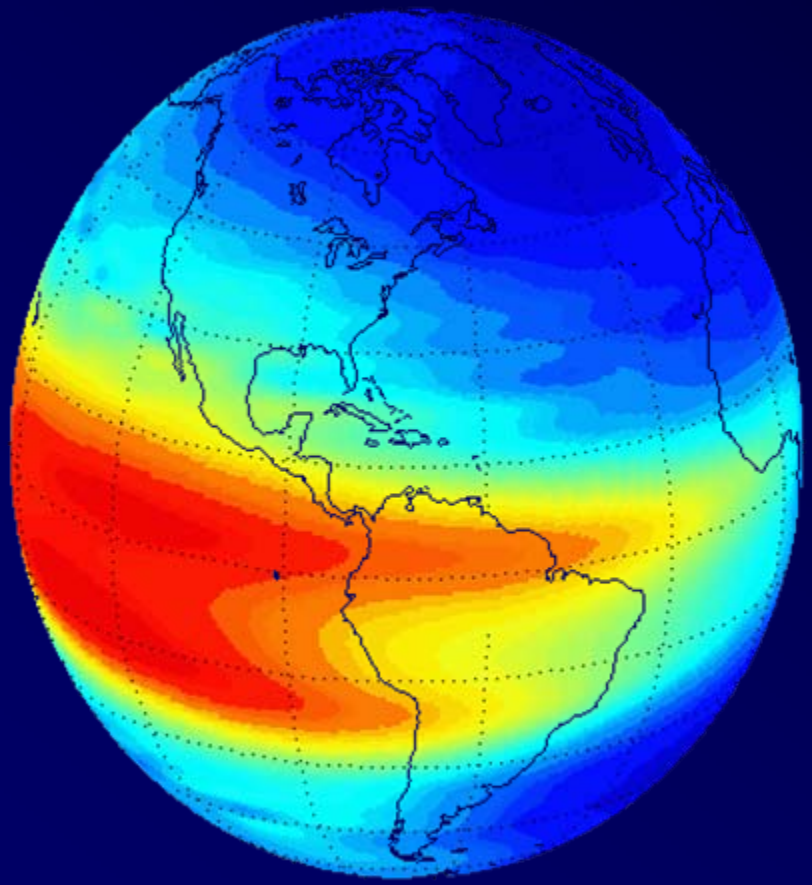
Results from CHAMP, SAC/C and IOX GPS Ionospheric Occultations Obtained by the Abel Inversion and Data Assimilation



Lukas Mandrake, JPL
George Hajj, JPL, USC
Byron Iijima, JPL
Xiaoqing Pi, JPL, USC
Gary Rosen, USC
Paul Straus, Aerospace
Chunming Wang, USC
Brian Wilson, JPL

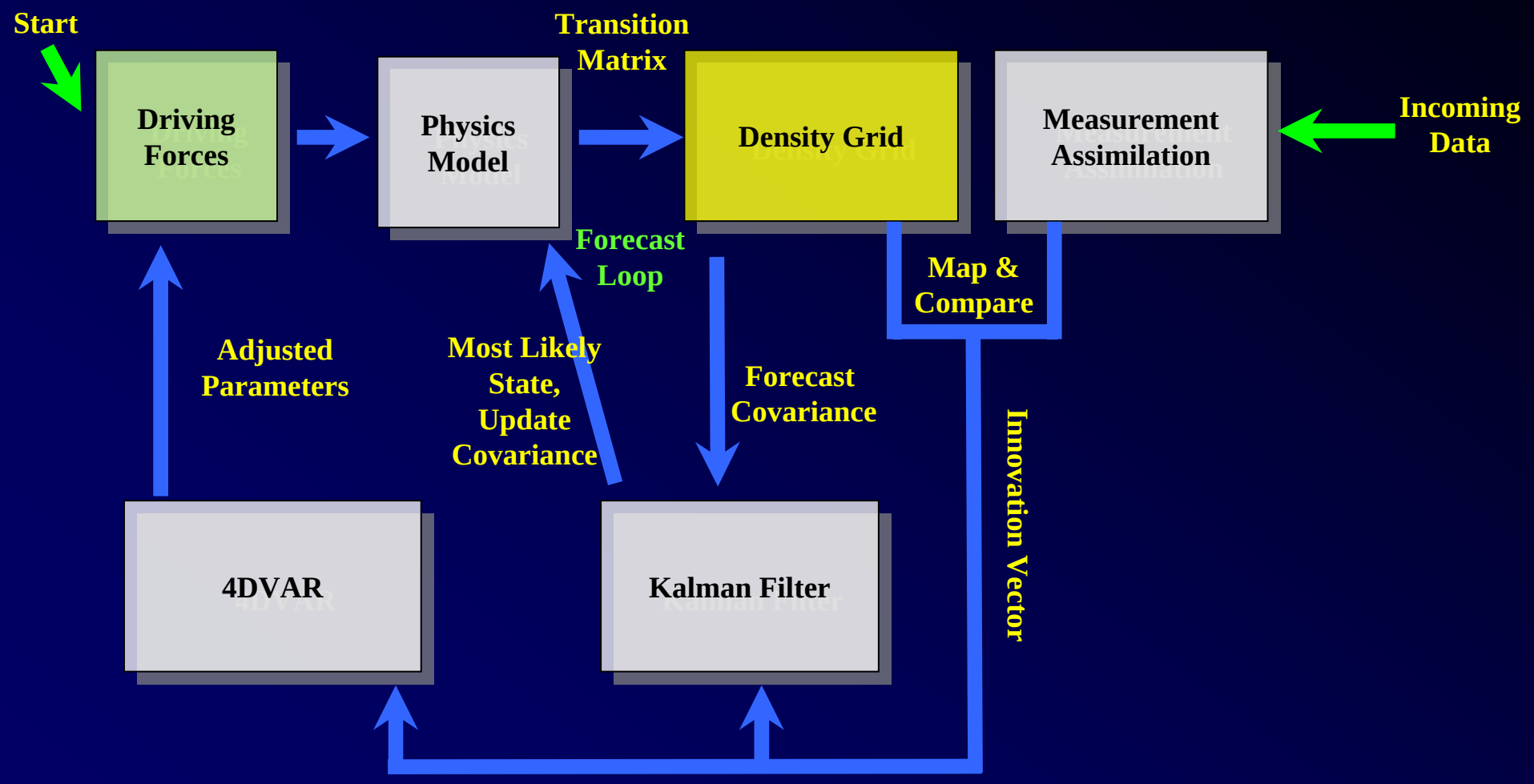
Outline

- Band Limited Kalman Filter Overview
- Assimilation of GPS Occultations
  - Focus on 3 day period (July 22-24, 2002)
- Validation against
  - Abel Inversions
  - Global Ionospheric Maps (GIM) of Vertical TEC
  - Topex Vertical TEC Measurements
  - Ionosonde NmF2 and HmF2
- Assessment of the Ground vs. Flight TEC Data
- Overview of Daily Global GAIM Runs

Model Overview

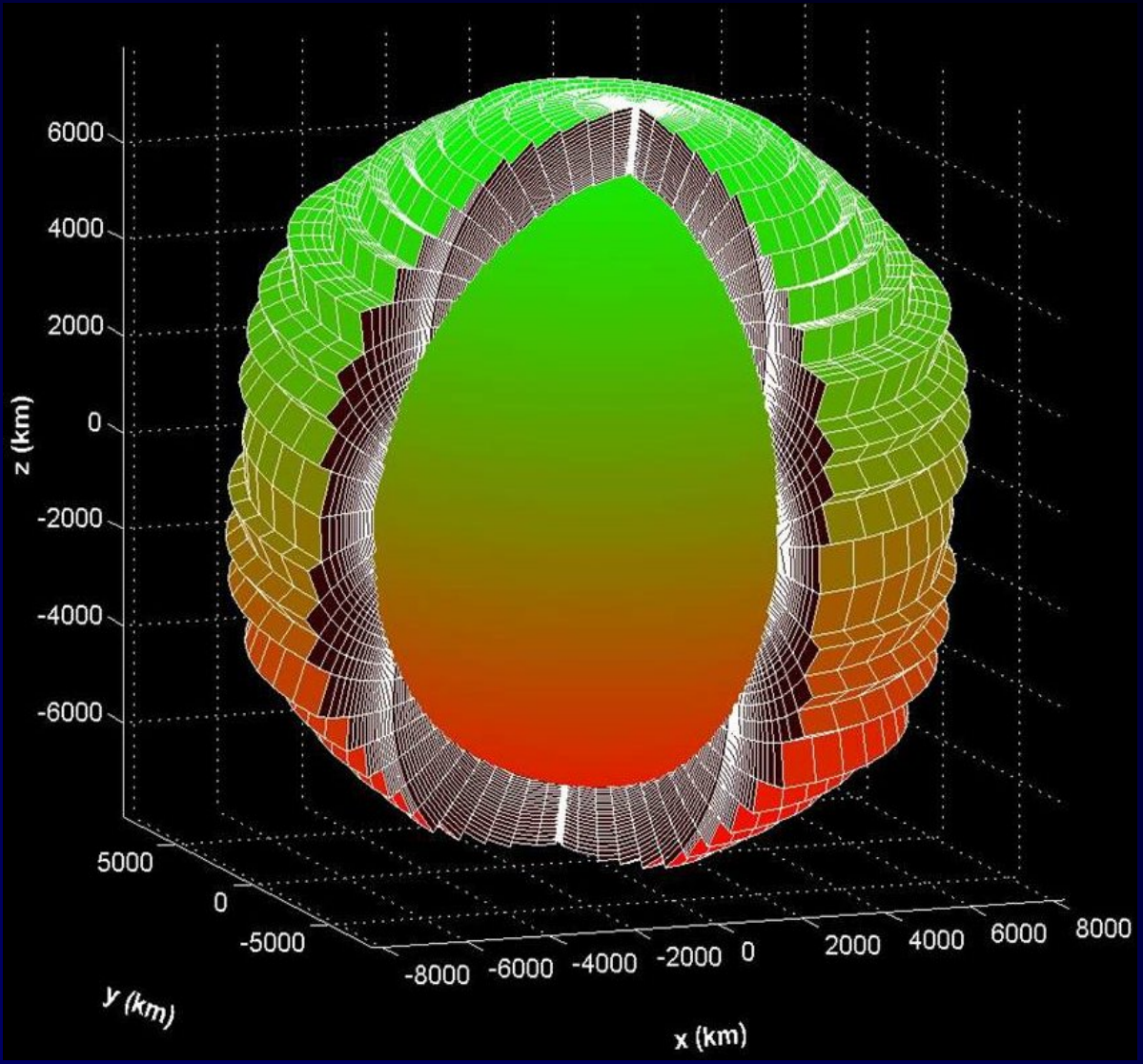
The Band-Limited Kalman

General Structure of GAIM



Grids of the Model

- Elements in p-q-l magnetic coordinates
- Variable element Size
- 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
- Eulerian frame (fixed grid in space)



Band Limited Kalman Filter

Advance State In Time

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

Measurement Model

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

Noise Model

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

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

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

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

Assimilate New Measurements

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

Calculate Kalman Gain

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

Update Covariance Matrix

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

Update State Forecast

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

Advance Covariance in Time

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

Time intensive

Gaussian Interpolation

$$\sigma_{ij} = \sigma_i \times \sigma_j \times \exp - \left\{ \left(\frac{r_i - r_j}{R} \right)^2 + \left(\frac{\theta_i - \theta_j}{\Theta} \right)^2 + \left(\frac{\phi_i - \phi_j}{\Phi} \right)^2 \right\}$$

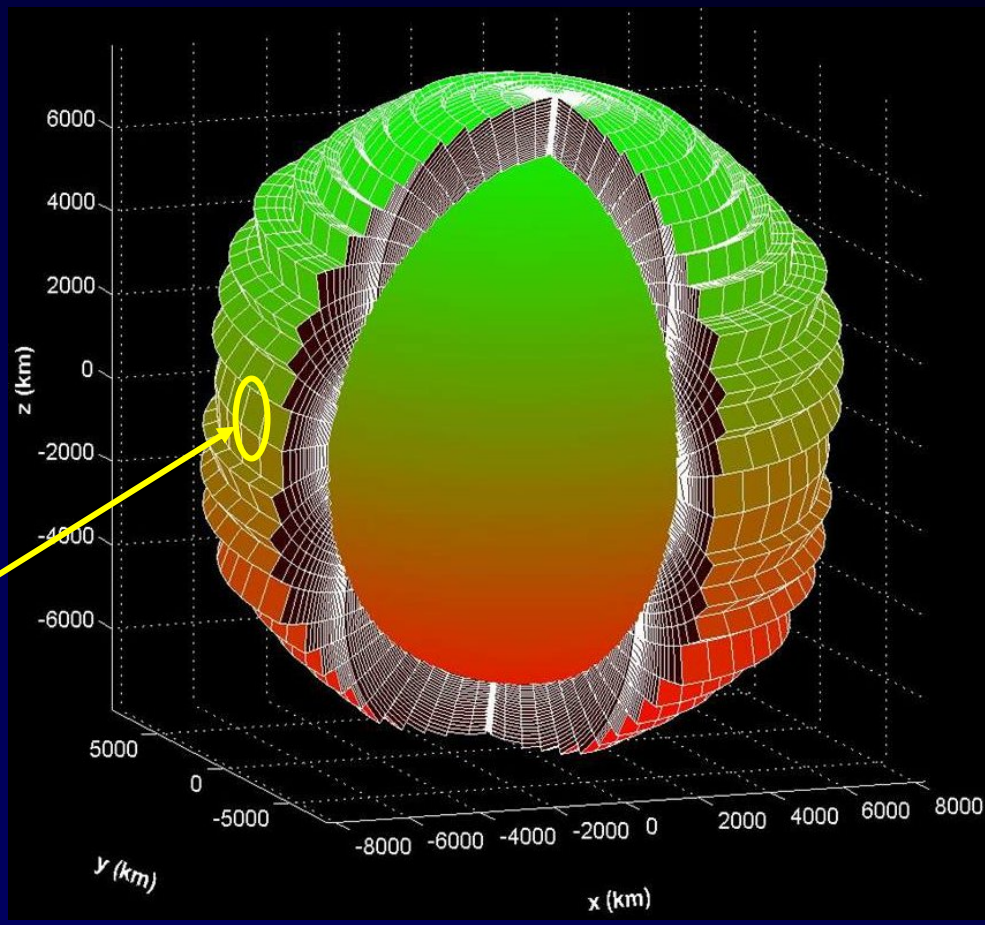
σ_{ij} = Corr. between voxel i and j

σ_i = Uncertainty in density in voxel i

R = Correlation length in altitude

Θ = Correlation length in latitude

Φ = Correlation length in longitude



Correlation Scale

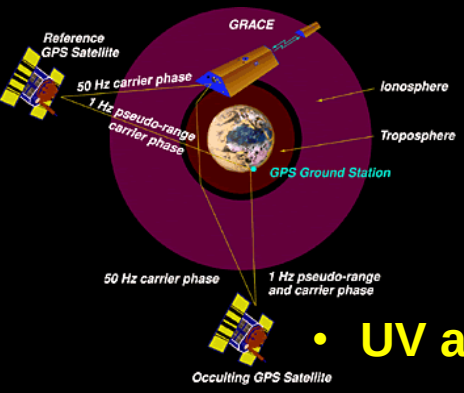
Summary - Number Of Operations

Approach	No. of Operations
Full Kalman	$O[M \times N^2]$
Optimal Interpolation	$O[M \times N]$
Band Limited	$A\ O[M \times N^2]$

M = # of measurements
N = # of Voxels
A = ratio of neighborhood volume / total volume

Data Types Available

- **Ground GPS Data (Absolute TEC)**
  - ~500 Global GPS Ground Stations
    - GAIM assimilates ~200,000 TEC links (@5 min rate)/day
- **Space GPS Occultation 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



- **UV airglow data (135.6 nm)**
  - LORAAS on ARGOS
  - GUVI on TIMED

- **Other Data Types**
  - TEC from TOPEX Altimeter
  - Ionosonde
  - DMSP in situ
  - CHAMP in situ
  - GRACE Cross links
  - ISR

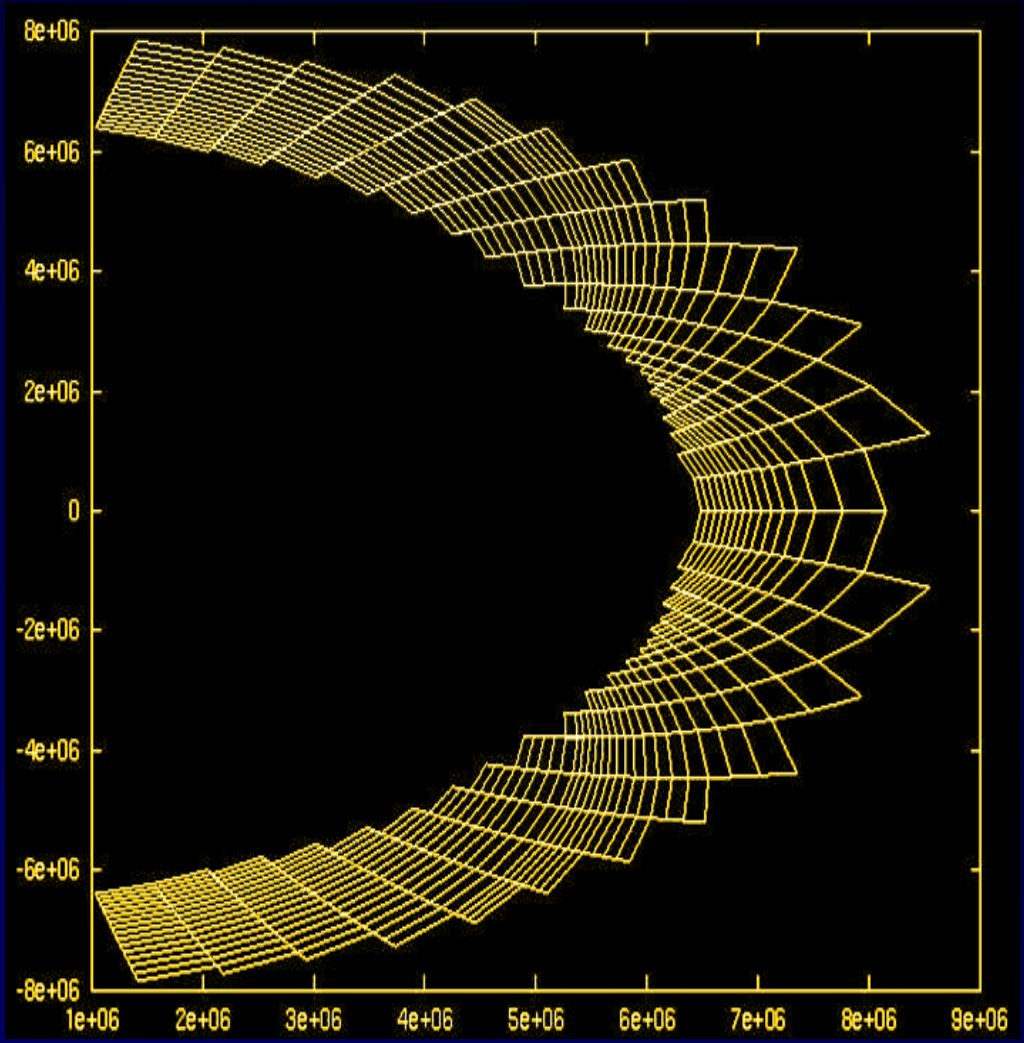
Sample Runs

Focus on Jul 22-24, 2002

Assimilation Run for July, 22-24, 2002

Grid Resolution

- **Resolution** — **5° Latitude**, **15° Longitude**, **80 km altitude**
- **# of voxels** — **13,107**
- **Correlation** — **nearest neighbor**
- **Resolution is actually higher**



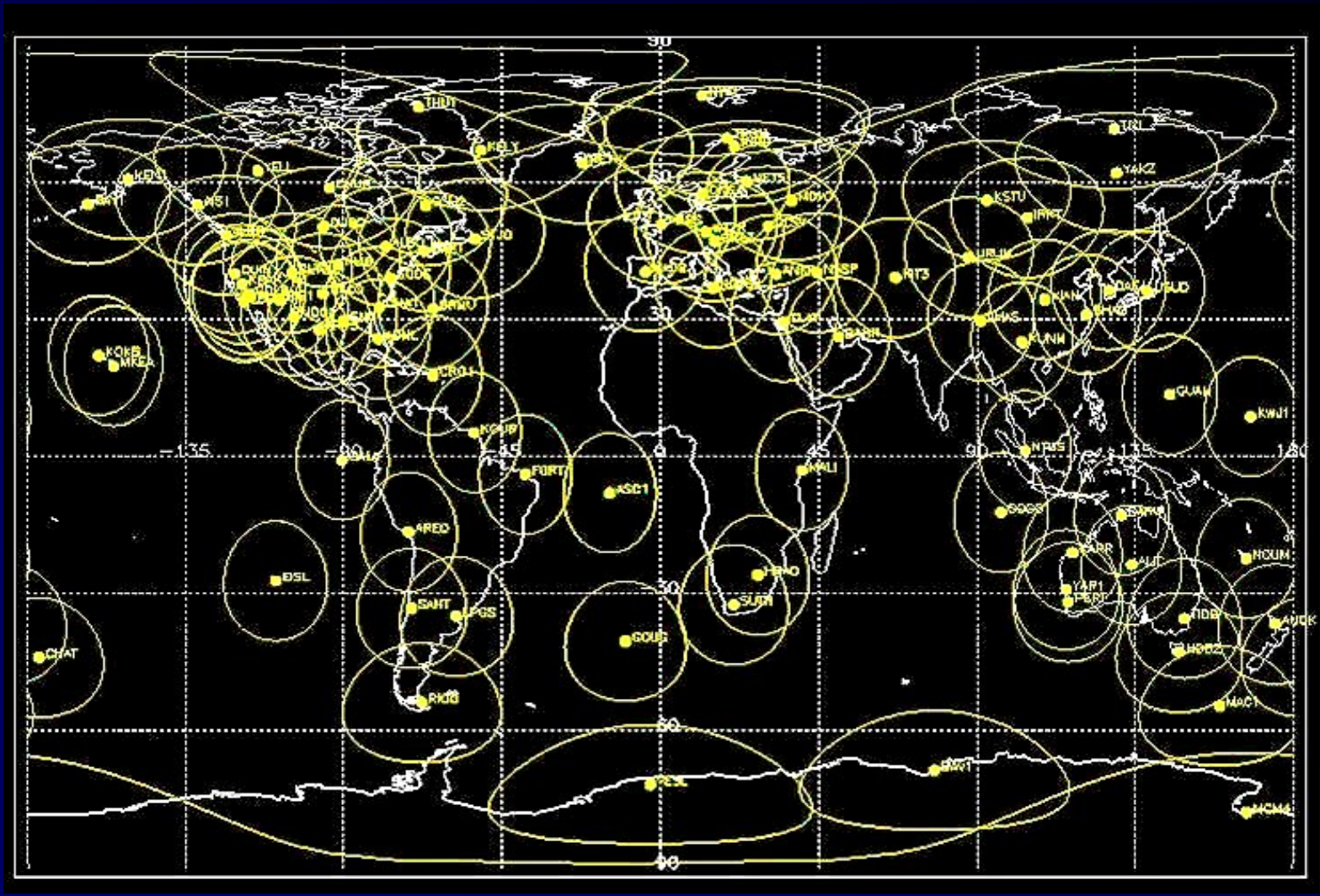
Assimilation Run for July, 22-24, 2002

Ground GPS Receiver TEC

(10 degree elevation mask; 450 km shell height)

100 GPS receivers used

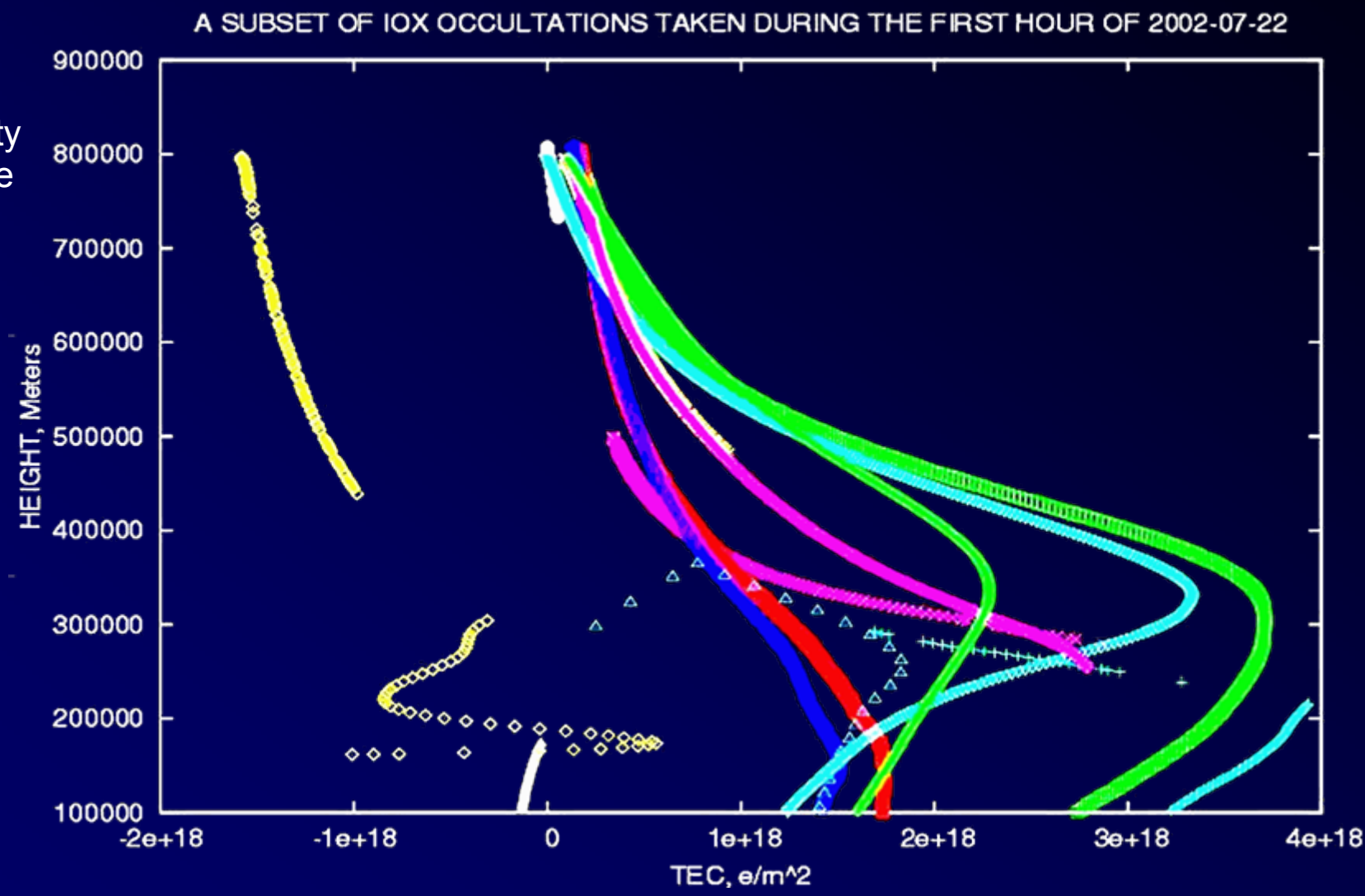
Note concentration in CONUS and Europe



Assimilation Run for July, 22-24, 2002

Examples of IOX occultation TEC Data

Clearly quality control will be of great importance



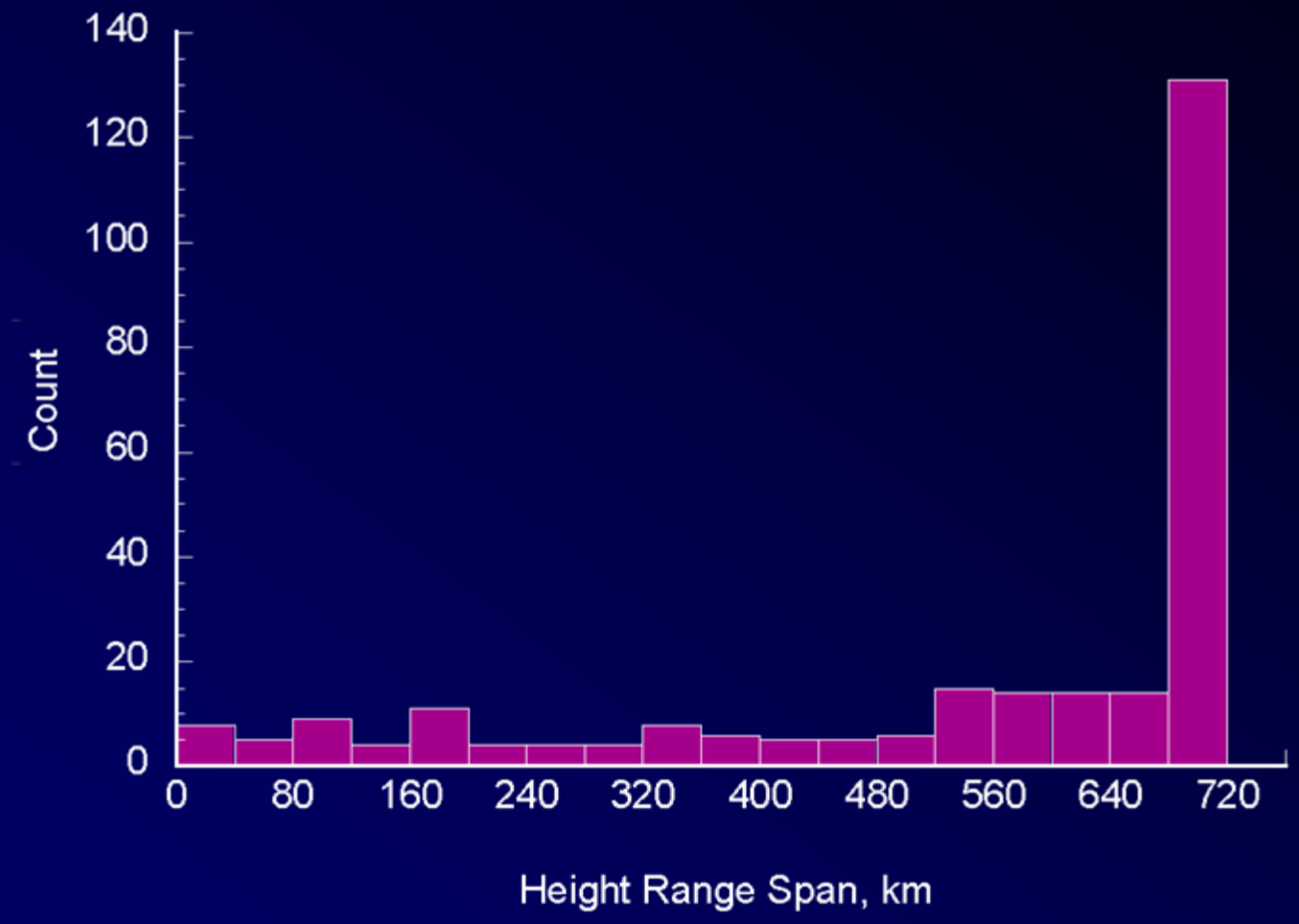
Assimilation Run for July, 22-24, 2002

Height Spanned by Occultations

A histogram of height range spanned by IOX occultations, 2002-Jul-22

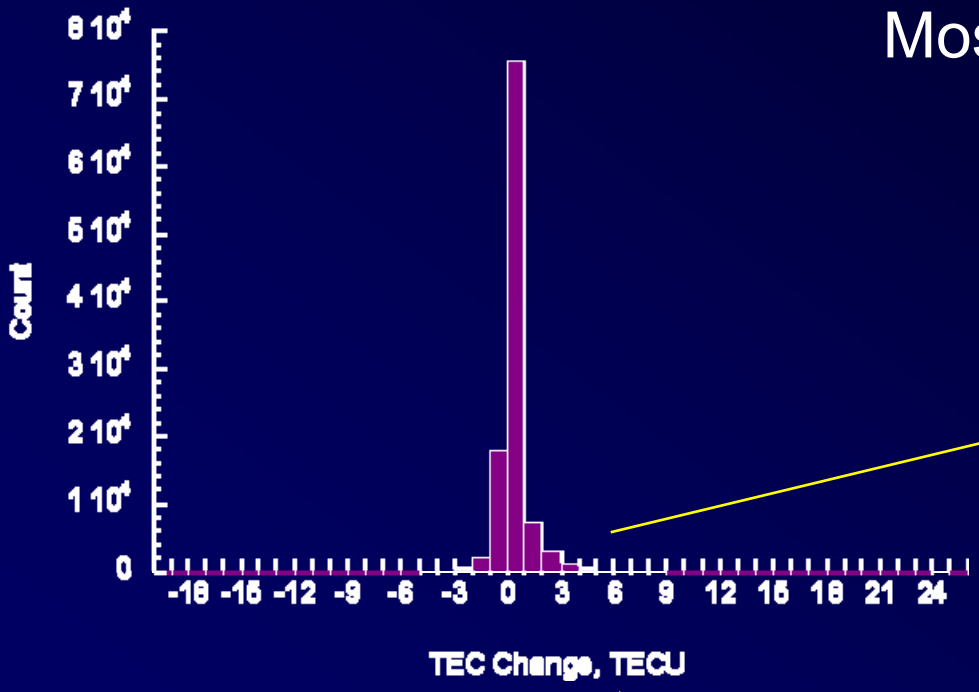
Most occultations span over 500 km in altitude

Short spans are likely erroneous broken tracks



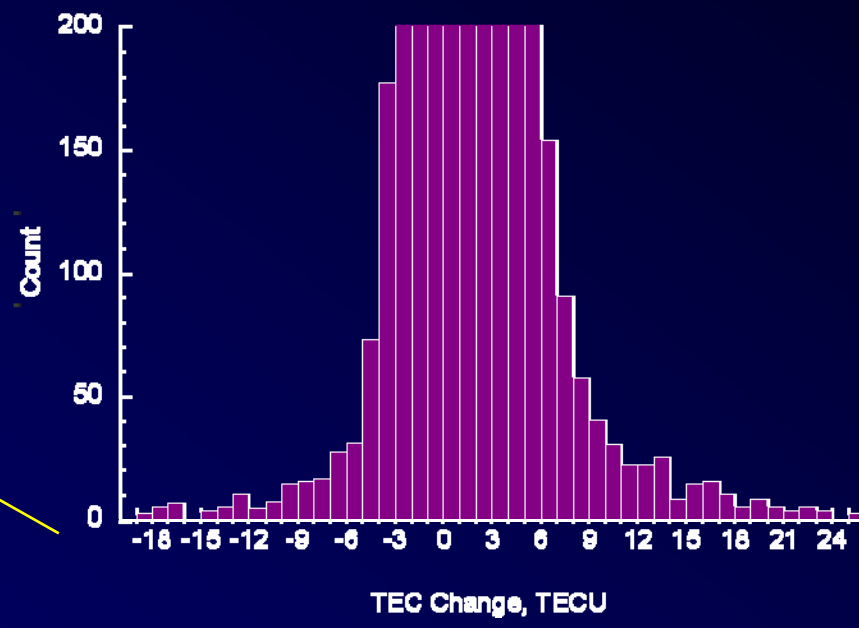
Assimilation Run for July, 22-24, 2002

TEC Change Between Successive Measurements



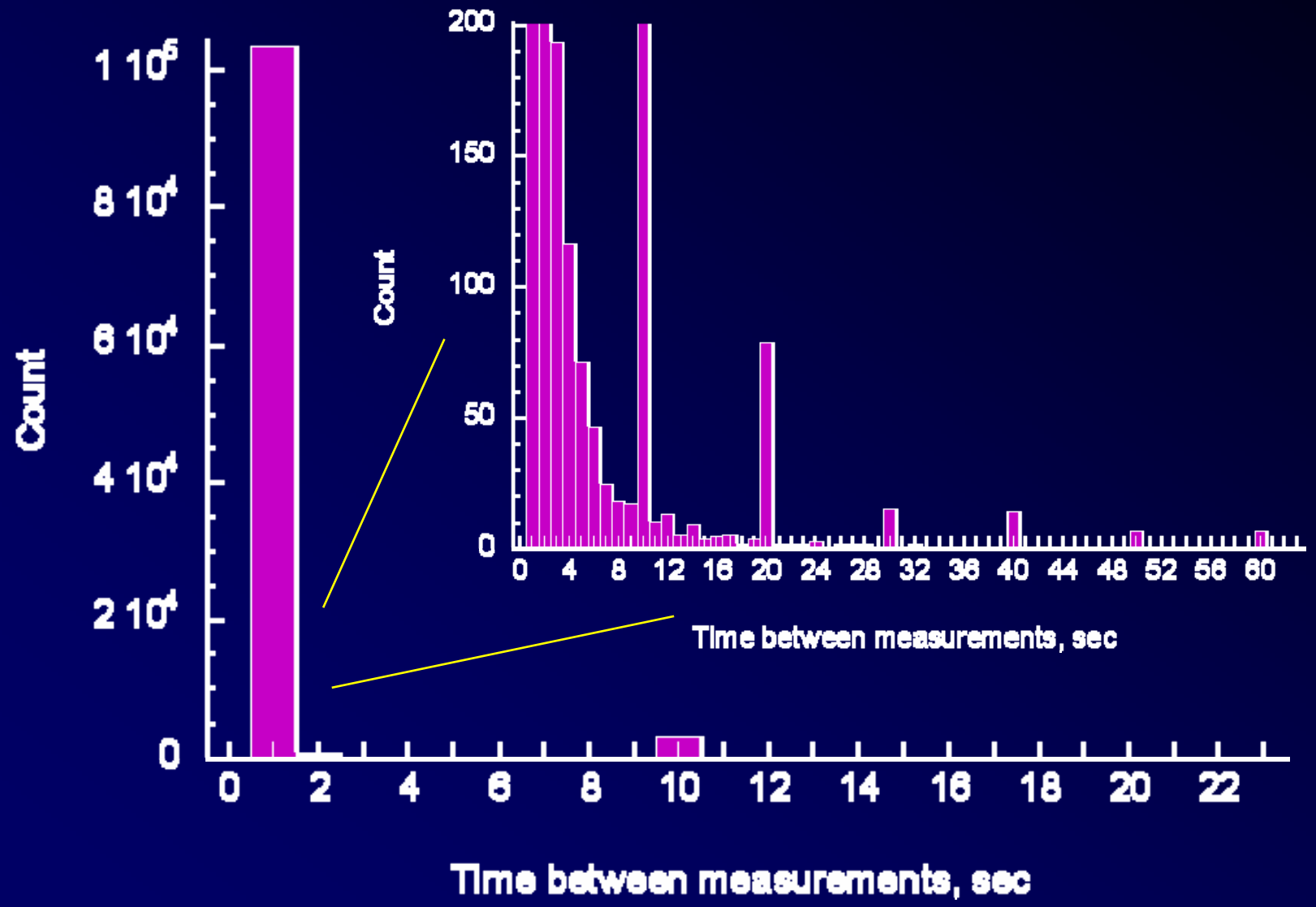
Most measurements change by 3 TEC or less

Remove those > 3 ΔTEC as likely broken tracks



Assimilation Run for July, 22-24, 2002

Time Between Measurements in Single Track



Assimilation Run for July, 22-24, 2002

GAIM Input Parameters

	Ground Data Points	IOX Data (all)	no upward IOX Data (Occ)	IOX Data (QC'ed)	F10.7	3 month Average F10.7	A_p
2002-Jul-22	194,935	132,054	113,678	86,931	195.8	173.7	16
2002-Jul-23	189,733	159,049	137,616	104,386	204.6	173.7	17
2002-Jul-24	193,913	164,036	134,529	94,187	215	173.7	7

Methods for Assimilation of Flight TEC Data

- **As absolute TEC**
  - Requires estimation of satellite <u>biases</u>
- **As relative TEC**
  (Difference from first measurement of a new arc)
  - Introduces strong correlation to the first data point
- **As differenced TEC**
  (TEC change between consecutive measurements)
  - Susceptible to larger measurement and representation noise

Focus on Jul 22-24, 2002

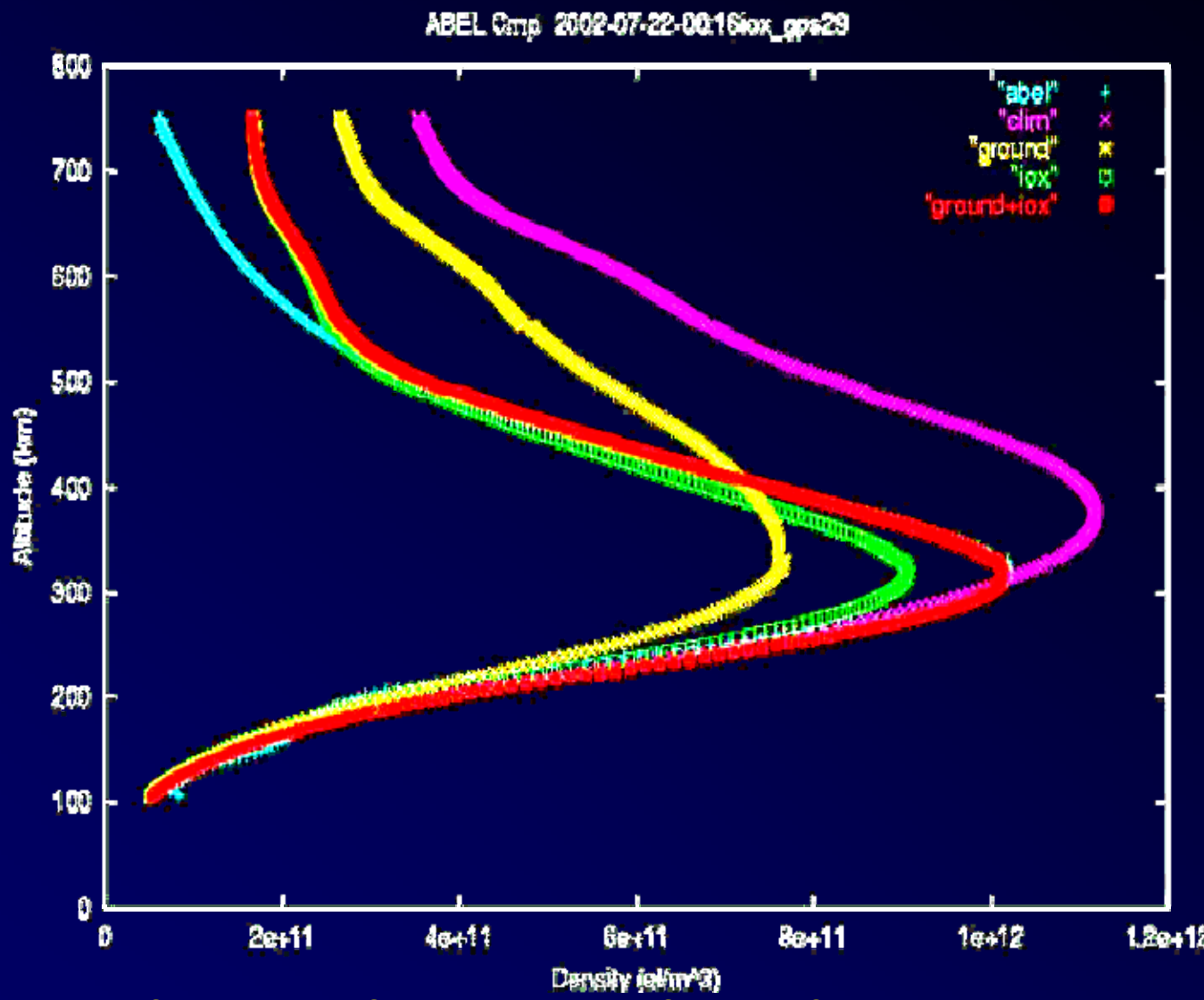
Validation Against Abel

Assimilation Run for July, 22-24, 2002

GAIM vs Abel at Occultation Tangent Point

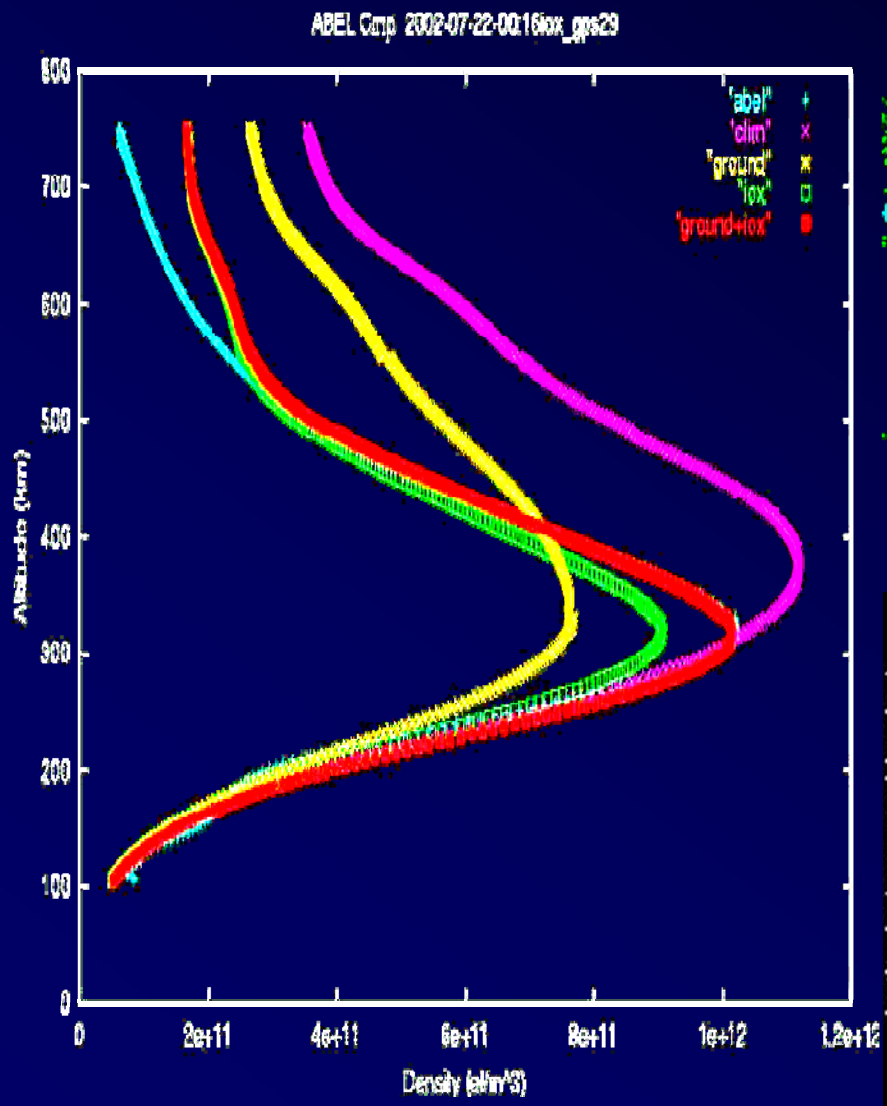
Profiles are obtained by:

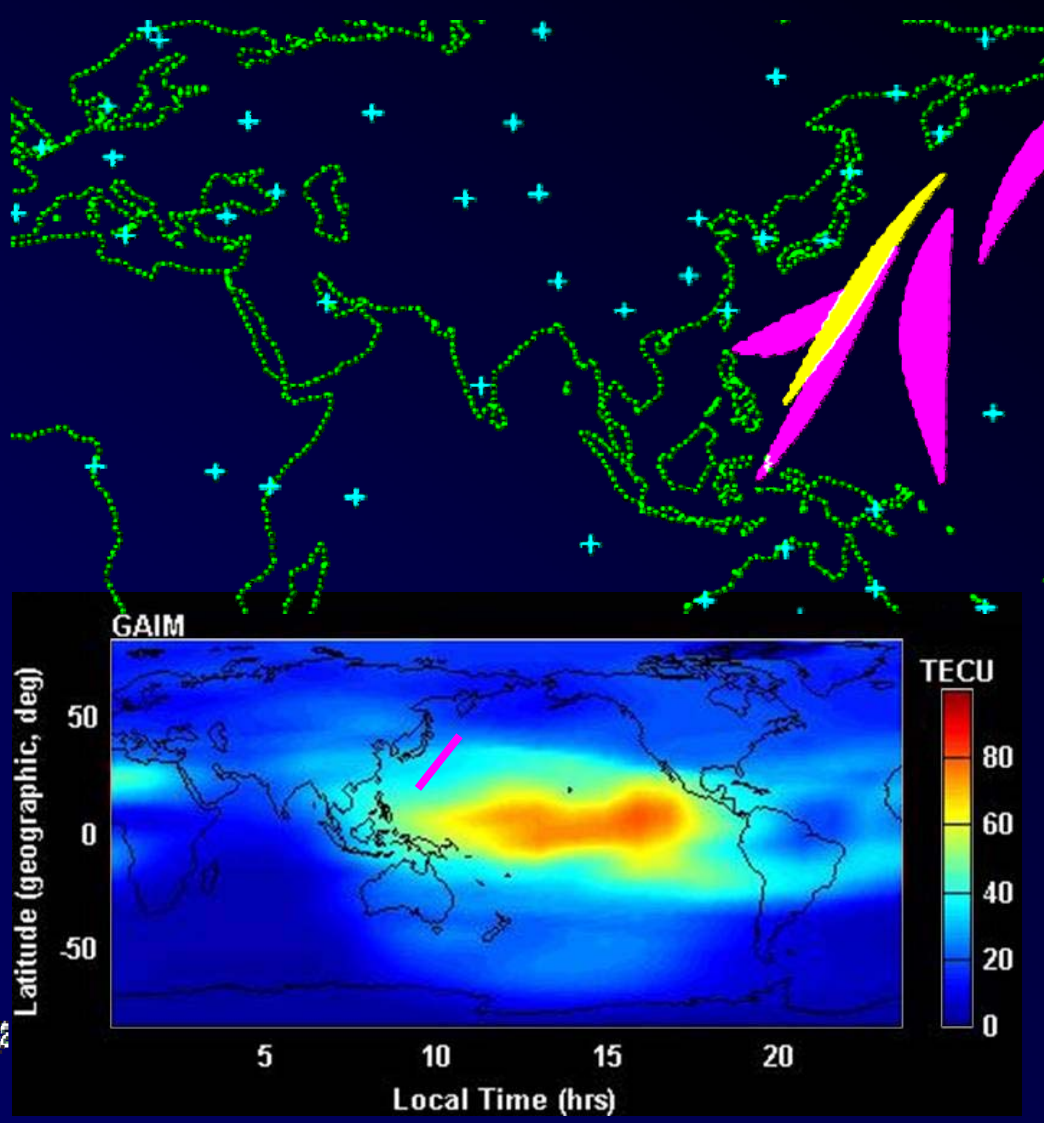
- **Abel Inversion ("abel")**
- **GAIM Climate (no data) ("clim")**
- **GAIM Analysis assimilating ground TEC data only ("ground")**
- **GAIM Analysis assimilating IOX TEC data only ("iox")**
- **GAIM Analysis assimilating both ground and IOX data ("ground+iox")**



Assimilation Run for July, 22-24, 2002

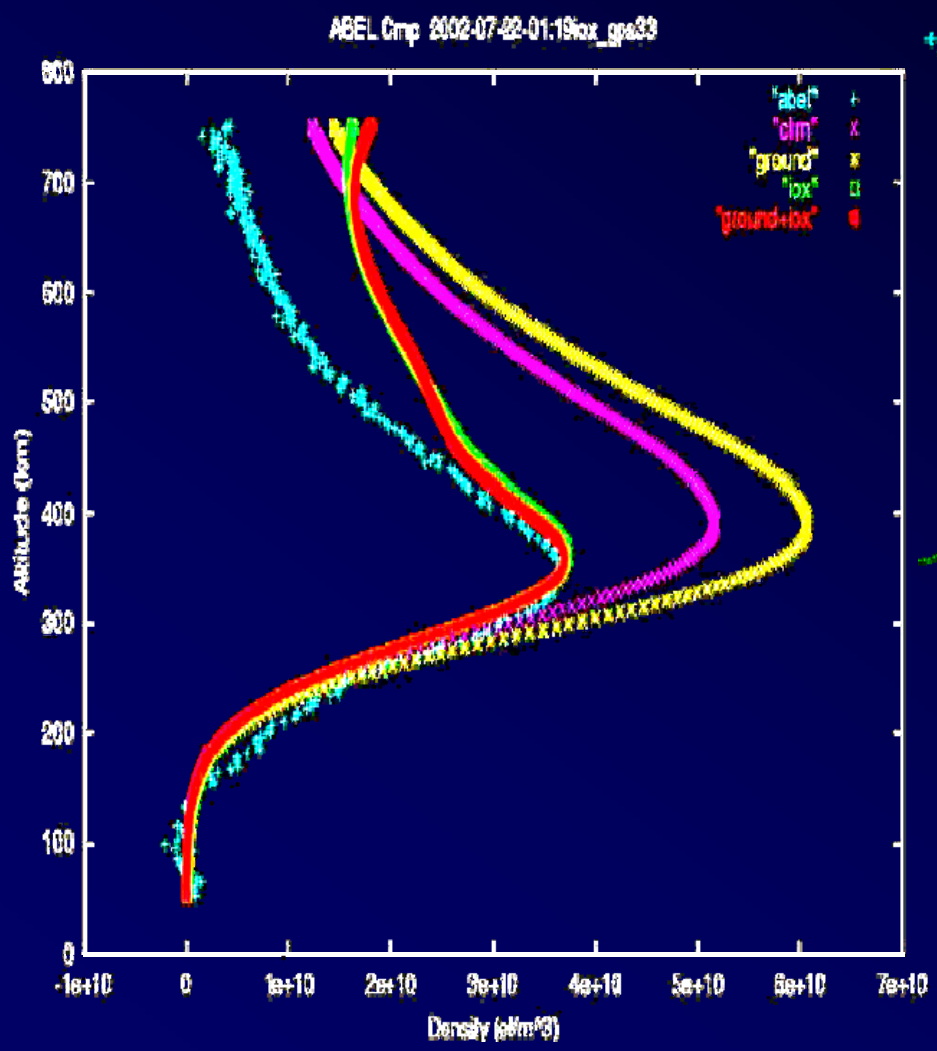
Geolocation of Occultation Tangent Example 1

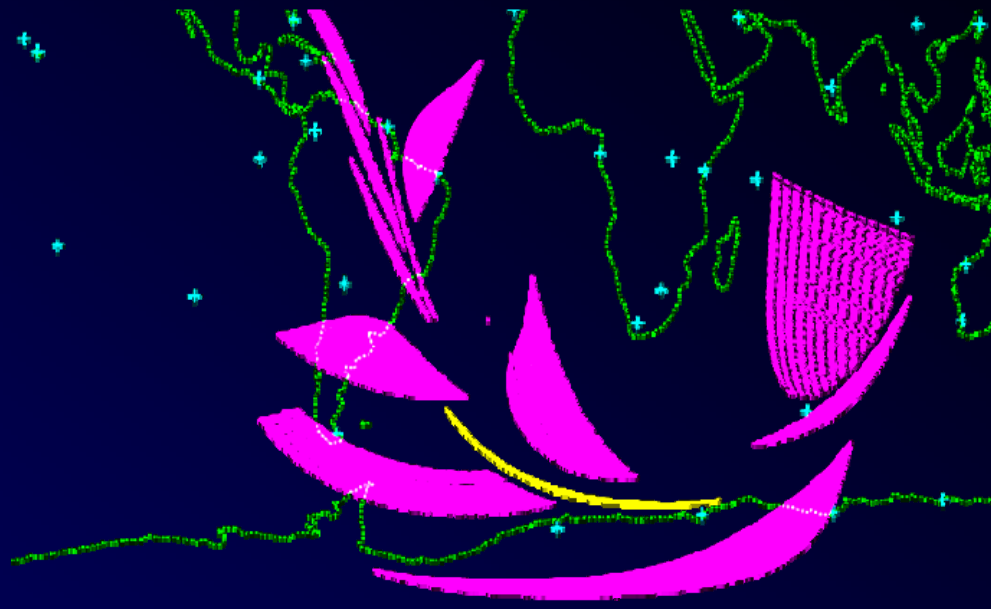


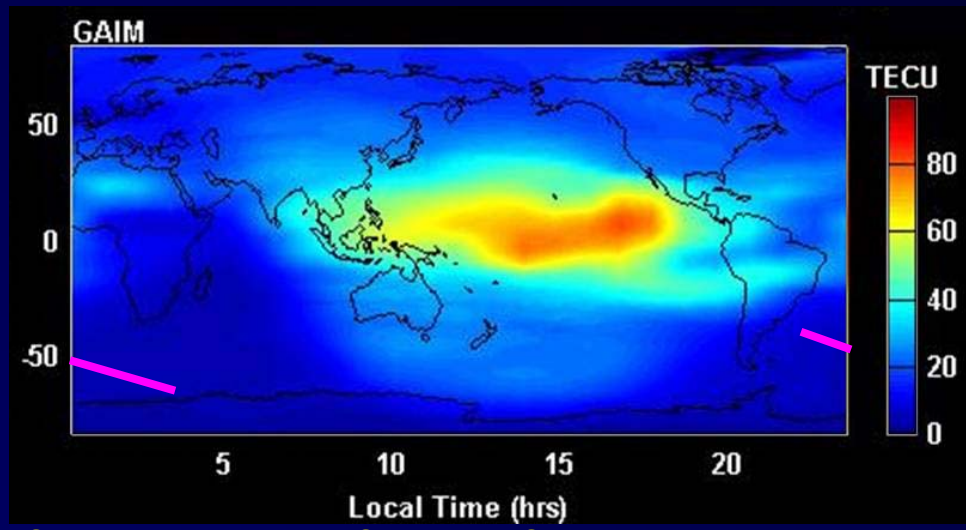


Assimilation Run for July, 22-24, 2002

Geolocation of Occultation Tangent Point 2

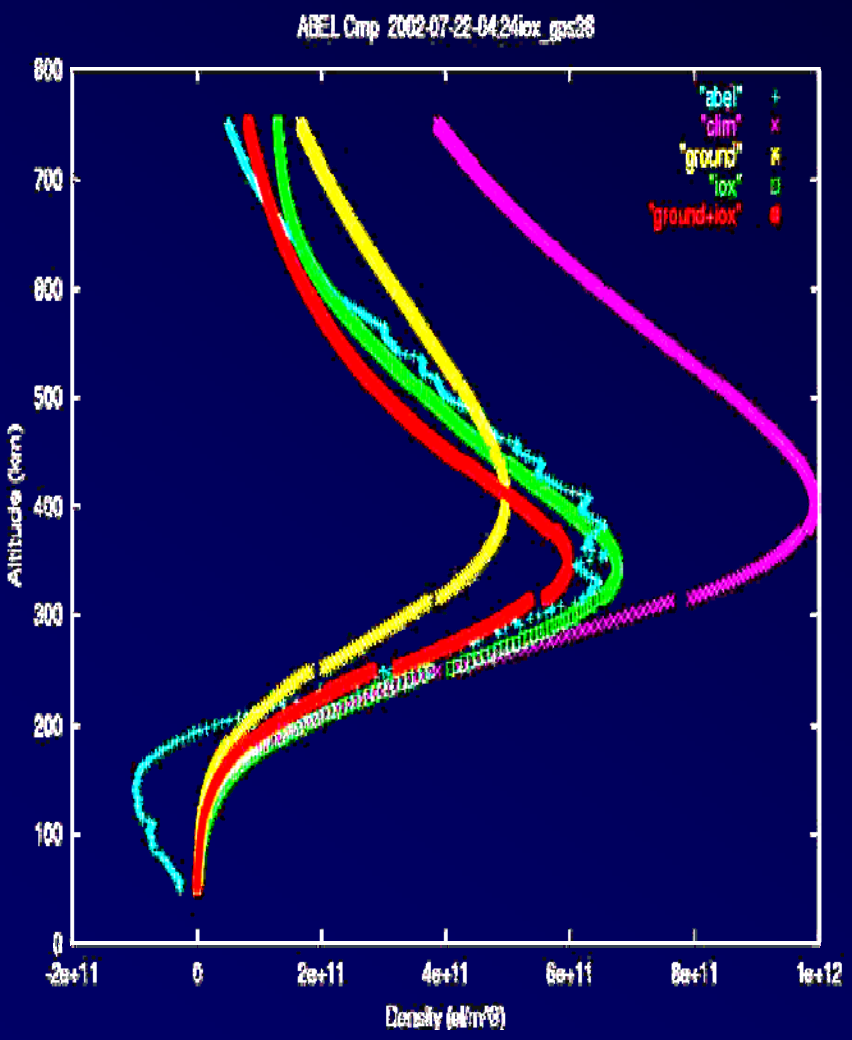


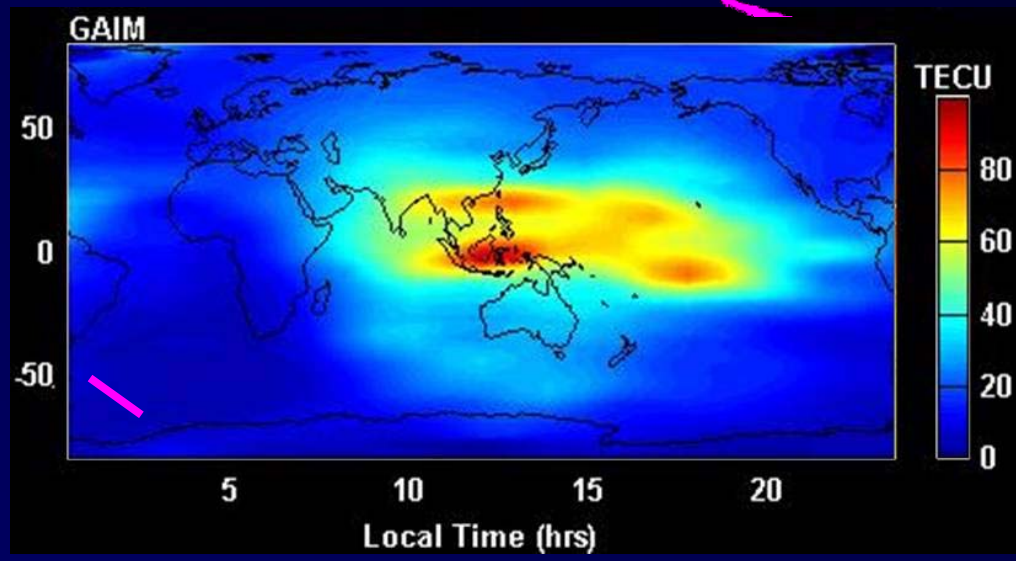




Assimilation Run for July, 22-24, 2002

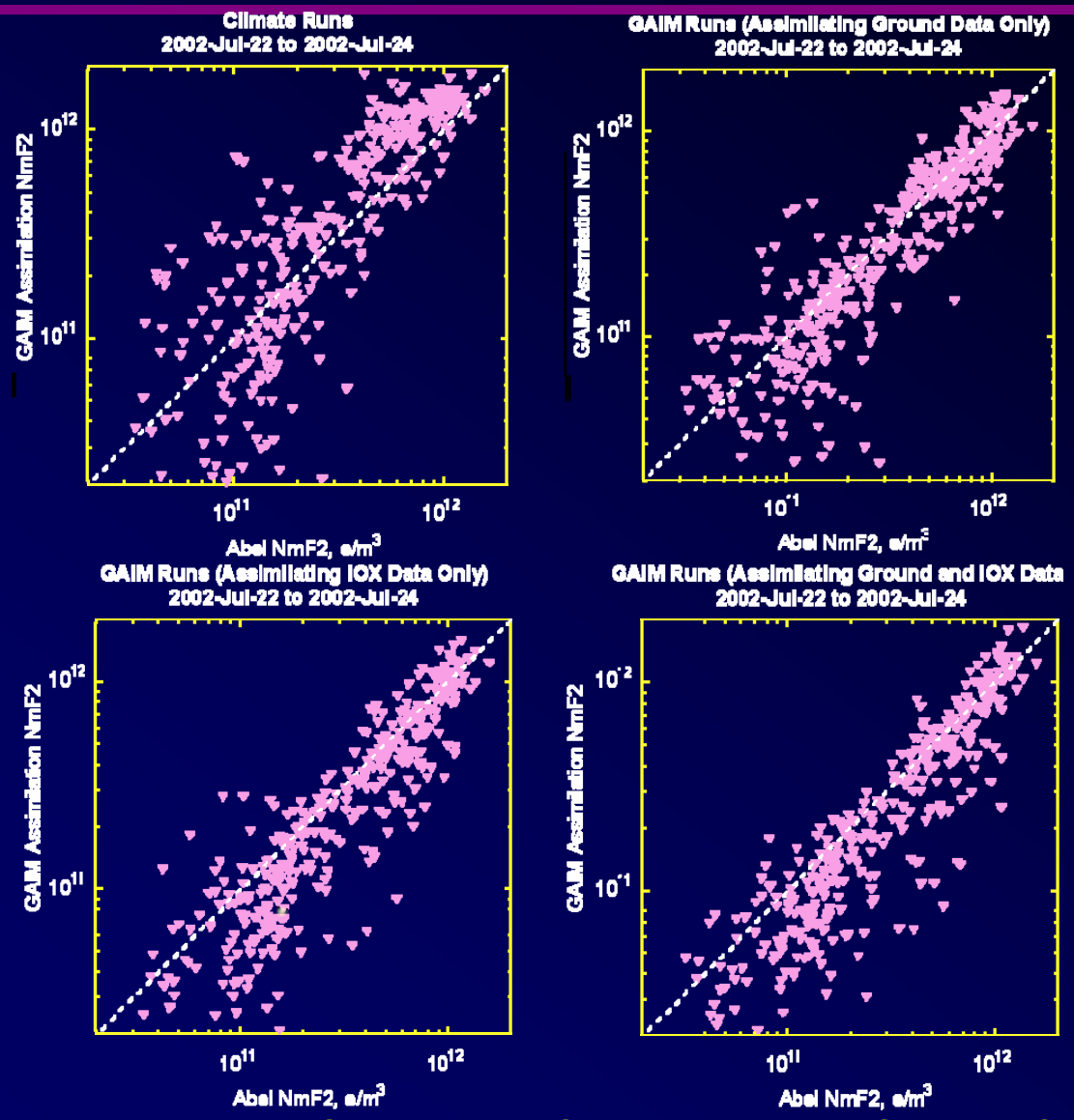
Geolocation of Occultation Tangent Point 3





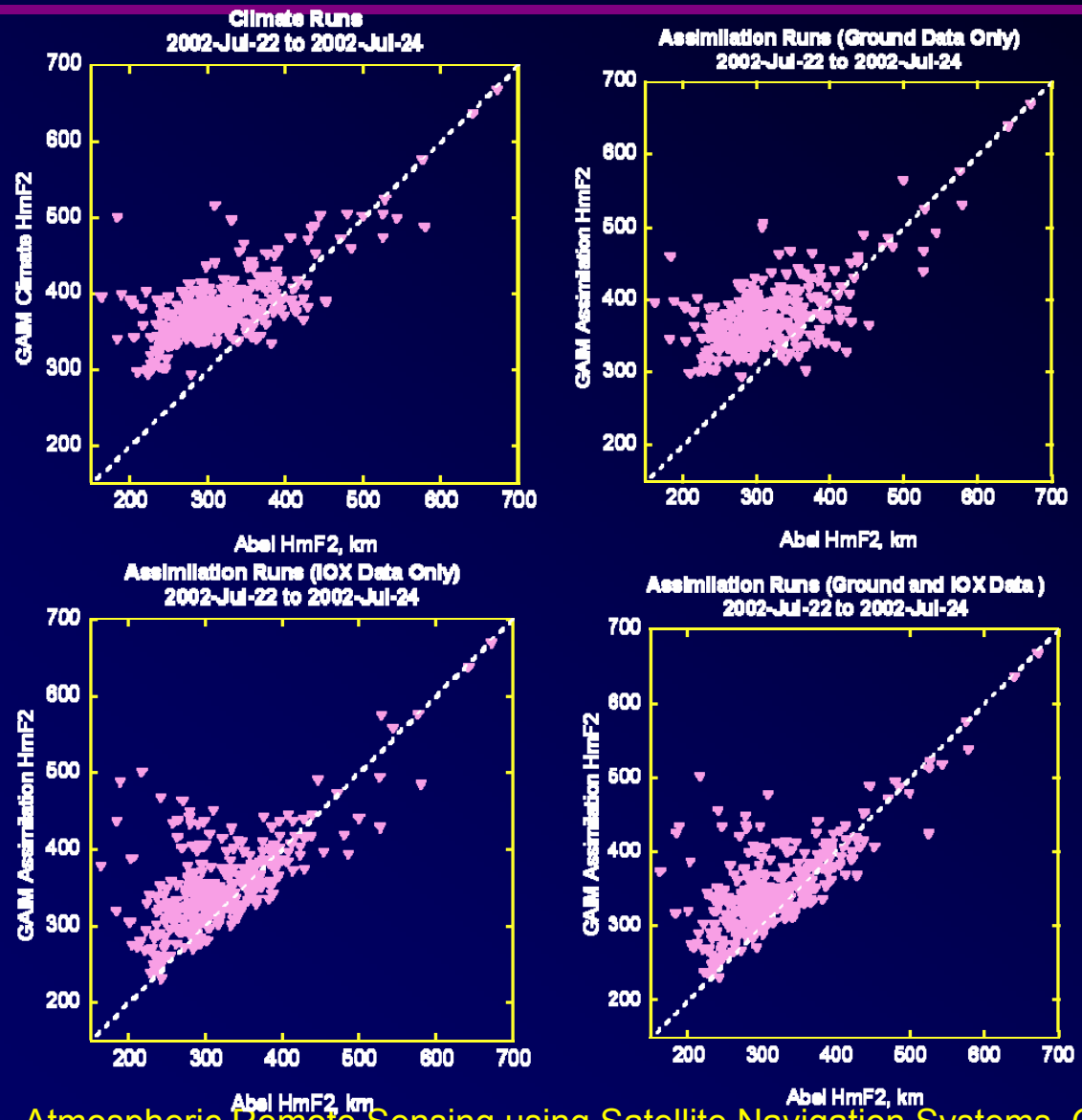
Assimilation Run for July, 22-24, 2002

GAIM vs. Abel NmF2 Comparison



Assimilation Run for July, 22-24, 2002

GAIM vs. Abel HmF2 Comparison



Assimilation Run for July, 22-24, 2002

Summary of NmF2 and HmF2 GAIM vs. Abel

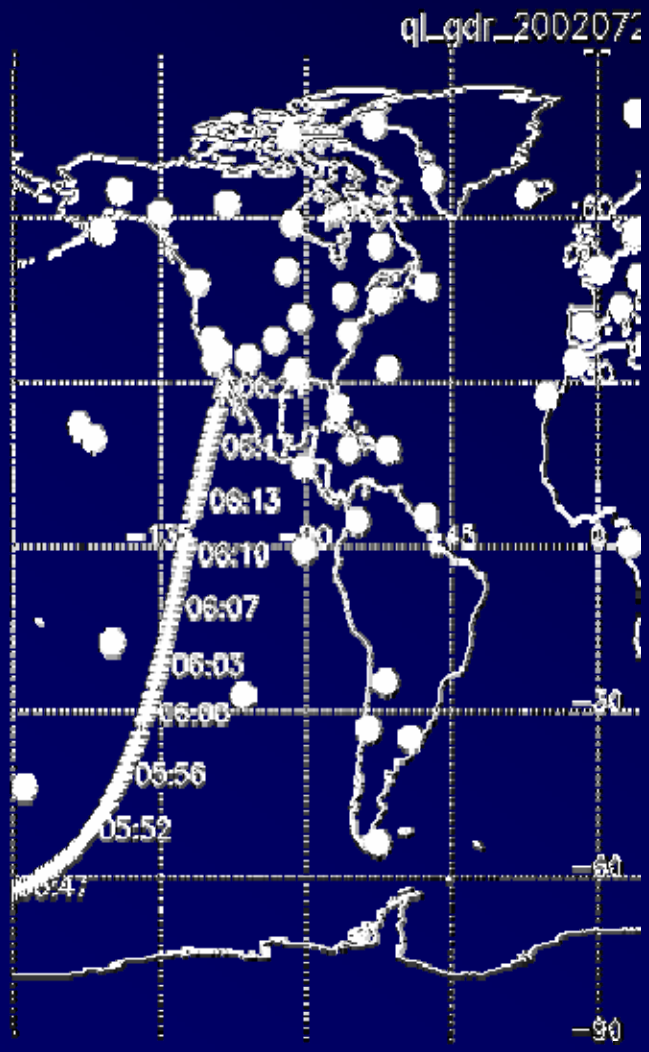
	HmF2 diff. Median (km)	HmF2 diff. 1 sigma Confidence interval (km)	Fractional NmF2 diff. median	Fractional NmF2 diff 1 sigma confidence interval
Climate	69.1	55.3	0.26	0.68
Ground	65.7	60.6	-0.08	0.34
IOX	25.4	57.1	-0.19	0.32
Ground and IOX	30.5	58.5	-0.19	0.34

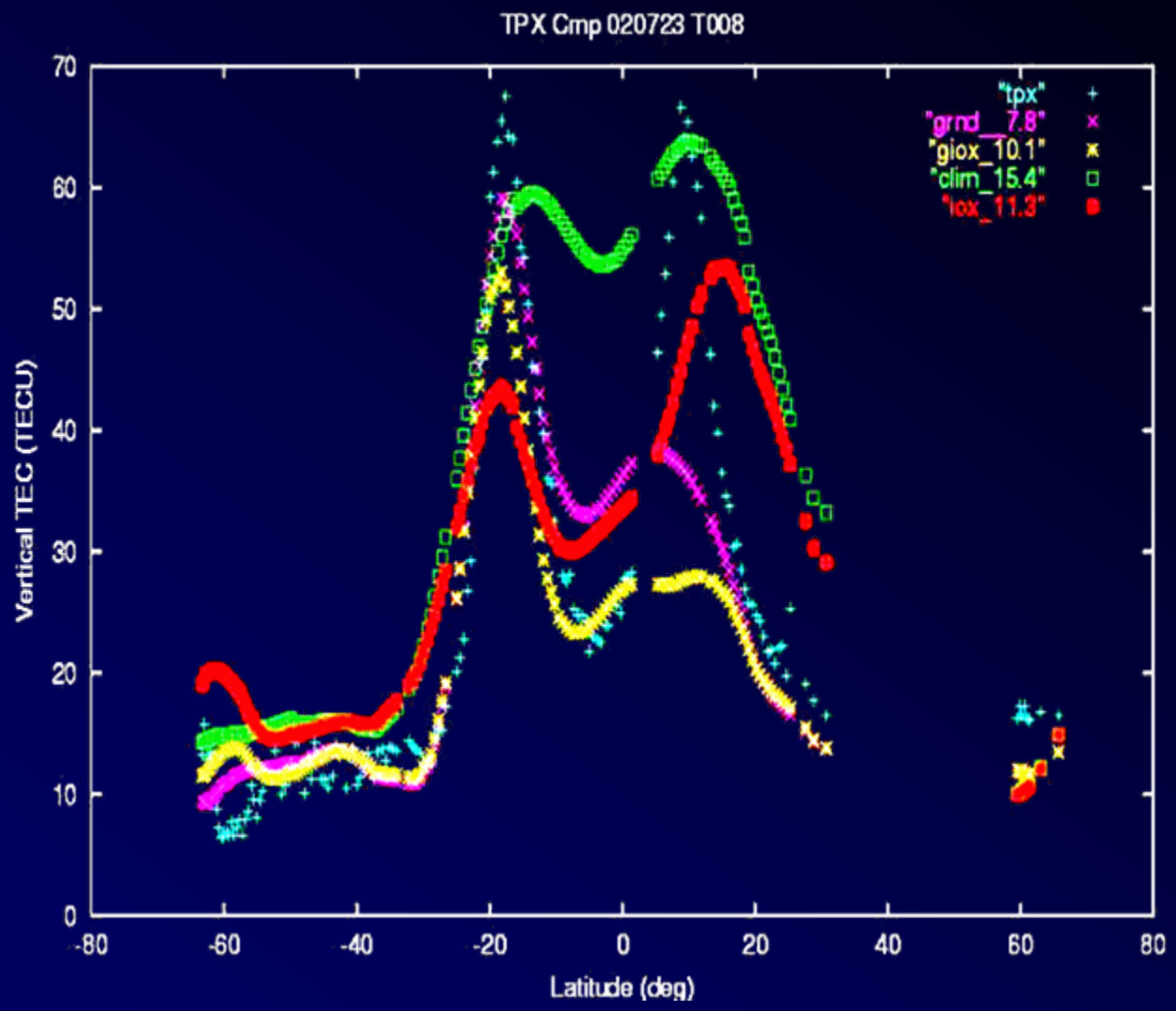
Focus on Jul 22-24, 2002

Validation Against Topex

Assimilation Run for July, 22-24, 2002

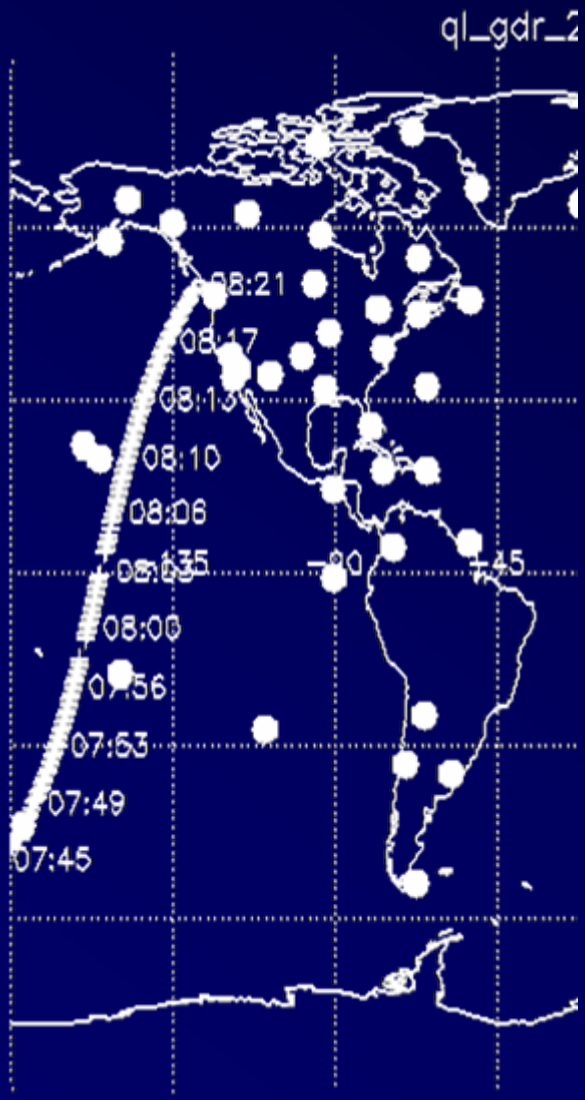
TOPEX Track #8 on 2002/07/23

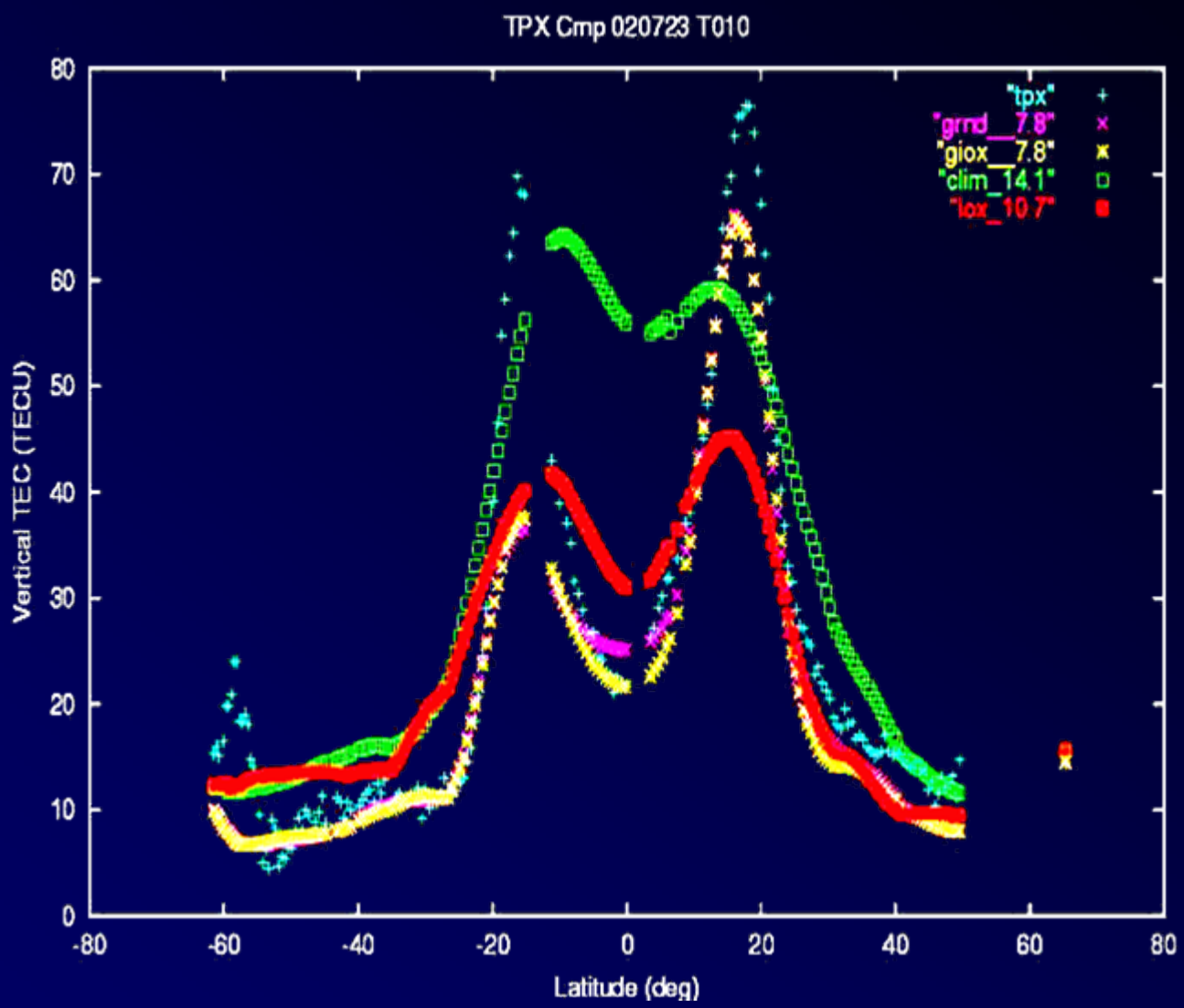




Assimilation Run for July, 22-24, 2002

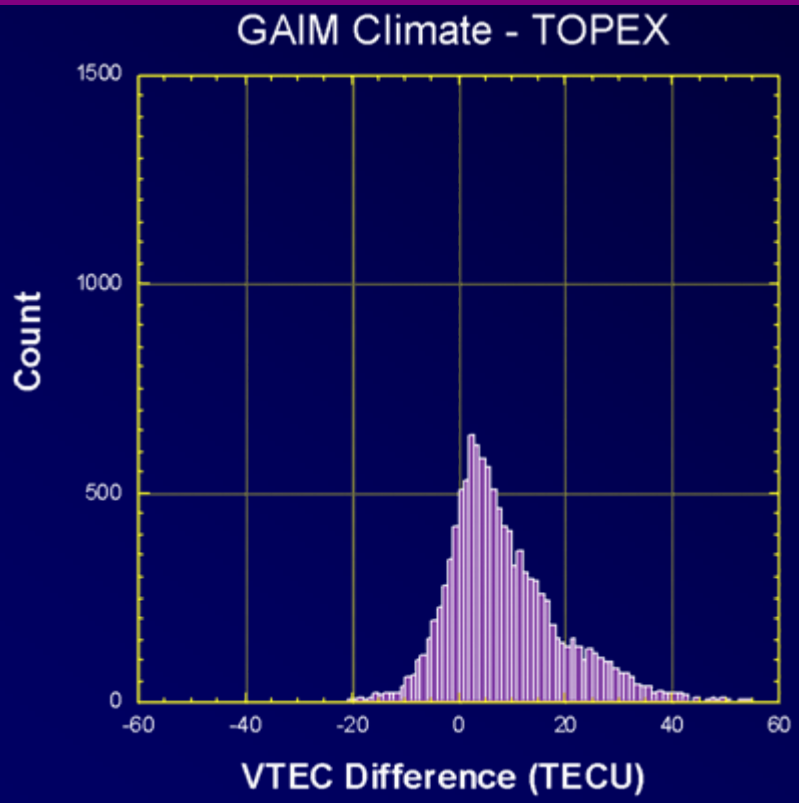
TOPEX Track #10 on 2002/07/23



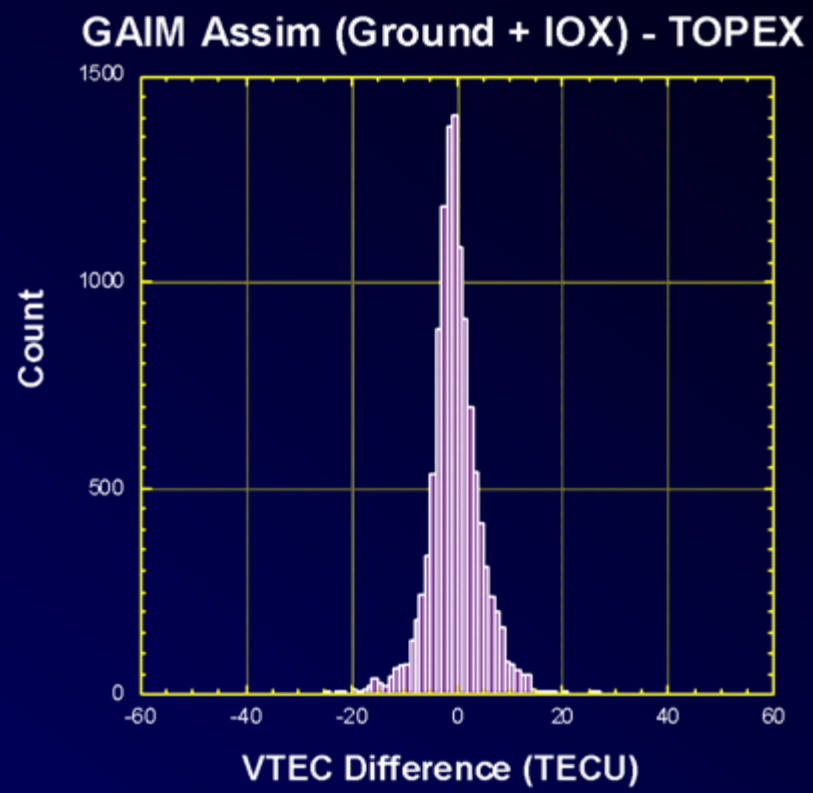


Assimilation Run for July, 22-24, 2002

TOPEX Summary



Mean 8.6 TECU
Std Dev 11.0 TECU
RMS 14.0 TECU



Mean -0.5 TECU
Std Dev 5.3 TECU
RMS 5.4 TECU

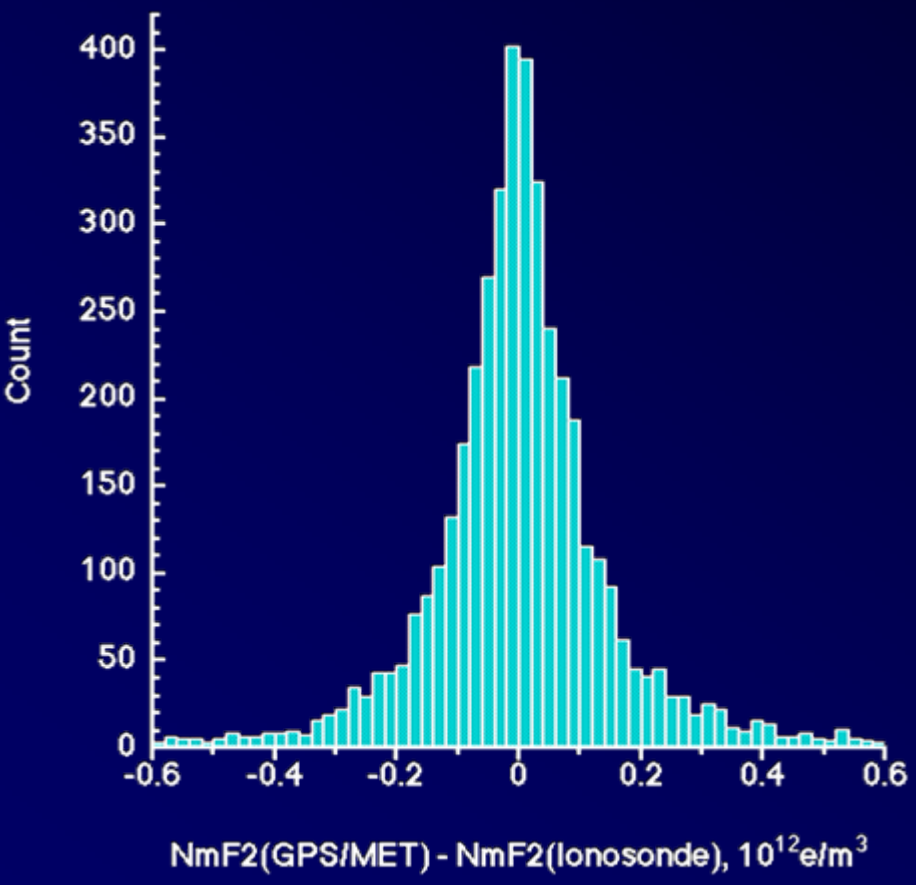
11,700 points over 3 days

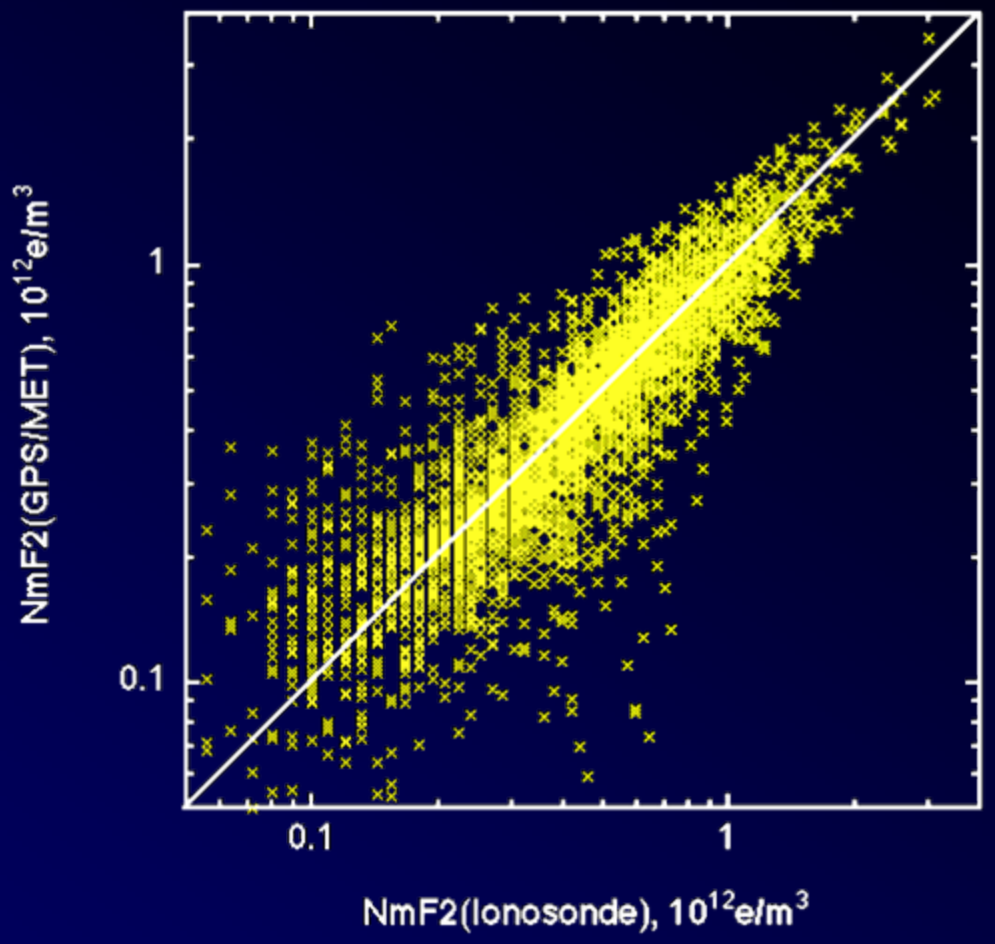
Focus on Jul 22-24, 2002

Validation Against Ionosonde

Previous Ionosonde Work

Comparisons of NmF2 derived from GPS/MET occultations and nearby ionosondes

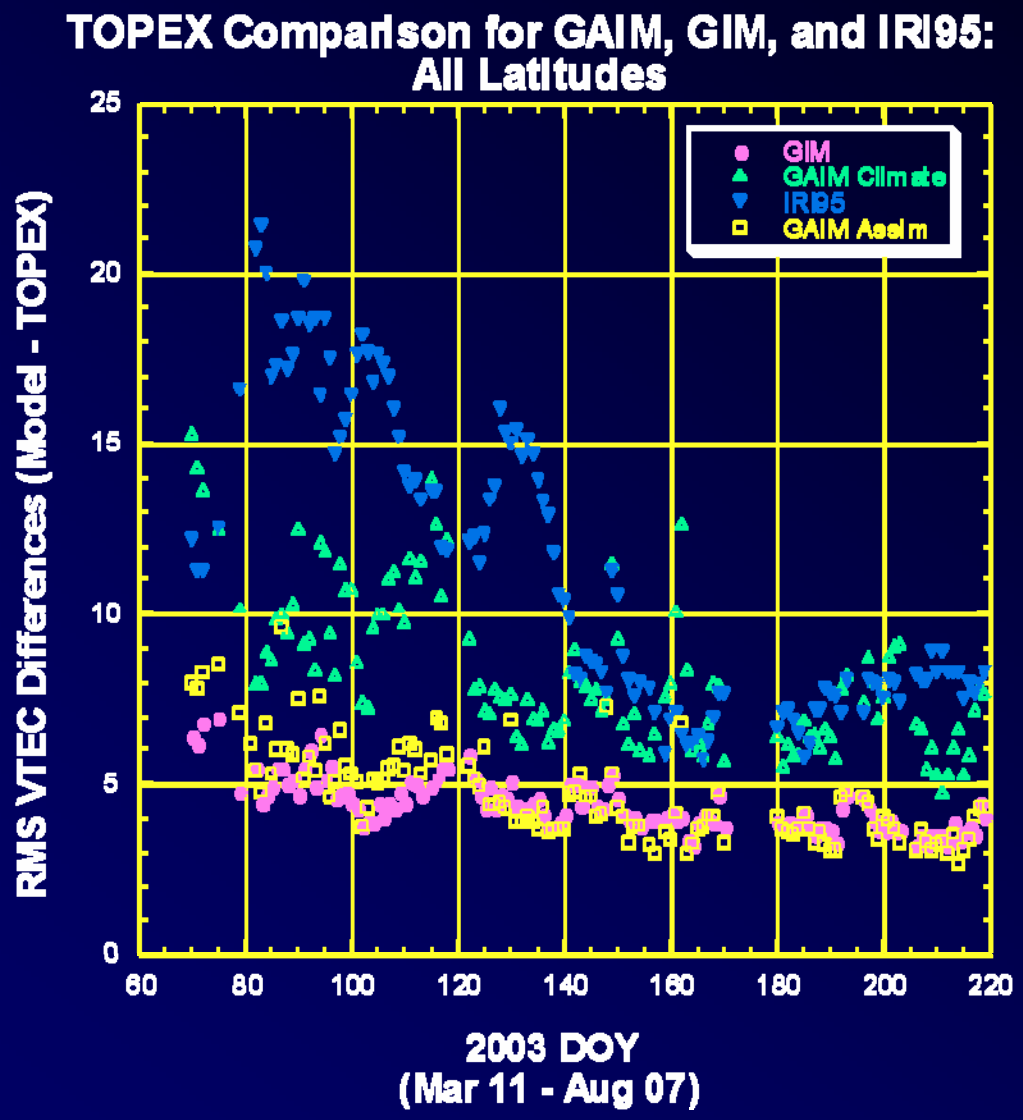




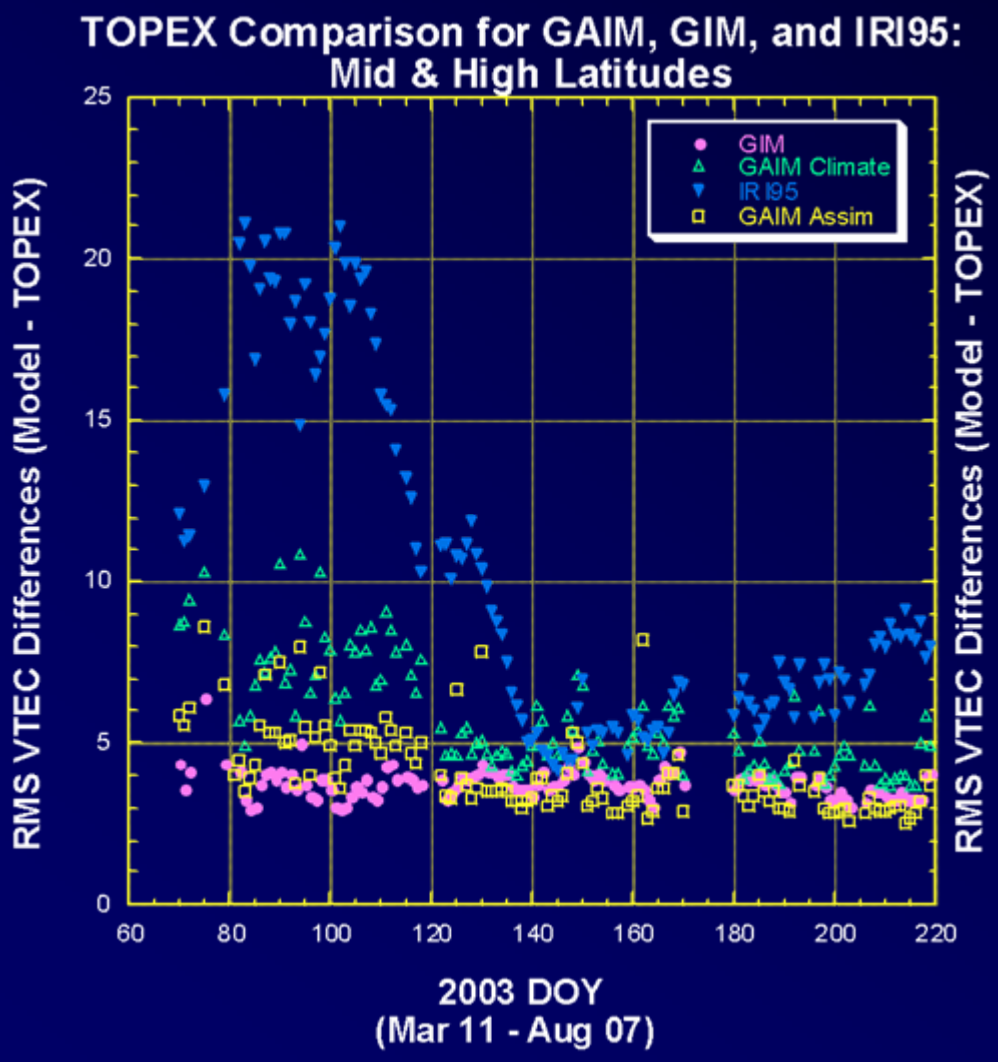
Daily GAIM Runs

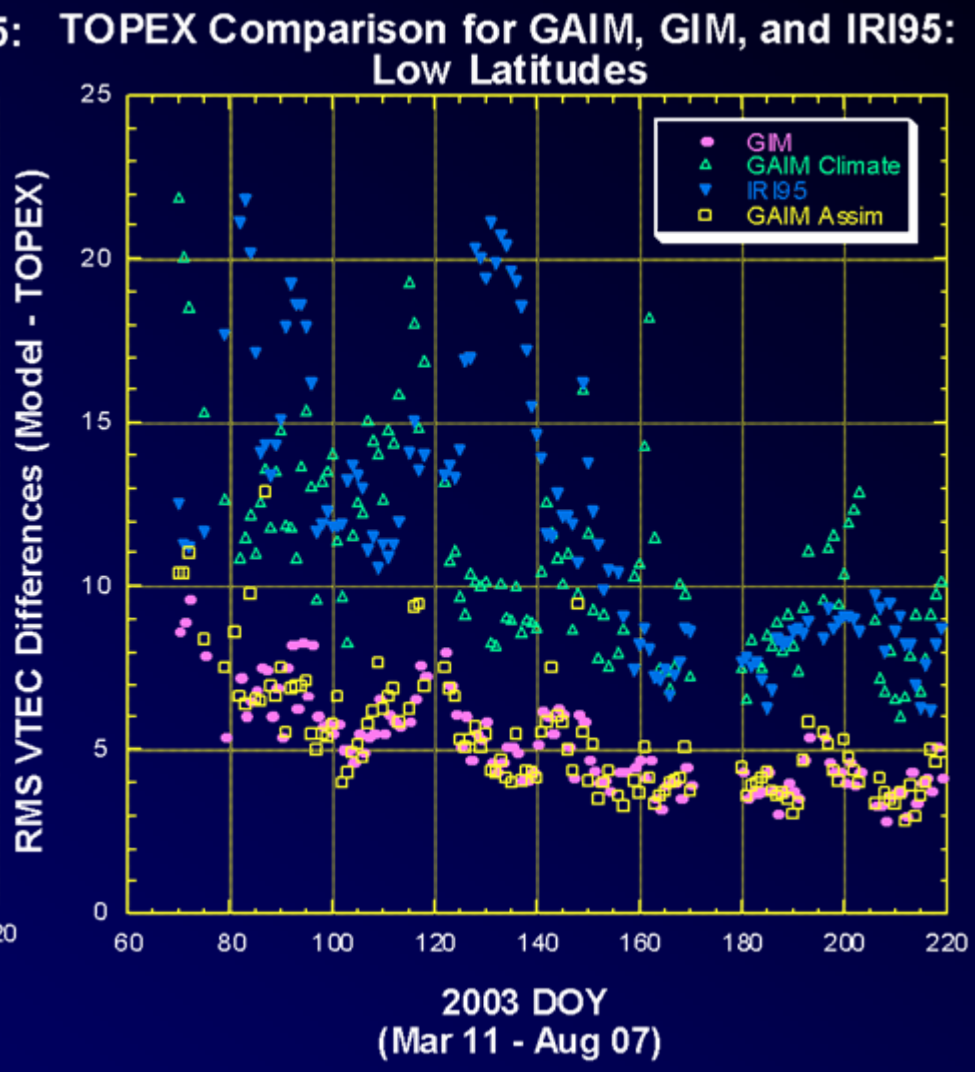
Long Term Performance

Daily GAIM Run Results



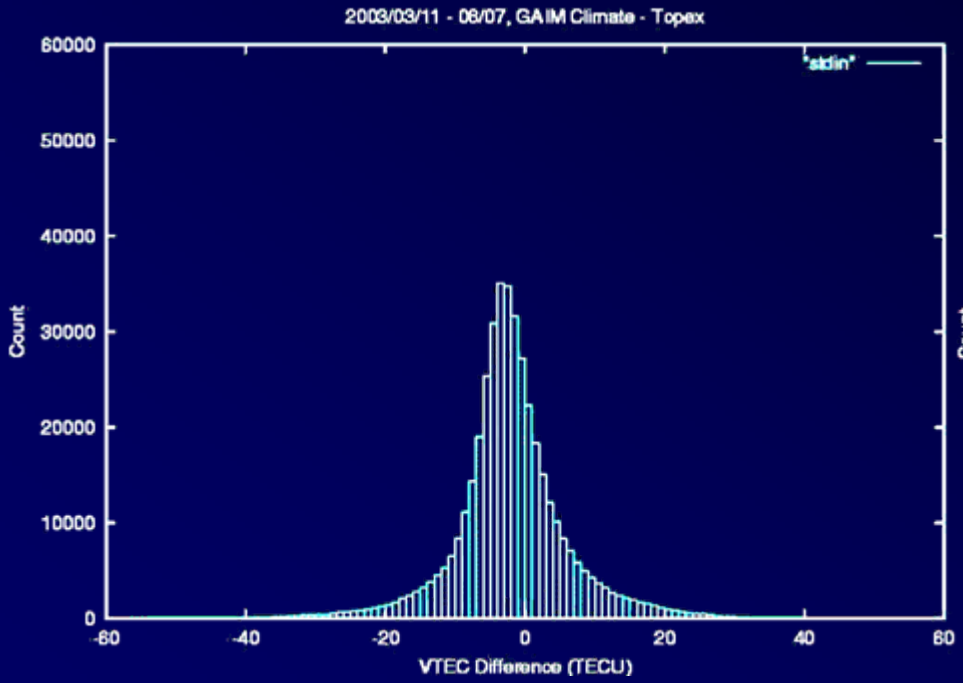
Daily GAIM Run Results Separated by Latitude





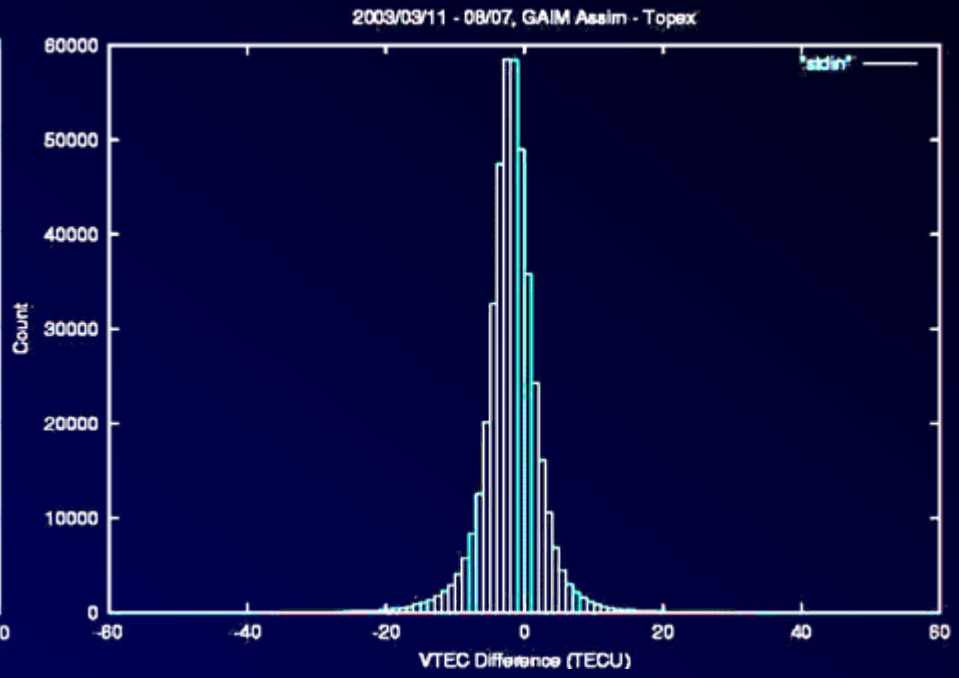
Daily GAIM Run Summary

GAIM Climate - TOPEX



Mean -2.1 TECU
StdDev 8.4 TECU
RMS 8.7 TECU

GAIM Assimilation - TOPEX



Mean -2.0 TECU
StdDev 4.5 TECU
RMS 4.9 TECU

418,000 points over 157 days

Lessons Learned

- **Validation serves two purposes:**
  - Quantify density and TEC specification accuracy
  - Understand assimilation effects: Why do TEC links here result in a given density there?
- **Each data type affects the resulting grid densities in a complex way in both space & time**
  - Ground data does not contribute well to HmF2
  - Pair-wise difference TEC does not produce as much sensitivity as relative TEC
  - Biases for satellites require models of high elevation
- **Even more challenging when combining data types**
  - Ground GPS + Occultations
  - Ground GPS + UV Radiances
  - Next: Ground GPS + Occultations + UV Radiances

Summary (I)

- **USC/JPL GAIM band-limited Kalman has been extensively tested with *real* data**
- **Case studies (single data type & combined)**
  - **TEC from ground GPS**
  - **ΔTEC from GPS occultations (IOX, CHAMP, SAC-C)**
  - **UV radiance obs from nighttime limb scans (ARGOS)**
- **Continuous daily runs using ground GPS data**
  - **Challenge of understanding multiple input data types**
  - **Plan to add COSMIC occultations & DMSP UV radiances**
  - **Add other data types as available**
  - **Intent: Run it forever using all available data.**
  - **Add estimated drivers from 4DVAR**

Summary (II)

- **Validation so far is encouraging**
  - •GAIM integrated TEC accuracy already comparable or superior to GIM 2D VTEC maps
  - •Density validation using ionsonde & Abel retrievals
  - •In-situ density from CHAMP, SAC/C
  - •Automating all validation techniques
- **Continuous validation emphasized rather than just case studies**
  - •Gain maximal experience, act as a test bed
  - •Capture seasonal or solar cycle effects
  - •Continuously tune covariance (iono correlation lengths)
  - •Challenge: Quality control & availability difficult for some data types (e.g., ionosonde)