Near-term new observational capabilities in magnetosphere-ionosphere coupling science:

AMPERE & Mid-latitude SuperDARN chain

What are they?
What good are they?

Brian J. Anderson
JHU/APL

2009 GEM Workshop, Friday June 26

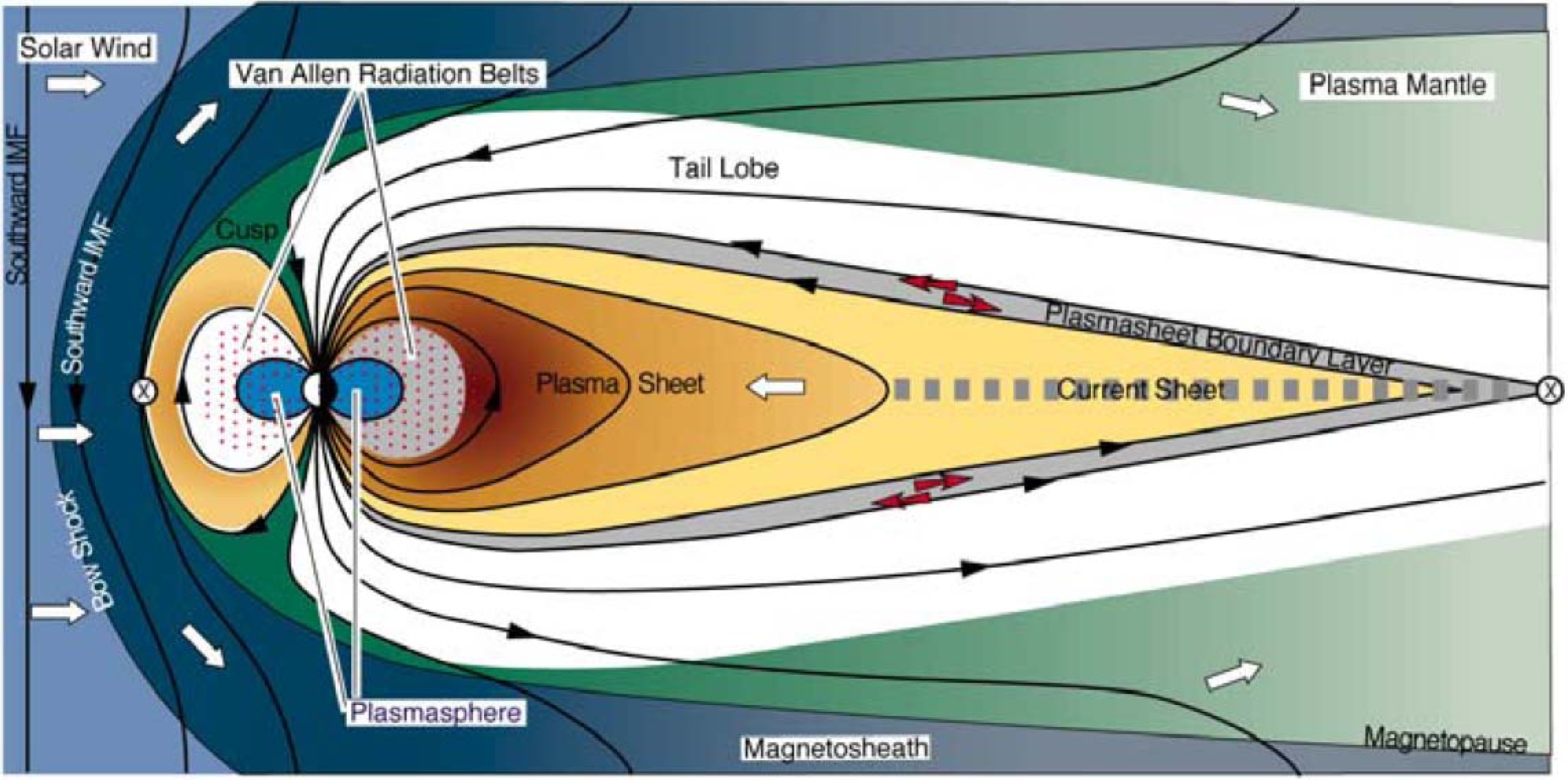
M-I Coupling in GEM

The session "AMPERE, Mid-latitude SuperDARN, and other opportunities for new MIC Focus Groups" will be held at 10:30 in the Erickson room.

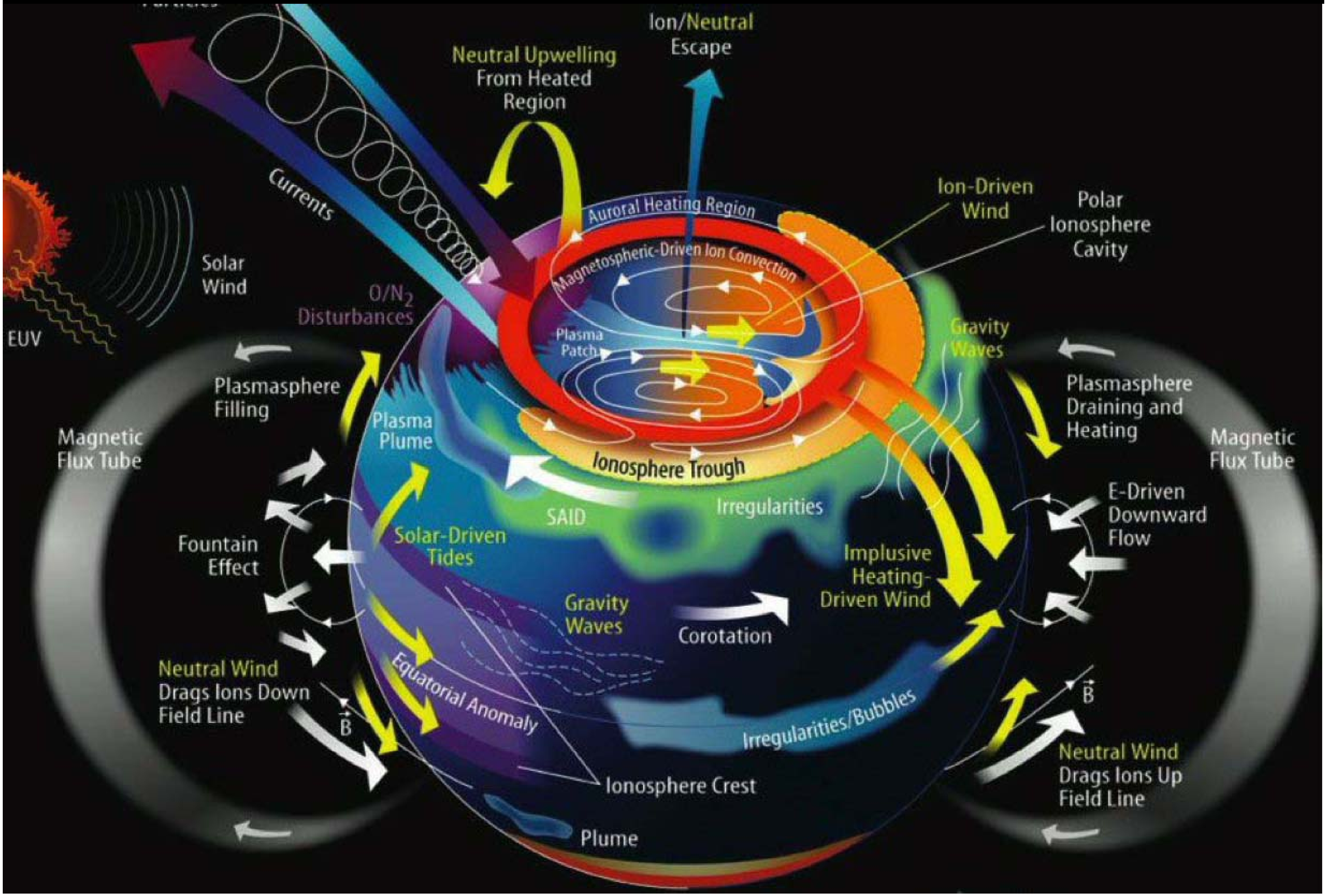
While you're listening, think of ways these assets used with other excellent tools/data (AMIE, TEC, CCMC) could be used to do MI coupling studies, write them down, and bring those ideas to the session at 10:30. Anyone that shows up with three good ideas wins a lollipop. (*Murr, 2009*)

What do we mean by the M-I system?

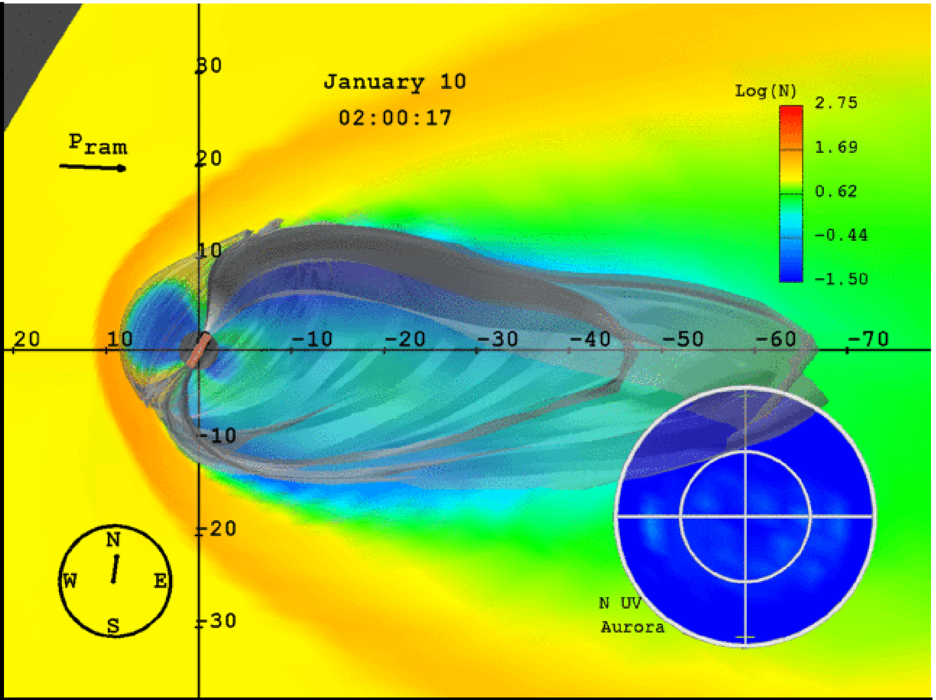
Is it this cartoon?

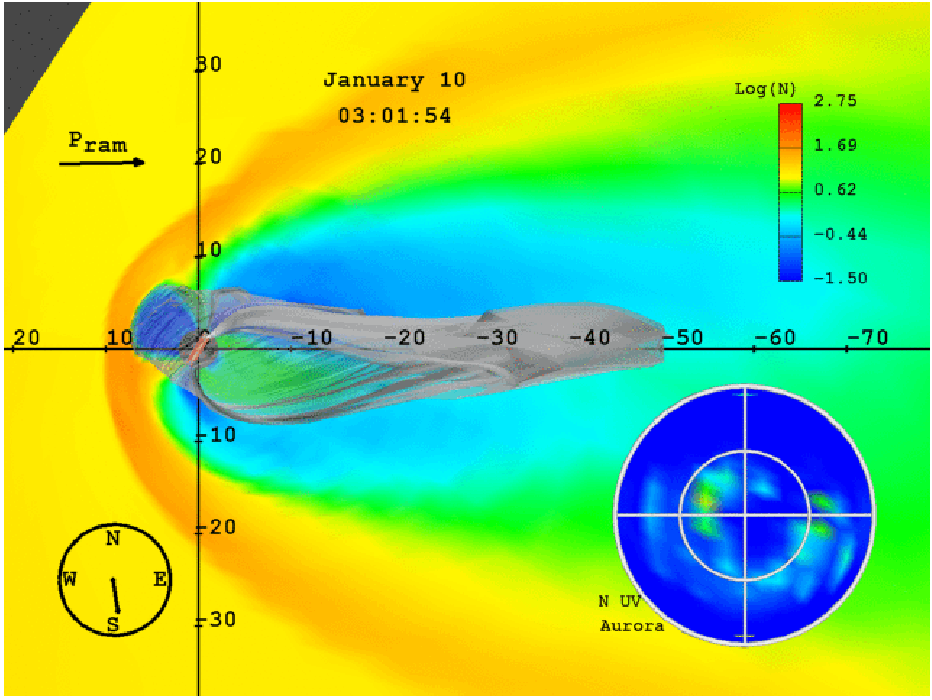


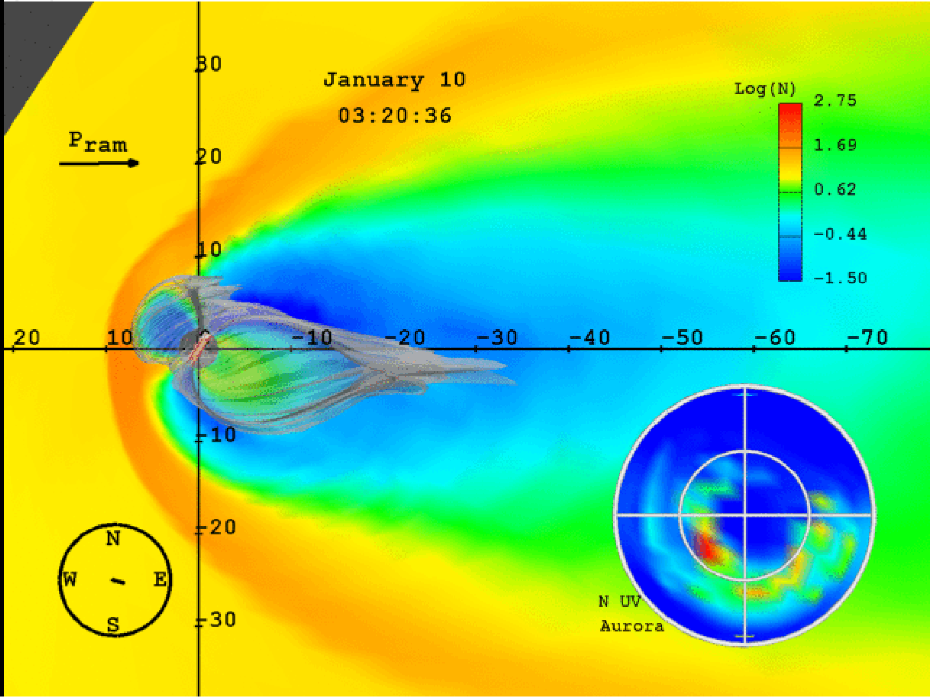
What about this one?



Or this simulation?







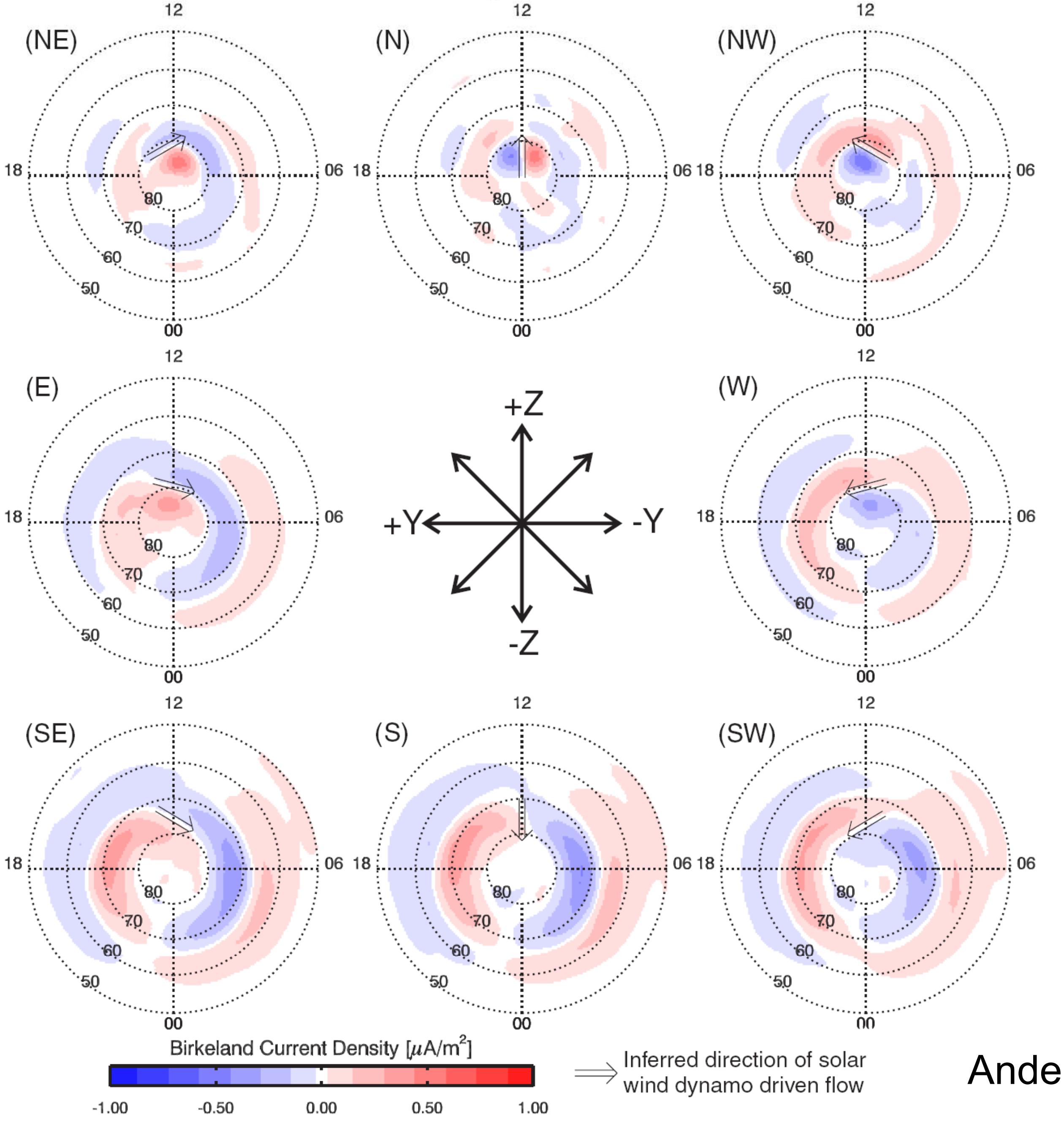
Claim: we have largely wrapped up system ‘climatology’

We know the distribution of currents, convection and ionospheric structure for typical ranges of the IMF, solar wind.

We even know a lot about their seasonal and solar cycle variability.

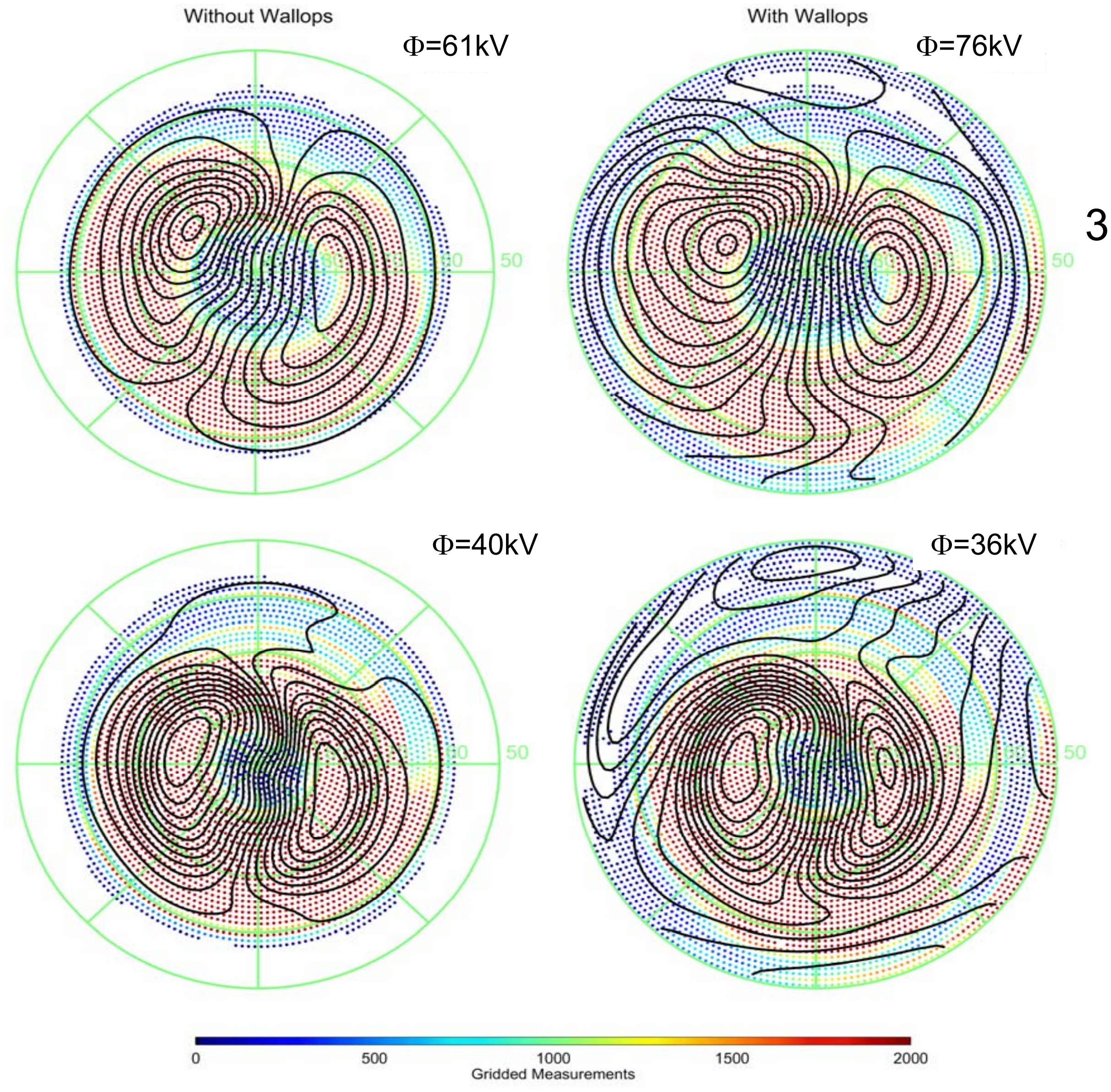
But the system never actually achieves its average state: no family has 2.2 children.

Iridium Statistical Birkeland Current Distributions
Database: 1999-2005, 1550 two-hour intervals



Anderson et al., 2006

Statistical Convection Patterns



“Disturbed” Conditions (Kp > 3):

Average cross polar potential increased by 25%.

“Quiet” Conditions (Kp < 3):

Two-cell convection pattern is fed from lower latitudes on the evening side and drained on the morning side.

***Baker et al.*, [2007]**

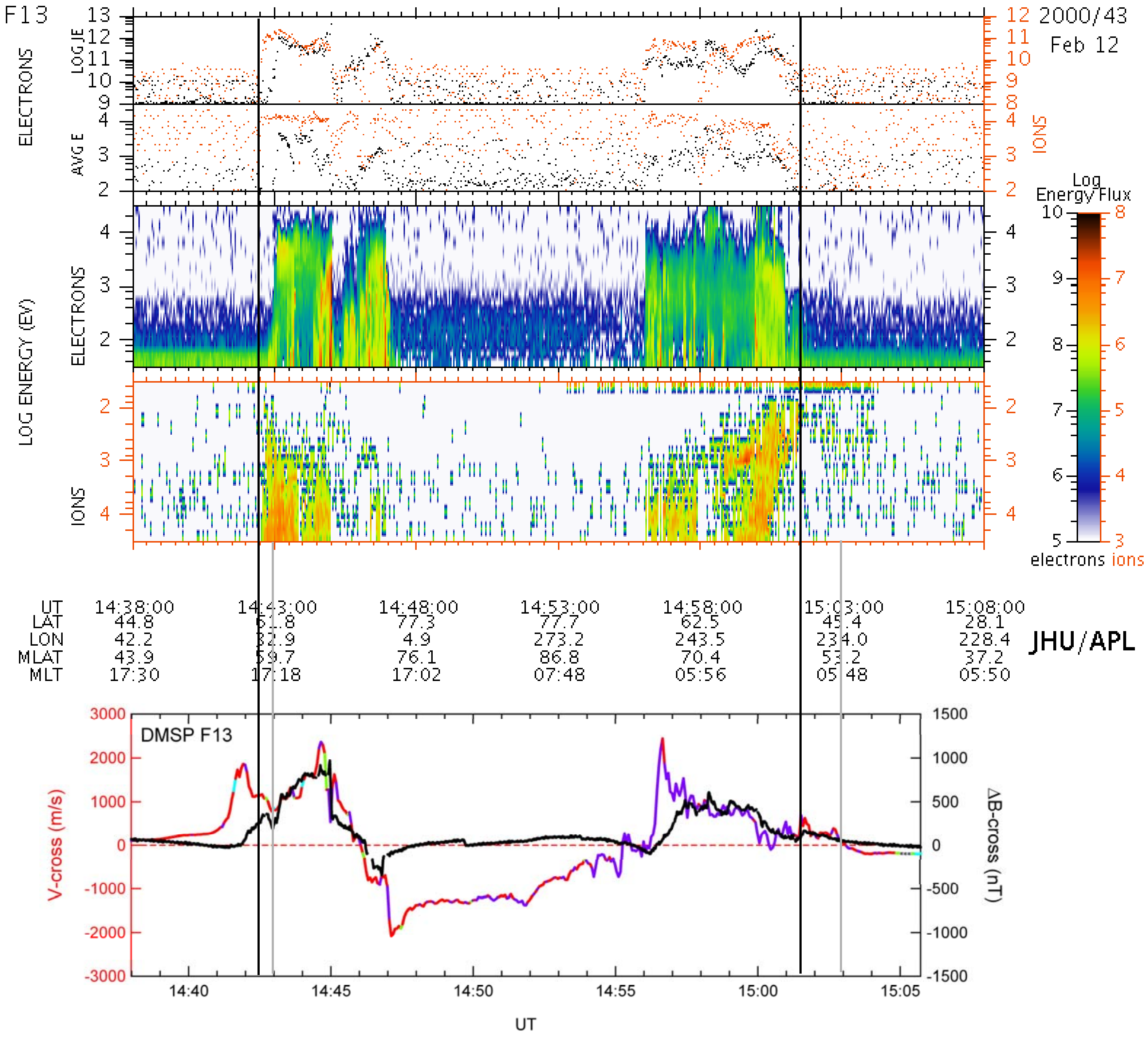
The system is not the average

Dynamic events display convection in different latitudes and local times

Gradients are far sharper than the smeared averages

Structured flows, precipitation, currents necessarily imply dynamics, mass, momentum and energy transport.

System is as system does.



F13
2000/43
Feb 12
ELECTRONS
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electrons ions
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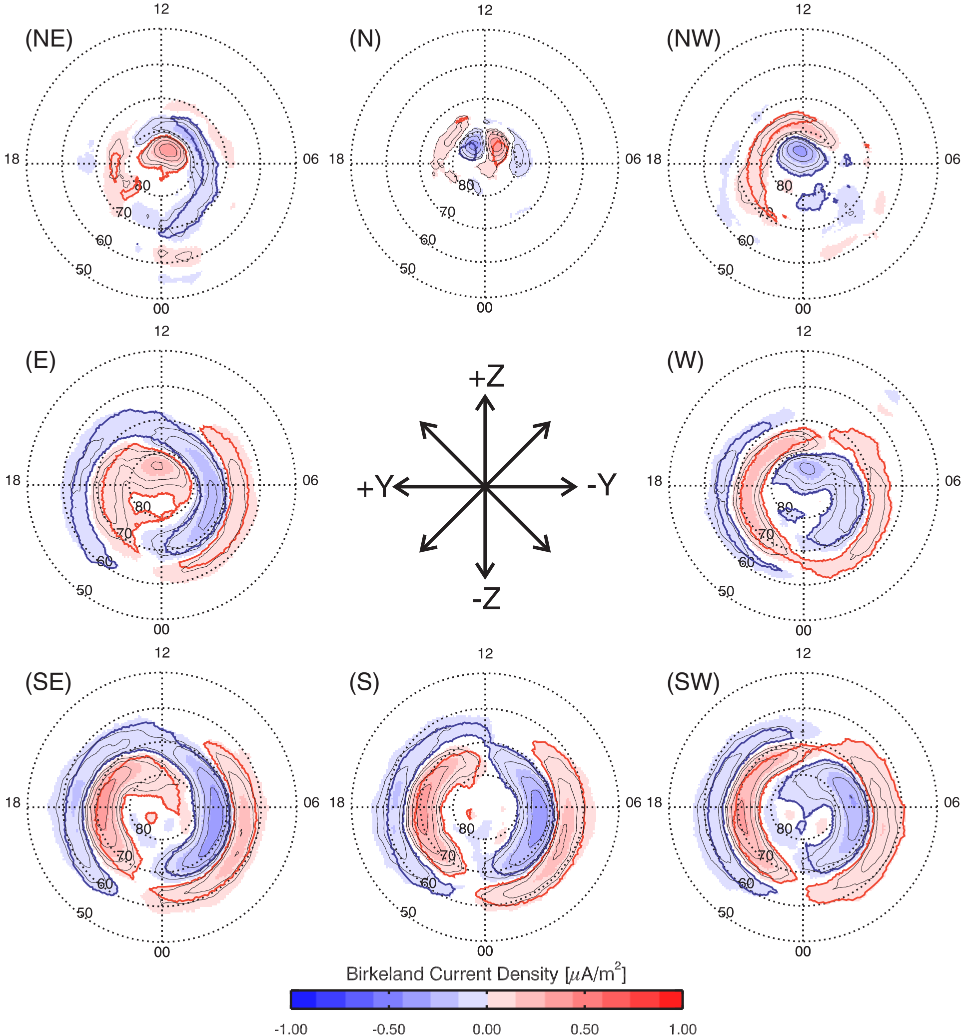
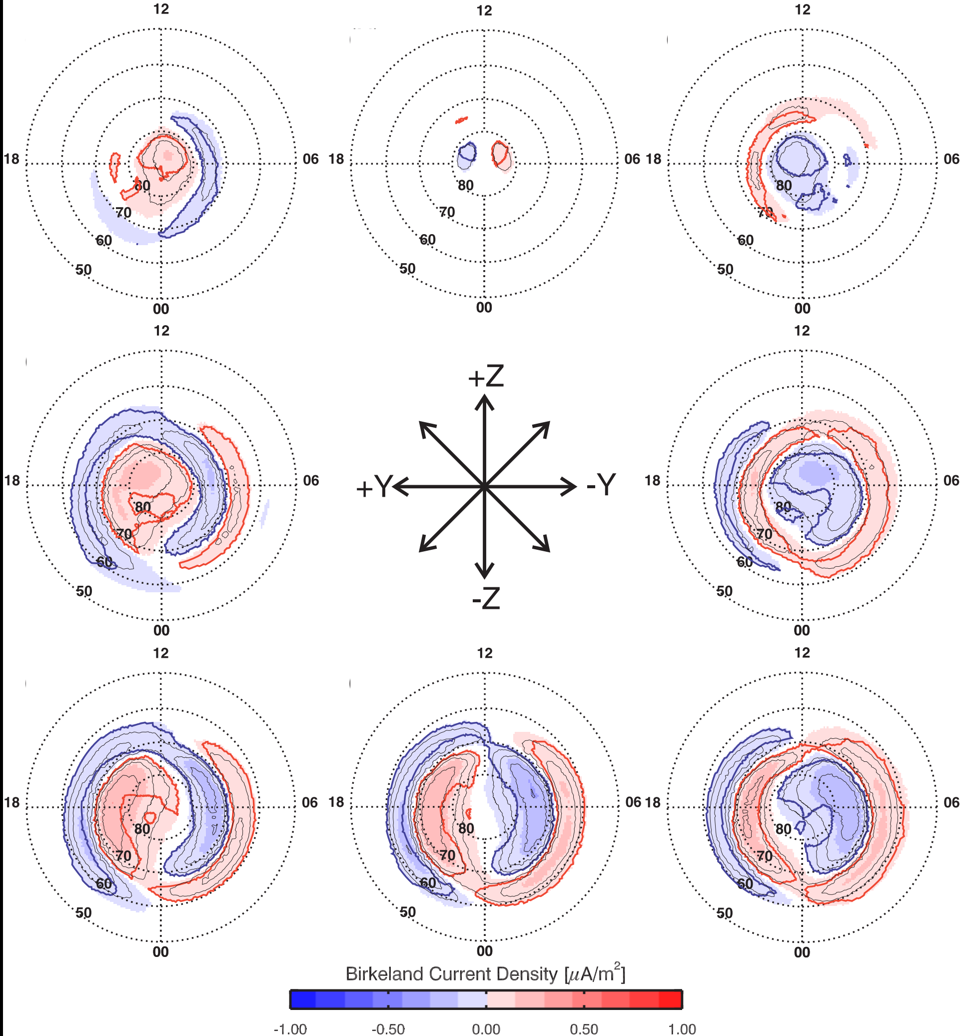
LAT 44.8 61.8 77.3 77.7 62.5 45.4 28.1
LON 42.2 32.9 4.9 273.2 243.5 234.0 228.4
MLAT 43.9 59.7 76.1 86.8 70.4 53.2 37.2
MLT 17:30 17:18 17:02 07:48 05:56 05:48 05:50
JHU/APL
DMSP F13
V-cross (m/s)
3000
2000
1000
0
-1000
-2000
-3000
ΔB-cross (nT)
1500
1000
500
0
-500
-1000
-1500
14:40
14:45
14:50
14:55
15:00
15:05
UT

Iridium Statistical Birkeland Current Distributions
Database: 1999-2007, 1536 two-hour intervals



Birkeland Current Distributions From
CCMC BATS-R-US+RCM MHD Simulations



Note that agreement is between an ‘*instantaneous*’ simulation and a statistical *climate average*

Strong smearing, ~5x low wrt any real case.

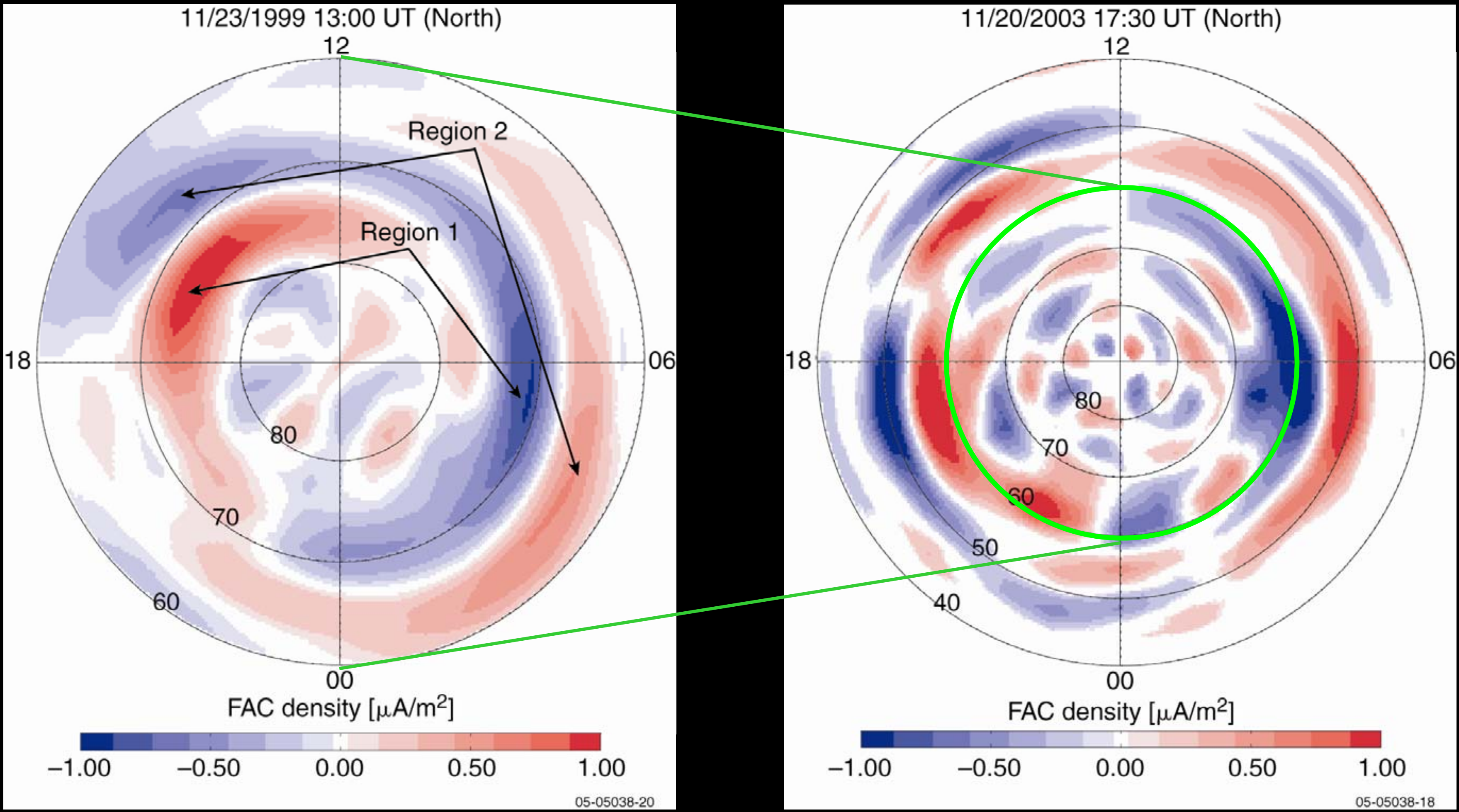
Active-time dynamics

The strongly driven M-I system achieves states that are qualitatively different – with new ‘features’ and phenomena: e.g.

- Saturation (an M-I coupling response)
- Sawtooth events (global substorm events)
- SMC events
- Ionospheric storms, positive and negative
- SAPS/SAID
- Radiation belt re-population or depletion …

These are large, factors of 2 to >10 departures from ‘climate’

Currents from Iridium*

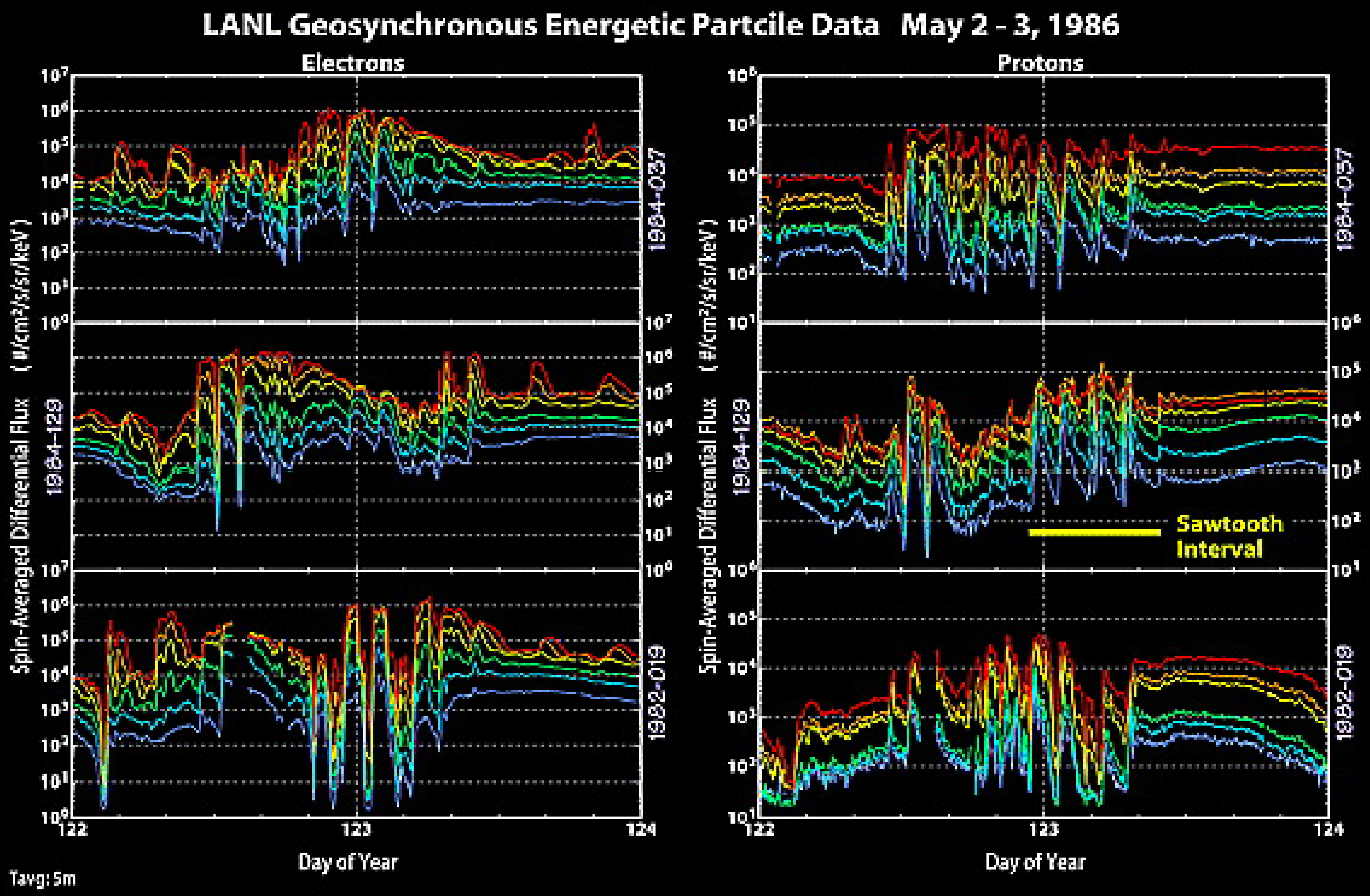


Non-storm

Severe storm

*** 3 hour averages!**

Quasi-periodic instability states



Henderson et al. 2004

Why the climate approach cannot work for storms

Reeves: “If you’ve studied one geomagnetic storm, you’ve studied one geomagnetic storm.”

Even with the assets we have had available to date, we know that every storm is unique.

There are common aspects between them, e.g. main phase, recovery, equatorward expansion, plasmasphere erosion/plumes.

But the end-points that the system achieves (e.g. wrt relativistic electrons) can vary widely – for reasons that we don’t understand.

A few questions we can’t answer (yet?)

What are the different strongly driven convective states? How are they related to nominal activity? How do they arise, evolve and transition? What gives rise to quasi-periodicities?

What is the mechanism for saturation or is there more than one?

Where does the ionospheric energy dissipation occur during active-times? How much of it is Joule/particle heating?

How does evolution and dynamics in the ‘driver’ correspond (lead to?) ionospheric positive and negative storms?

What are the time-lags/delays in the active system? What governs them?

What do we need to measure to make major progress?

Fundamental quantities: minimize uncertainties due to inversions and modeling assumptions.

Globally distributed: ‘all’ local times, ‘all’ latitudes

Short cadence: less than a reconfiguration time-scale (~20 minutes or so).

Magnetosphere

Ionosphere

Flow

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B}$$

Field lines convey potential

Convection

$$\mathbf{E}_\mathrm{c} = -\mathbf{u}_\mathrm{c} \times \mathbf{B}_\mathrm{i}$$

Momentum

$$\rho \frac{d\mathbf{u}}{dt} = -\nabla P + \mathbf{J} \times \mathbf{B}$$

$$\mathbf{J}_{\perp,\mathrm{m}} = \frac{\mathbf{B} \times \nabla P}{B^2} + \rho \frac{\mathbf{B}}{B^2} \times \frac{d\mathbf{u}_\perp}{dt}$$

$$J_{\|} \propto \int \nabla_\perp \cdot \mathbf{J}_{\perp,\mathrm{m}} ds$$

Finite conductance - current

$$\mathbf{J}_{\perp,\mathrm{i}} = \underline{\mathbf{\Sigma}} \cdot \mathbf{E}_\mathrm{c} = \Sigma_\mathrm{P} \mathbf{E}_\mathrm{c} + \Sigma_\mathrm{H} \mathbf{b} \times \mathbf{E}_\mathrm{c}$$

Currents convey stress

$$J_{\|} = \nabla \cdot \mathbf{J}_{\perp,\mathrm{i}} = \nabla \cdot (\underline{\mathbf{\Sigma}} \cdot \mathbf{E}_\mathrm{c})$$

Energy dynamo

$$\mathbf{E} \cdot \mathbf{J} < 0$$

EM Energy Flux

$$S_\mathrm{z} = \frac{1}{\mu_0} \mathbf{E}_\mathrm{c} \times \delta\mathbf{B}$$

Dissipation - drag

$$\mathbf{E}_\mathrm{c} \cdot \mathbf{J}_{\perp,\mathrm{i}} > 0$$

The Ionospheric electrodynamics view

Convection $\mathbf{E}_c = -\mathbf{V}_c \times \mathbf{B} \qquad \mathbf{E}_c = -\nabla \varphi$

Horizontal currents $\mathbf{J}_{\perp,\mathrm{i}} = \underline{\mathbf{\Sigma}} \cdot \mathbf{E}_{\mathrm{c}} = \Sigma_{\mathrm{P}} \mathbf{E}_{\mathrm{c}} + \Sigma_{\mathrm{H}} \mathbf{b} \times \mathbf{E}_{\mathrm{c}}$

ψ = equivalent current potential

Birkeland currents $J_{\|} = \nabla \cdot \mathbf{J}_{\perp,\mathrm{i}} = \nabla \cdot (\underline{\mathbf{\Sigma}} \cdot \mathbf{E}_{\mathrm{c}})$

Electrodynamics equations: 2 eqs, 5 unknowns

$$\nabla^2 \psi = \Sigma_{\mathrm{H}} \nabla^2 \varphi + \nabla \Sigma_{\mathrm{H}} \cdot \nabla \varphi + \hat{\mathbf{r}} \cdot (\nabla \Sigma_{\mathrm{P}} \times \nabla \varphi)$$

$$J_{\|} = -\Sigma_{\mathrm{P}} \nabla^2 \varphi - \nabla \Sigma_{\mathrm{P}} \cdot \nabla \varphi + \hat{\mathbf{r}} \cdot (\nabla \Sigma_{\mathrm{H}} \times \nabla \varphi)$$

Quantity	Technique	Strengths	Operational Considerations
Ψ Equivalent currents	Ground magnetometers	Excellent time resolution; continuous data; coverage improving in latitude, density and southern hemisphere	Non-uniform coverage (oceans, concentration at nominal auroral latitudes, local time gaps)
φ Potential convection	**SuperDARN:** mid-latitudes	Broad field of regard; continuous operation; both hemispheres; 2-min cadence; 10s km resolution	Requires irregularities; D-region absorption (mitigated somewhat by mid-latitude radars)
	IS radars	Indep. of conditions	Focussed (limited) coverage (few sites)
	LEO ion drift	Direct ion drift observations	100 minute revisit time Restricted local time cuts (4)
Σ_P, Σ_H	IS radars	Accurate density meas.	Focussed (limited) coverage (few sites)
	UV imaging	Hemispheric image	Significant uncertainties Not operational routinely
$J_{\|\|}$ Birkeland currents	LEO mags	Direct signature of currents	Iridium: long accumulation times (>2 hrs) Other: ~3 satellites, 100 minute revisit time, Requires geometrical assumptions
	AMPERE	Direct signature of currents >70 satellites 9 minute revisit time 12 local time cuts	30 nT resolution – S:N ~ 10:1 Latitude resolution: 1° nominal Event driven sub-degree sampling

Mid-Latitude SuperDARN

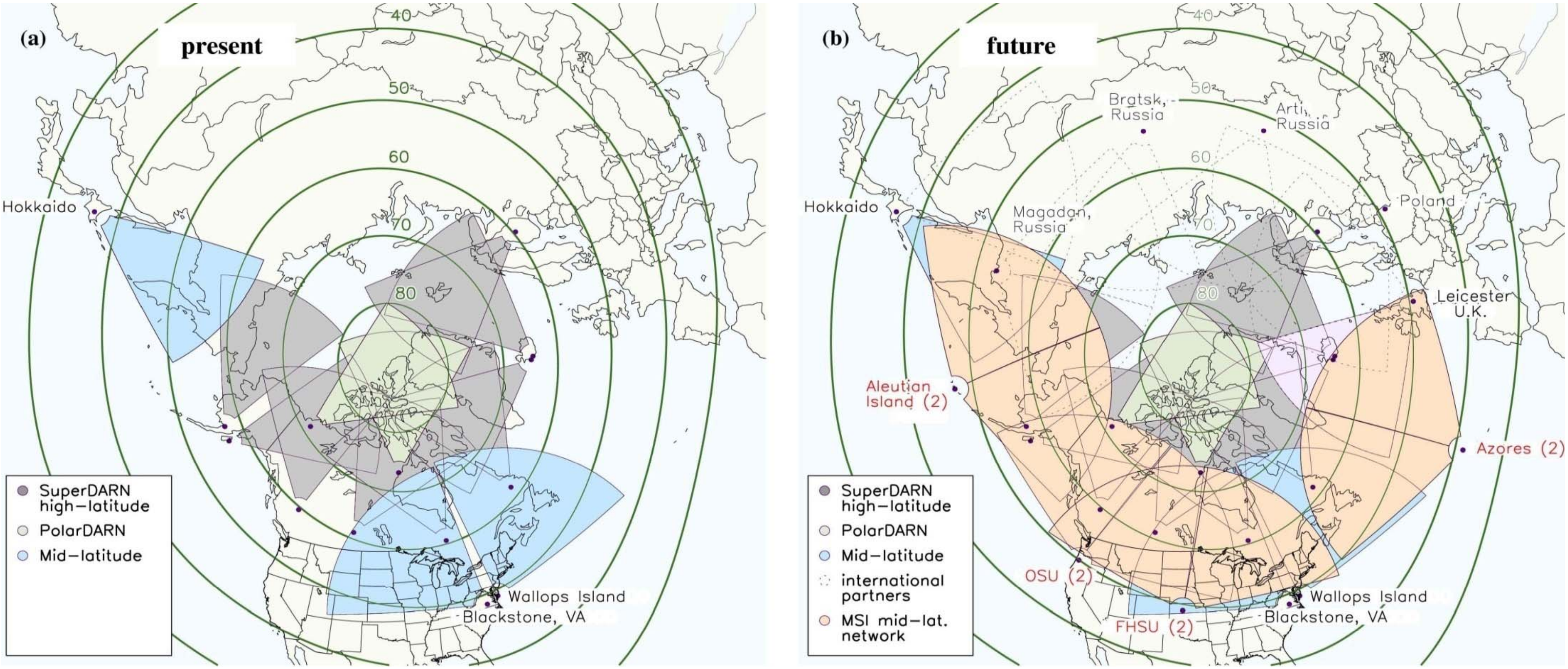
Core Team:
Mike Ruohoniemi, Jo Baker, Ray Greenwald
Virginia Tech

Bill Bristow
University of Alaska

Simon Shepherd
Dartmouth College

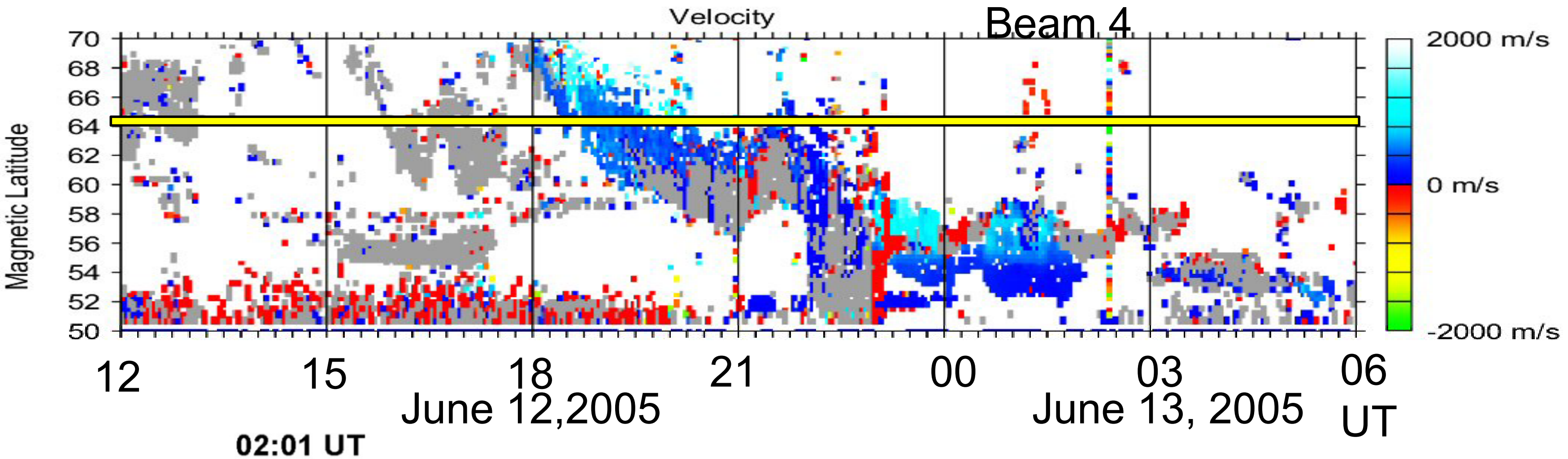
Elsayed Talaat
JHU/APL

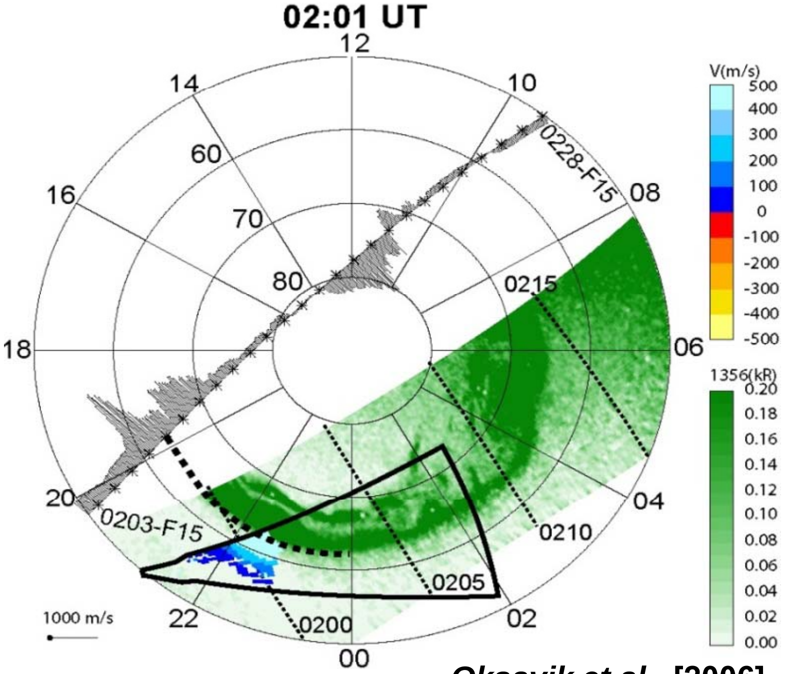
New Mid-Latitude Radars



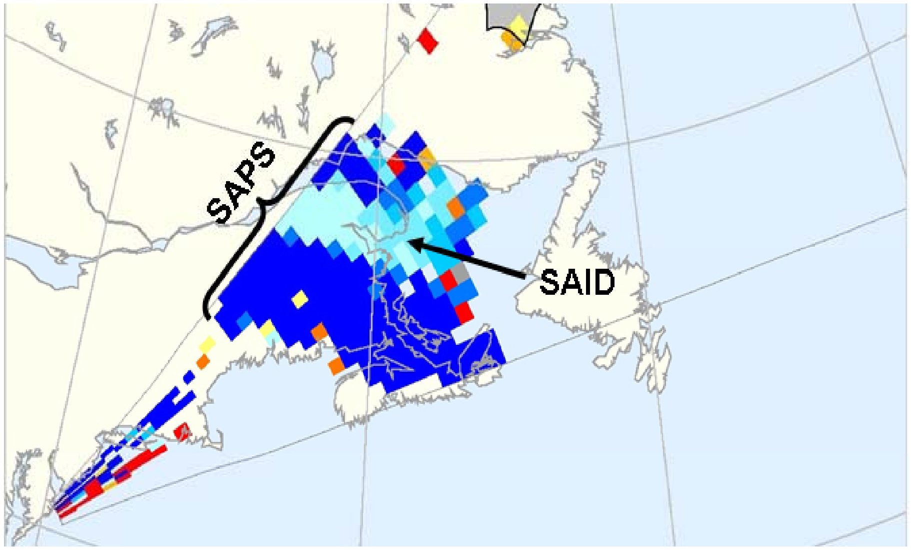
- Funds to build 8 new radars at middle latitudes have been provided through the NSF MSI Program.
- Partners: Virginia Tech, University of Alaska, Dartmouth College, JHU/APL.
- There are also plans to build mid-latitude radars in Australia, South Africa, and Eastern Europe

Wallops Measurements: SAPS/SAIDs



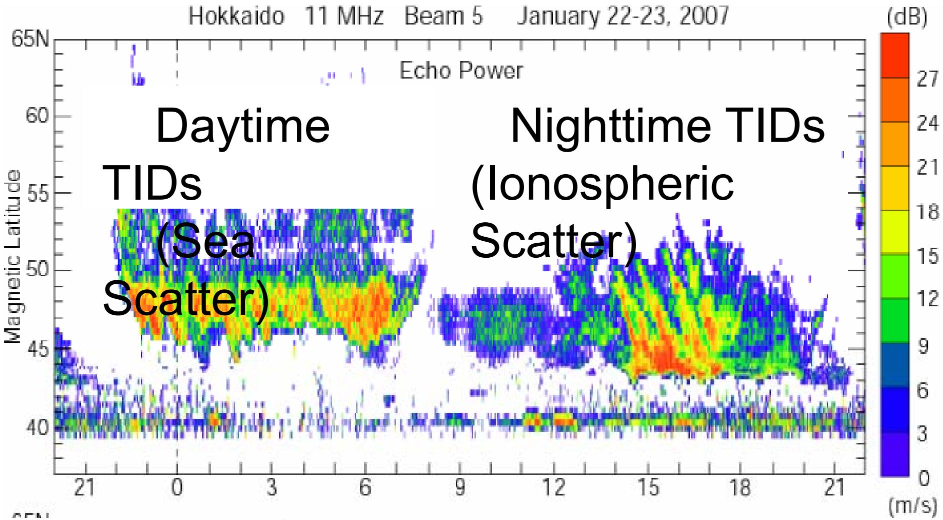


***Oksavik et al.*, [2006]**



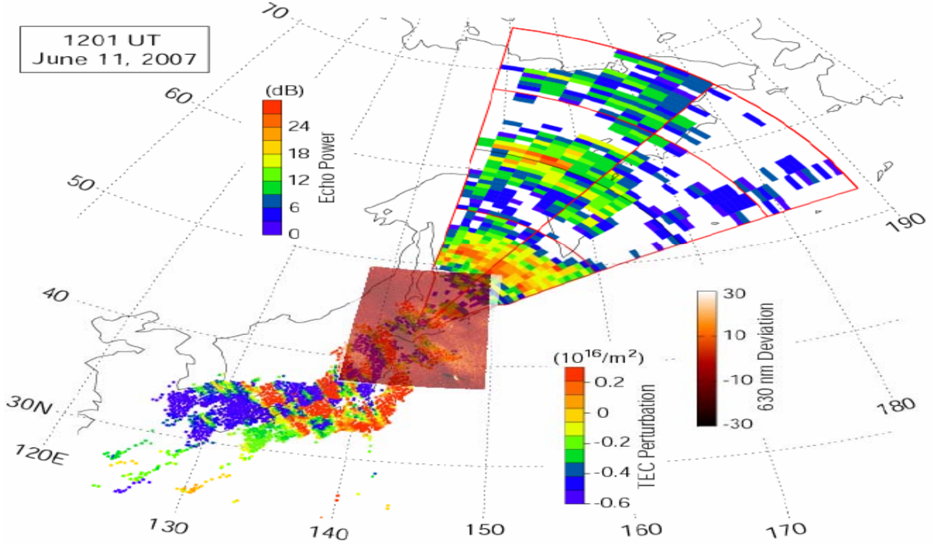
Two-Dimensional Image of Sub Auroral Ion Drifts (SAID) within the Sub Auroral Polarization Stream

Hokkaido Measurements: TIDs



Daytime TIDs (Sea Scatter)

Nighttime TIDs (Ionospheric Scatter)



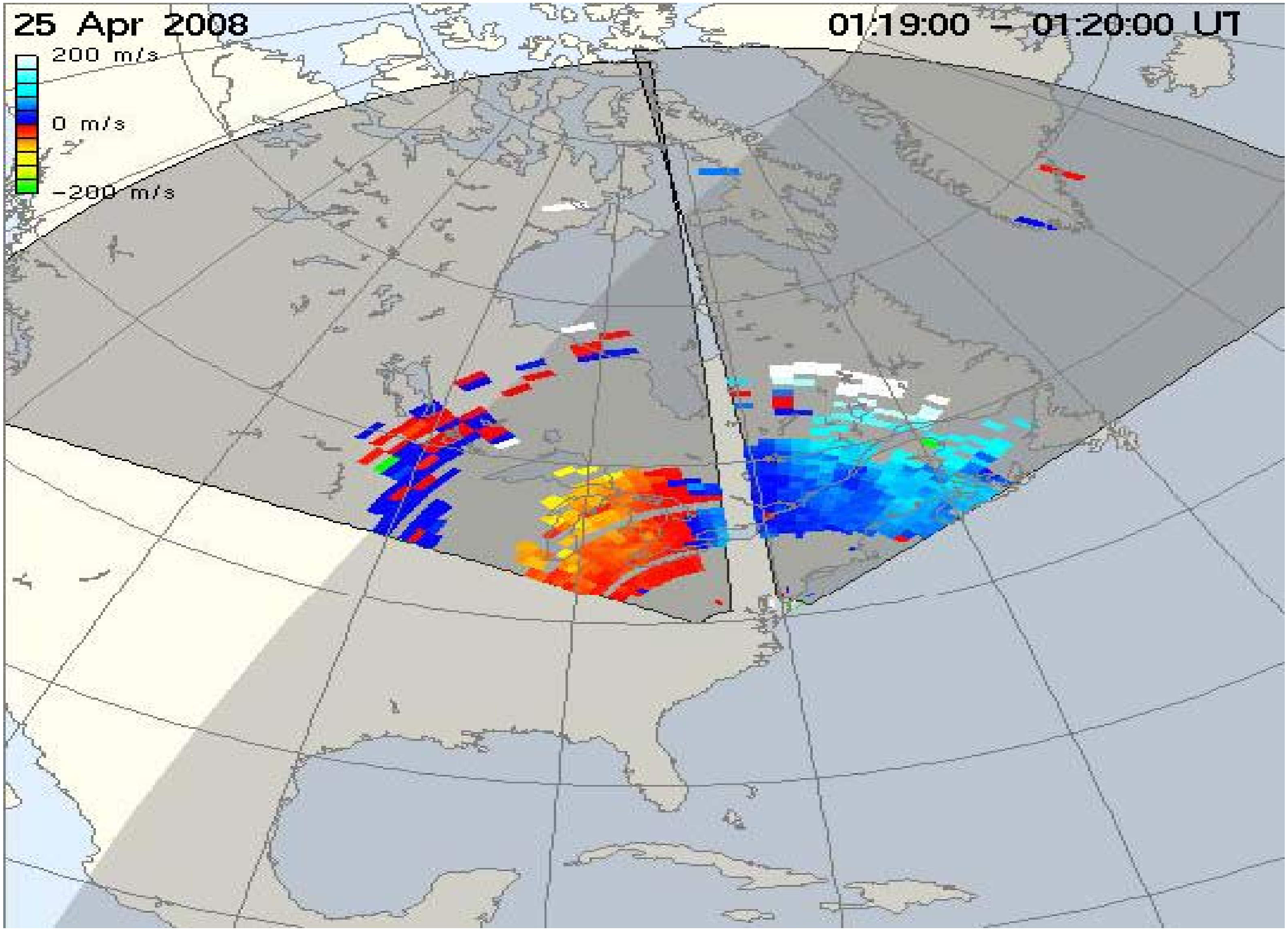
Figures courtesy of T. Ogawa, STE Lab, Nagoya University

- The second mid-latitude SuperDARN radar became operational at Rikubetsu, Hokkaido, in December, 2006.
- PI: N. Nishitani
- By combining Hokkaido radar data with ground-based 630nm all-sky imaging and GPS TEC measurements it is possible to continuously monitor the propagation of TID wave fronts over a scale length of 6000km.

The Blackstone Radar

- The third mid-latitude SuperDARN radar became operational at Blackstone, VA, on February 2nd, 2008.
- The Blackstone radar is a collaboration between:
  - Virginia Tech
  - Johns Hopkins University Applied Physics Laboratory
  - University of Leicester

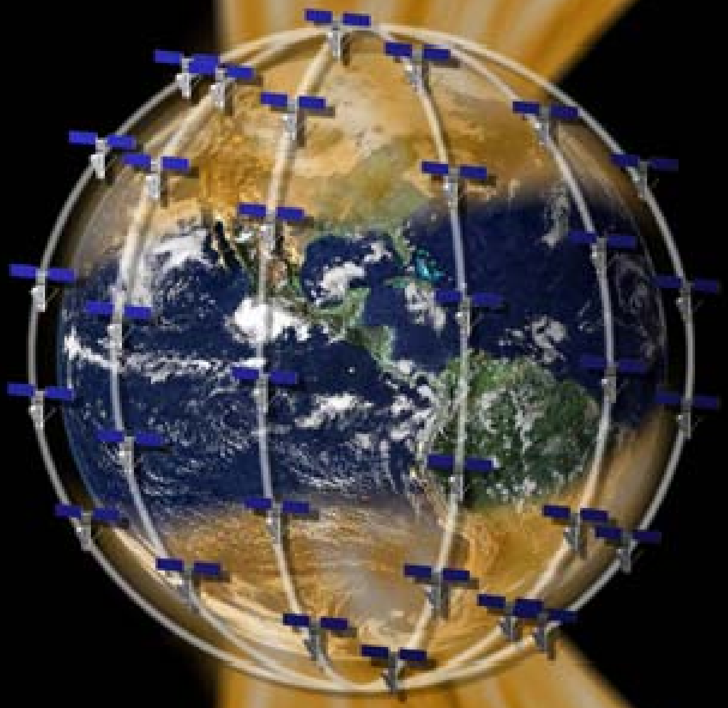
Blackstone/Wallops Field of View



Summary

- New SuperDARN radars at middle latitudes are providing:
    - Improved Coverage of Ionospheric Convection During Magnetic Storms
    - New Details of the Temporal Evolution of SAPS/SAIDs
    - Information about Generation Mechanisms for Mid-Latitude Plasma Irregularities
    - Information about ULF Electric Field Pulsations at Substorm Onset
    - New Capabilities to Investigate Penetration Electric Fields
- A 4-year proposal to build 8 additional mid-latitude radars across the North American sector has recently been funded through the NSF MSI Program.

AMPERE



Continuous Global Birkeland Currents from the Active Magnetosphere and Planetary Electrodynamics Response Experiment

Brian J Anderson, The Johns Hopkins University Applied Physics Laboratory

Jeremy Anderson

Partners

Sponsor
National Science Foundation

Data provider
Boeing Service Company

Data source
Iridium Satellite LLC

PI Institution, Science Data Center
The Johns Hopkins University
Applied Physics Laboratory

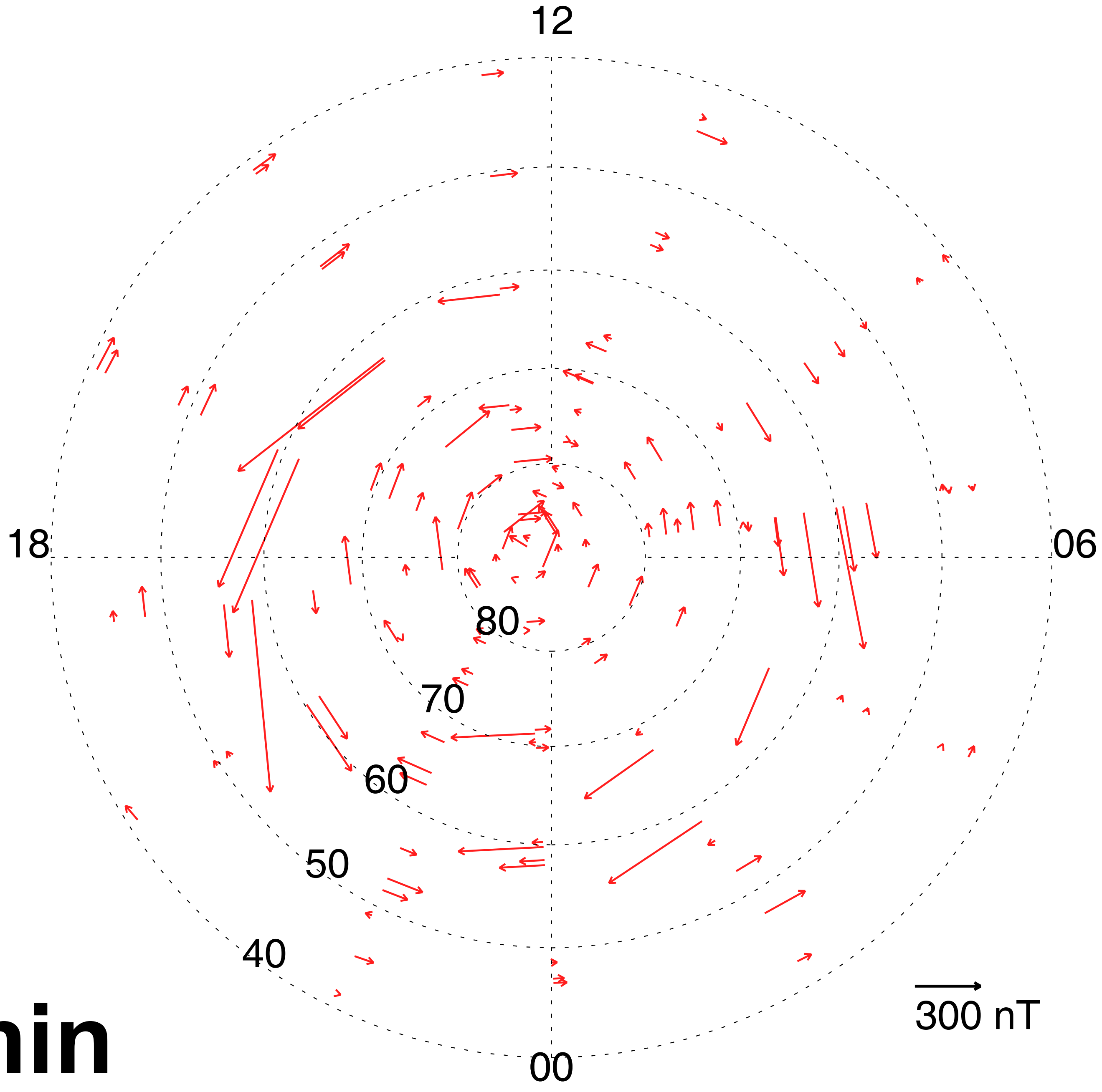
Iridium Constellation for Science

- **Magnetometer on every satellite**
  - **Part of avionics**
  - **30 nT resolution: S/N ~ 10**
- **>70 satellites, 6 orbit planes, ~11 satellites/plane**
- Six orbit planes provide 12 cuts in local time
- 9 minute spacing: re-sampling cadence
- **780 km altitude, circular, polar orbits**
- Polar orbits guarantee coverage of auroral zone
- Global currents never expand equatorward of system

Iridium Satellite LLC

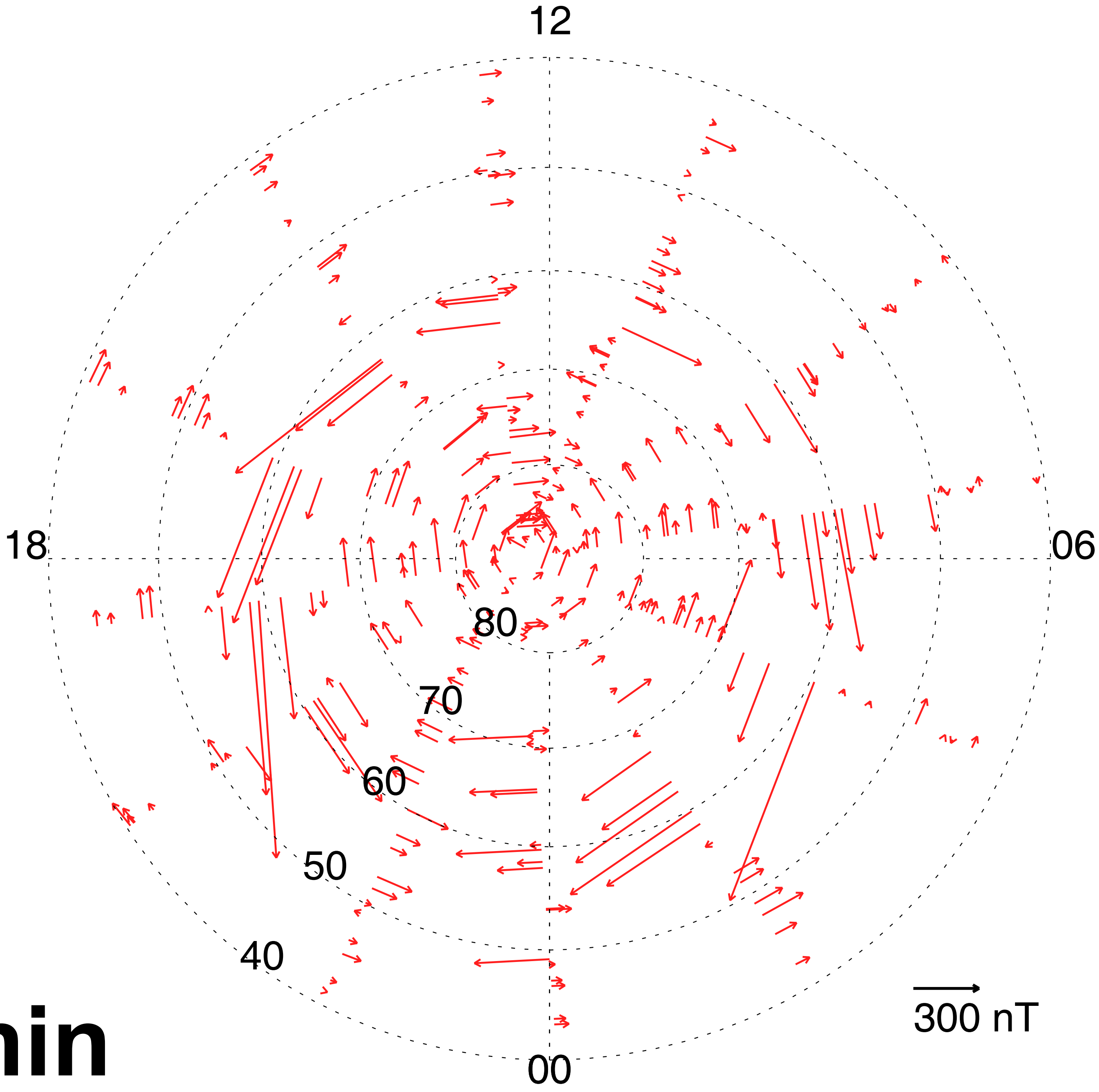
- New company founded in 2000
- Assumed assets of original Iridium
- Profitable since 2001
- Majority of revenue non DoD
- Estimated satellite constellation life: 2014+

10/01/2002 11:50 - 12:10 UT (North)

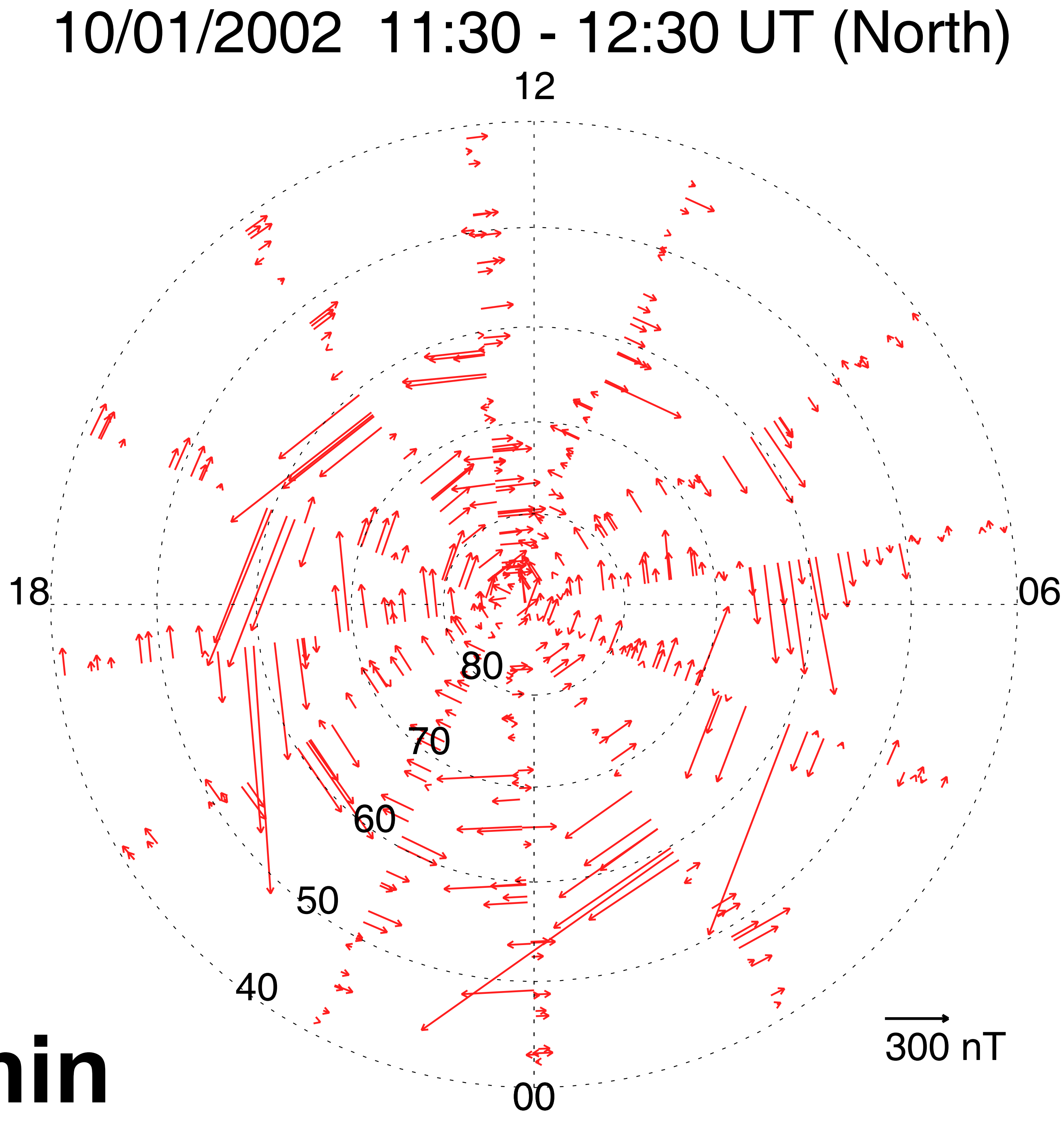


20 min

10/01/2002 11:40 - 12:20 UT (North)

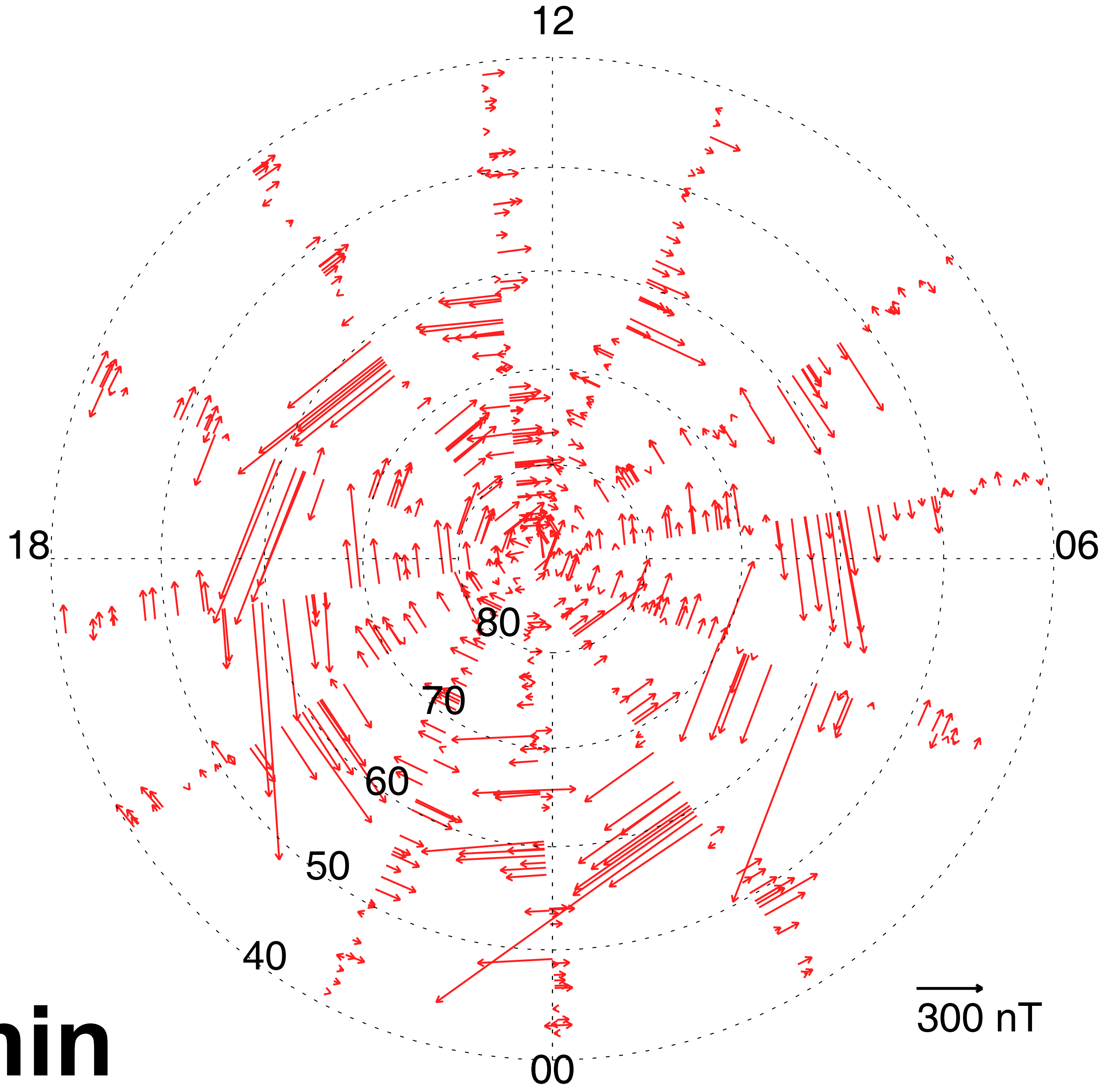


40 min



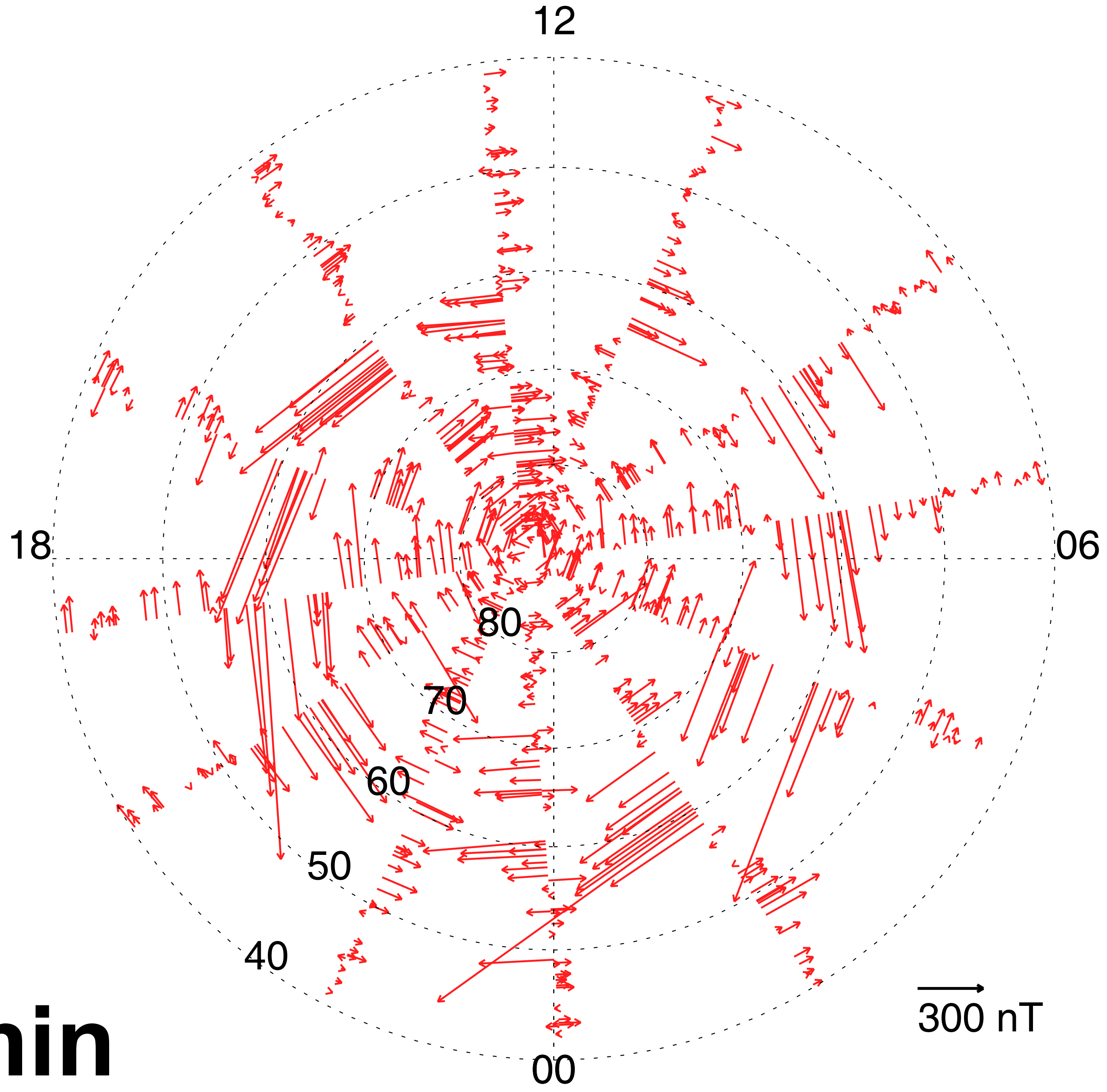
60 min

10/01/2002 11:20 - 12:40 UT (North)



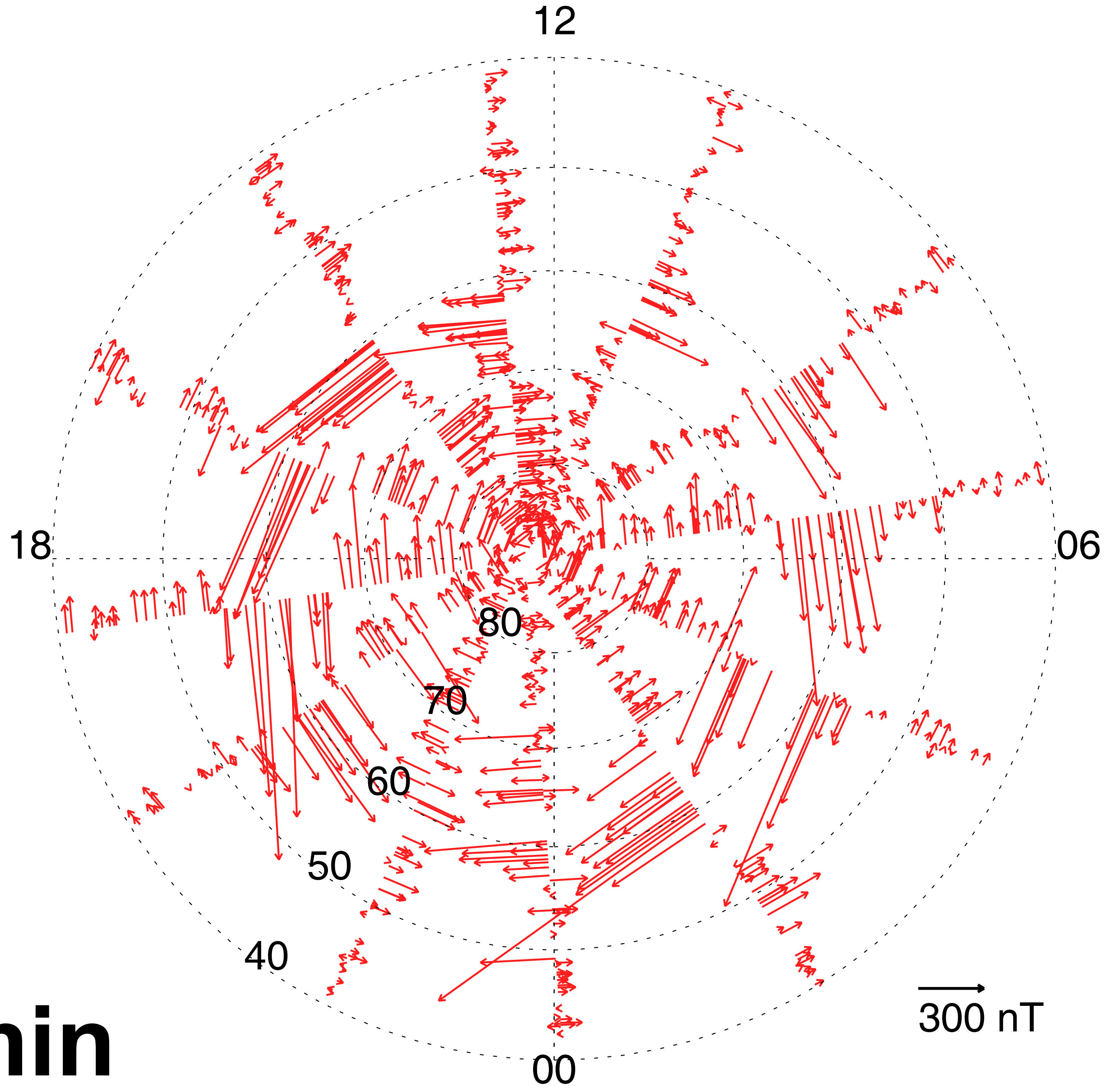
80 min

10/01/2002 11:10 - 12:50 UT (North)



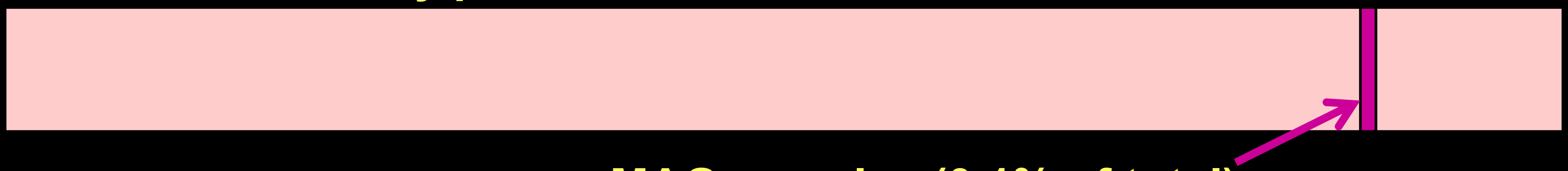
100 min

10/01/2002 11:00 - 13:00 UT (North)



120 min

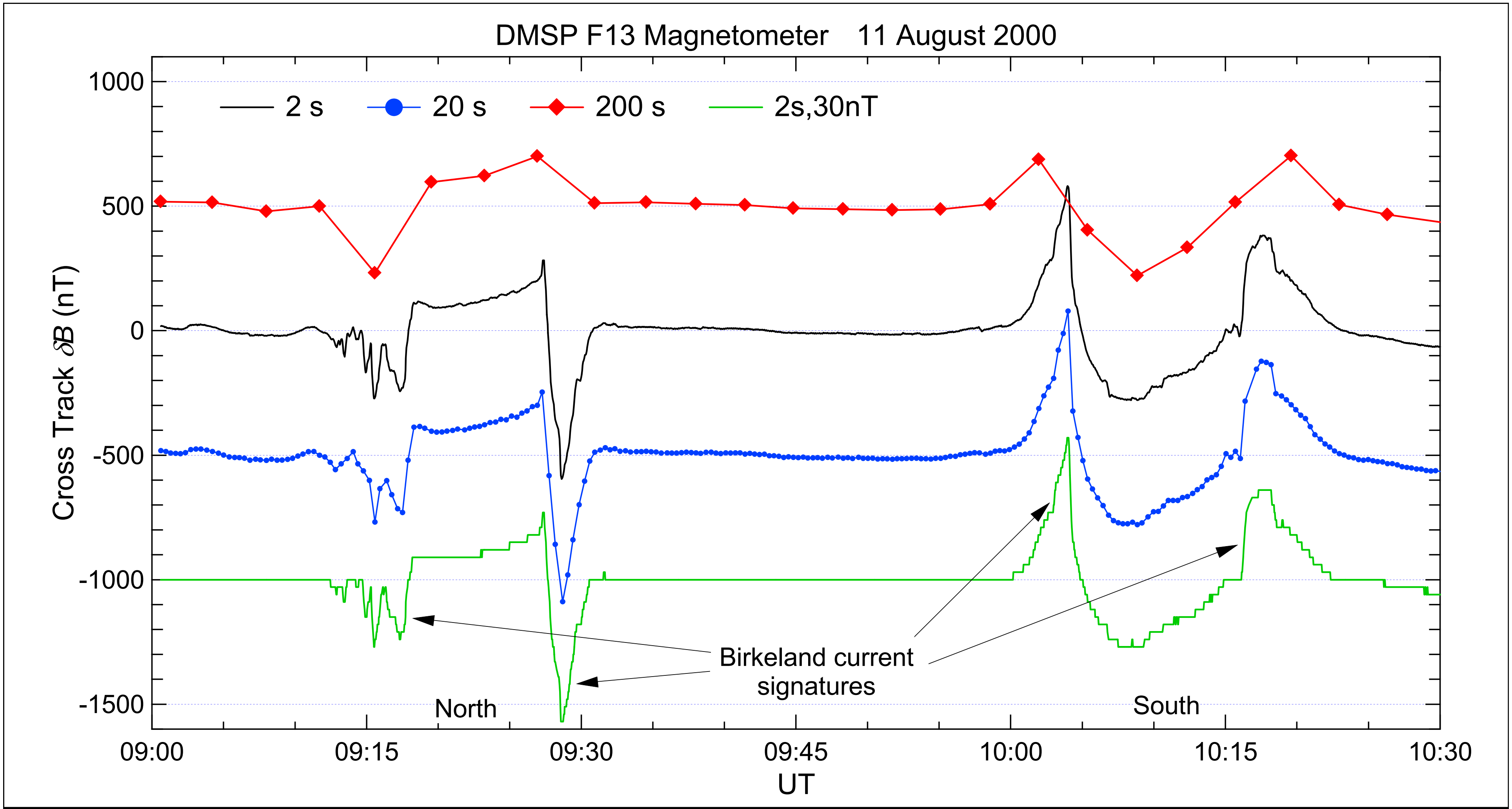
Telemetry Issue & Solution



SC health telemetry packet

MAG samples (0.1% of total)

- Existing system:
  - Magnetometer data embedded in satellite engineering data packet
  - Enormous quantity of engineering data: voltages, currents, temperatures, other attitude sensors, RF system (rec’d intensities), power system (arrays/batteries), computer/memory monitors …
- Modification:
  - Use alternate path: event message. Designed for satellite to report ‘event’ of interest to operators
  - New software to query magnetic field from attitude system processor
  - Pack set of magnetic samples (~10 to 100) in an event message.
  - Event messages delivered in continuously, sequentially (SV001, 002 …) using satellite network to ground station in true real-time



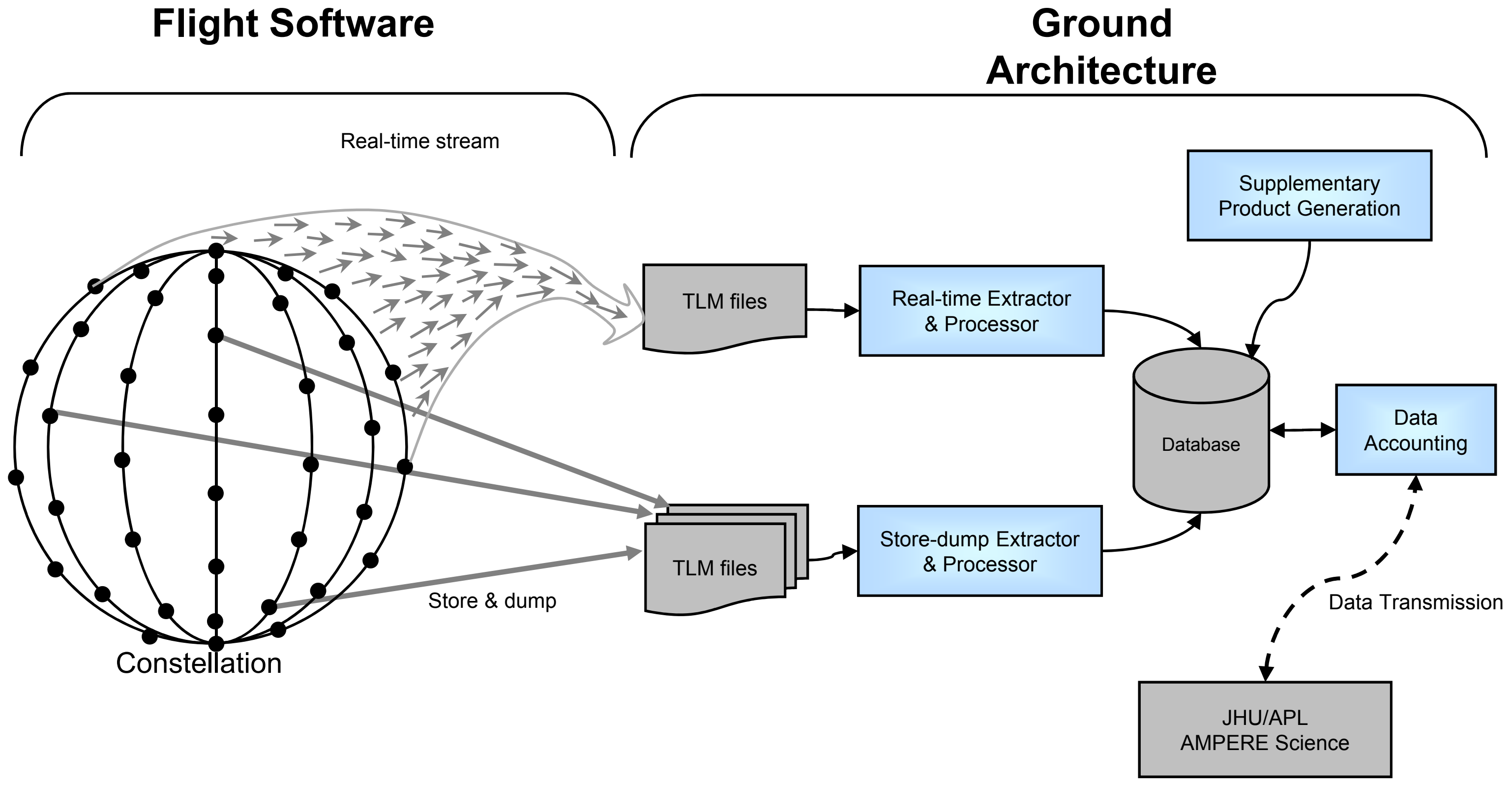
- Existing 200-s sampling often misses signatures
- 2-s sampling captures small-scale features
- 20-s sampling captures all large scale currents
- 30-nT resolution is sufficient

AMPERE Development Effort

- Space software upgrade and installation
- Ground data system to extract and archive data at Iridium operations center
- Data exchange to Science Data Center at JHU/APL
- AMPERE Science Data Center: capability to ingest real-time, 24/7 data and process data products
- Promotion to highest rate:
  - 2 s on all satellites (normally ~20 s)
  - 36-hour promotion span
  - 16 per year
  - Effected in ~1 hour

AMPERE: Boeing/Iridium - Data Provider

- Iridium system upgrade: concept in place and ready
  - satellite constellation flight software
  - ground system development
- Real-time data stream
- Store & dump data: fill any gaps; definitive orbit/attitude



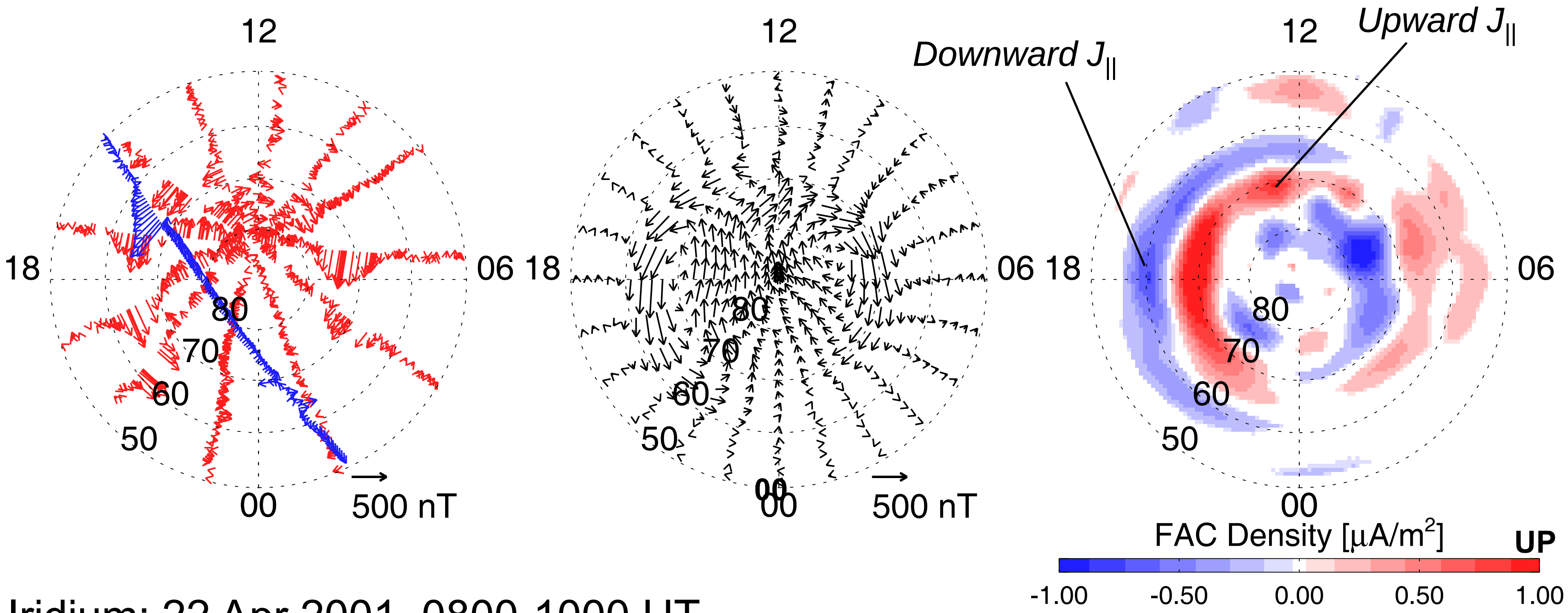
AMPERE: JHUAPL - Science Data Center

- Cross track ΔB, vector **ΔB** map via spherical harmonic fit
- $j_{||}$ from Ampere's law (arbitrary geometry, no stats or cond.)
- Convert all code to common platform: new algorithms for real-time detrending and current inversion
- Derived data products

Cross-track ΔB

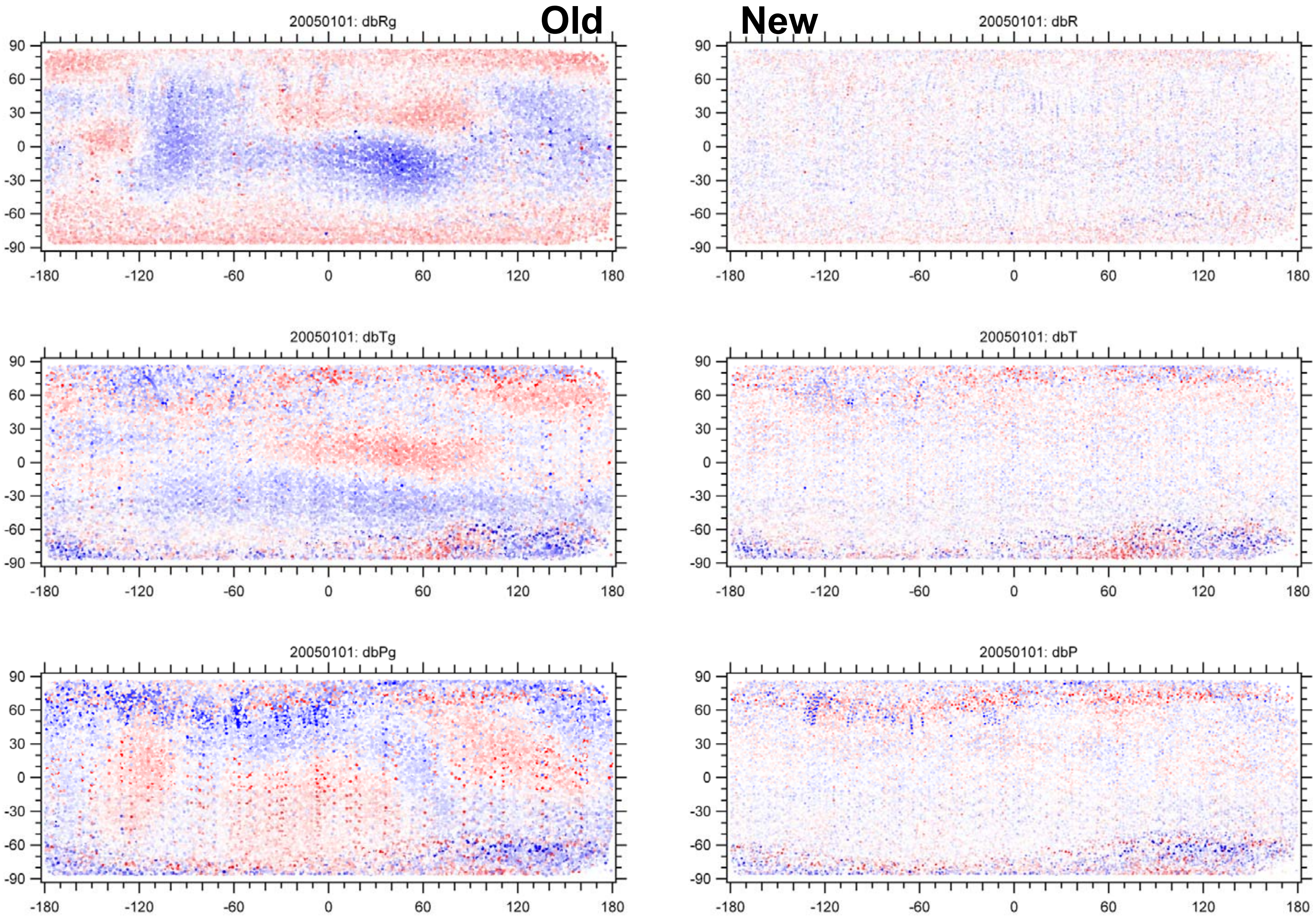
Spherical harmonic fit: **ΔB**

$j_{||}$ = **curl ΔB**



Iridium: 22 Apr 2001 0800-1000 UT

db in Earth fixed r-θ-ϕ (RTP)



Development Timeline

Release of upgraded 'historical' data	Fall 2009
First 'light'	Dec 2009
Testing and validation	CY 2010
Real-time development	CY 2011
'Burst' promotion	CY 2012
Completion	May 2013

- Release of products will occur during development as they are ready