In situ or Direct Measurements in the Ionosphere and Thermosphere

Presentation at:

CEDAR Meeting

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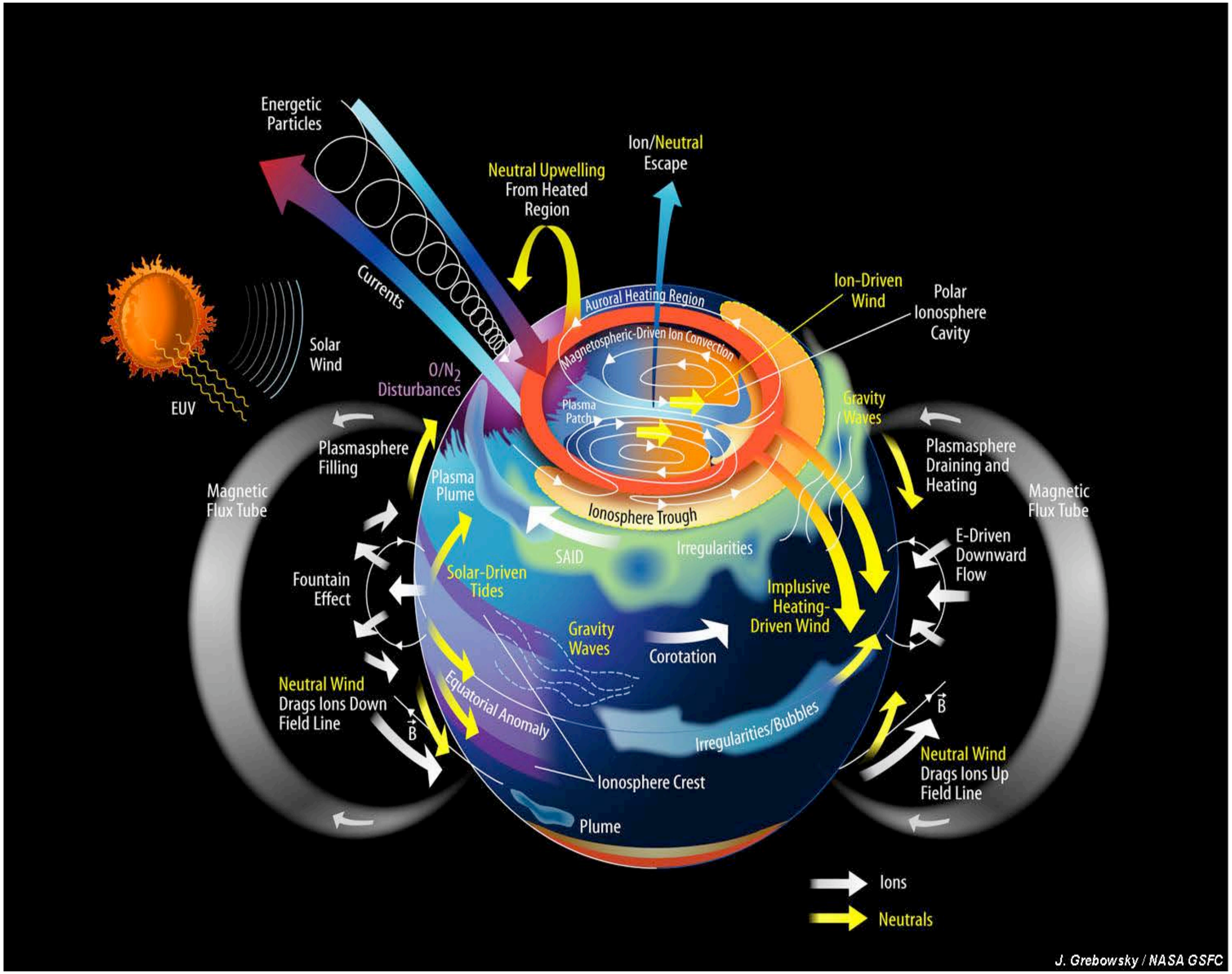
Introduction

The upper atmosphere is highly complex, dynamic, and variable, and is strongly coupled to the magnetosphere above and the troposphere below.



Introduction

In situ measurements reveal fundamental physical processes at work in the upper atmosphere and how they are related to the magnetosphere above and the troposphere below.

Continuous measurements provide evolution of ionosphere, dynamic processes as a function of magnetic activity, storms, etc.

Probes provide highly accurate data that provide statistical “pictures” as a function of local time, latitude, season, magnetic activity that form input to models and show how I-T system “works”.

There remain many critical regions of the earth’s upper atmosphere that have not yet been sampled, or have been sampled very poorly, even by single satellite missions.

Multiple satellite missions are needed to address science questions related to the structured and dynamic I-T system and can be expected to revolutionize our knowledge of the upper atmosphere.

Comprehensive *In situ* Instrument Suite

Basic Measurements can be organized into 3 groups:

Gas Properties Instruments

Neutral density, velocity, temperature
Ion density, velocity, temperature
Neutral and Ion mass discrimination and relative densities

Electrodynamics Instruments

Vector DC electric and magnetic field (currents)
Plasma waves (AC Electric and magnetic fields)
Electron density and temperature

Energetic Particles Instruments

Supra-thermal electrons and ions (0.05 to 50 eV, all pitch angles)
Energetic electrons, ions (5 eV to 30 keV, all pitch angles)
Very energetic electrons and ions (e.g., 500 keV, 1 MeV)

Basic Instruments are all well-characterized.

Consolidation of instruments, e.g., in such groupings, saves considerable resources (mass, power, $, time).

Also provides for simultaneous sampling, efficient burst memories, etc.

GEC Nominal Measurement Requirements
(for reference)

Science Parameter	Measurement Requirements: Range	Accuracy	Temporal Resolution
Electric Fields (vector)	0 – 500 mV/m	0.1 mV/m	0.1 sec
Ion Velocity (vector)	0 – 3 km/s	3 m/s	0.1 sec
Neutral Velocity (vector)	0 – 2 km/s	5 m/s	1 sec
Magnetic Field (vector)	0 – 65000 nT	10 nT	0.1 sec
Energetic Electrons			
0 – 20 eV (full pitch angle, 20° res.)	$10^8 – 10^{12}$ eV/cm^2/s/st/eV	ΔE/E = 0.15	0.1 sec
20 eV – 30 keV (2-D pitch angle, 20° res.)	$10^6 – 10^{10}$ eV/cm^2/s/st/eV	ΔE/E = 0.15	0.1 sec
30 keV – 300 keV (downward flux)	$10^4 – 10^8$ eV/cm^2/s/st/eV	ΔE/E = 0.25	1 sec
Energetic Ions			
20 eV – 20 keV (2-D pitch angle, 20° res.)	$10^5 – 10^9$ eV/cm^2/s/st/eV	ΔE/E = 0.15	0.1 sec
20 keV – 1MeV (downward flux)	$10^3 – 10^7$ eV/cm^2/s/st/eV	ΔE/E = 0.25	1 sec
Plasma Density	$10^2 – 10^7$ cm^{-3}	± 1%	0.1 sec
Ion & Electron Temperature	300 -10000 K	± 5%	1 sec
Neutral Density	$10^6 – 10^{12}$ cm^{-3}	± 10%	1 sec
Neutral Temperature	300 – 5000 K	± 5%	1 sec
Ion Composition (H^+, He^+, N^+, O^+, NO^+, O_2^+, N_2^+, Mg^+, Fe^+)	relative concentration	± 1%	1 sec
Neutral Composition (O, NO, N_2, O_2)	relative concentration	± 1%	1 sec

NASA I-T Missions with *in situ* probes since 1970

Atmosphere Explorer (C,D,E) satellites launched in 1970's designed to study the thermosphere. Very successful;

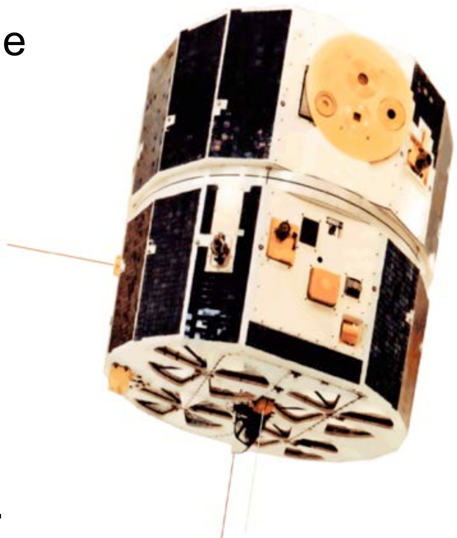
yet had very limited electrodynamic (e.g., no E or B) or particle instruments. Spacecraft included propulsion. Some dipping.

AE-C (1973-1978); Incl. 68.1°. Mainly circular at **390 km**;

AE-D (1975); Incl. 90.1°. Spacecraft failed after 4 months.

AE-E (1975-1981); Incl. 19.7°. Circular at **390 km**.

Atmospheric Explorer-C



Dynamics Explorer-2 contained a full complement of I-T instruments. Very successful. Launch: Aug. 1981.

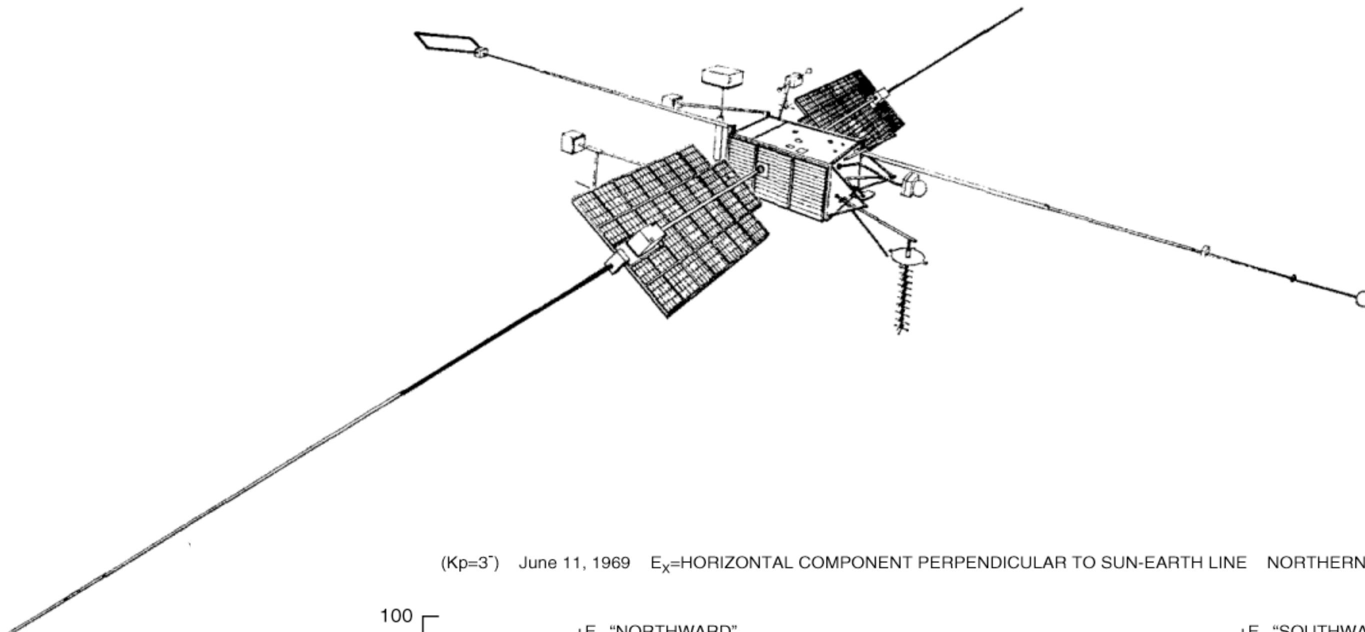
Incl. 90°, **309 km by 1012 km** orbit. Operated for 18 months.

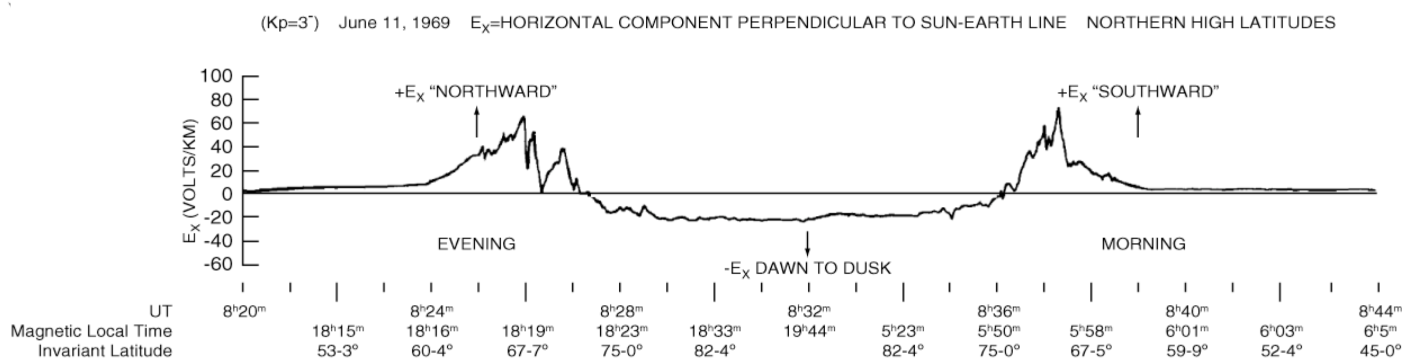
DE-2 limitations: e.g., no zonal electric fields, no local ram neutral wind (except from FPI at 6 month intervals), poor attitude compromised magnetometer data, very limited plasma waves, no suprathermal electrons, low duty cycle ~25%, No propulsion.

NASA also provided *in situ* probes on Italian **San Marco-D** satellite including DC E-fields, ion drift meter, Langmuir probe, mass spec./wind instr. (which failed after 3 weeks). Operated for 8 mos in 1988; 6% duty cycle. Incl. 3°, **263 km by 615 km**.

NASA/Orbiting Geophysical Observatory-6 -- 1969–1971

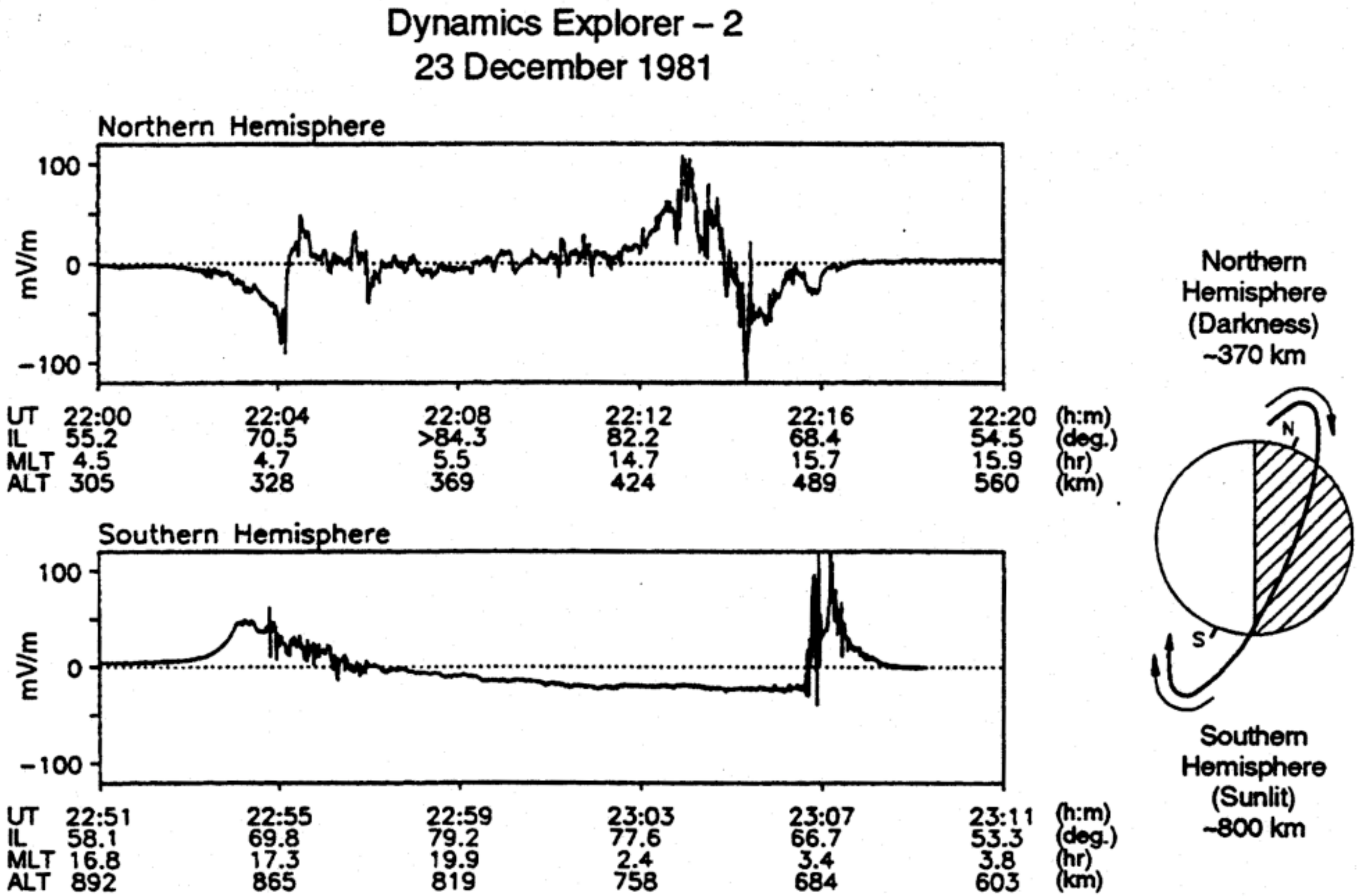
82° incl., 400 x 1100 km





- Single-axis E-field detector reveals fundamental 2-cell convection pattern.

[Heppner, 1972]

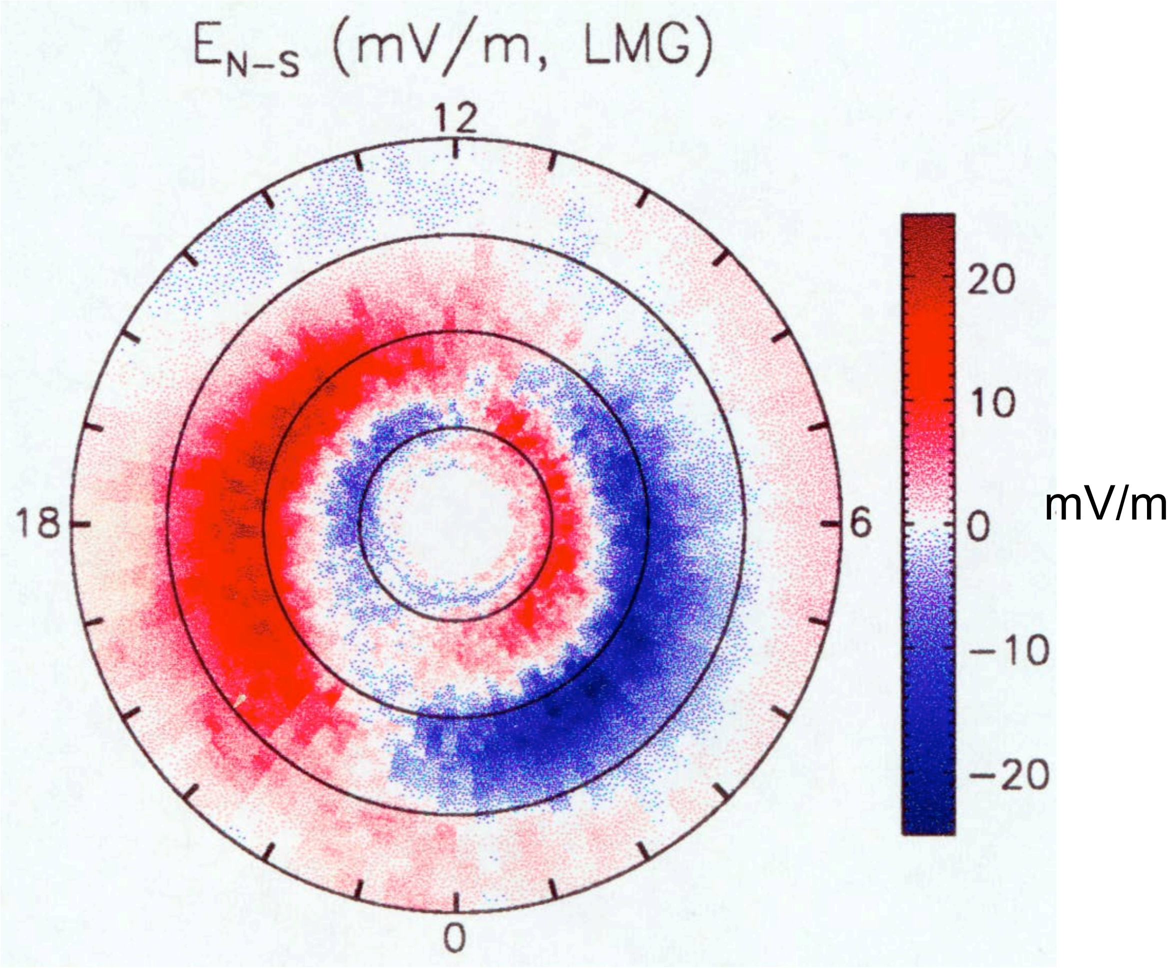


Pfaff, 1996

E is positive, along the spacecraft velocity.

Composite DE-2 Electric Field Data

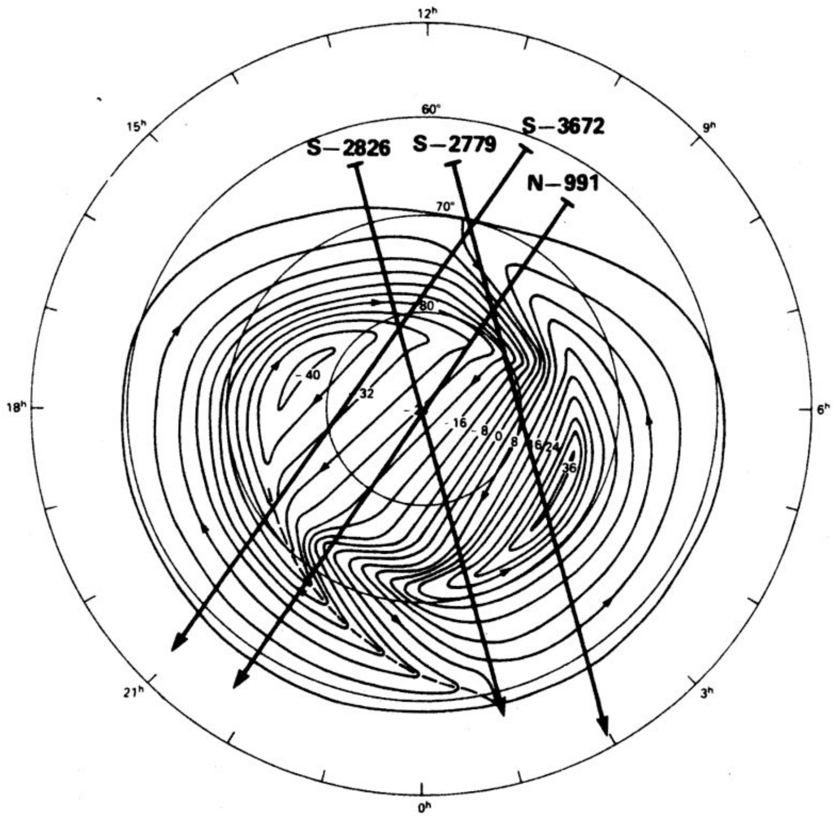
All Seasons, All IMFs



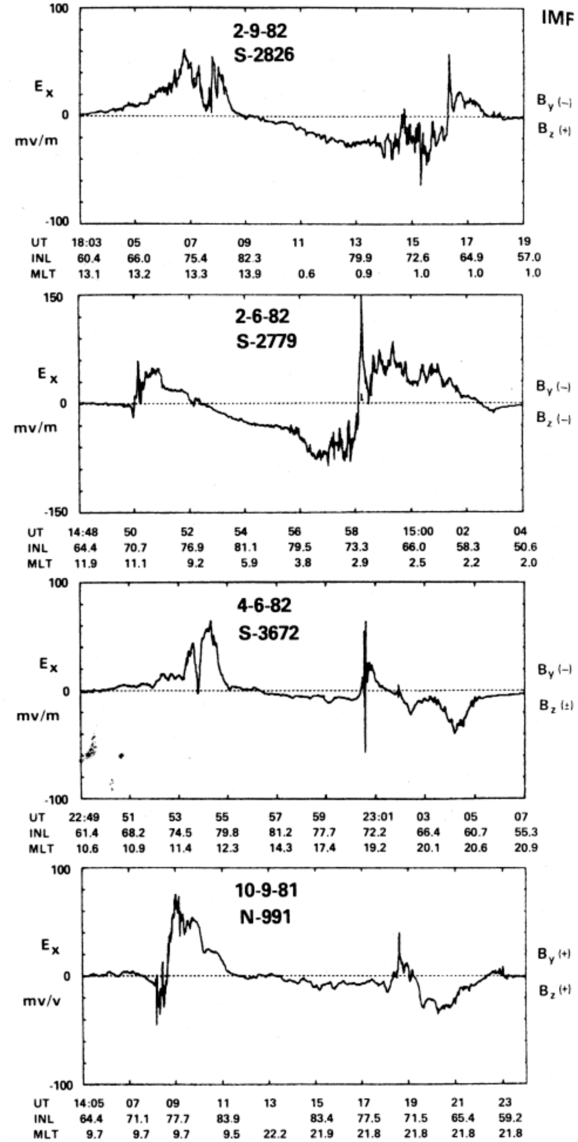
Poleward Component

Empirical High Latitude Electric Field Model

+ IMF By (No. Hemisphere)



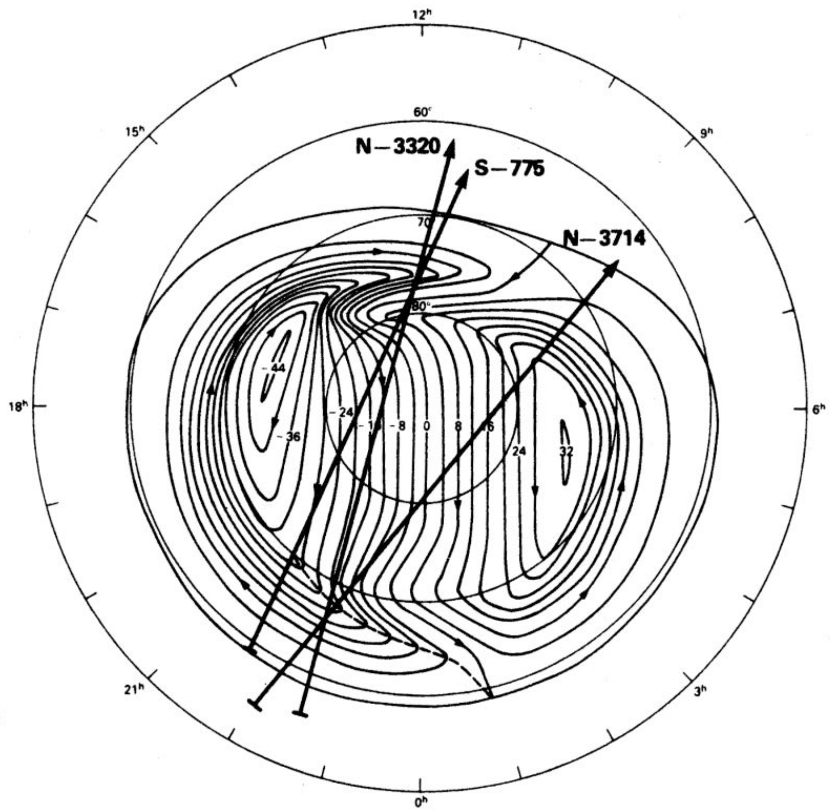
Model BC

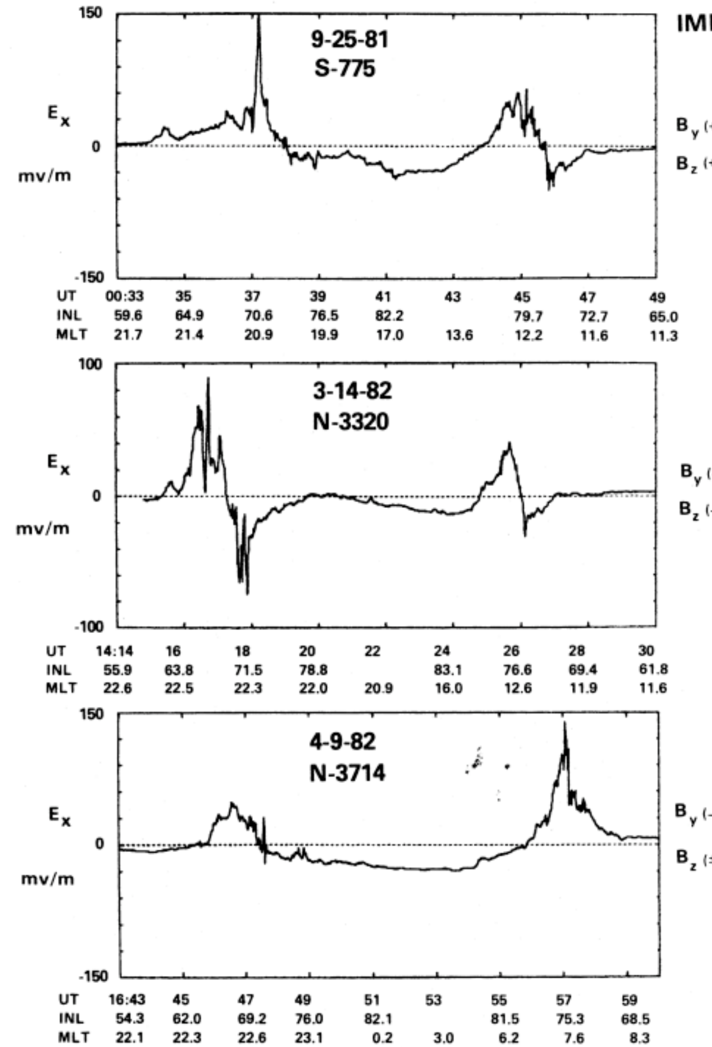


[Heppner and Maynard, 1987]

Empirical High Latitude Electric Field Model

– IMF By (No. Hemisphere)





[Heppner and Maynard, 1987]

“Weimer model” performed a spherical harmonic analysis of the DE-2 E-field data

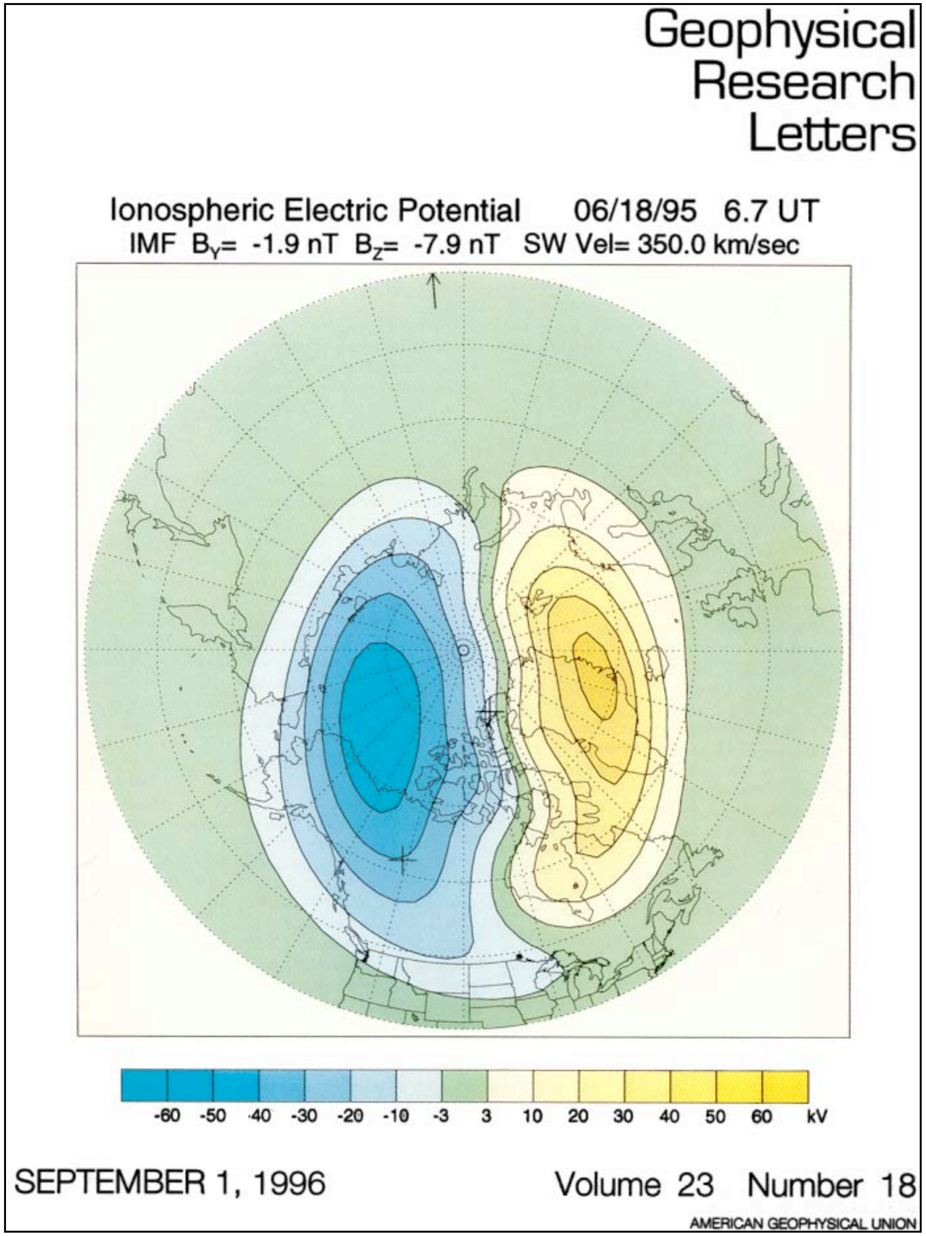
$$\Phi(\theta,\phi) = \sum_{l=0}^{8} \sum_{m=0}^{Min(l,3)} \left(A_{lm} \cos m\phi + B_{lm} \sin m\phi\right) P_l^m(\cos\theta)$$

$$B_{11}(\omega) = \sum_{n=0}^{4} \left(C_n \cos n\omega + D_n \sin n\omega\right)$$

$$C_{B_{lm}n} = R_0 + R_1 B_T + R_2 \sin\mu + R_3 V_{SW}$$

The 1996 model could create a potential map for any arbitrary IMF.

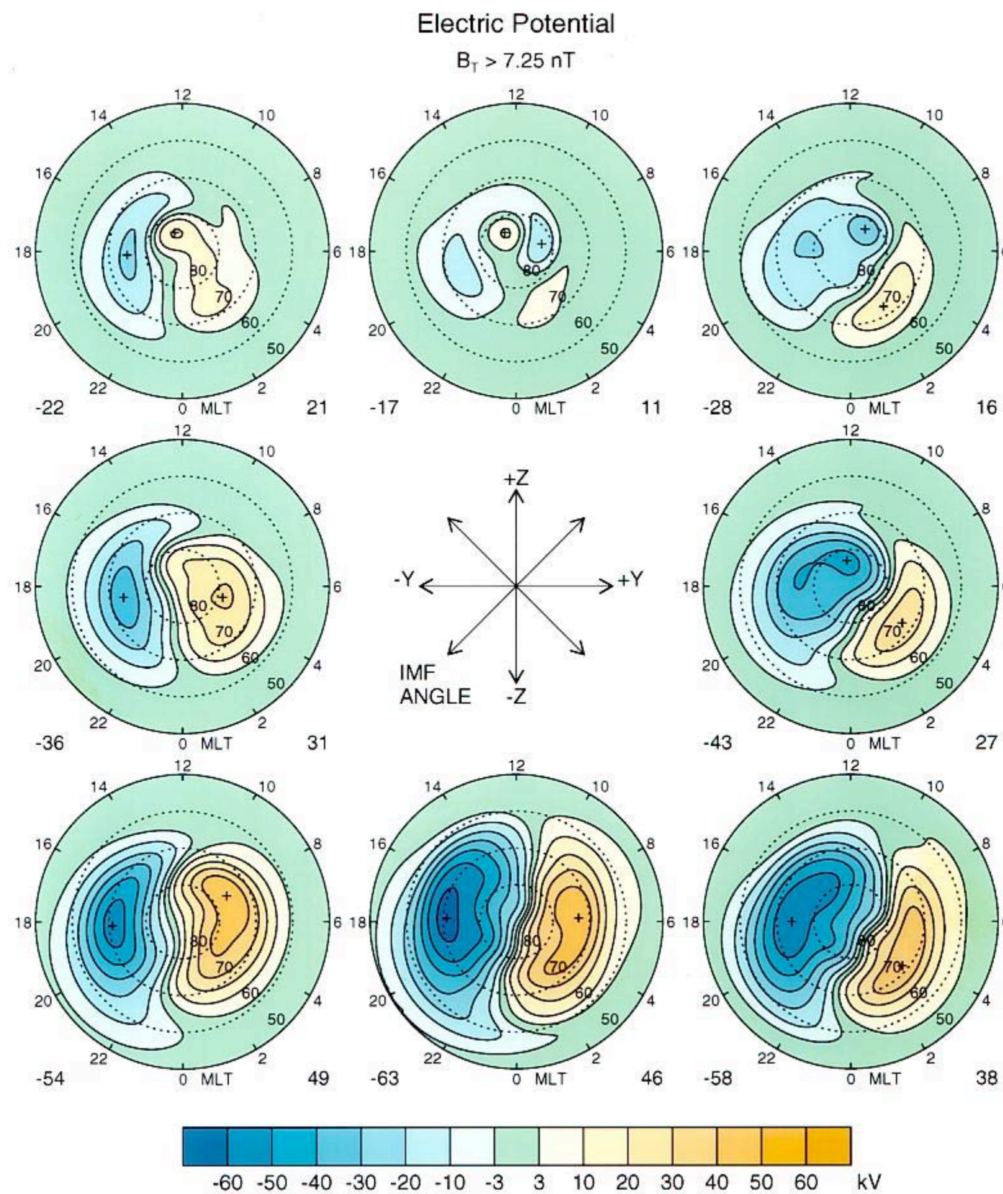
The coefficients from the sorted, “binned” patterns, with their average IMF values, were used as the inputs.

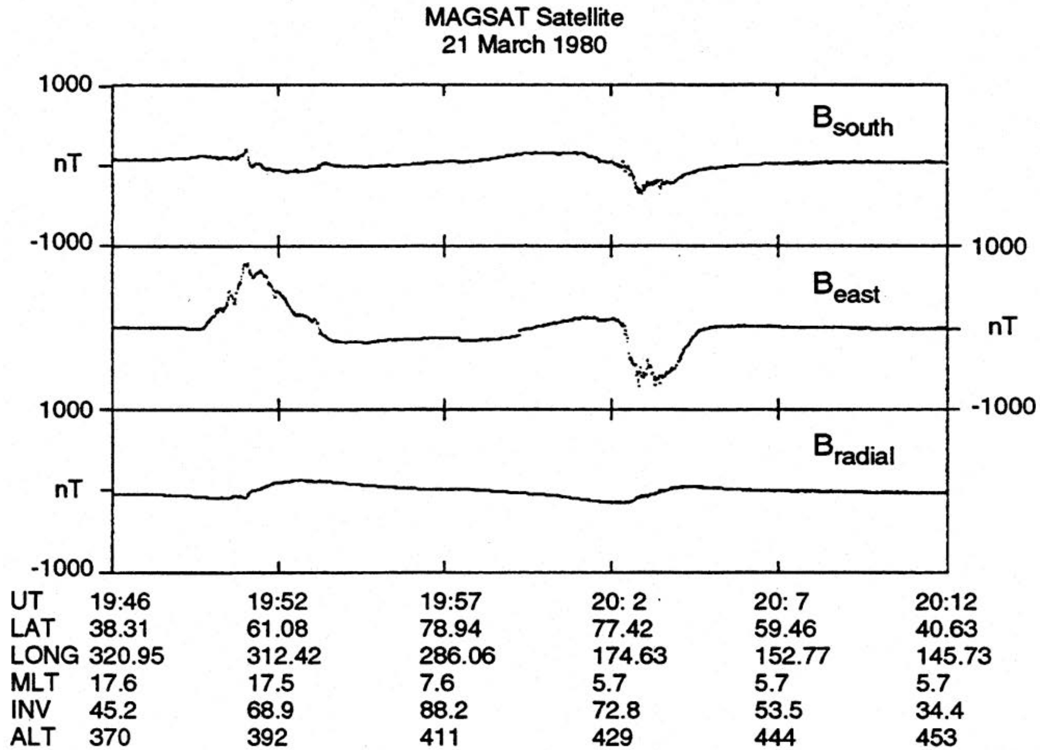


The 1995 Weimer et al. paper used a least-error fit of spherical harmonic coefficients to derive the potential patterns from the sparse and randomly distributed measurements.

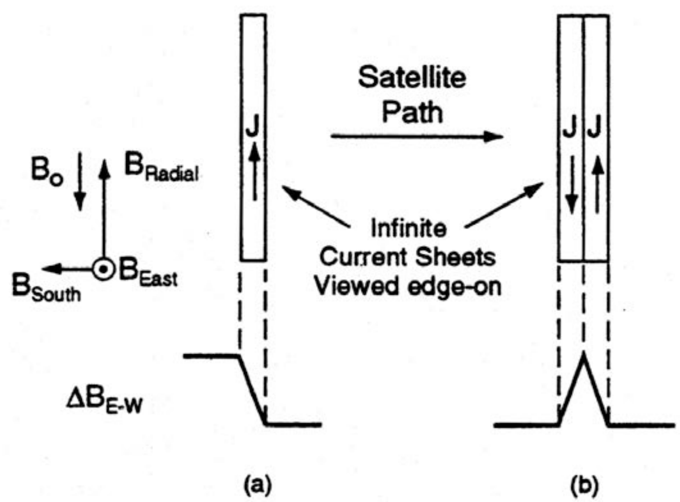
The passes were sorted into “bins” by IMF magnitude, clock angle, and dipole tilt angle.

A fixed, low-latitude boundary of 45° was used.



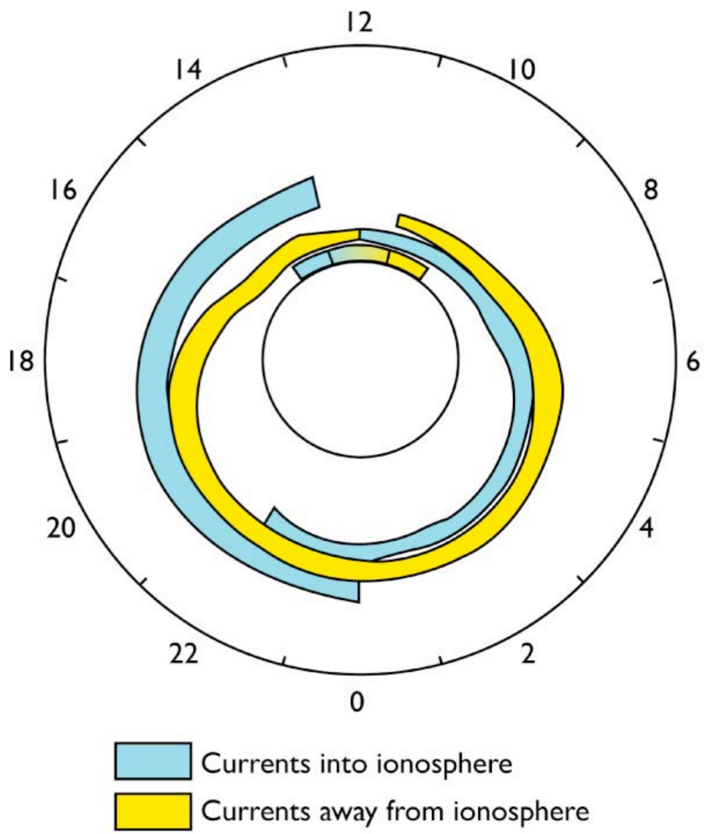


Zanetti et al., 1984



Pfaff, 1996

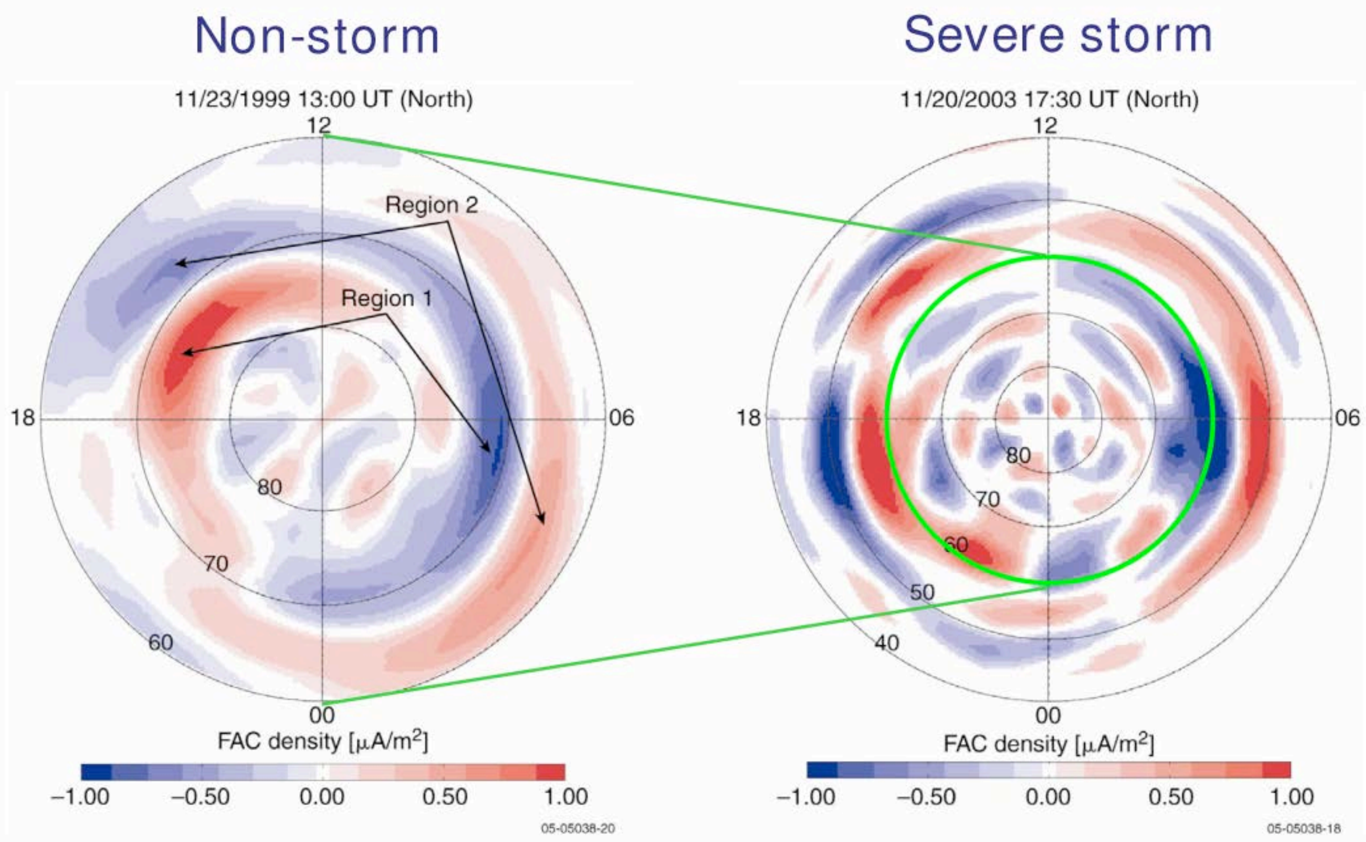
TRIAD magnetometer measurements of ~300 passes reveal fundamental current patterns.



Iijima and Potemra, 1976

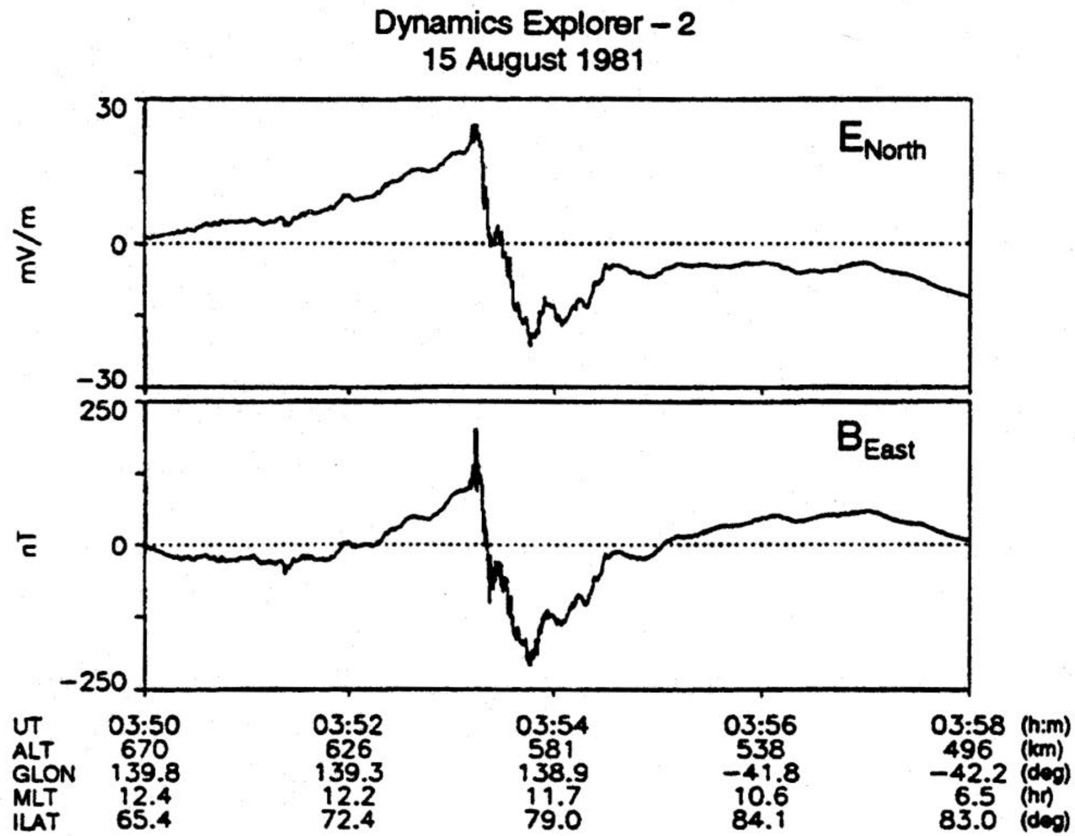
Statistical Survey
Reveals fundamental physics

Currents from Iridium*



* 3 hour averages!

Data courtesy Brian Anderson, 2007



Sugiura et al., 1982

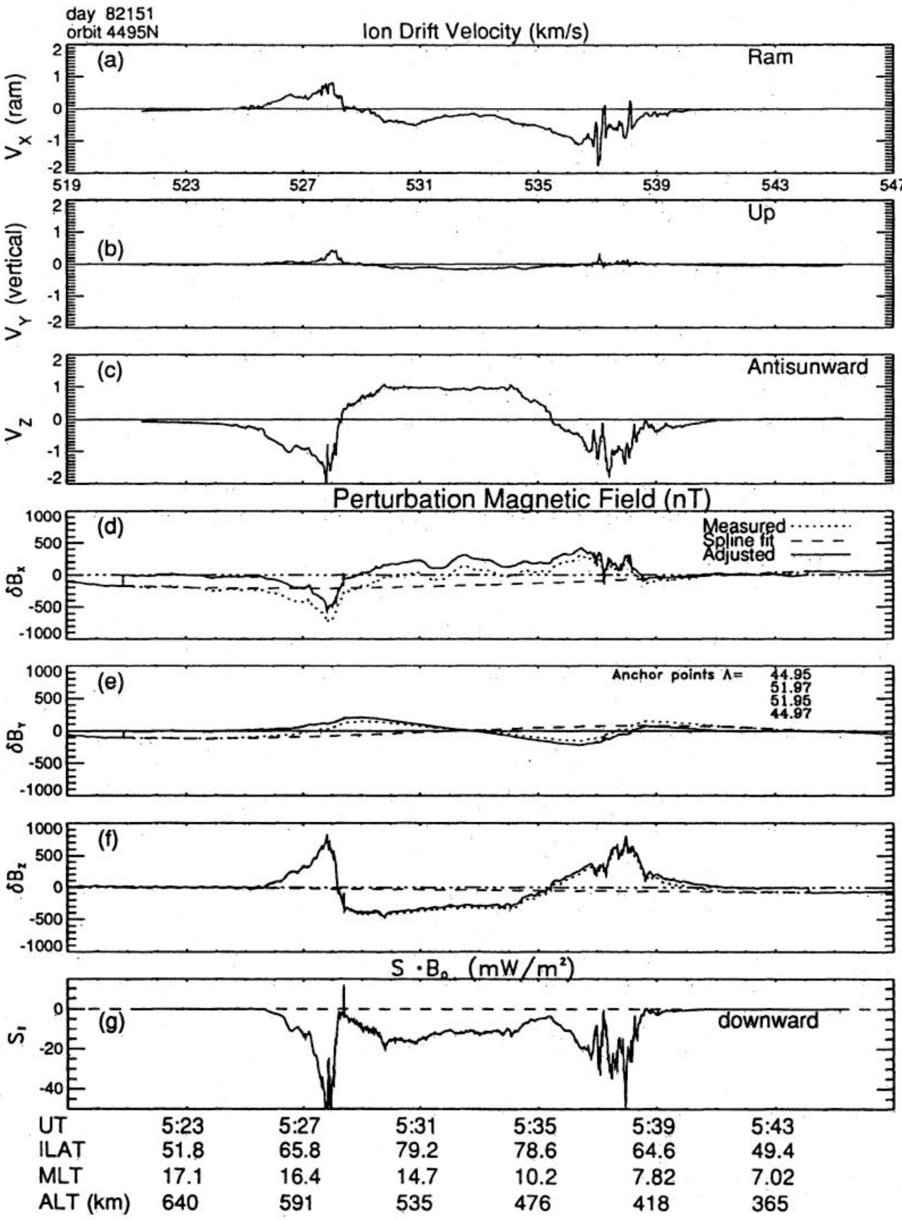
- Simultaneous E and B signatures provide information concerning the current sheet geometry and that current closure is along meridian;
- E/B provides measure of Height Integrated Pederson Conductivity.

Combined **E** (**V**$_i$) and **B** provide Poynting Flux, providing a direct measure of the rate of conversion of EM energy into thermal particle energy.

$$\mathbf{S} = 1/\mu_o\,(\delta\mathbf{E} \times \delta\mathbf{B})$$

[Gary et al., 1994]

Field-aligned Poynting Flux →

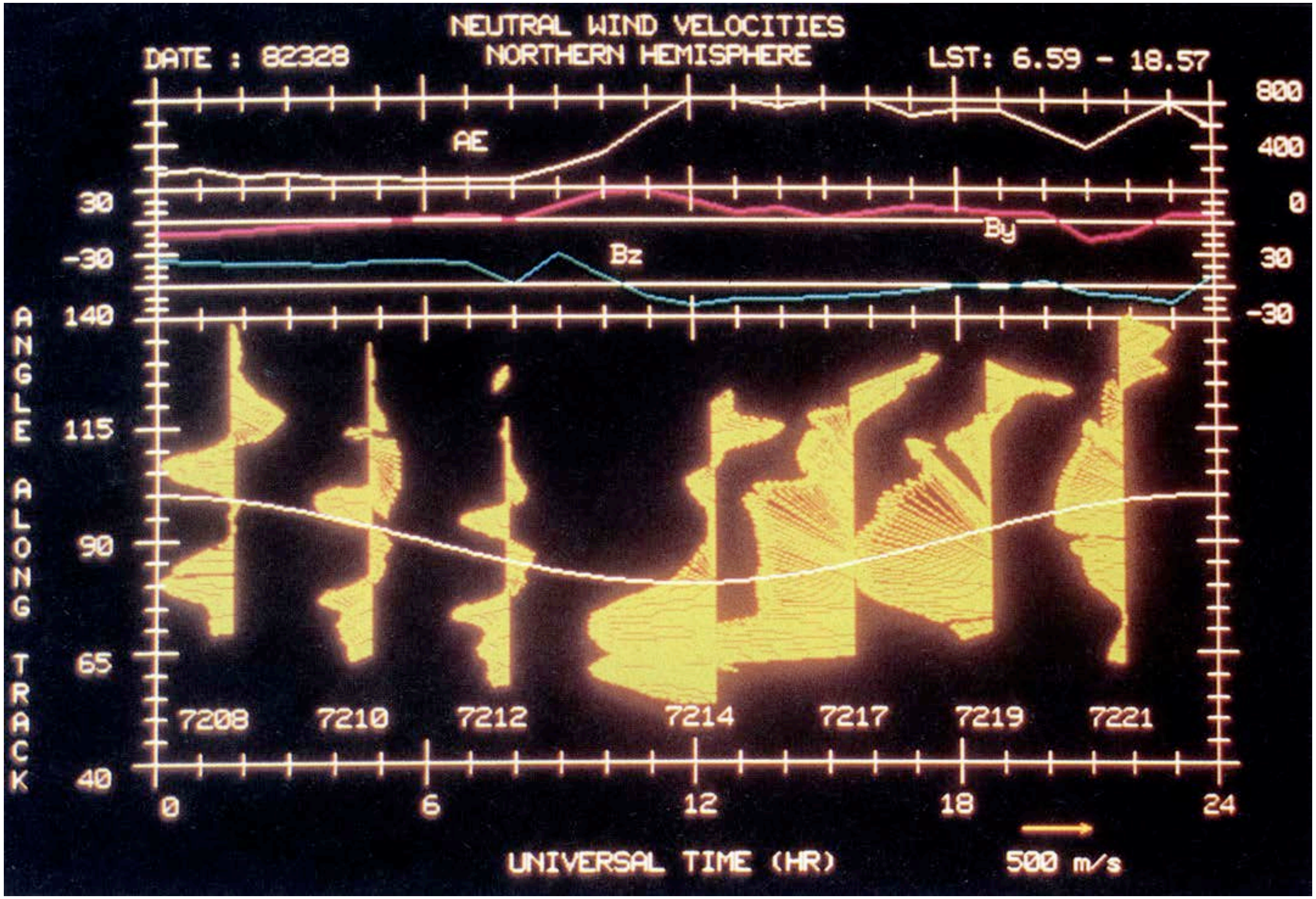


Ion Drifts

δ**B**

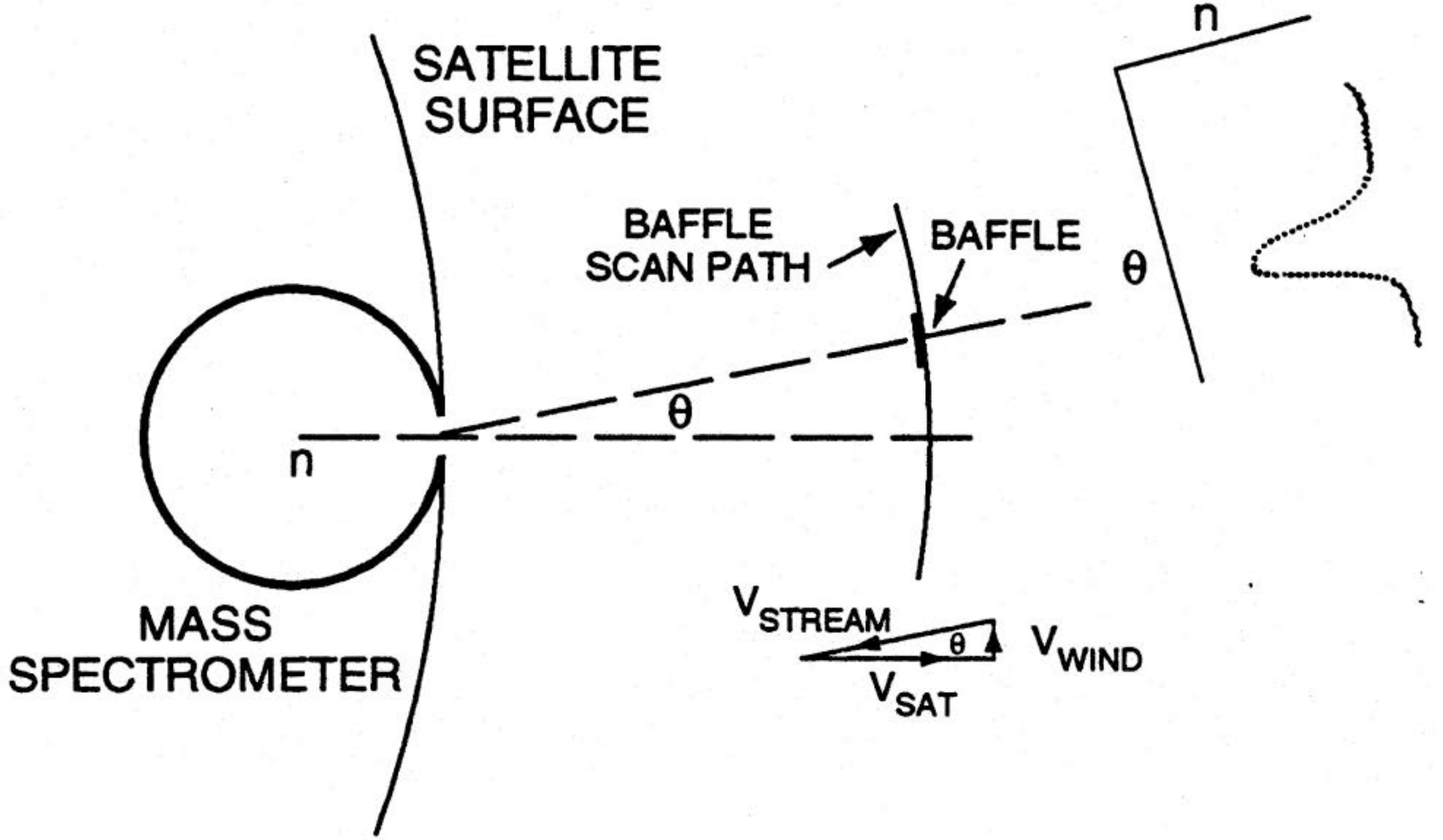
S$_{||}$

DE-2 measurements of neutral winds on successive orbits related to IMF variations



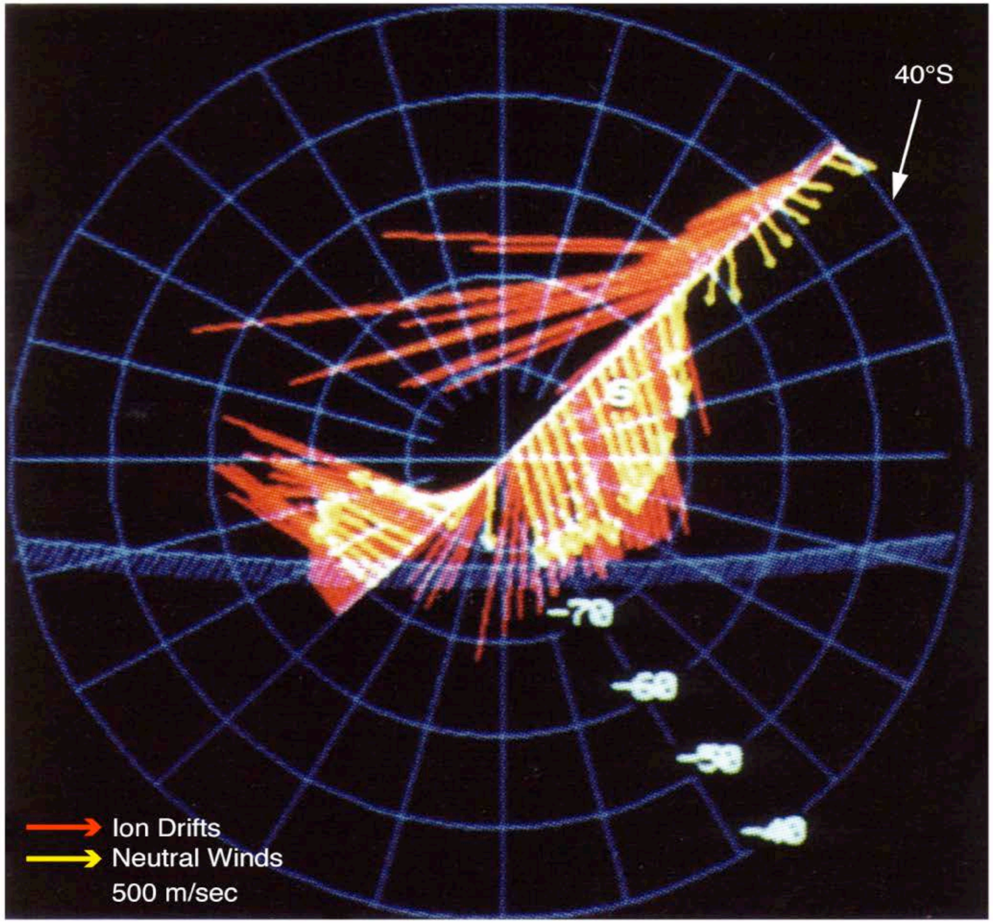
[Killeen and Roble, 1988]

Neutral Wind and Temperature Sensor -- Principles



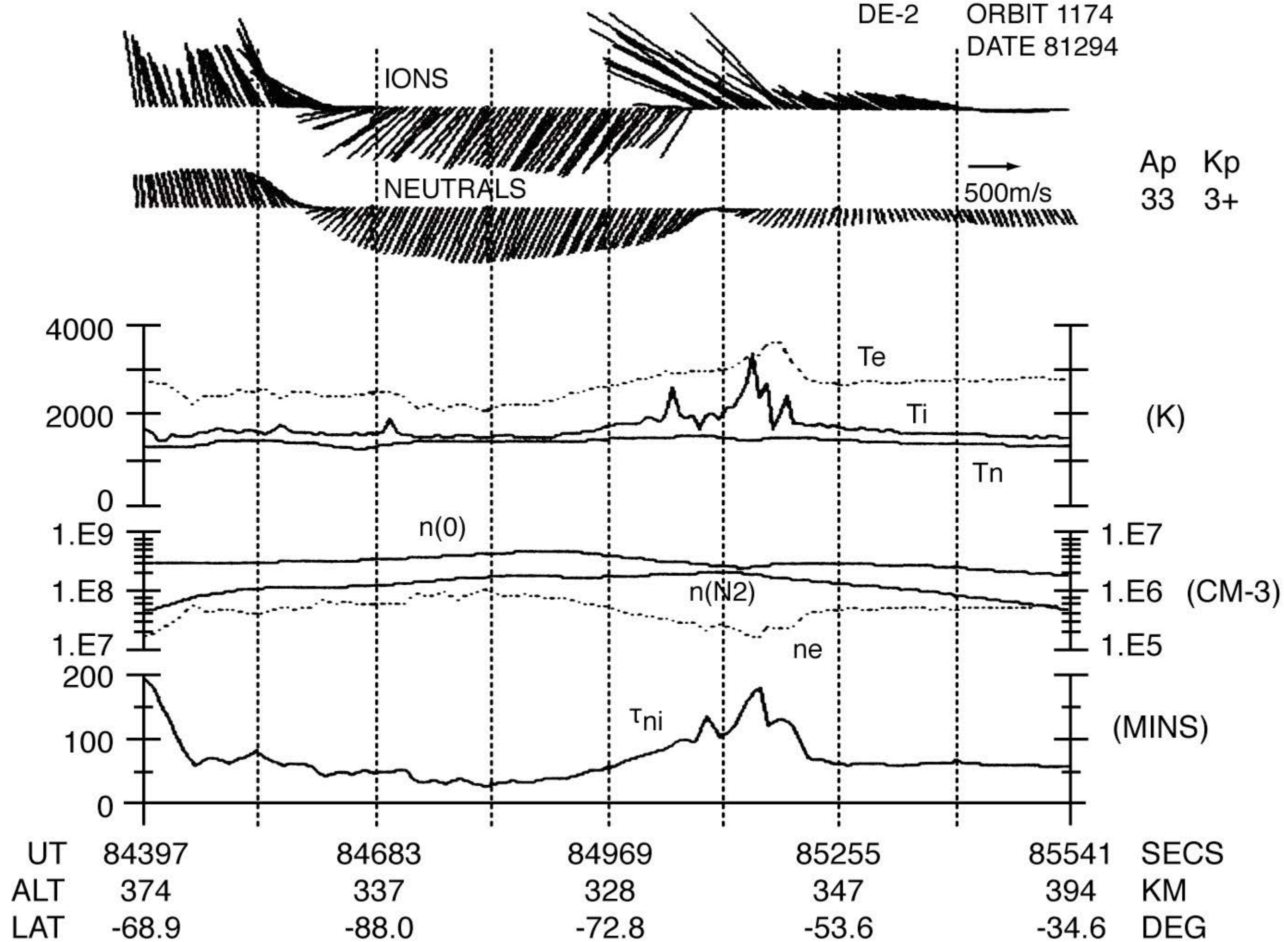
[after Spencer et al., 1981]

DE-2 Case Studies Reveal Fundamental Ion-Neutral Processes



Killeen et al., 1984

DE-2 Quantitative Measurements of Important Physical Processes (Joule Heating)



[Killeen et al. 1984]

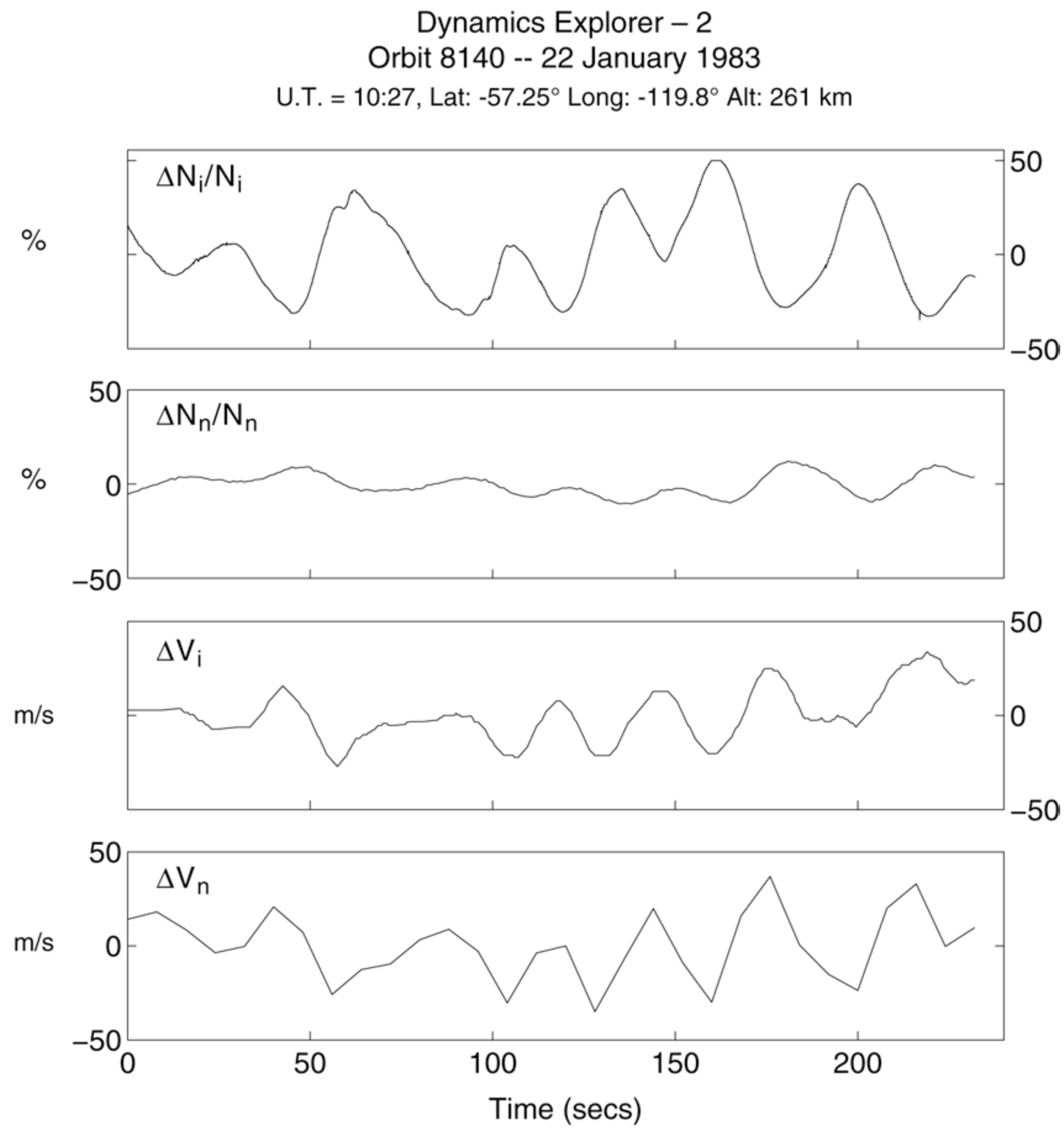
DE-2 Observations of *Gravity Waves* in neutral and ion measurements at 260 km at night.

$\lambda \geq 100$ km

$V_\phi \sim 10$ m/s

Consistent with upward propagation from below.

[Earle et al., *in press*, 2007]



[Earle et al., 2007]

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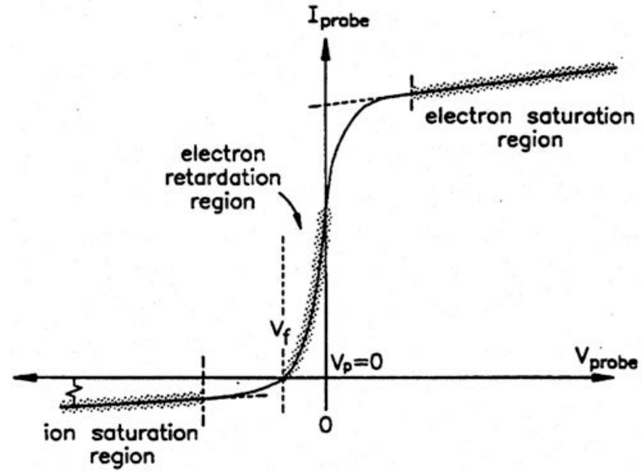
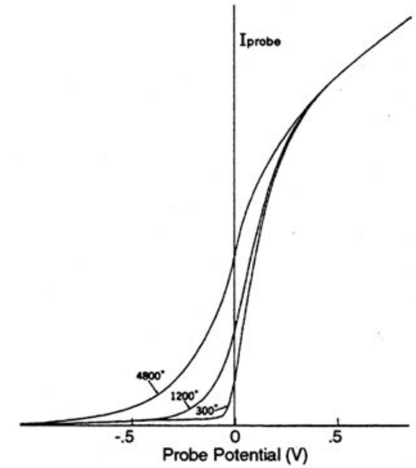
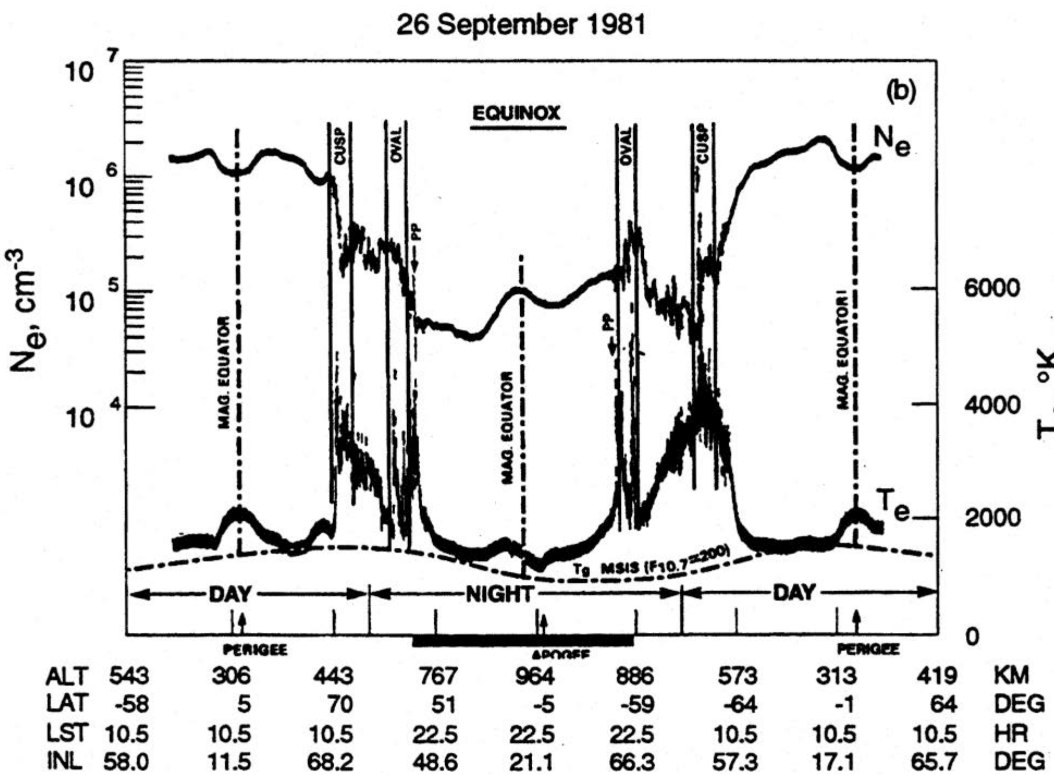
Langmuir probes provide Ne and Te



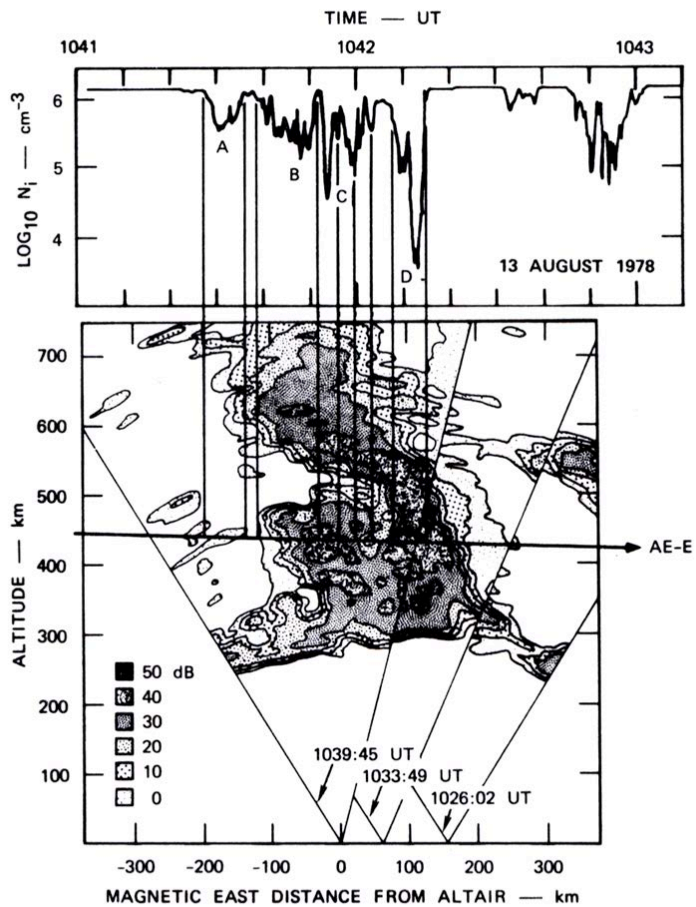


Brace et al., 1973



Full orbit of DE-2 Ne and Te data; Perigee at equator during the day.

Brace et al., 1982

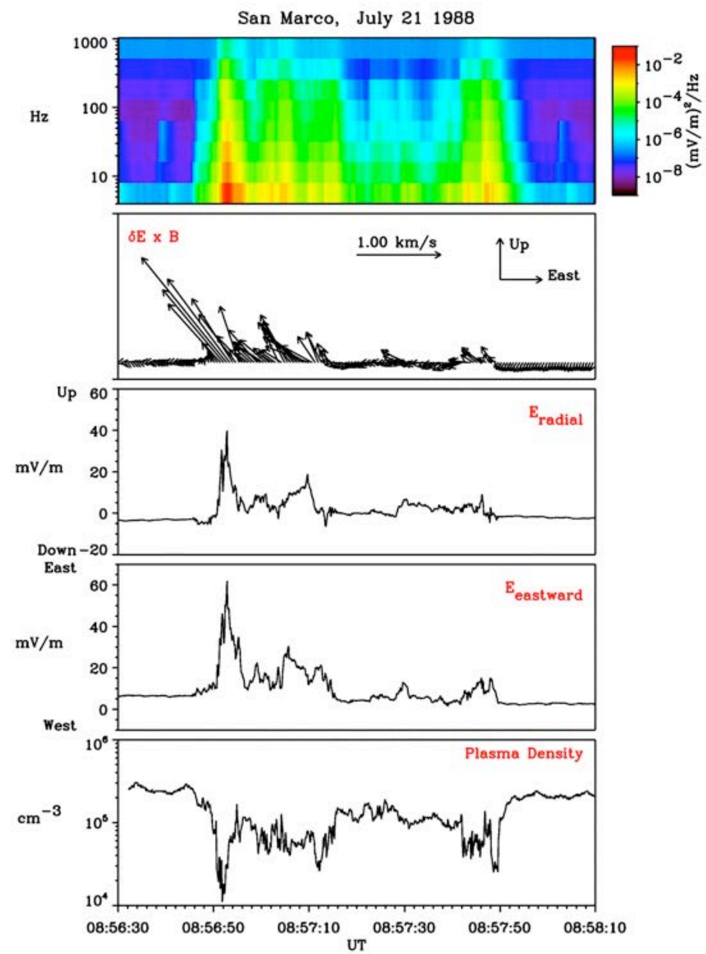


Atmosphere Explorer
Plasma Density

Altair Radar,
Kwajalein Atoll

Coordinated Measurements with Ground-Based Radar

San Marco Satellite Observations of Spread-F Density Depletions



E-field irregularities

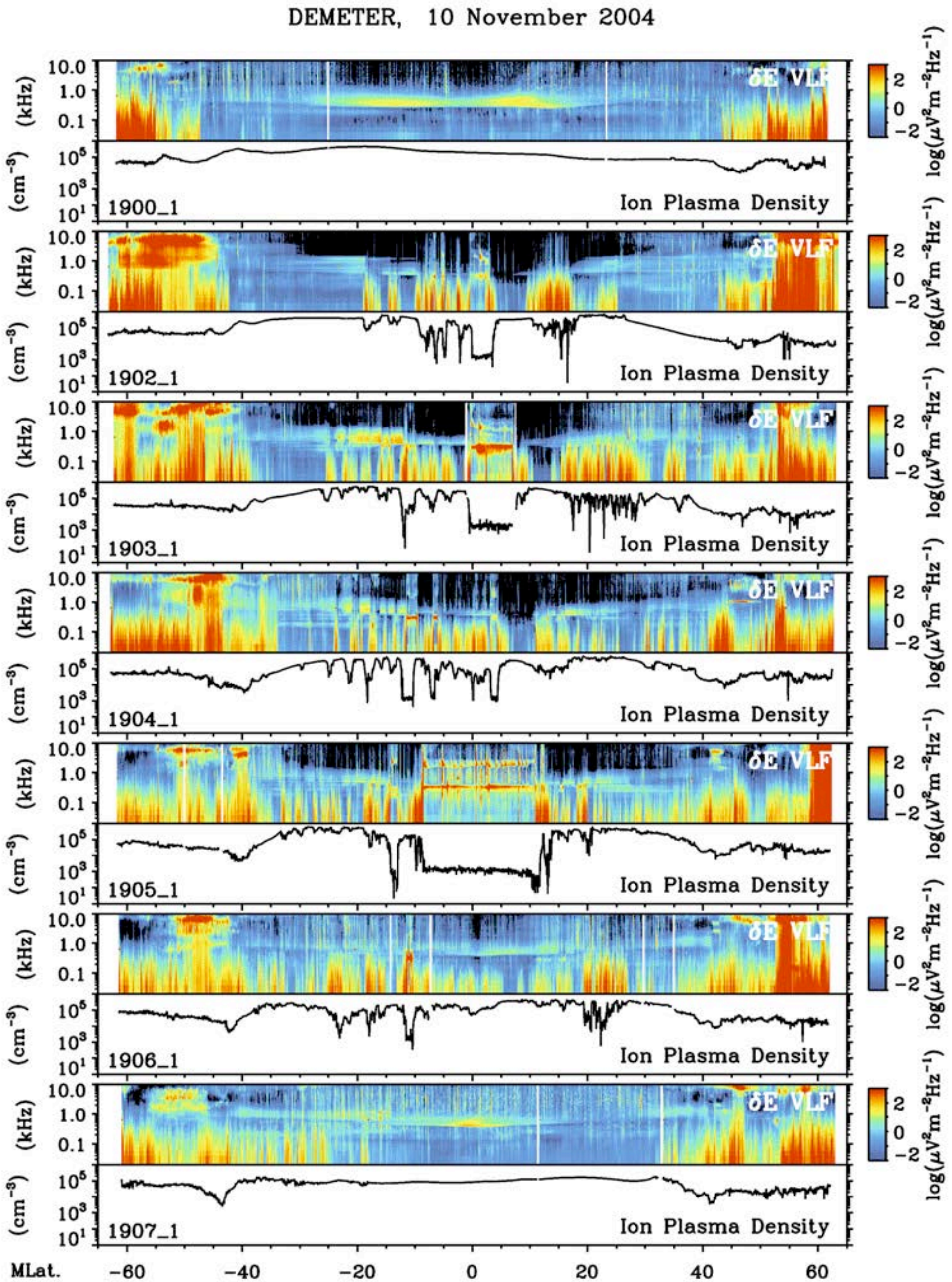
DC Electric fields

Plasma Density

Studies of the Inter-dependency of Spread-F
Electric fields, Plasma Density, Irregularities

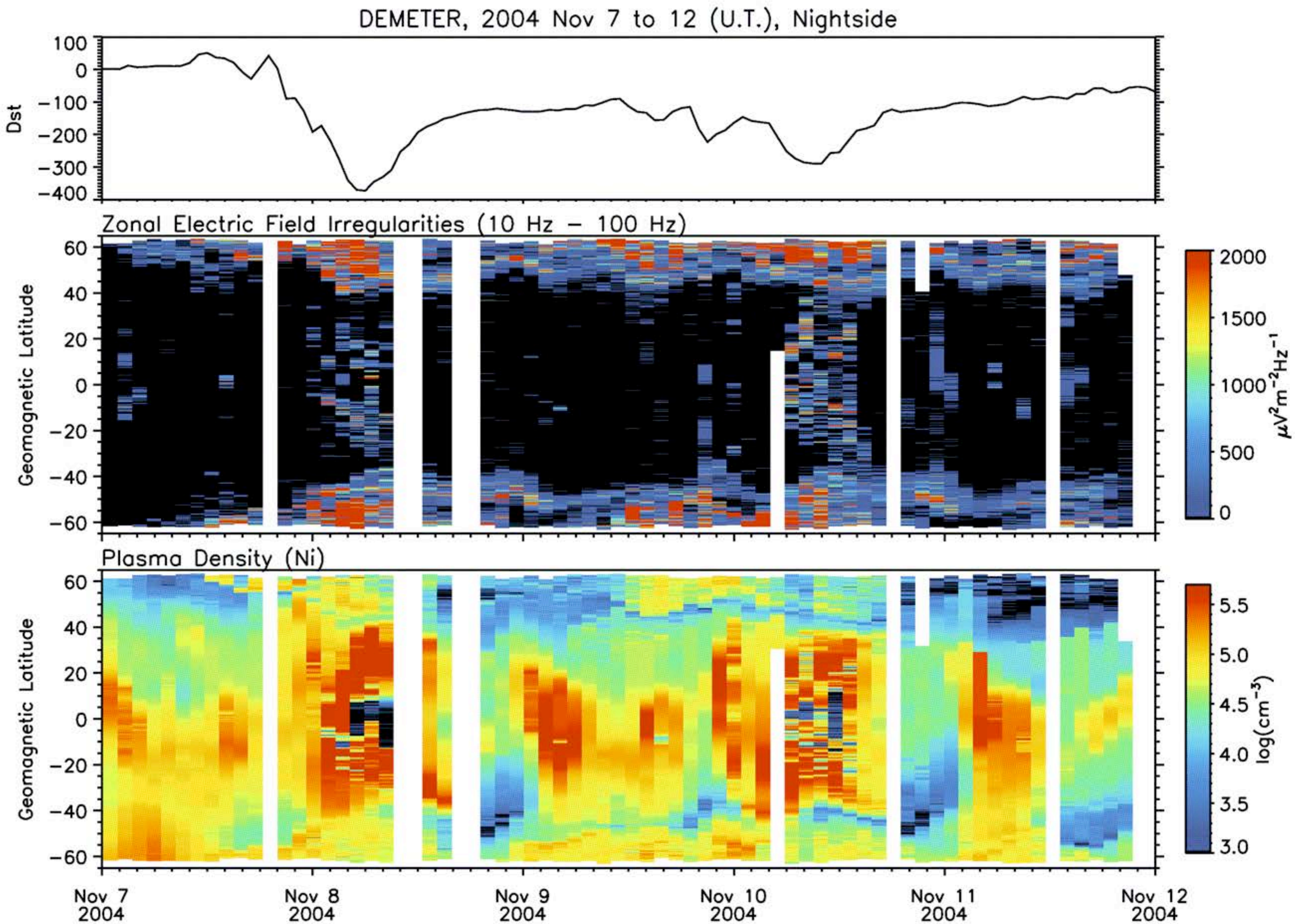
Consecutive DEMETER orbits at 22 h L.T. during major storm.

(~ 700 km)



Missing one orbit.

Magnetic Latitude

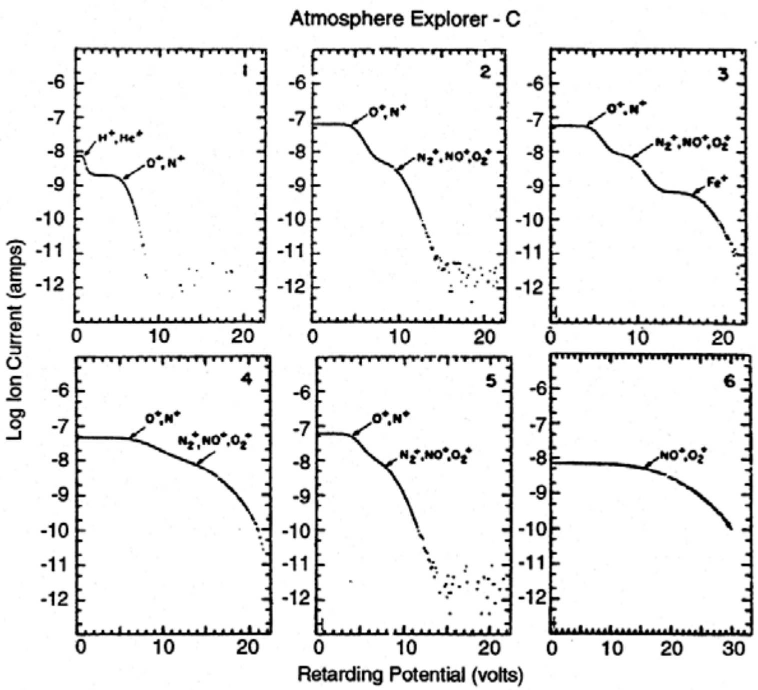


DEMETER, 2004 Nov 7 to 12 (U.T.), Nightside
Dst
100
0
−100
−200
−300
−400
Zonal Electric Field Irregularities (10 Hz − 100 Hz)
Geomagnetic Latitude
60
40
20
0
−20
−40
−60
2000
1500
1000
500
0
$\mu V^2 m^{-2} Hz^{-1}$
Plasma Density (Ni)
5.5
5.0
4.5
4.0
3.5
3.0
$\log(cm^{-3})$
Nov 7 2004
Nov 8 2004
Nov 9 2004
Nov 10 2004
Nov 11 2004
Nov 12 2004

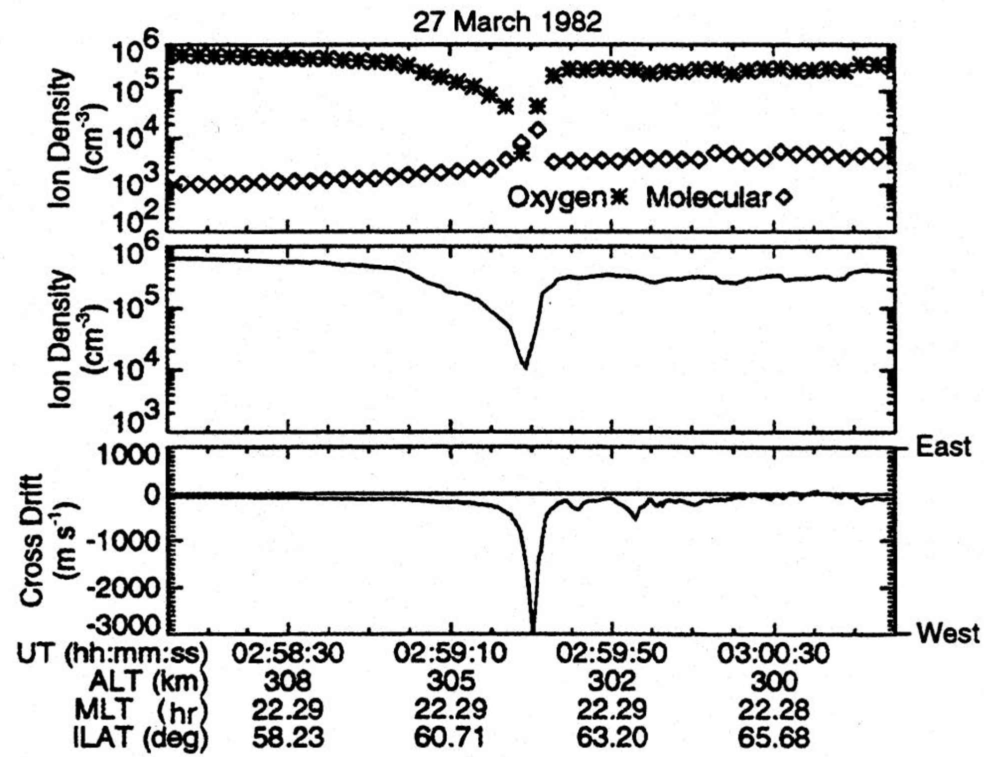
Retarding Potential Analyzers provide: Ram Vi, Ti, Ni, and Distinguish between Ion Groups

(H^+ or He^+, O^+ or N^+, NO^+ or O_2^+, Fe^+)

Dynamics Explorer-2

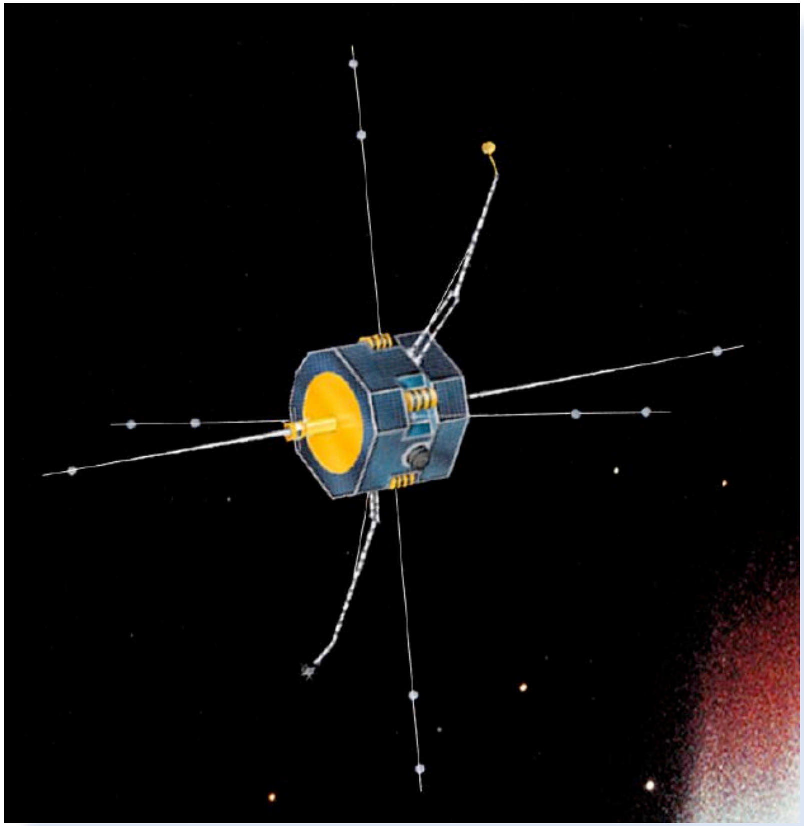


[Hanson and Heelis, 1975]



[Anderson et al., 1991]

NASA's FAST Satellite -- Consolidated Instruments
Highly successful "P.I." mode mission



- One instrument with several sensors
  - Electric fields (AC, DC)
  - Magnetic fields (AC, DC)
  - Energetic particles (ions, electrons) with full pitch angles
  - Energetic Ions -- mass discrimination with pitch angles
- One main instrument box, power regulator, IDPU, control
- Efficient burst memory controls all instruments, gathers high resolution data from all instruments
- One data system creates highly efficient data system on ground.

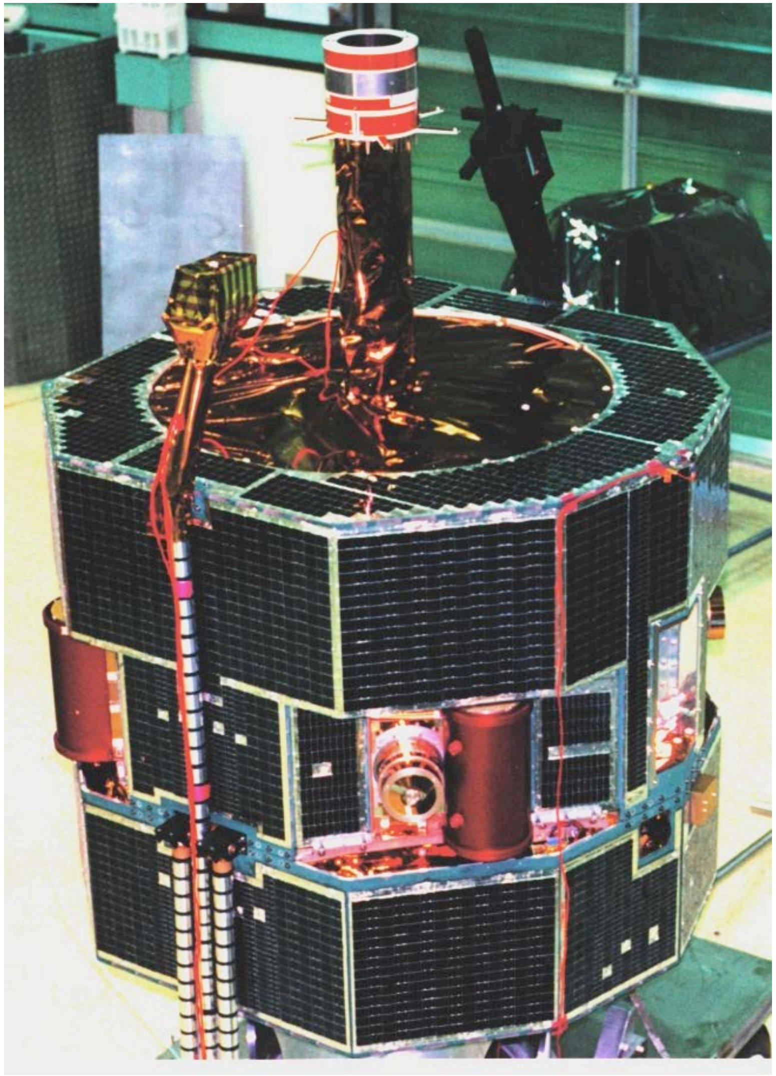
FAST Satellite

NASA Small Explorer -- UCB (C. Carlson, P.I.)

FAST Satellite characteristics

- Launch: August 21, 1996 on Pegasus XL
- 83^o inclination, 350 km by 4175 km
- 191 kg
- 1.02 m diameter, 0.93 m high
- Telemetry: 2.25/1.5/0.9 Mbps
- On board storage: 1 Gbit
- Power: $2.6m^2$ single junction GaAs.
- Orbit average power: 52 W
- Instrument power incl. IDPU: 39W (peak)
- Attitude: sun sensor, horizon crossing sensors, 3-axis magnetometer
- Nominal mission lifetime: 1 year

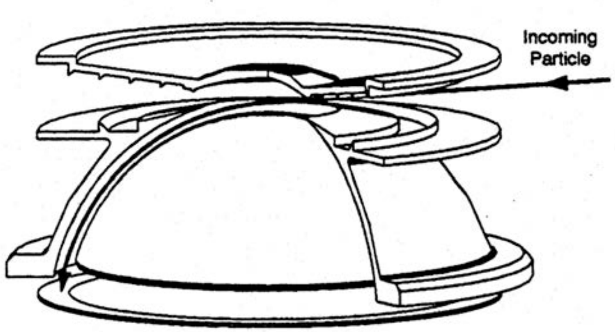
(We are now in our 12th year of observations!)



FAST resolves numerous key auroral processes

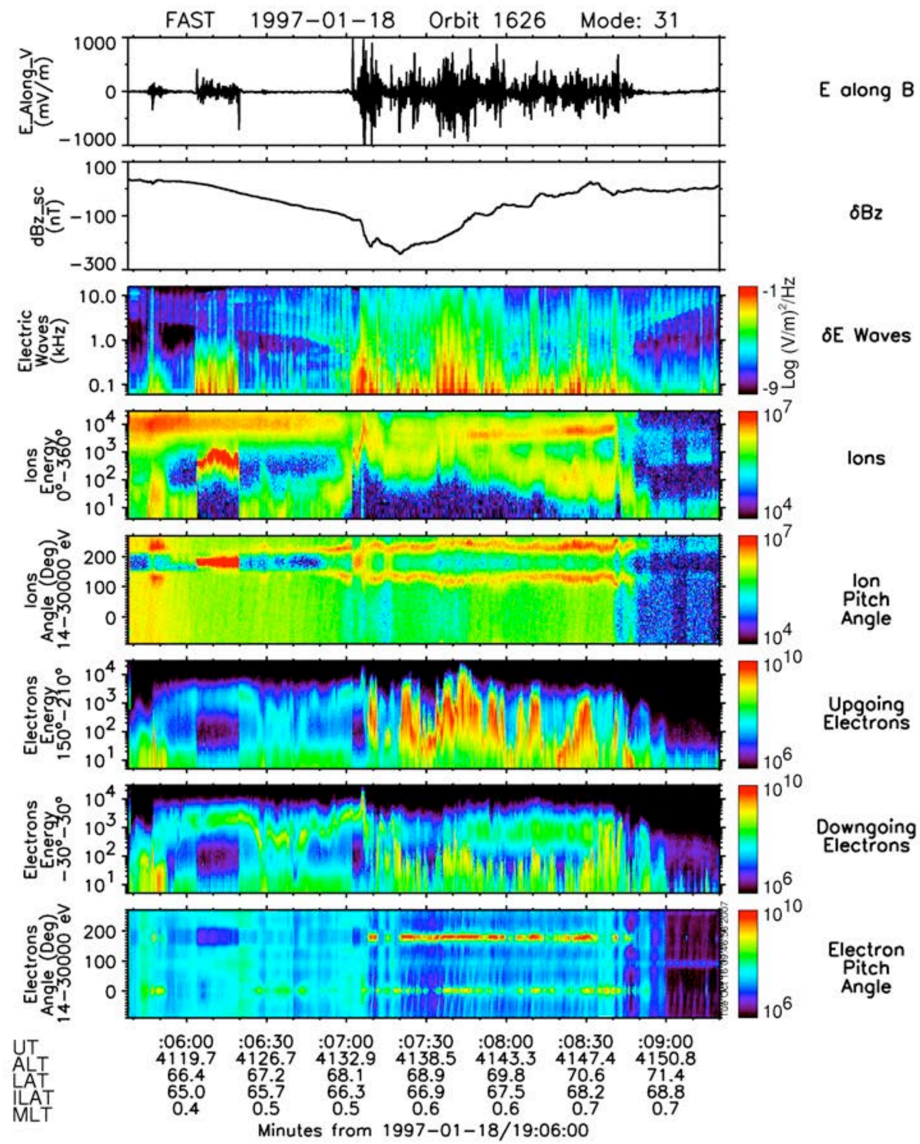
FAST accomplished this because:

- Continuous, high resolution energetic electron and ion particle observations at all pitch angles independent of spin.
- High resolution electric field and magnetic field data
- “Smart” burst data capture of all measurements, triggered on a variety of auroral phenomena.
- A high altitude apogee and high inclination orbit



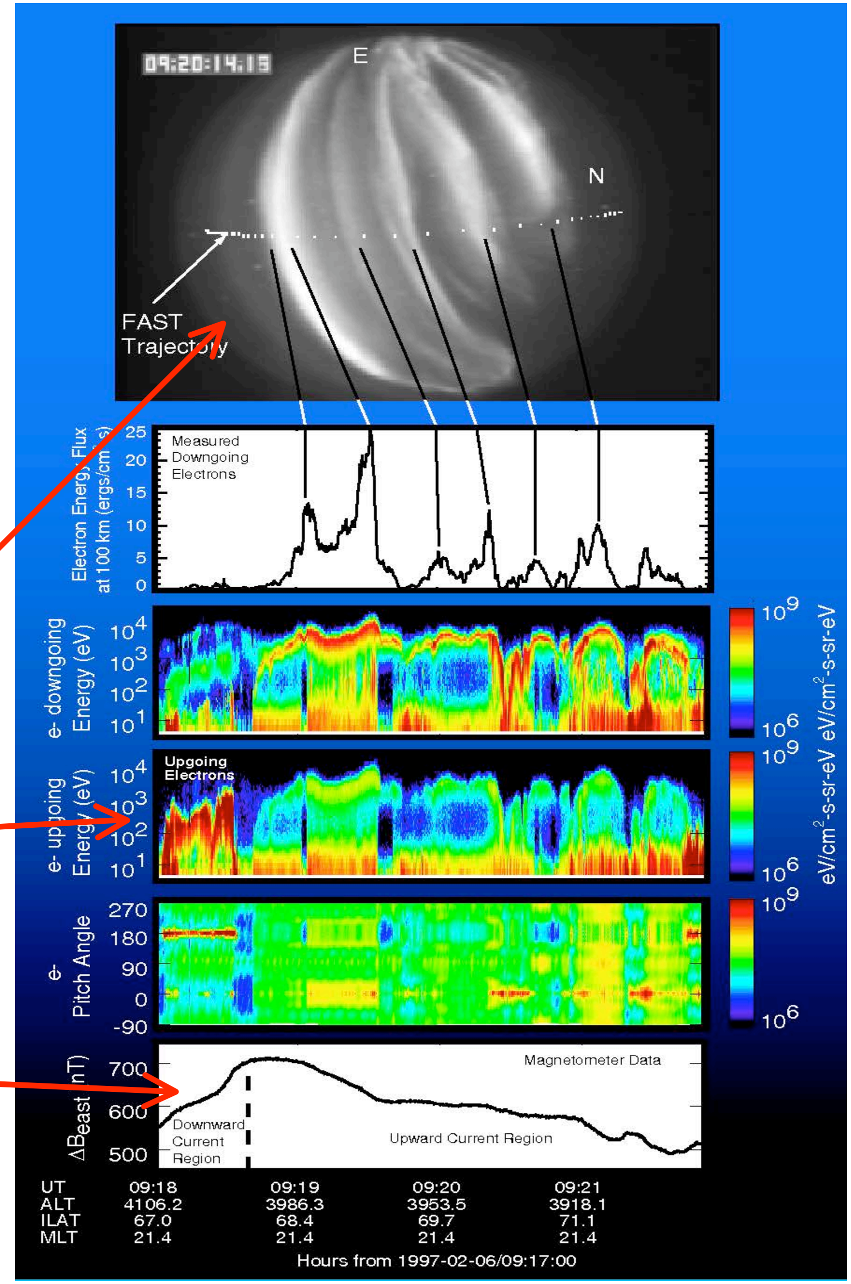
“Top Hat” electrostatic analzer

[See Carlson et al., 1983]



FAST particle detectors reveal accelerated upwards electrons associated with downward current region equatorward of the aurora in the evening sector.

[See Carlson et al., 1998]



Upwards electrons have no auroral light signature!

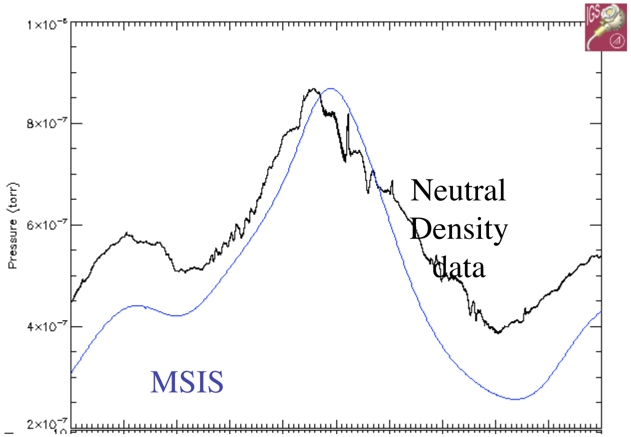
[after Stenbaeck-Nielsen et al., 1998]

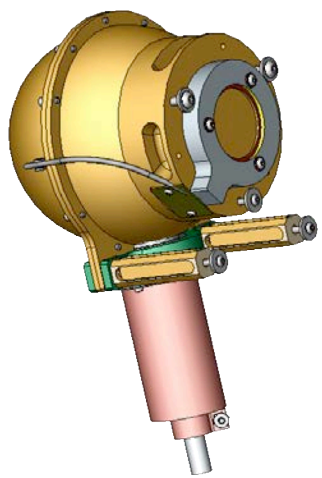
Neutral Density Measurements on STREAK

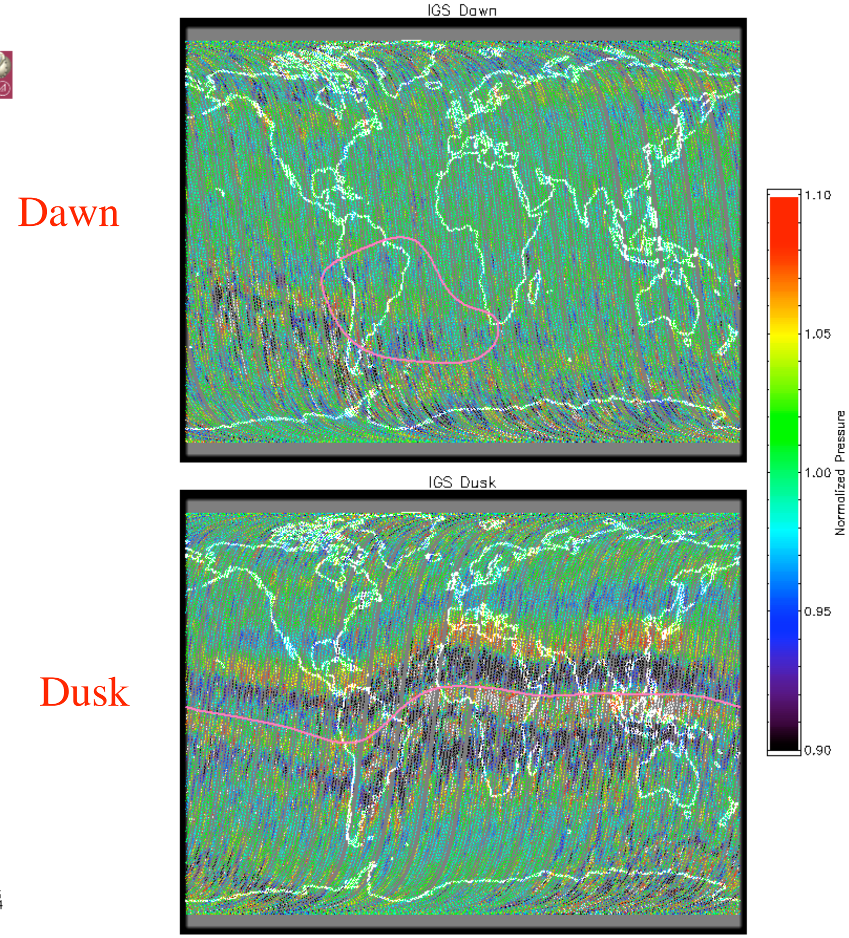
Neutral density between 300-330 km

Large variations due to altitude excursions.

11 October 2005







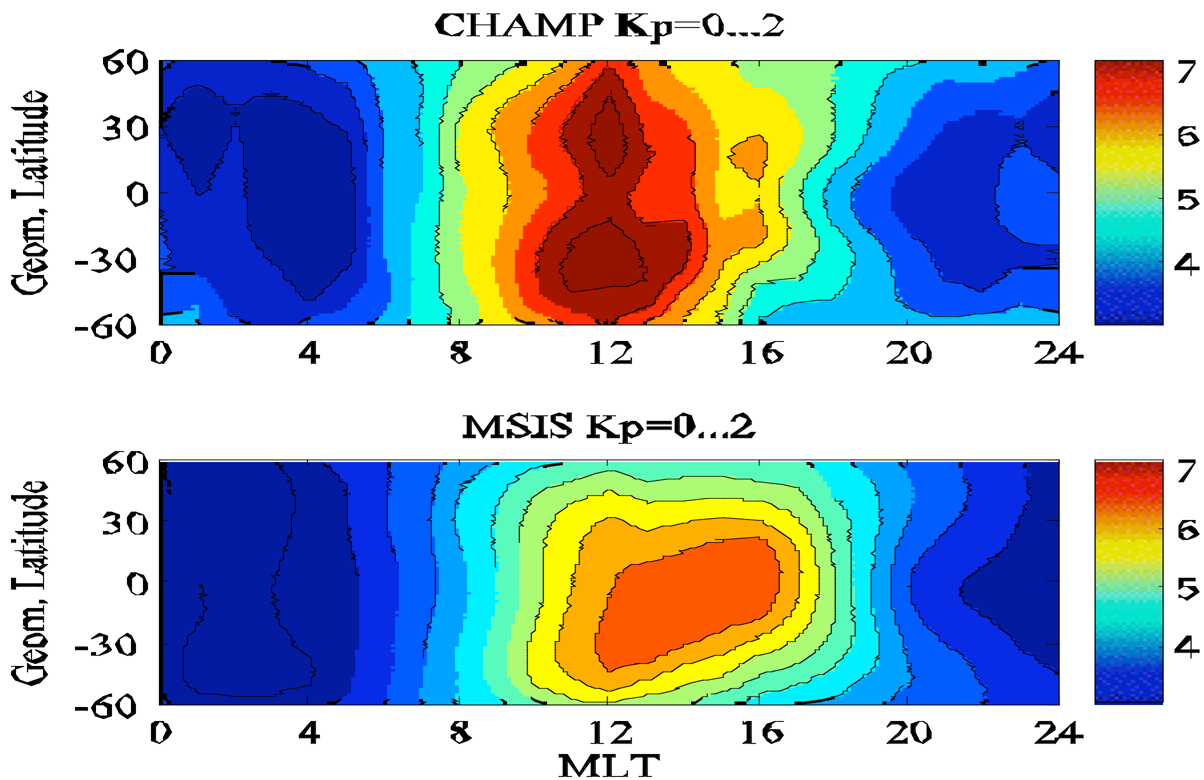
DARPA Streak Satellite (20 days) near 300 km

[Clemmons et al., 2006]

Neutral density structure at low latitudes appears to be controlled by the Appleton anomaly and other *ionospheric* processes that defy simple explanations.

Sensitive Accelerometer Measurements

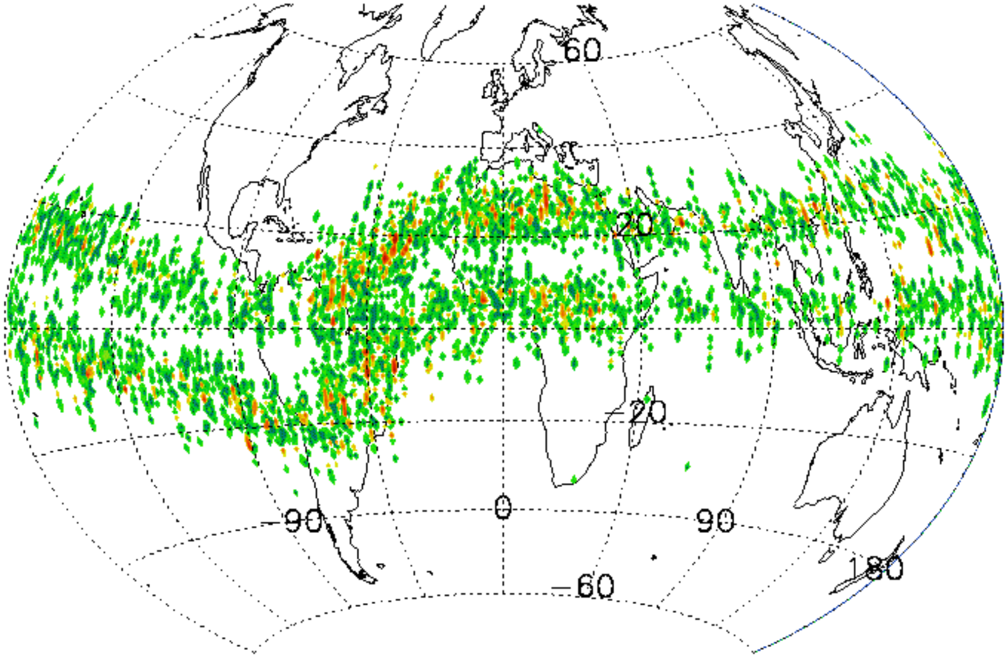
Neutral Density Variations CHAMP Satellite



Statistical Survey and Comparison with Models

[Luehr et al., 2005]

Nightside δB -- CHAMP Satellite



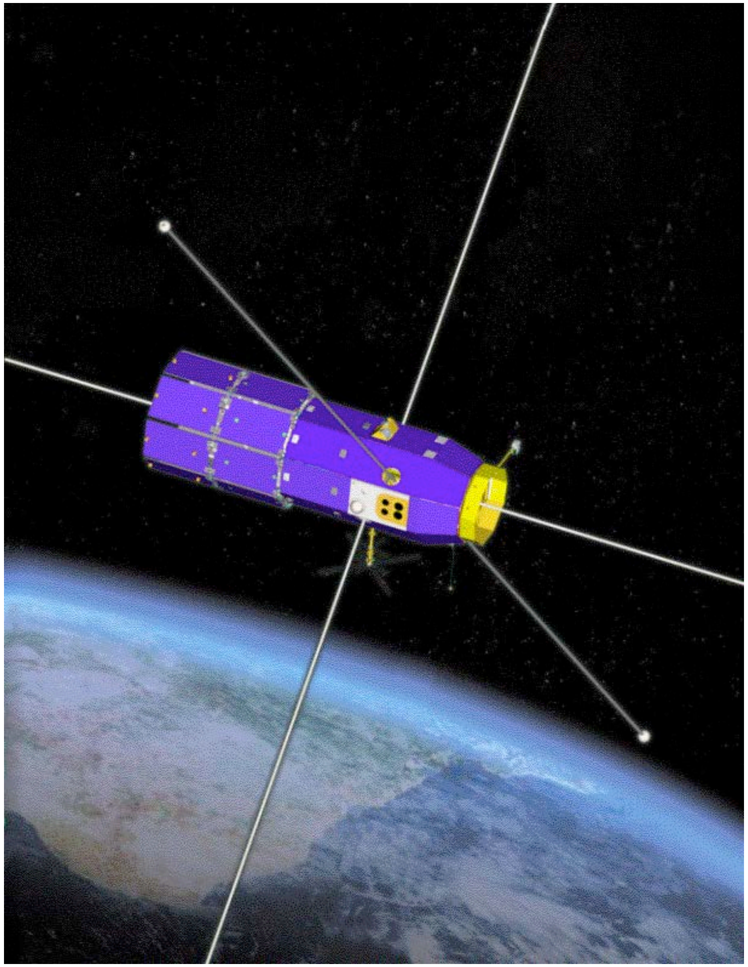
Stolle et al., 2005

Statistical Survey
Unveils magnetic current signatures
associated with Spread-F

C/NOFS Satellite, Launch, Mission

- Satellite Overview
  - 810 lbs
  - 400W solar array / 250W power usage
  - Body-mounted solar panels
    (avoids E-field disruption)
  - Six 10m booms with electric field sensors
  - Three-axis attitude control; Ram pointing
  - Largely off-the-shelf components,
    re-packaged for C/NOFS Mission
  - Continuous, near real-time payload downlink
    via TDRSS MA service

- Low-altitude / Low-inclination orbit
  - 401 x 867 km / 13 degree inclination
  - Covers entire equatorial region every 96 min.
  - Launched on April 17, 2008 on Pegasus from Kwajalein Atoll

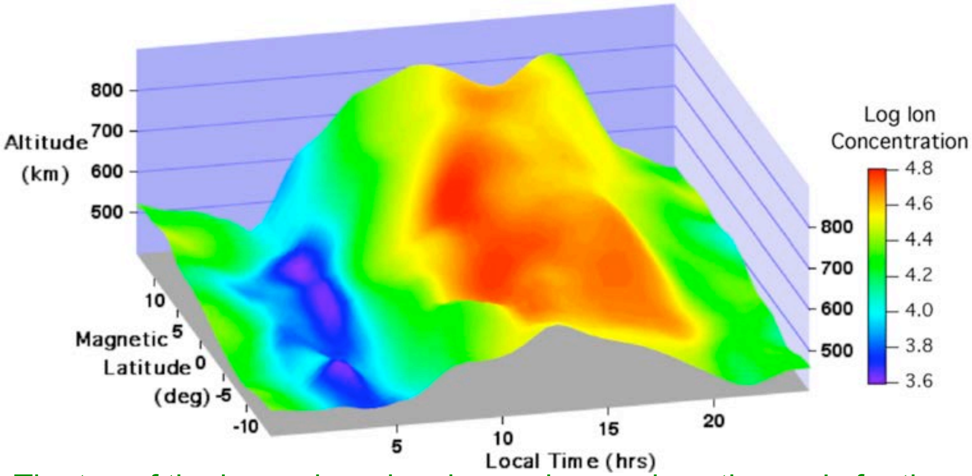


C/NOFS Instruments

Investigation	***P.I.***	***Funding Source***	***Instruments***
PLP	D. Hunton AFRL	AFRL	Planar Langmuir Probe
CINDI	R. Heelis UTD	NASA	Neutral Wind Meter
			Ion Velocity Meter
VEFI	R. Pfaff GSFC	AFRL	DC Electric Fields
			AC Electric Fields, irregularities, plasma waves
			Magnetometer
			Fixed Bias Langmuir Probe (“Trigger Probe”)
			Lightning Detector
CORISS	P. Strauss Aerospace	AFRL, NPOES	GPS occultation receiver
CERTO	P. Bernhardt NRL	NAVY	Multi-frequency beacon for tomographic studies

Coupled Ion Neutral Dynamics Investigation

CINDI observations of O+/H+ Transition Height



The top of the ionosphere has been observed continuously for the first time. It is a surface that is much closer to Earth than expected.

CINDI: Coupled Ion Neutral Dynamics Investigation

Goal: Understand how ion-neutral interactions control the behavior of the ionosphere and thermosphere.

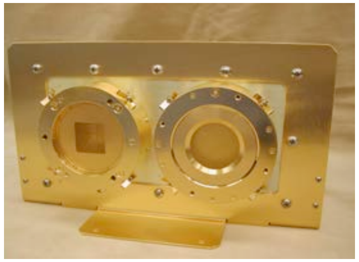
Objectives:

- Determine the relationships between neutral winds and the daily variability of vertical plasma drifts.
  - Discover the combination of neutral winds and plasma drifts that promotes the growth of plasma structure.
  - Discover how the temporal evolution of plasma structure is influenced by neutral winds and plasma drifts.

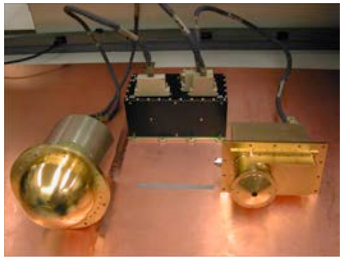
Key Information:

- Mission of Opportunity Launched on C/NOFS Satellite: 4/17/08
- Two year mission plus TBD extensions
- Potential Lifetime: 2015 (depends on solar activity)
- Satellite provided by AFRL and Space Test Program

Ion Velocity Meter



Neutral Wind Meter



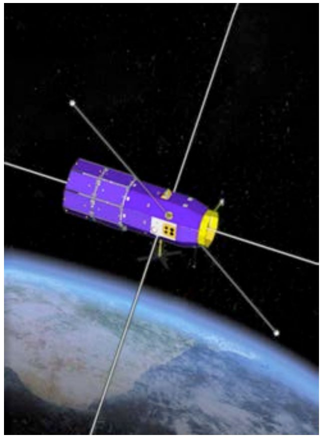
CINDI Mission Overview

The CINDI mission is comprised of two instruments that measure the concentration and kinetic energy of the electrically charged particles (ions) and neutral particles in space as the satellite passes through them at the equator. The data gathered are used to understand the various structures or boundaries of ionospheric plasma depletions, and the different densities of ions in the ionosphere at the equator. These can interfere with radio signals between the Earth and spacecraft in orbit, thus causing errors in tracking and loss of valuable communication.

Communications/Navigation Outage Forecast System (C/NOFS) satellite

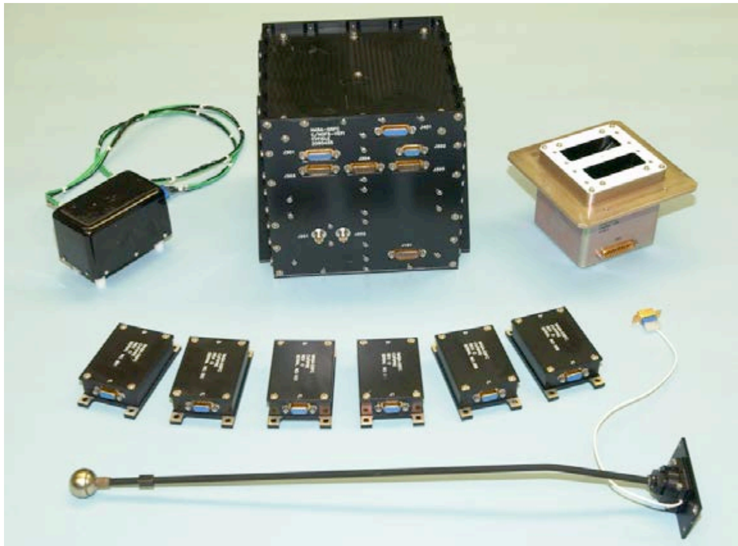
Apogee and Perigee:

401 km by 867 km
13 deg inclination



Vector Electric Field Investigation (VEFI) Hardware

Main VEFI Electronics Box,
Pre-amps(6), Magnetometer Sensor,
Lightning Detector, Trigger Probe:

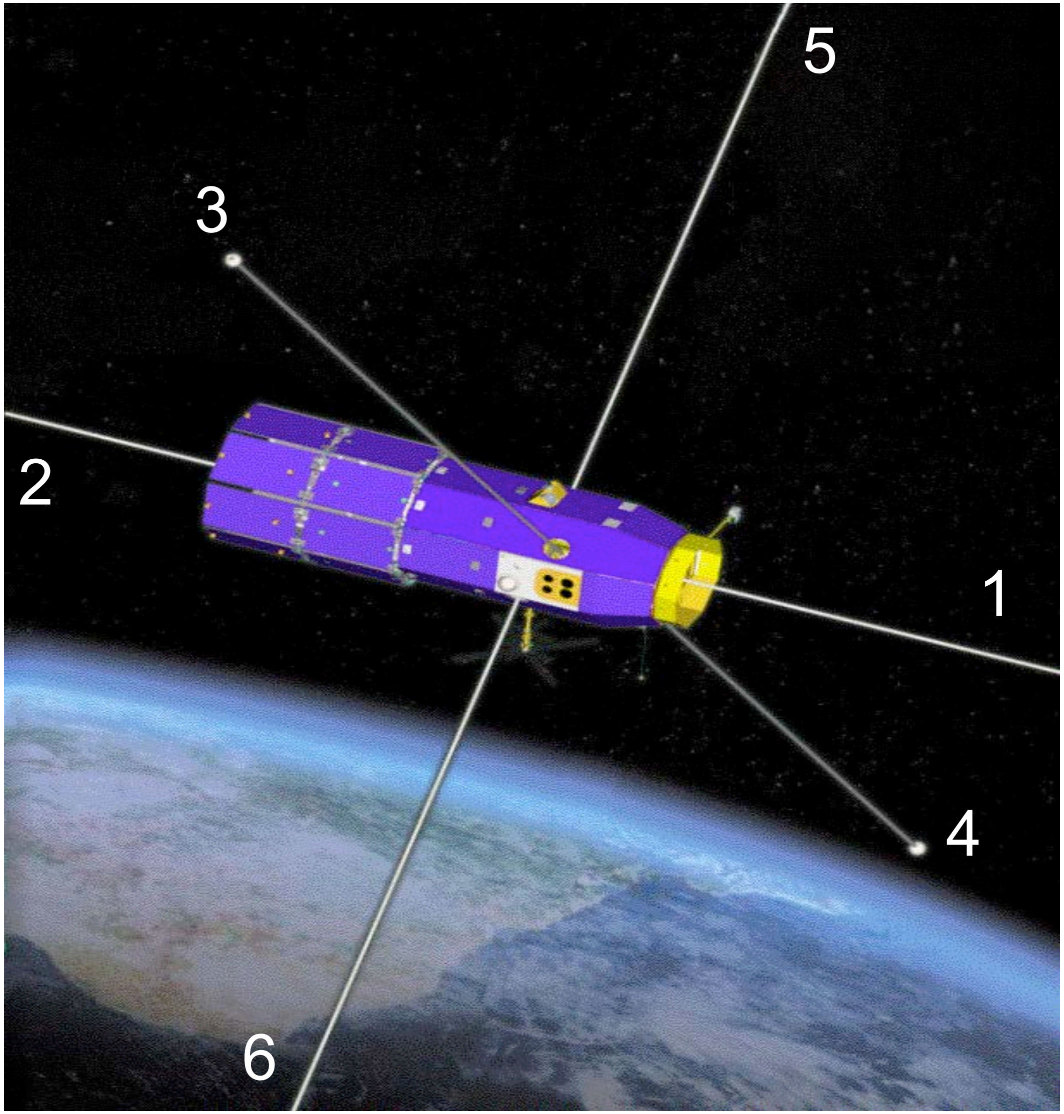


and

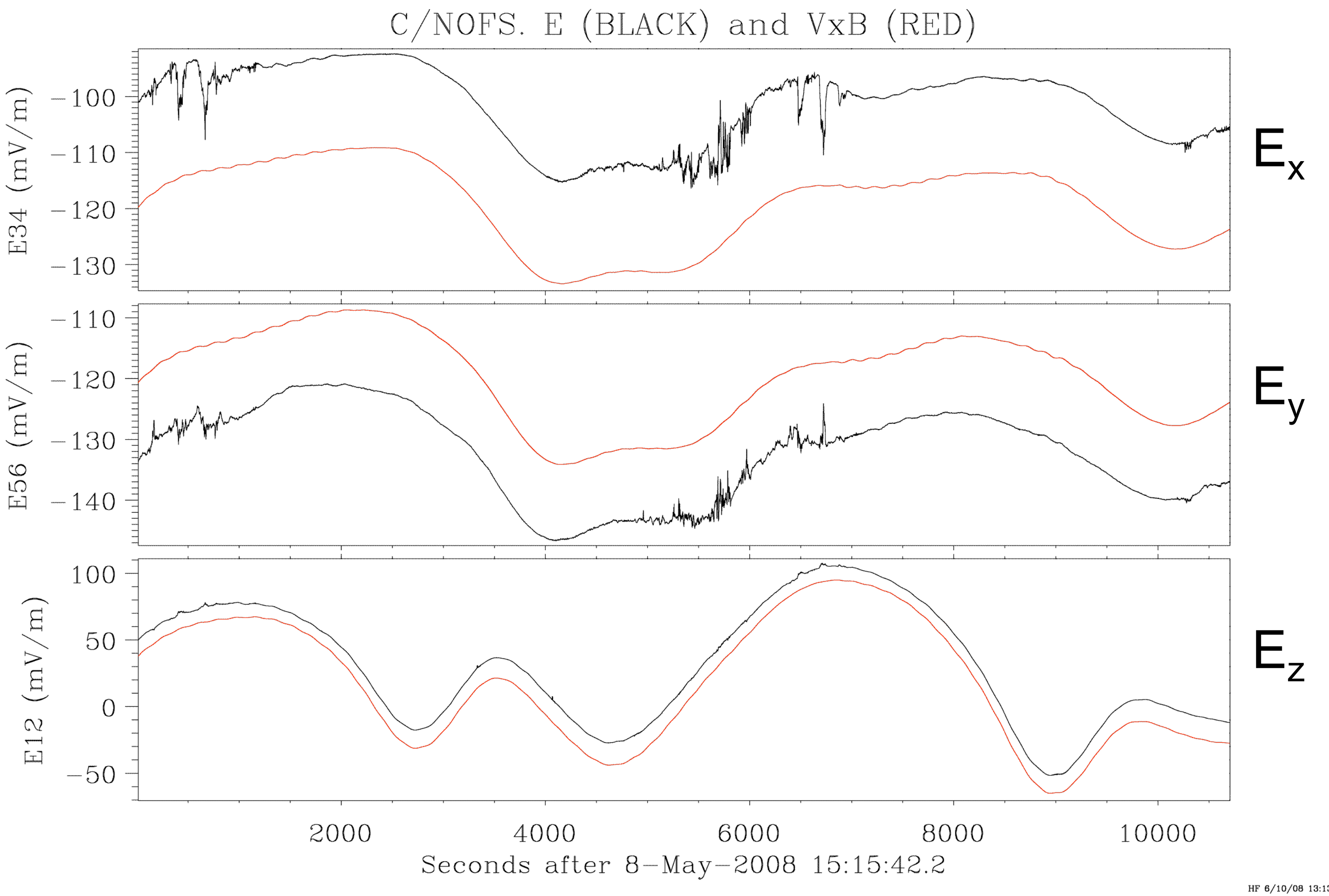
6 Electric Field Booms
with Spherical Sensors:

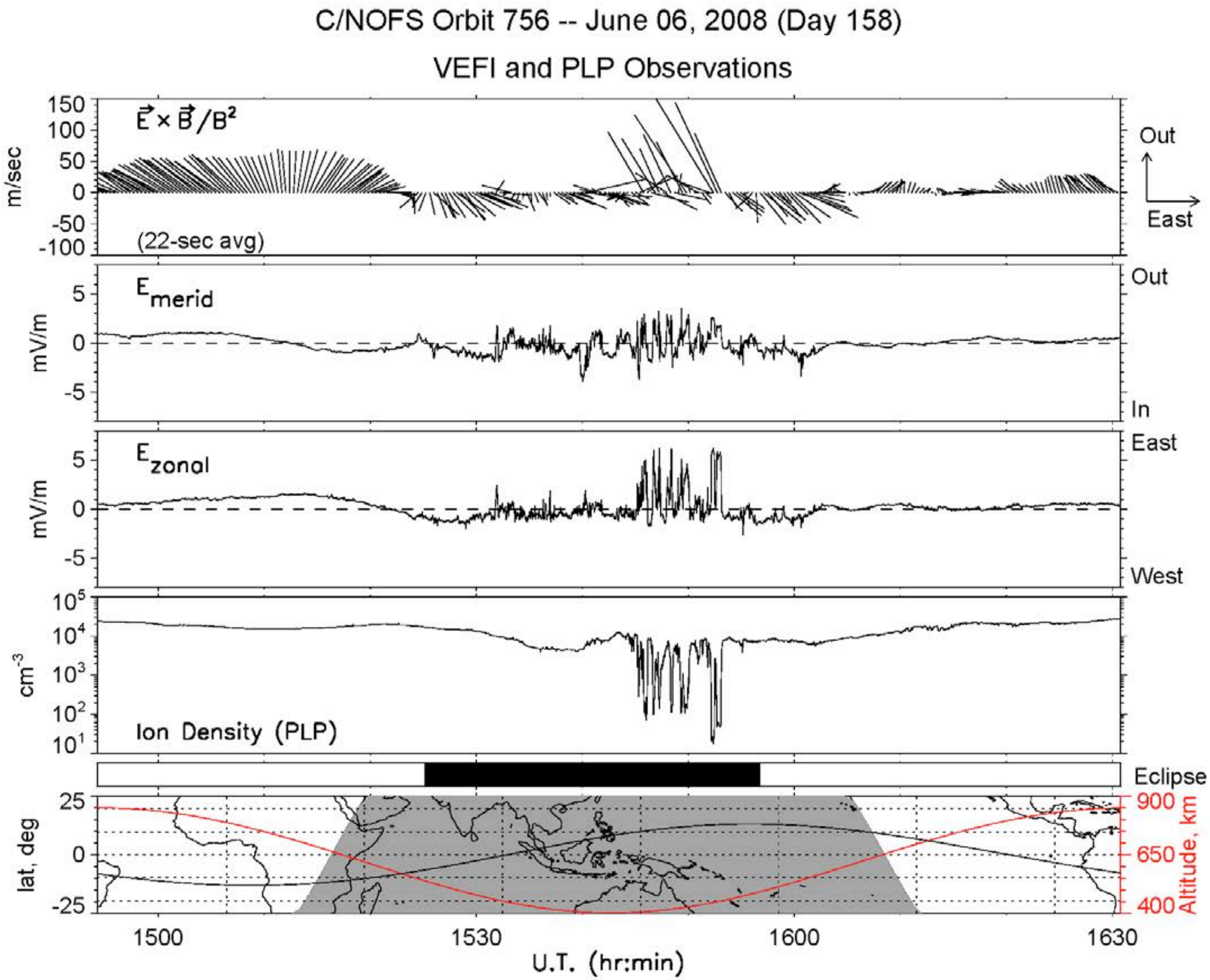
VEFI Is One Instrument
with several sensors

VEFI Boom Orientation



E_{meas} and V x B -- 8 May 2008

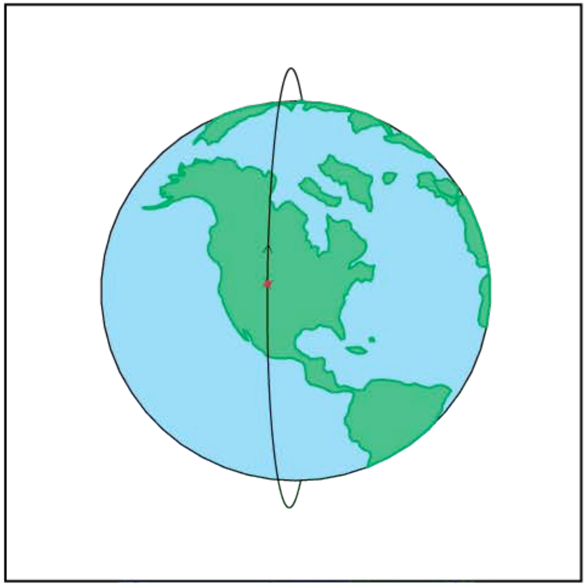




C/NOFS Orbit 756 -- June 06, 2008 (Day 158)
VEFI and PLP Observations
E × B / B²
(22-sec avg)
m/sec
Out
East
E merid
mV/m
Out
In
E zonal
mV/m
East
West
cm⁻³
Ion Density (PLP)
Eclipse
lat, deg
Altitude, km
1500
1530
1600
1630
U.T. (hr:min)

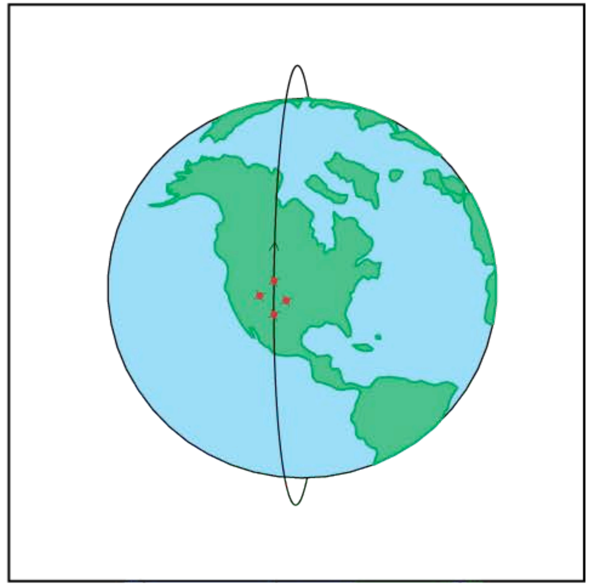
Ionosphere/Thermosphere Orbits, Multiple Satellites

Single Satellite



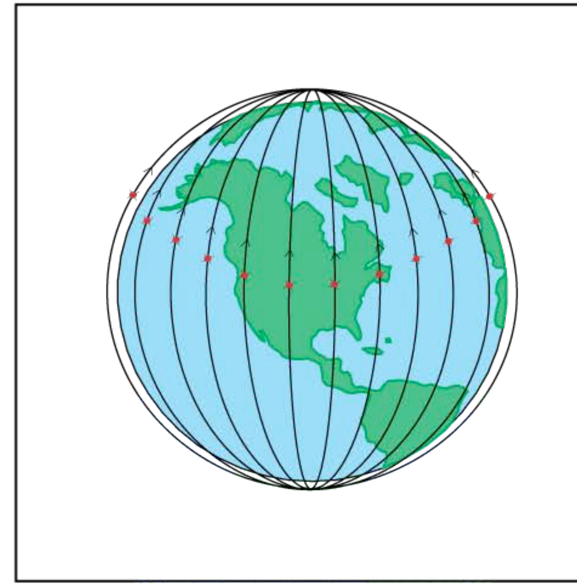
- Event Studies, Exploration
- Provide Average Global Conditions
- Example: **Dynamics Explorer-2**

Cluster of Satellites

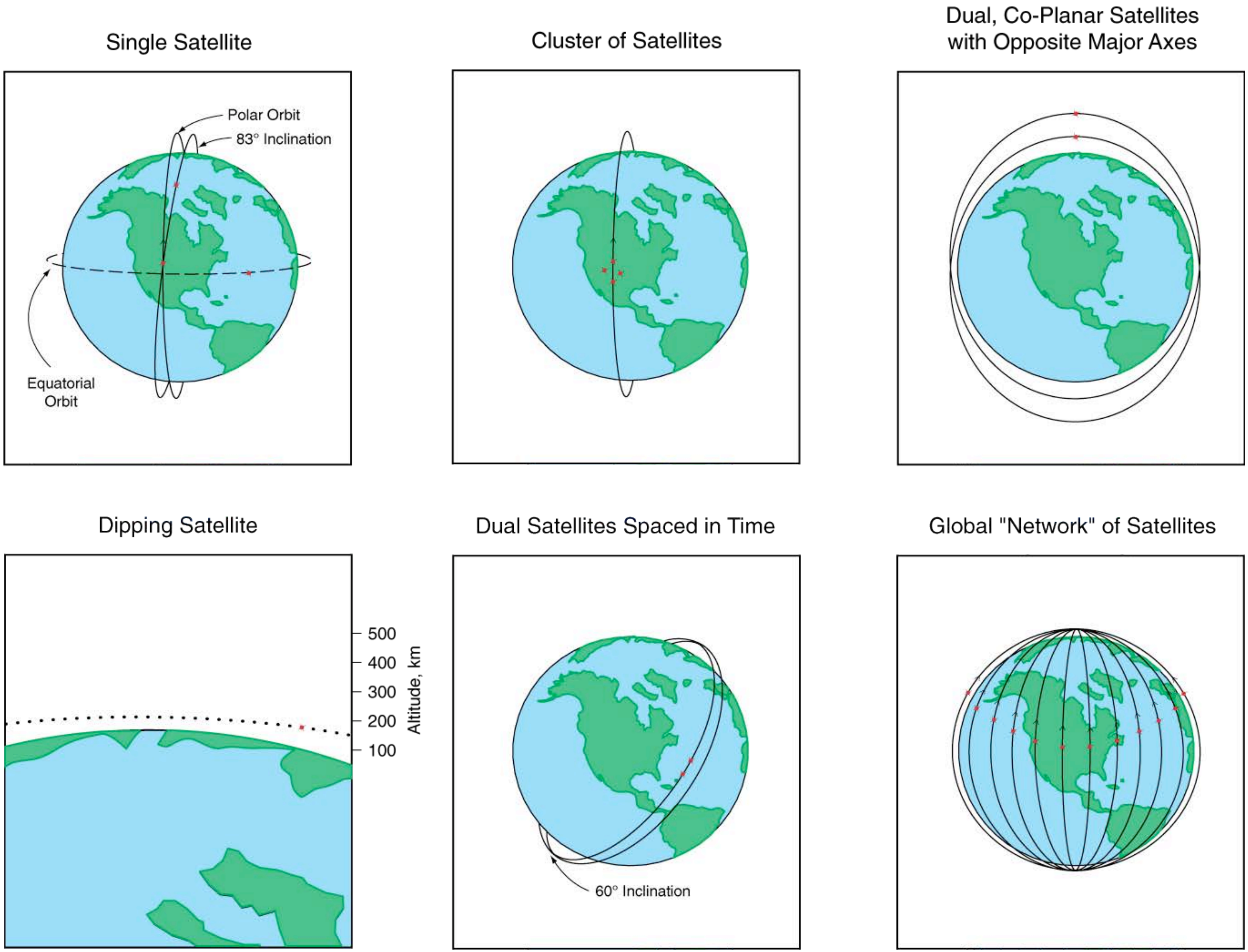


- Event Studies that are resolved in Space and Time
- Provide refined Average Global Conditions
- Example: **Geospace Electrodynamics Connections**

Global Network of Satellites

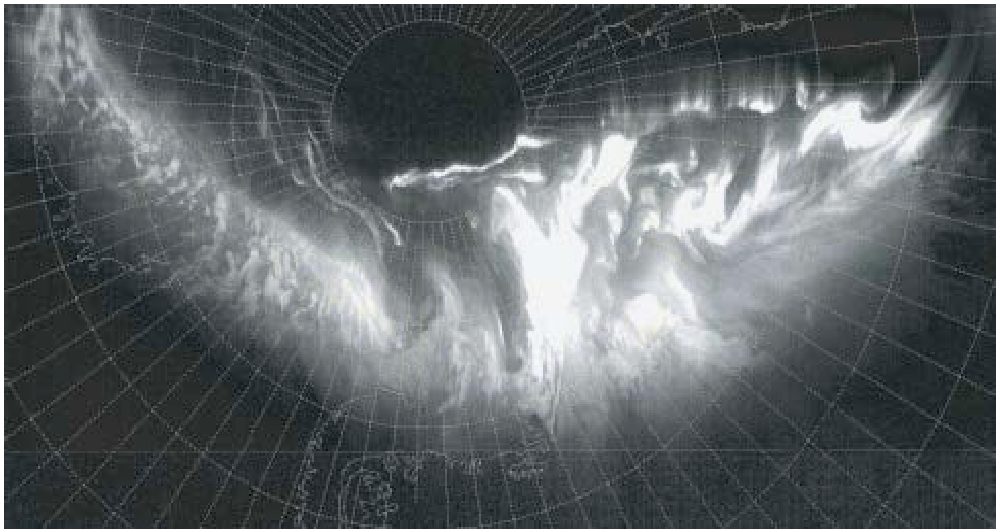


- Global, simultaneous observations covering all latitudes, local times
- Uncovers global-scale processes, coupling to other regions; provides event studies within“big picture”
- Enable tomography and other RF experiments (e.g., GPS occultations)
- Example: **Ionospheric Mappers**


Single Satellite
Polar Orbit
83° Inclination
Equatorial Orbit
Cluster of Satellites
Dual, Co-Planar Satellites with Opposite Major Axes
Dipping Satellite
500
400
300
200
100
Altitude, km
Dual Satellites Spaced in Time
60° Inclination
Global "Network" of Satellites

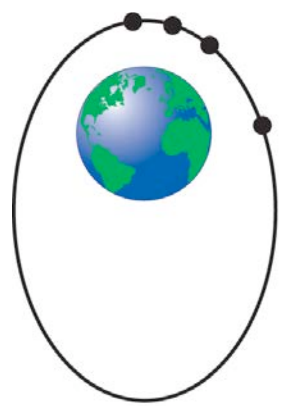
M1874_4.ai

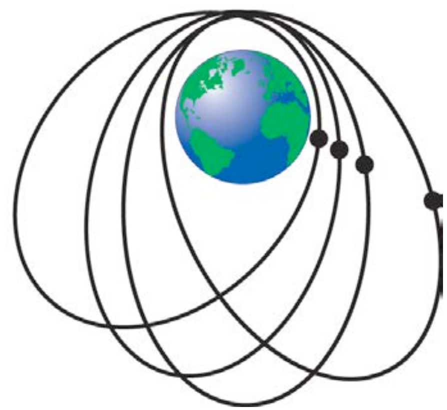
Possible Future Mission --
Geospace Electrodynamics Connections



GEC will be configured to sample the necessary scale sizes, bothspatial and temporal, to address the key energy input in the auroral region.

GEC s/c will fly in either a string of pearls or in a petal formation to sample at different altitudes.

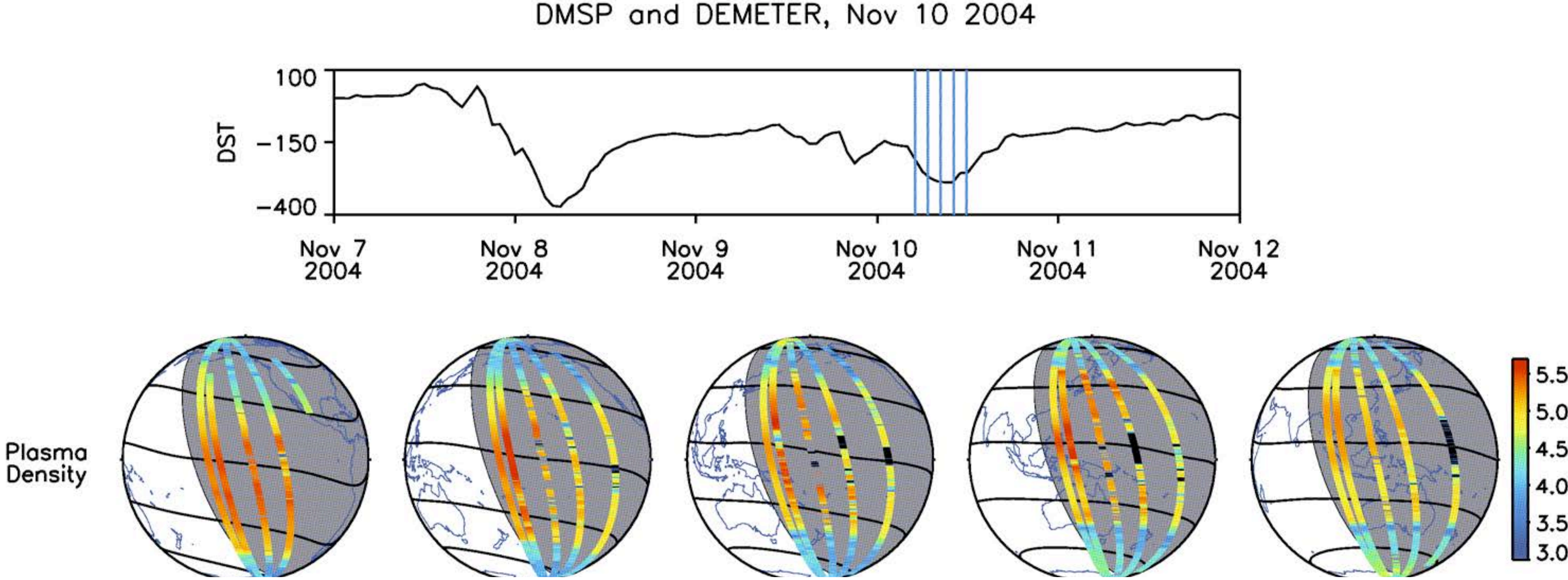




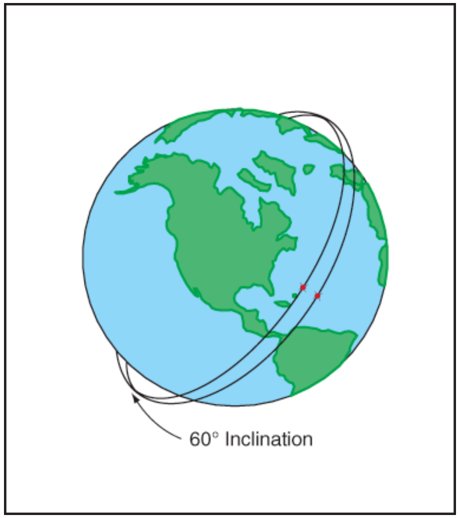
Possible Future Mission --
Ionospheric Constellation (ICon), Satellites Spaced in Local Time

- An unprecedented understanding of the global processes inherent in the I-T system would be obtained with a fleet of satellites deployed in a “network” surrounding the globe.

- Such a configuration would provide an immediate new picture of the I-T system with measurements of the I-T coupled processes on a global scale, such that the effects of external and internal influences and dynamics would be observed within the entire I-T envelope, and not just within a small sector. Such a configuration would provide input to models at all local times simultaneously.



Possible Future Mission --
Dual Satellites, Spaced in Local Time

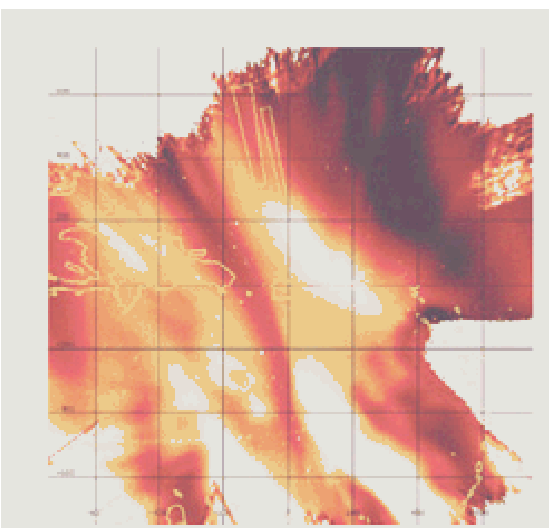


Example: LWS/I-T Storm Probes

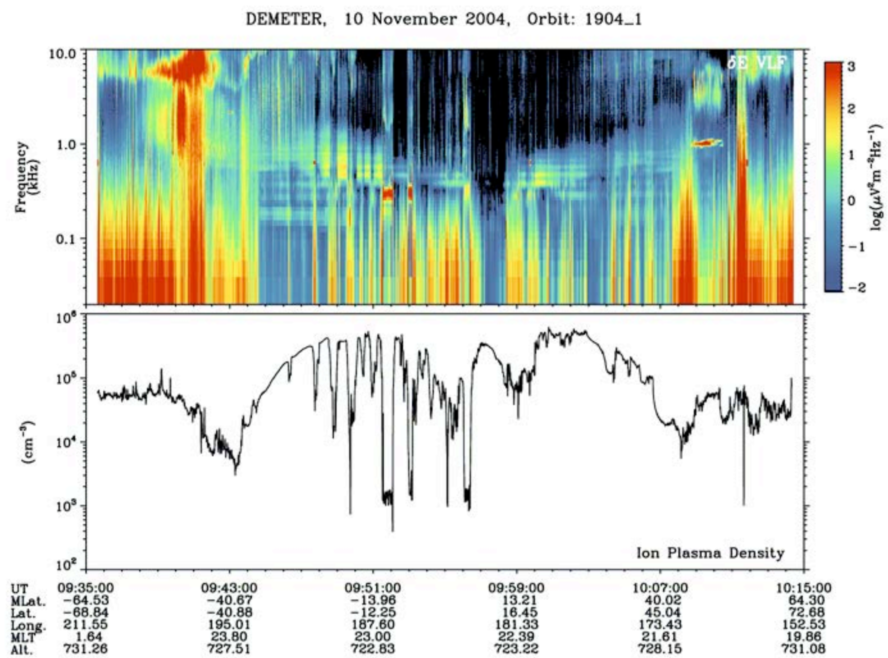
- Dual satellites with orbits spaced in local time enable either:

-- two satellites orbiting in tandem, sampling the same latitudes at "neighboring" local times, or

-- two satellites with appropriately spaced positions along their orbits such that the trailing satellite samples the same location as the earth turns beneath the satellites.



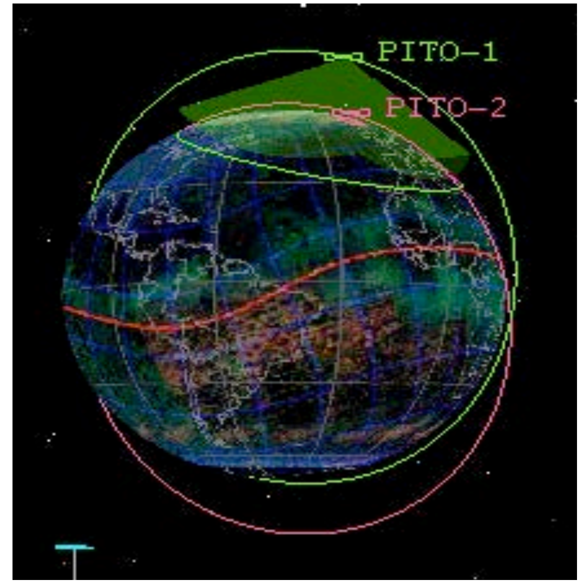
Airglow images ,J. Makela



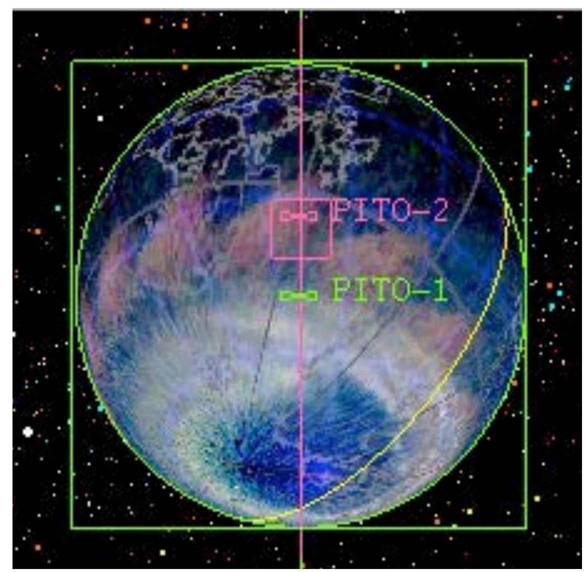
DEMETER satellite, Pfaff et al., 2008

Paired Ionosphere/Thermosphere Orbiters (PITO)

- General purpose I-T mission
  - Enables many science targets, including some objectives of the GEC and ITSP missions
- Two spacecraft in “equal but opposite” orbits
  - Arguments of perigee differ by 180 deg
- Three classes of instruments carried
  - In situ sampling
  - Remote sensing
  - Vertical profiling
- Scope is scalable
  - MIDEX or “MIDEX-Heavy” class
  - Two small launchers if no Delta 2



Orbit Concept



View from imager on PITO-1

Summary

- Direct measurements in the ionosphere /thermosphere have uncovered a rich and exciting environment of neutral and plasma processes influenced by energy and momentum sources from above and below.

- *In situ* instruments provide accurate measurements of physical parameters in the ionosphere/thermosphere system that:
    - *provide fundamental fields, particles, and gas properties*
    - *reveal key physical processes, particularly of energy and momentum exchange,*
    - *provide essential input for models,*
    - *provide global statistical "pictures" of the I-T system.*

- Measurements in conjunction with space-based imagers and ground-based measurements greatly enhance the *in situ* measurements.