JCSDA Seminar

Ionospheric Data Assimilation

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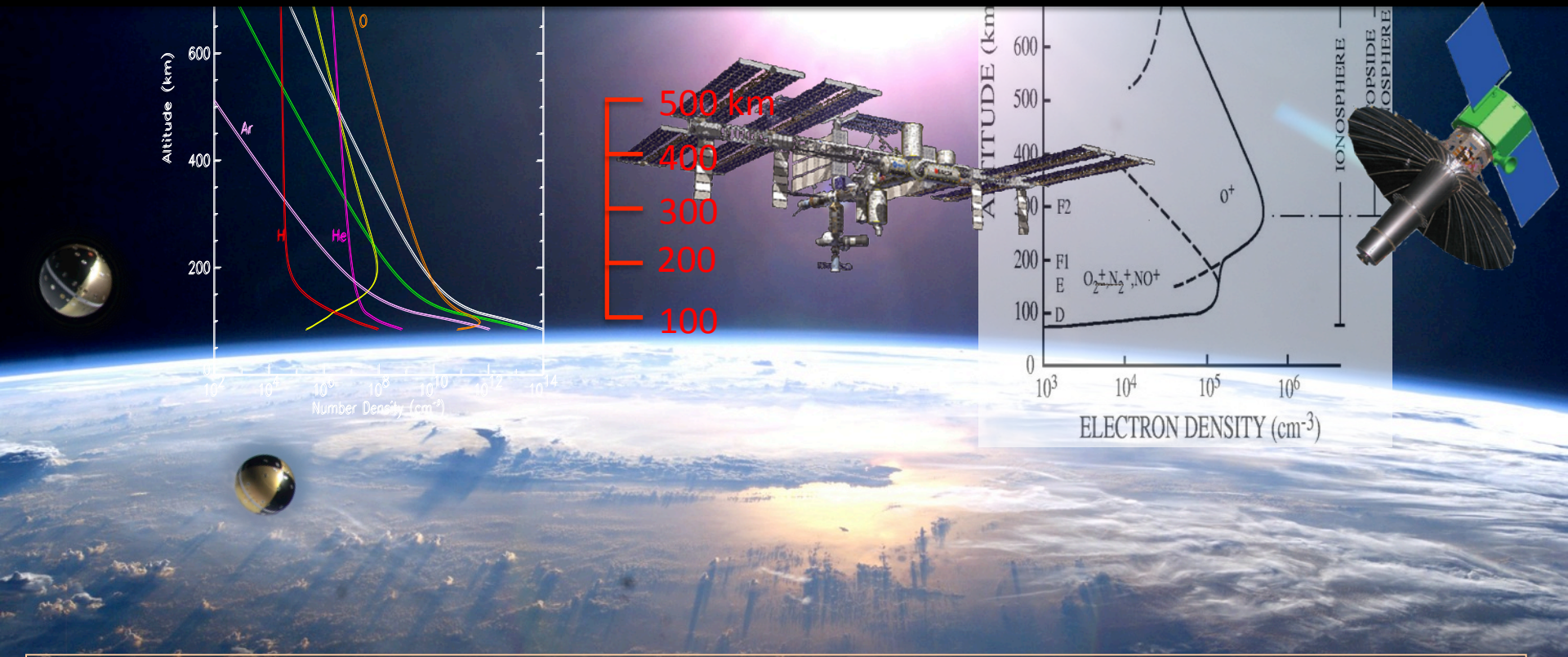
Ionosphere & Thermosphere



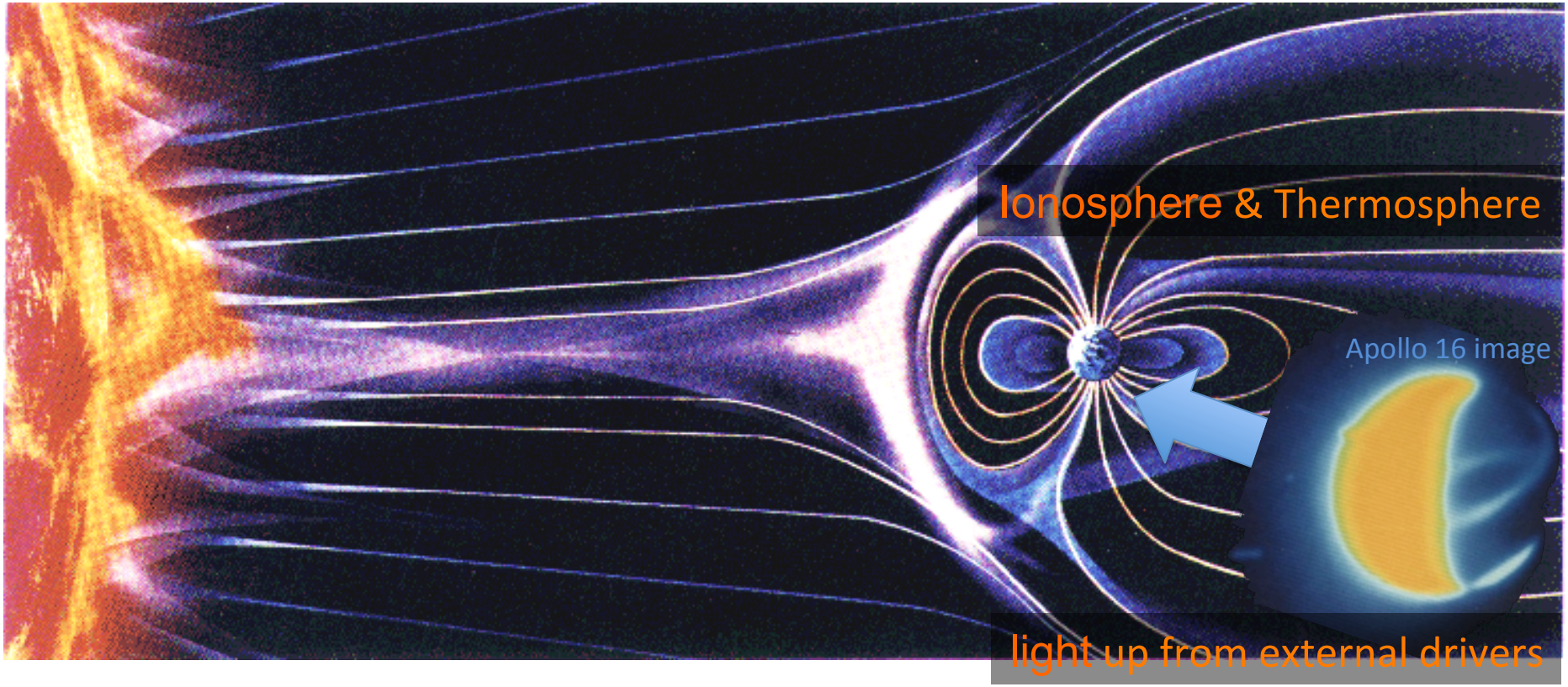
The upper atmosphere (100–500+ km) consists of

- ✧ Plasma of electrically charged gas (Ionosphere) – Highly variable
- ✧ Rarefied uncharged gases (Thermosphere) – Also highly variable

Thermosphere and ionosphere are societally-relevant

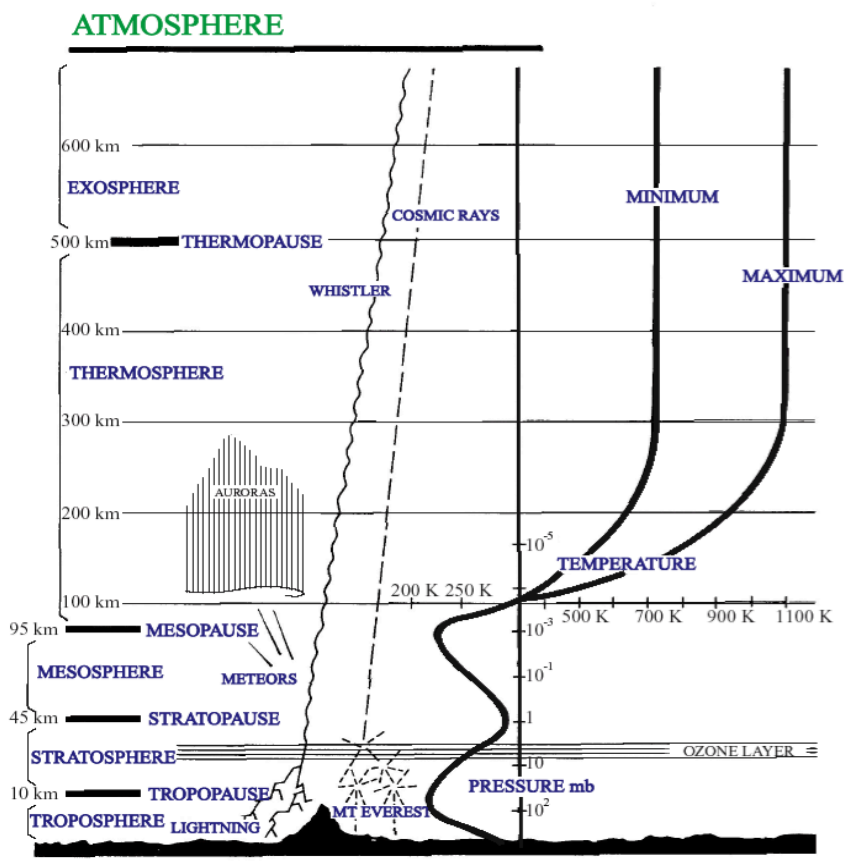
- ✧ Satellites and spacecraft operate there
- ✧ Electromagnetic signals must propagate through this region

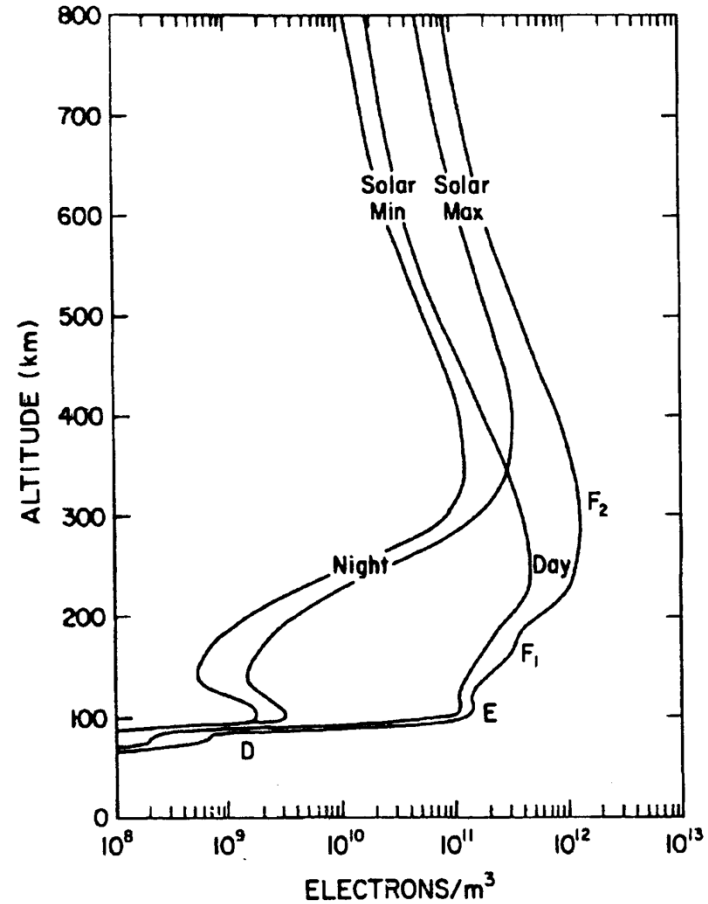
Space Weather – Drivers from Above



- Upper atmosphere is affected by strong external solar drivers
  - Variable solar wind/particles and solar irradiance
  - Importance of external drivers recognized for decades
- Terrestrial drivers from below also play a role
  - Atmospheric tides, gravity waves, meteorology

Thermosphere & Ionosphere Variability





F-Region

$O + h\nu \rightarrow O^+ + e^*$

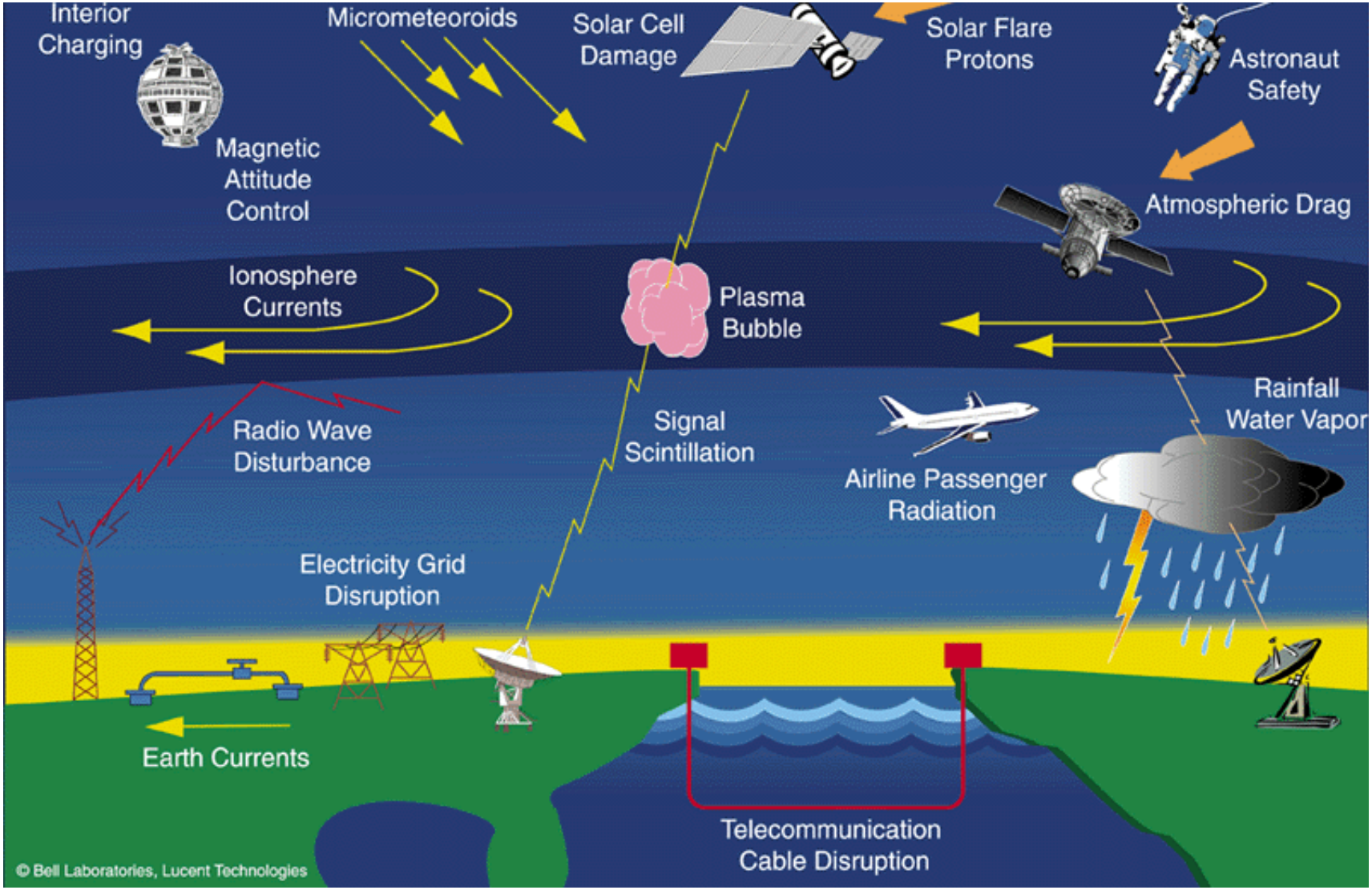
$O^+ + N_2 \rightarrow NO^+ + N$

$O^+ + O_2 \rightarrow O_2^+ + O$

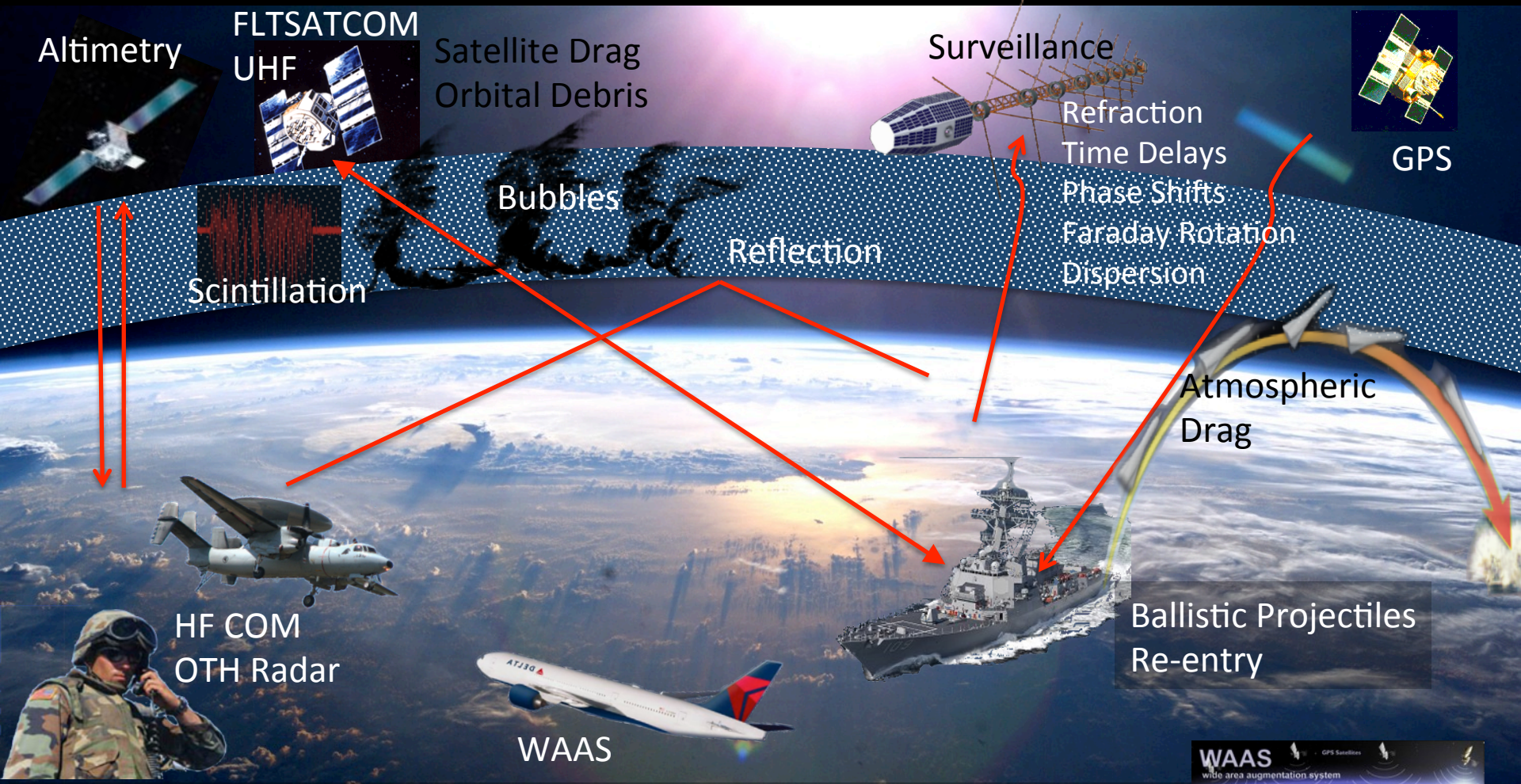
Topside

$O^+ + H \Leftrightarrow H^+ + O$

Space Weather Effects



Navy/Societal Relevance

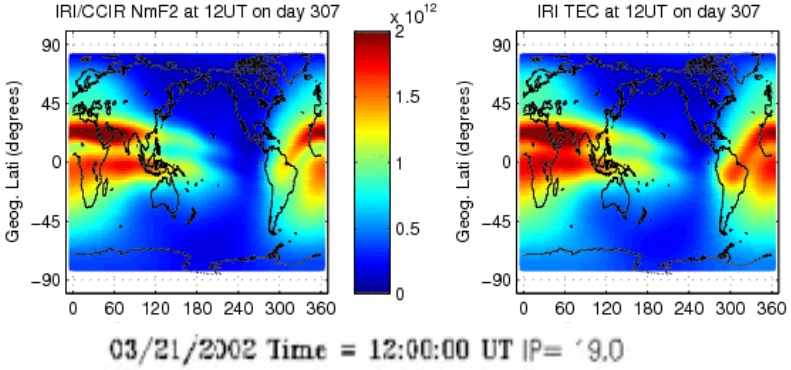


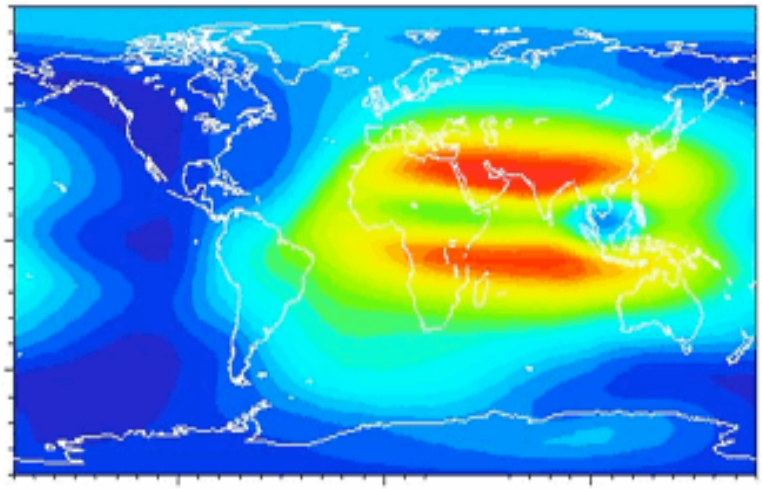
Naval assets are perpetually forward-deployed

- Heavy reliance on space for communication, navigation
- Similar dependence for many civilian systems, esp. aviation

Data Assimilation for Ionosphere

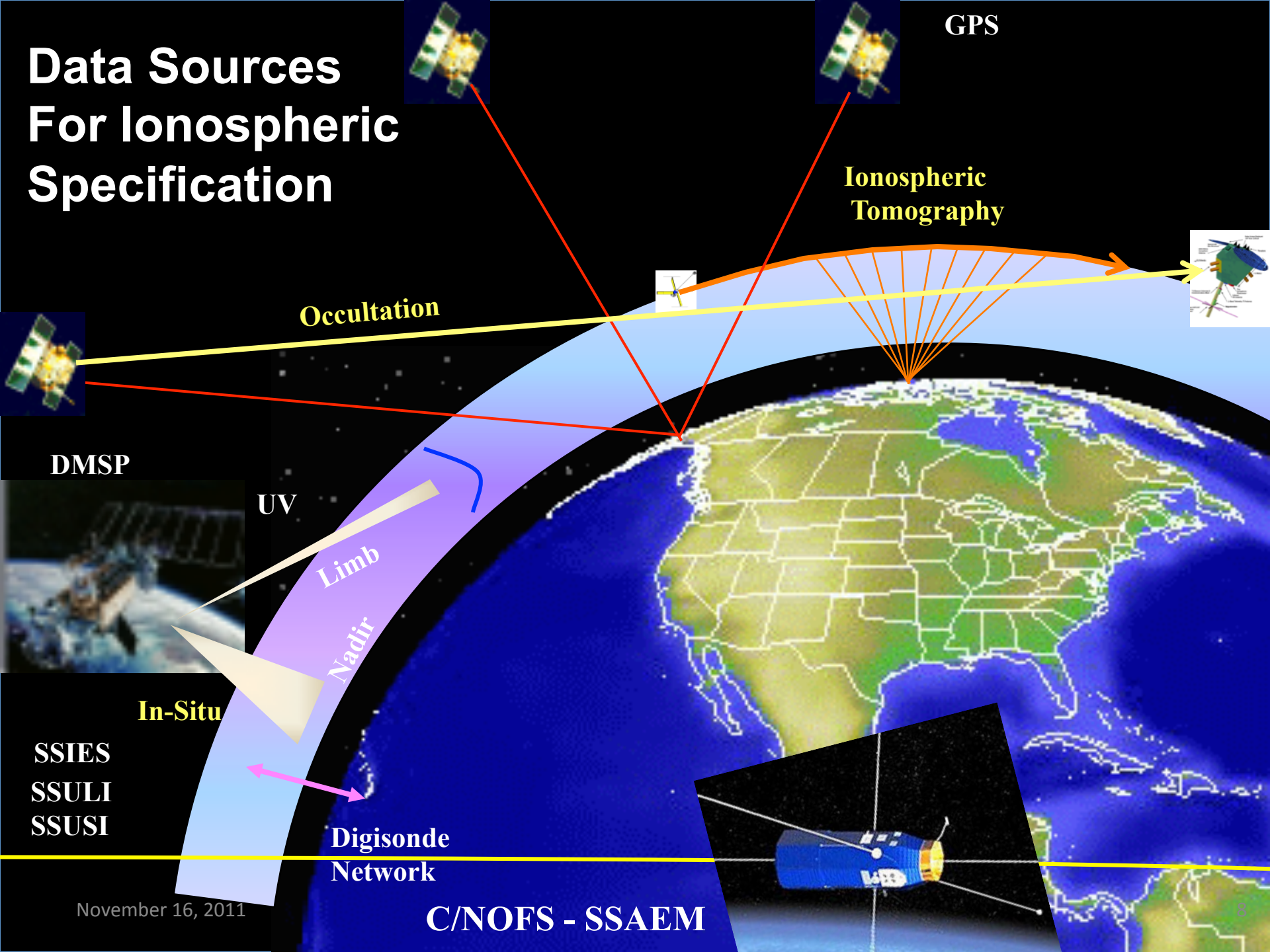
- Current Ionospheric Models
  - Empirical, climatological models
    - Statistics-based: Unable to accurately predict space weather events and evolution from statistical means
  - First principles models
    - Better physics: Qualitatively able to model space weather events and evolution
    - Tuning required: Quantitatively inaccurate due to limited specification of driver inputs and preconditioning considerations



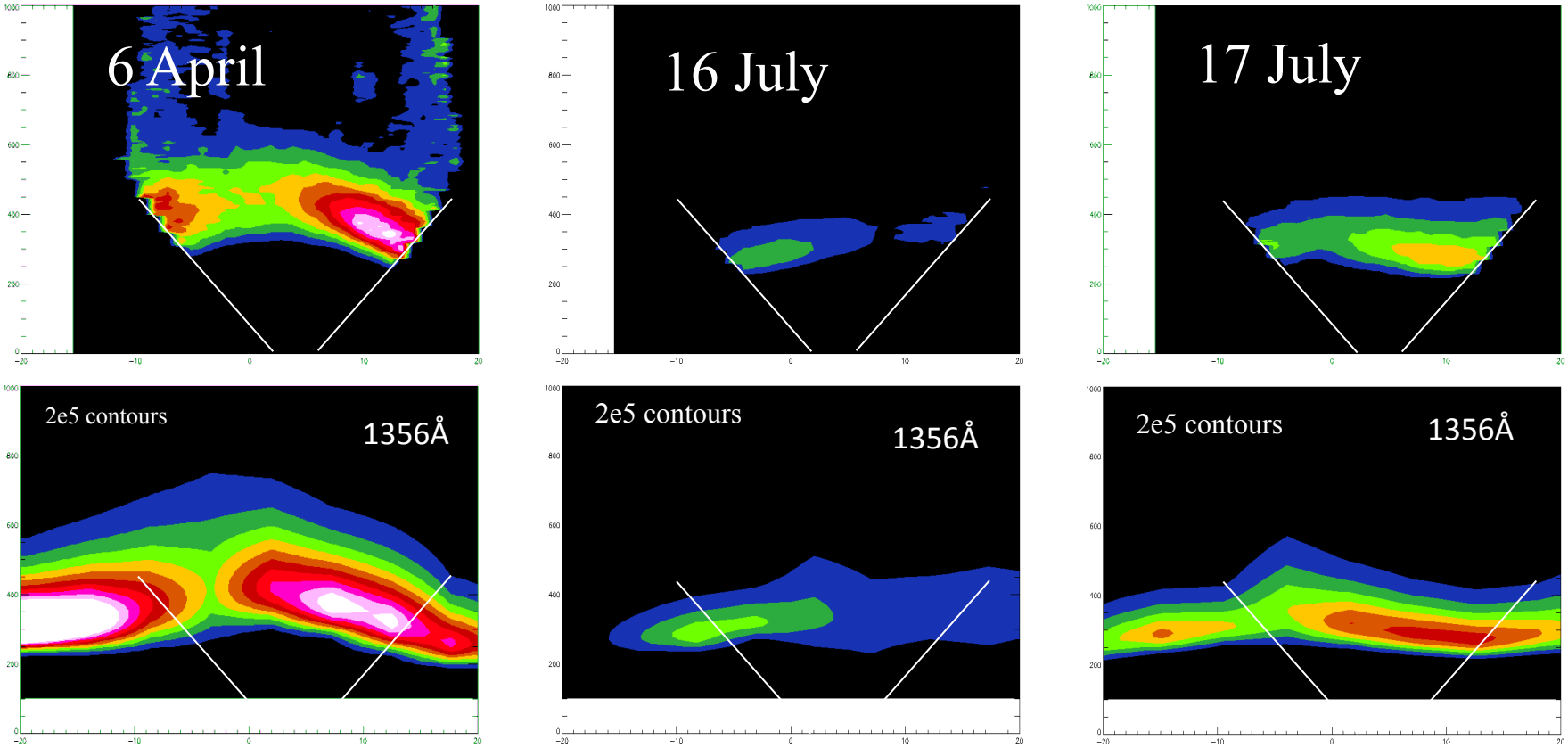


- Accurate specification and evolution
  - Sudden, unpredictable changes in external drivers significant challenge to forecasting
  - **Requires data assimilation to drive physical model to match current conditions globally1**

Data Sources For Ionospheric Specification

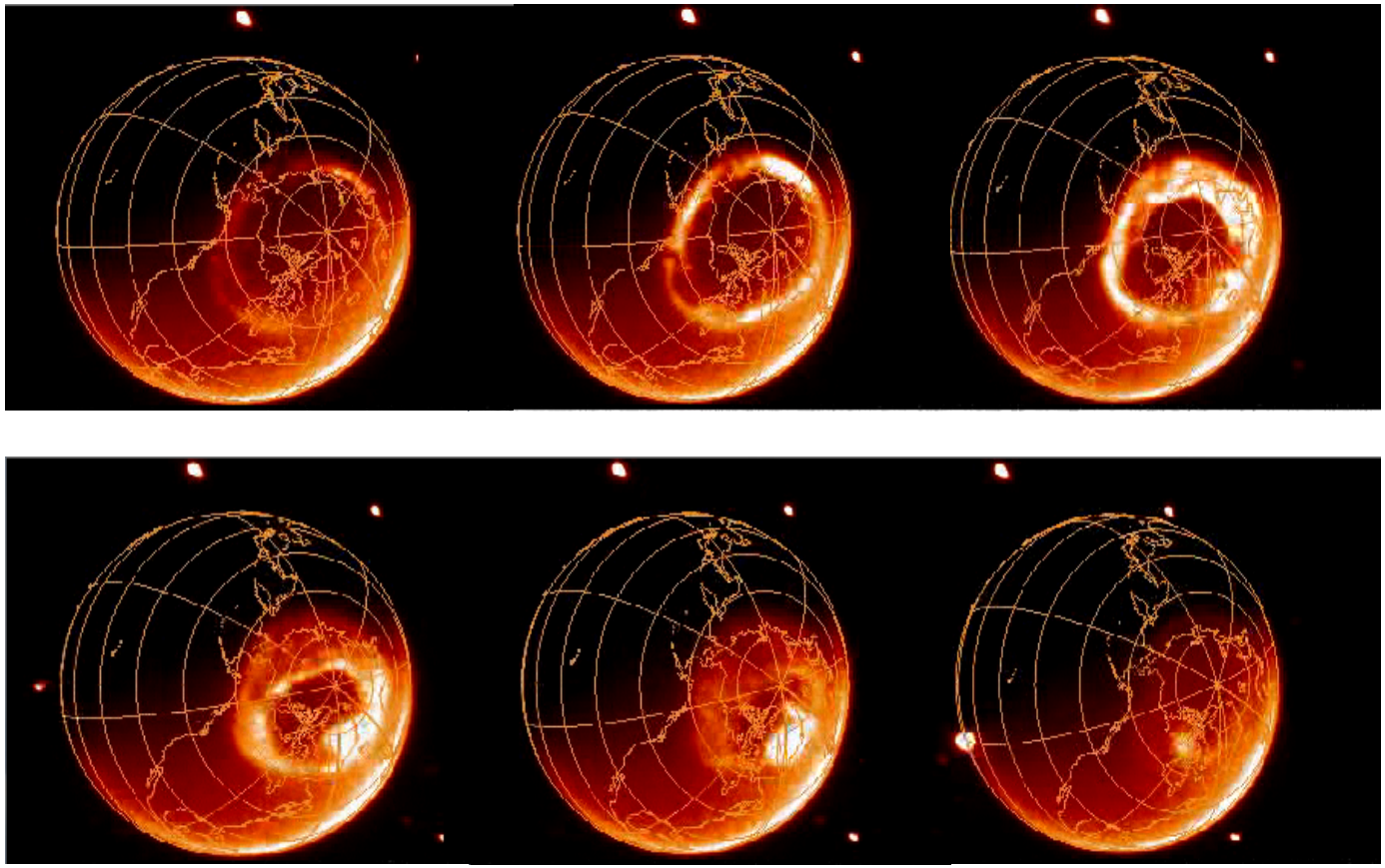


Satellite Remote Sensing from LEO



- Day-to-day variability of nighttime ionospheric electron density
- Satellite FUV remote sensing from DMSP SSULI instrument
- 2D algorithm captures morphology of low latitude ionosphere.
  - Validated against ground-based radar in Kwajelein
  - Satellite provides global coverage (all latitudes & over oceans)

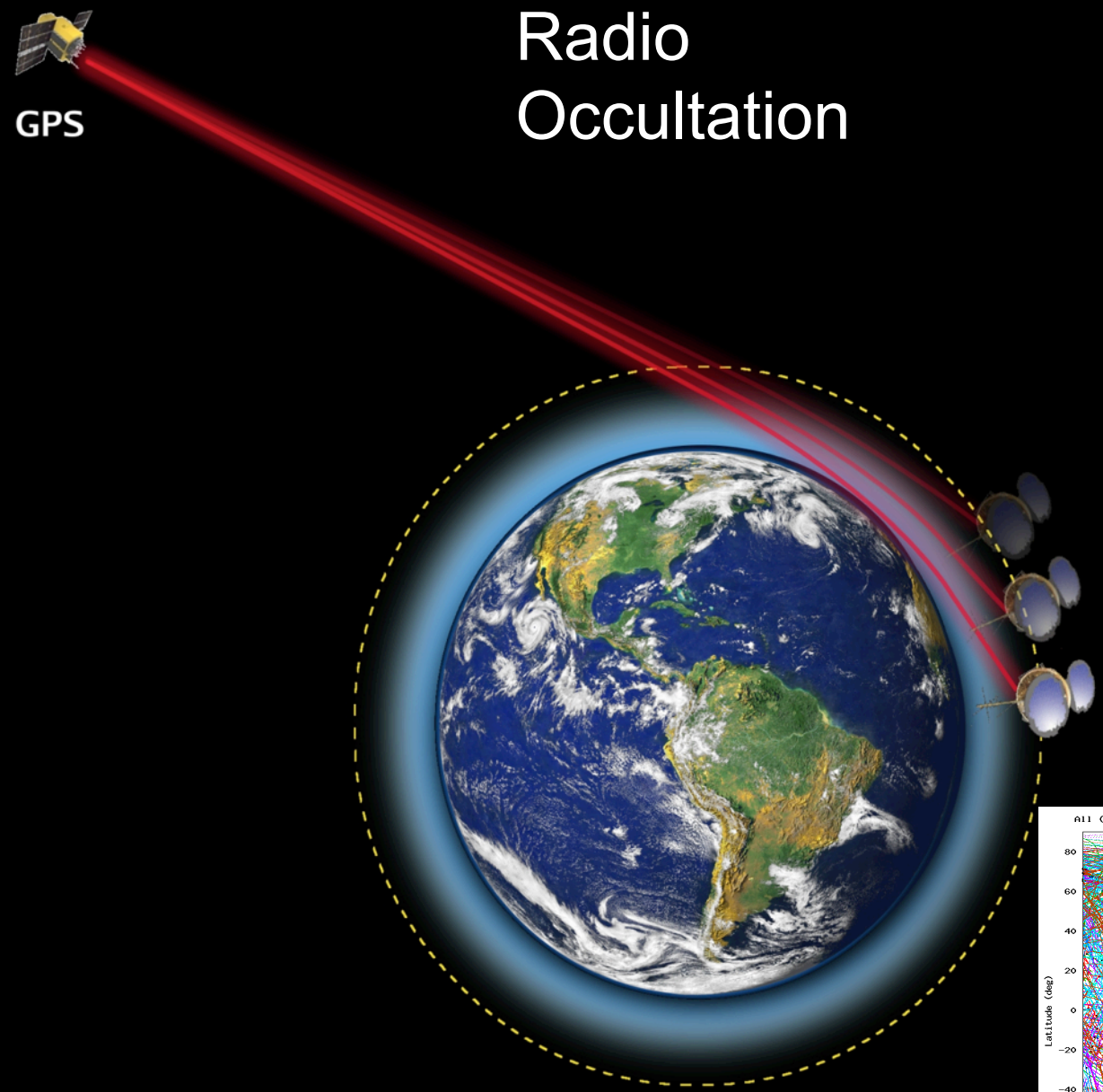
Satellite Images from HEO

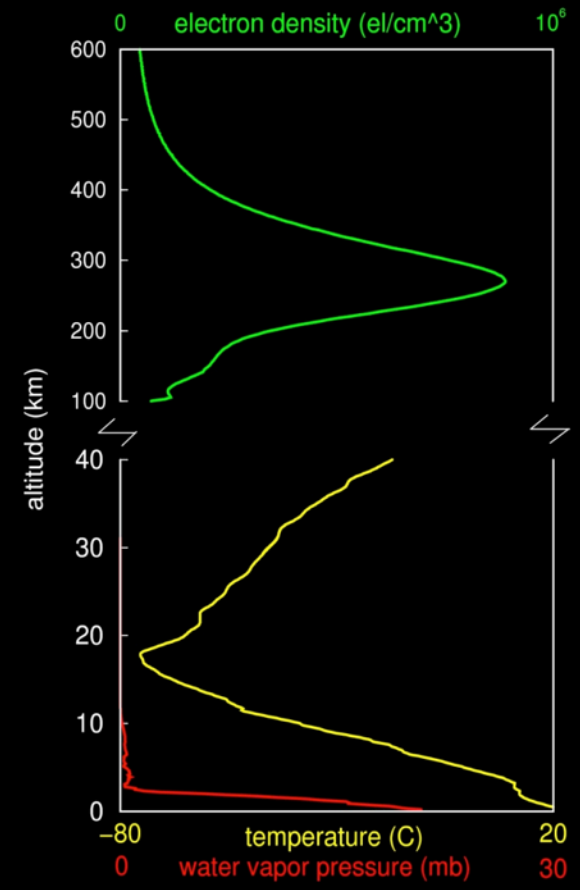


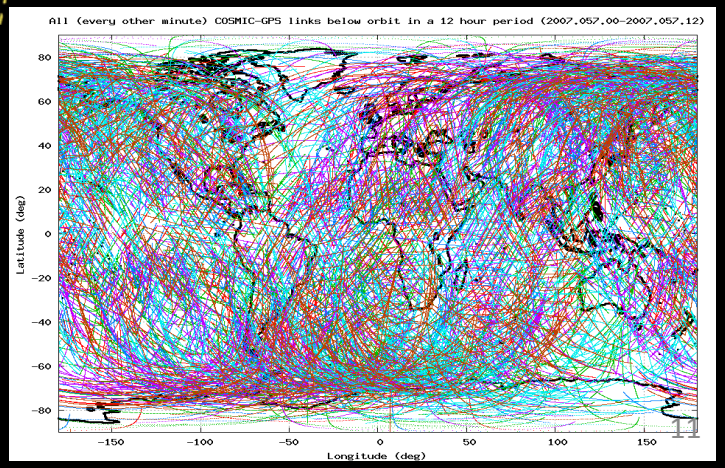
Burch, J. L., *Scientific American, 284*, 72-80, 2001

- **Bastille Day Storm, July 14-15, 2000**
- **Snapshots During a 1-Hour Period**
- **High-latitude energy deposition**

Radio Occultation

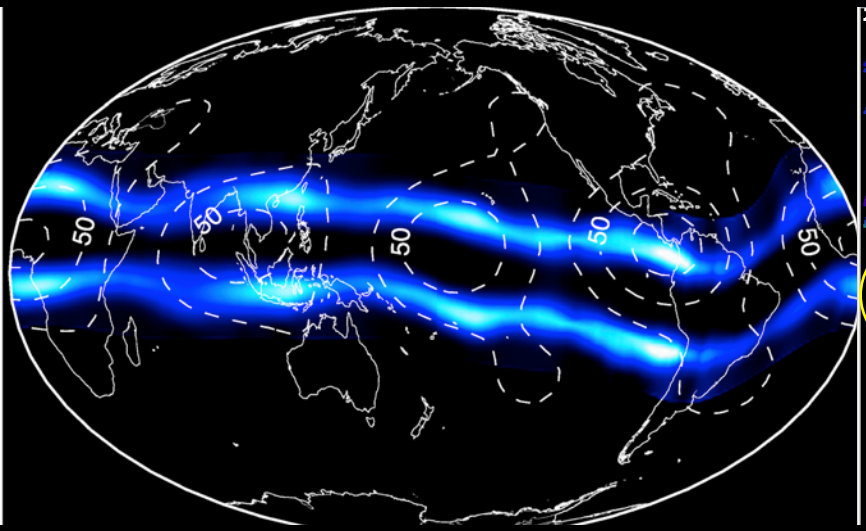




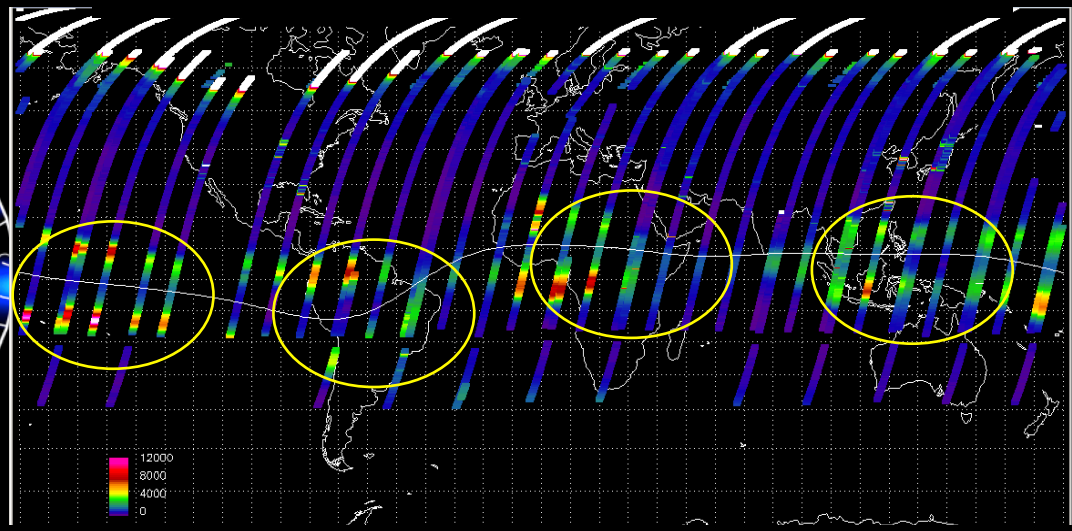


Ionospheric Impact of Atmospheric Tides

Composite airglow images for 8:00 pm local time. Contours show temperature tides in E region time



Scintillation strength is related to strength of this nighttime O+ airglow



Tides from the lower atmosphere modulate the ionosphere

- Ionospheric morphology is variable on a range of temporal (seconds to years) and spatial scales (meters to 1000 km)
- Tides are global-scale periodic oscillations of the atmosphere
  - Sun, meteorology, and surface features excite atmospheric tides
  - Ionospheric electron density is modulated by E region tides

Mitigation of Ionospheric Effects on Naval Systems

Sub-Goals

- Identification of the primary physical drivers of the ionosphere
- Development of data-assimilative specification model
- Physics & trigger mechanisms for ionospheric irregularities & scintillation
- RF & UV spaced-based remote sensing of global electron density
- Real-time, long-dwell high spatial/temporal ionospheric sensors
- Long-term global forecast & short term storm forecast

2006 2008 2010 2012 2014 2016

Investment Approach

- Ionospheric specification with Global Assimilation of Ionospheric Measurements (GAIM)
- Assimilation of ground-based GPS data
- Assimilation of satellite GPS data → Global ionospheric forecast model
- Assimilation of UV limb & nadir satellite data
- Neutral density remote sensing → Neutral density assimilation → Global Neutral density forecast
- UV ionospheric remote sensing from GEO → High time/space resolution assimilation
- UV neutral density remote sensing from GEO → Ionospheric irregularity & scintillation forecast
- Seamless models ocean to space
- Gravity wave forcing & coupling → Electrical & lightning coupling

2006 2008 2010 2012 2014 2016

Enablers

- NRL D&I in UV remote sensing
- DMSP UV sensors
- better forcing from atmospheric models
- COSMIC constellation of UV/RF satellites
- RAIDS spaceflight on ISS
- IMAGER GEO sensor
- AFOSR neutral density MURI
- DTRA Seamless Model initiative

Ten-Year Goal:

High fidelity ionospheric & neutral specification & forecast

Provide the scientific background necessary to produce 5-day predictions of the ionosphere and neutral density to allow advanced warning of C4I outages and improve performance of systems affected by propagation through the ionosphere

Remote Sensing of the ionosphere and neutral density from space
Explore new methods to use GPS/UHF refractivity, UV Chemistry & radiation transport to determine election & neutral densities from space

Assimilation Models
Determine techniques for data assimilation to allow predictions (nowcasts and forecasts)

Seamless Coupled Models
Pursue new type of model to incorporate tropospheric gravity wave forcing of the upper atmosphere

Global Assimilation of Ionospheric Measurements (GAIM Team)

R. W. Schunk, L. Scherliess, L. C. Gardner,

J. J. Sojka, & L. Zhu

GAIM

"Bringing The Pieces Together"

UtahStateUniversity

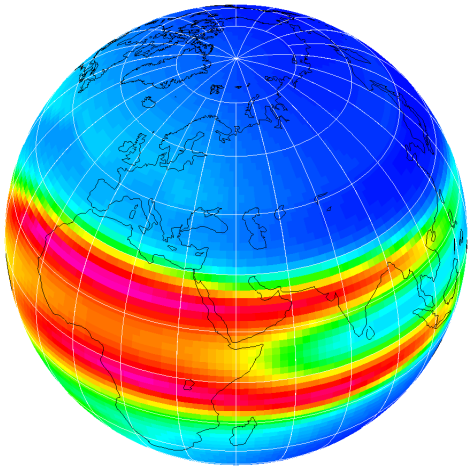
USU Physics-Based Data Assimilation Models

1. Kalman Filter Models of the Ionosphere
   - Gauss-Markov Model (GAIM-GM)
   - Full Physics Model (GAIM-FP)
   - GAIM-Solar Wind Coupling (GAIM-HAF)
2. Ensemble Kalman Filter Model of High-Latitude Electrodynamics & Ionosphere
3. Ensemble Kalman Filter Model of the Thermosphere

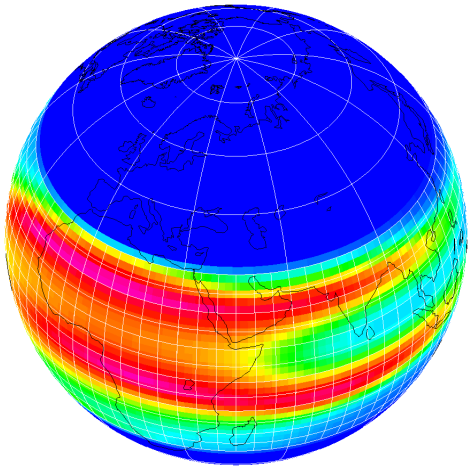
GAIM Basic Approach

We use a physics-based ionosphere or ionosphere-plasmasphere model as a basis for assimilating a diverse set of real-time measurements. GAIM provides both specifications and forecasts on a global, regional, or local grid.

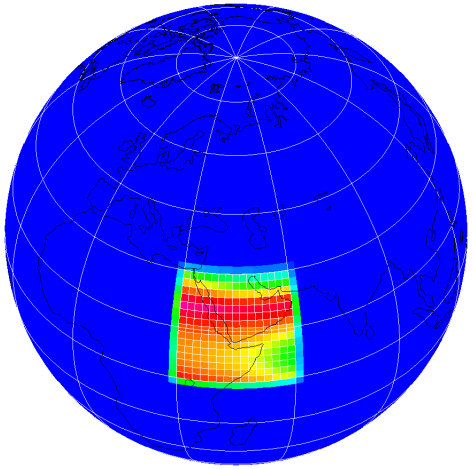
Global



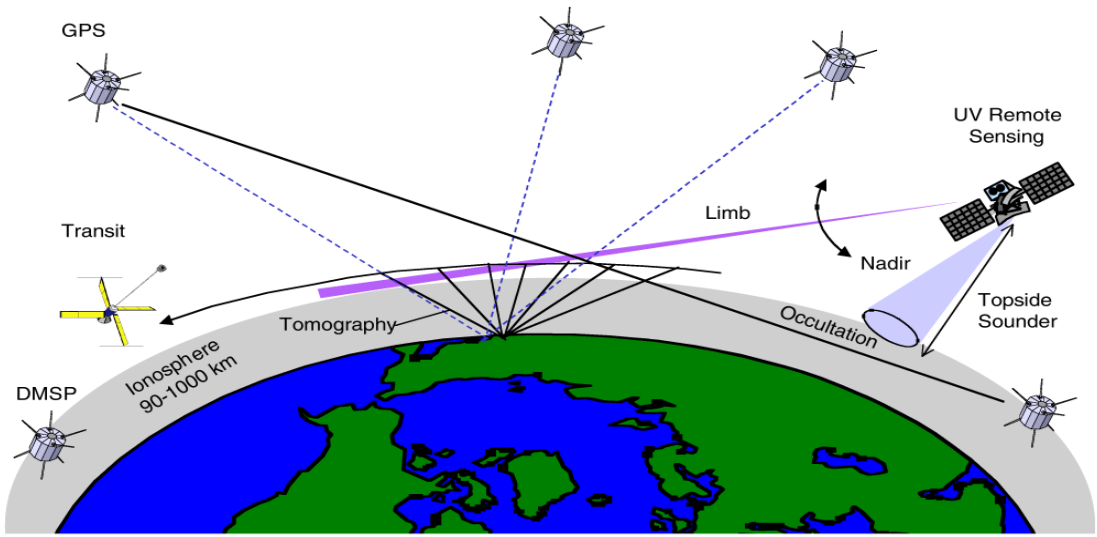
Regional



Local



GAIM Assimilates Multiple Data Sources



- **Data Assimilated Exactly as They Are Measured**
  - **Bottomside N_e Profiles from Digisondes (80)**
  - **Slant TEC from more than 1000 Ground GPS Receivers**
  - **N_e Along Satellite Tracks (4 DMSP satellites)**
  - **Integrated UV Emissions (LORAAS, SSULI, SSUSI)**
  - **Occultation Data (CHAMP, IOX, SAC-C, COSMIC)**

1. Gauss-Markov Kalman Filter Model (GAIM-GM)

Specification & Forecast of the Global Ionosphere

2-8 CPUs

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Gauss-Markov Kalman Filter Model (GAIM-GM)

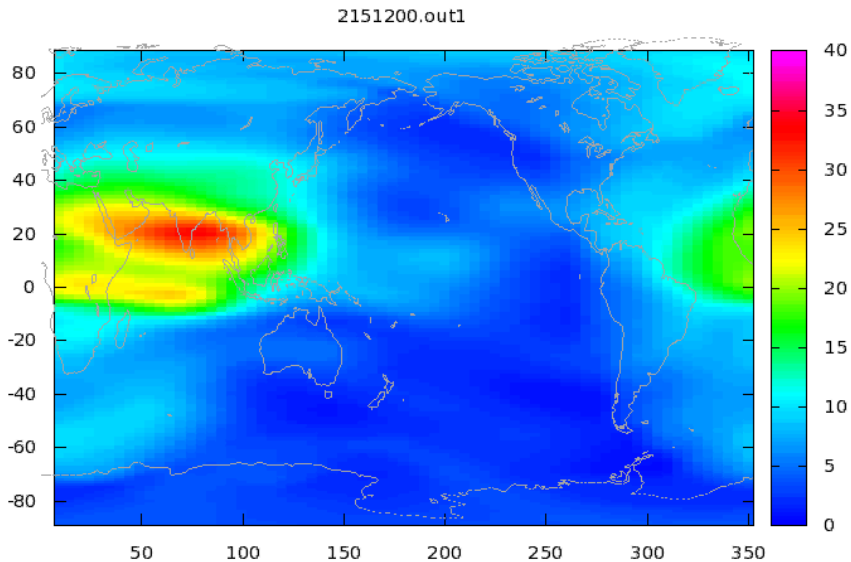
- Specification & Forecast of the Global Ionosphere
- Operational Model at AFWA
- Global Mode
- Regional Mode
- Nested Grid Combines Global and Regional Modes
- 3-hour Latent Data Acceptance Window
- 24-hour Forecast
- Independent Validation by AFRL

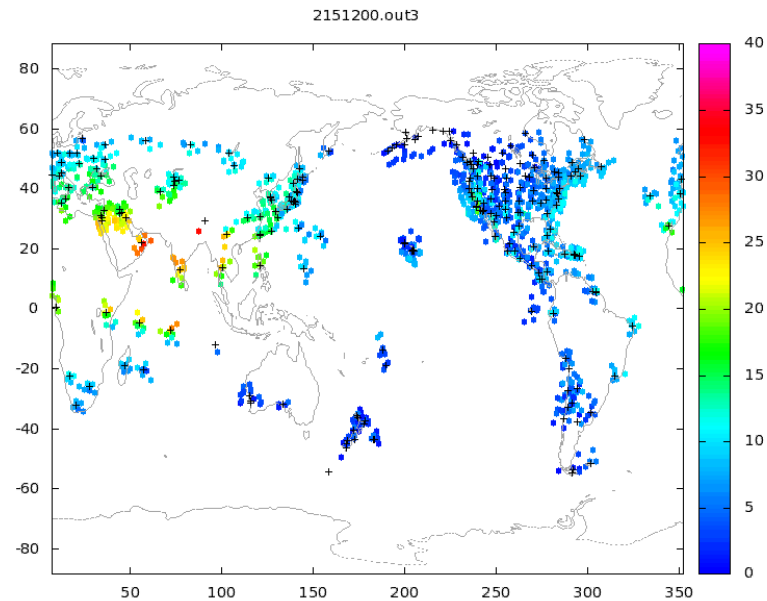
Ionosphere Forecast Model (IFM)

- Global physics-based model
- Provides background ionosphere
- 90 - 1400 km
- 15 - minute output cadence
- O^+, H^+, NO^+, N_2^+, O_2^+, T_e, T_i
  - Only uses N_e
- Kalman solves for deviations from background

GAIM-GM global Run

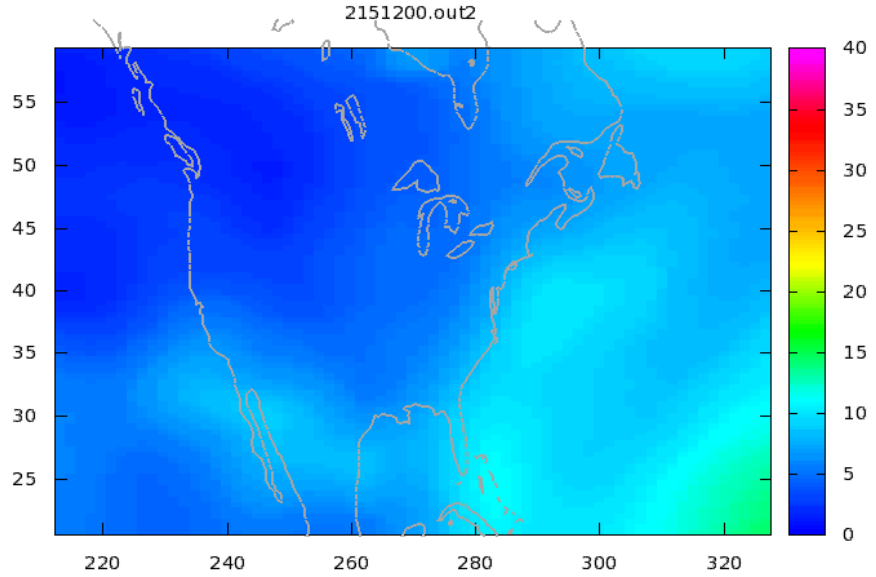
- 357 global TEC stations (IGS network) used in real-time at USU Space Weather Center
- Up to 10,000 measurements assimilated every 15- min

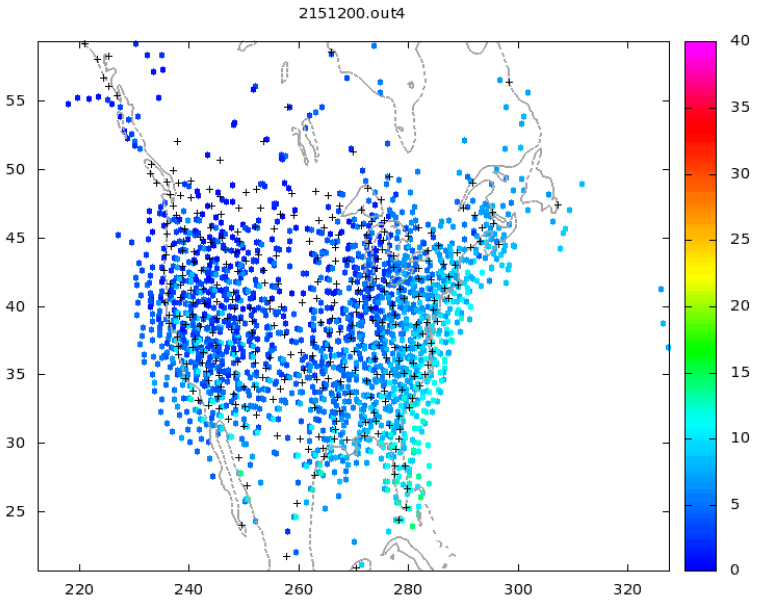




GAIM-GM regional (High Resolution) Run:

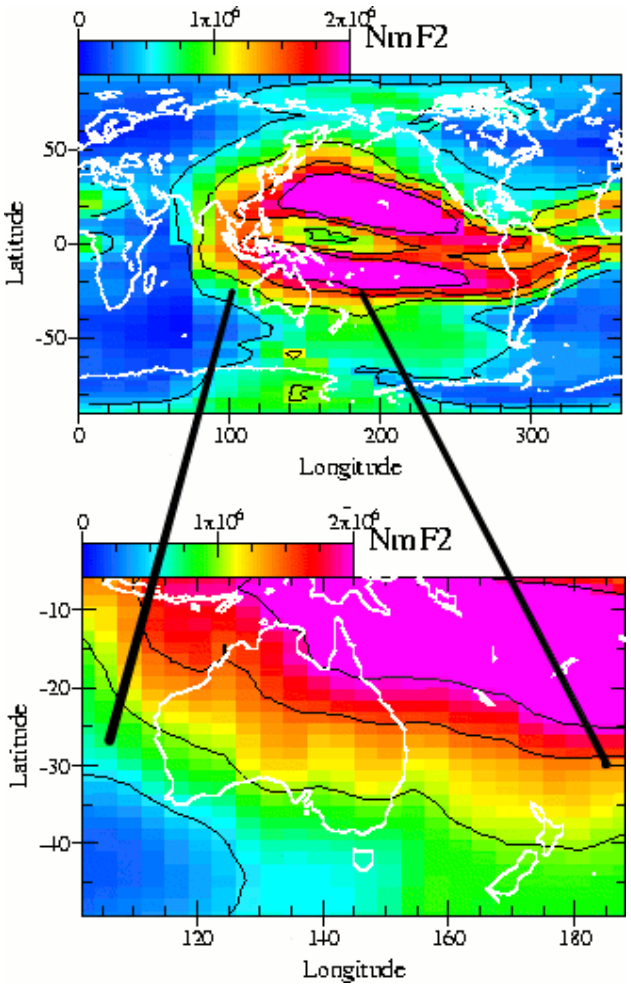
- 424 USTEC stations (CORS network) used in real-time at USU Space Weather Center
- Up to 10,000 measurements assimilated every 15-min





GAIM-GM Nested Grid Capability

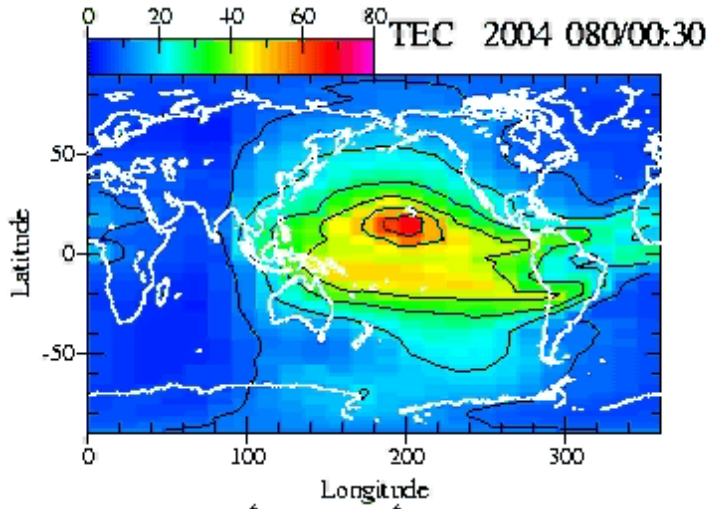
- Improved Spatial Resolution
  - 1˚ Latitude (variable)
  - 3.75˚ Longitude (variable)
- Usefulness Depends on Data
- Capability Since 2004 in GAIM-GM Operational Model
- In 2004 Run - 11 ionosondes & 15 GPS in Nested Grid Region
- Captures Edge of Anomaly

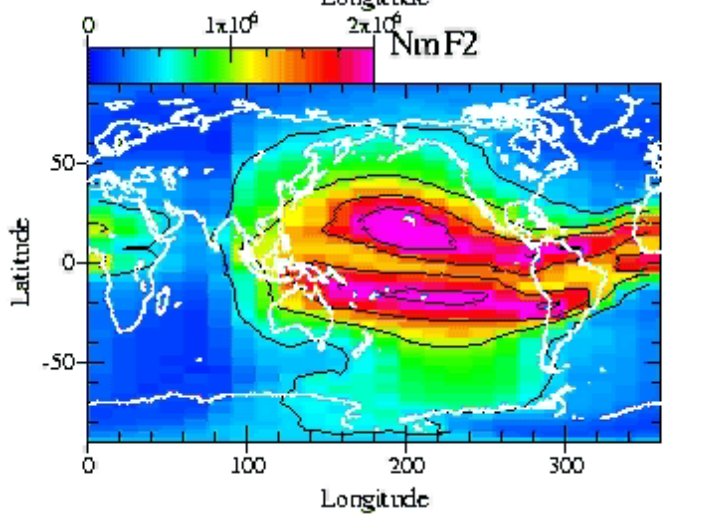


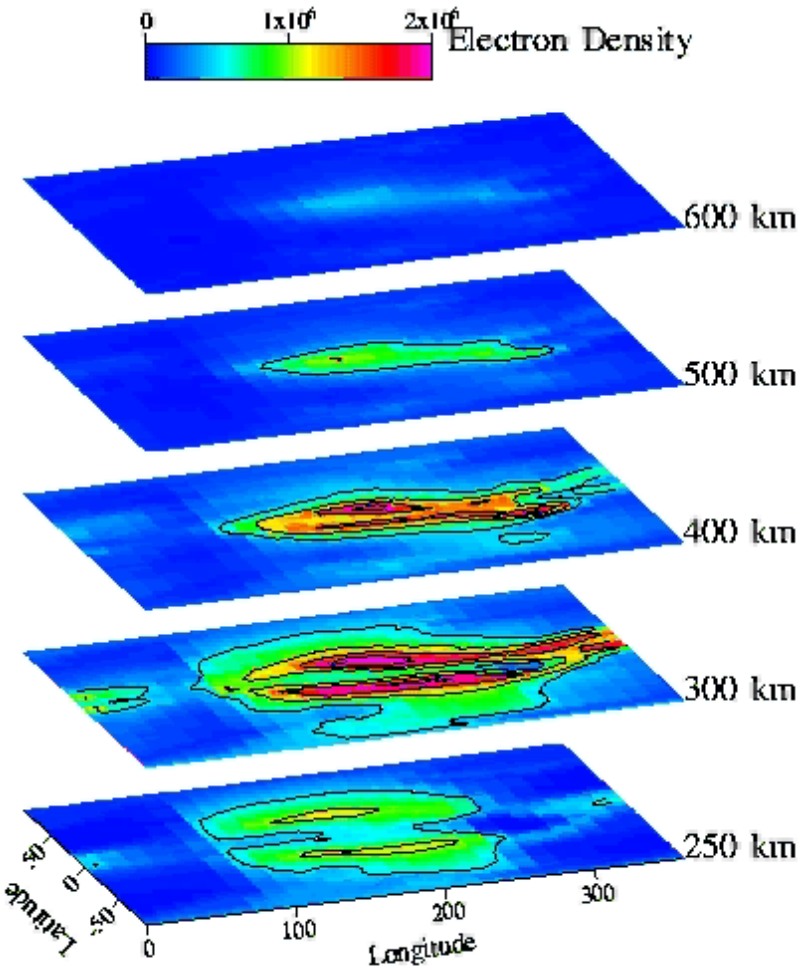
GAIM-GM Example
Global Mode

- **30-Day Run**
- **Equinox (Days 80 - 110 of 2004)**
- **Data Assimilated**
  - **Slant TEC from 162 GPS Ground Receivers**
  - **Bottom-side Ne Profiles from 17 Digisondes**
  - **In situ Ne from DMSP Satellites F13, F14, F15**

GAIM-GM Example
Global Mode





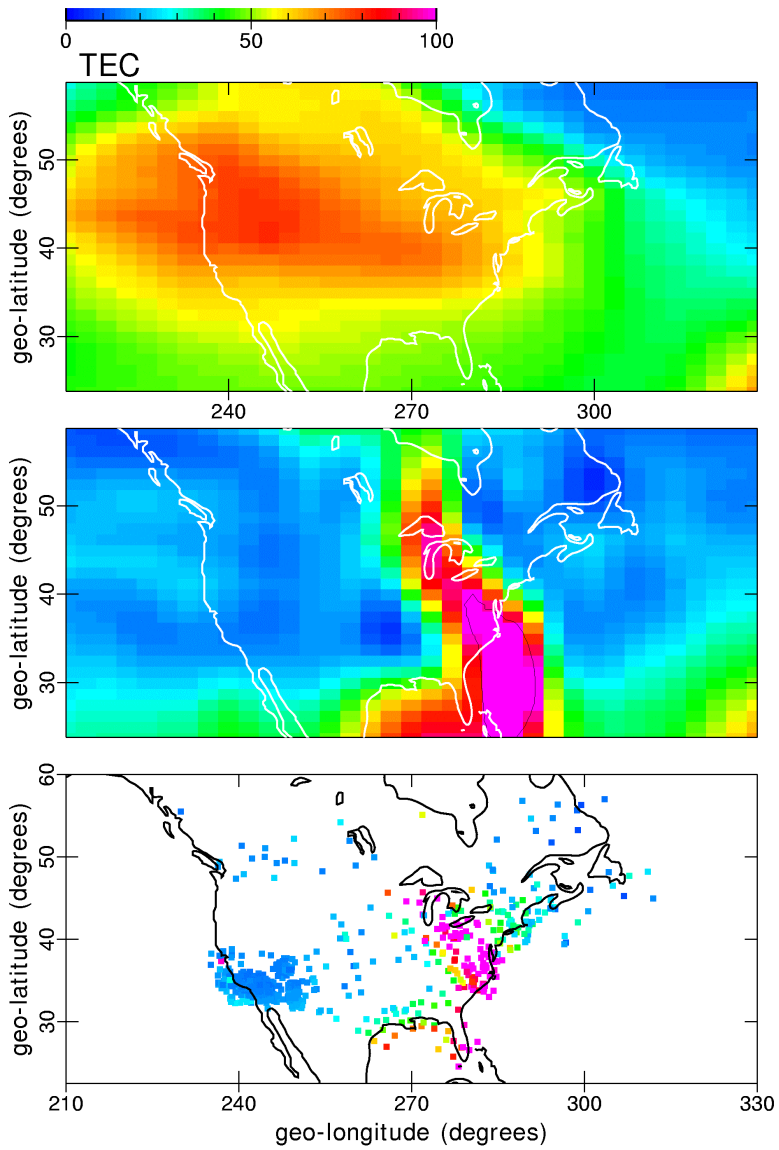


GAIM-GM Example
Regional Mode

- 3-D Ionospheric N_e Reconstruction over North America
- Large Geomagnetic Storm on November 20-21, 2003
- GPS Ground TEC Measurements from more than 300 GPS Receivers (CORS GPS Network + other) over the continental US and Canada
- 2 Ionosondes at Dyess and Eglin

→ Observe large TEC Enhancements over the Great Lakes during November 20, 2003 @ 2000 UT.

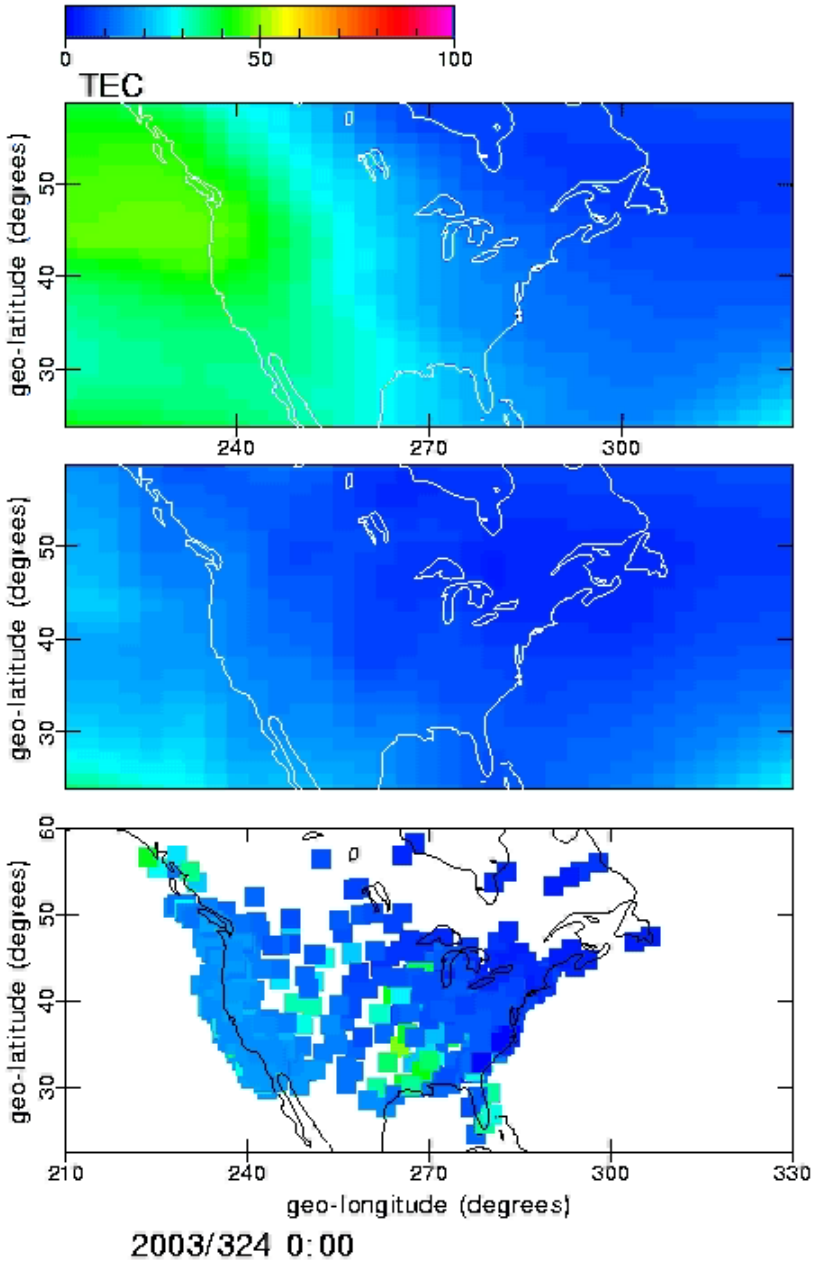
GAIM-GM regional Run: Halloween Storm



IFM Alone

GAIM-GM Reconstruction

About 2000 Slant TEC Values are Assimilated every 15 min



IFM

Kalman Filter

About 2000 Slant TEC Values are Assimilated every 15 min

2. Full Physics Kalman Filter Model (GAIM-FP)

Specification & Forecast of the Global Ionosphere

30 CPUs

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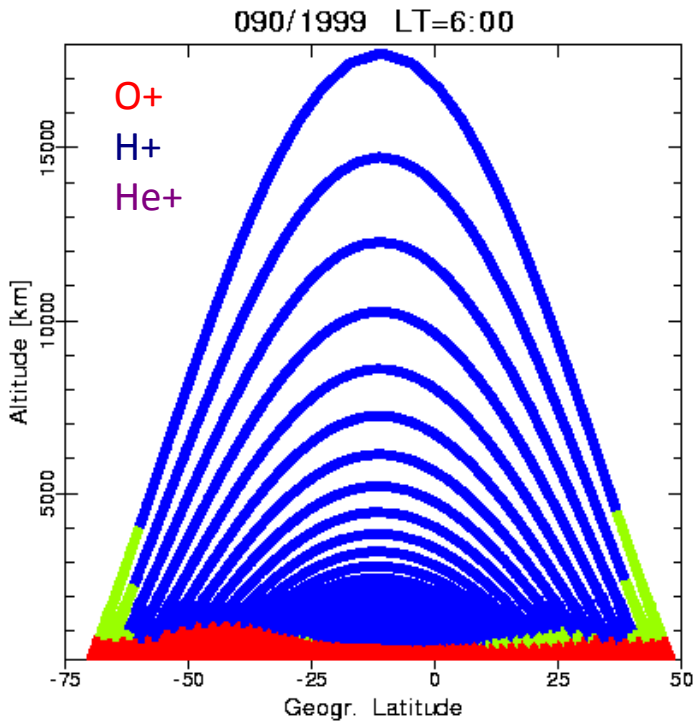
GAIM-FP

- Ensemble Kalman Filter
- Physics-based Ionosphere-Plasmasphere Model
- Same 5 Data Sources as Gauss-Markov Model
- Altitude, Latitude, Longitude Grids Set by User

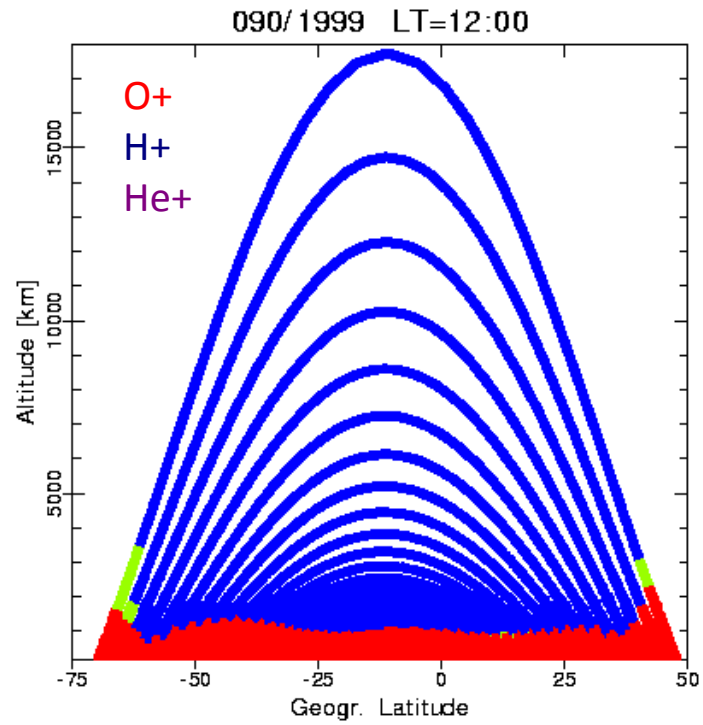
Ionosphere/Plasmasphere Ion Composition

American Sector (292.5° Longitude)

Early Morning

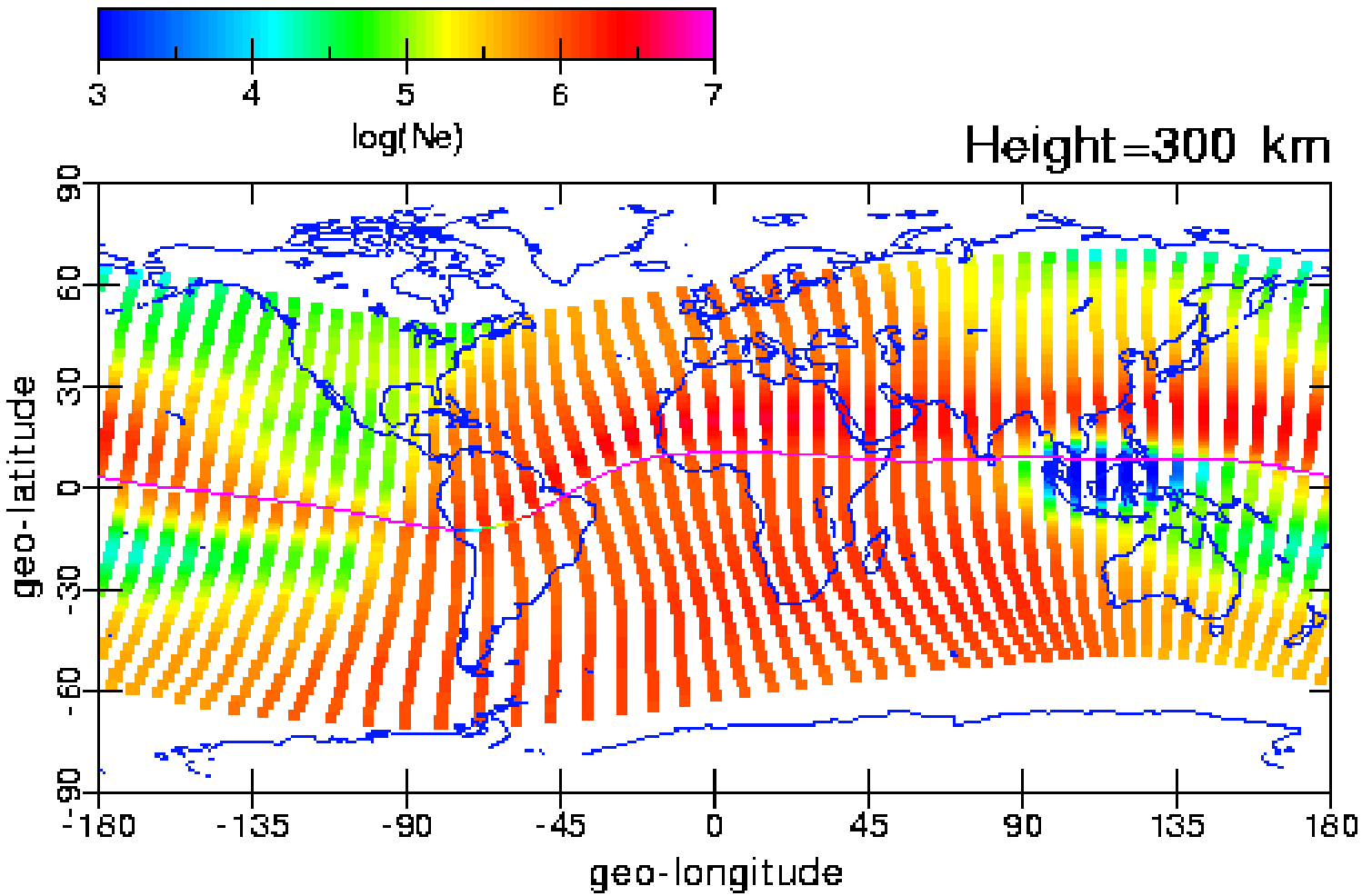


Noon



All three ions are needed in the topside ionosphere and plasmasphere.

IGRF Magnetic Field



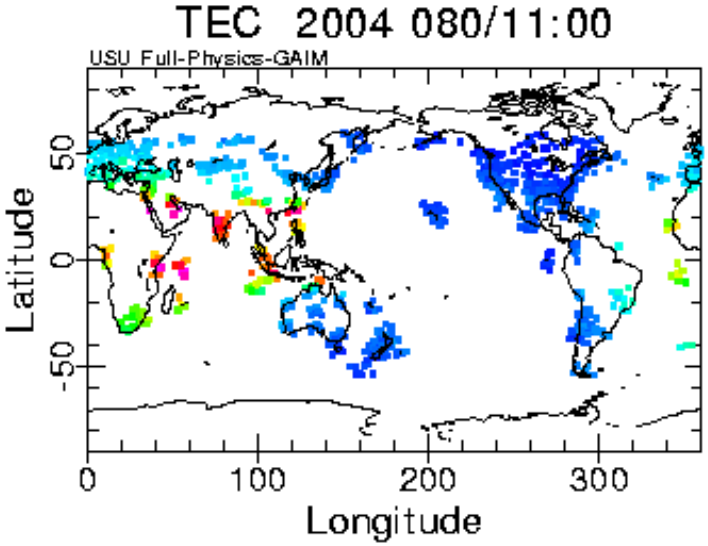
GAIM-FP Output

- Continuous Reconstruction of Global N_e Distribution
  - Ionosphere-Plasmasphere
  - 90-30,000 km
- Quantitative Estimates of the Accuracy of Reconstruction
- Auxiliary Parameters
  - N_mF_2, h_mF_2, N_mE, h_mE
  - Slant and vertical TEC
- Model Drivers
  - Electric Fields
  - Global Neutral Winds
  - Global Neutral Composition

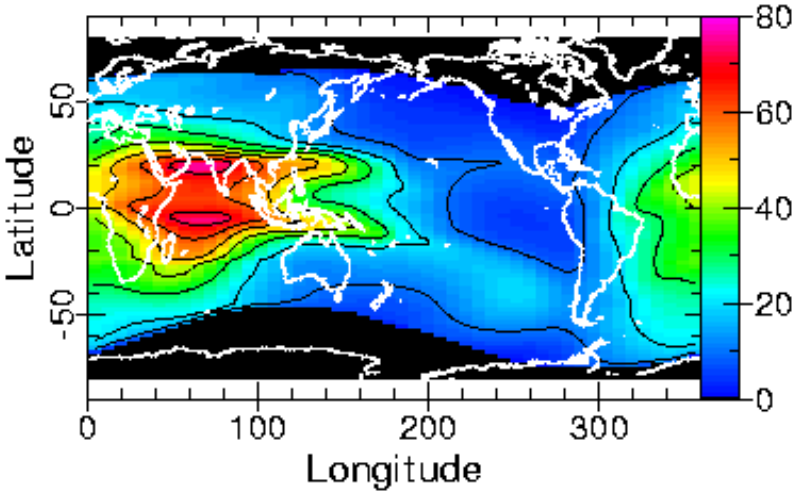
GAIM-FP Example
Global Mode

- Several Days in March/April of 2004
- Magnetically Quiet Period
- Data Assimilated
  - Slant TEC from 162 GPS Ground Receivers
- Use Ionosonde Data for Validation
- 3-D Electron Density Reconstruction
  - Neutral Wind and Electric Field

Full-Physics-Based Kalman Filter Example



GPS/TEC Data: Slant TEC Values have been mapped to the Vertical Direction



GAIM Specification of Global TEC Distribution

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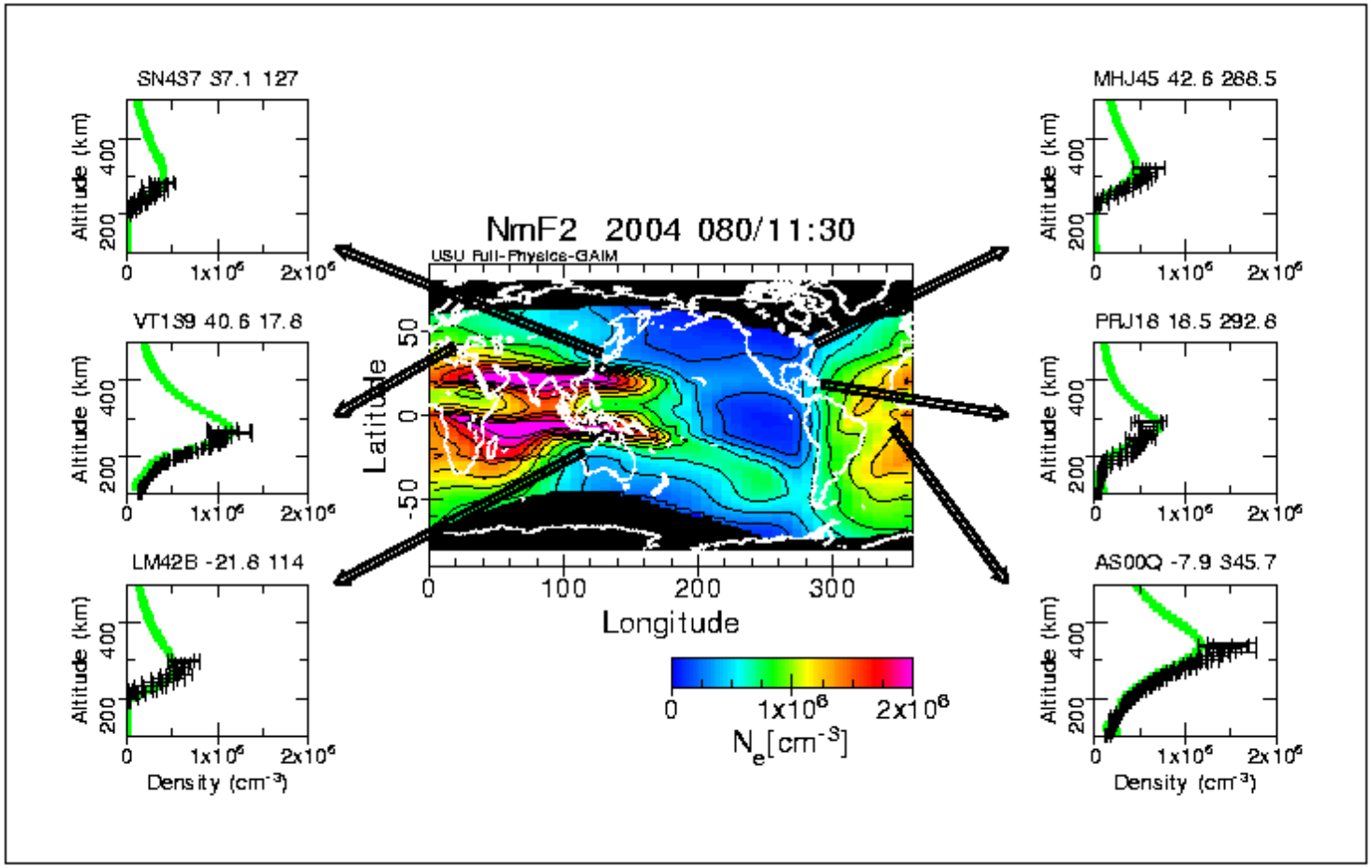
Comparison with Ionosonde Data



Ionosonde Data were NOT assimilated!

3. Ensemble Kalman Filter for High-Latitude Electrodynamics & Ionosphere (GAIM-HL)

High-Resolution Specification of Convection, Precipitation, Currents & Ionosphere

30 CPUs

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Physics-Based Model Behind GAIM-HL

Time-Dependent Ionosphere Model

- 3-D Density Distributions (NO^+,O_2^+,N_2^+,O^+,H^+,He^+)
- 3-D T_e and T_i Distributions
- Ion Drifts Parallel & Perpendicular to B
- Hall & Pedersen Conductances

M-I Electrodynamics Model

- MHD Transport Equations & Ohm's Law
- Alfven Wave Propagation
- Active Ionosphere
- 10 km & 5 sec Resolutions
- Potential, E-field, Currents, Joule Heating

Magnetic Induction Model

- Calculates B Perturbations in Space & on Ground
- Includes Earth's Induction Effect

Data Assimilated by GAIM-HL

- Ground Magnetic Data from 100 Sites
- Cross-Track Velocities from 4 DMSP Satellites
- Line-of-Sight Velocities from 9 SuperDARN Radars
- In-situ Magnetic Perturbations from the 66 IRIDIUM Satellites

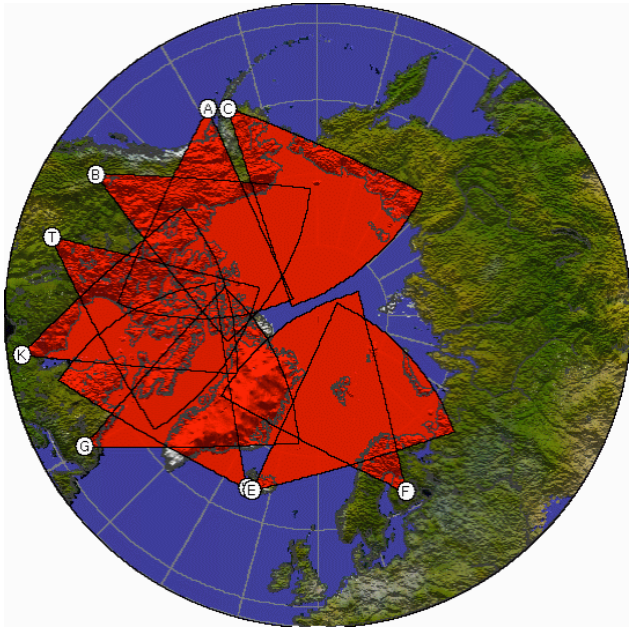
Output of GAIM-HL (High Resolution)

- Electric Potential
- Convection Electric Field
- Energy Flux and Average Energy of Precipitation
- Field-Aligned and Horizontal Currents
- Hall and Pedersen Conductances
- Joule Heating Rates
- 3-D Electron and Ion Densities
- 3-D Electron and Ion Temperatures
- TEC
- Ground and Space Magnetic Disturbances

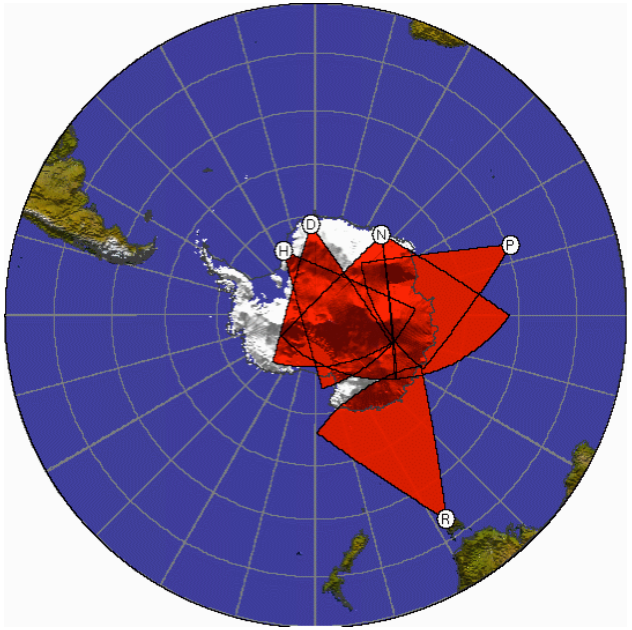
Assimilation of SuperDARN Data

- 9 Coherent Scatter Radars in the Northern High Latitudes
- 70% Coverage of Area
- Measures Line-of-Sight Velocities of Plasma Irregularities
- Line-of-Sight Velocities are Assimilated

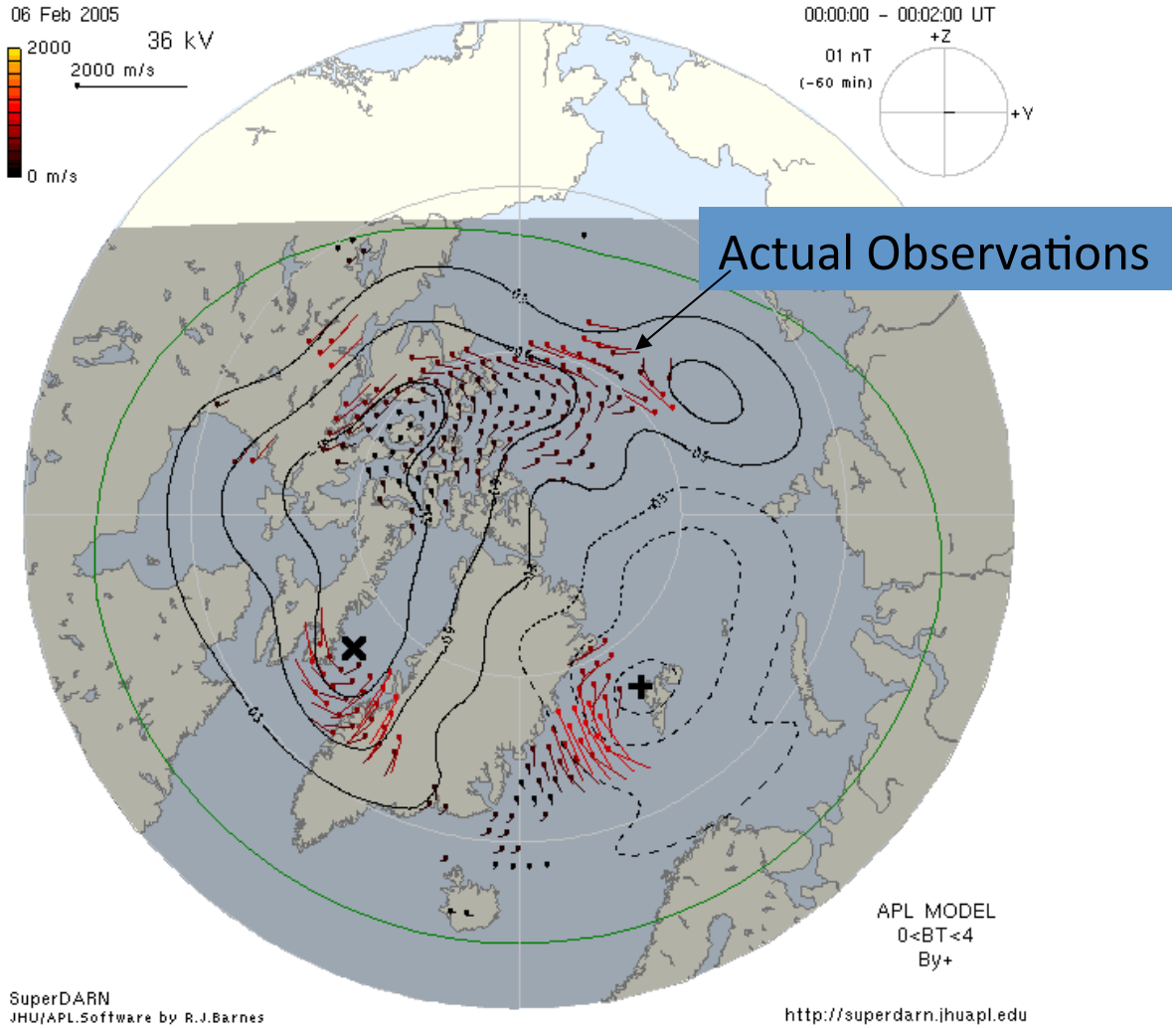
North



South

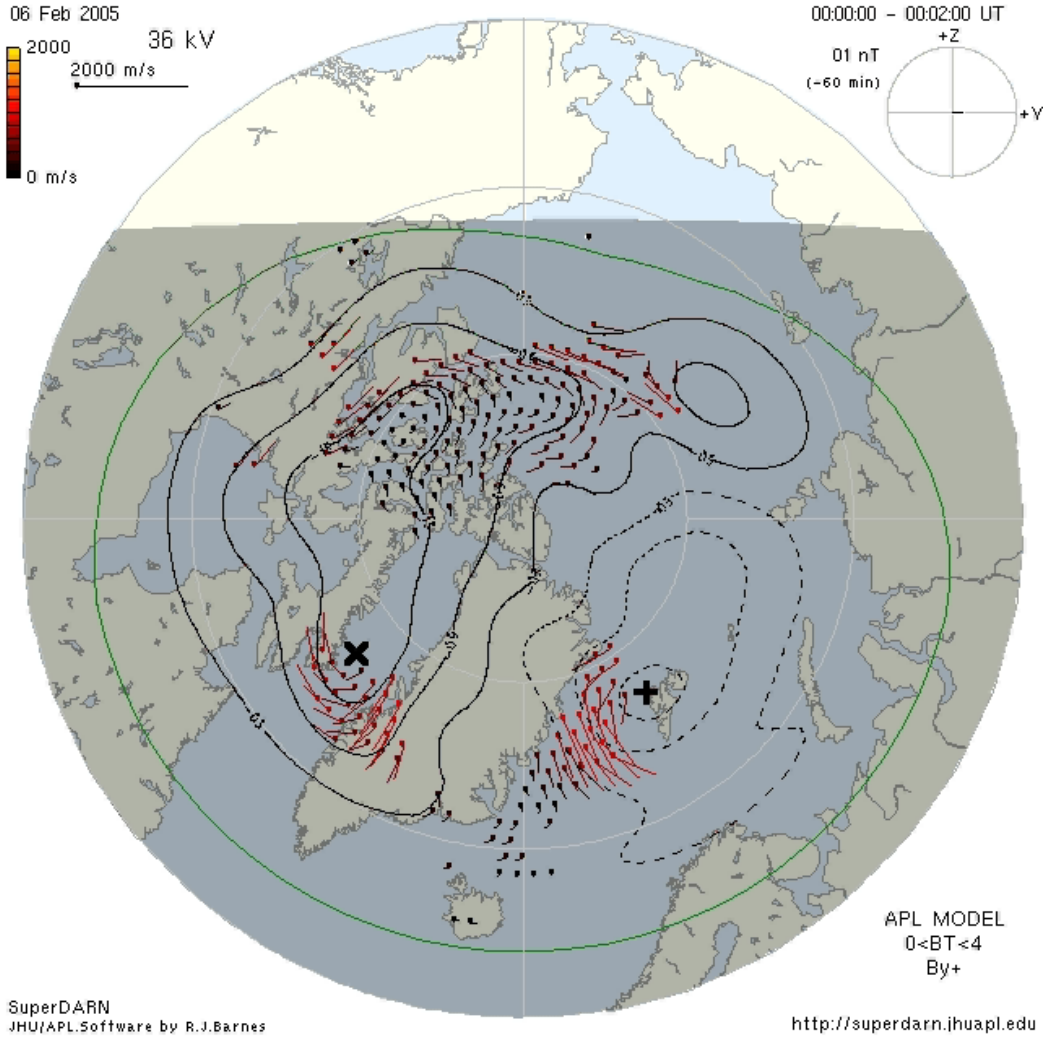


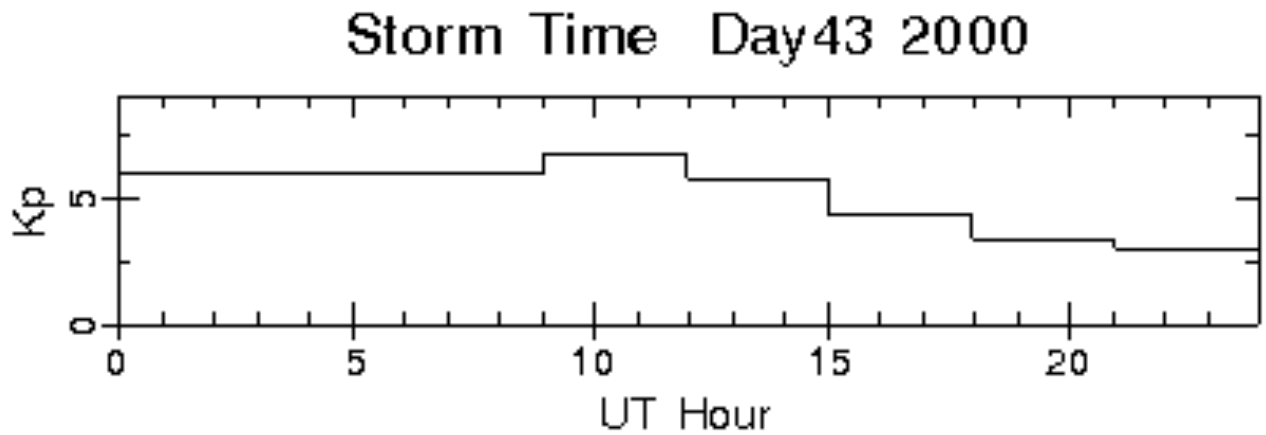
SuperDARN Data Coverage



SuperDARN Data Coverage

The actual data coverage is constantly changing

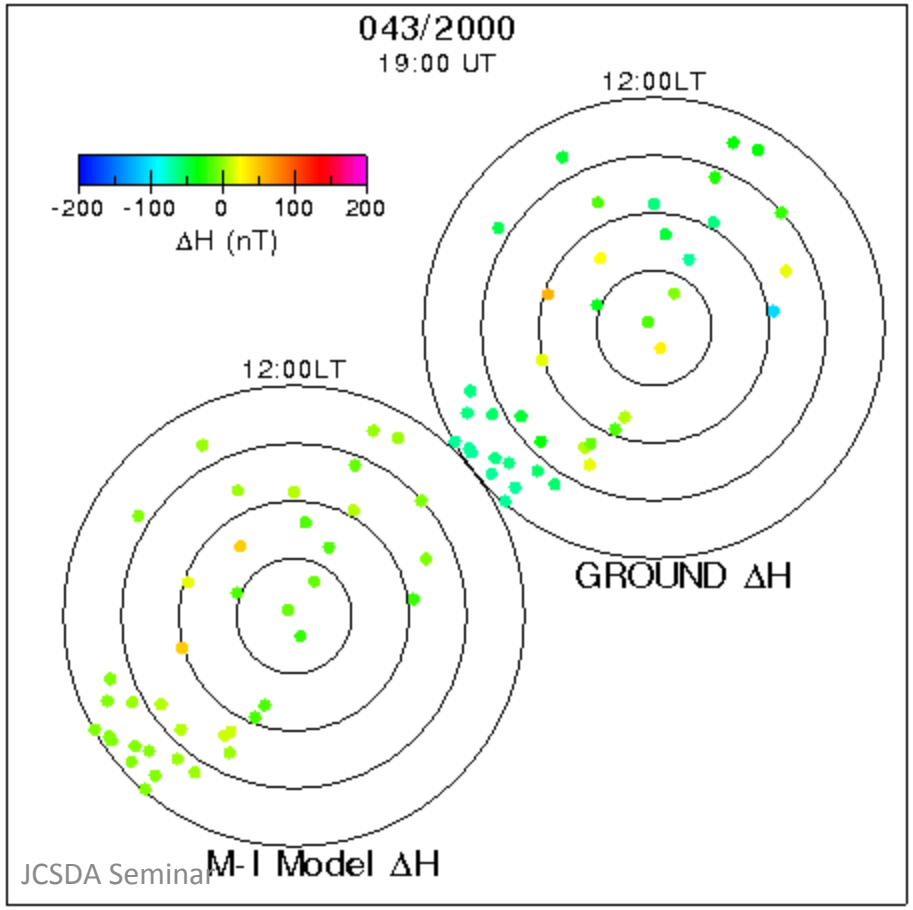




Kp = 6 – 7
ΔΦ = 90 kV

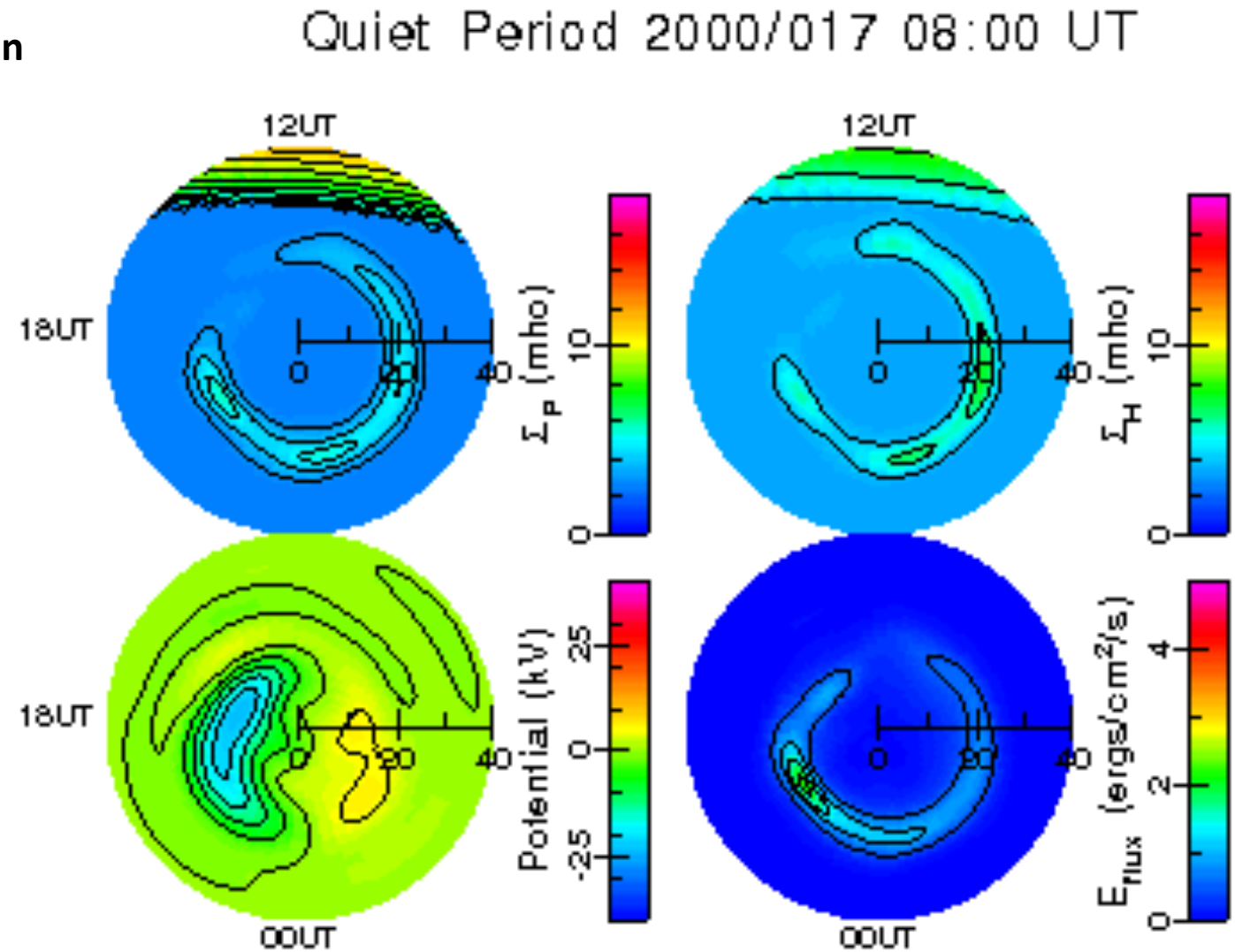
Δt = 10 sec
Assim step = 5 min

ACE data
40 magnetometers



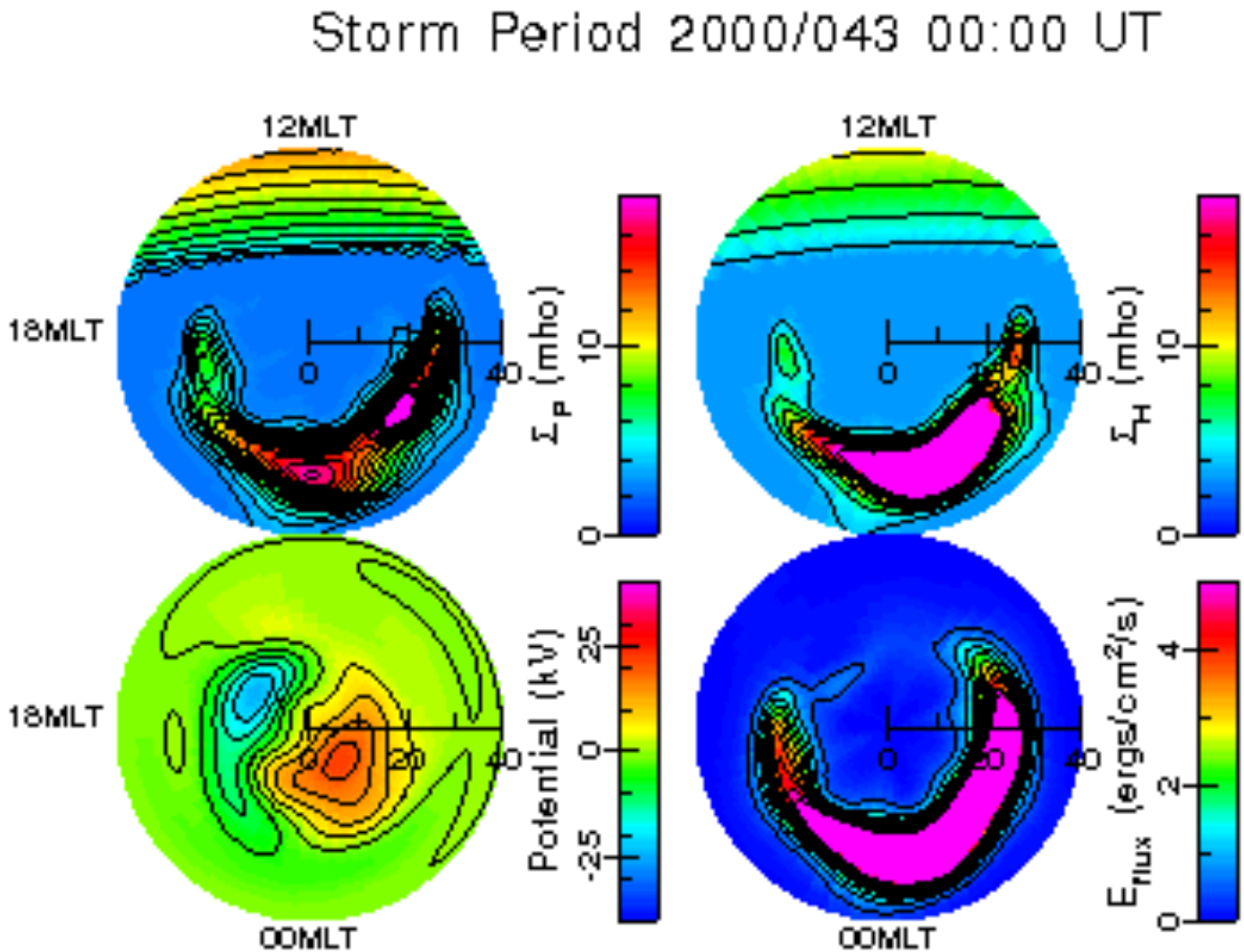
Kp = 1
Δt = 10 sec
Assim step = 5 min

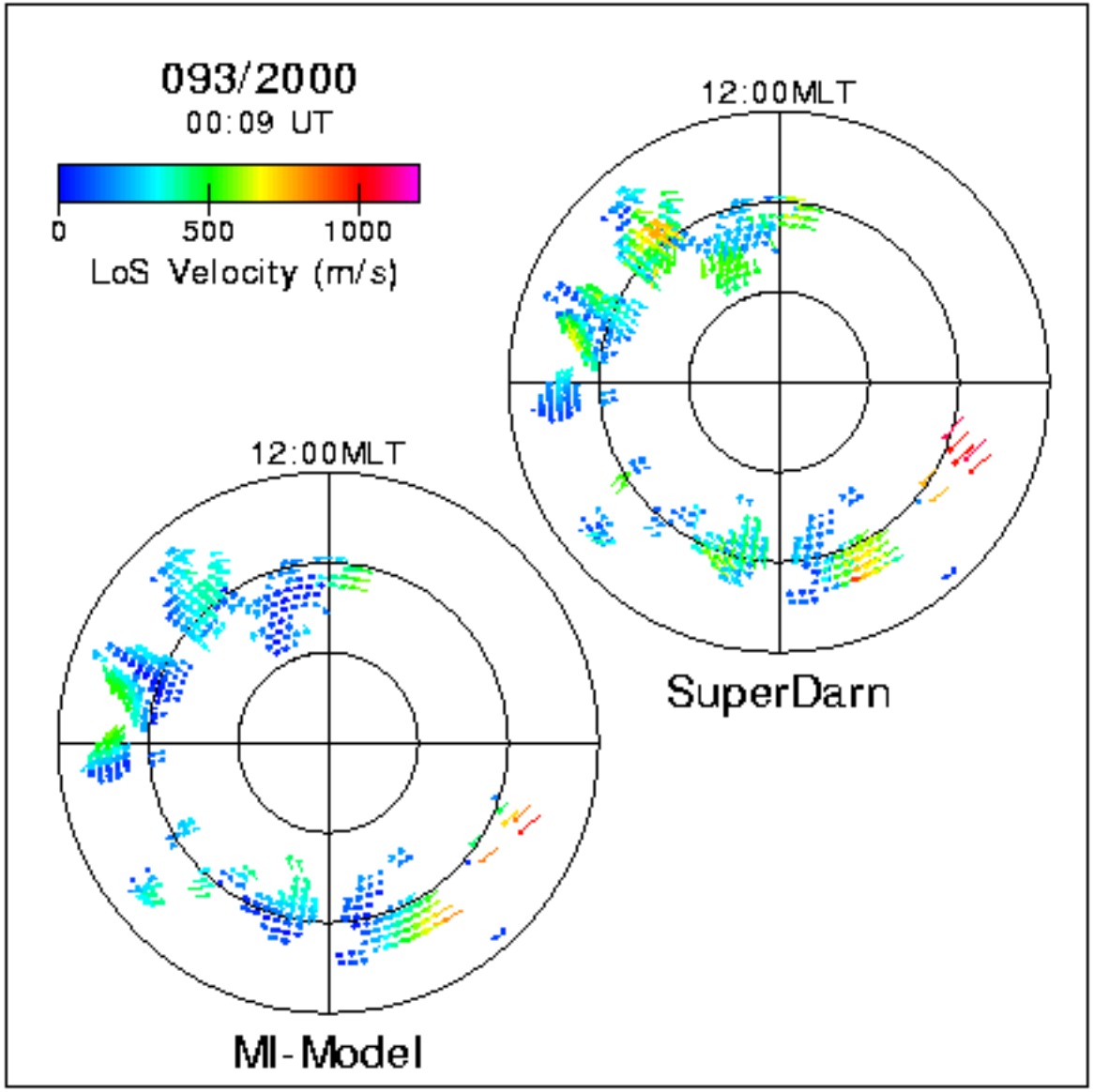
ΔΦ = 30 kV



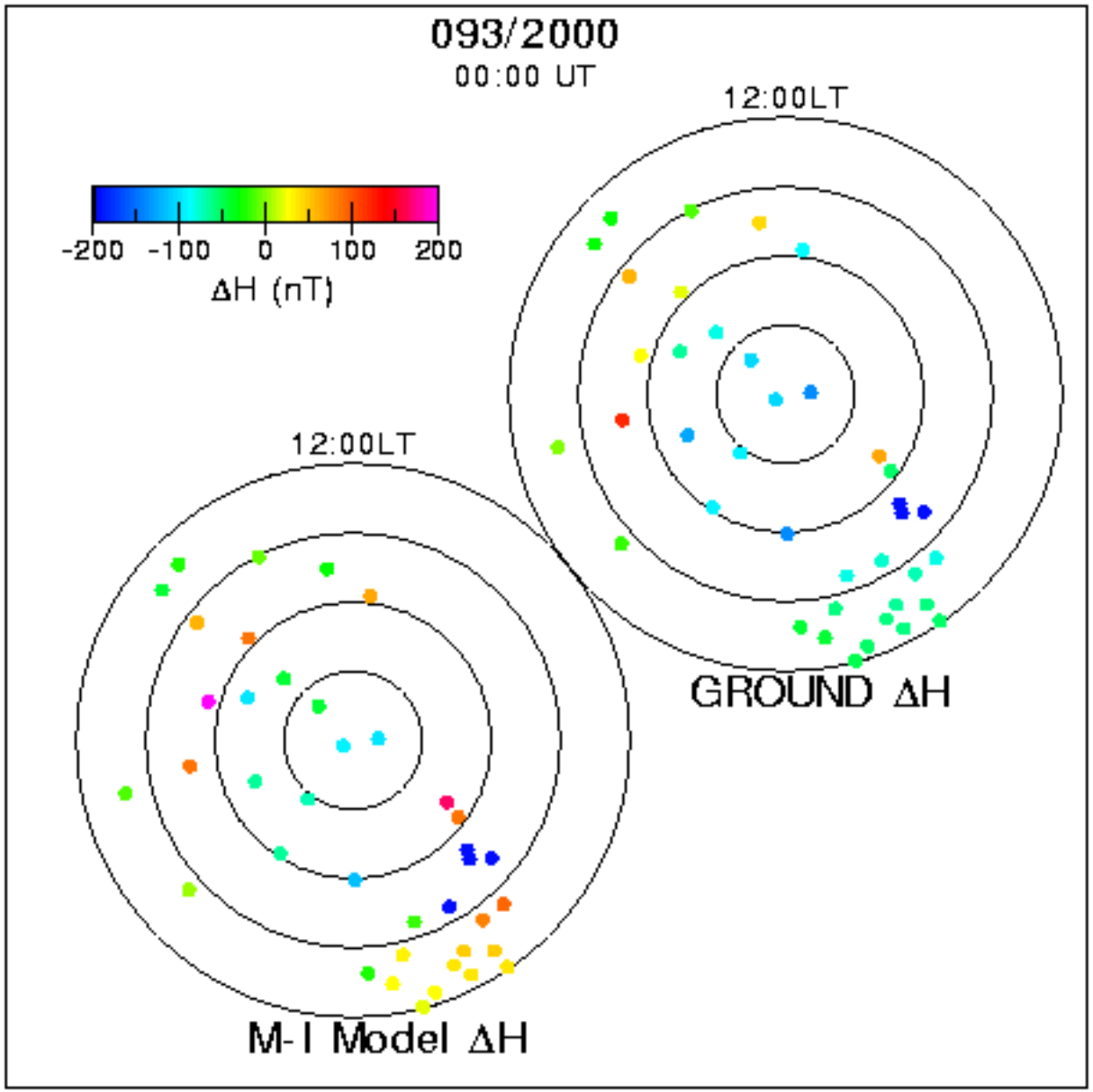
Kp = 6 - 7
Δt = 10 sec
Assim step =

ΔΦ = 90 kV

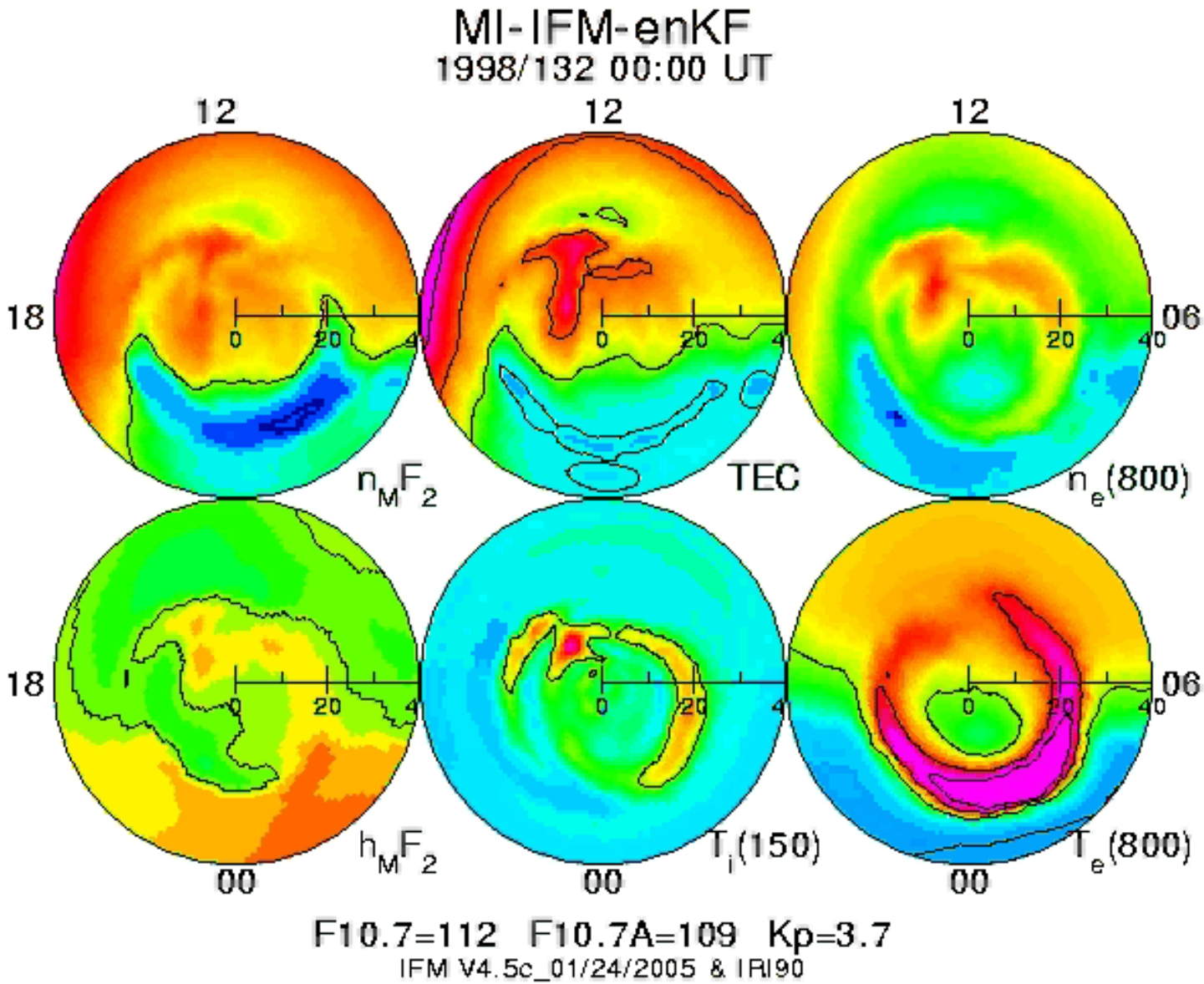




Ensemble Kalman Filter



Ensemble Kalman Filter



"Bringing The Pieces Together"