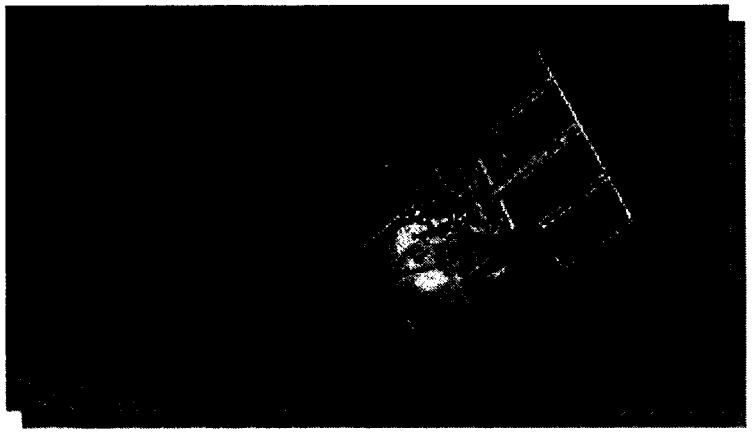
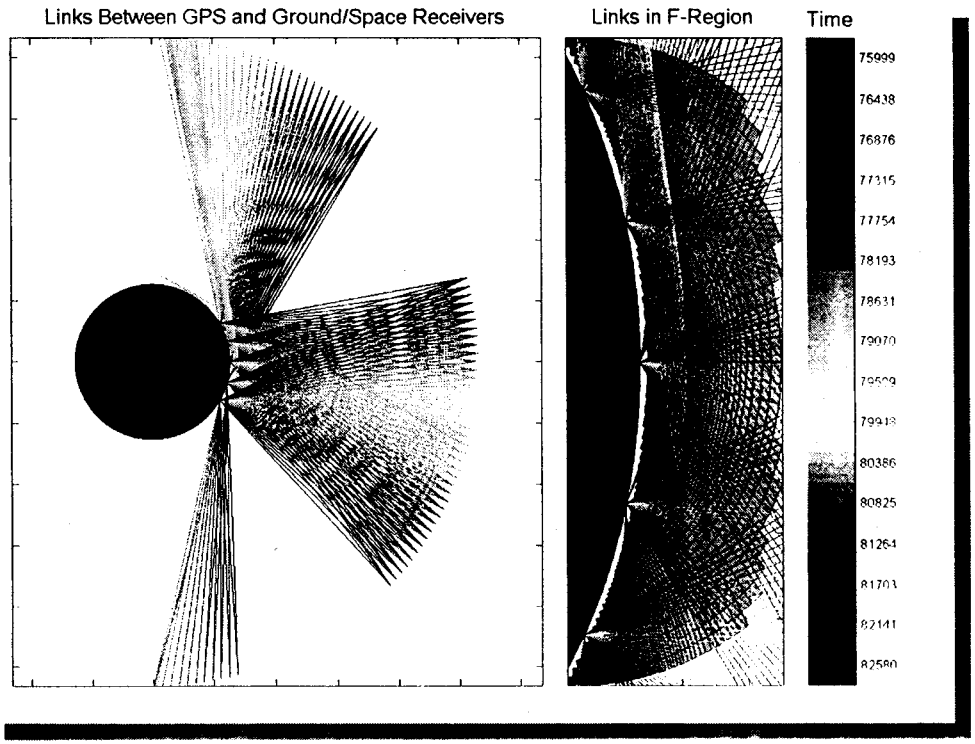
Global Mapping of the Ionosphere Using GPS

Xiaoqing Pi
Jet Propulsion Laboratory, California Institute of Technology

- **GPS Measurements and Global GPS Network**
- **Global Mapping of TEC**
- **Global Mapping of Irregularities**
- **Large-Scale Disturbances & Smaller-Scale Irregularities**
- **Ionospheric Scintillation Monitoring System**
- **Global Assimilative Ionospheric Model (GAIM)**
- **Applications**

Global Positioning System





GPS Observables and Ionospheric Measurements

$$P_i^{tr} = \rho^{tr} + \delta^{tr} + k\frac{TEC^{tr}}{f_i^2} + c^t + c^r + E_i^{tr} + \alpha_i$$

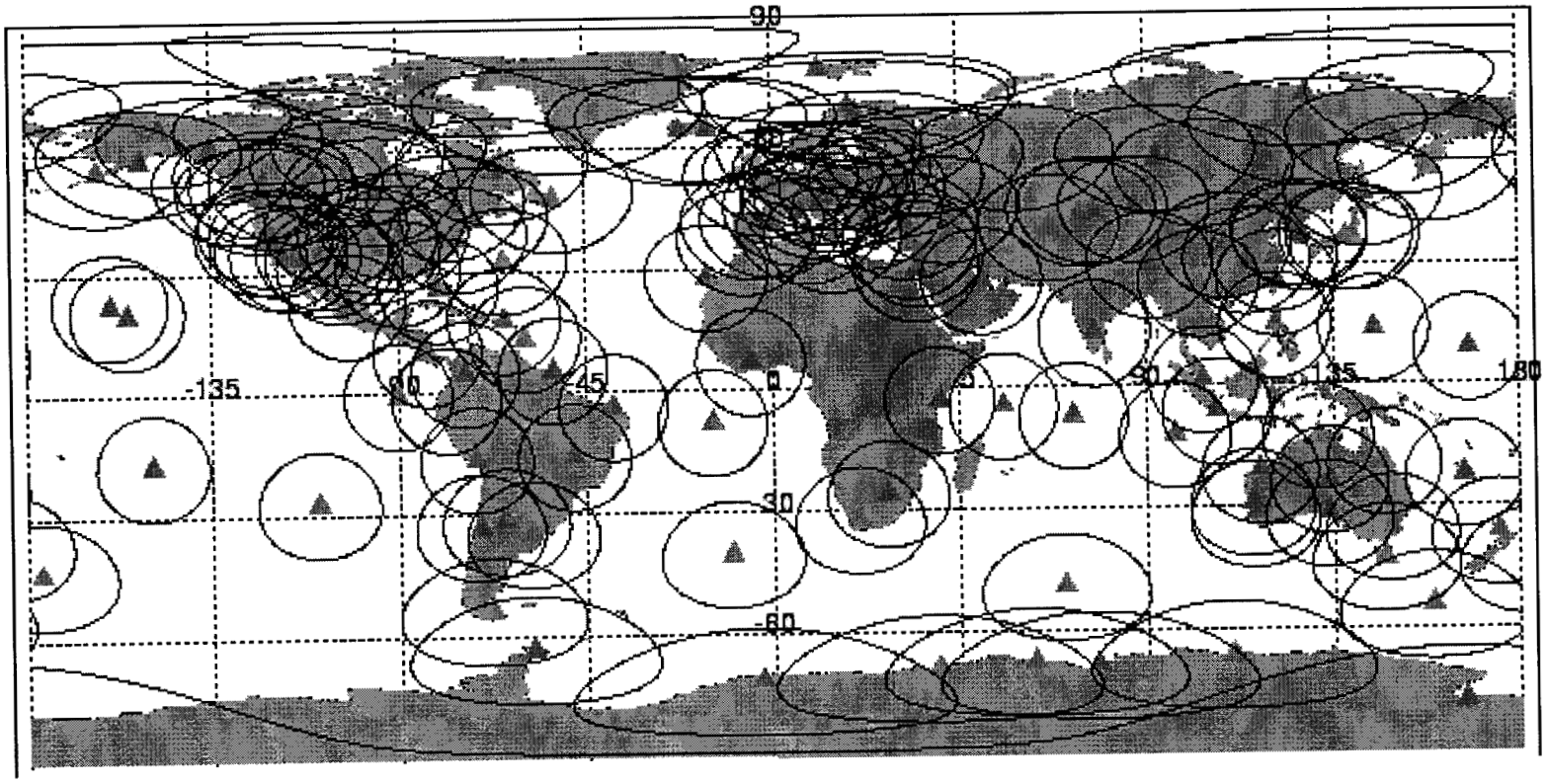
$$L_i^{tr} = -\frac{c}{f_i}\phi_i^{tr} = \rho^{tr} + \delta^{tr} - k\frac{TEC^{tr}}{f_i^2} + n_i^{tr}\lambda + c^t + c^r + F_i^{tr} + \beta_i$$

$$TEC_{a,n} = \frac{1}{k}\frac{f_1^2 f_2^2}{(f_1^2 - f_2^1)}\left(P_2 - P_1\right) + \Gamma + \varepsilon_P$$

$$TEC_{r,p} = \frac{1}{k}\frac{f_1^2 f_2^2}{(f_1^2 - f_2^2)}\left(L_1 - L_2\right) + \Omega + \varepsilon_L$$

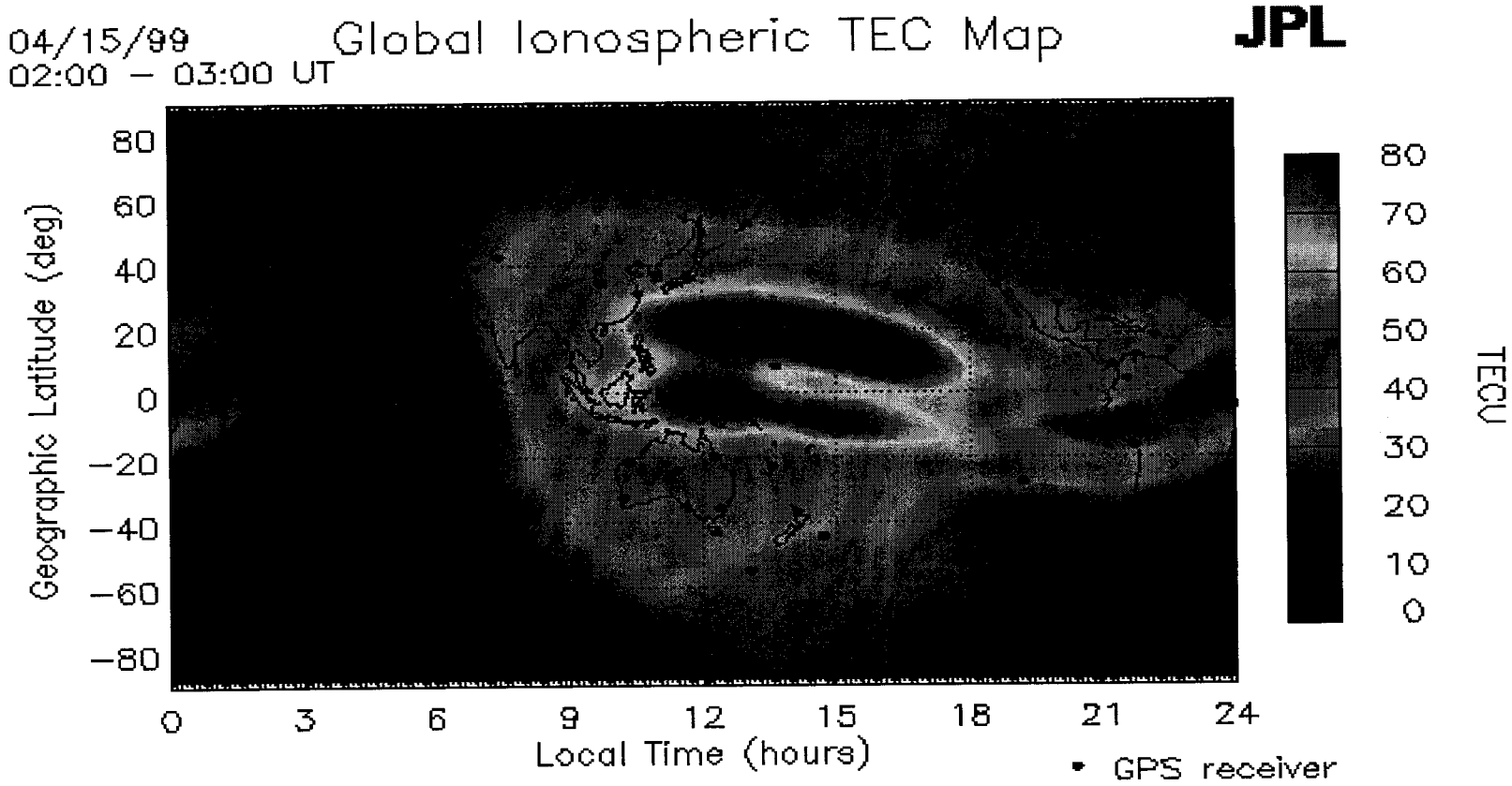
IGS Global GPS Network

Global GPS Network (present): Coverage at Ionospheric Altitudes

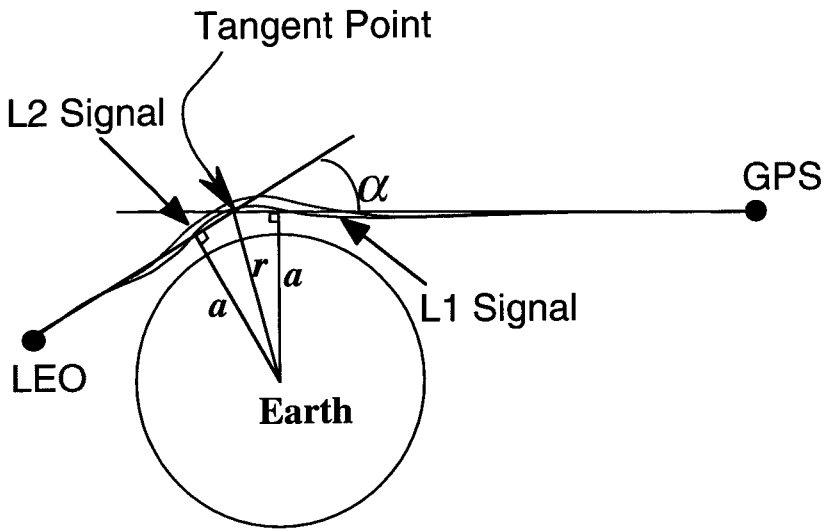


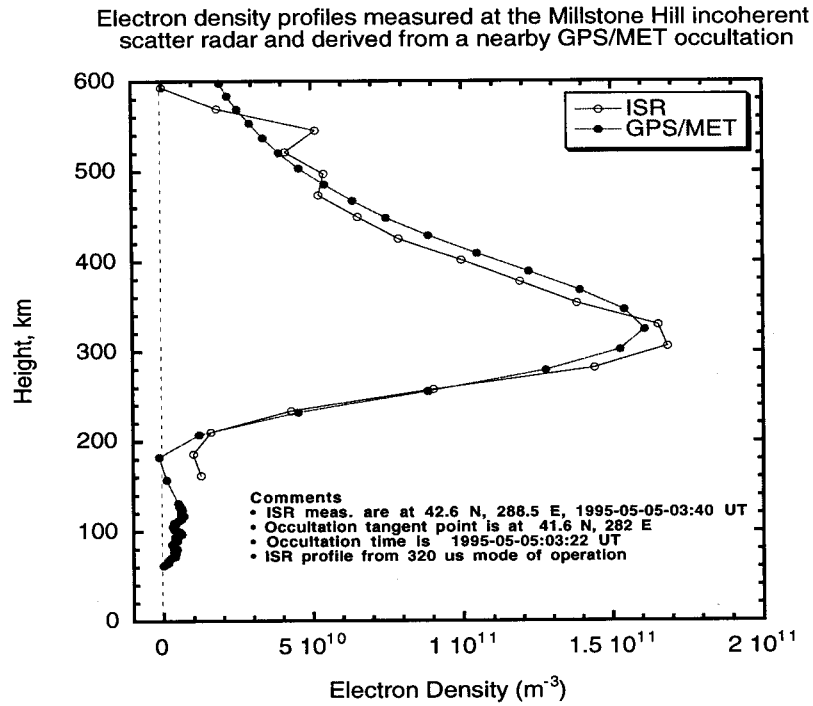
10 degree elevation mask. Effective shell height of 450 km.

Global Ionospheric Map



N_e Profiling Using GPS Occultations





- Assuming spherical symmetry:

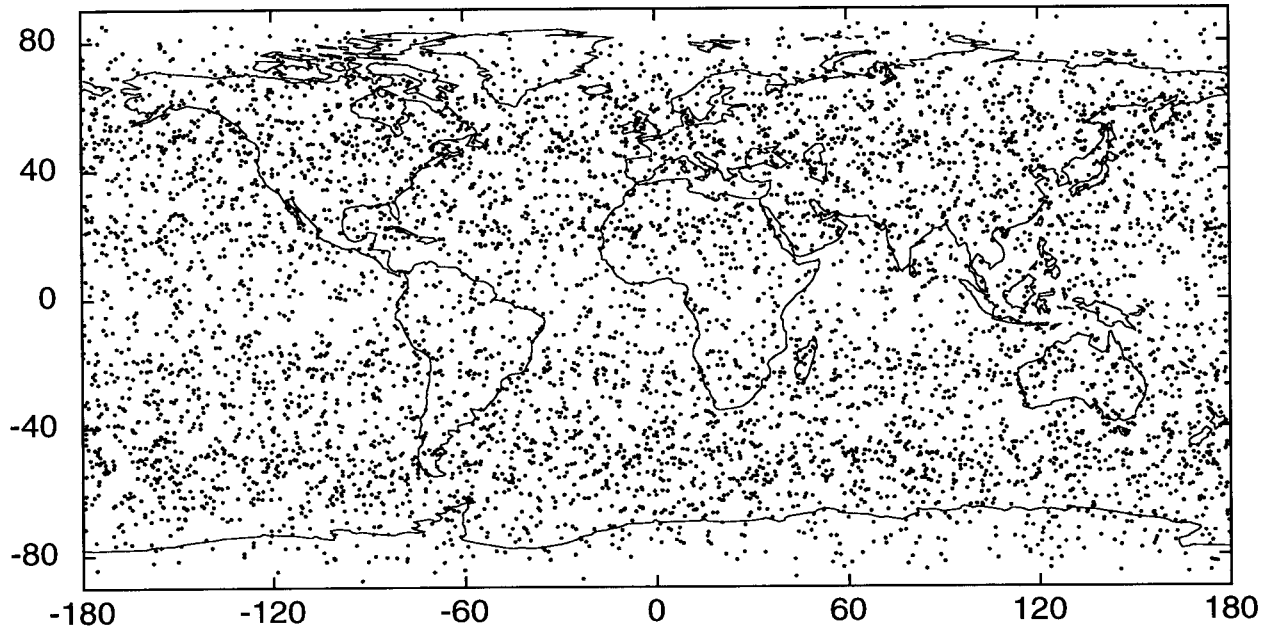
Forward propagation

Abel inversion

$$\alpha = -2a\int_{r_0}^{\infty} \frac{d\ln(n)/dr}{\sqrt{r^2n^2 - a^2}}dr \Rightarrow$$

$$\ln(n(r)) = \frac{1}{\pi}\int_{nr}^{\infty} \frac{\alpha}{\sqrt{a^2 - r^2n^2}}da$$

Expected Missions and Daily Coverage



Mission	Occultation Antennas	Altitude (km)	Inclination	Daily Profiles	Launch	Lifetime
Oersted	aft only	400x800	98°	250	Jan 99	3 yrs
Sunsat	aft only	400x800	98°	250	Jan 99	3 yrs
CHAMP	aft only	470	83°	350	June 99	5 yrs
SAC-C	fore/aft	702	97°	700	Sept 99	3 yrs
Jason-1	plasma-sphere	1300	63°	500	Dec 99	5 yrs
GRACE	fore/aft	450	90°	700	Mar 01	5 yrs
COSMIC	fore/aft	700	70°	4000	Jan 02	4 yrs

Measurements of Ionospheric Irregularities

GPS Data (dual frequency carrier phase, pseudorange, and SNR)

- 30-second sampling rate

Rate of TEC (ROT)

- **Differential phase** (*L1-L2*)

$$L_1 - L_2 \longrightarrow L_i \quad (\textit{in TEC units},\ 10^{16}\ \textit{electrons}/m^2)$$

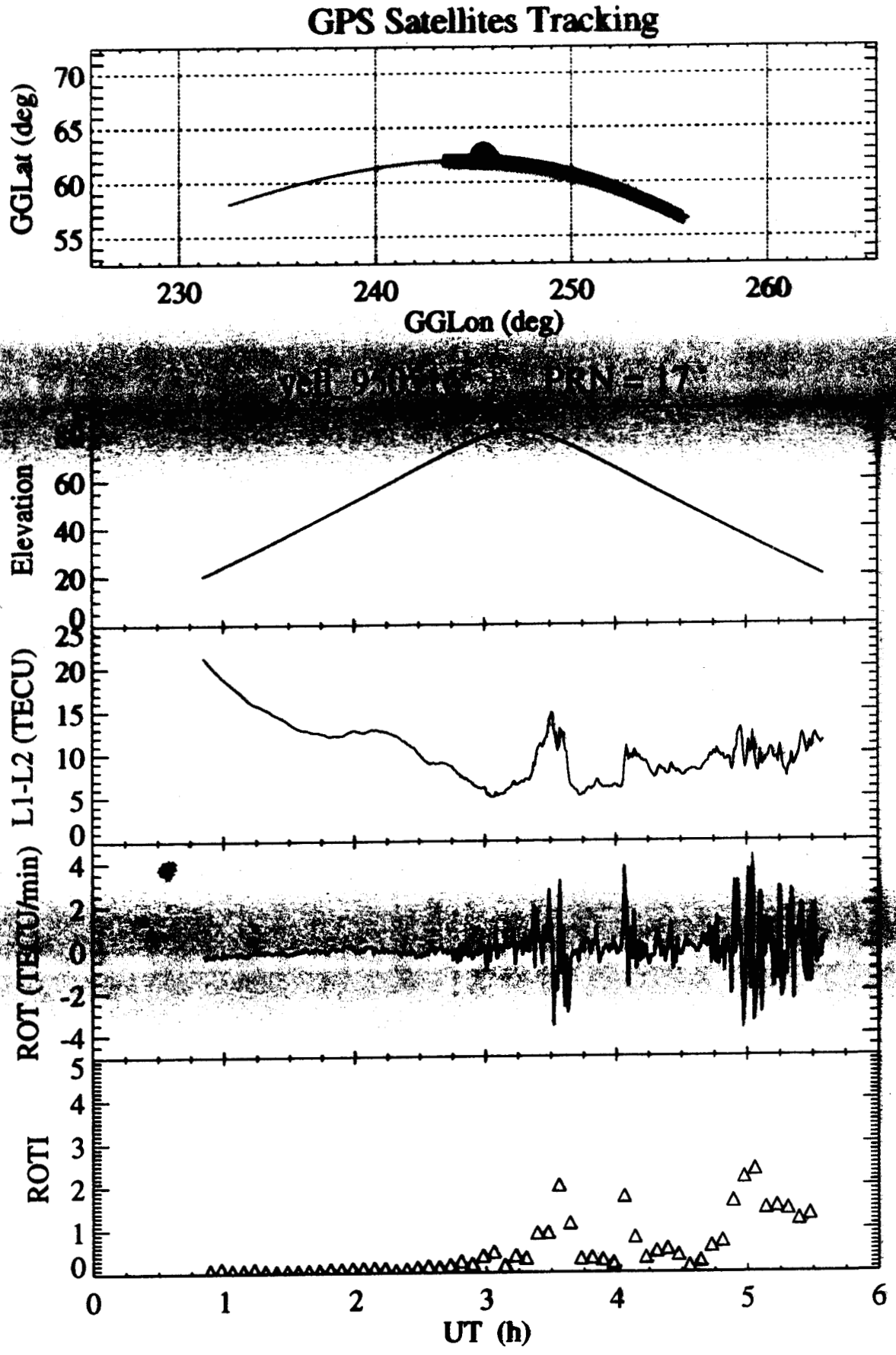
$$\longrightarrow ROT_j = \frac{L_i(j+1) - L_i(j)}{t(j+1) - t(j)} \qquad (\textit{TEC}/\textit{min})$$

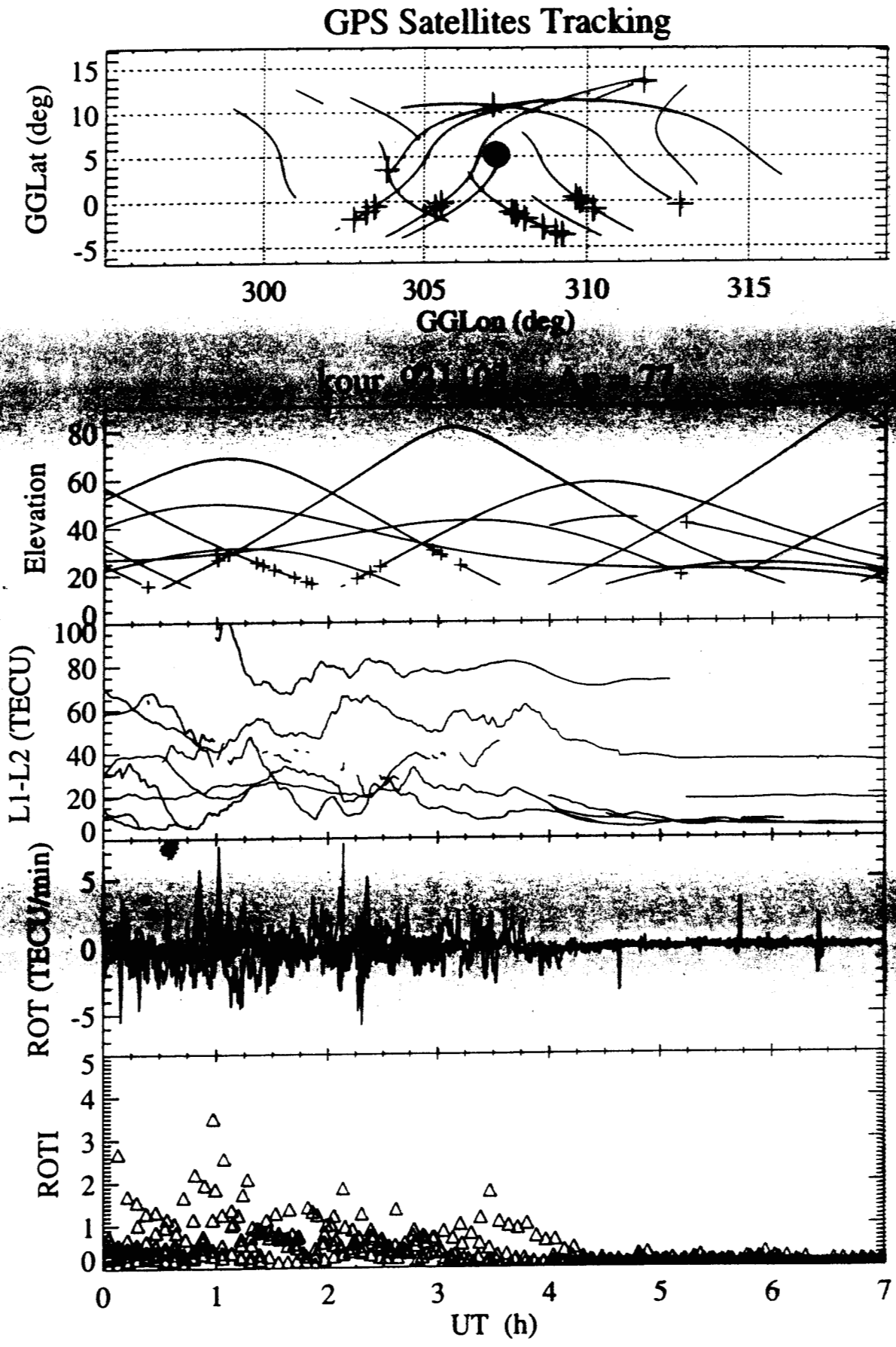
Rate of TEC Index (ROTI)

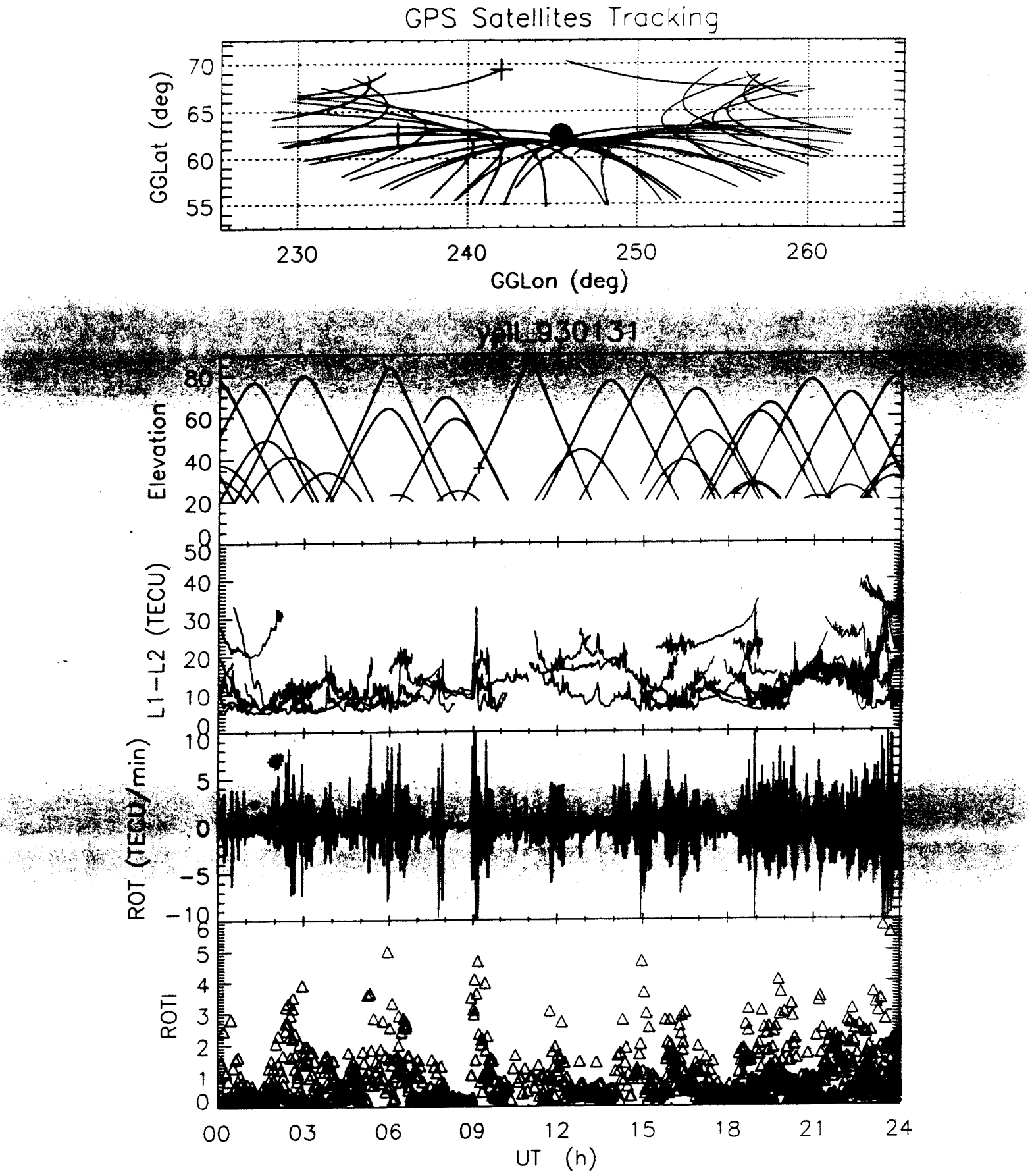
- **Standard deviation of ROT**

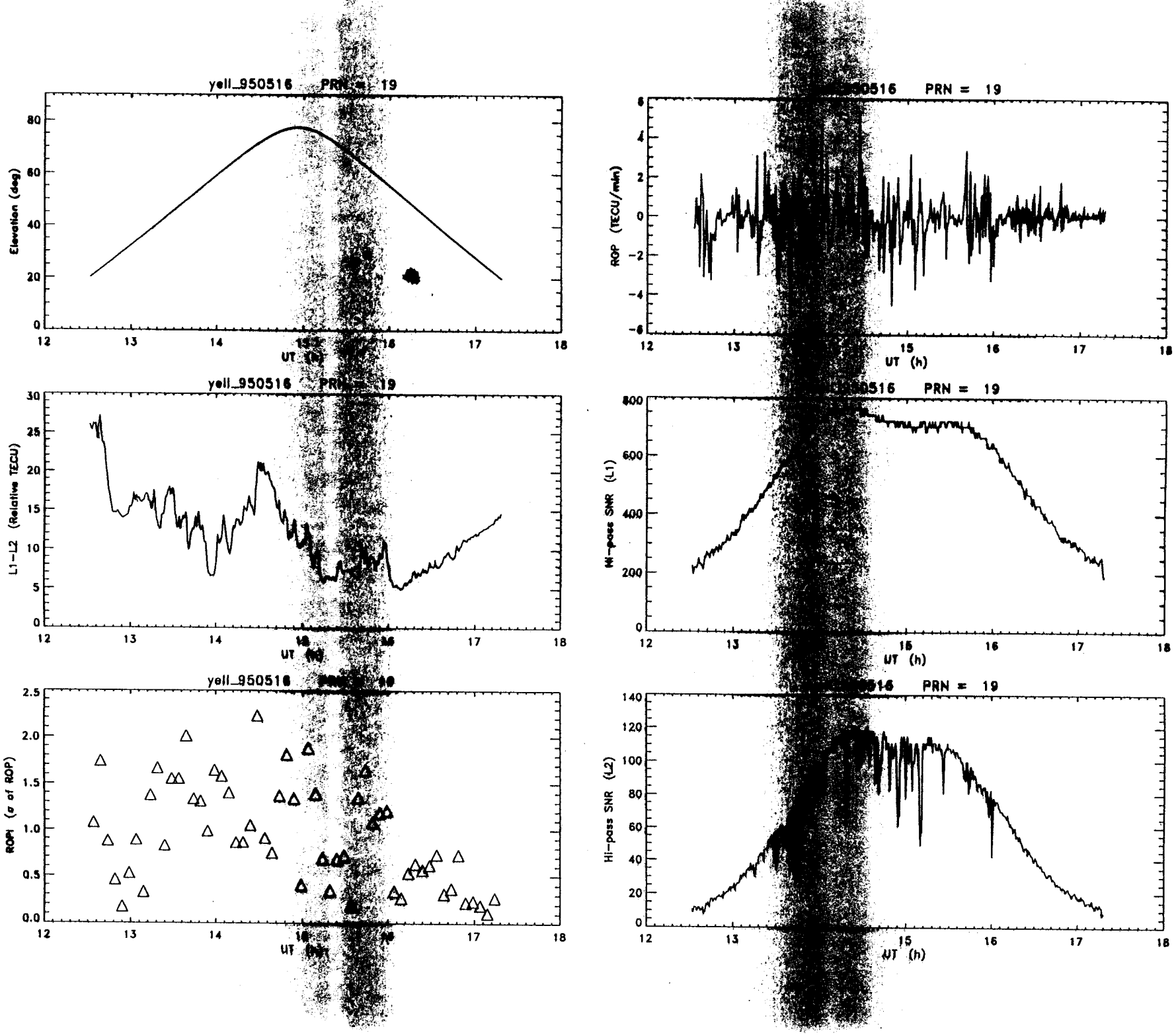
$$\longrightarrow \sigma_{ROT} = \sqrt{\frac{1}{N-1}\sum_{j=1}^{N}\left[ROT_j - \frac{1}{N}\sum_{j=1}^{N}(ROT_j)\right]^2}$$

(each 5-minute interval)

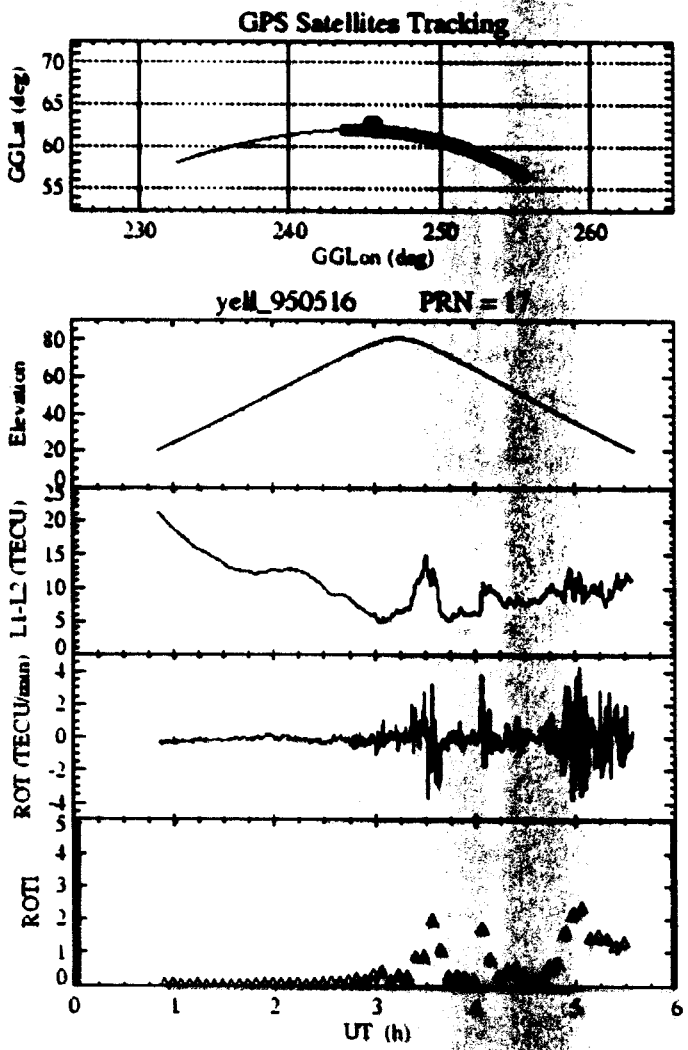

GPS Satellites Tracking
GGLat (deg)
70
65
60
55
230
240
250
260
GGLon (deg)
PRN = 17
Elevation
60
40
20
0
L1-L2 (TECU)
25
20
15
10
5
0
ROT (TECU/min)
4
2
0
-2
-4
ROTI
5
4
3
2
1
0
0
1
2
3
4
5
6
UT (h)

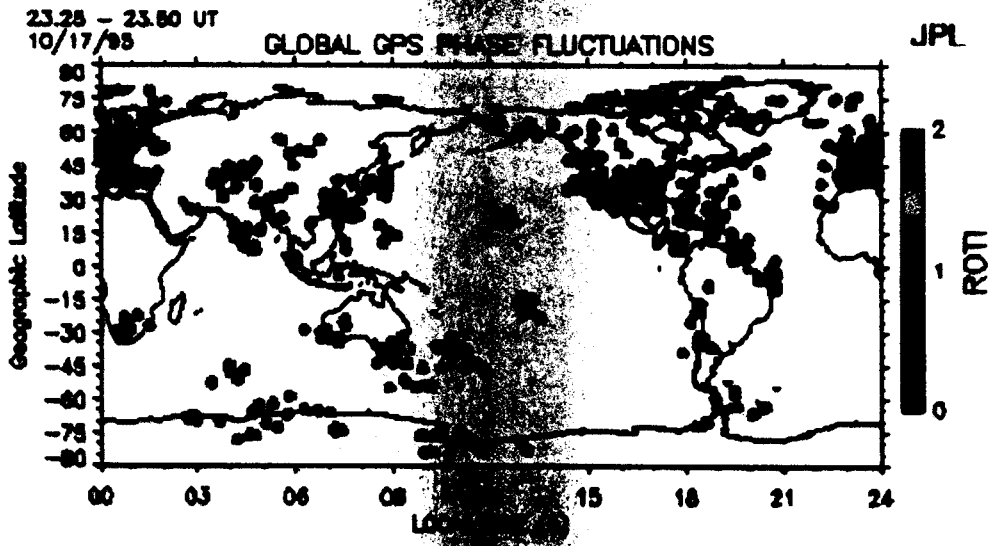

GPS Satellites Tracking
GGLat (deg)
GGLon (deg)
Elevation
L1-L2 (TECU)
ROT (TECU/min)
ROTI
UT (h)

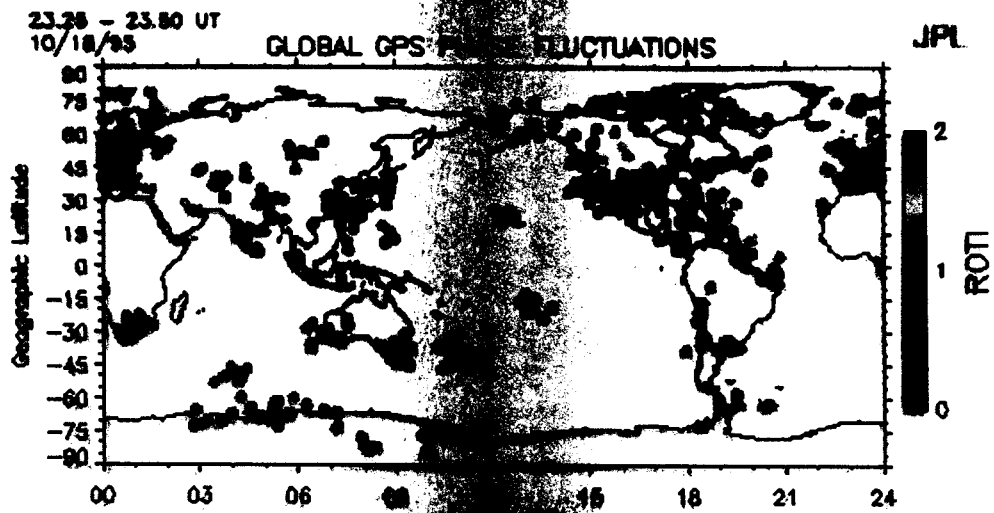

GPS Satellites Tracking
GGLat (deg)
70
65
60
55
230
240
250
260
GGLon (deg)
yel_930131
Elevation
80
60
40
20
0
L1-L2 (TECU)
50
40
30
20
10
0
ROT (TECU/min)
10
5
0
-5
-10
ROTI
6
5
4
3
2
1
0
00
03
06
09
12
15
18
21
24
UT (h)


yell_950516 PRN = 19
Elevation (deg)
UT (h)
ROP (TECU/min)
L1-L2 (Relative TECU)
Hi-pass SNR (L1)
ROPI (σ of ROP)
Hi-pass SNR (L2)

Global Ionospheric Map - ROTI







Mid-Latitude Irregularities during Storms

Magnetic Storm Main Phase
Dusk & Midnight Sectors
(Particularly the US longitudes, where mlat =~ glat + 11 deg.)

- Convection E-field penetration
- Auroral oval expansion
- Disturbance dynamo

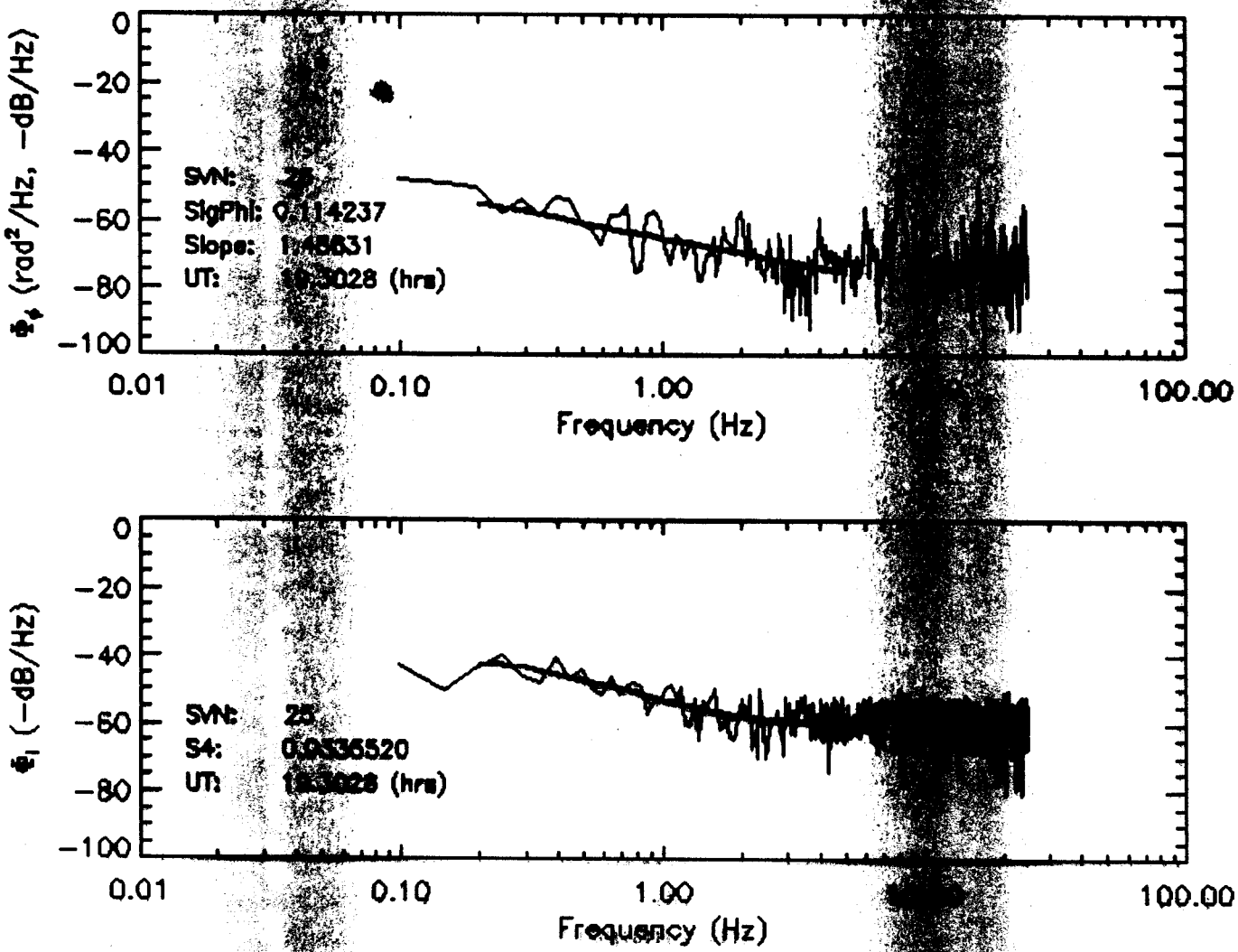
- Plasma convection reversal down to middle latitudes
- Plasma sheared flow

Enhanced charge exchange
$(O^+ + N_2 \longrightarrow NO^+ + N)$
$(O^+ + O_2 \longrightarrow O_2^+ + O)$
$(T_{eff} = T_n + 0.33E^2$, increase)
& dissociative recombination

Deepening of ionospheric trough and TEC spatial gradient

Kelvin-Helmholtz instability
Plasma undulations
Ionospheric irregularities

Spectra of L1-C/A Signal Intensity and Phase



Scintillation Indices

$$\sigma_\phi = \sqrt{\langle \phi^2 \rangle - \langle \phi \rangle^2}$$

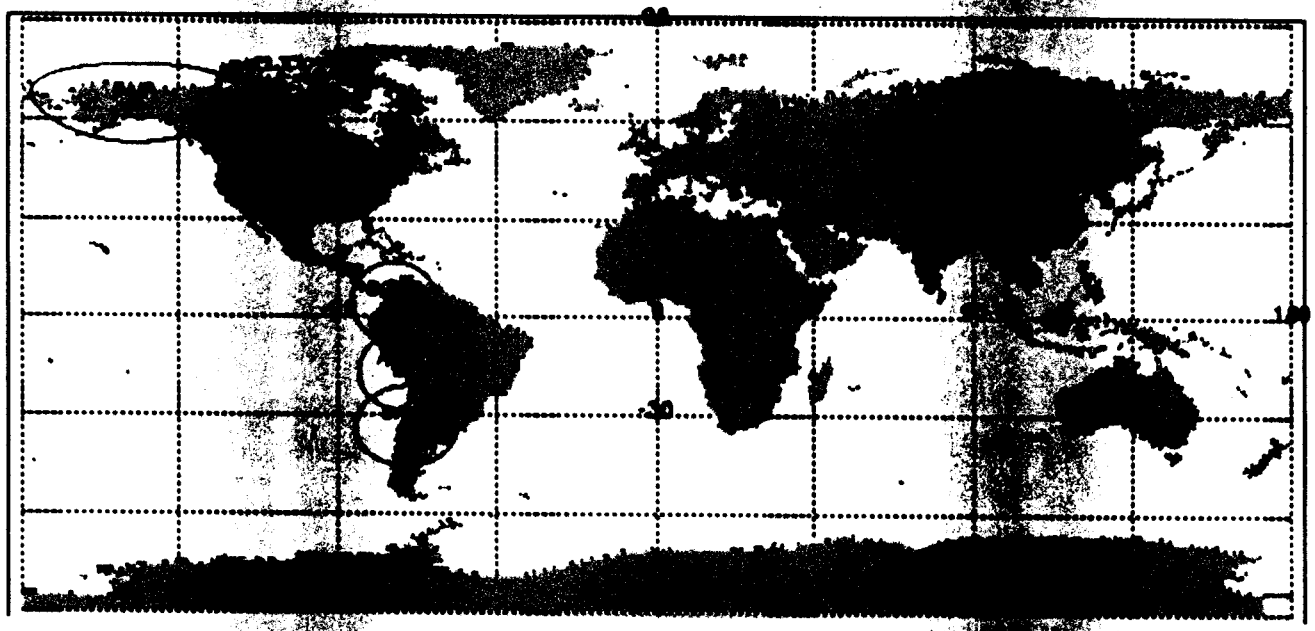
$$S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}}$$

$$S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2} - \frac{100}{\langle S/N \rangle}\left[1 + \frac{500}{19\langle S/N \rangle}\right]}$$

- L1-C/A sampled at 20-ms
- Detrended phase and intensity
- Signal-to-noise ratio
- 30-sec intervals

Ionospheric Scintillation Monitoring System (NASA/FAA)

Global GPS Network (ISM Sites): Coverage at Ionospheric Altitudes



10 degree elevation mask. Effective shell height of 400

Data

* GPS Observables (*8-12 chn*)
* S_4 *and* σ_ϕ (Indices, *8-12 chn*)
* Φ_A *and* Φ_ϕ (spectra)
* HR data (50 Hz)

Analysis

* Irregularities: L ~ 100 - 400 m
* Effects on nav & comm systems
* Effects on earth & space missions
* Renovation of receiver design

Ionospheric Modeling

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{v}_i) = P_i - L_i$$

$$\mathbf{u}_{i\parallel} = \mathbf{u}_{n\parallel} - D_i\left[\frac{1}{n_i}\nabla_{\parallel} n_i + \frac{(\nabla \cdot \tau_i)_{\parallel}}{n_i k T_i} - \frac{m_i \mathbf{G}_{\parallel}}{k T_i} + \frac{1}{T_i}\nabla_{\parallel}(T_e + T_i) + \frac{(T_e / T_i)}{n_i}\nabla_{\parallel} n_e\right]$$

$$\frac{3}{2} n_i k \frac{\partial T_i}{\partial t} = -\nabla \cdot \mathbf{q}_i + \sum_j \frac{n_i m_i \nu_{ij}}{m_i + m_j}\left[3k(T_j - T_i) + m_j(u_i - u_j)^2\right]$$

$$\frac{3}{2} n_e k \frac{\partial Te}{\partial t} = -n_e k T_e (\nabla \cdot \mathbf{u}_e) - \frac{3}{2} n_e k \mathbf{u}_e \cdot \nabla T_e - \nabla \cdot \mathbf{q}_e + \sum_j \frac{n_e m_e \nu_{ej}}{m_e + m_j}\left[3k(T_j - T_e) + m_j(u_e - u_j)^2\right] + Q_e - L_e$$

Weather Inputs:

- **Solar EUV radiation spectrum**
- **Thermosphere (densities and temperature)**
- **Thermospheric Wind**
- **Electric field**
- **Particle precipitation & plasma convection**
- **Nighttime ionization sources & mechanisms**

Compute and Minimize the Cost Functional

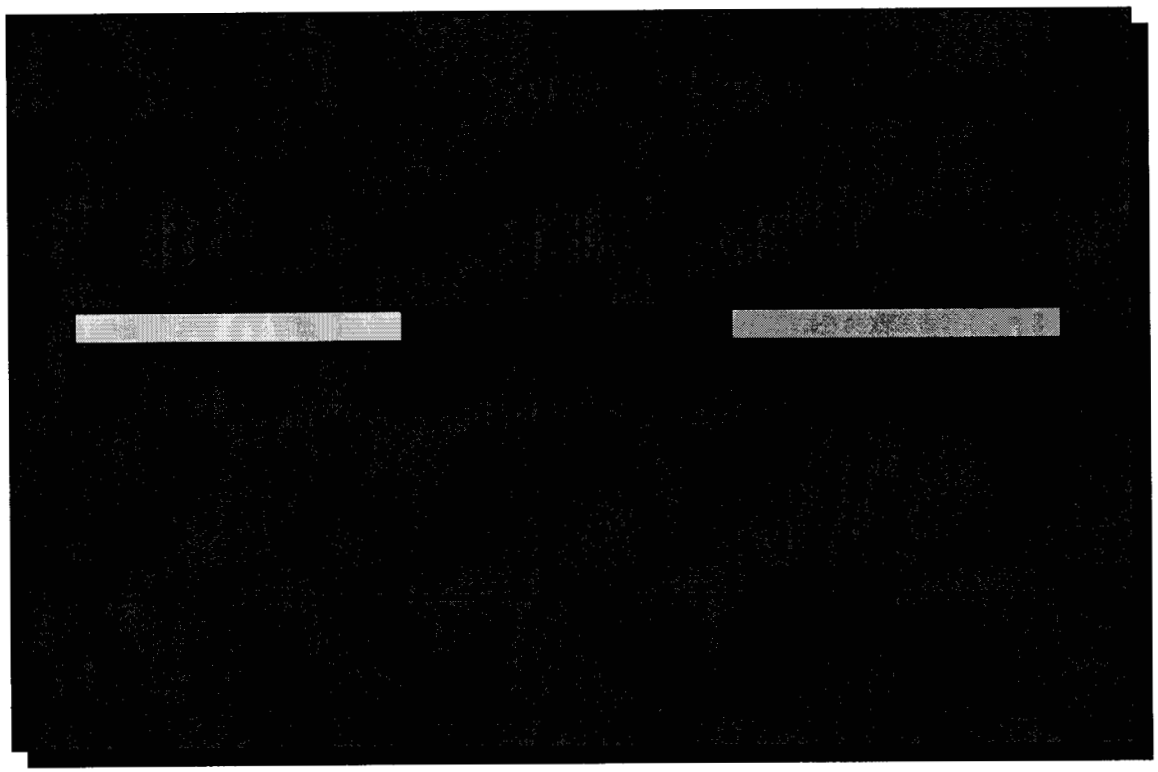
Cost Functional:

$$J_k(\alpha) = \sum_{j=1}^{K}\sum_{l=1}^{N}\left|TEC^o{}_{jl} - H_{jl}n_j(\alpha)\right|^2 + \sum_{m=1}^{W}\lambda_{mk}\left|\alpha_{mk}\right|^2$$

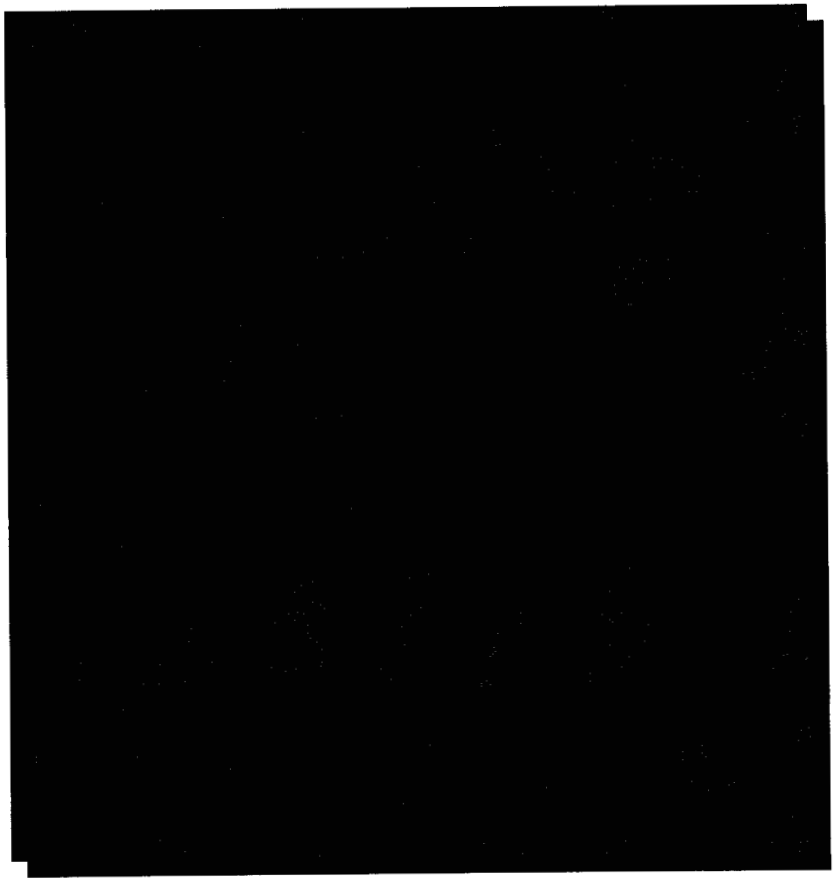
$$\frac{\partial J}{\partial \alpha} = 0$$

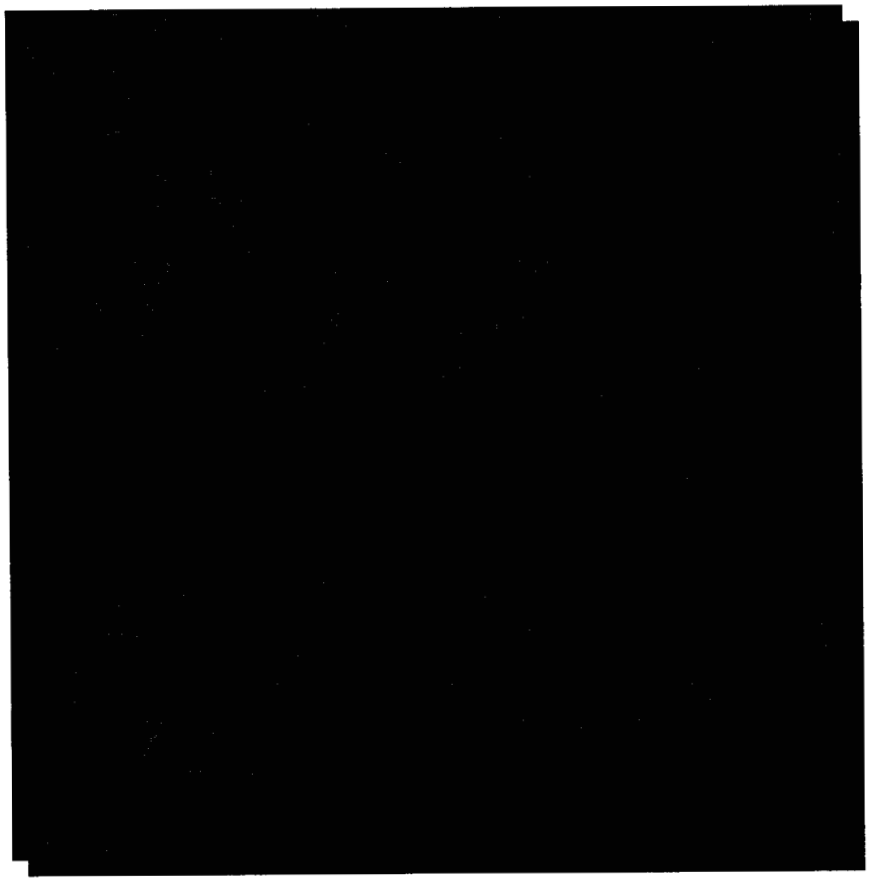
Quasi-Newton method to minimize cost functional.
α_m - parameters related to driving forces to be estimated

Continuous Assimilation of GPS/TEC



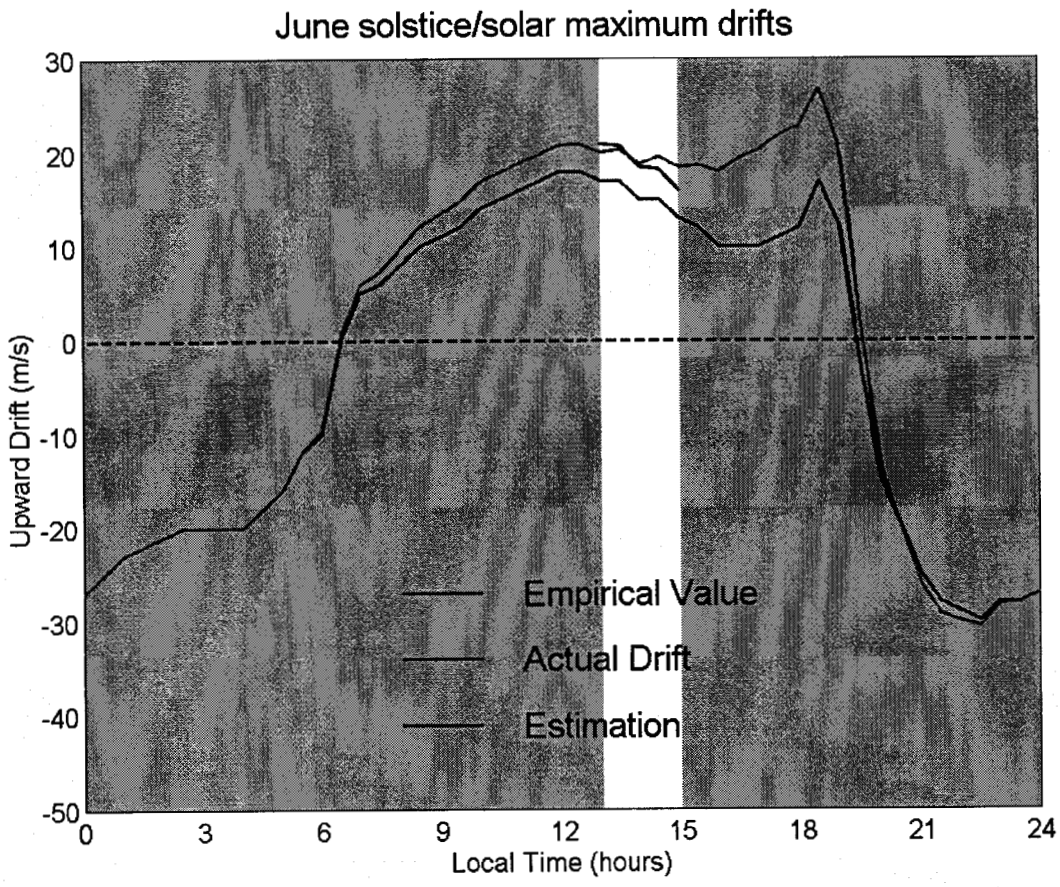
Ionospheric Model for OSSE





OSSE: Observation Simulation System Experiment

ExB Drift Perturbation for OSSE

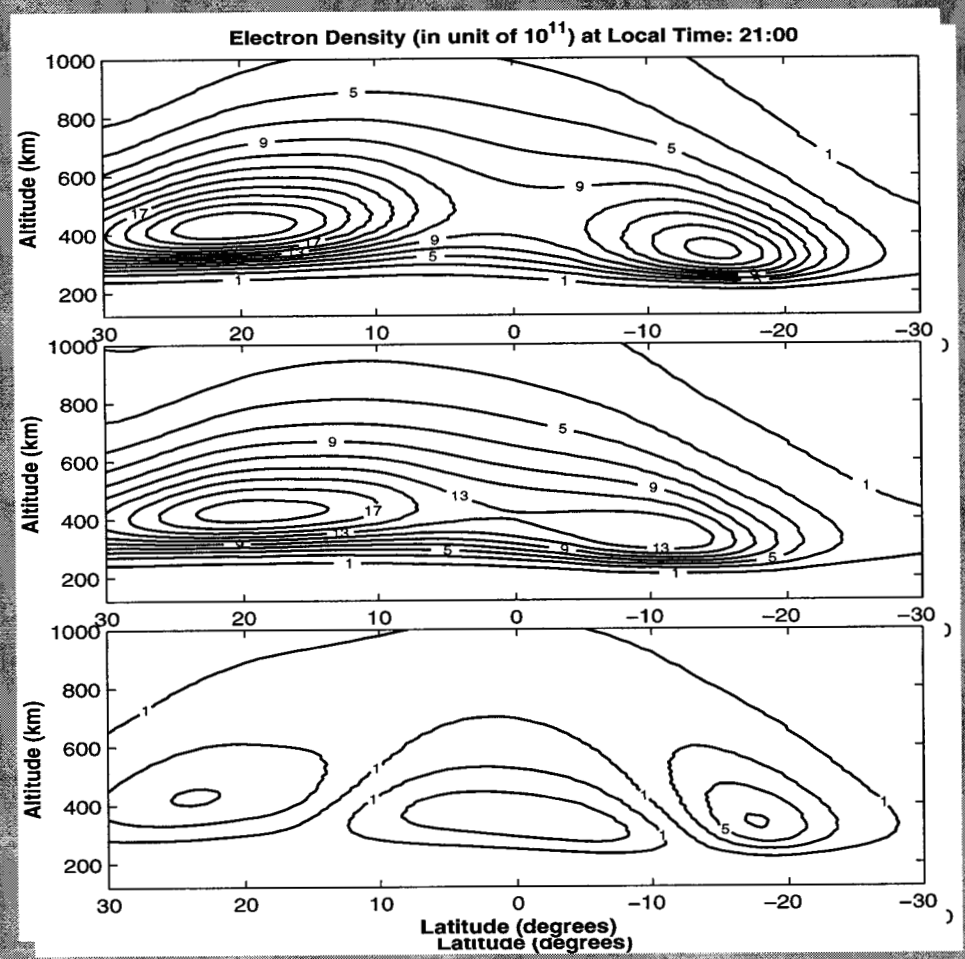


Model Runs to Produce OSSE "Data"

Top: "Truth"

Middle: Climate

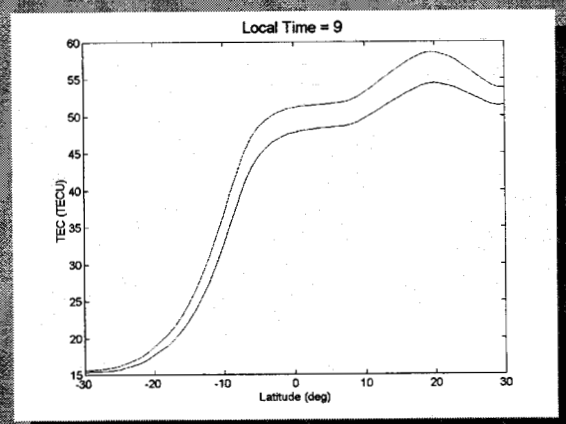
Bottom: Difference

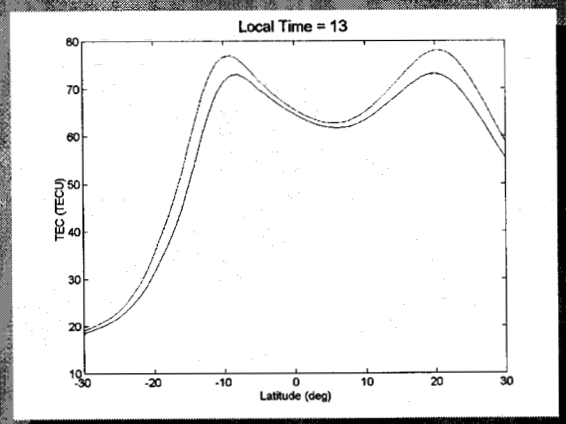


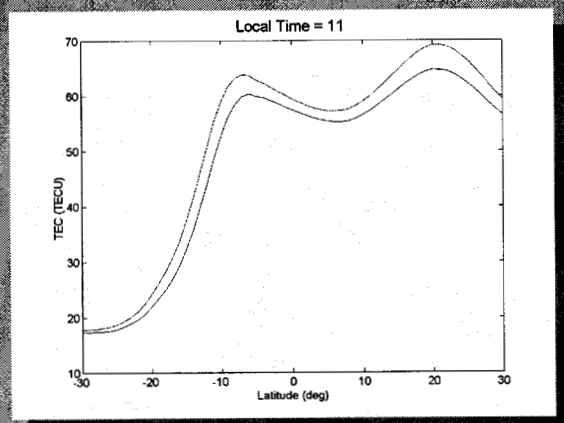
OSSE - TEC: Weather vs. Climate

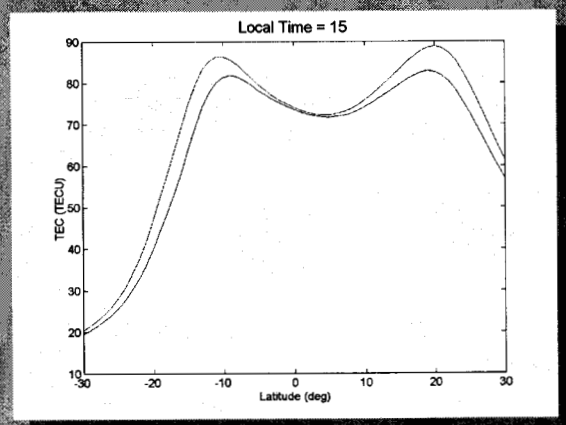
Red curve -
"True" ionosphere

Blue curve -
Climate









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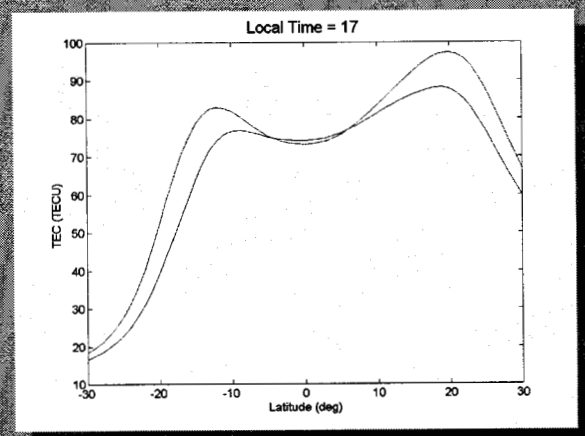
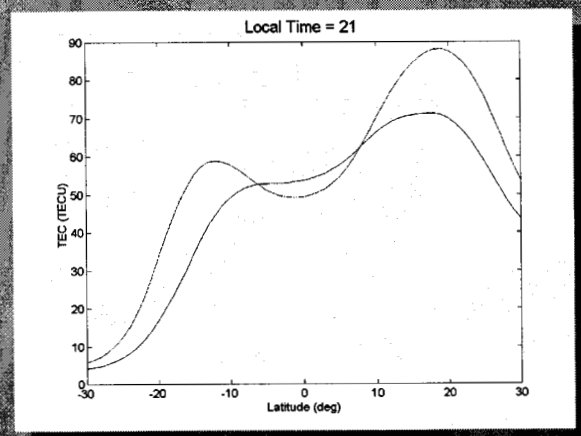
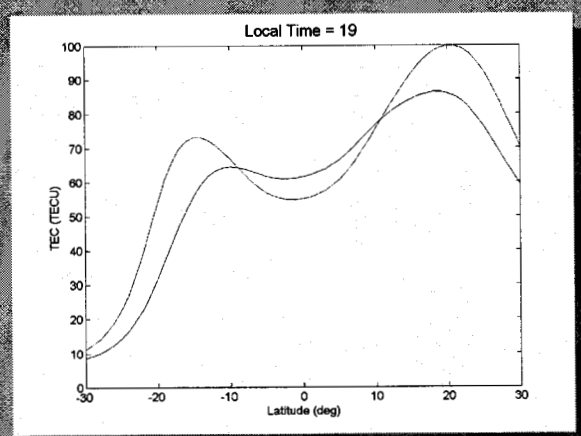
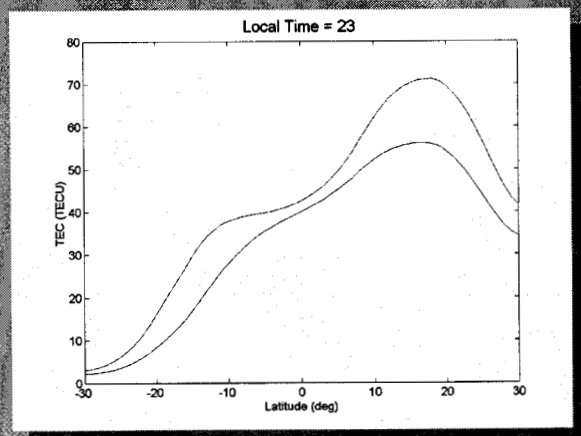


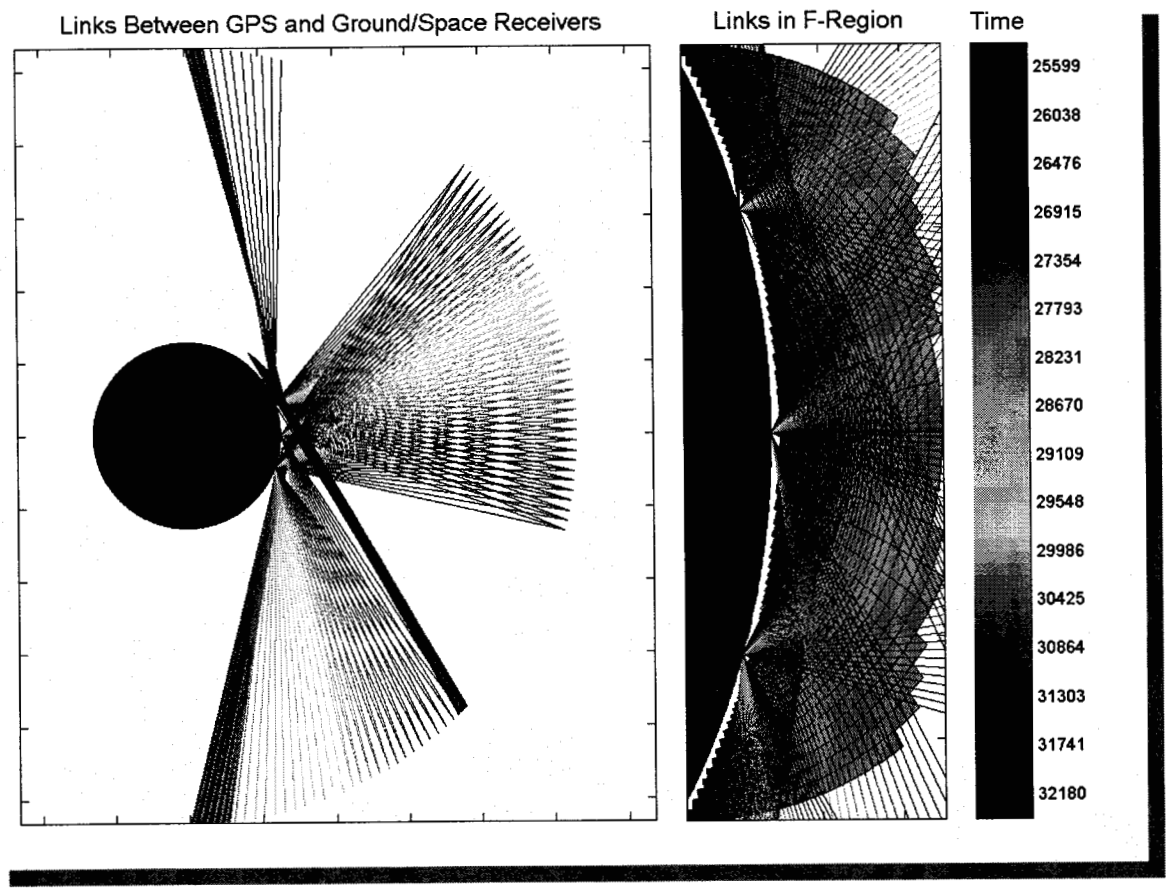






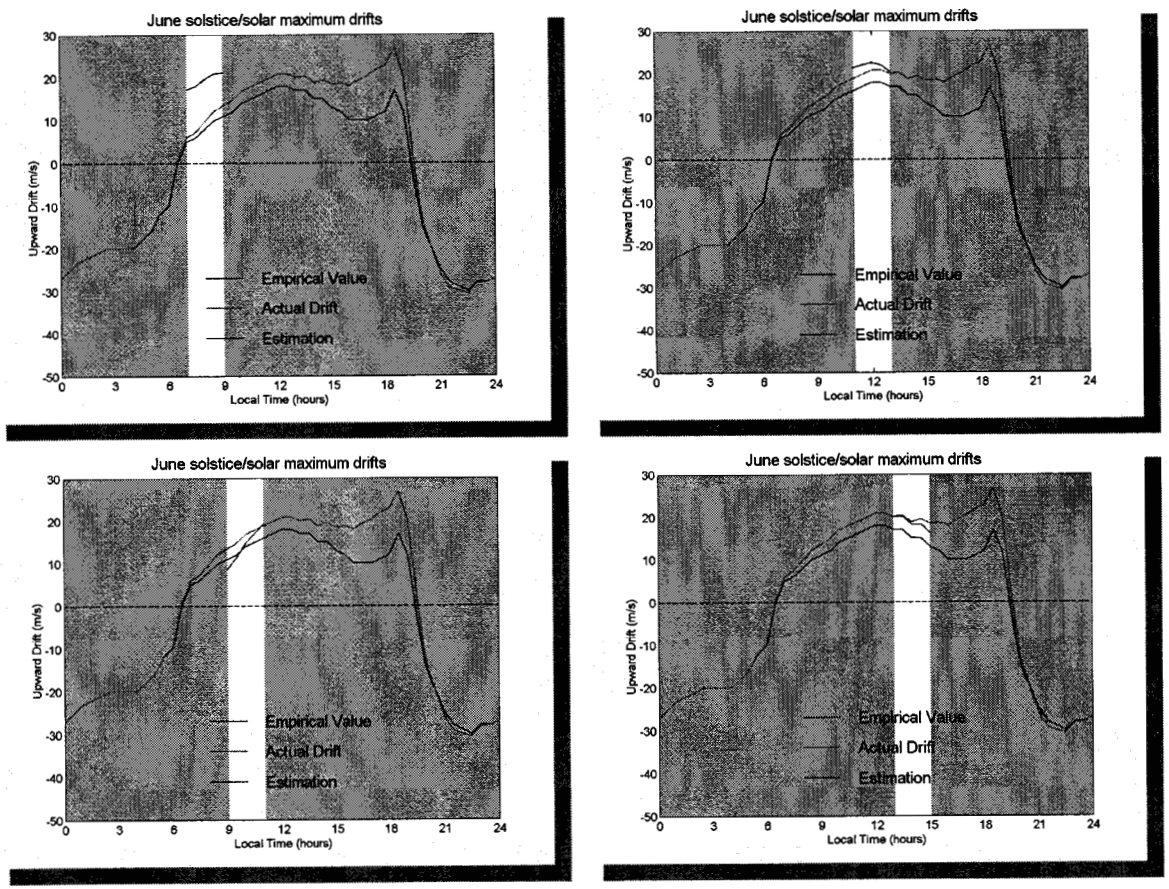
GPS Observation Links

- 4 GPS satellites
- 3 ground rcvs
- (20° apart)
- 1 LEO
- (700 km)
- 2-hour intervals



OSSE Results - Drift: 3-ground/1-LEO Receivers

- 4 GPS satellites
- time-dependent λ
- climate initial
- condition



OSSE Results - Drift: 3-ground/1-LEO Receivers

- 4 GPS satellites
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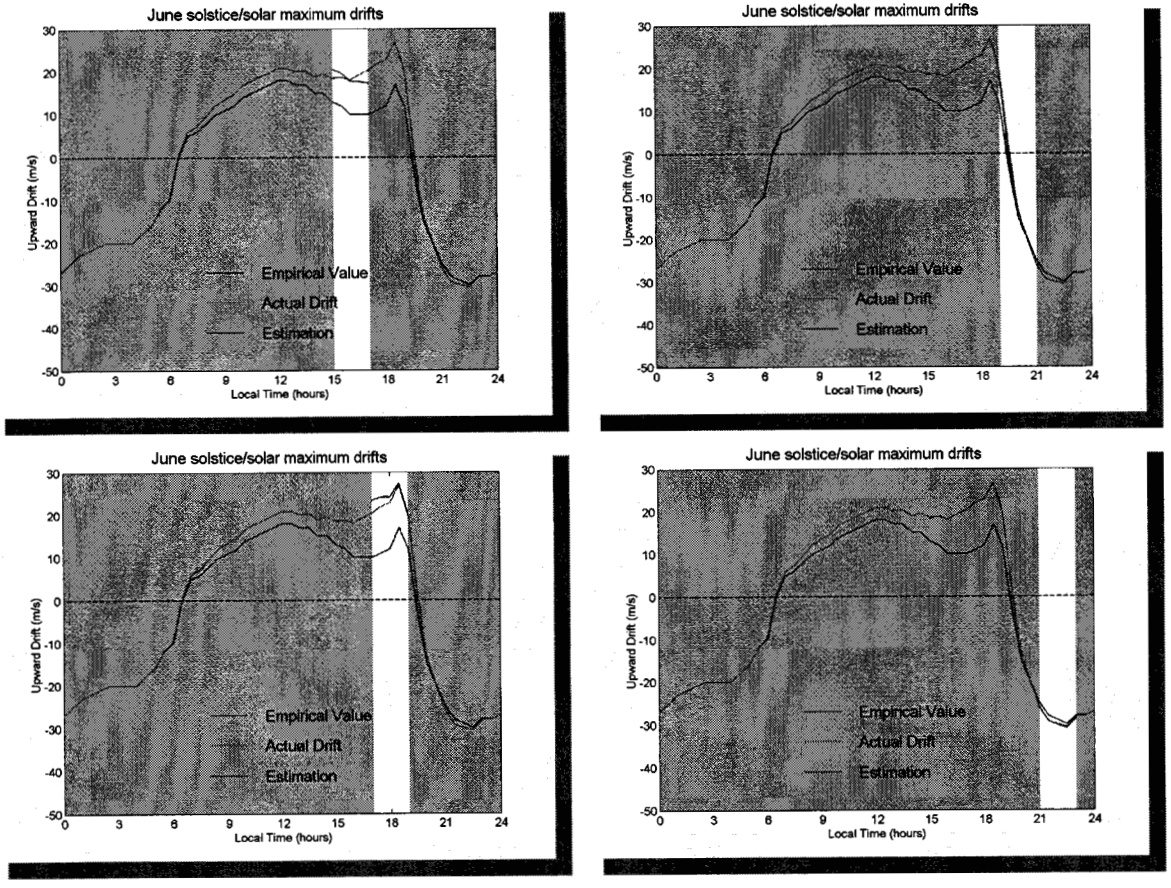
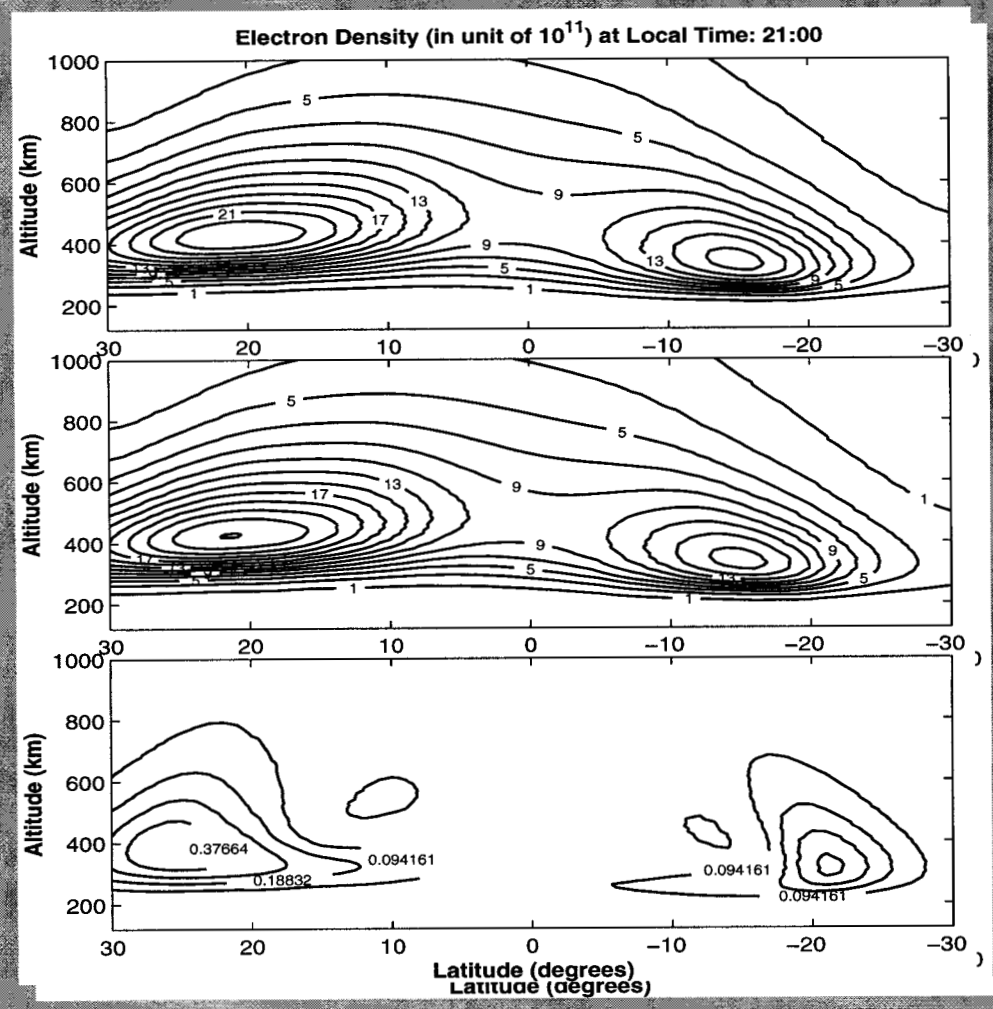


OSSE Results-Ne: 3-ground/1-LEO Receivers

Top: "Truth"

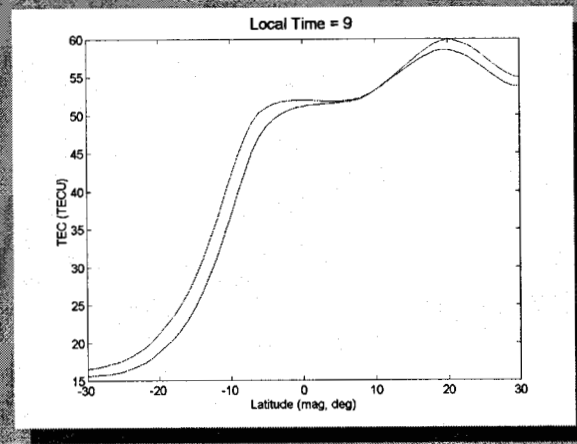
Middle: Assimilation

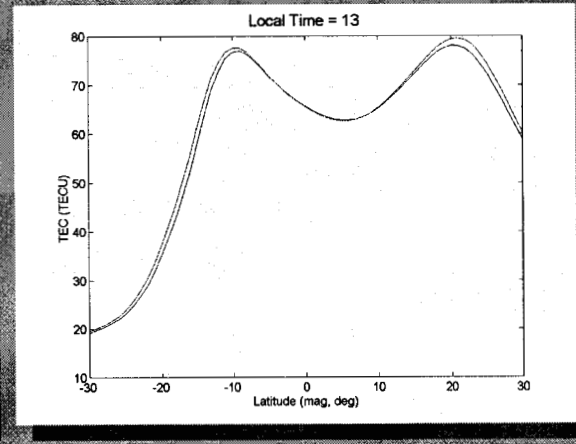
Bottom: Difference

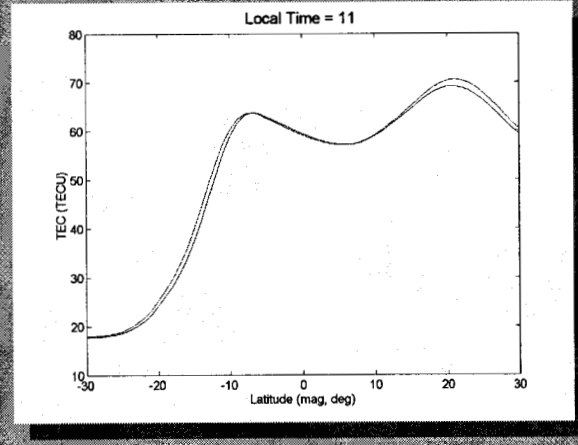


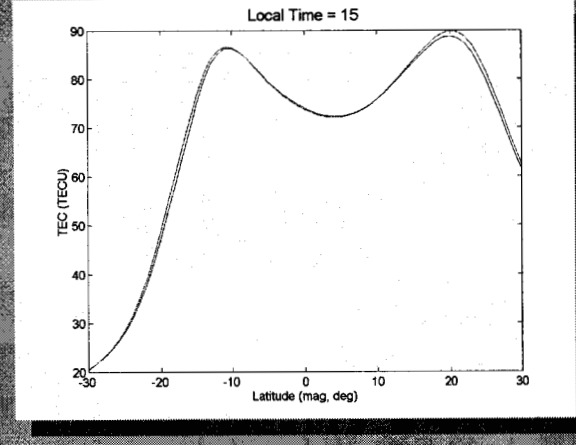
Vertical TEC of Assimilation Results

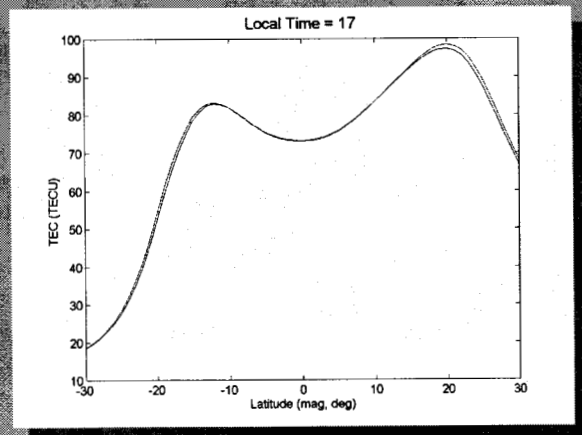
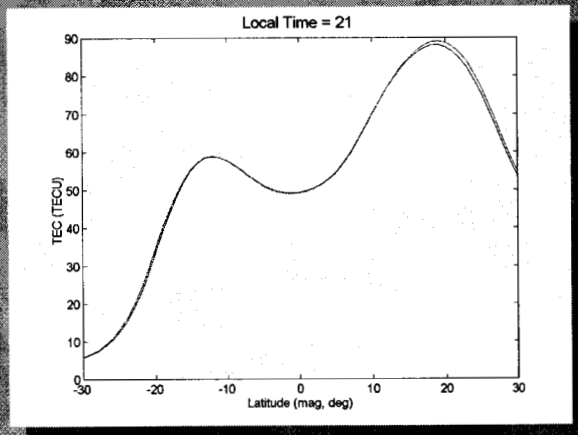
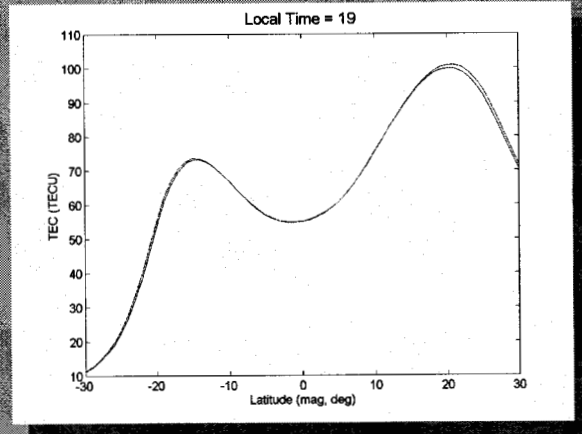
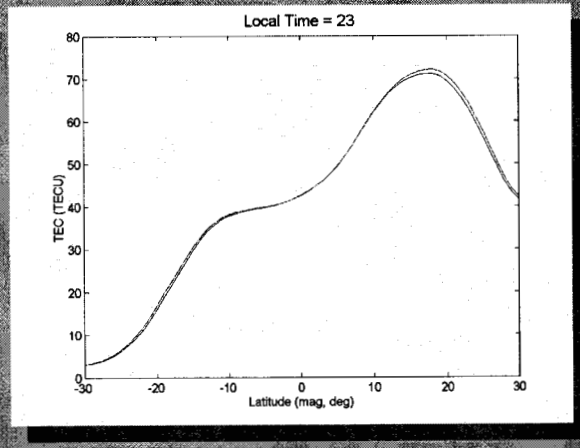
- 4 GPS satellites
- 3 ground receivers
- 1 LEO receiver
- time-dependent λ
- climate initial
- condition









Vertical TEC of Assimilation Results

- 4 GPS satellites
- 3 ground receivers
- 1 LEO receiver
- time-dependent λ
- climate initial condition