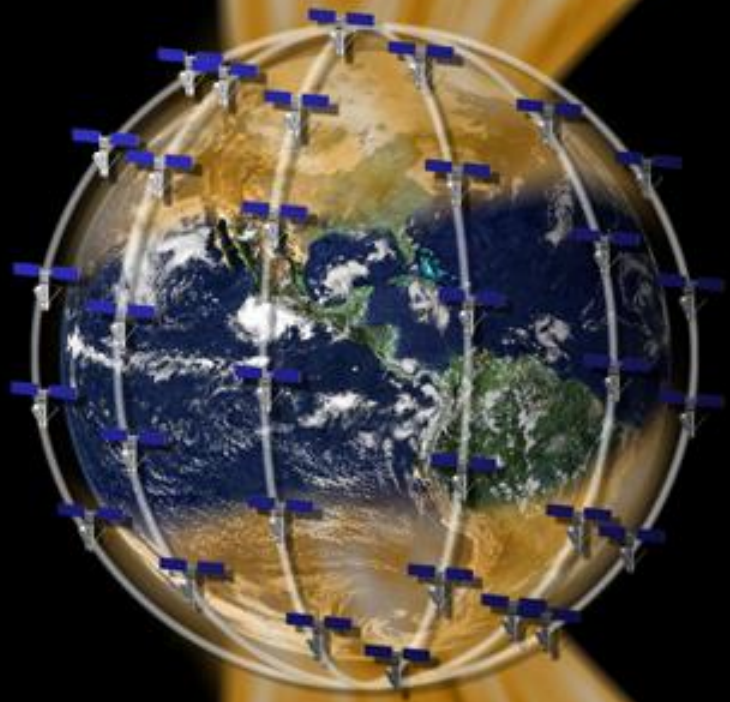
AMPERE



Active Magnetosphere and Planetary Electrodynamics Response Experiment Development Status

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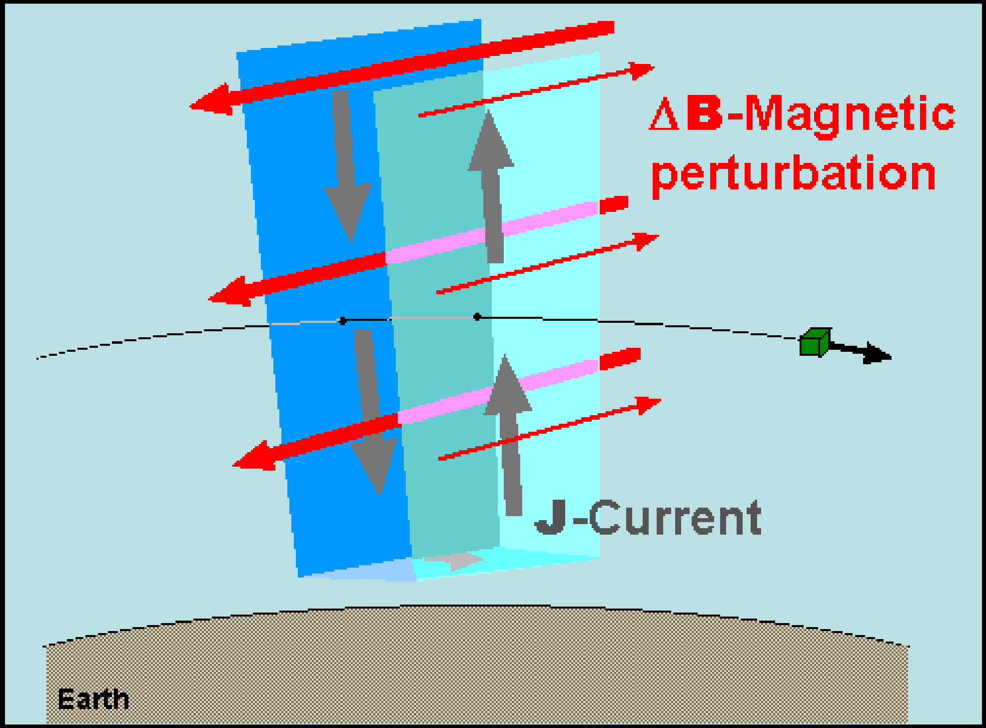
Outline

Overview of AMPERE as it completes development (31 May 2013)

- Satellite system, sensors, data acquisition, and transmission architecture
- Data, data processing, and products
- Performance, coverage, and initial results
- Future: Continuation and NEXT

Birkeland Current δB signatures



- LEO satellites pass through the Birkeland currents.
- Magnetic perturbations are present primarily between sheets of current.
- Ionospheric currents shield signatures from below.

Iridium 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 Communications Inc.

- New company founded in 2000
- Assumed assets of original Iridium
- Profitable since 2001
- Majority of revenue non DoD
- Estimated satellite constellation life: 2015+
- Iridium NEXT funded and going forward: launches 2015-2017
- AMPERE continuation is under negotiation for NEXT. NSF proposal in preparation.

Magnetosphere

Ionosphere

Flow

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

Field lines convey potential

Convection

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

Momentum

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

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

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

Currents convey stress

Finite conductance - current

$$\mathbf{J}_{\perp,i} = \underline{\boldsymbol{\Sigma}} \cdot \mathbf{E}_c = \Sigma_P \mathbf{E}_c + \Sigma_H \mathbf{b} \times \mathbf{E}_c$$

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

Energy dynamo

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

EM Energy Flux

$$S_z = \frac{1}{\mu_0} \mathbf{E}_c \times \delta\mathbf{B}$$

Dissipation - drag

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

The Ionospheric electrodynamics view

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

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

ψ = equivalent current potential

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

Electrodynamics equations: 2 eqs, 5 unknowns

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

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

Other Applications

E-M Energy Flux

- **No δB, no S_z**
- **|δB|** locates regions of S_z

$$S_z = \frac{1}{\mu_0} \mathbf{E}_c \times \delta\mathbf{B}$$

Useful for assimilation

- Global and 'uniformly' distributed
- Fundamental physical quantity: δ**B** or $j_{||}$
- Relevant to multiple efforts
  - Ongoing: AMIE, GAIM
  - Potential: RCM, MHD

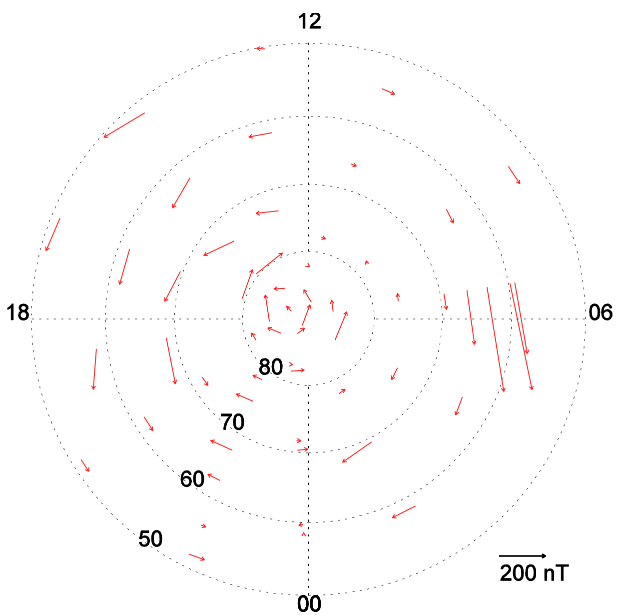
Data Acquisition

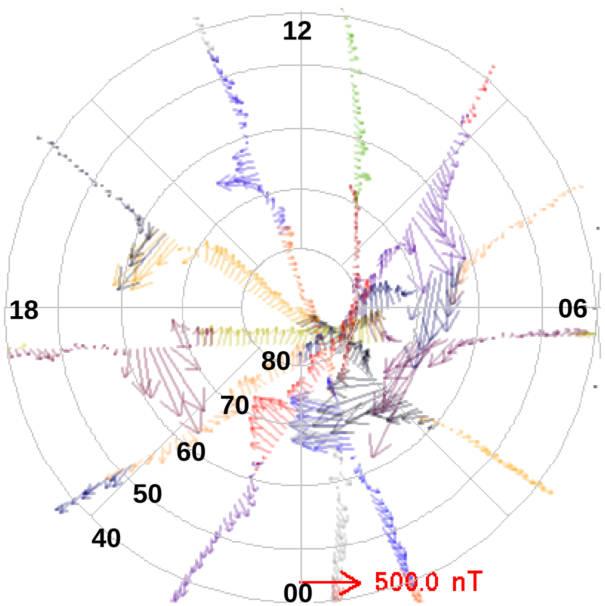
Side-by-side comparison of data acquired in 10 minutes — Old: ~200 s/sample

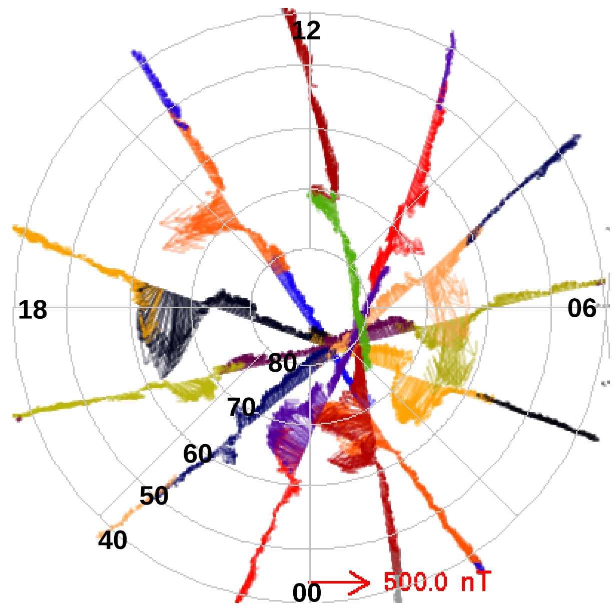
Standard AMPERE: complete coverage with ~1° lat. res. — 19.4 s/sample

High rate AMPERE: ~ 0.1° lat. res. — 2.16 s/sample

Old Data	AMPERE: Standard	AMPERE: High
10/01/2002 11:55-12:05	10/08/2012 21:24-21:34	09/30/2012 20:42-20:52





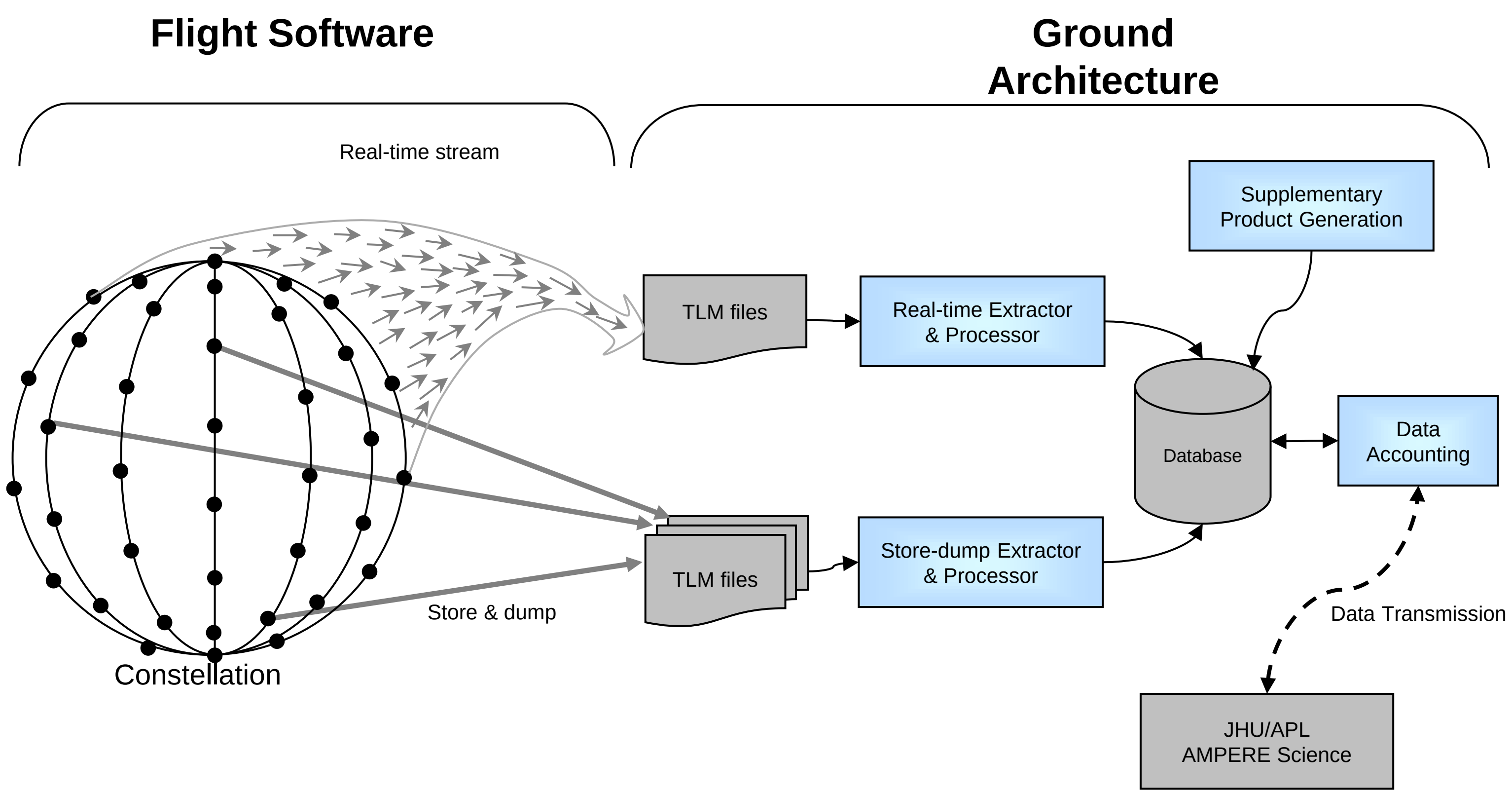


TLM data from all satellites

Different colors denote different satellites

AMPERE System Overview

- Flight software acquires magnetometer samples at 20-s or 2-s intervals on every satellite 24/7
- Transmits to ground over satellite network
- Store & dump data: fills in gaps, definitive orbit/attitude
- Definitive data: data accounting & post-facto ephemeris & attitude



Data Acquisition Status

- Space segment
  - Space software development, test, upload and commissioning completed 31 May 2010
  - AMPERE acquisition fully functional 10 June 2010

- Ground data system
  - Data ingestion and accounting completed (Boeing)
  - Transition to new hardware gradual (Boeing)
  - Data transfer to Science Data Center (secure ftp, 24/7)

Science Data Center

- Data pre-processing
  - Archive, merge, attitude analysis
  - Inter-comparison/calibration, model field comparison
  - Conditioning: residuals, quantify ‘noise’, weighting
- Inversions: fit to δ**B**; derivation of J_r
  - Data ingestion and quality/completeness checks
  - Orthogonal function fits to δ**B**. $\boldsymbol{J}_r$ via Ampere’s law.
  - Compiled code: run-time for AMPERE high 10-minute segment: ~30 seconds per hemisphere
- Data access system
  - Summary products: 10 min windows every 2 min
  - Browser and custom display tool
  - Processing product download (input δ**B** digital)

Magnetic Field Pre-processing

Read initial hourly files

↓

Filter SC attitude

← Step we didn't expect. Only evident in AMPERE data

↓

Rotate IGRF into SC coordinates

↓

Cross calibrate against IGRF: scale factorsLinear regression

$\Delta B_j = a_j + \Sigma c_i * B_i$

← Since we are only interested in δ**B,** the accuracy of IGRF is not critical for this

↓

Subtract IGRF

↓

Fill in data gaps

← Identifying gaps and fill automatically with valid data from other satellites

↓

Filter: *T*< 120 minutes

← Would prefer to eliminate this step

↓

Produce Daily files for Final processing

↓

Produce initial survey plots

Raw data: B_{meas}

Initial main field residuals
dB errors ~ 1%

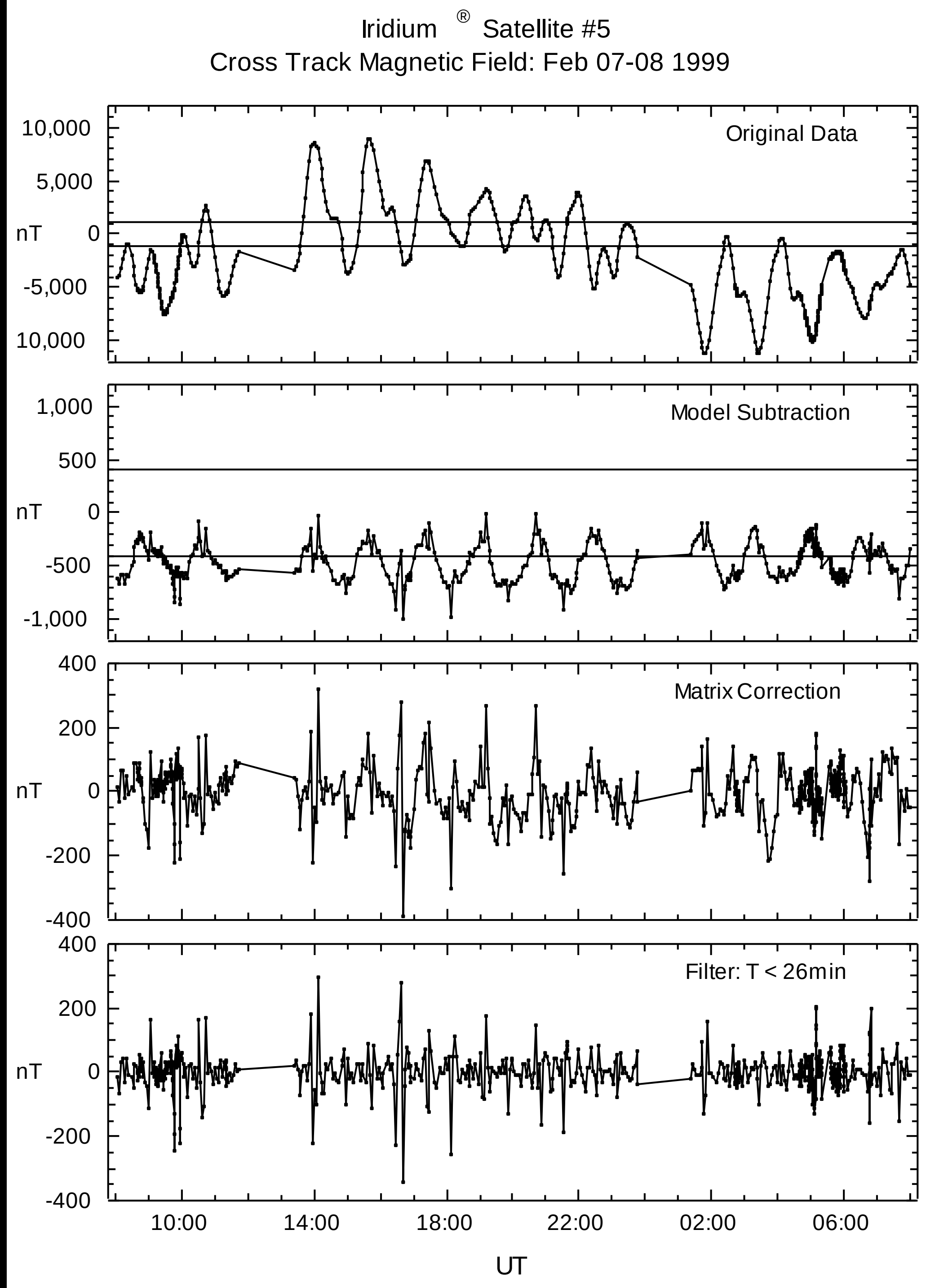
Gain & mag orientation corrections:

dB_{cor} errors ~ 0.4%

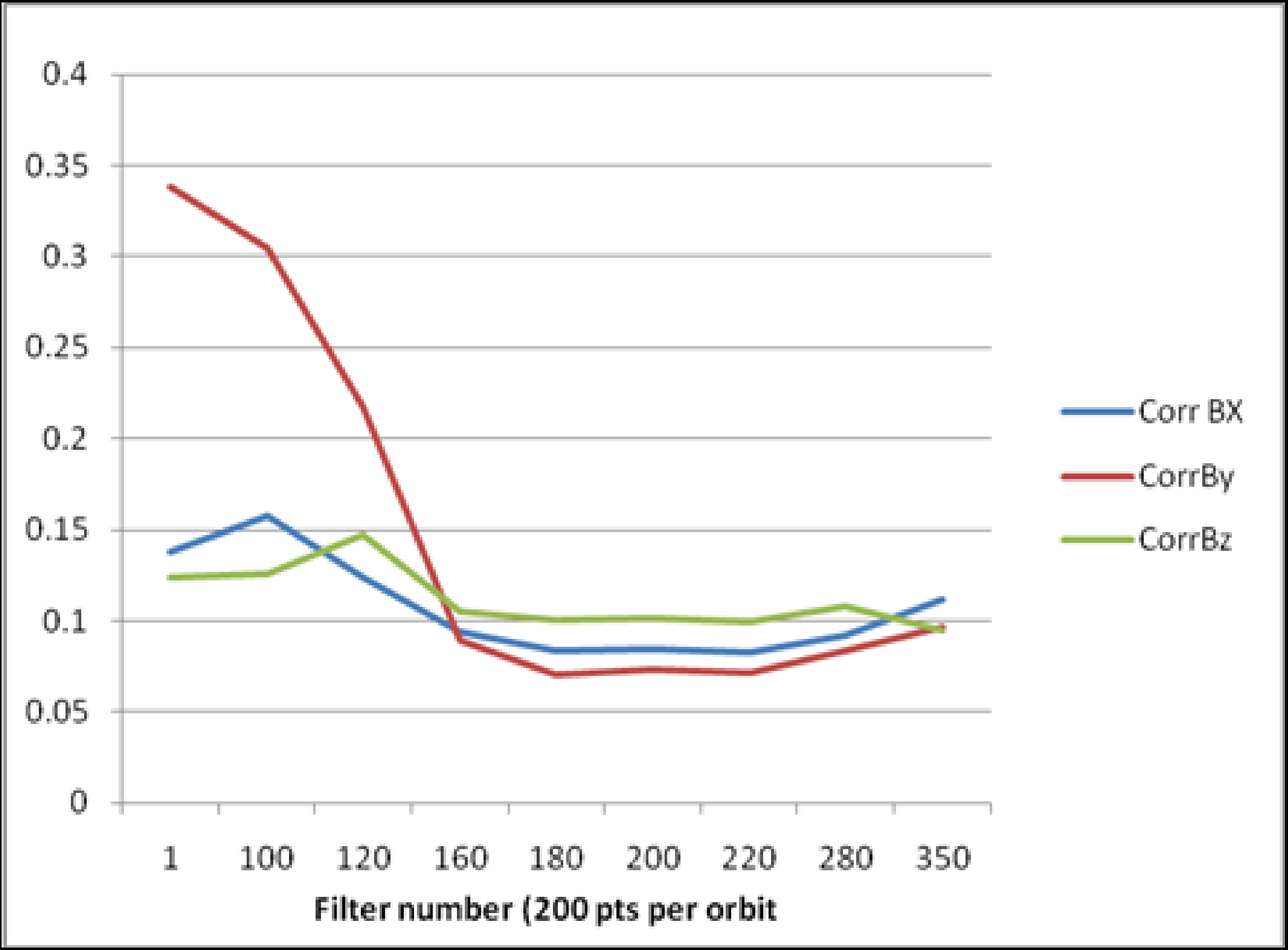
Attitude corrections:

dB_{cor} errors ~ 0.05%

Comparable to 30 nT (12-bit) resolution.



Attitude Conditioning



- Attitude data conditioning filter determined by reducing correlation between attitude and magnetic residuals.

Test Data

First light: 17 Feb 2009 (brief)

Partial constellation tests selected days/periods: Mar – Sep 2009

Operational testing:

- **1 Oct 2009 – 31 May 2010**
- **Temporal coverage: >90%**
- **Sporadic time gaps in data from individual SVs**
- **Occasional high rate test data**

Activity / Development Task	Dates
Third flight test and first high rate test	14 - 21 Apr 2009
Fourth flight test	19 May 2009
First full constellation data test	23 Jun - 8 Jul 2009
Second full constellation test, first high rate tests	29 Sep - 30 Nov 2009
Formal AMPERE space systems operations test	1 Dec 2009 - 31 May 2010
AMPERE data collection	1 Jun 2010 - present

Data Coverage

- Test Data: Oct 2009 – May 2010
  - Gaps in coverage from constellation (rare)
  - Gaps in individual satellites (fairly frequent)
  - Very few days entirely missing
- AMPERE operations:
  - June 2010 – May 2013
  - >99% data coverage
  - Very few missing inversions
- High rate data:
  - 512 hours per year of high rate data
  - CME-driven storms and campaigns

AMPERE-High

Short-term: PI makes a decision based on CME-predicted storms (GSFC bulletins)

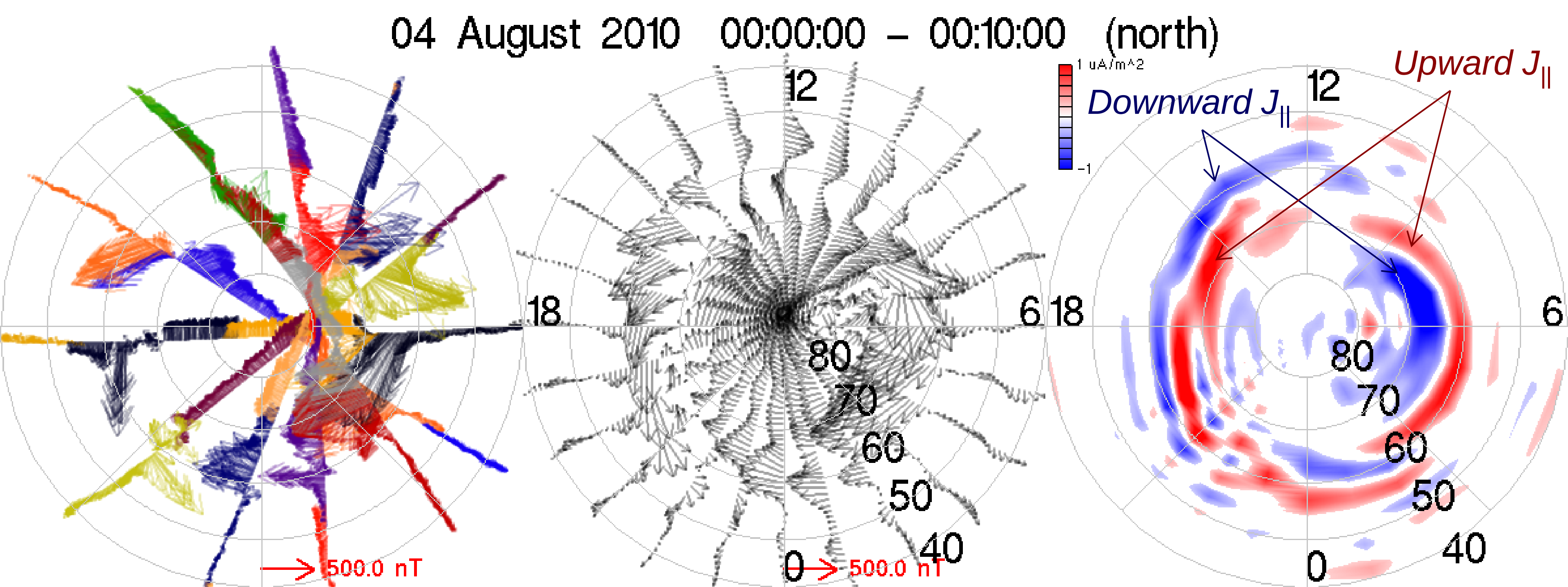
Scheduled: to support campaigns (THEMIS, sounding rocket, …)

2010		2011		2012		2013	
0120	0122	0111	0125	0121	0123	0117	0118
0224	0226	0216	0218	0126		0316	0318
0324	0325	0309	0311	0214	0223	0410	0411
0415	0429	0406	0408	0617	0618	0413	0414
0523	0524	0515	0630	0714	0716		
0527	0529	0711	0712	0902	0904		
0803	0805	0804	0807	0929	1002		
1022	1025	0909	0910	1112	1114		
1113	1115	0917	0918	1124	1125		
1207	1212	0926	0927				
1228	1230	1129	1130				
		1228	1230				

Analysis for δB, J_r

- Vector **δB**, data, continuous **δB** map via SH fit
- J_r from Ampere's law applied to horizontal **δB**
- Time cadence: 9 min set by inter-spacecraft separation
- Lat res: 1.15° for 19.44s sampling, 0.13° for 2.16s sampling

δB | Spherical harmonic fit: **δB** | J_r = **curl δB**



Inversion Steps: Cap Inversions

- Data Preparation:
  - For each 10 minute segment N and S separately
  - Sort by track and by slot within each track.
  - Convert to AACGM, positions and vector data (two options since AACGM is not an orthonormal system).
  - Track overlap conditioning.
  - Nyquist condition checks and regularization.

- Basis Set Computation:
  - Must be orthonormal set: required for curl computation (fitting data using a re-defined polar angle in standard Y_l^m is not sufficient).
  - Given latitude range, latitude order and longitude order: compute cap inversion basis functions.
  - Non-integral Legendre functions derived from series of hypergeometric functions).

- Design Matrix Inversion
  - Compute design matrix convolution of cap functions and measurement locations.
  - Matrix inversion.
  - Gridded output: $\delta\mathbf{B}$, j_r.

Formal Inversion Problem

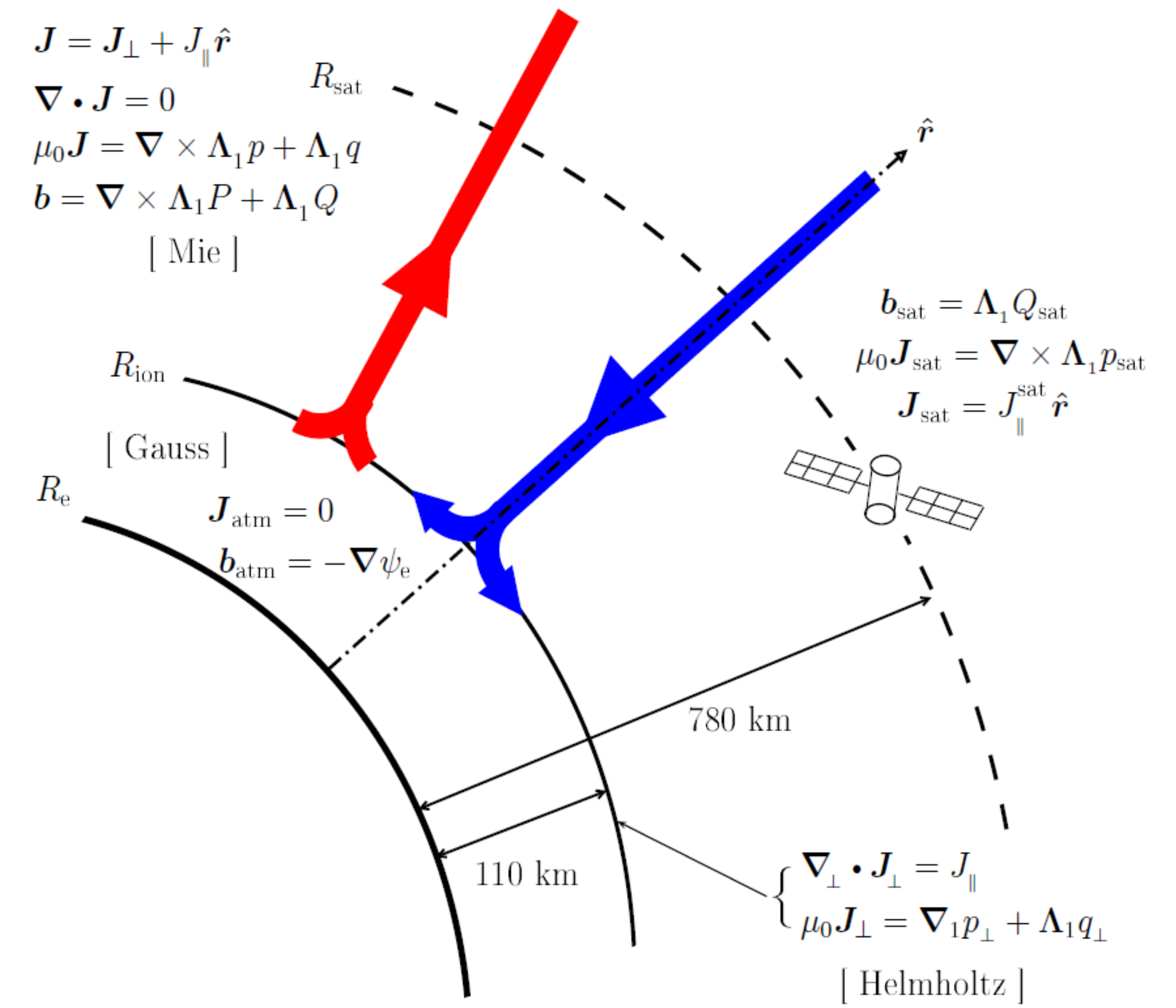
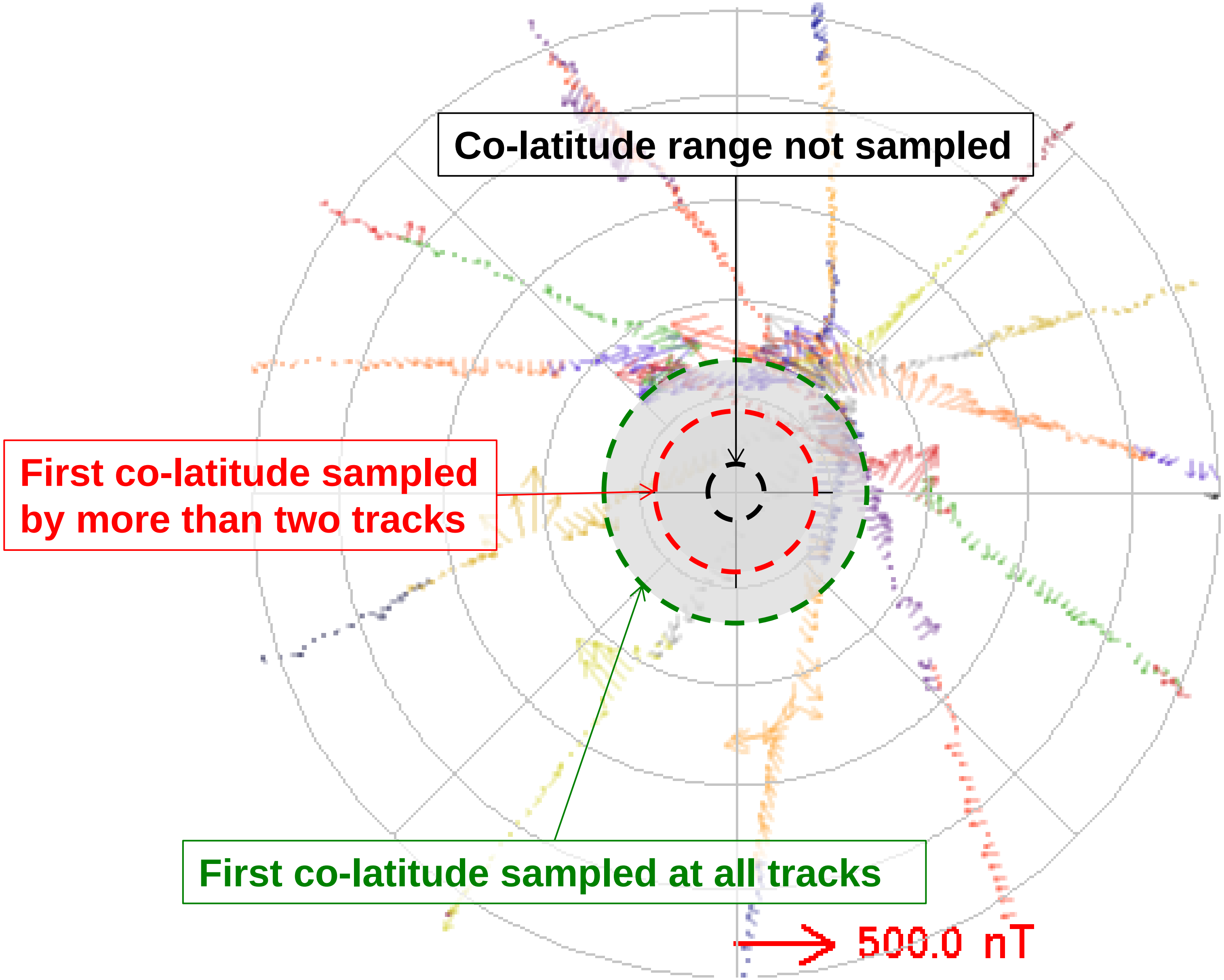


Fig. 1 Magnetic fields and currents and relevant mathematics below, in and above the ionosphere. The surface curl operator $\Lambda_1 = \mathbf{r} \times \nabla$ (Green 2006).

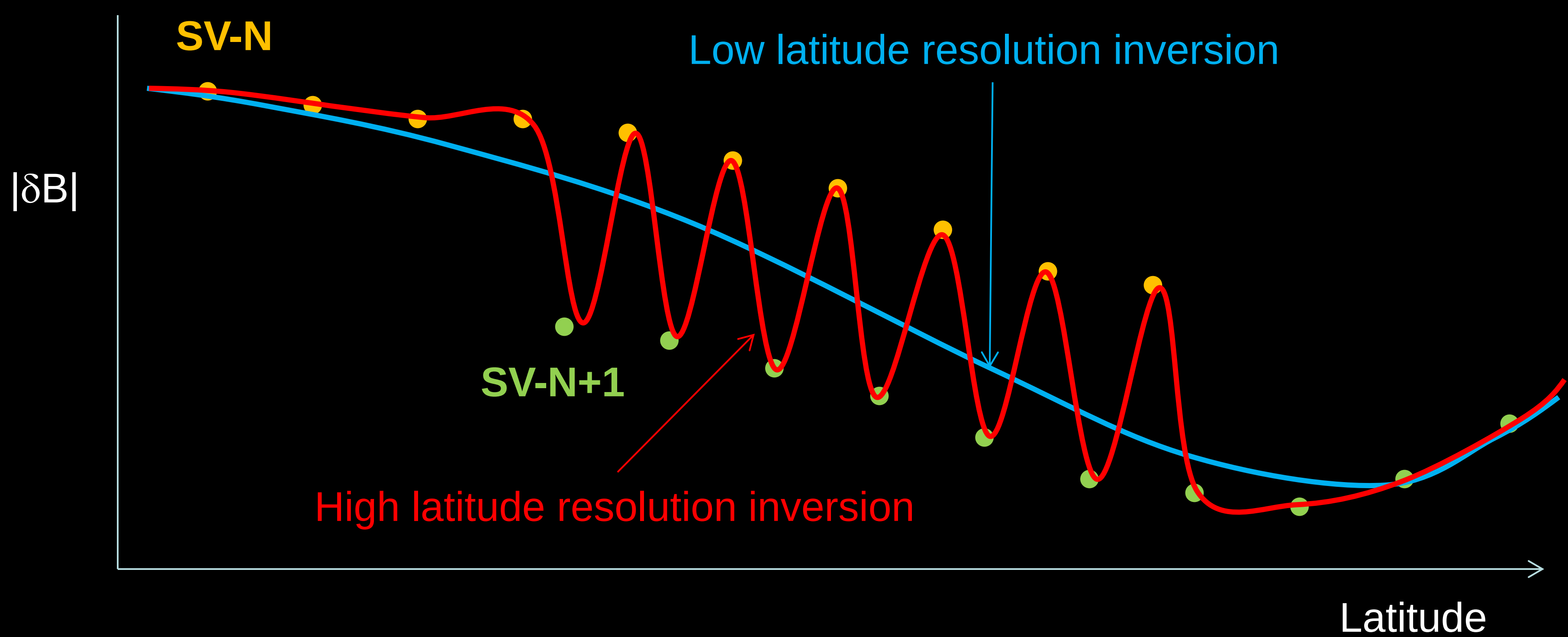
Challenges

- Coordinate system matters: pole origin
- Nyquist condition: requires interpolation over areas w/o data. Pick the lesser evil (gaps are fatal to inversion).
- Satellite track overlaps: requires special treatment.
- Consequences of one missing or bad slot: requires filling in from satellite ahead. Again, choose the lesser evil.

AACGM Nyquist condition violation



High Latitude Resolution



Baselines between SVs are generally somewhat different.

Causes moderate phantom signals in low latitude resolution fits.

Overlap in track segments causes severe corruption in high latitude resolution fits.

Validation

- Somewhat self-checking via consistency between **δB** signatures on multiple satellites.

- DMSP MAG comparisons: Iridium under-samples the smaller-scale, higher time resolution, but the large-scale **δB**s agree.

- Inversions: E-field
  - SuperDARN flows: agree in location and directions – but not in magnitude – topic for work on conductance.
  - DMSP drift: located correctly but under-estimate magnitudes (low latitude resolution of inversions).

Data Products

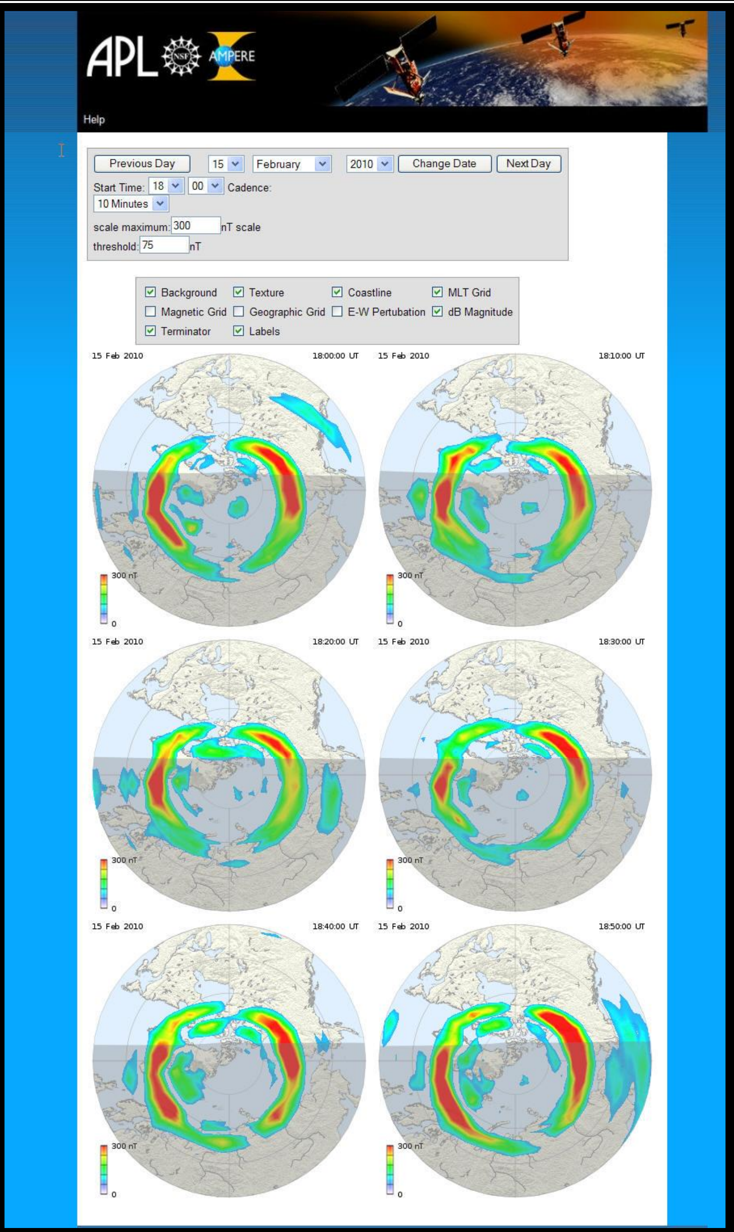
- All products re-run since February 2013 with latest pre-processing and inversion codes.
- Inventory tools and graphics displays.
- Gridded output
  - 1 hr x 1 deg (MLAT) in AACGM
  - $\delta\mathbf{B}$ fit, J_r
- Digital data (in review)
  - Detrended $\delta\mathbf{B}$ in geographic
  - Netcdf files
- Data browser
  - Overlay displays
  - Graphics
- Summary statistics (just implemented)
  - Birkeland current analogs of AE etc.
  - Daily and monthly

AMPERE Data Center
http://ampere.jhuapl.edu

- AMPERE Science Data Center data center browser

- Accesses auto-processed data: As soon as we process data it shows up for the browser.

- Products available for display:
    - Input horizontal δ**B** vectors
    - Fit δ**B**
    - **|δB|** magnitude
    - δ**B** E-W component
    - Radial current density: J_r

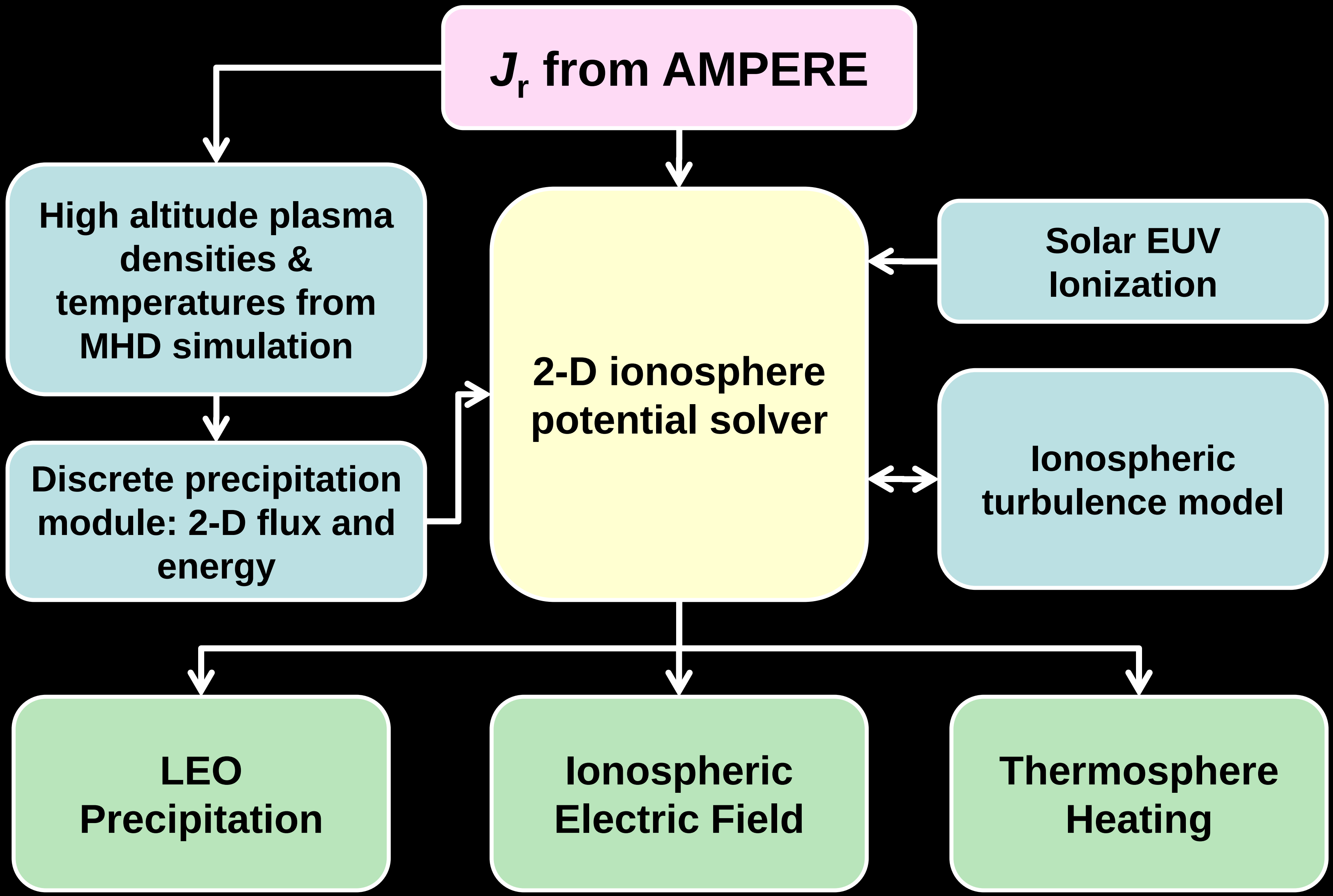


Science Results

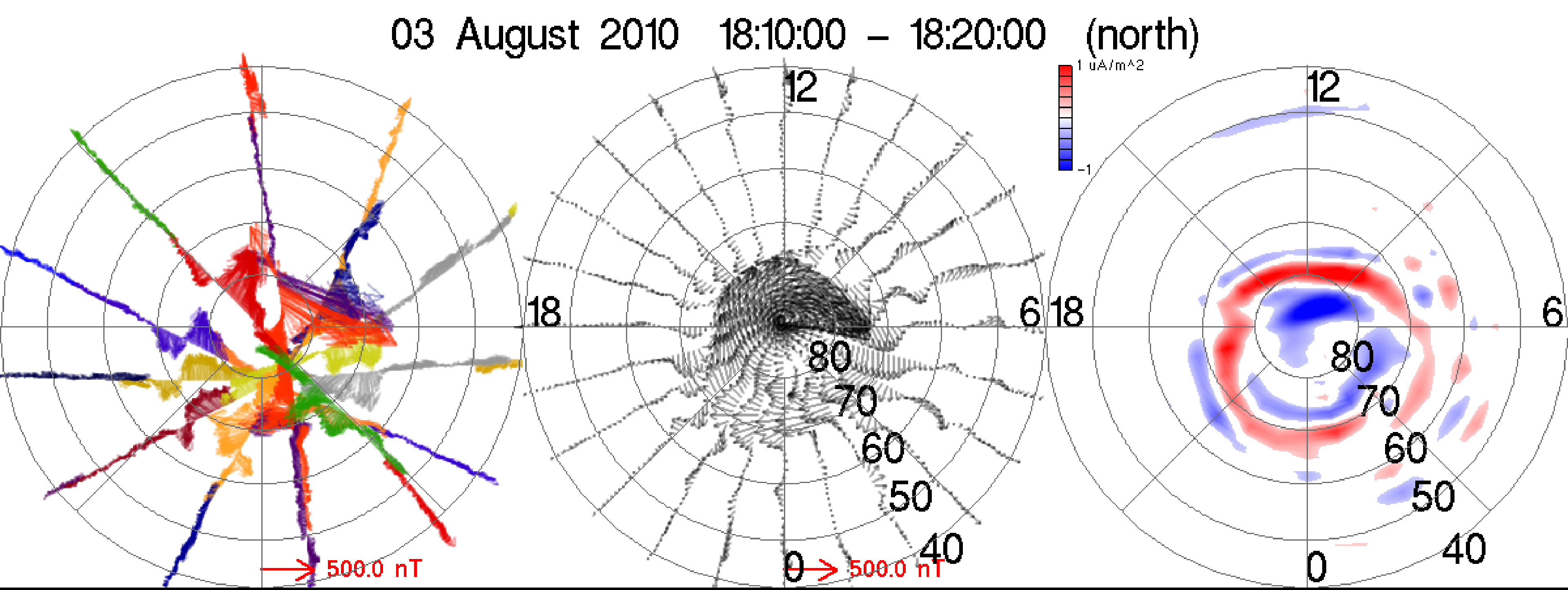
- Almost exclusively outside the AMPERE team.
- Thermospheric response (Wilder et al., 2011, 2013)
- Polar cap dynamics (Claussen et al., 2012, 2013; Merkin et al., 2013; …)
- Ionospheric electrodynamics (Marsal et al., 2012; Lu et al., this meeting; Knipp et al., this meeting)
- *Substorm dynamics: numerous (Murphy et al., 2013; and others)
- NASA mission and NSF & NASA grant proposals: numerous …

* If AMPERE had been proposed as a sub-storm project – would you have believed it?

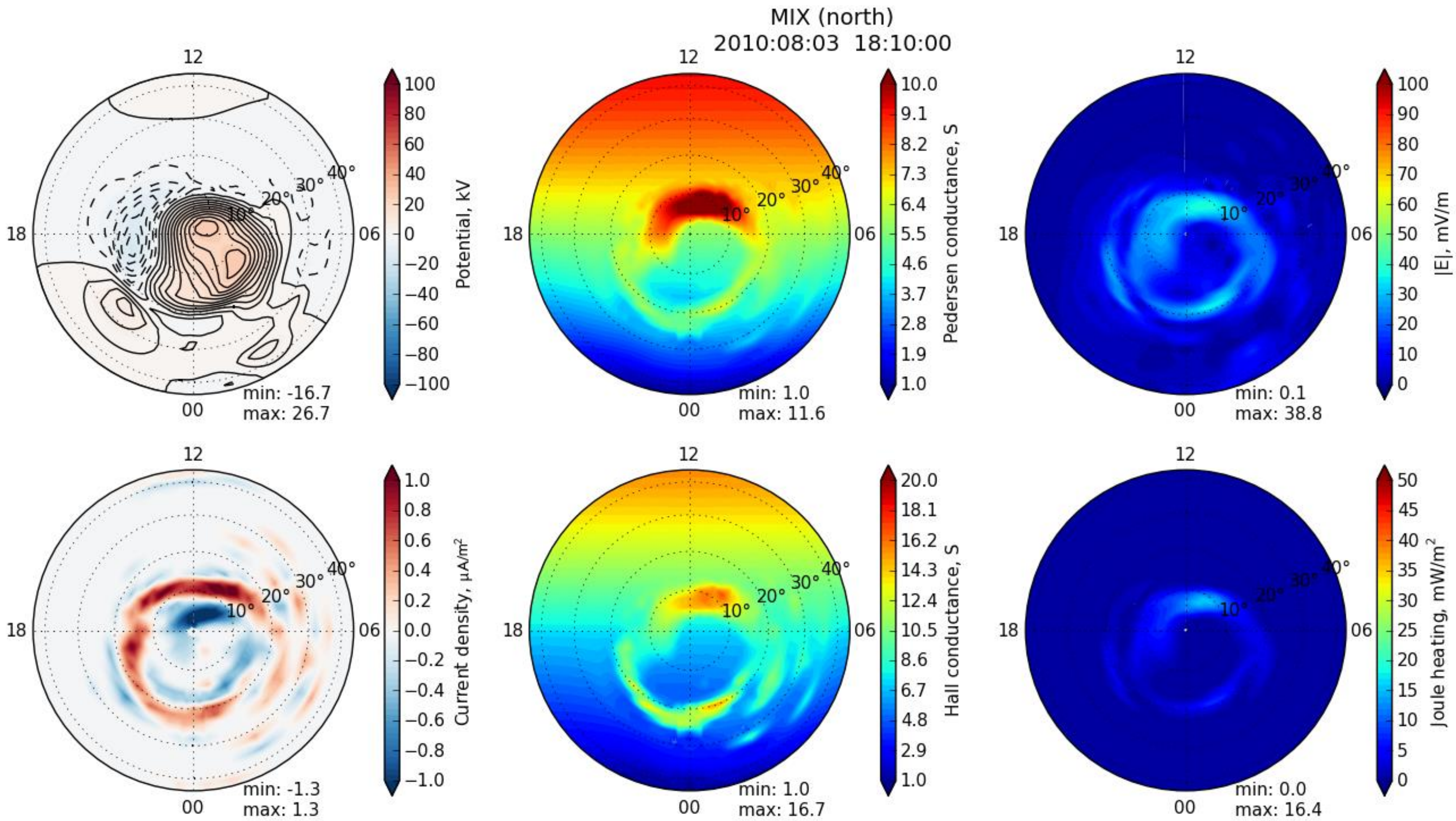
Concept: Science Case Study



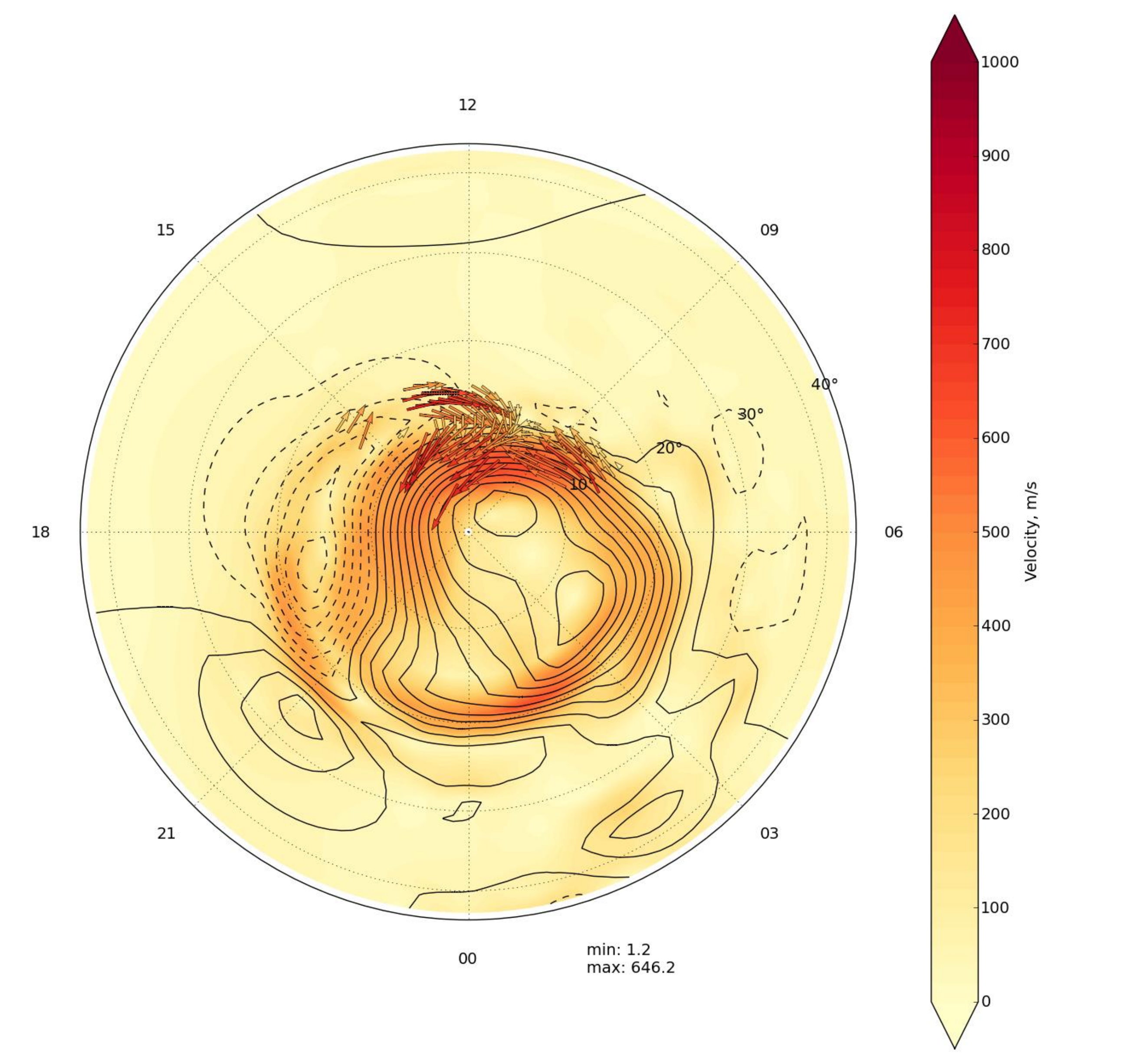
Summary Frame: 1810-1820 UT



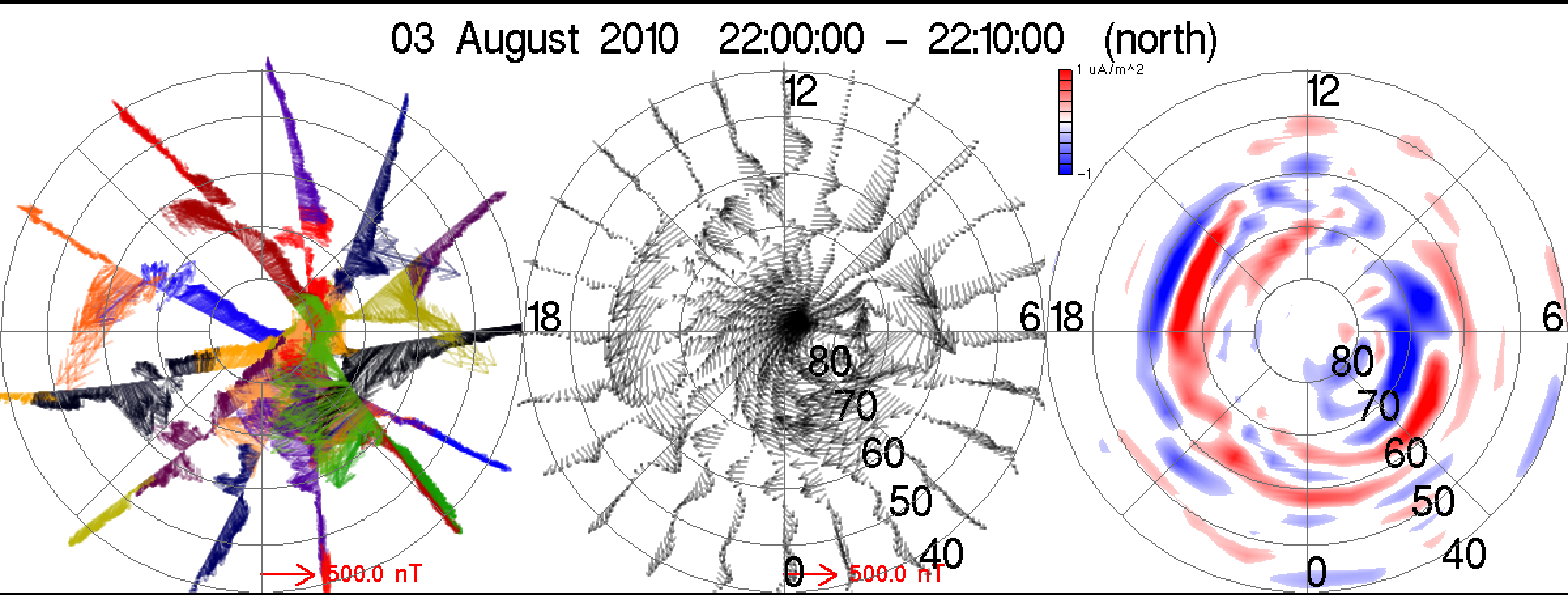
MIX solution (Merkin et al.)



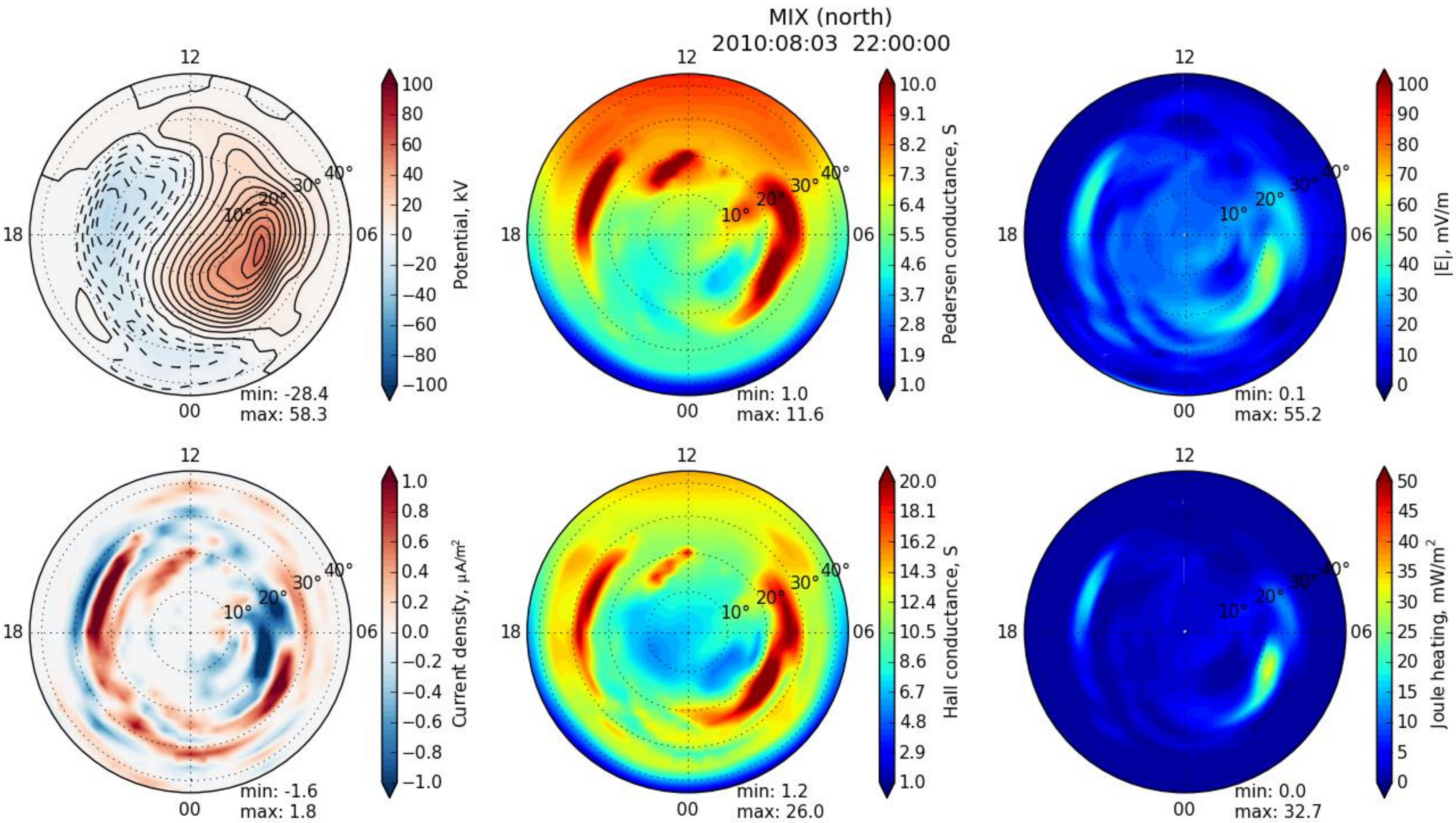
SuperDARN overlay: 1810-1820 UT



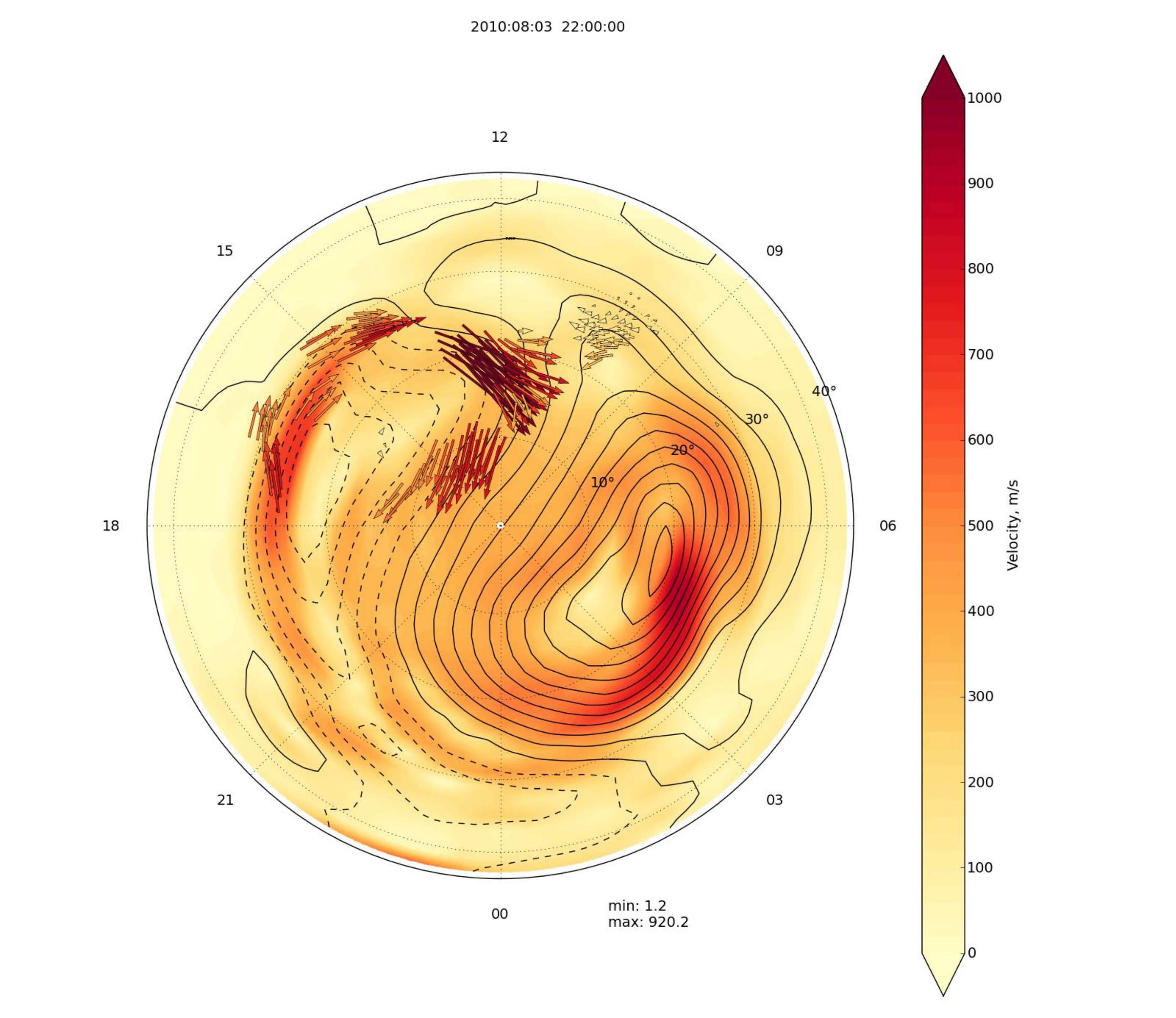
Summary Frame: 2200-2210 UT



MIX inversion (Merkin et al.)



SuperDARN overlay: 2200-2210 UT



Real-time and Latencies

- Raw data transfer to APL within 100 s from transmission of data from satellite.
- Real-time processing
  - AMPERE high test April 13-14, 2013
  - Median 6 minute total latency to J_r. (End of data interval to ‘now’.)
- Limiting step is data packet time span:
  - Standard: 19.44s → packet takes 24 minutes to fill: latency = 24 min + 6 min
  - High rate: 2.16s → packet takes 160 sec to fill: latency = 160 sec + 6 min

Real-time Lessons Learned

- Even best-effort real-time is labor intensive.
  - Contingency preparedness & testing.
  - Performance monitoring.
  - User service.
- Operational real-time is expensive.
  - Hot backups. Operational code.
  - Flow-down of real-time requirements on data purchase (assured reliability).
- Dubious trade: loss of science value.
  - Science analysis is retrospective & needs best data.
  - Detracted AMPERE labor from maximizing science value of data and products.

The Future: Getting to NEXT

- AMPERE-II concept:
  - AMPERE-Continuation: on Iridium Block-1
  - AMPERE-NEXT: on Iridium Block-2
- AMPERE-NEXT:
  - Iridium-NEXT satellites do have magnetometers.
  - AMPERE on NEXT will be different but superior.
  - Same orbital configuration: 6 orbit planes with 11 SVs equally spaced in each plane.
  - Time sampling will be fixed but return more than twice as much data as the present AMPERE standard rate: <0.5° latitude resolution 24/7.
  - Attitude knowledge: more than 10x greater precision than present system. Higher quality **δB** data, more stable baselines.

Advancing AMPERE

- Add community products: e.g. Claussen R1/2 fit, etc.
- Analyze stepwise noise
  - Identify operational causes. Corrections?
  - Reduce 'noise': ~2x reduction in δJ_r to ~0.07 mA/m^2.
- Higher latitude resolution inversions:
  - Data support down to 1.2° resolution
  - Need faster inversion algorithm
- Ingest other magnetometer data: DMSP, CHAMP?, SWARM?, …
- Regional inversions
  - Along track of higher time resolution data (DMSP etc.)
  - Orbit crossing region is often in cusp or substorm onset
  - Apply finite-element or other inversion algorithms
- Multi-data type inversions: E-field, ground mag, auroral imagery
- Community
  - User working meetings virtual (webinars) and real (SWW, GEM/CEDAR)
  - Student workshops