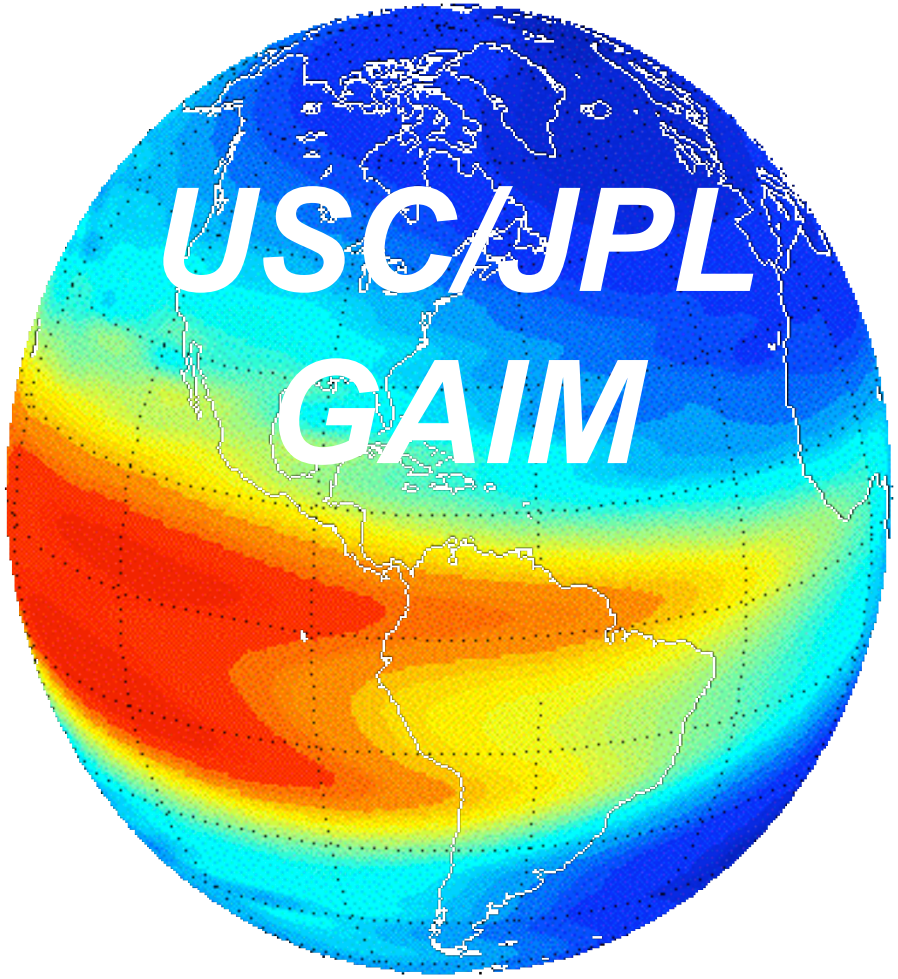
Daily Operation and Validation of a Global Assimilative Ionosphere Model



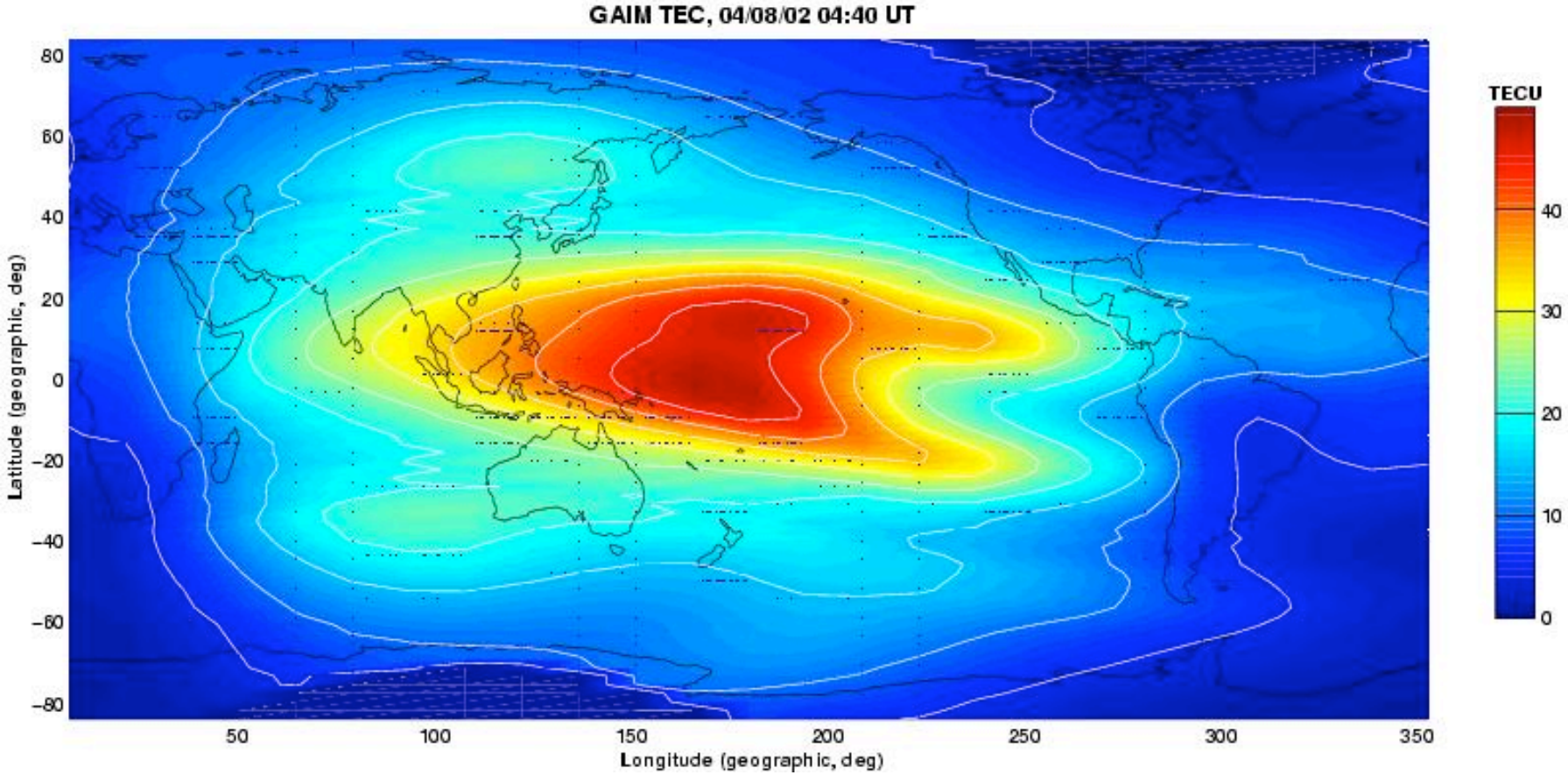
Brian Wilson, JPL
George Hajj, JPL, USC
Lukas Mandrake, JPL
Xiaoqing Pi, JPL, USC
Chunming Wang, USC
Gary Rosen, USC

AF Space Command Briefing, Colorado Springs, Aug. 2, 2004

USC/JPL Global Assimilative Ionosphere Model (GAIM)

- Physics-Based Forward Model, Matching Adjoint Model
  - Developed to explicitly support data assimilation
- Use Kalman filter and 4DVAR (with adjoint model) to simultaneously solve for:
  - 3D ion & electron density state every 5 minutes
  - Key ionospheric drivers such as low-latitude ExB vertical drift, neutral winds, & production terms
- Opportunity to take advantage of new global data sources:
  - Ground GPS network (>900 daily sites, >160 hourly sites)
  - FUV radiances (LORAAS, GUVI, DMSP SSUSI/SSULI)
  - COSMIC GPS occultation constellation (6 sats.)
- Continuous daily GAIM runs & validation against:
  - TOPEX vertical TEC, independent GPS slant TEC
  - Ionosonde FoF2, HmF2, & bottom-side profiles
  - Density profiles from Abel Inversions of occultation data

USC/JPL GAIM: Real-Time TEC Map



USC/ JPL GAIM

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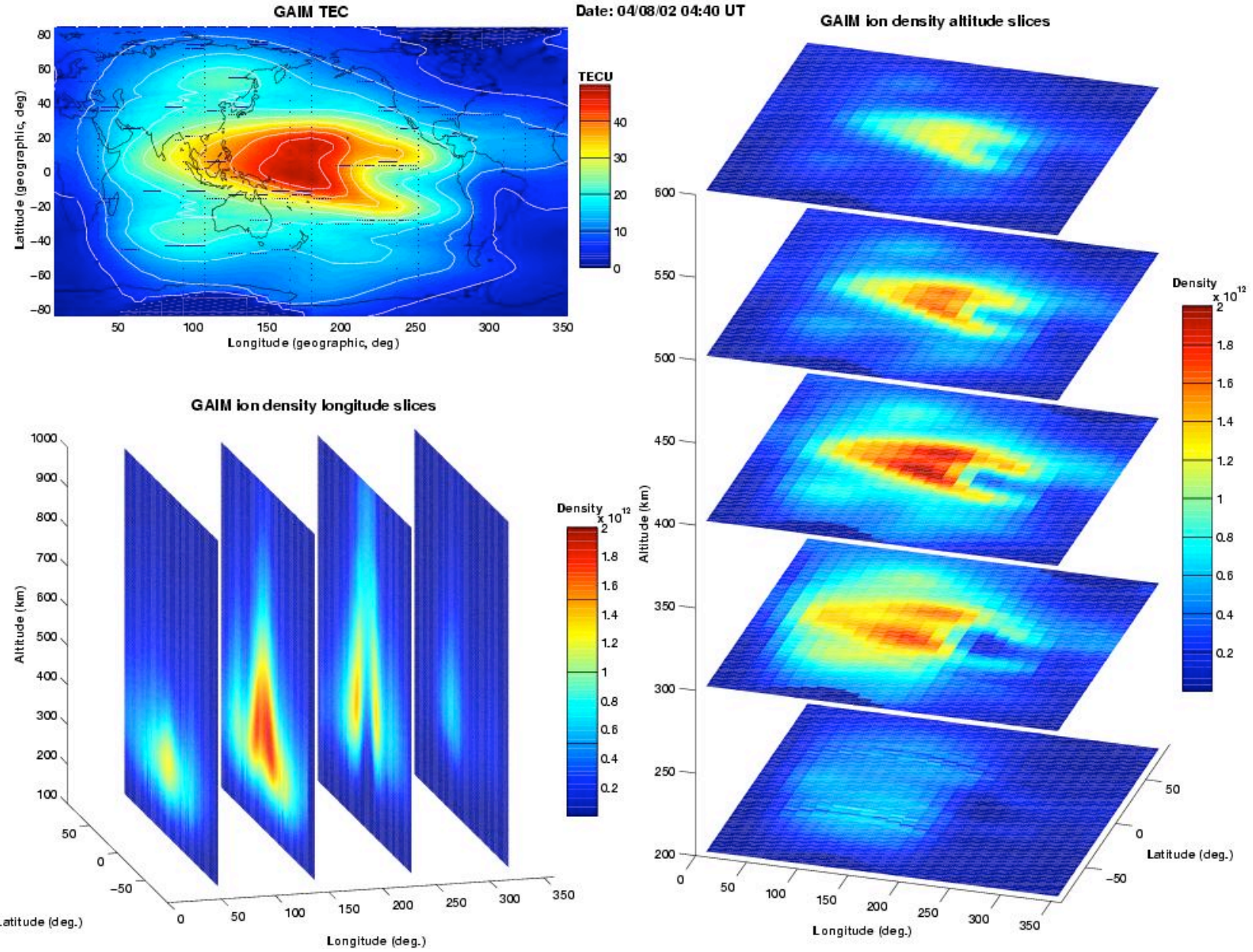
USC/JPL GAIM: RT TEC Map & Density Slices



Introduction

- **USC/JPL GAIM uses two assimilation techniques:**
  - **4DVAR with an Adjoint model to estimate drivers**
  - **Sparse Kalman filter**
- **Daily GAIM Kalman Runs**
  - **Specify Yesterday's Ionosphere**
  - **Daily since March 2003**
- **Extensive Validation**
  - **Case Studies and Continuous, Daily Validation**
- **RT GAIM: Operational Prototype**
  - Demonstrated April-May 2004
  - Input GPS data every 5 minutes and estimate new density grid
  - Validate every hour against GPS, every 3-4 hrs with JASON

Outline

- Motivation: It's All About the Data!
- USC/JPL GAIM: 4DVAR & Sparse Kalman
- Daily GAIM Kalman Runs & Validation
- Extensive Validation, Case Studies
- RT GAIM: Operational Prototype
- Ionospheric Data Assimilation In-A-Box
- Validation Datasets & Collaboration

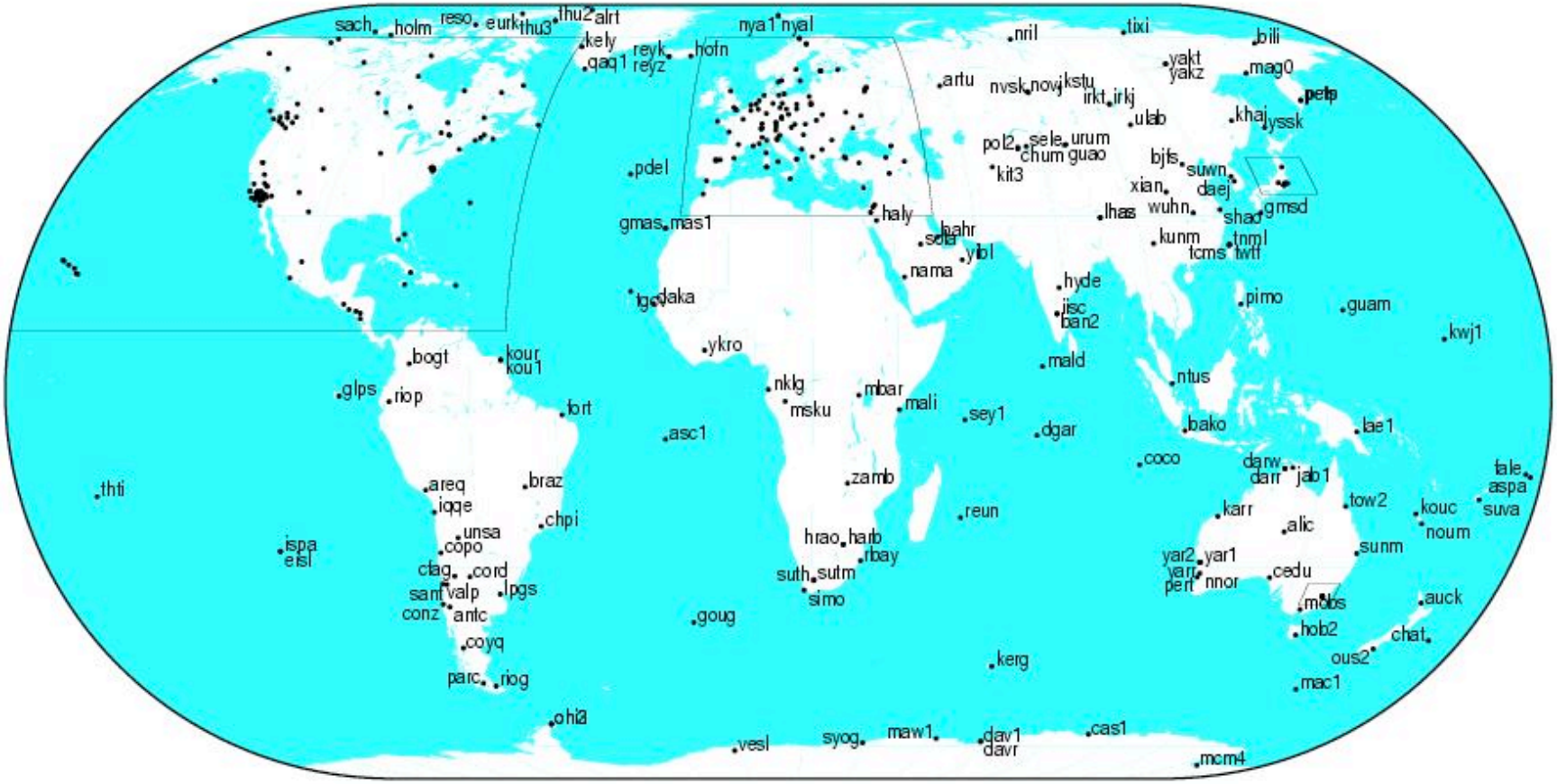
Motivation:

It's All About the Data!

GAIM Input Datatypes

- **Absolute slant TEC from ground GPS sites (5-60 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?)**

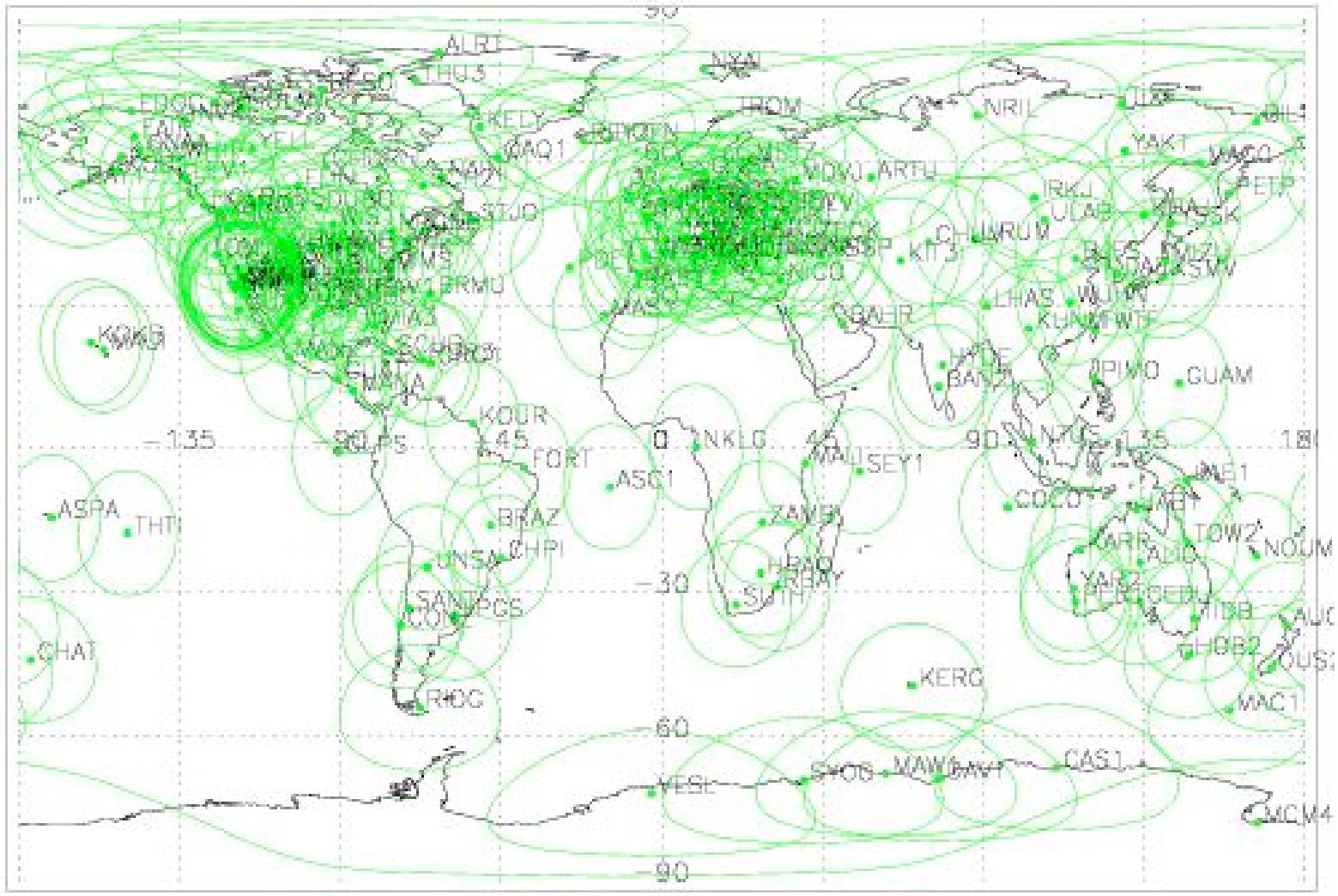
Coverage of Daily IGS Ground Network

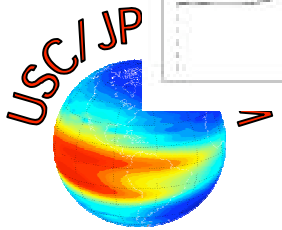


GMT Jul 30 17:22:08 2004

Maps at http://igscb.jpl.nasa.gov/network/netindex.html

200 Daily GPS Sites (04/2004)





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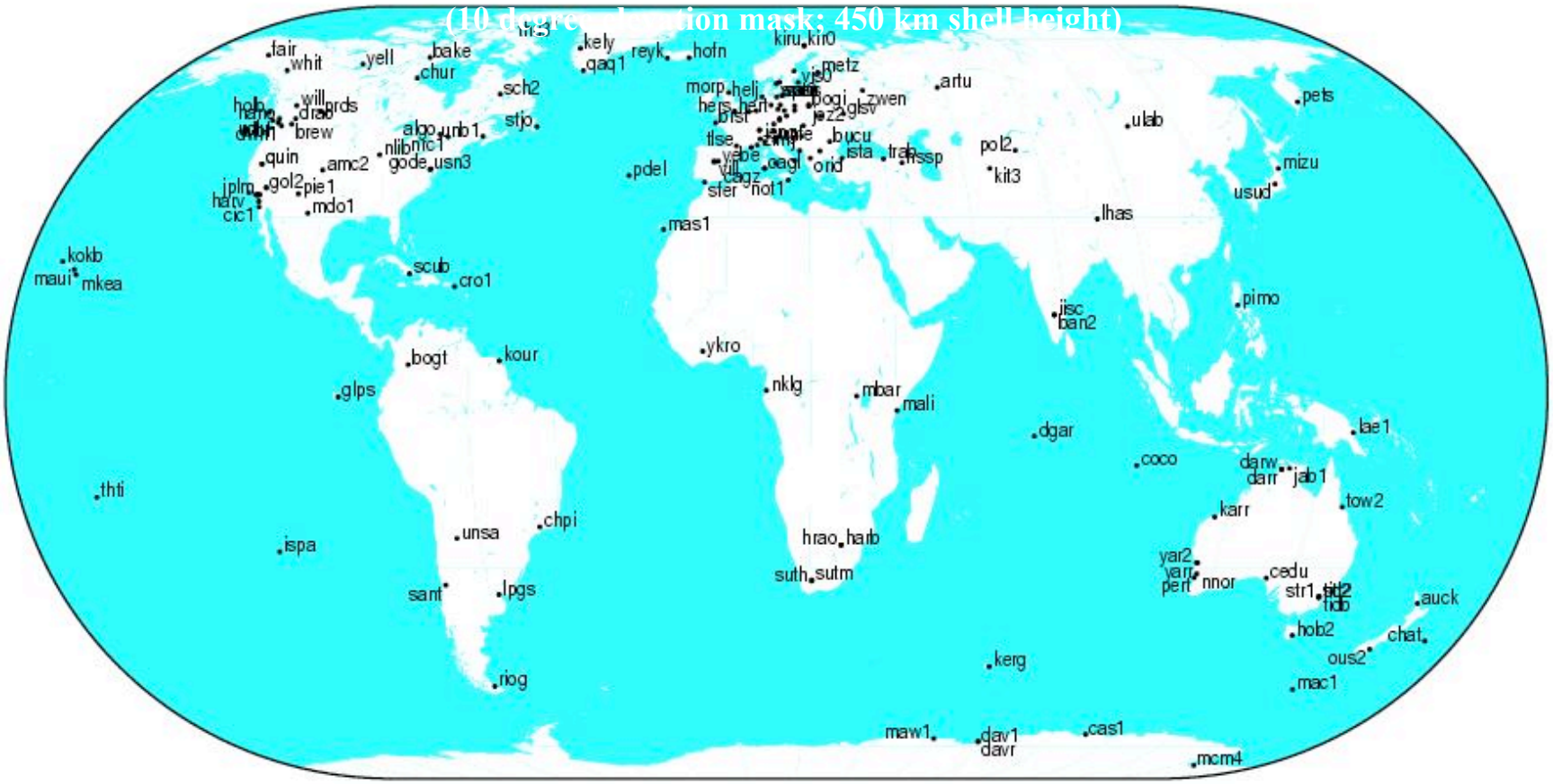
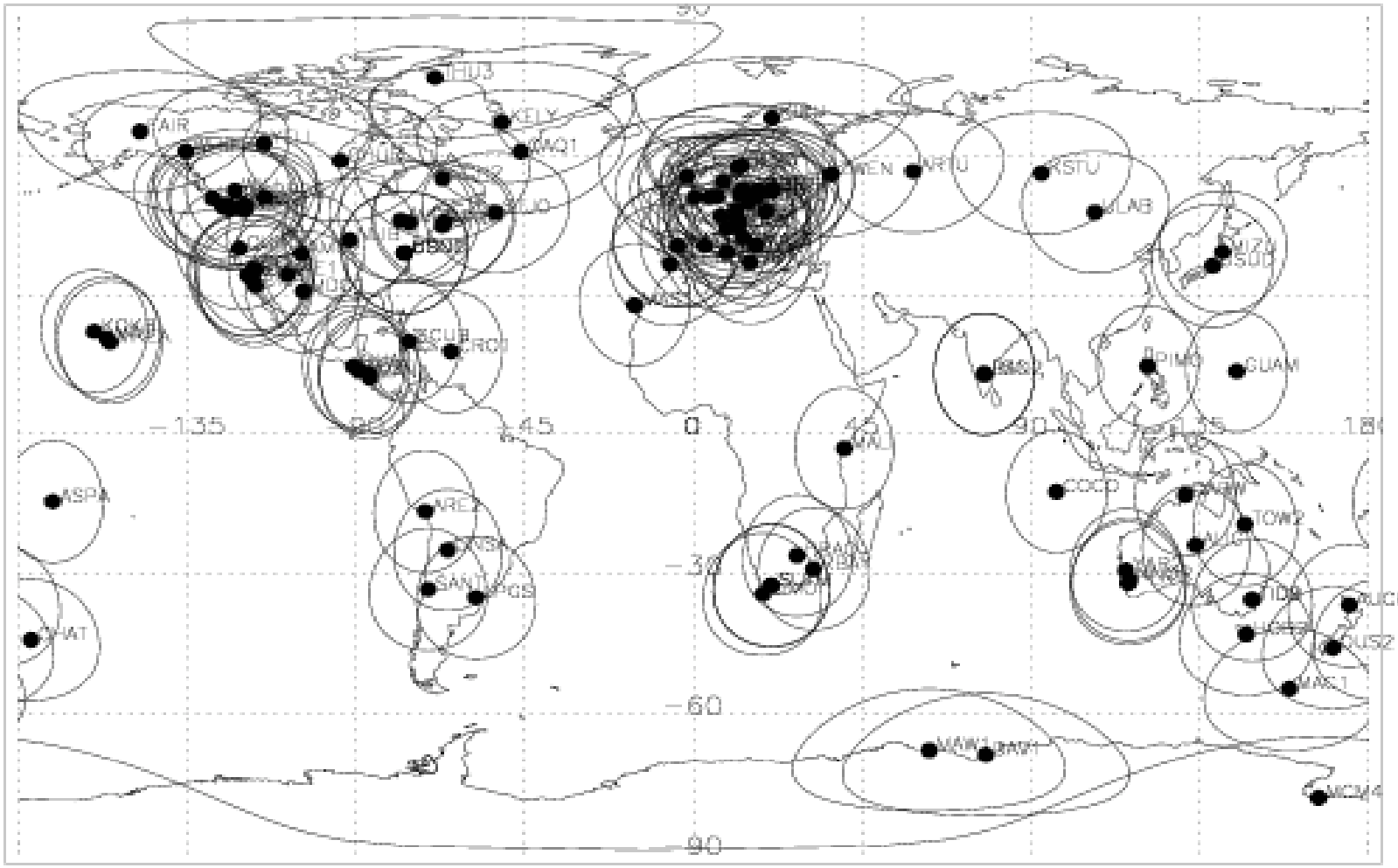
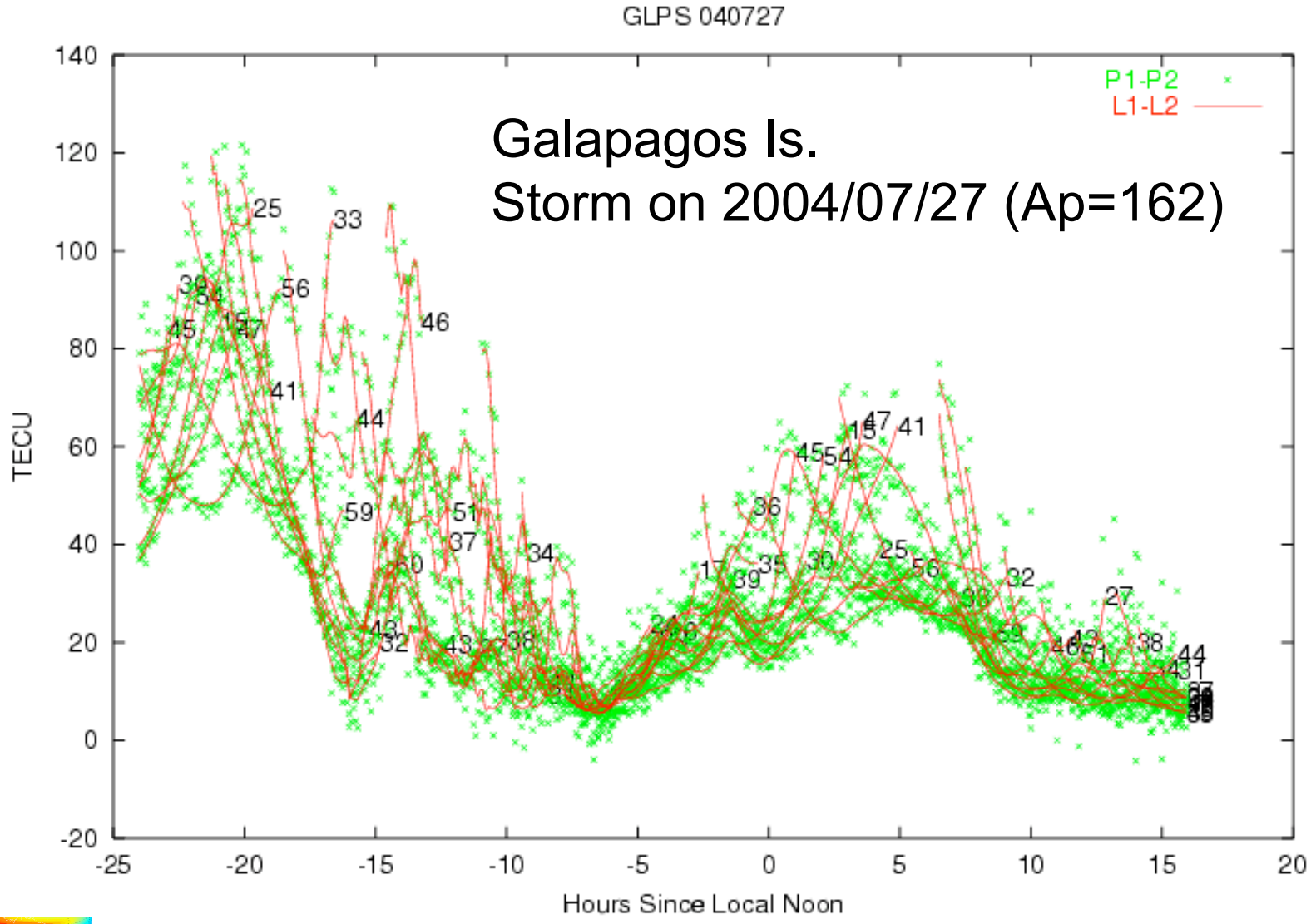
Coverage of Hourly IGS Ground Network



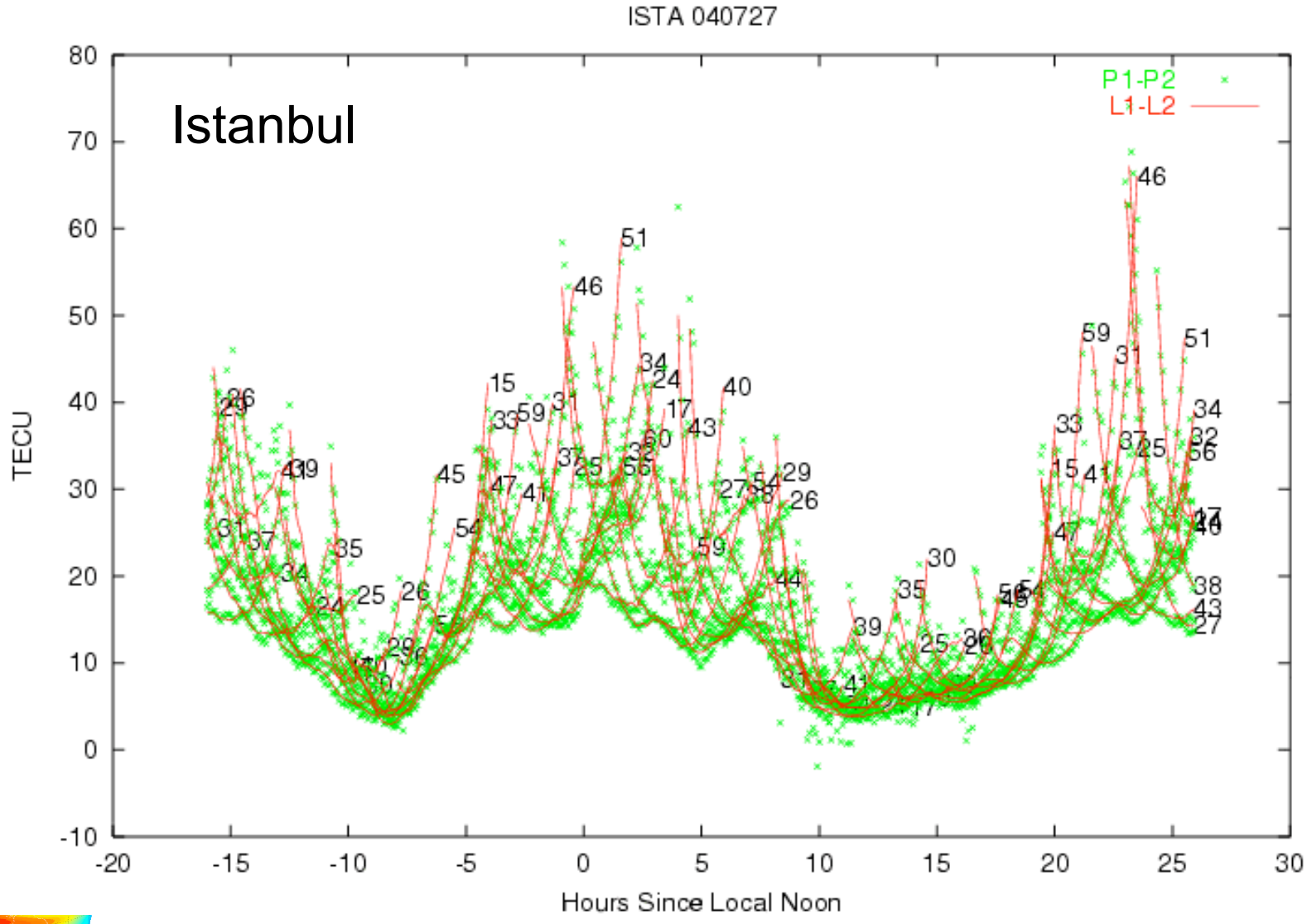
Coverage of Hourly IGS Ground Network



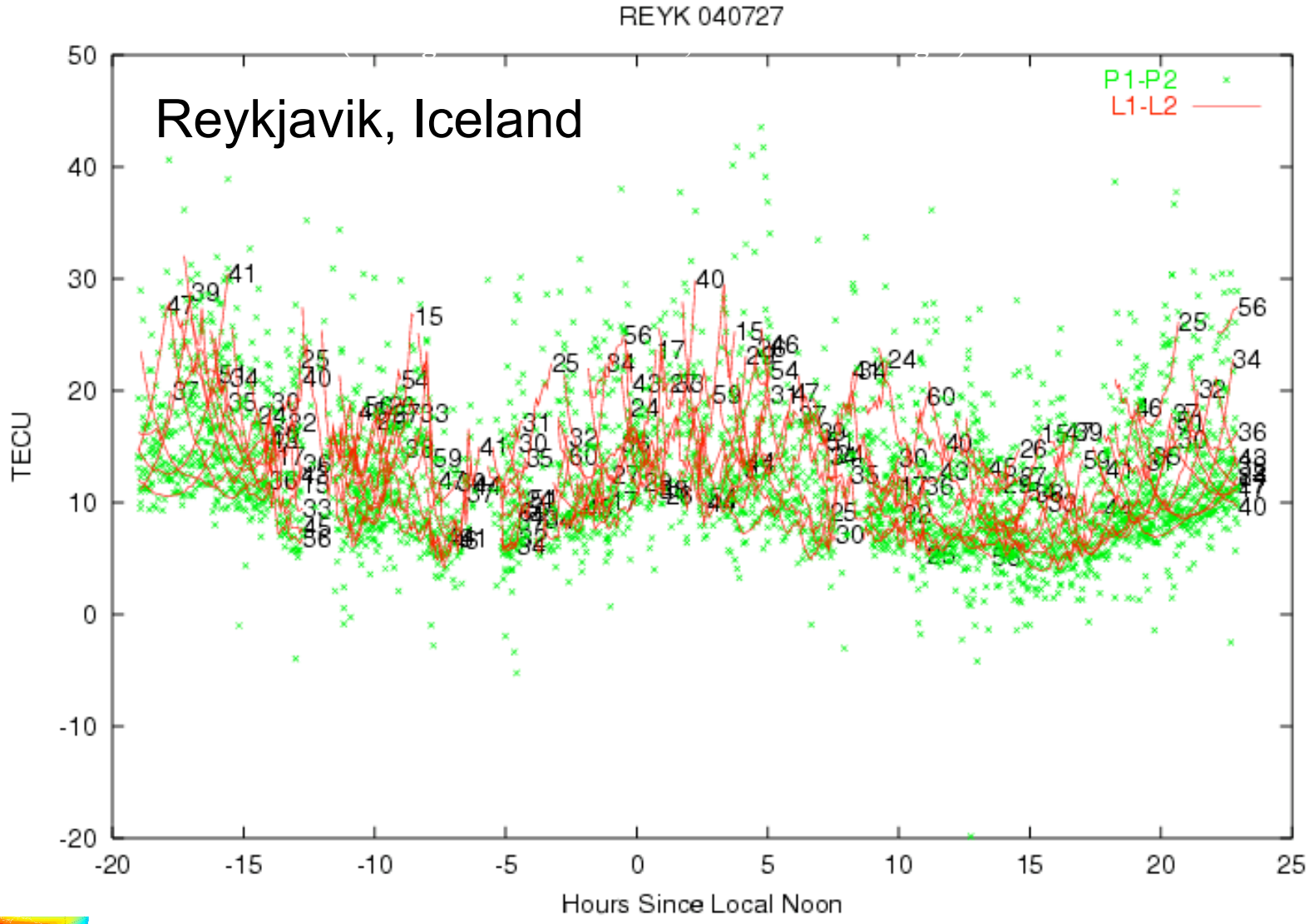
Information Content of GPS Slant TEC: Low Latitude



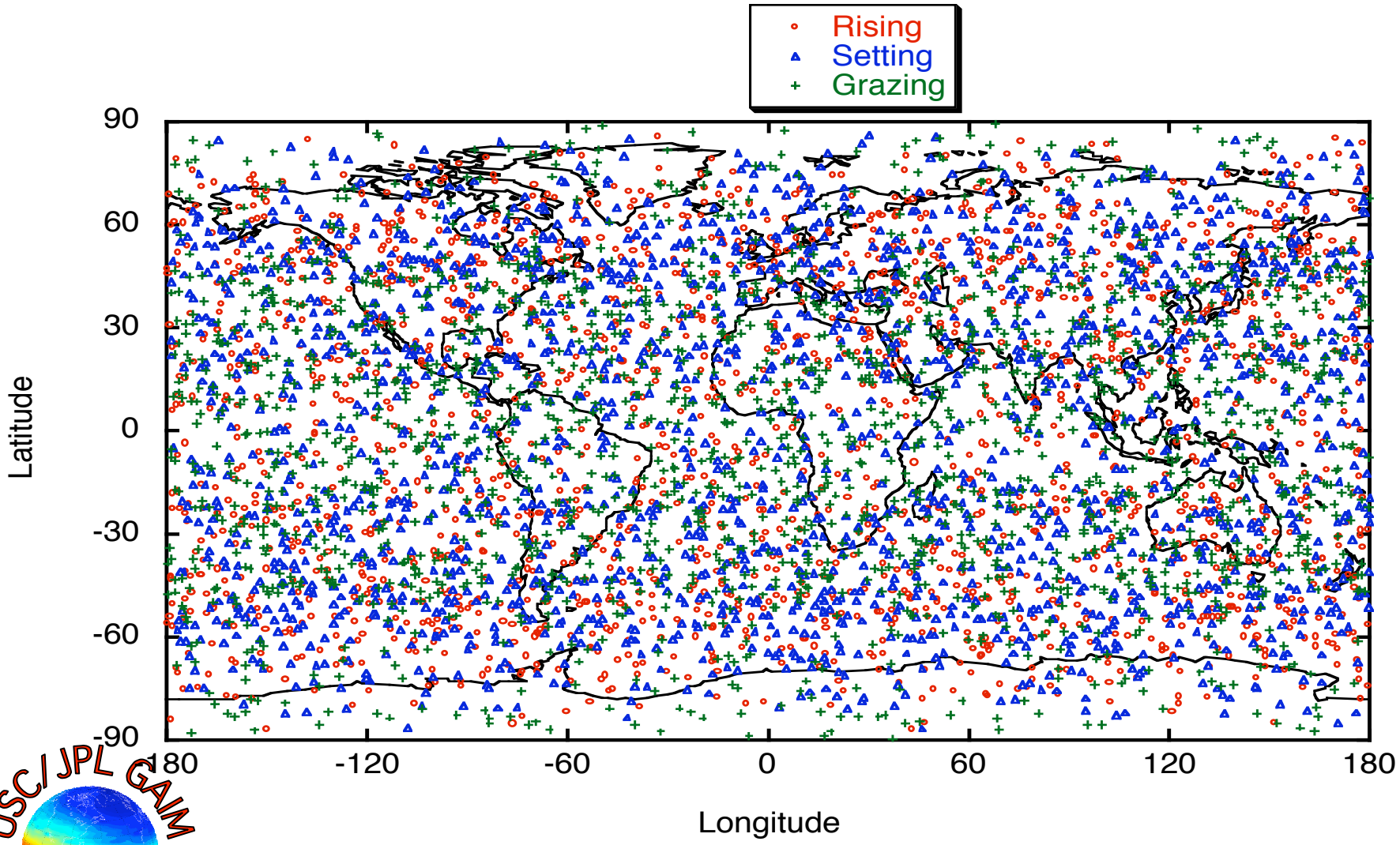
Information Content of GPS Slant TEC: Mid Latitude



Information Content of GPS Slant TEC: High Latitude



GPS Occultations:
COSMIC Coverage in 24 Hours



USC/ JPL GAIM

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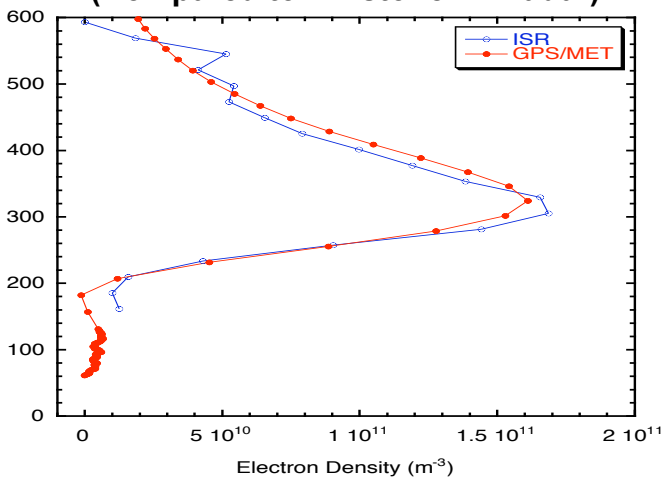
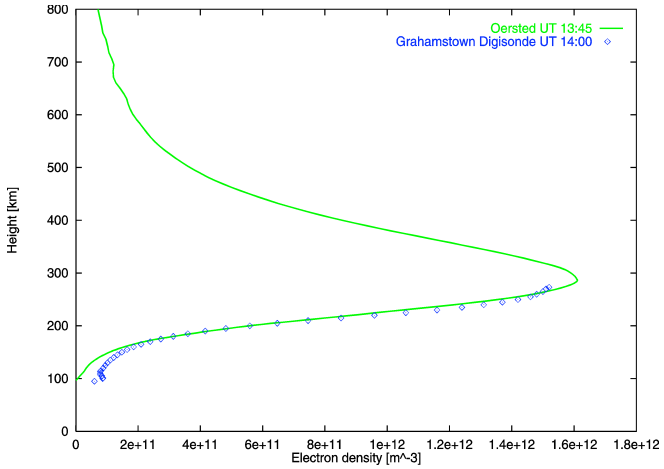
Examples of electron density profiles

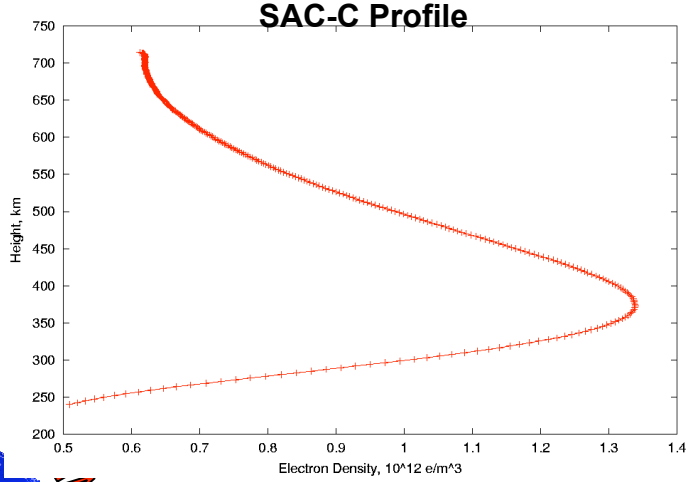
GPS/MET Profile
(Compared to Millstone hill radar)



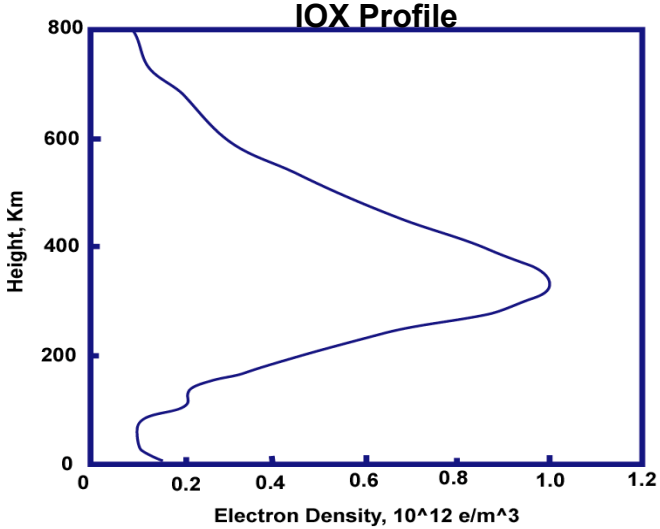
Oersted Profile
(Compared to nearby ionosonde)

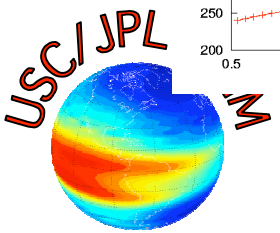


SAC-C Profile



IOX Profile





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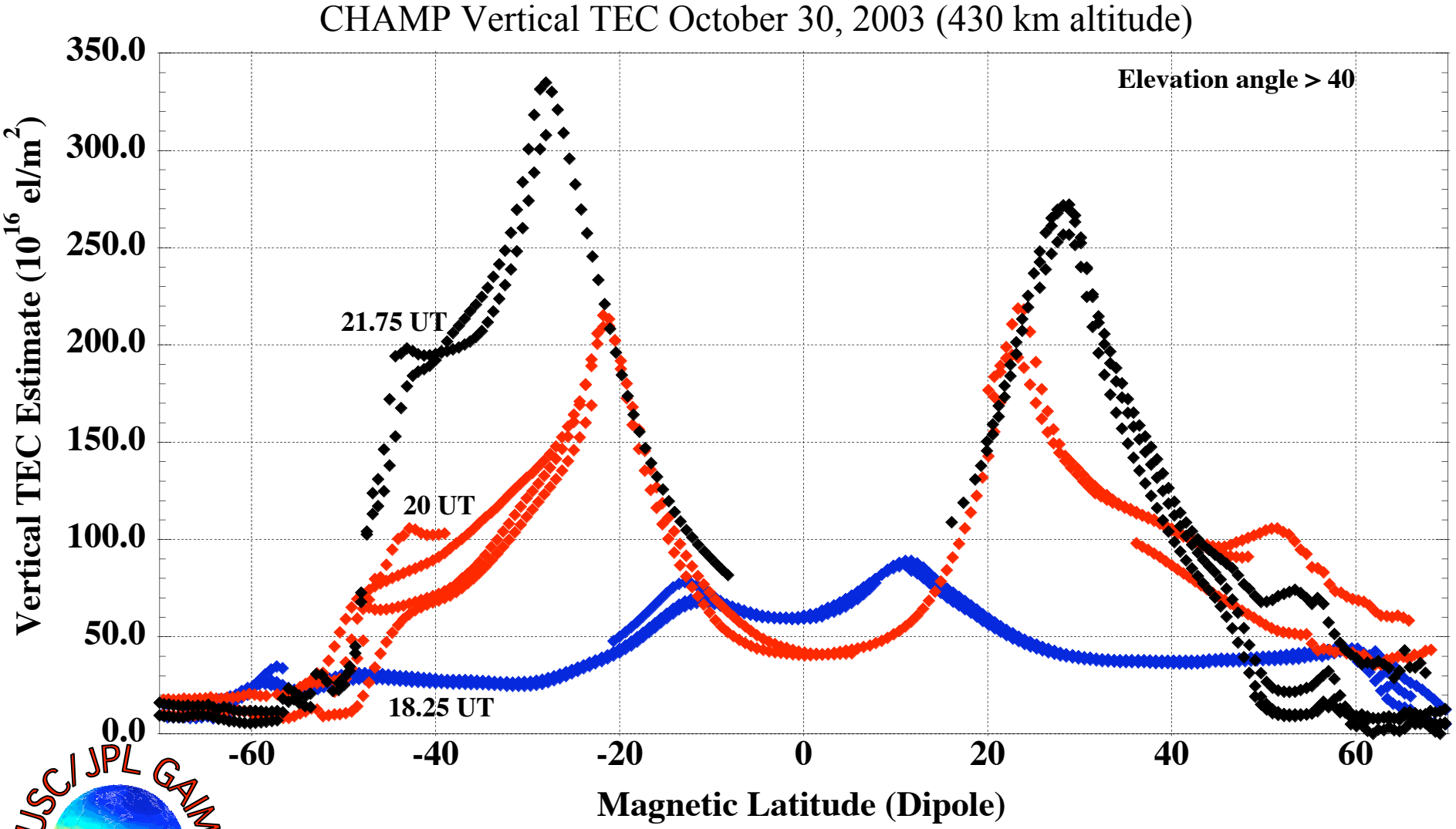
Plasma Redistribution During Halloween Storm, October 30, 2003



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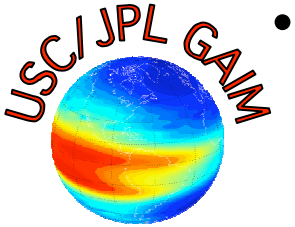
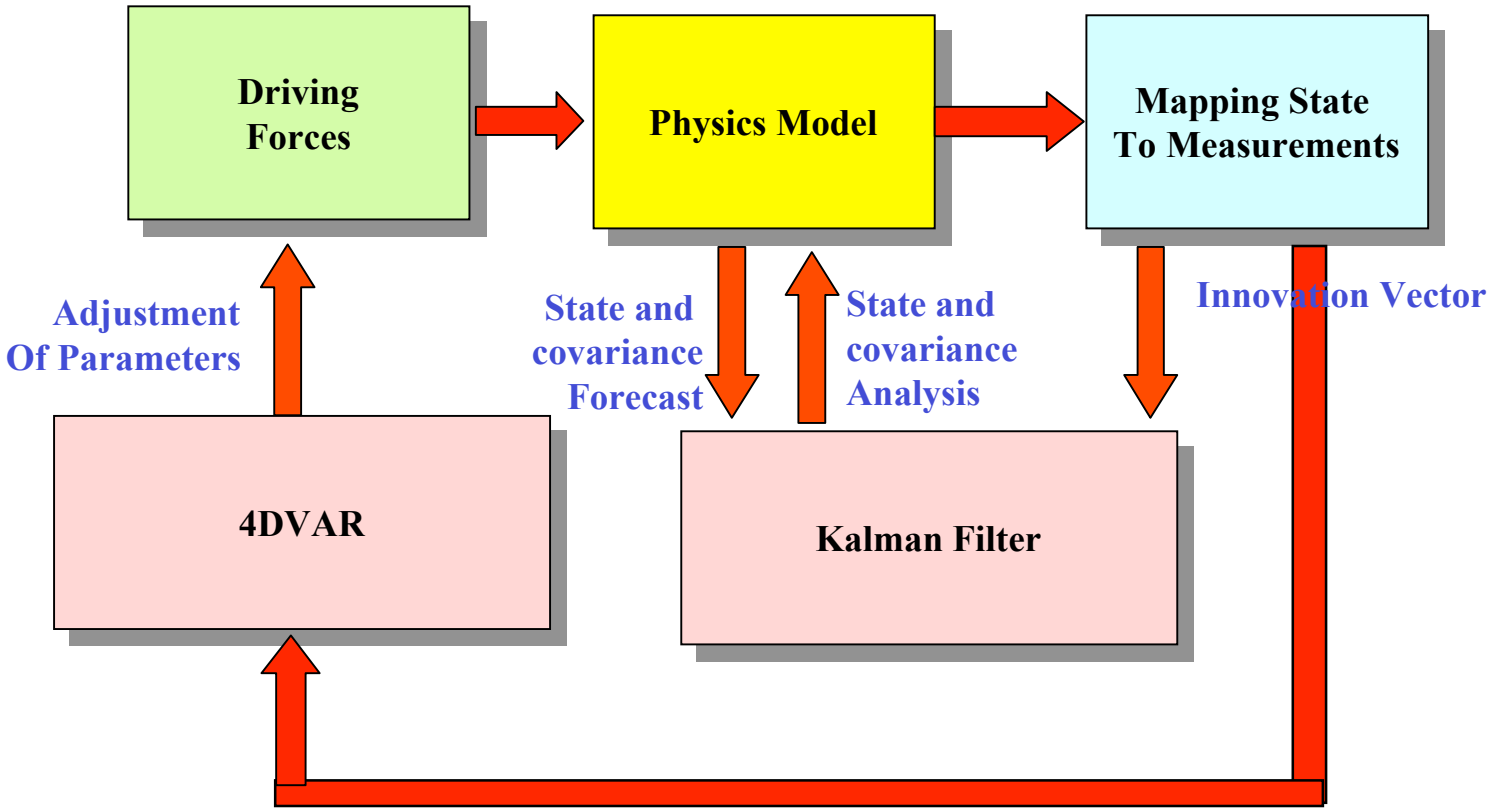
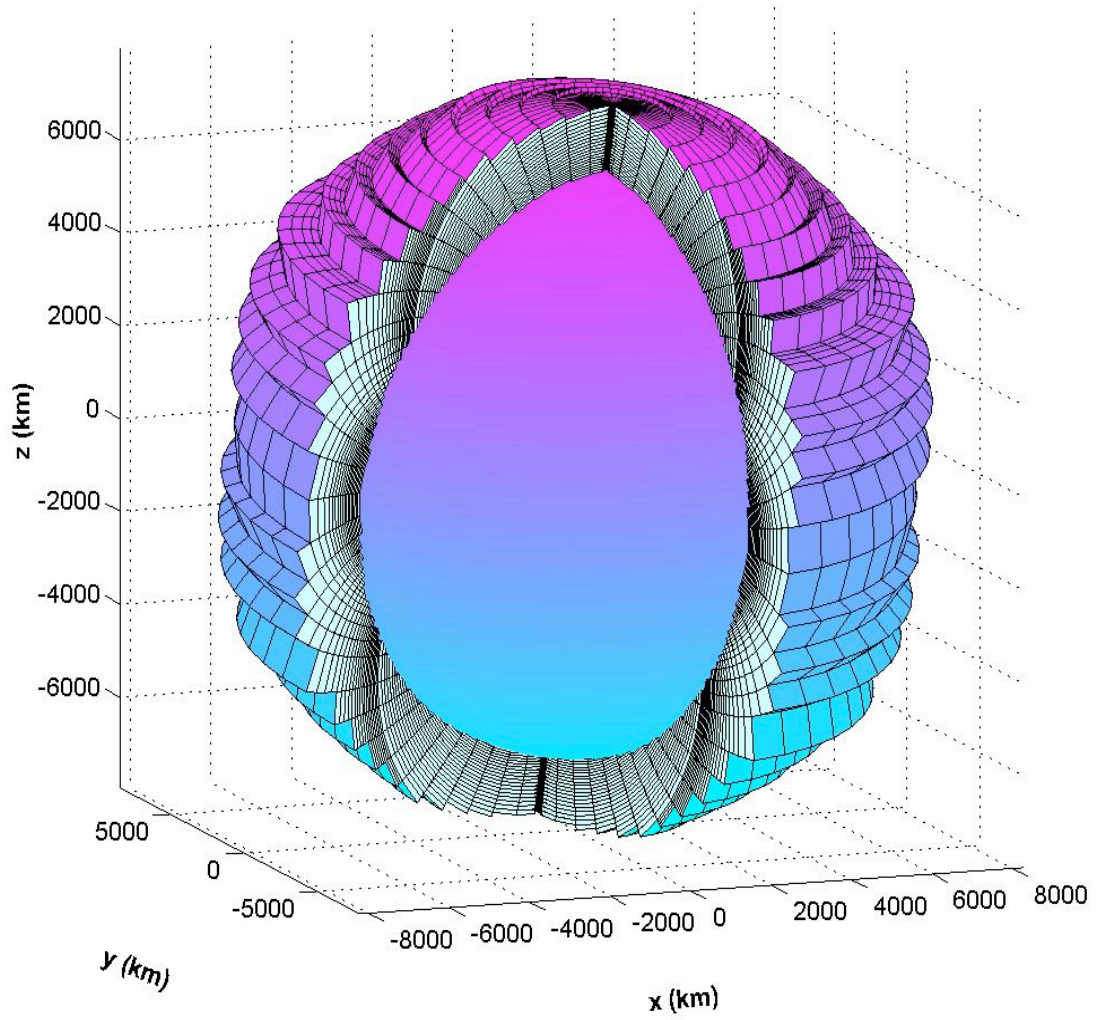


General Structure of GAIM



Forward Model

- Eulerian Grid Elements in p-q Magnetic Coordinates
- Variable Element Size
- Solve for Ion densities using Finite Volume Method
- Efficient Forward Propagation of the State
- Unconditionally Stable Time Integration
- Explicitly Compute Partial Derivatives needed for Kalman & 4DVAR optimization.



Optimization Approach: 4DVAR

$$J(n;\alpha) = \sum_{k=1}^{m} \left\| y_k - H_k n(t_k;\alpha) \right\|^2 + \beta \left\| n - n_0 \right\|^2 + \gamma \left\| \alpha - \alpha_0 \right\|^2$$

$$\nabla J(\hat{\alpha})$$

$$\nabla J(\hat{\alpha}) = 0$$

$$v_{eq}(t) = v_{eq,0}(t) + \sum_{k=1}^{N} \alpha_k \beta_k(t)$$

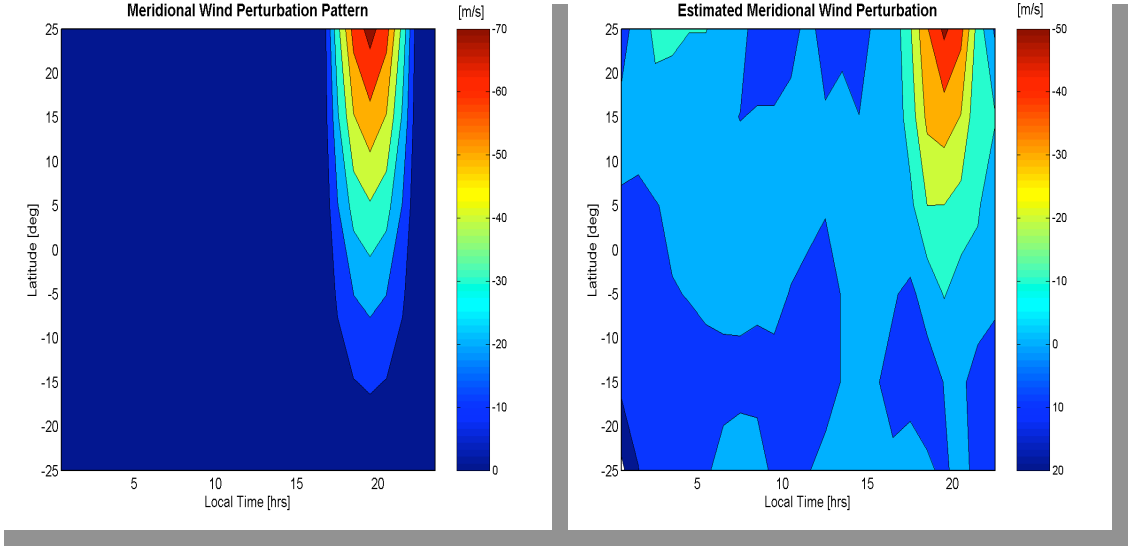
$$F(\mathbf{r}) = F_0(\mathbf{r}) + \frac{1}{\sum_{i=1}^{7} w_i} \sum_{i=1}^{7} w_i(\alpha', \beta) f_i(\mathbf{r}')$$

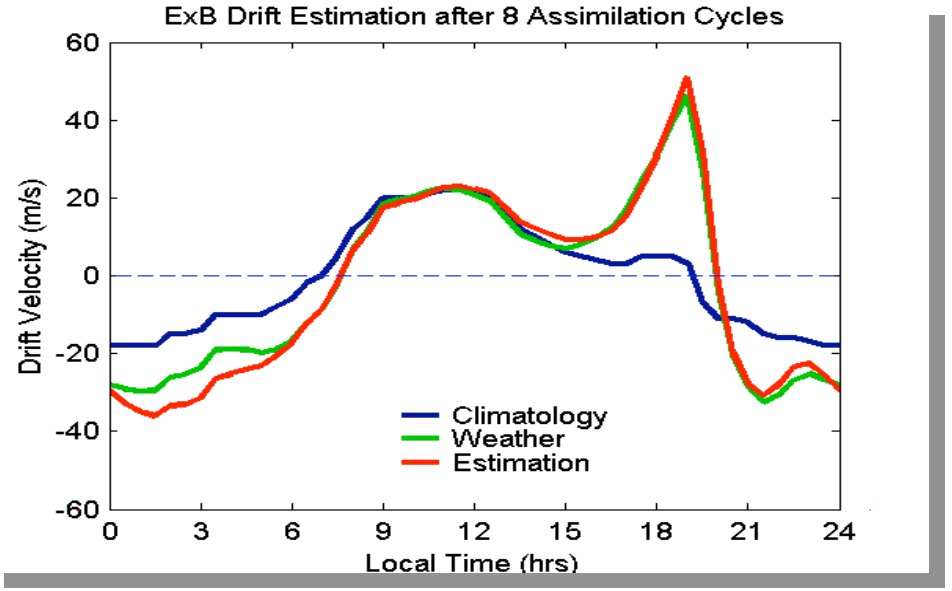
- **Non-linear least squares minimization**
  - *Cost function* to compute model deviation from observations
  - *Adjoint method* to compute gradient of cost function: computational efficiency
  - *Minimization*: finding roots using Newton's method by estimating driving parameters
  - *Parameterization* of model drivers

Estimate ionospheric drivers and optimize the state

Estimation of Ionospheric Dynamical Drivers

- Observation System Simulation Experiments (OSSE) to estimate "perturbed" drivers at low latitudes:
  - Neutral winds
  - **E×B** vertical drift velocity
  - Production terms
- Synthetic ground GPS TEC data

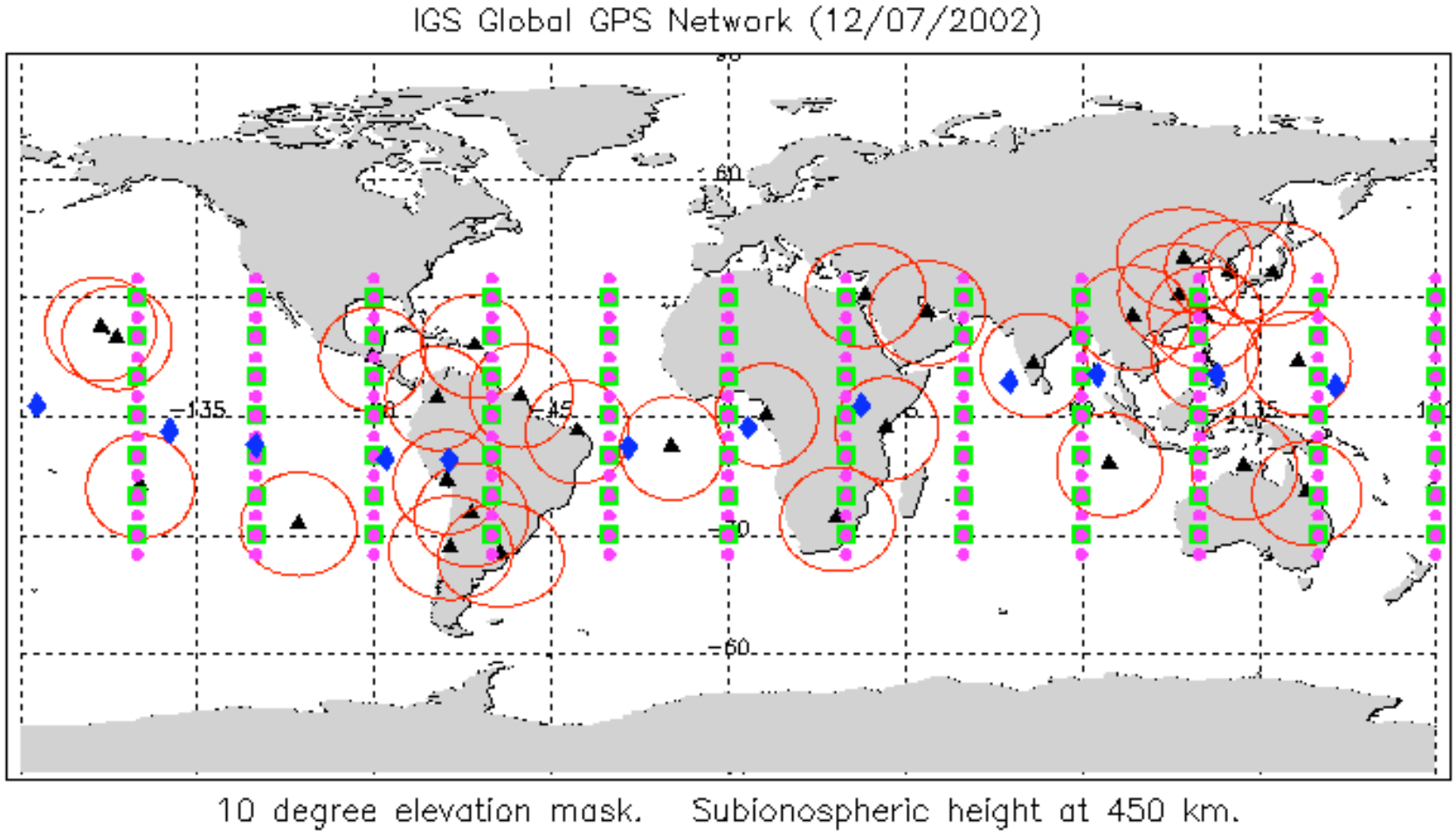




Need Sensitivities to Adjust Drivers

- Use Physics Model as a Black Box
  - Run Forward Model twice for different parameter choices
  - Difference resulting densities to compute numerical derivatives (grid of sensitivities)
  - Repeat for each driver parameter
  - Implies large number of forward model runs
- Develop Adjoint Model corresponding to the Forward Model
  - Run Forward Model once
  - Run Adjoint Model once
  - During Adjoint run all parameter sensitivities are computed
  - Use sensitivities in 4DVAR optimization or extended Kalman filter to adjust drivers

Parameter Grid and GPS Stations

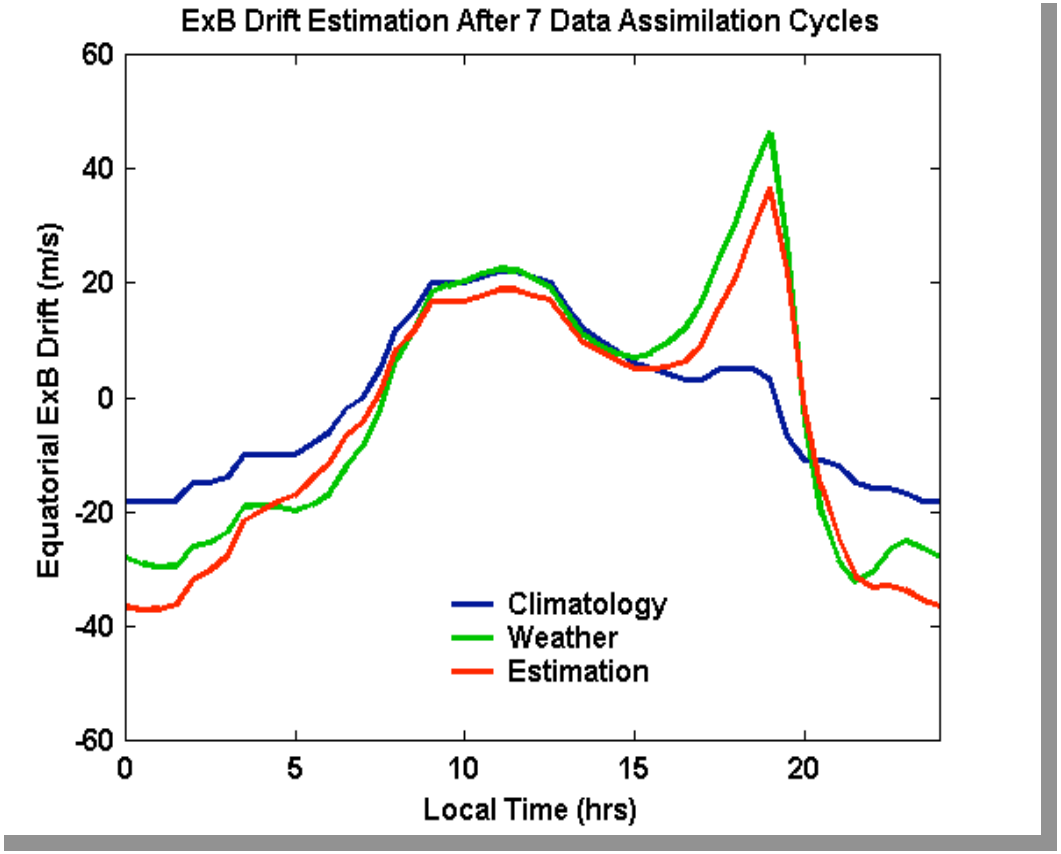


4DVAR OSSE Results: ExB Drift

- **Simulation Experiment**
  - **24 GPS Satellites**
  - **48 ground receivers**
  - **0 LEO**
- **Climate initial condition & drivers**
- **Assimilation period:**

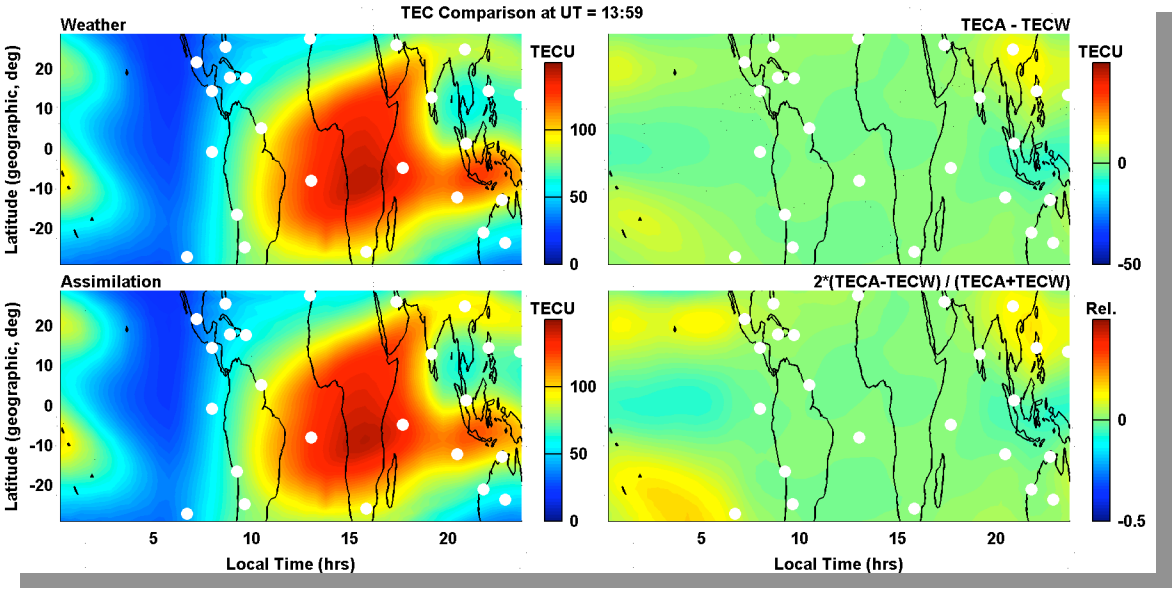
  2 hours
- **Noise:**

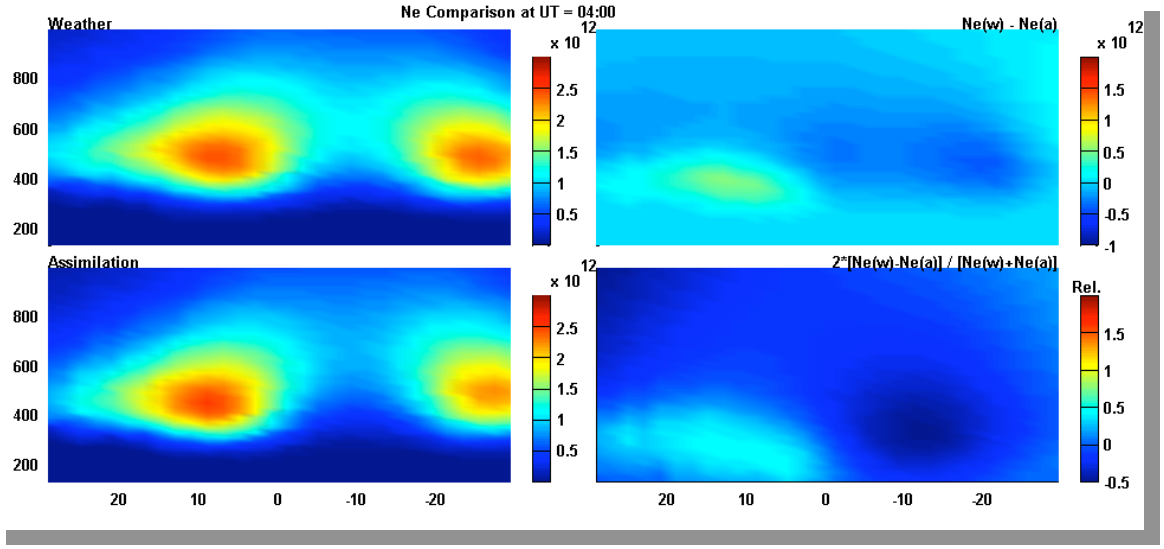
  20 TECU sigma



Improved Drivers => Improved Forecasting

- Improved drivers enable more accurate “nowcast” and forecast of 3D electron density.
- Plot differences between simulated ionospheric “weather” and assimilation results for vertical TEC and Ne profiles.





Kalman Filter Equations

State Model

$$x_{k+1}^{t} = \Phi_k x_k^{t} + \Gamma_k^{q}$$

Measurement Model

$$m_k^{o} = H_k x_k^{t} + \Gamma_k^{o}$$

Noise Model

$$\Gamma_k^{o} = \Gamma_k^{m} + \Gamma_k^{r}$$

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

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

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

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

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

$$P_k^{a} = P_k^{f} - K_k H_k P_k^{f}$$

$$x_{k+1}^{f} = \Phi_k x_k^{a}$$

$$P_{k+1}^{f} = \Phi_k P_k^{a} \Phi_k^{T} + Q_k$$

Band-Limited Kalman Using Physical Correlation Lengths

$$\rho_{ij} = \sigma_i \sigma_j \exp\left[-\left(\frac{r_i - r_j}{R}\right)^2 + \left(\frac{\phi_i - \phi_j}{\Phi}\right)^2 + \left(\frac{\lambda_i - \lambda_j}{\Lambda}\right)^2\right]$$

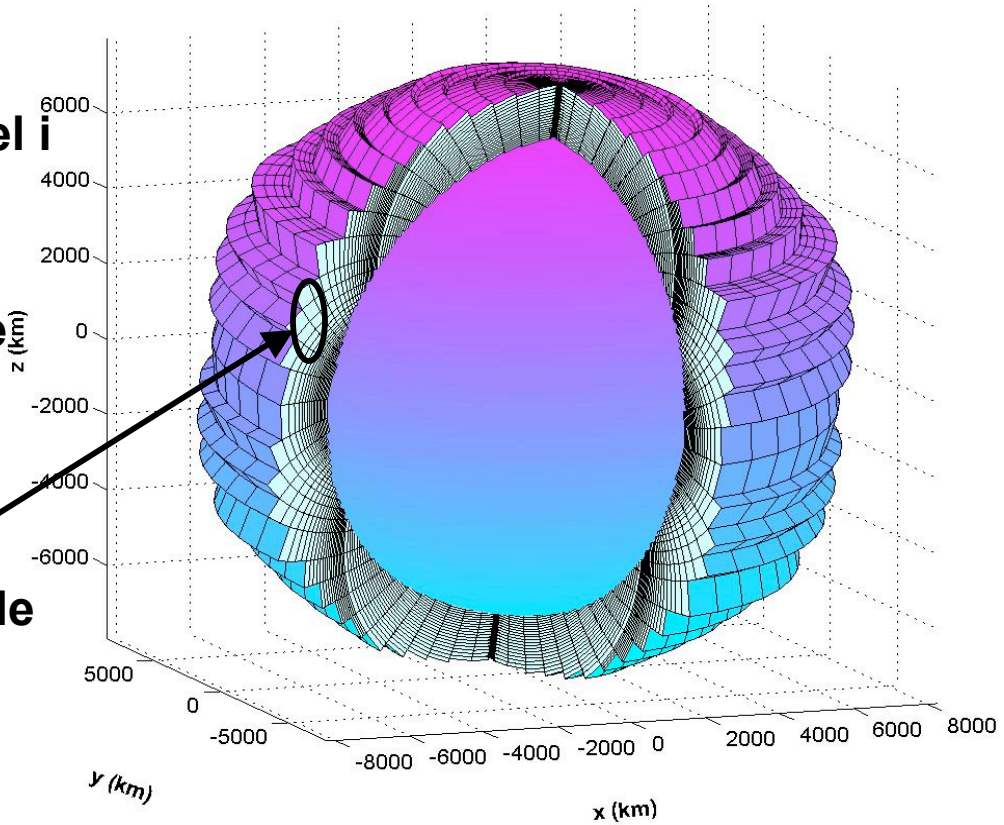
ρ_{ij} = Corr. between voxel i and j

σ_i = Uncertainty in density in voxel i

R = Correlation length in altitude

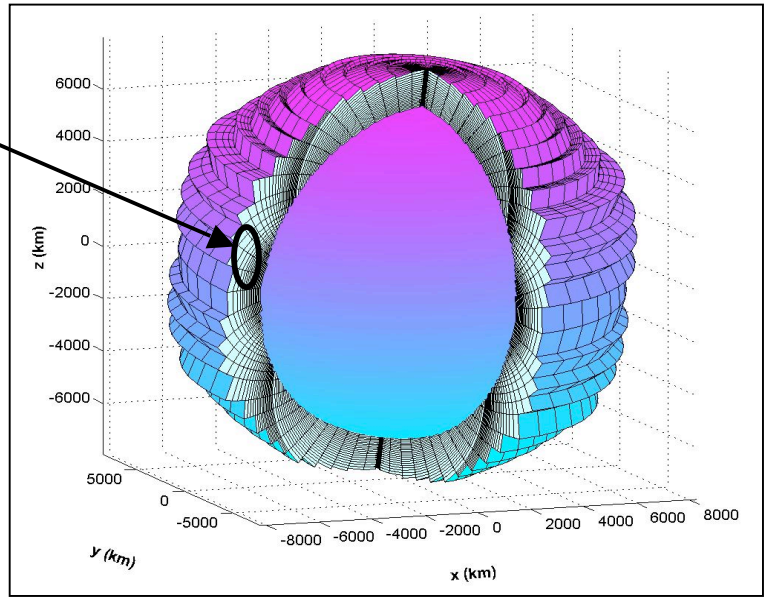
Φ = Correlation length in latitude

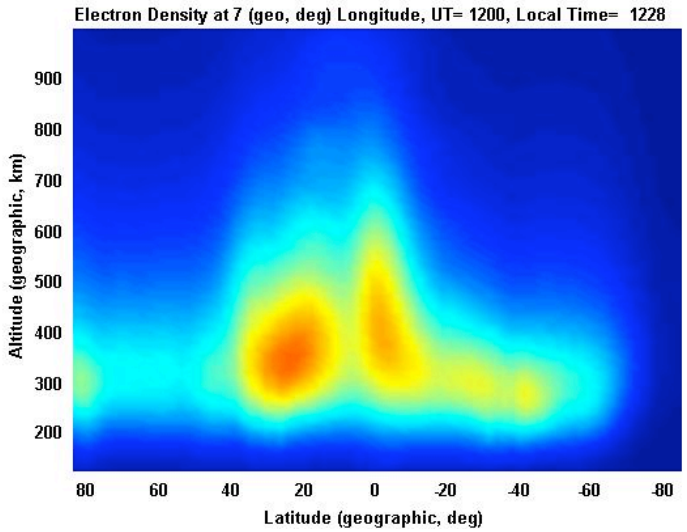
Λ = Correlation length in longitude



Band-Limited Kalman Filter

- Approximate Kalman: Save only part of covariance matrix based on physical correlation lengths.
- Tested extensively with **real** data: Ground GPS TEC from 100-200 global sites.
- 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



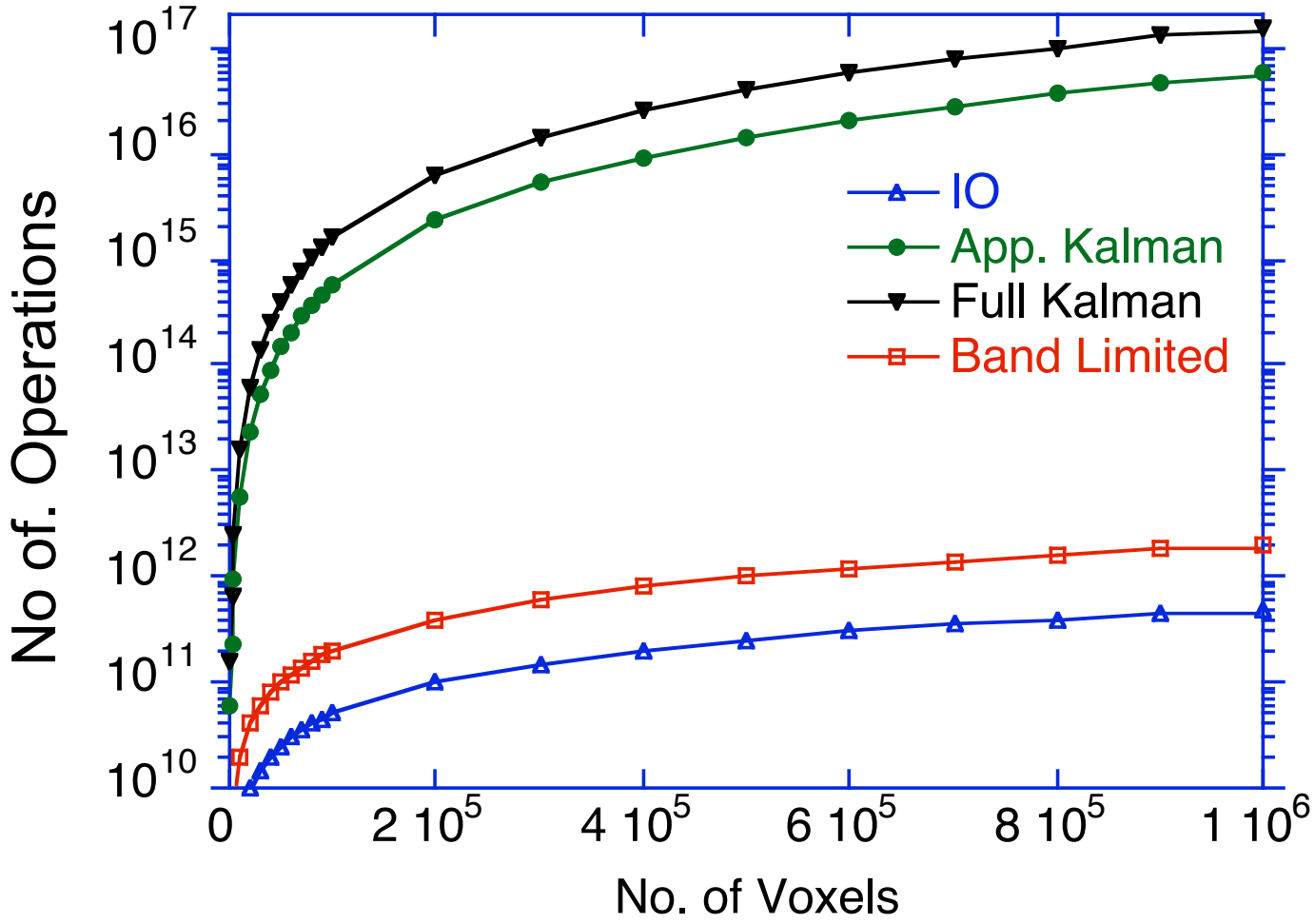


Summary Of No. Of Operations

Approach	No. of Operations
Full Kalman	$28800 \cdot N^2 + M \cdot N^2$
Optimal Interpolation	$2 \cdot N \cdot M$
Band Limited	$A \cdot N \cdot M$

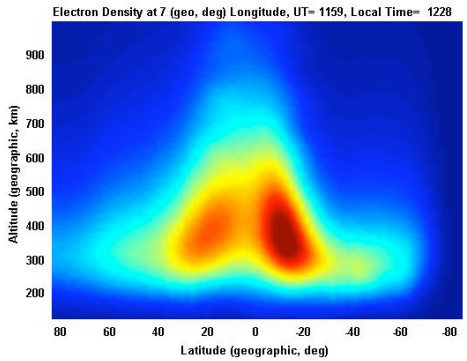
M = No. of measurements
N = No. of Voxels
A = No. of neighbor elements with non-zero covariance

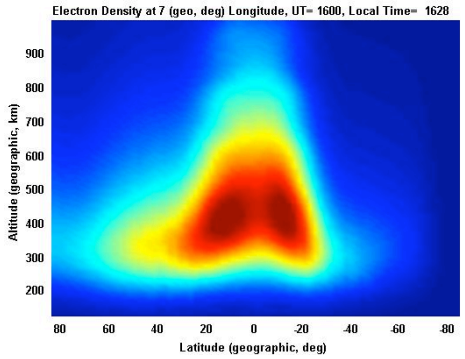
No. of Operations per 100,000 TEC Measurements

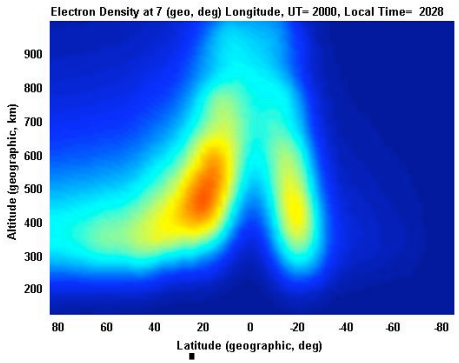


GAIM Density, Climate vs. Assimilation
June 15, 2002

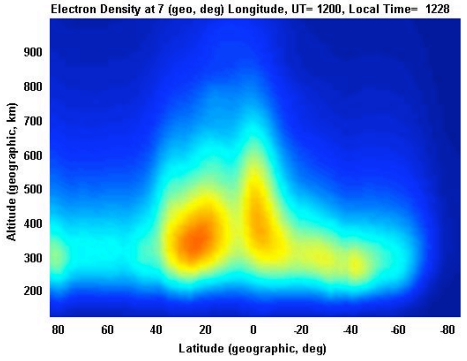
Climate

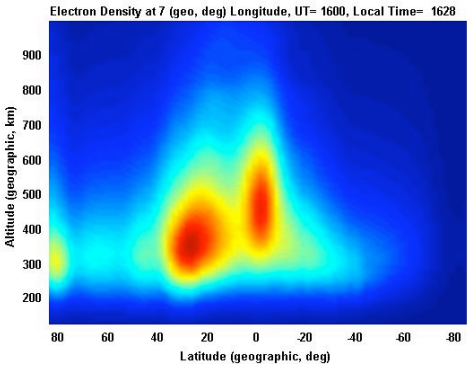


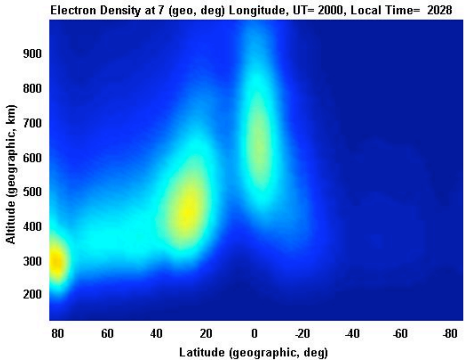




Assimilation







1200 UT

1600 UT

2000 UT

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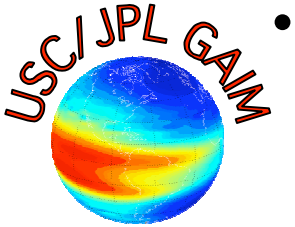


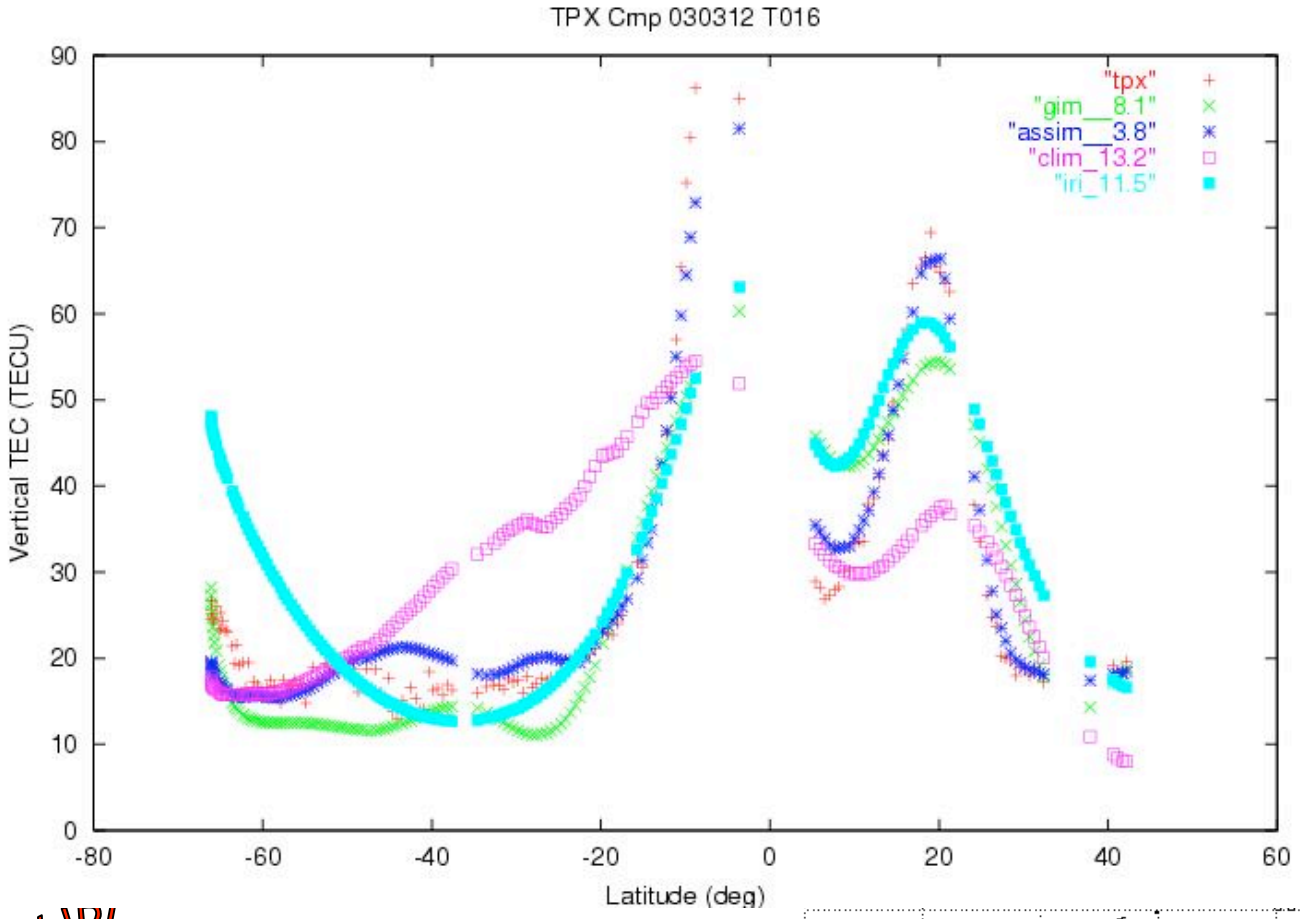
Emphasizing Continuous Validation

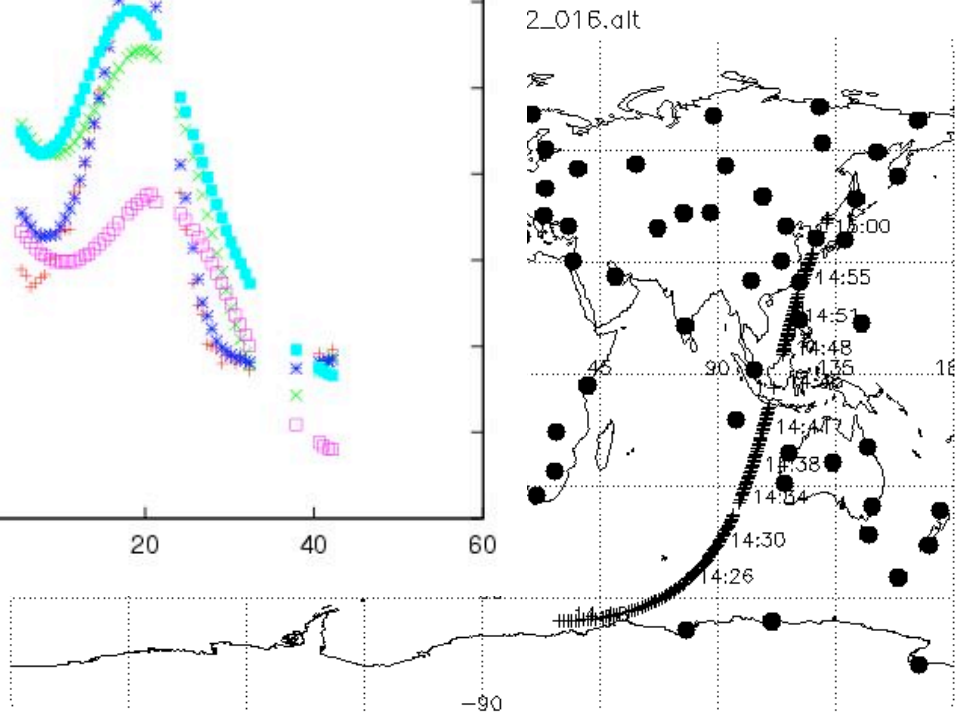
- **Data Assimilation is complicated!**
  - Estimating drivers and density state
  - Combining 3 or 4 potentially inconsistent datatypes
- **Continuous Validation is crucial.**
  - Daily accuracy statistics
  - Validate densities and TEC
  - Validate resulting application products
    - OpSend products
    - Ray tracing

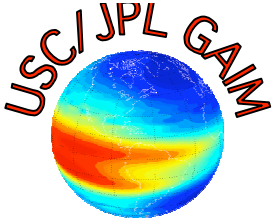
Daily GAIM Operations (Mar 2003 - Present)

- Using Physics-Based, Band-Limited Kalman Filter
- Driver adjustment will be added soon
- Actually two runs each day:
  - Test bed to compare different covariance strategies and grid resolutions
- Input 100-200 globally-distributed GPS TEC sites
- Continuous validation against:
  - Vertical TEC from TOPEX
  - Slant TEC from independent GPS sites
  - FoF2 & HmF2 from ionosondes (but QC issue)

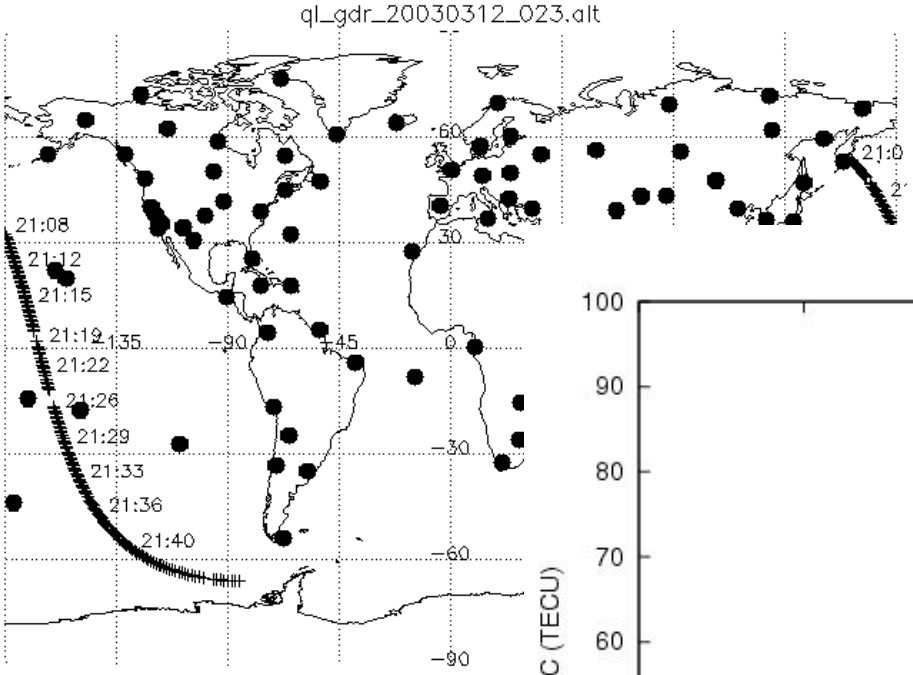
TOPEX Track #16 on 2003/03/12

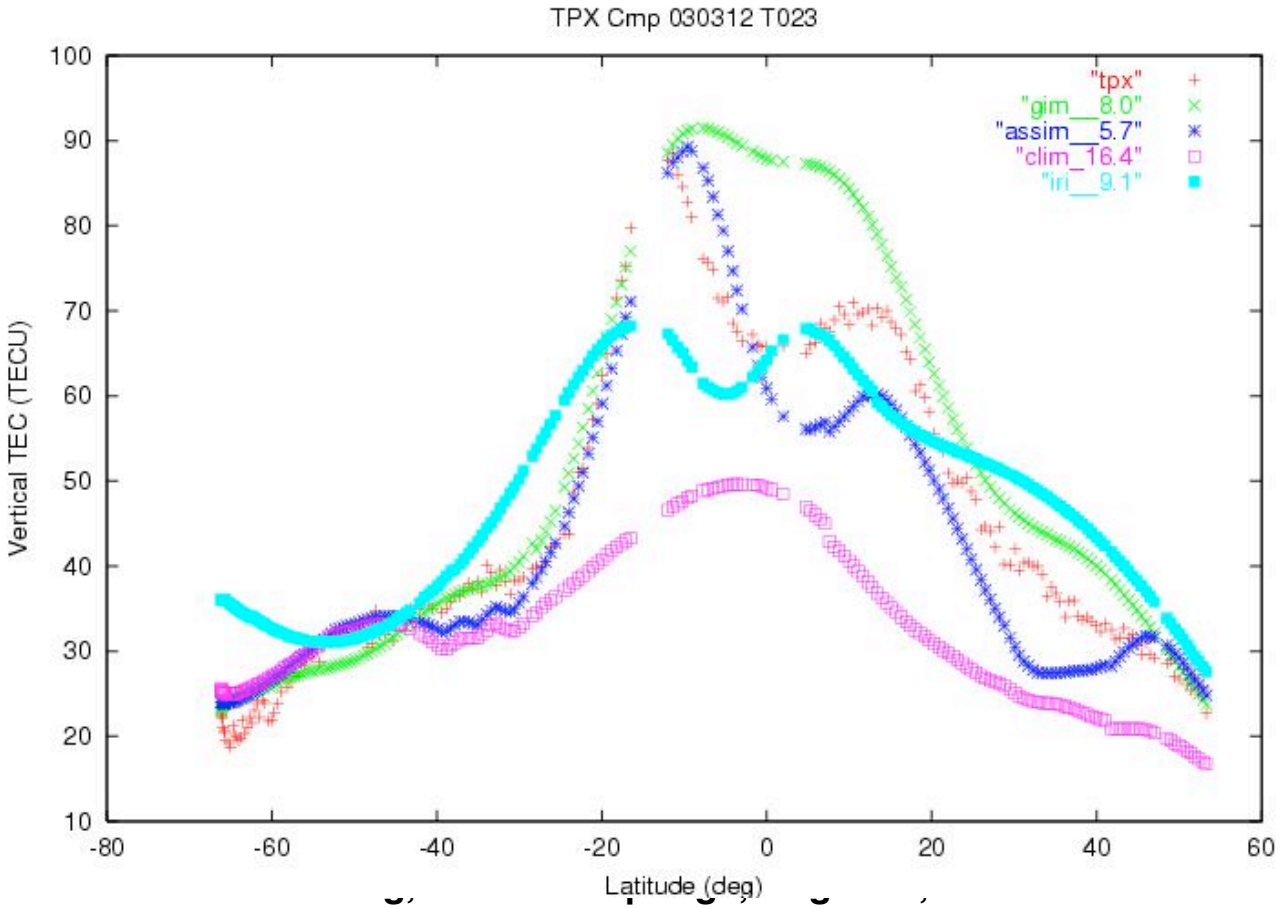






TOPEX Track #23 on 2003/03/12

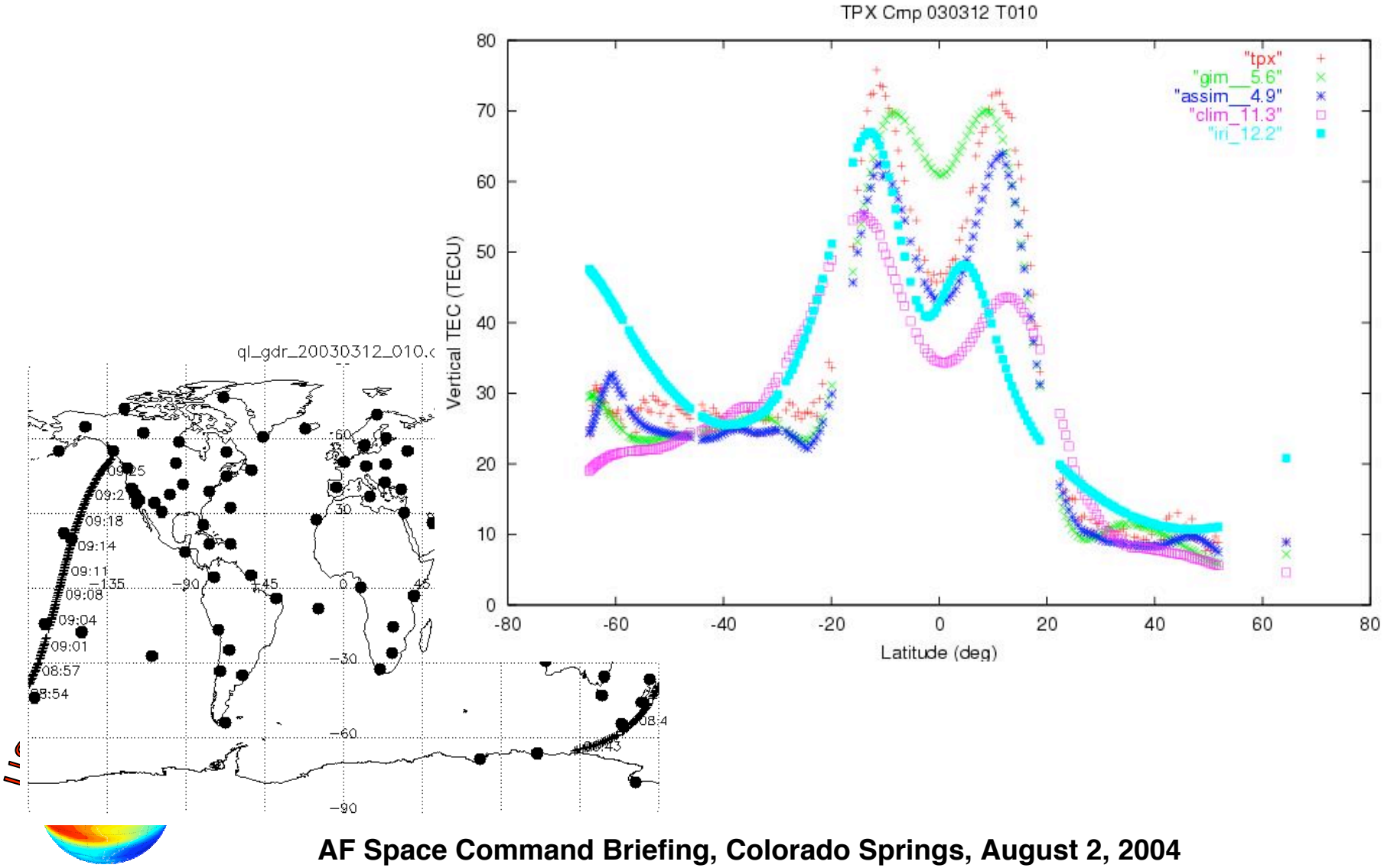




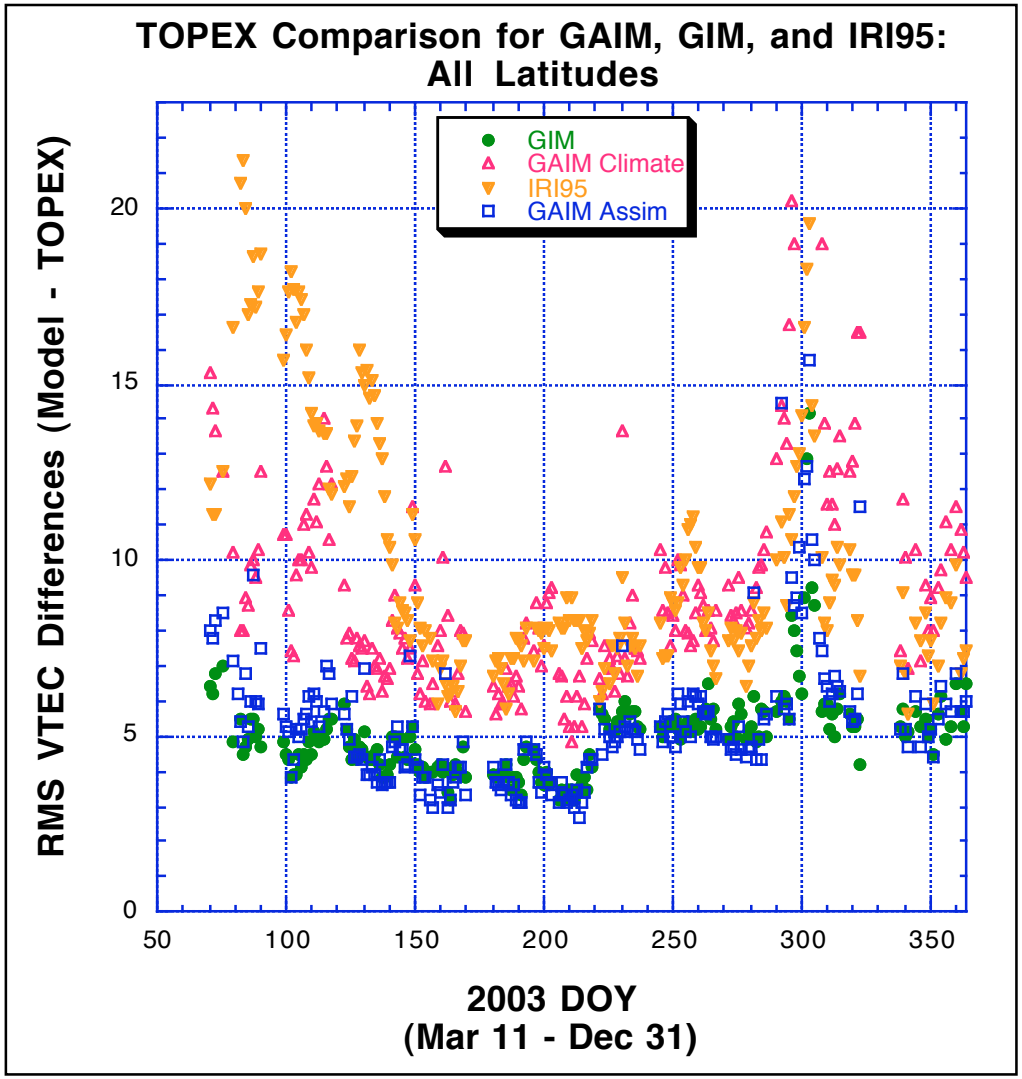
USC/ JPL GAIM

AF Sp

TOPEX vs. GAIM using ground GPS



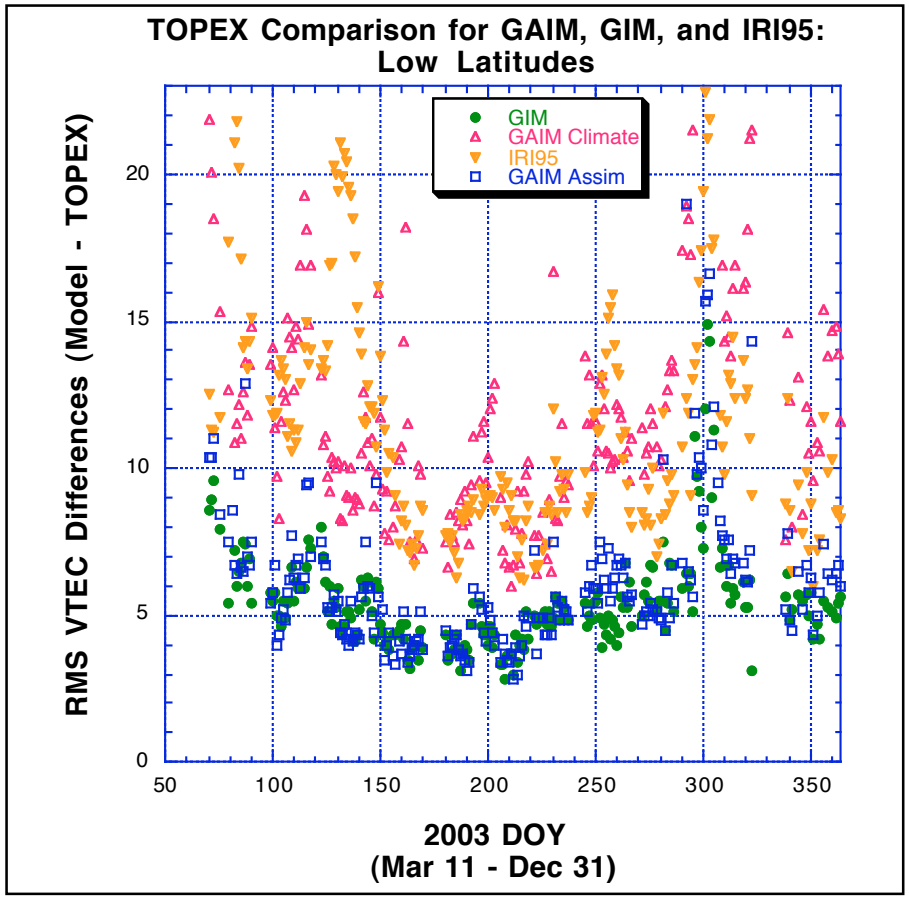
TOPEX Comparisons for Mar 11 - Dec 31, 2003: GAIM versus GIM & IRI95

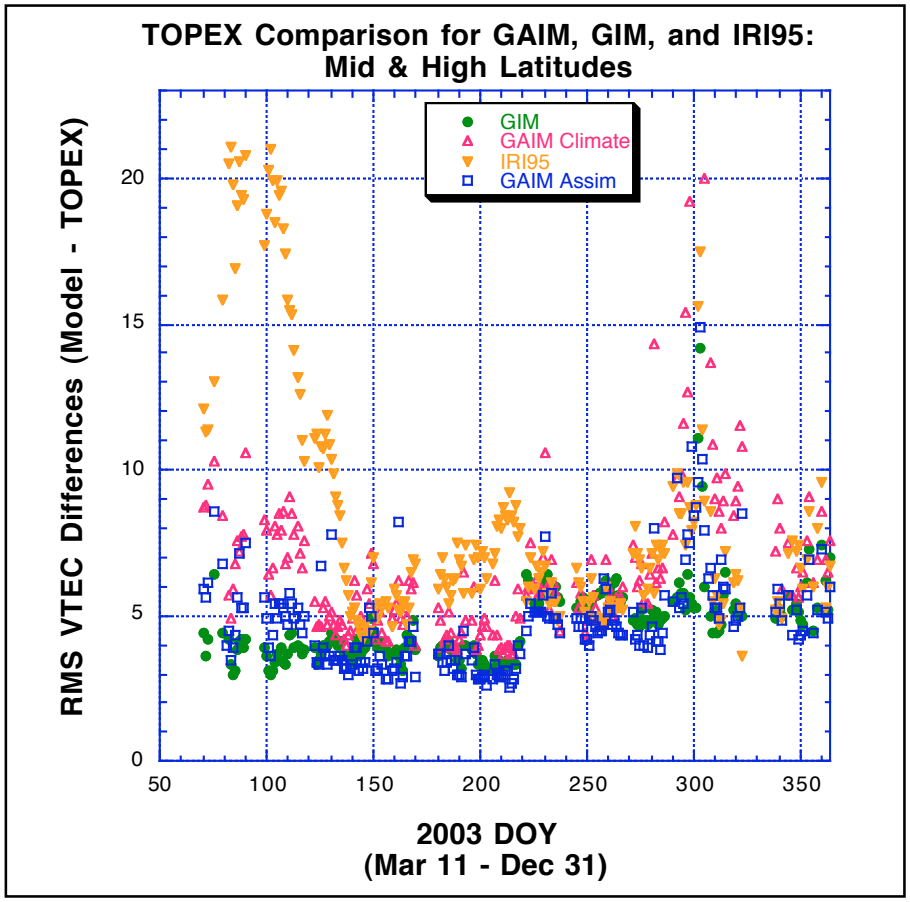


USC/ JPL GAIM

AF Space Command Briefing, Colorado Springs, August 2, 2004

TOPEX Comparisons for Mar 11 - Dec 31, 2003: GAIM Assim. at Low vs. Mid & High Latitudes





USC/ JPL GAIM

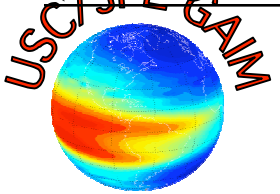
AF Space Command Briefing, Colorado Springs, August 2, 2004

Validation Modes

- **Case Studies**
  - Gather quality-controlled data from instrument PI's
  - Selected time periods
- **Automated Validation**
  - Automatic data retrieval and QC
  - Push button operation for any day
- **Continuous Validation: Post-processing**
  - Few weeks to months behind RT (e.g., ISR)
  - But continuously accumulate GAIM accuracy statistics
- **Continuous Validation: Daily**
  - Validate yesterday's specification & forecast every day
  - Immediately discover data problems
- **Continuous Validation: Hourly**
  - Validate every 15 minutes to a few hours (e.g., JASON)
  - Withheld input data (e.g., ionosonde, GPS TEC)

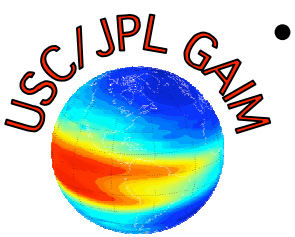
Table of Validation Modes vs. Datatypes

	Case Studies	Automated pushbutton	Continuous: Post-process	Continuous: Daily	Continuous: NRT
TOPEX/JASON VTEC	Done	Done	Done	Done	Done (JASON 3-hr)
Independent GPS STEC	Done	Done	--	Done	Done
Ionosonde NmF2,HmF2	Done	Done	Coming	Possible	Possible
SSUSI/SSULI pre-processing	NRL 2D retrievals	Possible	Possible	Possible	Possible
DMSP in-situ density	Done	Pending	Pending	Possible	Possible
C/NOFS density & E fields	Planned	Planned	Possible (72 hour delay)	Possible (at AFWA?)	Possible (at AFWA?)
COSMIC data/retrievals	Planned	Planned	Planned	Possible (at JPL)	Possible (at JPL, 3-hr)
ISR profiles (Madrigal db)	Done	Coming	Coming	Possible for some sites?	Not possible



Outline

- Motivation: It's All About the Data!
- USC/JPL GAIM: 4DVAR & Sparse Kalman
- Daily GAIM Kalman Runs & Validation
- **Extensive Validation, Case Studies**
- RT GAIM: Operational Prototype
- Ionospheric Data Assimilation In-A-Box
- Validation Datasets & Collaboration



Data Types Available

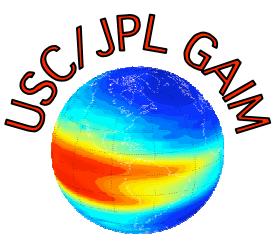
- **Ground GPS Data (Absolute TEC)**
  - >160 5-min. to Hourly Global GPS Ground Stations
  - Assimilate >300,000 TEC points per day
- **Space GPS Data (Relative TEC)**
  - CHAMP (@ 440 km)
  - SAC-C (@ 700 km)
  - IOX (@ 800 km)
  - GRACE (@ 350 km)
  - Topex/Poseidon (@1330 km) (Upward looking only)
  - Jason 1 (@1330 km) (Upward looking only)
  - C/NOFS & COSMIC constellation
- **UV airglow data (135.6 nm)**
  - LORAAS on ARGOS, GUVI on TIMED
  - SSUSI/SSULI on DMSP
- **Other Data Types**
  - TEC from TOPEX Altimeter
  - Ionosonde
  - DMSP in situ
  - CHAMP in situ
  - GRACE Cross links
  - ISR

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**

Case Studies

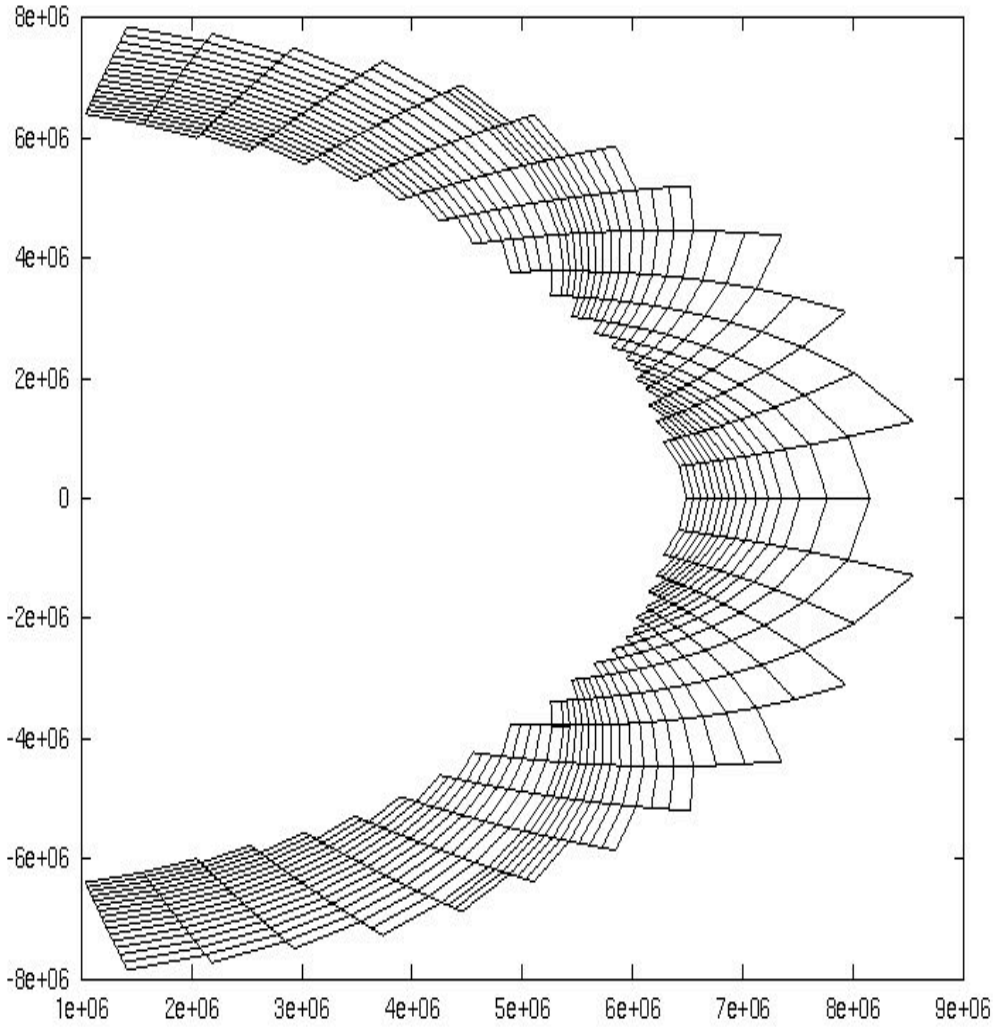
- **Ingest GPS occultations**
  - Input: Ground GPS + IOX occultations
  - Validation: Abel profiles + TOPEX
- **Slant TEC Prediction (Interpolation) Accuracy**
  - Input: 200 ground GPS sites
  - Predict: TEC from 11 independent GPS sites
- **Ionosonde Validation (now daily)**
  - Input: 200 ground GPS sites
  - Validation: Ionosonde NmF2 & Hmf2
- **Ingest UV Radiances**
  - Input: Ground GPS + LORAAS limb scans
  - Validation: NRL profile retrieval



Assimilation Runs for July, 22-24, 2002

- **Four runs:**
  - **GAIM Climate (no data)**
  - **Ground GPS only**
  - **IOX occ. Only**
  - **Ground + IOX**

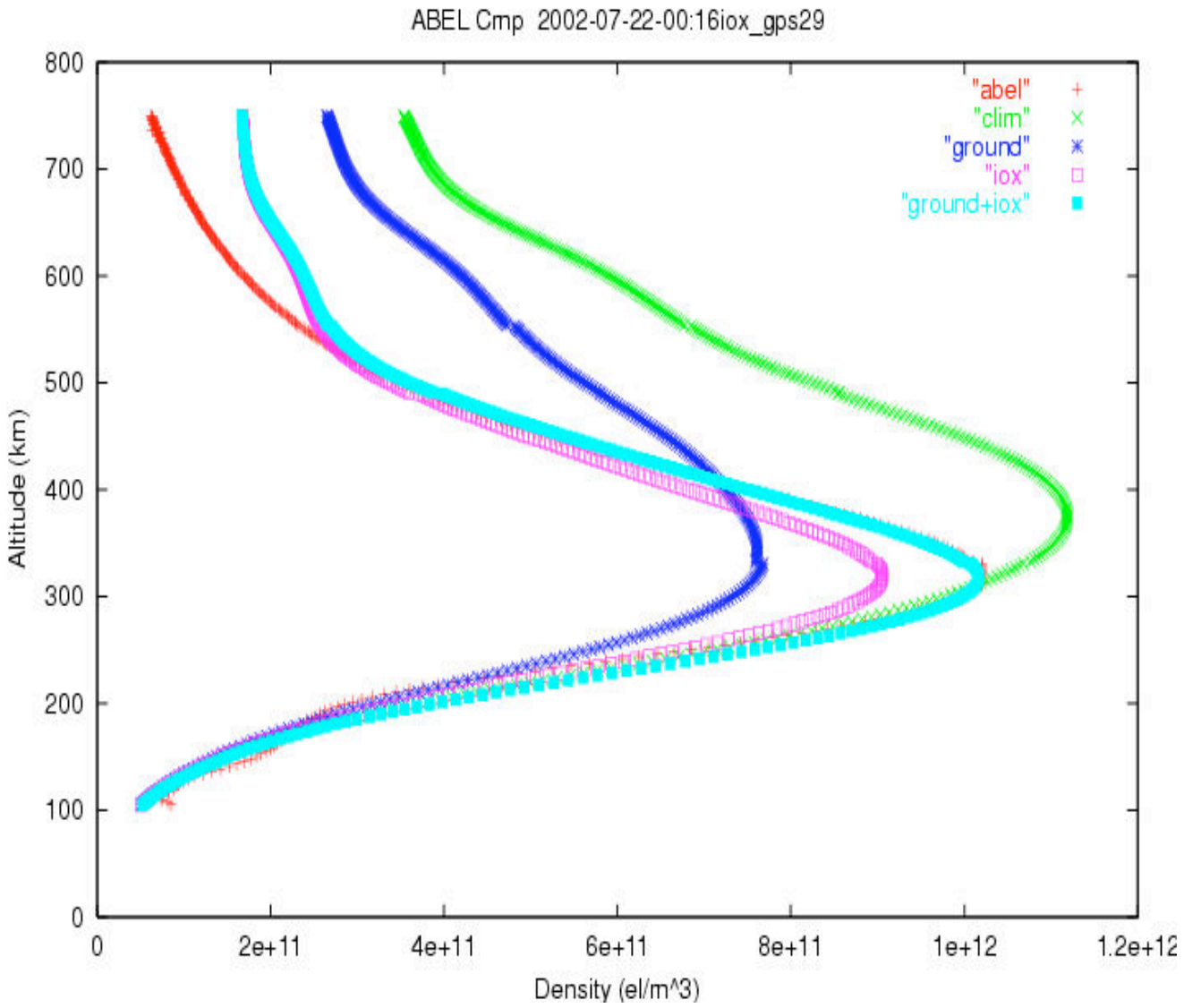
- **Resolution:** **5 deg. Lat.**
  15 deg. Lon.
  80 km alt.
- **No. of voxels** **13107**
- **Correlation length** **5 deg. Lat.**
  15 deg. Lon.
  80 km alt.



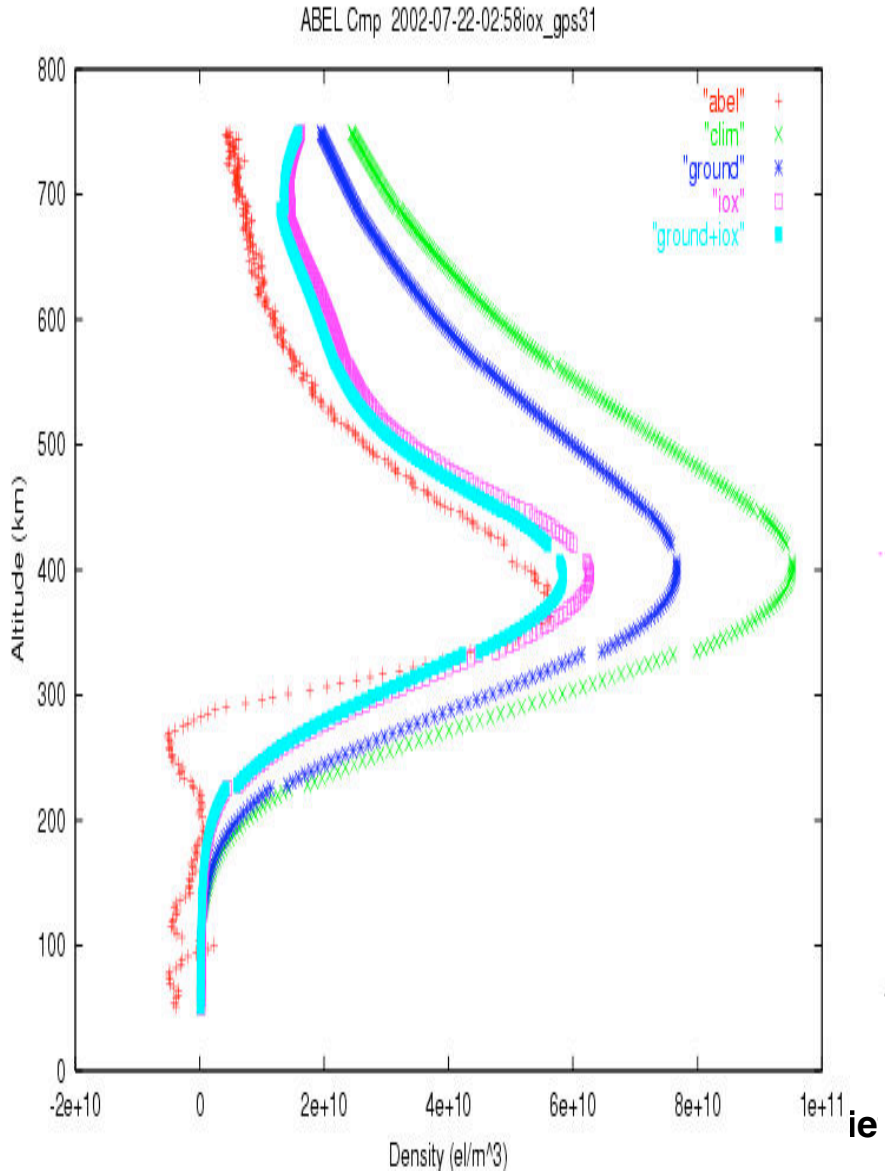
GAIM vs. Abel
Comparisons at the Occultation Tangent Point

Profiles are obtained by:

- **Abel Inversion (“abel”)**
- **GAIM Climate (no data) (“clim”)**
- **GAIM Analysis assimilating ground TEC data only (“ground”)**
- **GAIM Analysis assimilating IOX TEC data only (“iox”)**
- **GAIM Analysis assimilating both ground and IOX data (“ground+iox”)**



EXAMPLES OF PROFILES RETRIEVED BY USE OF DIFFERENT DATA SETS



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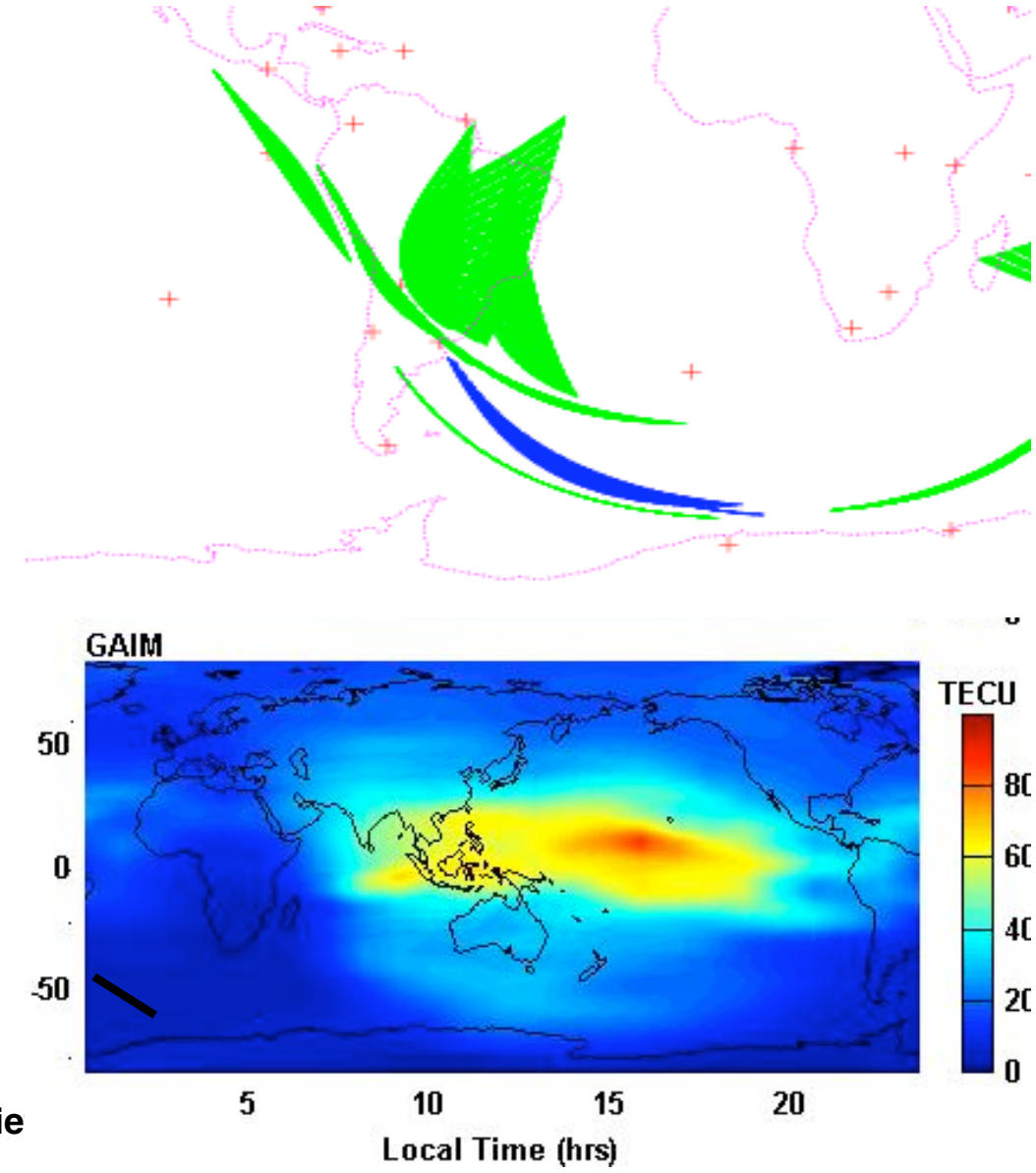
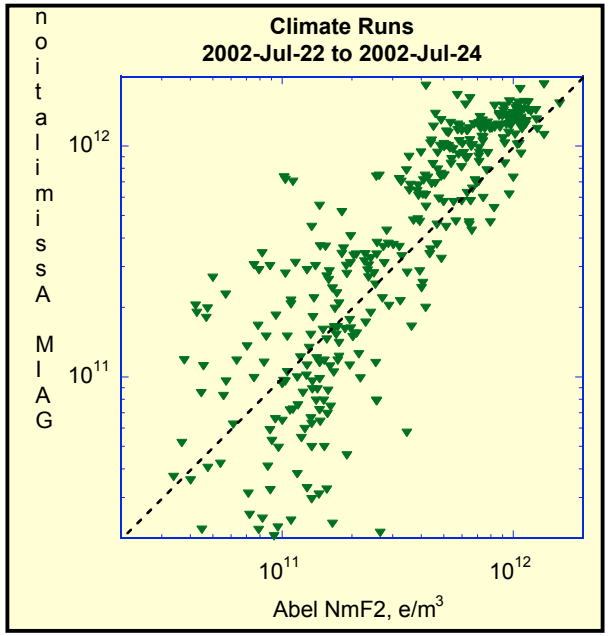
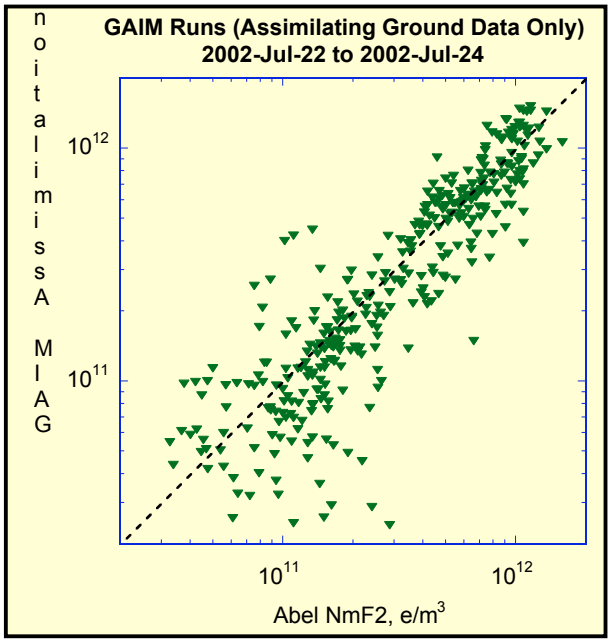
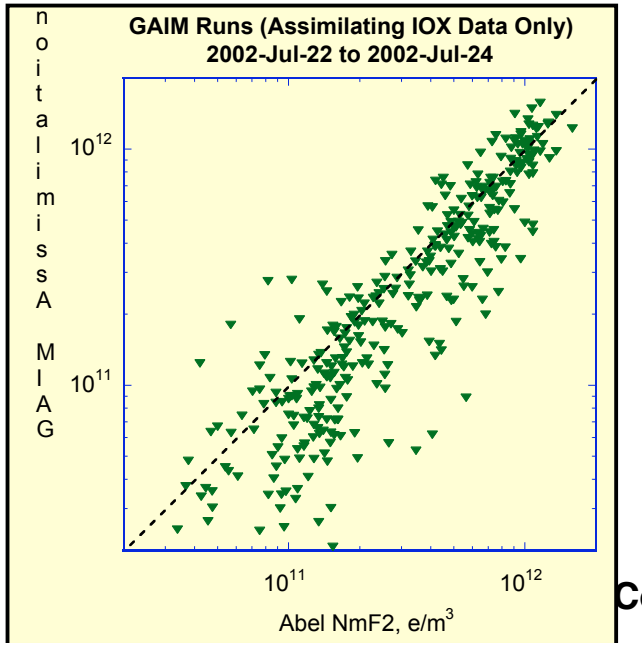
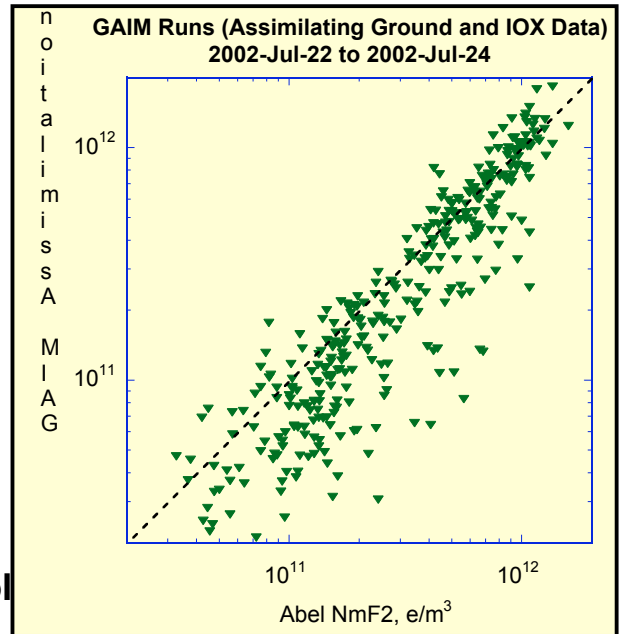


GAIM vs. Abel NmF2 Comparison



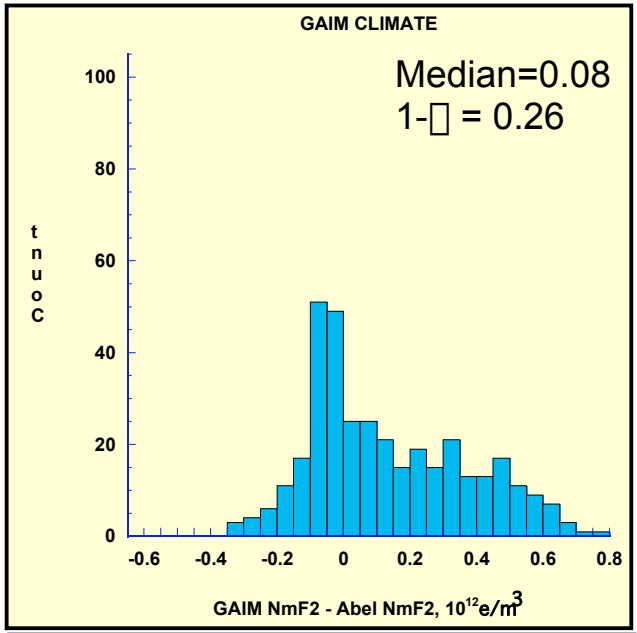


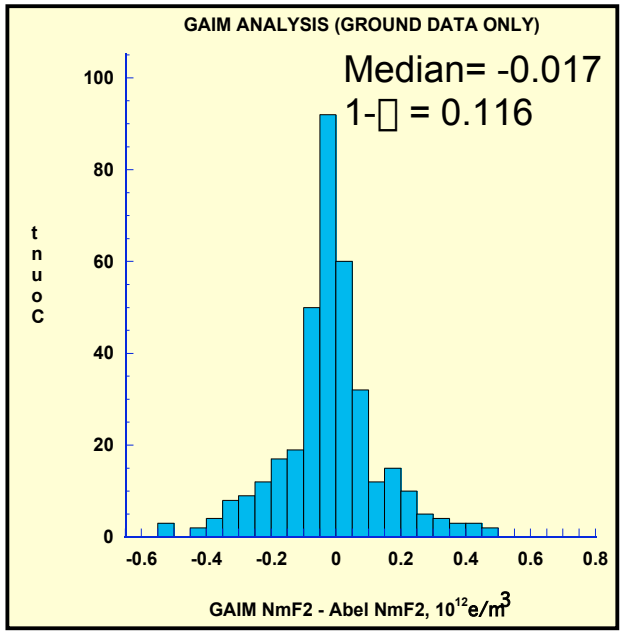


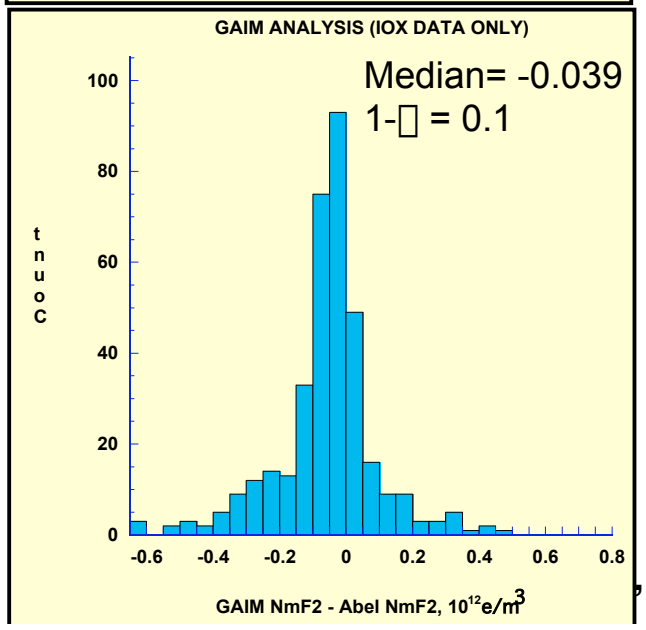


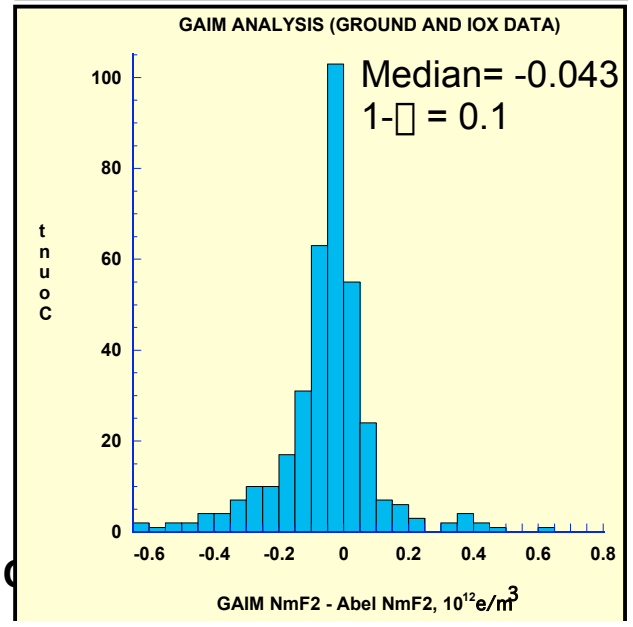
Col

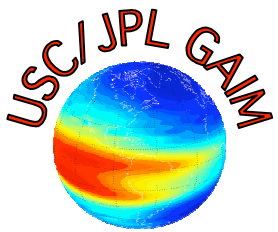
Histograms of GAIM - Abel NmF2 Difference



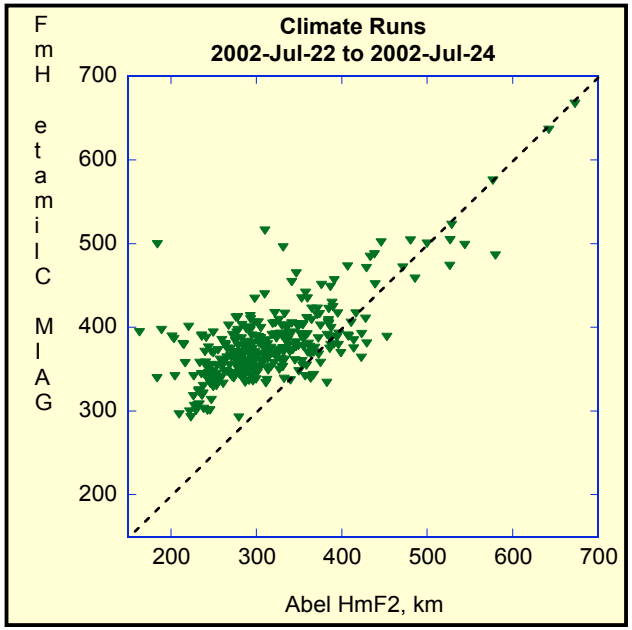


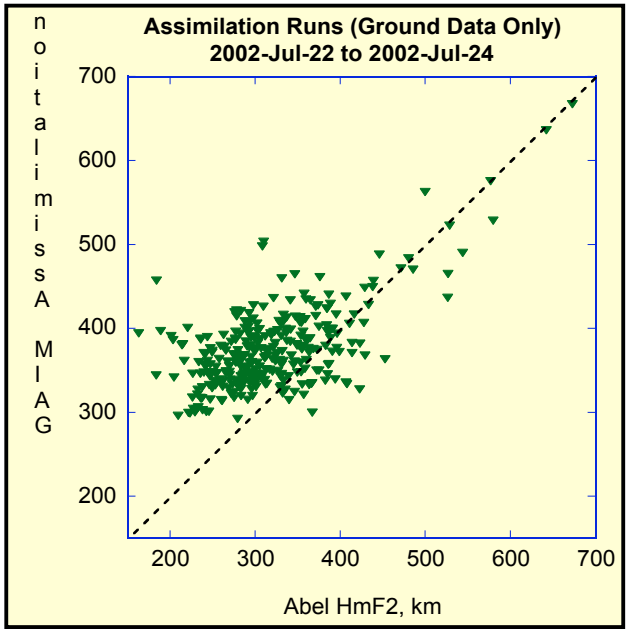


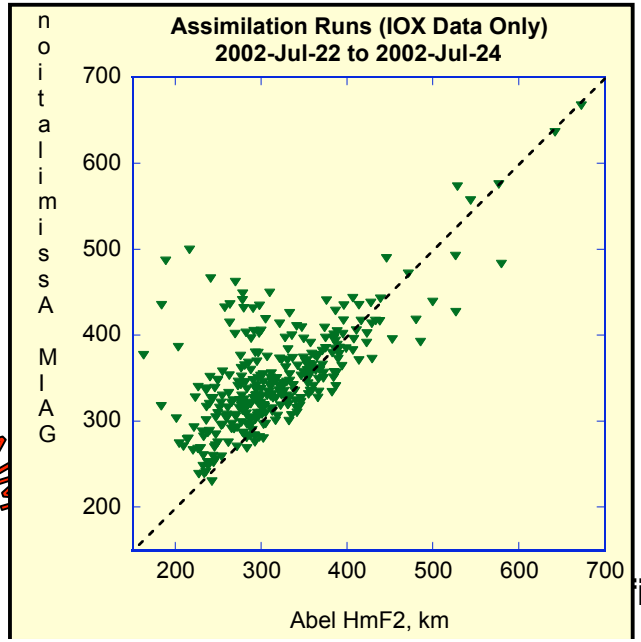


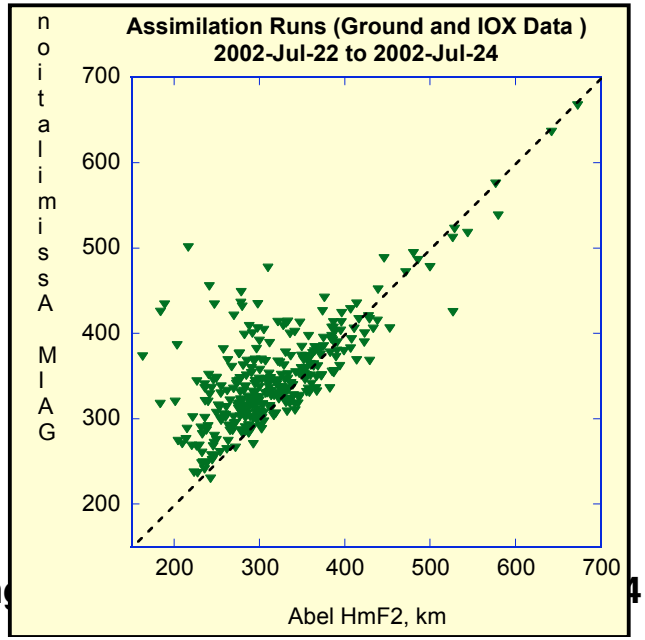


GAIM vs. Abel HmF2 Comparison



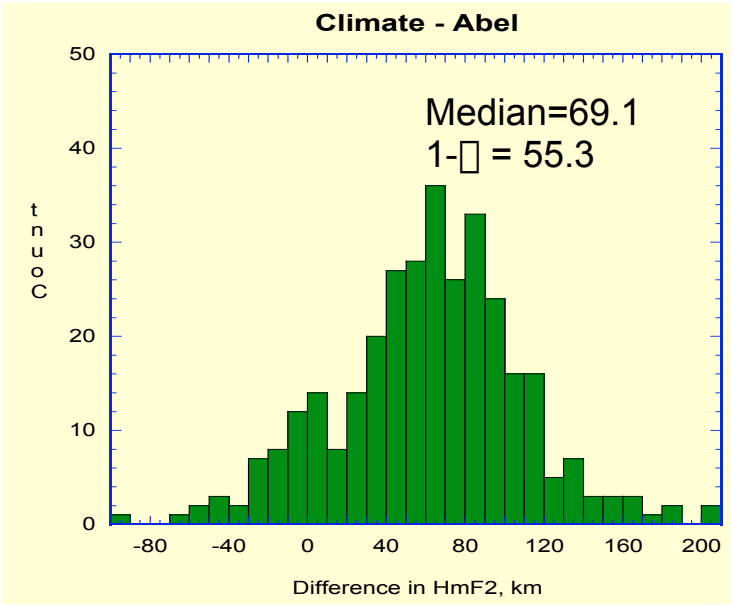


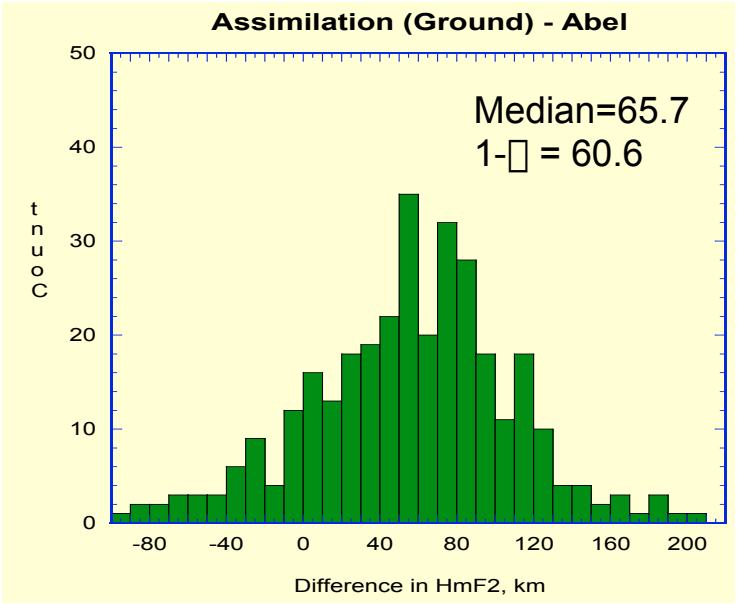


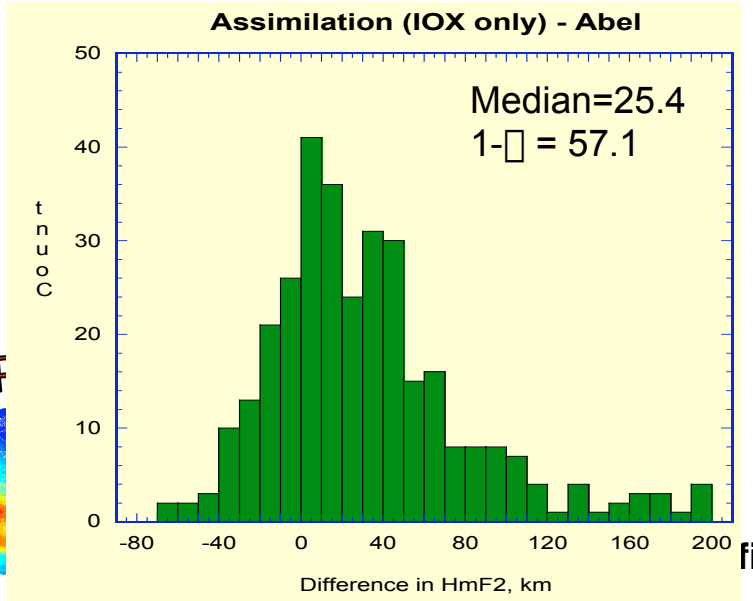


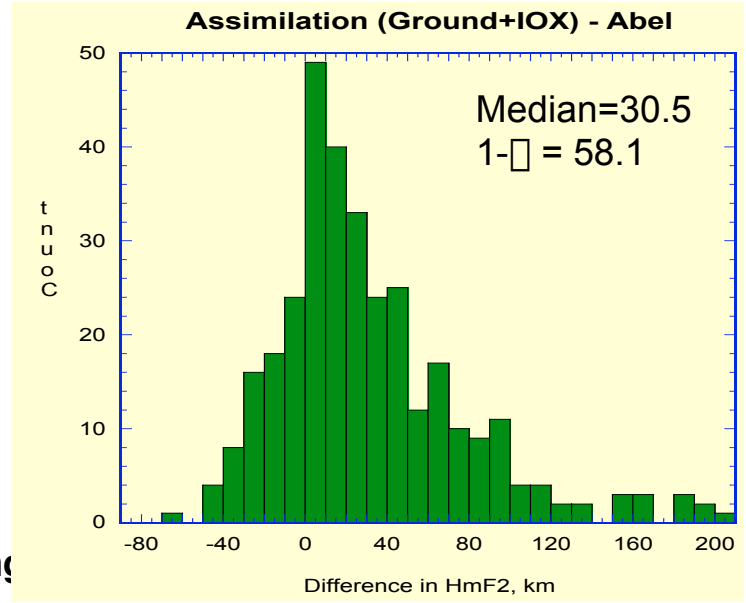
USC/ JPL GAI

Histograms of GAIM - Abel HmF2 Difference



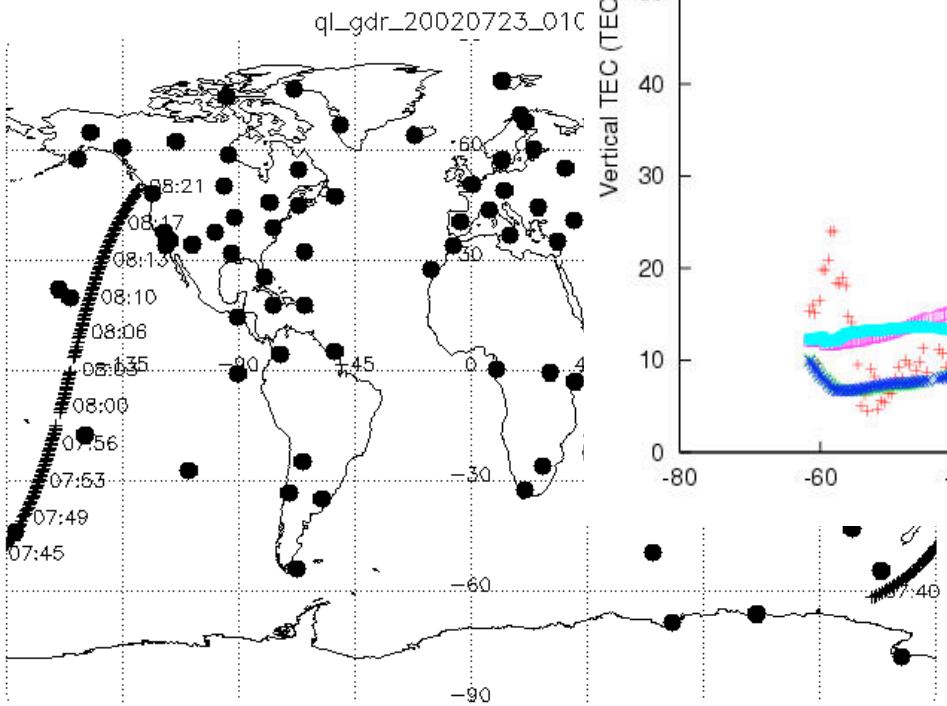


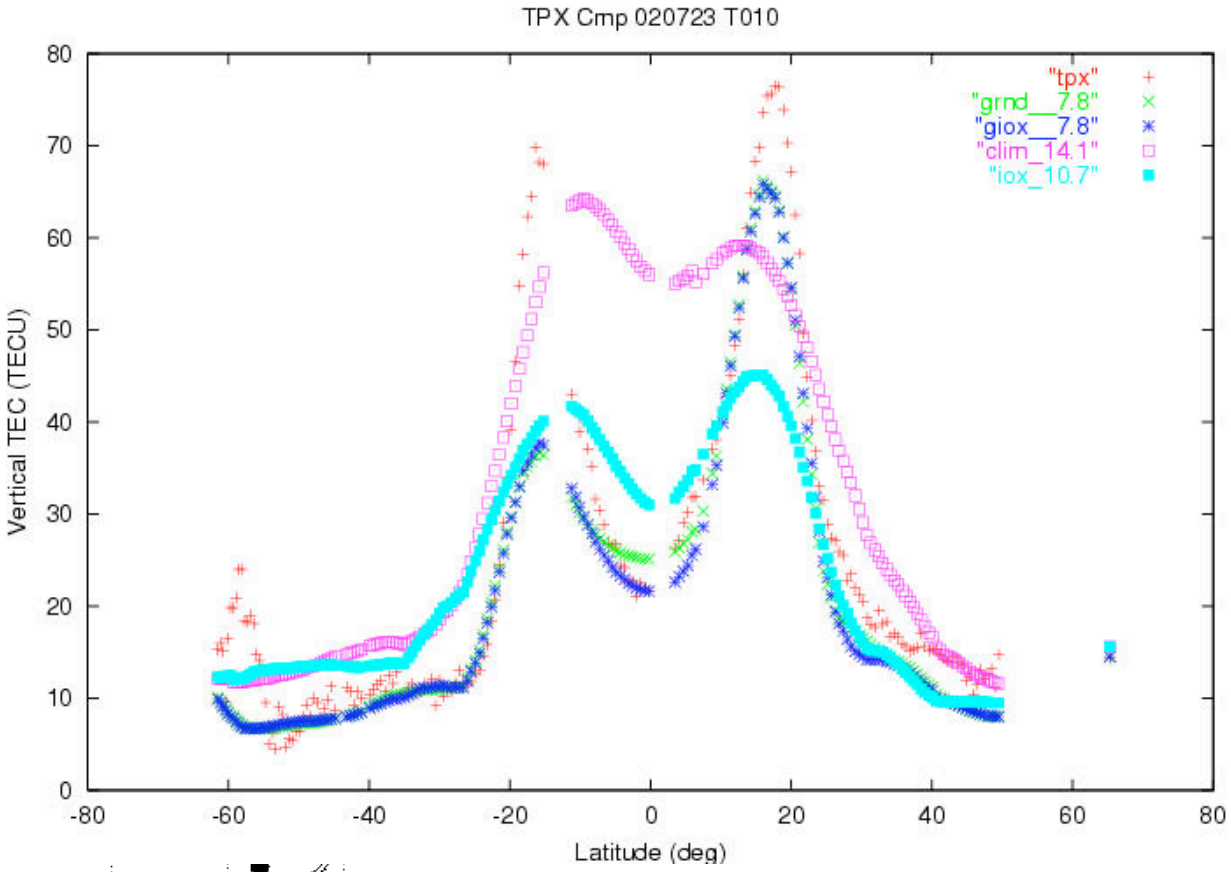


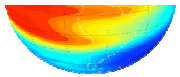


TOPEX vs. GAIM using ground GPS and IOX Occultations

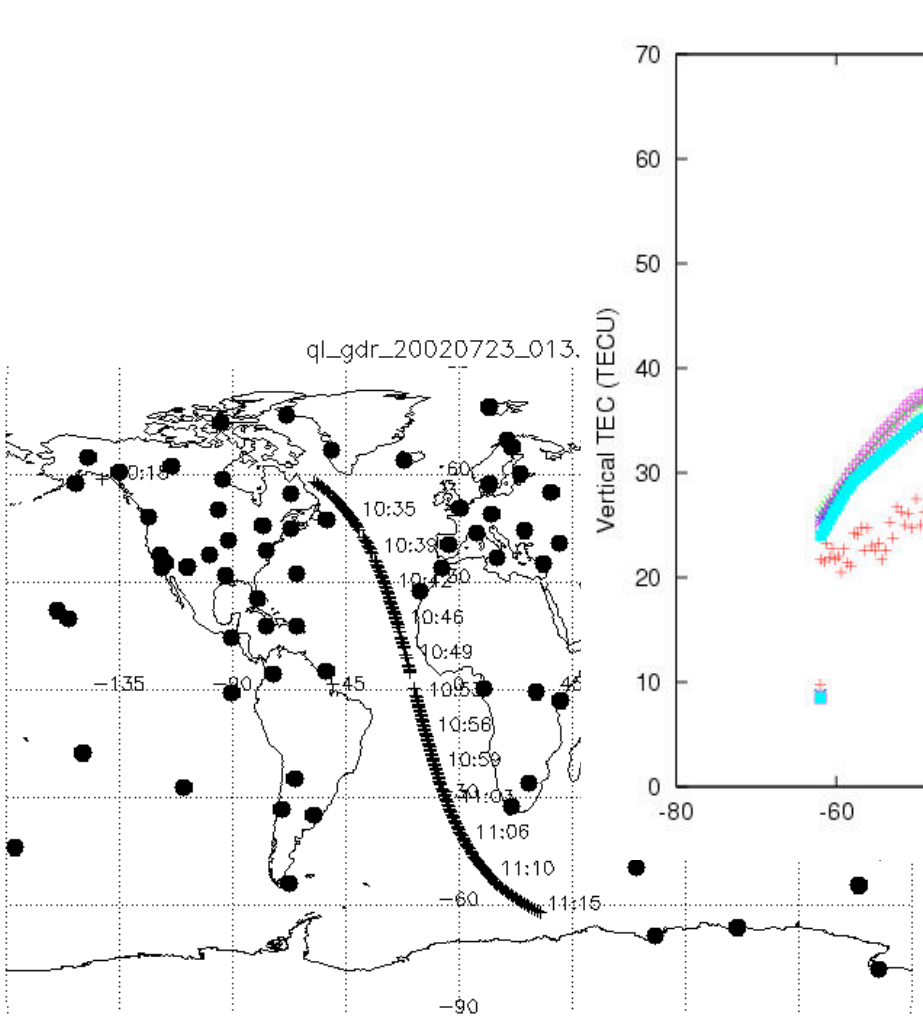
Track #10 on 2002/07/23

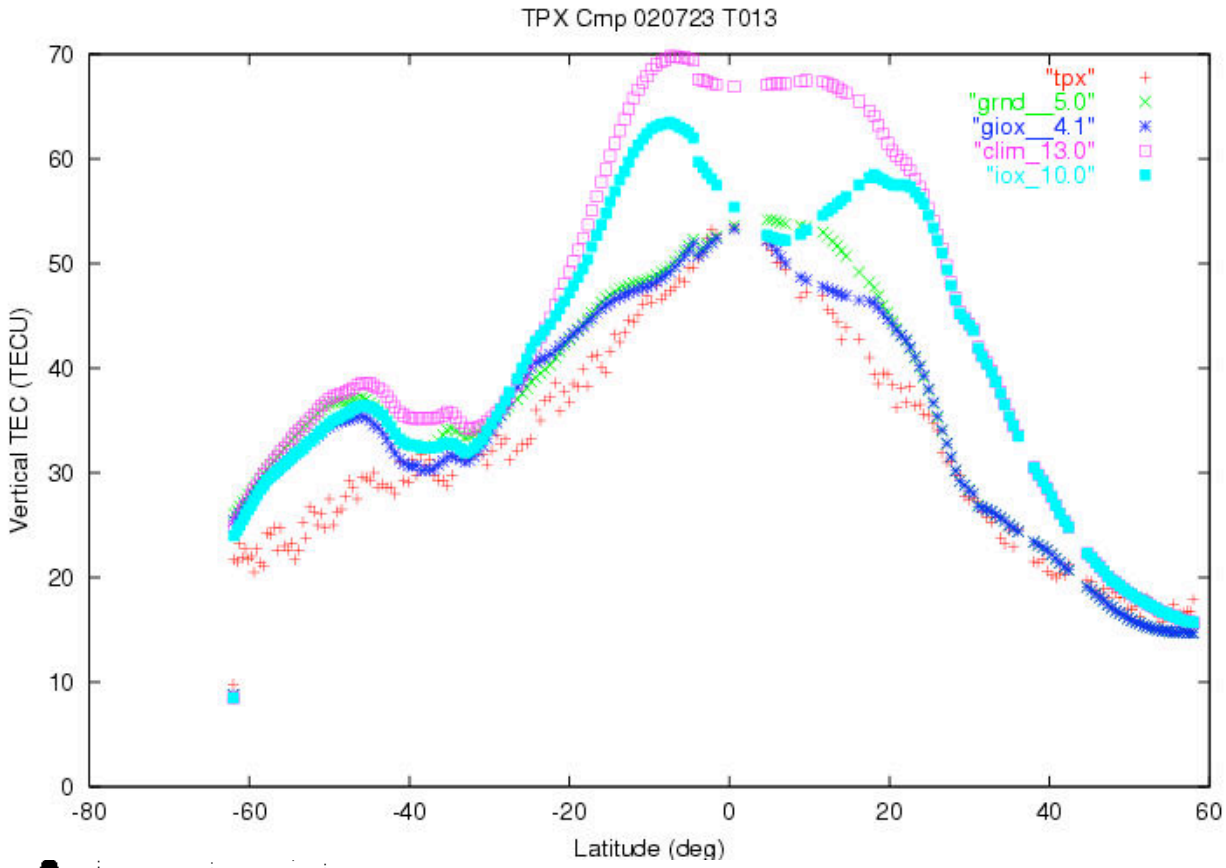


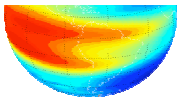




TOPEX Track #13 on 2002/07/23

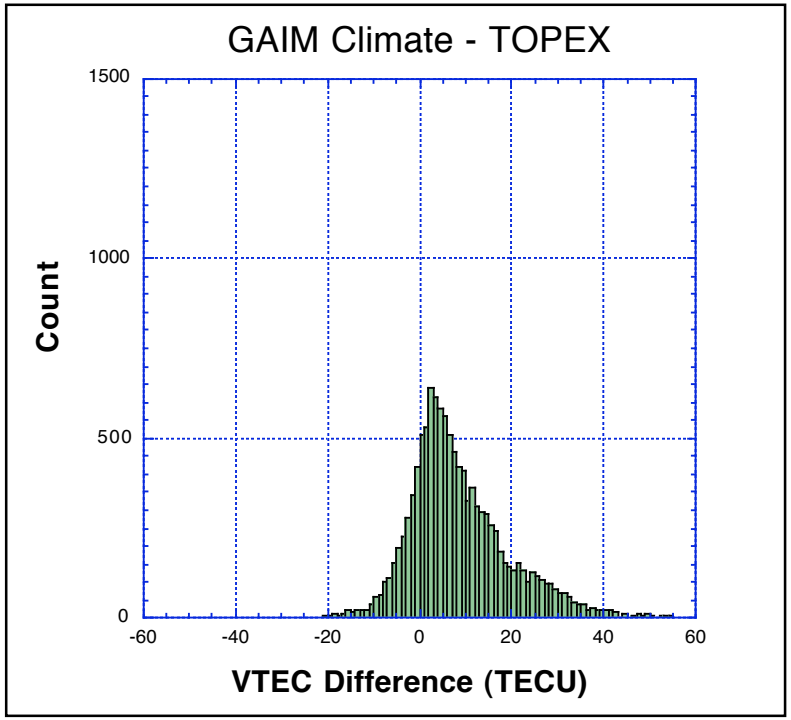






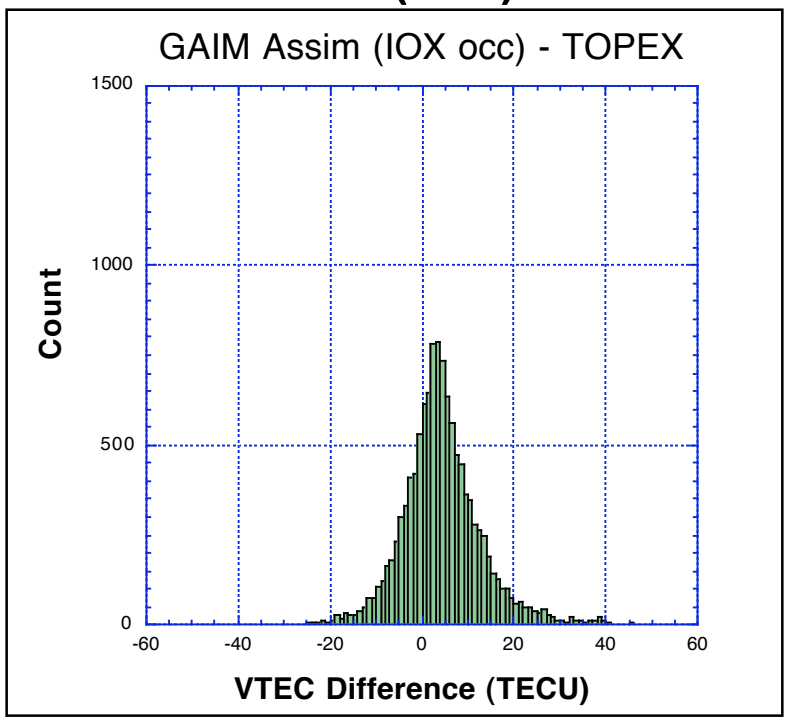
TOPEX Comparisons for July 22-24, 2002: Histograms (I)

GAIM Climate - TOPEX



Mean 8.6 TECU
Std Dev 11.0 TECU
RMS 14.0 TECU

GAIM Assim (IOX) - TOPEX

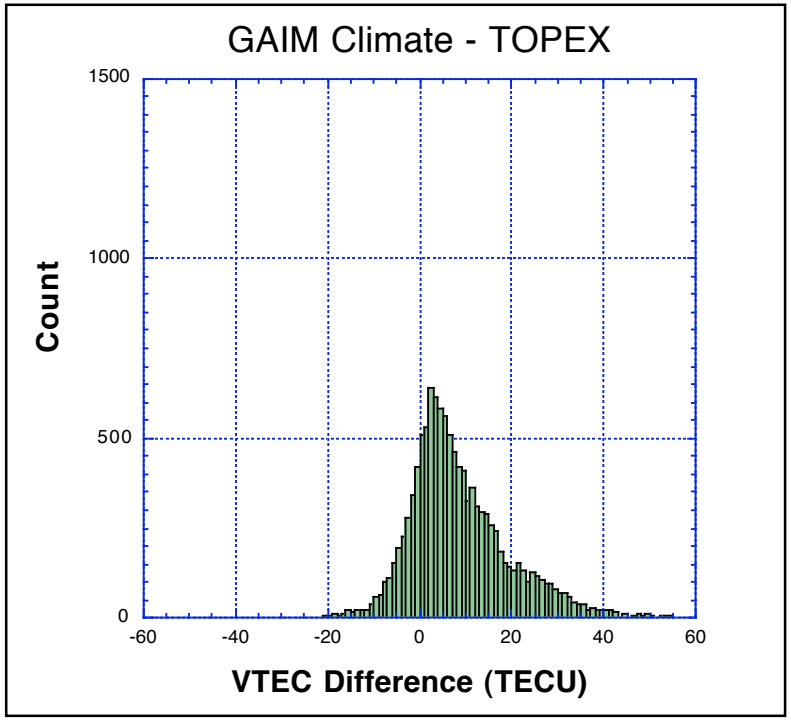


Mean 4.3 TECU
Std Dev 8.9 TECU
RMS 9.9 TECU

11,700 points over 3 days

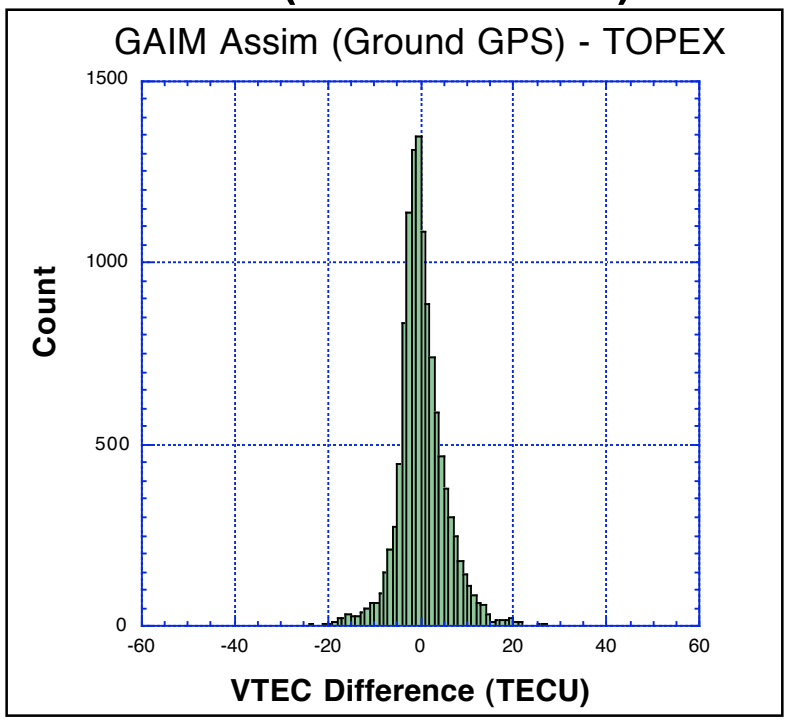
TOPEX Comparisons for July 22-24, 2002: Histograms (II)

Climate



Mean 8.6 TECU
Std Dev 11.0 TECU
RMS 14.0 TECU

GAIM Assim (Ground GPS) - TOPEX

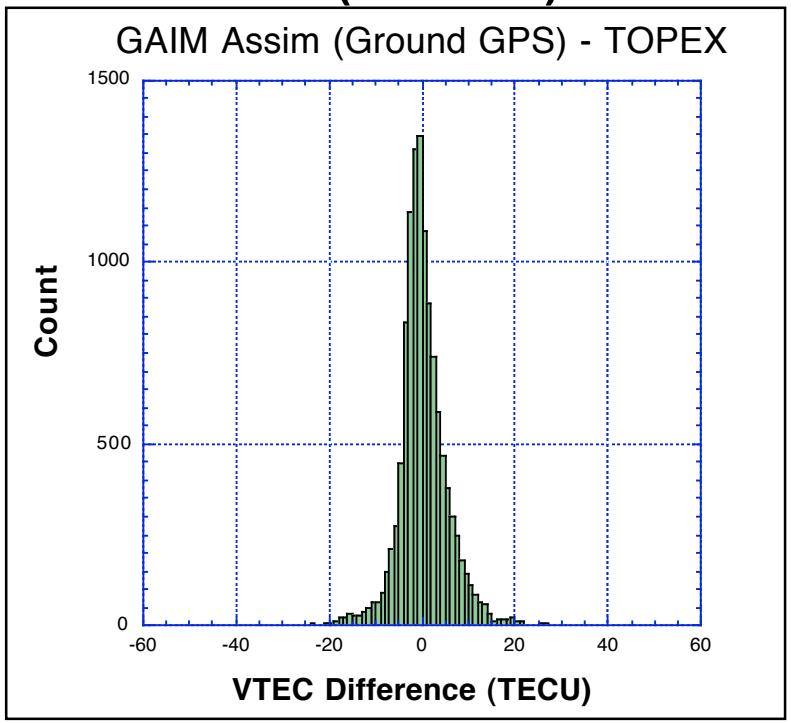


Mean 0.2 TECU
Std Dev 5.5 TECU
RMS 5.5 TECU

11,700 points over 3 days

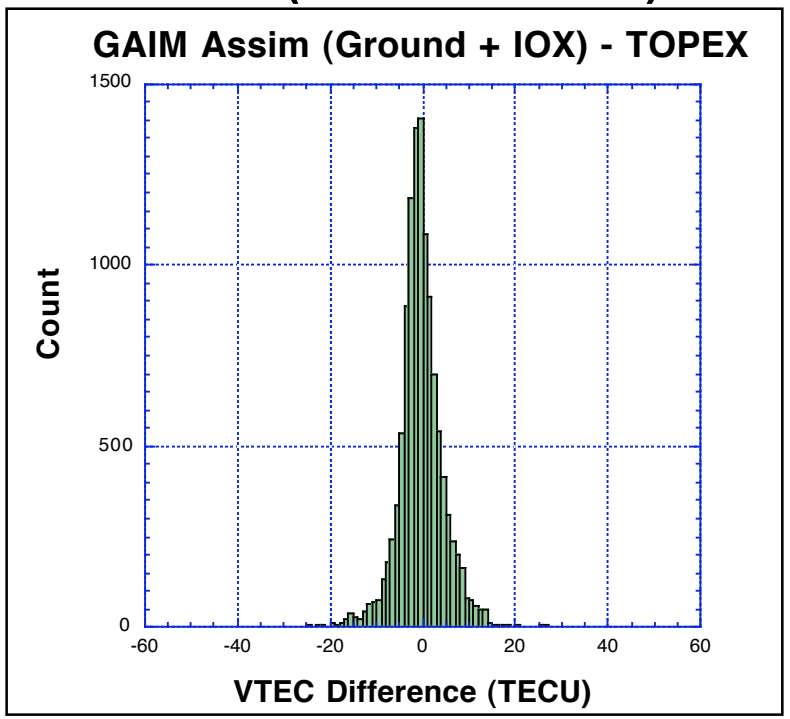
TOPEX Comparisons for July 22-24, 2002: Histograms (III)

GAIM Assim (Ground) - TOPEX



Mean 0.2 TECU
Std Dev 5.5 TECU
RMS 5.5 TECU

GAIM Assim (Ground + IOX) - TOPEX



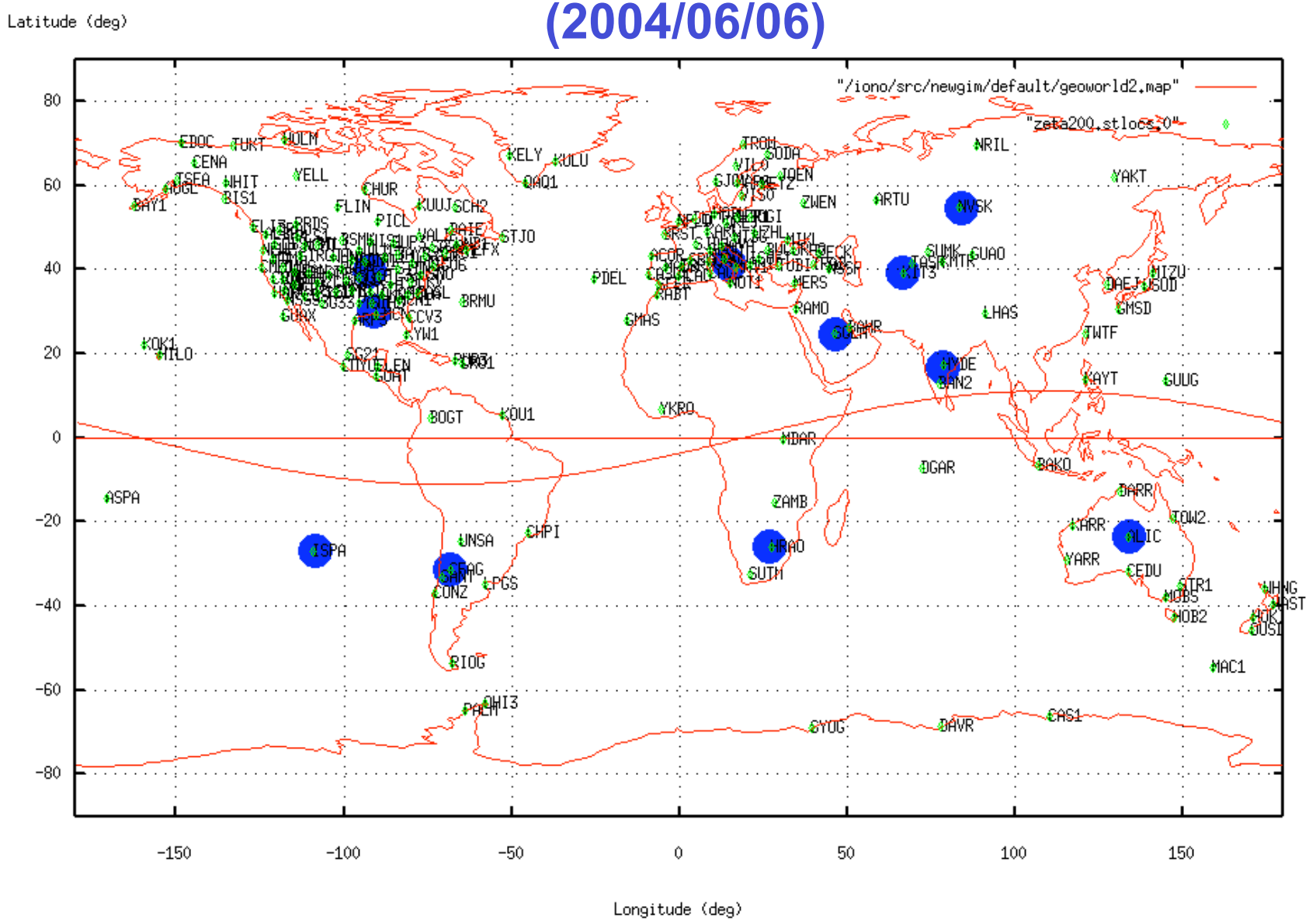
Mean -0.5 TECU
Std Dev 5.3 TECU
RMS 5.4 TECU

11,700 points over 3 days

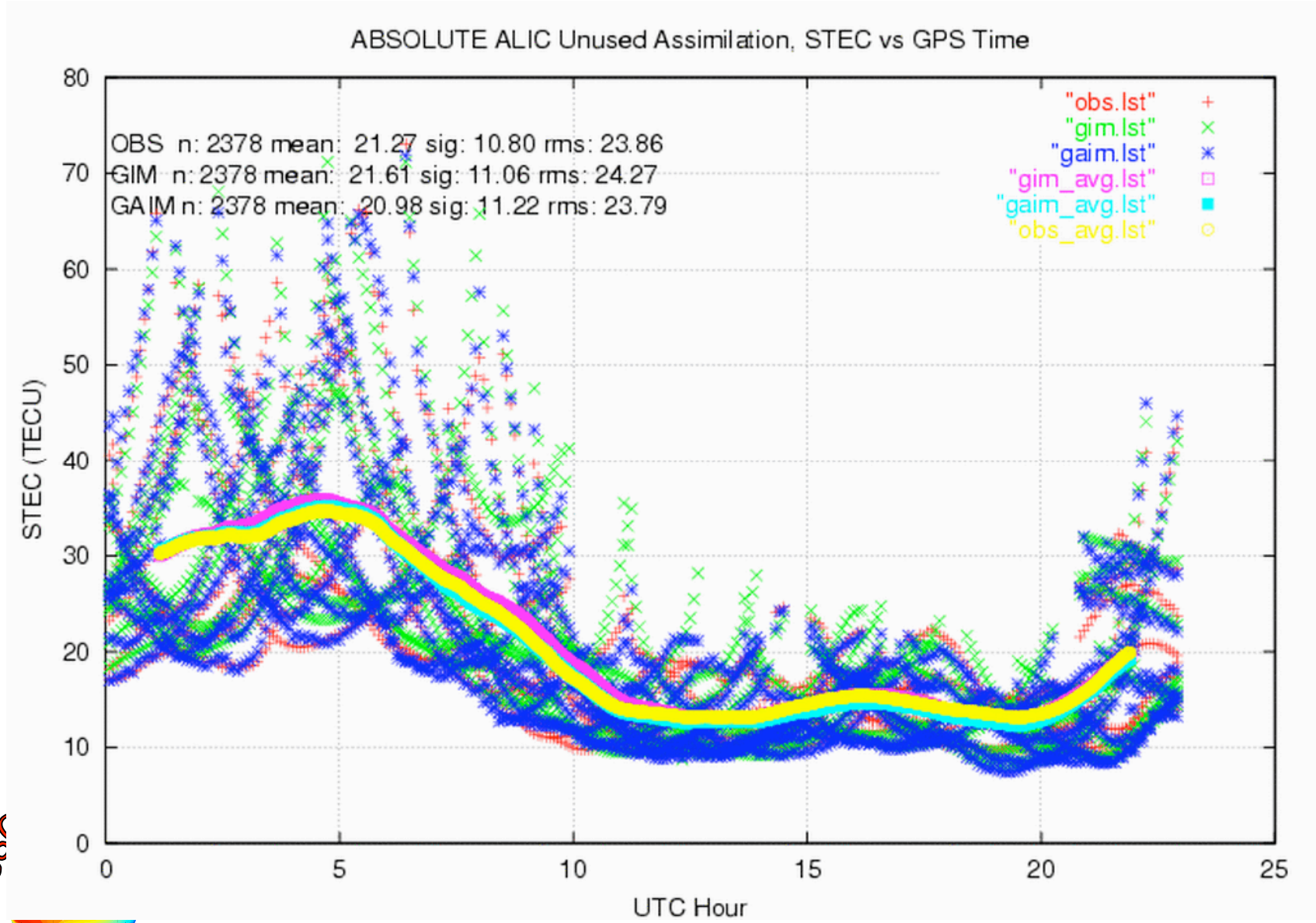
Case Studies

- **Ingest GPS occultations**
  - **Input: Ground GPS + IOX occultations**
  - **Validation: Abel profiles + TOPEX**
- **Slant TEC Prediction (Interpolation) Accuracy**
  - **Input: 189 ground GPS sites**
  - **Predict: TEC from 11 independent GPS sites**
- **Ionosonde Validation (now daily)**
  - **Input: 200 ground GPS sites**
  - **Validation: Ionosonde NmF2 & Hmf2**
- **Ingest UV Radiances**
  - **Input: Ground GPS + LORAAS limb scans**
  - **Validation: NRL profile retrieval**

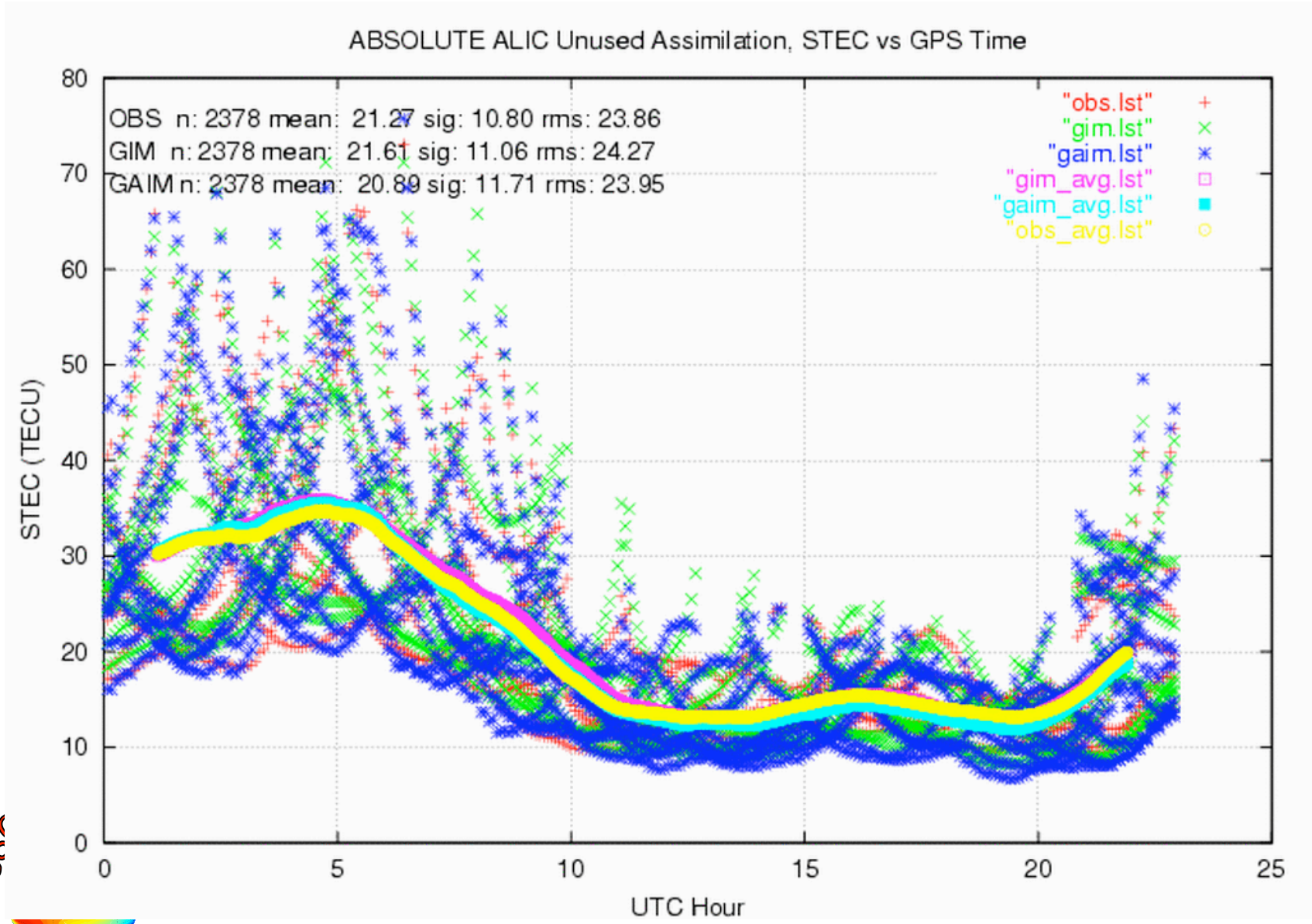
Input GPS sites plus 11 validation sites (2004/06/06)



GAIM Slant TEC Postfit Residuals



GAIM Spatial Interpolation Accuracy



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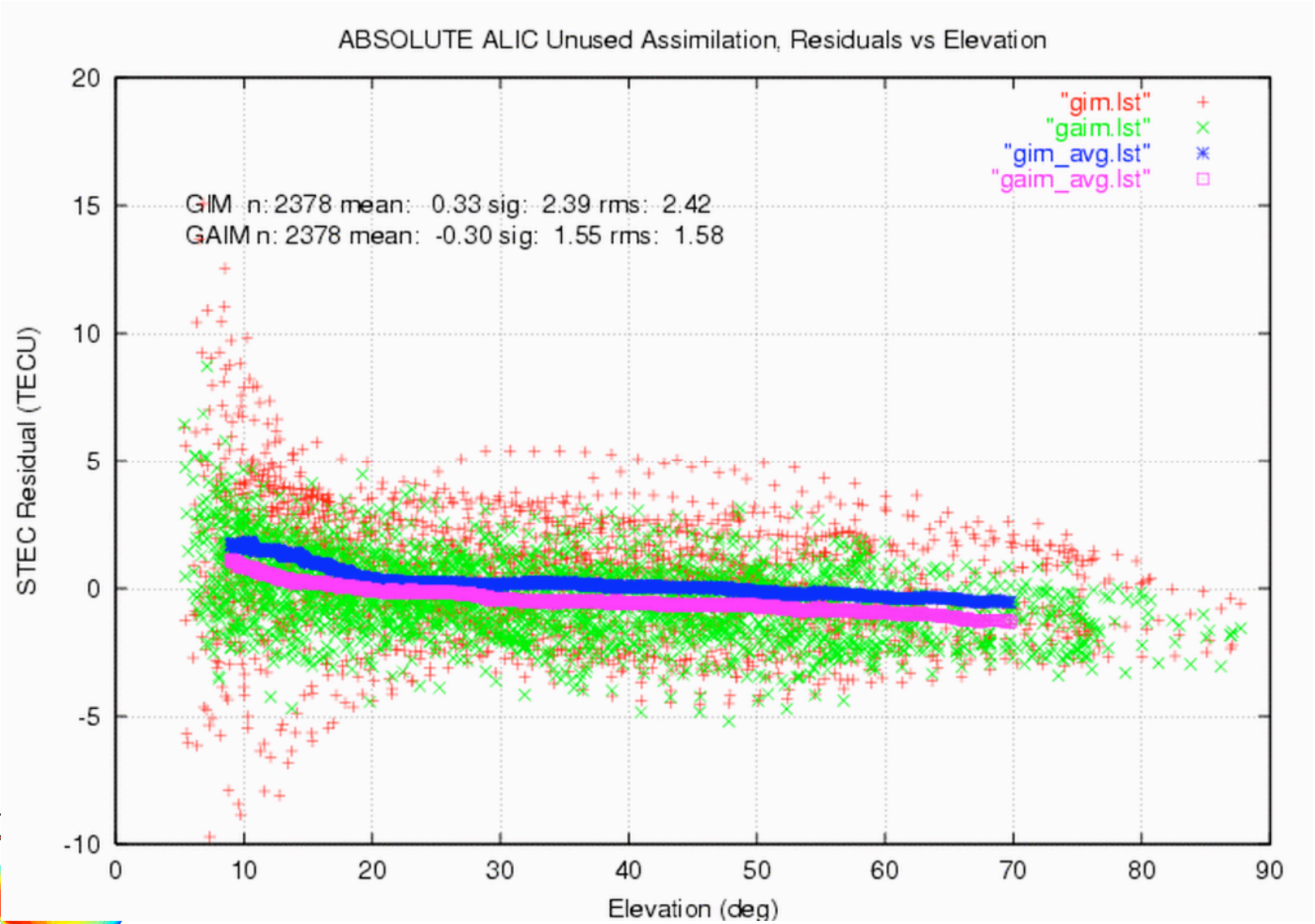
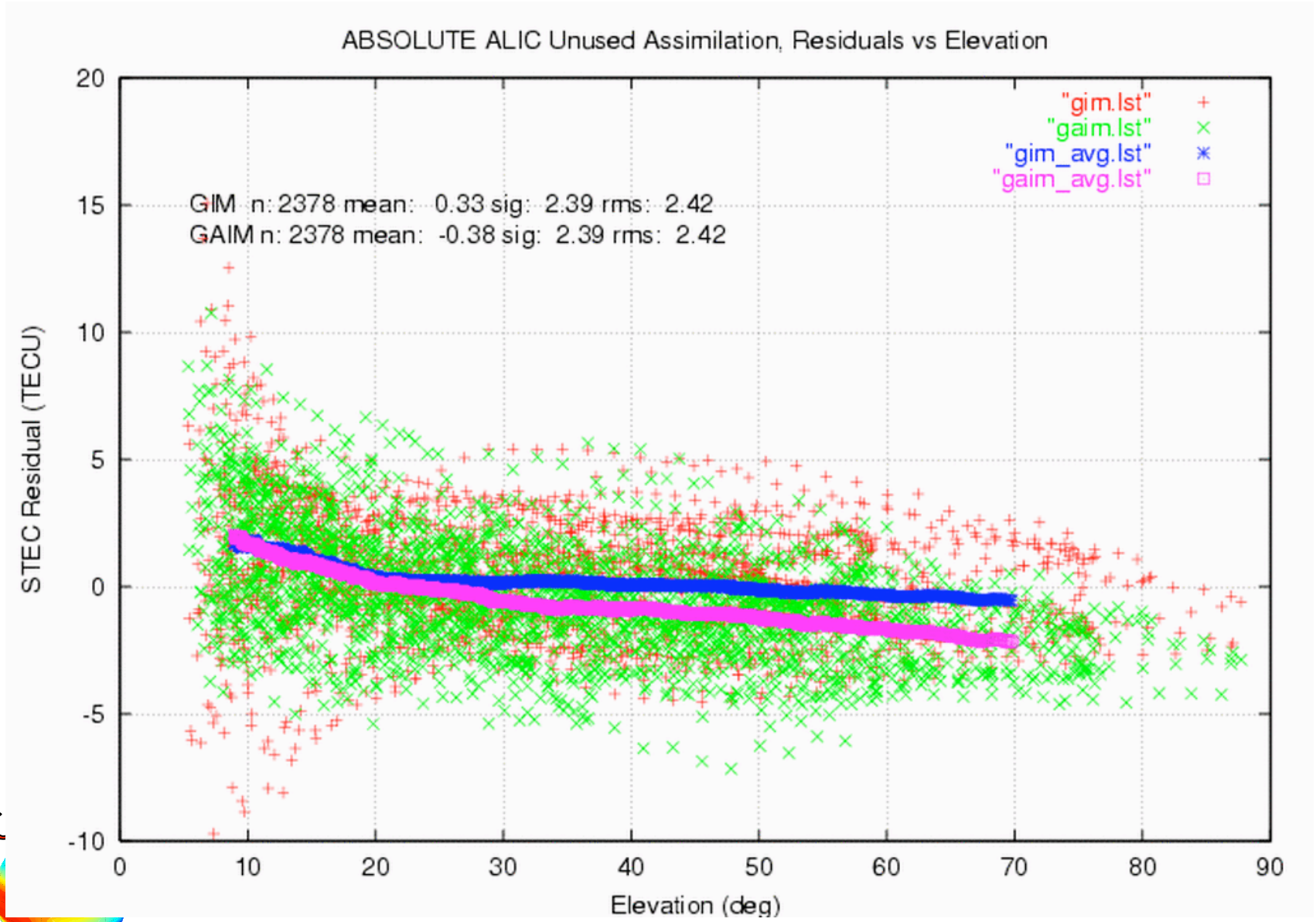
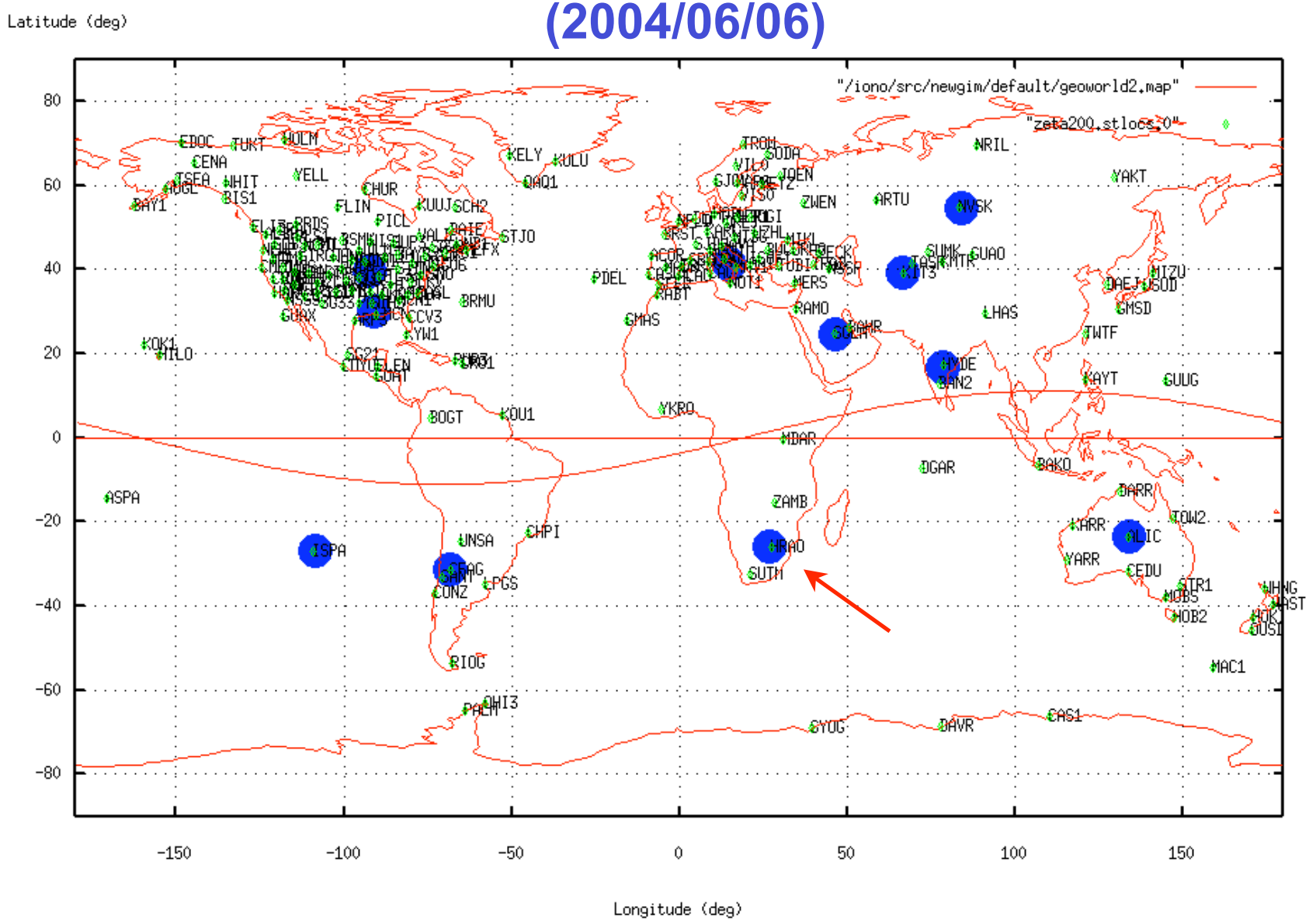


GAIM Spatial Interpolation Accuracy



Input GPS sites plus 11 validation sites (2004/06/06)



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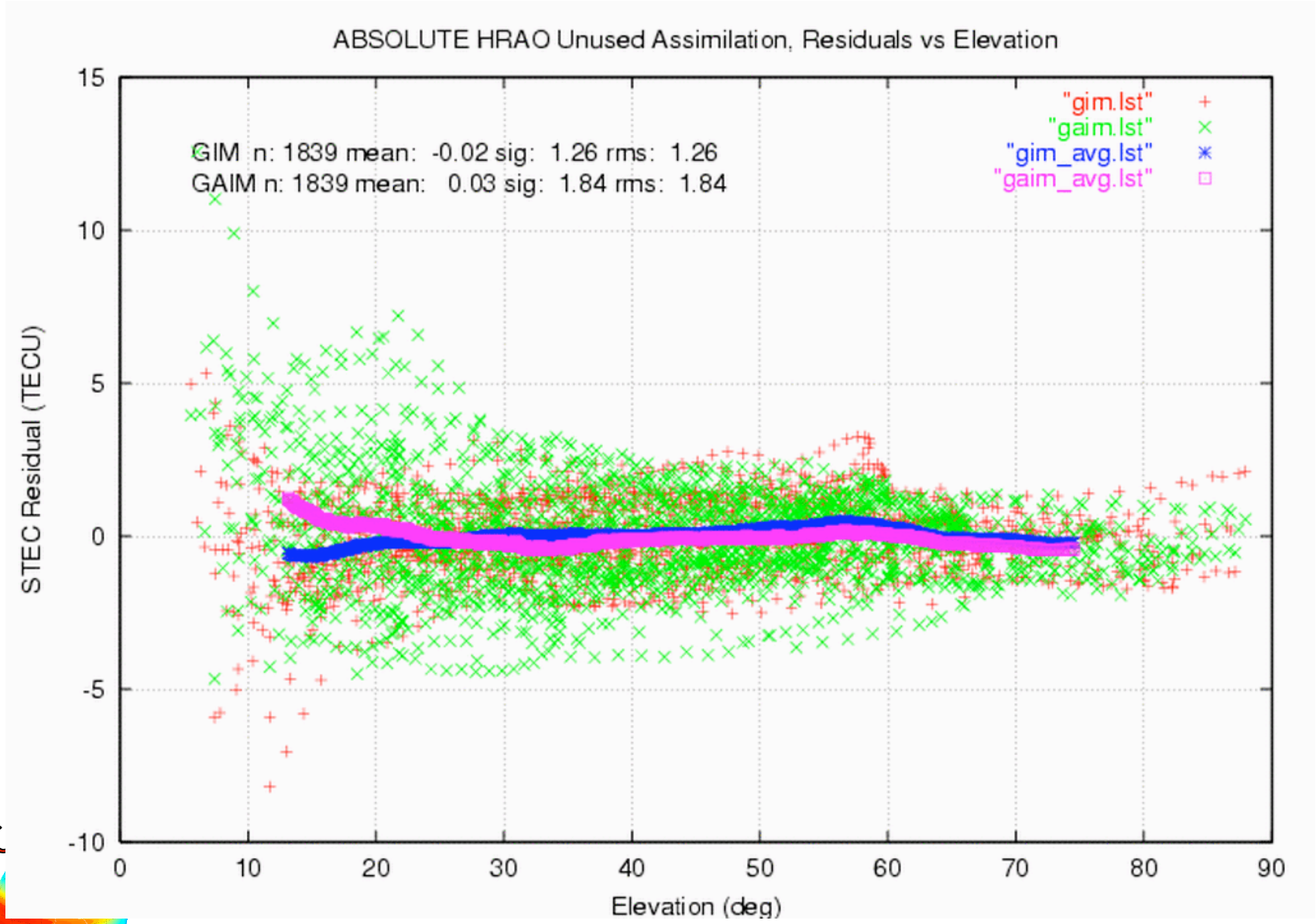

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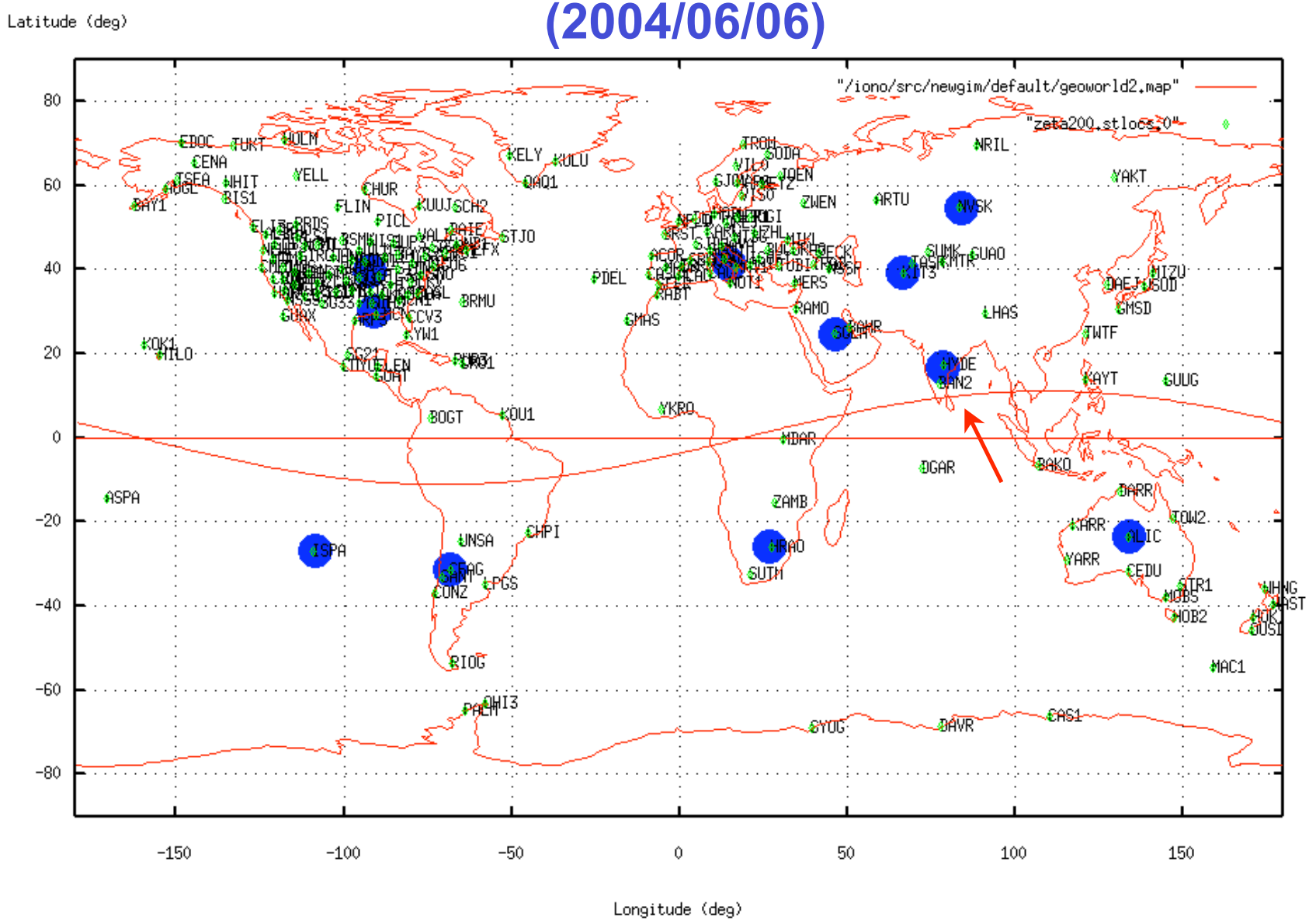
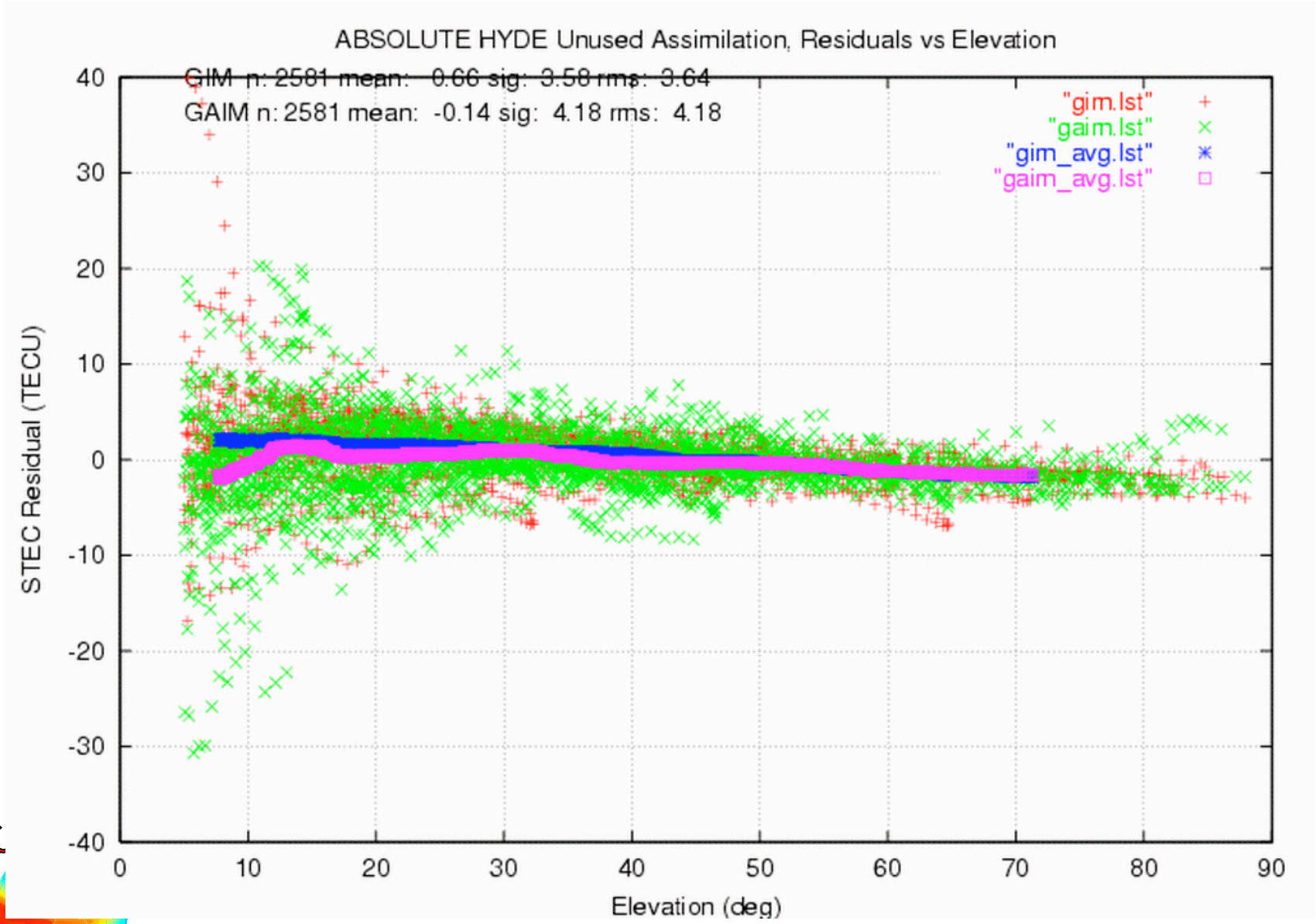


GAIM Spatial Interpolation Accuracy



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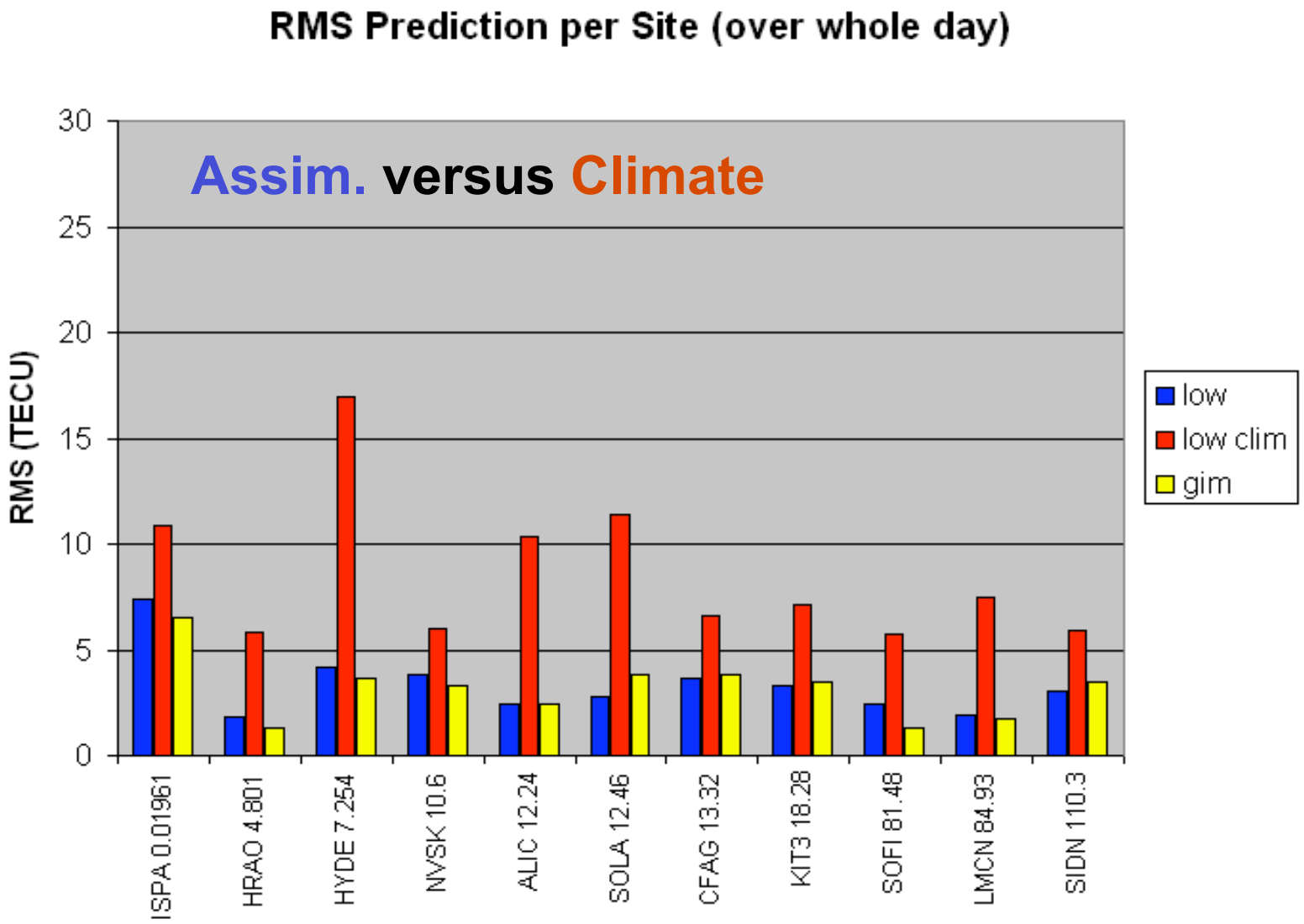

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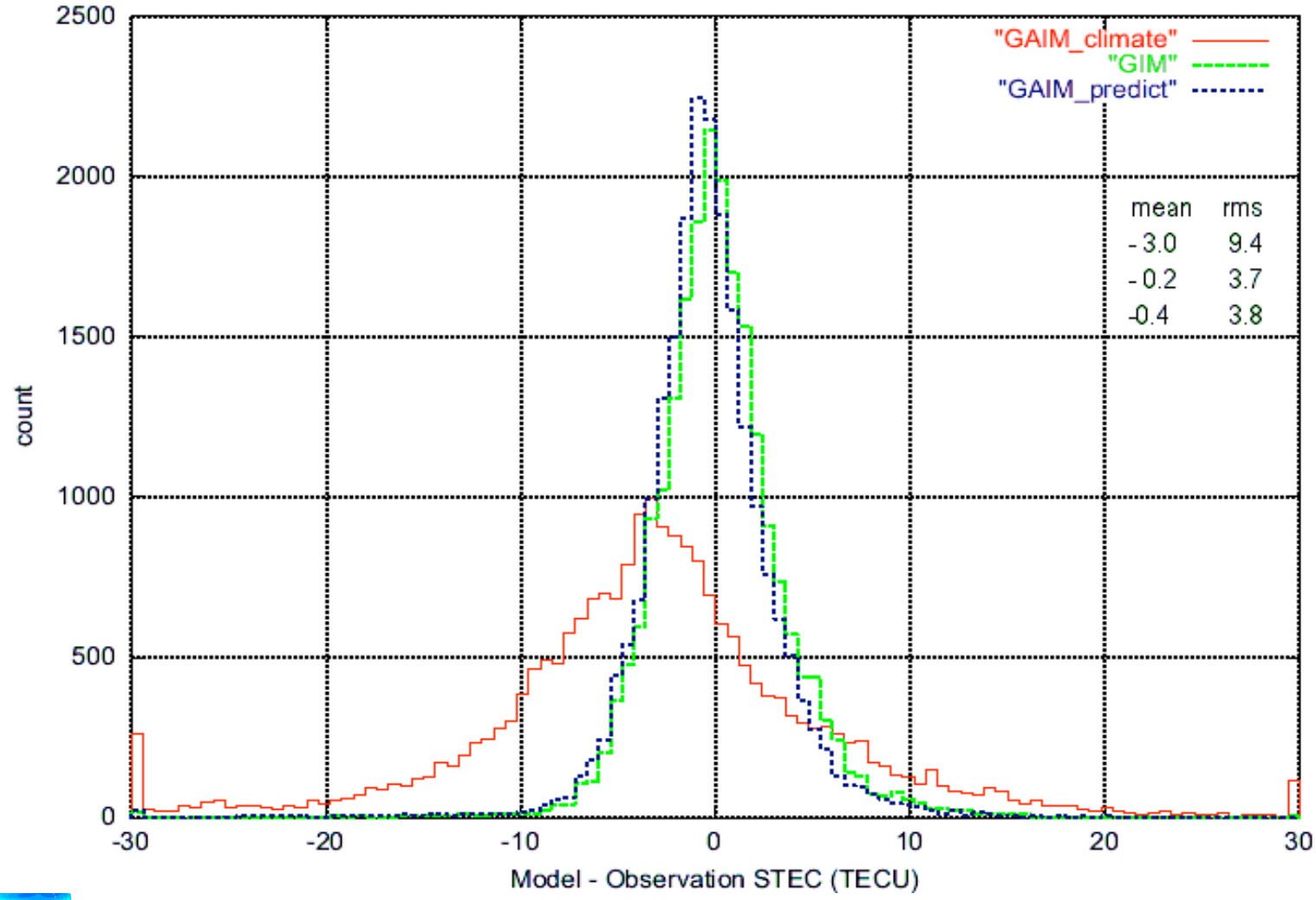
GAIM Spatial Interpolation Accuracy: Histogram for 2004/06/06



USC/ JP

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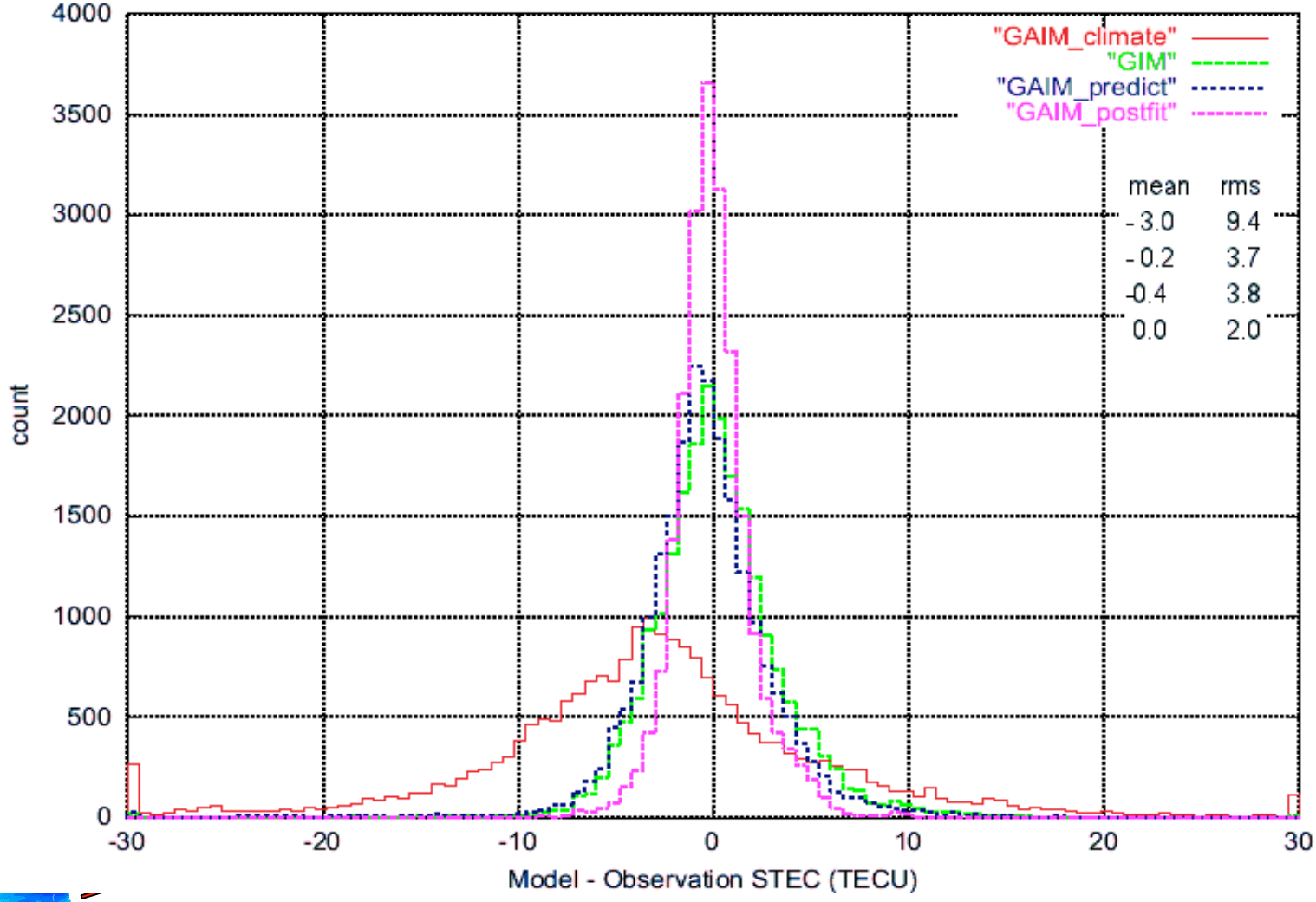
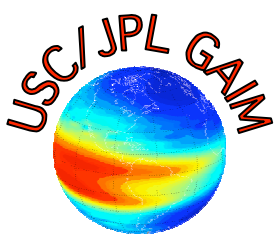
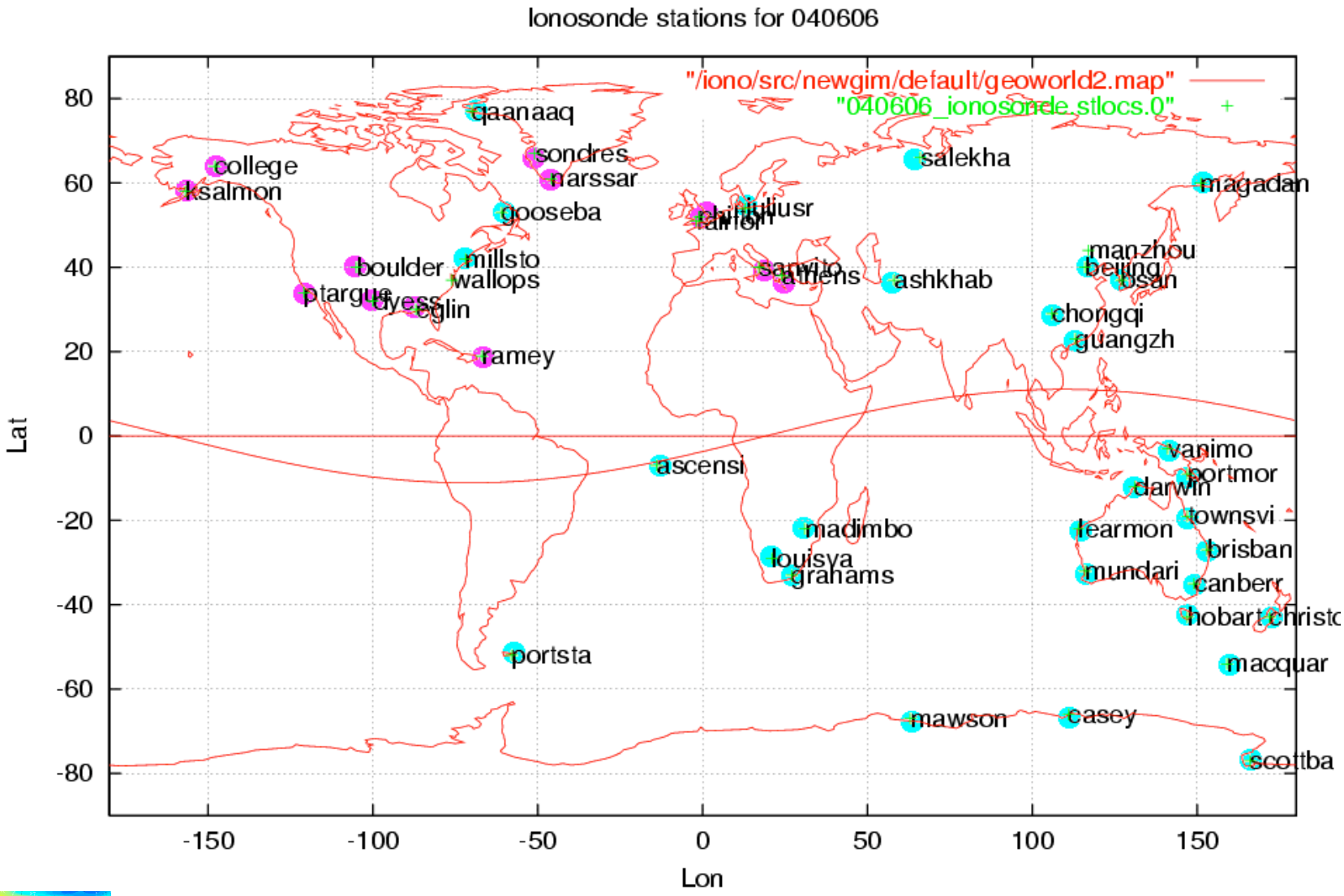


Case Studies

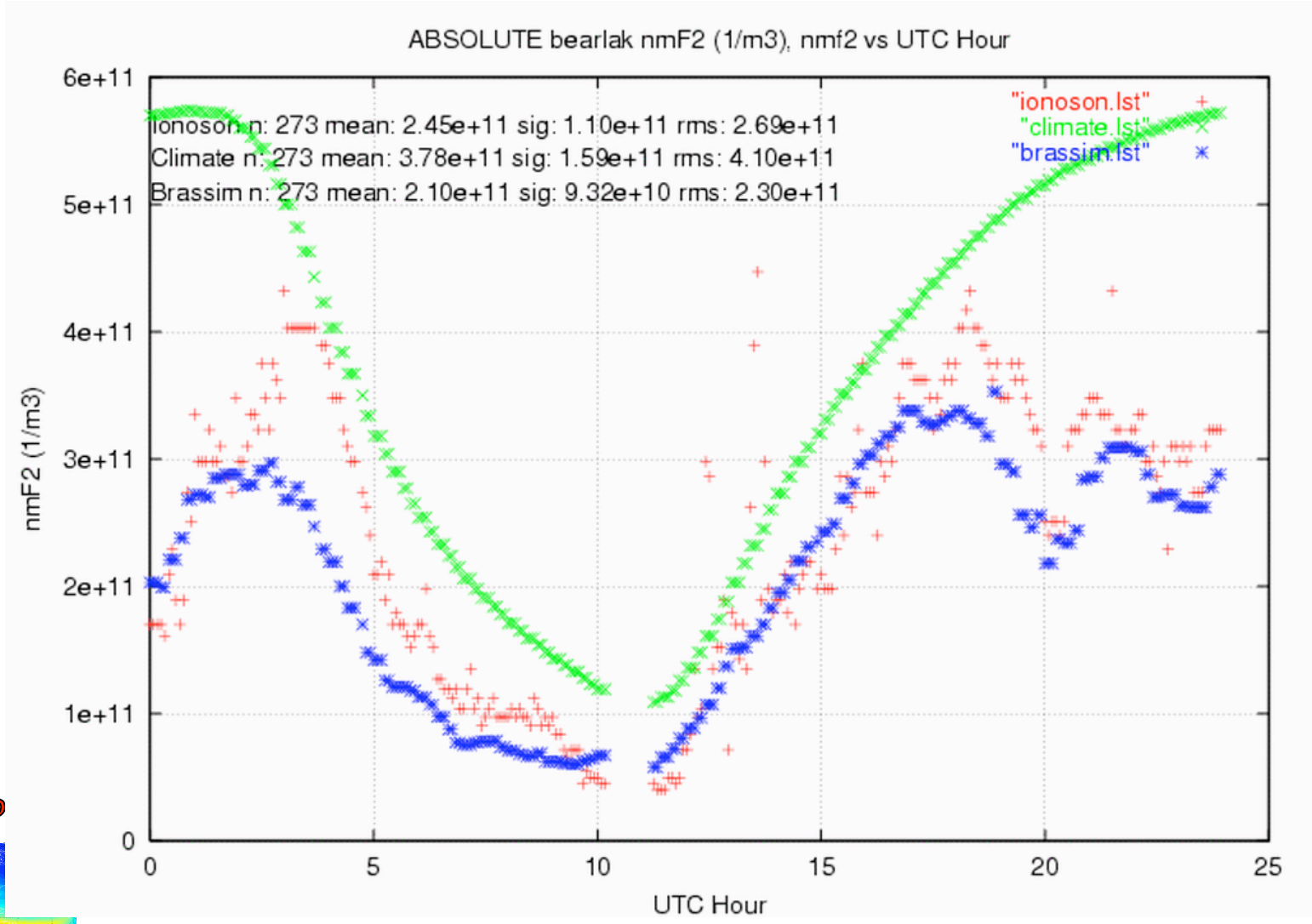
- **Ingest GPS occultations**
  - Input: Ground GPS + IOX occultations
  - Validation: Abel profiles + TOPEX
- **Slant TEC Prediction (Interpolation) Accuracy**
  - Input: 200 ground GPS sites
  - Predict: TEC from 11 independent GPS sites
- **Ionosonde Validation (now daily)**
  - Input: 200 ground GPS sites
  - Validation: Ionosonde NmF2 & Hmf2
- **Ingest UV Radiances**
  - Input: Ground GPS + LORAAS limb scans
  - Validation: NRL profile retrieval



Global Ionosonde Sites



NmF2 Comparison: Bear Lake on 2004/07/28



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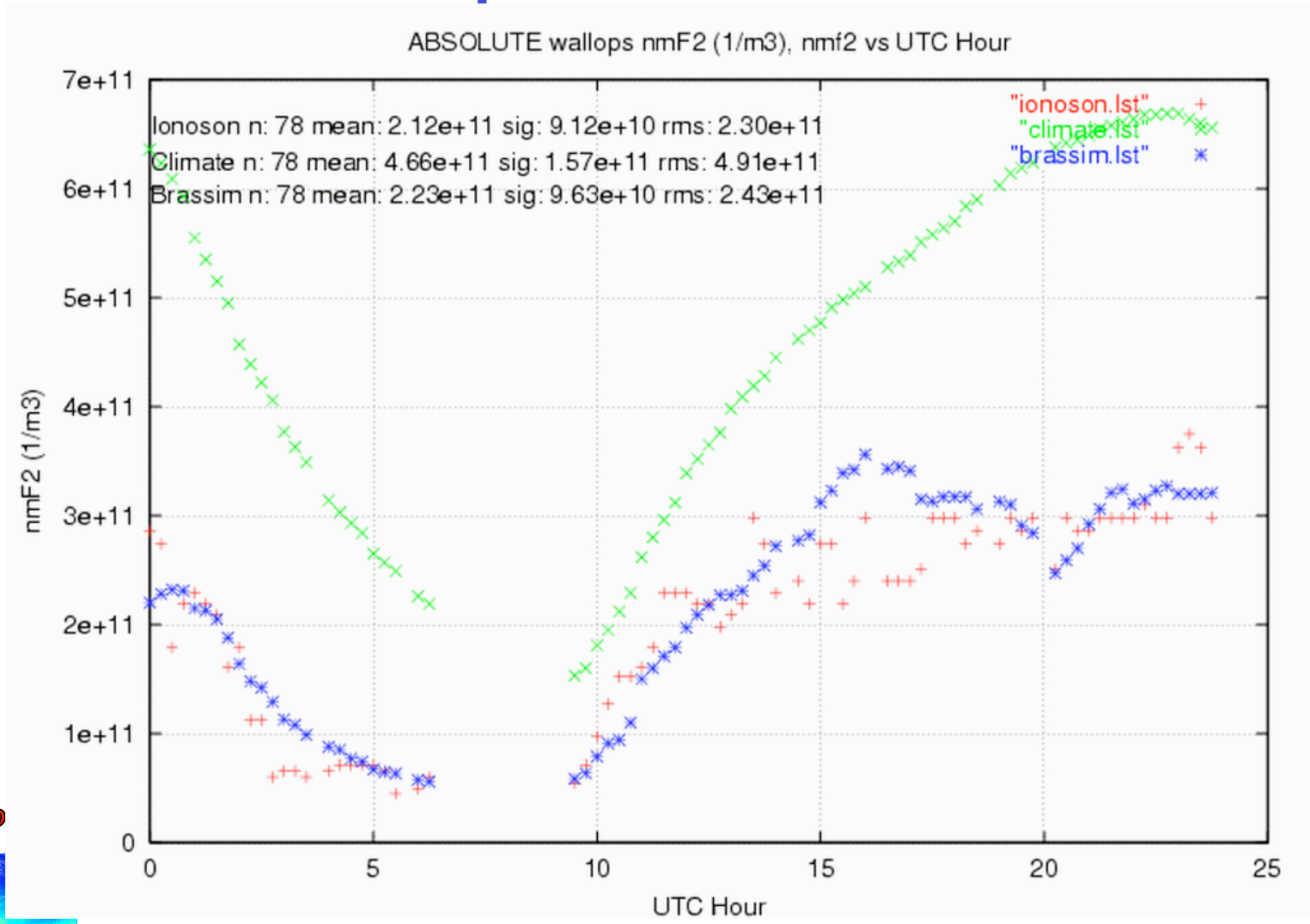
NmF2 Comparison: Wallops Is. on 2004/07/28



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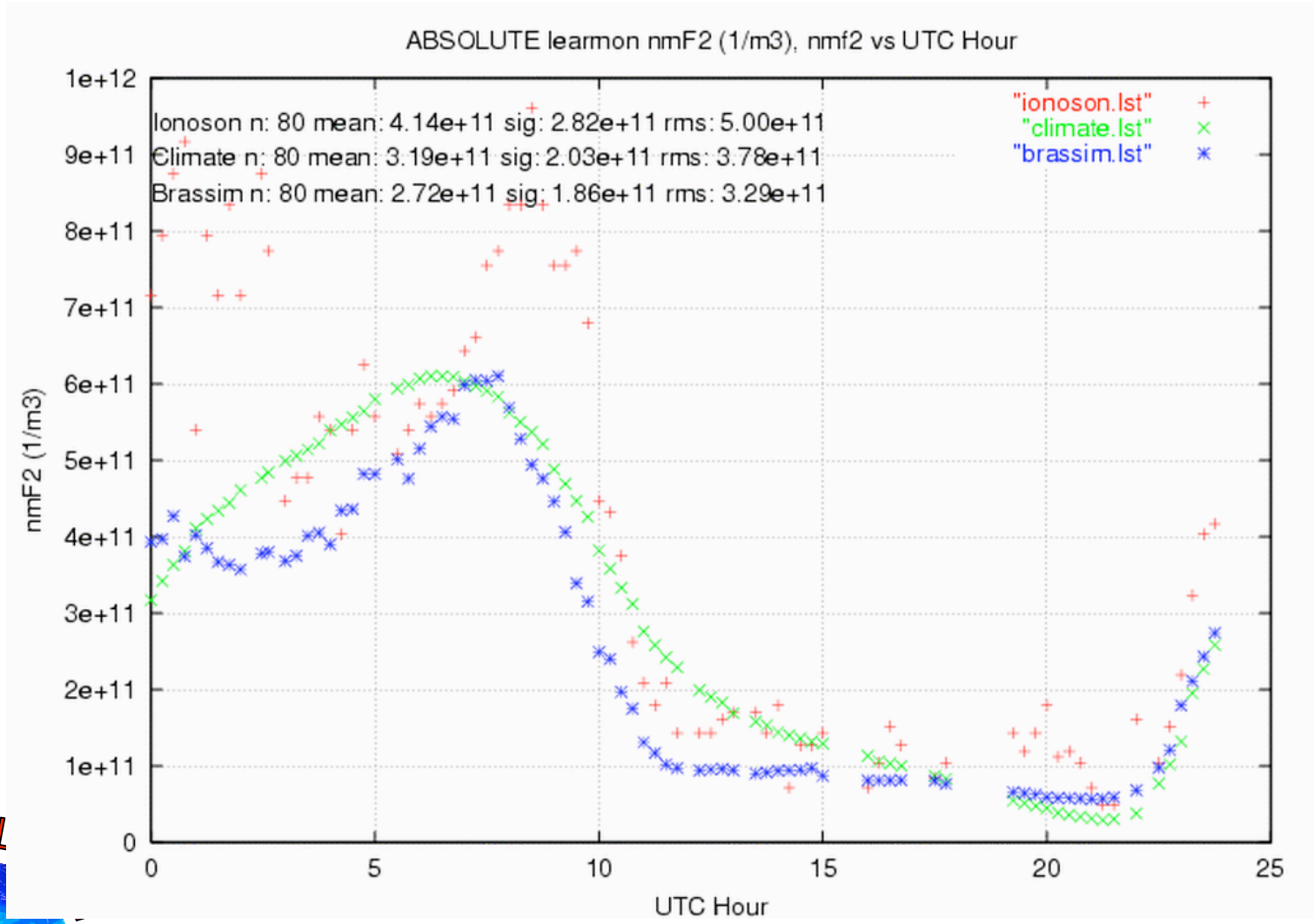
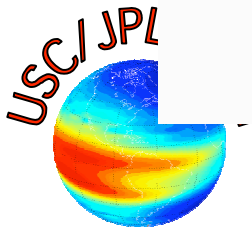
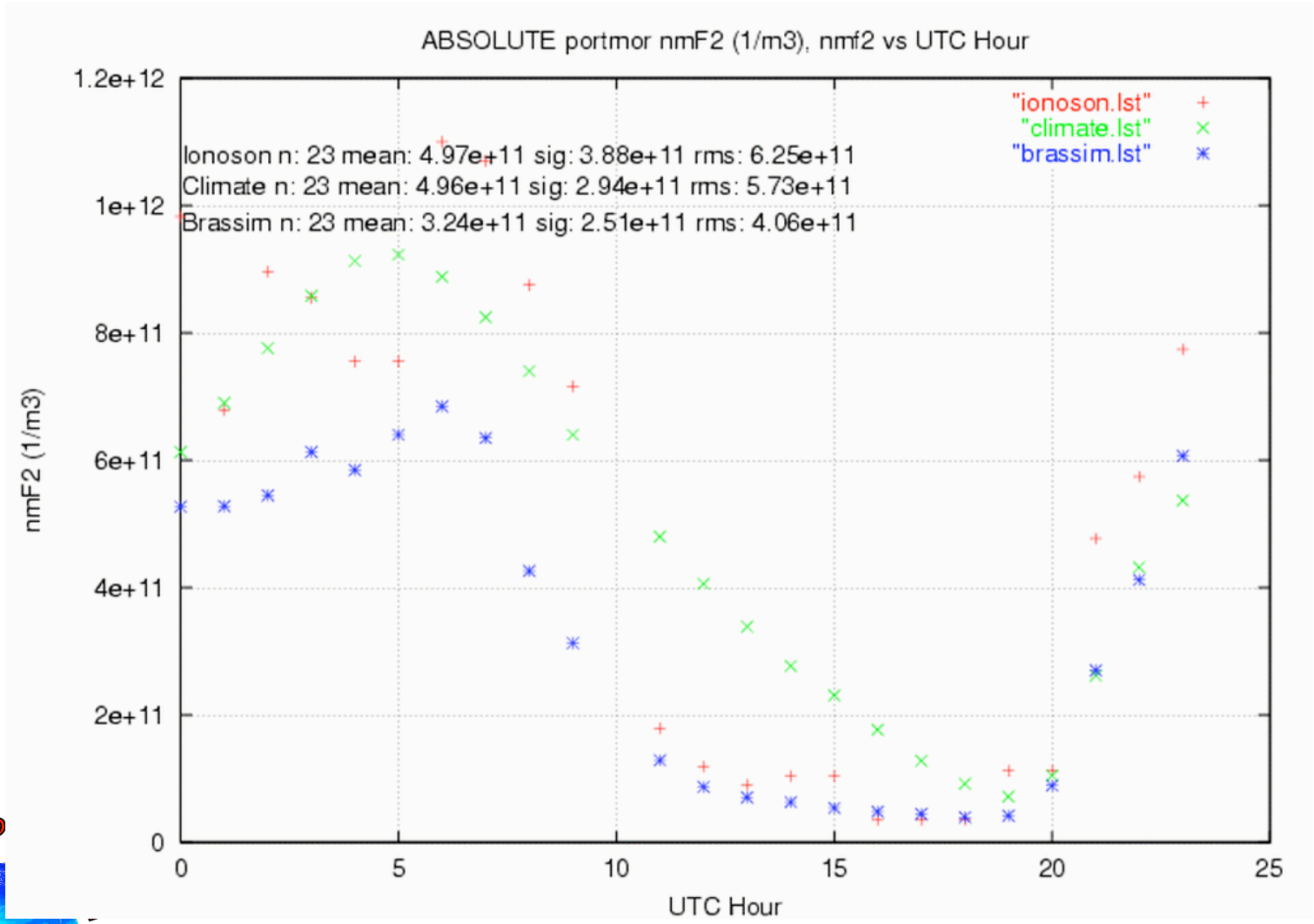
NmF2 Comparison: Learmon on 2004/07/28





NmF2 Comparison: Portmor on 2004/07/28



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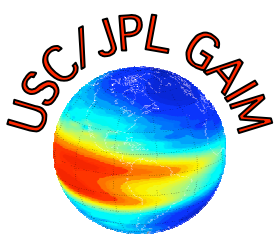
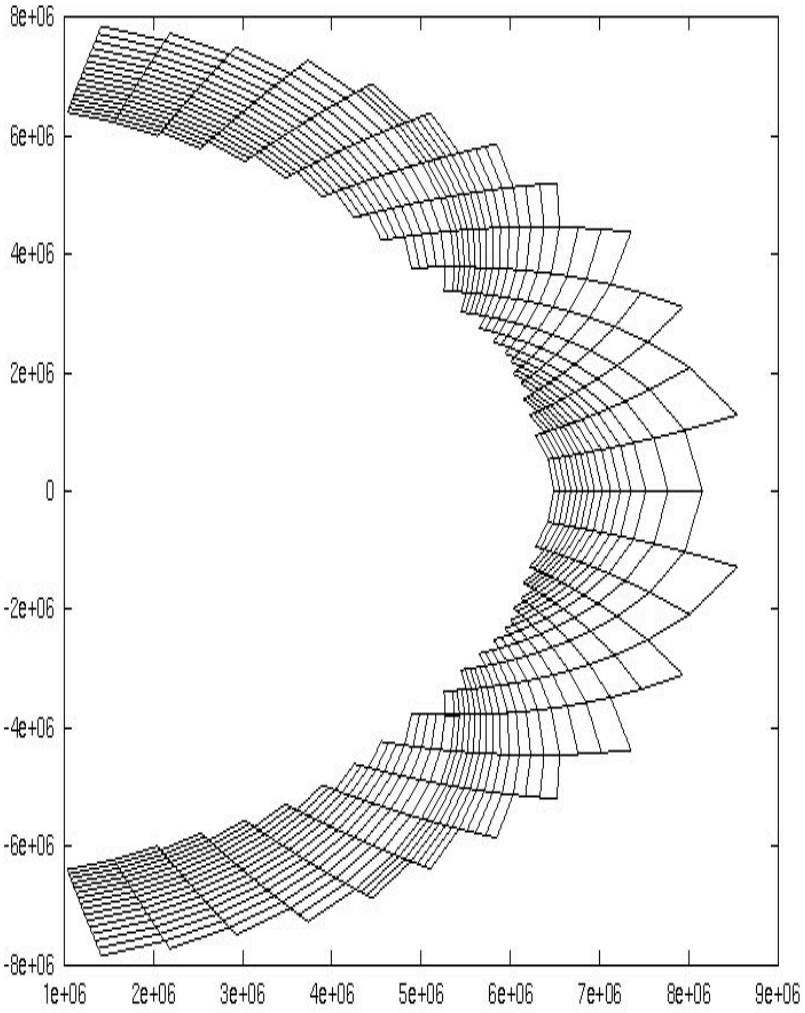
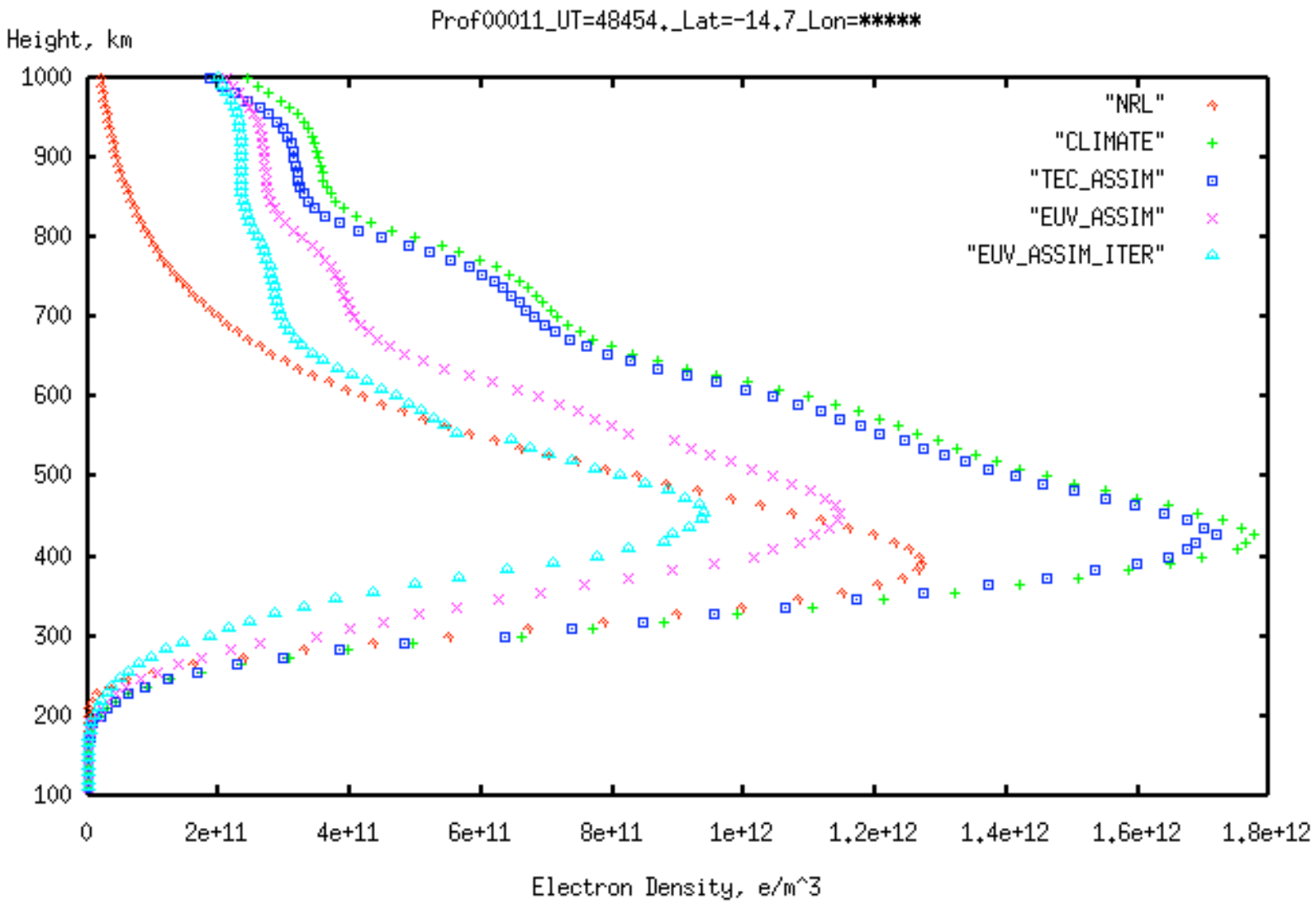


LORAAS UV Assimilation Run for 2000-10-03

F10.7	192.1
Average F10.7	175.6
Ap	30
Latitude Resolution	5 deg.
Longitude Resolution	15 deg.
Height Resolution	80 km
No. of Volume Elements	13,107
State Covariance	Diagonal, Update
A priori covariance	10^10 + 0.4 Ne
Process noise covariance	10^10 + 0.2 Ne
Data	166,103 TEC links
Data source	97 ground stations
Data noise	1 TECU
Representation noise	2 TECU

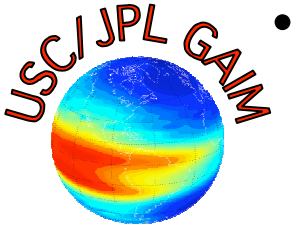


GAIM UV Analysis vs. NRL Chapman Retrieval



Outline

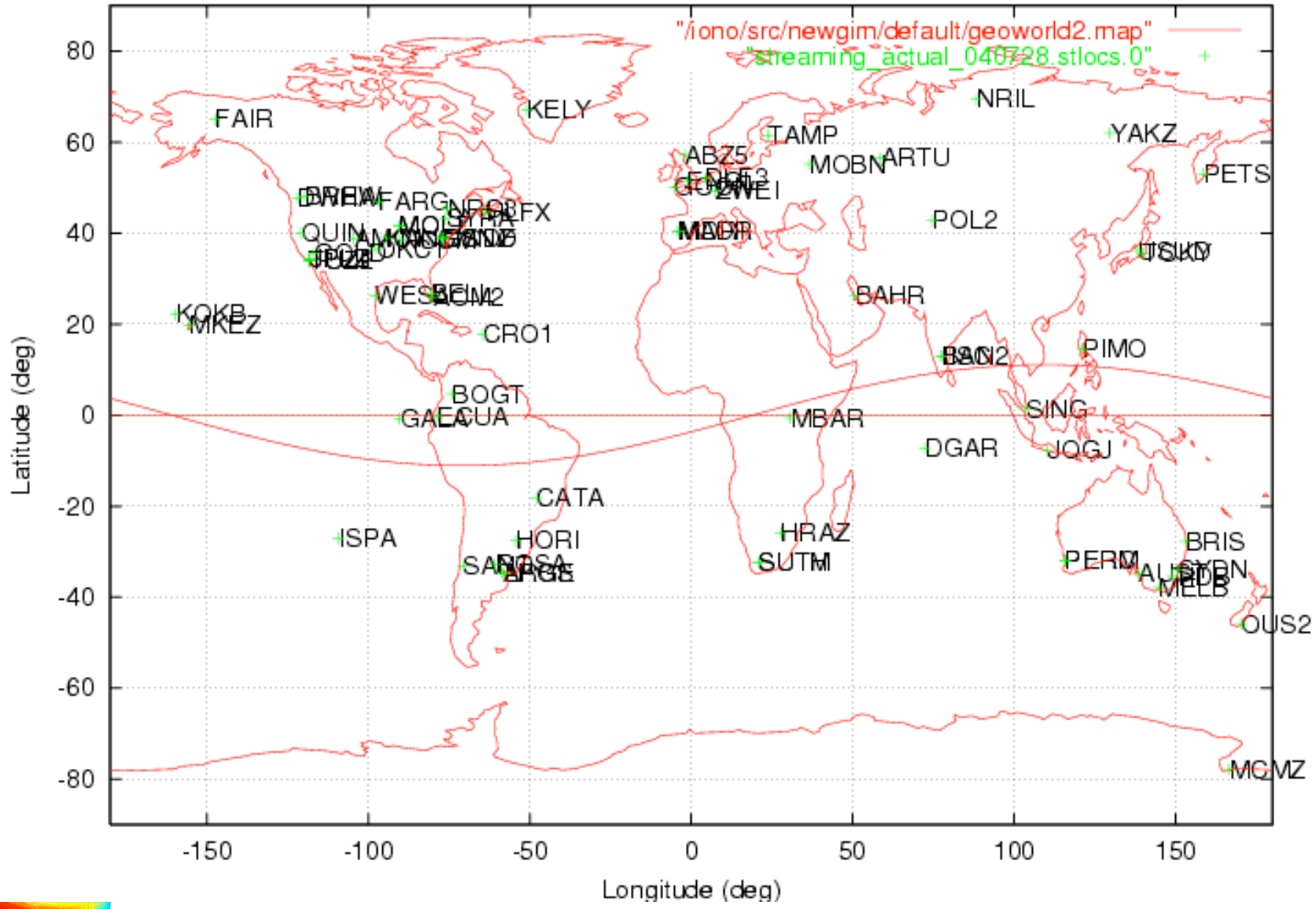
- Motivation: It's All About the Data!
- USC/JPL GAIM: 4DVAR & Sparse Kalman
- Daily GAIM Kalman Runs & Validation
- Extensive Validation, Case Studies
- **RT GAIM: Operational Prototype**
- Ionospheric Data Assimilation In-A-Box
- Validation Datasets & Collaboration



Global RT GAIM Prototype

- **Input data is ground GPS TEC:**
  - **Every 5 minutes from 58 1-sec. streaming sites (~450 pts)**
  - **Every hour from ~150 sites**
- **Sparse Kalman Filter**
  - **Update global 3D density grid every 5 minutes**
  - **30,000 elements in variable grid**
  - **Res: 2-3^{o} in latitude, 7^{o} in longitude, 30-50 km in altitude**
  - **Runs on a dual-CPU Linux workstation**
- **Validation:**
  - **Every hour against independent GPS TEC values**
  - **Every 3-4 hours against vertical TEC from JASON**
  - **Every day (post-analysis) against ionosonde and other data**

77 Streaming GPS Sites (08/2004)



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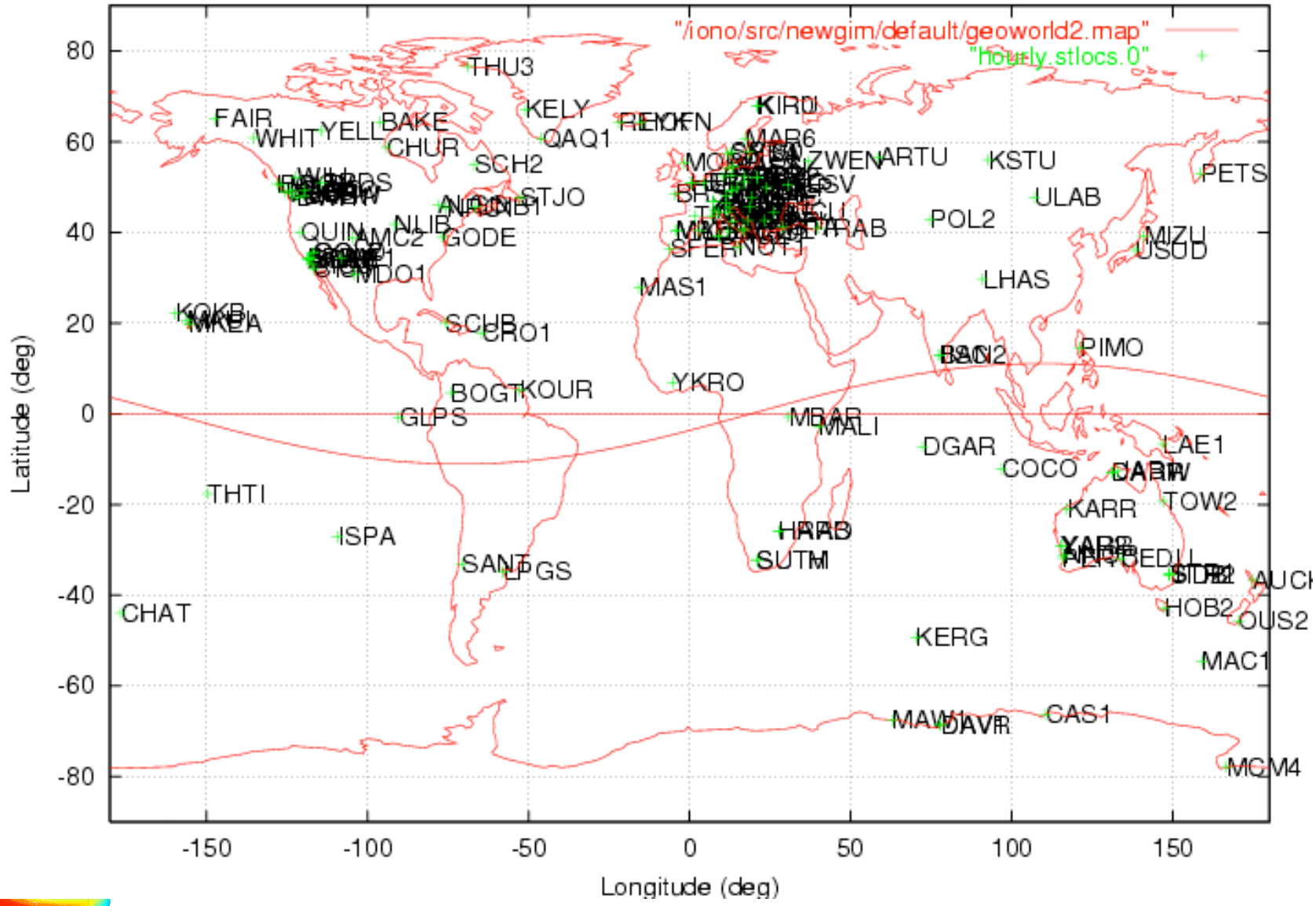
150+ Hourly GPS Sites (08/2004)



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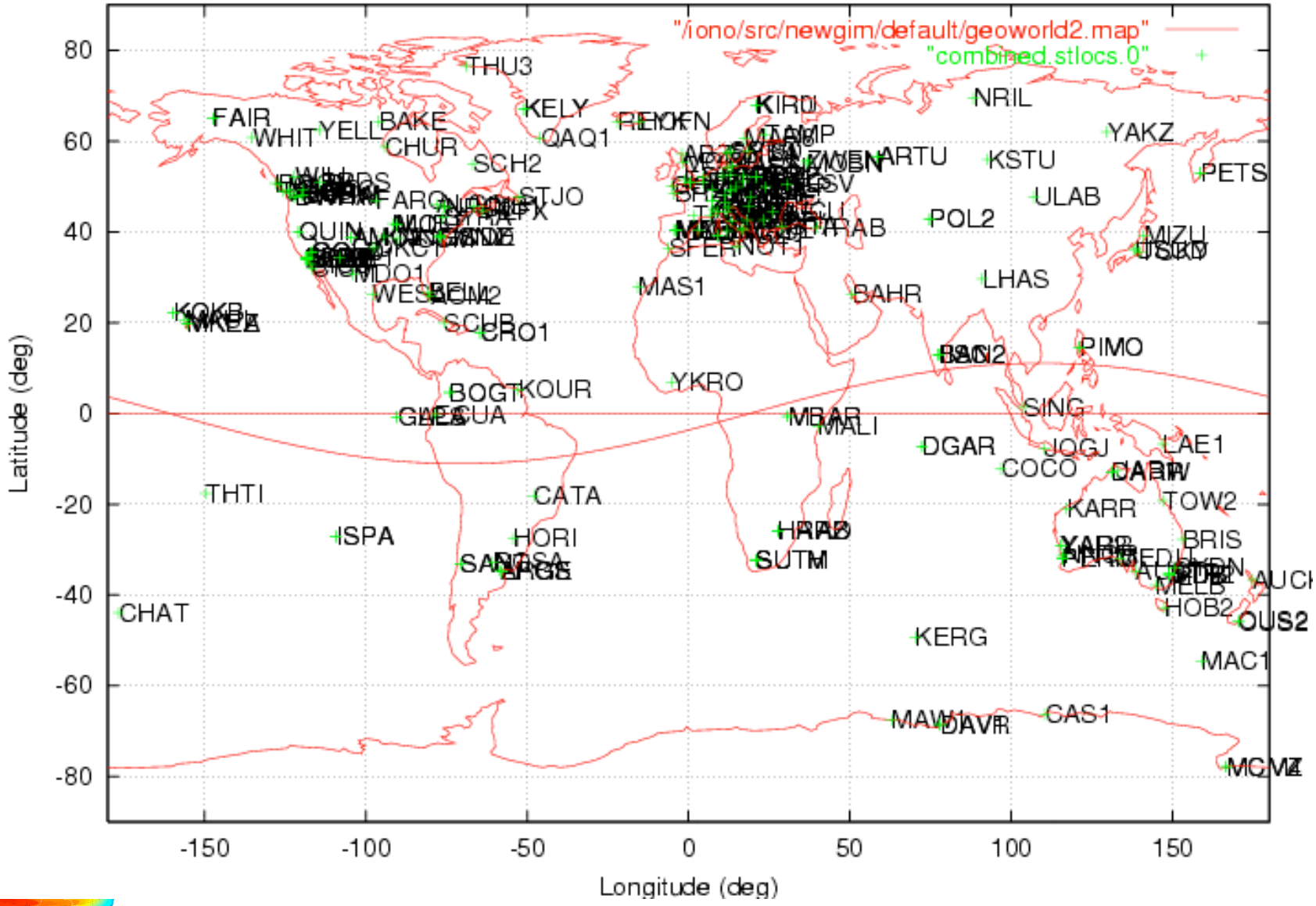
Streaming + Hourly GPS Sites (08/2004)



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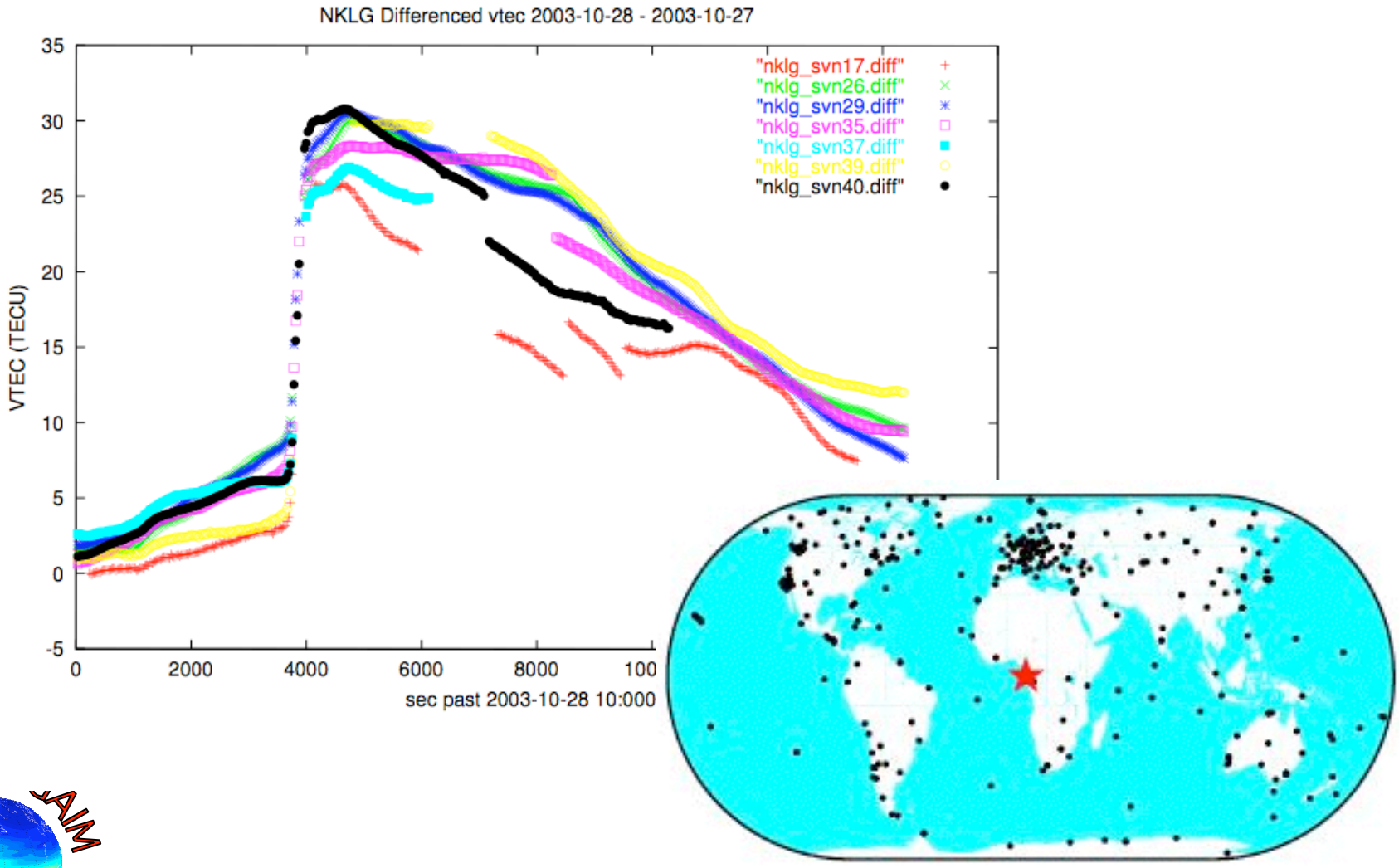
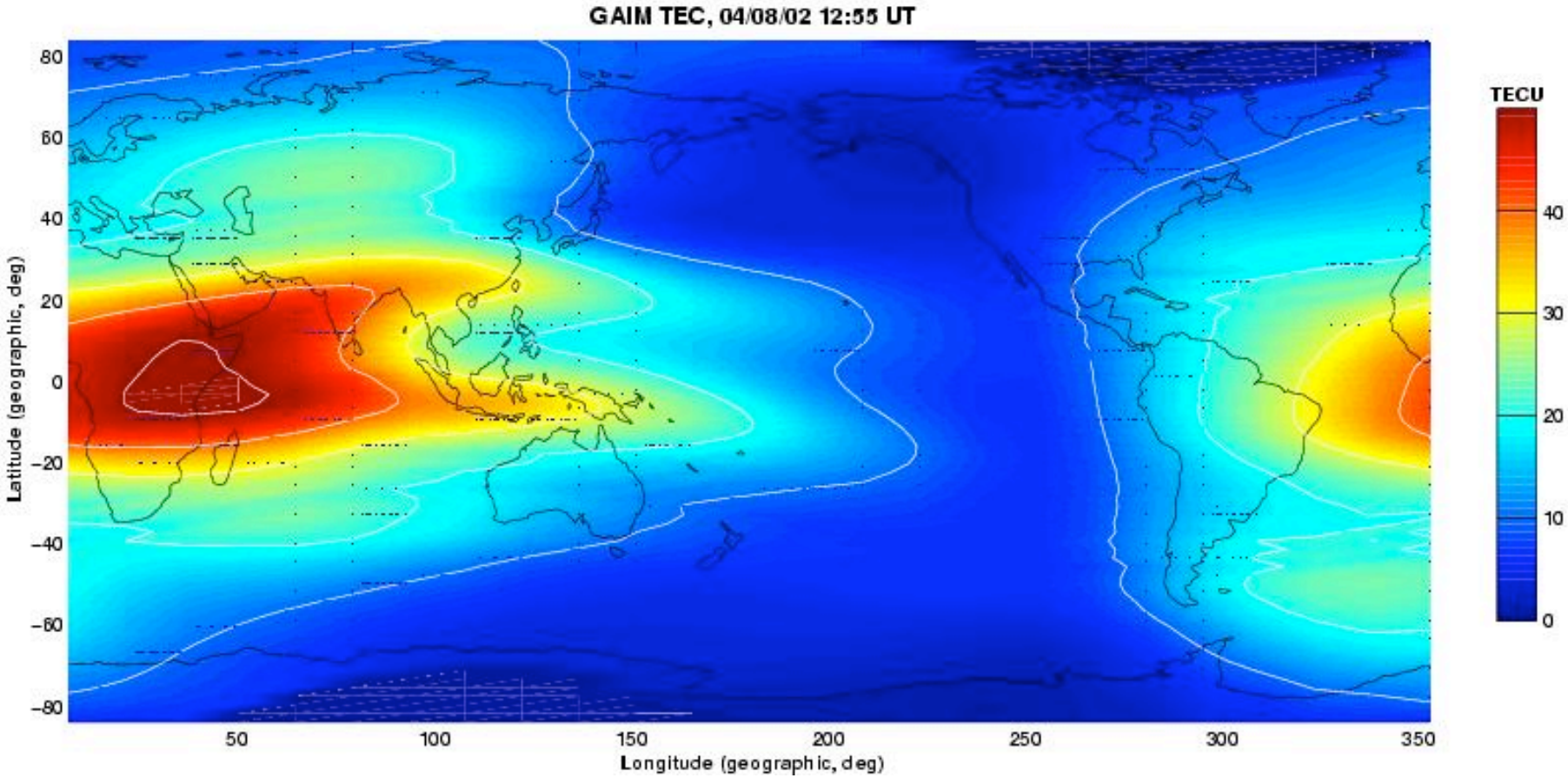
Ionization Response to Flare, Oct. 28, 2003



Global TEC Map Generated Every 5 Minutes



USC/ JPL GAIM

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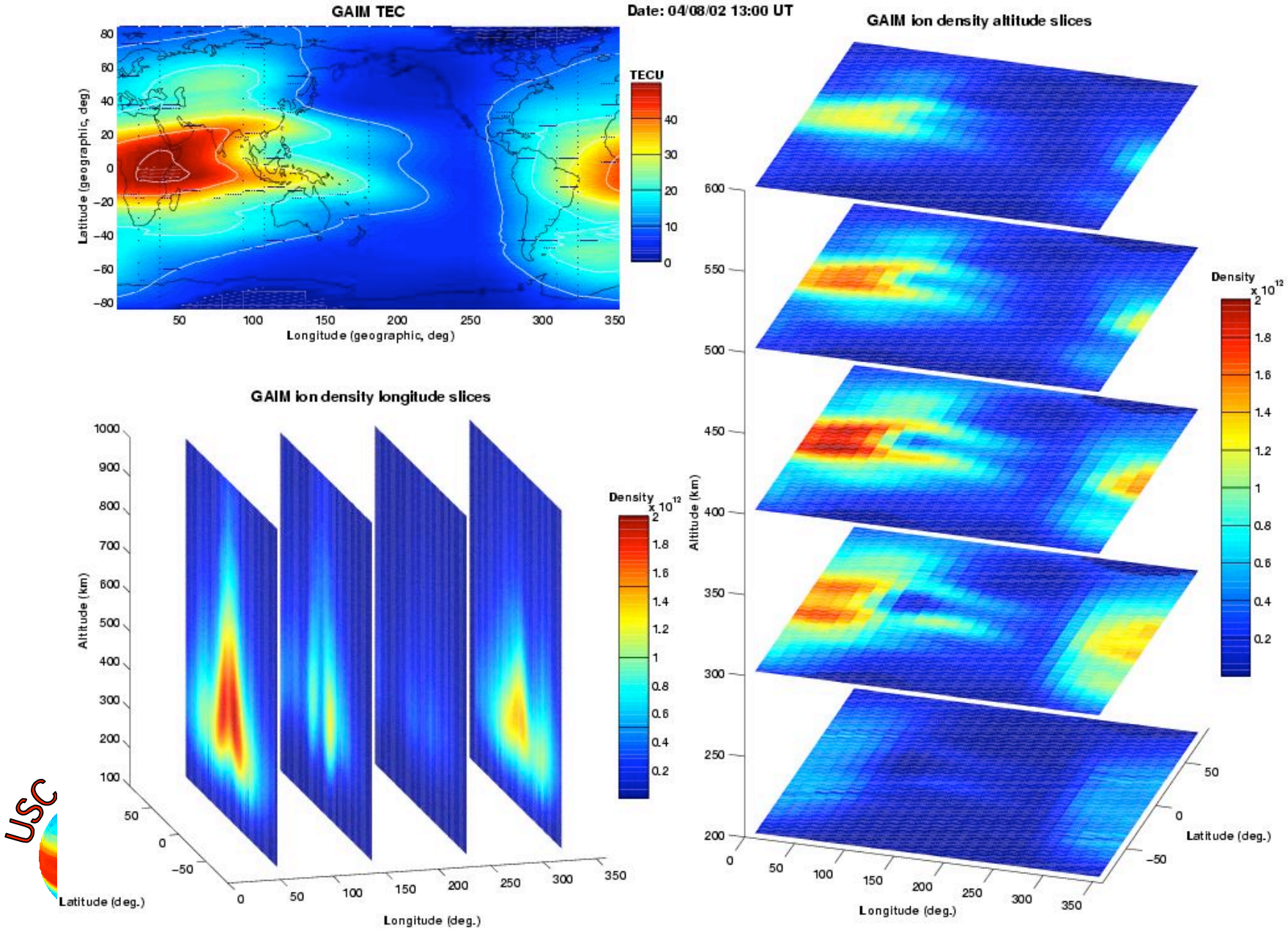
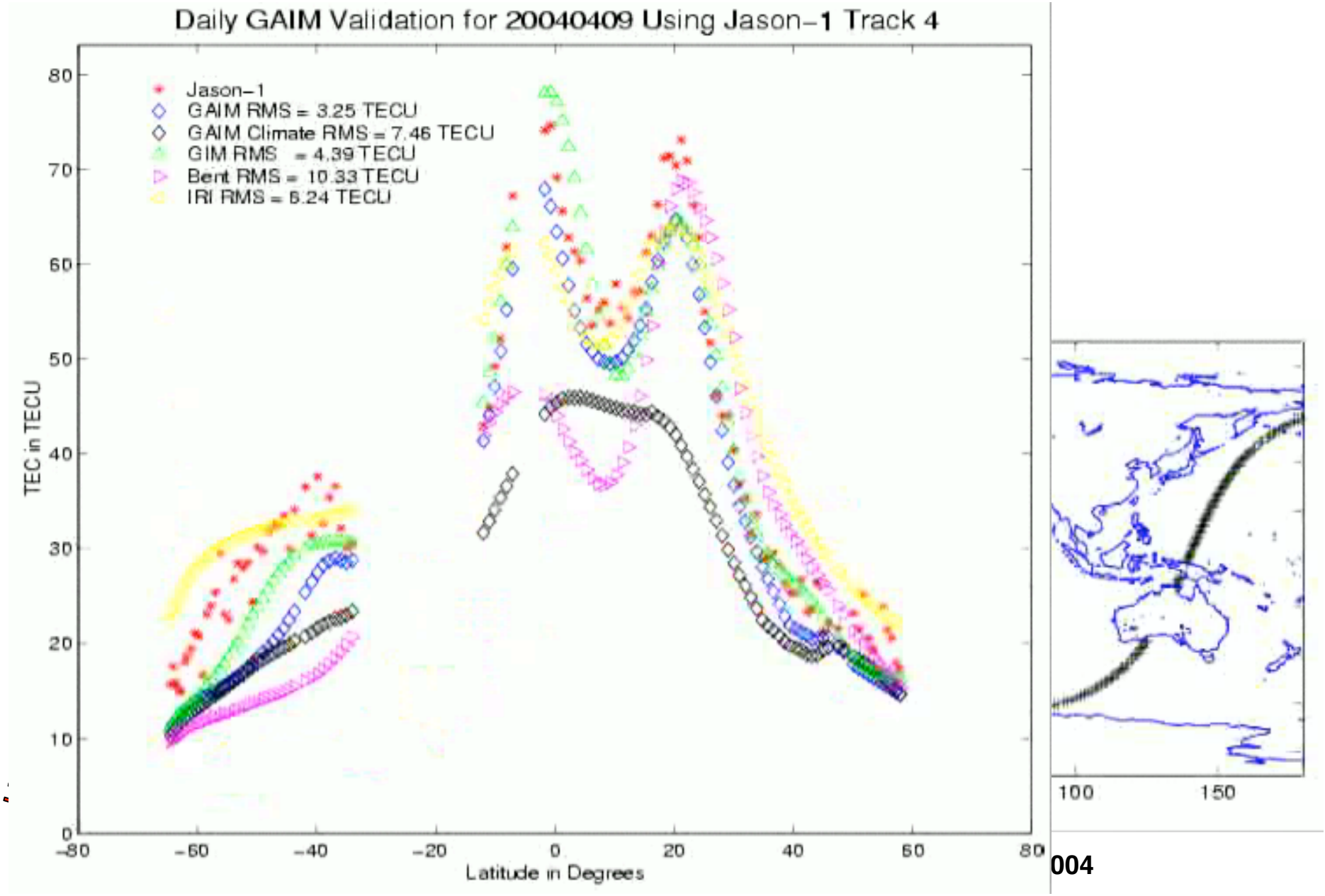
Add Frame to Density Movie Every 15 Minutes



JASON TEC Comparison - Daytime Track



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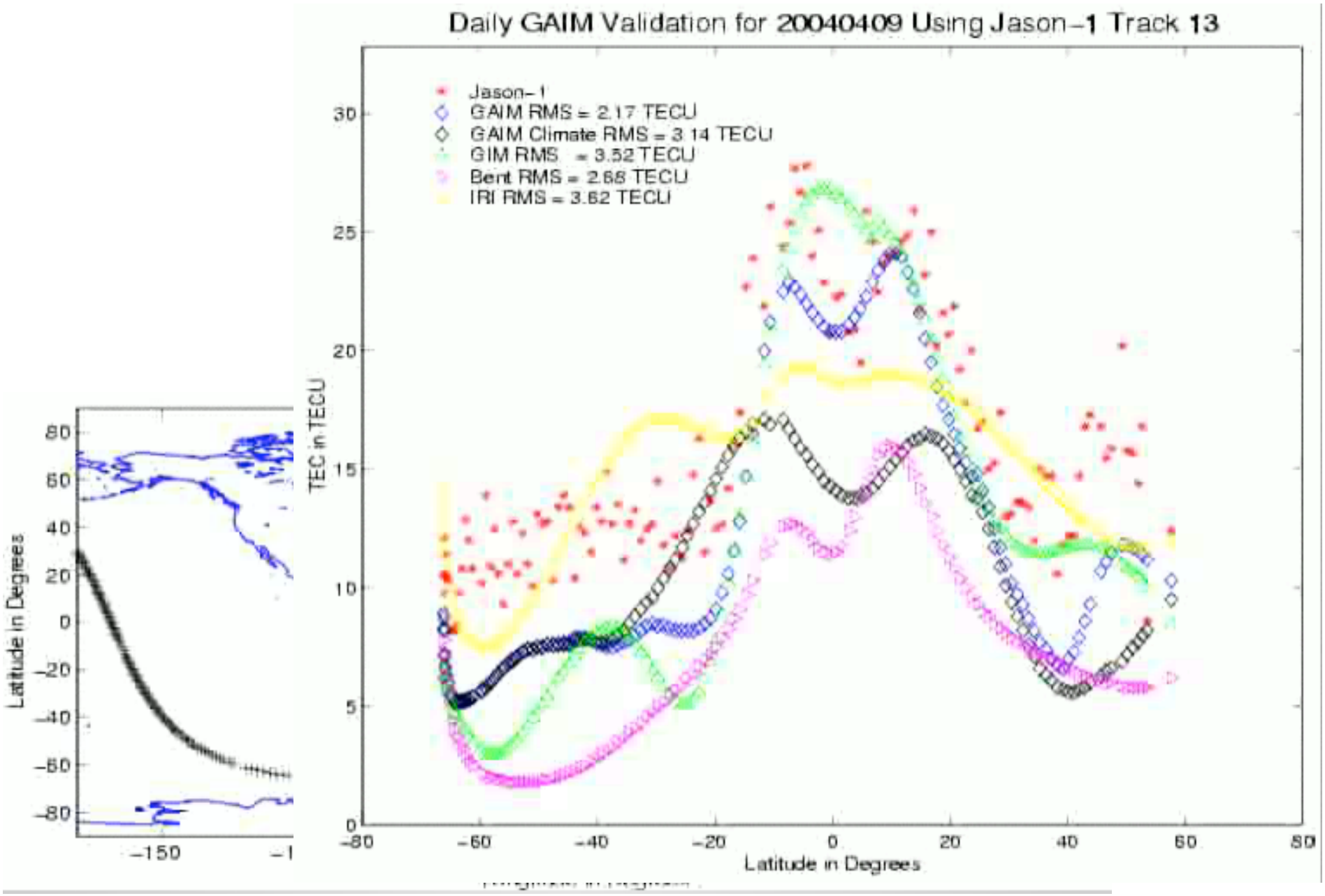

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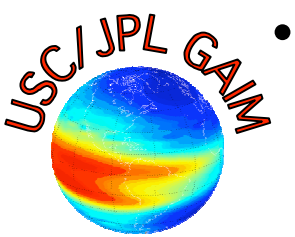
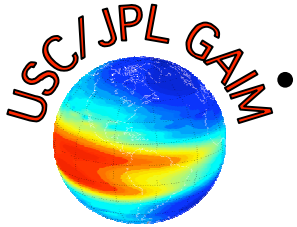


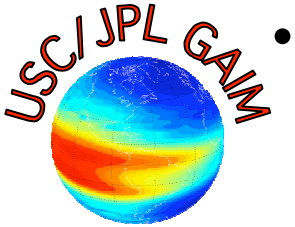
Programmatic Issues in the Era of Space Weather Data Assimilation

- **A robust ionospheric data assimilation program must include *continuous* cross-comparisons of multiple models.**
  - **As in weather, NCEP vs. ECMWF, etc.**
- **All sensors should be or plan to be real-time.**
- **All datasets should be publicly available, at least after a time delay.**
- **Data quality and model accuracies must be *continuously* validated.**
- **Need RT validation and long-term reanalysis.**



Concept: Ionosphere "In A Box"

- Deliver a software system that contains much more than a physics-based ionosphere model.
- Also an Operational System right out of the box:
  - Pulls input data feeds in over the Internet.
  - Pull input drivers in from upstream models running at other centers.
  - Automated NRT & daily validation
  - Pushes output density grids to multiple customers.
  - Could be embedded in the field.



Ionosphere In-A-Box v1.0

- USC/JPL GAIM forward model and Kalman filter
- Hardware: One dual-CPU Linux Workstation
- Data Feeds! -
  - Geophysical indices from NOAA SEC
  - TEC data every 5 minutes from 77+ GPS sites
  - Ionosonde data every 15 minutes from SEC
  - JASON validation TEC every 3 hours
  - Post-processing GPS TEC from 200-900 sites
- Outputs:
  - Updated 3D density grid every 5 minutes
  - Automated validation (JASON, ionosonde, GPS)
- Applications:
  - Trans-ionospheric ray path calibration, etc.

Later Versions

- Forecast capability: 6 to 12 hours
- Update drivers using 4DVAR (running on 2nd CPU)
- More Input Datatypes
  - TEC links from COSMIC constellation
  - UV radiances from SSUSI/SSULI on DMSP
  - Sensors on C/NOFS (vertical drifts, winds)
- More Applications:
  - Ray tracing, etc.
- More Enhancements
  - Interests?

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Validation Datasets & Collaboration

- Contribute to validation cases
  - Expertise
  - Run USC/JPL GAIM for comparisons
- Datasets:
  - GPS TEC: From 200-900 sites on any day
  - JASON/TOPEX: Vertical TEC for most days in last 5 years
  - Calibrated GPS occultation data from CHAMP, SAC-C, & IOX for input, and Abel profiles for validation
- Interests? Priorities?

Potential GPS TEC Upgrades at AFWA

- Provide slant TEC data every 5 minutes from 77+ 1-second streaming GPS sites
- Upgrade some of current (~50) hourly GPS sites to 15-minute cadence
- Compute 5-minute rate TEC data regardless of the delivery cadence (5, 15, or 60 minutes)
- Deliver data from all available streaming & hourly sites (~160 total and still growing)
- Deliver TEC data from 200-900+ sites daily for validation in a post-processing mode

Summary of USC/JPL GAIM Status

- **USC/JPL GAIM band-limited Kalman filter has been extensively tested with *real* data.**
- **Case studies (single datatype & combined):**
  - **TEC from ground GPS**
  - **DTEC from GPS occultations (IOX, CHAMP, SAC-C)**
  - **UV radiances from nighttime scans (LORAAS, GUVI)**
- **Daily and RT Kalman runs using ground GPS**
  - **Global and regional high-resolution runs**
  - **Add COSMIC occultations & DMSP UV radiances**
  - **Add other datatypes as available: ionosonde, C/NOFS**
  - **Challenge of understanding multiple input datatypes!**
  - **Intent: Run Daily and RT forever using all available data.**
  - **Add adjusted drivers from 4DVAR soon**