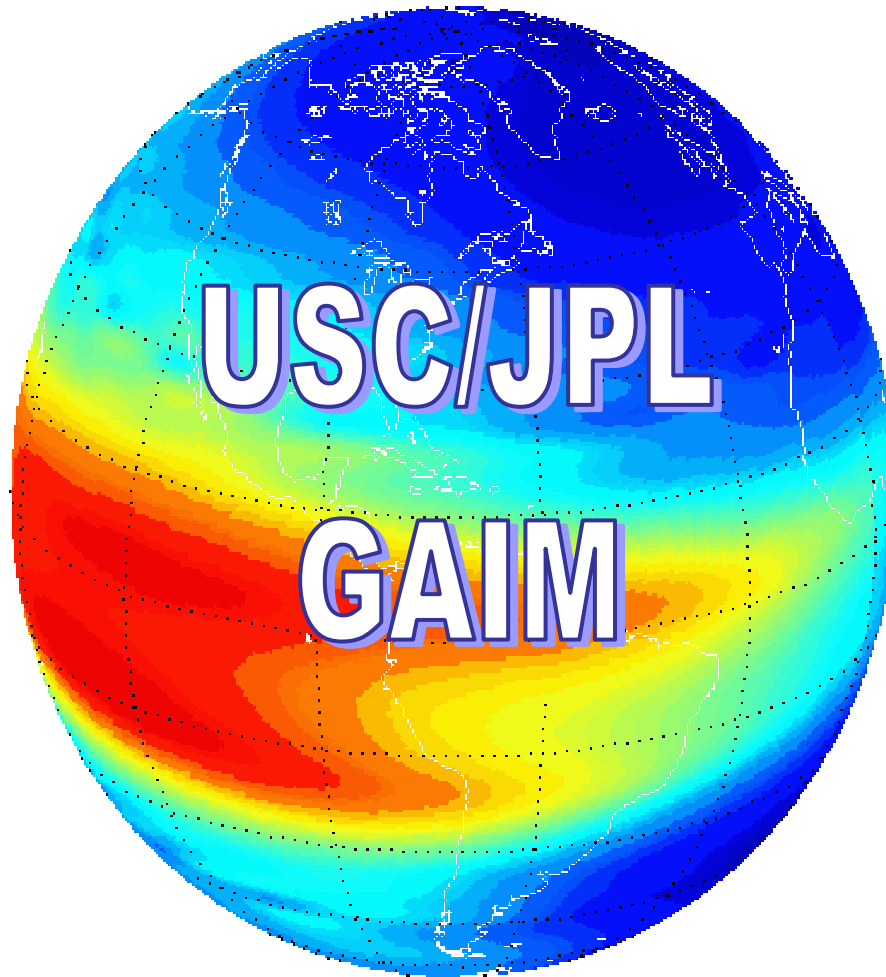# Global Ionospheric Data Assimilation &
IGS Collaboration with Space Weather Programs

USC/JPL GAIM

Brian Wilson, JPL
Chunming Wang, USC
George Hajj, JPL, USC
Xiaoqing Pi, JPL, USC
Lukas Mandrake, JPL
Attila Komjathy, JPL
Anthony Mannucci, JPL

IGS Workshop, Berne, Switzerland, March 1-5, 2004

Activities of the JPL Ionosphere Group

- **On-going GIM work**
  - Submit rapid and final GIM TEC maps for IGS combined ionosphere products

- **FAA WAAS & SBAS analysis**
  - Error bounds for Brazilian sector, increasing availability

- **Ionospheric Storm Studies (using GPS + other data)**
  - Oct & Nov 2003 storms

- **GAIM: 3D Global Assimilative Ionosphere Model**
  - Daily GAIM runs since March 2003

- **Global Ground Observatory for Space Weather**
  - In U. S. Decadal Plan for Aeronomy, NSF initiative

USC/JPL GAIM

Broader Space Weather Context

- **2D GIM TEC maps are mature**
  - Many global & regional applications (not always free)

- **Ionospheric Storm Studies: Magnetosphere-Ionosphere Coupling**
  - GPS now an accepted data type for **science** (at last)
  - Combine GPS with other measurement types

- **Era of 3D Data Assimilation Has Arrived**
  - Ground GPS TEC data: 150+ hourly sites
  - Space data: COSMIC GPS occultations & DMSP UV scans

- **Global Ground Observatory for Space Weather**
  - Yet Another Global Sensor Network ("YAGSN")
  - Opportunity for IGS Contribution & Benefit
  - Challenge of integrating ionosphere, troposphere, & geodesy requirements
 - IGS Ionosphere part of larger International Space Weather Program

USC/JPL GAIM

U.S. Space Weather Program

- **Coordinated effort involving NSF, NASA, NOAA, & DoD**

- **Operational Ionospheric Nowcast & Forecast**
  - Driven by DoD
  - Global ionospheric specification: Background density & irregularities
  - 3 to 72 hour forecast

- **Sun-Earth Connections Modeling ("Sun to Mud")**
  - Solar, Magnetospheric, Ionospheric, & Climate Modeling
  - Coupled Models

- **NASA's Living With a Star**
  - Magnetospheric Mappers
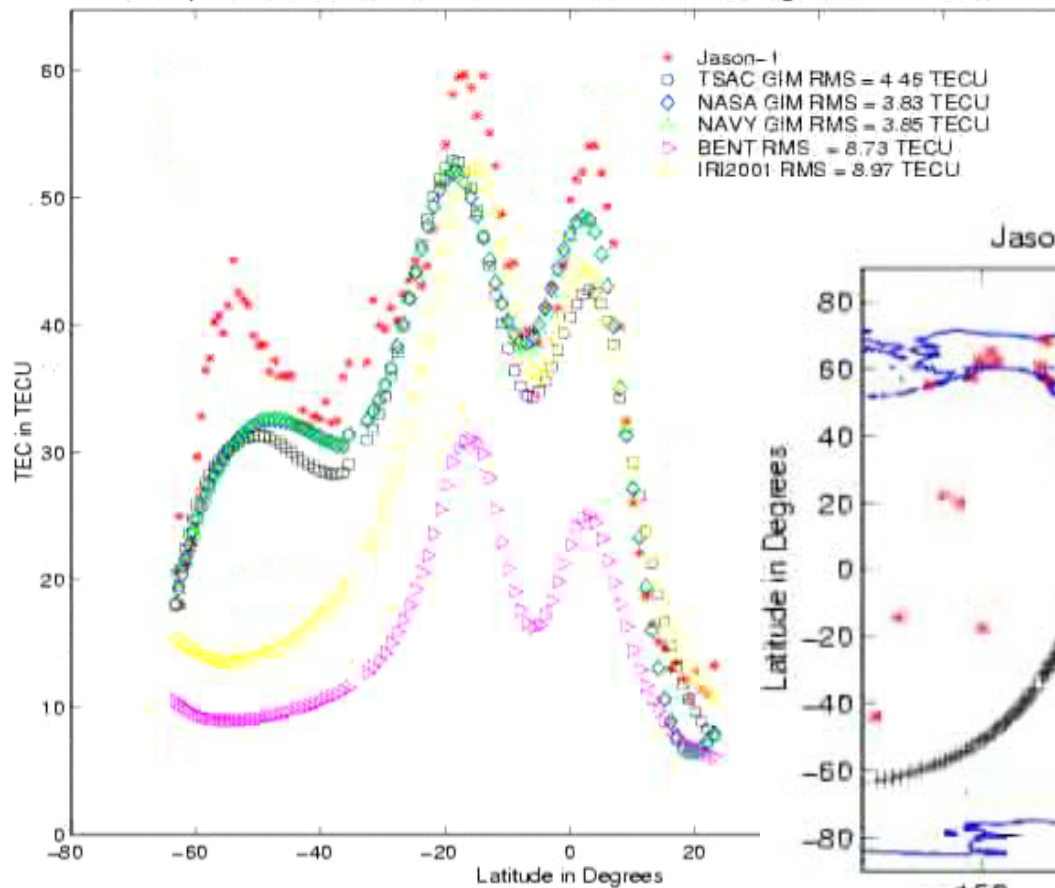 - Ionospheric Mappers

USC/JPL GAIM

AF-Geospace, Courtesy of Greg Ginet, AFRL
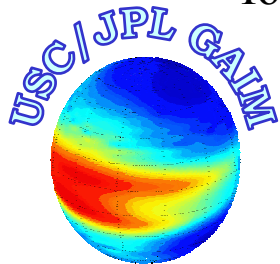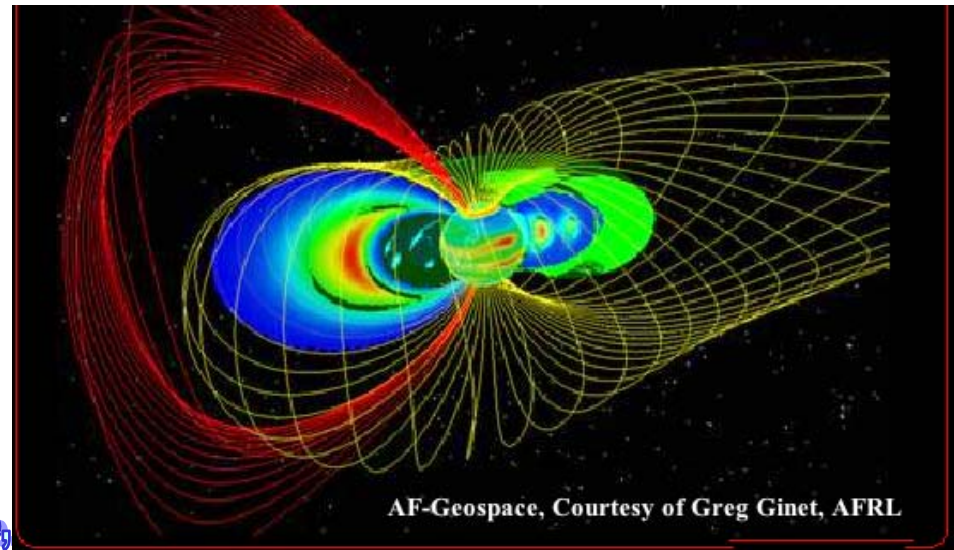
On-going JASON Validation of JPL GIM

Ionospheric Product Validation for 20031028 Using Jason-1 Track 7

Legend:
- Jason-1
- TSAC GIM RMS = 4.45 TECU
- NASA GIM RMS = 3.83 TECU
- NAVY GIM RMS = 3.85 TECU
- BENT RMS = 8.73 TECU
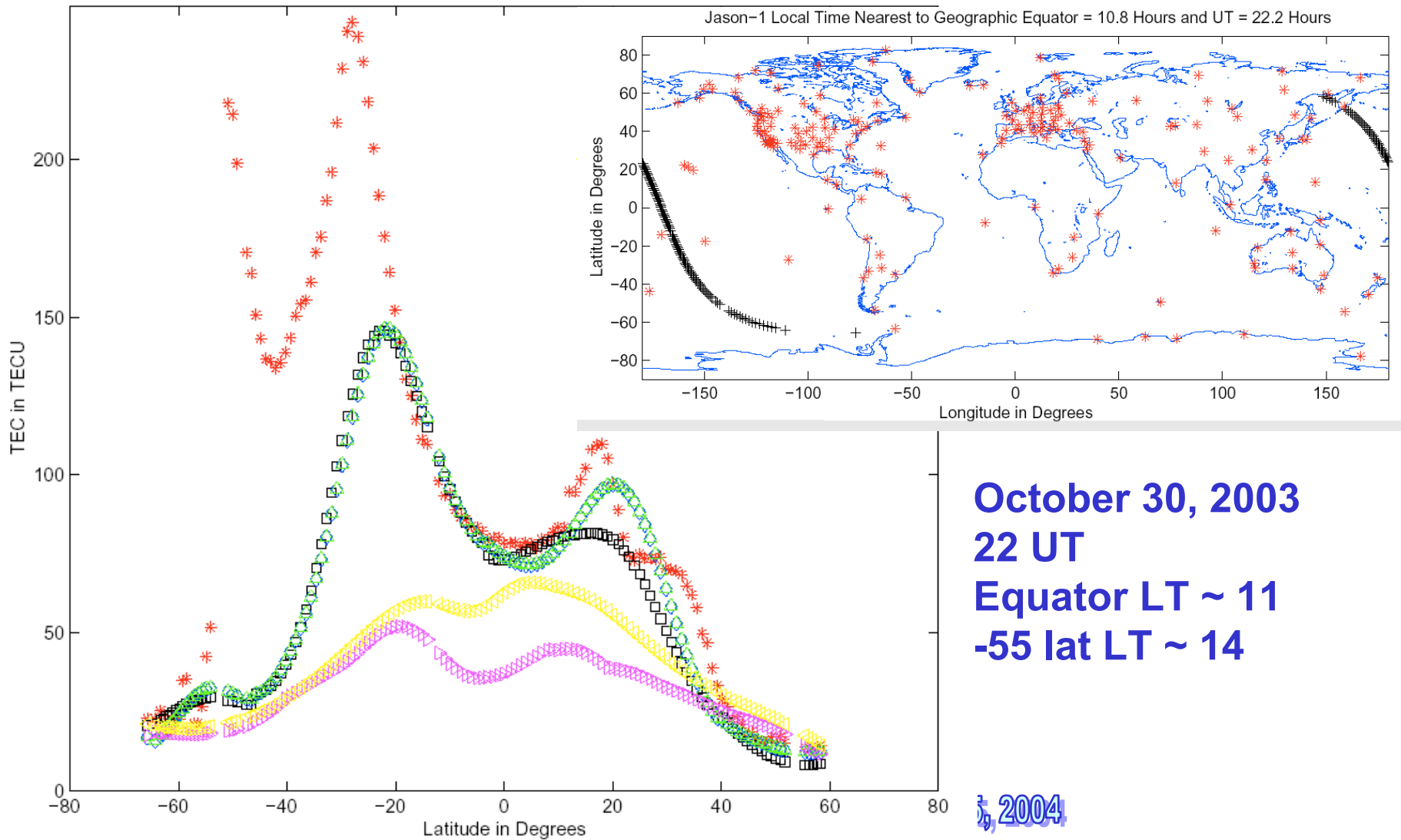- IRI2001 RMS = 8.97 TECU

Compute daily statistics for (GIM - JASON) differences

Jason-1 Local Time Nearest to Geographic Equator = 23.4
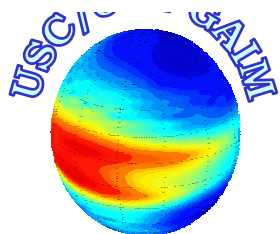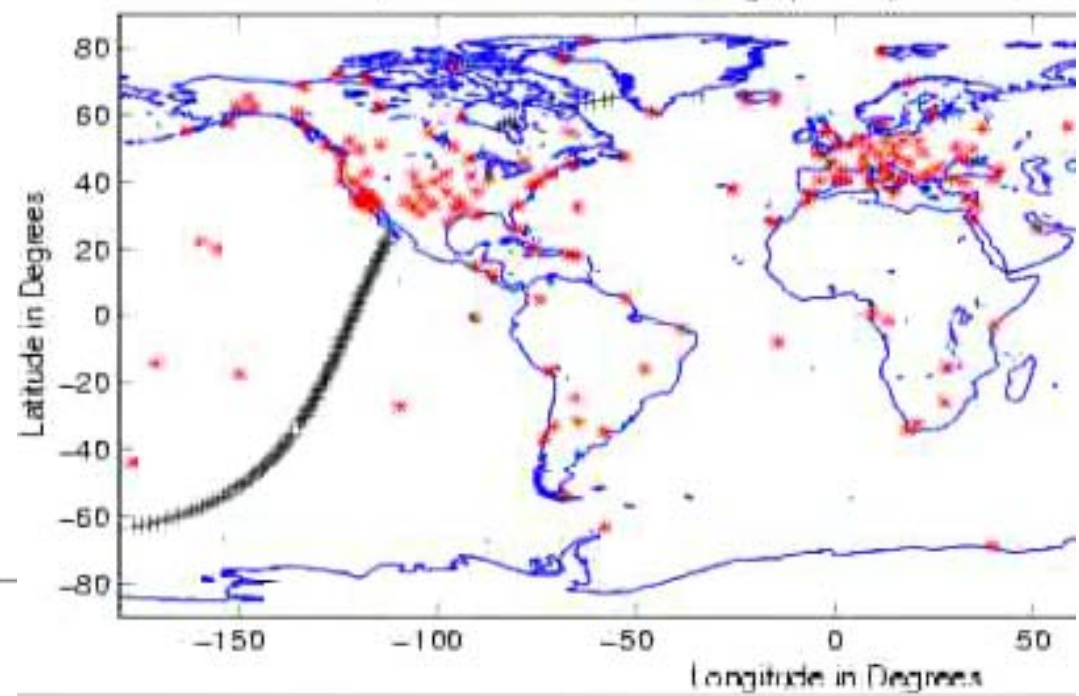
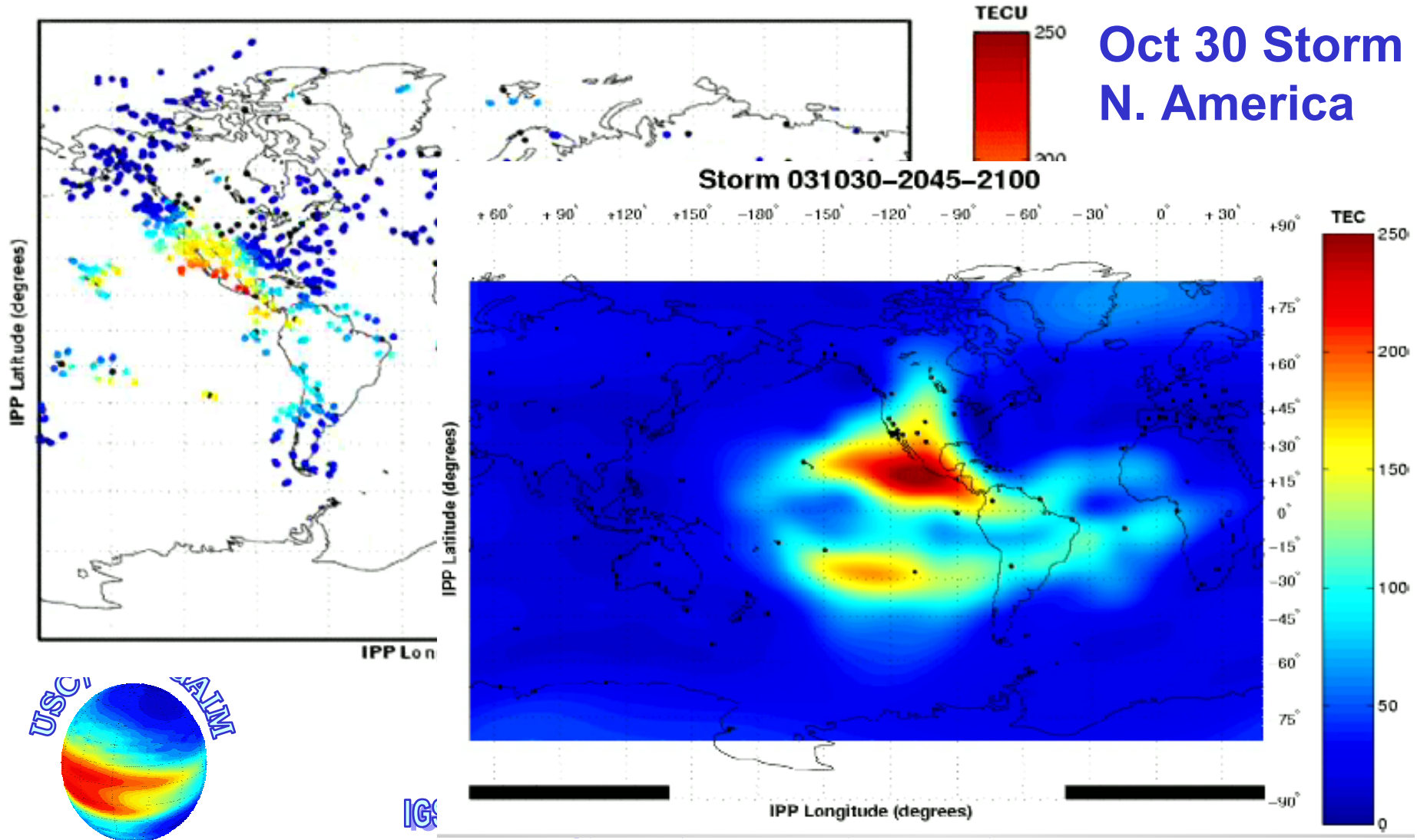# Large Geomagnetic Storm: Oct. 30, 2003

Ionospheric Product Validation for 20031030 Using Jason−1 Track 24

Jason−1 Local Time Nearest to Geographic Equator = 10.8 Hours and UT = 22.2 Hours

**October 30, 2003
22 UT
Equator LT ~ 11
-55 lat LT ~ 14**

Movies of TEC Observations and GIM

Obs Vertical TEC 031030–2045–2100

Oct 30 Storm N. America

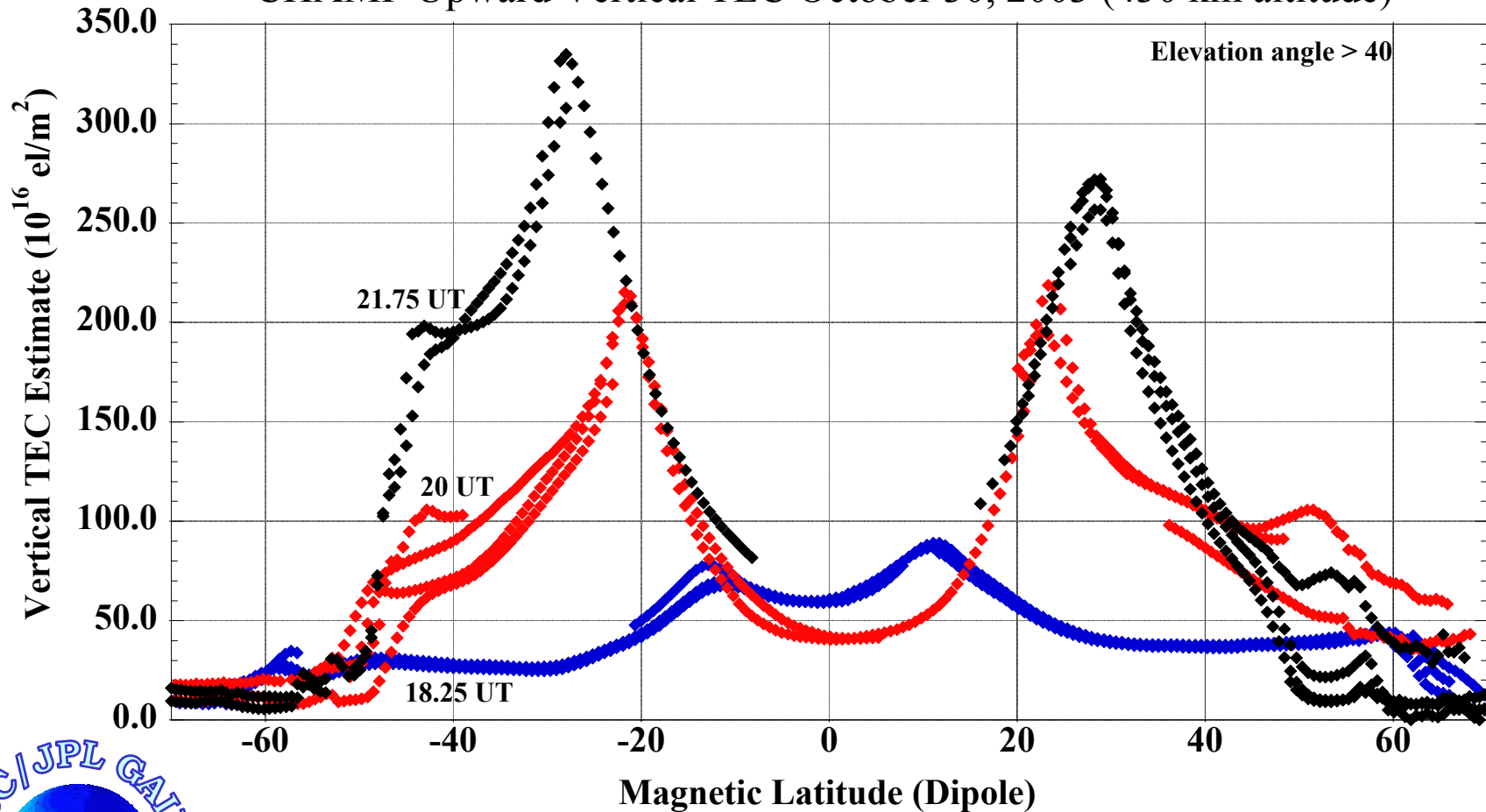Storm 031030–2045–2100

Large Geomagnetic Storm: Oct. 30, 2003

Ionospheric Product Validation for 20031030 Using Jason-1 Track 24

Jason-1 Local Time Nearest to Geographic Equator = 10.8 Hours and UT = 22.2 Hours

October 30, 2003
22 UT
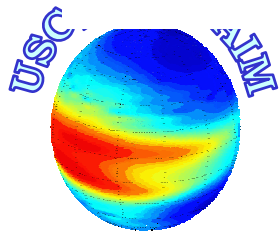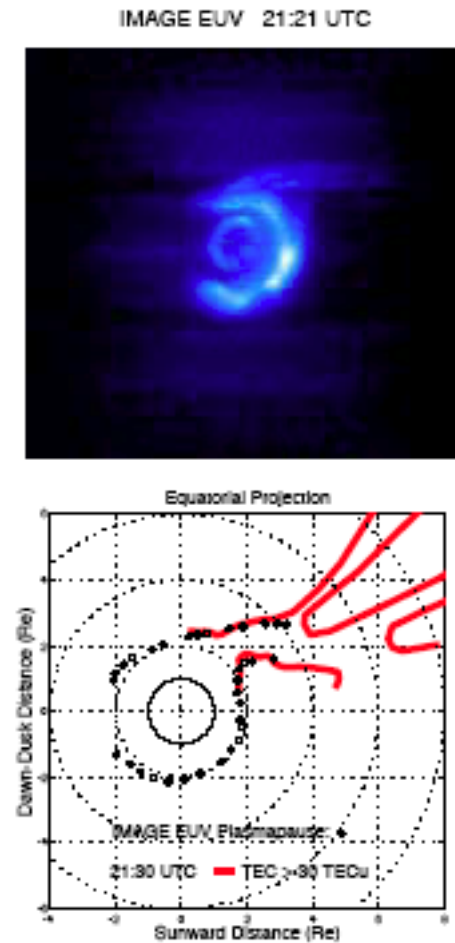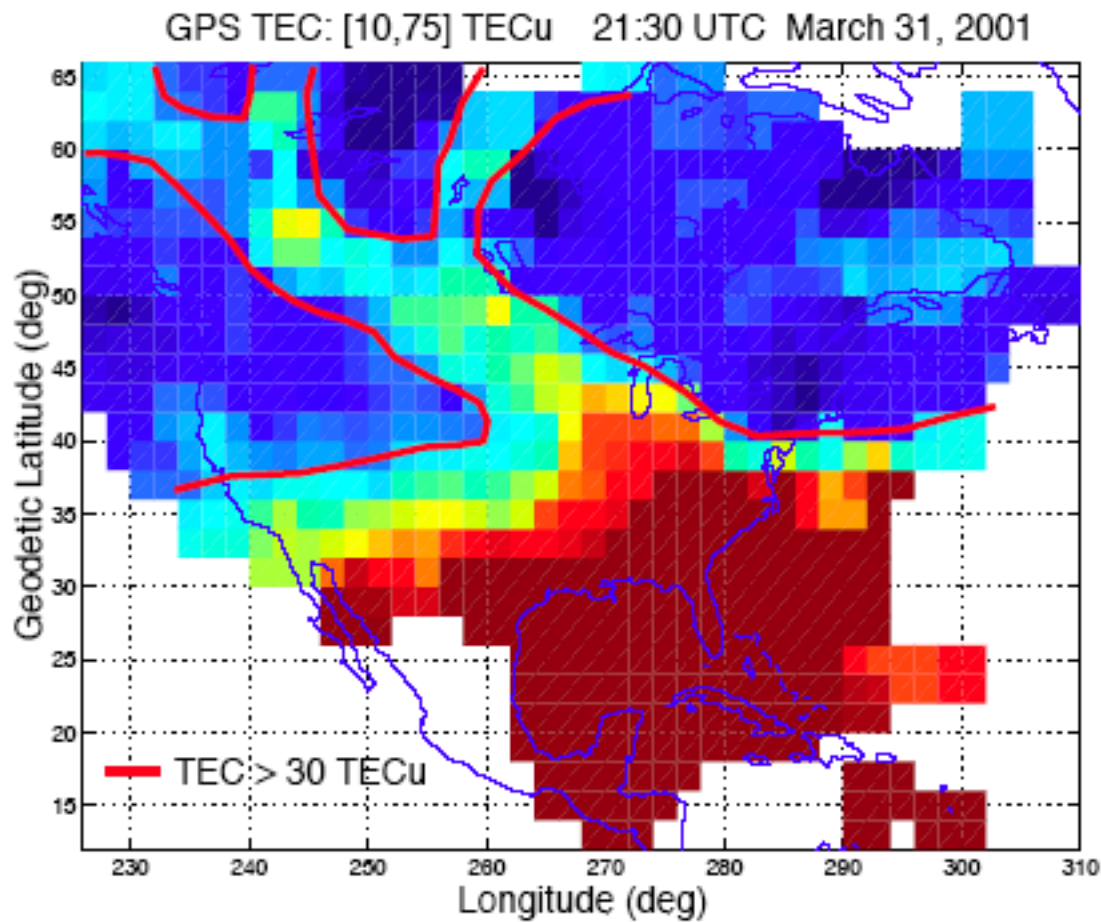**Equator LT ~ 11**
-55 lat LT ~ 14
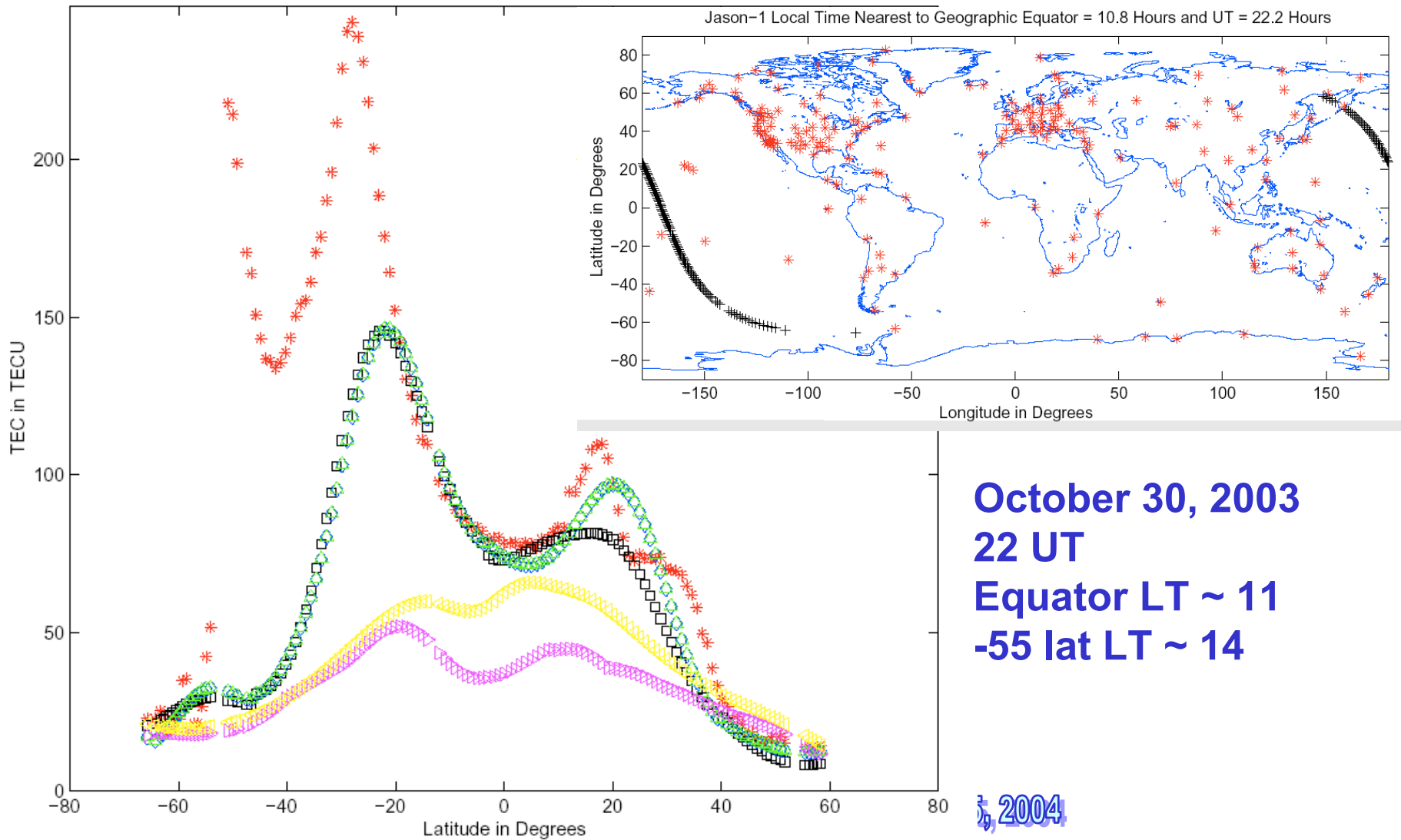
Plasma Redistribution Oct. 30, 2003

CHAMP Upward Vertical TEC October 30, 2003 (430 km altitude)
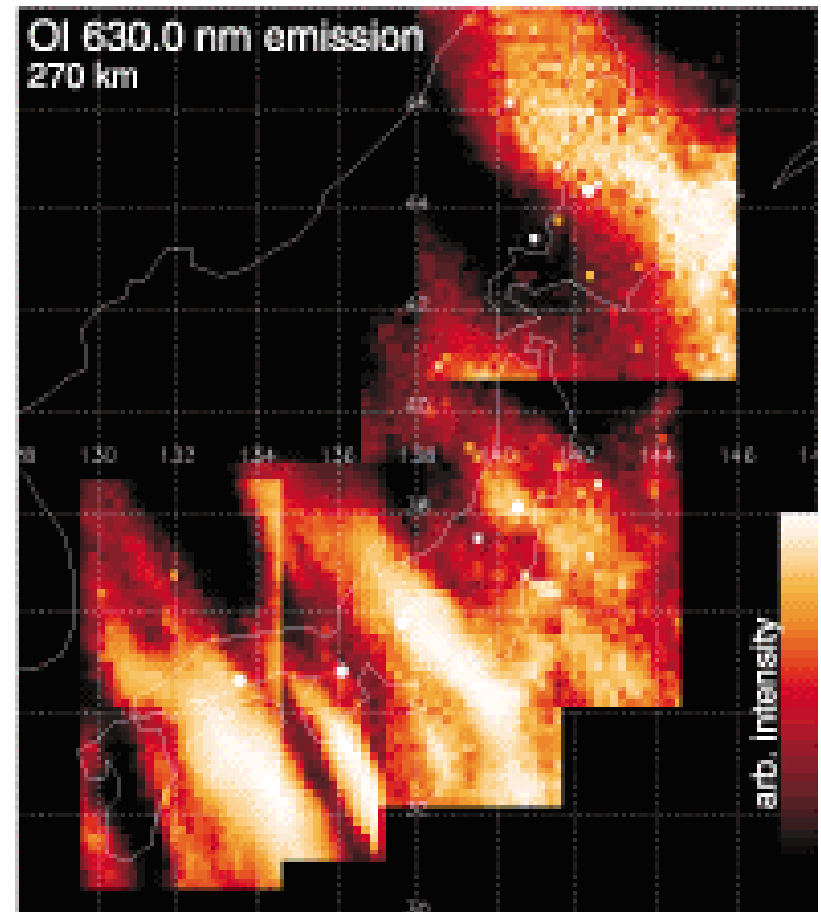
Ionospheric Signatures of Plasmaspheric Tails

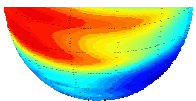Foster, et al., GRL, April 2002.

Images of TID's over Japan
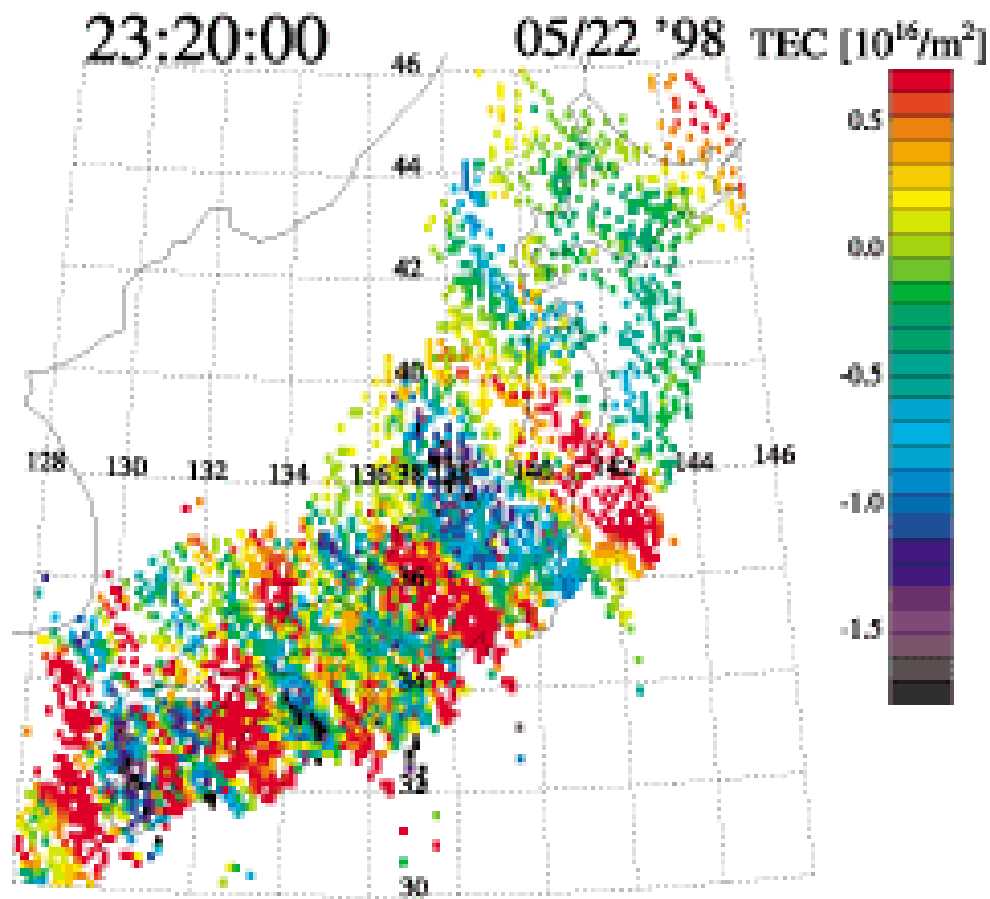
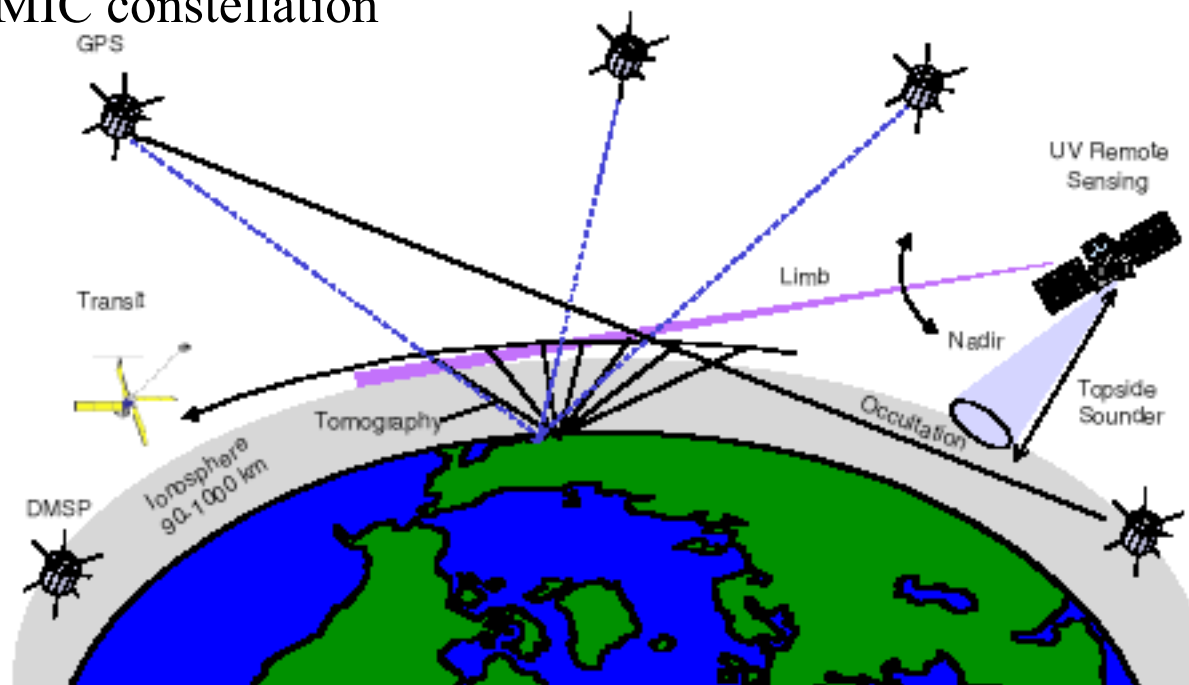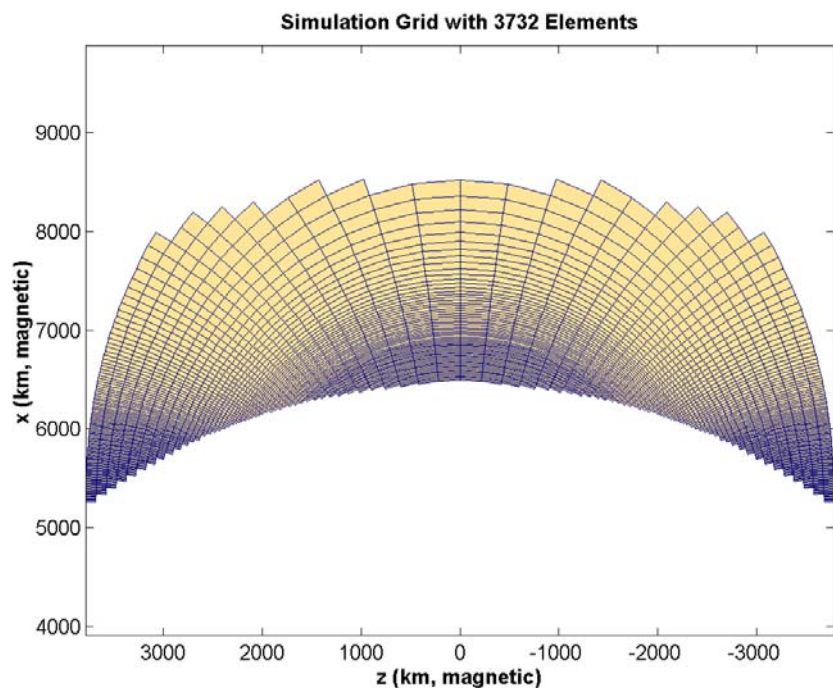(a) Saito *et al*., GRL, Feb 2001.

(b)

Why Data Assimilation?
Growing Wealth of Ionospheric Data

- ## Ground GPS TEC
  - 150+ hourly sites
  - 900+ daily sites

- ## GPS occultation
  - CHAMP, SAC-C, IOX
  - COSMIC constellation

- ## UV limb & nadir scans
  - DMSP F16
  - NPOESS

- In situ density, ionosonde, radio tomography, etc.

GAIM 1st Principles Physics Model

Simulation Grid with 3732 Elements

- Elements in p-q Magnetic Coordinates
- Variable Element Size
- Off-Line Computation of Observation Operator
- Solve for ion density using Finite Volume Method
- Efficient Forward Propagation of the State
- Unconditionally Stable Time Integration
- Explicitly Compute Partial Derivatives needed for Kalman & 4DVAR updates.
- Leverage Knowledge Gained in Numerical Weather Prediction.

**For more info –> http://iono.jpl.nasa.gov/gaim**

IGS Workshop, Berne, Switzerland, March 1-5, 2004

GAIM Band-Limited Kalman Filter

- Physics-based forward model
- Approximate Kalman: Save only part of covariance matrix based on physical correlation lengths.
- Tested with **real** data: Input is ground GPS TEC from 200 global sites; solve for 3D density grid.
- Validate densities against:
  - Vertical TEC obs. From TOPEX
  - Ionosonde FoF2, HmF2, & bottomside profiles
  - Slant TEC obs. from independent ground GPS sites.
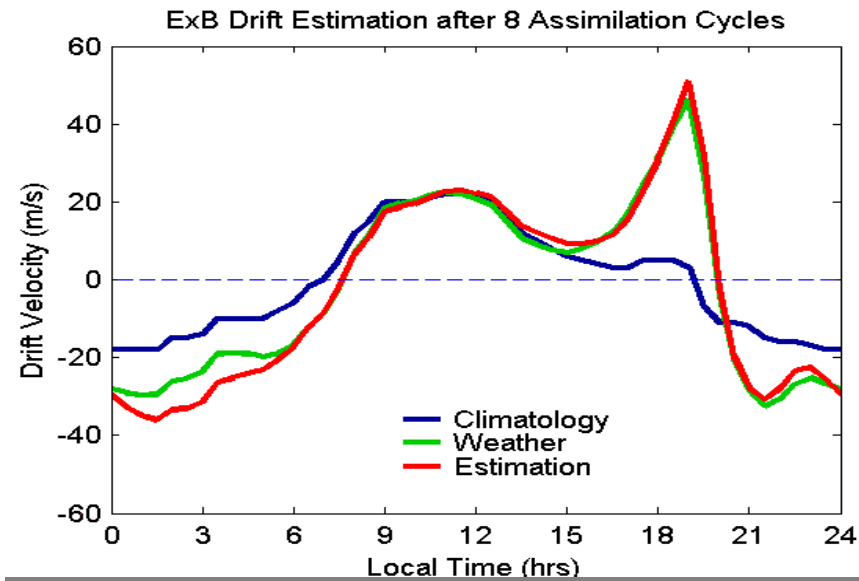 - Density profiles retrieved from space-based GPS occultations
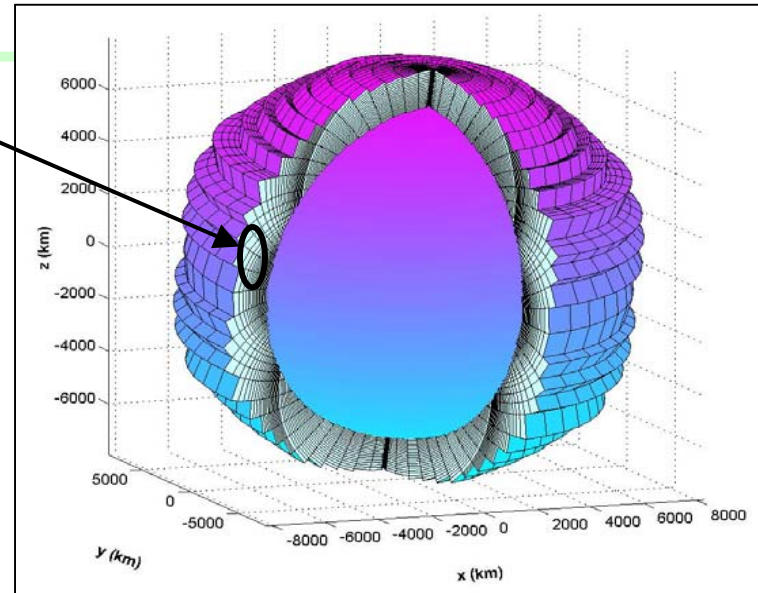
Electron Density at 7 (geo, deg) Longitude, UT= 1200, Local Time= 1228
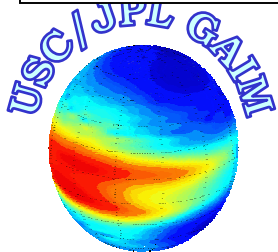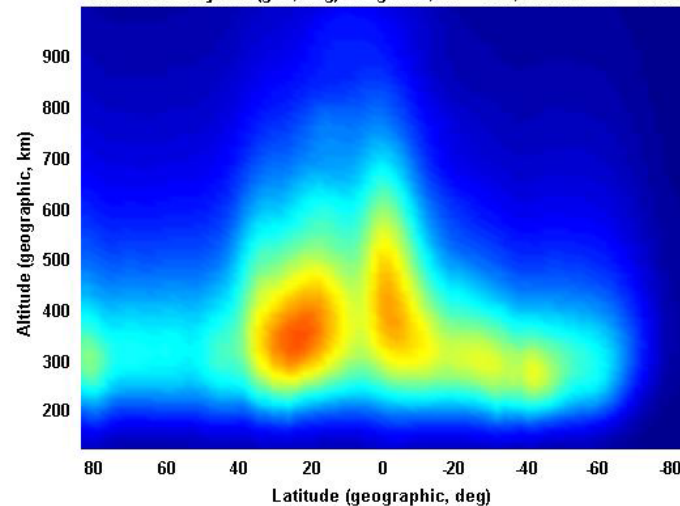
4DVAR Estimation of Dynamical Drivers

- 4DVAR is an advanced variational approach: Minimize nonlinear cost functional.

- Currently can estimate corrections to neutral wind and $\mathbf{E} \times \mathbf{B}$ vertical drift at low latitudes.

- Improved drivers enable more accurate forecasting.

Meridional Wind Perturbation Pattern [m/s]

Estimated Meridional Wind Perturbation [m/s]

ExB Drift Estimation after 8 Assimilation Cycles

Climatology
Weather
Estimation

USC/JPL GAIM
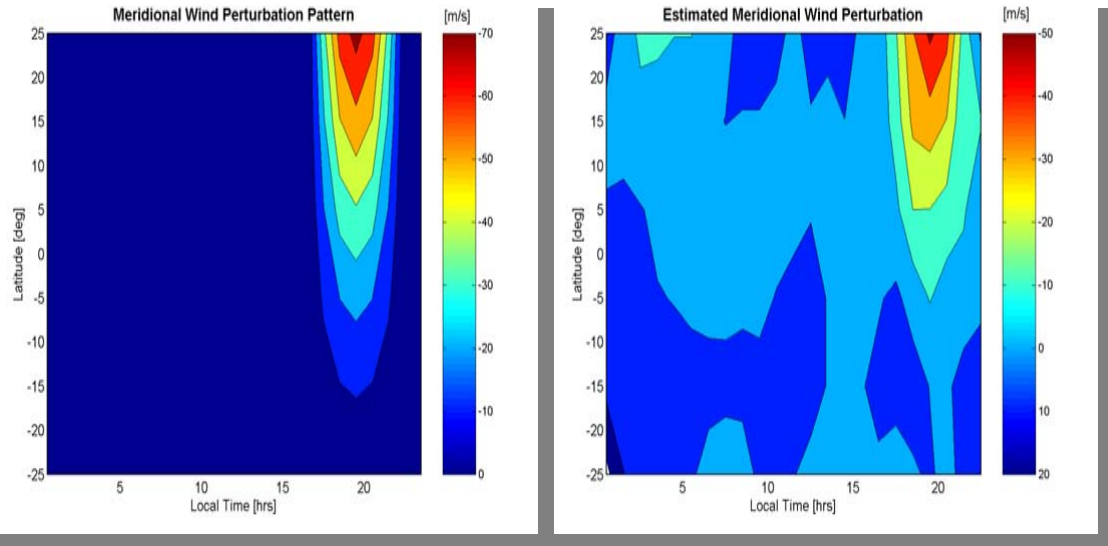
GAIM Input Datatypes

- **Absolute slant TEC from ground GPS sites (5-15 min)**
 - Global networks of 900+ sites
  - NRT networks of 150+ sites (5, 15, or 60 minute cadence)
- **Relative TEC links from flight GPS receivers (1-3 hrs)**
  - Occultation links (Abel retrieval of density profile)
  - Upward linking TEC links (plasmasphere)
  - IOX, CHAMP, SAC-C, C/NOFS, COSMIC constellation
- **Ionosonde sites (DISS, 15 min)**
  - NmF2 & HmF2 parameters
  - Preferably bottom-side profile or virtual heights
- **UV limb and nadir scans (1-2 hrs)**
  - Nighttime limb scans from LORAAS on ARGOS
  - GUVI disk scans on TIMED
  - SSUSI/SSULI on DMSP F16 and future NPOESS
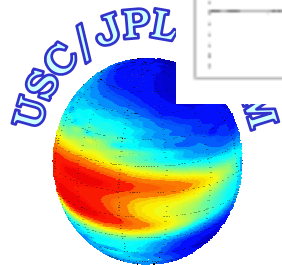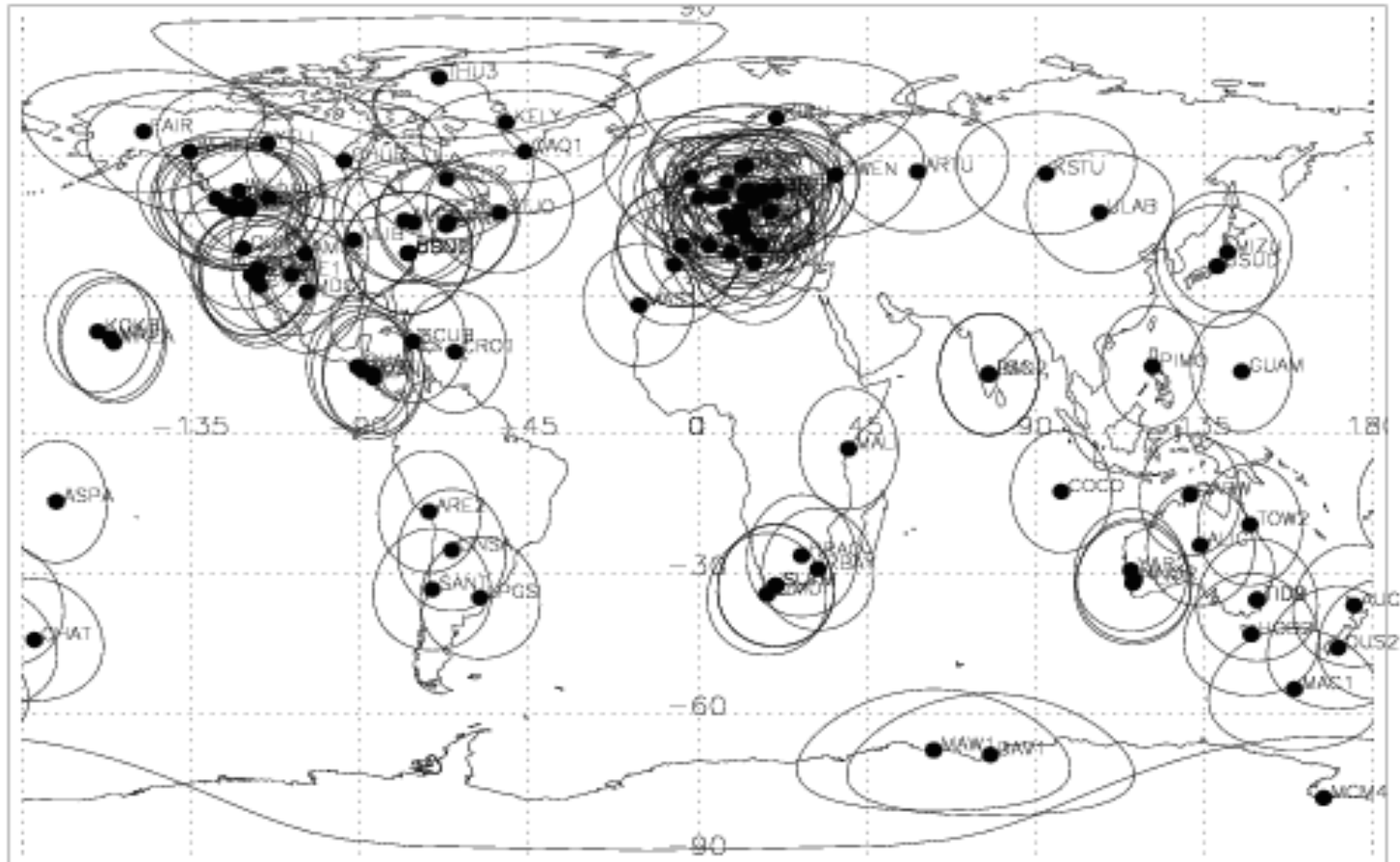- **C/NOFS in-situ densities & Electric fields (1-2 hrs)**

Coverage of <u>Daily</u> IGS Ground Network
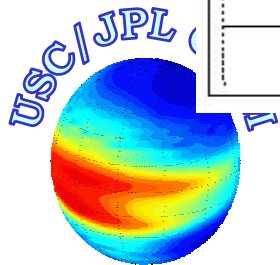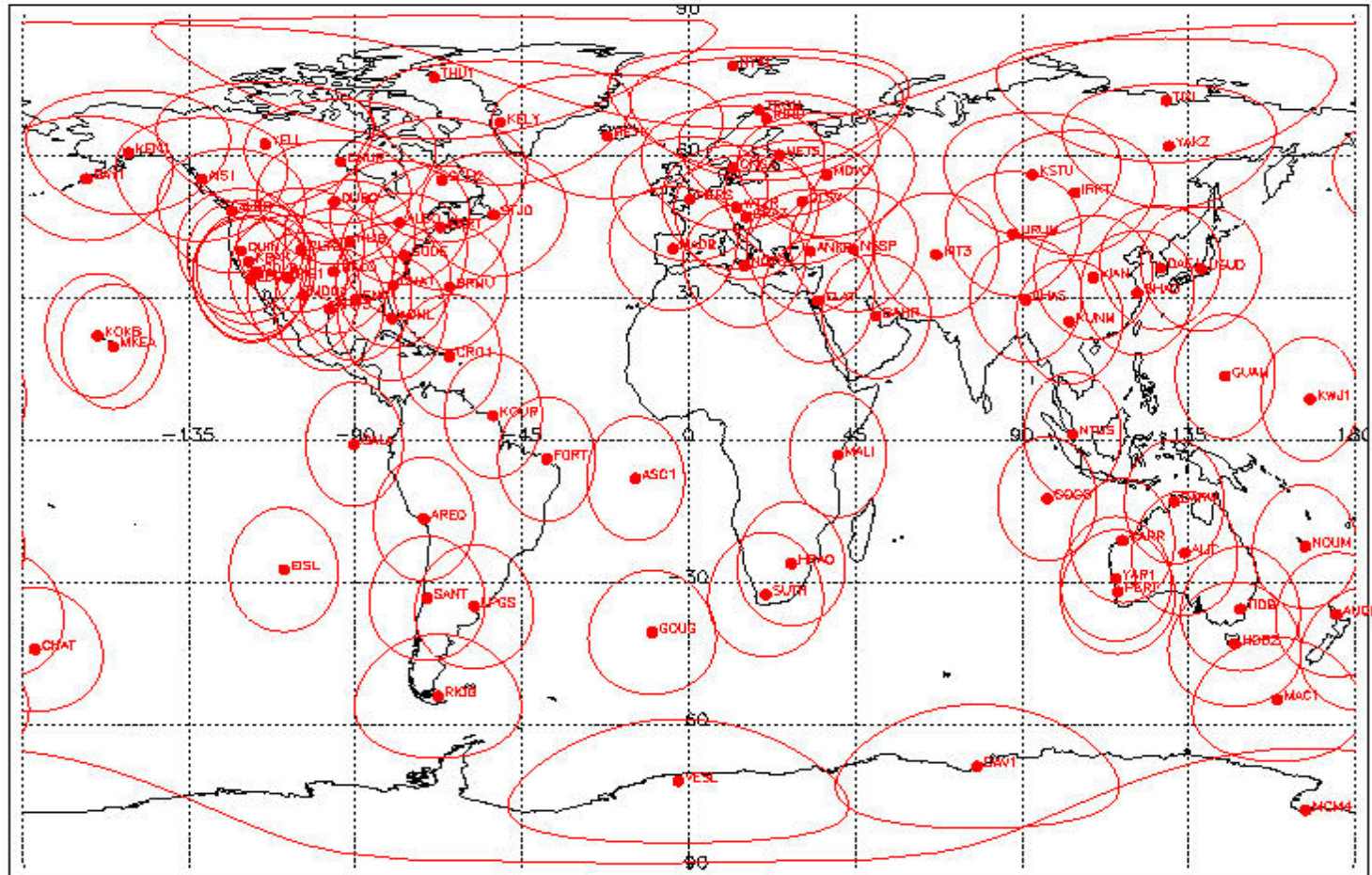
Coverage of <u>Hourly</u> IGS Ground Network

Validation Case Studies using GAIM Kalman

GAIM band-limited Kalman runs	Period	Input data	Validation data
2 runs: -GAIM climate -Ground GPS	Many cases and daily since Mar. 2003	-98 ground GPS sites	-TOPEX vert. TEC -Independent GPS slant TEC -Ionosonde NmF2, Hmf2
4 runs: -GAIM climate -GPS ground, -GPS occultations -Combined dataset	2002/07/22 – 2002/07/28	-98 ground GPS sites -IOX occultations (-GUVI in progress)	-TOPEX vert. TEC -GPS slant TEC -Ionosonde -Abel density profile retrievals -CHAMP in-situ densities
4 runs: -GAIM climate -GPS ground, -UV Radiances from nighttime limb scans, -Combined dataset	Oct. 2000	-98 ground GPS sites -LORAAS UV from ARGOS	-TOPEX TEC -GPS slant TEC -Ionosonde -NRL 2D density retrievals

USC/JPL GAIM
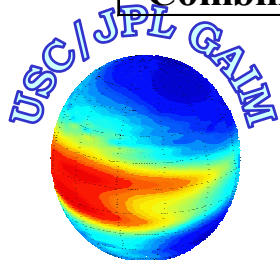
Daily GAIM Operations (Mar 2003 - present)

- Using Physics-Based, Band-Limited Kalman Filter
- Driver adjustment will be operational soon.
- Actually two runs each day:
  - Test bed to compare different covariance strategies and grid resolutions
- Input 200+ ground GPS TEC sites
- Continuous validation against:
  - Vertical TEC from TOPEX
  - Slant TEC from independent GPS sites
  - FoF2 & HmF2 from ionosondes (QC issue)

For more info –> http://iono.jpl.nasa.gov/gaim

IGS Workshop, Berne, Switzerland, March 1-5, 2004

USC/JPL GAIM
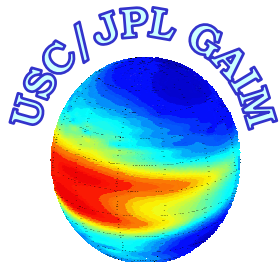
Band-Limited Kalman Filter

State Model

$$x_{k+1}^t = \Psi_k x_k^t + \varepsilon_k^q$$

Measurement Model

$$m_k^o = H_k x_k^t + \varepsilon_k^o$$

Noise Model

$$\varepsilon_k^o = \varepsilon_k^m + \varepsilon_k^r$$

$$E\left(\varepsilon_k^m, \varepsilon_k^{mT}\right) = M_k$$

$$E\left(\varepsilon_k^r, \varepsilon_k^{rT}\right) = R_k$$

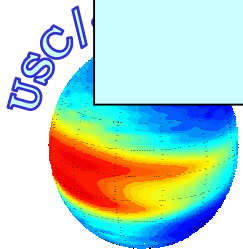$$E\left(\varepsilon_k^q, \varepsilon_k^{qT}\right) = Q_k$$

$$x_k^a = x_k^f + K_k\left(m_k^o - H_k x_k^f\right)$$

$$K_k = P_k^f H_k^T \left(H_k P_k^f H_k^T + R_k + Q_k\right)^{-1}$$
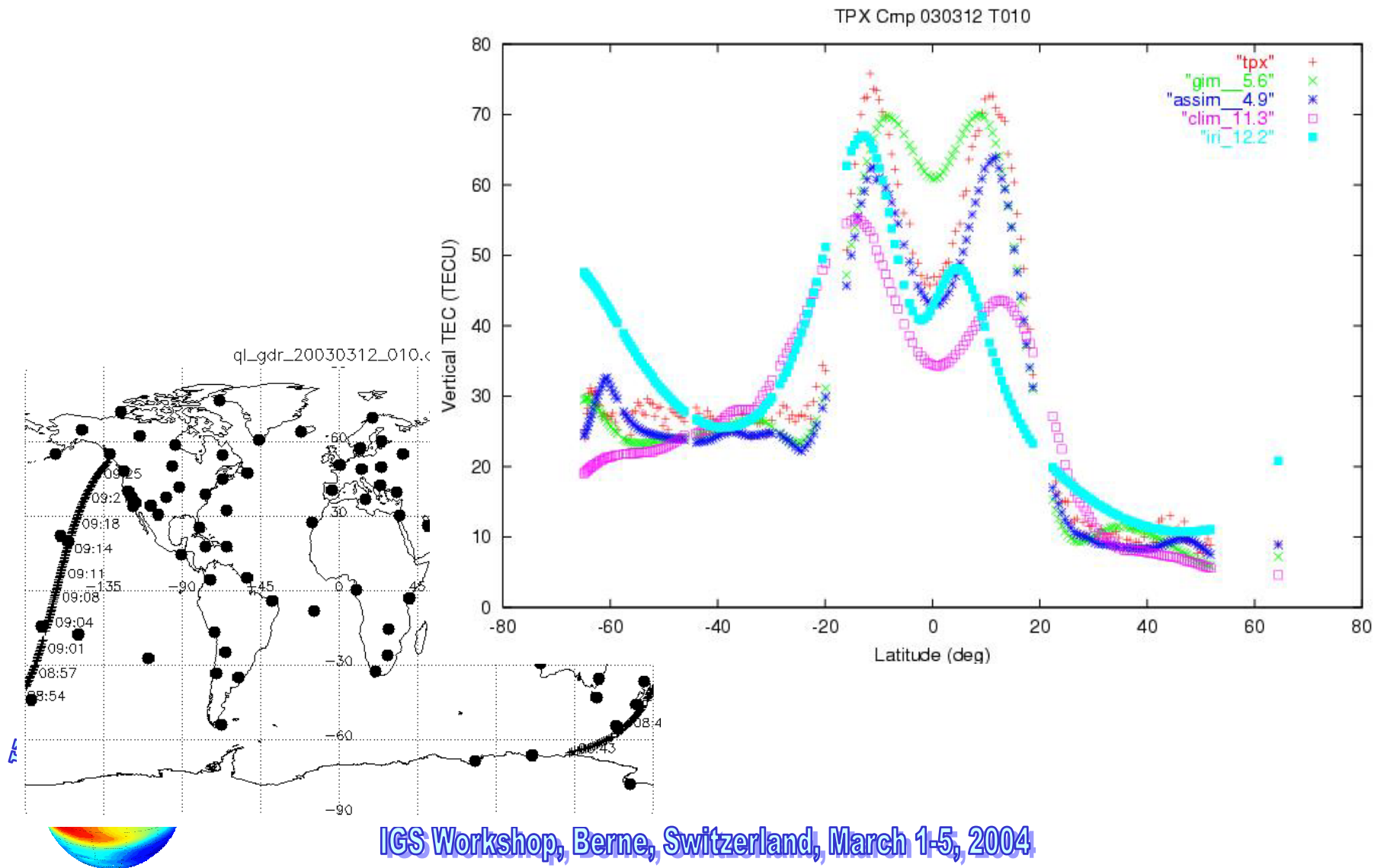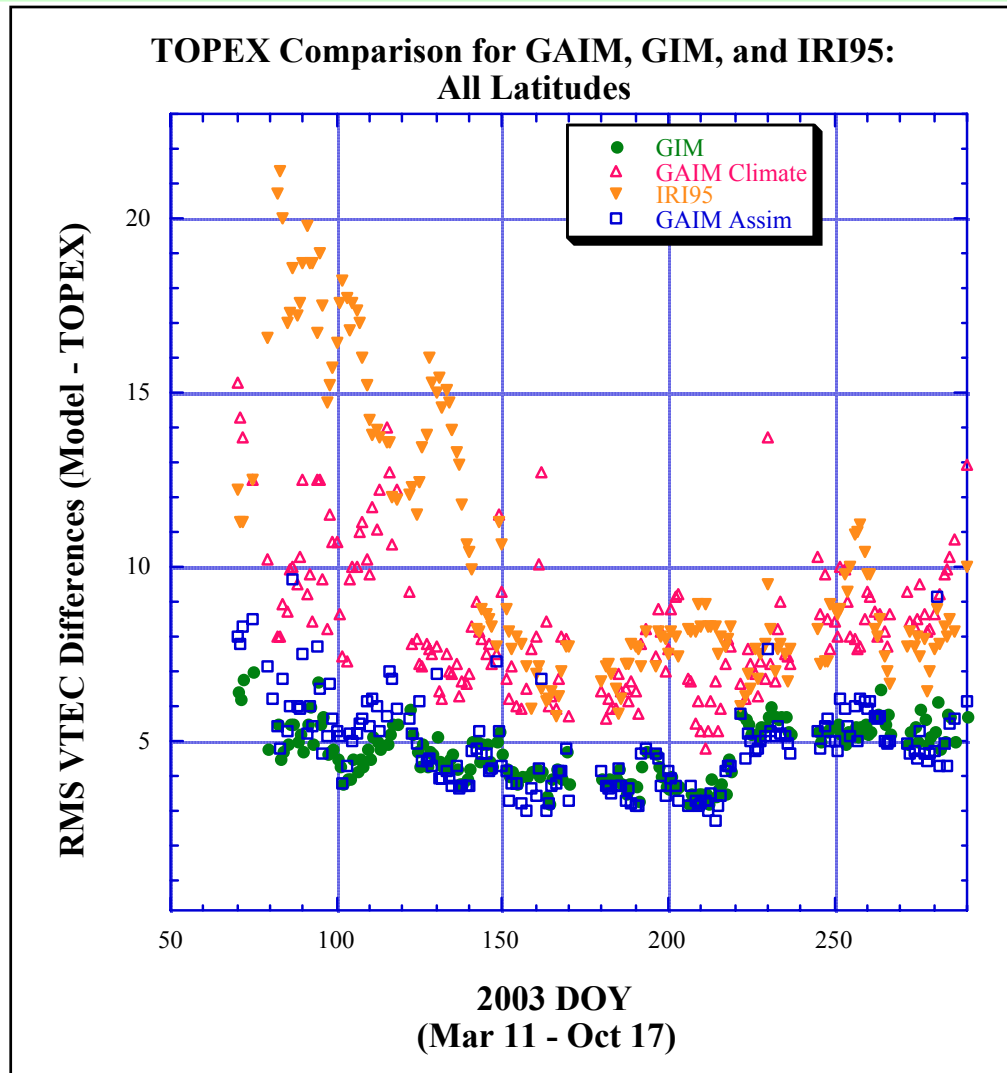
$$P_k^a = P_k^f - K_k H_k P_k^f$$

$$x_{k+1}^f = \Psi_k x_k^a$$
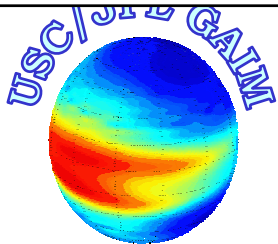
$$P_{k+1}^f = \Psi_k P_k^a \Psi_k^T + Q_k$$

TOPEX Track #10 on 2003/03/12

TOPEX Comparisons for Mar 11 - Oct 17, 2003: GAIM versus GIM & IRI95

TOPEX Comparison for GAIM, GIM, and IRI95: All Latitudes

TOPEX Comparisons for Mar 11 - Oct 17, 2003:
GAIM Assim. at Low vs. Mid & High Latitudes

TOPEX Comparison for GAIM, GIM, and IRI95:
Low Latitudes

Legend:
- GIM
- GAIM Climate
- IRI95
- GAIM Assim

RMS VTEC Differences (Model - TOPEX)

2003 DOY
(Mar 11 - Oct 17)

TOPEX Comparison for GAIM, GIM, and IRI95:
Mid & High Latitudes

Legend:
- GIM
- GAIM Climate
- IRI95
- GAIM Assim

RMS VTEC Differences (Model - TOPEX)

2003 DOY
(Mar 11 - Oct 17)

USC/JPL GAIM
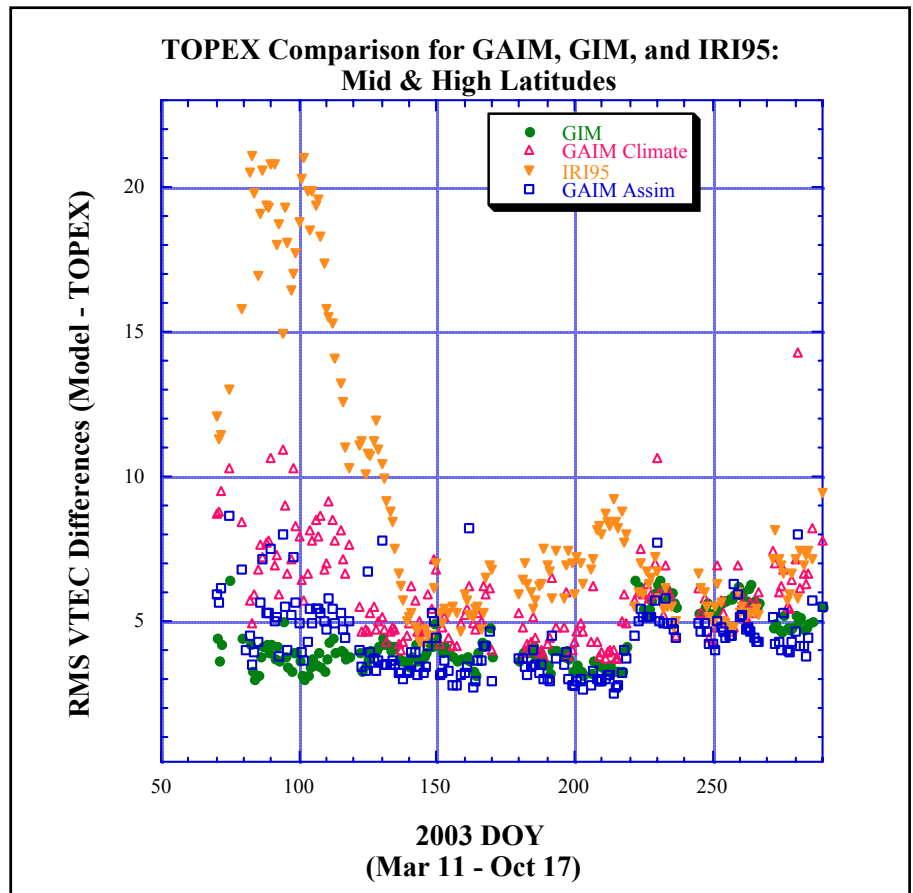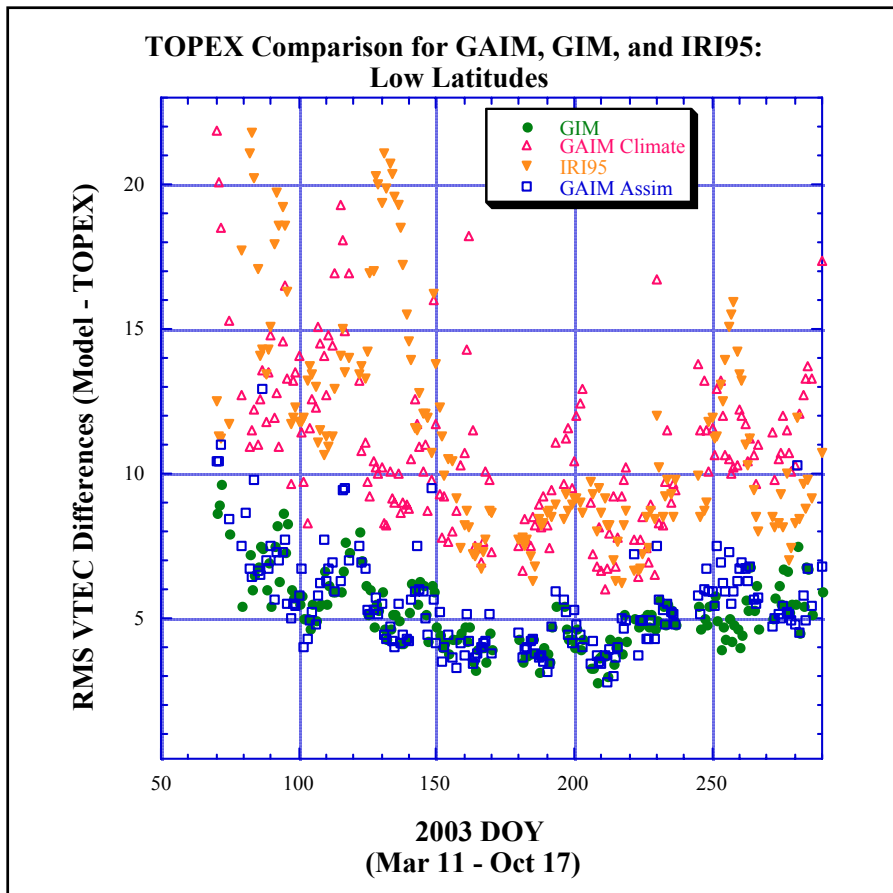
Global Ground Observatory for Space Weather

- **Chance for Version 3 of the Global Network**
  - 1000+ global sites with denser regions, selected for ionospheric purposes

- **RT Data Collection via Cellular Comm.**

- **Potential Instruments at Each Node**
  - Cheap, Modern Receiver that uses all GPS, Galileo, & GLONASS signals
  - Same Receiver does TEC and scintillation indices (for irregularities)
  - Digital Ionosonde
  - All-sky Imager
  - Passive Radar

- **Multiple-Use Challenge**
  - Combine Iono + Tropo Requirements (weather + space weather)
  - Combine Iono + Tropo + Geodesy Requirements (monumentation!)

USC/JPL GAIM

Conclusions

- **GIM TEC maps are mature.**
  - **Generated by many scientific & commercial entities**

- **GPS has revolutionized ionospheric science by enabling continuous global-scale studies.**

- **3D Global Ionospheric Data Assimilation has arrived.**
  - **Millions of observations per day**
  - **RT GAIM will be running soon.**
  - **Input data and update density grid every 5 minutes.**

- **Yet Another Global Ground Sensor Network**
  - **SWx Community Needs Experience of the IGS.**
  - **IGS Will Benefit from YAGN.**
  - **We can't afford single or merely dual-use sensor networks!**

USC/JPL GAIM