GNSS-Based Space Weather Systems Including COSMIC Ionospheric Measurements

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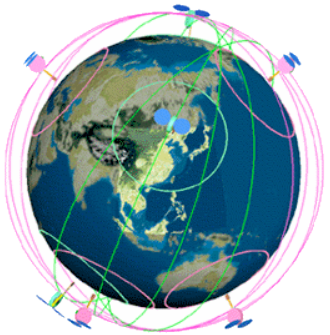
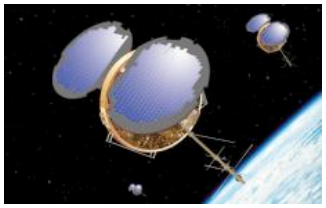
Outline

- Introduction
- UCAR and JPL product comparisons
  - Abel profiles
  - Calibrated TEC
- Assimilating ground-based GPS and COSMIC into JPL/USC GAIM (June 2006)
- JPL/USC GAIM Validation using:
  - Arecibo ISR
  - Jason-2 VTEC
  - Abel profiles
- Conclusions & Future Plans

FORMOSAT-3 / COSMIC

- Successful launch April 14, 2006
- Six satellite constellation
- Initial configuration: single orbital plane
- Final configuration:
  - 800 km altitude
  - Separate orbital planes
  - 72 degrees inclination
- JPL-designed flight GPS receiver
- Broad Reach Engineering built
- Near real-time feed to NOAA

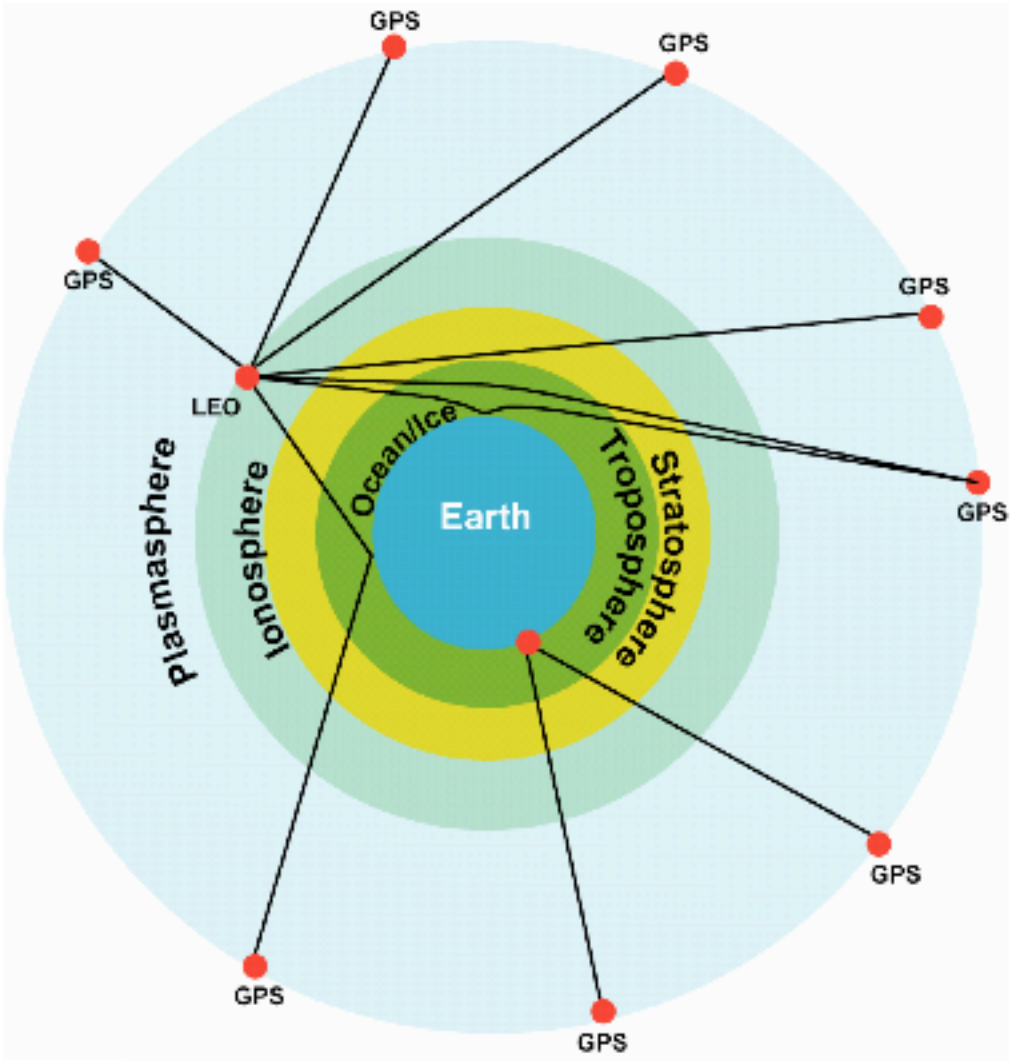




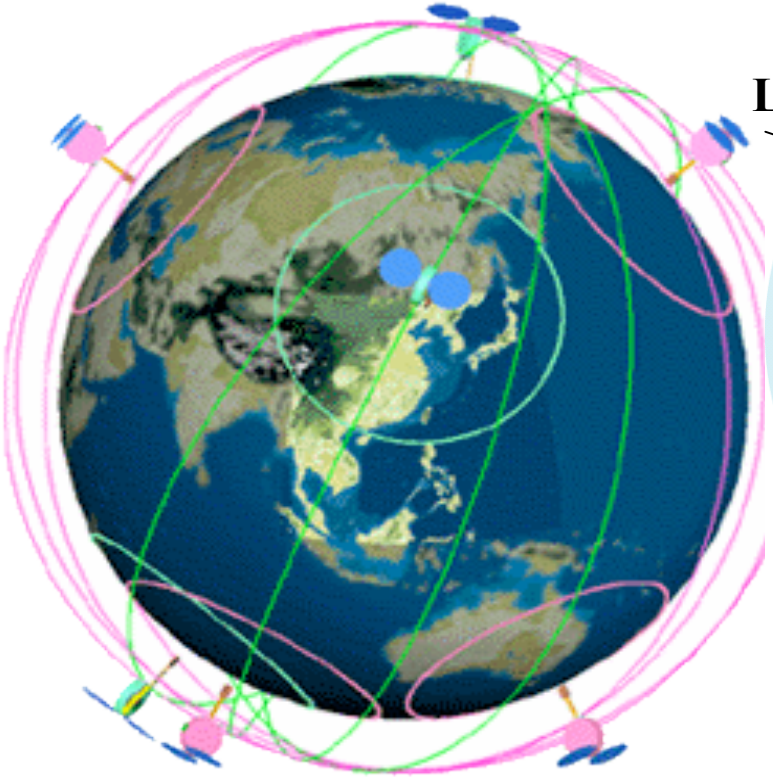
UCAR NSF NASA USAF NOAA NSPO ONR

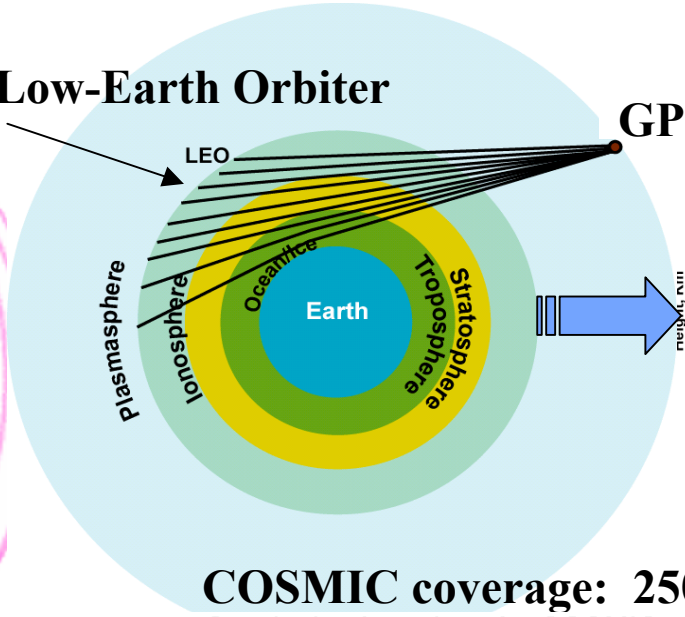
Overview of GPS Remote Sensing Applications

- **FROM GROUND**
  - Troposphere
  - Ionosphere
- **FROM SPACE**
  - Troposphere
  - Stratosphere
  - Ionosphere
  - Plasmasphere
- **Ocean Reflection**

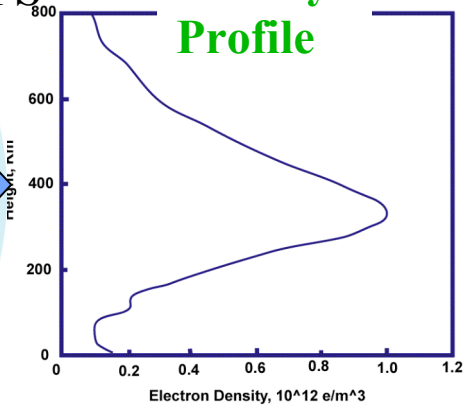


COSMIC
Ionospheric Weather Constellation



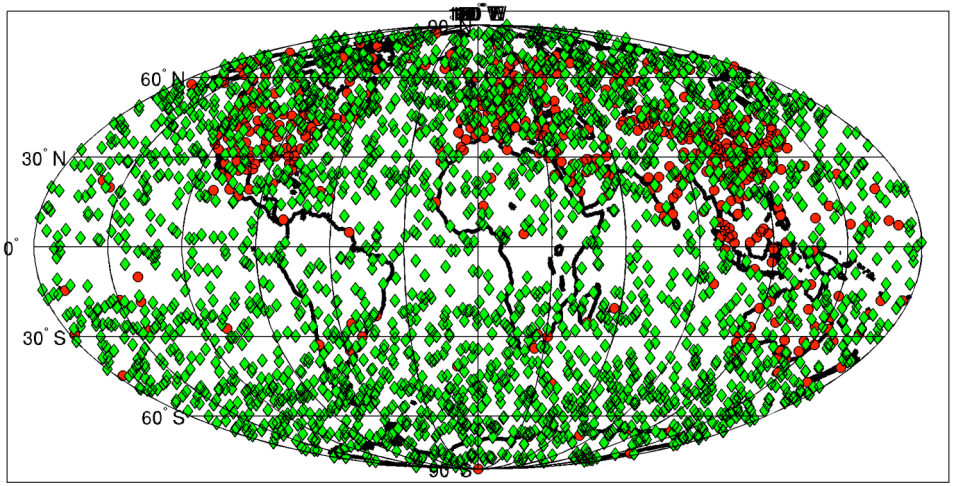


Electron Density Profile



COSMIC coverage: 2500 profiles/day

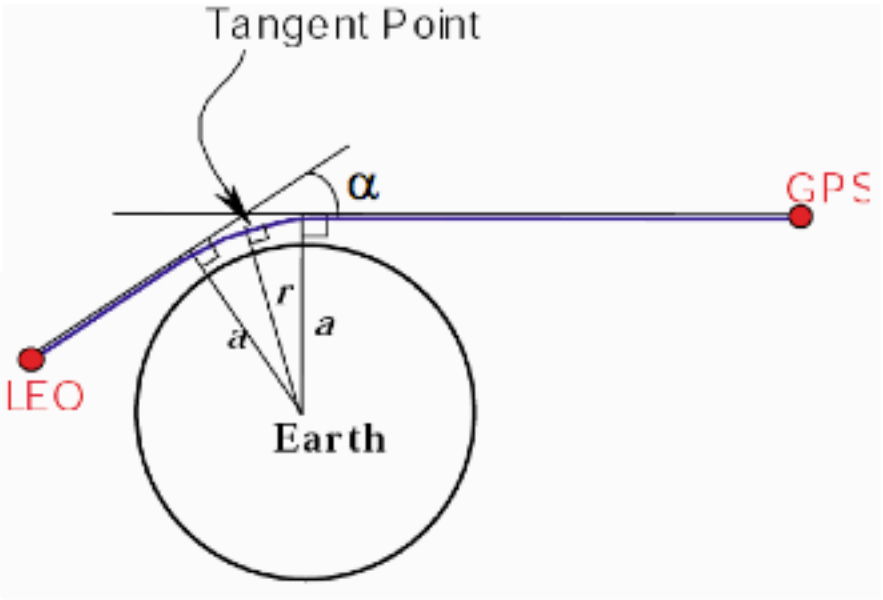
Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs

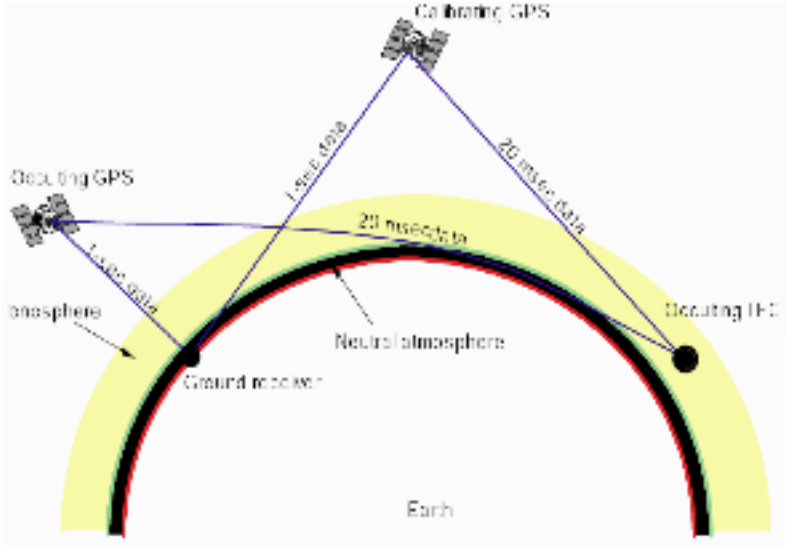


Six-satellite COSMIC constellation
Launched April 14, 2006

NSF NASA USAF NOAA NSPO ONR

Occultation Geometry





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

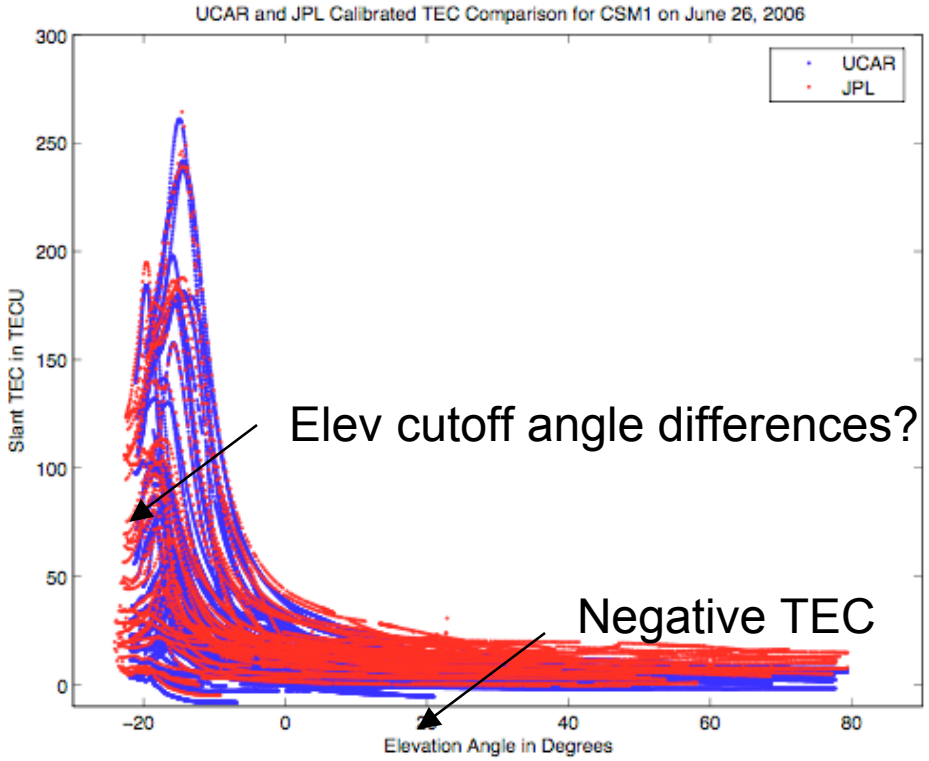
$$\alpha(a) = 2a\int_{a}^{\infty} \frac{1}{\sqrt{a'^2 - a^2}} \frac{d\ln(n)}{da'} da'$$

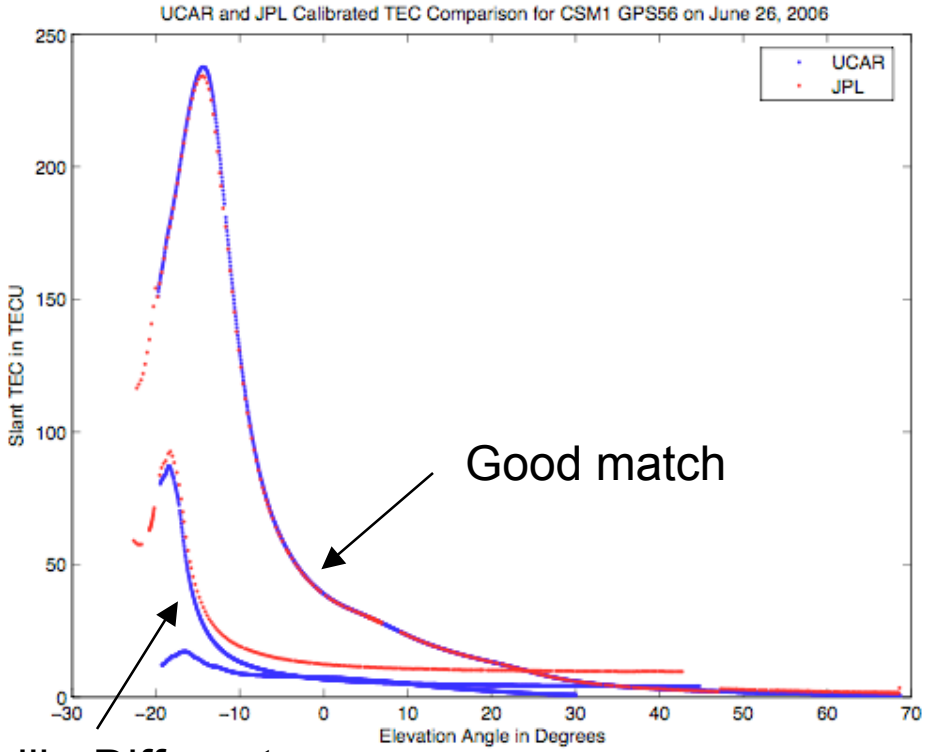
$$\ln(n(r)) = \frac{1}{\pi}\int_{nr}^{\infty} \frac{\alpha}{\sqrt{a^2 - r^2 n^2}} da$$

Derivation of Electron Density

$$N = (n-1)\times 10^6 = a_1 \frac{P}{T} + a_2 \frac{P_w}{T^2} - 40.3\times 10^6 \frac{n_e}{f^2}$$

Comparison of Calibrated Slant TEC Measurements for June 26, 2006

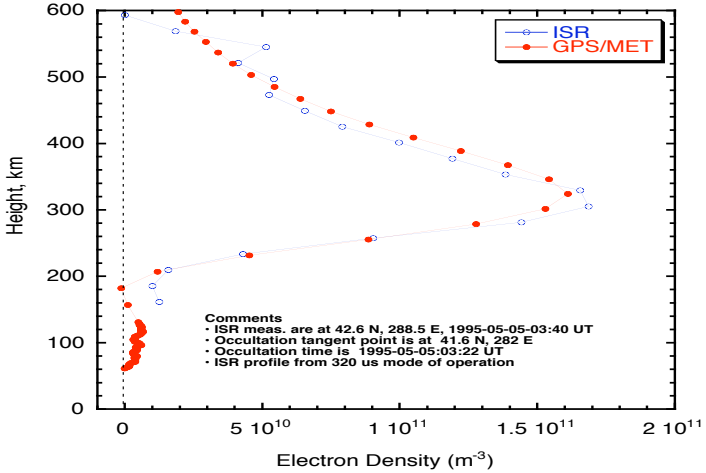




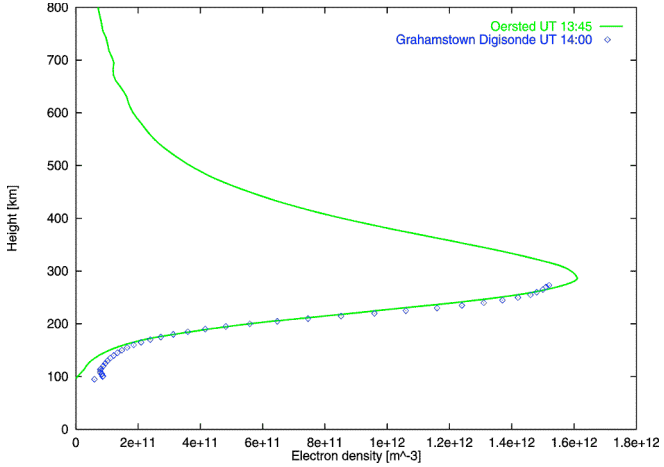
- An example of comparison of calibrated TEC between JPL and UCAR
- There appears to be a 2-3 TECU bias between JPL and UCAR slant TEC
- Negative TEC, differences between UCAR and JPL elevation cutoff angles
- Similar data volumes between JPL and UCAR

Historic examples of Abel electron density profiles

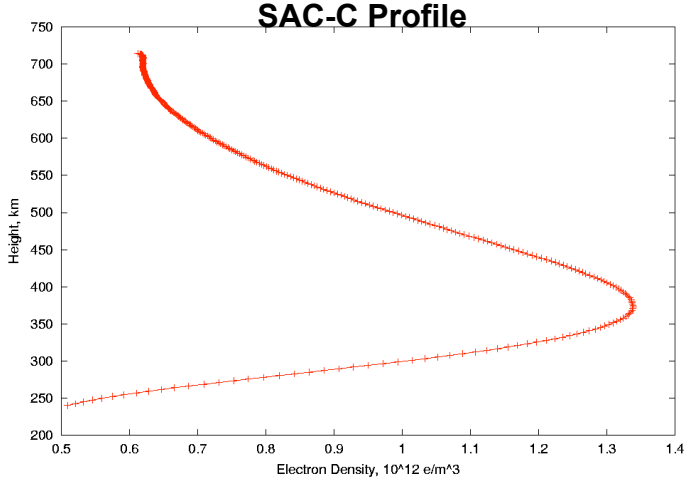
GPS/MET Profile
(Compared to Millstone hill radar)



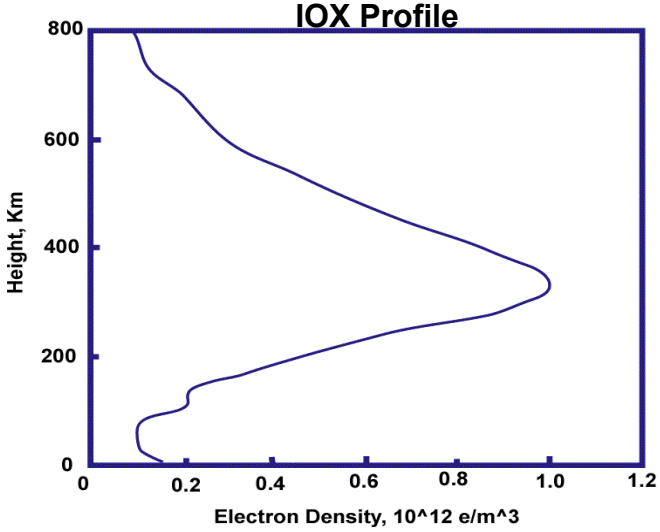
Oersted Profile
(Compared to nearby ionosonde)



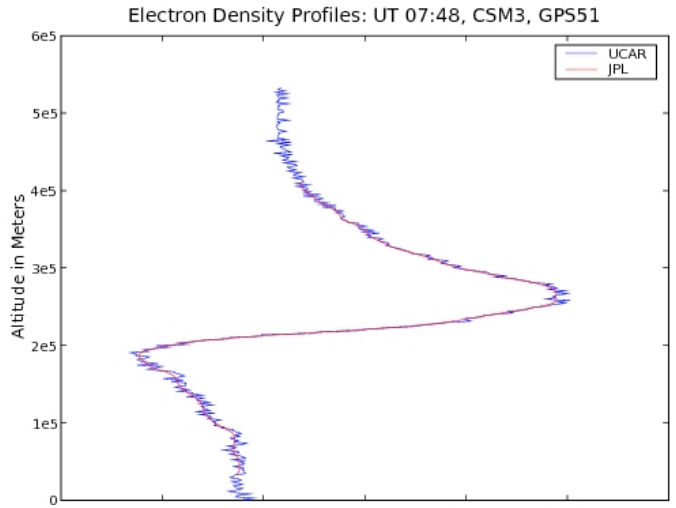
SAC-C Profile

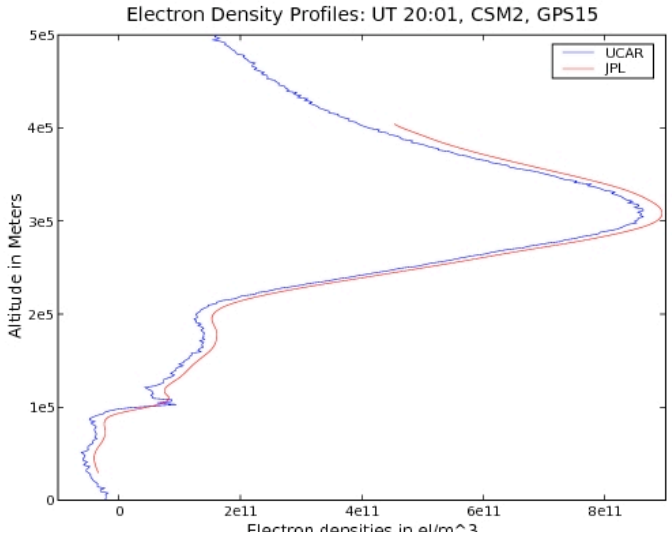


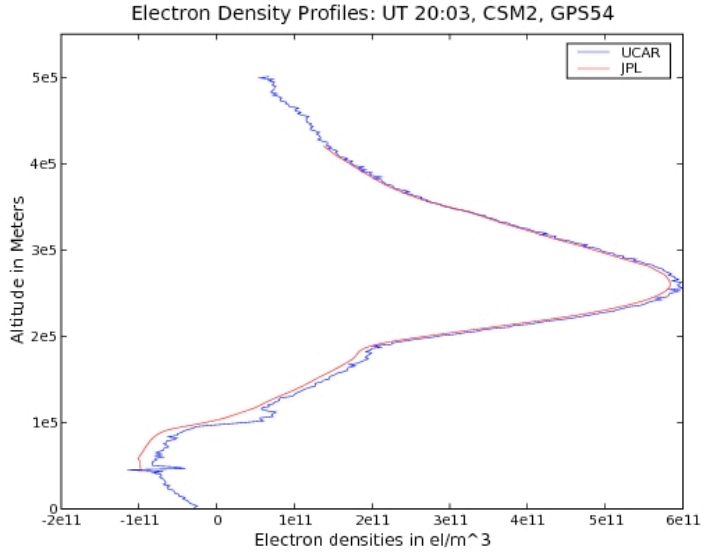
IOX Profile

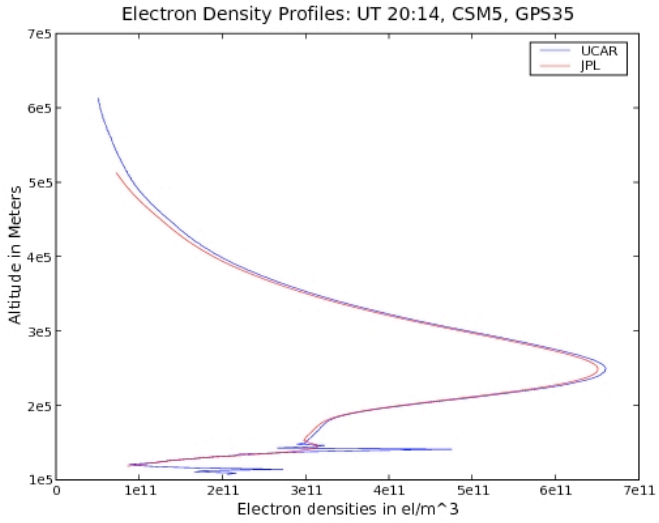


Comparison of UCAR and JPL Abel Profiles June 26, 2006



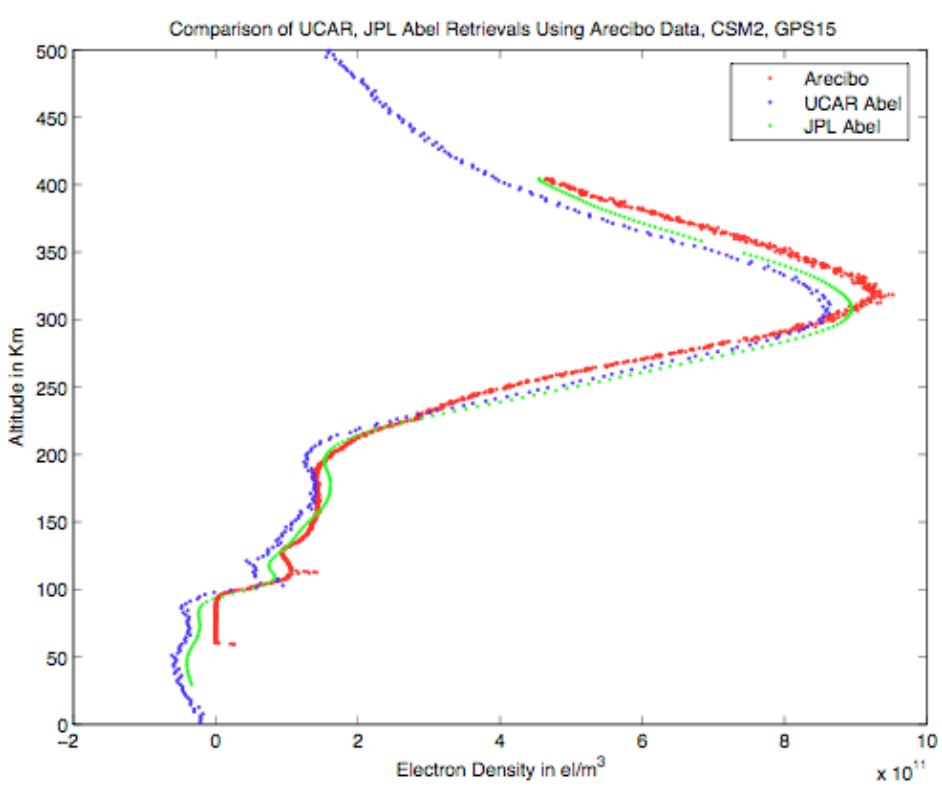


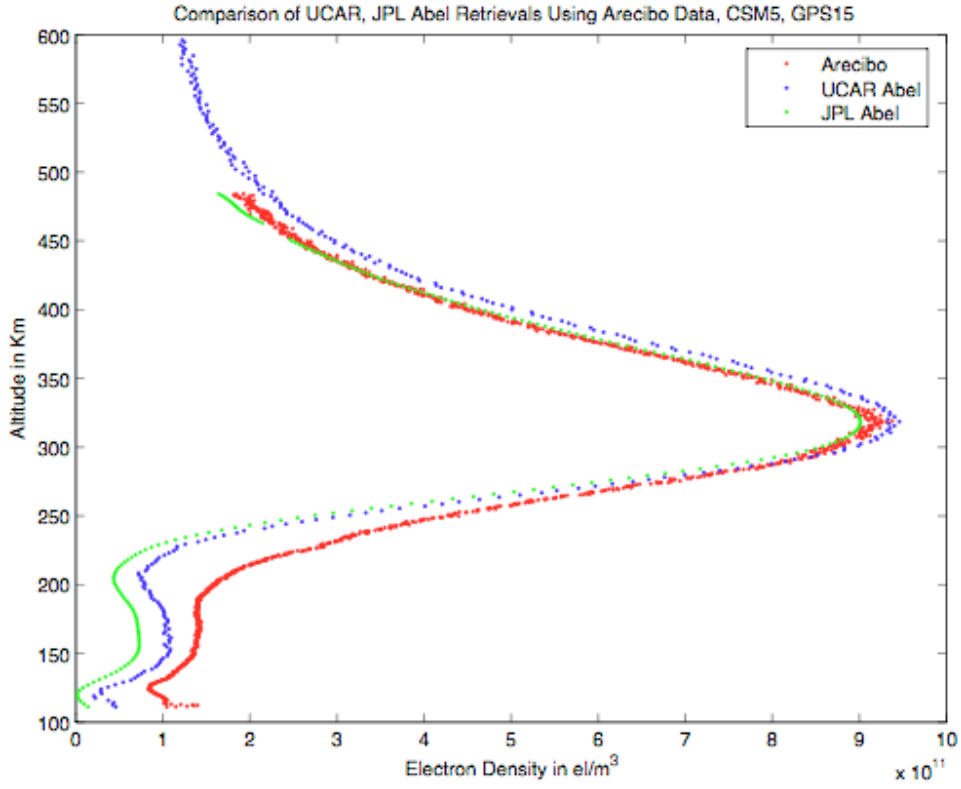




UCAR and JPL Abel profiles usually agree well

Validating UCAR and JPL Abel Profiles Using Arecibo ISR Measurements for June 26, 2006

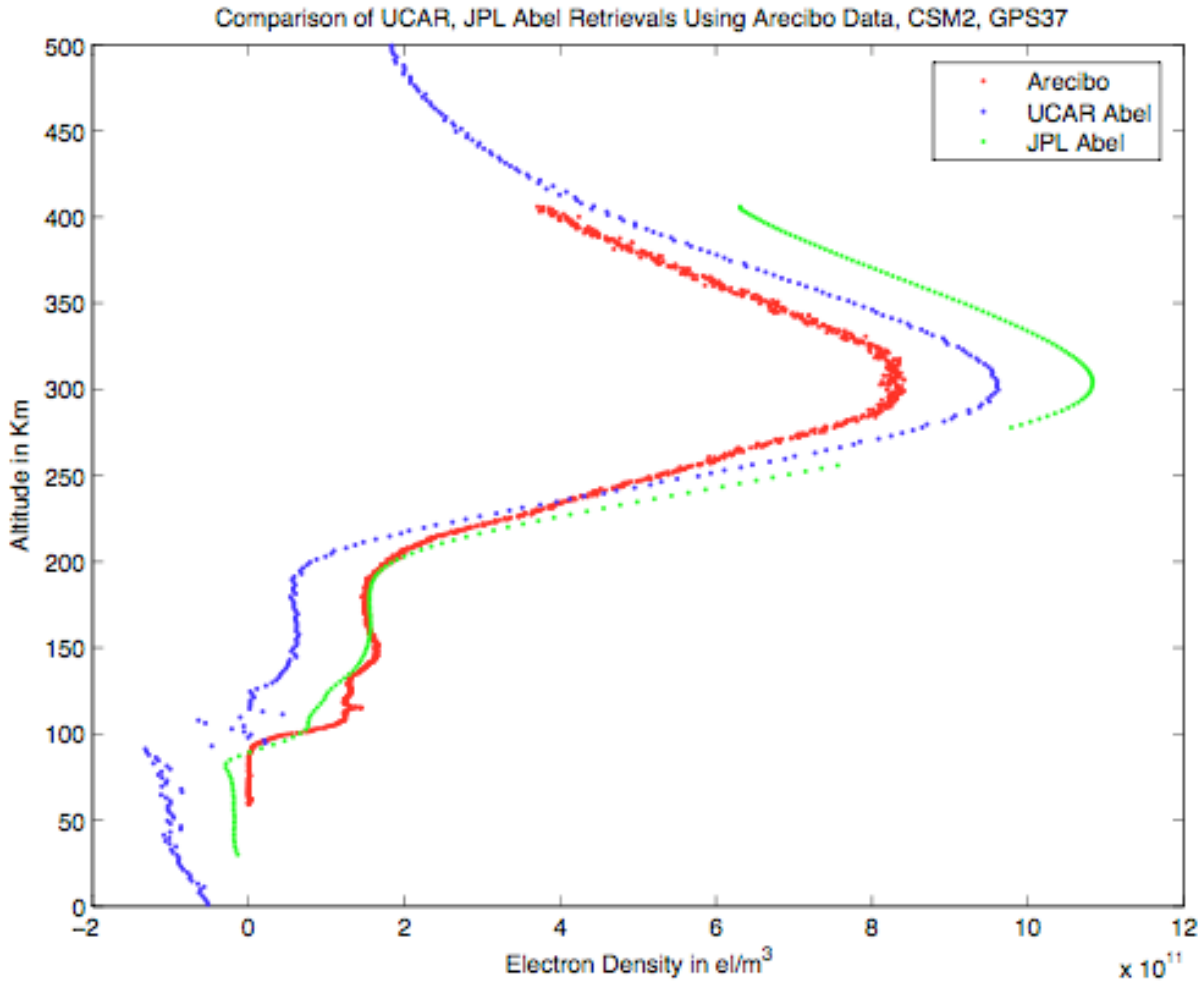




- E-region error in naive Abel profiles: negative electron densities
- Spacecraft not yet in final orbital altitudes so Abel inversions more difficult
- JPL smoothed, UCAR unsmoothed profiles

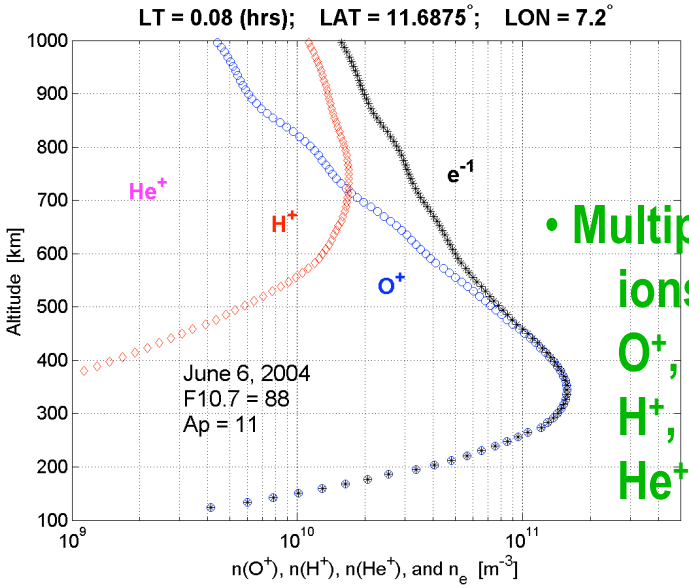
Arecibo calibrated profiles are courtesy of Prof M. Kelley and V. Wong of Cornell University

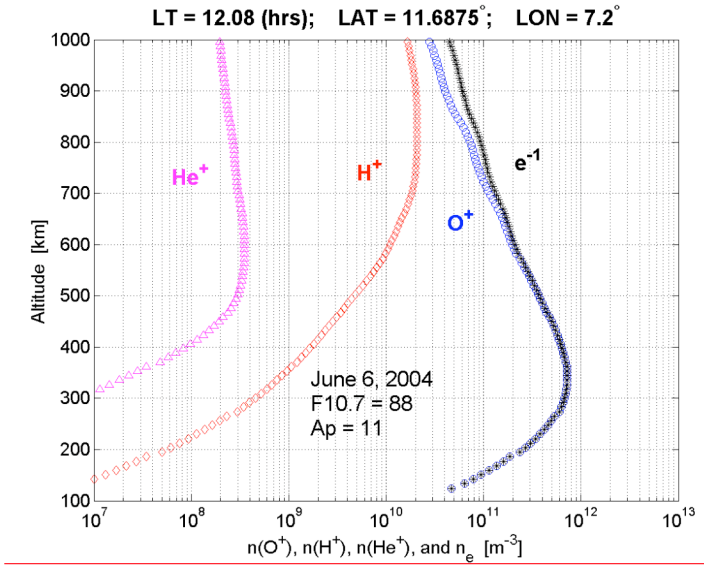
Validating UCAR and JPL Abel Profiles Using Arecibo ISR Measurements for June 26, 2006



- Some cases: Larger differences between Arecibo, JPL, UCAR

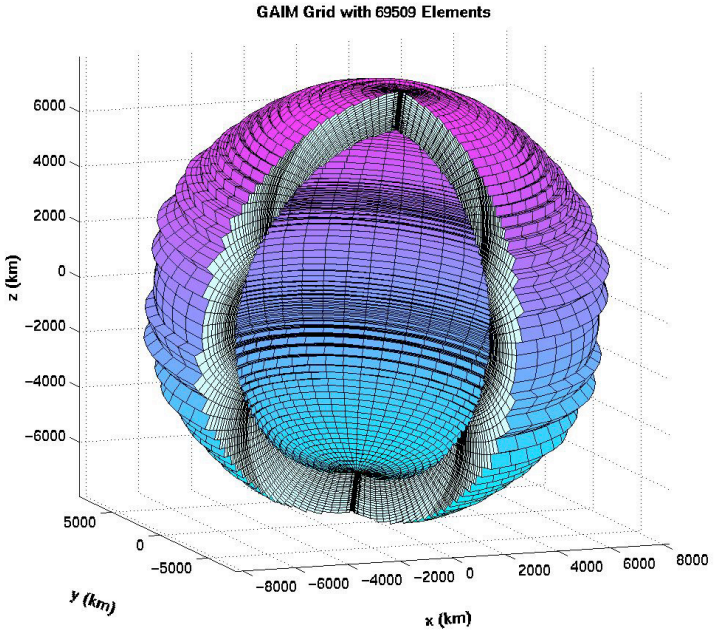
GAIM: Global Assimilative Ionosphere Model



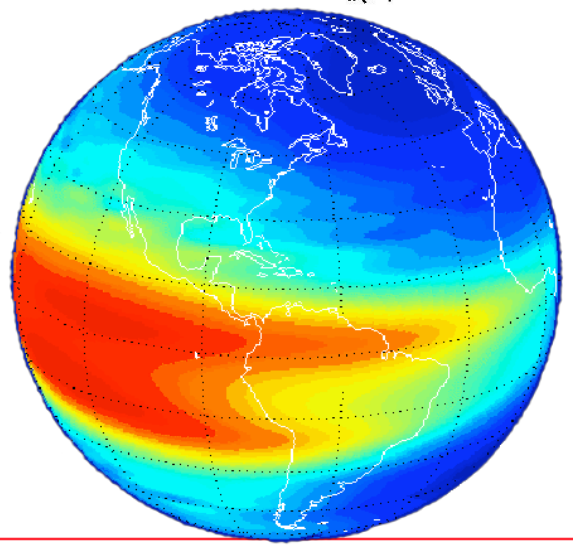


- 3-D grid in a Magnetic frame
- Multiple ions: O^+, H^+, He^+

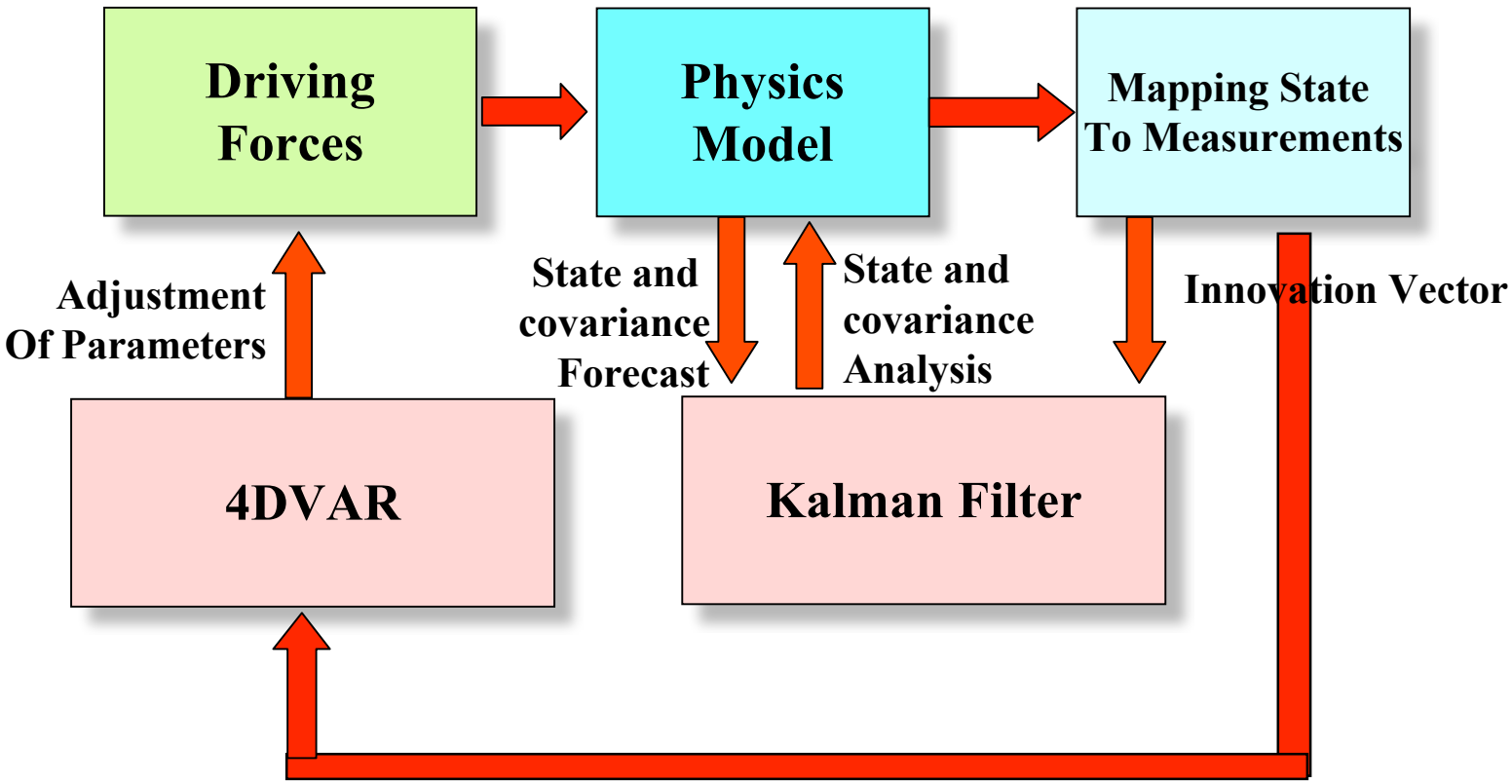
Numerical Scheme
- Finite volume on a fixed Eulerian grid
- Hybrid explicit-implicit time integration scheme



- Global and regional modeling by solving plasma hydrodynamic equations



Global Assimilative Ionospheric Model
Data Assimilation Process



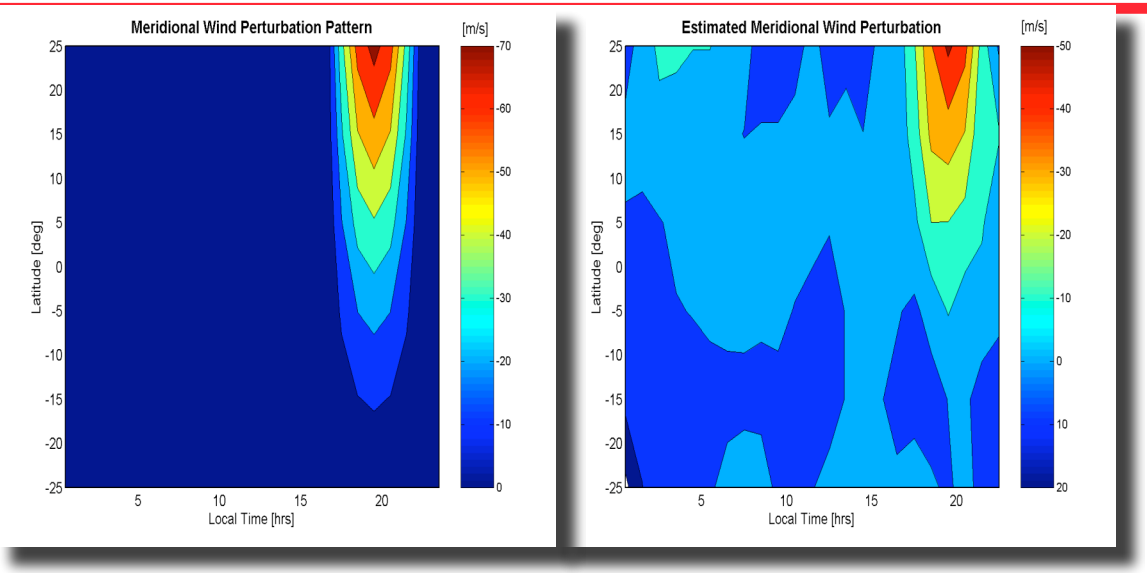
- 4-Dimensional Variational Approach
  - **Minimization of cost function by estimating driving parameters**
  - **Non-linear least-square minimization**
  - **Adjoint method to efficiently compute the gradient of cost function**
  - **Parameterization of model "drivers"**
- Kalman Filter
  - **Recursive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

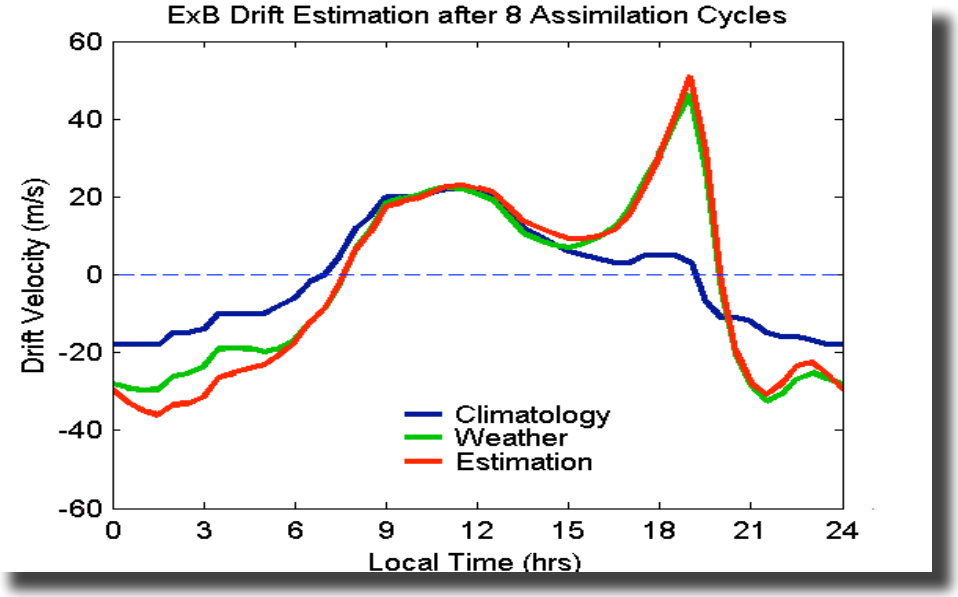
    Optimal interpolation

    Band-Limited Kalman filter

Estimation of Ionospheric Dynamical Drivers

- **Observation System Simulation Experiments (OSSE) to estimate "perturbed" drivers at low latitudes:**
  - **Neutral winds**
  - **E×B vertical drift velocity**
  - **Production terms**
- **Synthetic ground GPS TEC data**
- **Real Data:**
  - **Ground GPS TEC**
  - **COSMIC TEC: upward & occultation**

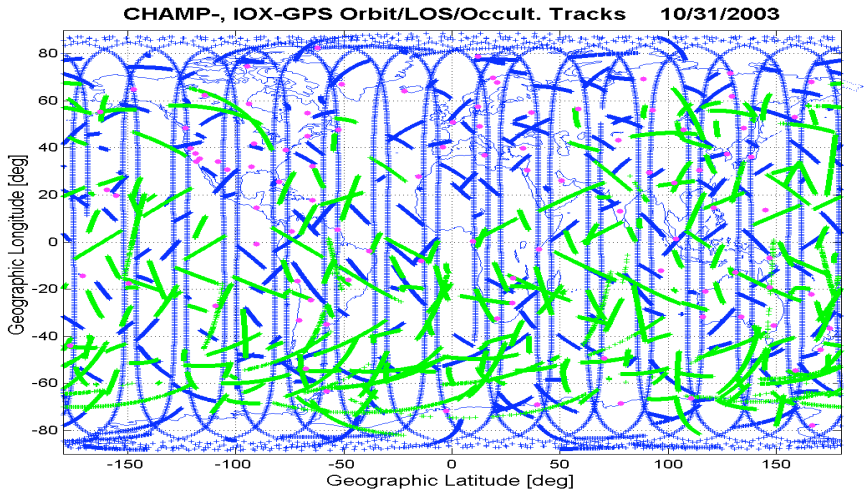


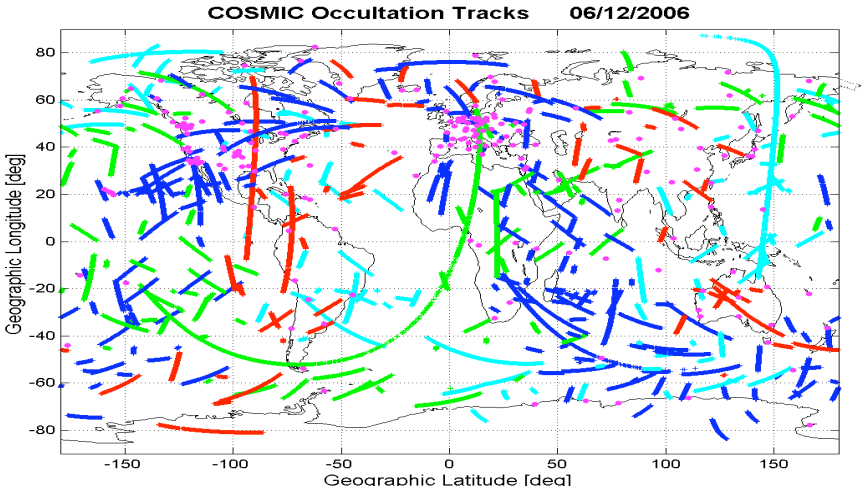


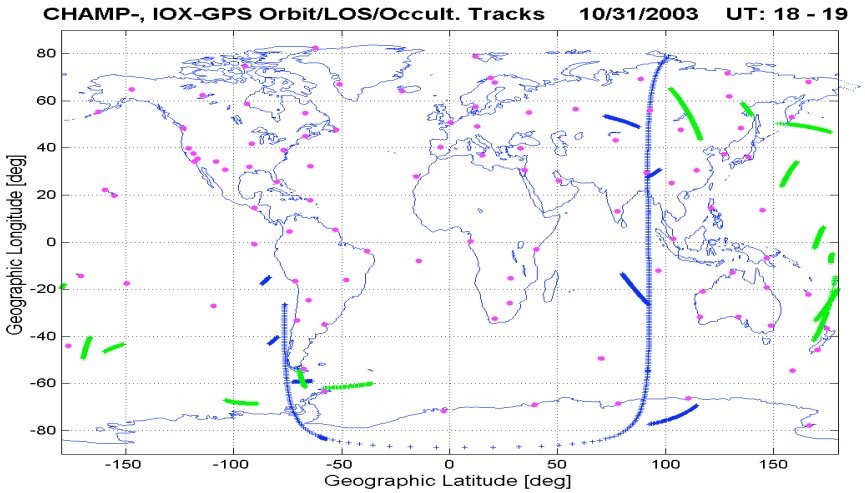
Input Data Types

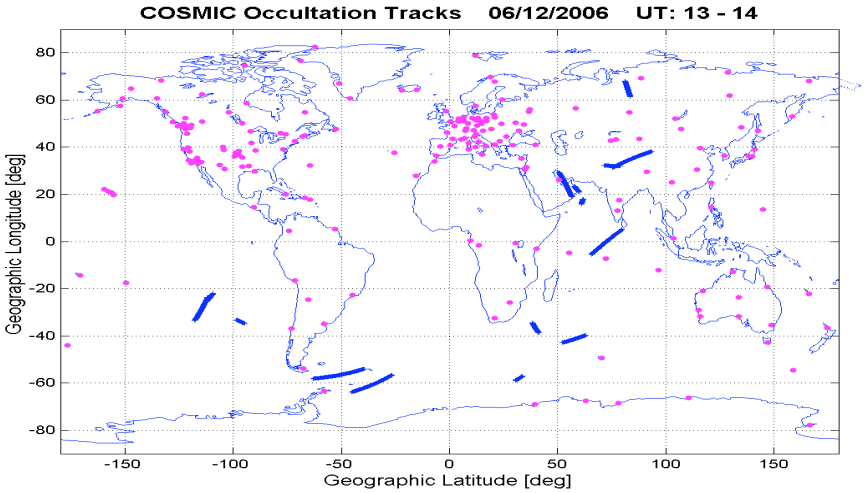
- **Ground GPS Data (Absolute TEC)**
  - >150 5-min. to Hourly Global GPS Ground Stations
  - Assimilate >300,000 TEC points per day
- **Space GPS Data (Absolute or Relative TEC)**
  - CHAMP (@ 440 km)
  - SAC-C (@ 700 km)
  - IOX (@ 800 km)
  - GRACE (@ 350 km)
  - Topex/Poseidon (@1330 km) (Upward looking only)
  - Jason 1 (@1330 km) (Upward looking only)
  - C/NOFS & COSMIC constellation
- **UV airglow data (135.6 nm radiance)**
  - LORAAS on ARGOS, GUVI on TIMED
  - SSUSI/SSULI on DMSP
  - TIP on COSMIC
- **Other Data Types**
  - TEC from TOPEX/JASON Altimeters
  - Ionosonde bottomside profiles
  - DMSP in situ
  - CHAMP in situ
  - GRACE cross-links

COSMIC Ground and Spatial Coverage







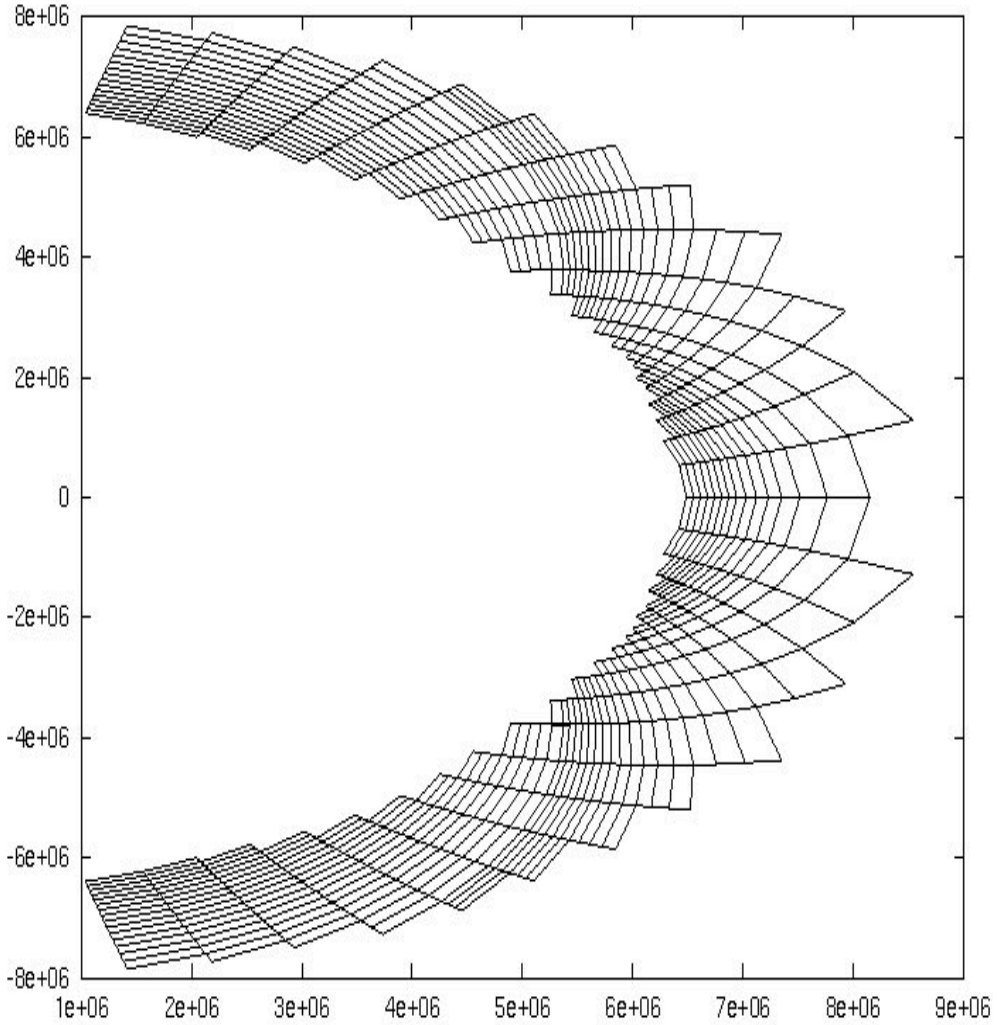


Coverage by CHAMP and IOX

6 COSMIC satellites: moving into their final orbits.

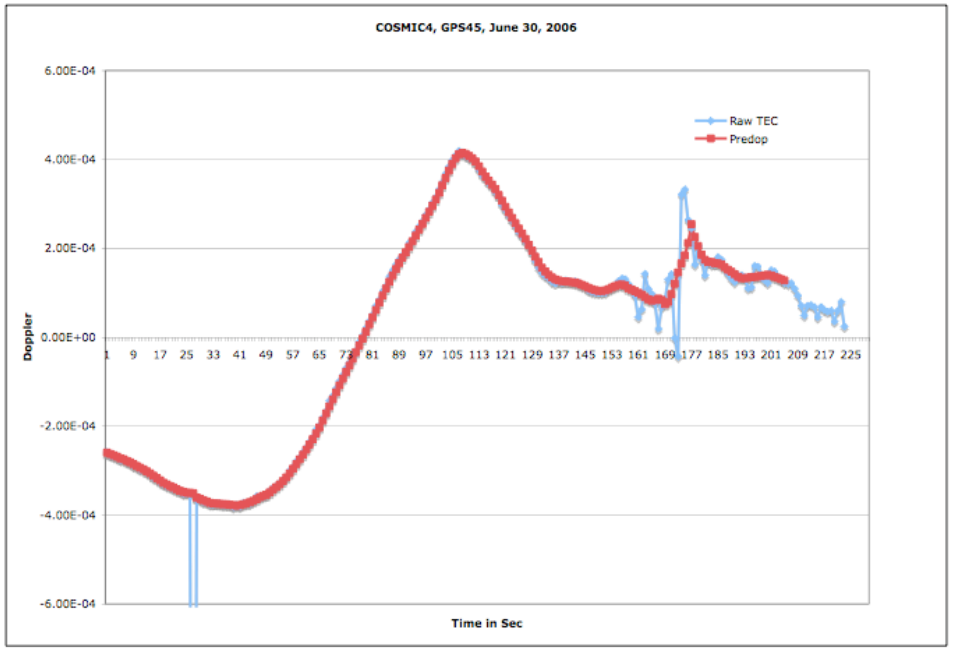
Kalman Assimilation Runs for June 26, 2006

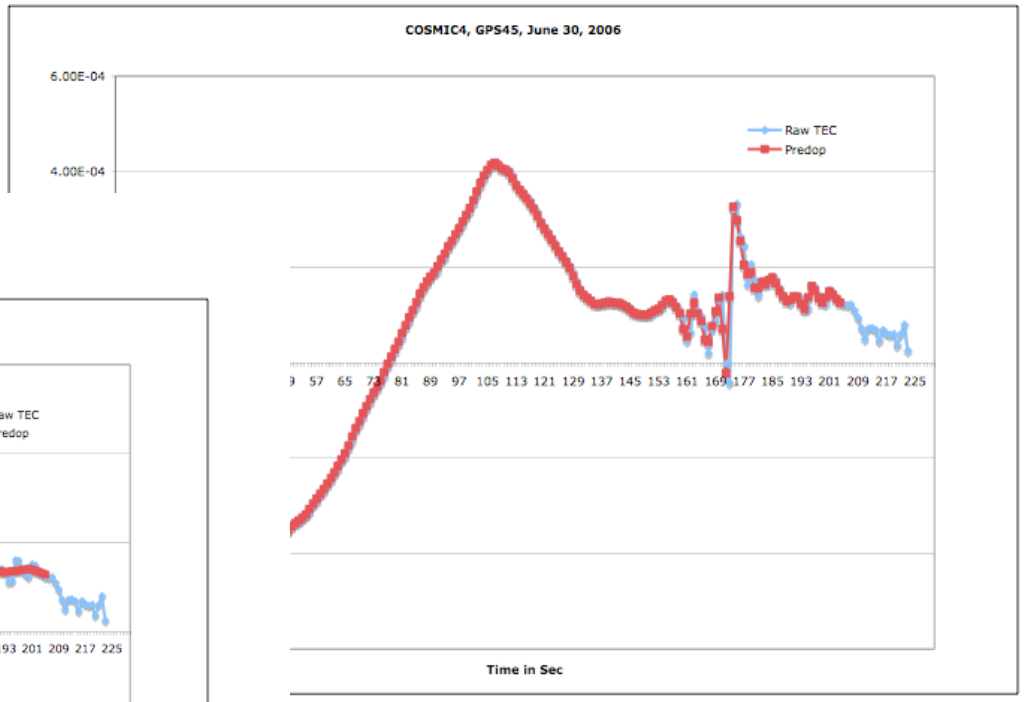
- **Three runs:**
  - **GAIM Climate (no data)**
  - **Ground GPS TEC (200 sites)**
  - **Ground + COSMIC links (upward & occultation)**
- **Resolution: 2.5 deg. Lat.**
  10 deg. Lon.
  40 km Alt.
- **No. of grid cells: 100,000**
- **Sparse Kalman filter:**
  - Update & propagate covariance
  - Truncate off-diagonal covariance that is beyond physical correlation lengths



The Impact of Smoothing on Abel for June 26, 2006

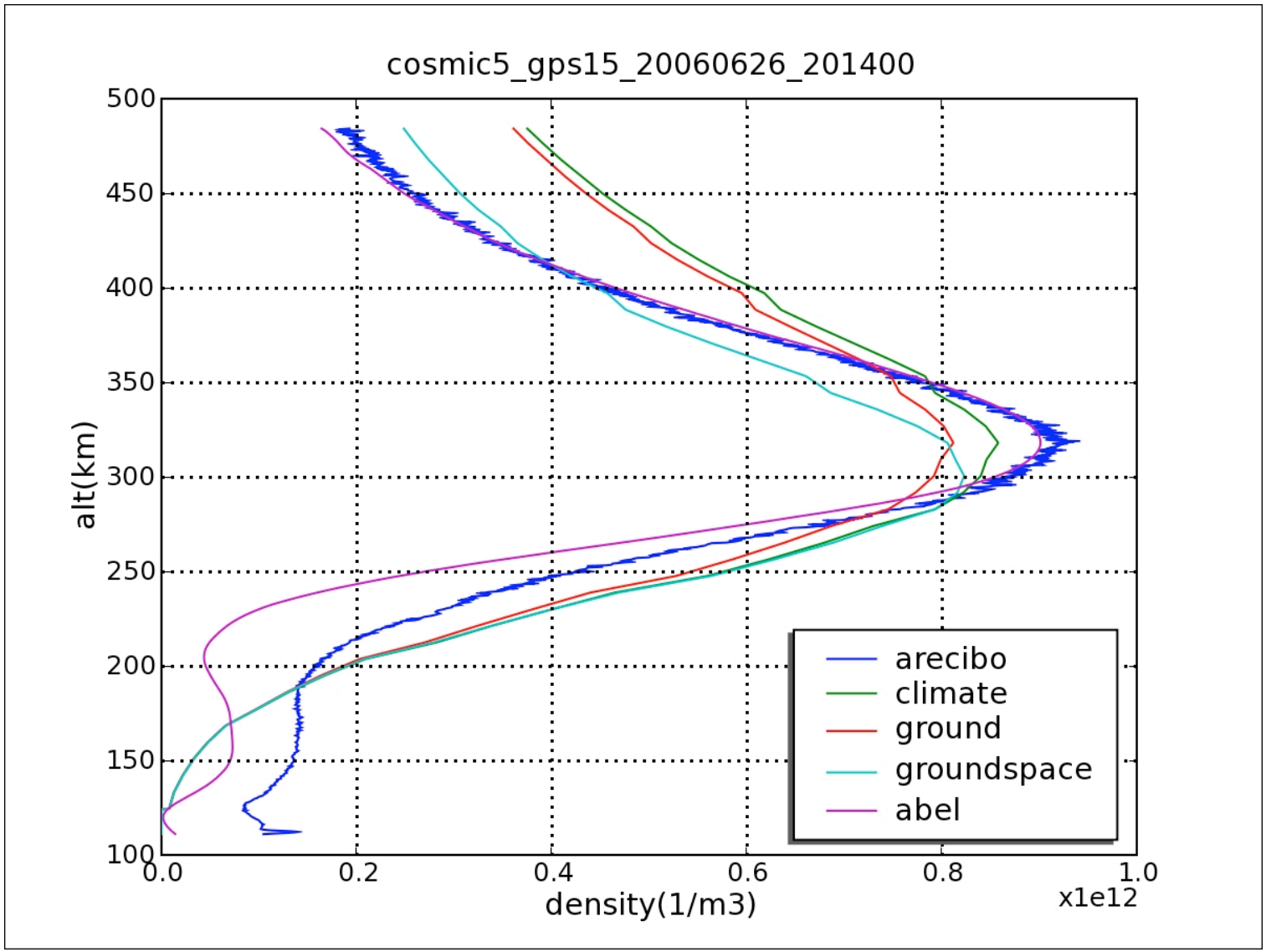
Smoothing filter



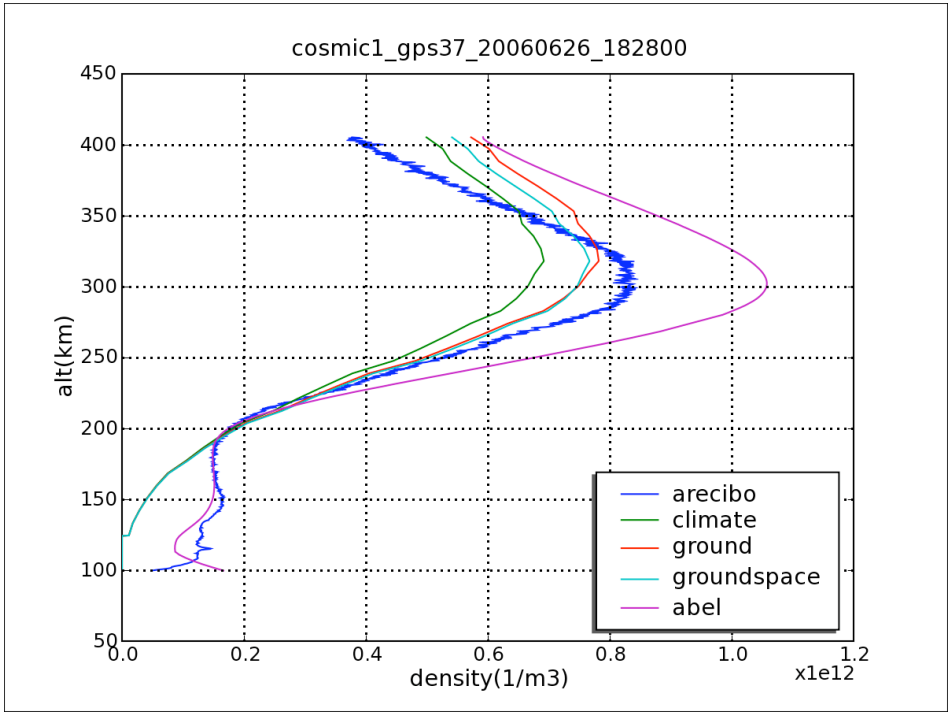


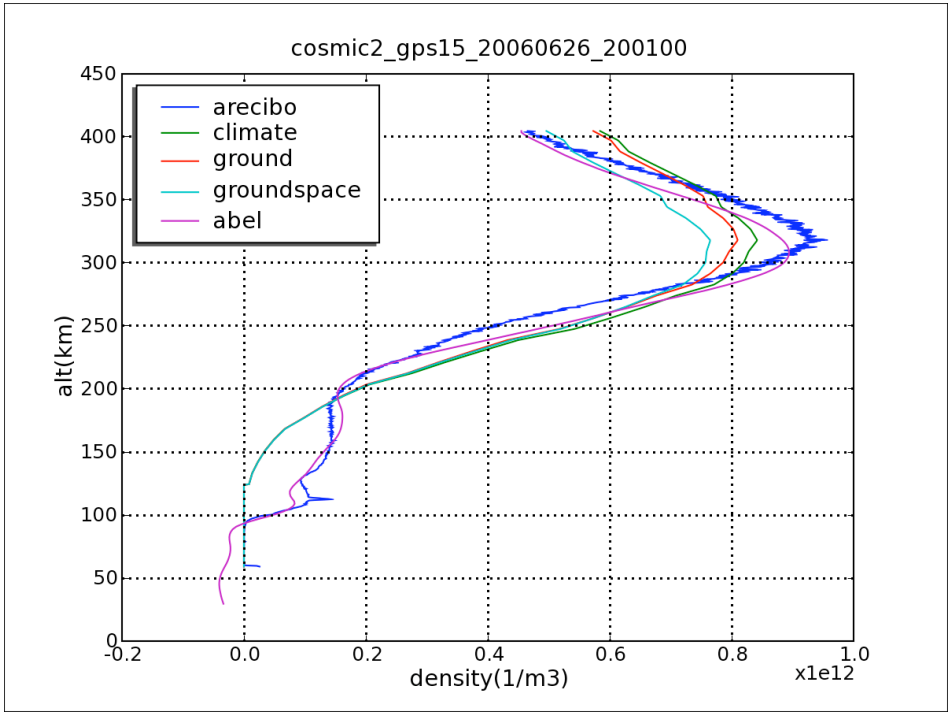
No Smoothing

GAIM Validation Using Arecibo Data
June 26, 2006



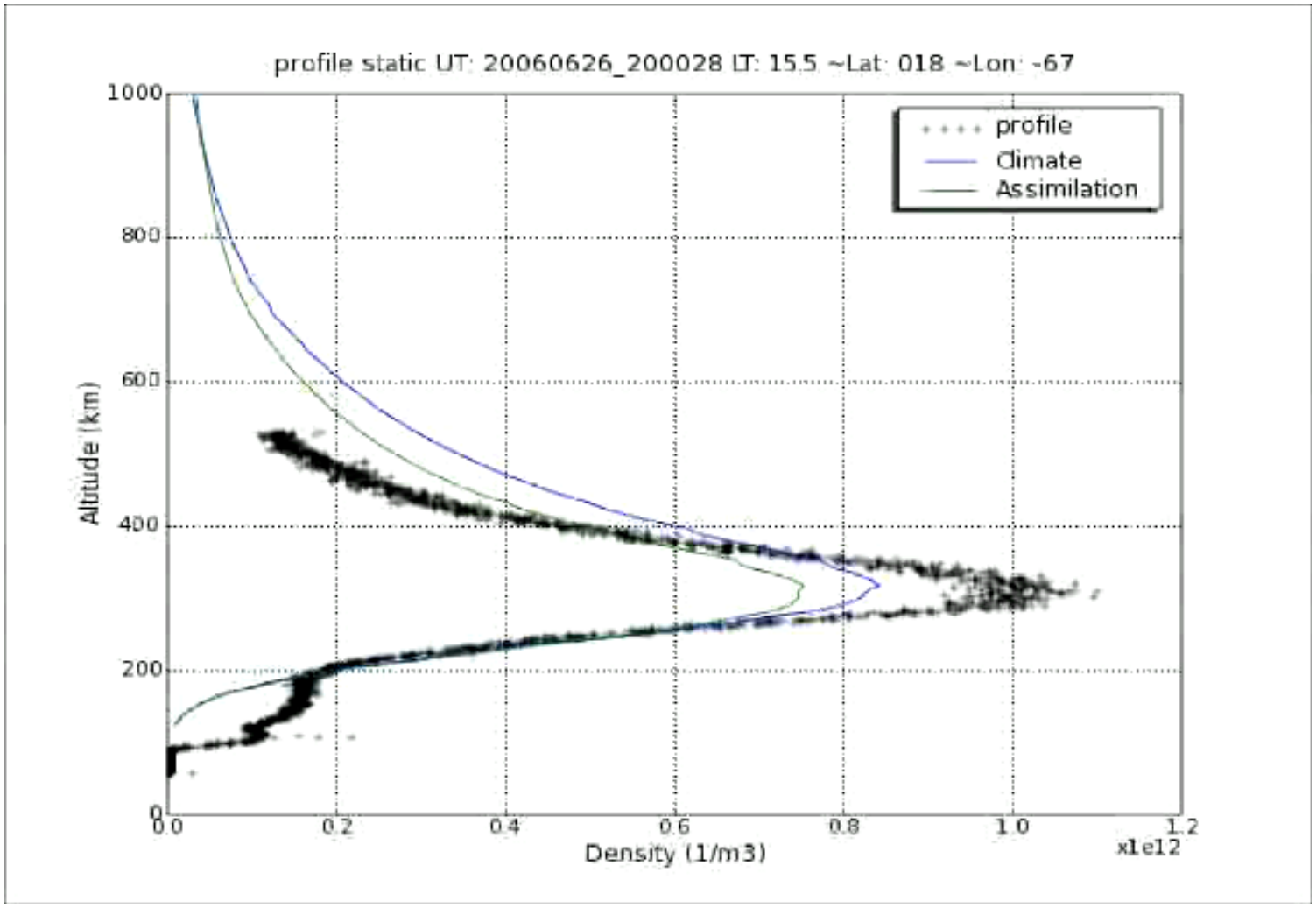
GAIM Validation Using Arecibo Data June 26, 2006



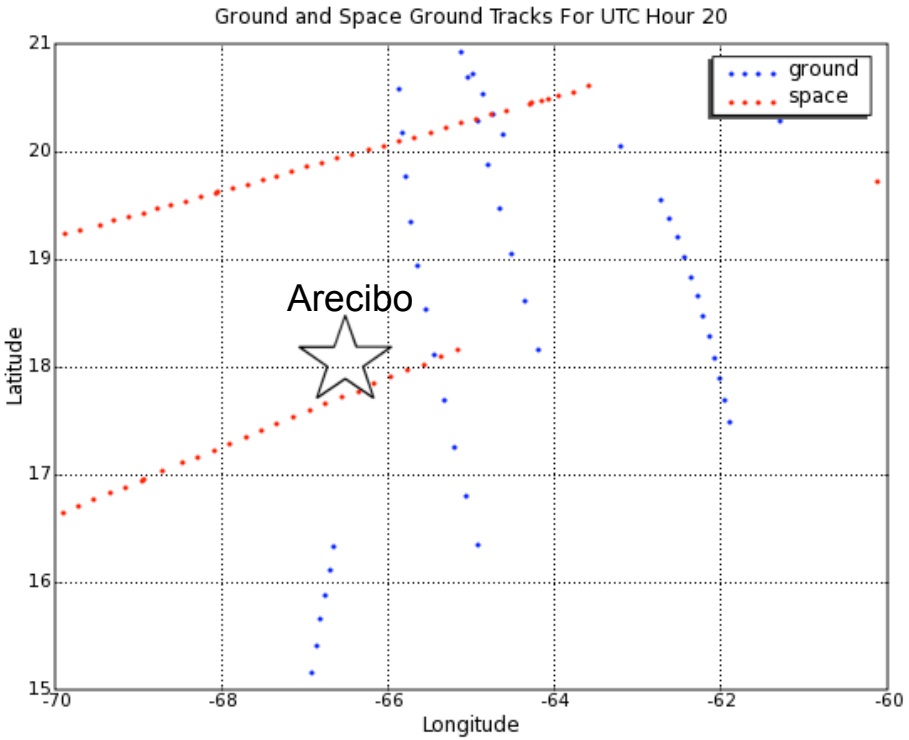


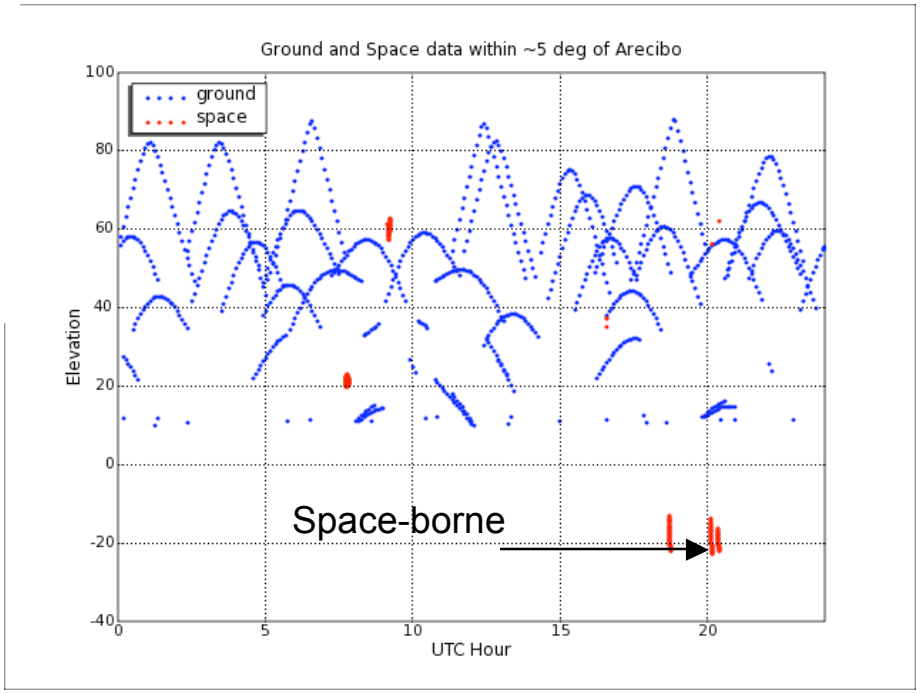
Arecibo calibrated profiles are courtesy of Prof M. Kelley and V. Wong of Cornell University

GAIM Assimilation Using Ground and COSMIC Data

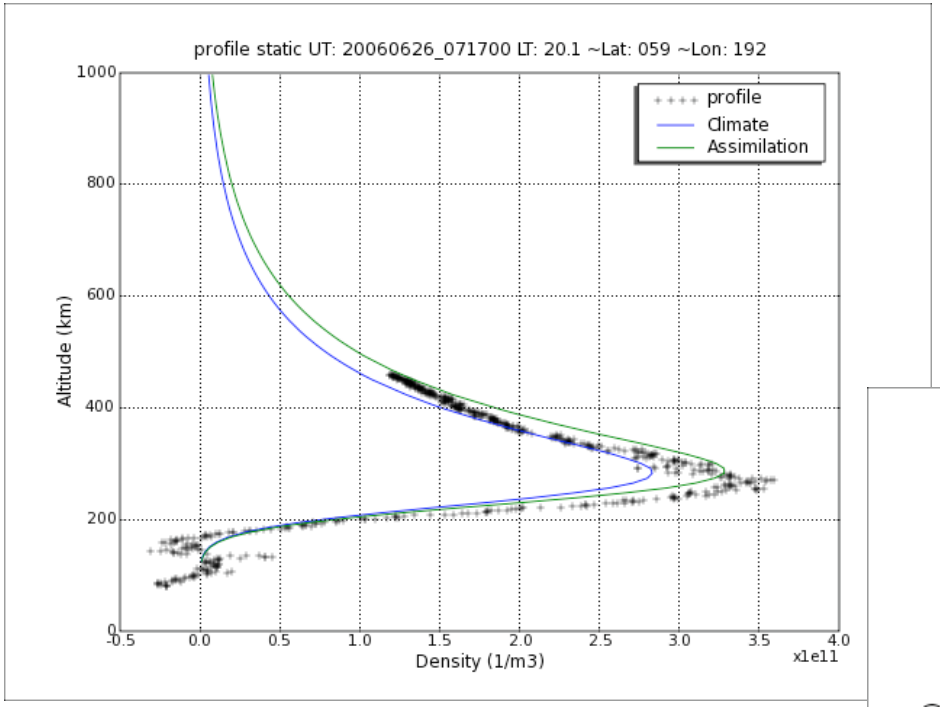


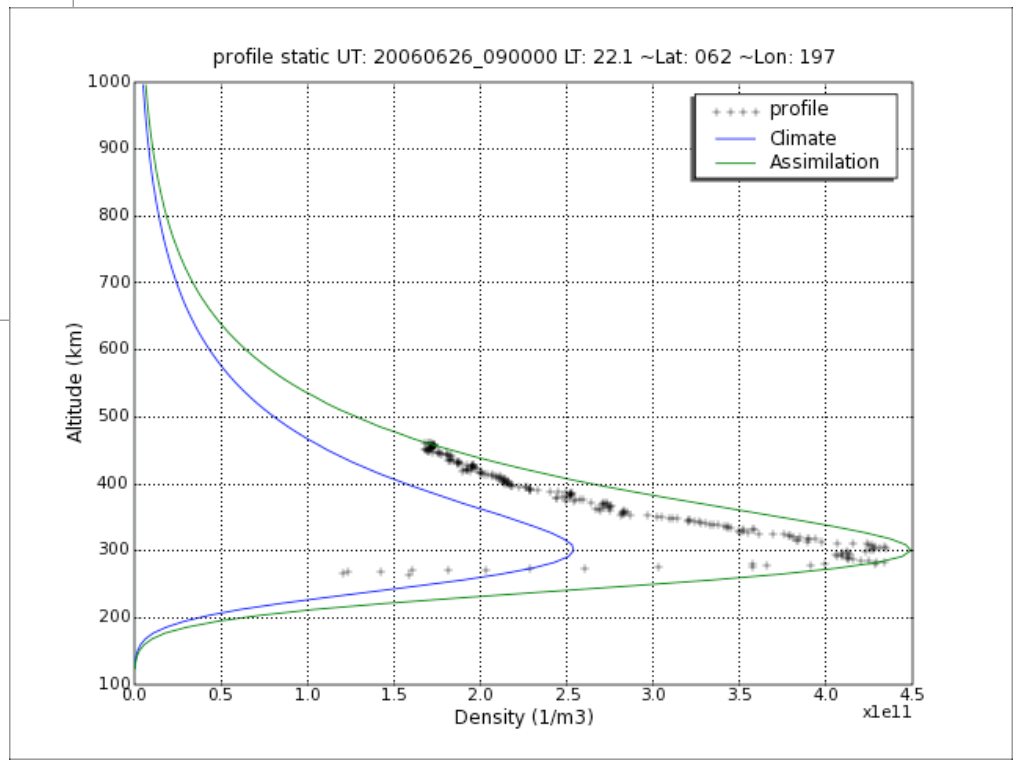
Ground Tracks: GAIM Assimilation for June 26, 2006 Using Ground and COSMIC Data



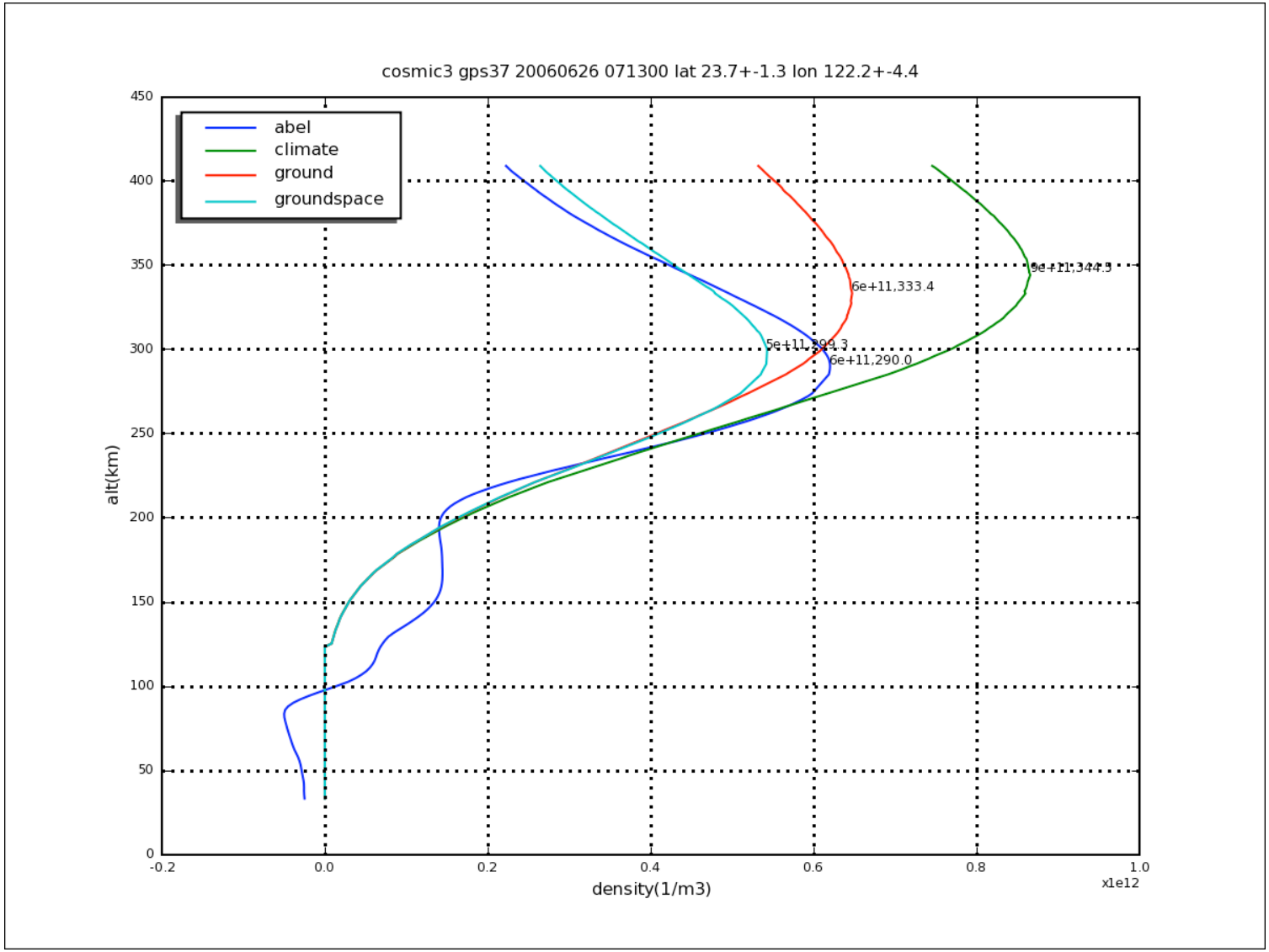


GAIM Validation Using Arecibo Profiles

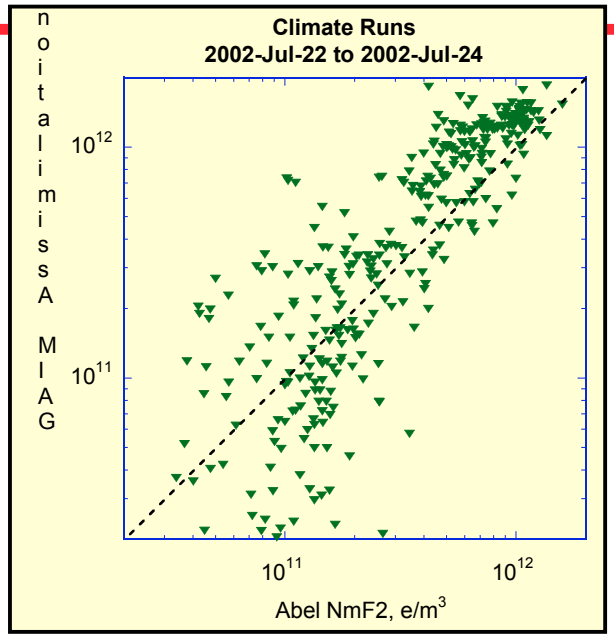


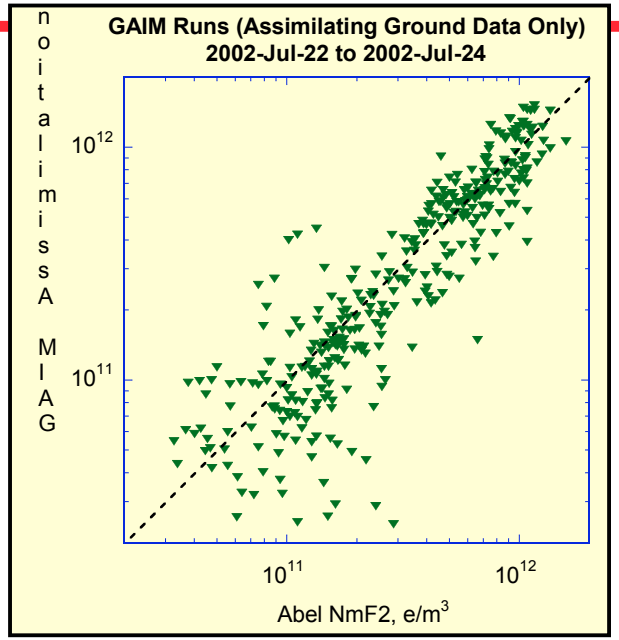


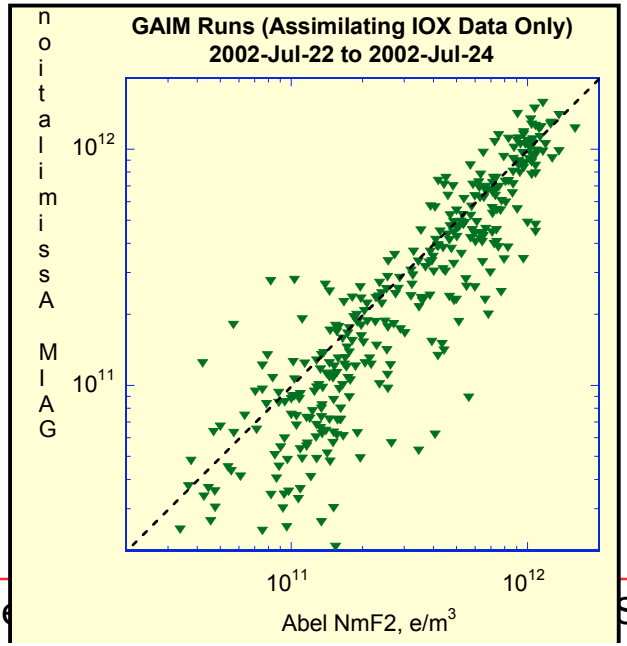
GAIM Validation Using Abel Profiles

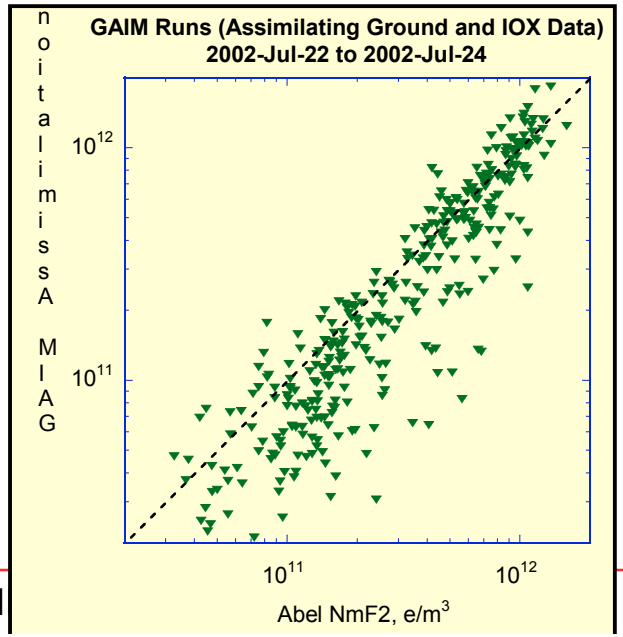


GAIM vs. Abel NmF2 Comparison

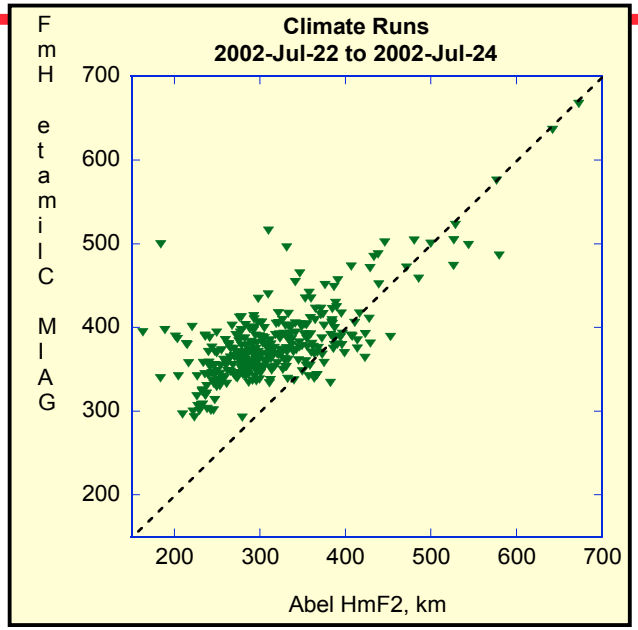


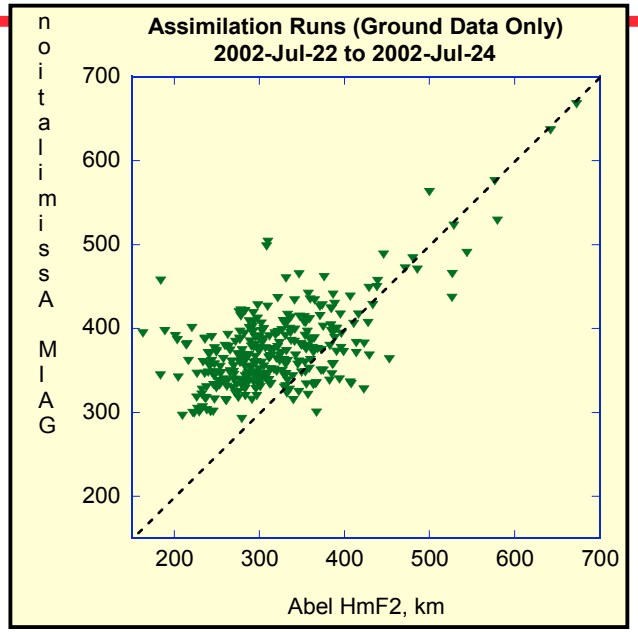


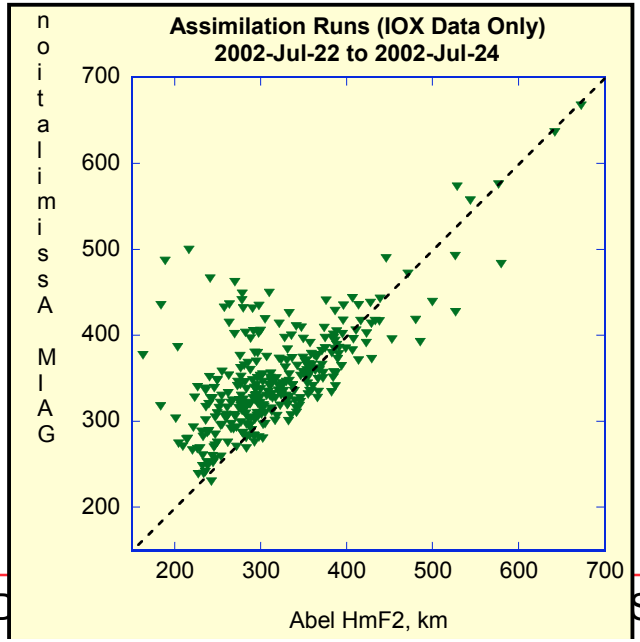


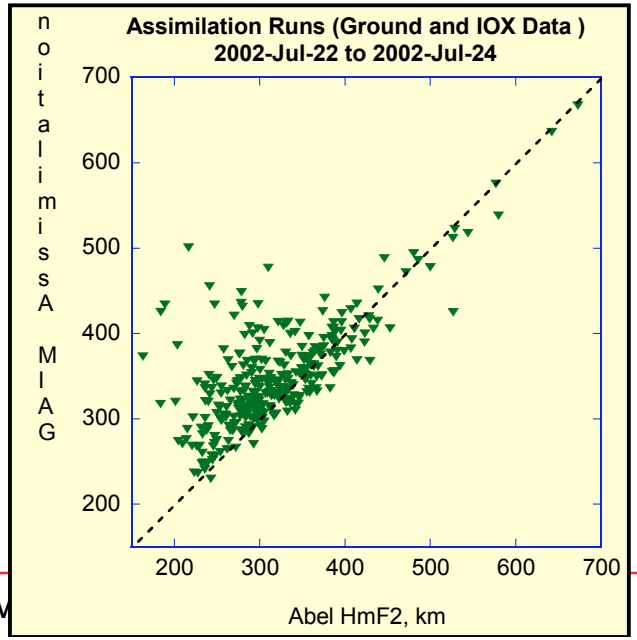


GAIM vs. Abel HmF2 Comparison

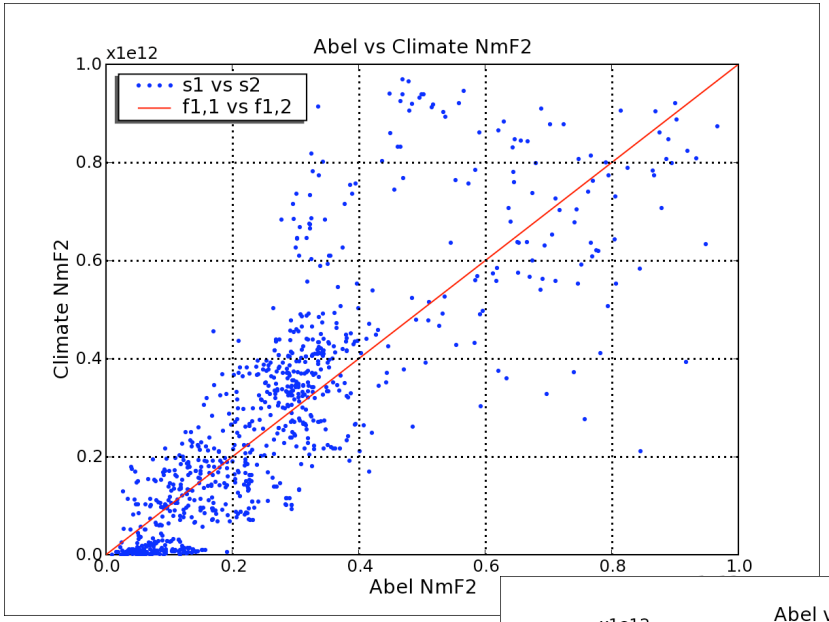




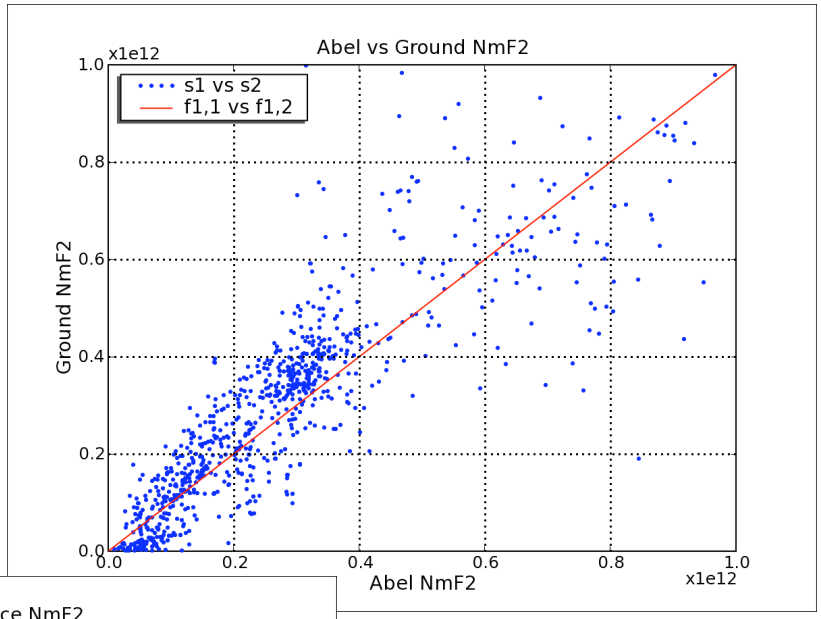




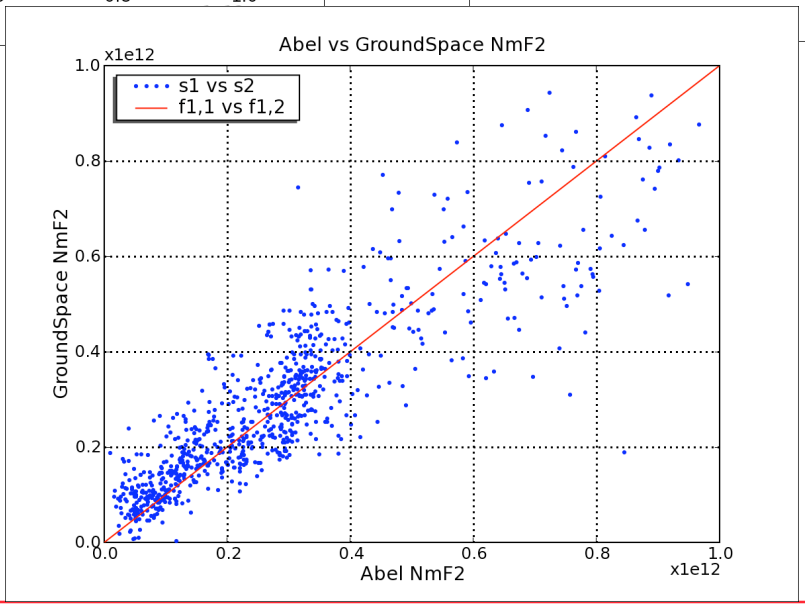
Comparing GAIM NmF2 to Abel: June 26, 2006



Climate (no data)

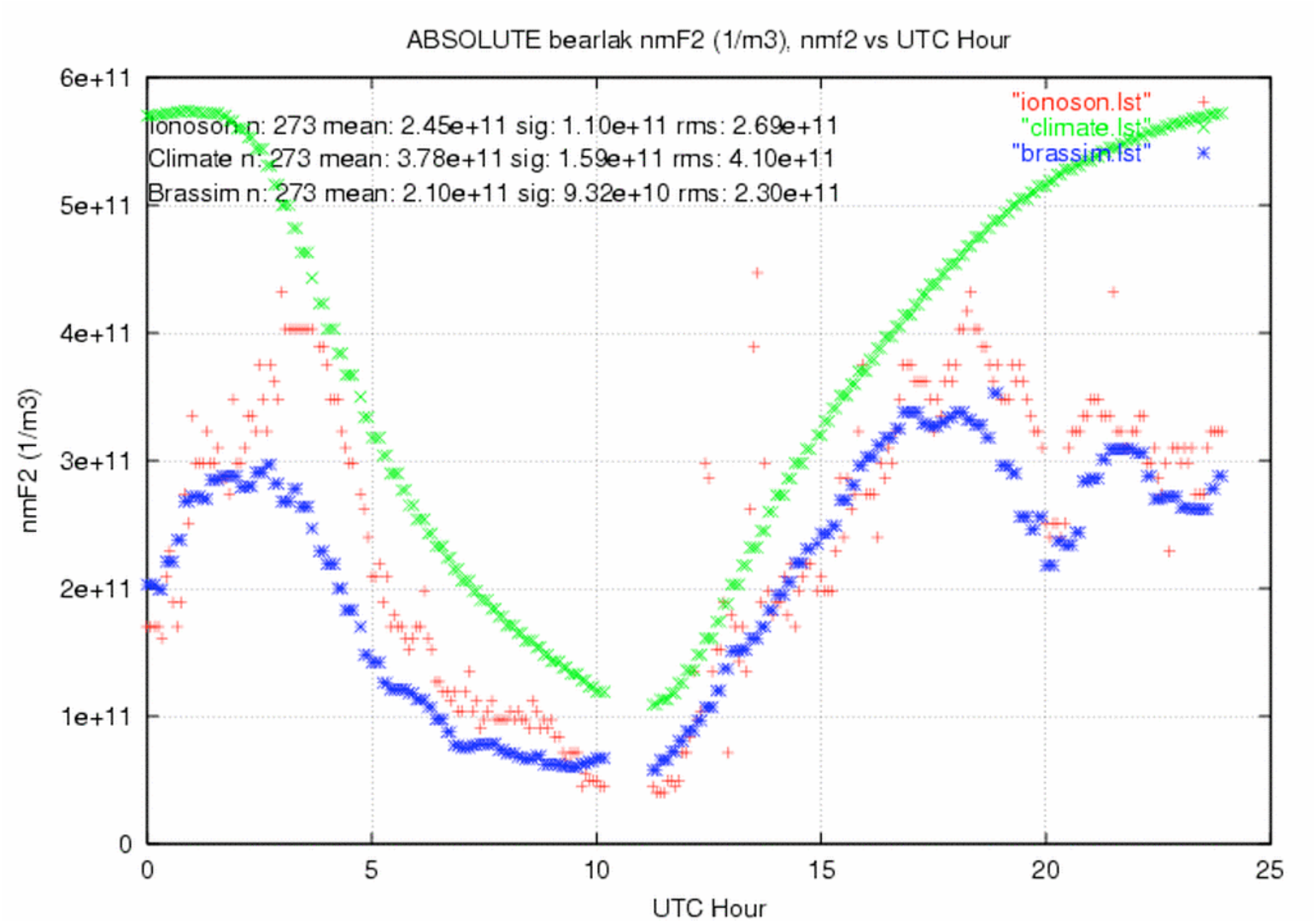


Ground only

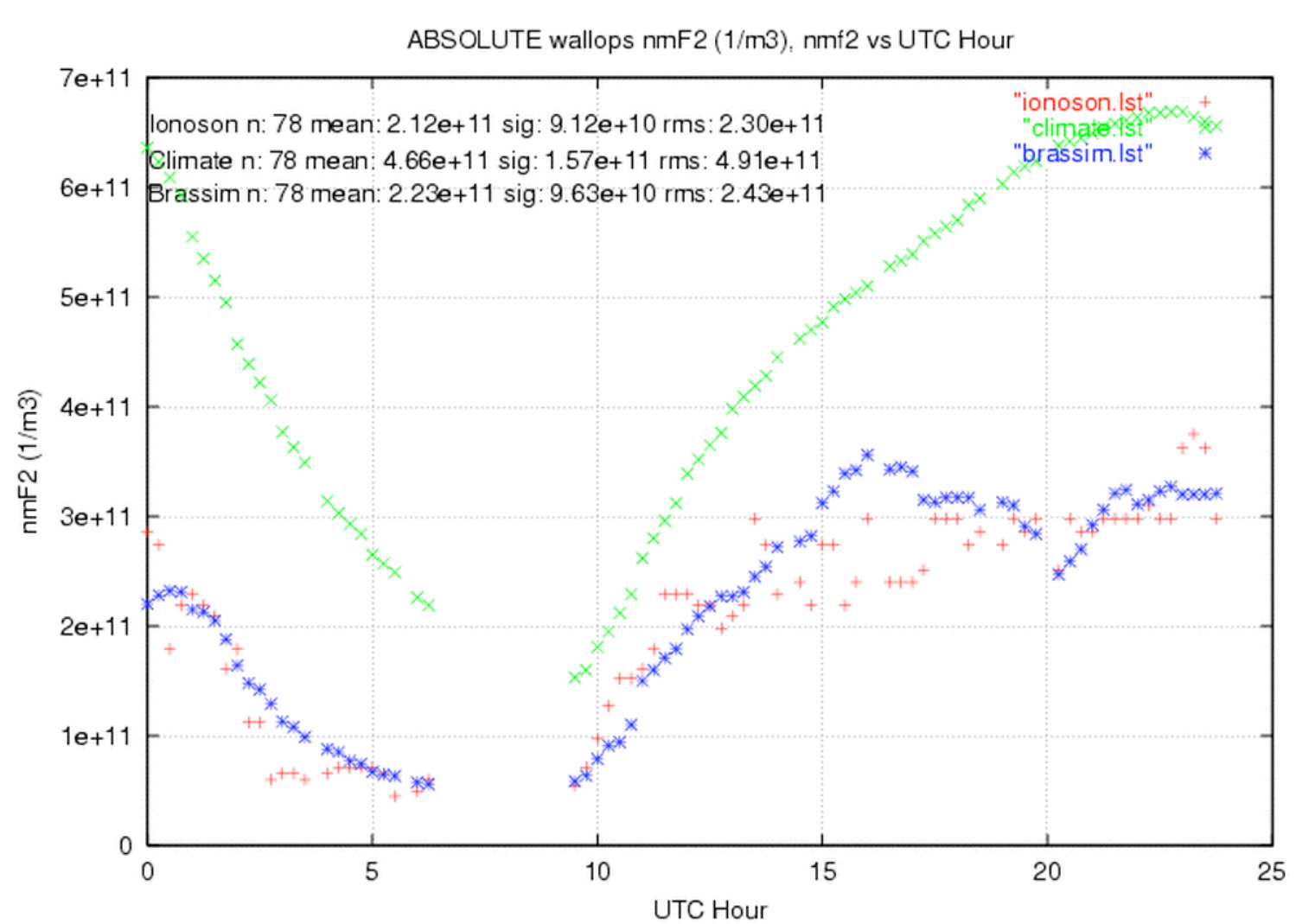


Ground + Space

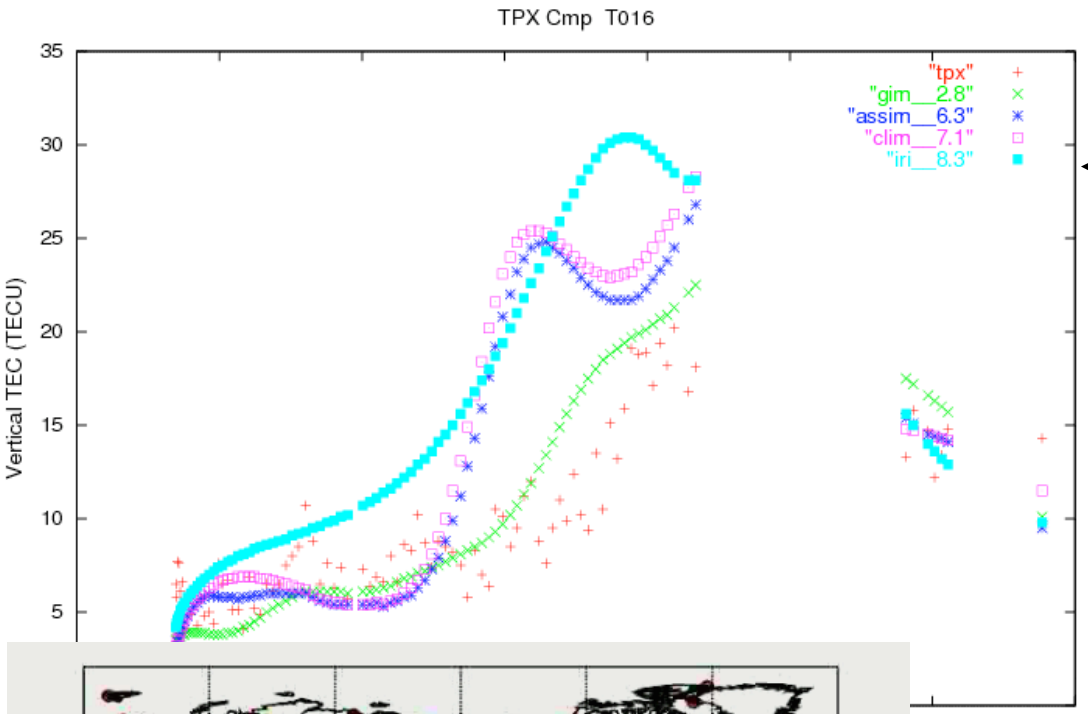
NmF2 Comparison: Bear Lake



NmF2 Comparison: Wallops Is.

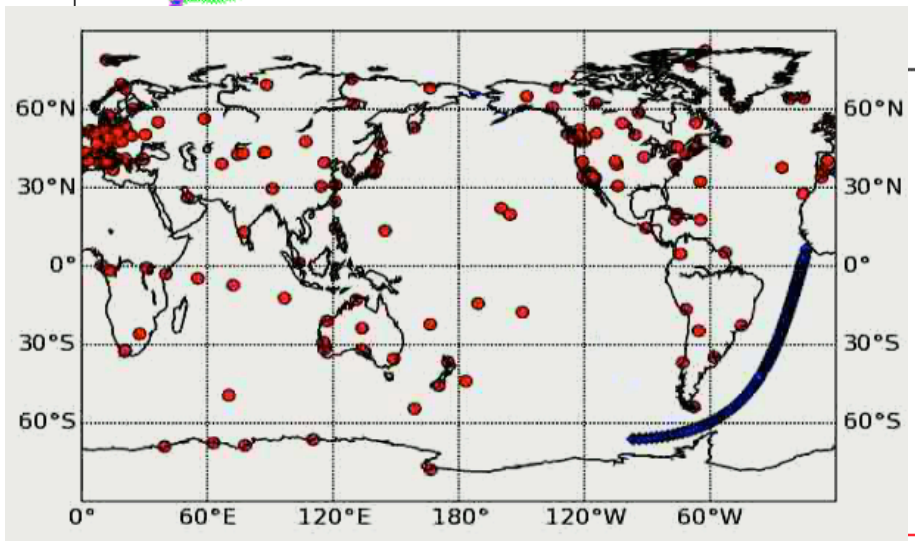


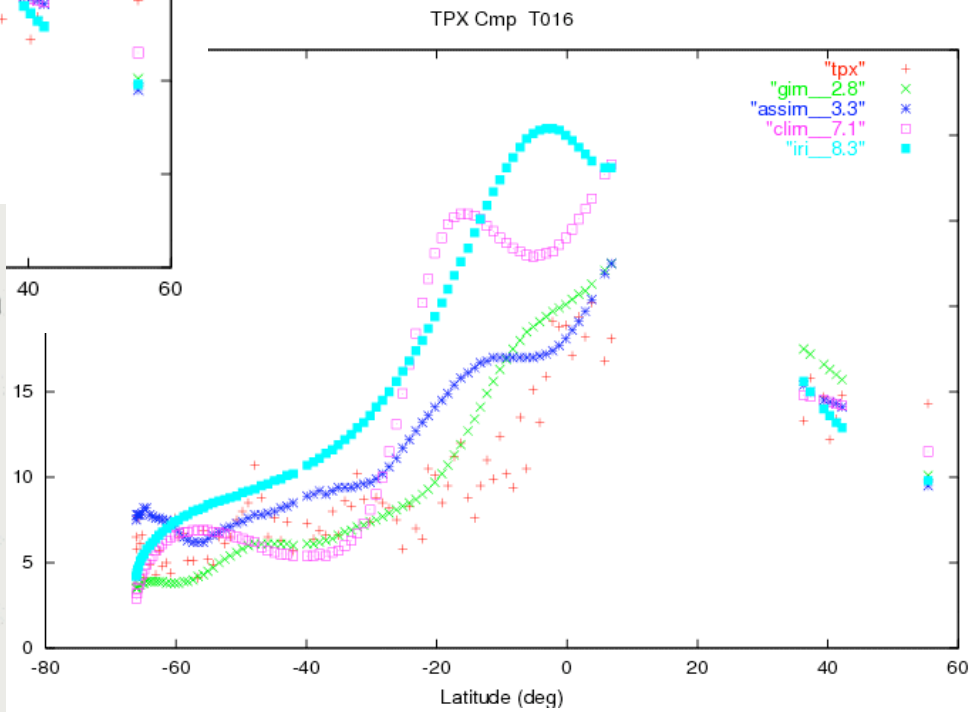
GAIM Validation Using Jason-2 Vertical TEC



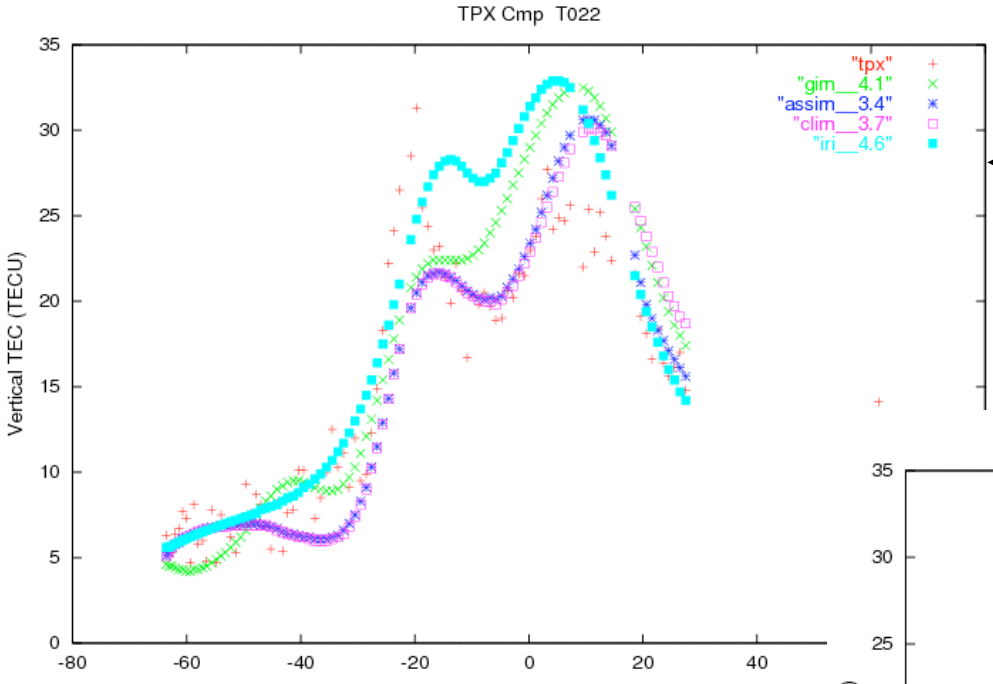
Ground-data only

Ground and space data



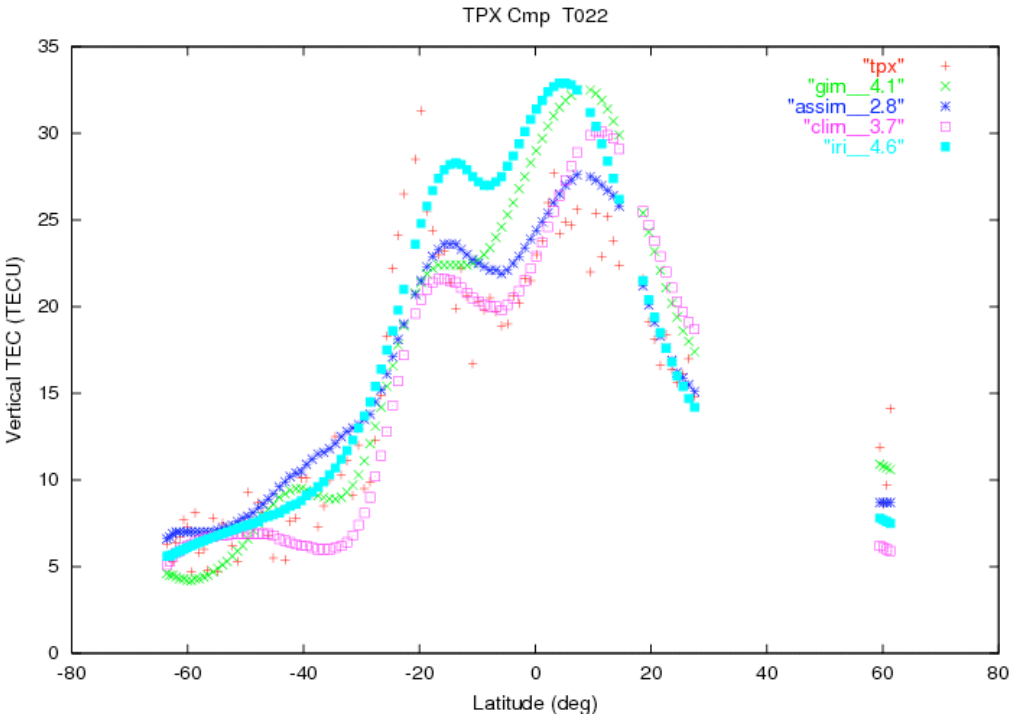


GAIM Validation Using Jason-2 Vertical TEC

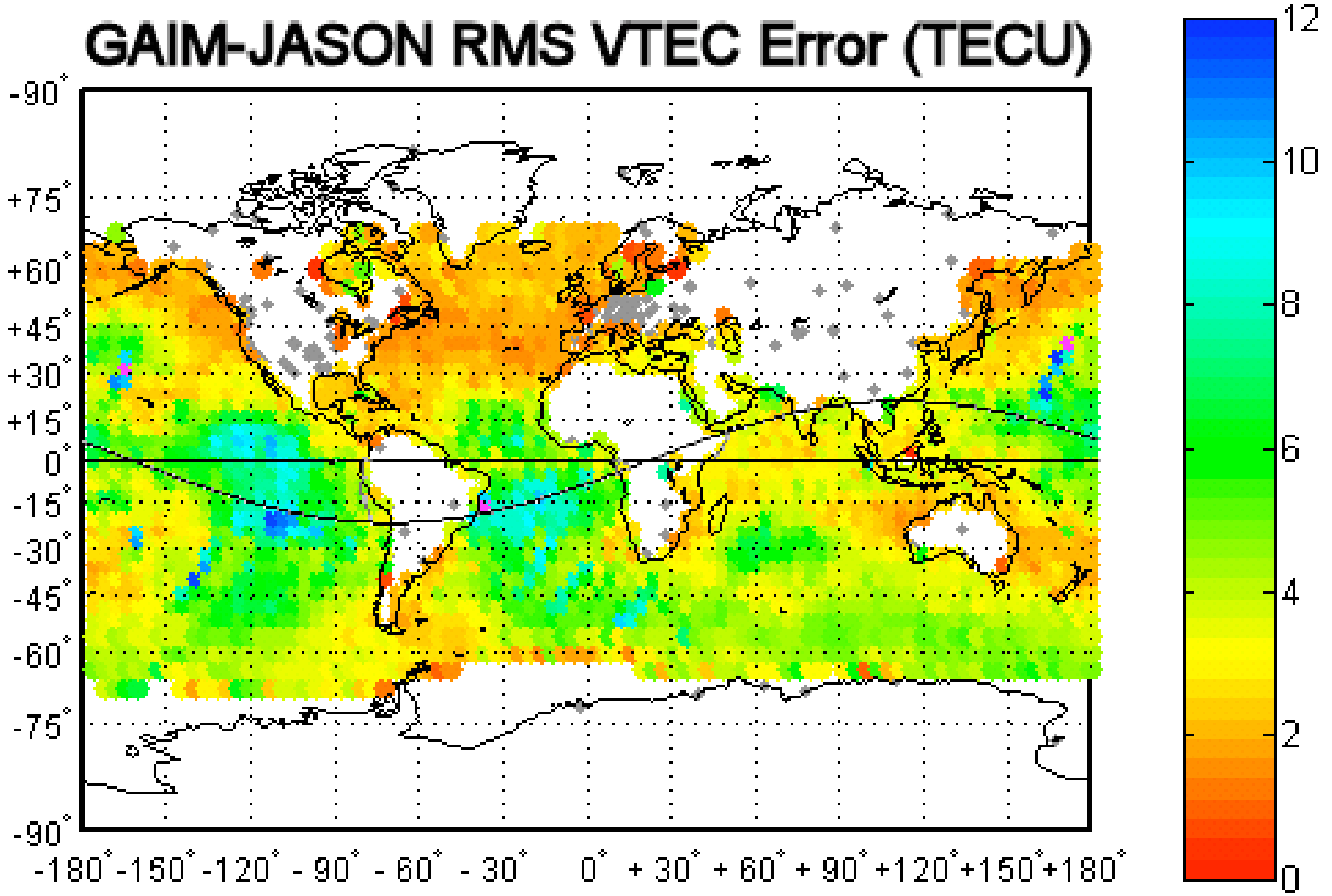


Ground-data only

Ground and space data



GAIM Driven By Ground GPS Only versus JASON VTEC

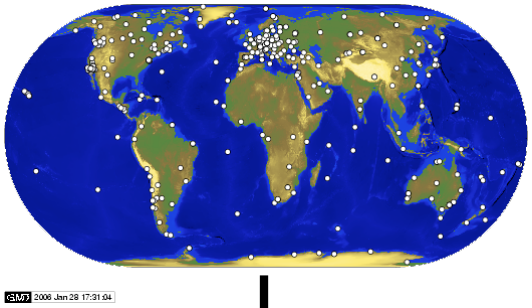


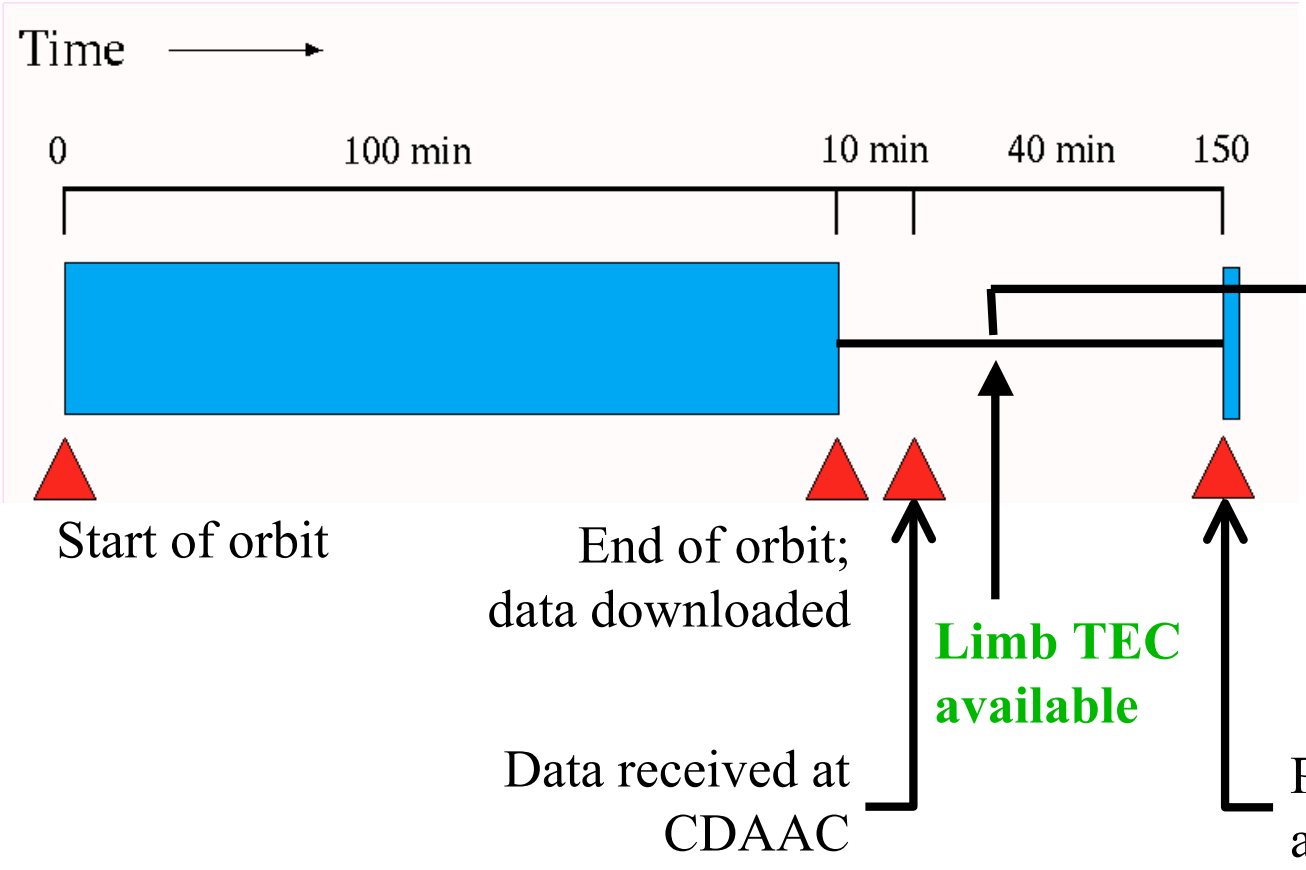
June – Nov. 2004: 137 days

COSMIC Demo 2007

Global ground network data: 5-minute and 1-hour latency

COSMIC data: 120+ minutes latency





GAIM

3-D global electron density grids 15-minute cadence

CDAAC: COSMIC Data Analysis and Archiving Center at UCAR

Conclusions

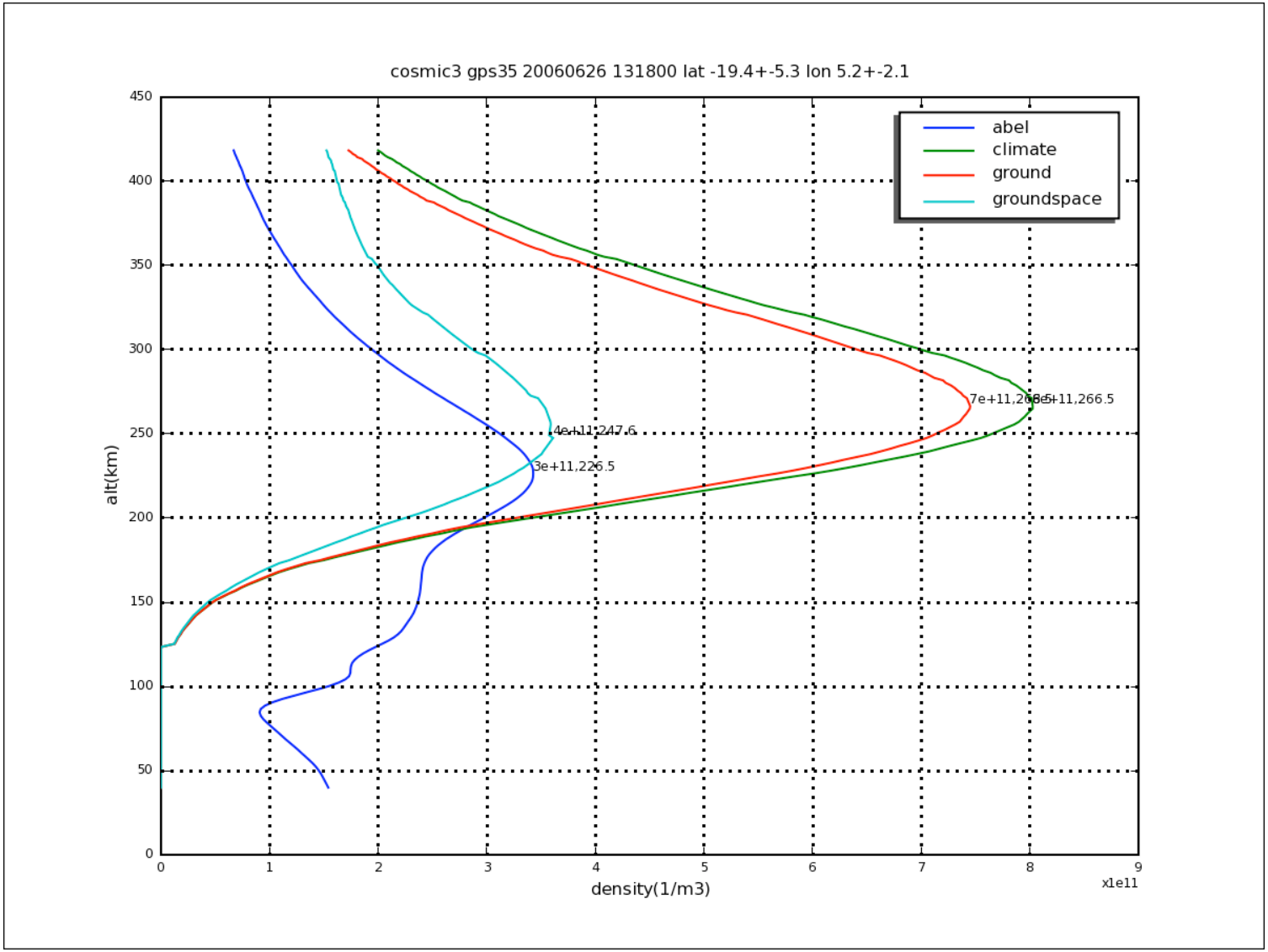
- Now routinely generate calibrated TEC and Abel electron density retrievals using COSMIC data.
- Have compared UCAR and JPL COSMIC products for June 26, 2006:
  - There appears to be a 2-3 TECU level bias between JPL and UCAR calibrated TEC files.
  - JPL and UCAR Abel profiles usually match well.
- Performed GAIM assimilation using data from 200 ground-based GPS and six COSMIC satellites for June 26.
  - GAIM profiles are validated using Arecibo density, Jason VTEC and Abel profiles.
  - After assimilation Nmf2 shows very good improvement over climate predictions.
  - Jason validation shows “ground+space” improvement over “ground-only” assimilation in all cases.

Future Plans

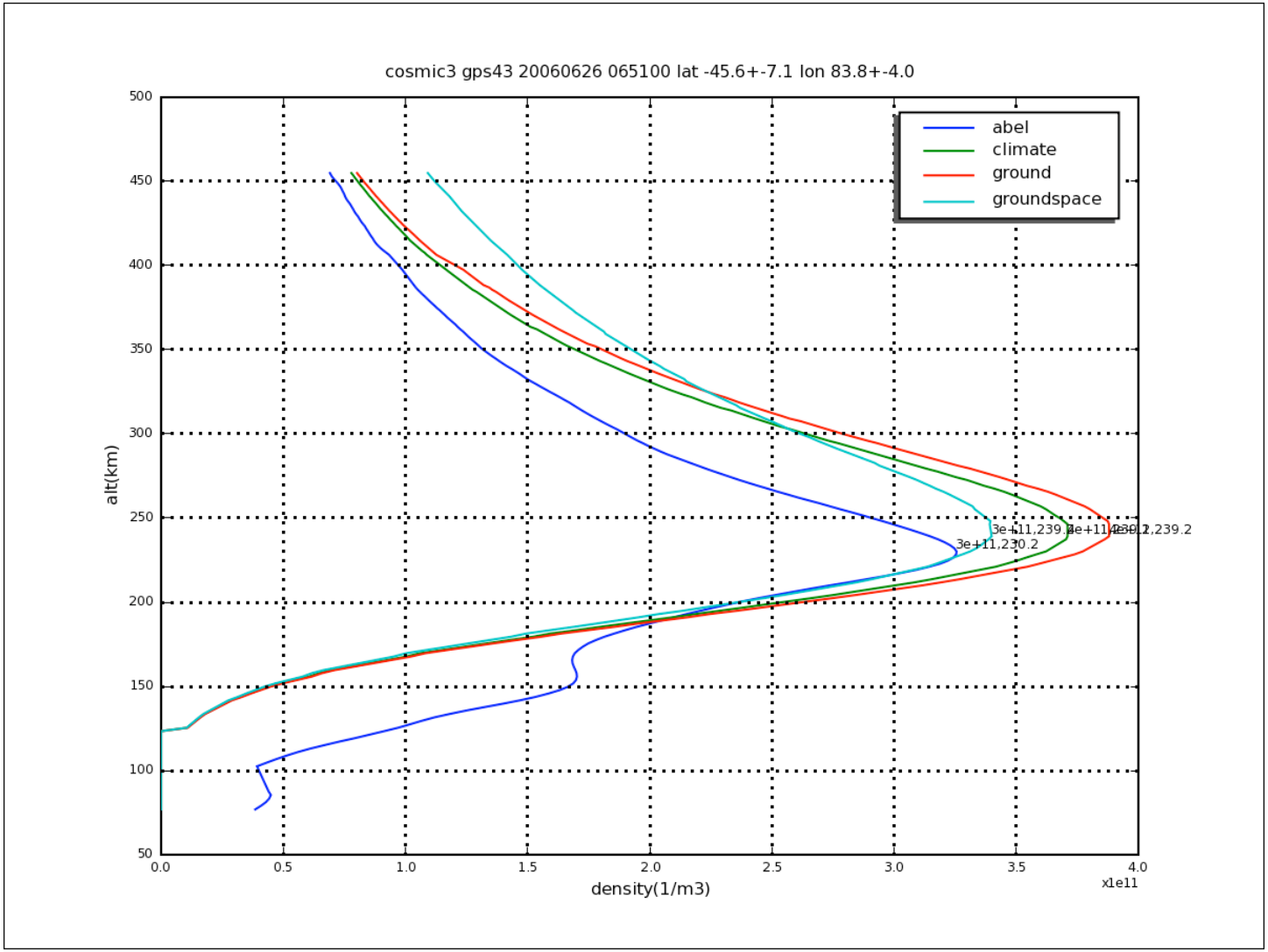
- **Inter-compare receiver bias estimates, calibrated TEC, and Abel profiles between UCAR and JPL.**
- **Compare GAIM and Abel profiles to ISR's for Sep. 20-22, 2006**
- **NRT GAIM Demo ingesting Ground GPS TEC and COSMIC TEC**
  - Operational demo
  - Accumulate validation statistics
    - Density profiles vs. Abel
    - Density profiles vs. ISR
    - VTEC vs. JASON
- **4DVAR Driver Estimation for low & mid-latitudes**
  - Input Ground and COSMIC TEC
  - Estimate two drivers simultaneously:
    - **ExB drift velocity**
    - **Neutral wind**

Backup Slides

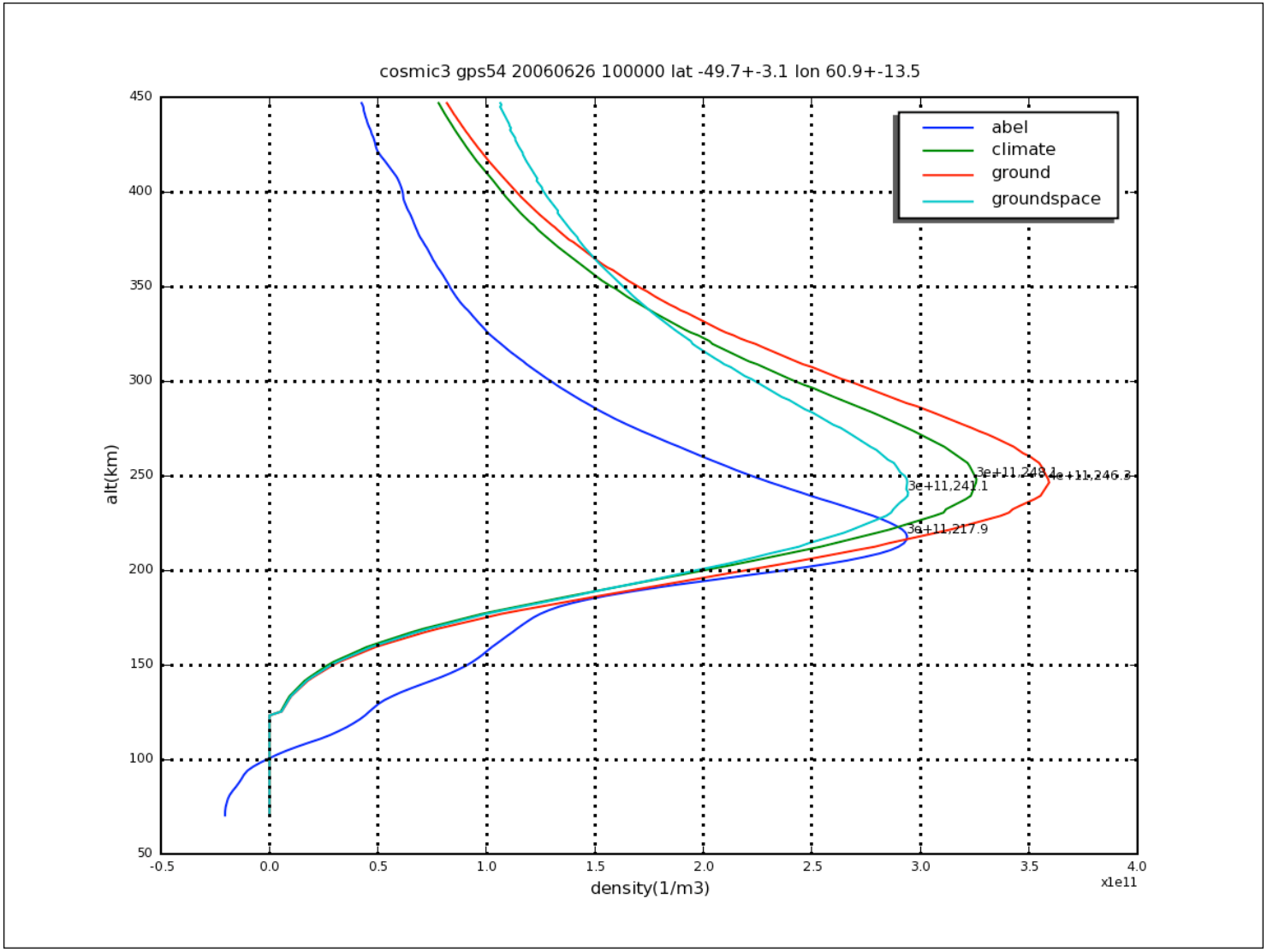
GAIM Validation Using Abel Profiles



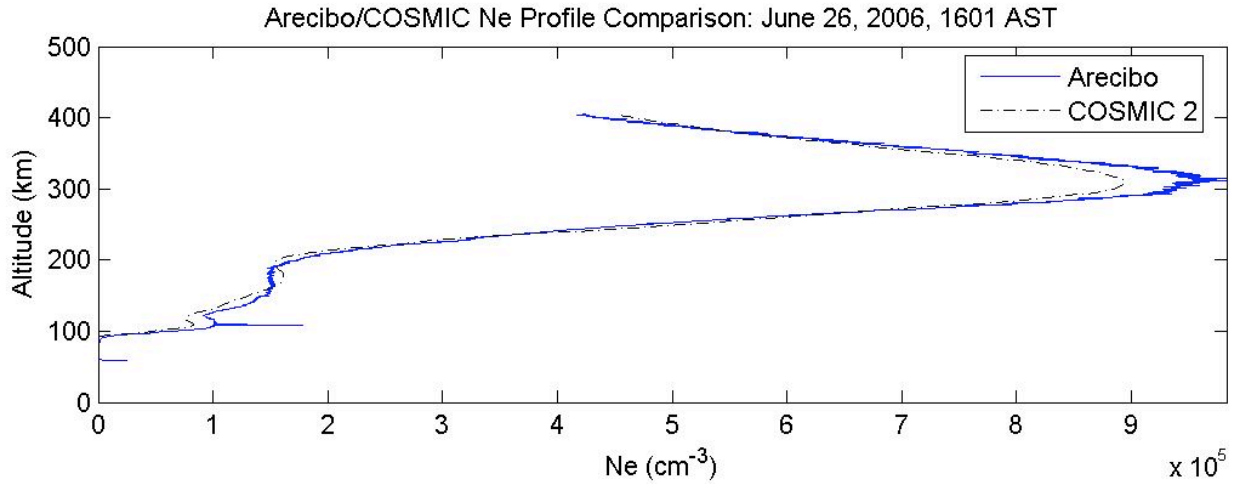
GAIM Validation Using Abel Profiles

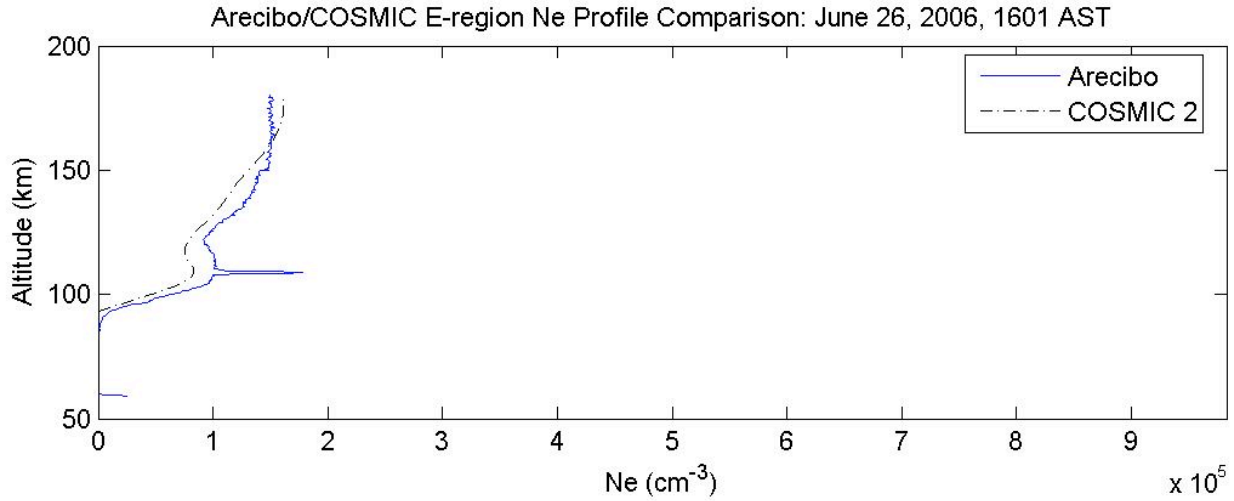


GAIM Validation Using Abel Profiles

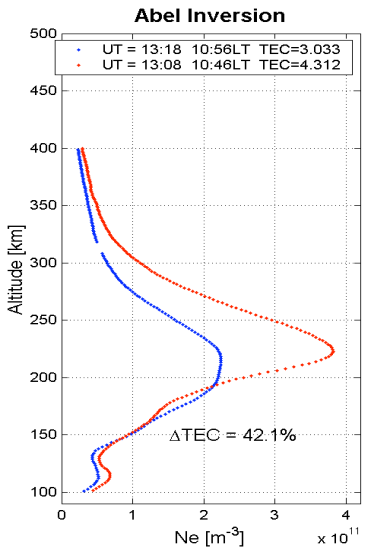


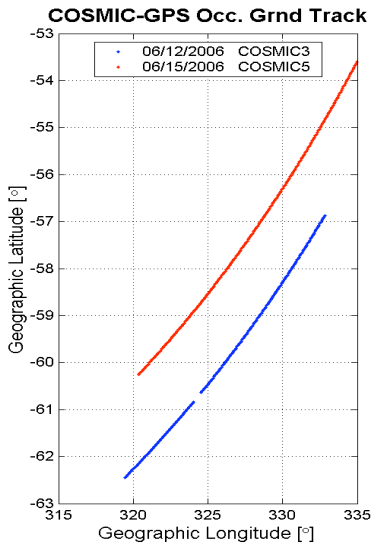
Validation Using Arecibo ISR for June 26, 2006

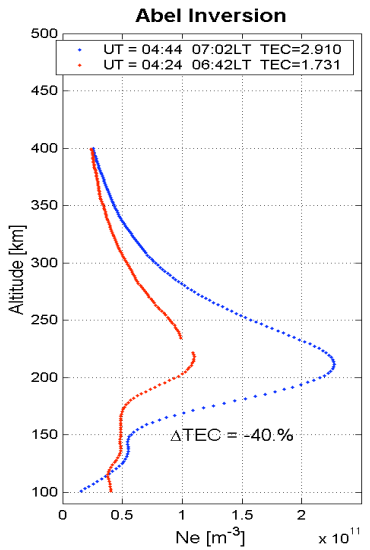


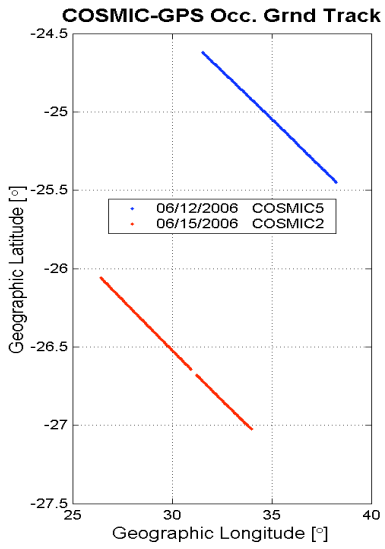


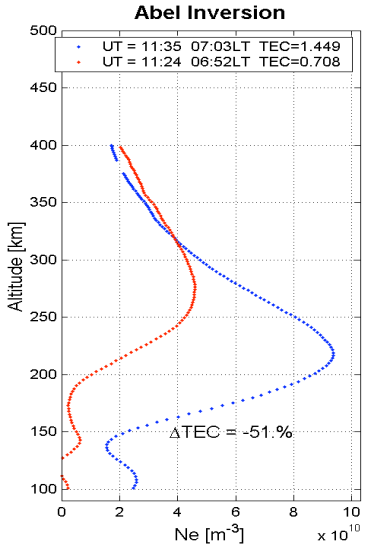
Ne Profiles during a Storm Derived from COSMIC Occultation Data

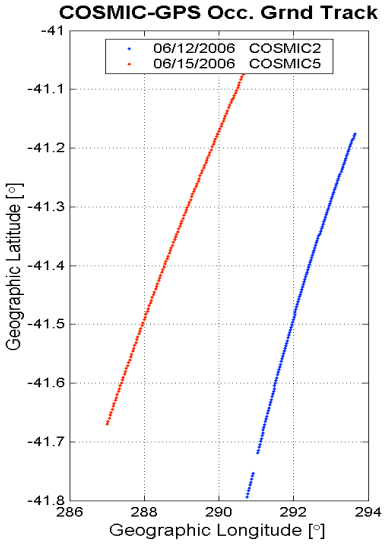


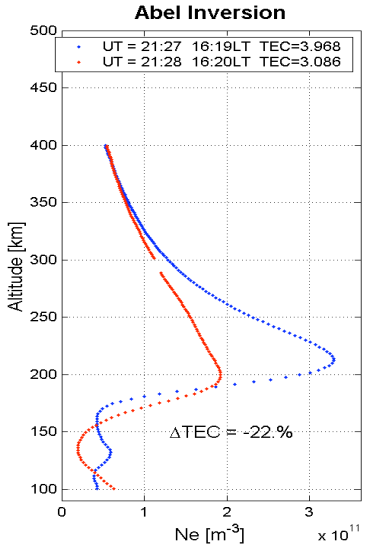


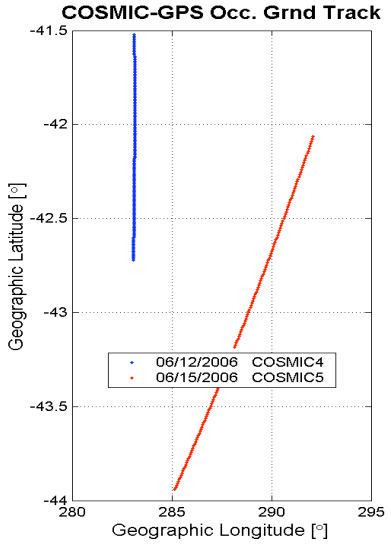












GAIM Assimilating Ground & COSMIC Data Compared with Jason-1 Measurements