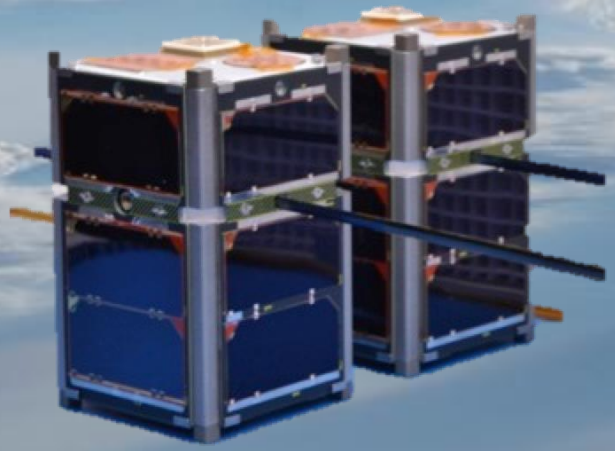
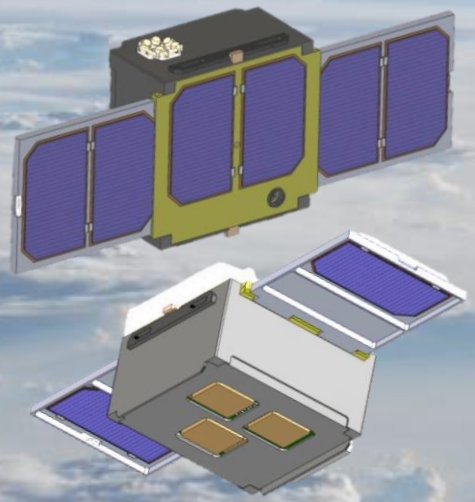
On-Orbit Performance and Lessons Learned from the FIREBIRD-II and AC-6 CubeSat Missions:



Little Packages

Big Science



Harlan E. Spence *(UNH),* ***David Klumpar*** *(MSU),* ***Sonya Smith*** *(UNH)*

With special thanks to J. B. Blake, FIREBIRD and AC6 Teams, "KISS" Team, and T. J. Moretto

University of New Hampshire
Institute for the Study of Earth, Oceans, and Space

SSEL

MONTANA STATE UNIVERSITY

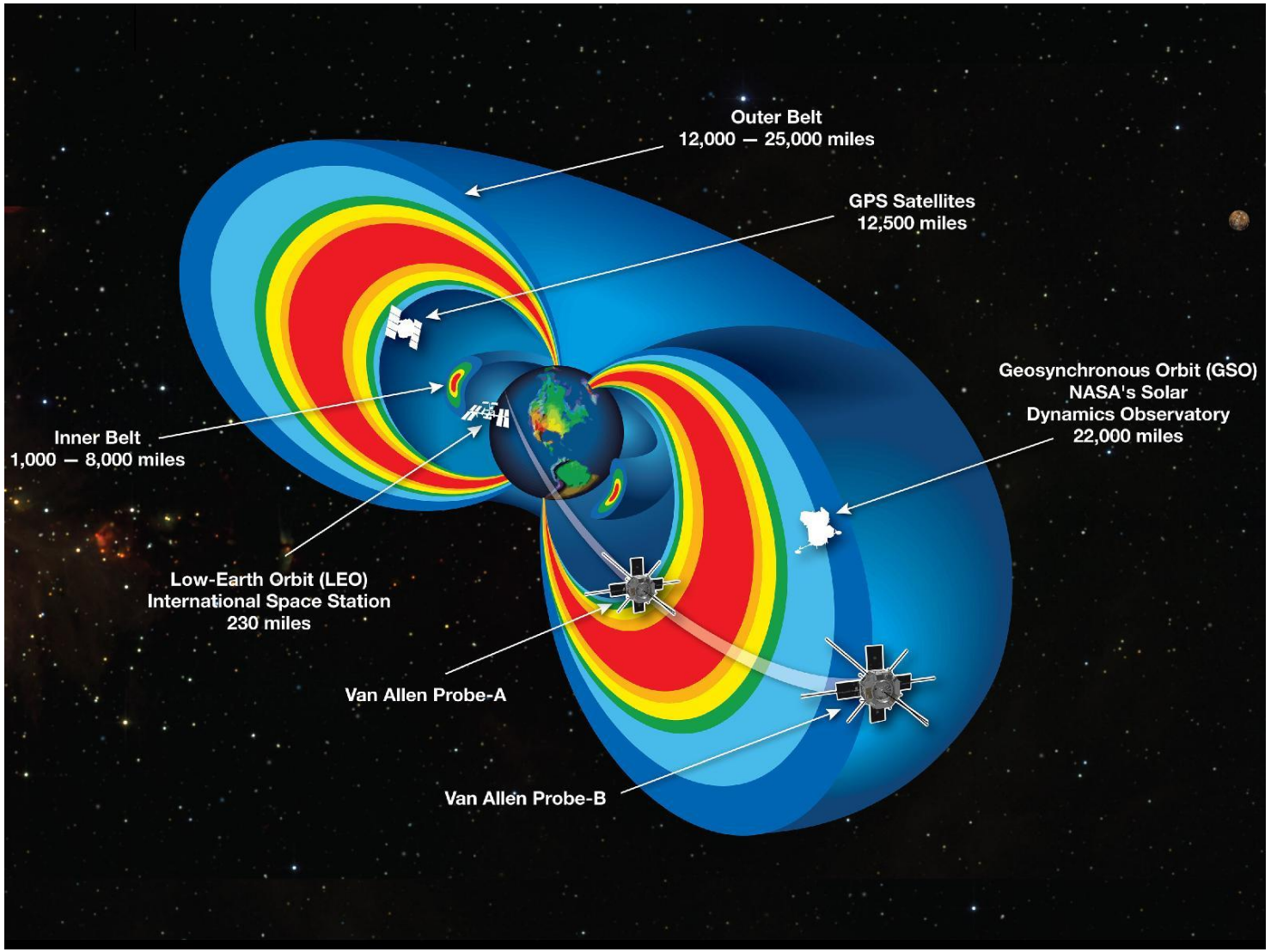
14th Annual CubeSat Developer's Workshop, Cal Poly, San Luis Obispo, CA
Wednesday, 26 April 2017, 10:15-10:45

Background and Overview

- Next decade poses great challenges but also promises great opportunities for space science missions
- 2012 Solar and Space Physics Decadal Survey notes low cadence of new flagship or even large- and medium-cost missions in coming decade (same for Earth Science, Planetary Science, and Astrophysics)
- Survey points out critical value low cost missions (i.e., **CubeSat-base**d) play in providing targeted scientific discovery and training next generation of space scientists/engineers
- **FIREBIRD** and **AC6** – first ongoing examples of such CubeSat missions
- We review these missions, provide a status update, and outline **BIG** science these **little** missions are accomplishing
- Finally, we end with one important lesson learned (bigger straw…)

Motivating Science: Relativistic Electron Microbursts

Electron Microbursts are short (<100ms) bursts of **R**elativistic (>100's keV) **E**lectron "**P**recipitation" (**REP**) into Earth's atmosphere from the radiation belts



Motivating Science: Relativistic Electron Microbursts

- REP important to understand and quantify for two reasons:
  - Potential major source for draining radiation belts
  - Potential major missing source of middle atmosphere physics
- Initial studies in 1960s from indirect balloon x-ray measurements
- REP studied directly in LEO most notably by SAMPEX mission; long lasting mission quantified REP to a great extent (but at limited energies and with a single large spacecraft)
- Despite decades of study with **single spacecraft**, fundamental **space-time ambiguity persists** – REP scientific understanding stalled

2-s/c CubeSat Mission Concepts

- **FIREBIRD-I and -II**: Fly **two** **1.5u** CubeSats in **close proximity** to assess the spatial scale, spatial temporal ambiguity, and energetics of relativistic electron microbursts
  1) What is the spatial scale size of an individual burst? (excellent/very good)
  2) **What is the energy dependence of an individual burst? (excellent)**

- **AeroCube-6 (AC6)**: Fly **two** **0.5U** CubeSat spacecraft in close **time-variable** proximity to assess the spatial scale and spatial temporal ambiguity of magnetospheric microbursts
  1) What is the spatial scale size of an individual burst? (excellent)
  2) What is the energy dependence of an individual burst? (good)

- Low-cost, multi-point CubeSat measurements at low altitudes highly complementary to flagship NA$A Van Allen Probes mission
  - Targeted science highly leveraged; accomplishes science flagship cannot
  - Enormous science return per $

Summary of NSF FIREBIRD-I and -II Missions

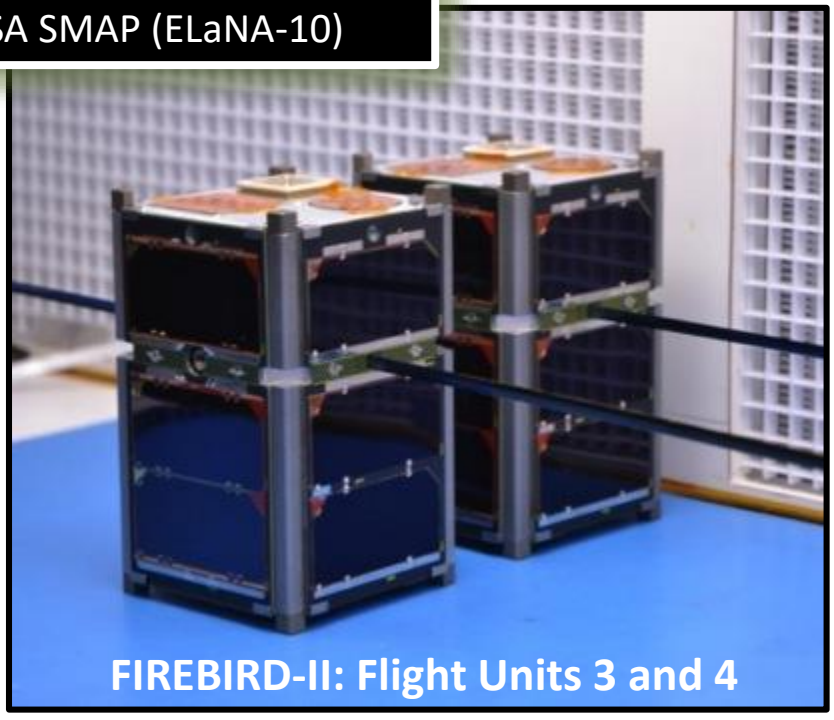
PIs: Harlan Spence (UNH) and David Klumpar (MSU)

FB-I LAUNCHED: Dec 6, 2013
VAFB Atlas-5 NROL-39

FB-II Launched late 2015
VAFB Delta-II 7320 NASA SMAP (ELaNA-10)

FIREBIRD- I: Flight Units 1 and 2

Provided excellent science results;
FU1: 12/13 - 1/14, FU2: 4/14 – 9/14



FIREBIRD-II: Flight Units 3 and 4

Improved version of FB-I mission;
Launched and beautiful data since 1/2015

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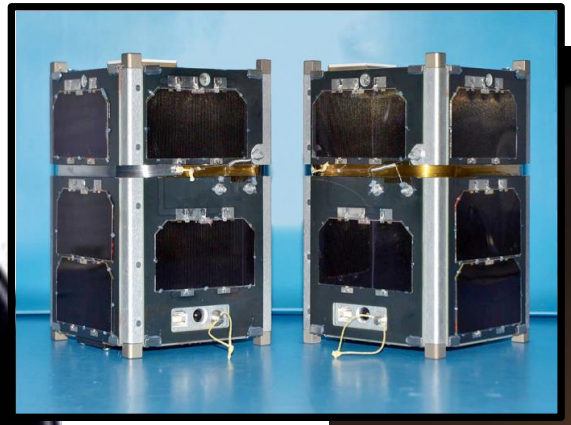
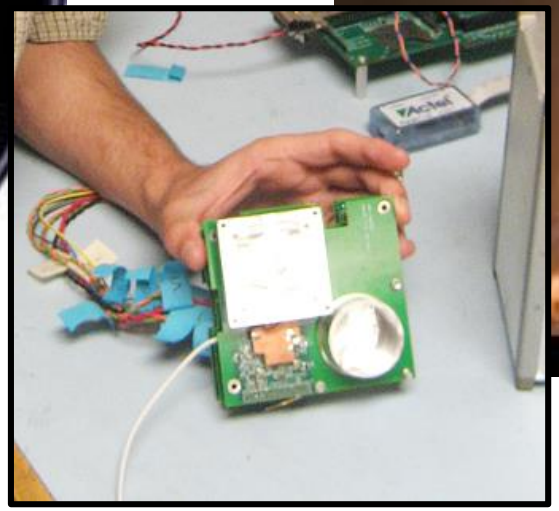
AEROSPACE

Los Alamos NATIONAL LABORATORY

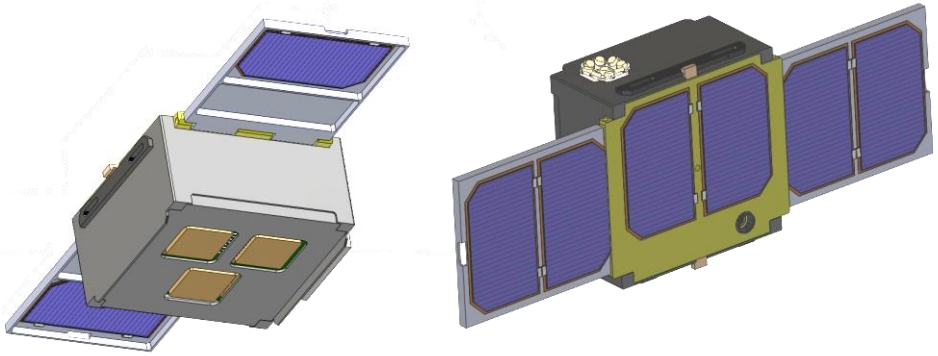
FIREBIRD-I Overview

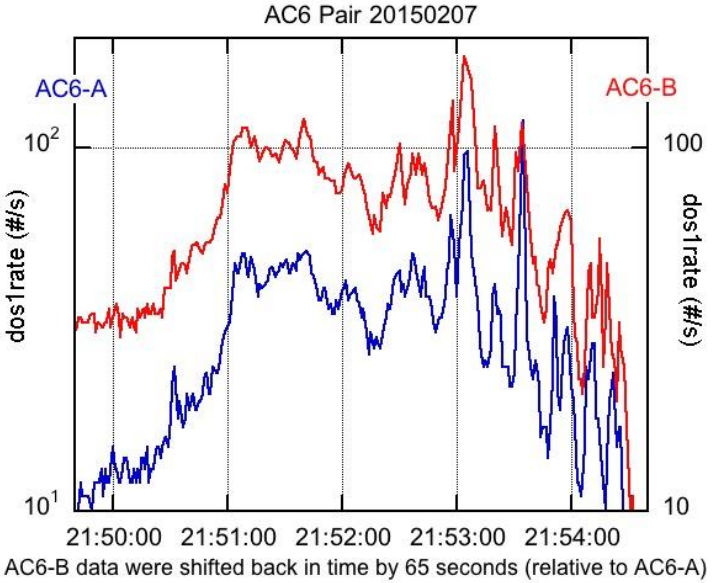
- Initial FIREBIRD-I mission launched in late 2013 from VAFB on an Atlas V, piggy-backing on an NRO launch (“Nothing is beyond our reach”)





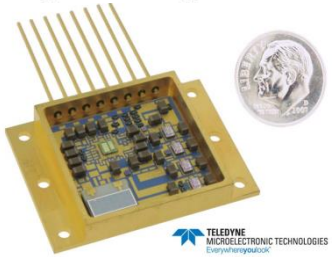
AeroCube-6





- Dnepr launch: **19 June 2014**
- Orbit: 620 x 700 km at 98° incl.
- Payload: **3 dosimeters per s/c**
  – 3 variants never flown before
- Nominal sample rate 1 Hz (i.e., lower) and crude energy spectra
- **Uses differential drag to control spacecraft in-track separation**
- **Still in operation – nearing 3 years – beautiful data!**

Dosimeter Payload:



S/C	ID#	Dosimeter	Measures
A	1	Thin Window Low LET Variant	>50 keV electrons & >600 keV protons
A	2	Thin Window High LET Variant	>600 keV protons
A	3	Standard Teledyne	>1 MeV electrons & >10 MeV protons
B	1	Thin Window Low LET Variant	>50 keV electrons & >600 keV protons
B	2	Thin Window High LET Variant	>600 keV protons
B	3	High LET Variant	>10 MeV protons

FIREBIRD-II Overview

- Follow-on FIREBIRD-II mission launched 31 January 2015 from VAFB on SMAP launch (ELaNA-X) – still going strong – lessons learned

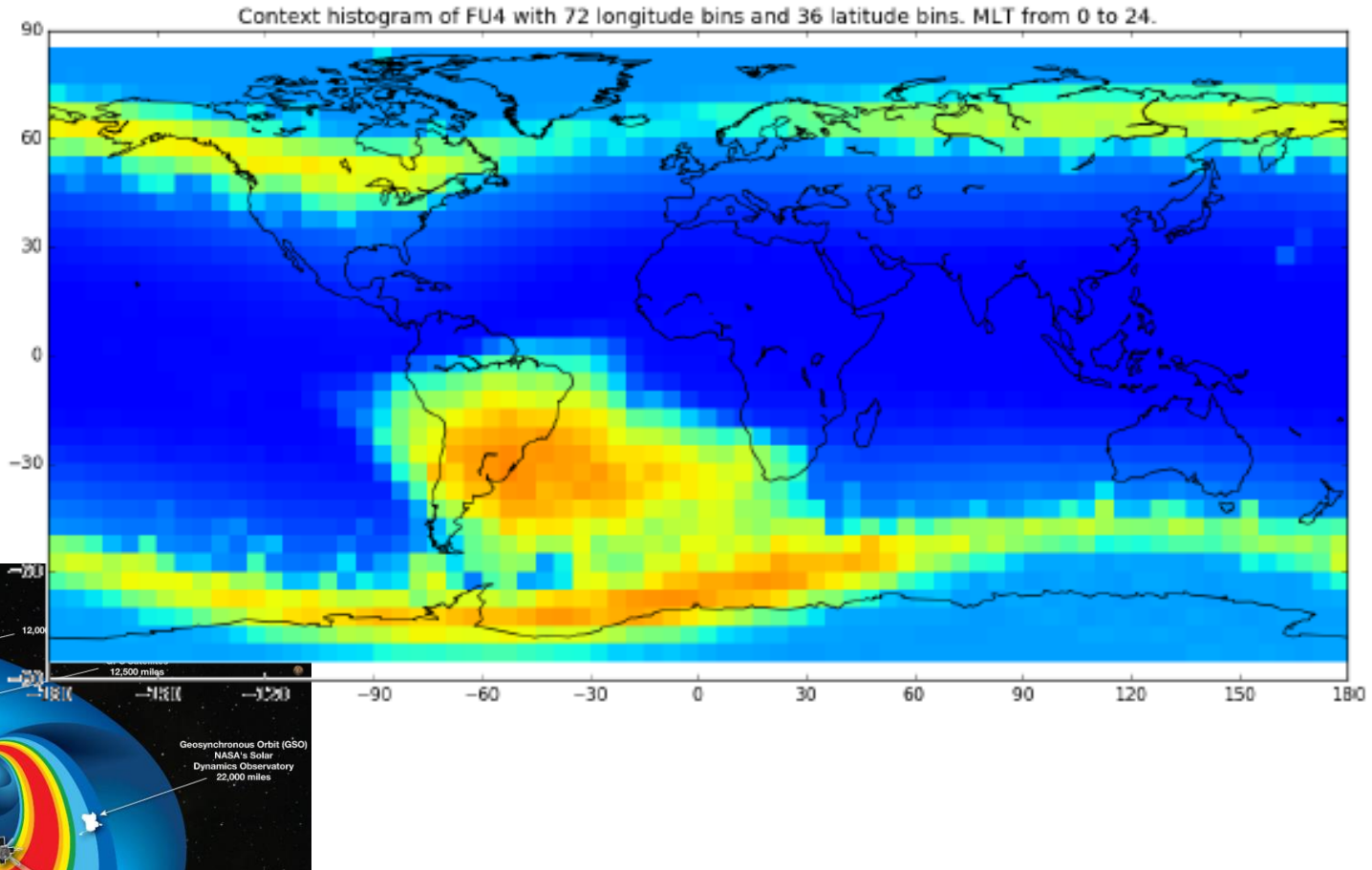
FIREBIRD-II:

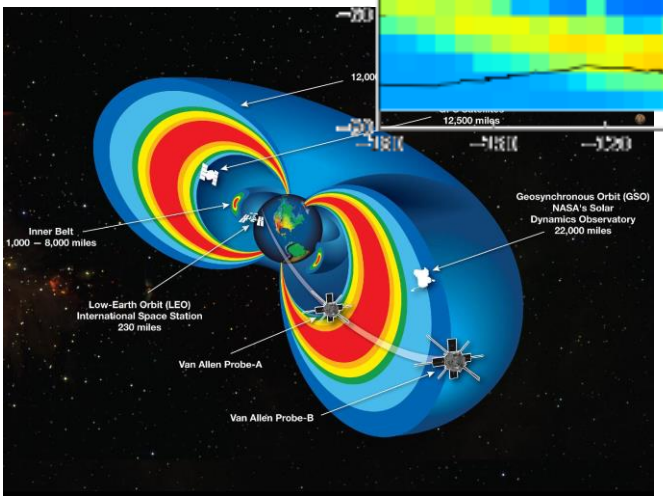
Flight Units 3 and 4
Improved version of FB-I mission (lessons learned);
AWESOME DATA SINCE LAUNCH (2+ years)!!!

FIREBIRD-II Orbit/Data

- 650 x 430km orbit, 99 degree inclination – ground station at MSU
- Typically one Morning (~0600-0800) and one evening (~1800-2000) pass per orbit, but morning passes are heavily prioritized
- “Context” data – low time/energy resolution – minimal volume

FU4 Context Data (Campaigns 1-9)
~ 1 MeV electrons





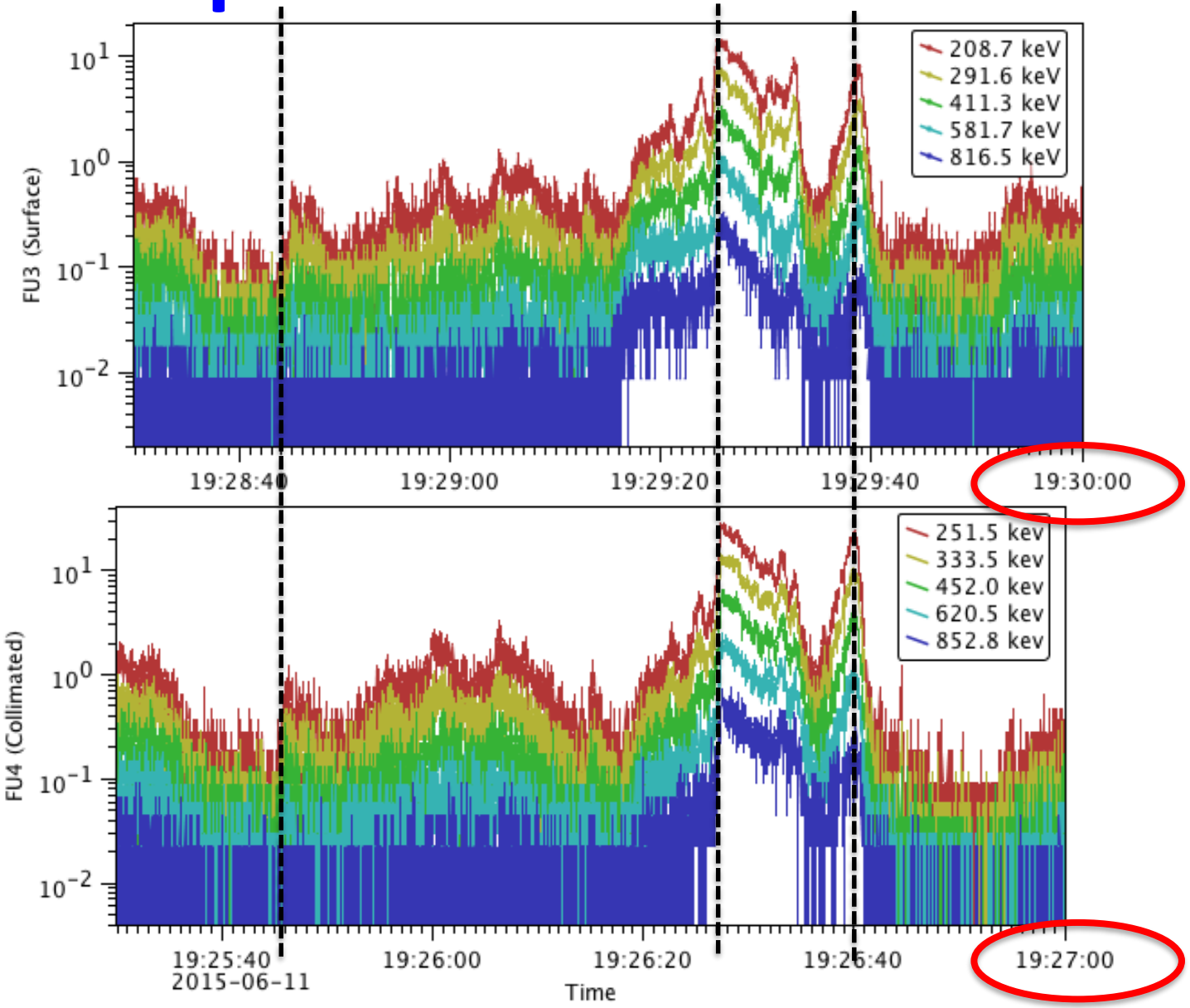
FIREBIRD-II Orbit/Data

- Hi-Res data – high time/energy resolution - LARGE volume
  - **VERY** limited HiRes data availability - ConOPS uses context data to hunt for proverbial scientific “needles in haystack”

- ConOPS successful but **big lesson learned** – we return to this at the end of this talk - **need a MUCH bigger data pipe for science**!!)

First unambiguous evidence of REP spatial structure

- Examples of temporally persisting (3 minutes) spatial REP bands
- A single s/c interprets REP as temporal
- Similar REP spatial structures seen also by AC-6



FIREBIRD-II/AC6 Science Summary

- **New Science and Discoveries – Big things come in little packages!**
  - ✓ First spatio-temporal disambiguation of microbursts down to 1.5 seconds (~10 km) of dual spacecraft separation
  - ✓ Highest combined time (12 ms) and energy resolution (12-point energy spectra from 200 keV to ~1.1 MeV) of REP microbursts
  - ✓ First observation of energy-dispersed REP microbursts

- **FIREBIRD science and mission overview**
  - **Spence, H. E., et al., (2012)**, Focusing on Size and Energy Dependence of Electron Microbursts From the Van Allen Radiation Belts, *Space Weather, 10*, S11004, doi:10.1029/2012SW000869.
- **FIREBIRD mission technical details**
  - **Klumpar, D., et al.,(2015)** Flight system technologies enabling the twin-CubeSat FIREBIRD-II scientific mission, *Proceedings of the 29th Annual AIAA/USU Conference on Small Satellites,* Technical Section V: Year in Review, SSC15-V-6.
- **FIREBIRD first science results**
  - **Crew, A.et al., (2016)** First Multipoint In Situ Observations of Electron Microbursts: Initial Results From the NSF FIREBIRD-II Mission, *J. Geophys. Res.,* DOI: 10.1002/2016JA022485.
  - **Anderson, B. R., et al., (2017)** Spatial Scale and Duration of Microbursts on 13 August 2015, *J. Geophys. Res - Space, in press.*

Optical Communication: An Enabling Technology for CubeSat Missions

- Low resolution "context" data (6-second resolution) – 4 kB/orbit
- High resolution "microburst" data collected at ~12 ms resolution x 2 instruments x 2 s/c – ~**11 kB/second** – dominates date volume
- Operate in science mode for entire orbit (rather than a small fraction) – 50 MB/orbit (or ~**800 MB/day** or ~24 GB/month)
- If better comm option when proposed, then design would have driven at least another factor of 4 in terms of data (x2 in time resolution, x2 in energy resolution) → **44 kB/sec** → **1.6 GB/day**
- **Keck Institute for Space Science (KISS) workshop currently finalizing report on optical communication as critical enabling technology for CubeSat missions; TRL is improving and will achieve this sort of requirement – please see me or David Klumpar this week for more information!**

Summary and Conclusions

- While CubeSat science missions such as described today will not likely ever replace the larger strategic missions, in the coming decade they will provide fresh, vibrant opportunities for innovative approaches on PI-led missions

- These missions would stand alone scientifically as well as complement, augment, and provide continuity and community engagement and opportunity between the larger strategic missions that demand more resources.

- The community should continue to develop these innovative approaches, and the **funding agencies should continue to grow a funding wedge to support them, including further development of enabling technologies such as optical laser communication!**

Those who assert …

"It cannot be done"

… should never interrupt those who are already doing it.

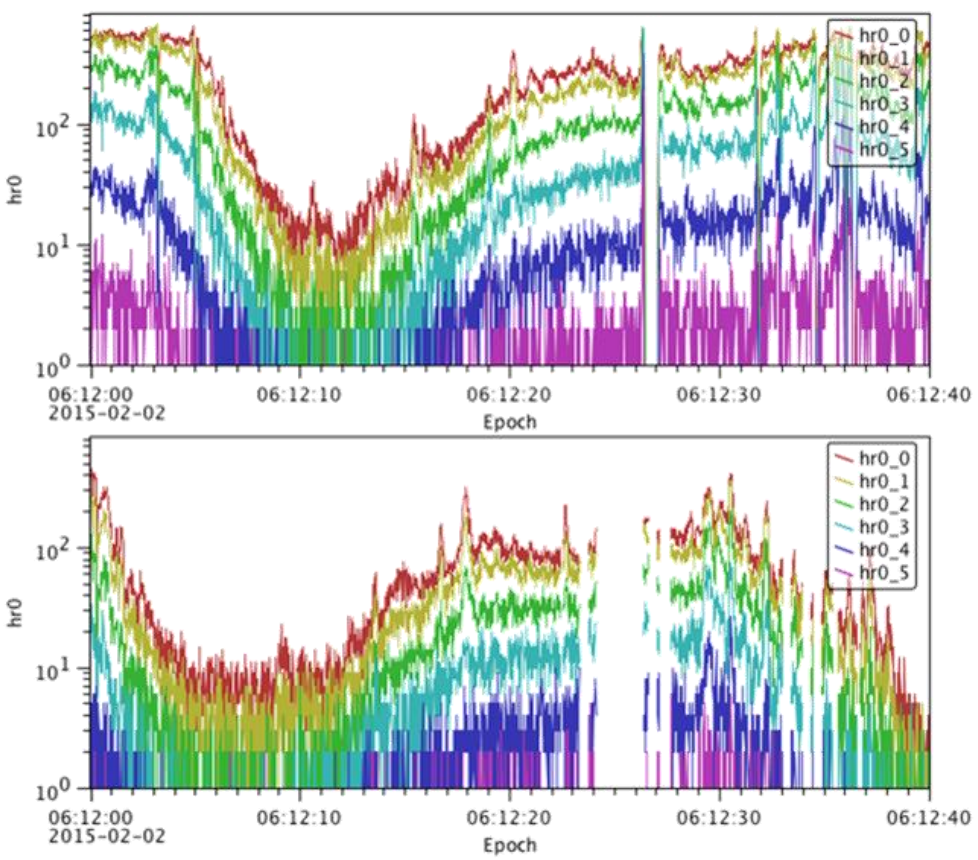
Back-up slides

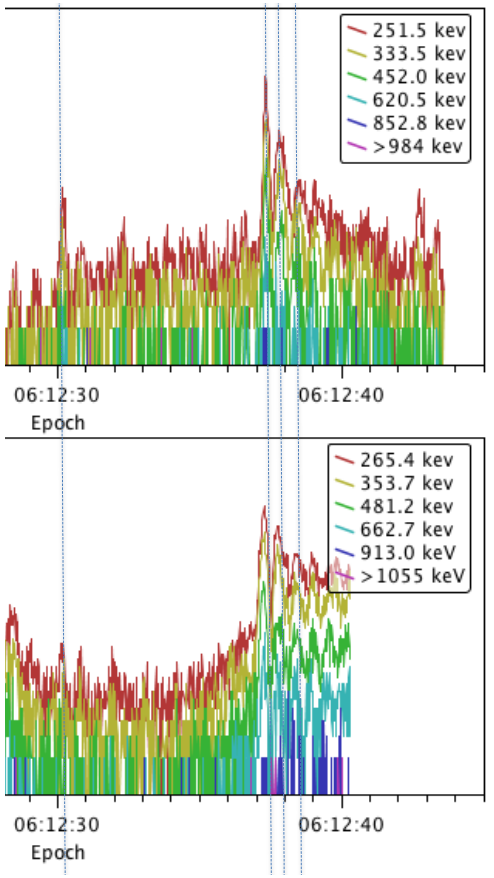
FIREBIRD-I: Flight Unit 1(FU1) and FU2 Timelines

Date	Mission Time (days)	FIREBIRD - FU1	FIREBIRD - FU2
12/15/2013	0	Launch!	Launch!
12/16/2013	1	No contact	First packet decoded, normal operations begin
12/30/2013	15	" "	2BG NAND flash drive full of science data
01/07/2014	17	" "	NAND flash cleared and data acquisition recommences
01/21/2014	31	" "	FU2 latches up, no signals heard
01/22/2014	32	" "	FU2 reset, beacons decoded
01/26/2014	36	" "	FU2 latches up again, end of regular data stream
04/12/2014		FU1 awakes and begins taking data	FU2 still sends occasional undecodable packets, and remains uncommandable
04/25/2014		First FU1 packet decoded	" "
04/27/2014		FU1 command sequence bug resolved	" "
04/28/2014		FU1 configured for normal ops, some decoding problems	" "
06/14/2014	Effective end of science ops	FU1's 2 GB NAND flash drive cleared	" "
09/15/2014		FU1 power system fading, downlinks limited to daylight only	Still booting and sending beacon occasionally, but not accepting commands; power system still not reporting telemetry, battery capacity continues to degrade
Mission Data Totals	28.7 MB	23.0 MB (including 18.5 and 2.25 MB of Hi-Res and Microburst data)	5.7 MB (including 3.6 and 2.0 MB of Context and Hi-Res data)

FIREBIRD-II: Microbursts Galore!

- Launched just before January 2015 storm - lots of examples when spacecraft were in close proximity and seeing REP microbursts
- Excellent energy spectra at highest time resolution over time when spacecraft were in the <100 km separation range (1/31 to 2/21/15)





References

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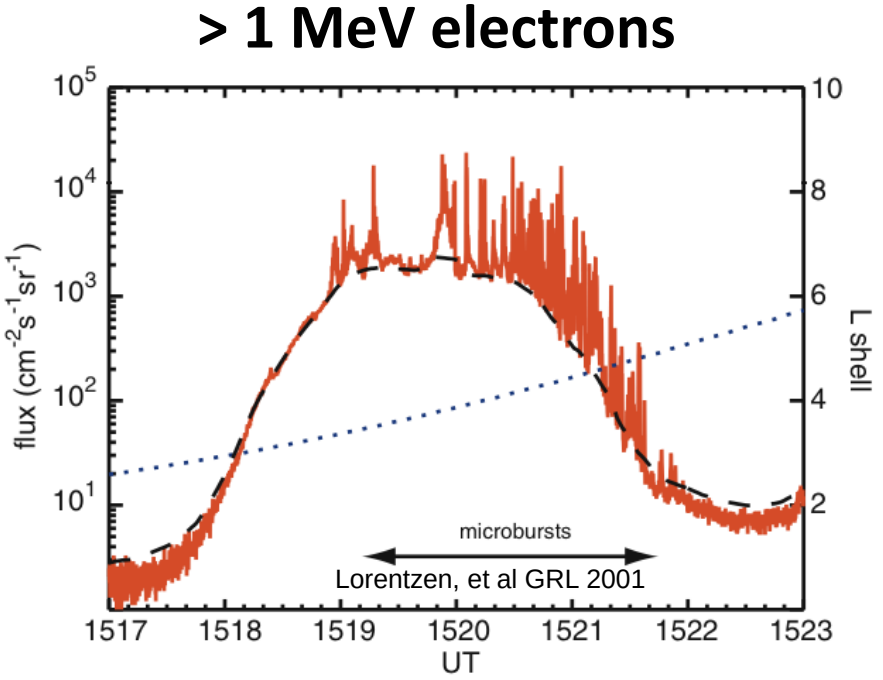
  - Anderson, B. R., et al., Spatial Scale and Duration of Microbursts on 13 August 2015, *J. Geophys. Res - Space, in press, 2017*.

SAMPEX Observations - Are REPs a Temporal or a Spatial Feature?



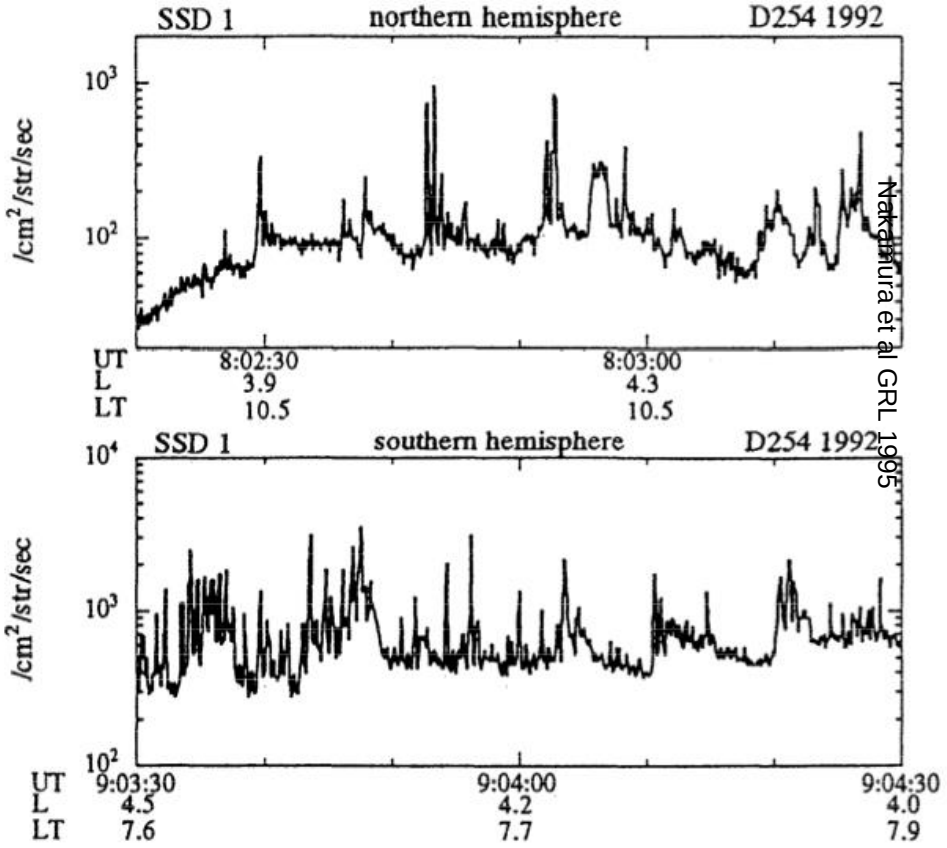
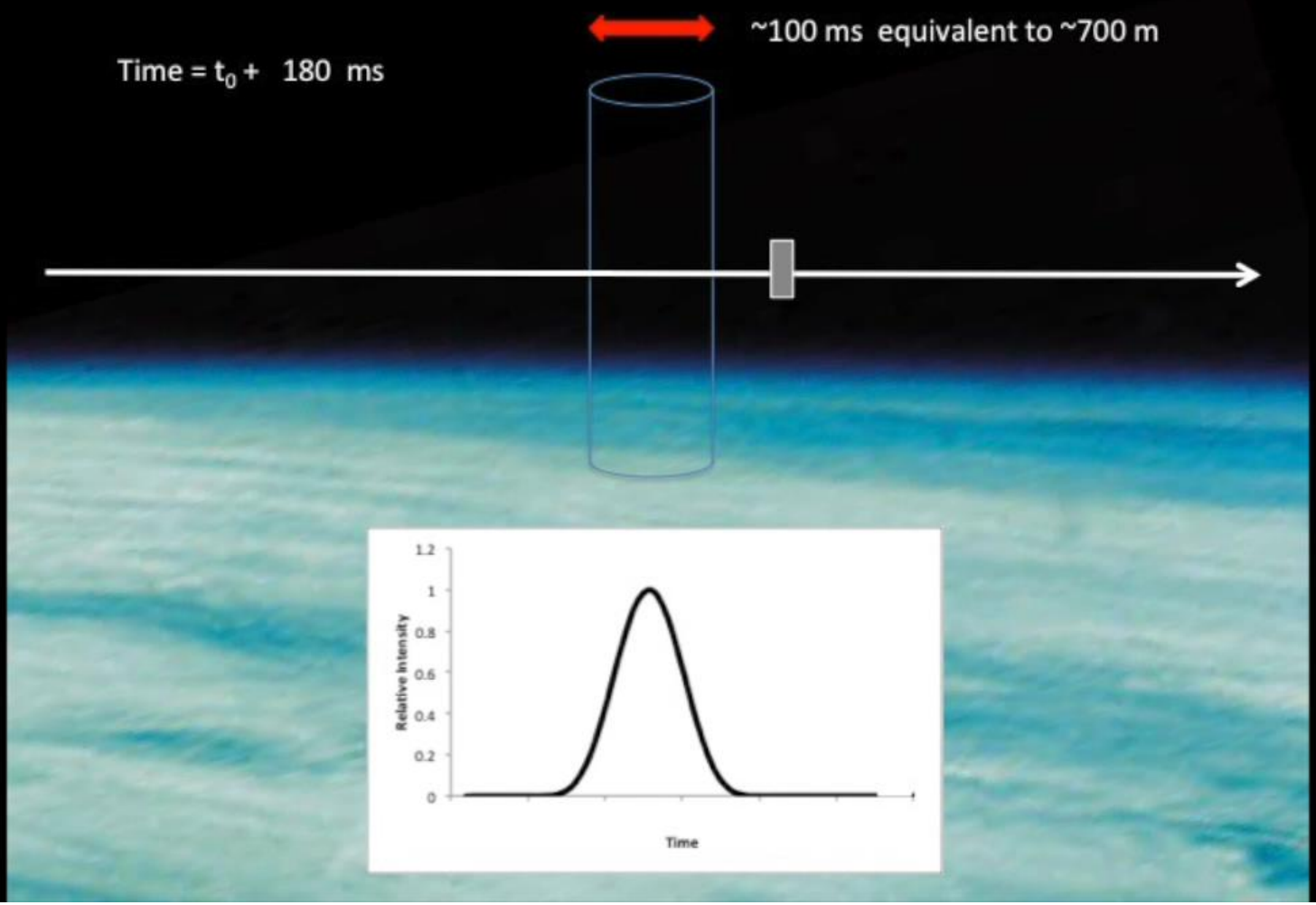


Figure 3. A plot of microbursts which occurred during two consecutive orbits on Day 254, 1992.

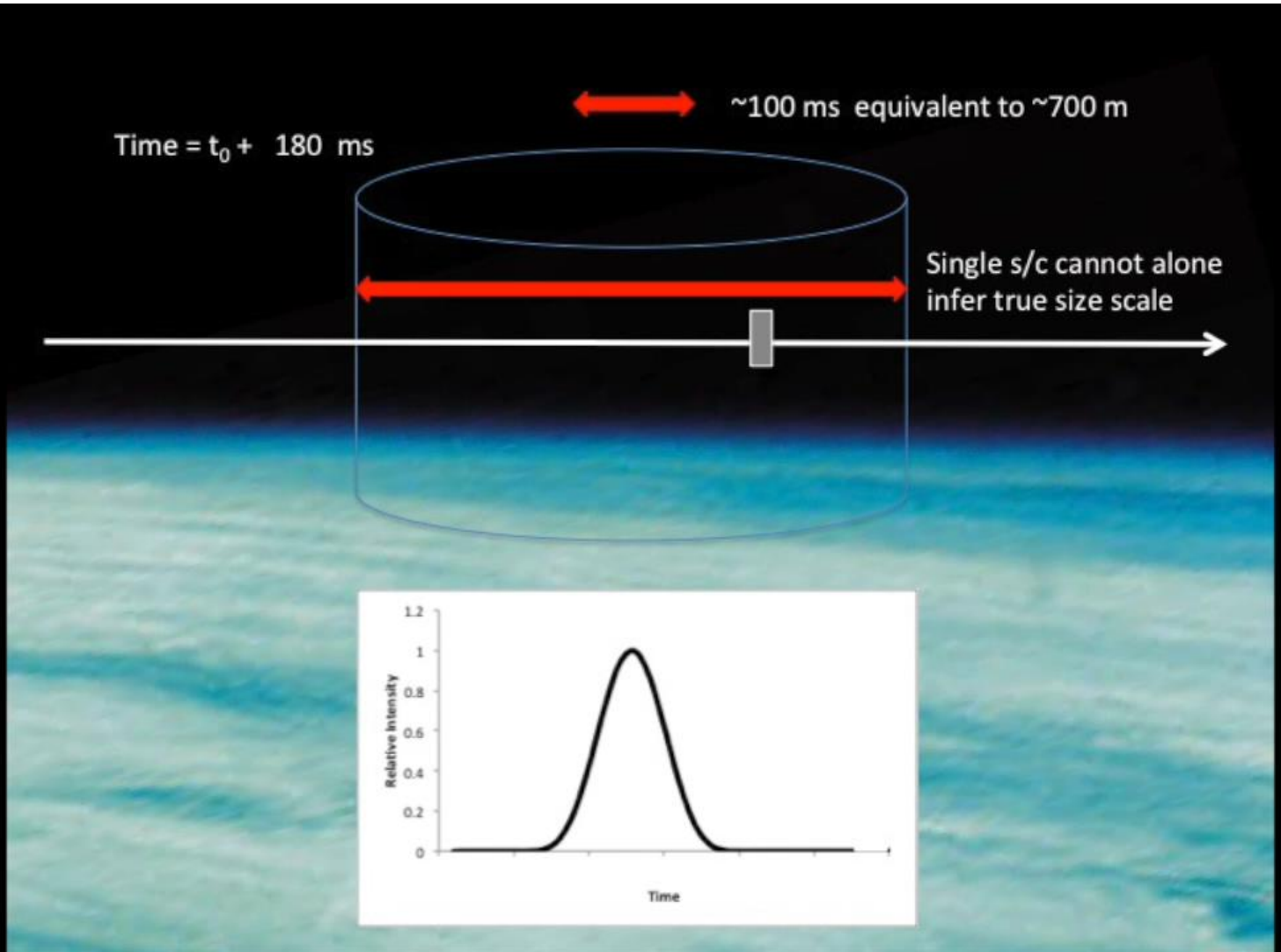
Disentangling Time/Size Scales (1)

- Typical LEO microburst durations are of order >100 ms →only puts lower limit on microburst scale
- FIREBIRD's time resolution is 18.75 ms; resolves all but shortest microbursts
- Smallest resolvable spatial scale by a single FIREBIRD spacecraft is ~130 meters



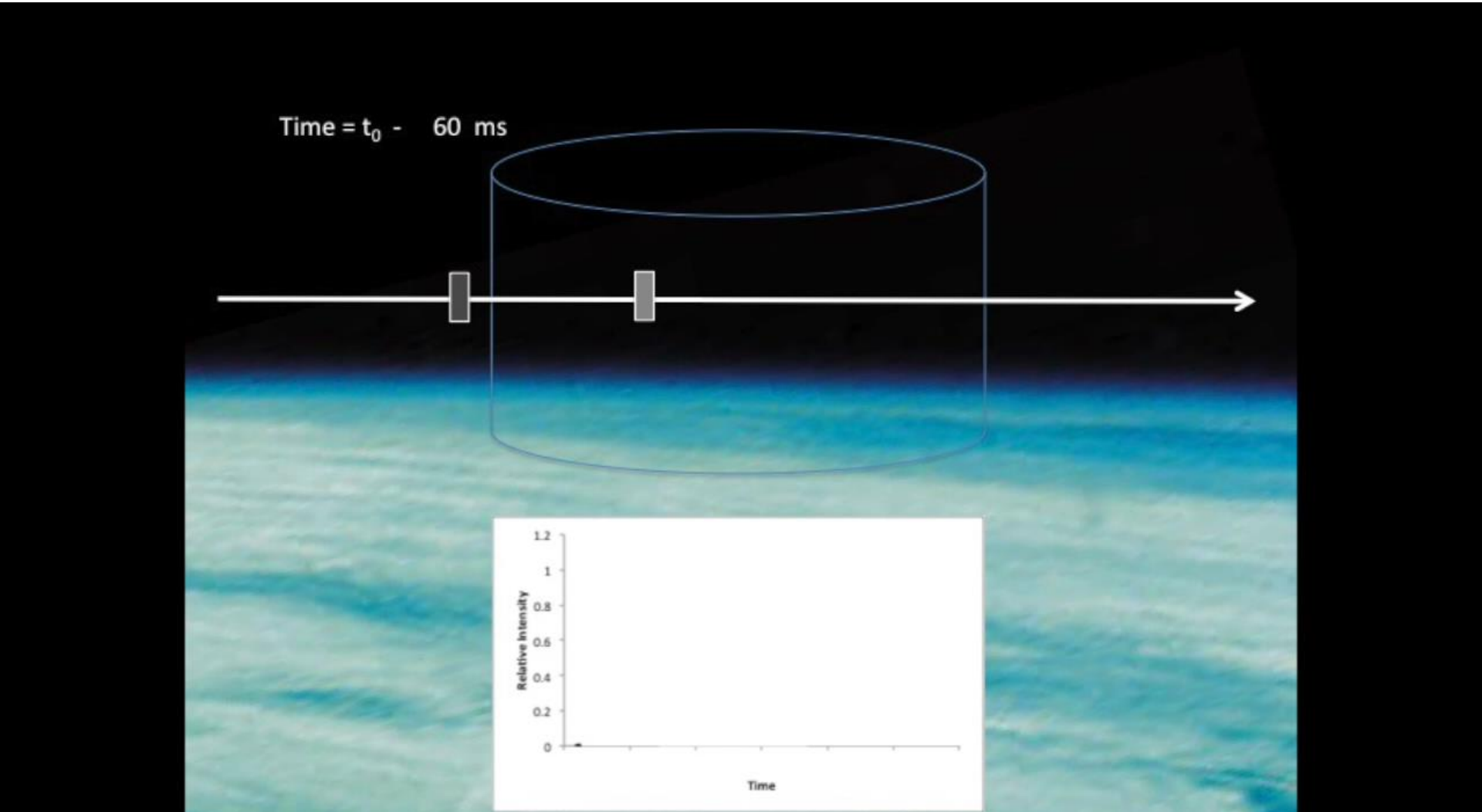
Disentangling Time/Size Scales (2)

- **Actual size is much larger? <u>How much larger is vitally important for correctly quantifying the overall source and consequences</u> of microbursts!**
- **Single spacecraft can only put lower bound on size scale….**

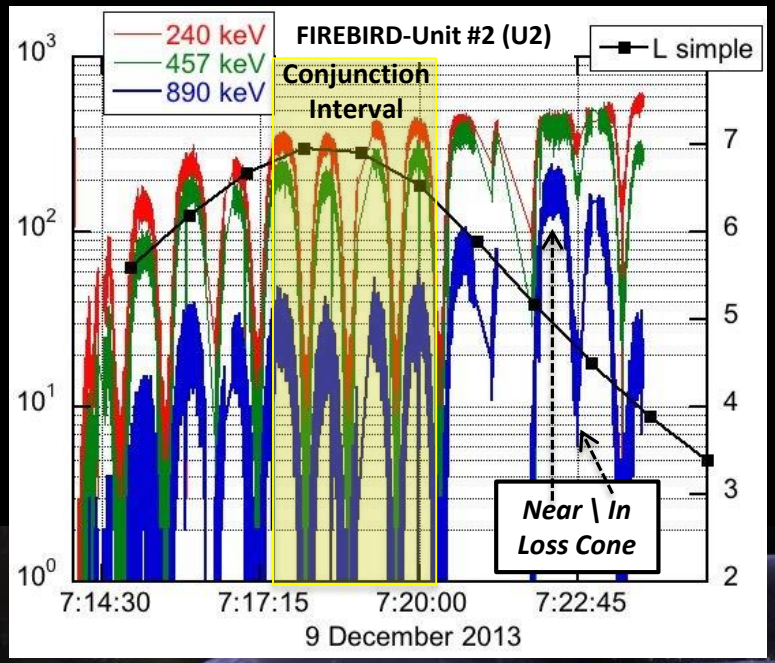


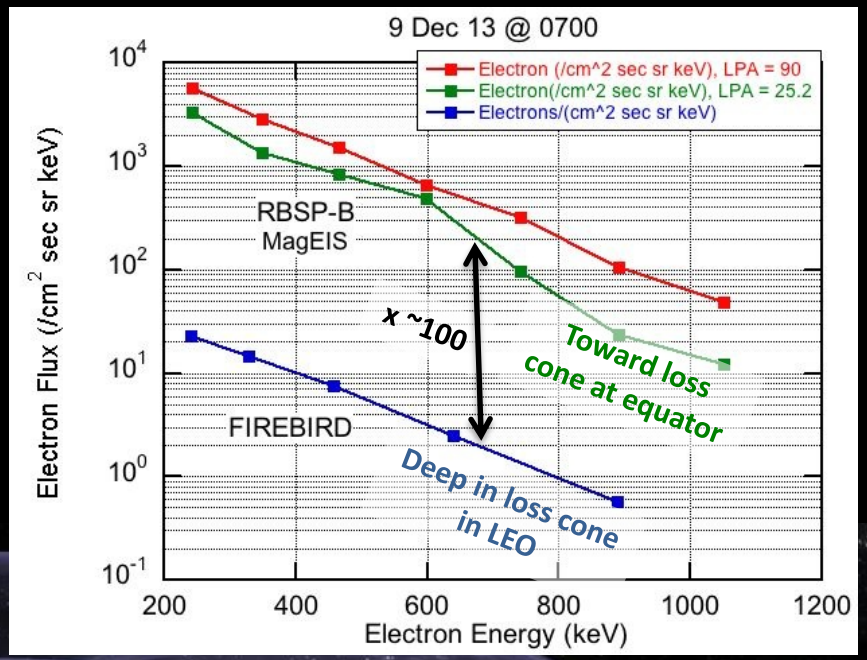
Two s/c Disambiguate Space/Time

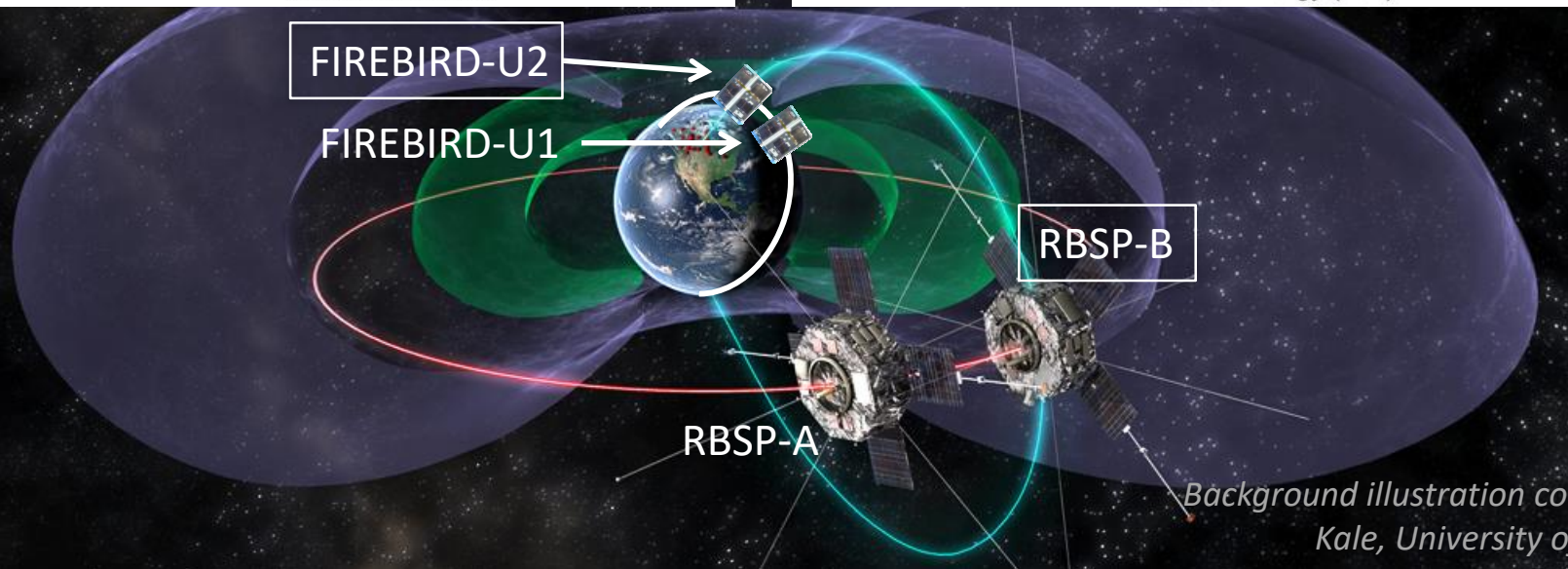
- **Dual FB (and AC6) in-track time (spatial) separations of order of seconds (~10 km) during first days of mission to several minutes (> 1500 km) after 10 months (~ 5 km/day average)**
- **Variable separations provide direct, in situ sampling of the spatial extent of precipitating microburst electrons for the first time, needed to constrain actual size**



Comparison of e- Energy Spectral Shape and Intensity (0.25 – 1 MeV) In/Near Loss Cone at LEO (FB-FU2) & Equator (RBSP-B) at L ~ 6.5





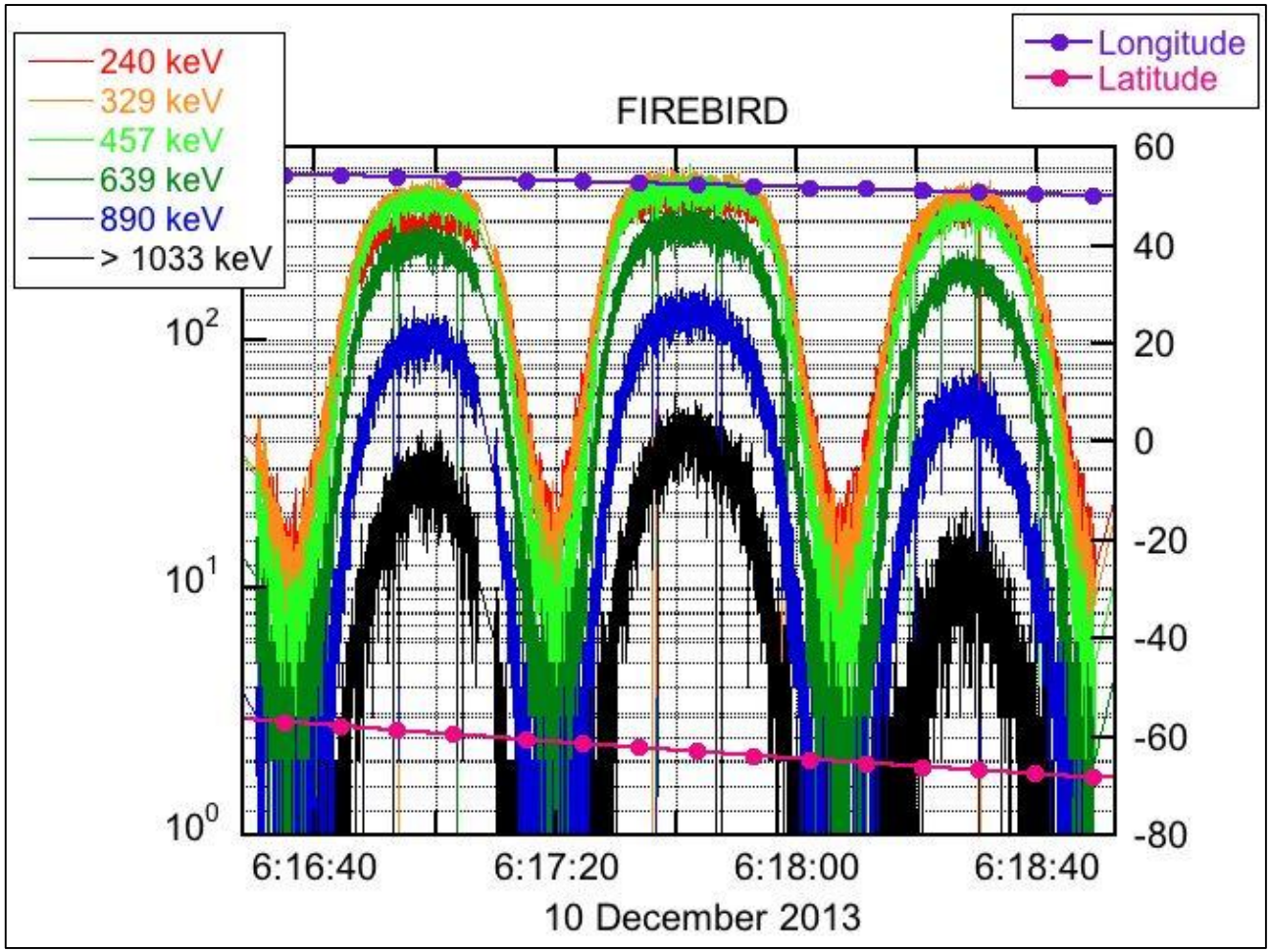


Background illustration courtesy A. Kale, University of Alberta

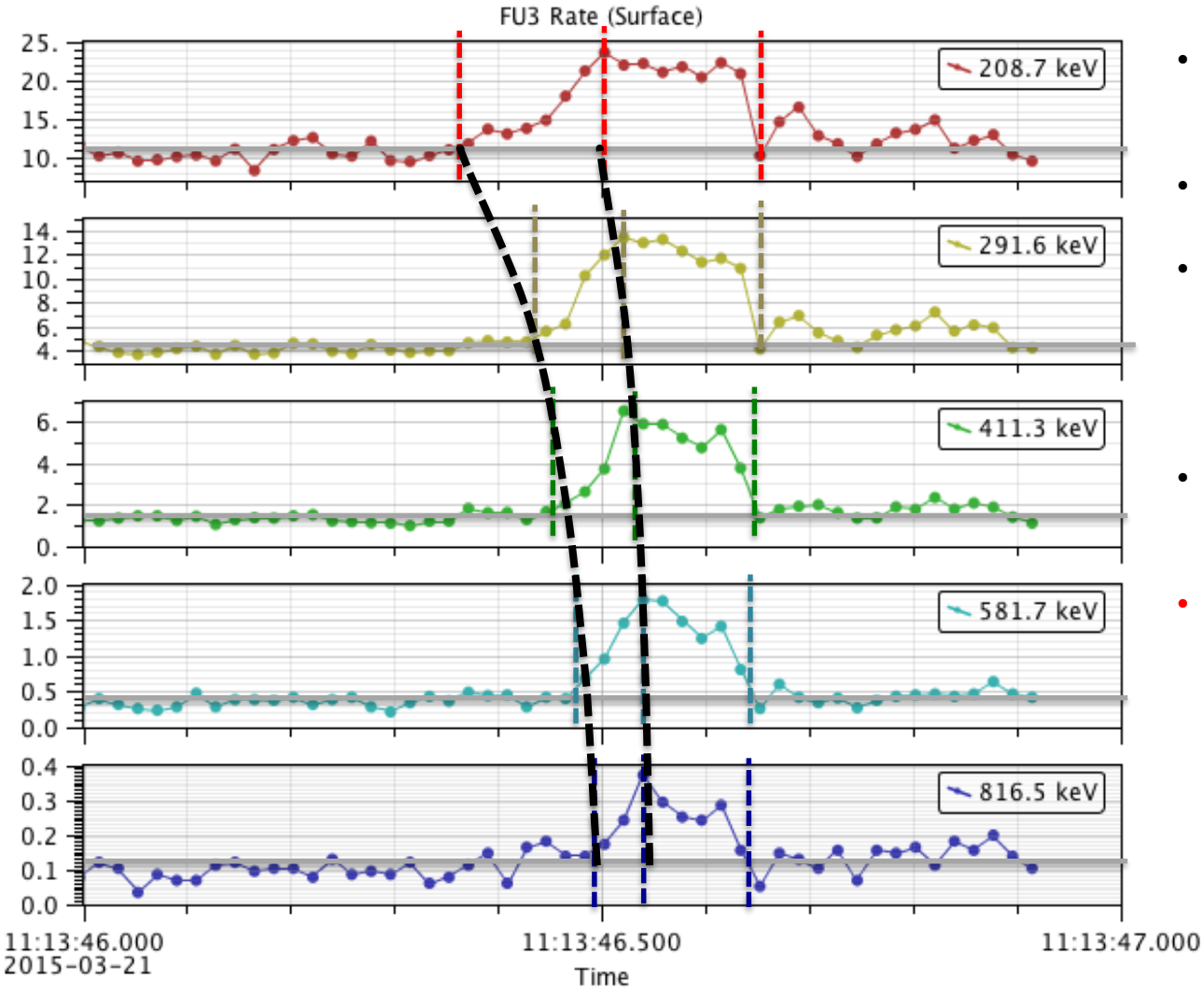
A KALE

FIREBIRD (Focused Investigation of Relativistic Electrons Bursts: Intensity, Range, and Dynamics) reveals energy spectra of precipitating radiation belt electrons with unprecedented detail

- FIREBIRD measures relativistic electrons precipitating into Earth's upper atmosphere from the radiation belt, both a diffuse "rain" as shown) as well as time-localized intense "microbursts" (not shown)
- Earlier missions measured e-'s at either high time or energy resolution; FIREBIRD provides both over this critical energy range
- Figure shows approximately two minutes of high time resolution (~18 ms) FIREBIRD data taken on 10 December 2013 shortly after launch from Vandenberg AFB
- As spacecraft spins, detailed pitch angle dependence of energy spectra revealed for first time
- Discovery of microburst energy spectra underway with FIREBIRD and planned for FIREBIRD-II mission (launch late 2014)

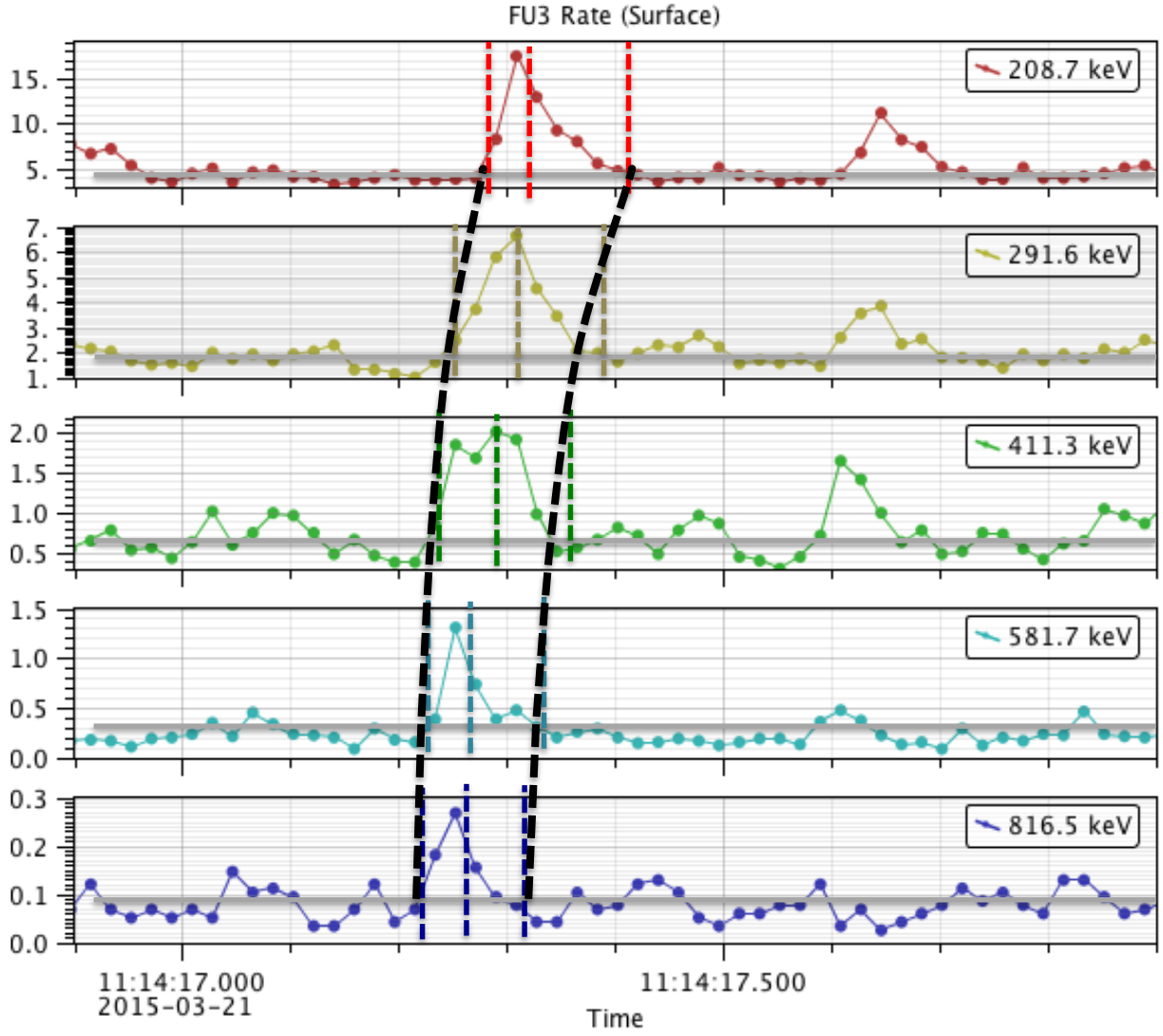


FB-II Observes "Inverse Velocity" REP Energy Dispersion – Test of Theories



- 1 second of data (18.75 ms resolution) at ~11:13:46UT on 21 Mar 2015
- FB-II FU3 was passing through outer zone electron radiation belt
- Isolated burst reveals inverse velocity style dispersion, with LOWEST energy electrons arriving first, followed successively by HIGHER energies
- Lowest energy (~200 keV) arrives ~100 ms earlier than highest energy (~800 keV)
- **Consistent with model predictions of Saito et al., Miyoshi et al. !! - whistler chorus resonance varies as wave propagates from equator (lower energies) to higher latitudes (higher energies)**

FB-II For First Time Quantifies REP Dispersion - "Regular TOF" Style



- 1 second of data (18.75 ms resolution) at ~11:14:17UT on 21 Mar 2015
- FB-II FU3 passing through outer zone electron belt
- Isolated burst reveals time-of-flight (TOF) style dispersion, with highest energy electrons arriving first, followed successively by lower energies
- Lowest energy (~200 keV) arrives ~60 ms later than highest energy (~800 keV)
- **Mapping back suggests common point only ~ 1.2 Re away**
- **But source of dispersion is complex….!**

FIREBIRD-II Campaigns aka Squeezing Watermelons Through a Soda Straw

- Month-long Campaigns: Campaign #11 starts this week
- Campaign duration set by quality/quantity of science data stored onboard satellites
  - Data storage allows data collection for ~4 weeks
  - High-value science data downloaded between campaigns
  - Only ~1% HiRes data downloaded! Missed opportunity!!

Campaign #	Dates (Approx)	Primary Science Goal
1	2/1->2/21	Spatial Scale of Individual Microbursts
2	3/20->4/16	St. Patrick's Day Storm
3	5/15->6/15	Van Allen Probes Conjunctions
4	7/1->8/1	July 4th Storm
5	8/7->9/3	BARREL Campaign Conjunctions
6	11/17->12/15	Conjunctions, Lightning induced precipitation
7	1/14->2/4	12.5ms time resolution, EFW and GRIPS conjunctions
8	5/14-> through summer	50ms res., context and COSI conjunctions (Alternate FU3 and FU4)
9	August 2016	Final BARREL Campaign
10	12/21/16	Conjunctions with ARASE and Van Allen Probes

FIREBIRD-II Communication System: Current Data Volume/Rate Limits

- Comm transceiver – AstroDev He-100 radio with VHF uplink and UHF downlink in HAM bands
- Telemetry beacons and science data downlinks at 19.2 kbps
- 1W power output using GMSK modulation and AX.25 packets
- Two monopole antennas; Single ground station at MSU
- 2GB memory filled in ~ 1 month (only partial data each orbit)
- **We have obtained only ~1% of all possible stored data**
- **We leave a huge volume of invaluable science data in space!**

Optical Communication on SmallSats – Enabling the Next Era in Space Science

http://kiss.caltech.edu/new_website/workshops/optcomm/optcomm.html