Daily JPL Processing of 1000+ Ground-Based GPS Receivers to Estimate Interfrequency Biases and Other Practical Applications

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Outline

- GIM versus Bias-Fixing Method
- An automated tool to estimate 1000+ interfrequency receiver biases that could help the following applications:
  - Provide receiver interfrequency biases calibration for IGS products
  - Investigate quiet vs storm-time ionospheric behavior for WAAS and other scientific studies
  - Help detect seismic ionospheric signatures during large earthquakes or tsunami event such as on Dec 26, 2004
- Update on 2nd order ionospheric correction development
- Update on Global Assimilative Ionospheric Model
  - potential impact of COSMIC data
  - RT GAIM
- Conclusions

The Single vs. Multi-Shell Model: Observation Equation

For single shell, our model is

$$TEC = M(h,E)\sum_i C_i B_i(lat, lon) + b_r + b_s$$

For three shells, our model is

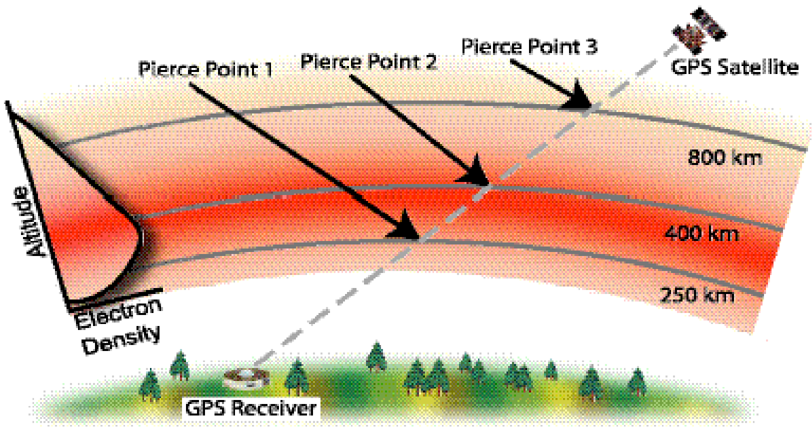
$$TEC = M(h_1,E)\sum_i C_{1i} B_i(lat, lon) + M(h_2,E)\sum_i C_{2i} B_i(lat, lon) + M(h_3,E)\sum_i C_{3i} B_i(lat, lon) + b_r + b_s$$

where

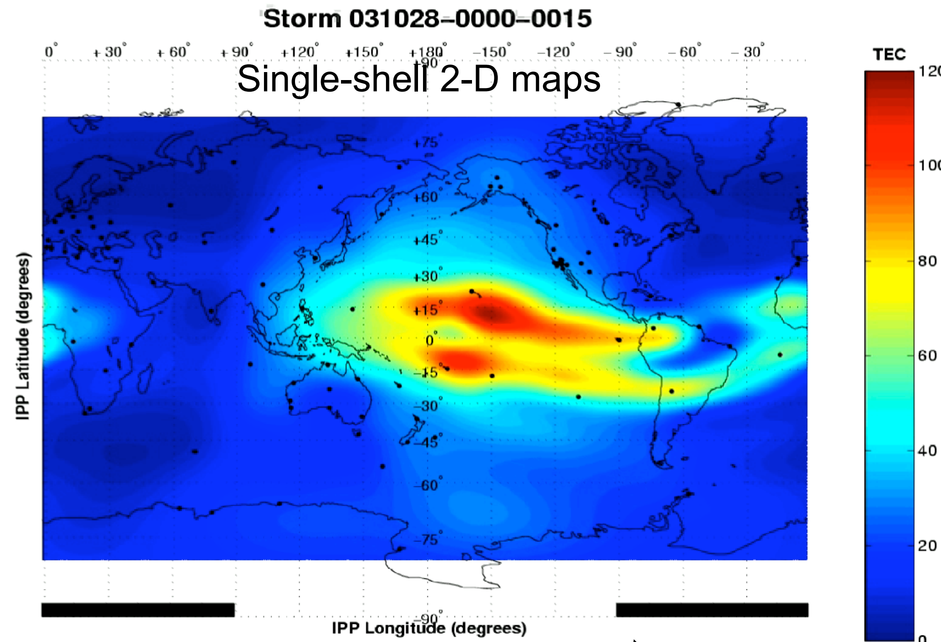
TEC	is the slant TEC;
$M(h_1,E)$	is the thin shell mapping function for shell 1, etc;
$B_i(lat, lon)$	is the horizontal basis function (C^2, TRIN, etc);
C_{1i}	are the basis function coefficients solved for in the filter, indexed by horizontal (i) and vertical (1,2,3 for three shells) indices;
b_r, b_s	are the satellite and receiver instrumental biases.

Single Vs. Three-Shell Model Limitations

The concept of multi-shell GIM:

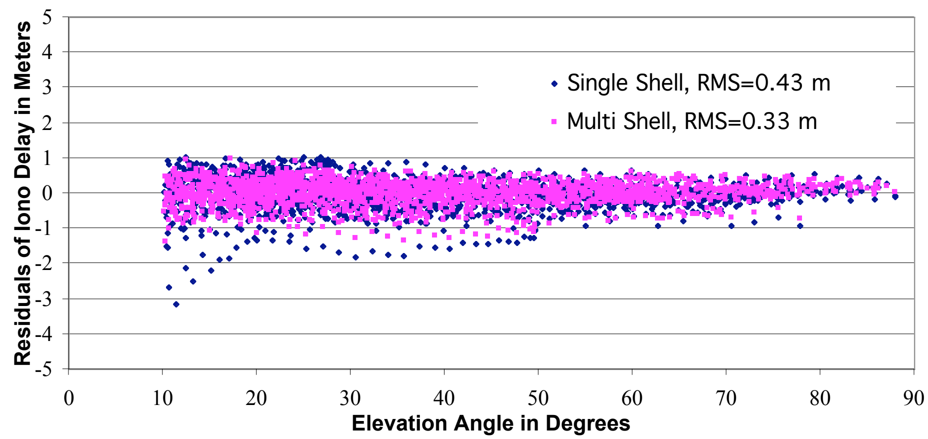


Single-shell 2-D maps



Does not capture small-scale variations in the ionosphere

Multi-shell is more realistic and accurate than the single-shell approximation



New: All-Site GPS Data Processing Algorithm

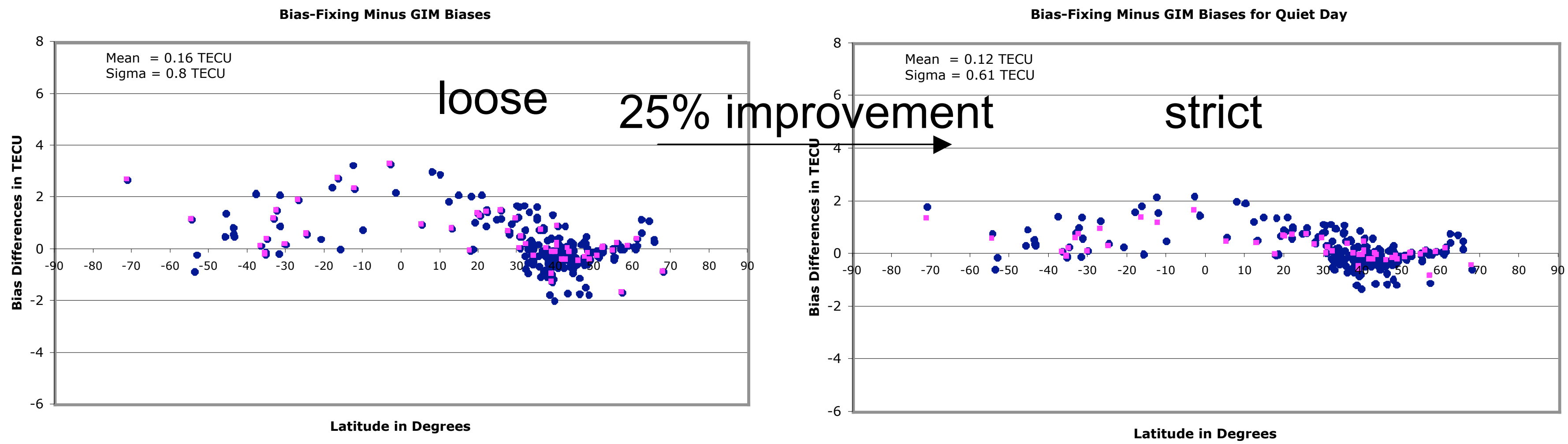
Bias Fixing Algorithm using all available GPS stations worldwide:

$$b_r = \underbrace{TEC}_{\text{Biased TEC observation}} - \underbrace{M(h,E)\sum_i C_i B_i(lat,lon)}_{\text{GIM TEC prediction}} - \underbrace{b_s}_{\text{GIM satellite bias estimate}}$$

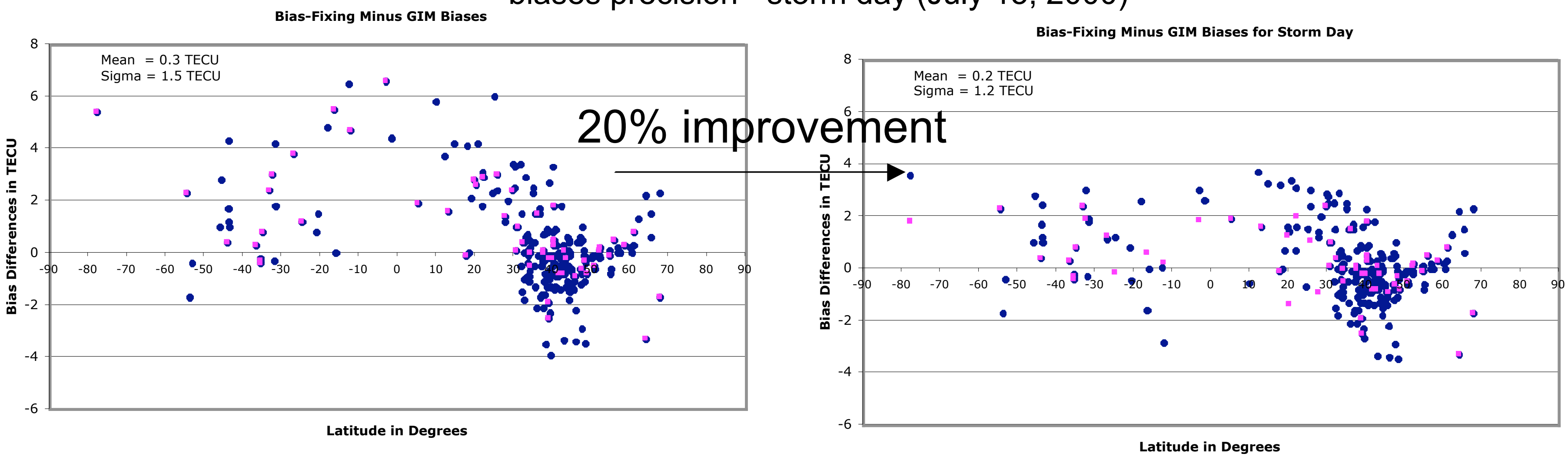
TEC	is the biased phase-levelled ionospheric observable
$M(h_1,E)$	is the thin shell mapping function for shell 1, etc;
$B_i(lat,lon)$	is the horizontal basis function (C^2, TRIN, etc);
C_{1i}	are the basis function coefficients solved for in the filter, indexed by horizontal (i) and vertical (1,2,3 for three shells) indices;
b_r, b_s	are the satellite and receiver instrumental biases.

Receiver Bias Estimation Precision

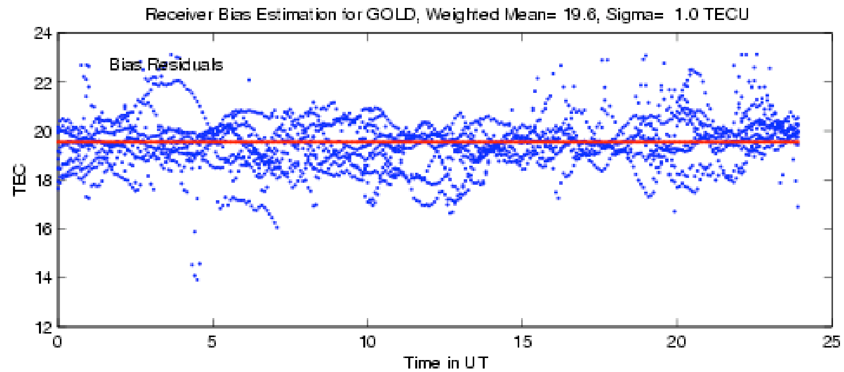
biases precision - quiet day (April 26, 2004)



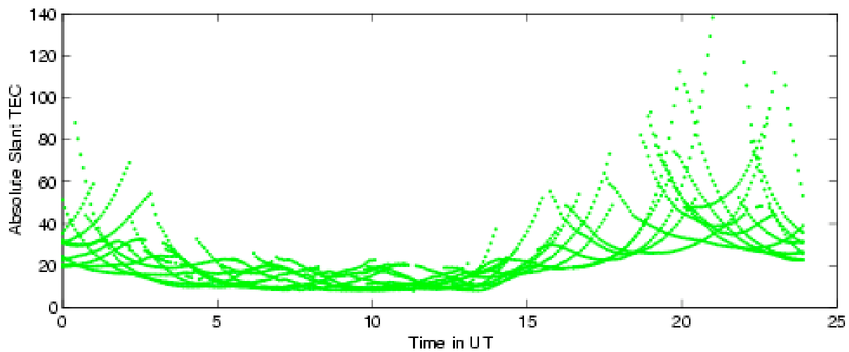
biases precision - storm day (July 15, 2000)



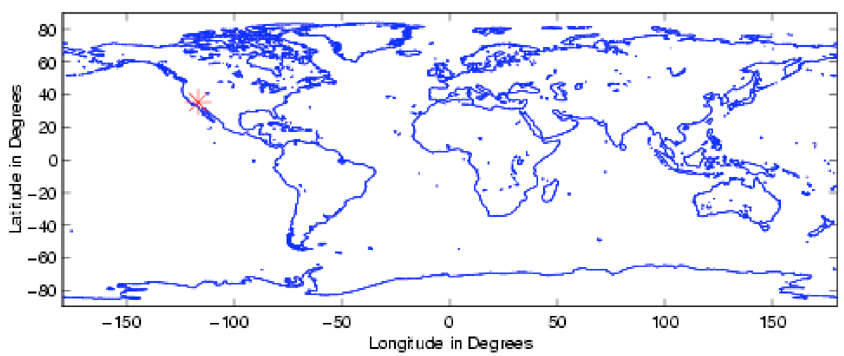
Slant TEC Bias-Fixing Method



Estimated bias time series: errors caused by GIM, multipath, noise, sub-daily bias drift



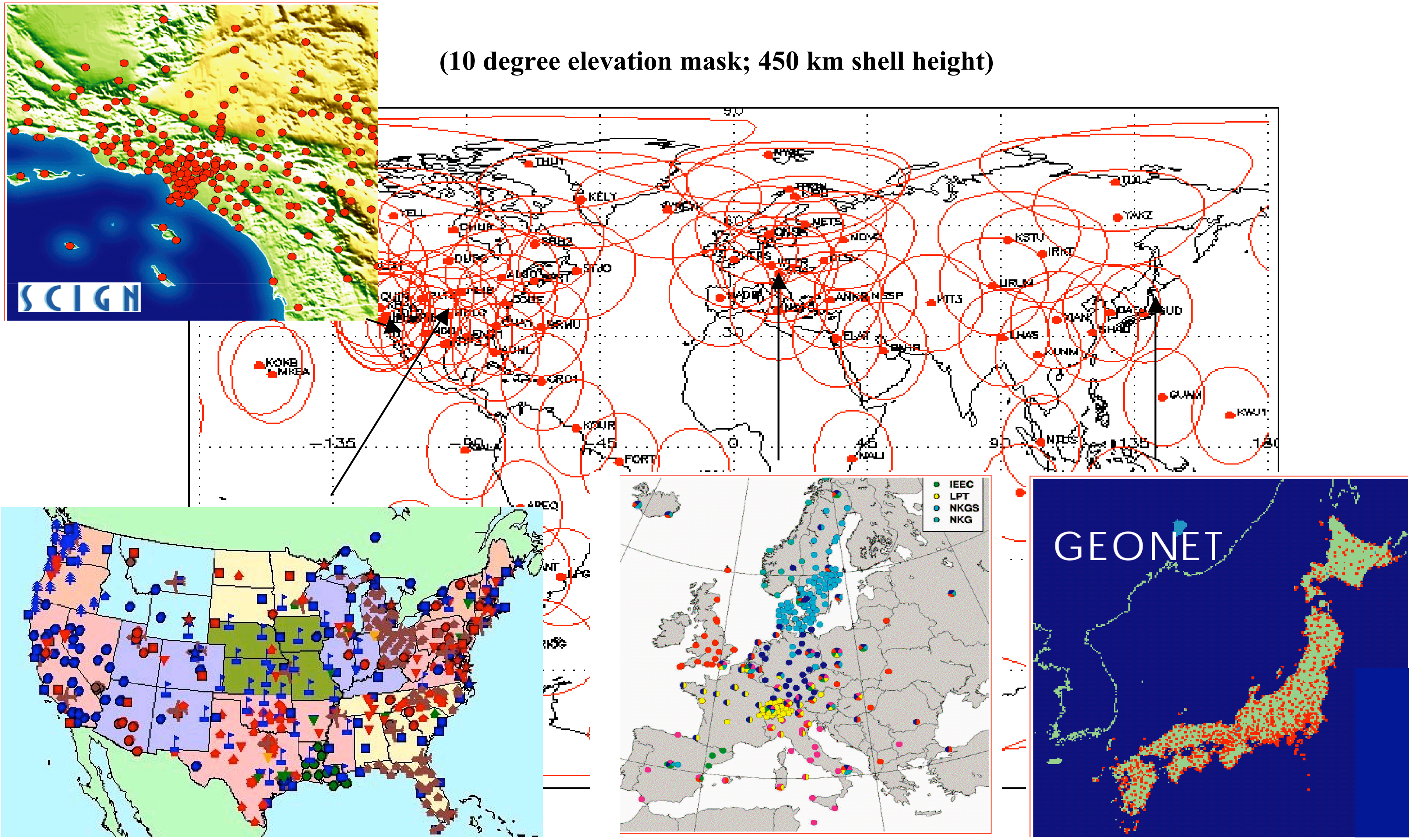
Bias-removed slant TEC



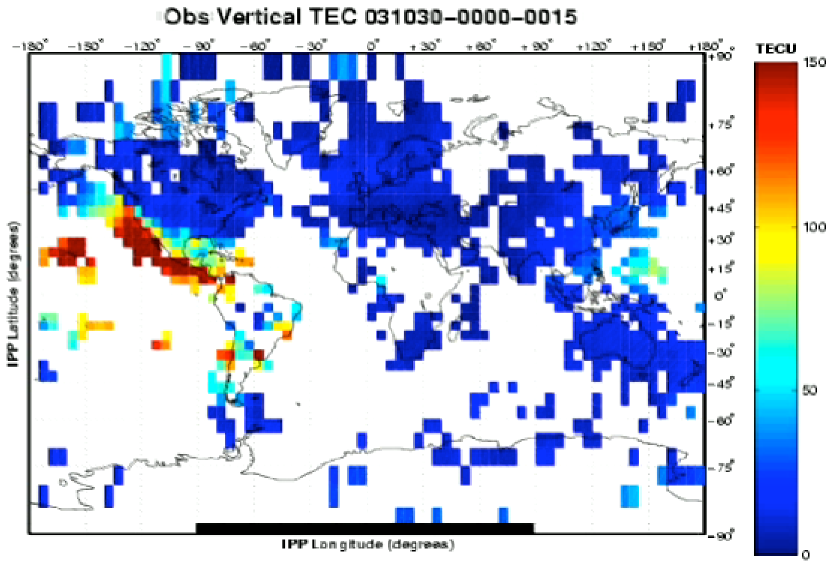
Location of station

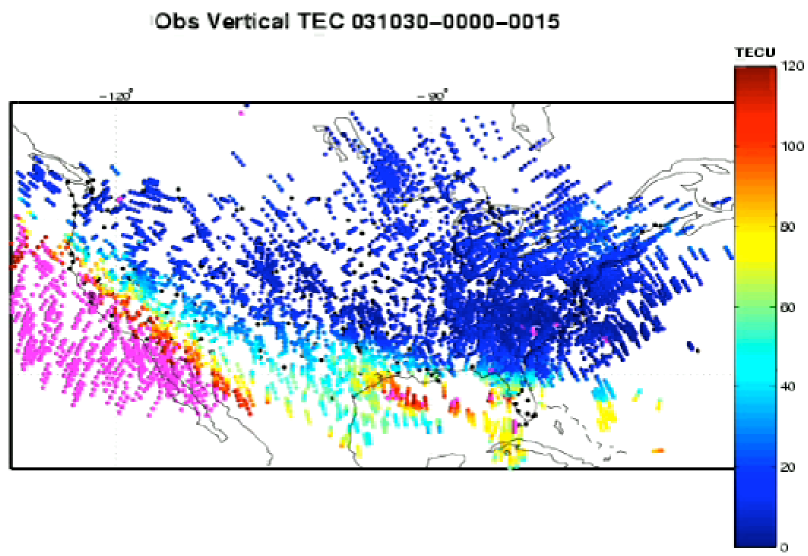
Coverage of Daily IGS Network and Regional Networks

(10 degree elevation mask; 450 km shell height)

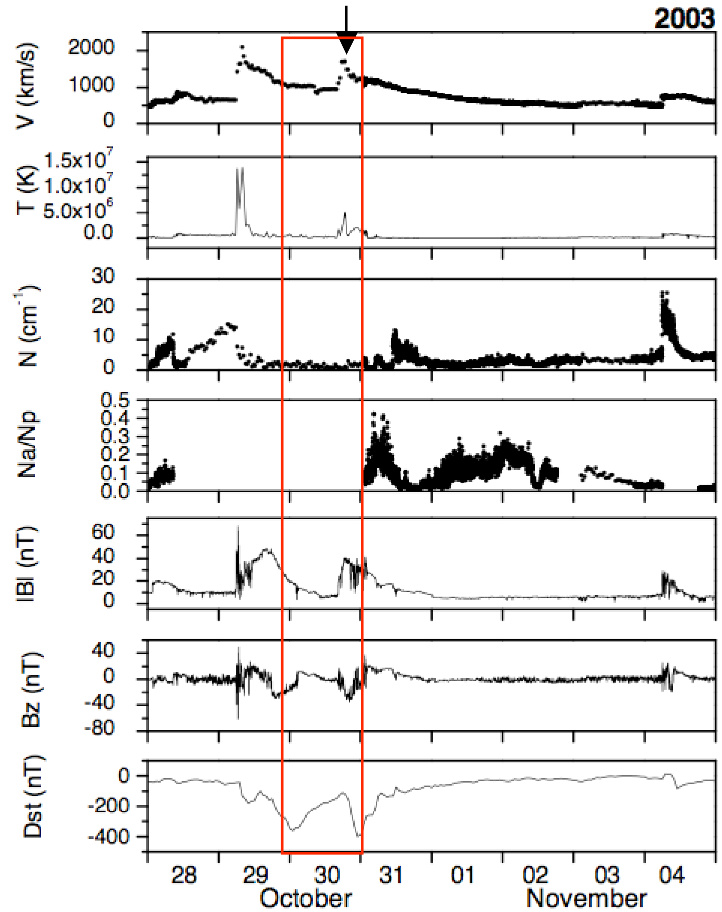


October 30, 2003



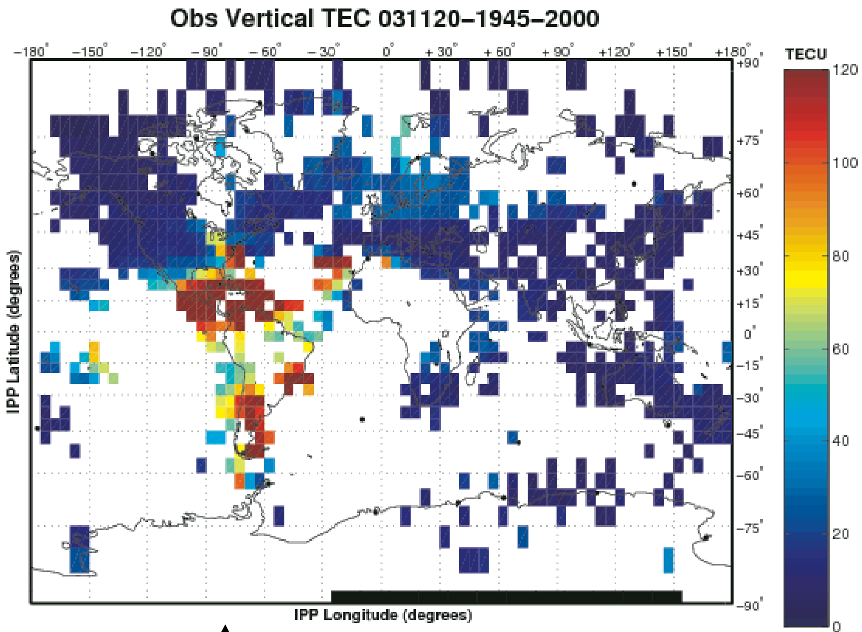


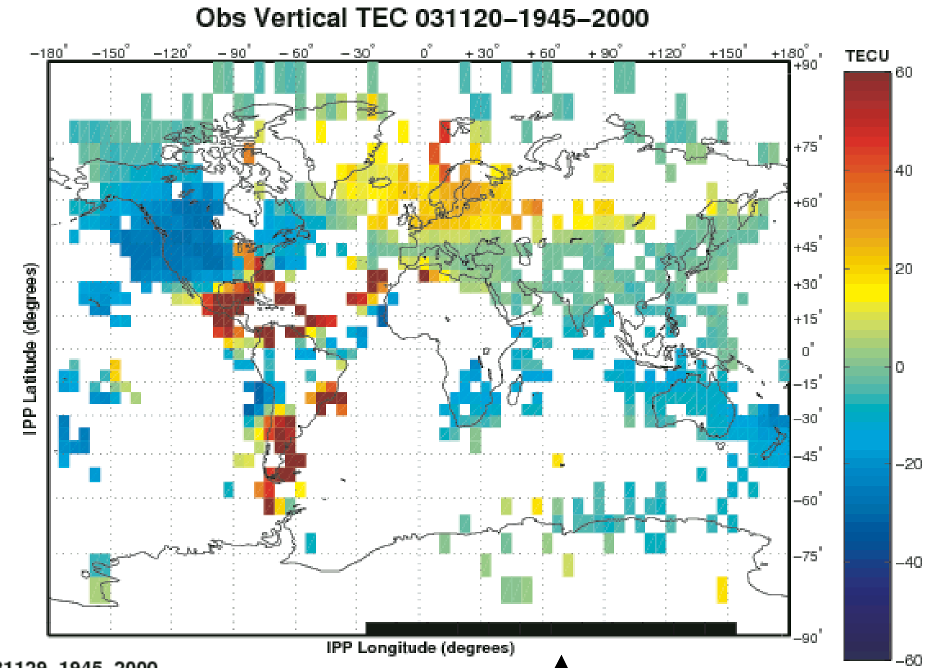
2nd Interplanetary Coronal Mass Ejection



DST -390 nT at 2315 UT on October 30

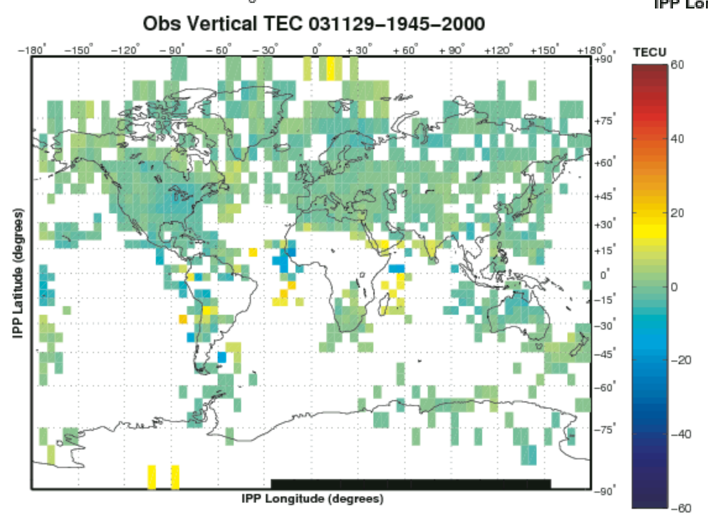
November 20, 2003 Storm





Details are difficult to interpret

Quiet ionosphere following the storm

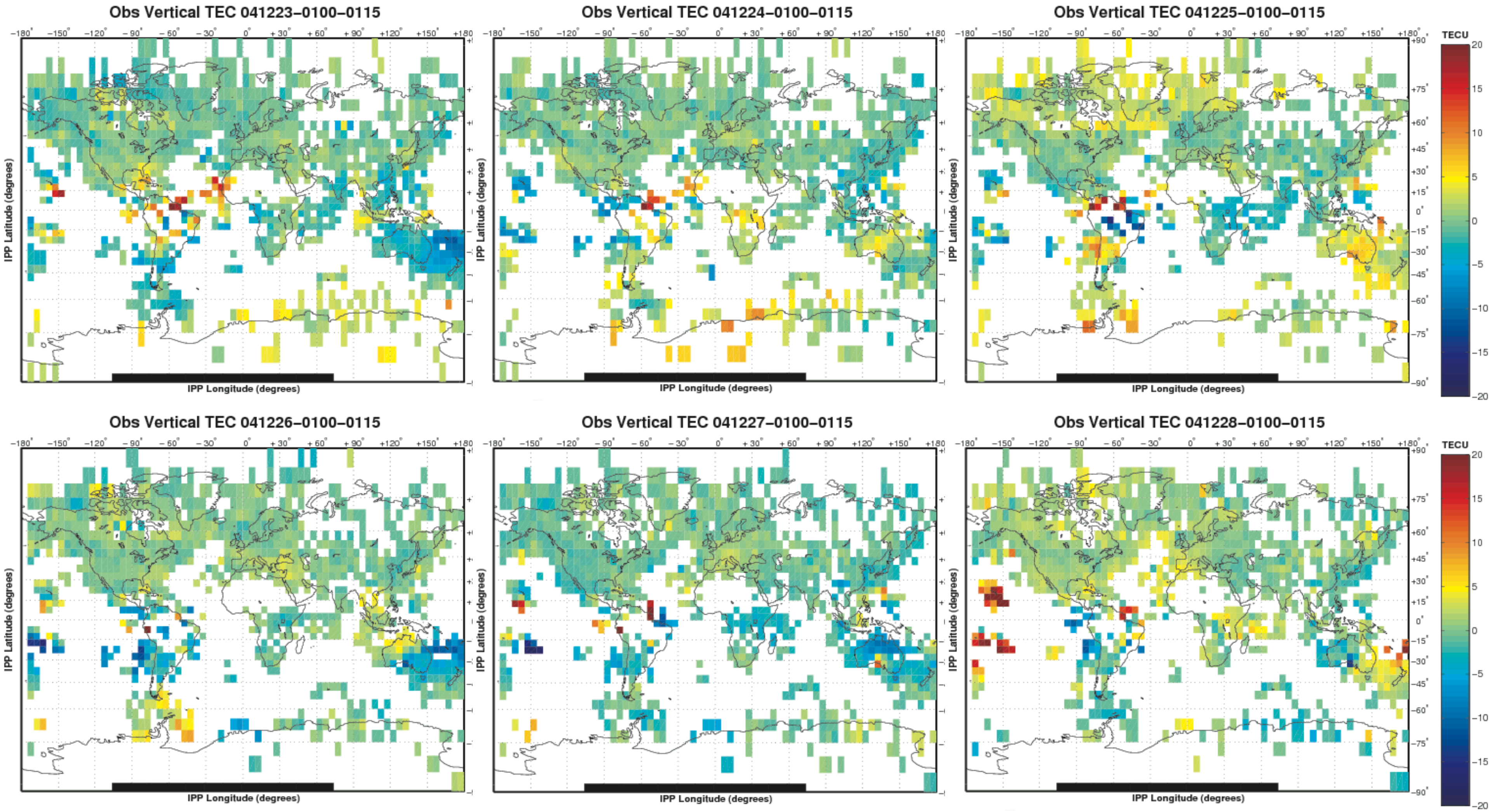


5-day average of quiet ionosphere removed: structures are easier to detect

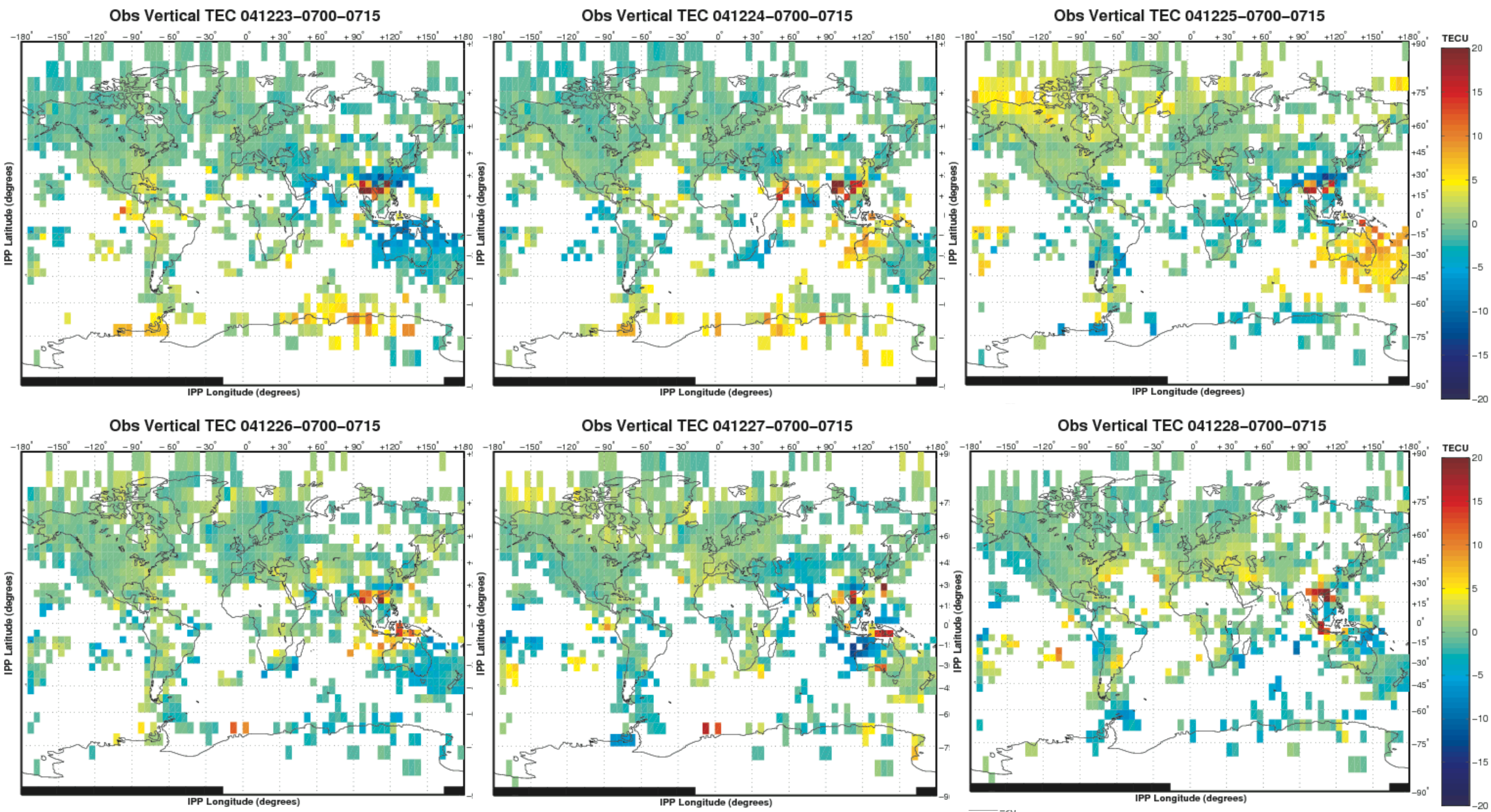
New Software Development

- We developed a comprehensive package to process individual GPS stations to extract ionospheric perturbations caused by TID:
  - Software estimates receiver and satellite interfrequency biases using 1000+ site bias-fixing method
  - Removes background ionospheric signature and forms the ionospheric residual as primary observable
  - It uses the supertruth processing technology developed for WAAS to form high-precision individual phase-connected arcs using tecdump files
  - Uses band-pass filter to extract perturbations starting at the 0.1 TECU level
  - Plots TID signatures using multiple satellites on a station-by-station basis.

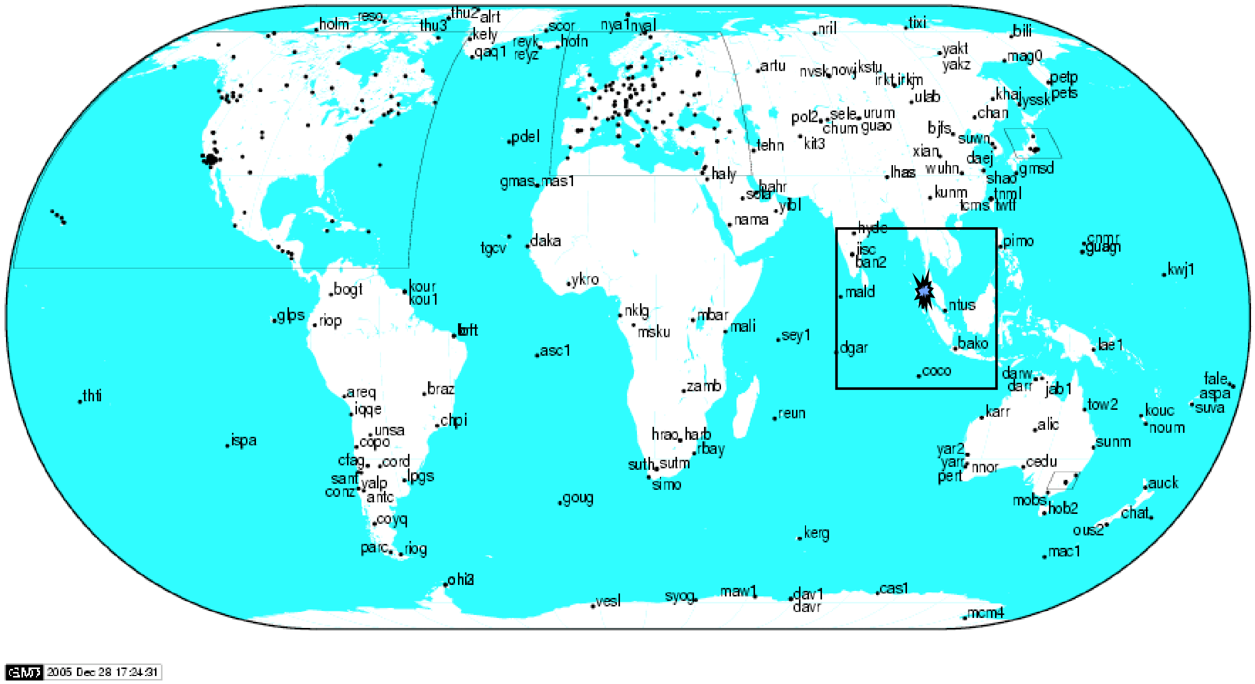
Dec 23-28, 2004 Vertical TEC for UT 0100-0115

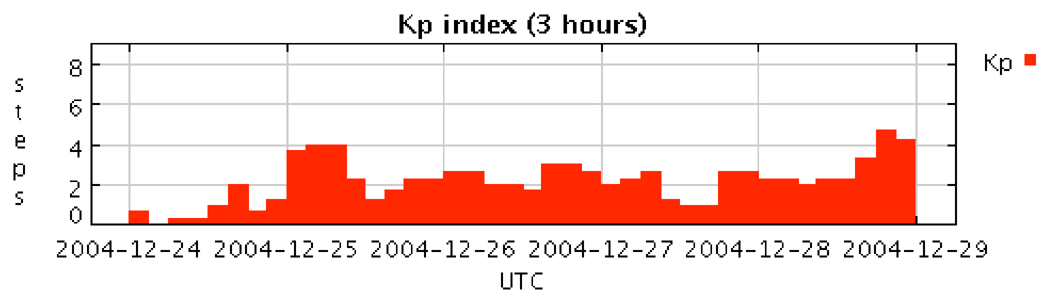


Dec 23-28, 2004 Vertical TEC for UT 0700-0715



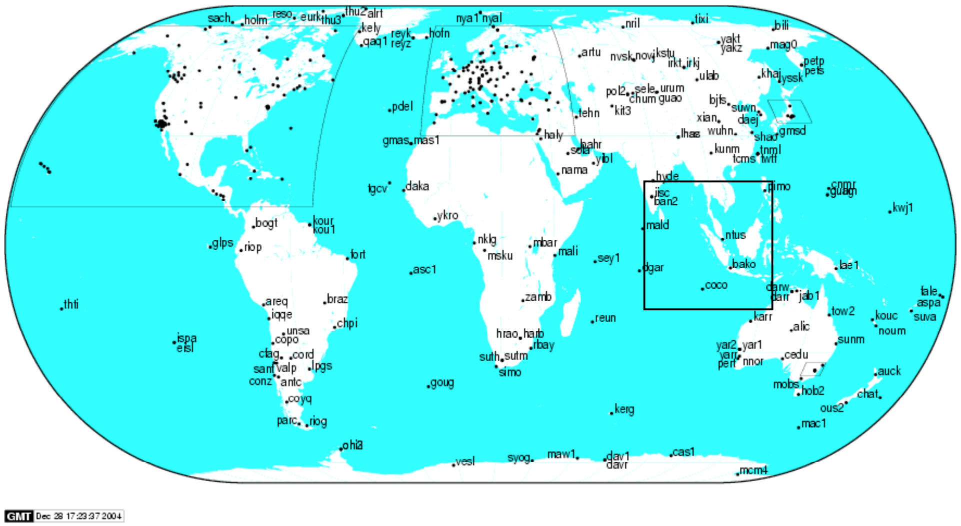
GPS Stations Near Sumatra and Geomagnetic Activity

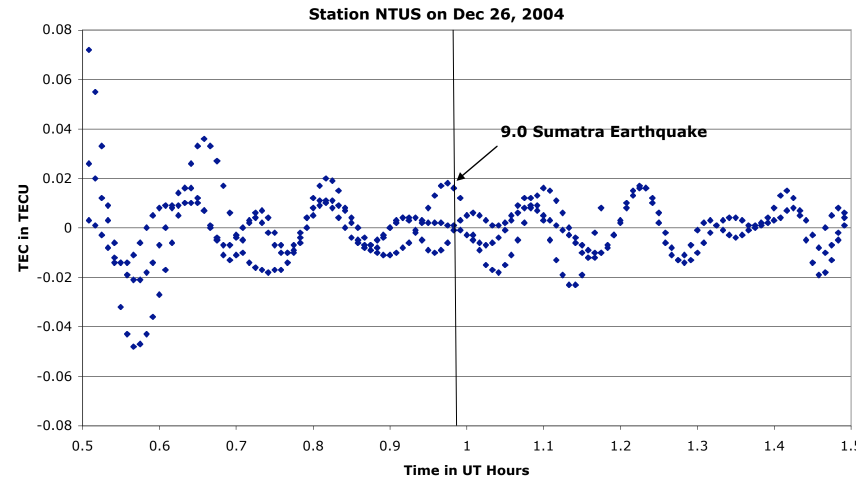


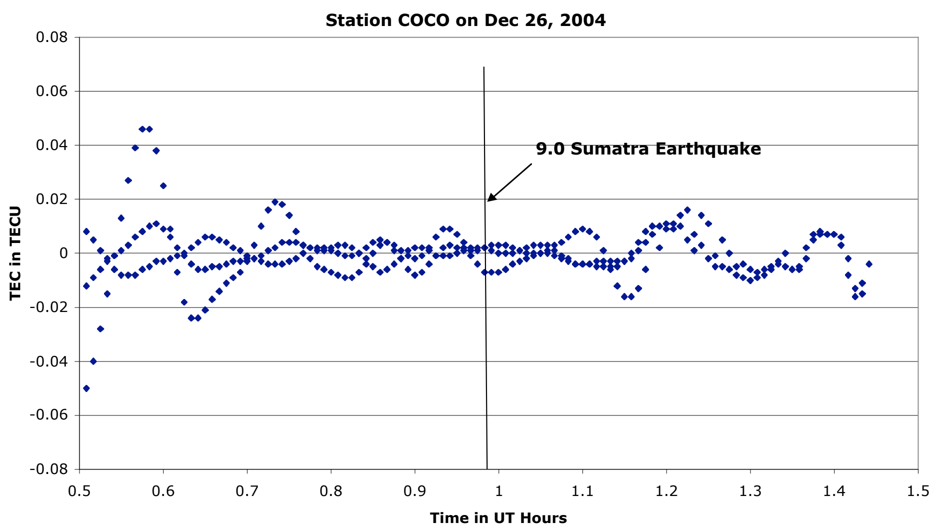


Geomagnetic Kp activity around the Sumatra event

Band-Pass Filtering Using 30-Second RINEX Data

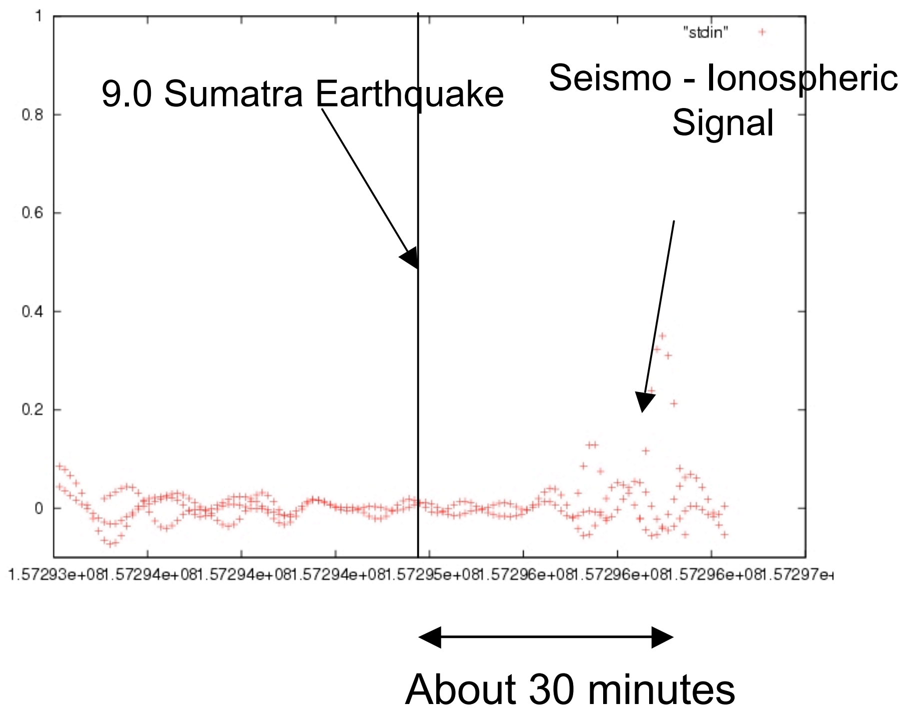






- Initially 30-sec RINEX-data from IGS stations used for development
- Dec 26, 2004 Sumatra Earthquake used to test algorithm
- Two stations processed above, separated by about 1500 km.
- No seismo-ionospheric signature found due to the low (30-sec) sampling rate
- Multiple satellites plotted at higher than 50 degrees elevation angles to minimize multipath effect

Band-Pass Filtered GPS TEC Data at 1-Second Sampling Rate



- We found 1-second data at station DGAR near the Sumatra Earthquake
- We applied the same algorithm and obtained the time series shown on the left
- Three satellites plotted at higher than 50 degrees elevation angle
- Lag between earthquake and disturbance in the ionosphere is what we would expect using propagation velocity of the waves in the atmosphere based on Afraimovich paper [2003].
- Amplitude of disturbance is also what we would expect (0.2 to 0.4 TECU).

The 2nd-Order Effect - Faraday Rotation

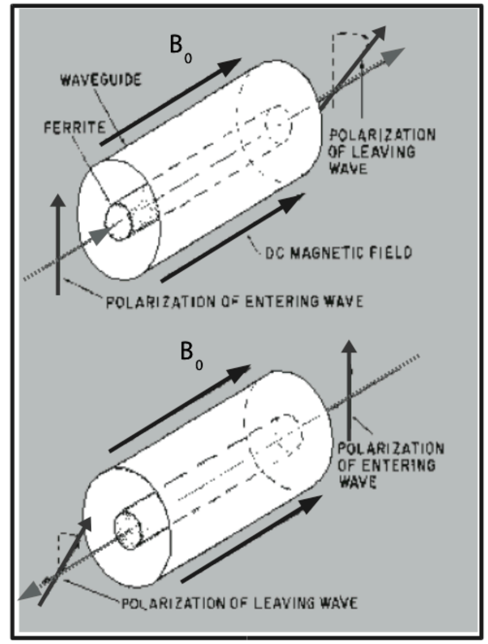
f_p = plasma frequency

f_g = gyro frequency

B_0 = Earth's magnetic field

θ_B = angle between signal propagation vector and magnetic field

c = speed of light

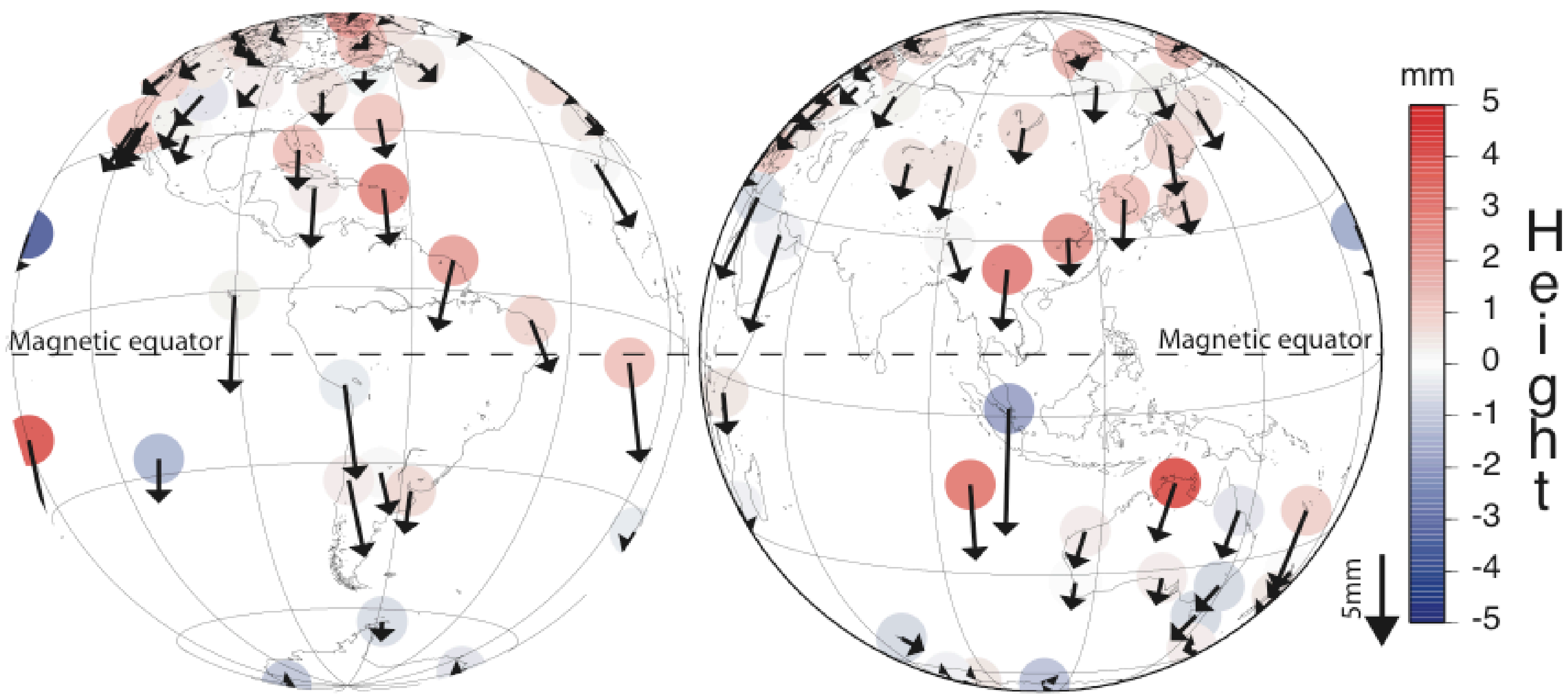


$$s = \int f_g \cdot f_p^2 \cdot \cos\theta_B dl = 7527 \cdot c \int N \cdot B_0 \cos\theta_B dl \cong$$
$$\cong 7257 \cdot c \cdot B_0 \cos\theta_B \int N \cdot dl \cong f(B, \theta_B, h_{ION}) \times TEC \quad (3)$$

[*Bassiri and Hajj*, 1993]

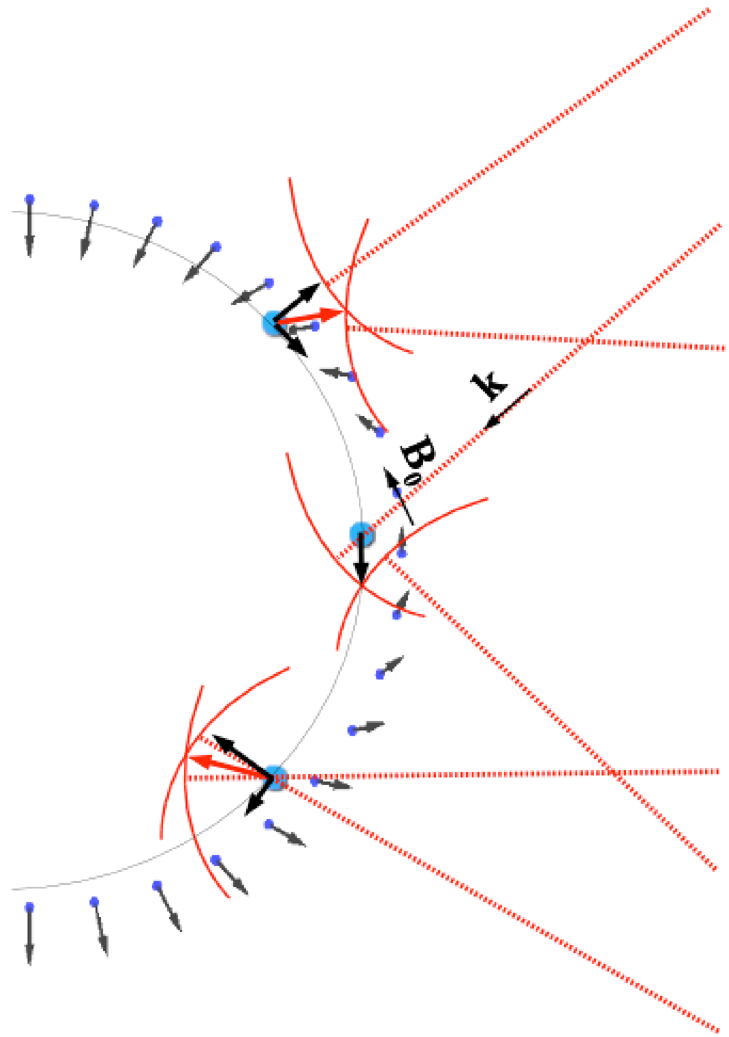
Effect on Station Positions

Systematic error in daily station positions estimate

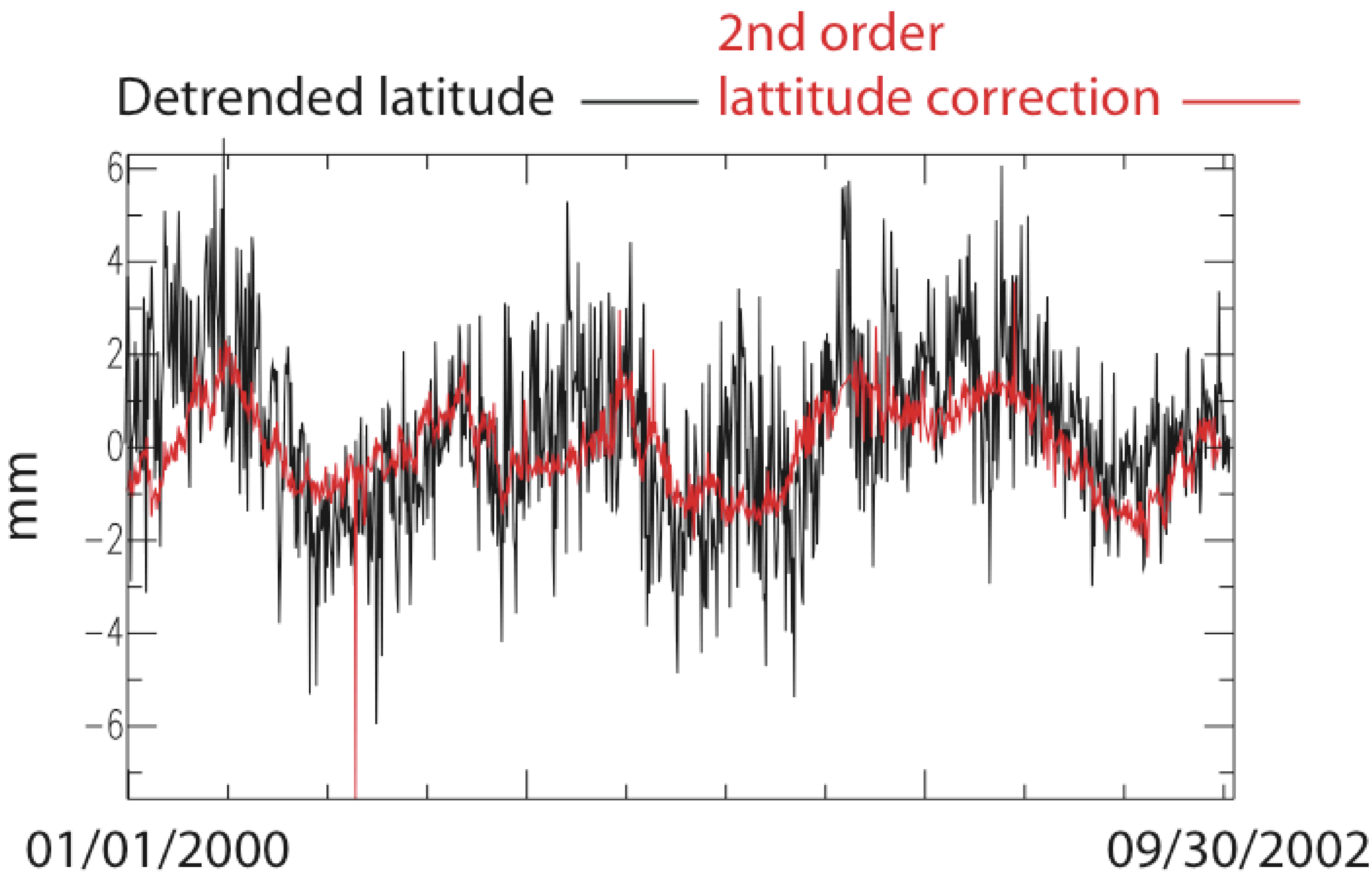


Interpretation

- Magnetic field direction: black arrow
- Satellite-station link: dotted red line
- Projection of the correction to the station's absolute position: red arrow



Seasonal Variation



Static VS Dynamic Corrections

$$L_i = \rho + n_i\lambda_i + \frac{q}{f_i^2} - \frac{1}{2}\frac{s}{f_i^3} = \rho + n_i\lambda - \frac{A}{f_i^2}\left[1 + \frac{B(t)}{2Af_i}\right] \times TEC \qquad (4)$$

"Static" approach [*Bassiri & Hajj*, 1993; *Kedar et al*, 2003]

- Use ionospheric combination and inter-frequency biases database to estimate *TEC* for each transmitter-receiver link
- Add 2nd order correction to L_i, P_i
- Form L_c combination
- Proceed as usual

$$L_C' = C_1L_1' - C_2L_2' \qquad C_1 = \frac{f_1^2}{f_1^2 - f_2^2} \qquad (5)$$

"Dynamic" approach [*Brunner & Gu*, 1991]

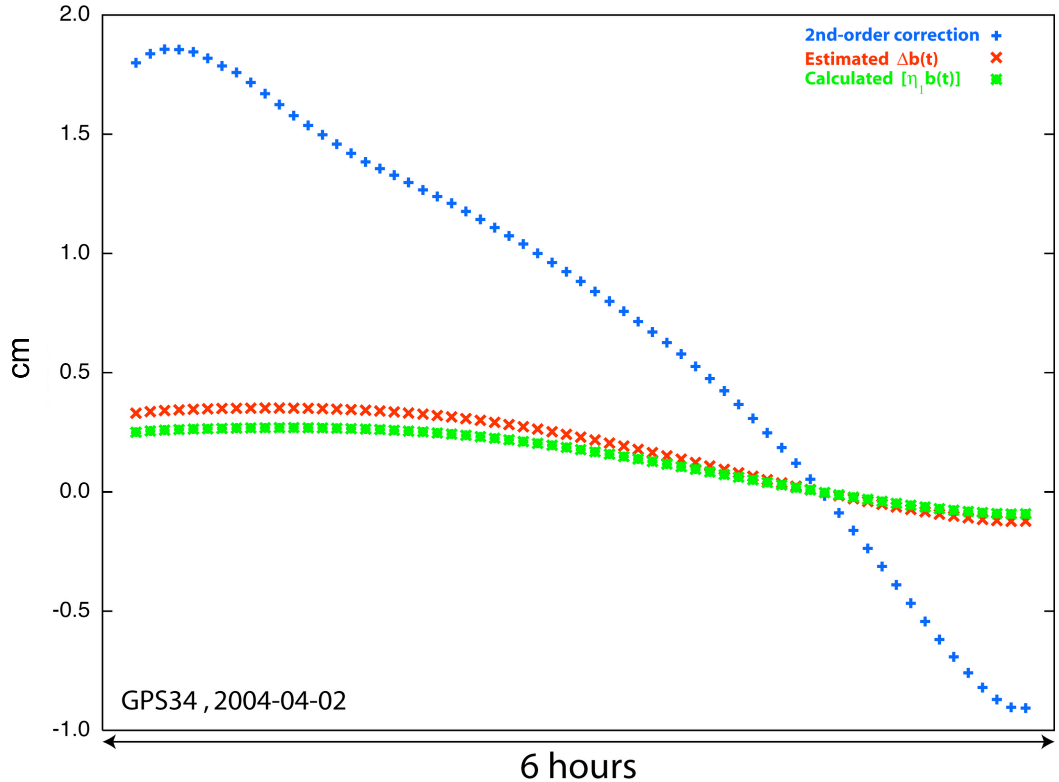
- Define new frequency

$$\frac{1}{f_i'^2} = \frac{1}{f_i^2}\left[1 + \frac{B(t)}{2Af_i}\right] \qquad (6)$$

- Form (now **time-dependent**) L'_C combination
- Proceed as usual

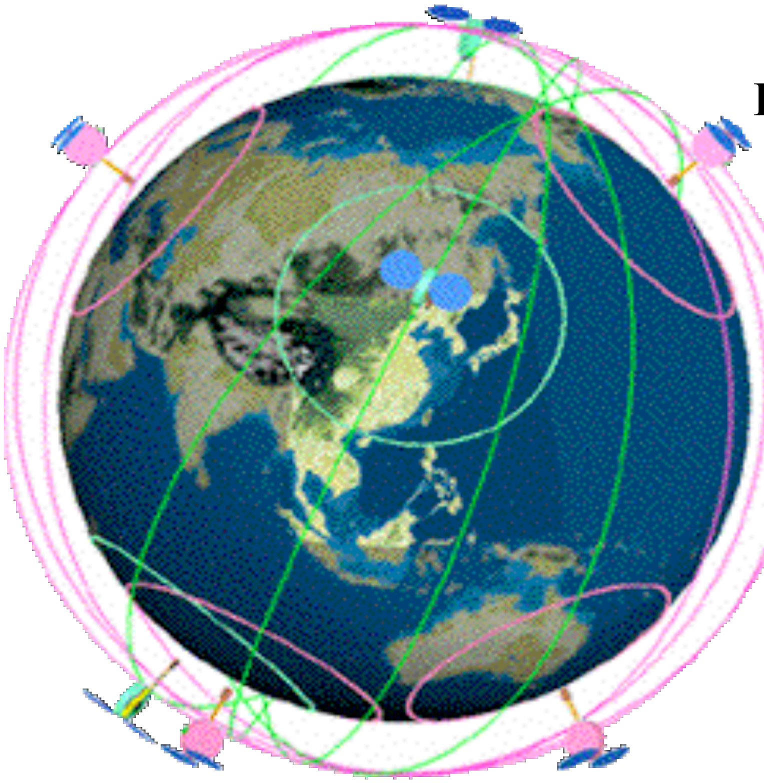
$$L_C' = C_1'L_1 - C_2'L_2 \qquad C_1' = \frac{f_1'^2}{f_1'^2 - f_2'^2} \qquad (7)$$

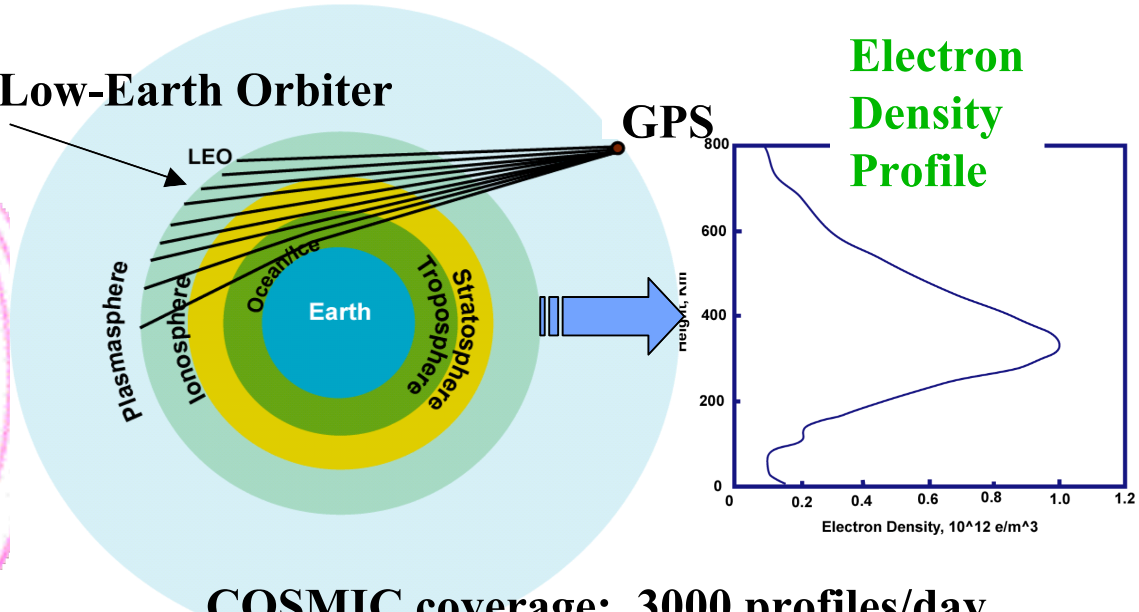
The Source of Dynamic Bias



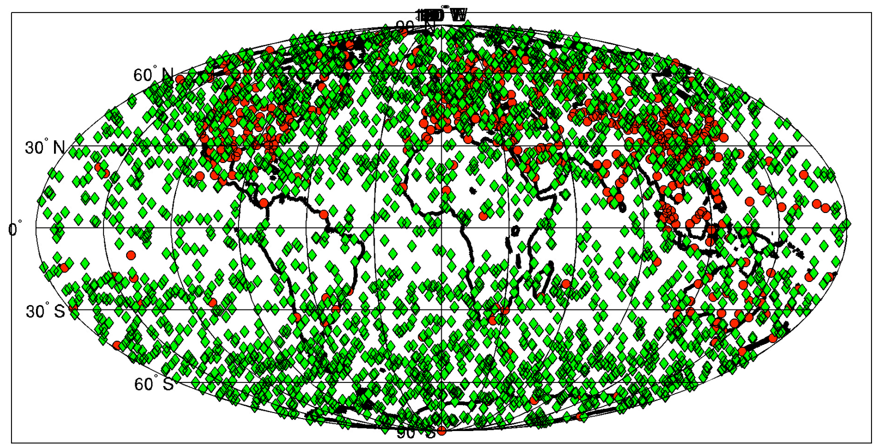
$$\begin{cases} \Delta b(t) = n_1 \lambda_1 \Delta C_1(t) - n_2 \lambda_2 \Delta C_2(t) \cong \overline{\eta}(t) b \\ \Delta C_i(t) = C_i'(t) - C_i(t) \\ \eta_i = B_{TEC}(t) / [2A(t) f_i] \end{cases}$$

COSMIC
Ionospheric Weather Constellation





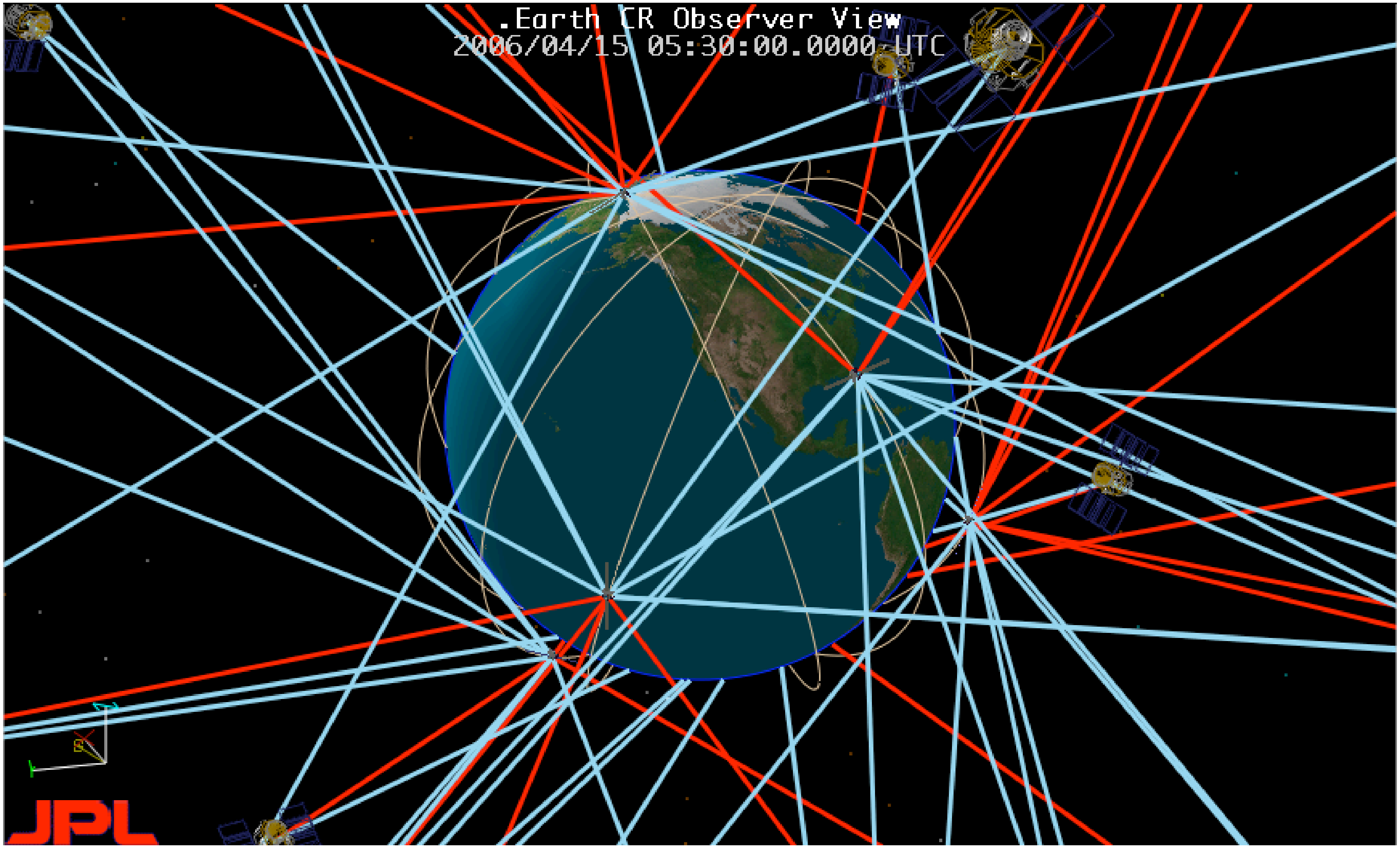
COSMIC coverage: 3000 profiles/day



Six-satellite COSMIC constellation
Launched April 14, 2006

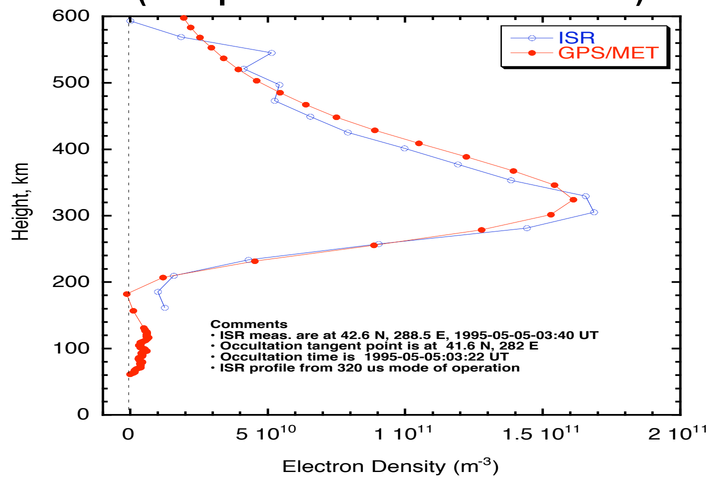
NSF NASA USAF NOAA NSPO ONR

COSMIC TEC Links

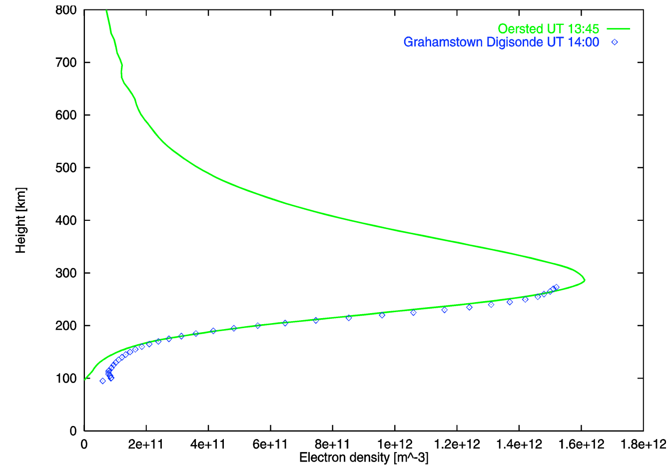


Examples of Electron Density Profiles

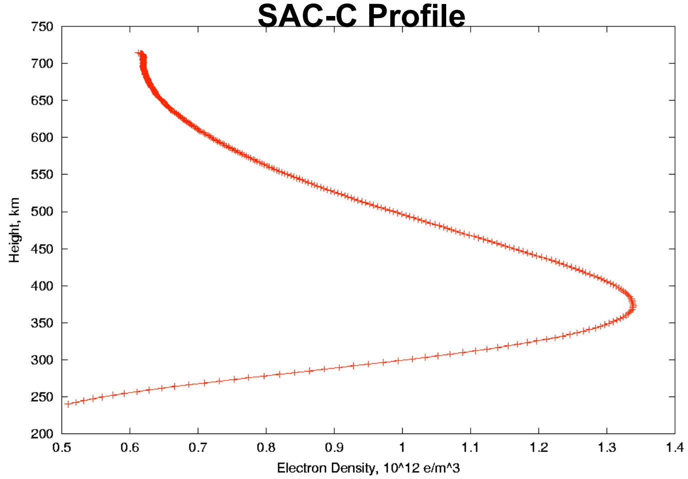
GPS/MET Profile
(Compared to Millstone hill radar)



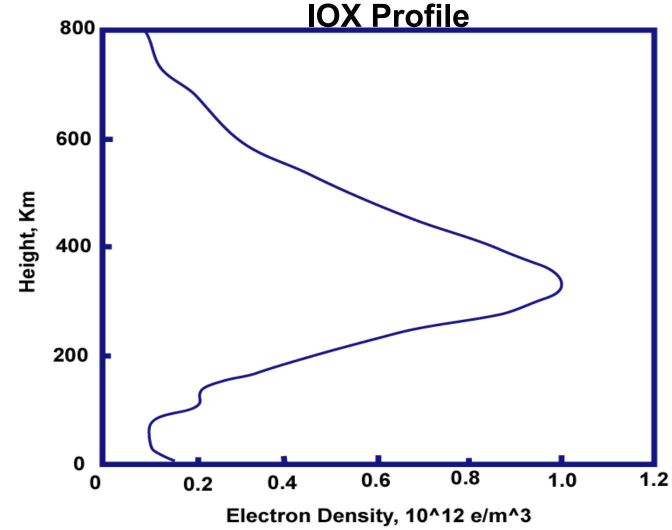
Oersted Profile
(Compared to nearby ionosonde)



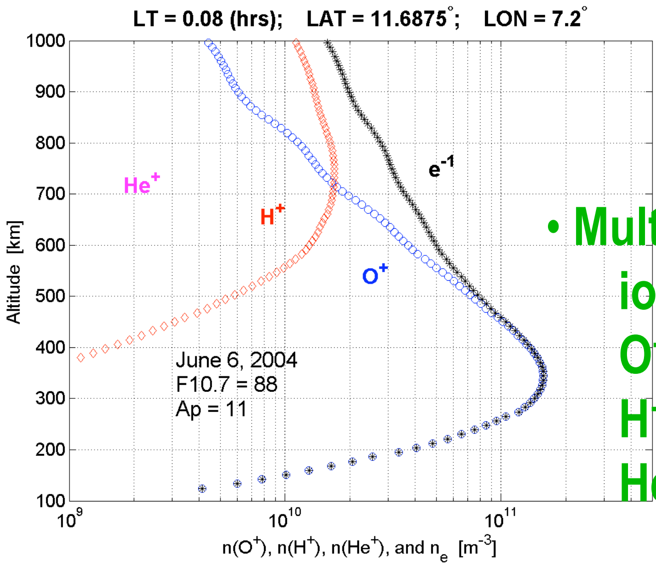
SAC-C Profile



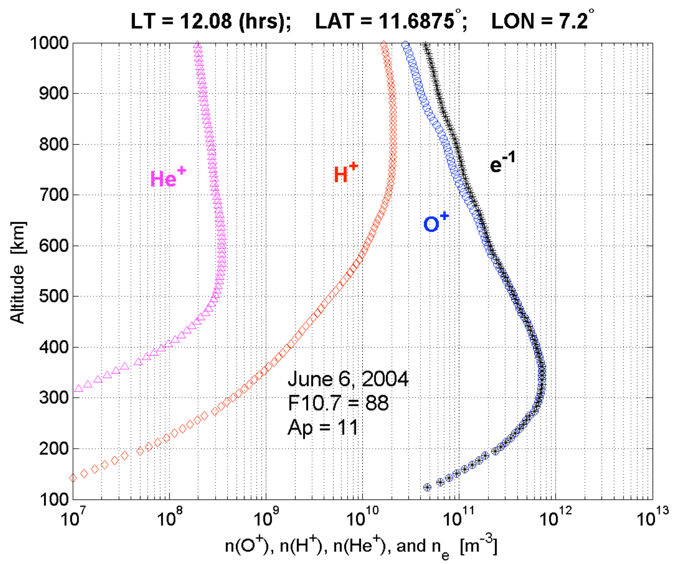
IOX Profile



GAIM First-Principles Model

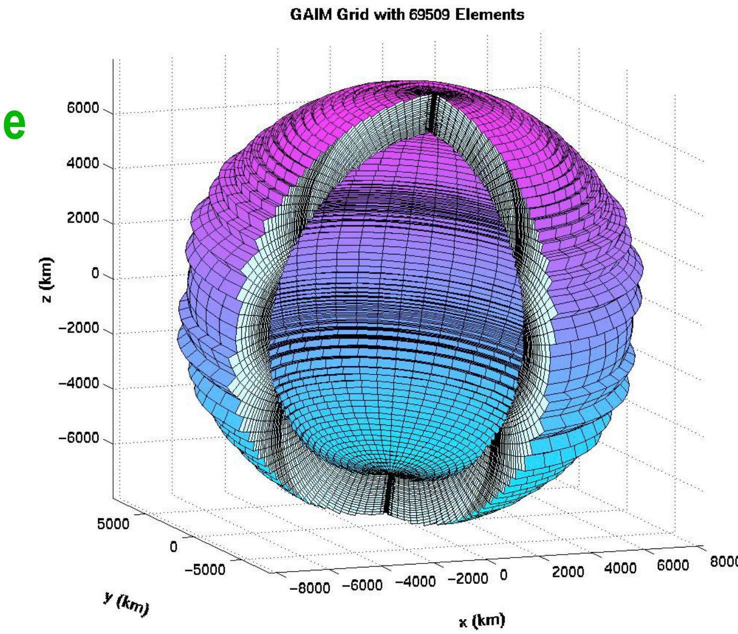


- Multiple ions: O^+, H^+, He^+

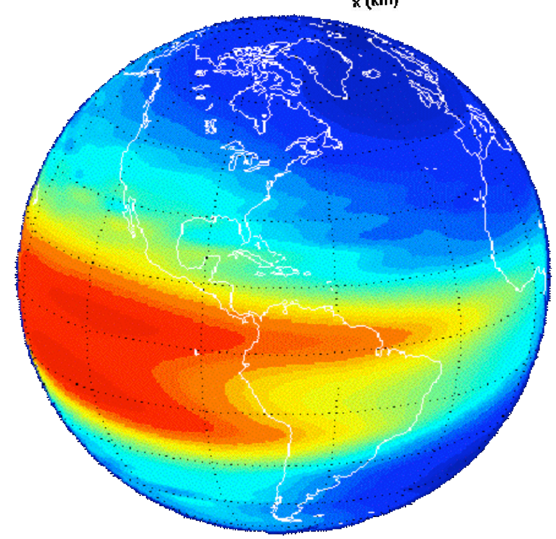


- 3-D grid in a magnetic frame

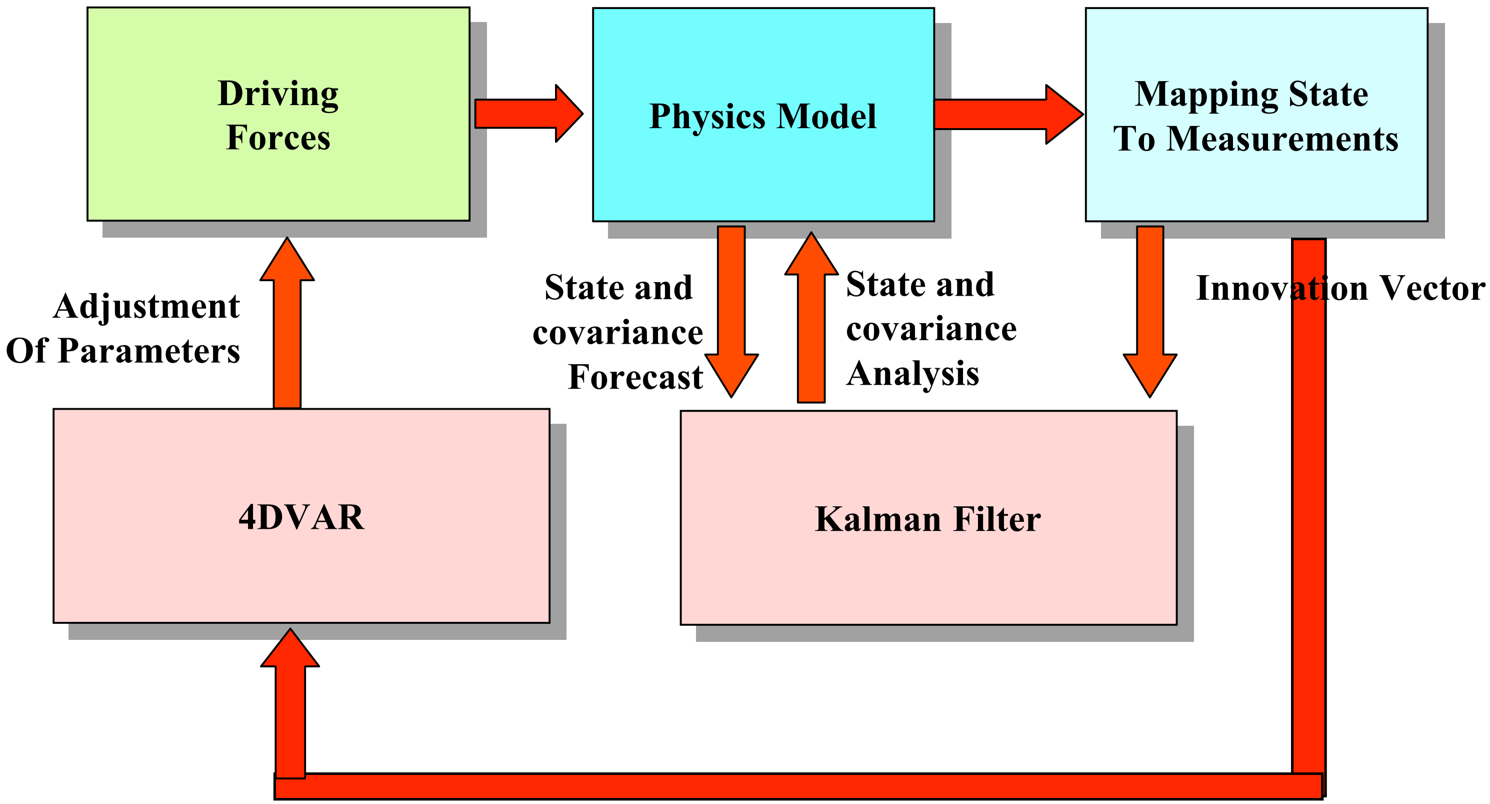
Numerical Scheme
- Finite volume on a fixed Eulerian grid
- Hybrid explicit-implicit time integration scheme



- Global and regional modeling by solving plasma hydrodynamic equations



Global Assimilative Ionospheric Model
Data Assimilation Process



- 4-Dimensional Variational Approach
  - Minimization of cost function by estimating driving parameters
  - Non-linear least-square minimization
  - Adjoint method to efficiently compute the gradient of cost function
  - Parameterization of model "drivers"
- Kalman Filter
  - **Recursive Filtering**
  - Covariance estimation and state correction

    Optimal interpolation

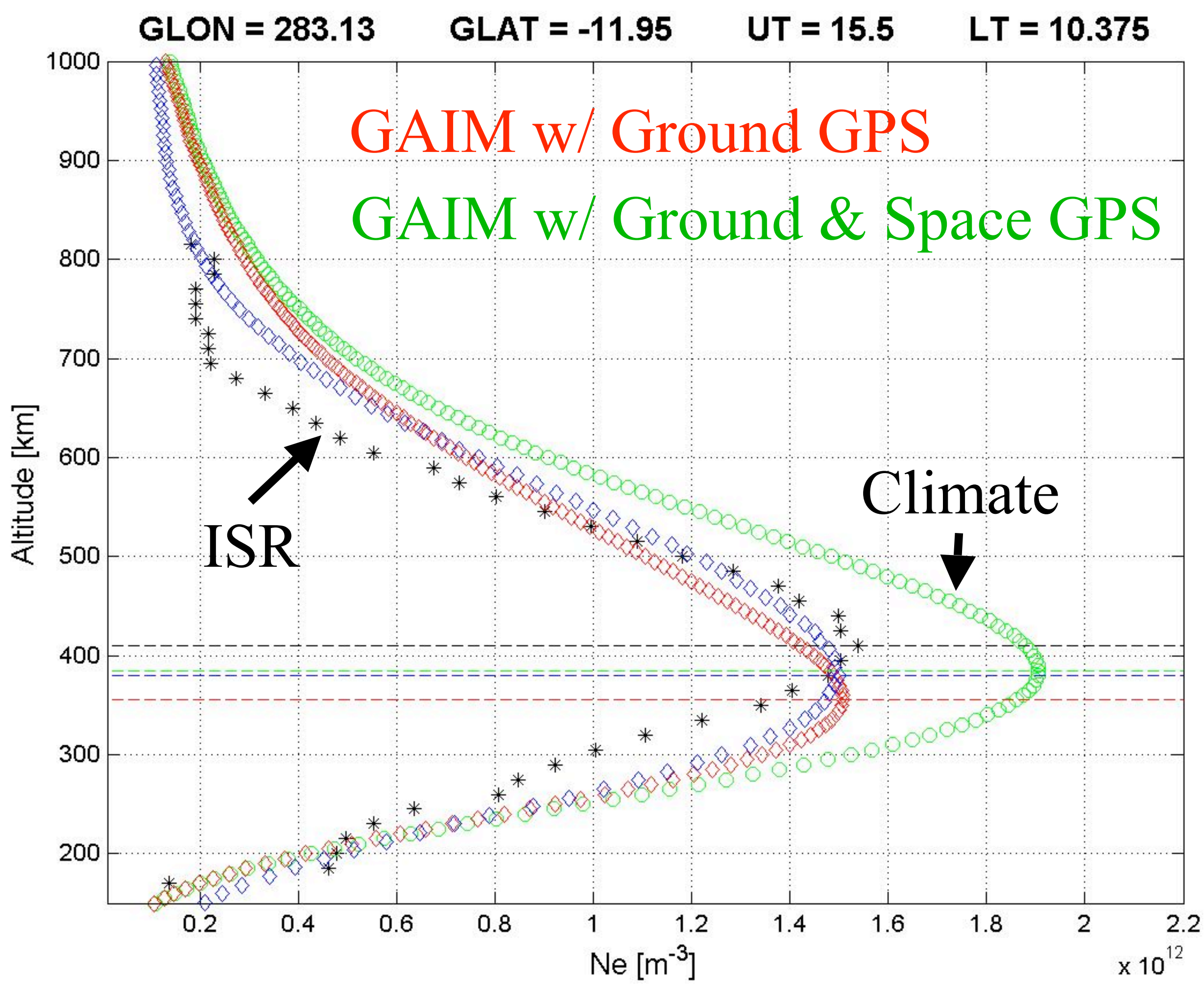
    Band-limited Kalman filter

Compare to Jicamarca ISR n_e Profiles

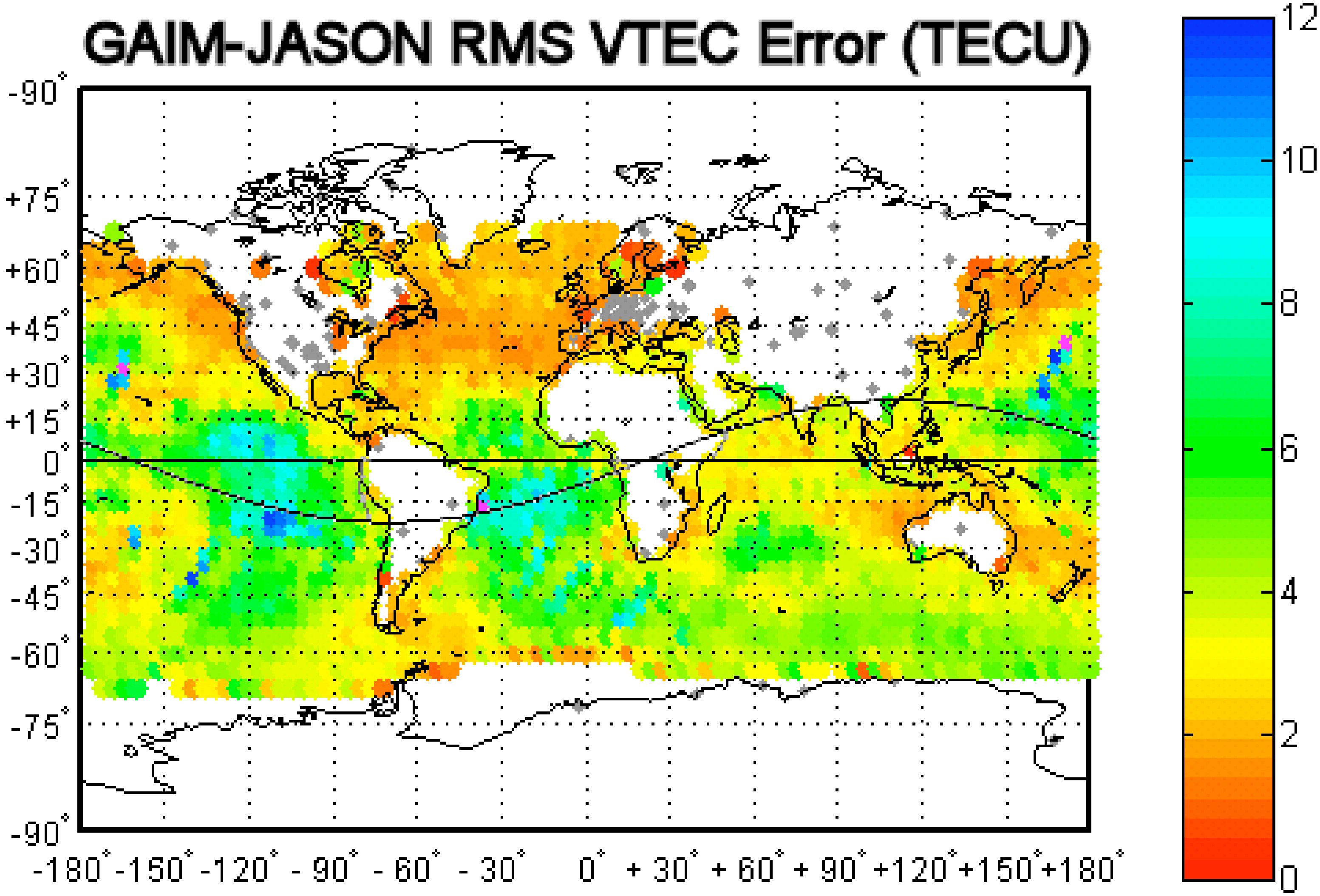
GAIM assimilating **ground** GPS data → improved n_mF_2

GAIM assimilating **ground and space** GPS data → improved and n_mF_2 and h_mF_2

05/31/2002



GAIM VTEC versus JASON Measurements

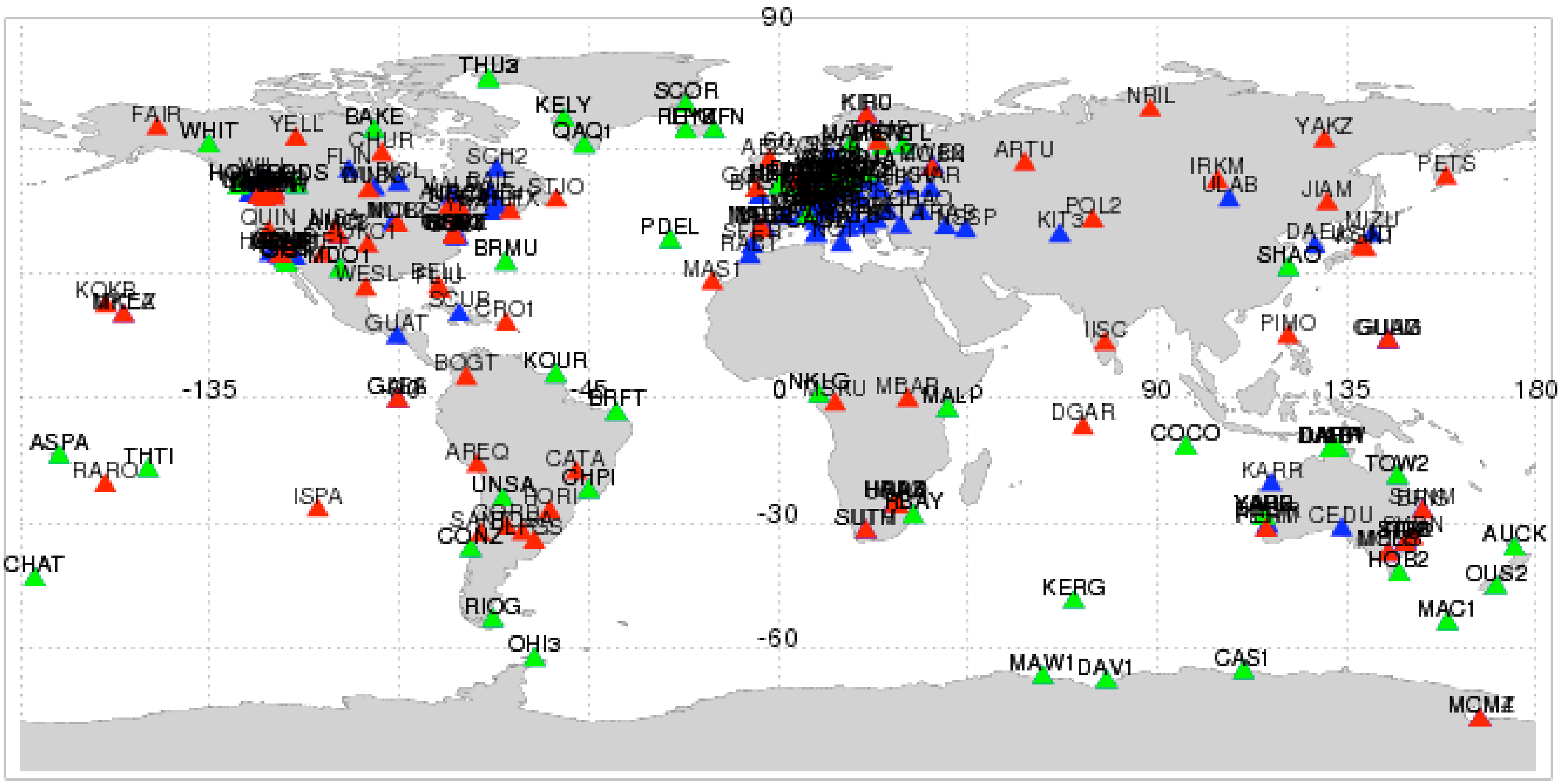


RT GAIM Prototype

- **Demonstrated last year at SWW**
- **Data being assimilated presently: ground GPS TEC**
  - Every 5 minutes from 77 1-sec. streaming sites (~600 pts)
  - Every hour from ~120 more sites for improved global coverage
- **Optimal estimation model: Kalman Filter**
  - Update global 3-D density grid every 5 minutes
- **Validation Data**
  - Every 3-4 hours against vertical TEC from JASON
  - Every day (post-analysis) against ionosonde and other data
- **Other global data sources**
  - Ground GPS network (>900 daily sites, >170 hourly sites)
  - FUV radiances (LORAAS, GUVI, DMSP SSUSI/SSULI)
  - COSMIC GPS occultation constellation (6 satellites)

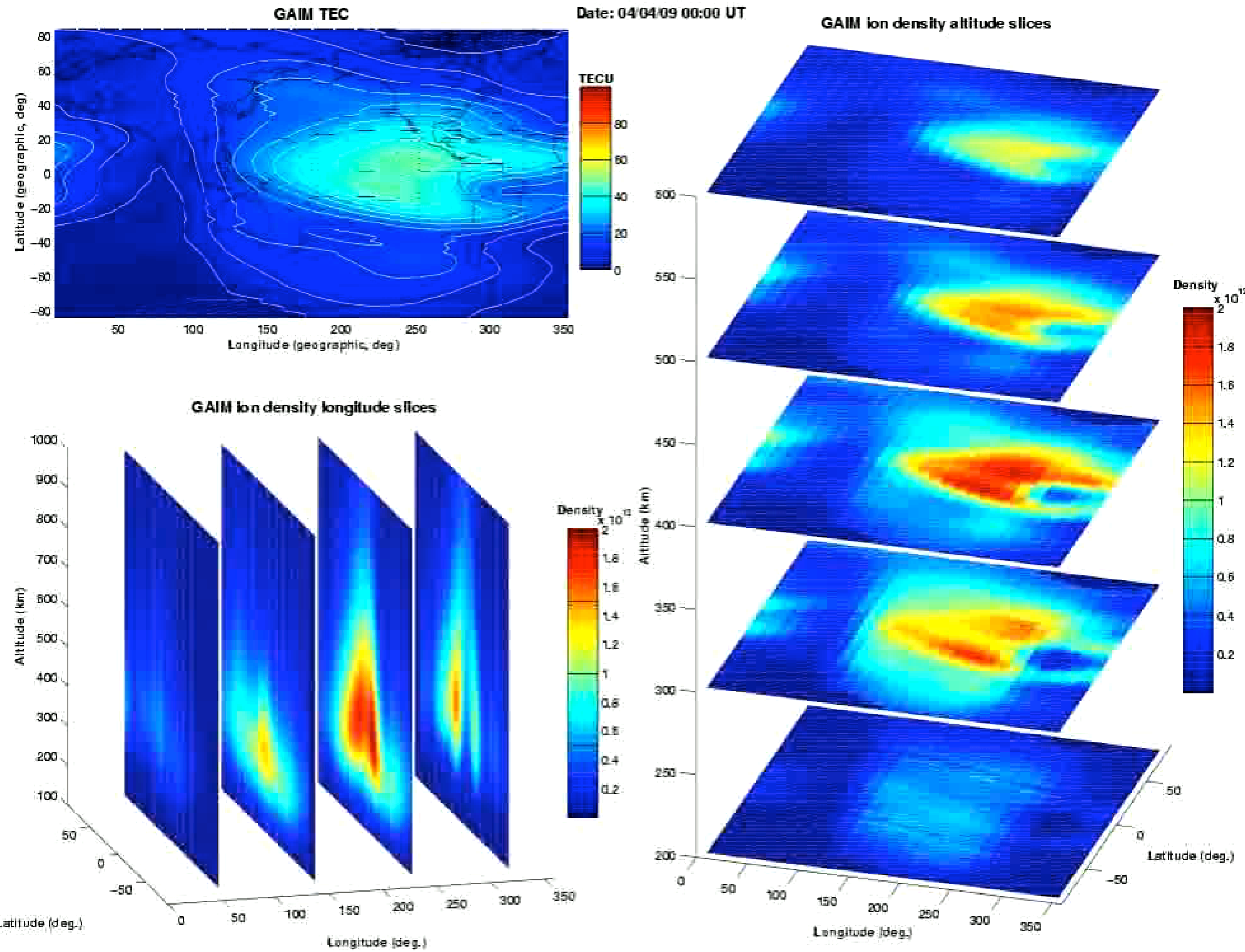
Ground GPS Streaming & Hourly sites

Current Streaming & Hourly GPS Sites (red=streaming, blue/green=hourly)



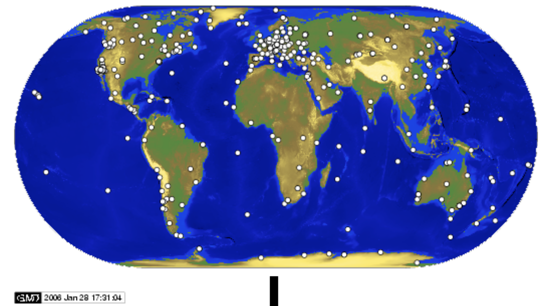
Red=5-min. sites, Green=Best 50 hourly, Blue=Rest of hourly

RTGAIM: TEC & Density Movie

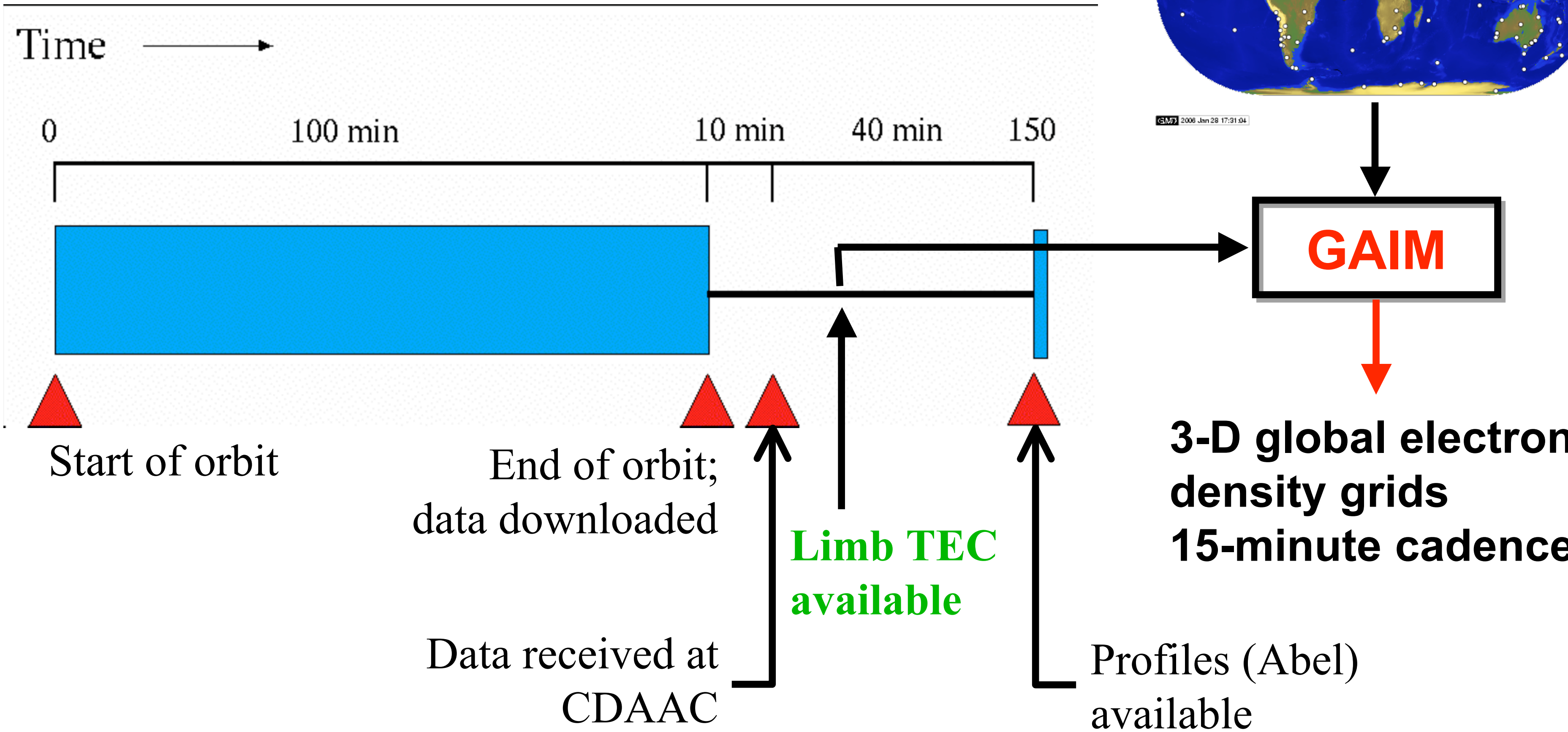


COSMIC Demo 2006

Global ground network data: 5-min. and 1-hour latency

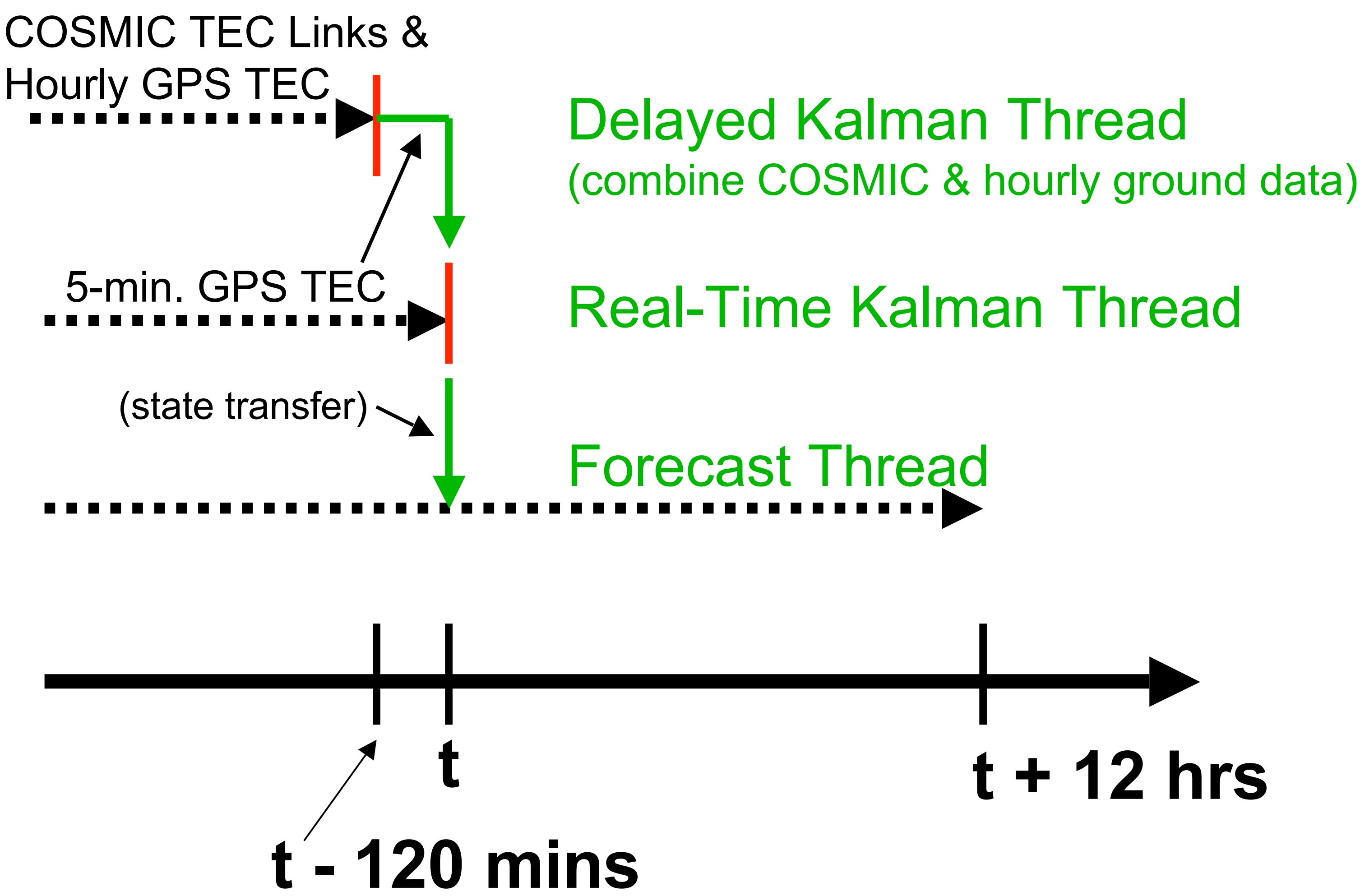


COSMIC data latency (courtesy of Chris Rocken, UCAR)



CDAAC: COSMIC Data Analysis and Archiving Center at UCAR

Concept of Operations: Three GAIM Threads



Summary

- Ionospheric weather modeling of TEC and altitude profiles, including n_mF_2 and h_mF_2, significantly benefits from assimilation of line-of-sight GPS TEC measurements into physics models, even in very structured regions (low latitudes).
- JPL/USC GAIM will assimilate in NRT ground-based GPS data (~77 5-min. sites & ~120 hourly sites) and 3000 COSMIC occultations per day.
- Besides the Kalman filter technique, 4DVAR will be further pursued to estimate model drivers and to explore short-term forecast capability.
- Ingest of COSMIC and SSUSI/SSULI data will revolutionize the accuracy of 3D ionospheric specification.