PC-Based System for Real Time Reconstruction of the Three Dimensional Ionosphere Using Data from Diverse Sources

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GPS Ionospheric Inversion (GPSII)

- **We present new capabilities of our algorithm for ionospheric inversion being developed for the task of monitoring the ionosphere over a fixed geographical area**
  - **Continuation of our work "Real-time reconstruction…," Radio Science, 41, RS5S12, 2006**
- **The algorithm utilizes raw data from GPS receivers:**
  - **Dual frequency group delay data (absolute TEC) and/or**
  - **Dual frequency phase delay data (relative TEC)**
    - **No need to "level" the TEC data**

- **Receiver and transmitter biases are estimated within the algorithm**

GPS Ionospheric Inversion (GPSII)

- The bulk of data comes from GPS receivers ⇨ GPSII
- Other Data Types
  - Vertical sounders
  - Plasma density data (such as from CHAMP, DMSP)
  - Vertical TEC (such as from JASON)
  - TEC data obtained with LEO beacons
  - Occultation-type oblique TEC (absolute and relative) from space-based GPS receivers (CHAMP, COSMIC).
    - No need for error-sensitive Abel inversion of occultation data.
- Features:
  - Real time characterization of the data noise variances (sliding window technique) for utilizing in GPSII solution

The Ionospheric Reconstruction Problem: Tikhonov Method

$$N(\mathbf{r},t) = N_0(\mathbf{r},t)e^{u(\mathbf{r},t)}$$
$$U = \{\{u(\mathbf{r},t)\}, \text{Biases}\}$$
$$Y \approx M[U]$$

Where Y is the set of measured absolute/relative TEC values and data points from other types of ionospheric measurements.

The smoothest solution ⇔ solution minimizing the stabilizing functional	$\rightarrow$ $U^T P^{-1} U \to \min$
The solution must fit the data within errors of measurements ...	$\rightarrow$ $(Y - M[U])^T S^{-1}(Y - M[U]) / \dim(Y) \le 1$

-The pseudo-covariance matrix is defined in such a way that the stabilizing functional tends to take on larger values for unreasonably behaving solutions ("reasonable" ⇔ "smooth").

-The nonlinear optimization problem is solved iteratively (Newton-Kontorovich).

Background Model of the Ionosphere. Available options:

$N_0(\mathbf{r},t)$ **above is a background model for electron density in the ionosphere**

Option 1 – Parameterized Ionospheric Model (PIM) with plasmasphere

Option 2 – IRI2007 with our analytical plasmaspheric extension

The Background Model Based on IRI

At h < h_{b1} =1500 km $N_0(\mathbf{r},t)$ is given by **IRI 2007.**

At h>h_{b2}=2000 km $N_0(\mathbf{r},t)$ =

$$N_0^{Top}(\mathbf{r},t) = N^{IRI}\Big|_{h_{b1}} \left(\sum_i \frac{N_i^{IRI}\Big|_{h=h_{b1}}}{N_0^{IRI}\Big|_{h=h_{b1}}} \exp\left(-M_i \frac{G(h)-G(h_{b1})}{kT_i} \right) \right)^{\frac{T_i}{T_e+T_i}}$$

An analytical model assuming that the plasma is in thermal diffuse equilibrium; the topside model is smoothly joined with the IRI

At 1500 ≤ h ≤ 2000 km:

$$N_0(h) = \frac{(h-h_{b1})N_0^{Top}(h) + (h_{b2}-h)N^{IRI}(h)}{h_{b2}-h_{b1}}$$

Linear Transition layer

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Recursive Processing

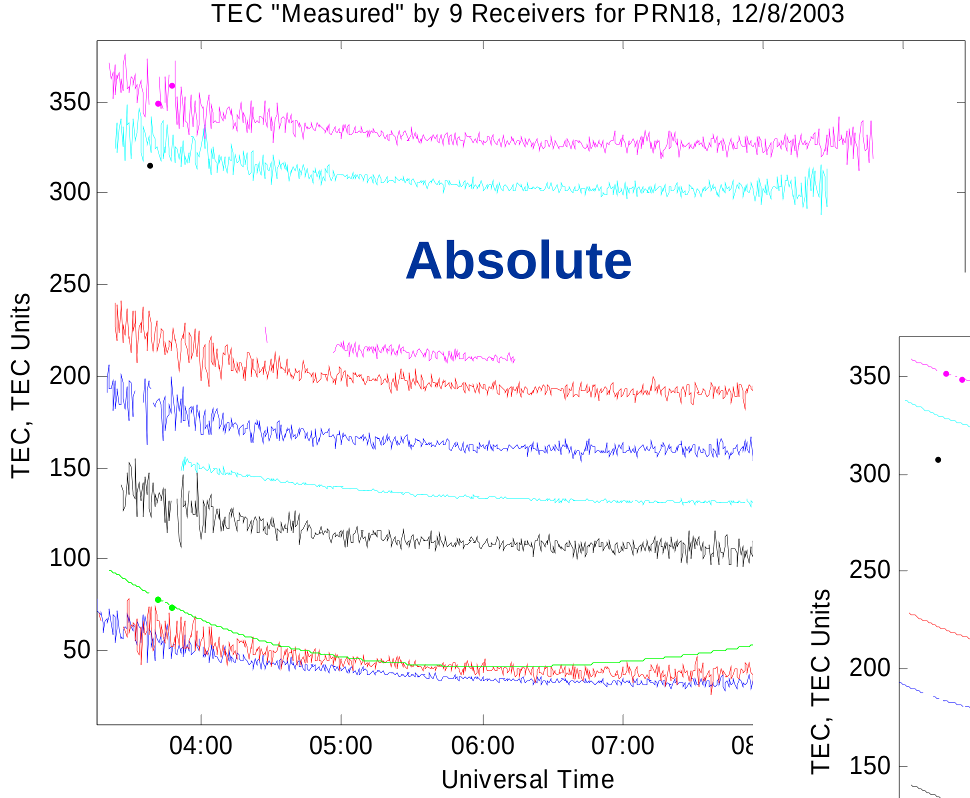
- **GPSII continuously updates the solution as new ionospheric measurements become available.**
- **We assume that the evolution of the solution obeys the following rule:**

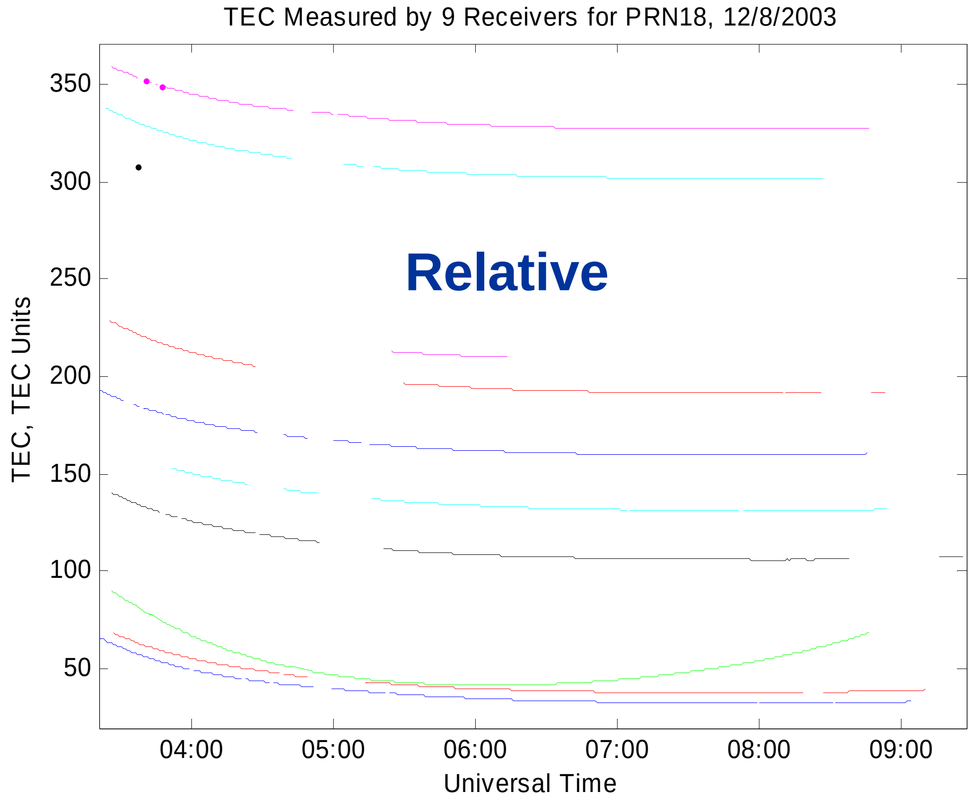
$$u(\mathbf{r},t_k) = \gamma u(\mathbf{r},t_{k-1}) + v(\mathbf{r},t_k)$$

- **To ensure proper treatment of the phase TEC data we adopt that the solution vector contains two time layers**

$$\left\{u(\mathbf{r},t_k), u(\mathbf{r},t_{k-1})\right\}$$

Sample of Synthetic TEC Data





Note: the synthetic TEC curves are arbitrarily offset for display purposes

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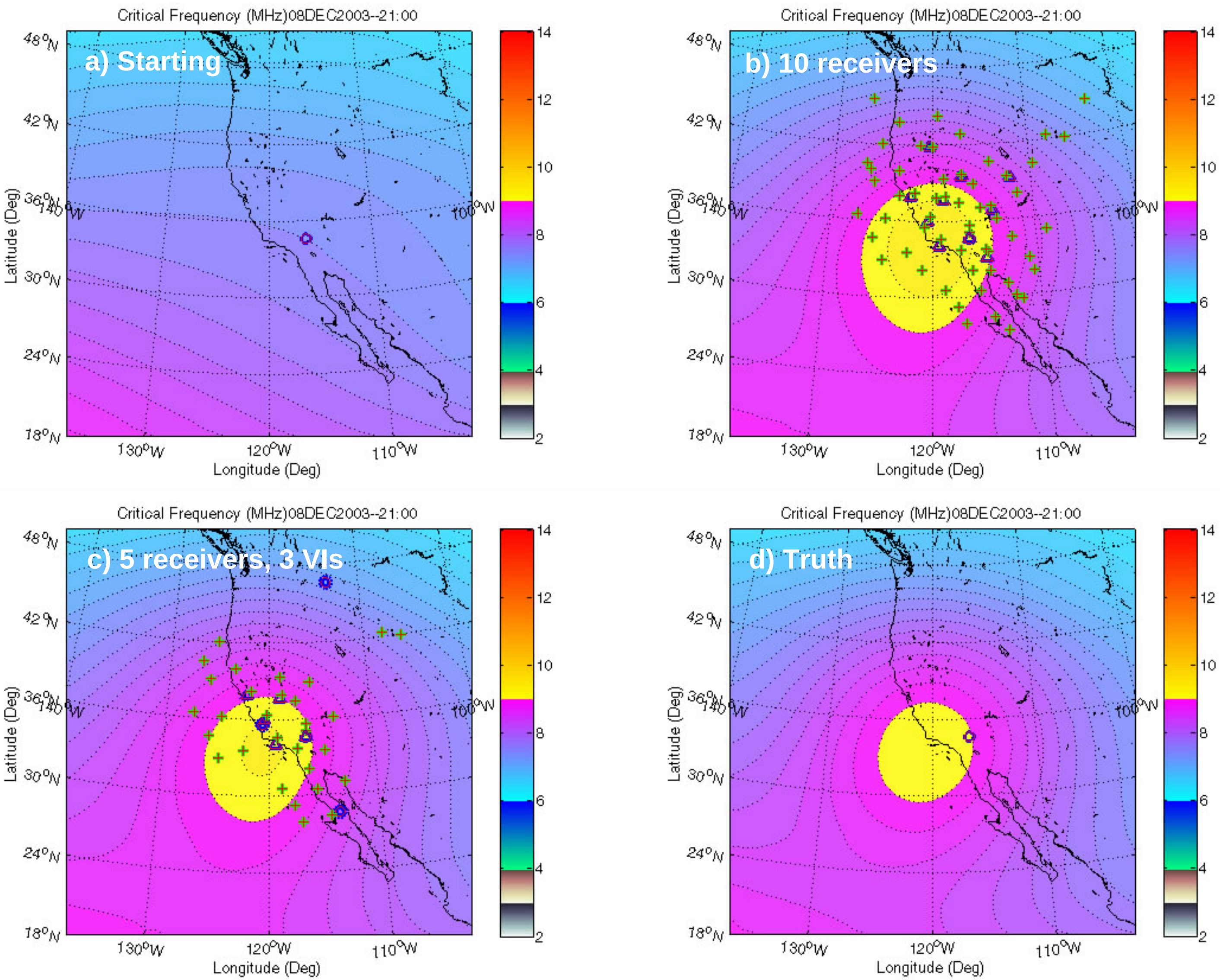
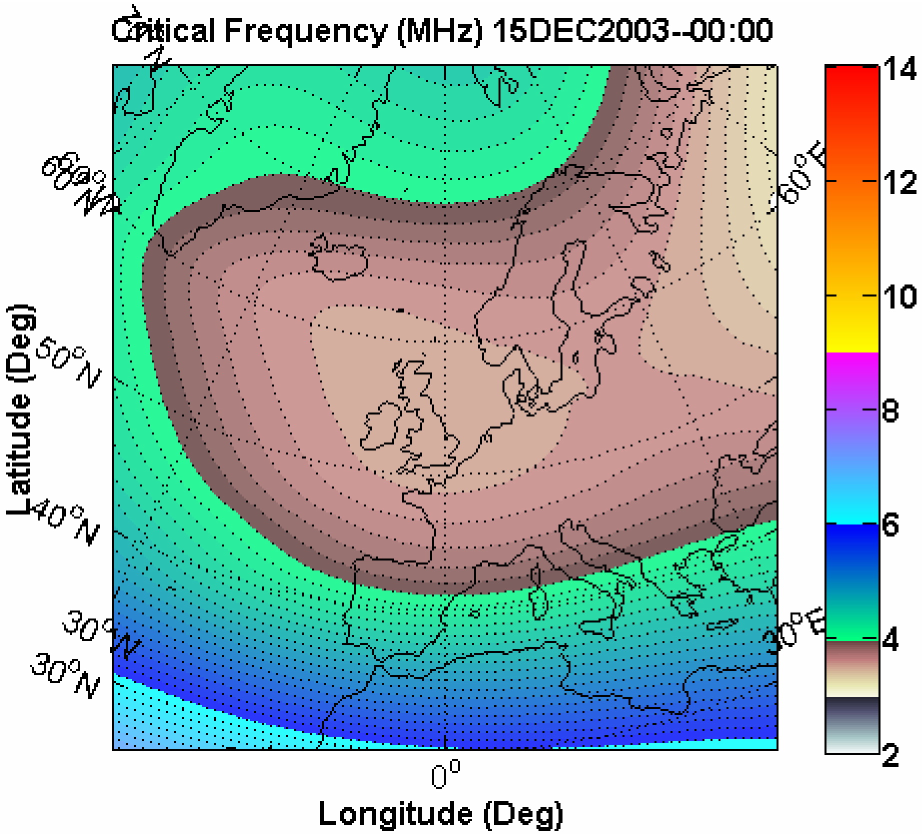
Comparison maps of critical frequency: 2100 UT



GPSII performance tests with diverse data

GPSII solution for the critical frequency



FmF2

VTEC

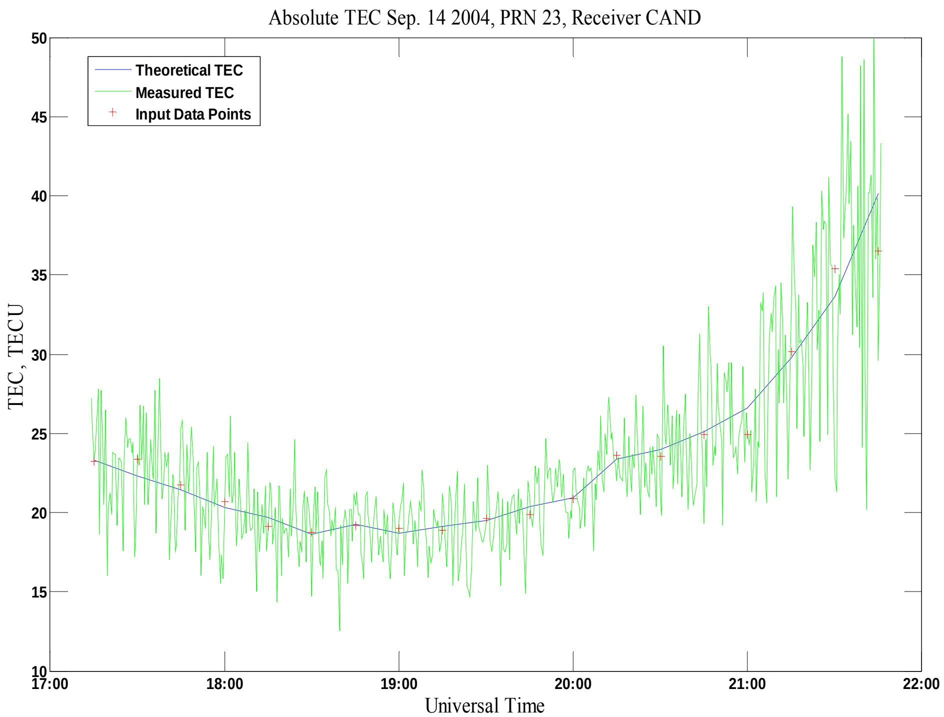
400km

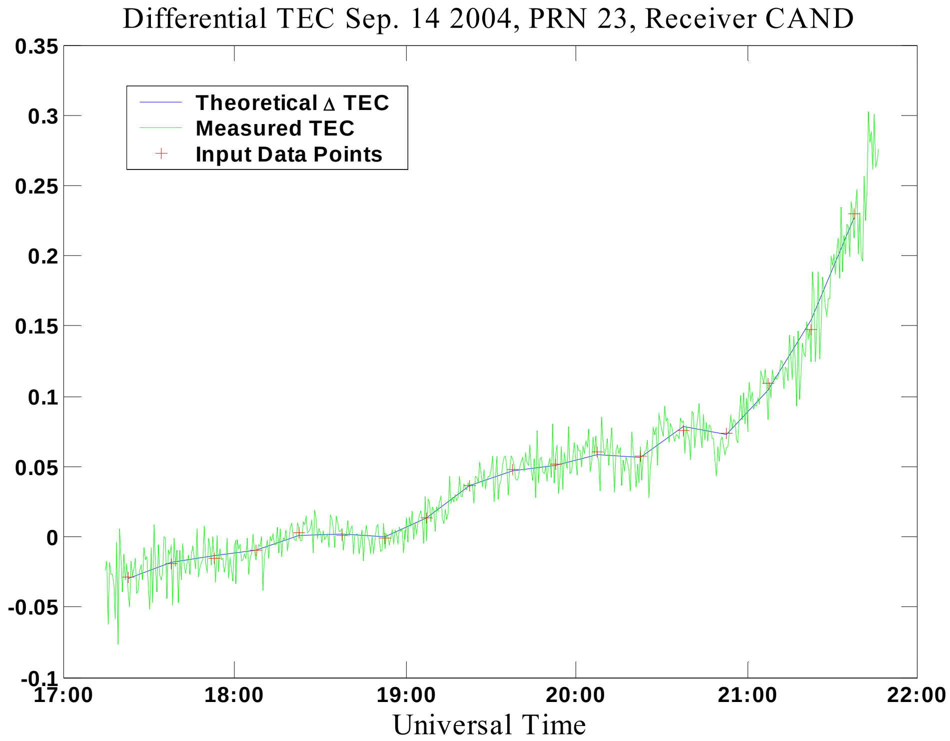
Data Type	Data Sources
Abs. TEC, Rel. TEC	13 GPS receivers
Plasma Density	CHAMP Plasma Probe
Vertical TEC	JASON

Horizontal grid spacing 70x70 km

Altitude from 80 to 20,000 km

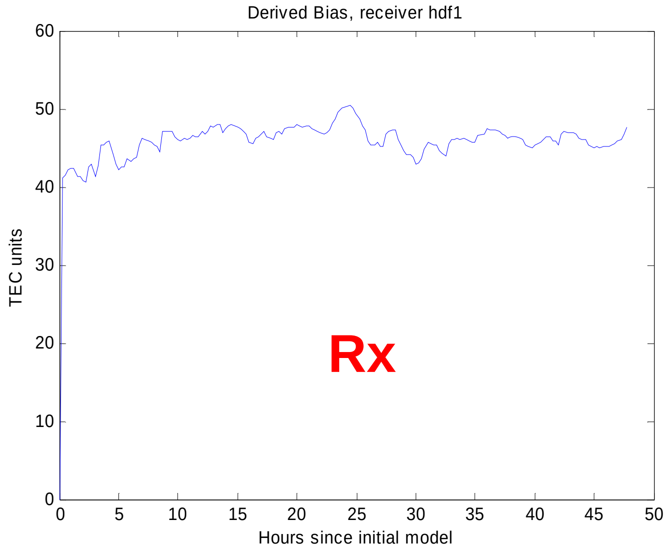
GPS TEC Inversion Results

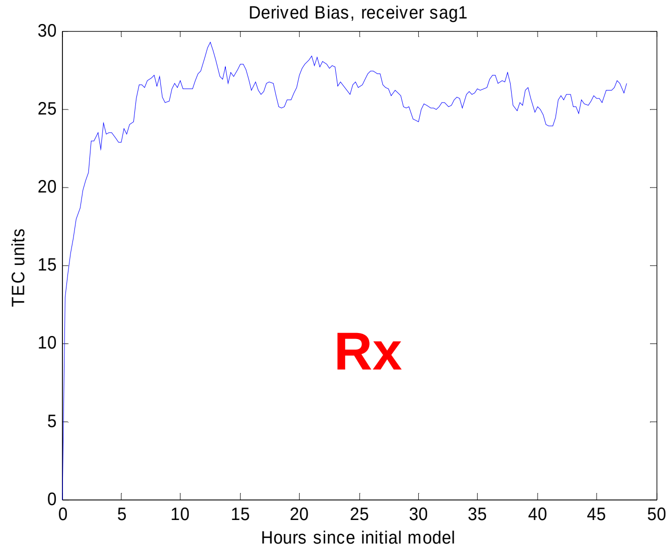


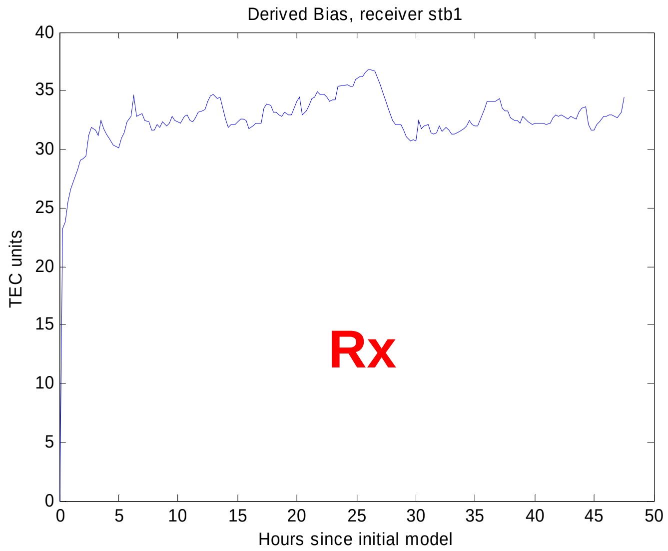


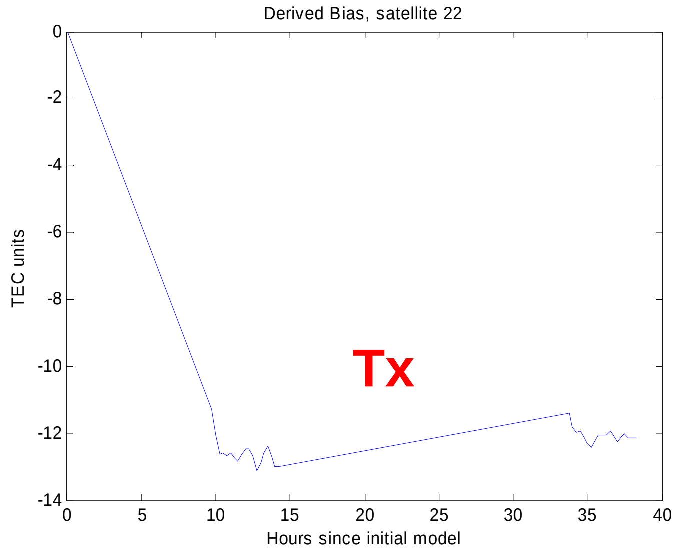
Examples of the measured absolute TEC (left) and the TEC rate (right) compared to simulated values (blue lines)

Bias computed from real data

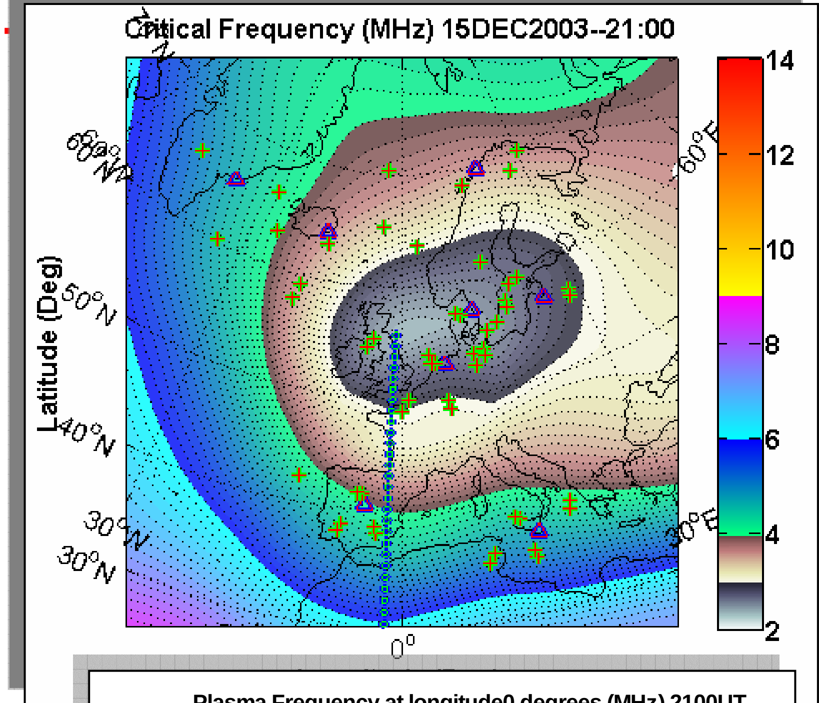


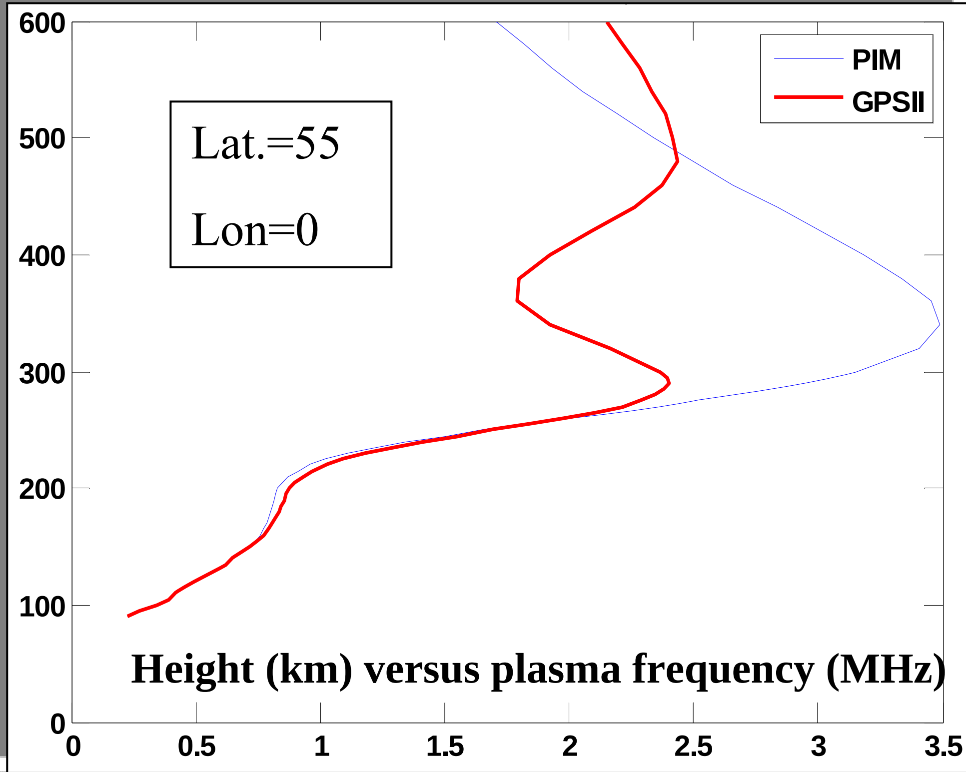


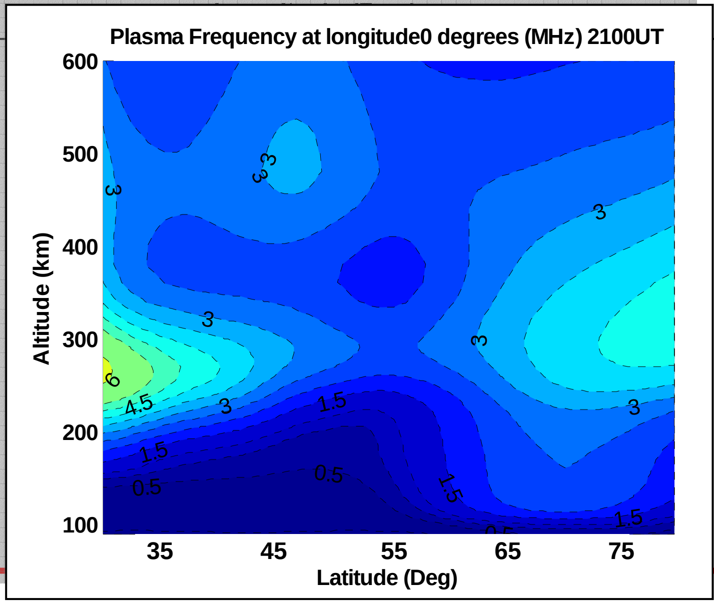




A Problem Revealed at Testing



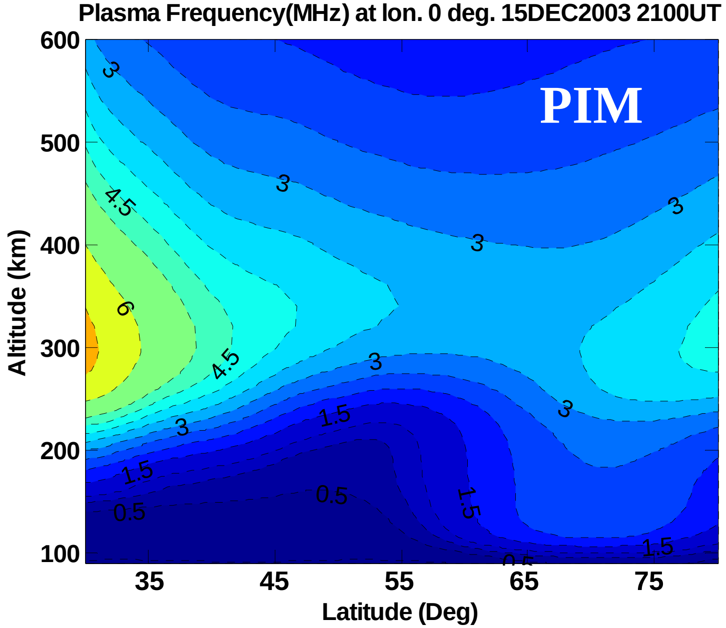


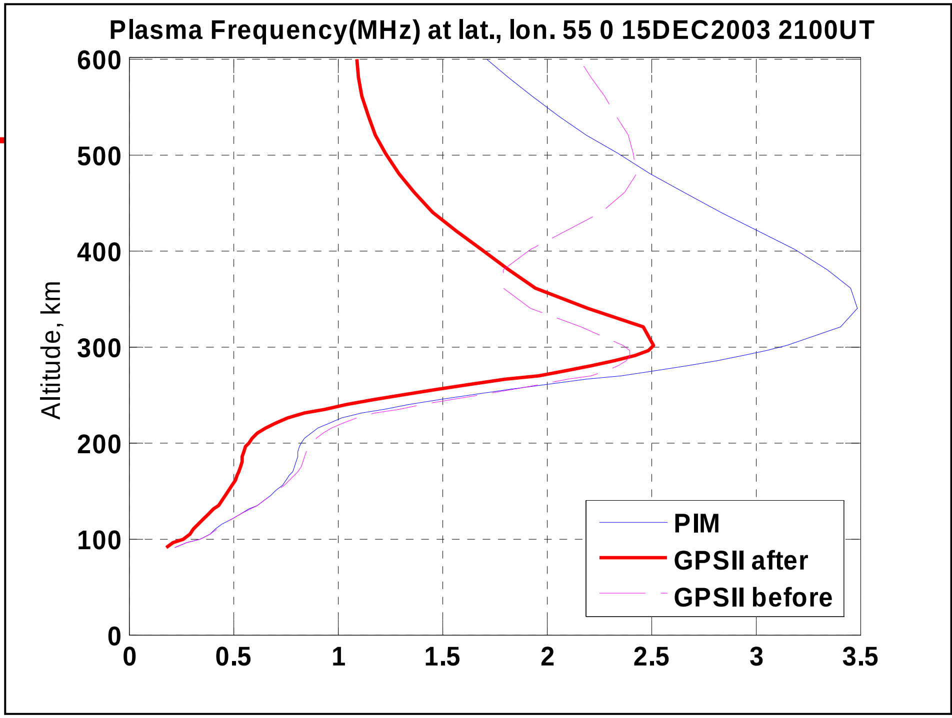


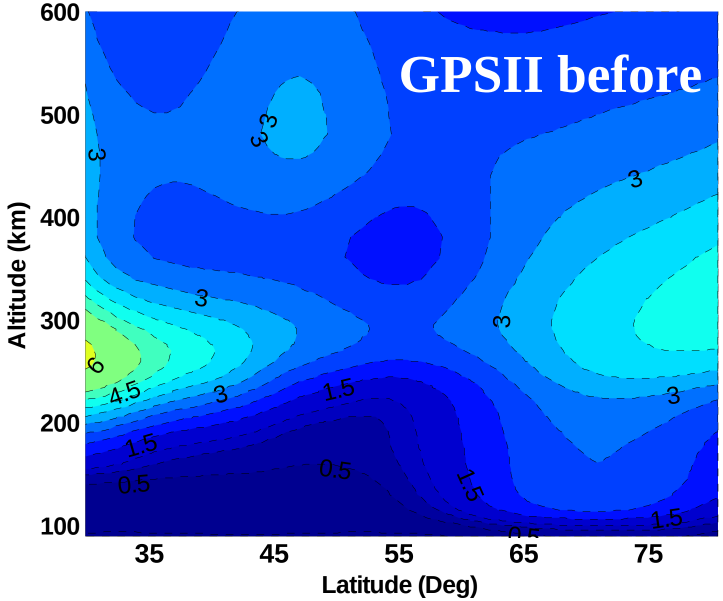
The unrealistic split of the F2-layer is caused by Ne data from CHAMP passing at 370 km altitude

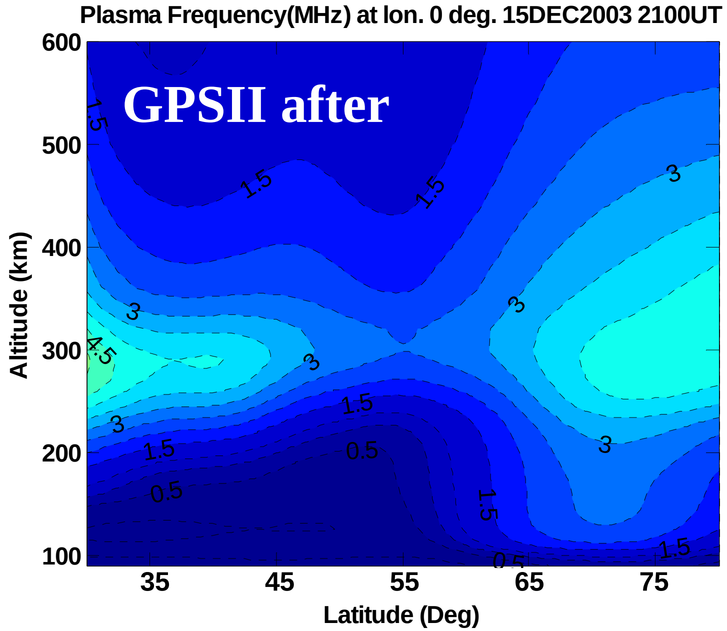
The pseudo-covariance matrix was modified to communicate to the GPSII code that it should try adjusting the height of the F-layer

Before and After









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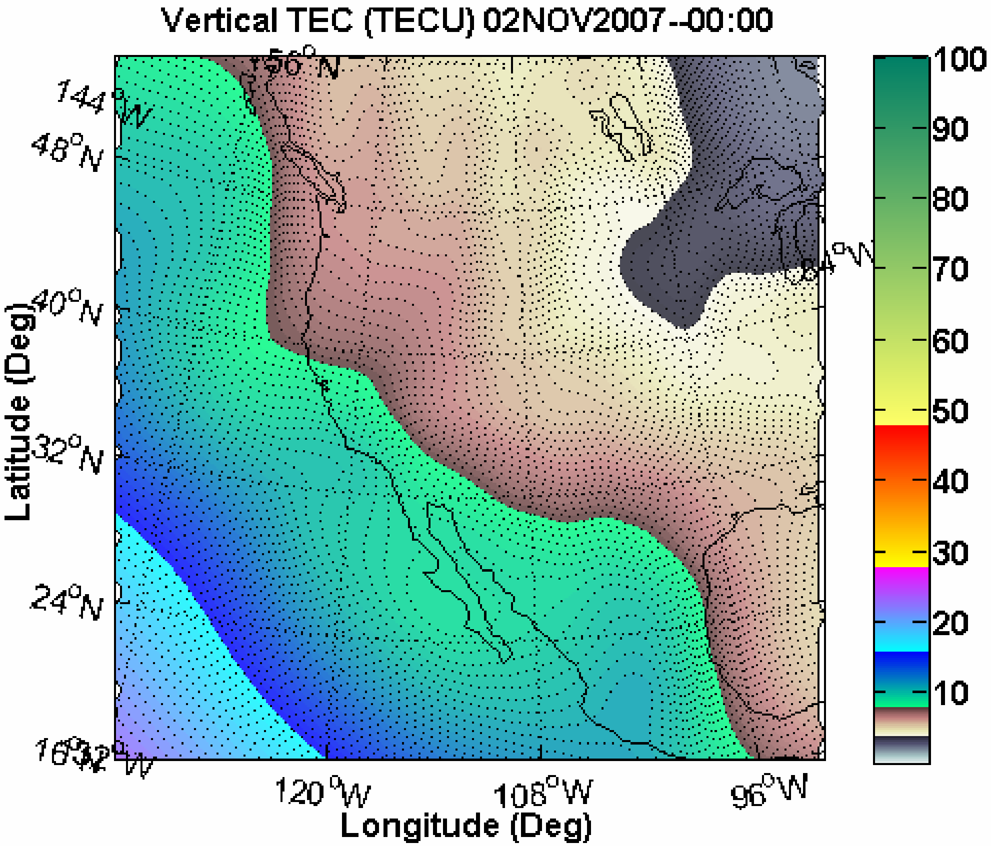
GPSII performance tests with diverse data

GPSII solution for the vertical TEC



FmF2

VTEC

FmIRI

TECIRI

Data Type	Data Sources
Abs. TEC, Rel. TEC	38 GPS ground receivers
Abs. TEC, Rel. TEC	4 COSMIC + CHAMP GPS receivers
Plasma Density	CHAMP Plasma Probe

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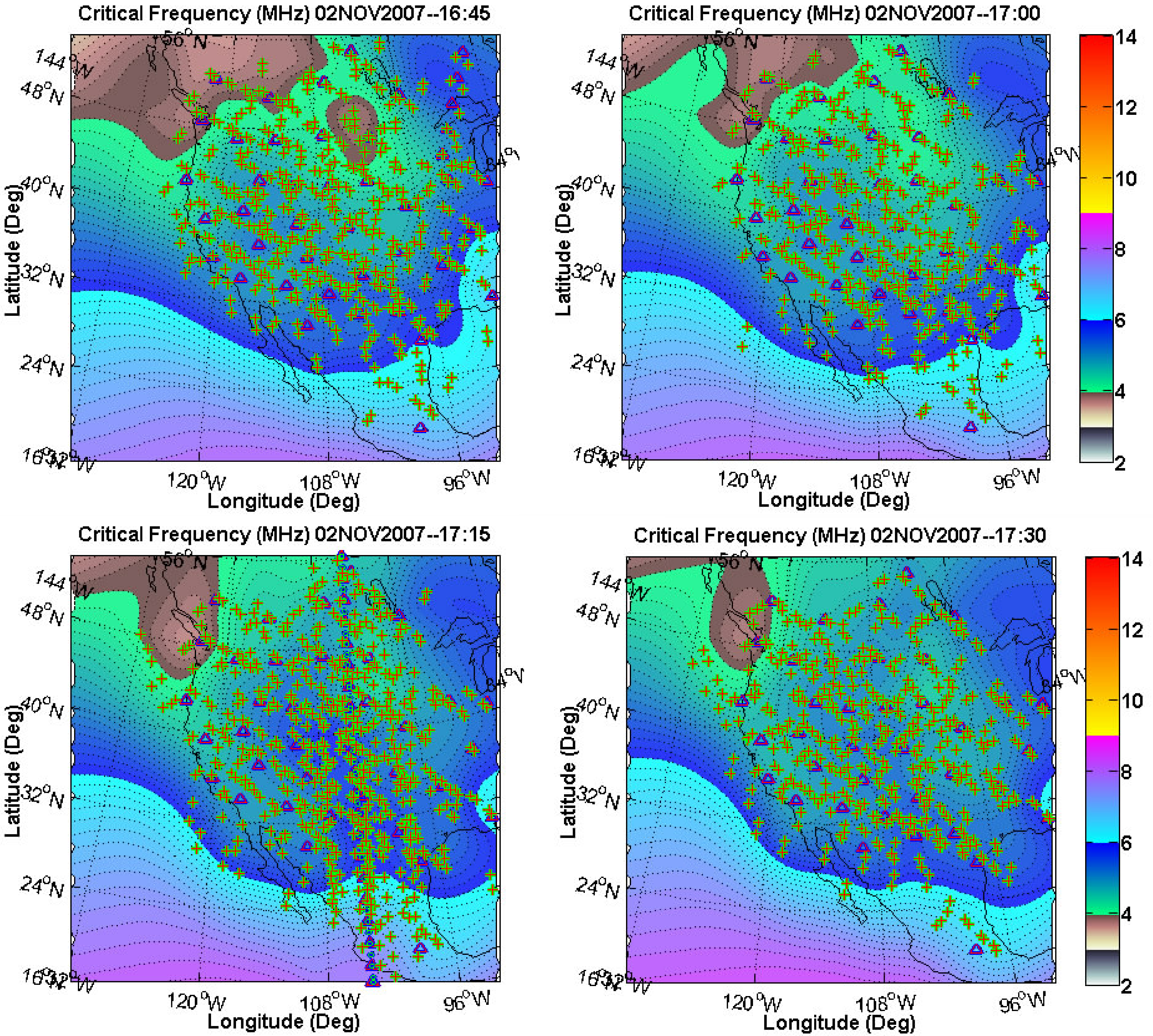
Passage of CHAMP Satellite, FmF2



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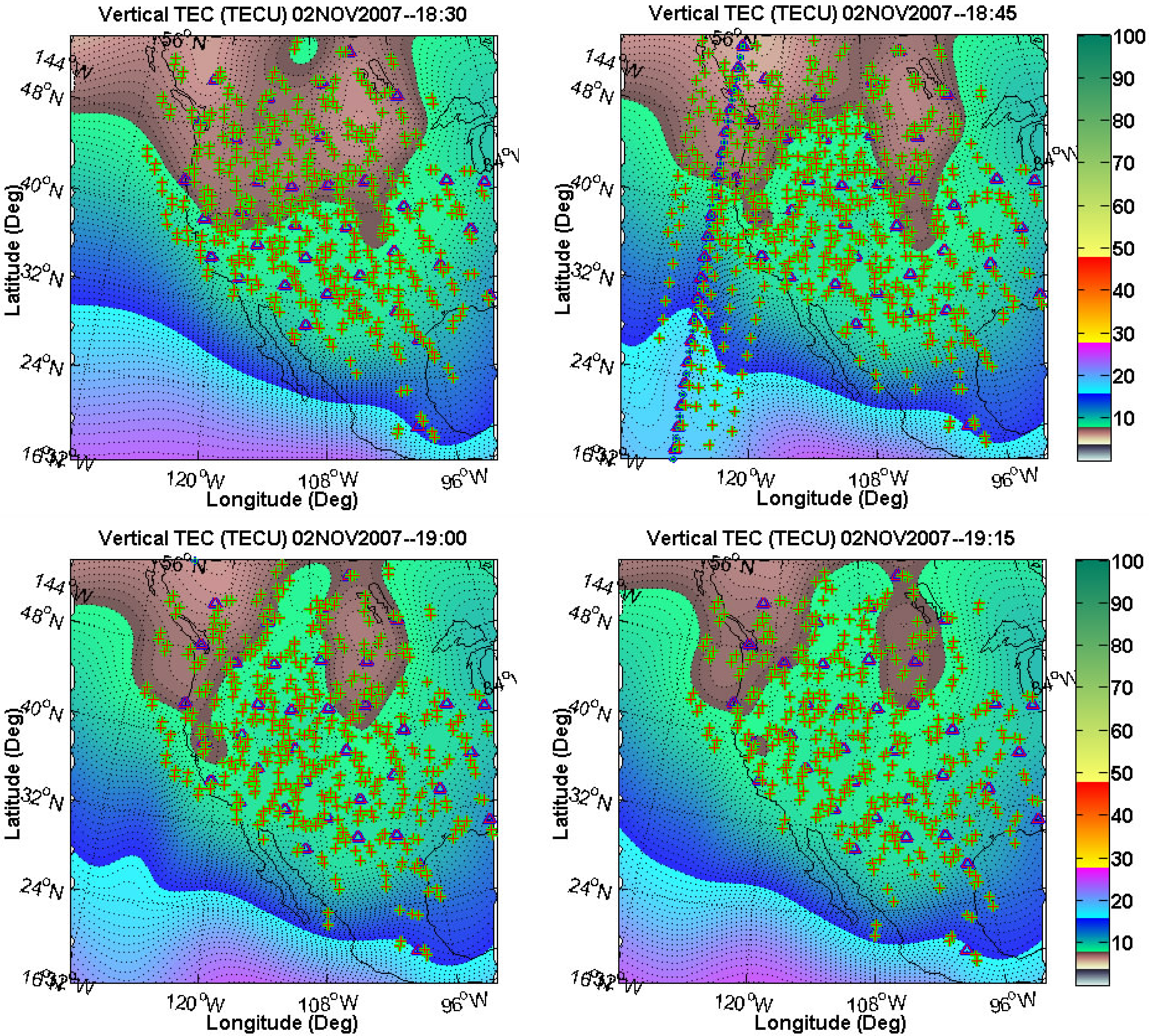
Passage of CHAMP Satellite, TEC



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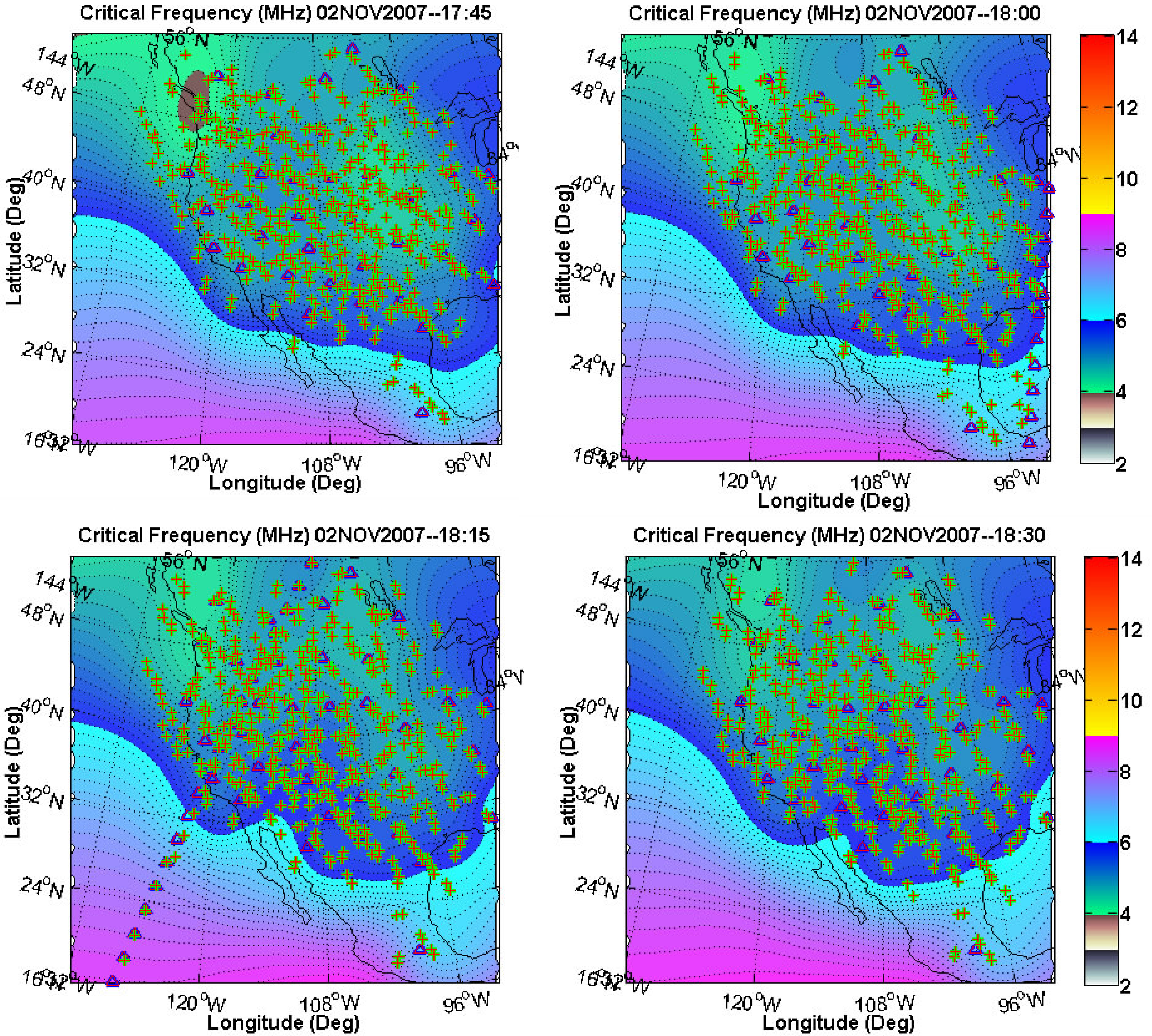
Passage of COSMIC Satellites, FmF2



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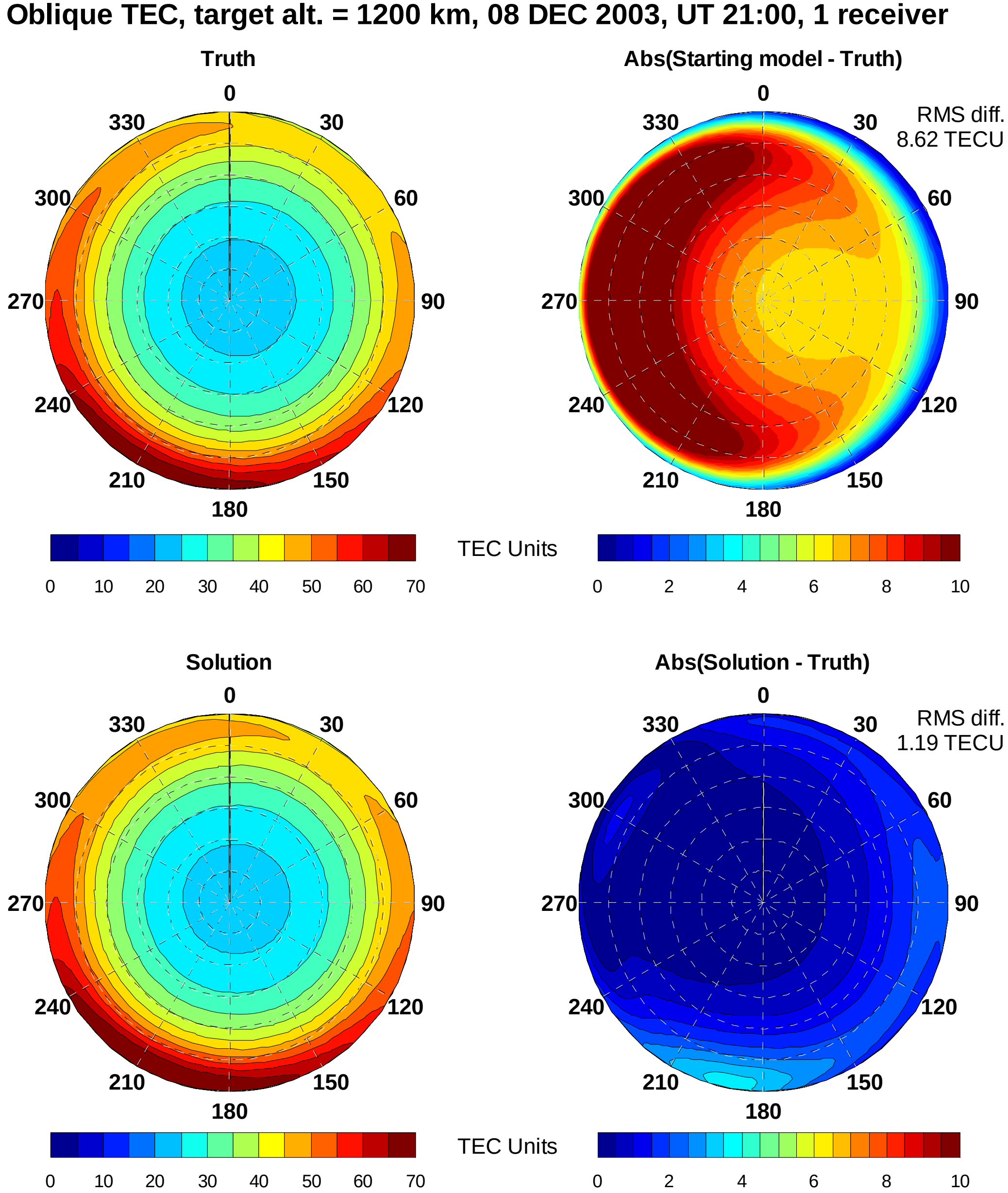
Summary

- Updated GPSII to handle consistently new data types
  - in-situ plasma data
  - Vertical TEC
  - Occultation-type oblique TEC (absolute and relative) from space-based GPS receivers
  - LEO TEC data
  - Simultaneously with ground-based GPS receivers and vertical sounders
- Validation with realistic simulated data
- Performing testing of the algorithm with diverse real data

Oblique TEC to 1200km Altitude



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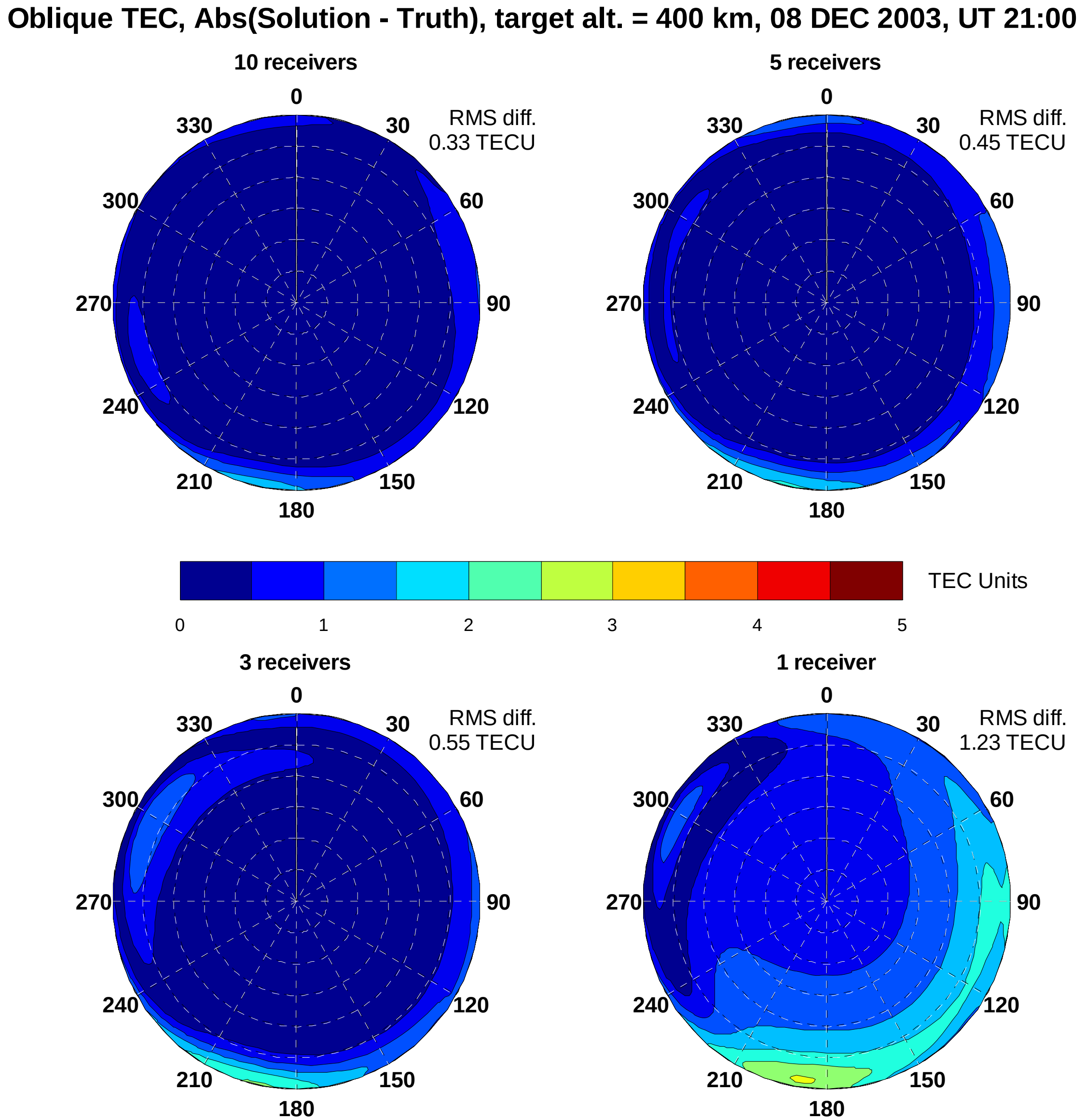
Accuracy of Oblique TEC to 400 km Altitude



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The Pseudo-Covariance Matrix

The Smoothing Functional:

$$\boxed{\alpha U' P^{-1} U + (Y - MU)' S^{-1} (Y - MU) \to \min}$$

We found that the following factorized representation of P guarantees smoothness of the solution and at the same time allows for very efficient multidimensional matrix computations:

$$P(x_1, x_1', x_2, x_2', x_3, x_3') = \Phi_1\left(\frac{x_1 - x_1'}{\lambda_1}\right)\Phi_2\left(\frac{x_2 - x_2'}{\lambda_2}\right)\Phi_3\left(\frac{x_3 - x_3'}{\lambda_3}\right)$$

$$\Phi_{1,2,3}(x) = \exp\left(-|x|\right)\cos\left(|x| - \frac{\pi}{4}\right)$$

x_1 and x_2 are geographical coordinates

x_3 is the scaled altitude: $x_3 = \int_0^h \frac{dh'}{H(h')}$ where $H(h)$ is a user-defined function

Covariance Matrix Associated with Layer Movement

Consider an ionospheric layer, with density distribution $N_0(h) = f(h)$

Then, the same layer shifted up by p is described by $N_p(h) = f(h-p)$

$$\Delta N(h) = f(h-p) - f(h) \approx -p\frac{\partial}{\partial h}f(h) = -pf'(h)$$

The covariance matrix associated with height variations:

$$C_{LH}(h_1,h_2) = \left\langle \Delta N(h_1)\Delta N(h_2)\right\rangle = \left\langle p^2\right\rangle f'(h_1)f'(h_2)$$

In order to enhance layer-height-type variations in GPSII solution we modify the altitudinal part of the pseudo-covariance matrix as follows:

$$\Phi_3(h,h') = \beta C_{LH}(h,h') + \Phi_0(x_3(h),x_3(h'))$$

Here β is a user-defined non-negative parameter, and C_{LH} is calculated using a representative functional form for F-layer. We obtained satisfactorily results using Gaussian shape for the representative profile and assuming layer height of 350km, and layer width of 100km.

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