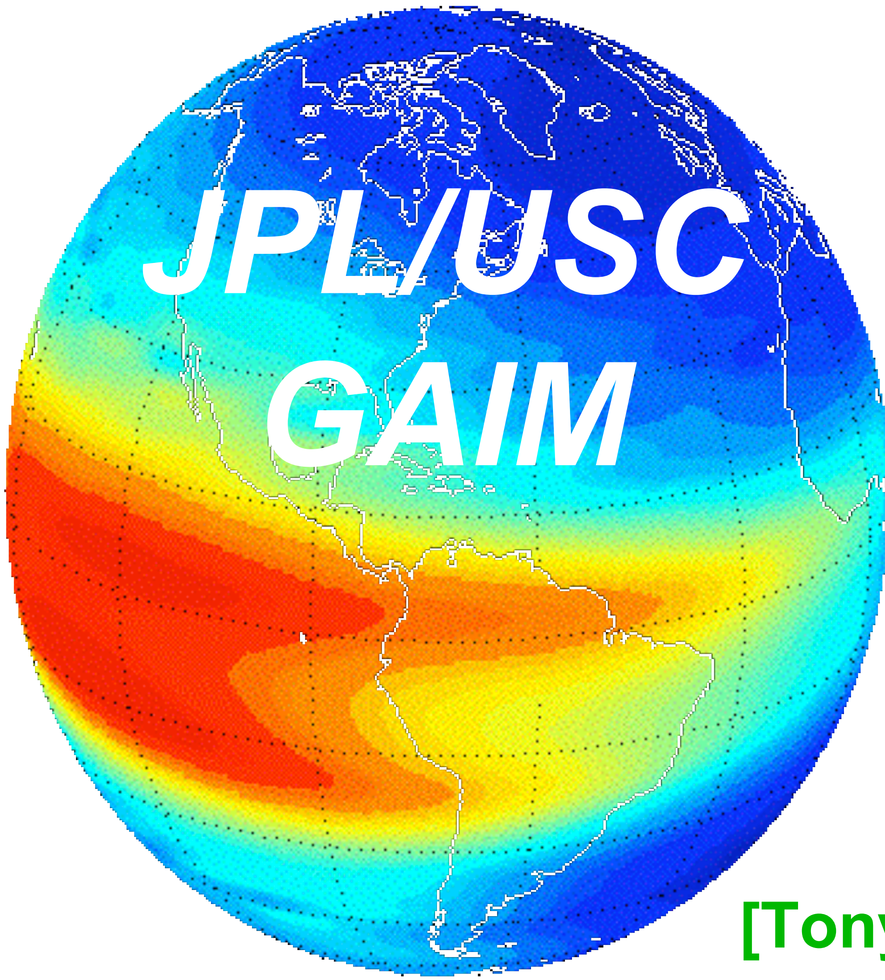
COSMIC and Space Weather



Anthony Mannucci, JPL
Brian Wilson, JPL
Vardan Akopian, JPL, USC
George Hajj, JPL, USC
Lukas Mandrake, JPL
Xiaoqing Pi, JPL, USC
Attila Komjathy, JPL
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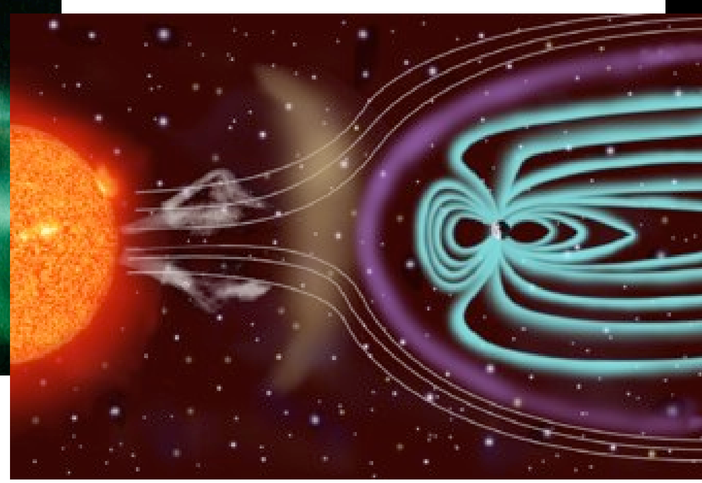
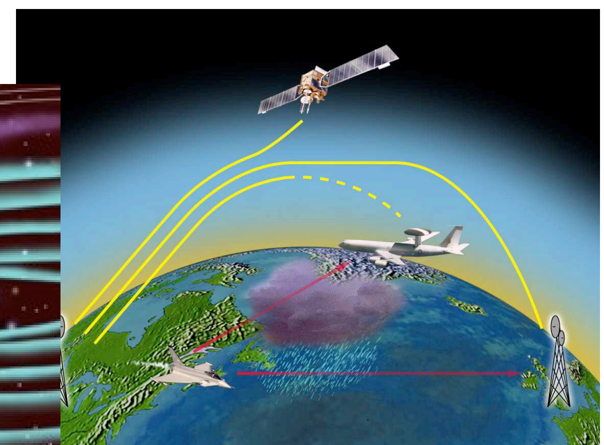
Agenda

- Ionospheric remote sensing the GPS way
- Ionospheric occultations
- The Global Assimilative Ionosphere Model
- Real-Time GAIM
- Goal

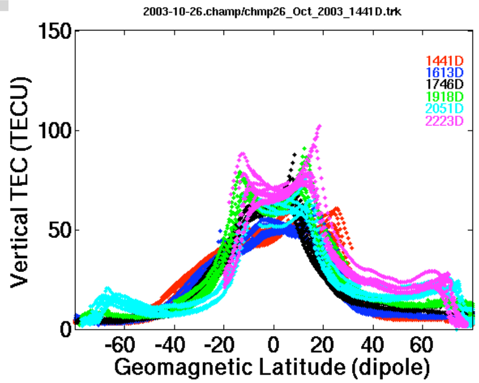
Motivation: Ionospheric Component of Space Weather

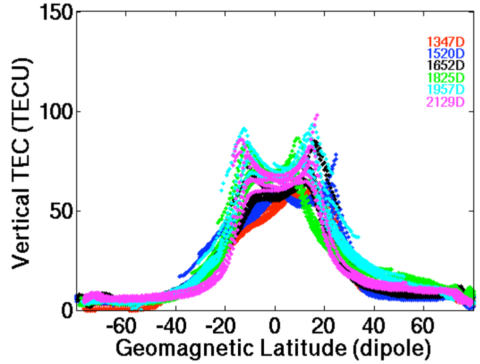
- Interest in the Earth's ionosphere stems from practical needs and scientific interest
- Scientifically, the ionosphere is a medium of extraordinary complexity combining the physics of:
  - Electromagnetism
  - Plasmas (free charges)
  - Neutral fluids
- Practically, the Earth's ionosphere strongly affects radio signal propagation and produces currents

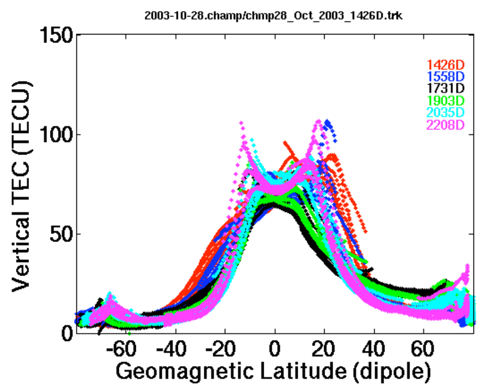




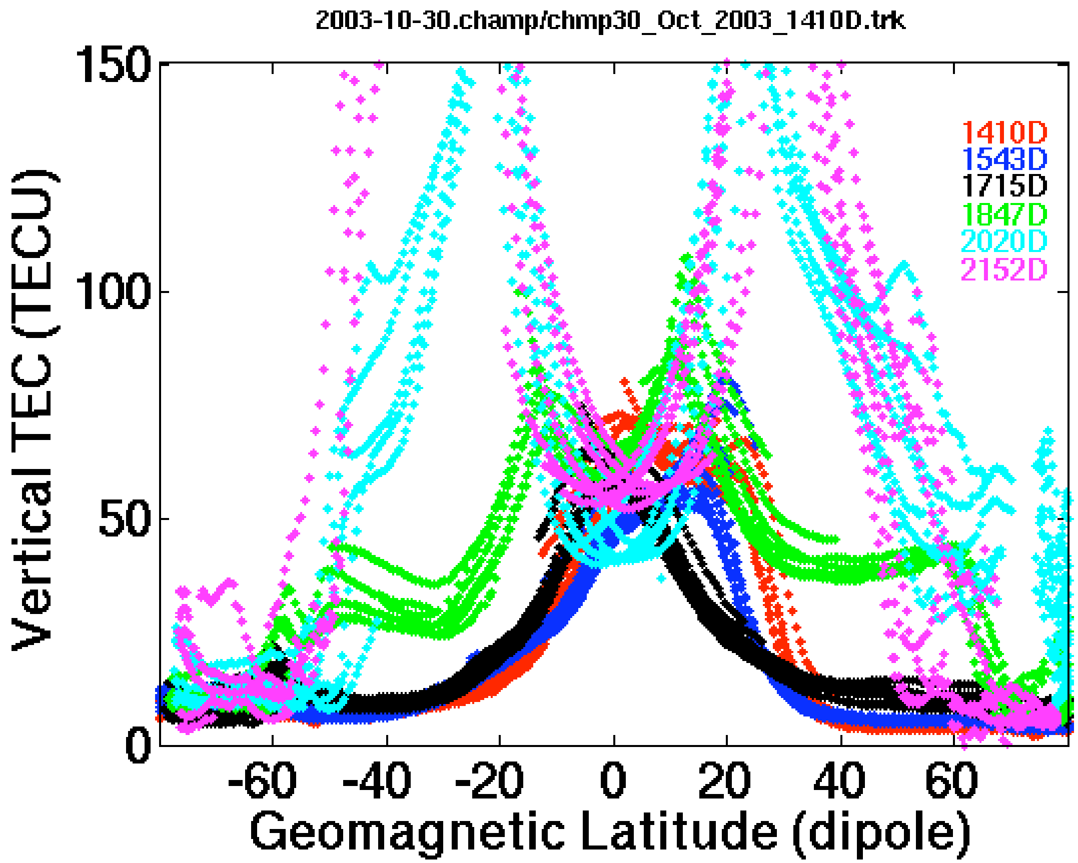
Ionospheric Regimes







Event Time: 18:00 UT   Local Time: 13:00

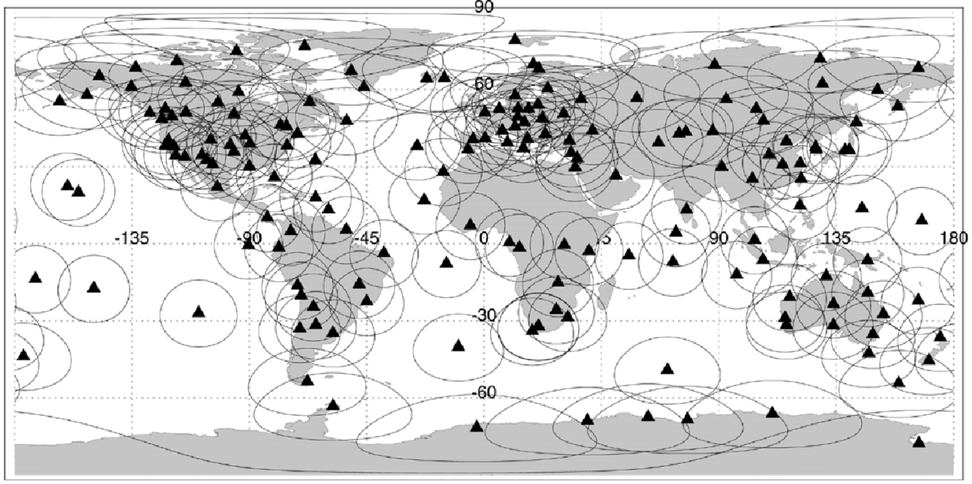


CHAMP Zenith TEC

See also:
Mannucci et al., *Geophys Res Lett* 2005

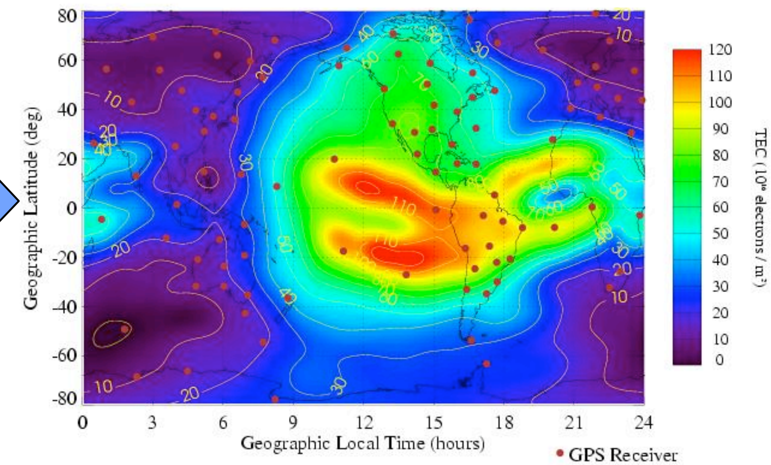
Ground-based GPS Remote Sensing

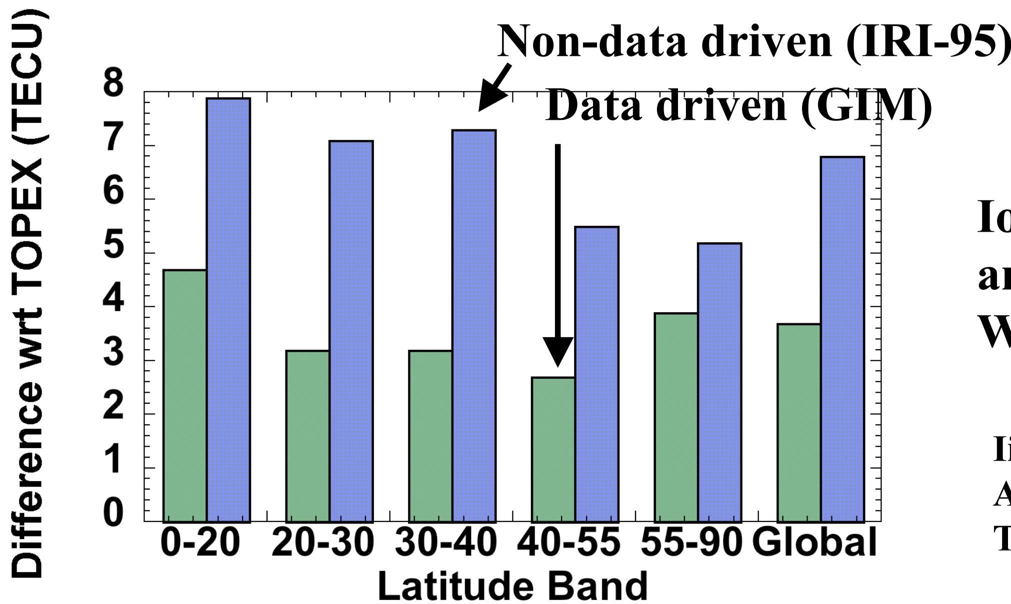
Global GPS Receiver Network



Global Ionospheric Map

02/19/02
21:00 - 21:15 UT



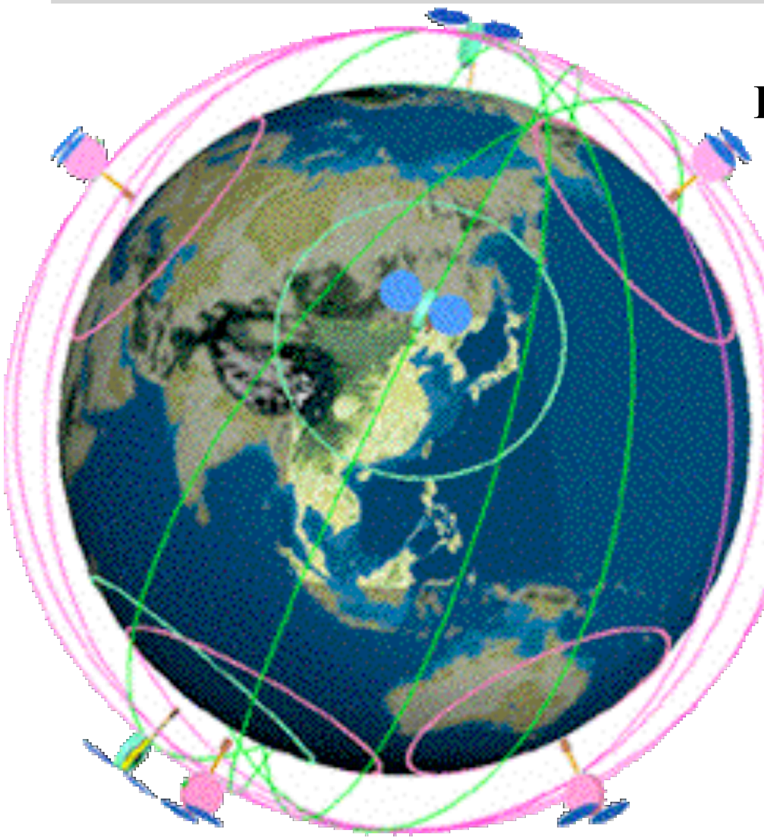


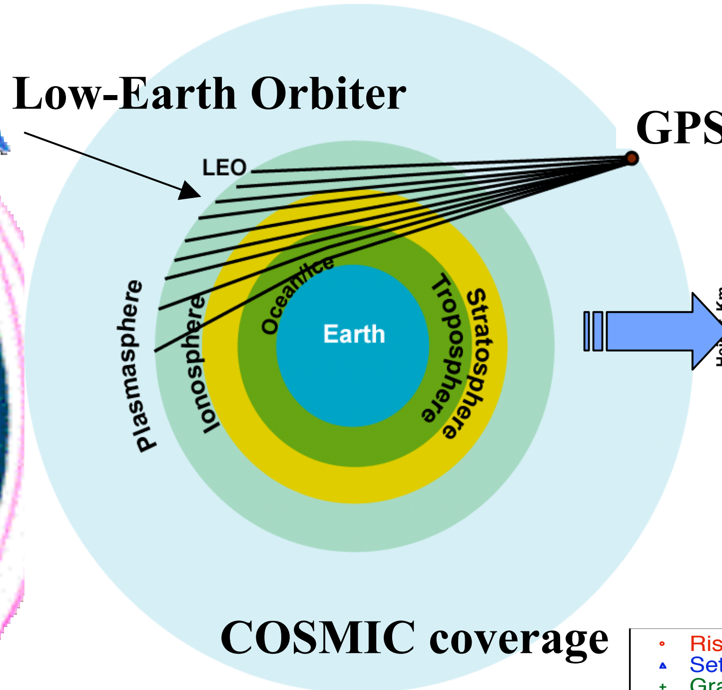
Low Solar Activity (1998)

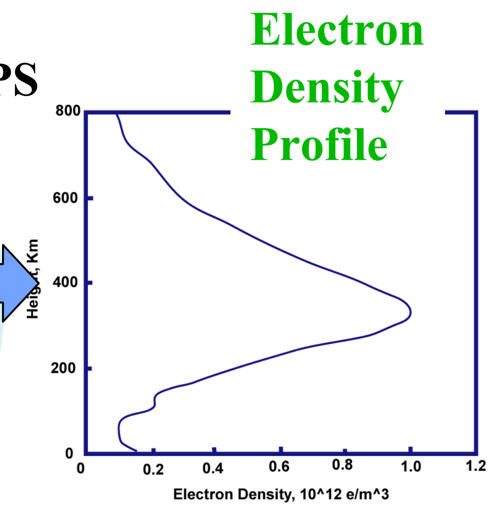
Ionospheric Specification and Determination Workshop, JPL 1998

Iijima et al., Journal of Atmospheric and Solar-Terrestrial Physics, 1999

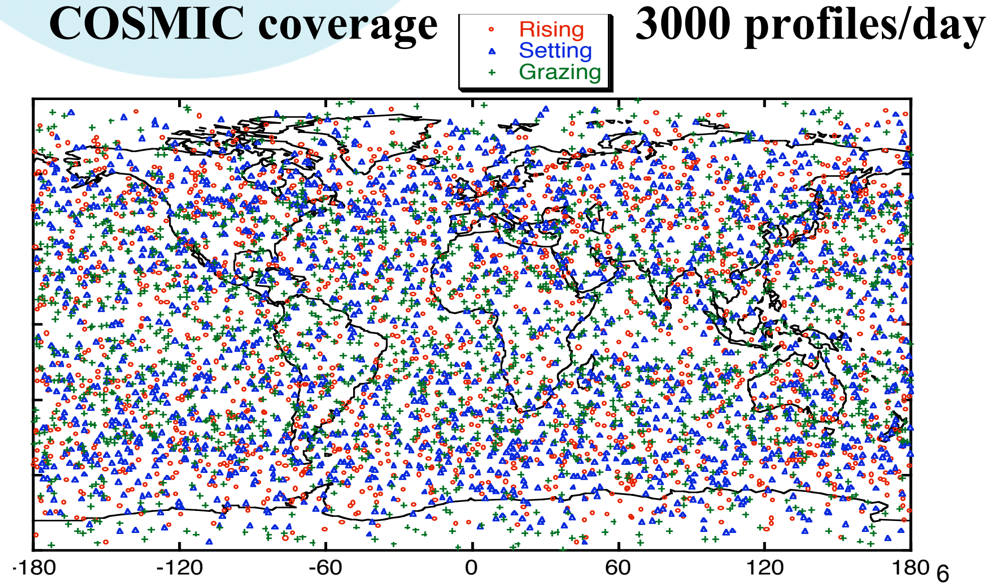
LEO-Based GPS Remote Sensing







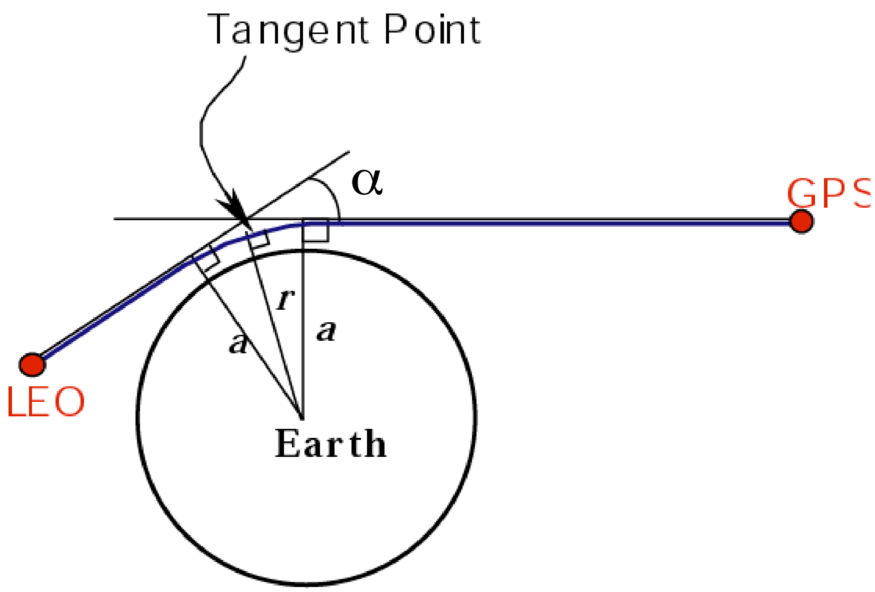
COSMIC coverage 3000 profiles/day

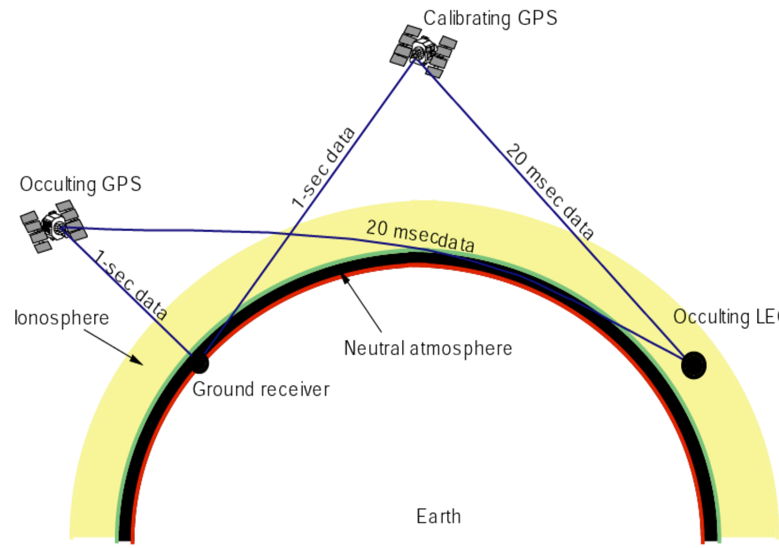


Six-satellite COSMIC constellation
Launch March 2006

NSF NASA USAF NOAA NSPO ONR

Occultation Geometry



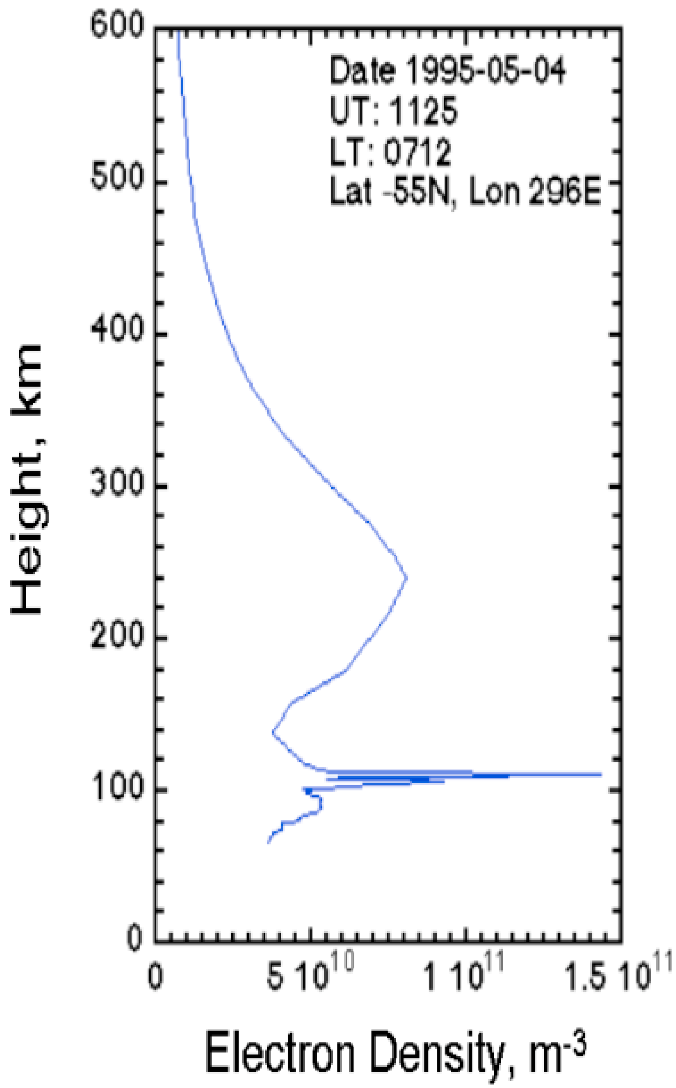


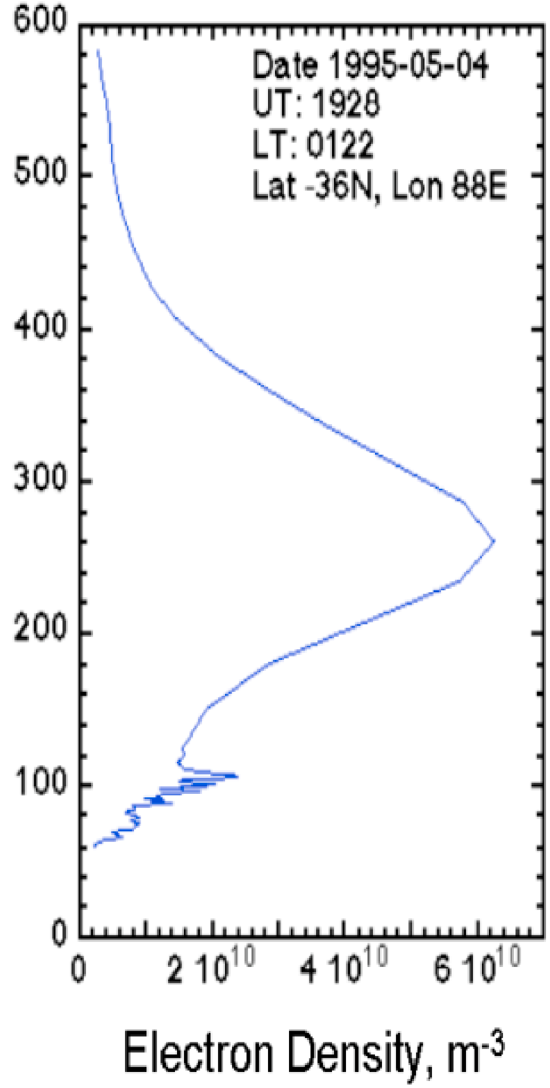
- **Single Frequency Retrievals**
- **Dual Frequency Retrievals**
  - **TEC = const. x (L1 – L2)**
  - **α ~ dTEC/dt**

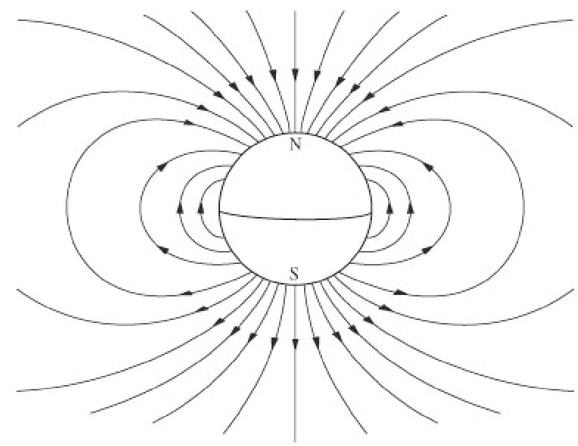
$$\alpha(a) = 2a \int_a^{\infty} \frac{1}{\sqrt{a'^2 - a^2}} \frac{d \ln(n)}{da'} da'$$

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

Electron Density Profiles from GPS/MET







See also:
Kelley, Wong, Hajj, Mannucci
Geophys Res Lett 2004

Ionospheric Measurements

	Space Assets		Land Assets	
	In-situ	**Remote**	**Network**	**Cal/Val Sites**
Present	• SSJ/4 (DMSP) • SSIES (DMSP) • SSMS (DMSP) • TED (POES) • MEPED (POES) • SSJ/5 (DMSP)	• CHAMP • SAC/C • IOX • GUVI (TIMED) • SSUSI (DMSP) • SSULI (DMSP)	• DISS • IGS • SumiNet • Regional GPS Network	• Incoherent Scattering Radar Sites
Future	• SESS (NPOESS)	• C/NOFS • COSMIC • GPSOS (NPOESS) • SESS (NPOESS)		

What is the Global Assimilative Ionosphere Model?

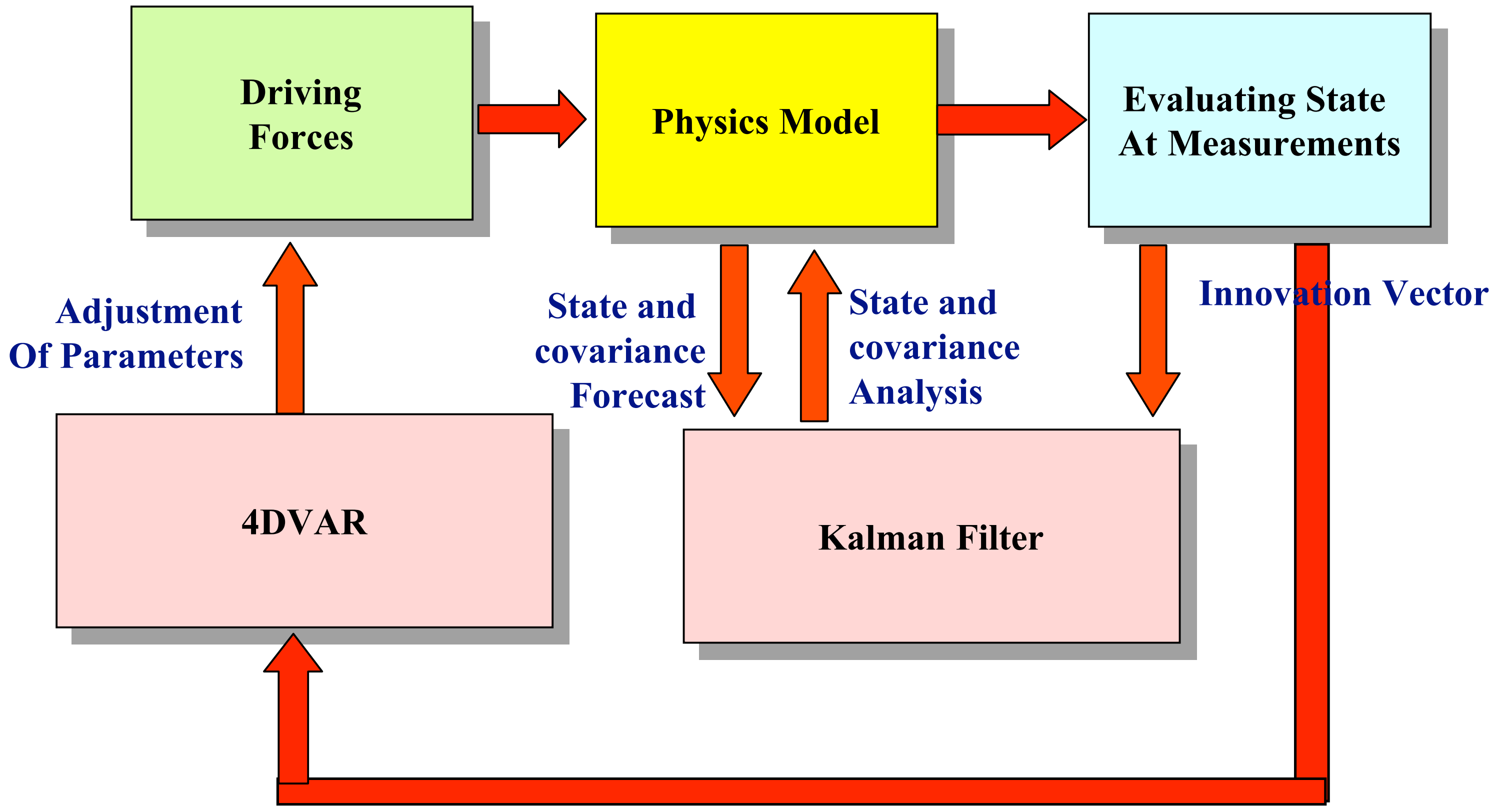
- A Global Assimilative Ionospheric Model
- Patterned after NWP models
- Based on first-principles physics (approximate)
- Solves the electro-hydrodynamics governing the spatial and temporal evolution of electron density in the ionosphere
- Assimilates various types of ionospheric data by use of the Kalman filter and 4DVAR
  - Ground-based TEC
  - Space-based absolute and relative TEC
  - In-situ under test
  - Beacon data under development
  - UV has undergone preliminary testing

Motivations for GAIM

- The existence of a wide range of ionospheric data
- Need for Accurate Ionospheric Calibration
    - Navigation
    - Communication
    - Radar
- Monitoring of space weather events
- Mapping ionospheric currents (early stage)
- Improve our understanding of ionospheric response to solar activities and magnetic storms
- Indirect observation of upper atmosphere

Data Assimilation in a Nutshell

"State" is electron density field



Driving Forces (Input to Physics Model)

Φ_{EUV}	Solar EUV radiation flux
P_a	Auroral production (NOAA's energy and flux patterns)
N_n	Neutral densities and composition (MSIS)
$\mathbf{E}$	Electric field
$\mathbf{U_n}$	Thermospheric wind (HWM)

Kalman Filter Formulation

State x is electron density within a voxel

State Model

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

Measurement Model

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

Noise Model

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

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

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

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

Kalman Filter

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

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

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

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

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

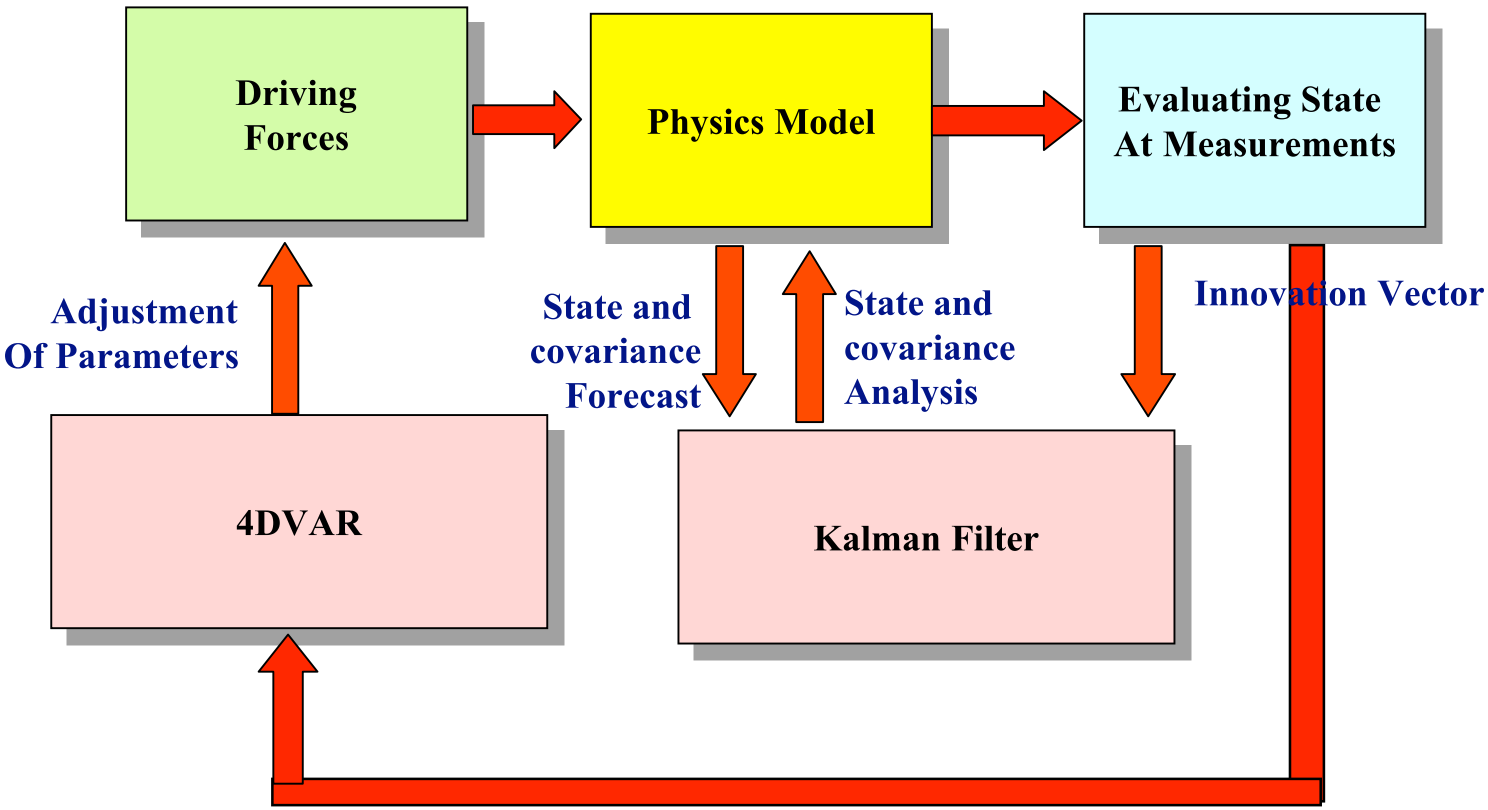
Simplification is to skip this update

Kalman Considerations

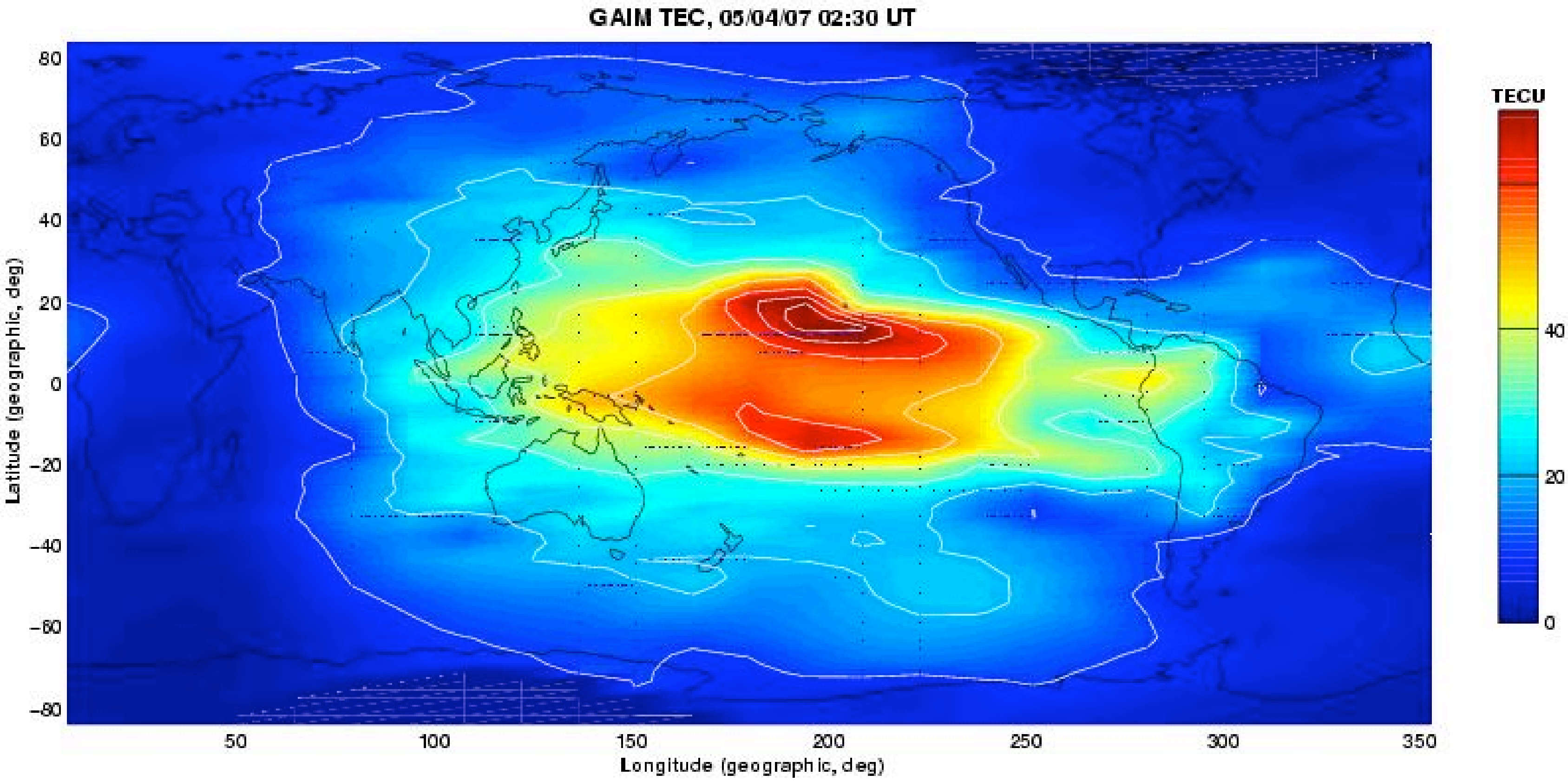
- Accurate covariance and measurement noise needed
- Physics errors assumed zero mean (unbiased)
- Variational methods can be used to improve mean behavior
  - Adjusts physics drivers to achieve zero-mean
  - Covariances not updated
  - Ensemble methods? (DART…)
- Implications of different data combinations not fully understood
  - Method of update
  - Variational methods maintain physical consistency of all data types

Assimilation Considerations

- GAIM I – Gauss Markov (Utah State U)
- GAIM II – Physics-based (Utah State U)
- JPL/USC – Physics-based
- JPL/USC 4DVAR – Driver adjustment
- It is important to maintain multiple methods and groups

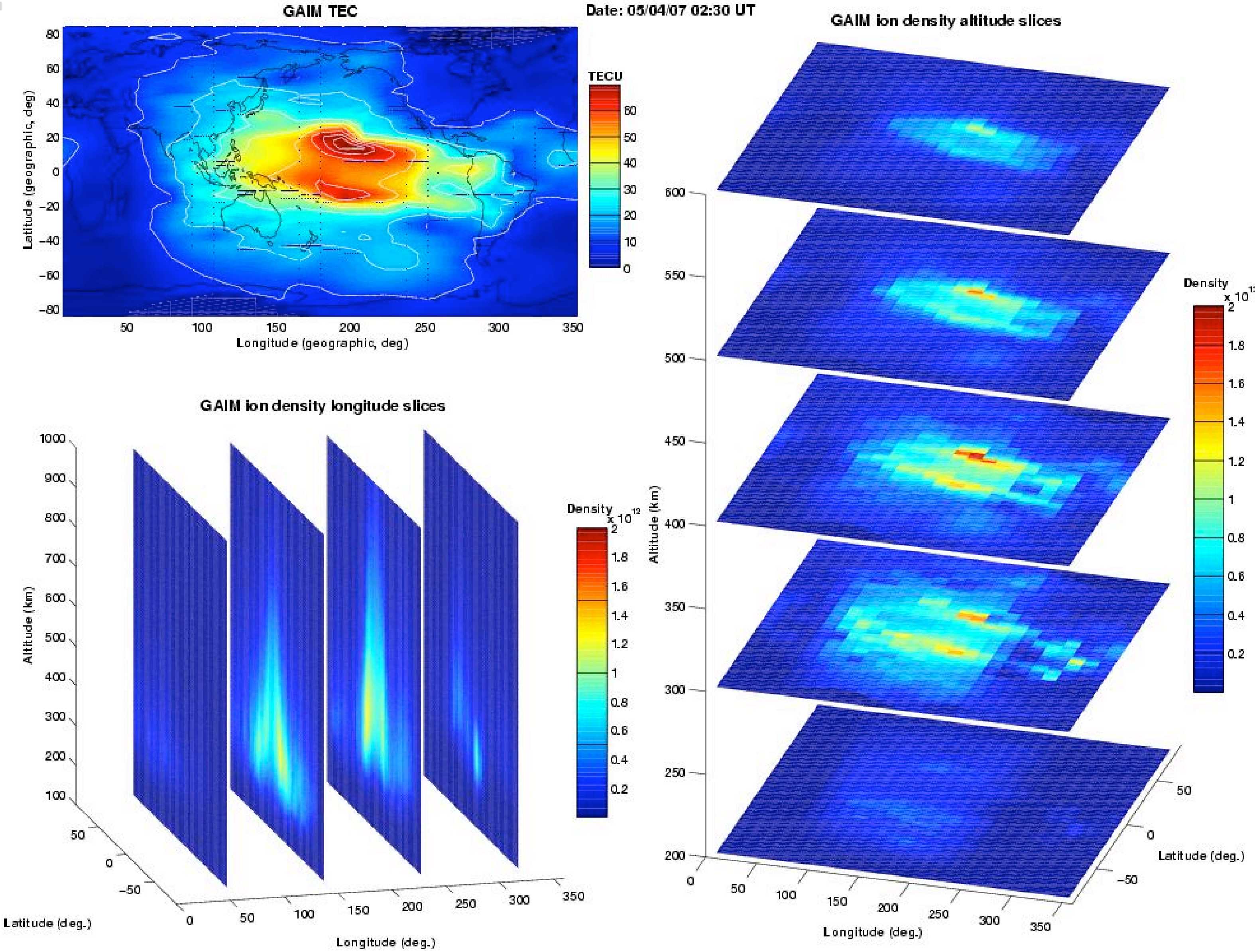


GPS Remote Sensing Started with TEC Maps



But 3D density fields are far more complicated…

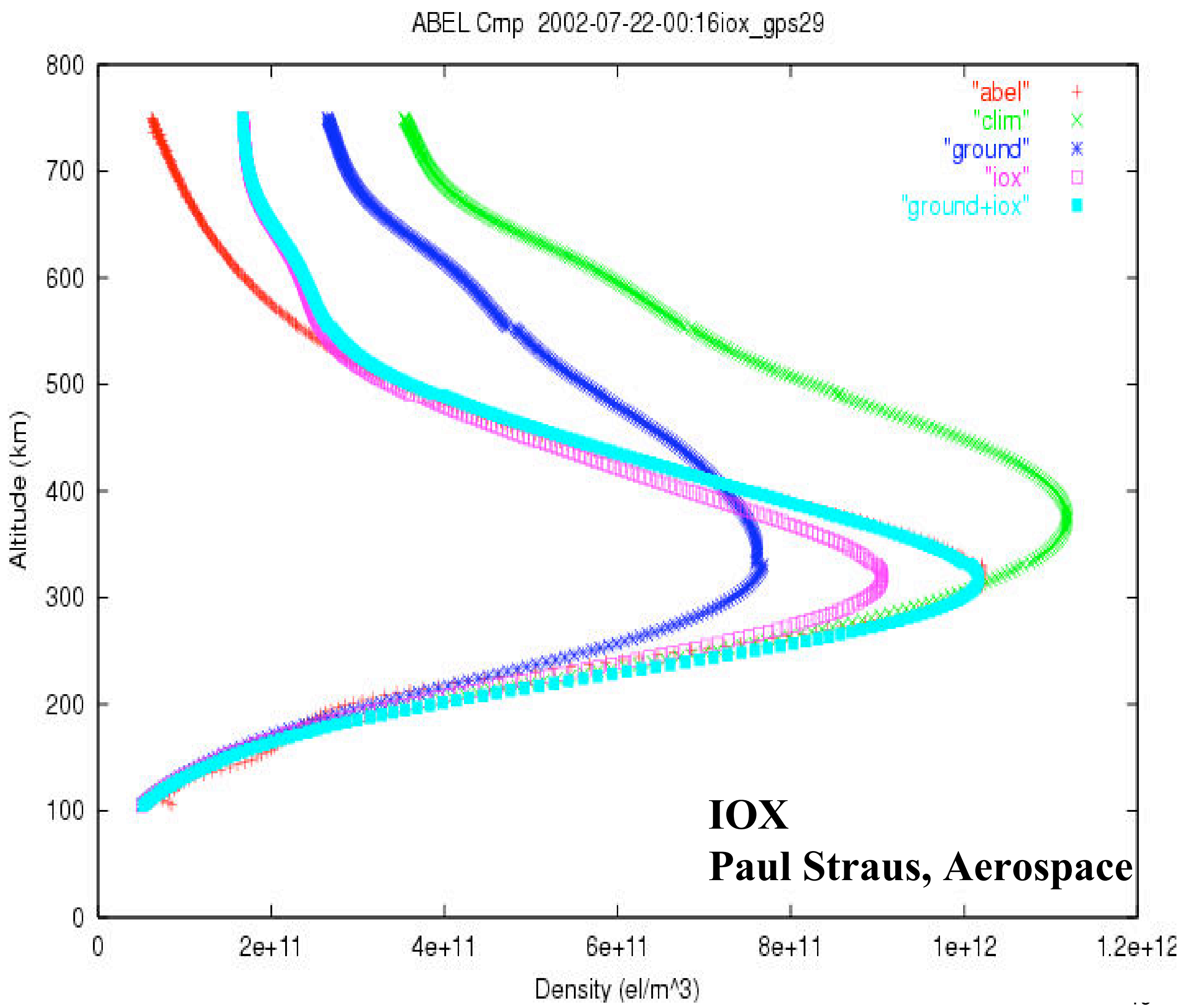
GAIM "Maps" Are Three Dimensional Electron Density Fields



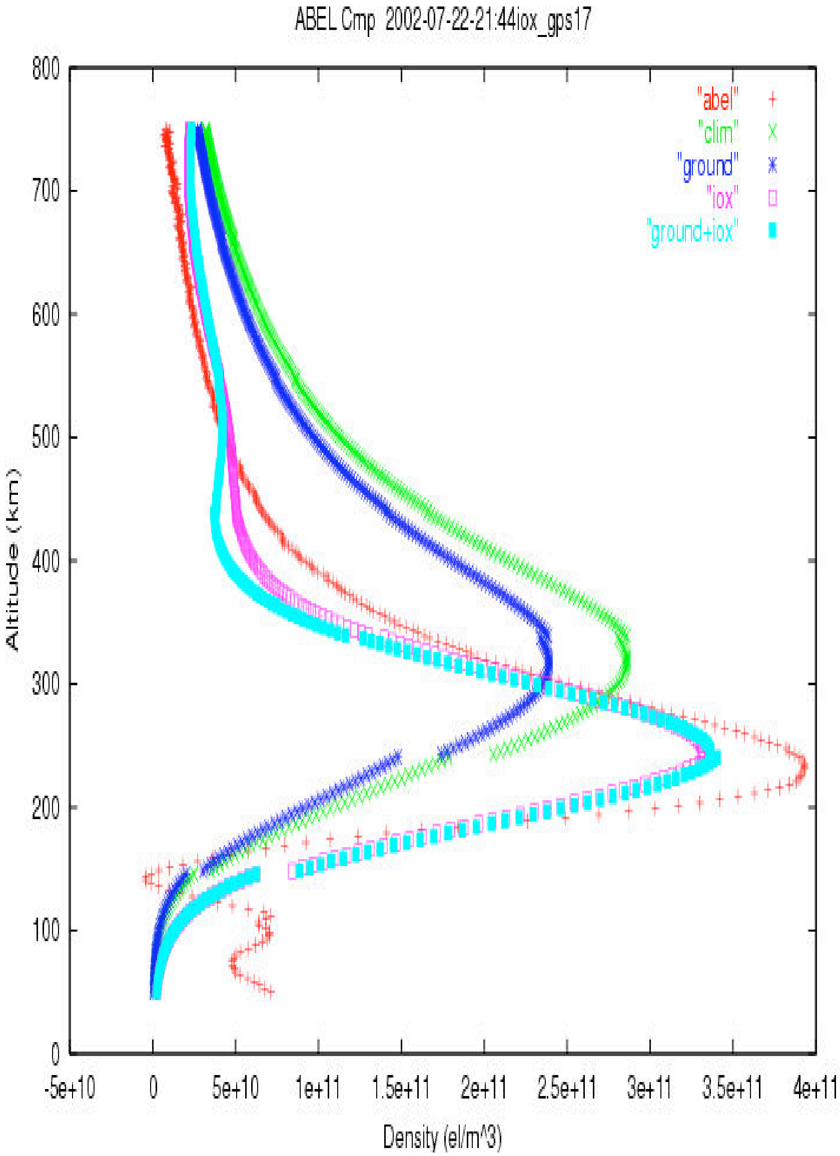
GAIM vs. Abel
Comparisons at the Occultation Tangent Point

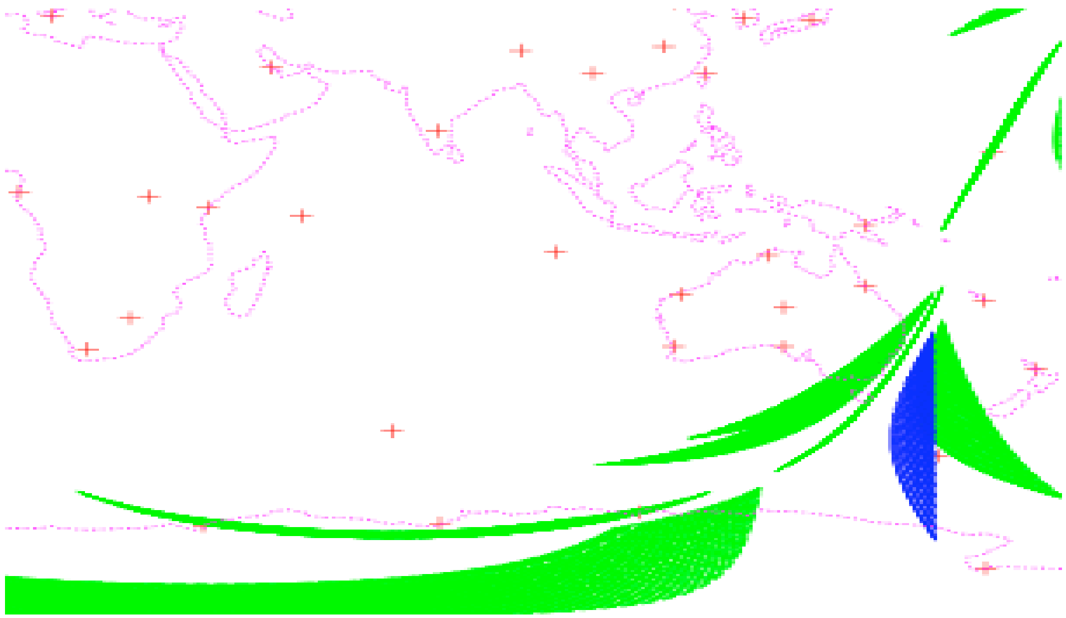
Profiles are obtained by:

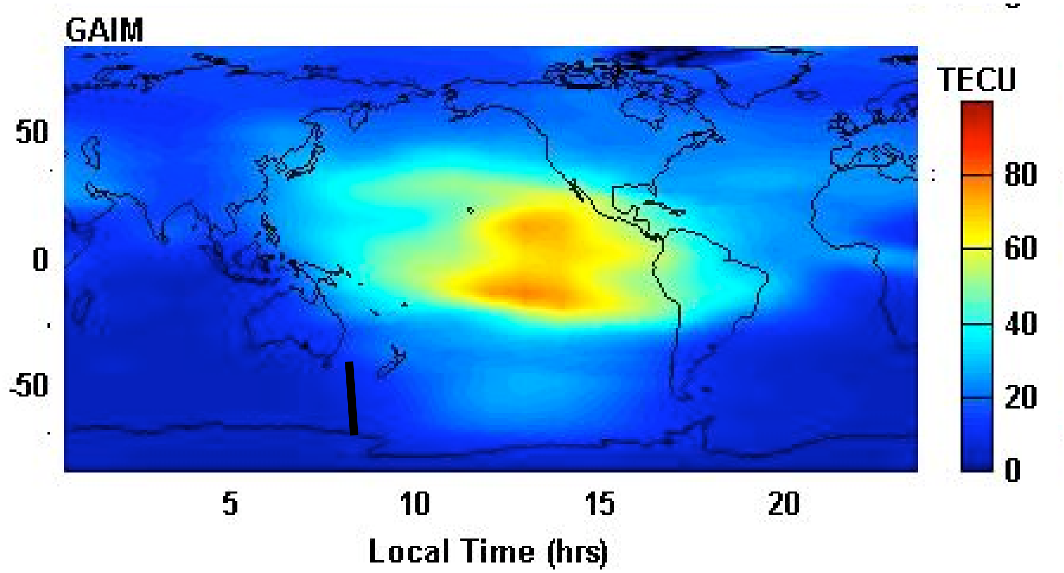
- Abel Inversion ("abel")
- GAIM Climate (no data) ("clim")
- GAIM Analysis assimilating ground TEC data only ("ground")
- GAIM Analysis assimilating IOX TEC data only ("iox")
- GAIM Analysis assimilating both ground and IOX data ("ground+iox")



EXAMPLES OF PROFILES RETRIEVED BY USE OF DIFFERENT DATA SETS







GAIM vs. Abel NmF2 Comparison

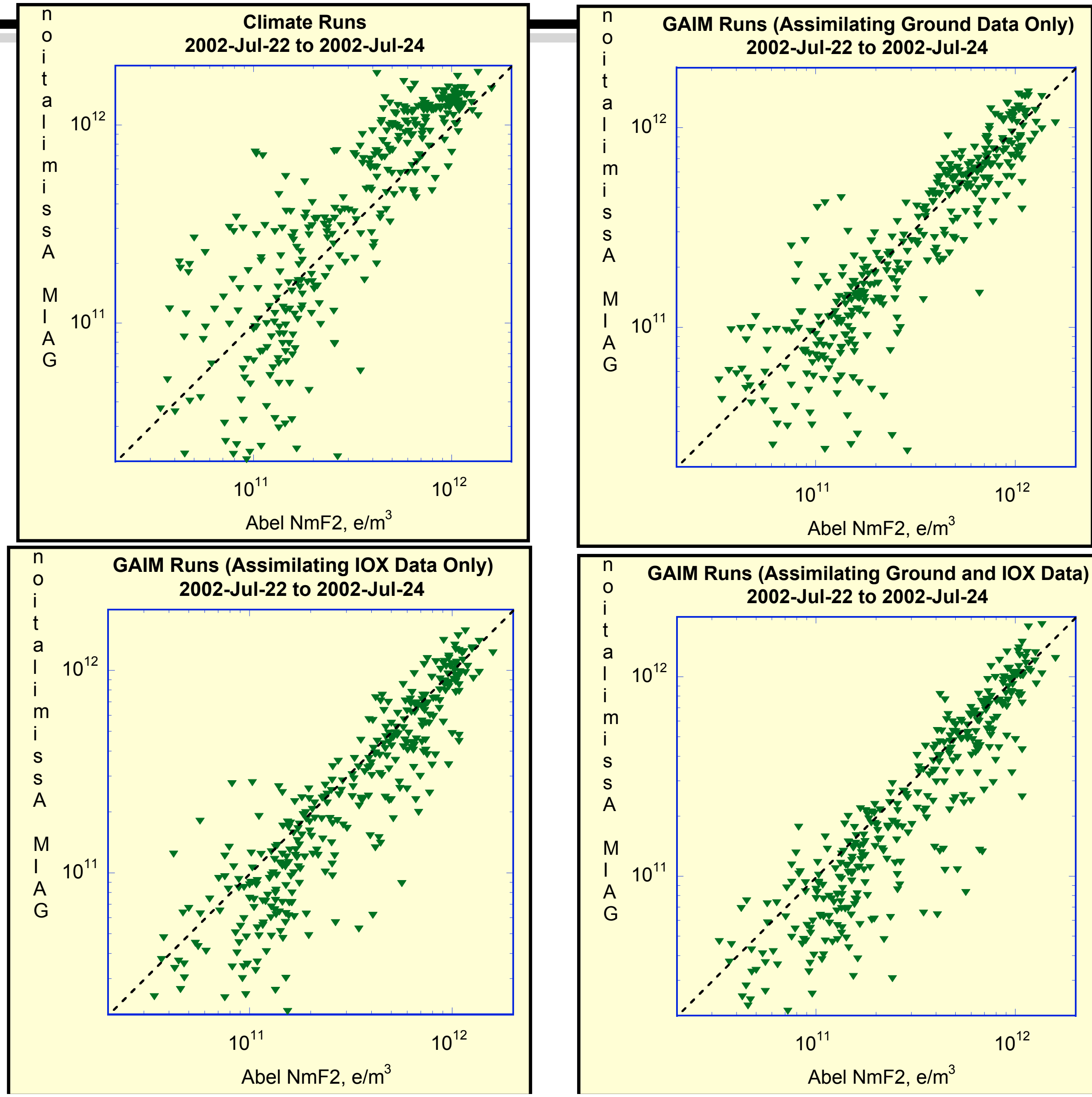
NmF2: peak Electron density

No Data

Ground Data

Occ Data

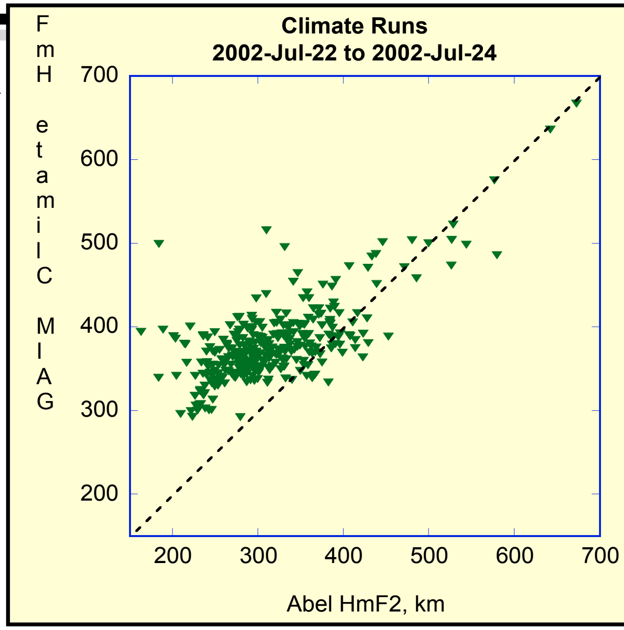
Ground & Occ



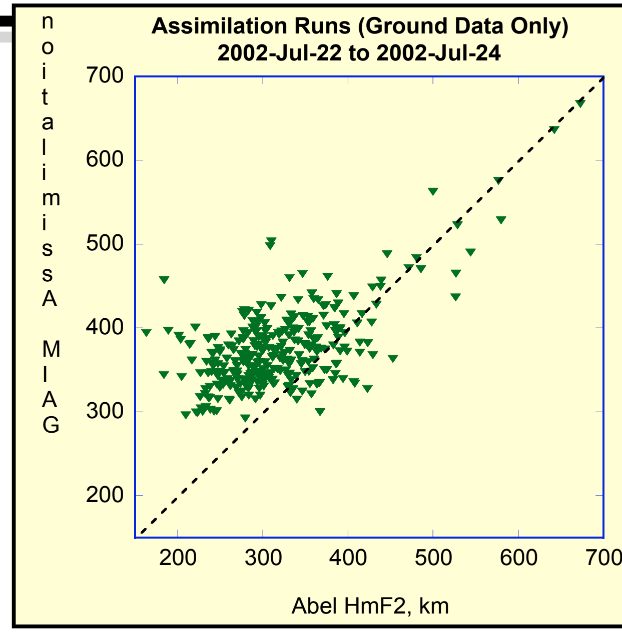
GAIM vs. Abel HmF2 Comparison

HmF2: peak height

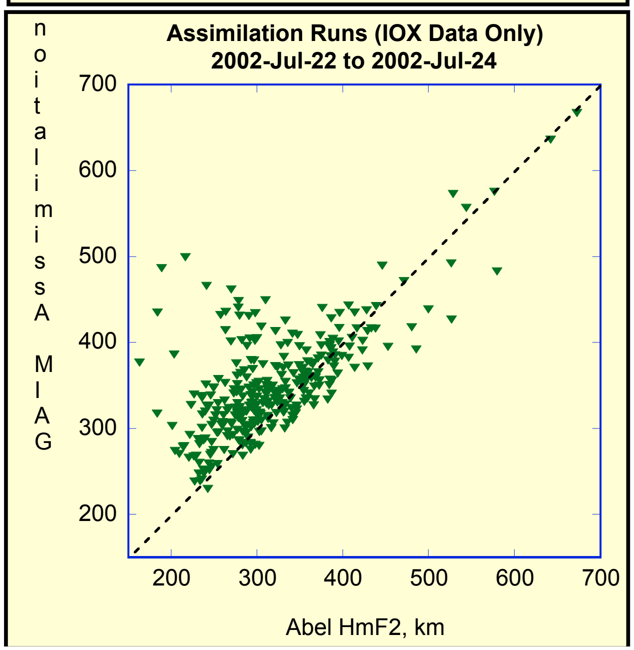
No Data



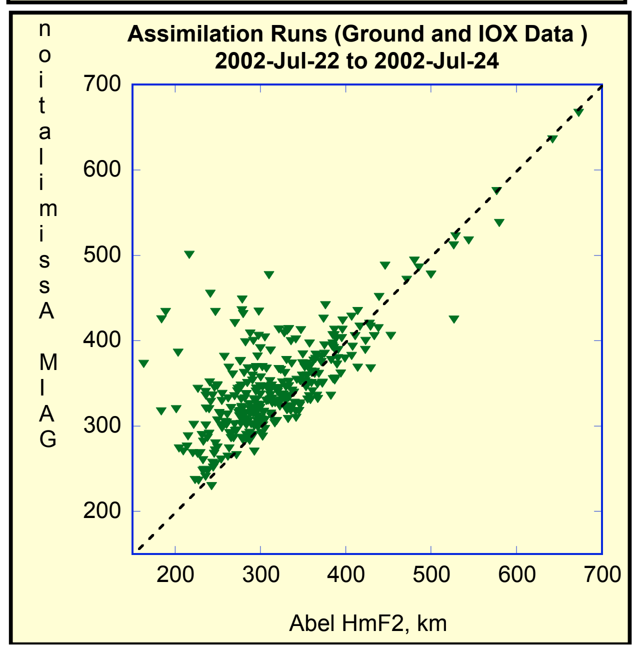
Ground Data



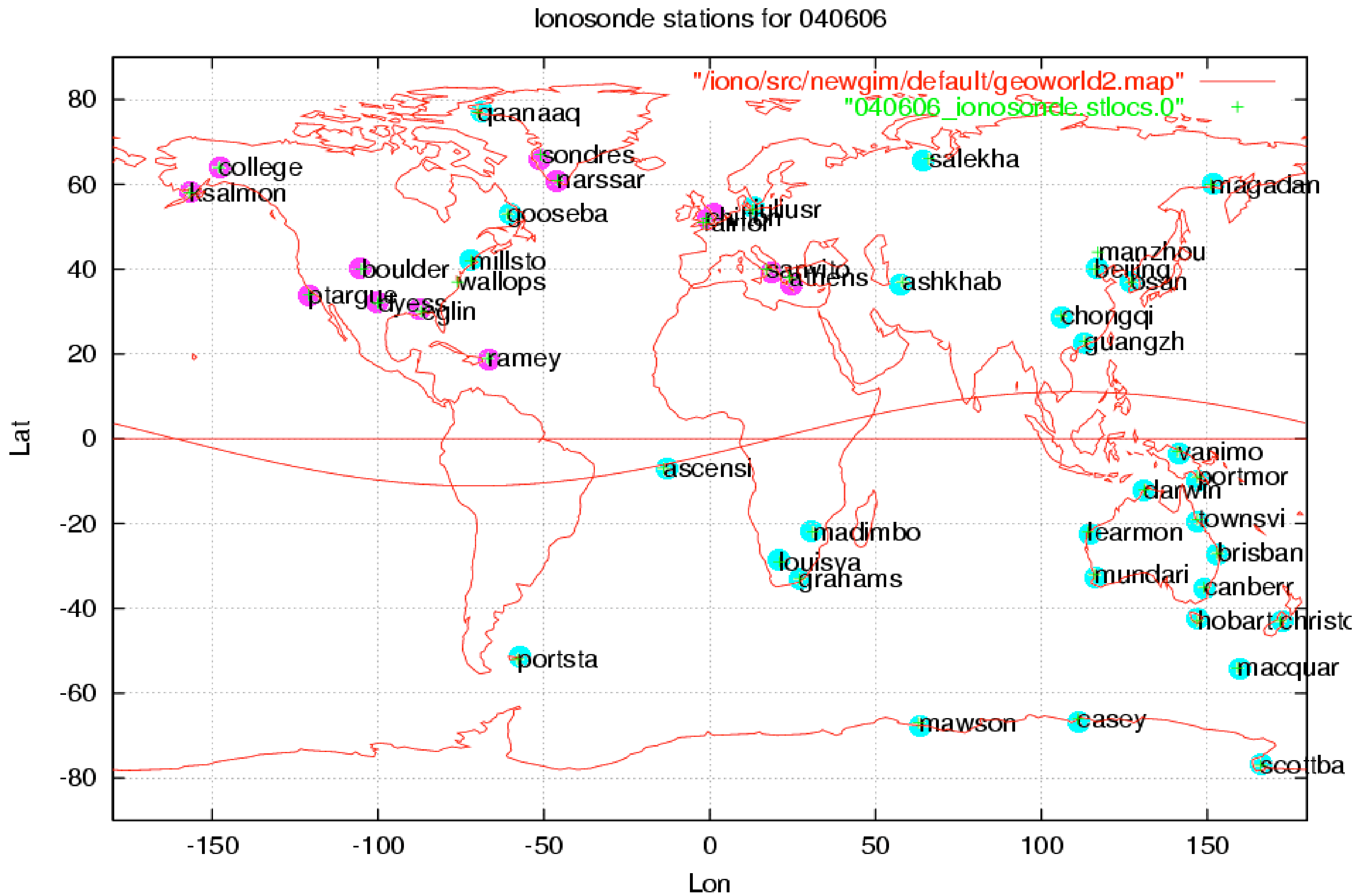
Occ Data



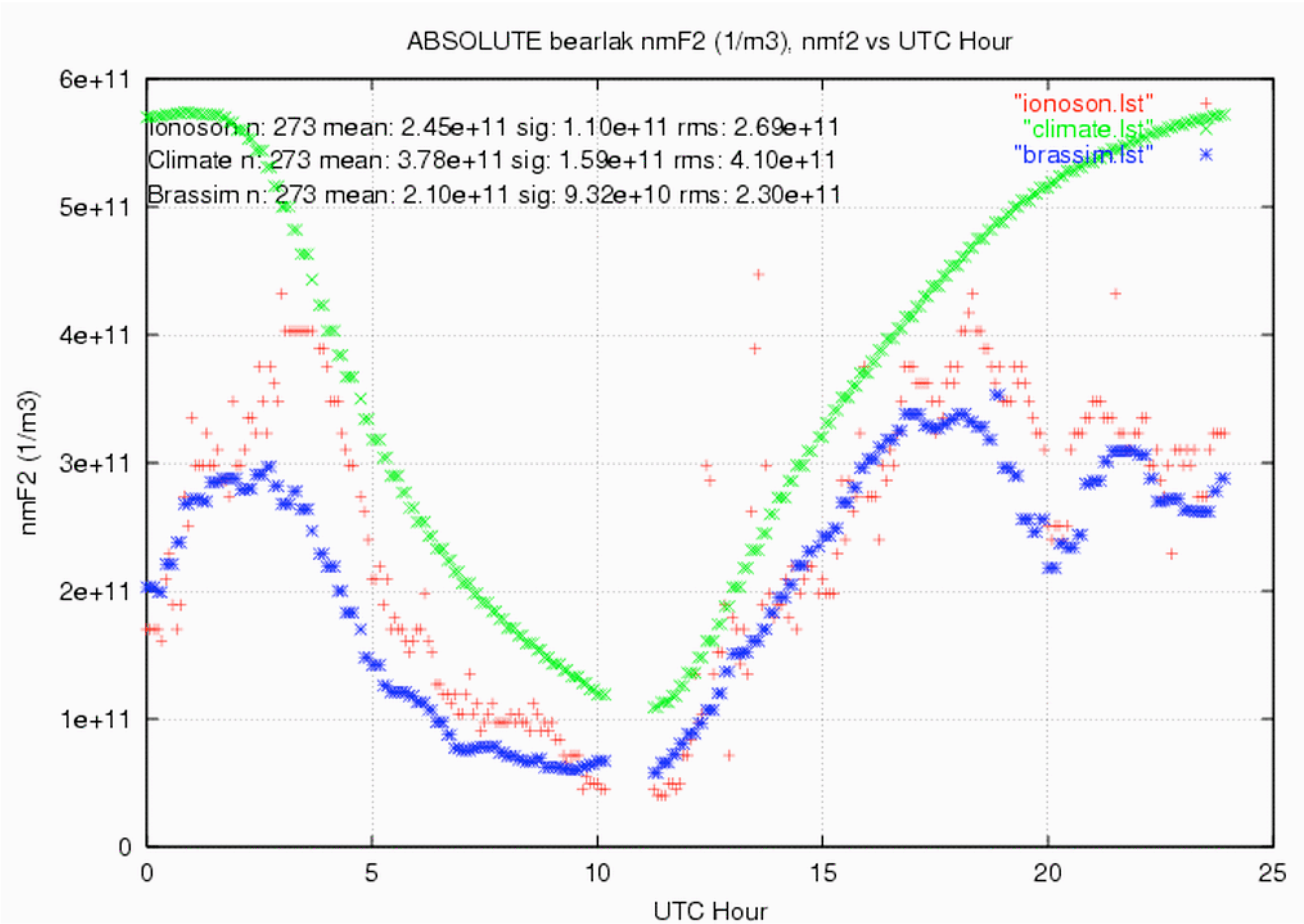
Ground & Occ



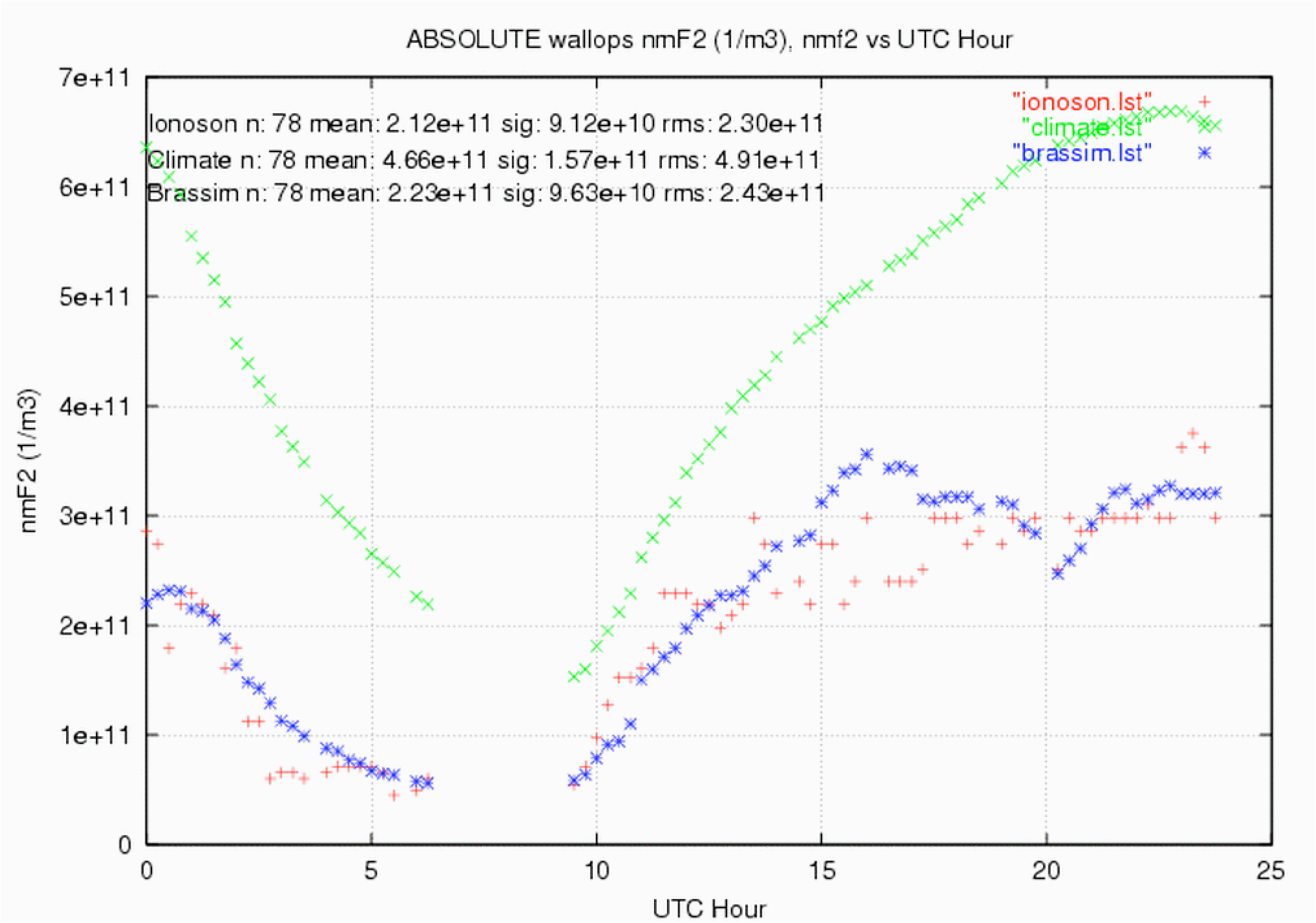
Global Ionosonde Sites



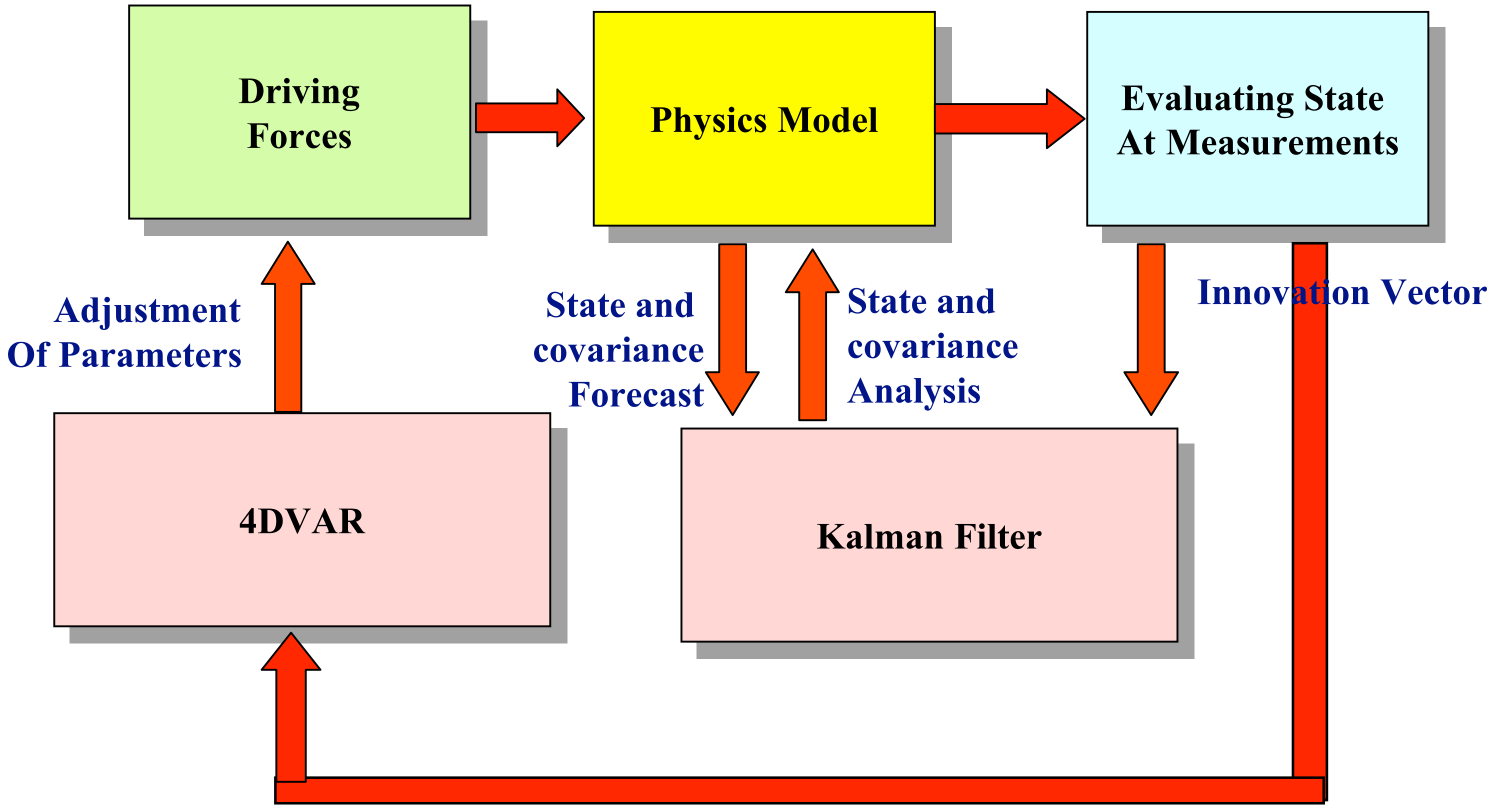
NmF2 Comparison:
Bear Lake on 2004/07/28



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



4DVAR



Driving Forces
Physics Model
Evaluating State At Measurements
Adjustment Of Parameters
State and covariance Forecast
State and covariance Analysis
Innovation Vector
4DVAR
Kalman Filter

Minimize the Cost Function:

$$J(n;\alpha) = \sum_{k=1}^{m} \left(y_k - H_k n(t_k;\alpha)\right)^T W^{-1} \left(y_k - H_k n(t_k;\alpha)\right) + \left(\alpha - \alpha_0\right)^T P^{-1} \left(\alpha - \alpha_0\right)$$

y_k **- Observations (e.g., total electron content - TEC) at epoch** t_k

W **Covariance of observation errors**

n **- State variables (volume density)**

H_k **- Observation operator**

α **- Model parameters related to driving forces or model inputs to be adjusted**

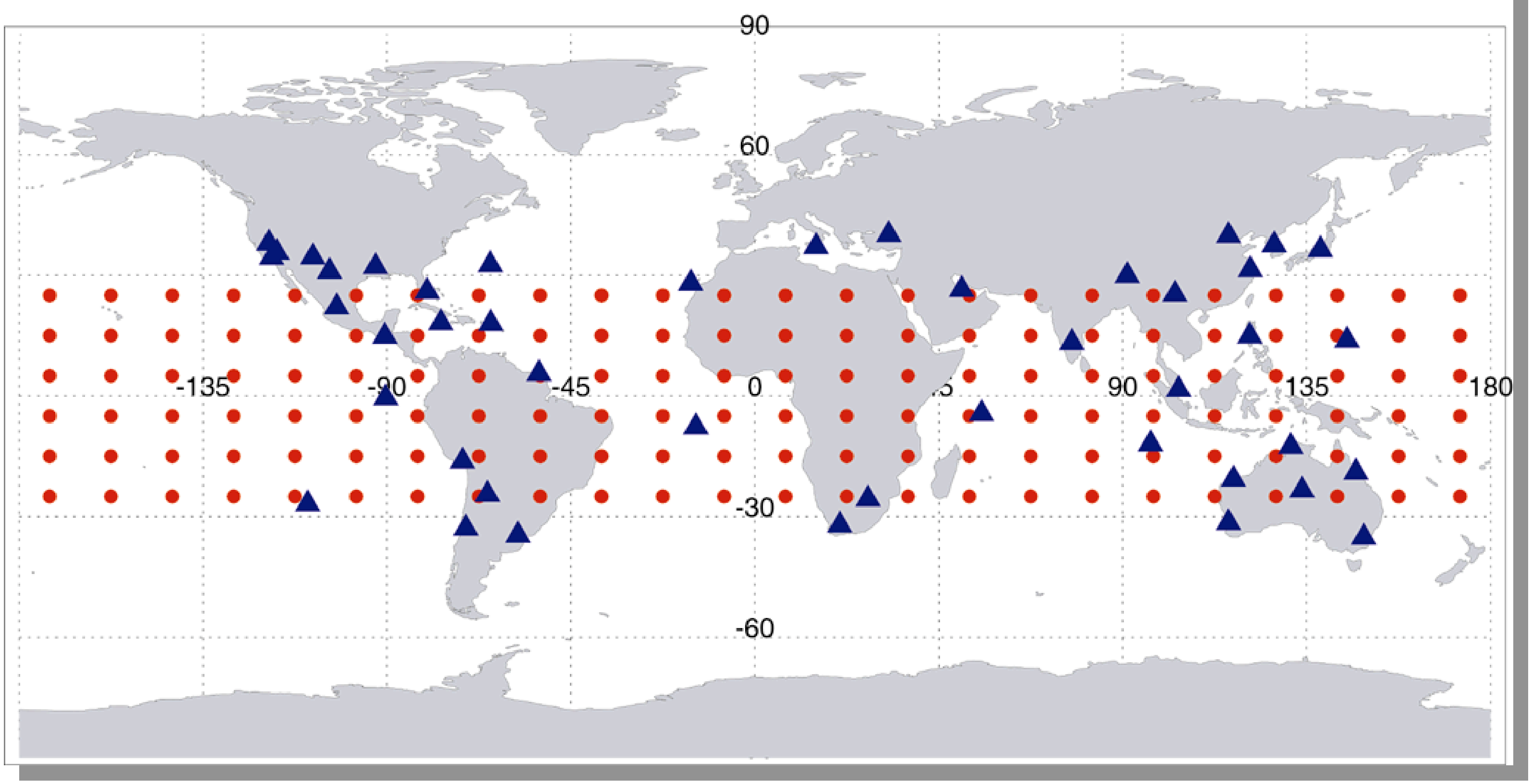
α_0 **- Empirical parameters**

P **- Covariance of error in** α_0

Parametrization of Wind

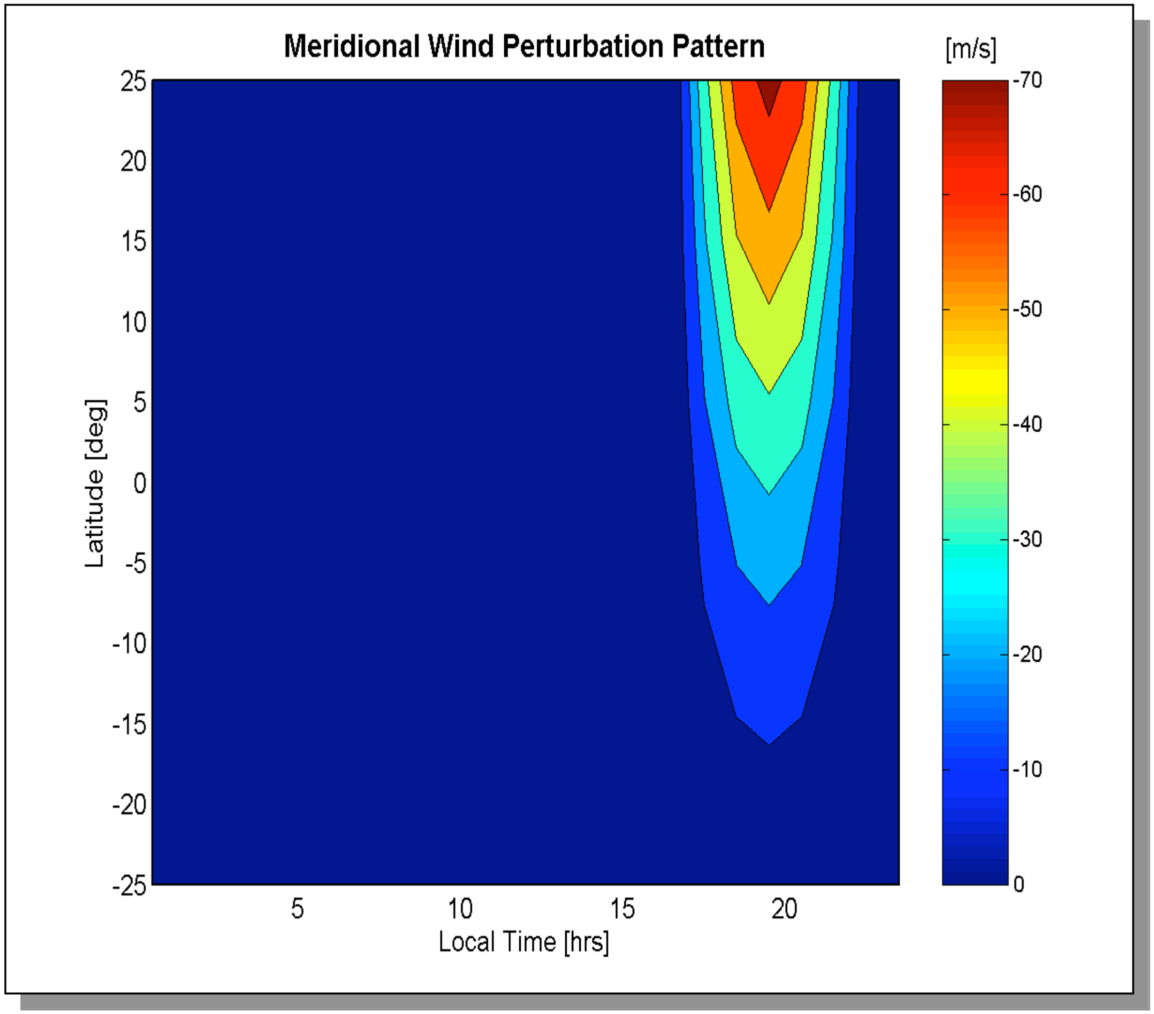
144 wind parameters covering ±30° latitudes globally

IGS Global GPS Network and Wind Parameter Grid

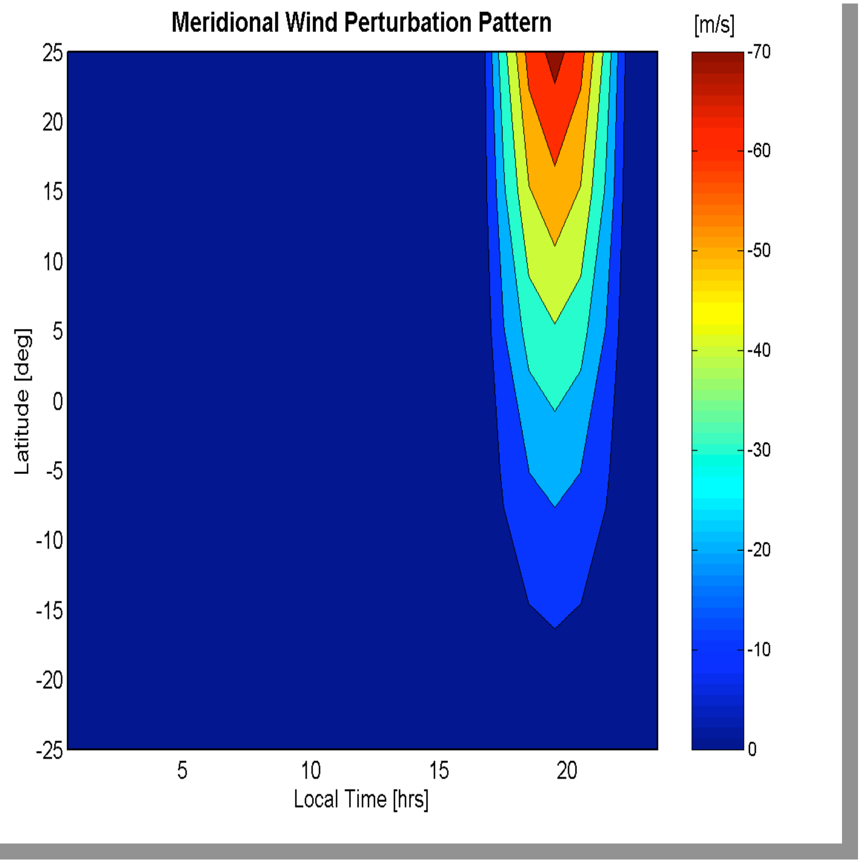


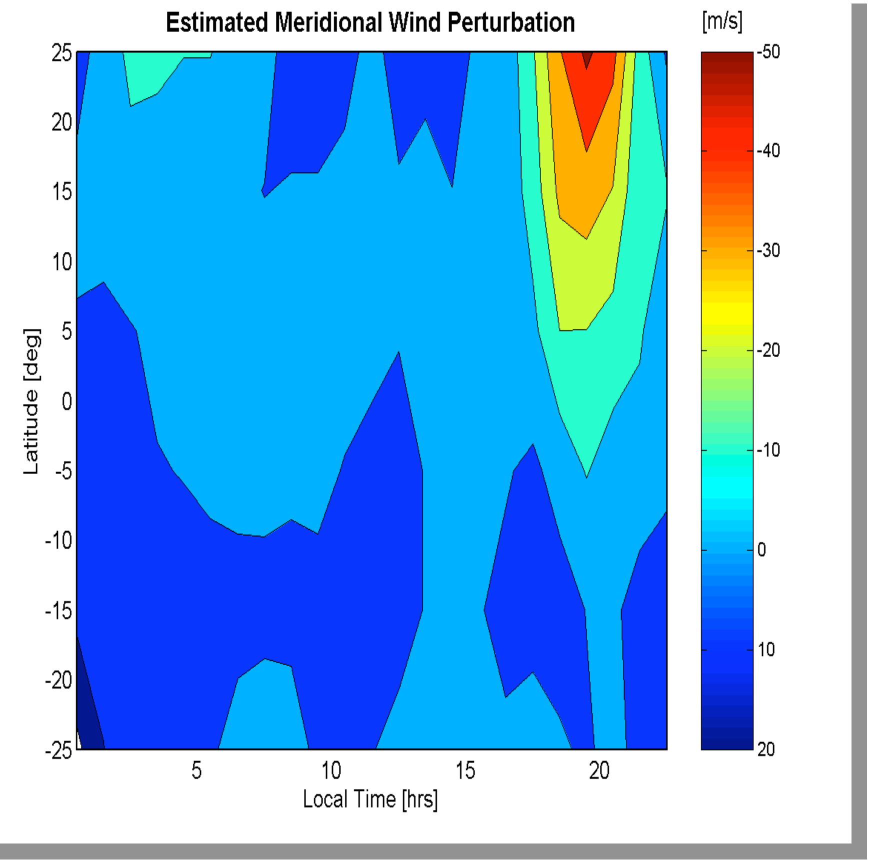
Meridional Wind Perturbation

- Southward wind to represent storm time equatorward wind perturbation
- Decay as approaching lower latitudes



Wind Estimation

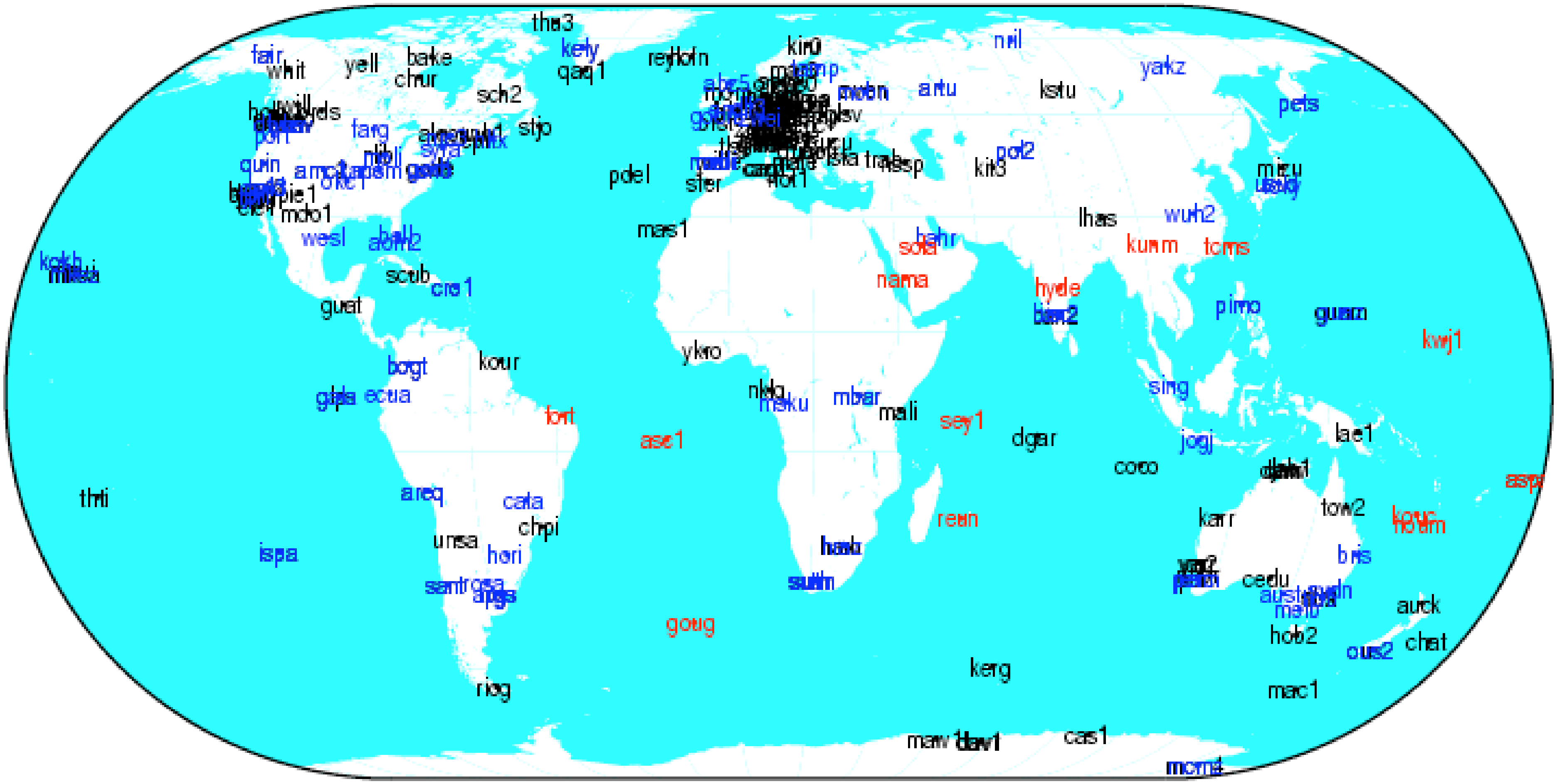




Global RT GAIM Prototype

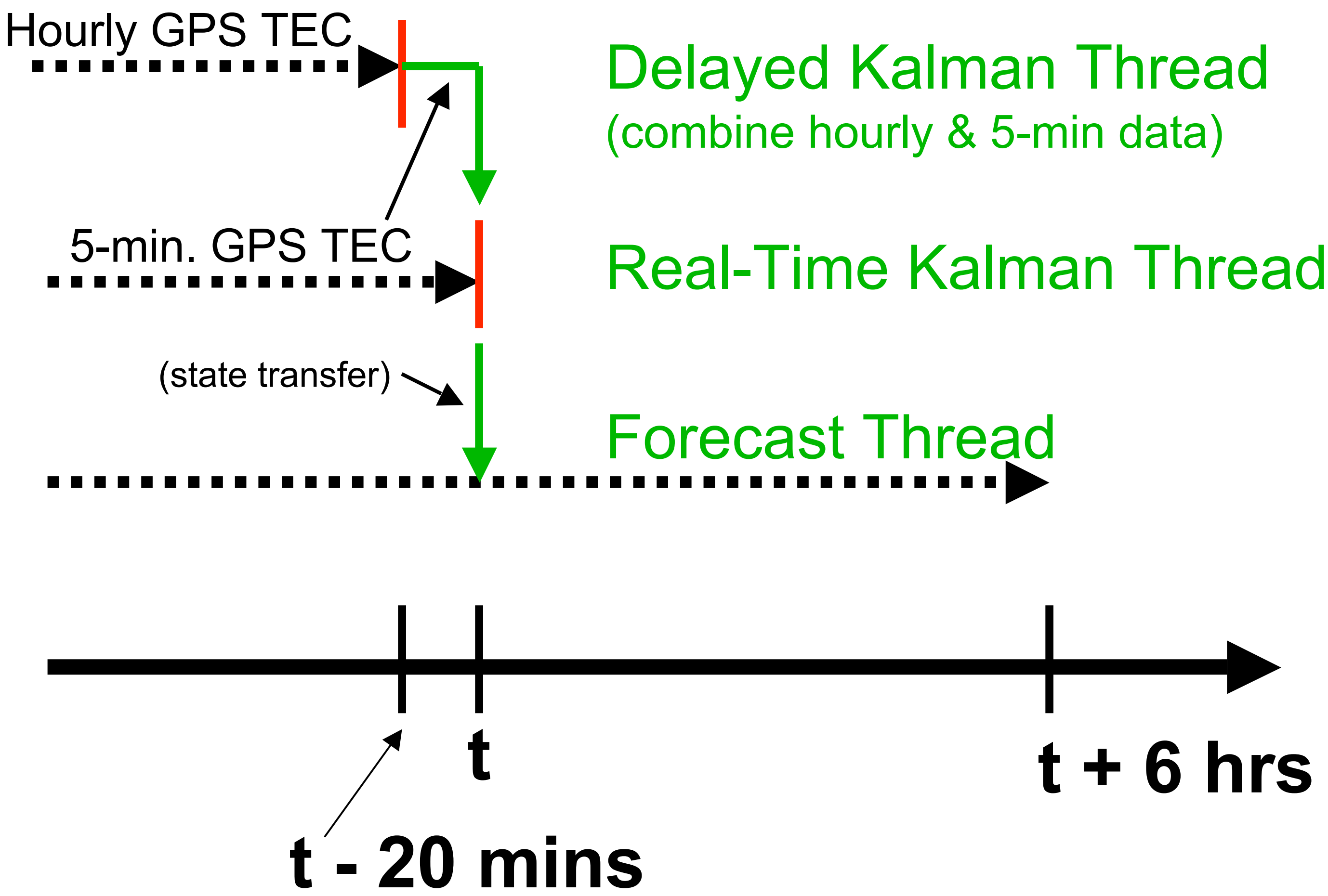
- **Input data is ground GPS TEC:**
  - **Every 5 minutes from 77 1-sec. streaming sites (~600 pts)**
  - **Every hour from more (~100) sites for global coverage**
- **Sparse Kalman Filter**
  - **Update global 3D density grid every 5 minutes**
  - **30,000 elements in variable grid**
  - **Res: 2-3^{o} 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**

Combined Hourly & Streaming Sites



Black = current all hourly, **Blue** = 77+ streaming, **Red** = potential add-ons

Concept of Operations: Three GAIM Threads



Considerations for COSMIC

- Use a variant of the real-time implementation
- Ionospheric observables can be generated locally of acquired directly from CDAAC
- Output an updated global electron density grid
  - Cadence TBD
  - High latitudes excepted
- JPL has software ready for COSMIC (in principle)
  - Observation matrix for GPS data type
  - Ground and space data
  - Model upgrades being worked
- Ionospheric work highly complementary to atmospheric studies for climate
- Data agreements…

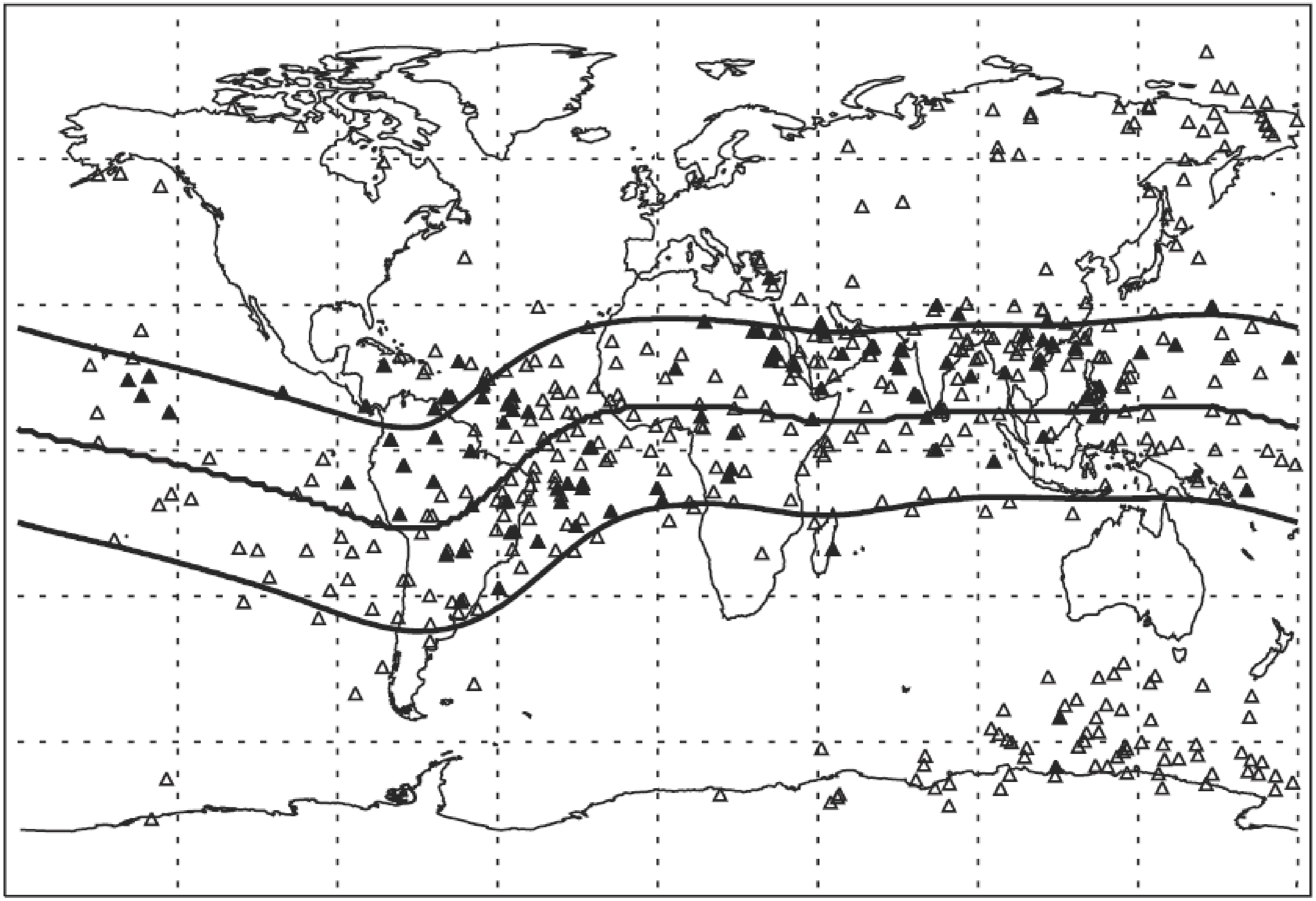
Conclusion

- GPS occultations provide very powerful and unique capabilities for ionospheric profiling/imaging
- COSMIC will be the first system to provide the 3D electron density in the ionosphere—greatly complemented by the existing ground system
- Data assimilation is a new comer to the ionosphere. Its importance is recognized by numerous scientists and many funding organization including NSF, DoD and NASA
- Importance of ionospheric specification and prediction
  - Operational users
  - Indirect sensing of the upper atmosphere, magnetic and solar activities
  - Improved understanding of the physical processes coupling the sun, heliosphere, magnetosphere and the ionosphere
  - Improved estimates of ionospheric currents

Goal

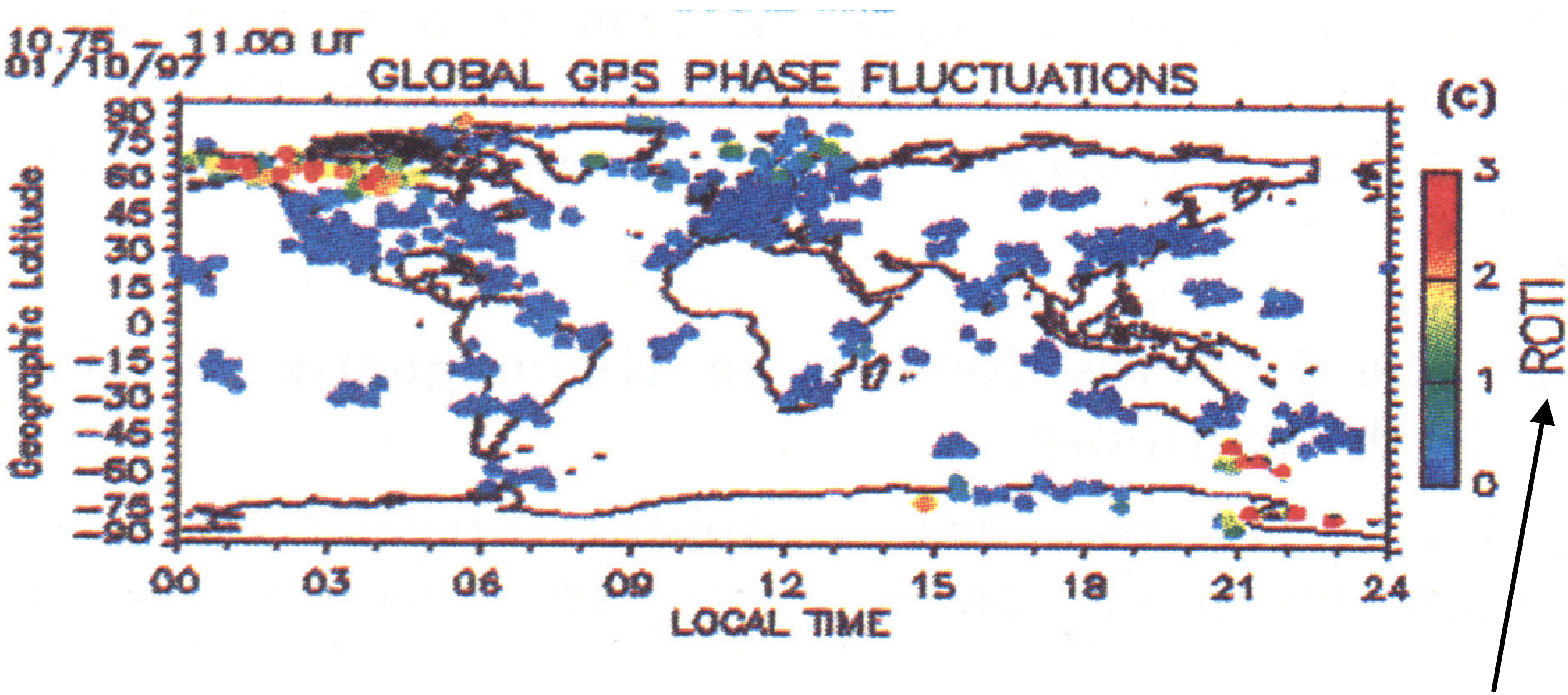
- Demonstrate value of GPS occultation constellation for scientific and practical applications
- 2-hour data latency should demonstrate improvement
- 15-minute data latency target should be maintained
- Much detailed work needs to be done

Location Of Strong Scintillation (Amplitude)



Straus et al., GRL 2003 February & March, 2002

High Latitude Scintillation At Solar Minimum (Phase)



Phase fluctuation index

Pi et al., GRL 1997

Global Morphology Of Scintillation

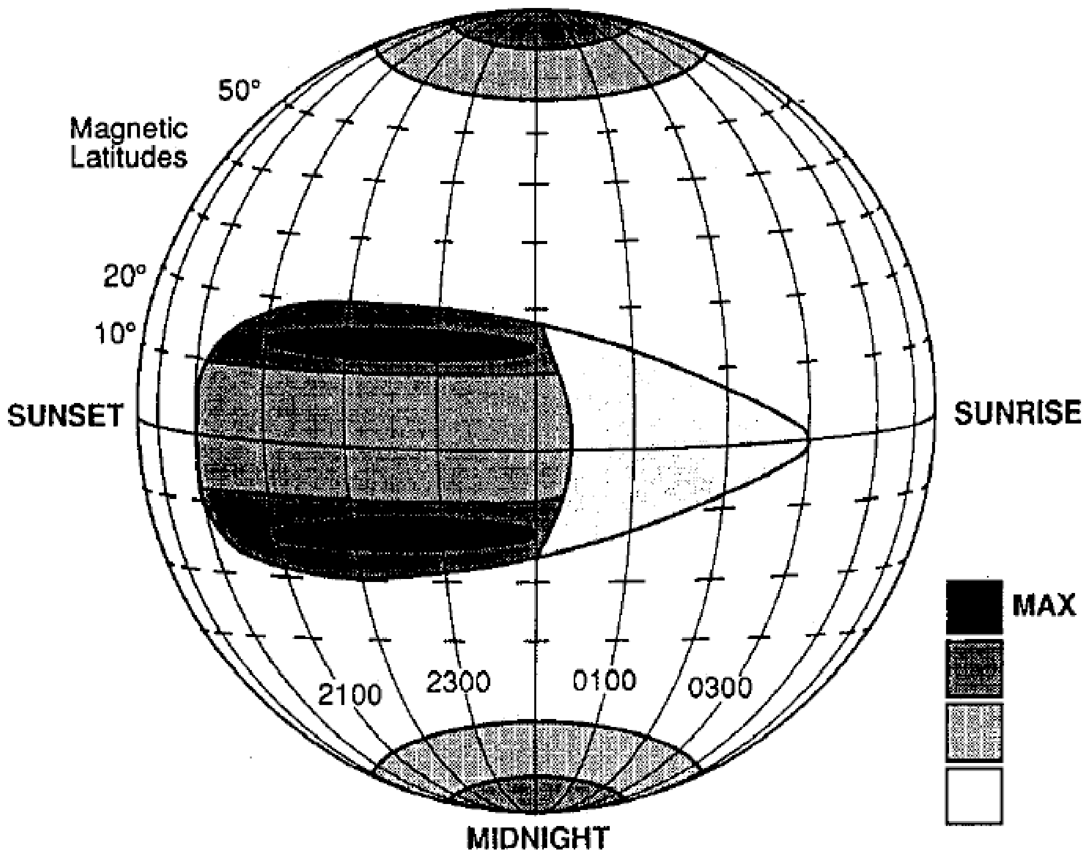


Figure 2. The nighttime scintillation activity during solar maximum. The anomaly regions of the equatorial ionosphere show the most intense scintillation.

Aarons, 1996