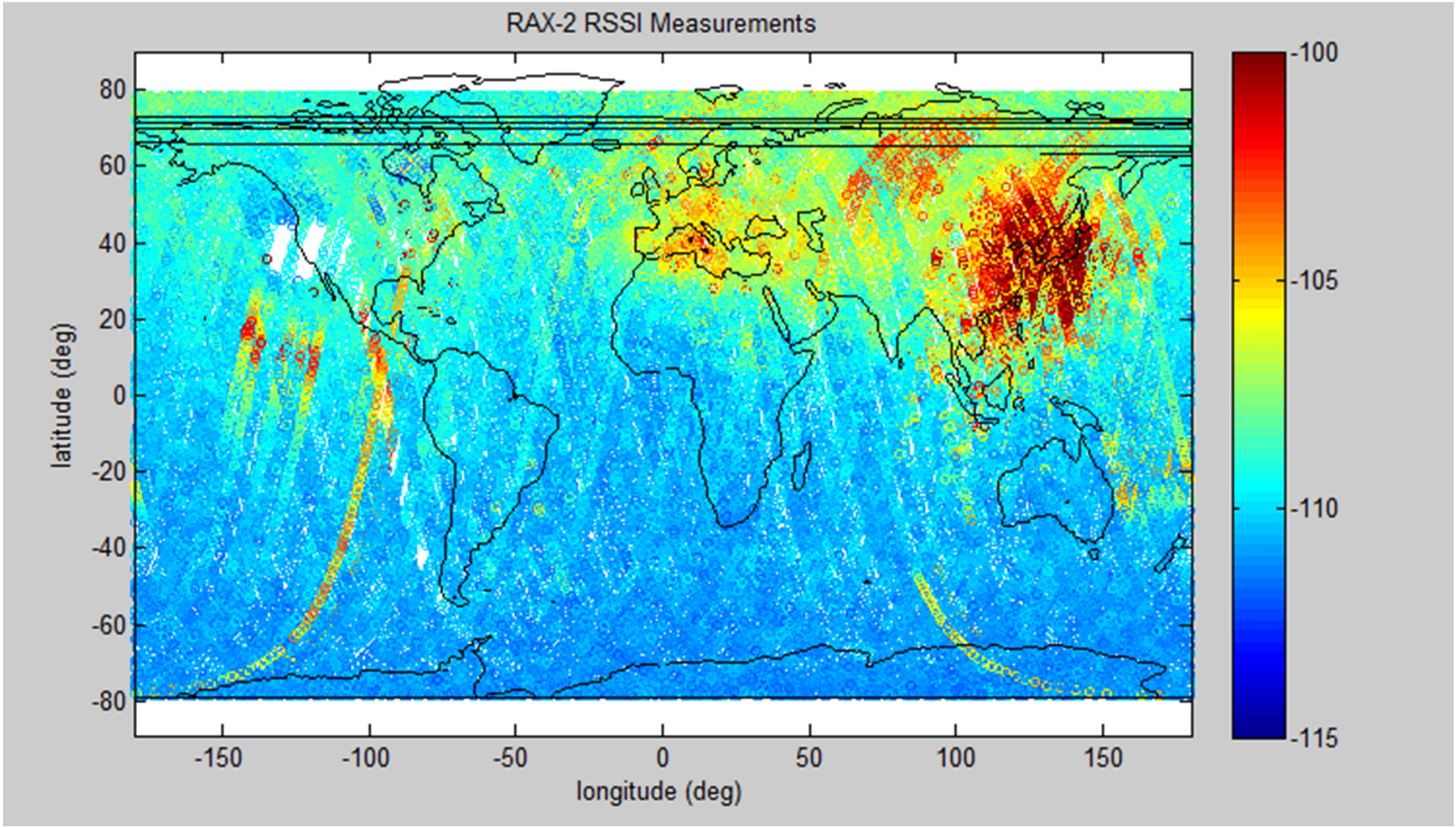
We are making global plots of RFI @ 437 MHz.



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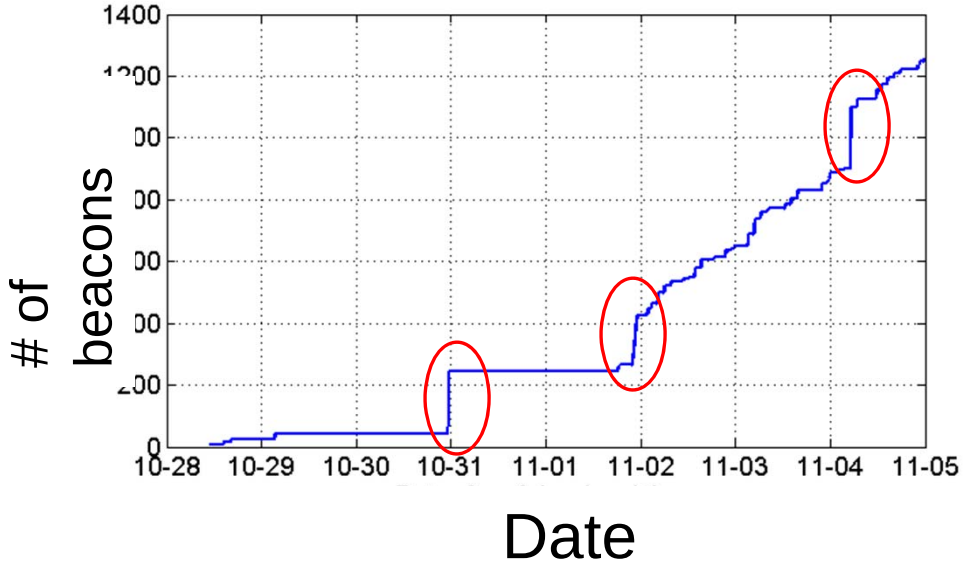
Successful launch, initial beacons heard hours after launch

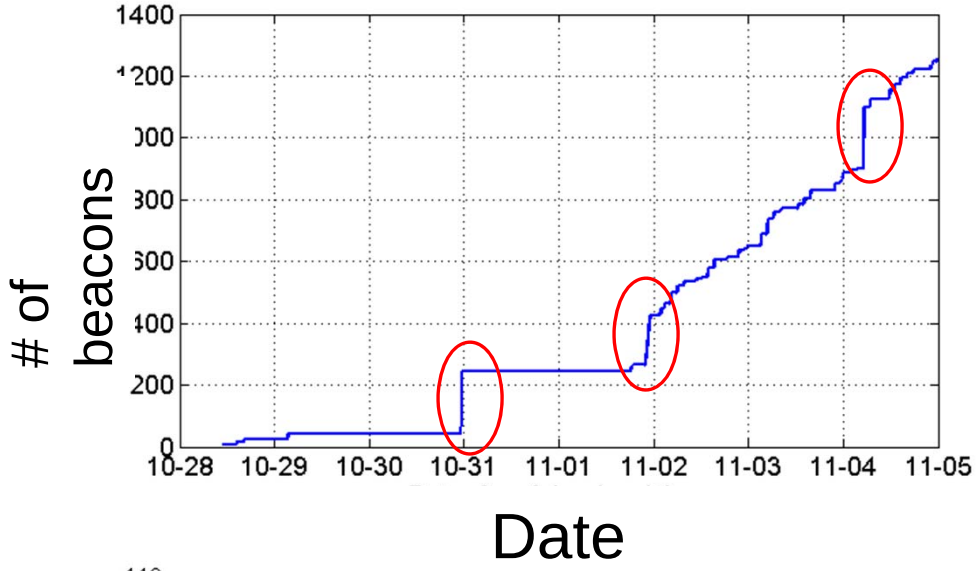
The cumulative number of ***beacons*** heard over the ***first week***:



Circles show batch uploads to the database, which are common early in the mission as HAMs begin using the RAX-2 client. Nominally, beacons are uploaded immediately after decoding.

Successful launch, initial beacons heard hours after launch

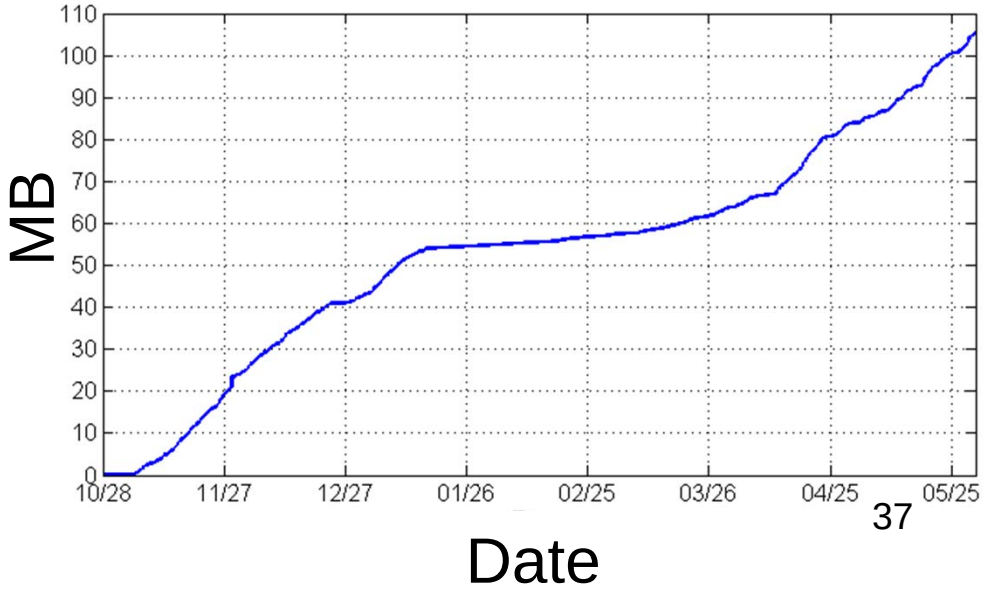
The cumulative number of beacons heard over the ***first week***:



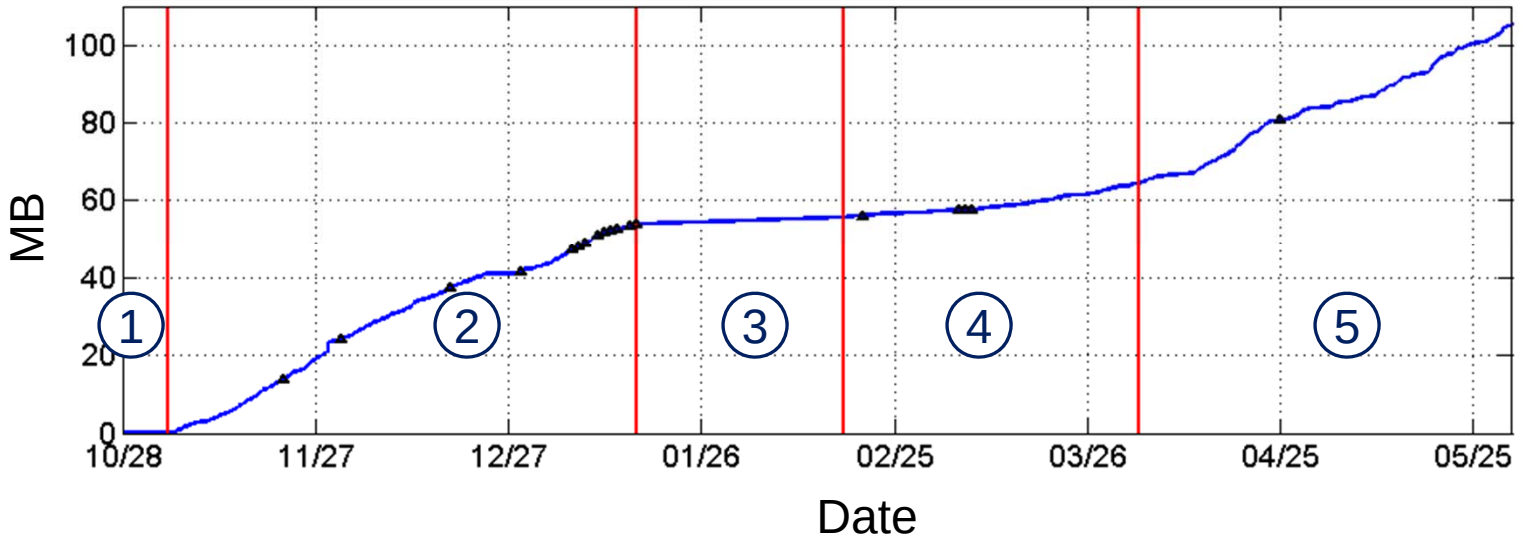
Cumulative sum of total data received, as of ***May 31***:

160,957 beacons and counting

106 MB of data



RAX is full time operations with distinct phases.



1. Initial acquisition, beacon collection , basic commands
2. Full checkout moving to nominal operations. Data downloads scheduled over global HAMs
3. SD card debugging
4. Science capabilities restored. Experiments and downloads resume
5. Full command scheduler implemented without SD card. Aggressive download of unprocessed radar measurements

There are 8 funded NSF Space Weather Missions

Name	PI Org	Science Target	Technique
RAX	SRI U Michigan	Auroral turbulence	Bistatic UHF radar - ISR measured E-Field
FIREFLY	Siena College & GSFC	Terrestrial Gamma Ray Flashes	RF and optical detectors
FIREBIRD	U New Hampshire Montana State U	Relativistic Electron Bursts	Ion Implanted solid-state detectors (2 S/C)
DICE	ASTRA LLc Utah State U	Stormtime E-fields and Plasma Density	Vector E-field, Langmuir probe, magnetometer (2 S/C)
CINEMA	U Cal Berkeley	Energetic Ion, electron and Neutral Drivers	Multi-particle telescope & magnetometer (3 S/C)
CSSWE	U Colorado	Outer Rad Belt & Solar Energetic e^- & H^+	Electron/proton telescope
CADRE	U Michigan	Thermospheric Neutral Comp & Dynamics	Wind, temp & mass spectrometer (WINCS)
EXOCUBE	Scientific Solutions U Wisconsin, Cal Poly	Exospheric Morphology & Dynamics	WINCS tuned for Light Ions and Neutrals

FIREFLY

- Selected in 2008
- Mission to investigate terrestrial gamma ray flashes associated with lightning
- Significant student participation at Siena College
- Currently in-work and awaiting flight manifest
- RAPID award will enable ISS payload deployment

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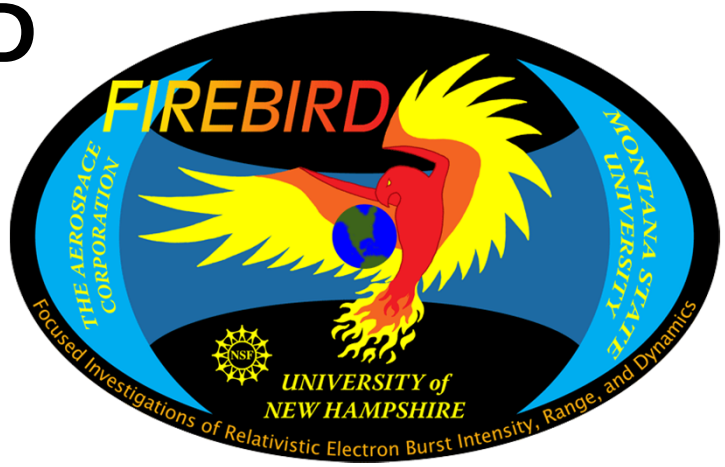
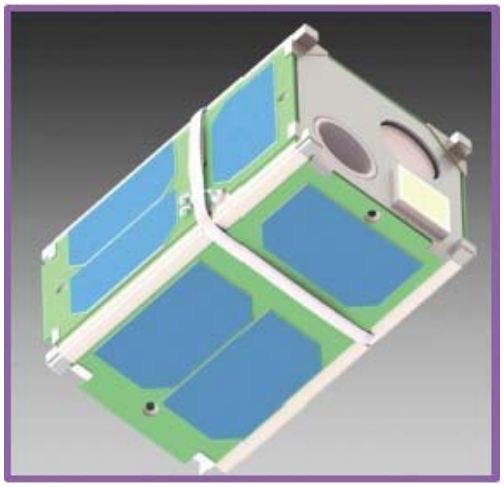
FIREBIRD





- Selected in 2009
- UNH initiated mission to continue the relativistic electron burst measurements of the SAMPEX mission
- 2 identical 1.5U's to explore a range of scale sizes
- Significant student participation at MSU
- Selected for launch 2010 - CDR complete and awaiting launch manifest

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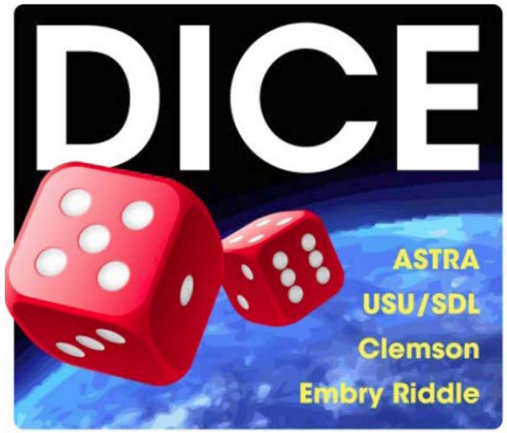
DICE



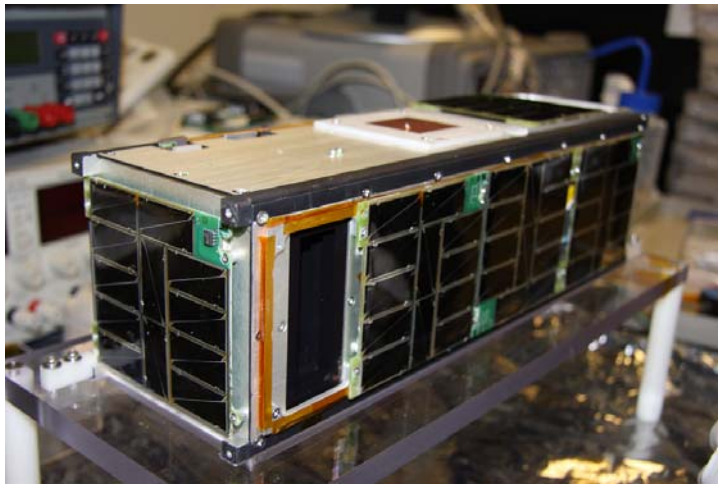
- Selected in 2009
- ASTRA LLC initiated mission to study electric field & plasma structuring associated with storm-enhanced density (SED) plume formation
- 2 identical 1.5Us to explore a range of scales
- Significant student participation at USU
- Launched 10/2011 - Langmuir probe & magnetometer operational - vector E-field sensor deployment initiated

CINEMA

CubeSat for Ions Neutrals Electrons and MAgnetic fields

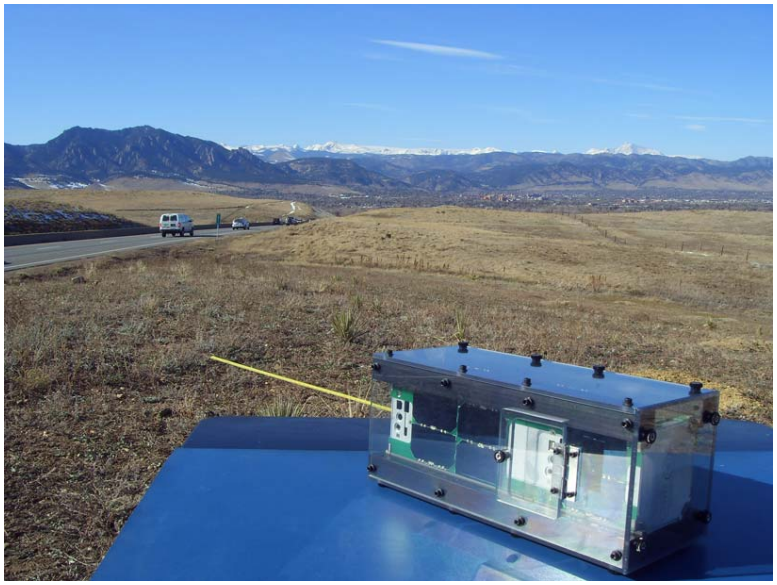
trio cinema

Space Sciences Laboratory, UC Berkeley
Kyung Hee University of South Korea
Imperial College London



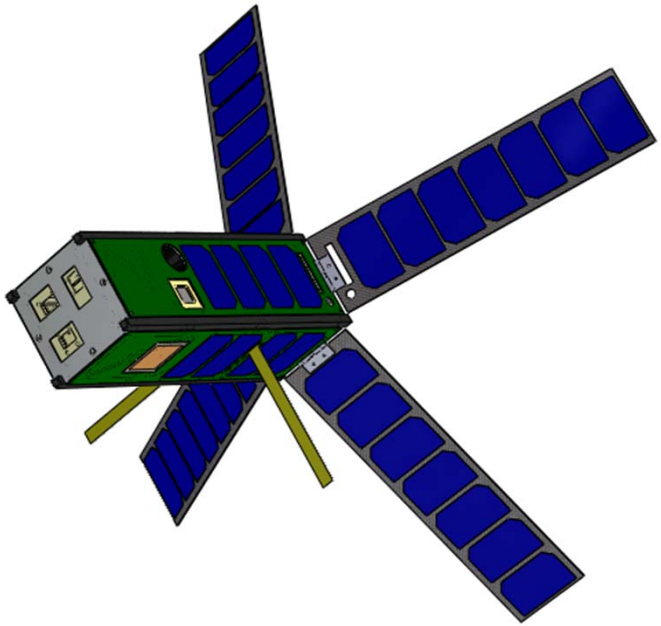
- Selected in 2009
- Berkeley initiated mission to study energetic electron, ion, and neutral fluxes from inner radiation belt
- 2 addition spacecraft provided by Kyung Hee University (South Korea) with ICL magnetometer make this NSF's first international space mission
- Significant student participation at Berkeley and KHU
- Delivered for August 2012 launch

CSSWE



- Selected in 2010
- UC Boulder initiated mission to study differential electron and proton flux spectra from outer radiation belt and the sun
- Delivered for August 2012 launch

CADRE



- Selected in 2011
- U Michigan initiated mission to study composition, winds, and thermal dynamics of the neutral atmosphere
- Selected for launch 2012 - awaiting flight manifest

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EXOCube

- Selected in 2011
- SSI and U Wisconsin initiated mission to study in situ exospheric light ions (H+, He+) and neutrals in coordination with ISRs and optical interferometers
- Significant student participation at Cal Poly SLO
- Selected for launch 2012 - awaiting flight manifest

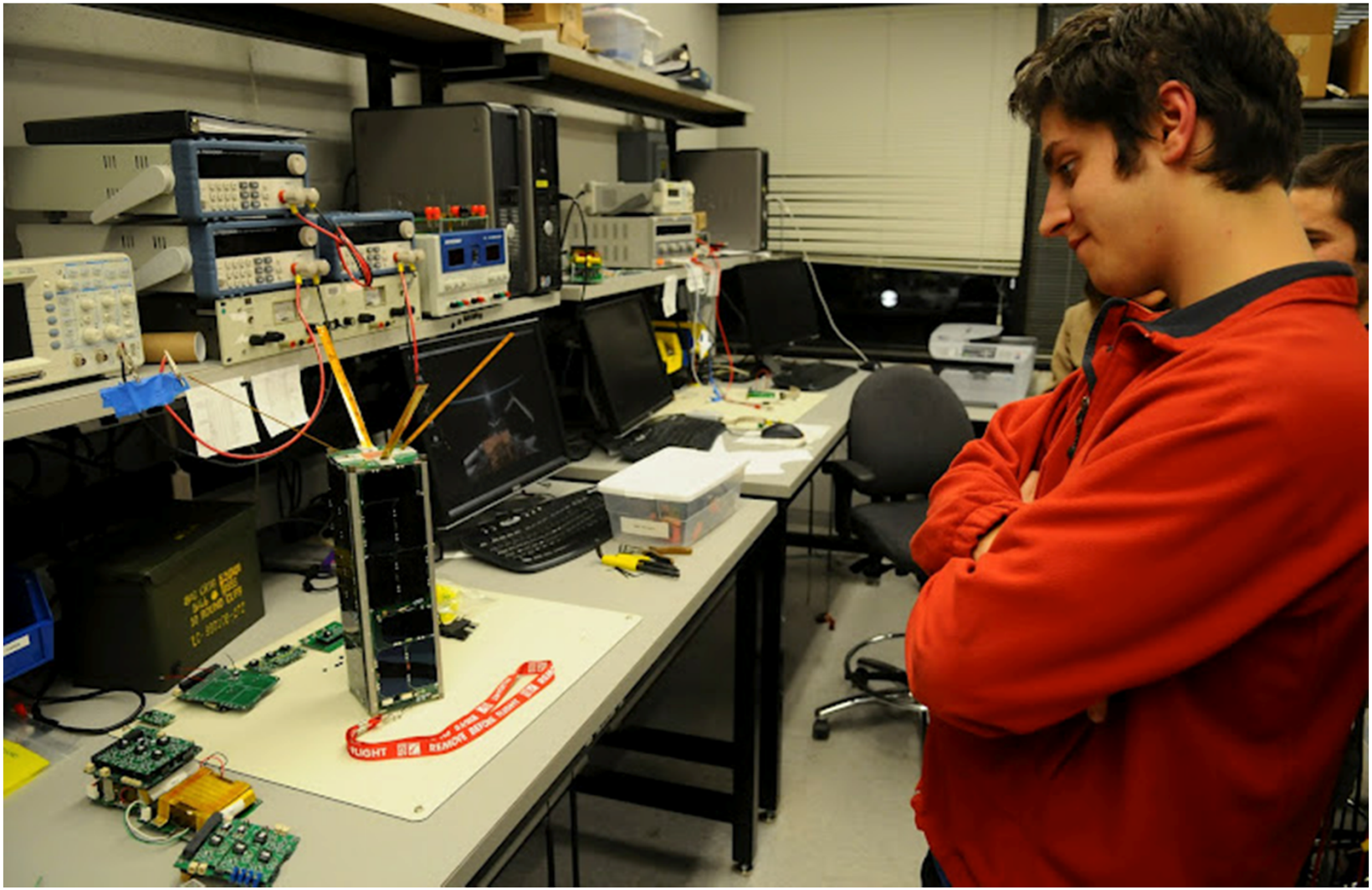
There is a mix of expertise and ages in the lab.

- We have freshmen, postdocs, professors, engineers, and even parents.
- We are local and global.
- Diverse departments
  - Aero, Space Science, EE, CS
  - Need more ME
  - Need writers/dreamers

The manual is in my brain – Matt

The manual is in my brain – Matt

“Why don’t you like me?” “You don’t do anything.”



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"Ben, he's unstoppable. He has reconfigurable pins!" – Eric

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At the heart of every good mission is a crazy scientist.

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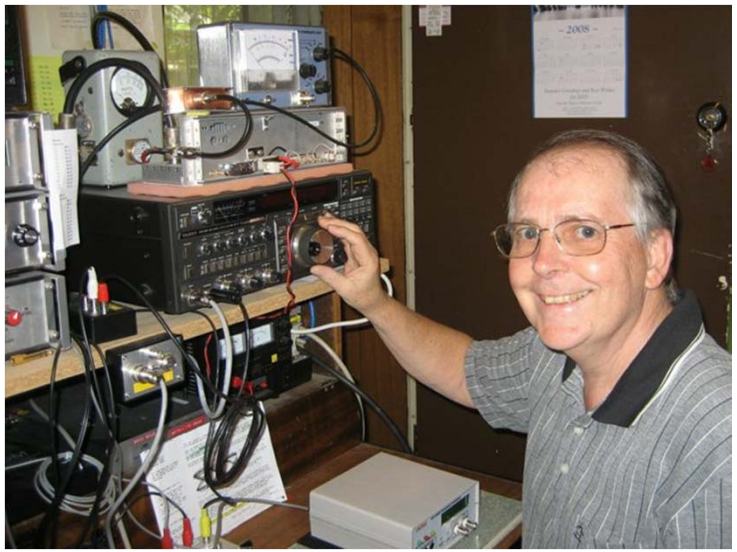
Global “HAMs” are receiving RAX data.



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There are many lessons learned, so here are a couple.

- Failure is a fact…deal with it.
- You need 2-3 benevolent dictators…that can work together.
- You need a sustainable pipeline…a mission machine.
- Open question…
  - Keep Science/Engineering teams on different coasts?

University-class missions are breaking paradigms, enabling new frontiers in innovations.

- NSF-funded missions (and others) are performing low-cost, novel measurements.
- There are *significant constraints* that force and require innovation.
- This is where the space program will be reborn and interest rekindled—it's *a new beginning*.