Processing Ground and COSMIC GPS Measurements for Use in Near-Real Time GAIM Assimilation

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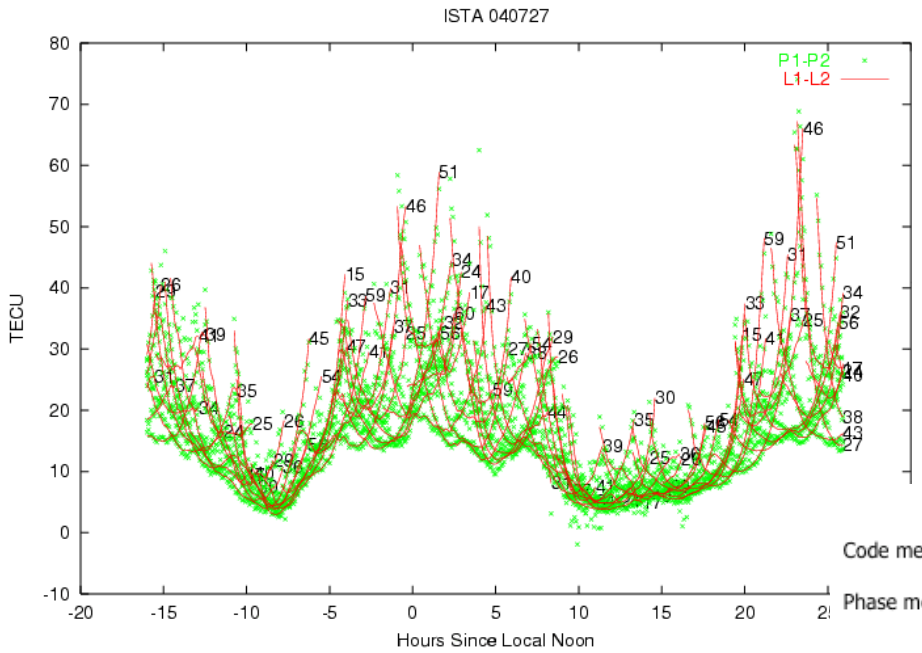
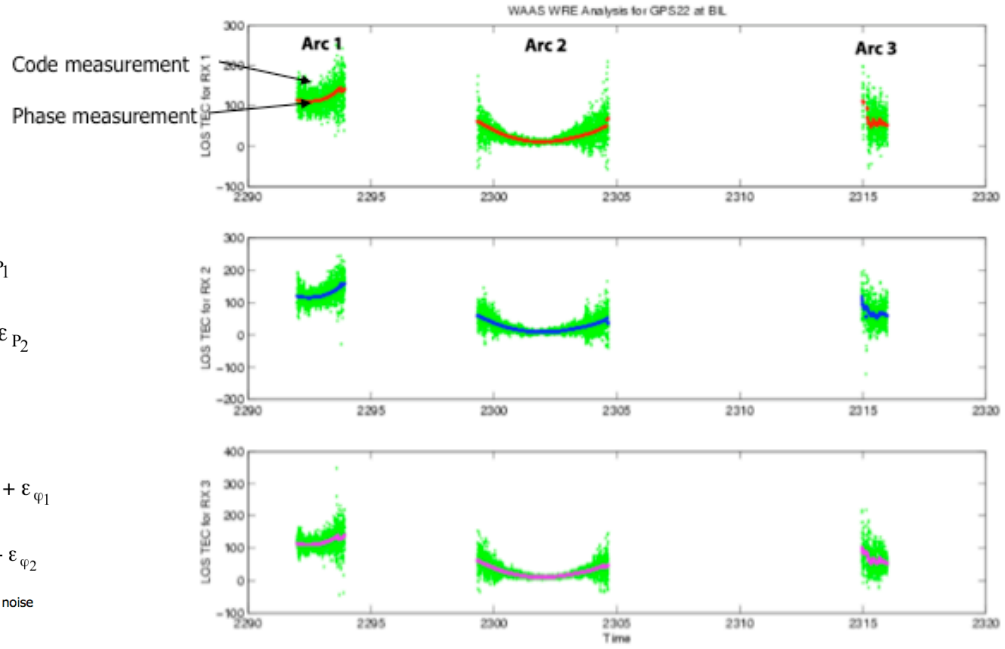
Outline

- Introduction
- GPS data sources and quality control
  - Ground
  - Space-based
- GAIM capabilities: Kalman-filter, 4DVAR, Nested Grid GAIM (NGAIM), Real-Time GAIM (RTGAIM)
- Real-time system
  - Overview
- Summary

Information Content of GPS Slant TEC (mid-latitude)



Examples of leveling phase ionospheric measurements using GIM as ground-truth



GPS pseudorange observation equation:

$$P_1 = \rho + c\cdot(dT - dt) + d_{ion,L_1} + d_{trop} + b^{s_i,L_1} + b_{r_j,L_1} + mp_{P_1} + \varepsilon_{P_1}$$

$$P_2 = \rho + c\cdot(dT - dt) + \gamma\cdot d_{ion,L_1} + d_{trop} + b^{s_i,L_2} + b_{r_j,L_2} + mp_{P_2} + \varepsilon_{P_2}$$

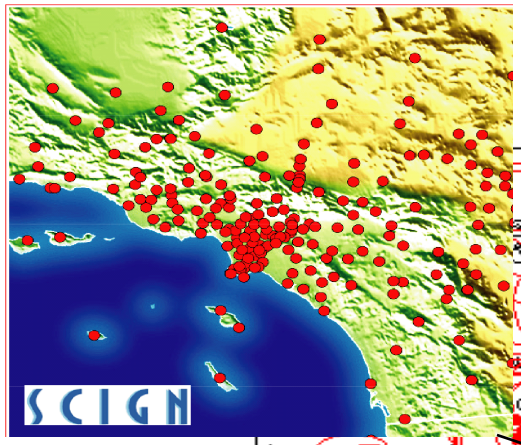
GPS carrier phase observation equation:

$$\Phi_1 = \rho + c\cdot(dT - dt) + \lambda_1 N_1 - d_{ion,L_1} + d_{trop} + b^{\varphi,s_i,L_1} + b_{\varphi,r_j,L_1} + mp_{\varphi_1} + \varepsilon_{\varphi_1}$$

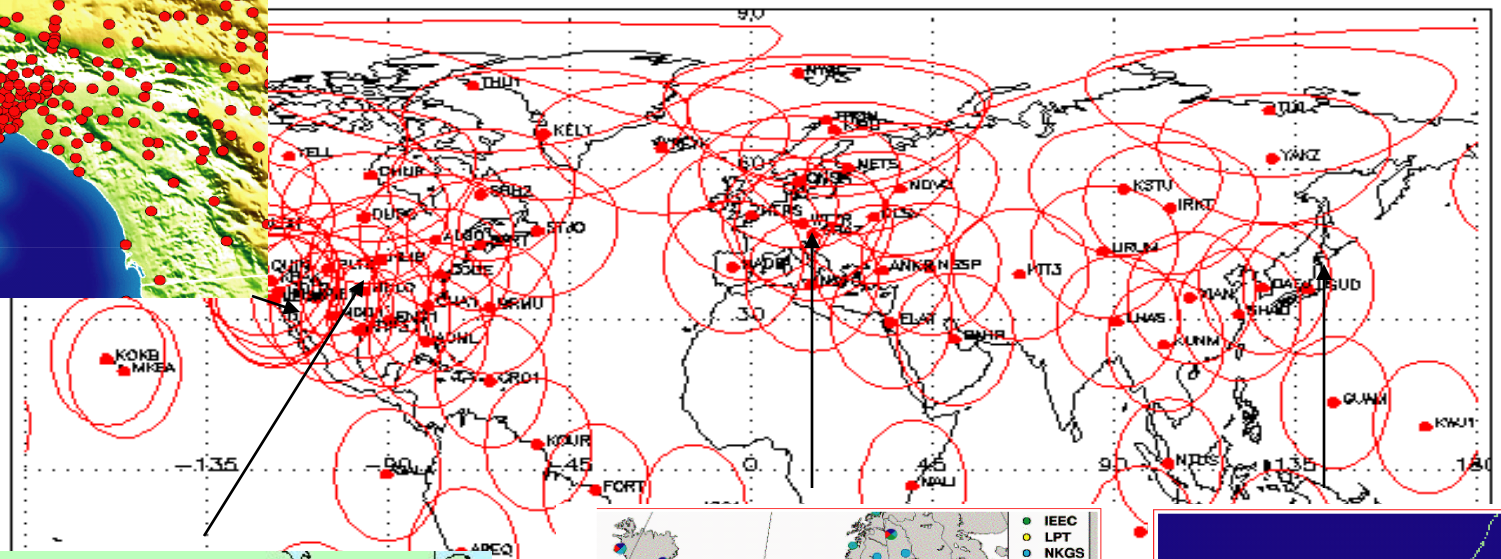
$$\Phi_2 = \rho + c\cdot(dT - dt) + \lambda_2 N_2 - \gamma\cdot d_{ion,L_1} + d_{trop} + b^{\varphi,s_i,L_2} + b_{\varphi,r_j,L_2} + mp_{\varphi_2} + \varepsilon_{\varphi_2}$$

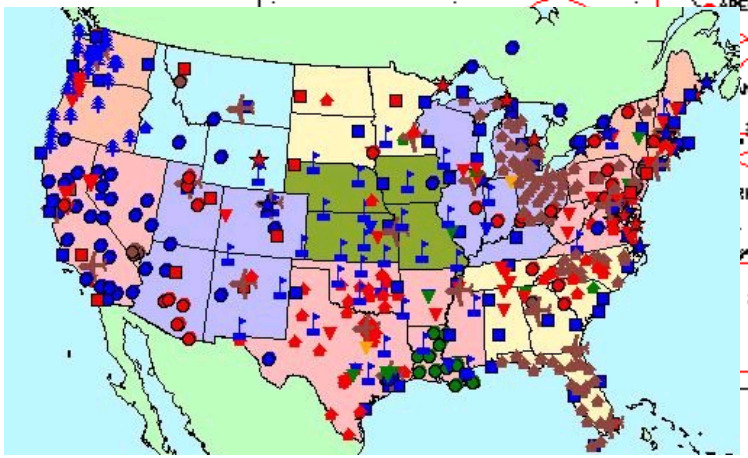
Range, clock, ambiguity, ionosphere, troposphere, satellite bias, receiver bias, multipath, noise

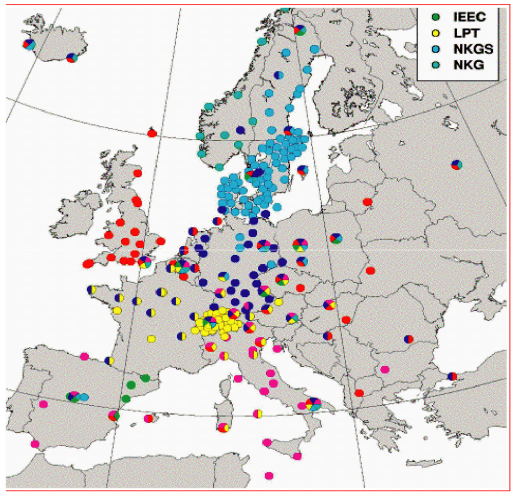
Coverage of Daily IGS Network and Regional Networks

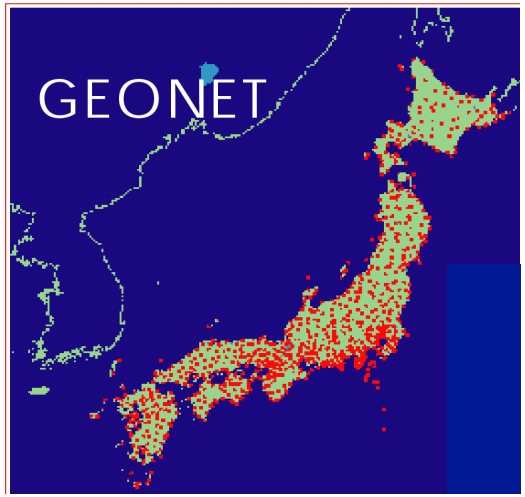


(10 degree elevation mask; 450 km shell height)

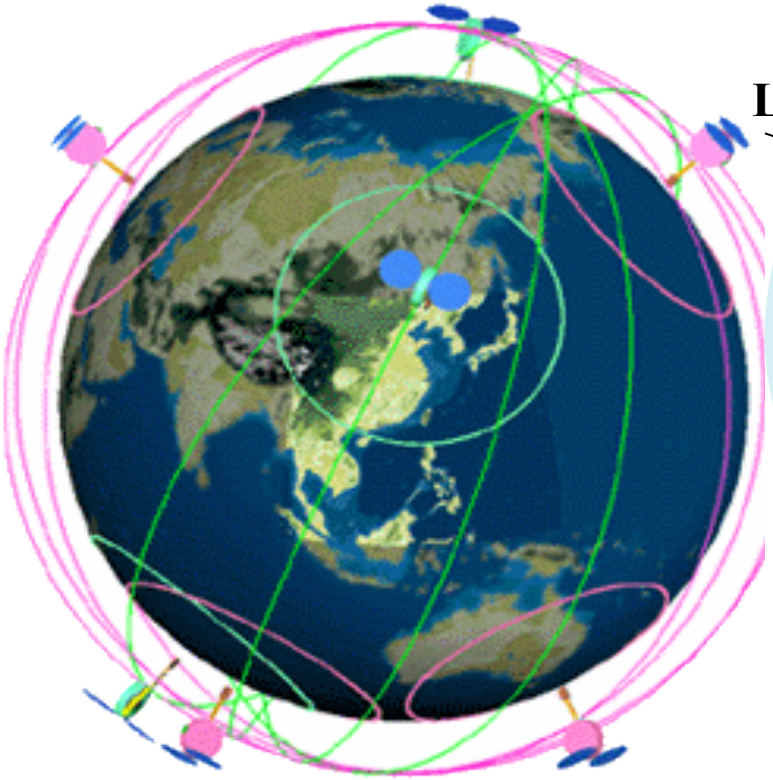


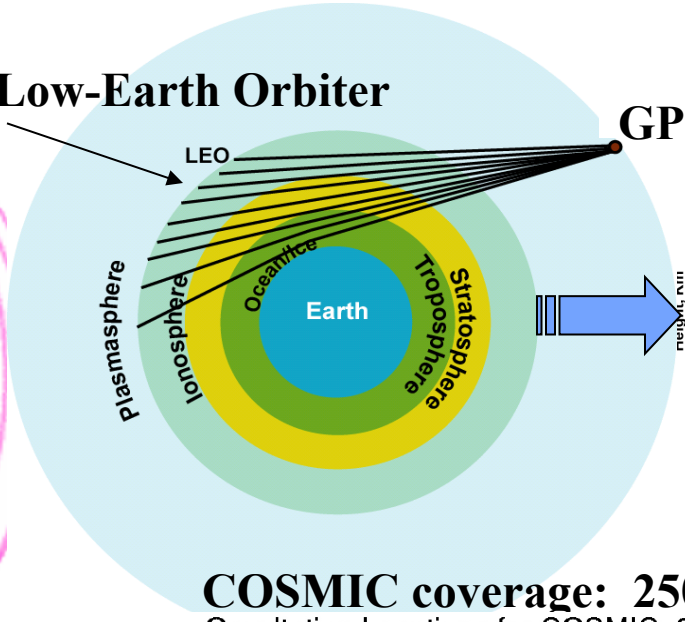


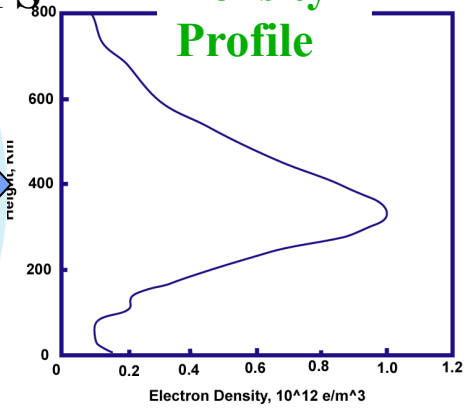




COSMIC
Ionospheric Weather Constellation

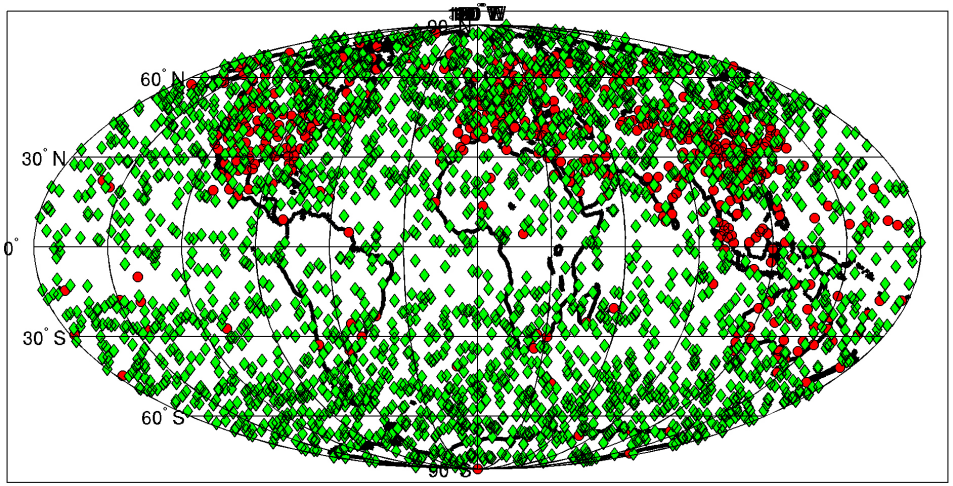






COSMIC coverage: 2500 profiles/day

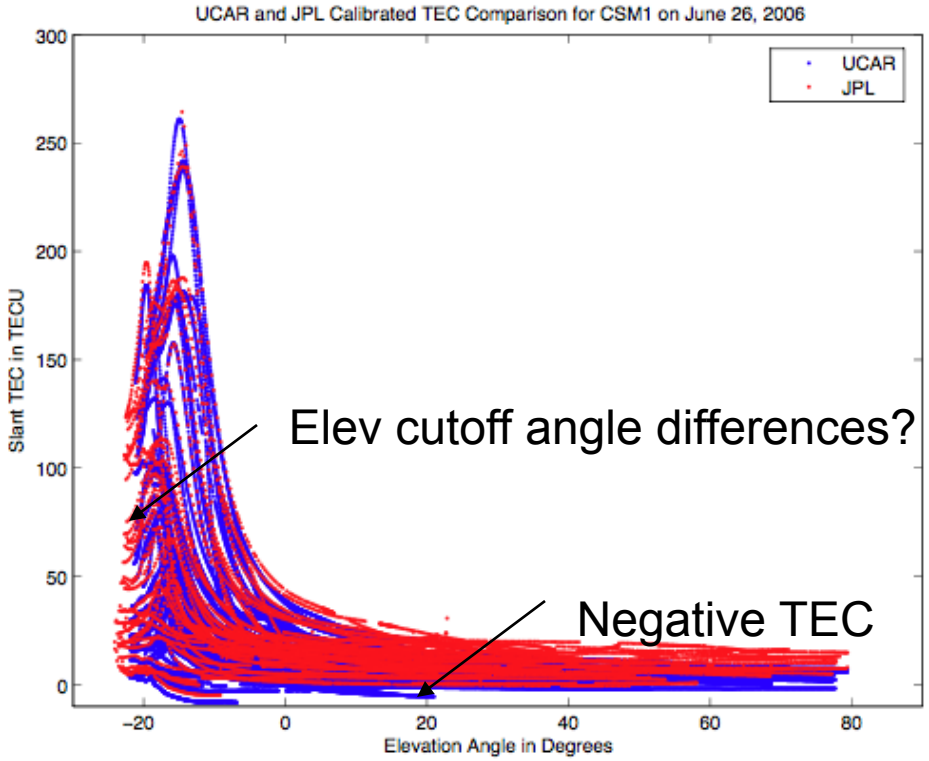
Occultation Locations for COSMIC, 6 S/C, 6 Planes, 24 Hrs

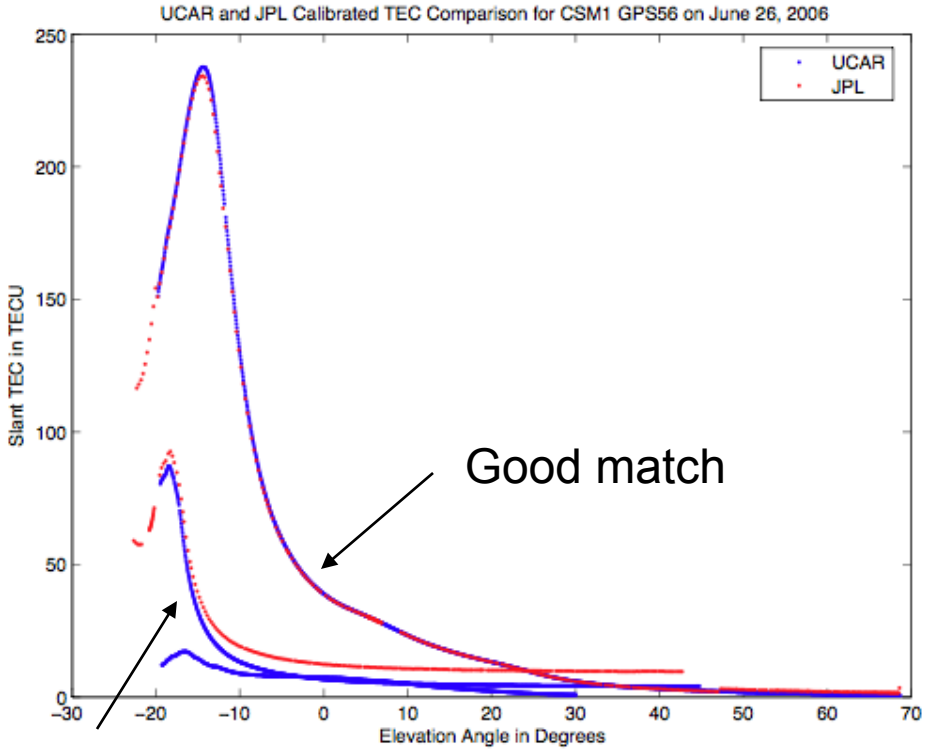


Six-satellite COSMIC constellation
Launched April 14, 2006

NSF NASA USAF NOAA NSPO ONR

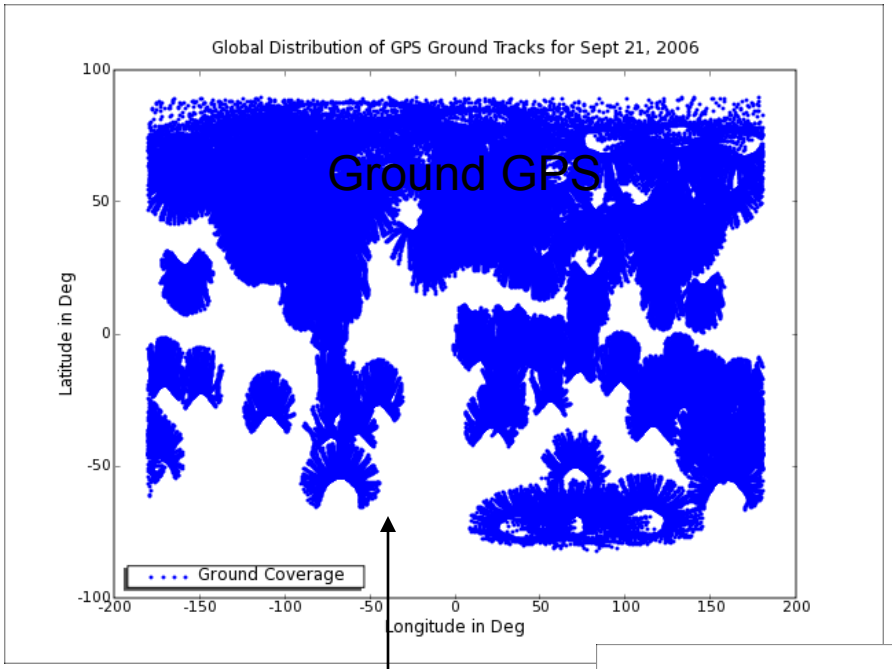
Comparison of Calibrated Slant TEC Measurements: An Example

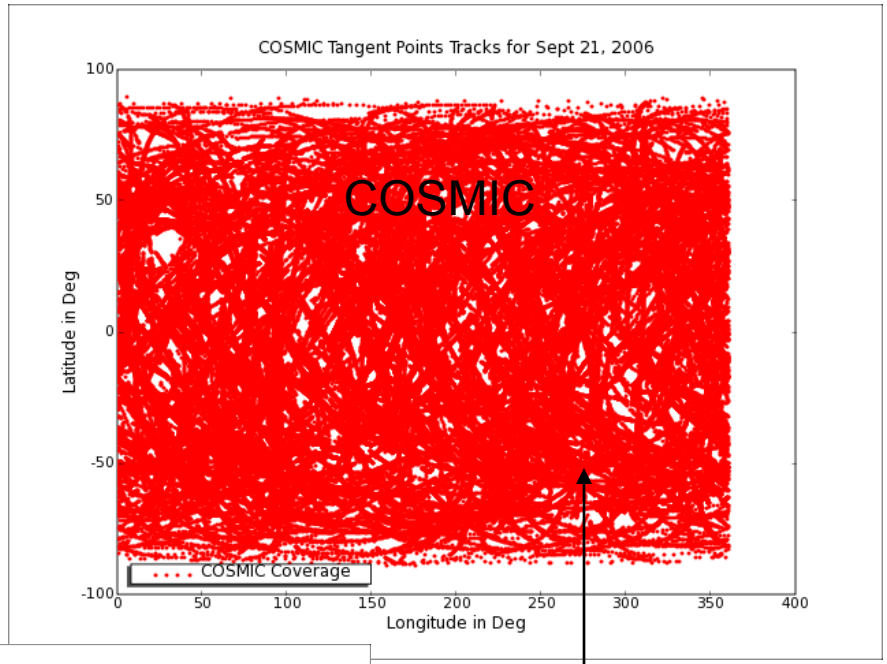


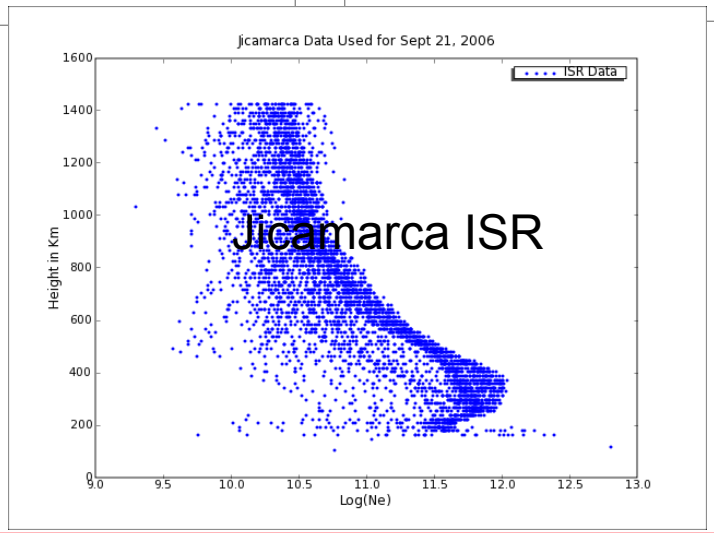


- An example of comparison of calibrated TEC between JPL and UCAR
- Currently there appears to be a 1-2 TECU bias between JPL and UCAR slant TEC
- Similar data volumes between JPL and UCAR

Case 2: Ground, COSMIC and Jicamarca ISR Coverage for Sept 21, 2006



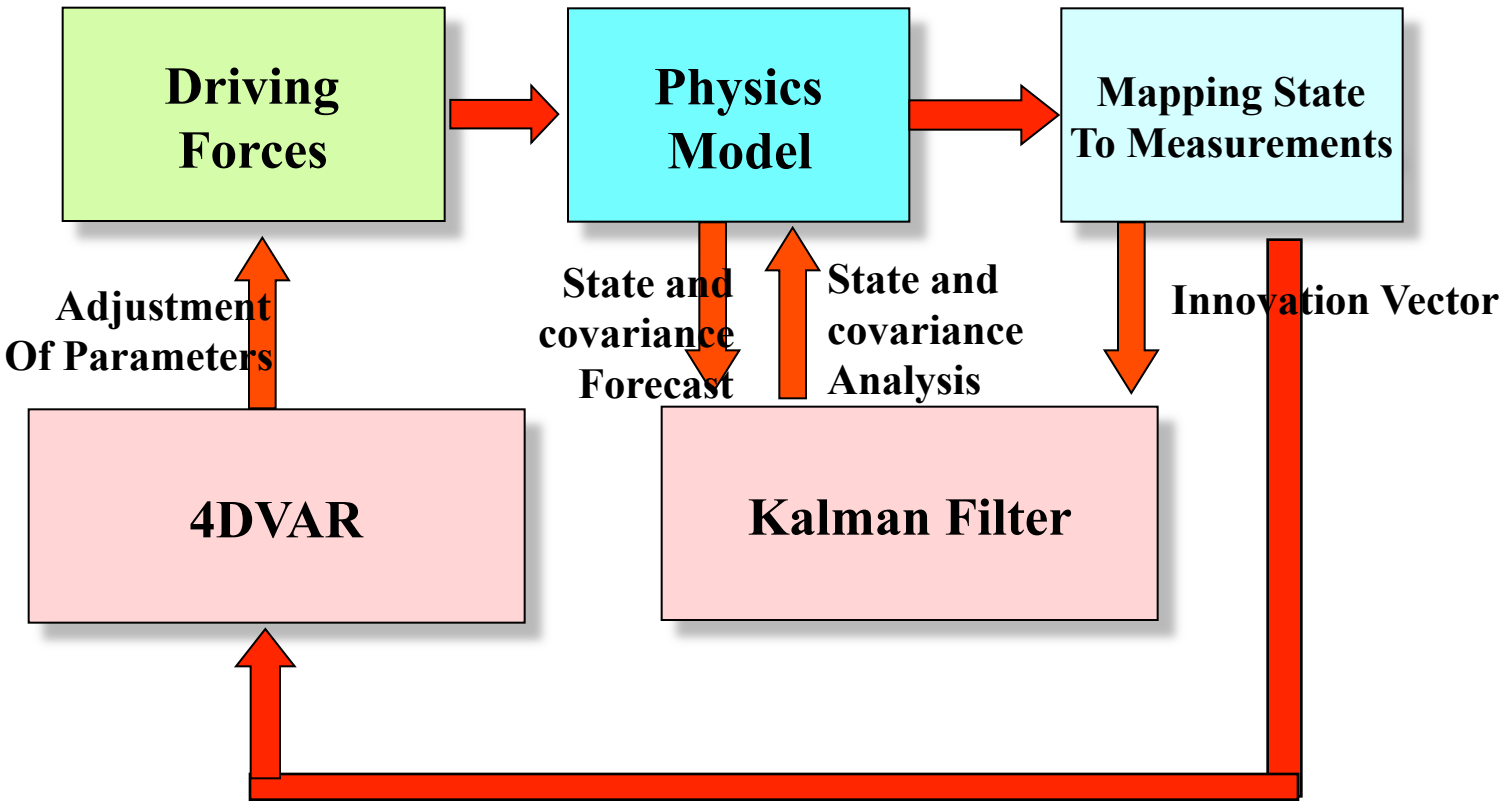




dense but unevenly distributed coverage

less dense yet evenly distributed coverage

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"**

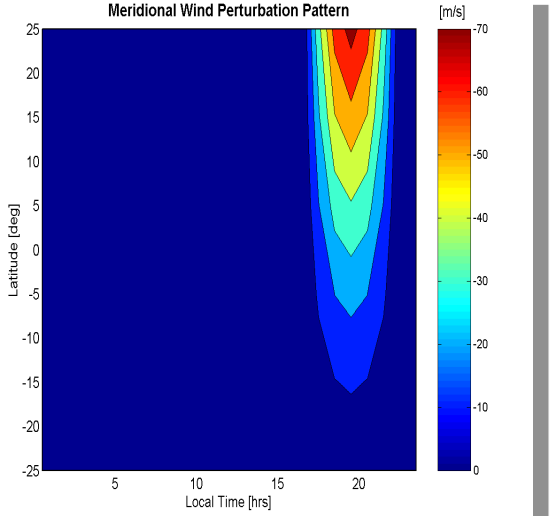
- **Kalman Filter**
  - **Recursive Filtering**
  - **Covariance estimation and state correction**

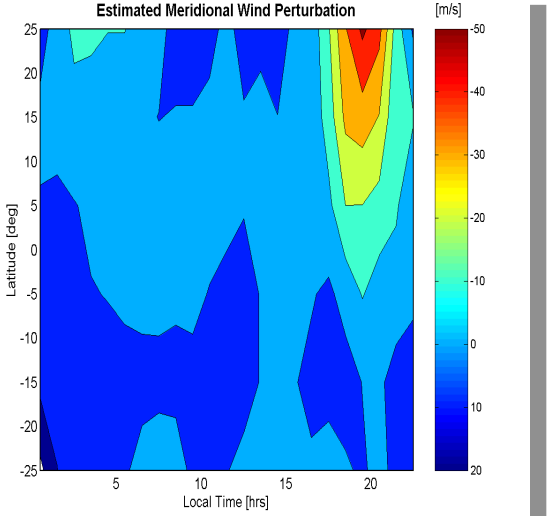
    Optimal interpolation

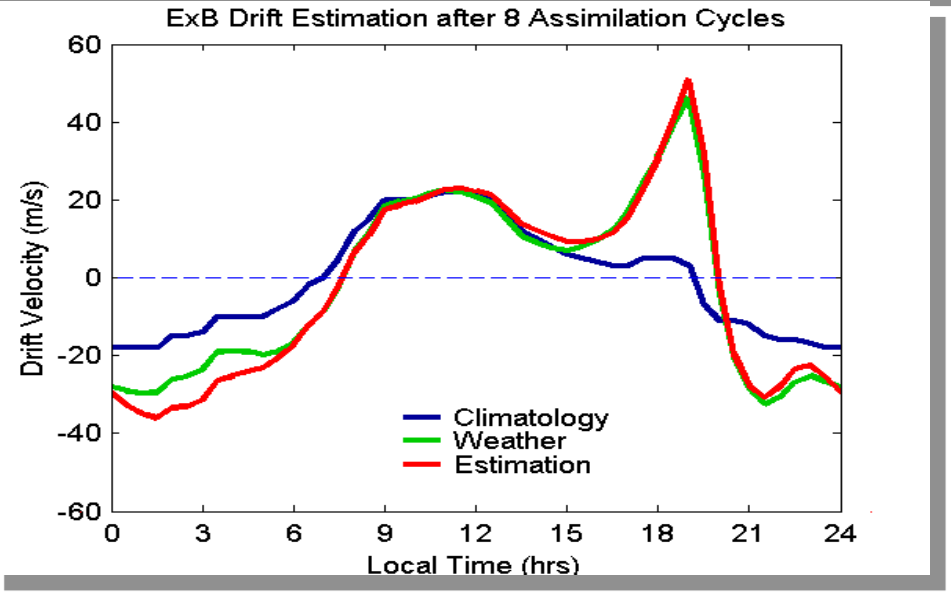
    Band-Limited Kalman filter

4DVAR Adjusted Drivers => Better Forecast

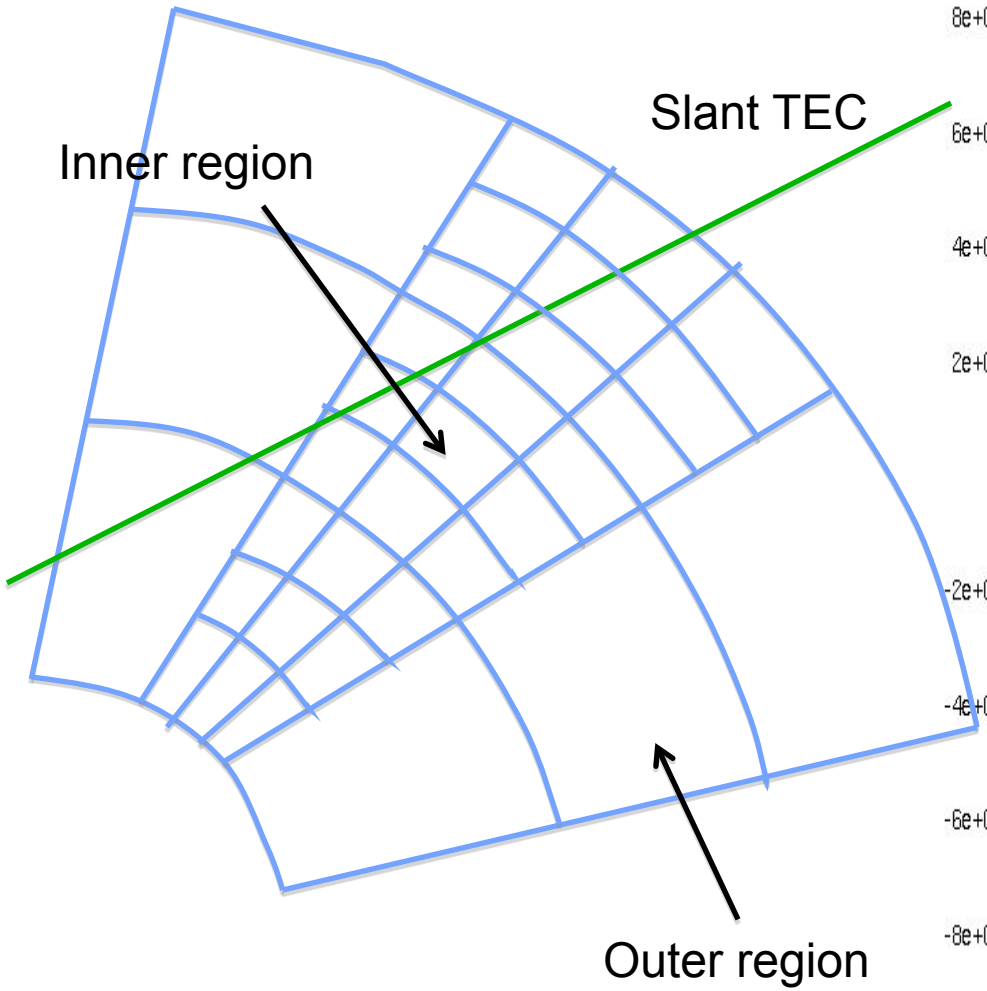
- Observation System Simulation Experiments (OSSE) to estimate "perturbed" drivers at low latitudes:
  - Neutral winds
  - **E×B** vertical drift velocity
  - Production terms
- Synthetic ground GPS TEC data



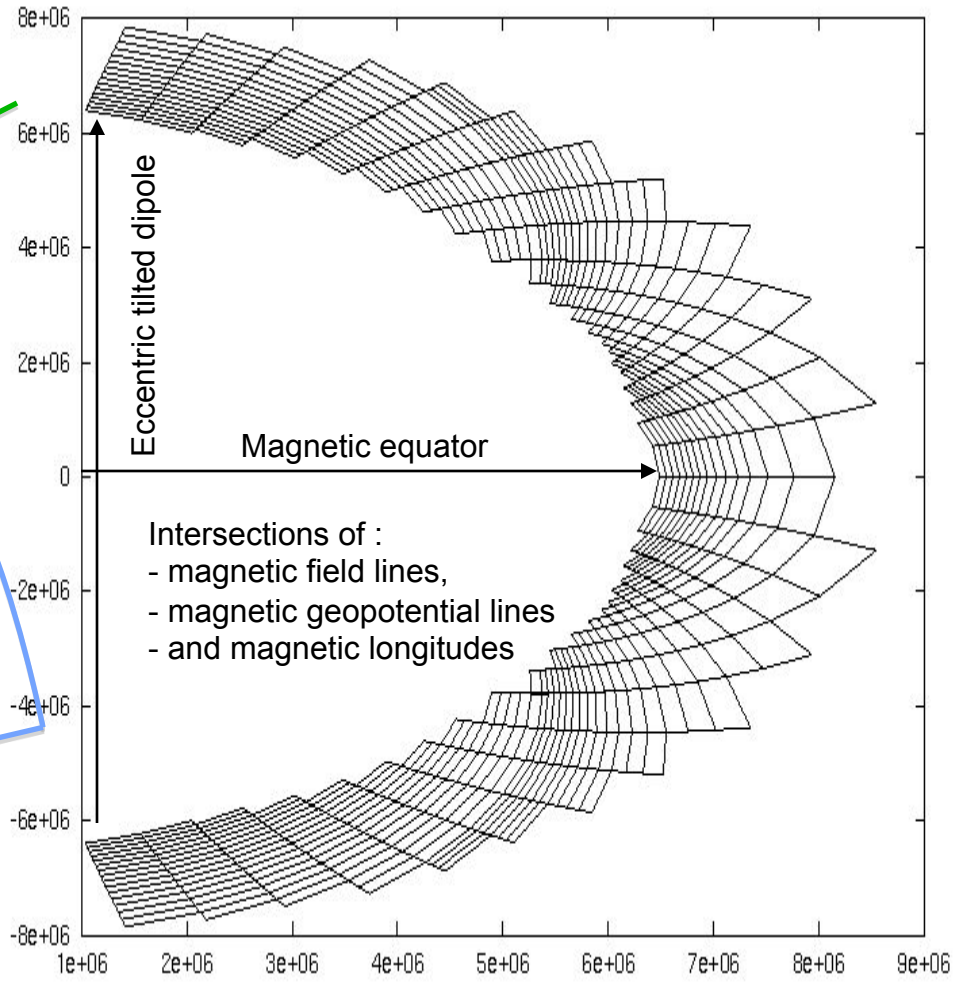




GAIM and Nested GAIM Grids



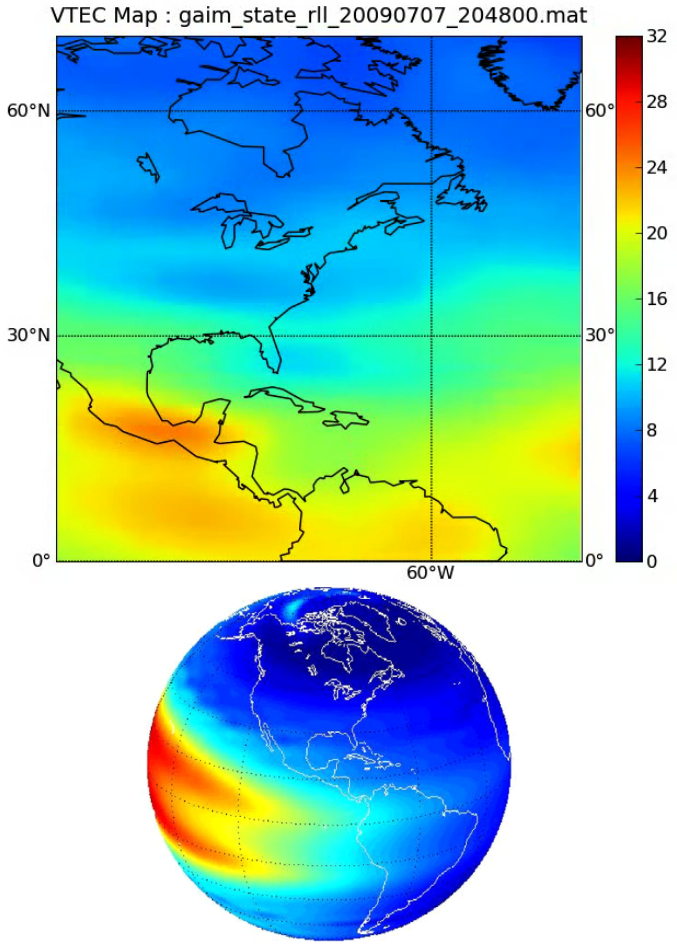
GAIM Nested Grid



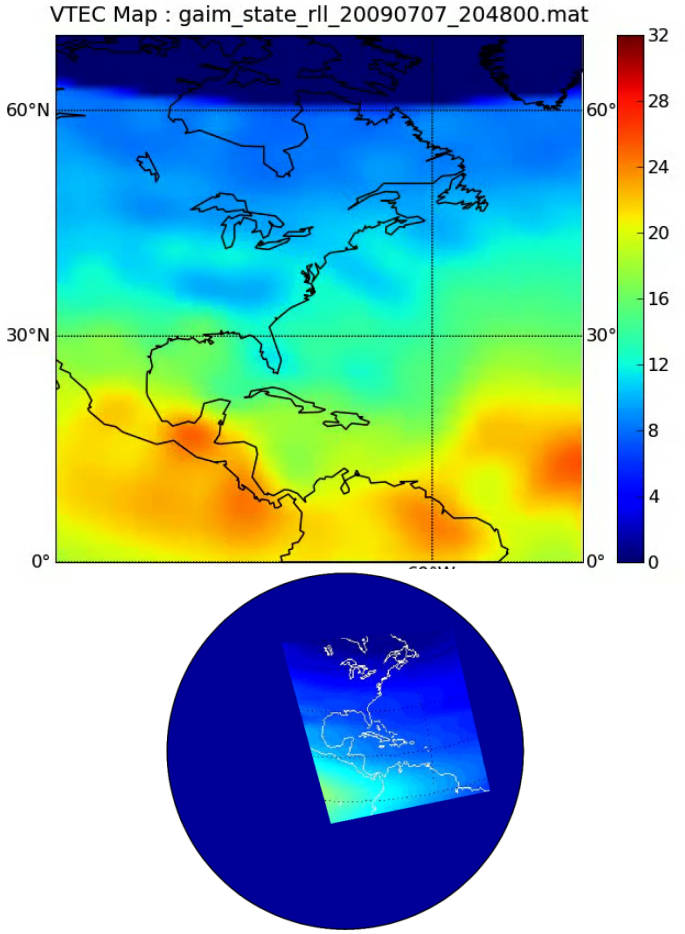
Regular GAIM Grid

Nested Grid Capability (NGAIM)

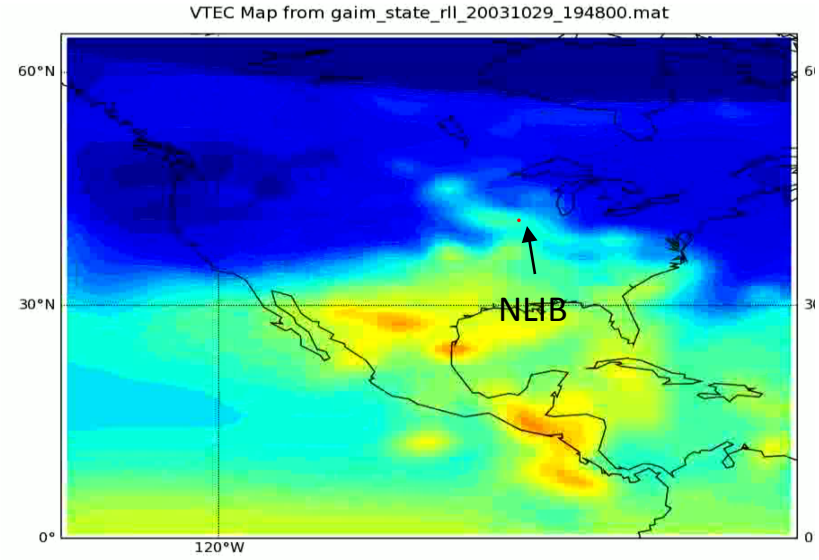
Global Model

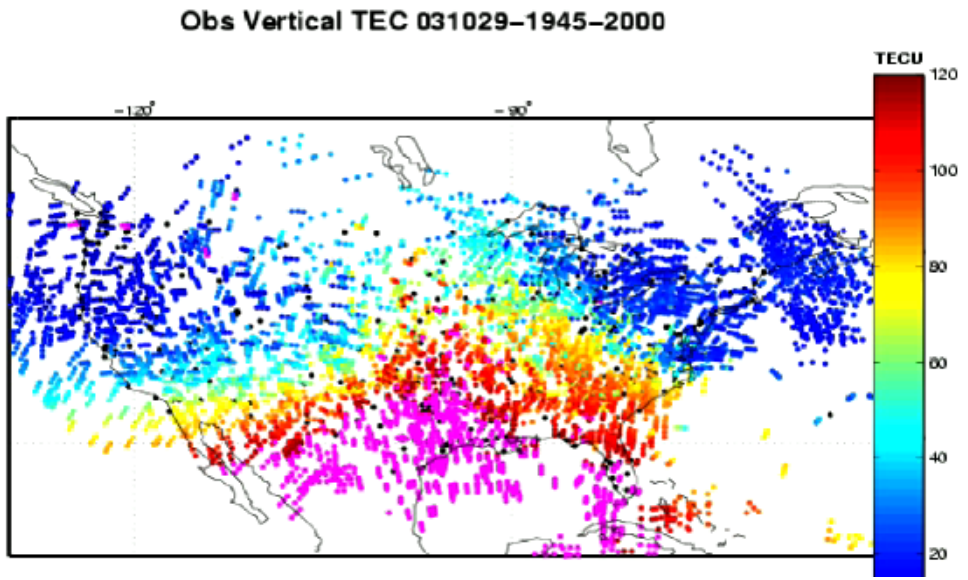


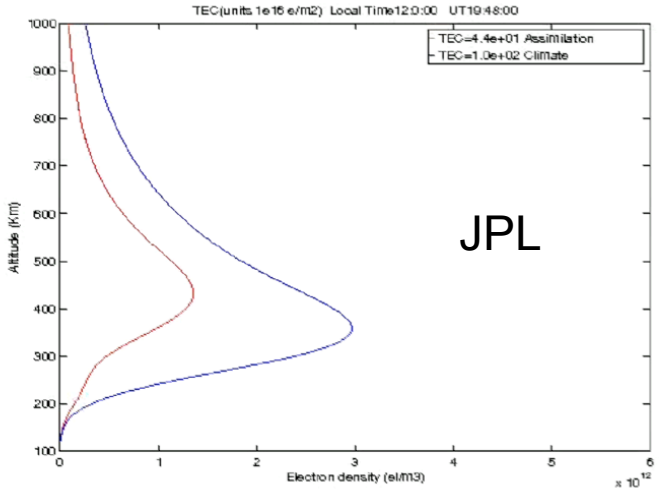
Nested Region

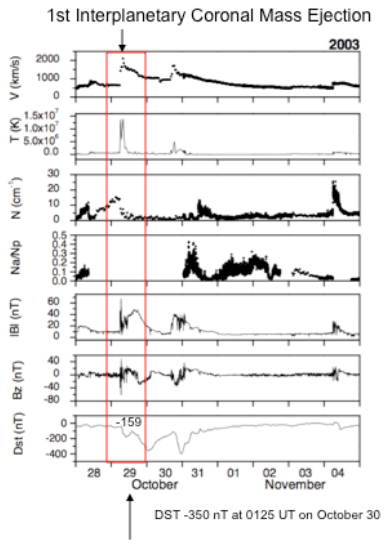


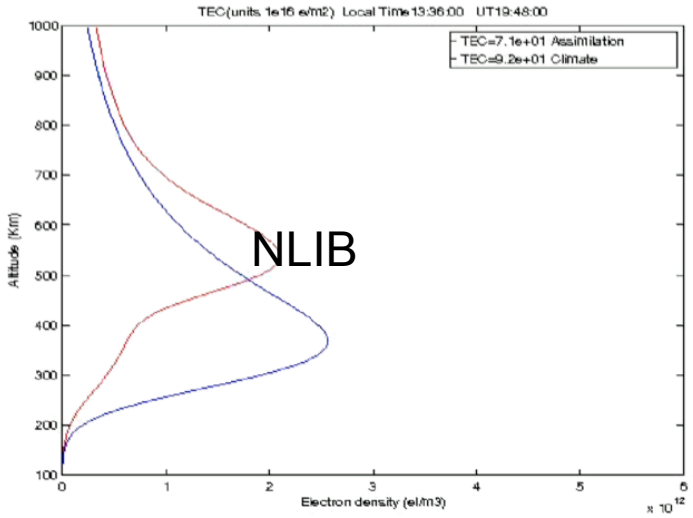
Storm Day: Oct 29, 2003, NGAIM And Truth Storm Features at NLIB



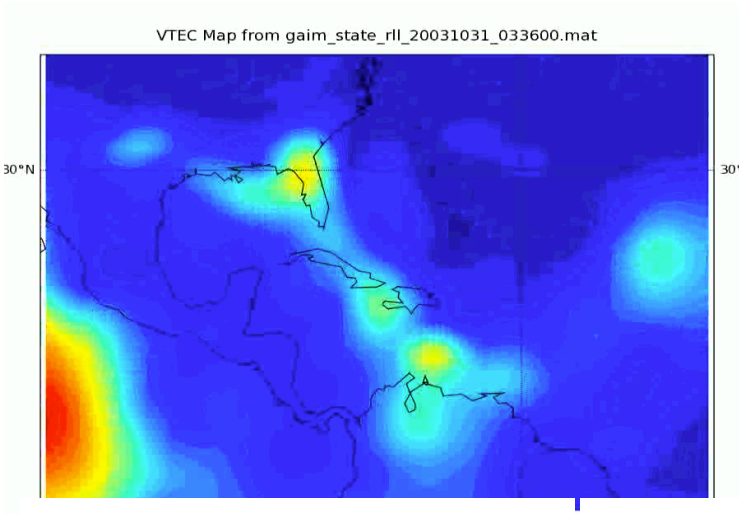


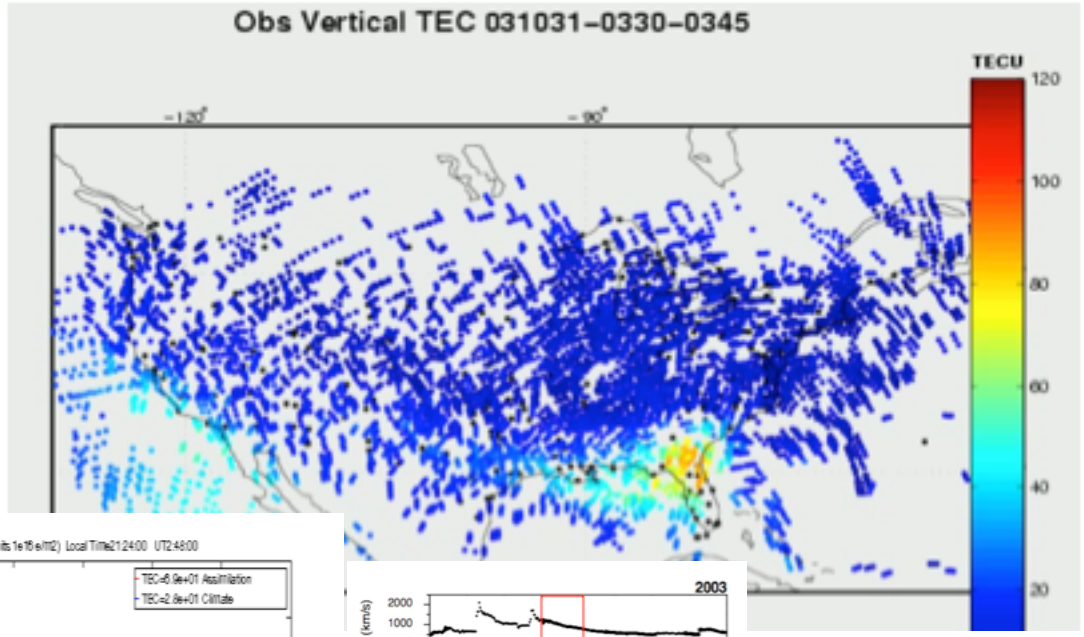


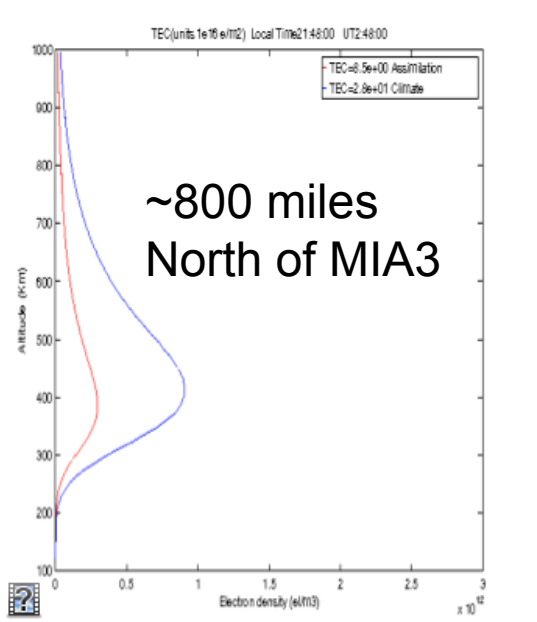


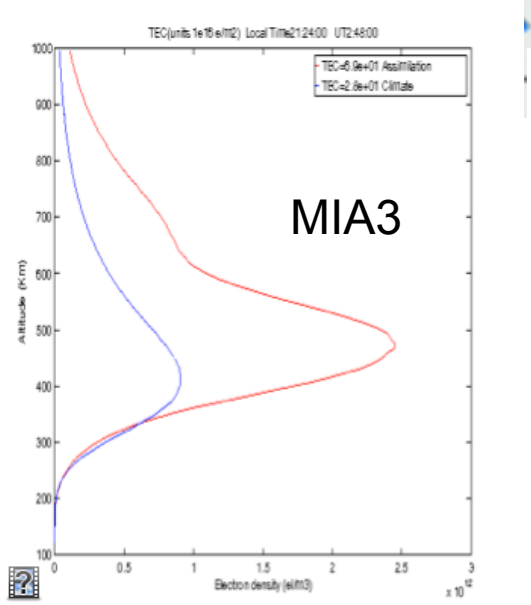


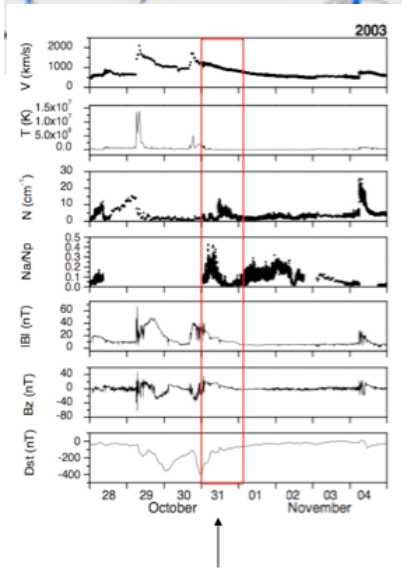
Storm Day: October 31, 2003 NGAIM VTEC Map, the Florida Feature



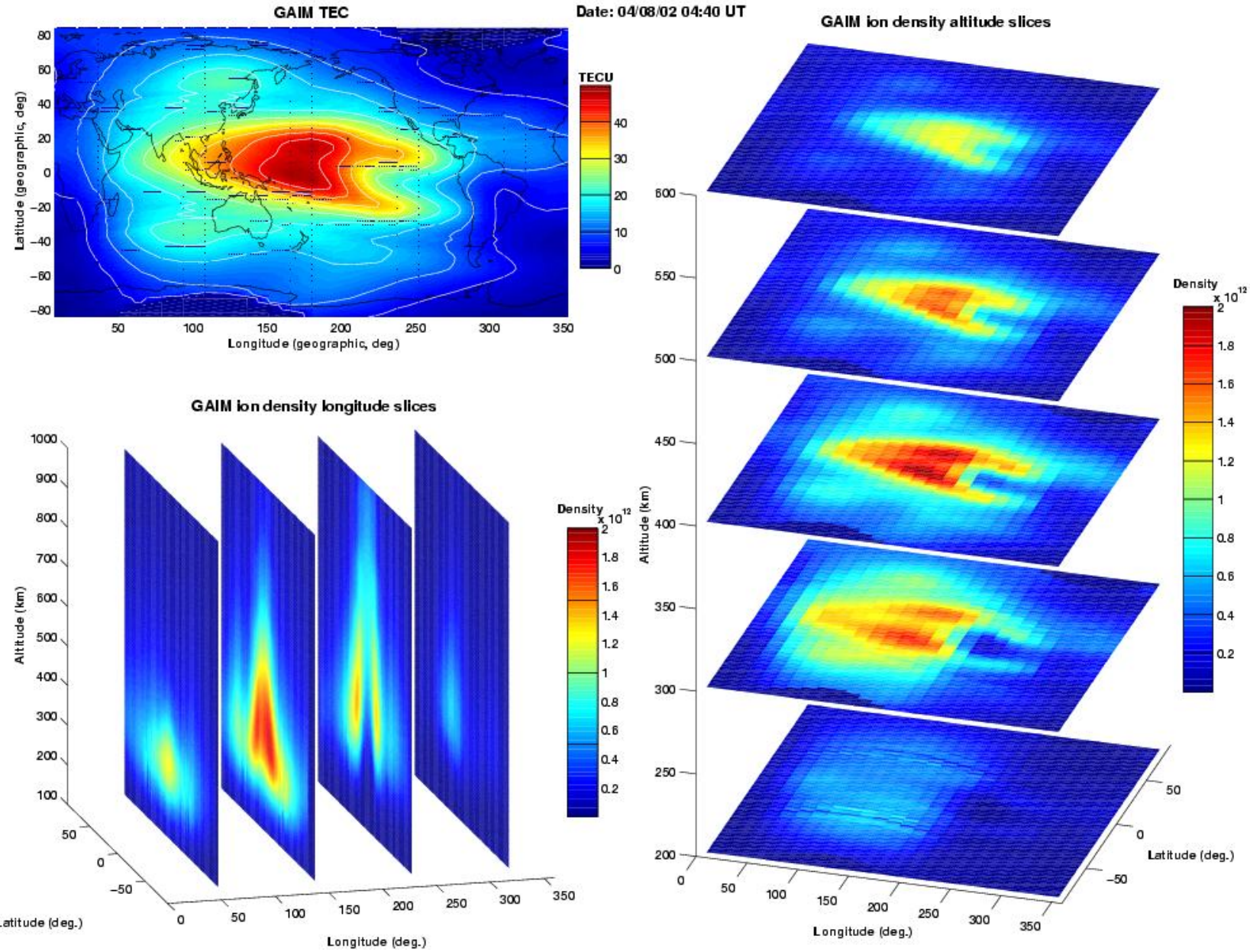








Real-Time GAIM:
TEC Map and Density Slices



PyTEC Design

- New code, written from scratch in Python
- Uses GIPSY's ninja data editing algorithm
  - Written in Fortran, compiled and 'glued' into python
- Uses rnxrdrpro library, written in C/C++ 'glued' into python
- Glued codes execute quickly and efficiently
- Additional compiled code for geometry and compressed file reading algorithms

Multipath in COSMIC

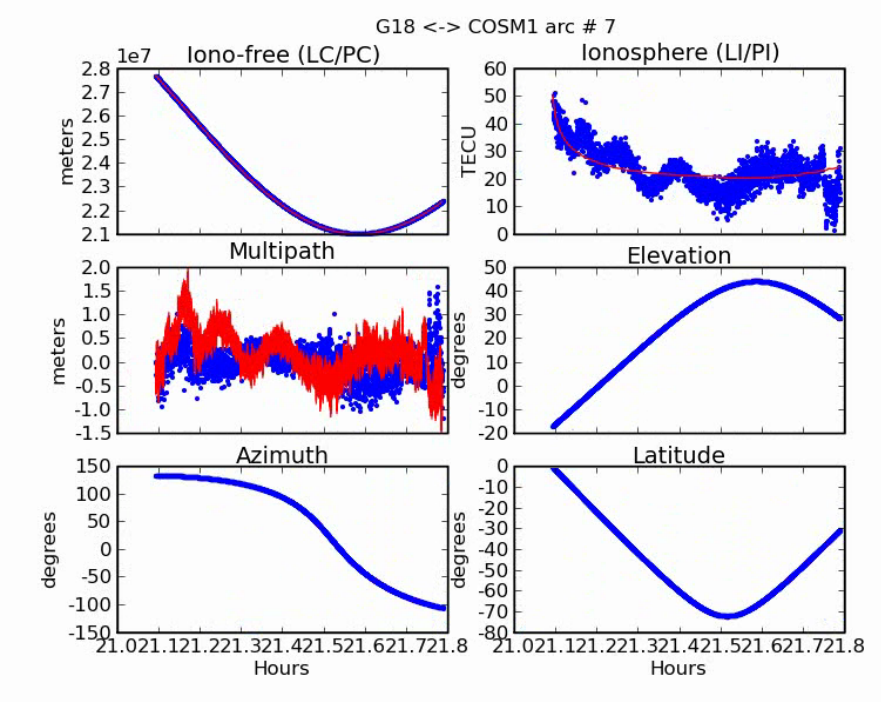
- Noise in PI combination correlated with multipath behavior
- We consider multipath in the leveling
  - Compute the mean and stdev of x = MP1-MP2
  - Weight for point i in leveling is then

$$w_i = \sqrt{\sqrt{2\pi}\exp\left(\frac{(x_i - \langle x \rangle)^2}{\sigma_x^2}\right)}$$

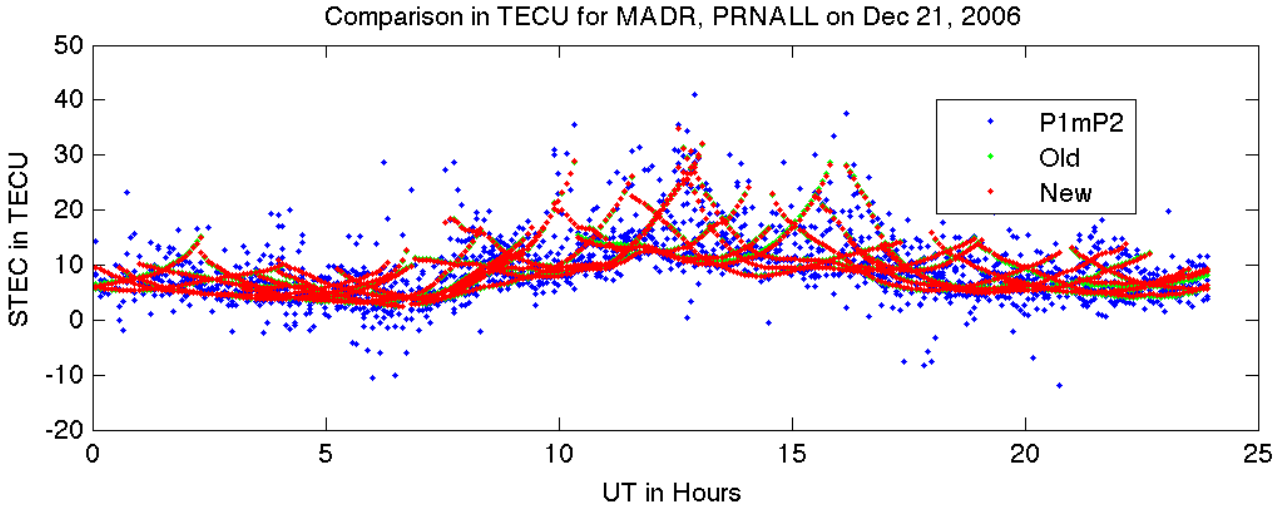
i.e. the weight squared is the inverse of Gaussian variable

$$MP1 \equiv p_1 - \left(1 + \frac{2}{\alpha - 1}\right)\Phi_1 + \left(\frac{2}{\alpha - 1}\right)\Phi_2$$

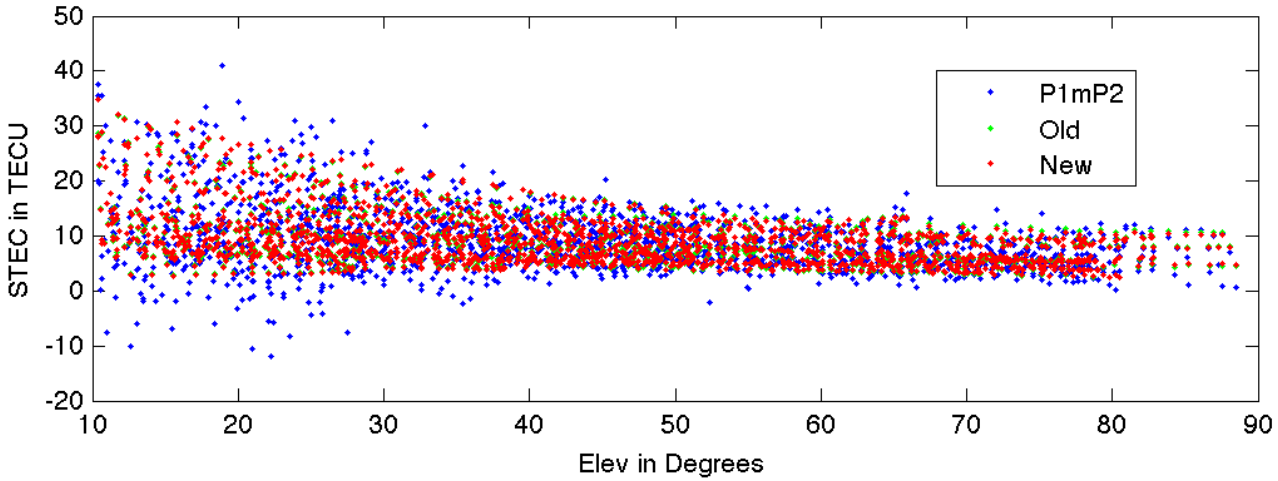
$$MP2 \equiv p_2 - \left(\frac{2\alpha}{\alpha - 1}\right)\Phi_1 + \left(\frac{2\alpha}{\alpha - 1} - 1\right)\Phi_2$$



Comparison of Old and New Slant TEC Processing for Ground GPS Measurements



RMS Old = 3.63 TECU RMS New = 3.62 TECU



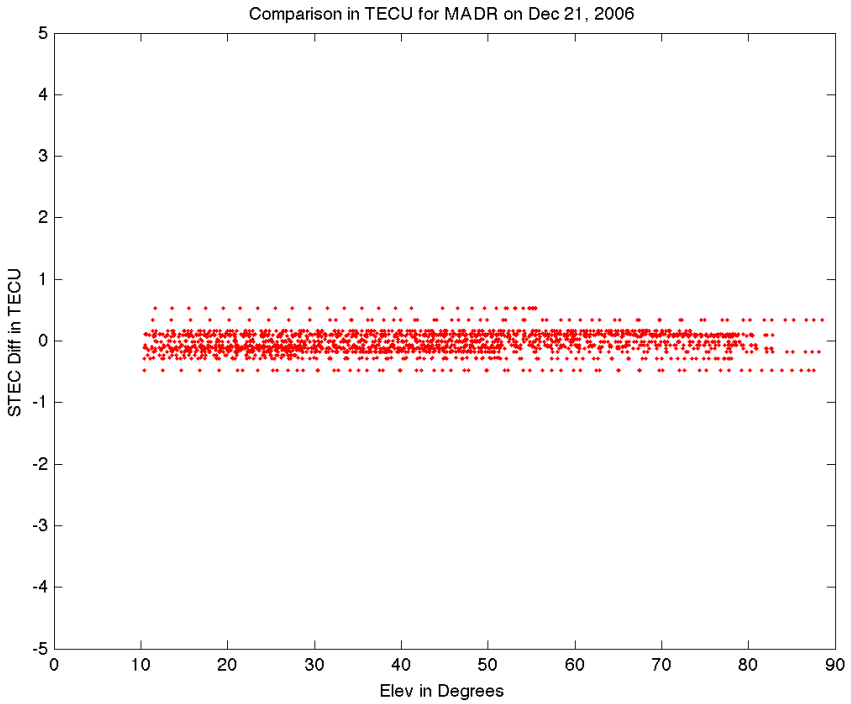
OLD: Ground-data elevation angle weighting:

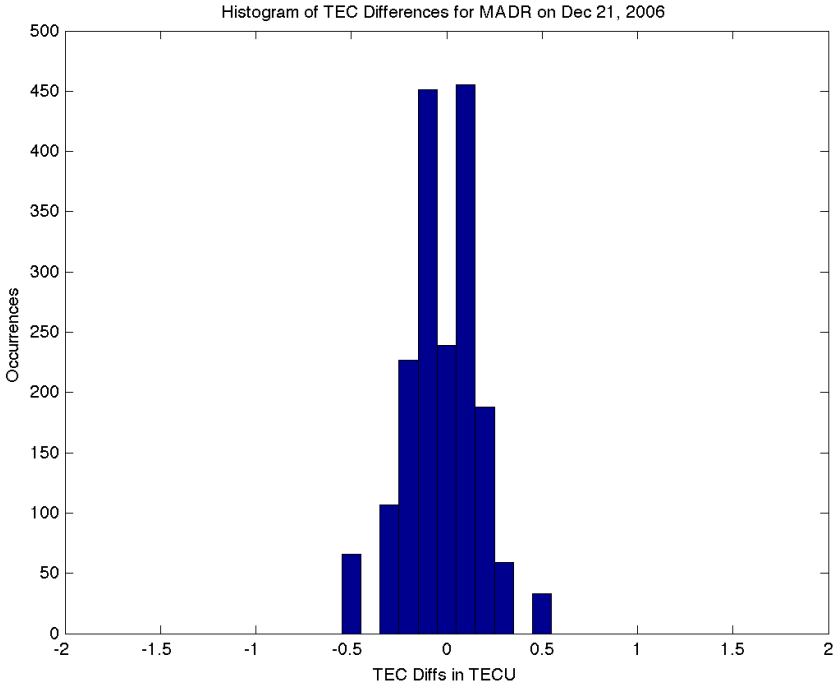
$$L = \frac{\sum_i \frac{1}{\sigma_{th}(E(t_i))^2}(PI(t_i) - LI(t_i))}{\sum_i \frac{1}{\sigma_{th}(E(t_i))^2}}$$

NEW: Ground-data multipath weighting:

$$w_i = \sqrt{\sqrt{2\pi}\exp\left(\frac{(x_i - \langle x \rangle)^2}{\sigma_x^2}\right)}$$

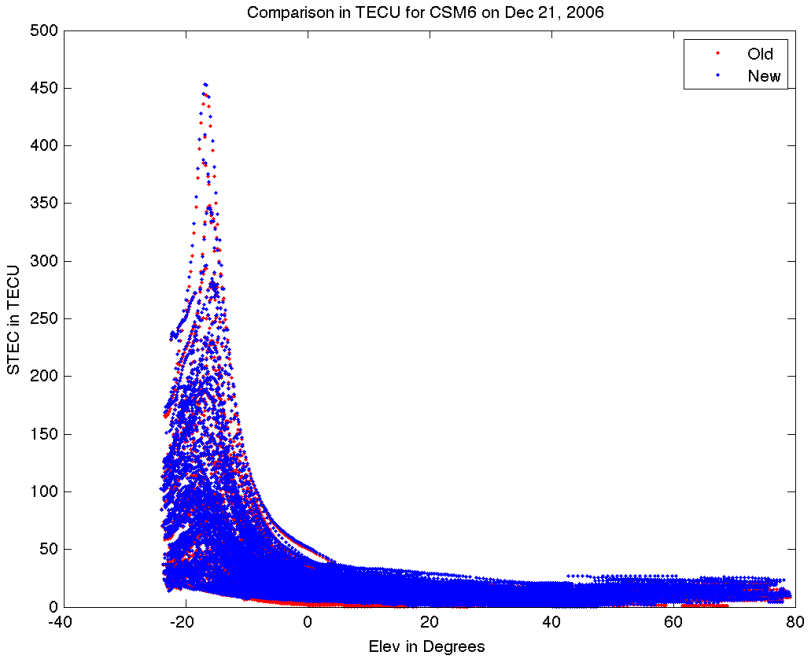
TEC Differences Between Old and New Processing Techniques at Station MADR on Dec 21, 2006

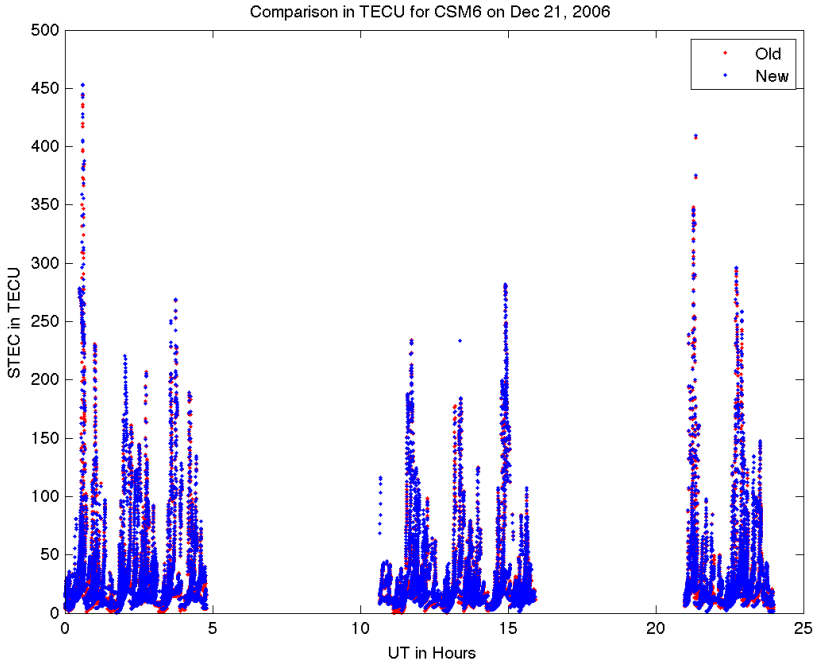




Processed ground GPS data comparison using station MADR

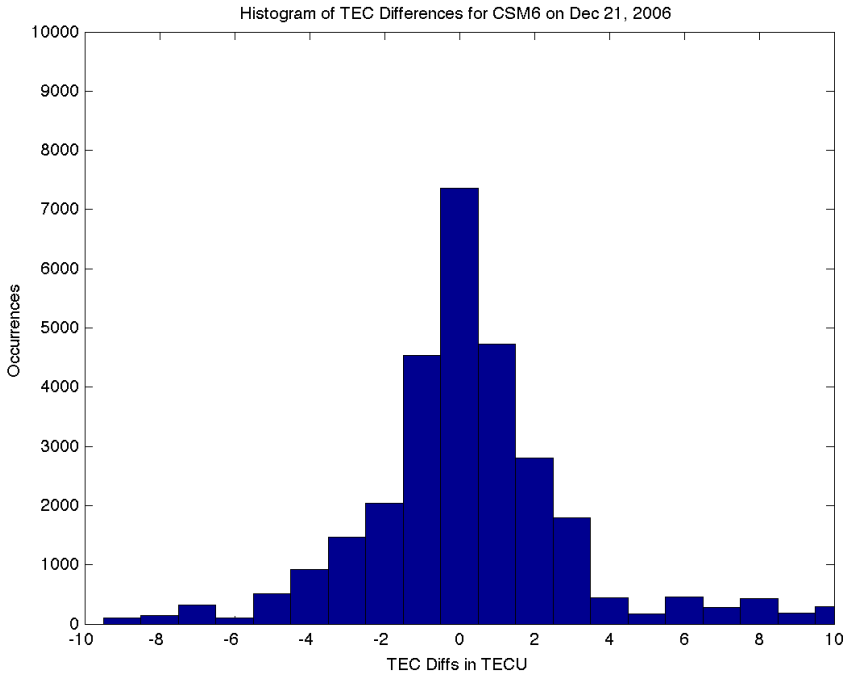
TEC Differences Between Old and New Processing Techniques for Entire CSM6 on Dec 21, 2006



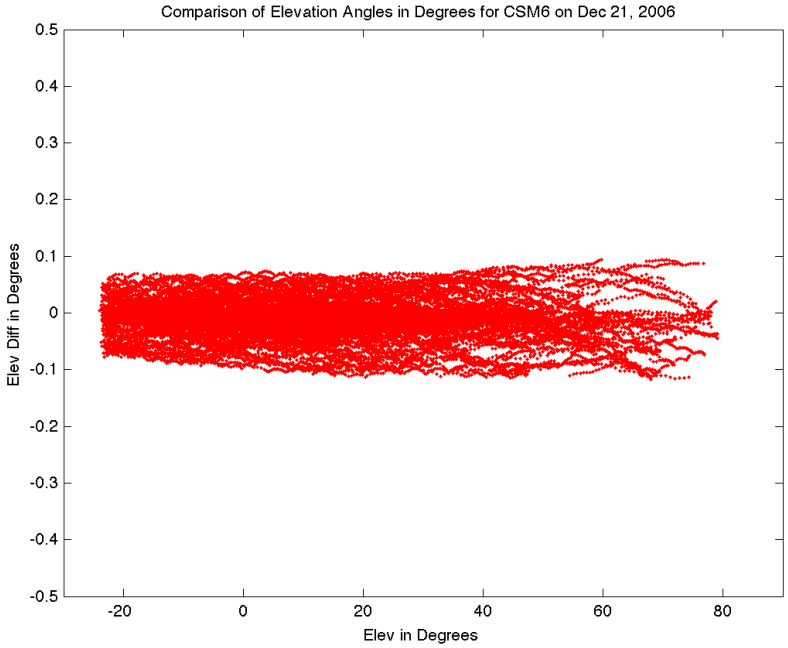


To validate our newly processing of COSMIC and ground GPS data we selected the data set of Dec 21, 2006 because of our prior experience and published results for that day

TEC and Elevation Angle Differences Between Old and New Processing Techniques for CSM6 on Dec 21, 2006

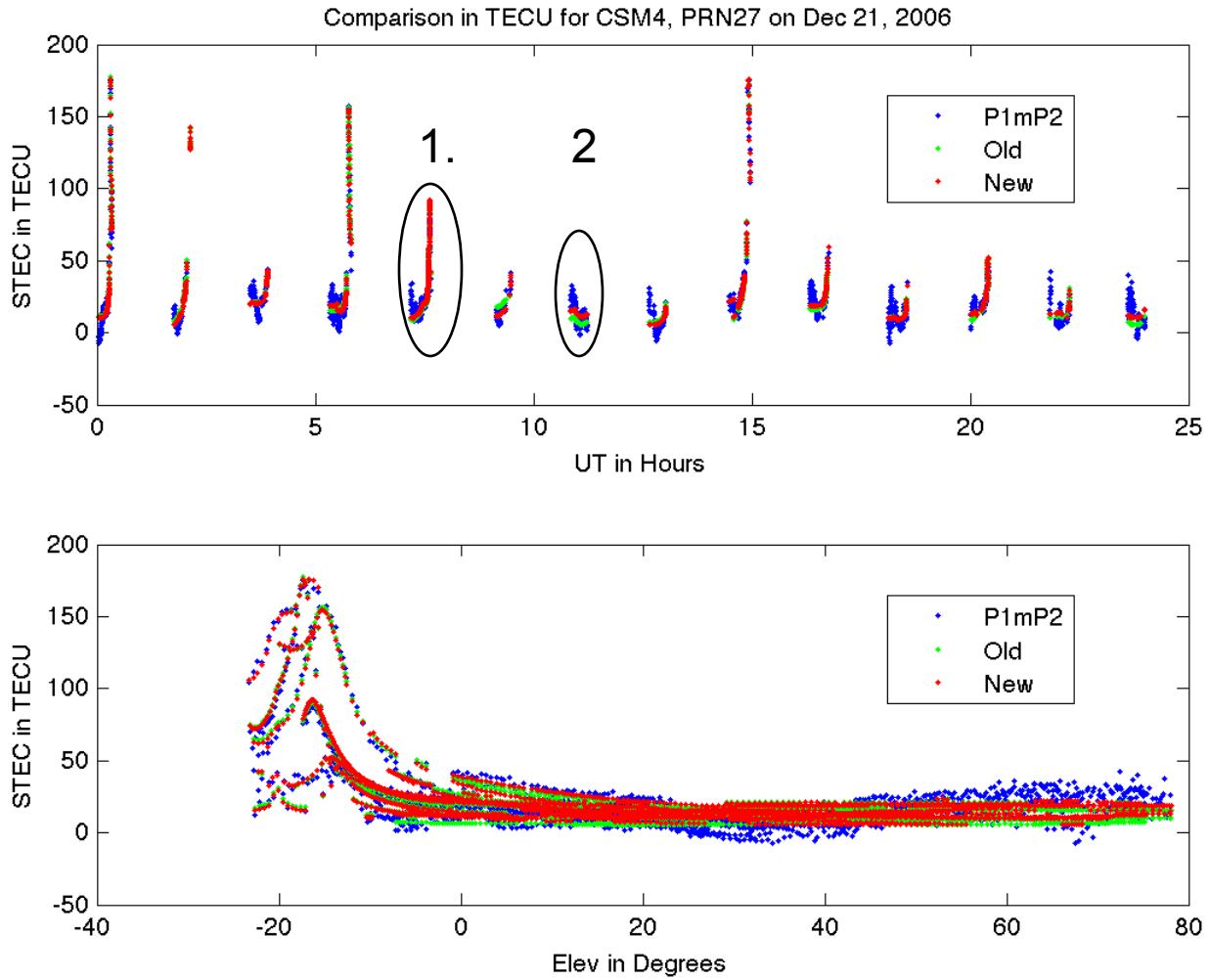


Differences are at 4 TECU level

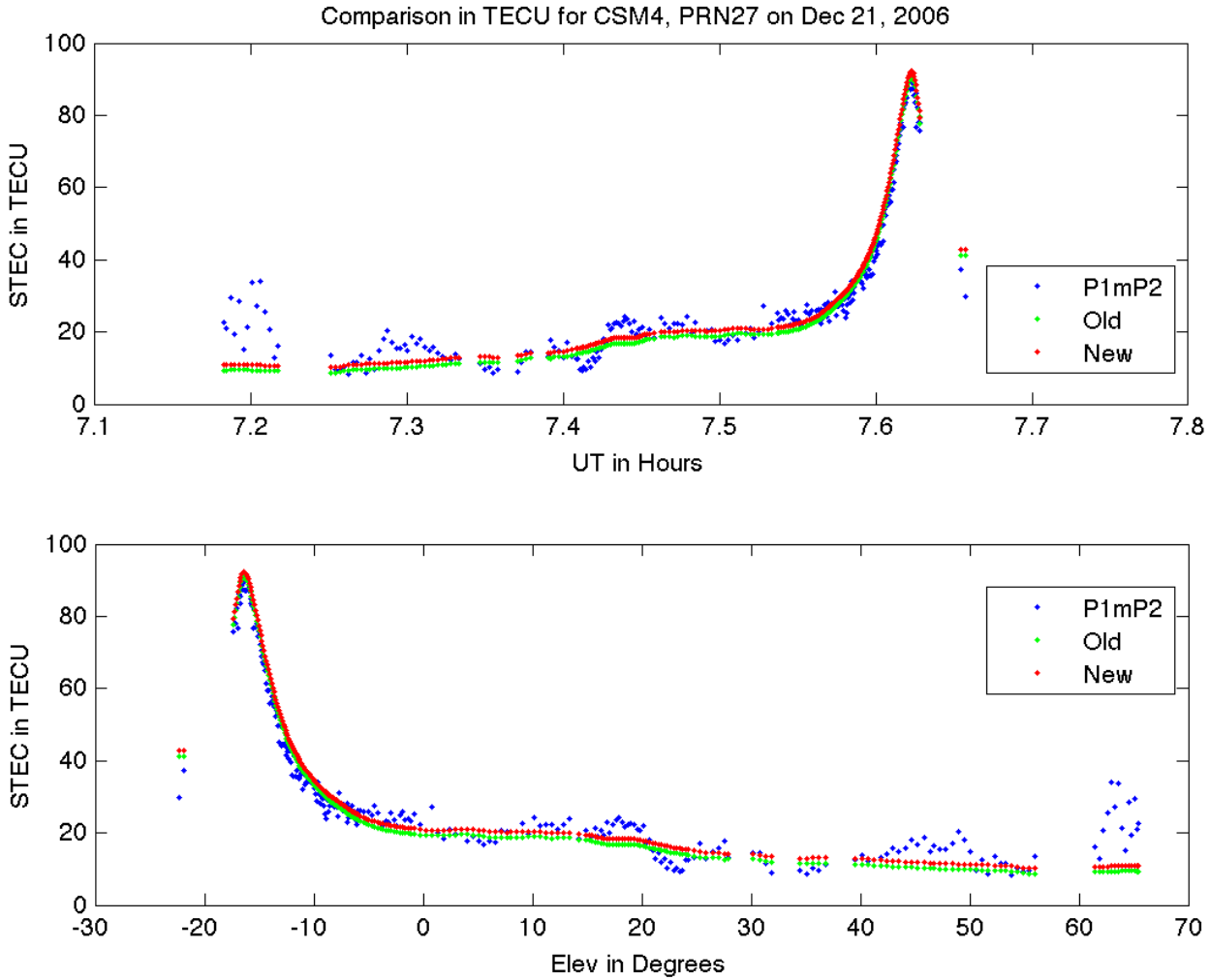


Differences in elevation angles < 0.1 degree

TEC Comparisons Between Old and New Processing Techniques for PRN27, CSM4 on Dec 21, 2006

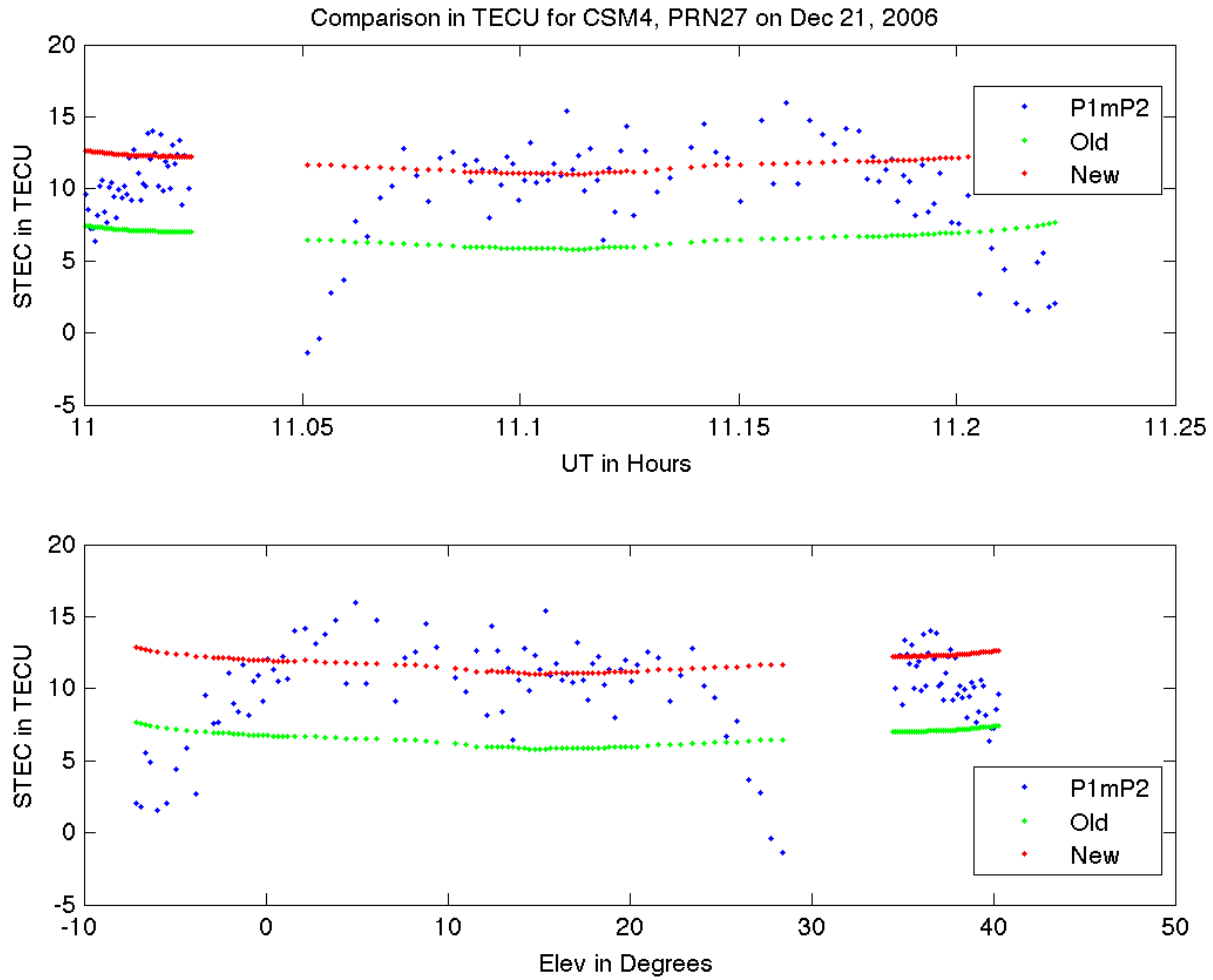


Occultation Case Examples (1): PRN27 for CSM4



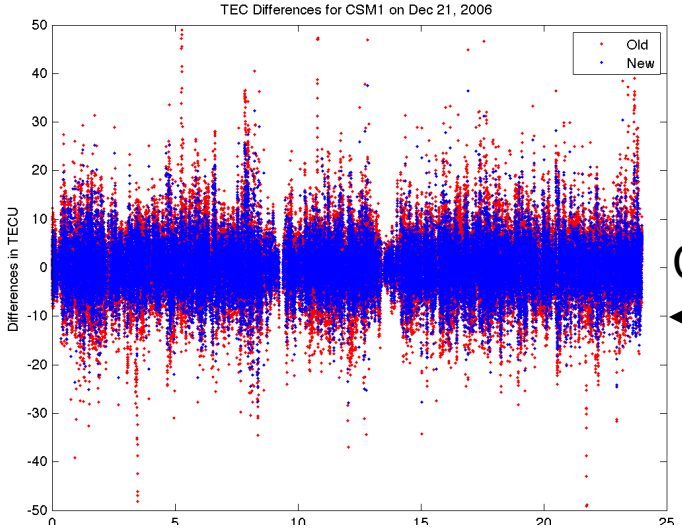
Continuous day-time occultations with no phase break agree well

Occultation Case Examples (2): PRN27 for CSM4

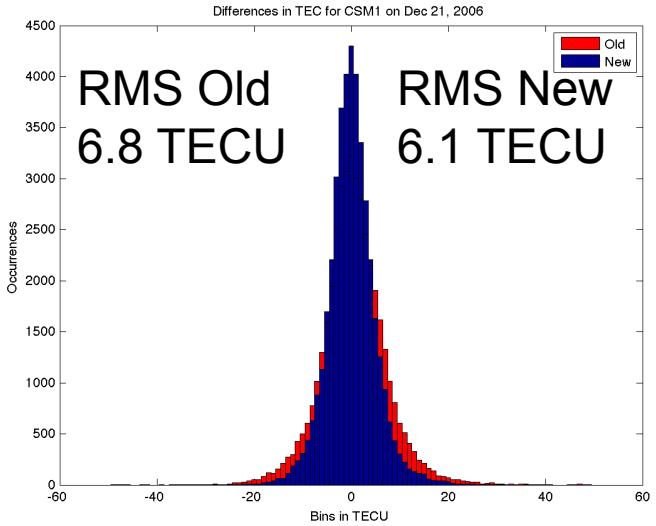


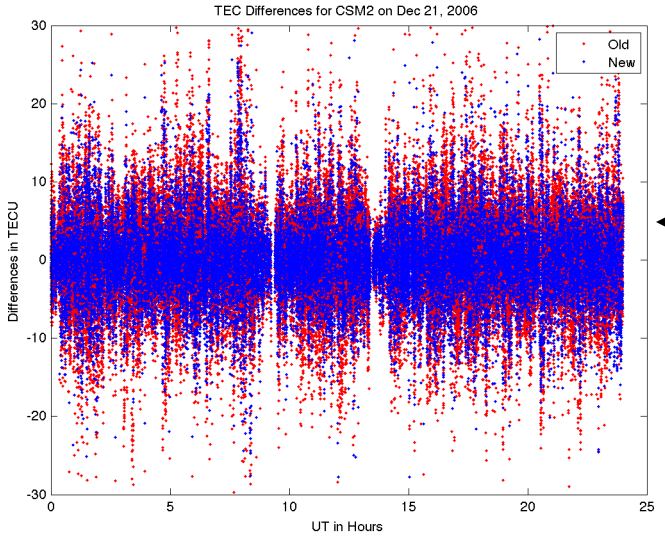
Leveling night-time occultations impacted by multipath shows poorer agreement

All CSM1 and CSM2 Residuals and Histogram for Dec 21, 2006

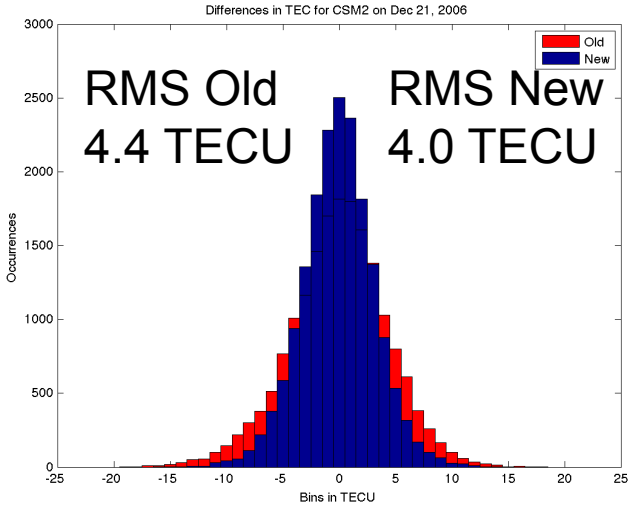


CSM1





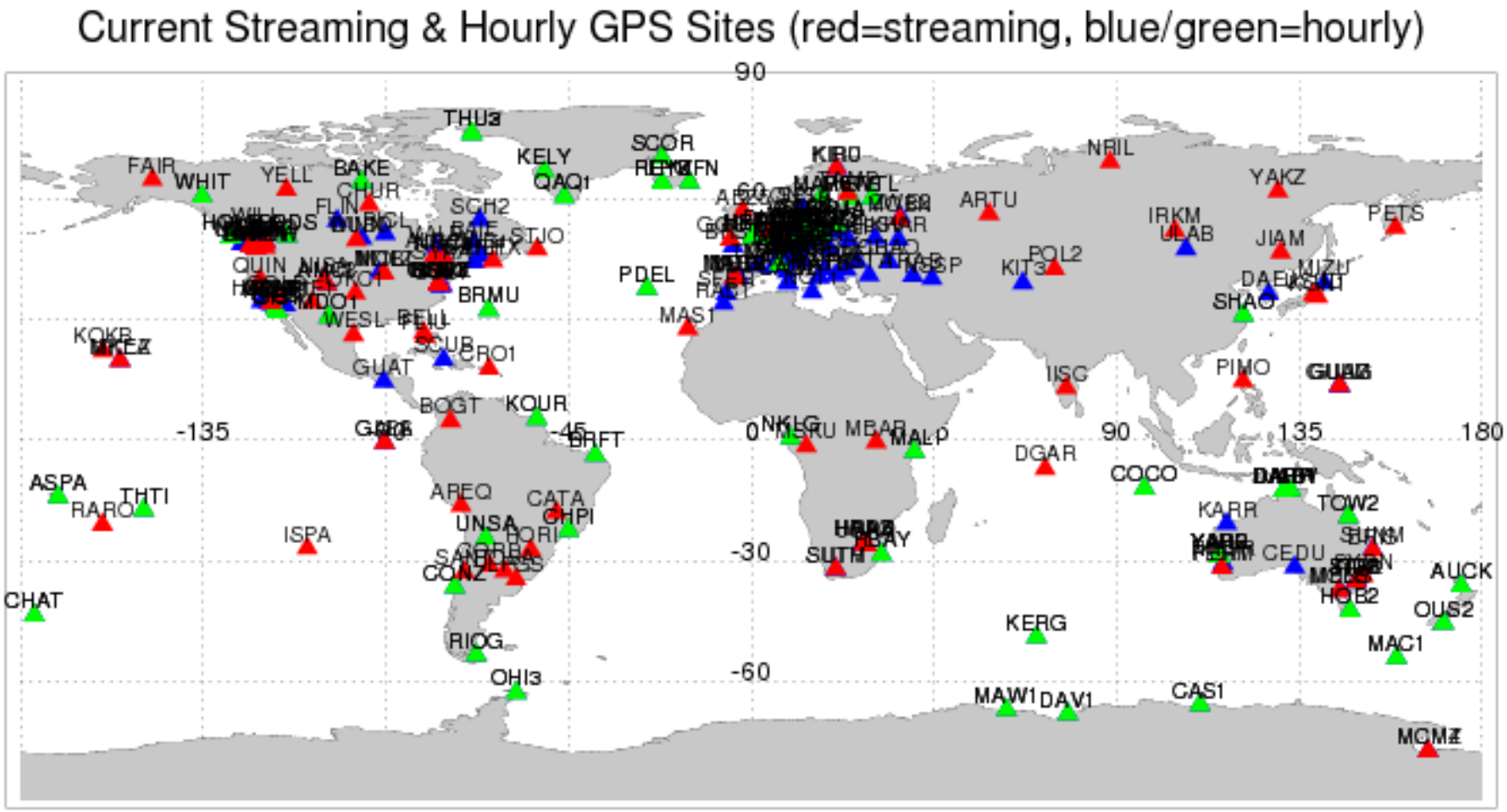
CSM2



Current Real-Time GAIM System

- **End-to-end automated system**
  - Takes GPS RINEX data as input, in real-time
    - Processed to STEC data using PyTEC software
- **5 or 15-min. Kalman filter updates**
  - Inputs from 1-second streaming GPS sites, and 15-min. to hourly sites
- **Second Kalman filter thread**
  - Waits for TEC links from the six COSMIC satellites (space-borne GPS receivers)
  - Then “catches up” to real-time and becomes primary thread
- **Continuous real-time validation (under development)**
  - Comparisons to independent obs. (e.g. JASON VTEC, or missing sites/sats)
  - Forecast skill score

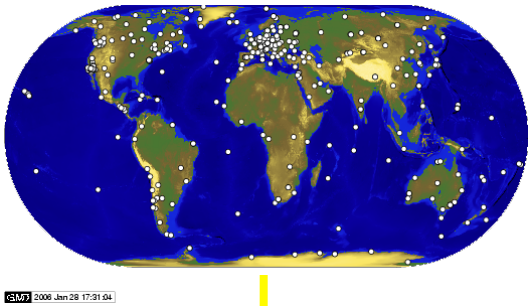
Ground GPS Streaming and Hourly Sites

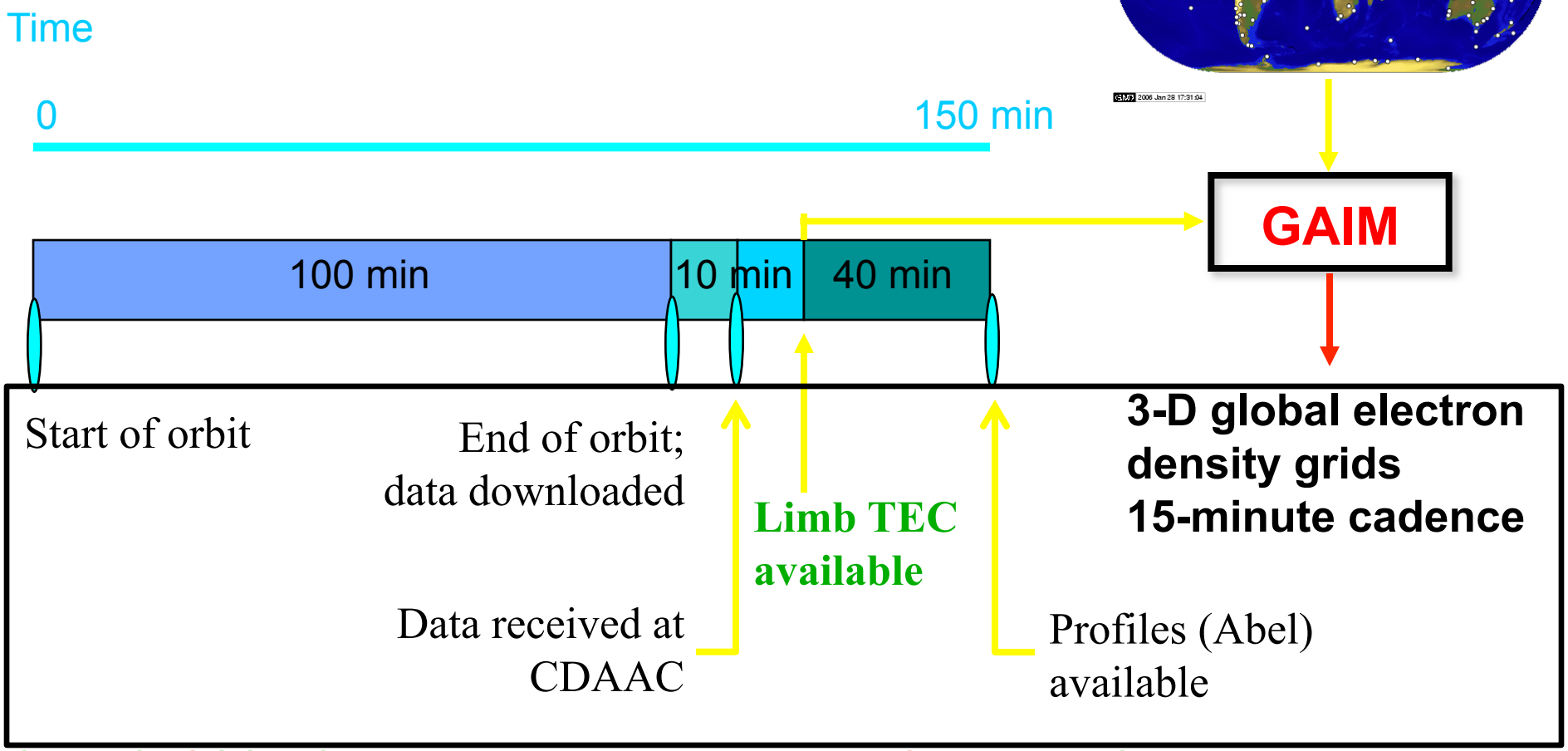


Real-Time COSMIC Schematic

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

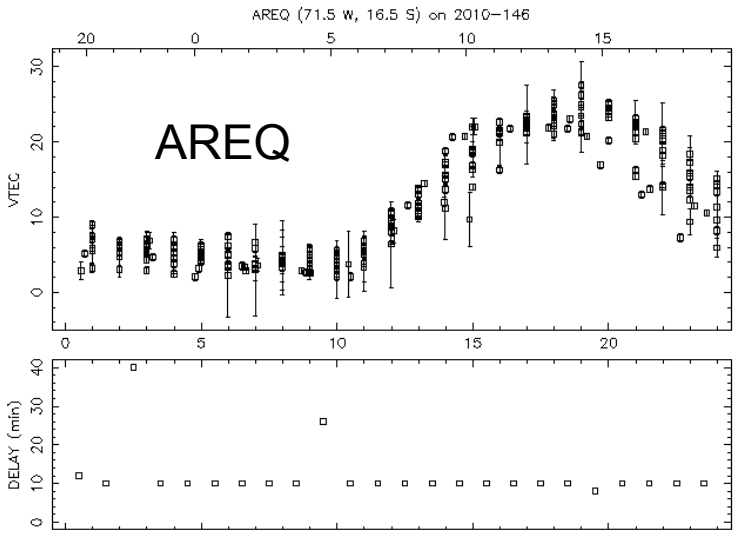
COSMIC data: 120+ minutes latency

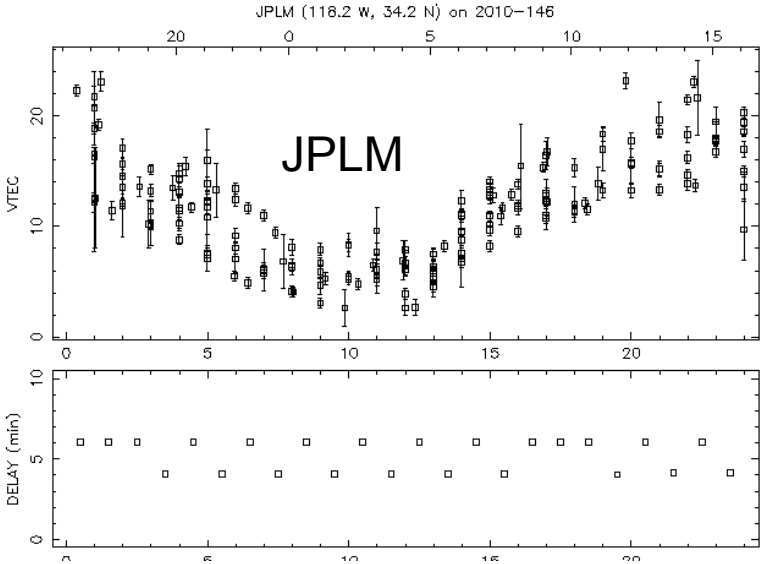


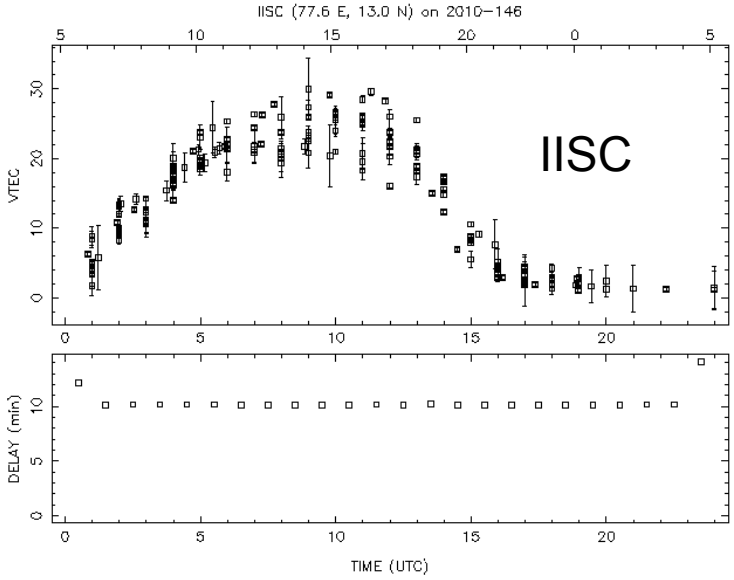


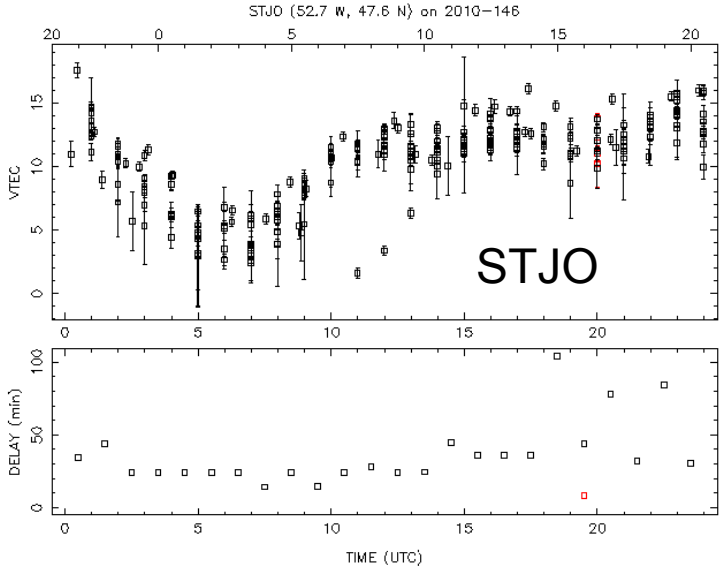
CDAAC: COSMIC Data Analysis and Archiving Center at UCAR

Real-Time 5-Minute TEC Data Feed

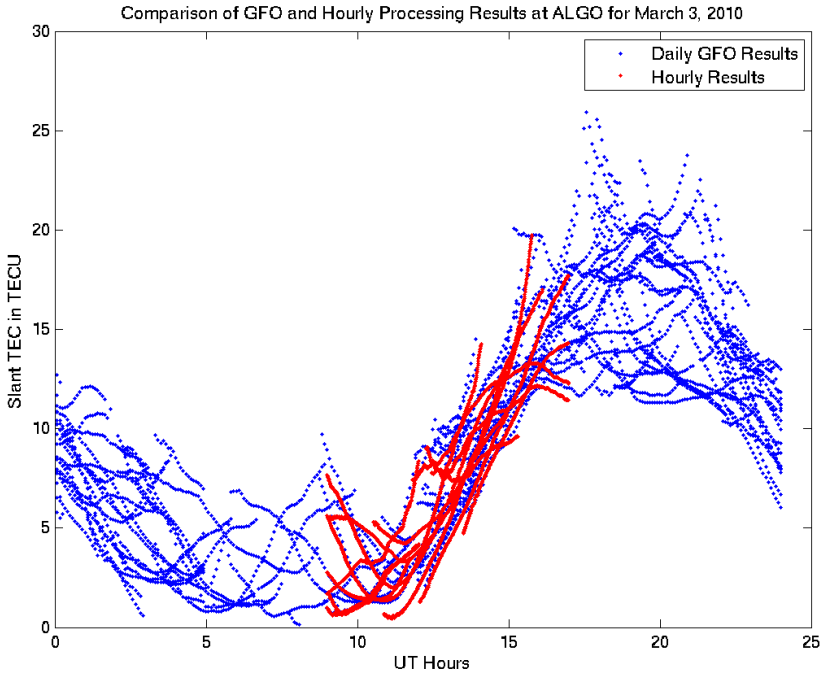






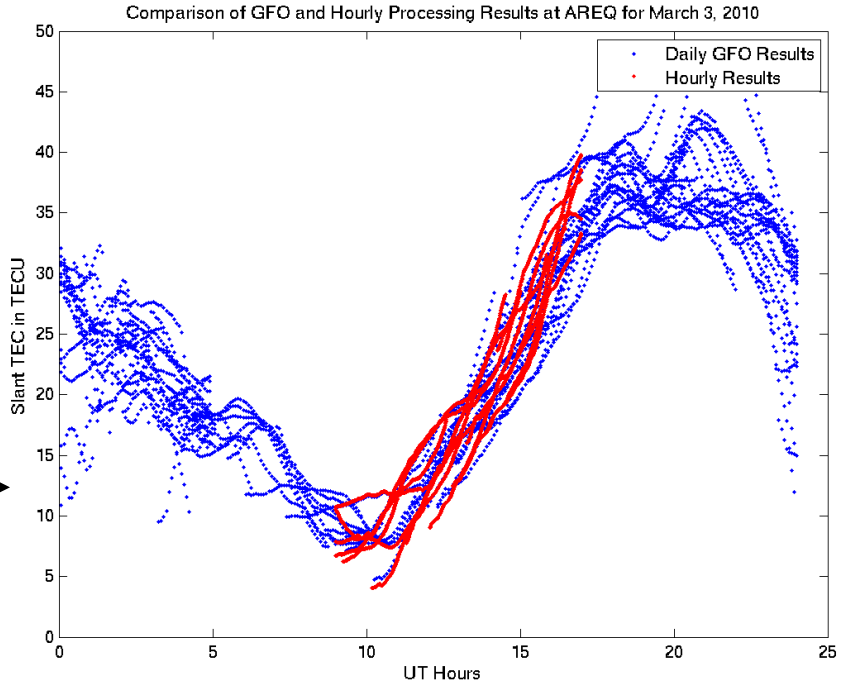


Hourly and Daily TEC Comparison for ALGO and AREQ



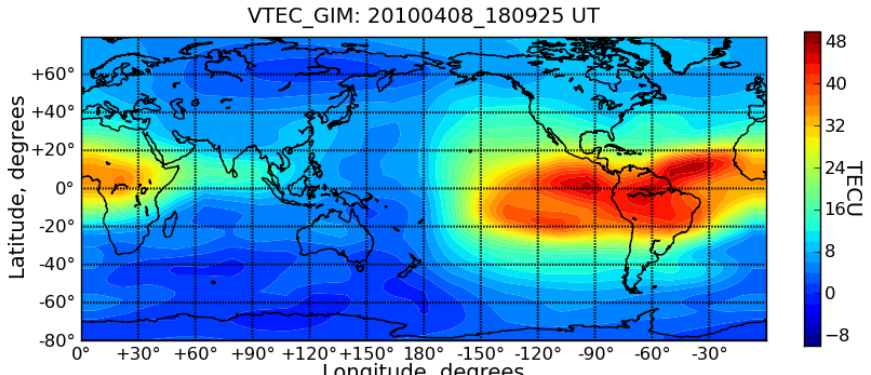
ALGO

AREQ

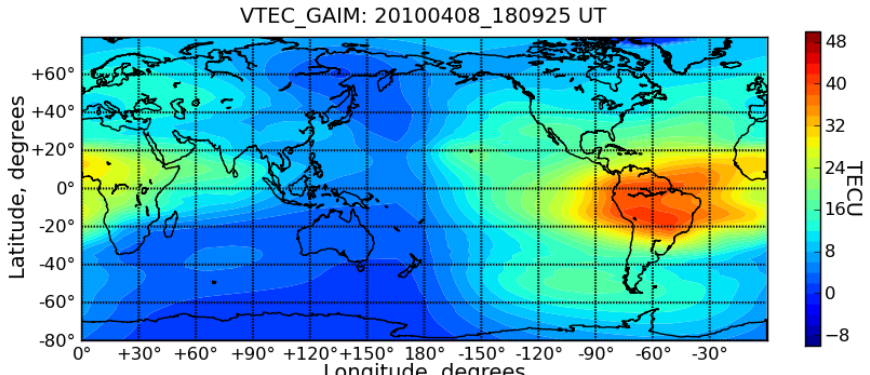


Example for GIM and Real-Time GAIM VTEC Comparisons

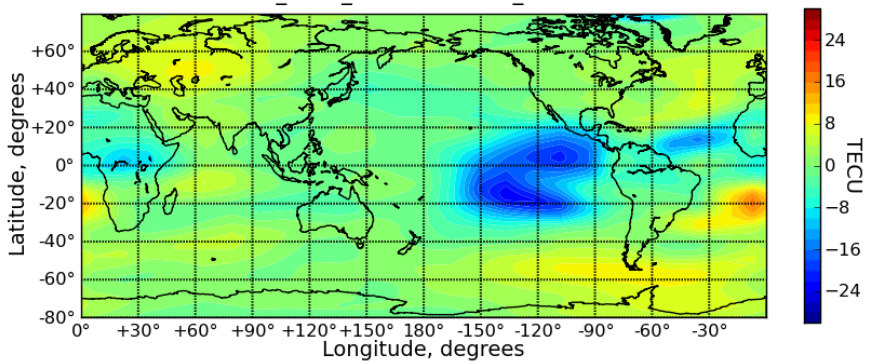
GIM VTEC Map



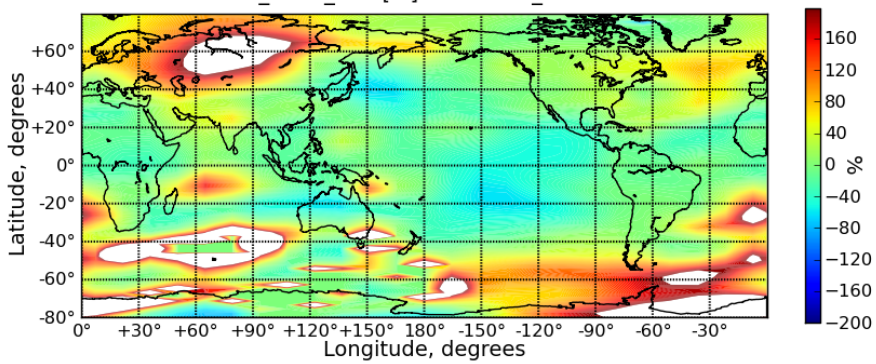
GAIM Real-Time VTEC Map



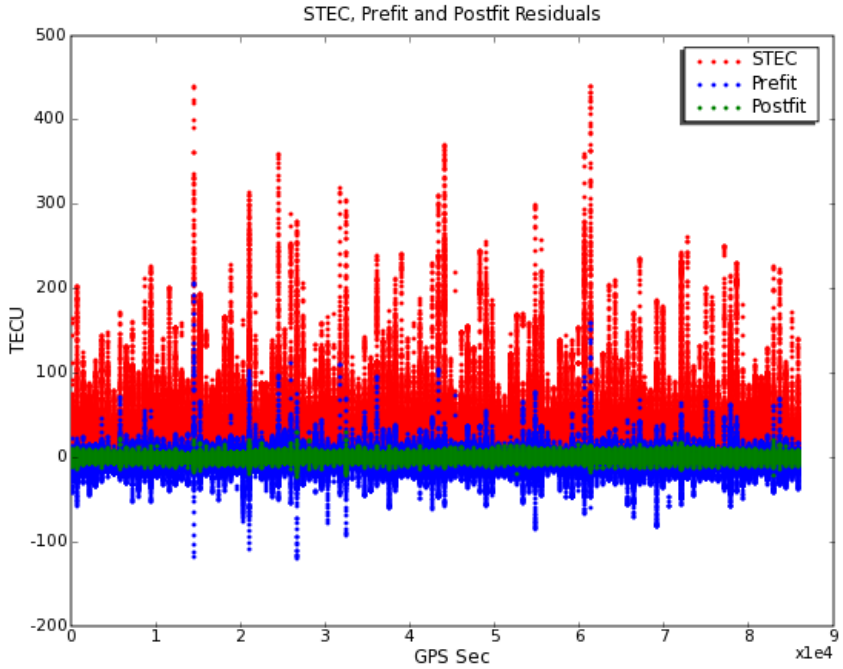
GAIM Minus GIM VTEC Map

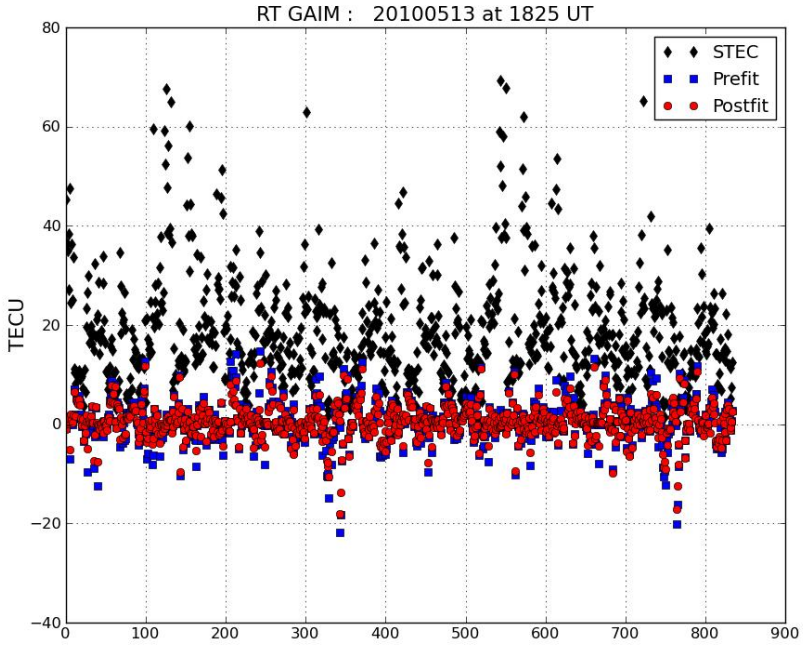


GAIM Minus GIM VTEC Map

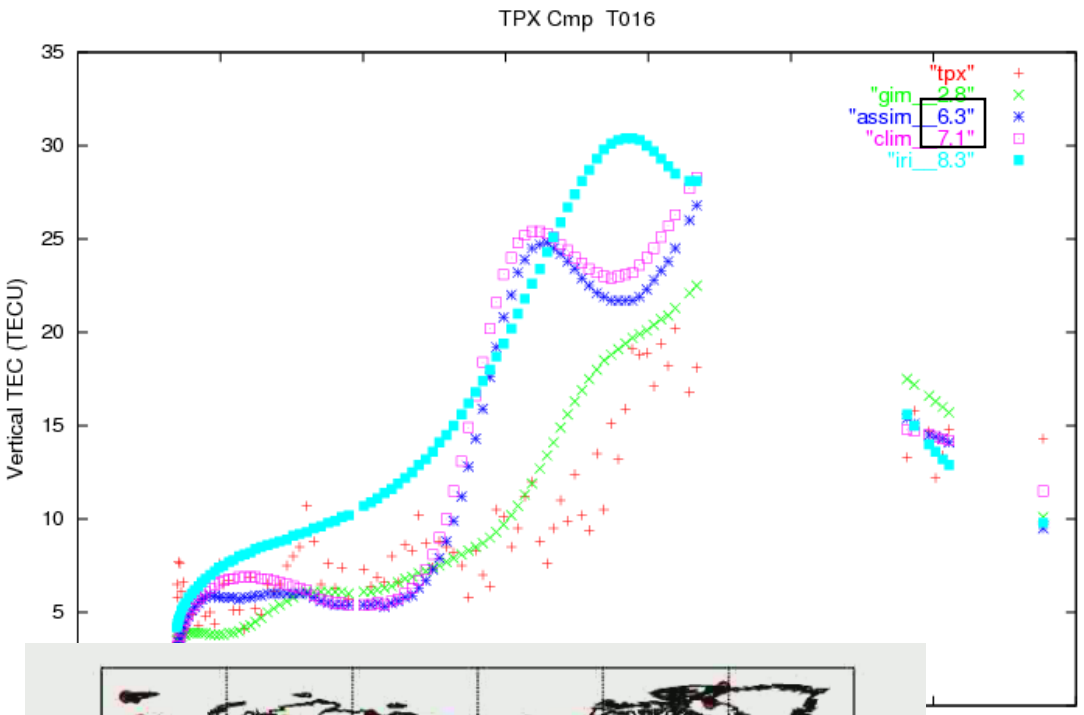


Real-Time GAIM Ground GPS Data Postfit Residuals



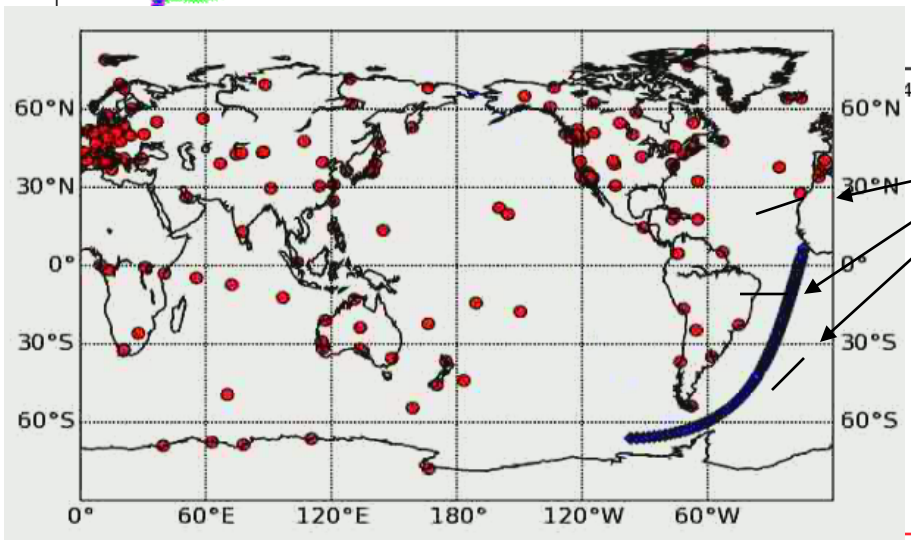


GAIM Validation Using Jason-2 Vertical TEC for June 26

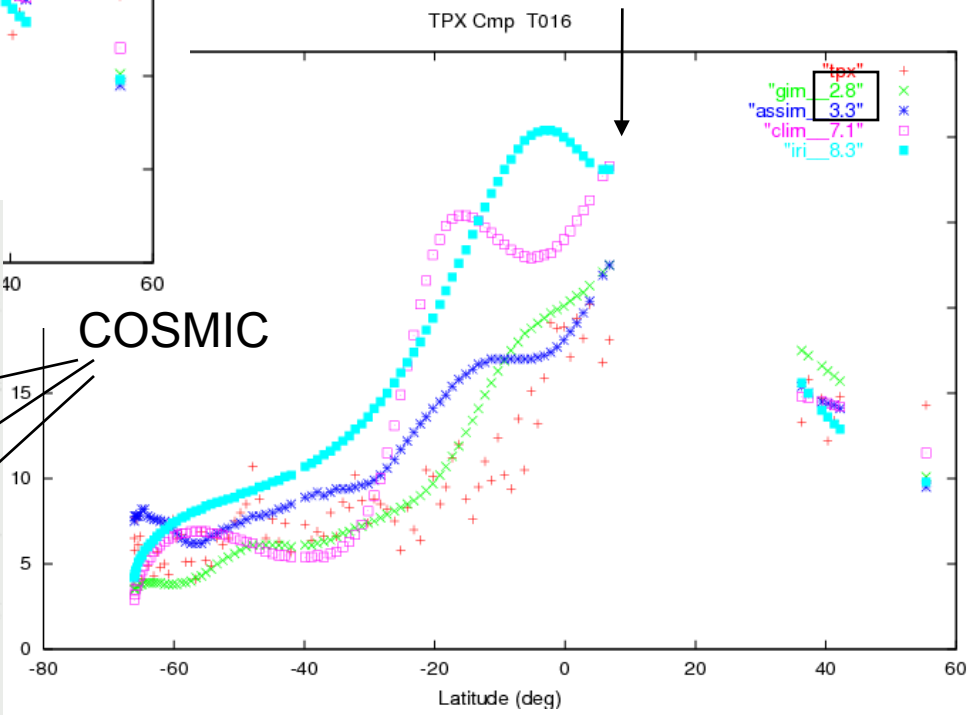


Ground-data only

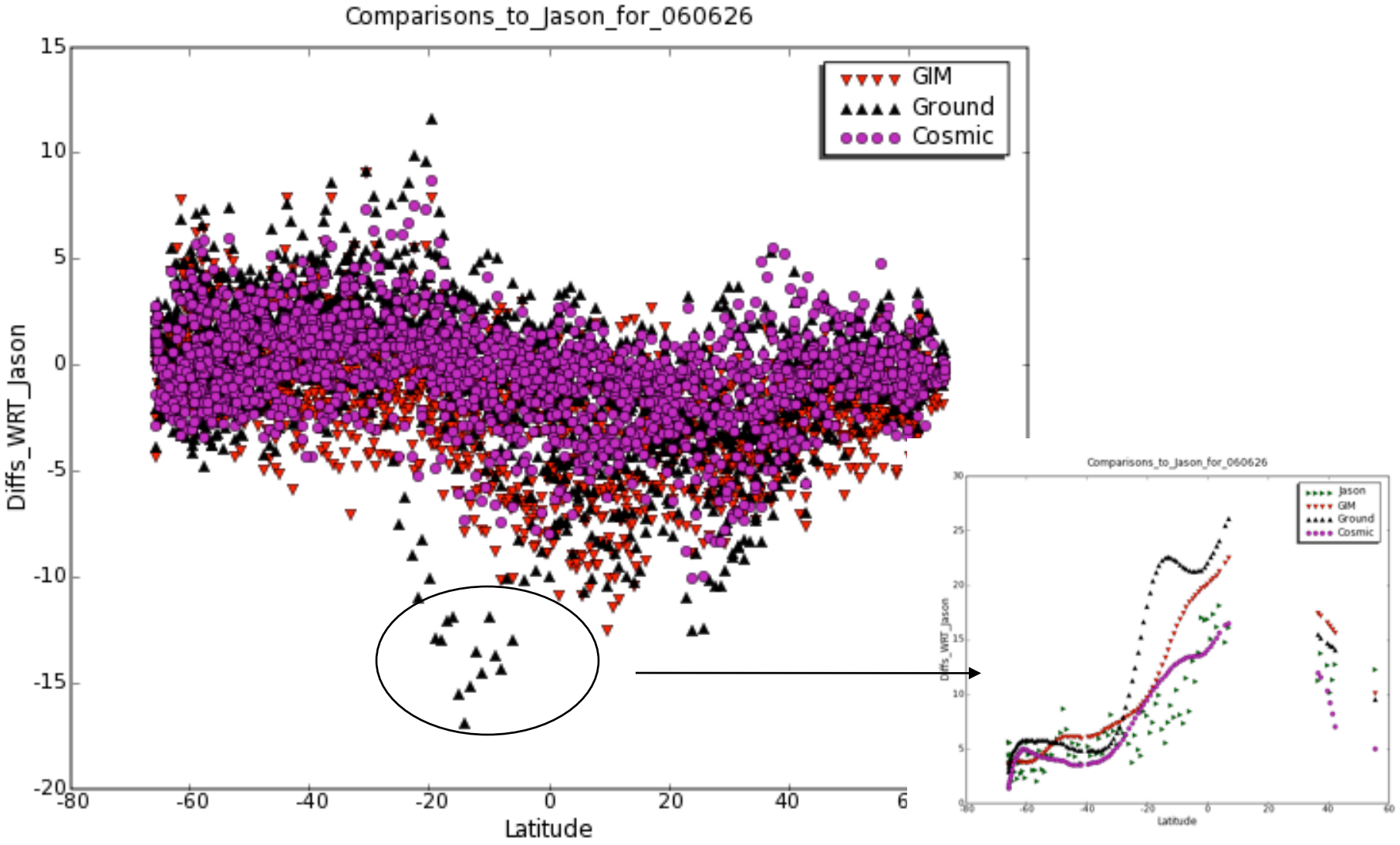
Ground and space data



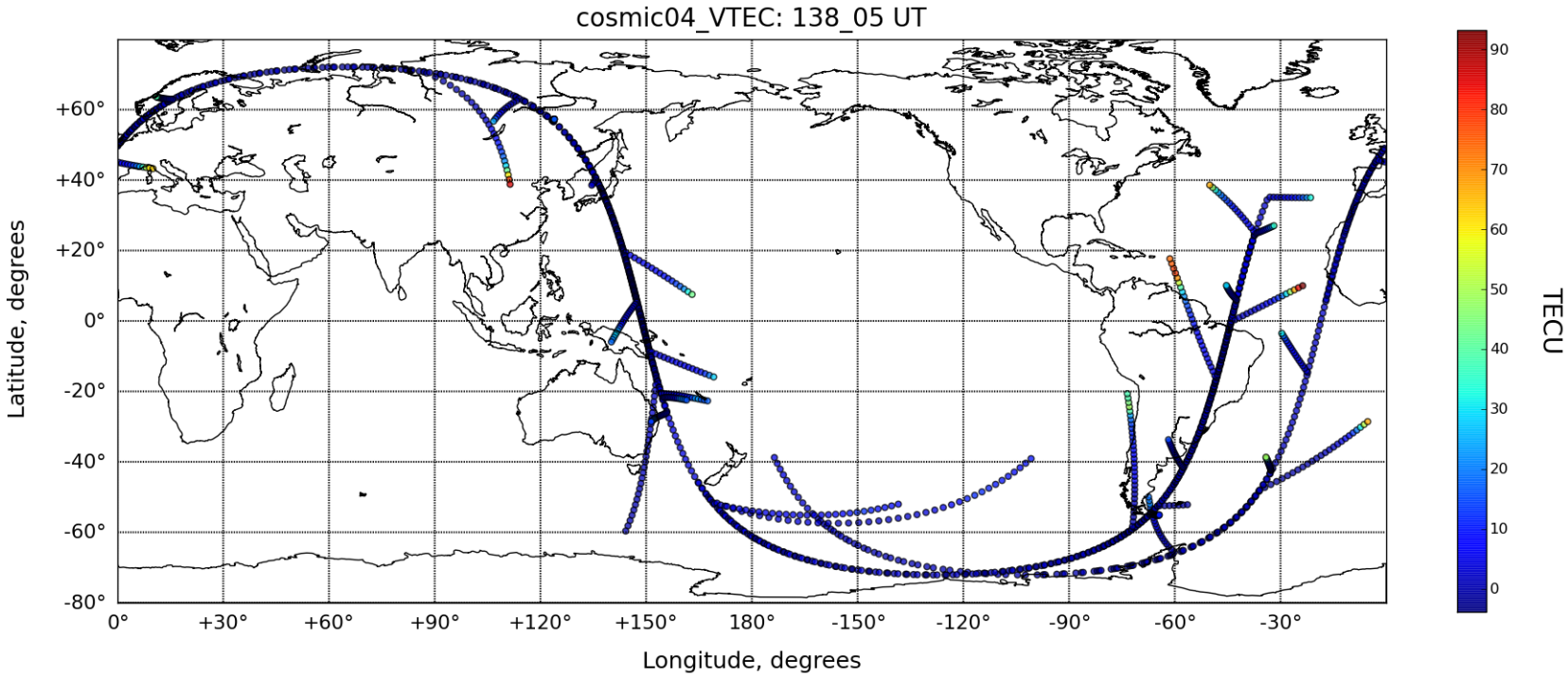
COSMIC



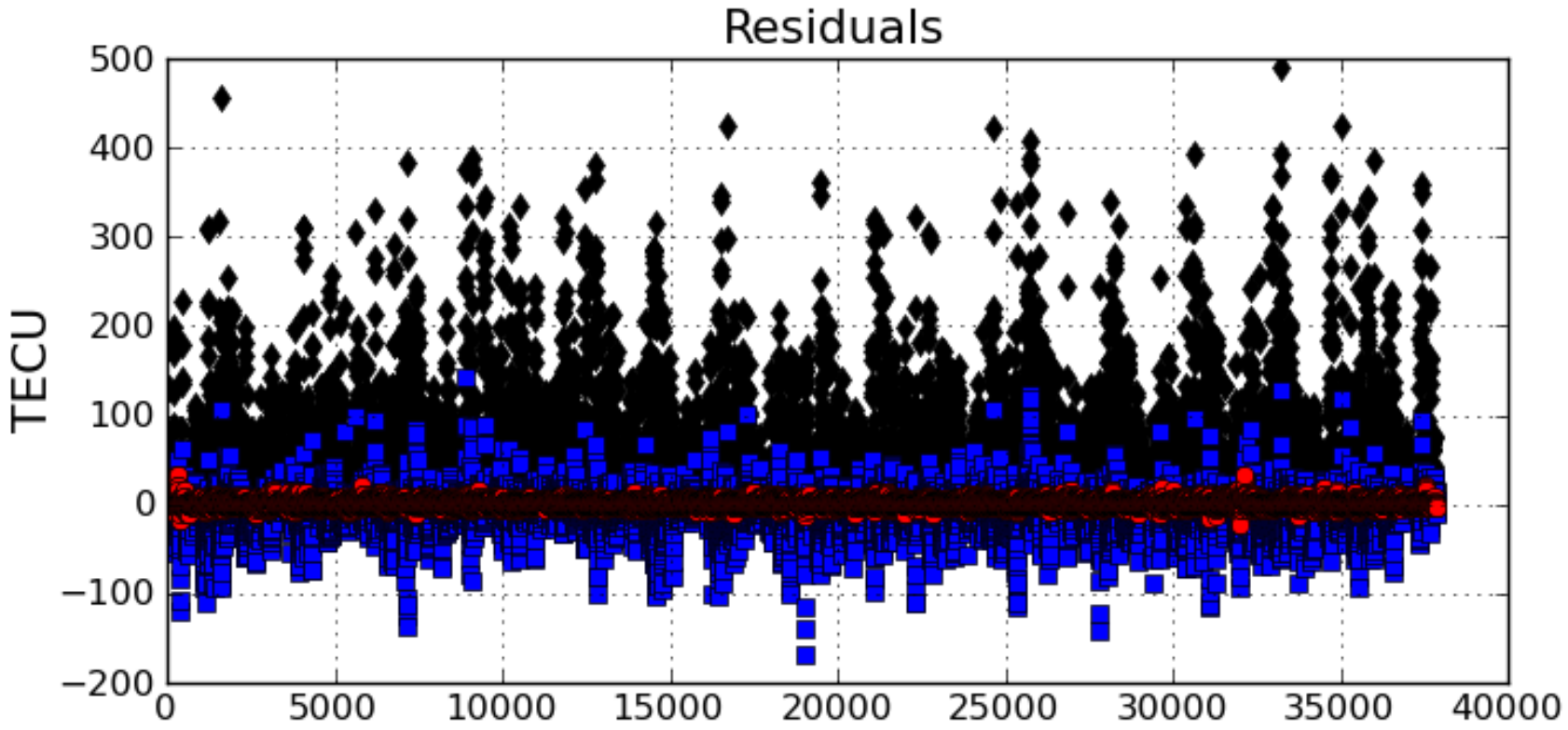
Comparison of Jason VTEC with Ground-only and COSMIC Assimilation for June 26, 2006



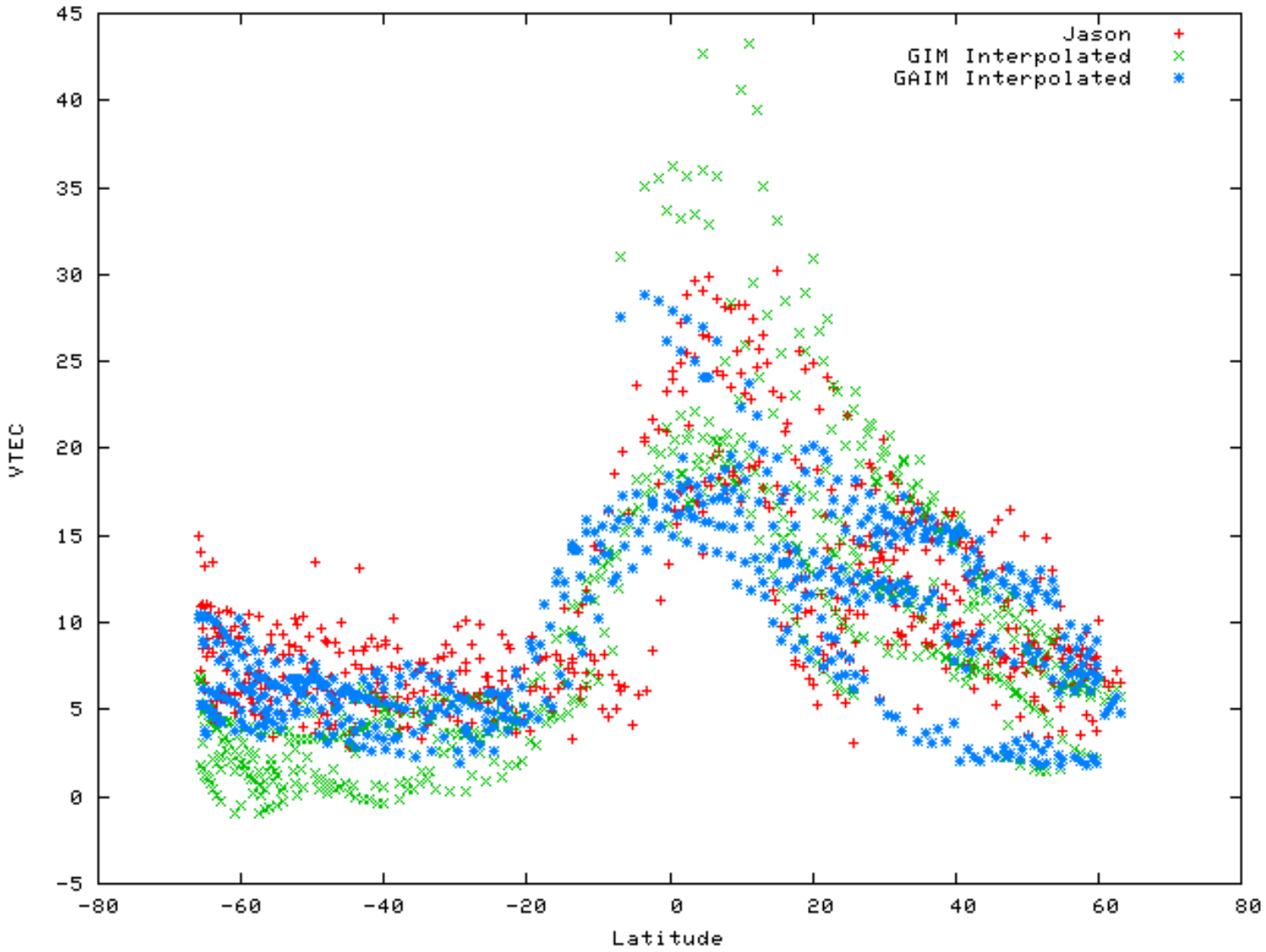
Example for COSMIC Near Real-Time Data Assimilated for May 8, 2010 at UT 5:00-6:00



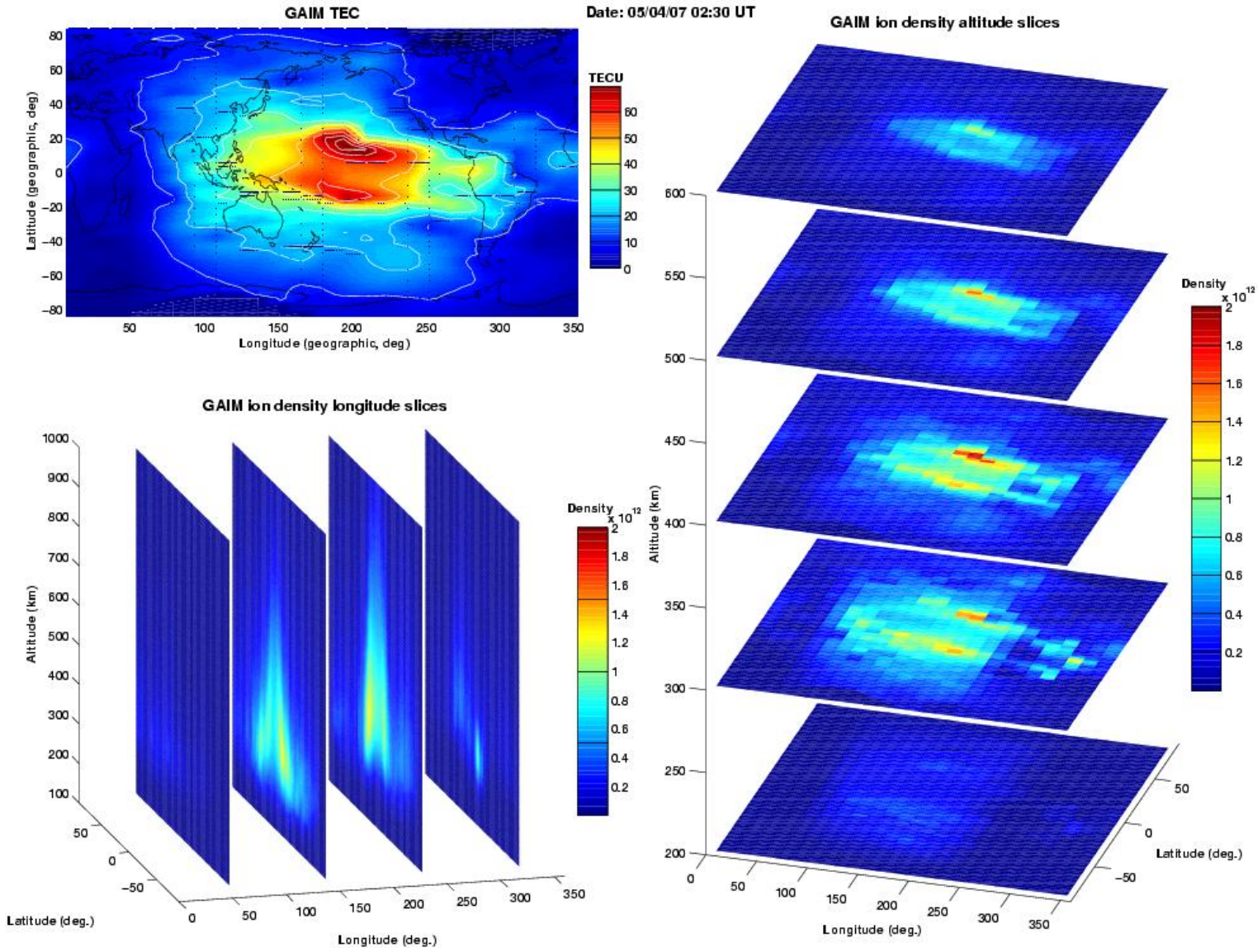
COSMIC Residuals for May 13, 2010 (CSM1 -6)



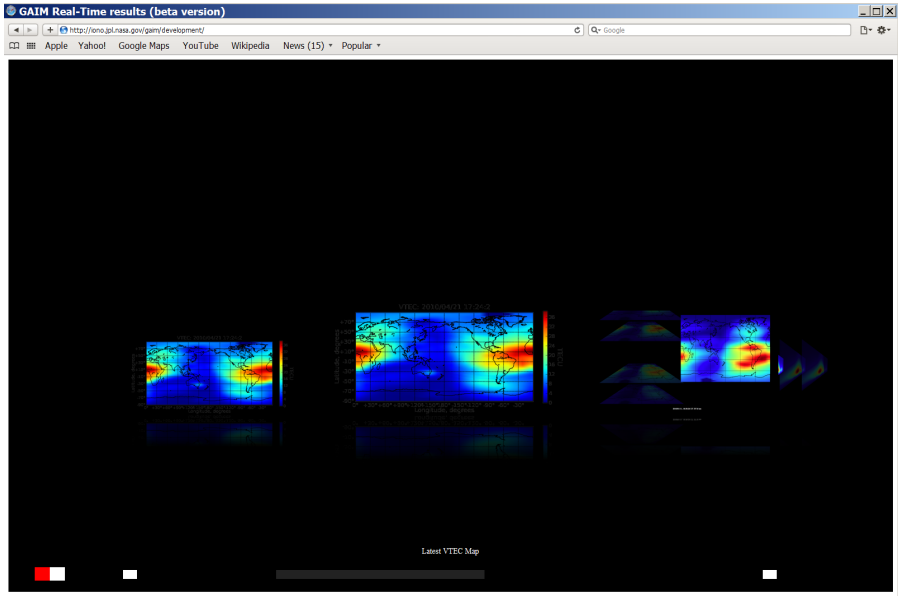
Real-Time GAIM Validation Using GIM and Jason on May 13, 2010

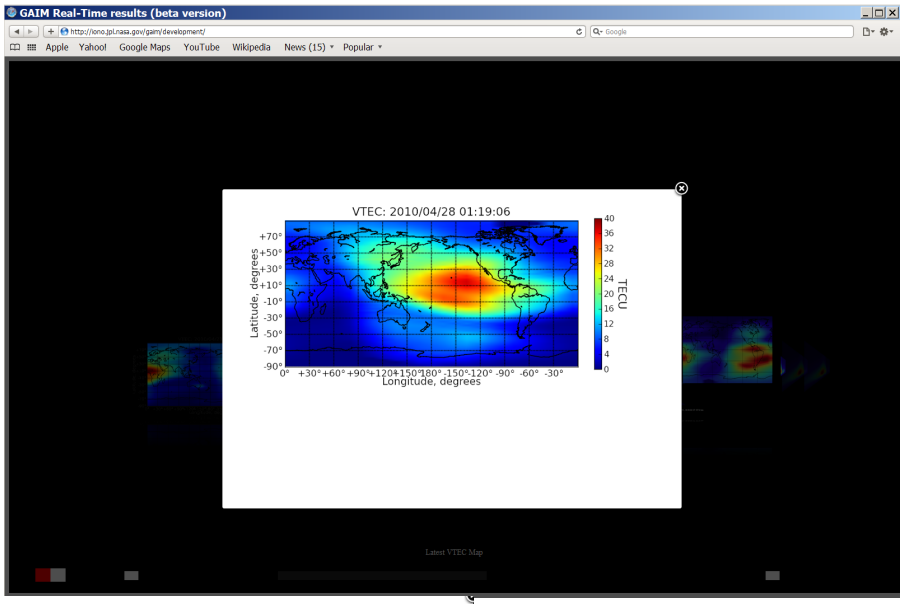


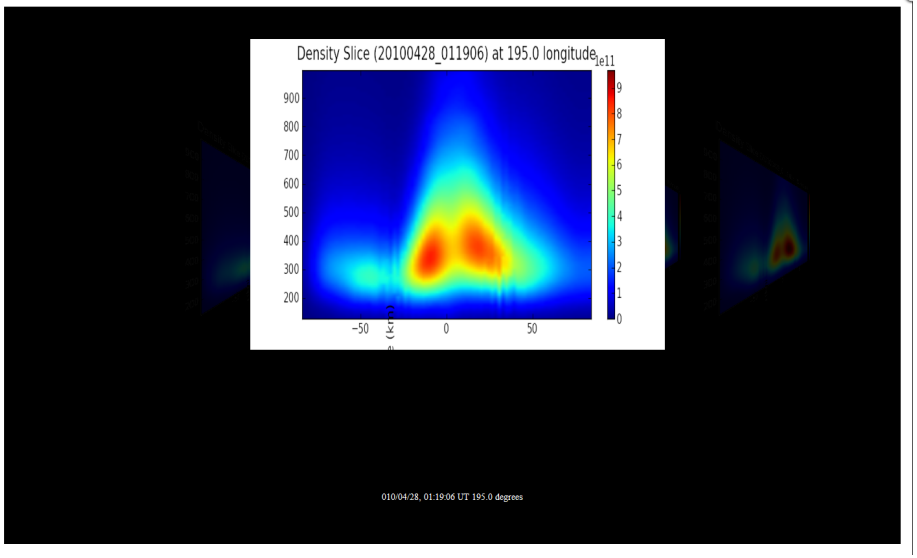
Add Frame to Density Movie Every 15 Minutes



Web Interface for RTGAIM Results







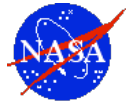
Conclusions

- New code, written from scratch in Python; developed for processing COSMIC data as well as ground GPS measurements
- End-to-end code to take raw data (RINEX format) as input and produce GPS TEC links in one monolithic code.
- Real-Time GAIM is now operational
  - We assimilate real-time ground-GPS and COSMIC data
  - Real-time validation of results is under development.
- Ground and COSMIC front-end processing validation in progress.
  - Leveling validation completed; quality of ground-based processing was very similar between the two techniques; space-borne processing with new algorithm resulted in significant improvement over old processing scheme
  - Bias estimation appears complete; full validation requires more statistics

Acknowledgements

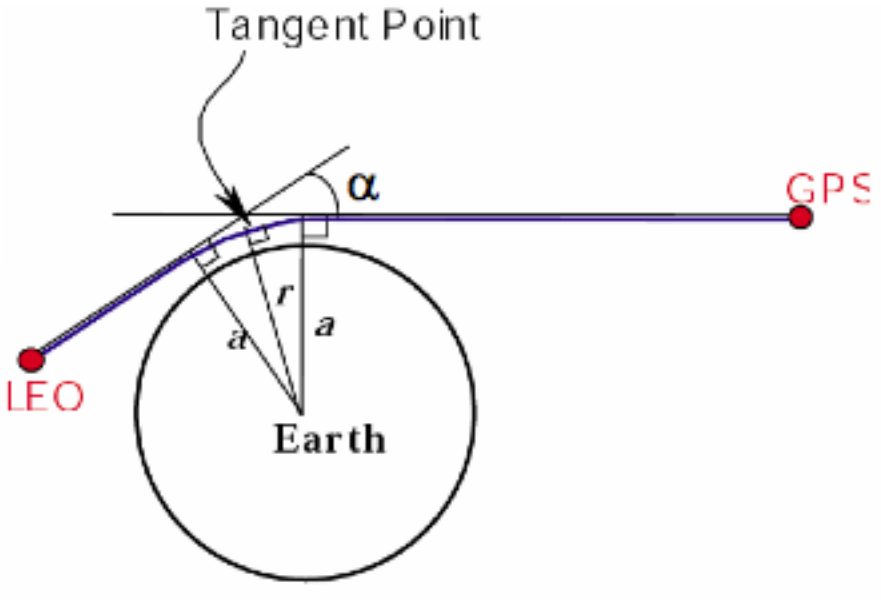
- This research was performed at the Jet Propulsion Laboratory/California Institute of Technology under contract to the National Aeronautics and Space Administration

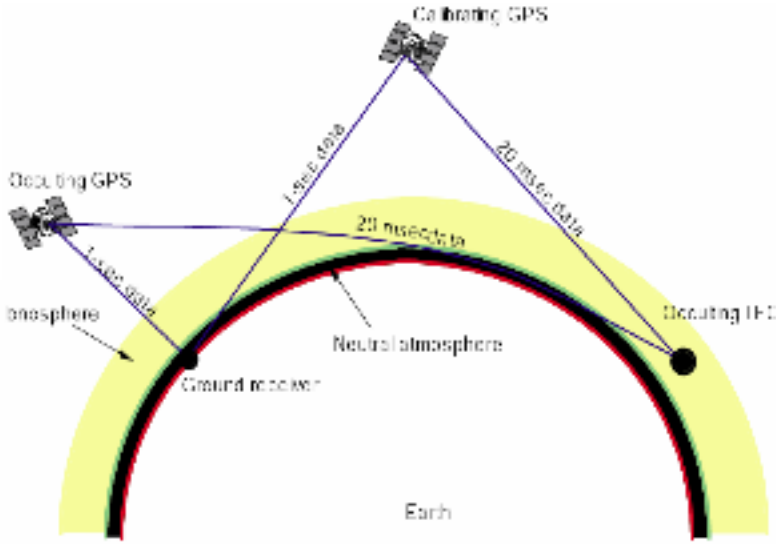
- Komjathy, A., B. Wilson, X. Pi, V. Akopian, M. Dumett, B. Iijima, O. Verkhoglyadova, and A. J. Mannucci (2010). JPL/ USC GAIM: On The Impact of Using COSMIC And Ground-Based GPS Measurements To Estimate Ionospheric Parameters, J. Geophys. Res., doi: 10.1029/2009JA014420, in press



Backup Slides

Occultation Geometry





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

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

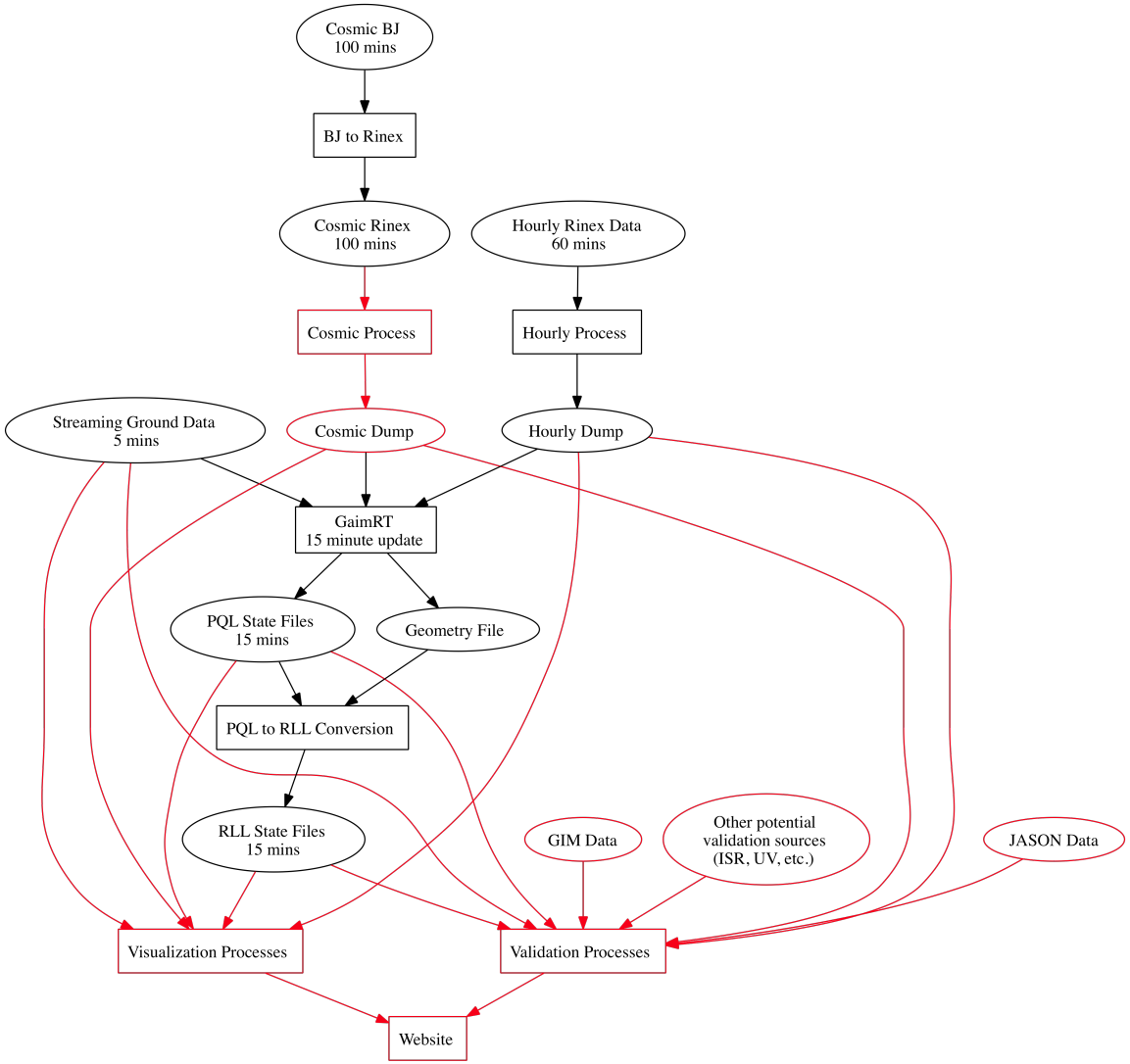
$$\ln(n(r)) = \frac{1}{\pi}\int_{nr}^\infty \frac{\alpha}{\sqrt{a^2 - r^2 n^2}} da$$

Nested Grid (NGAIM)

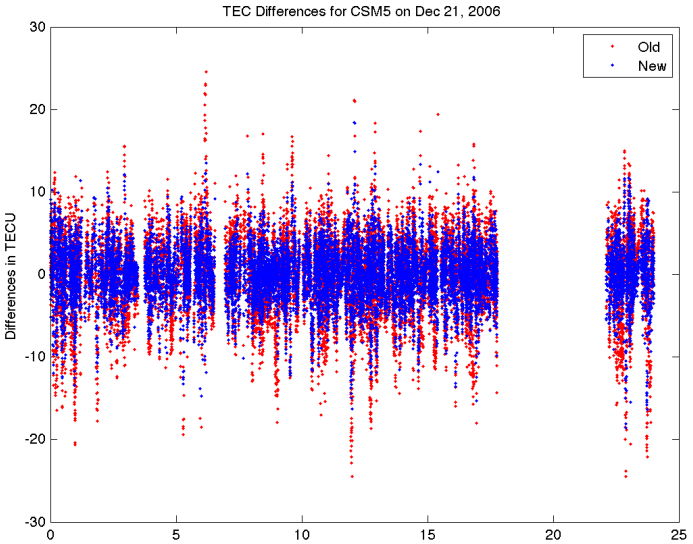
- NGAIM grid resolutions:
  - Global grid resolution: 2.5 x 10 degrees lat/lon, 40 km altitude
  - Nested grid resolution: 1 x 2 degrees lat/lon, 20 or 40 km altitude
- Forward physics models are coupled at boundary of nested region
  - Global grid provides density and flux on nested boundary using ghost cells
  - Two forward physics models, two Kalman filters
  - Both density grids used to properly model TEC links
- Show results from two periods:
  - Halloween storm (Oct 29-31, 2003)
    - ~300 IGS + CORS stations in US
  - Quiet days: July 7, 2009 and Jan. 16 – 18, 2010
    - 200 GPS stations globally, plus ~40 CORS stations near/in Florida
- Advantages:
  - Near real-time execution (3 to 4X faster than RT)
  - Can run multiple nested regions at one time (on separate CPUs)

PyTEC Considerations

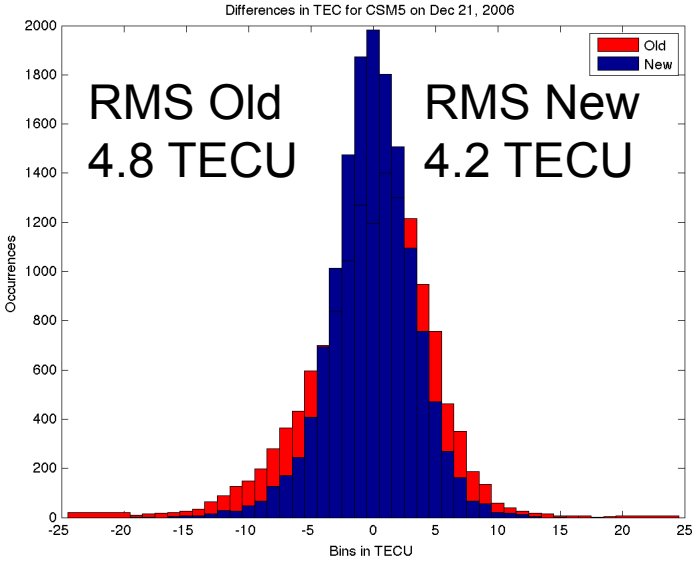
- Ground data – we have an operational code to validate algorithms against. Results to follow.
- COSMIC/LEO data
  - Leveling algorithms were developed for ground data, new algorithm developed for LEO data
  - Bias estimation must be performed for LEO satellites, non-trivial
- Analysis module design for implementing user specific analysis during processing, i.e.
  - TECDump module for writing results in tecdump format
  - BiasEstimator for LEO bias estimation

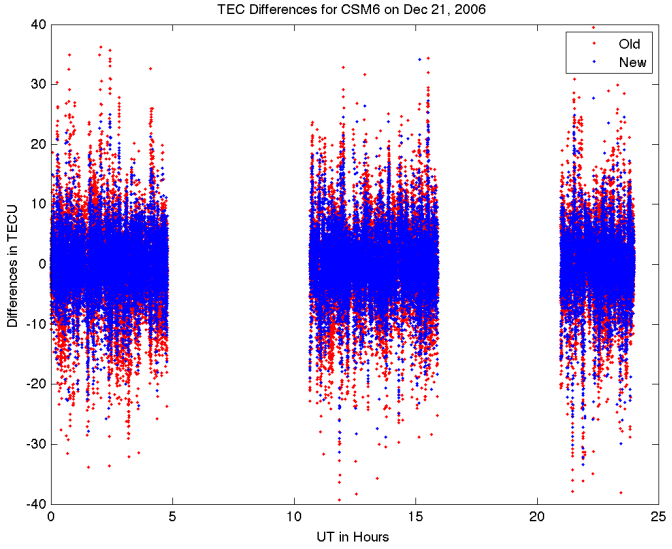

Cosmic BJ
100 mins
BJ to Rinex
Cosmic Rinex
100 mins
Hourly Rinex Data
60 mins
Cosmic Process
Hourly Process
Streaming Ground Data
5 mins
Cosmic Dump
Hourly Dump
GaimRT
15 minute update
PQL State Files
15 mins
Geometry File
PQL to RLL Conversion
RLL State Files
15 mins
GIM Data
Other potential
validation sources
(ISR, UV, etc.)
JASON Data
Visualization Processes
Validation Processes
Website

All CSM5 and CSM6 Residuals and Histogram for Dec 21, 2006

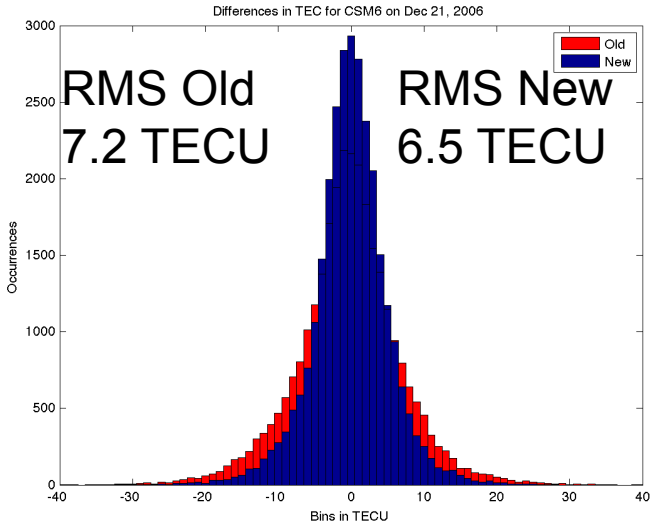


CSM5





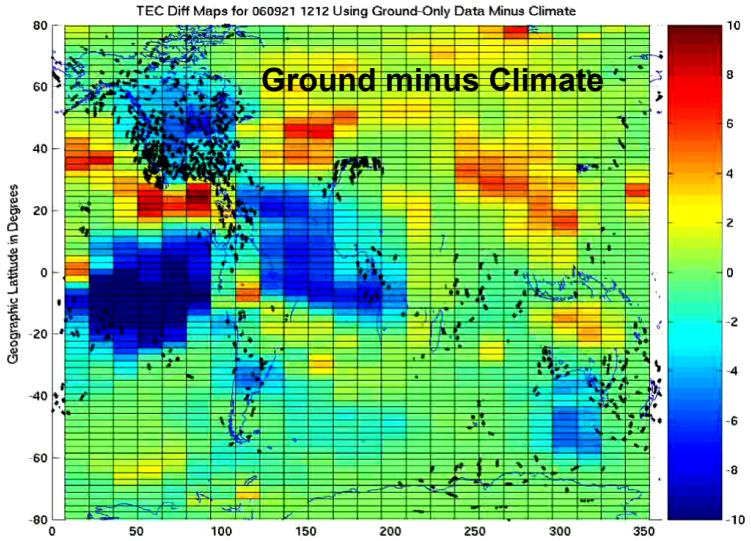
CSM6

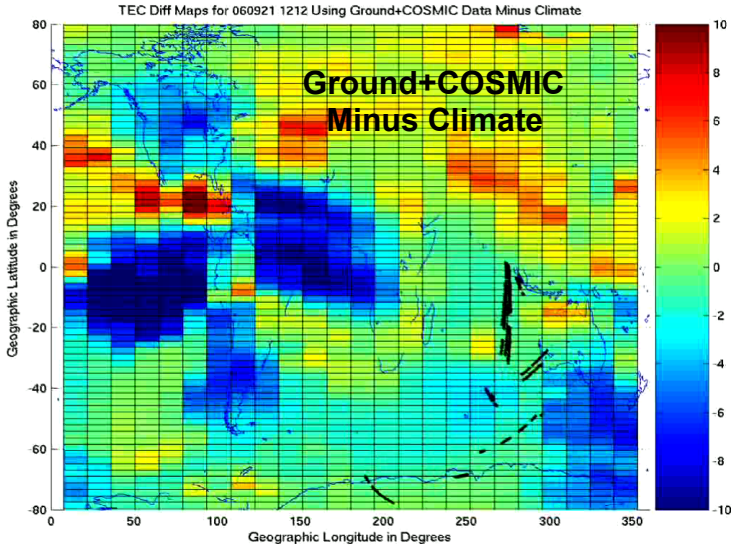


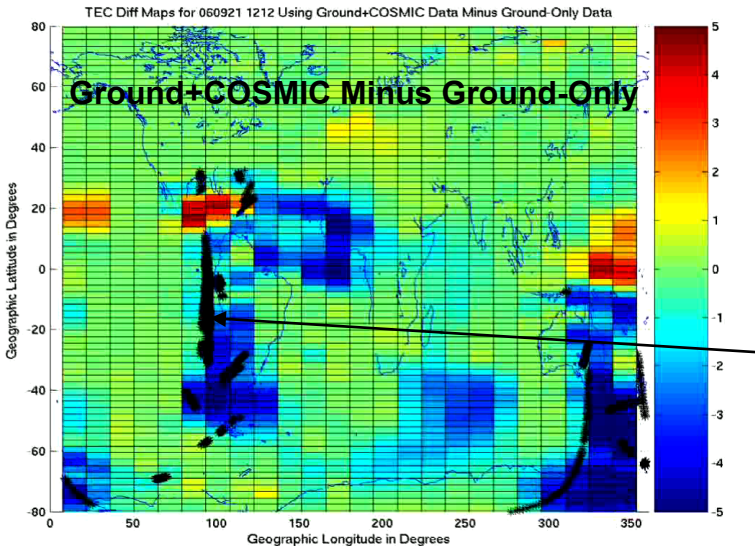
Data Processing System (PyTEC)

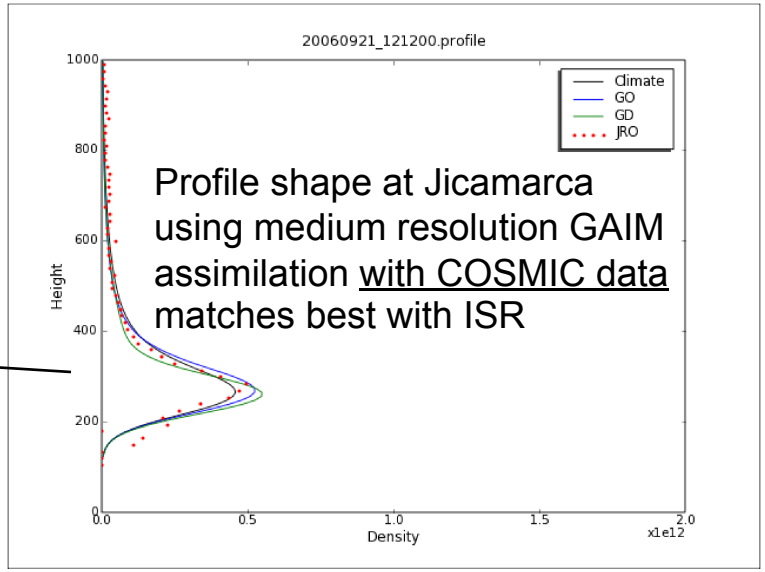
- New code, written from scratch in Python
- End-to-end code to take raw data (RINEX format) as input and produce GPS TEC links (in internal tecdump format) in one monolithic code.
  - Only external dependencies are common Python modules (numpy, scipy, matplotlib)
- Developed for processing COSMIC data as well as ground GPS measurements

Medium Resolution GAIM VTEC Difference Maps

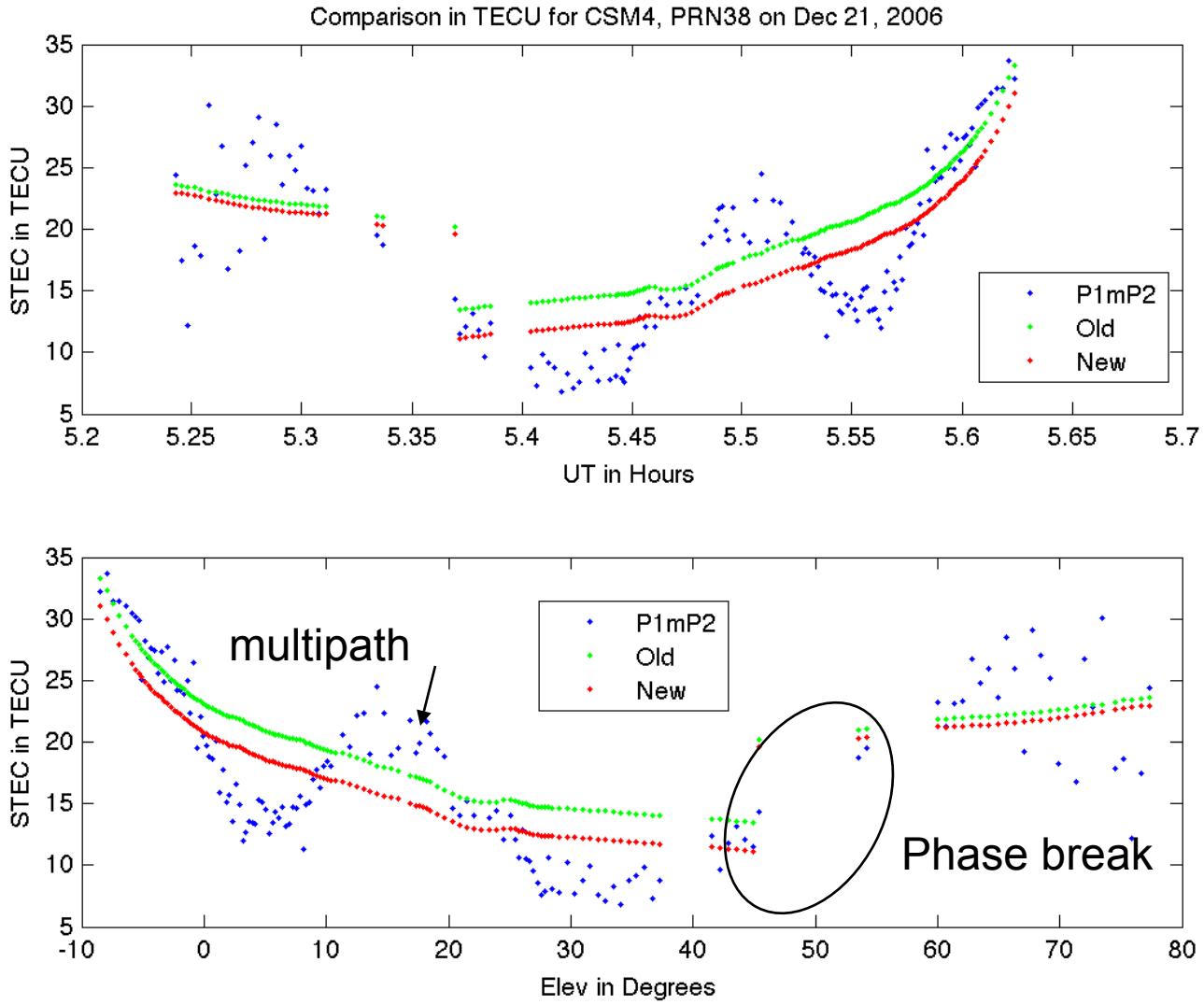








Occultation Case Examples (1): PRN38 for CSM4

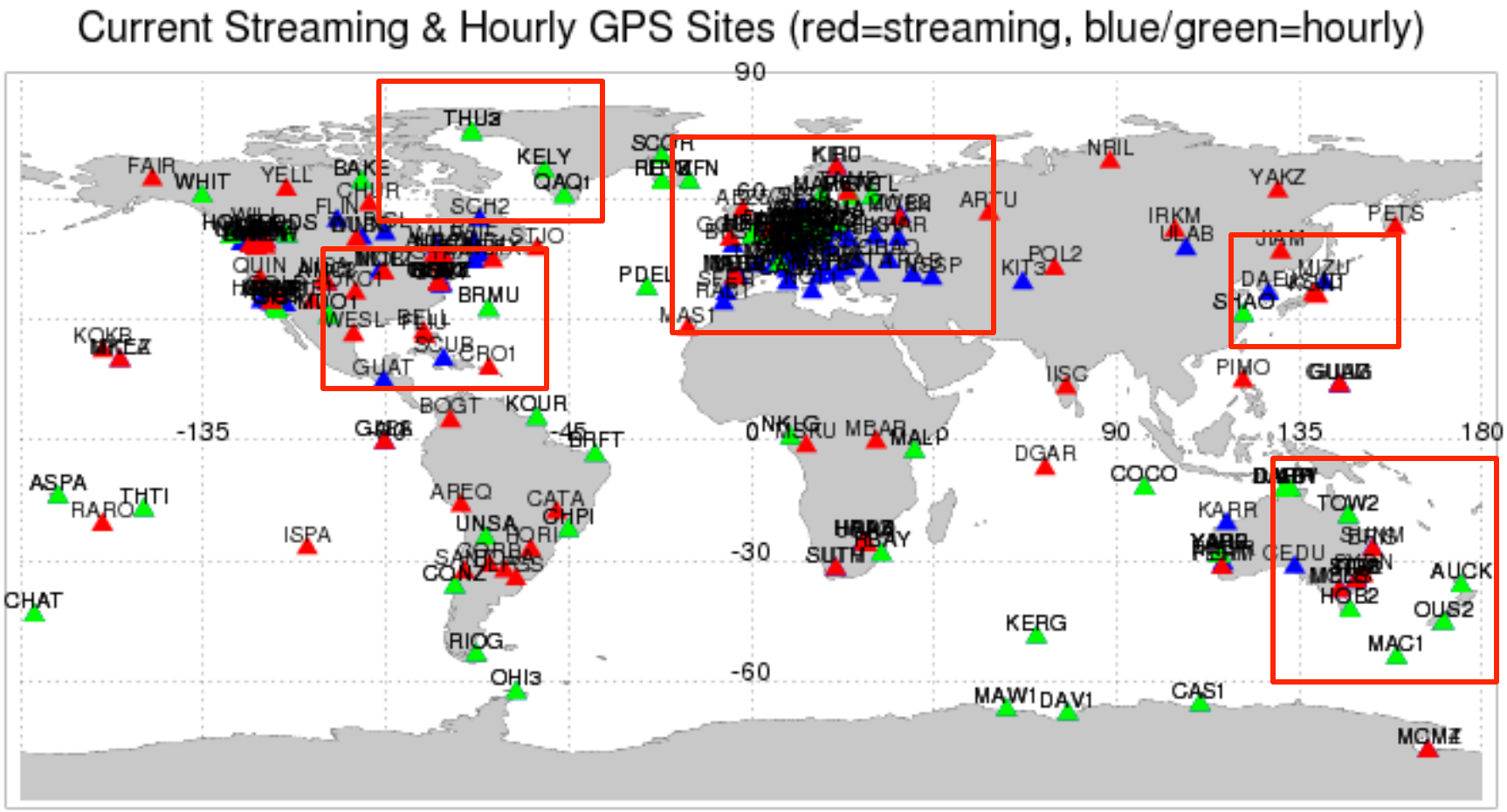


Leveling night-time occultations with phase break and multipath show poorer agreement

Real-Time System

- Designed to be an end-to-end product
  - Takes RINEX data as input, in real-time
    - Processed to TEC data via the PyTEC software
  - Real-time TEC data used in Kalman Filter
- 15 min update from 5 minute ground data
  - Currently running
- 2 hour update from COSMIC data, this is then propagated to 15 minute update thread to maximize data usage
  - Under development

Radar CONOPS: Multiple NGAIM Regions

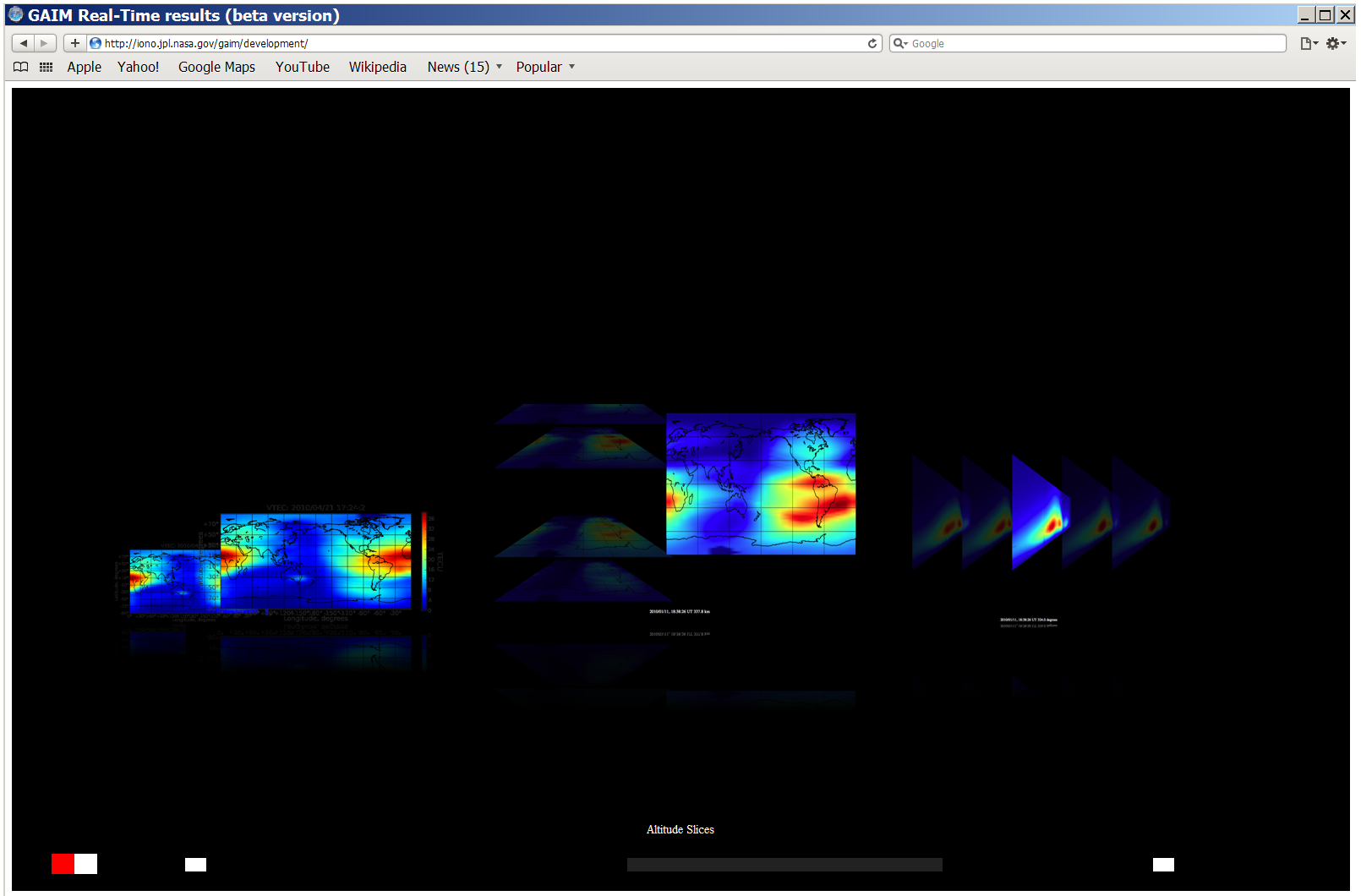


NGAIM regions for: Eglin, Thule, Europe/Mid-East, Japan, Australia

Bias Estimation

- Filter data to only consider some subset
- Assume this subset has some known TEC value
- Compute the shift needed to set the minimum to the known value
- Find the average of all these shifts over a day to compute the daily bias
- Take a running 10-day average of the daily bias as the satellite bias for the given day
- Currently in the testing and validation stage
  - Using filter of Elevation > 70 degrees, Latitude > 60 degrees
  - Assuming vertical TEC value is 0 (or some small value)

Image Browser, like ‘Cover Flow’



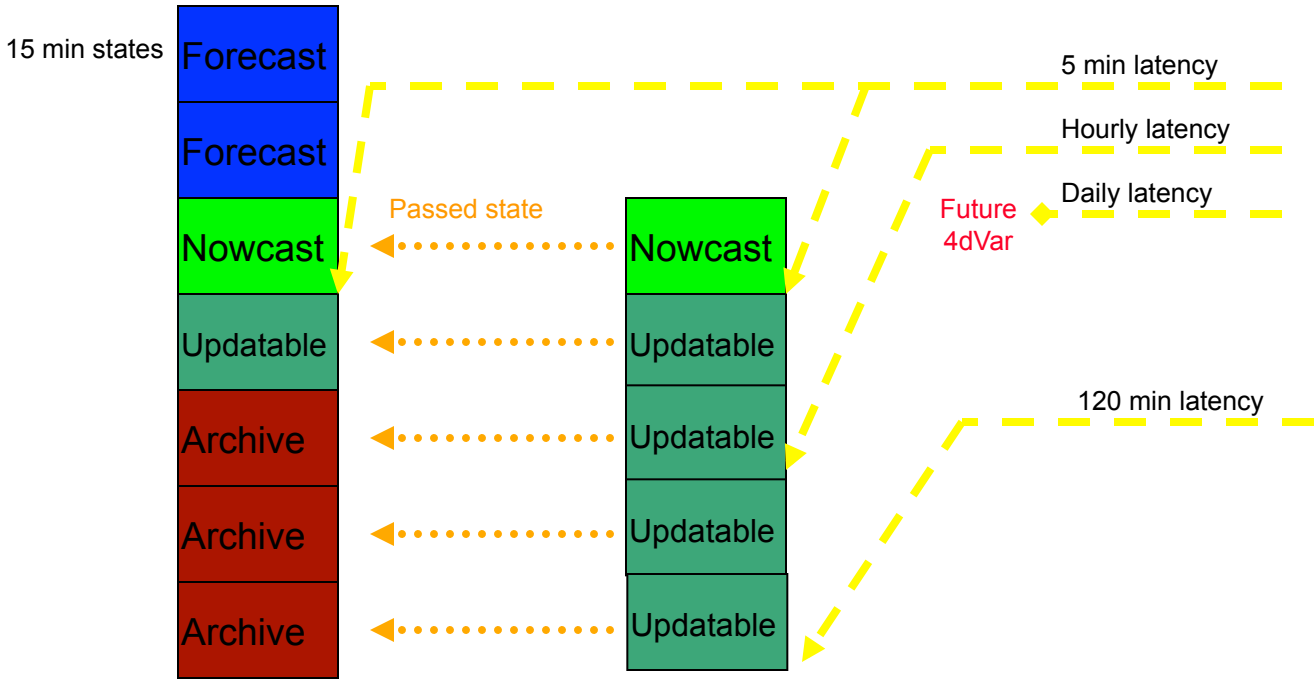
Leveling Algorithm

- We have noisy P1-P2 combination and biased L1-L2 combination. We use the P1-P2 to determine the level (offset) for the L1-L2 combination.
- Noise (multipath) for P1-P2 combination for ground data is highly correlated to the elevation angle of the link
  - Thus we consider lower noise data as more valid than higher noise data in determining the level of the P1-P2 combination.
- For LEOs, in particular COSMIC, we do not have such good behavior

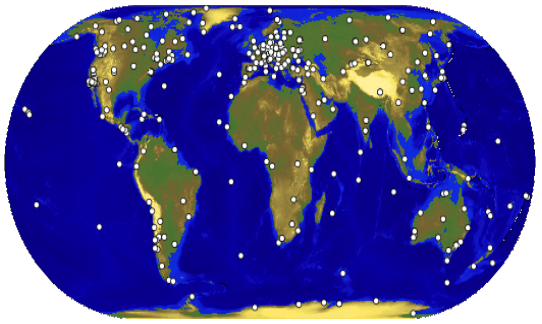
Multiple Latency Data Feeds

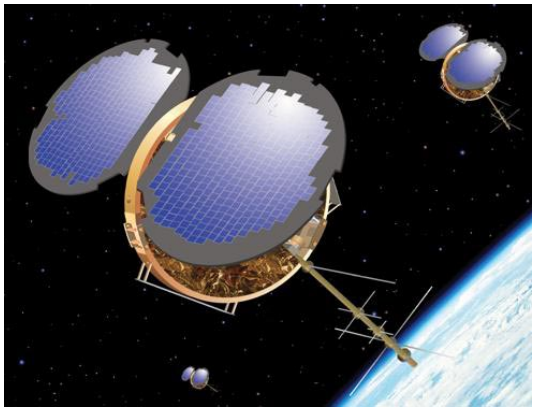
Main run proceeds with minimal latency tolerance, with states updated by catch-up processes

Catch-up run will process highly latent data and pass state once done



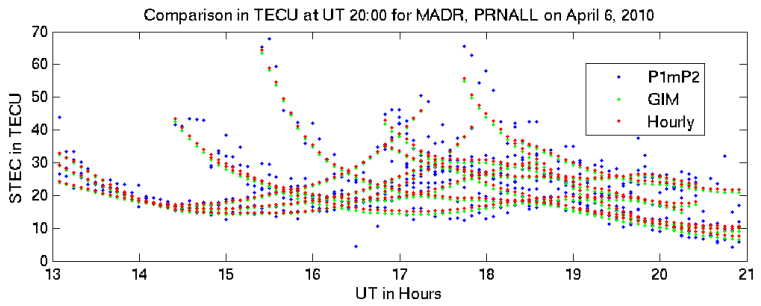
Global ground network



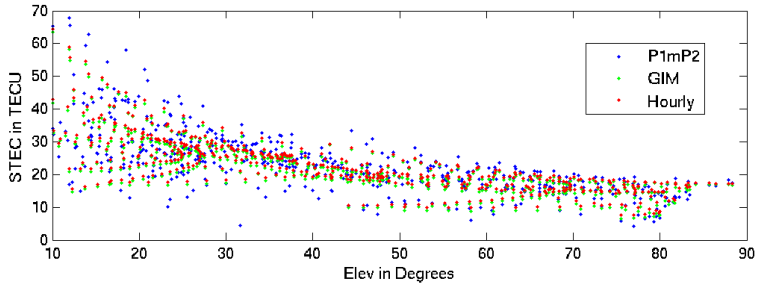


COSMIC occultations

Hourly and Daily TEC Comparison



UT 20



STEC for all matched observations between GIM and Hourly TEC files compared to P1-P2 unbiased observables

UT 22

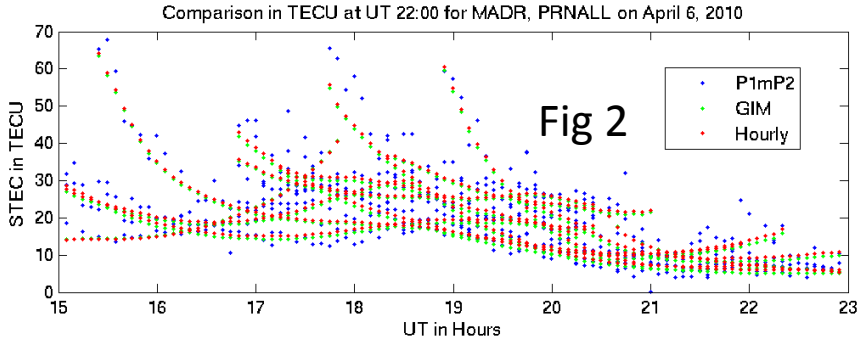
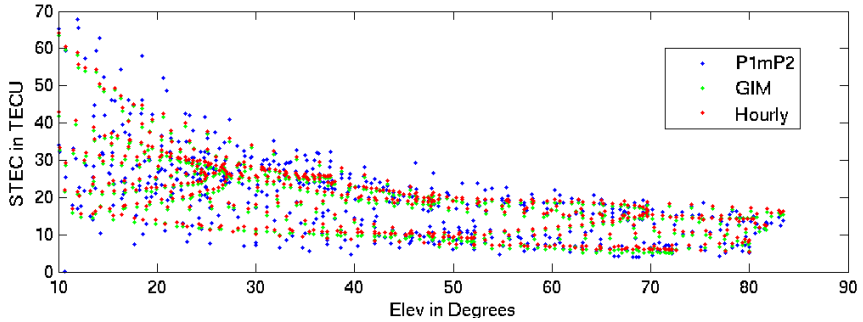


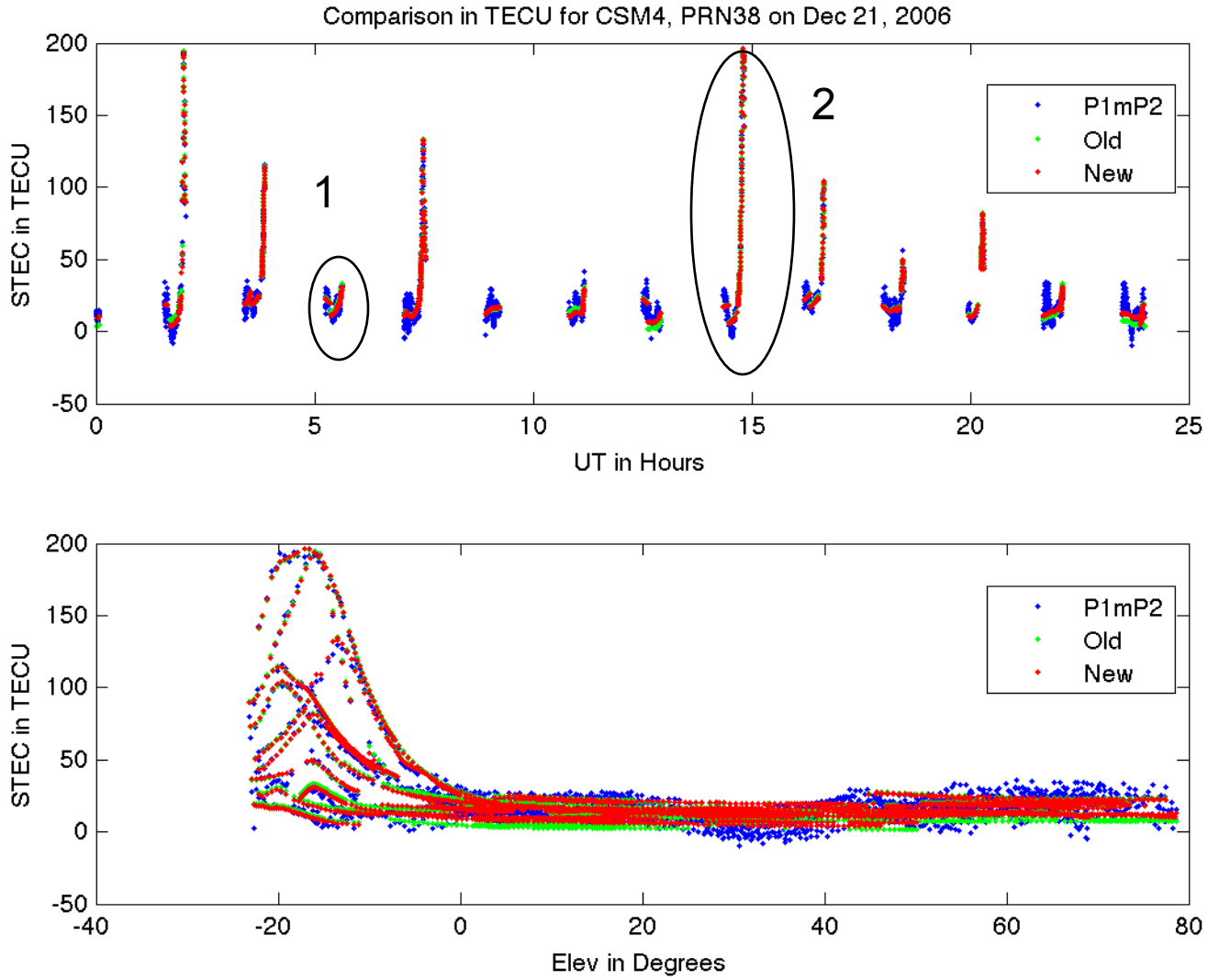
Fig 2



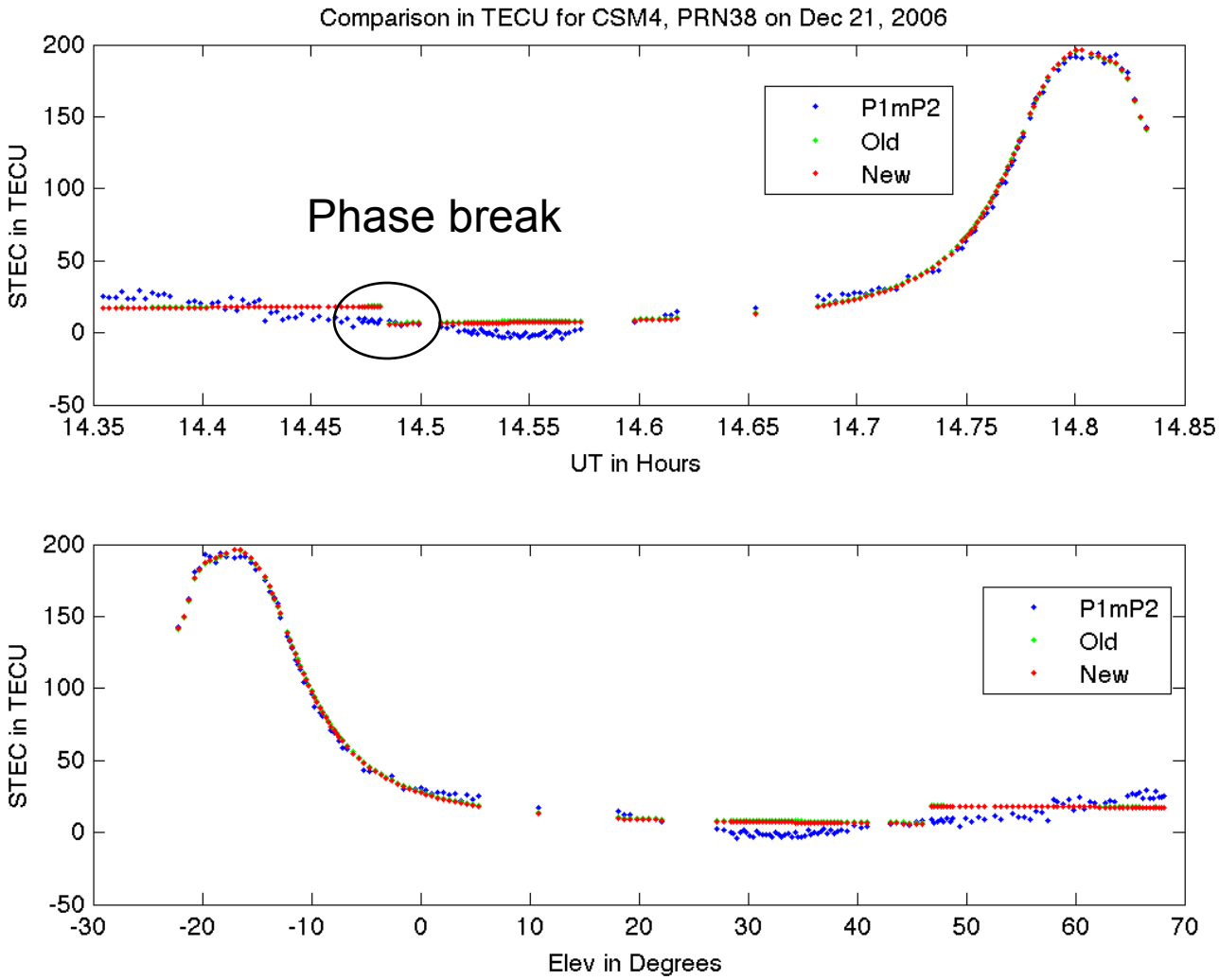
Differences with P1-P2 Observables Using Data Shown in Figs 1 and 2

	UT 20		UT 22	
	Mean in TECU	**Sigma in TECU**	**Mean in TECU**	**Sigma in TECU**
GIM	-0.26	3.72	-0.21	3.63
Hourly	-0.29	3.74	-0.18	3.61

TEC Comparisons Between Old and New Processing Techniques for PRN38 CSM4 on Dec 21, 2006

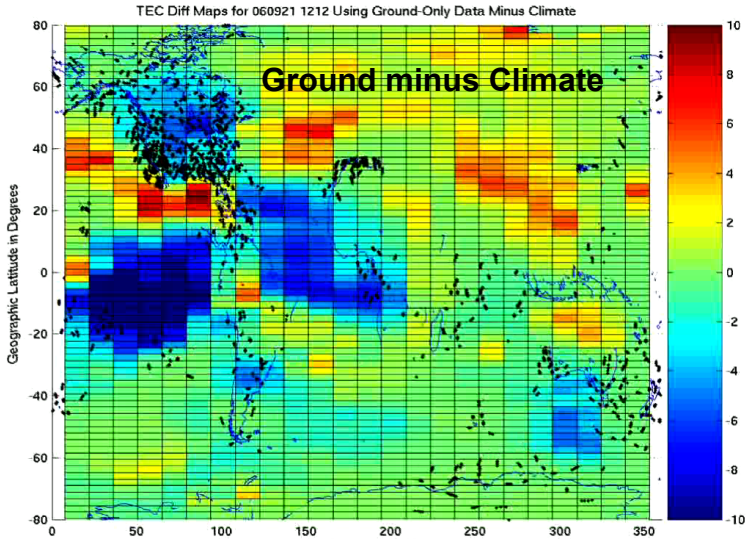


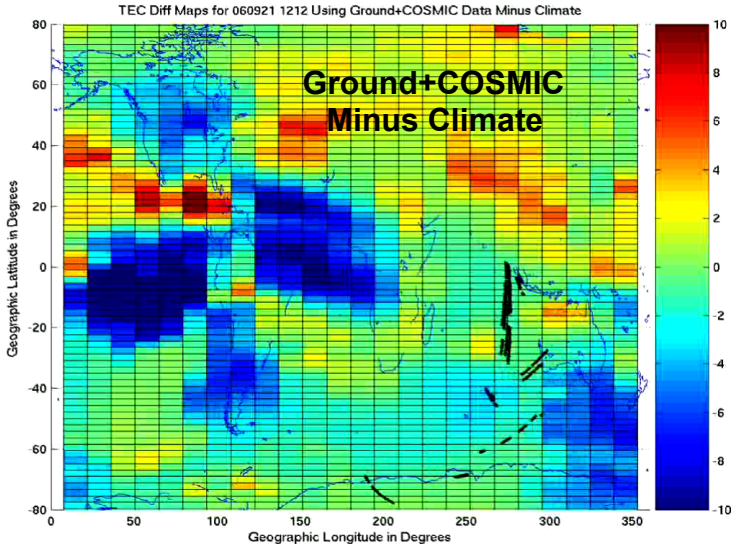
Occultation Case Examples (2): PRN38 for CSM4

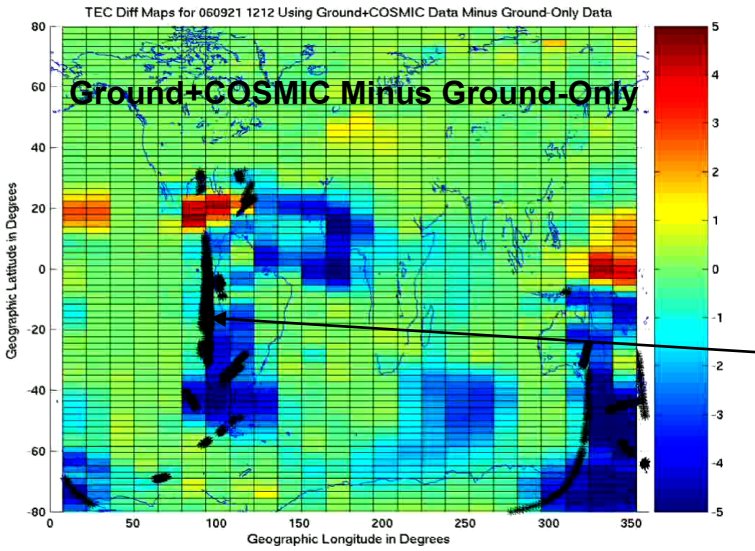


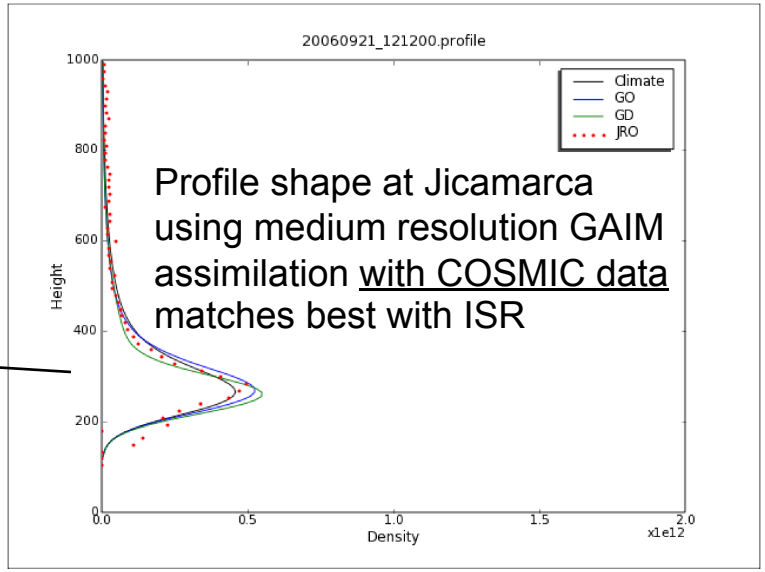
Continuous day-time occultations even with phase break agree well

Medium Resolution GAIM VTEC Difference Maps for Case 2

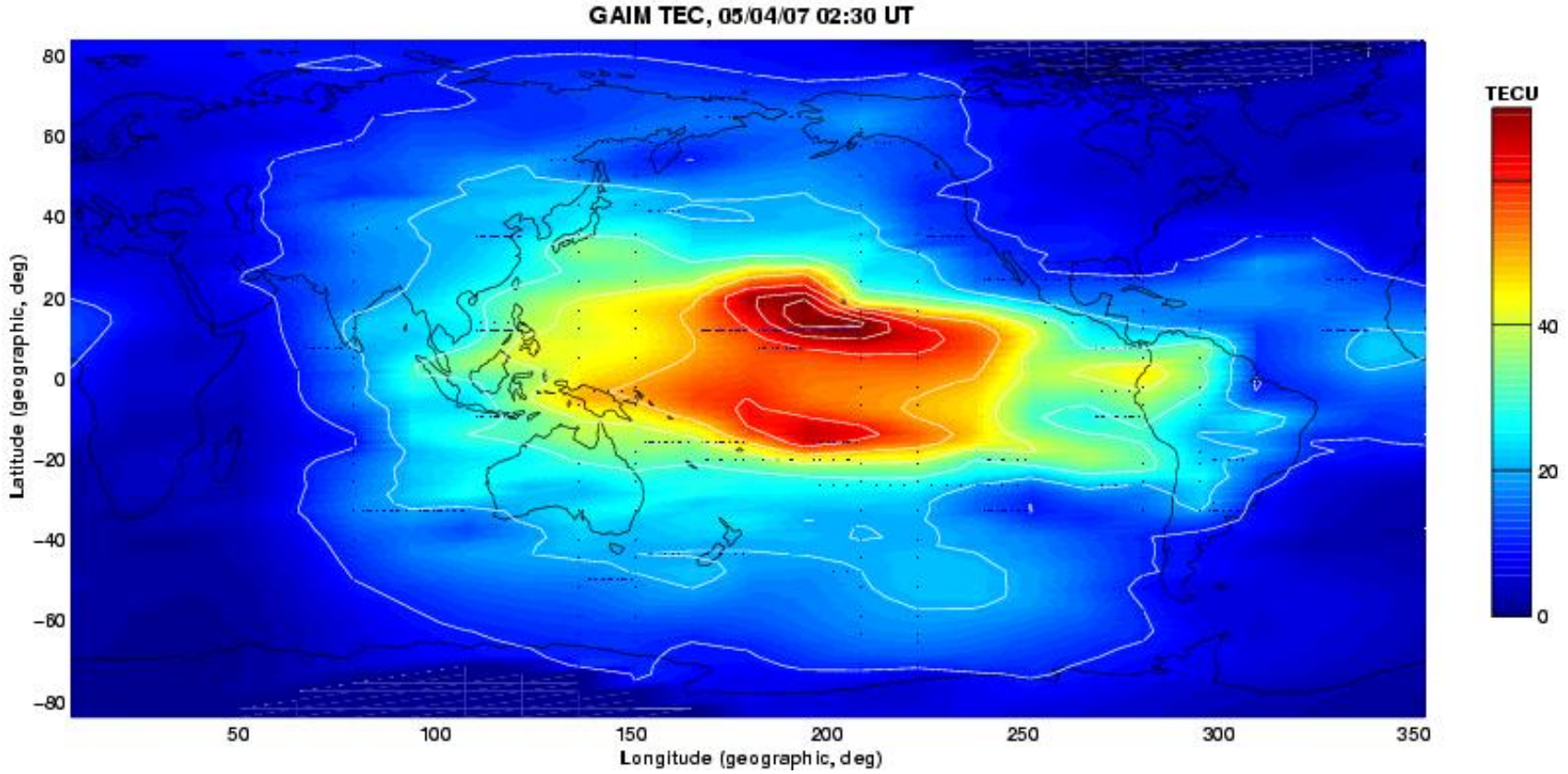




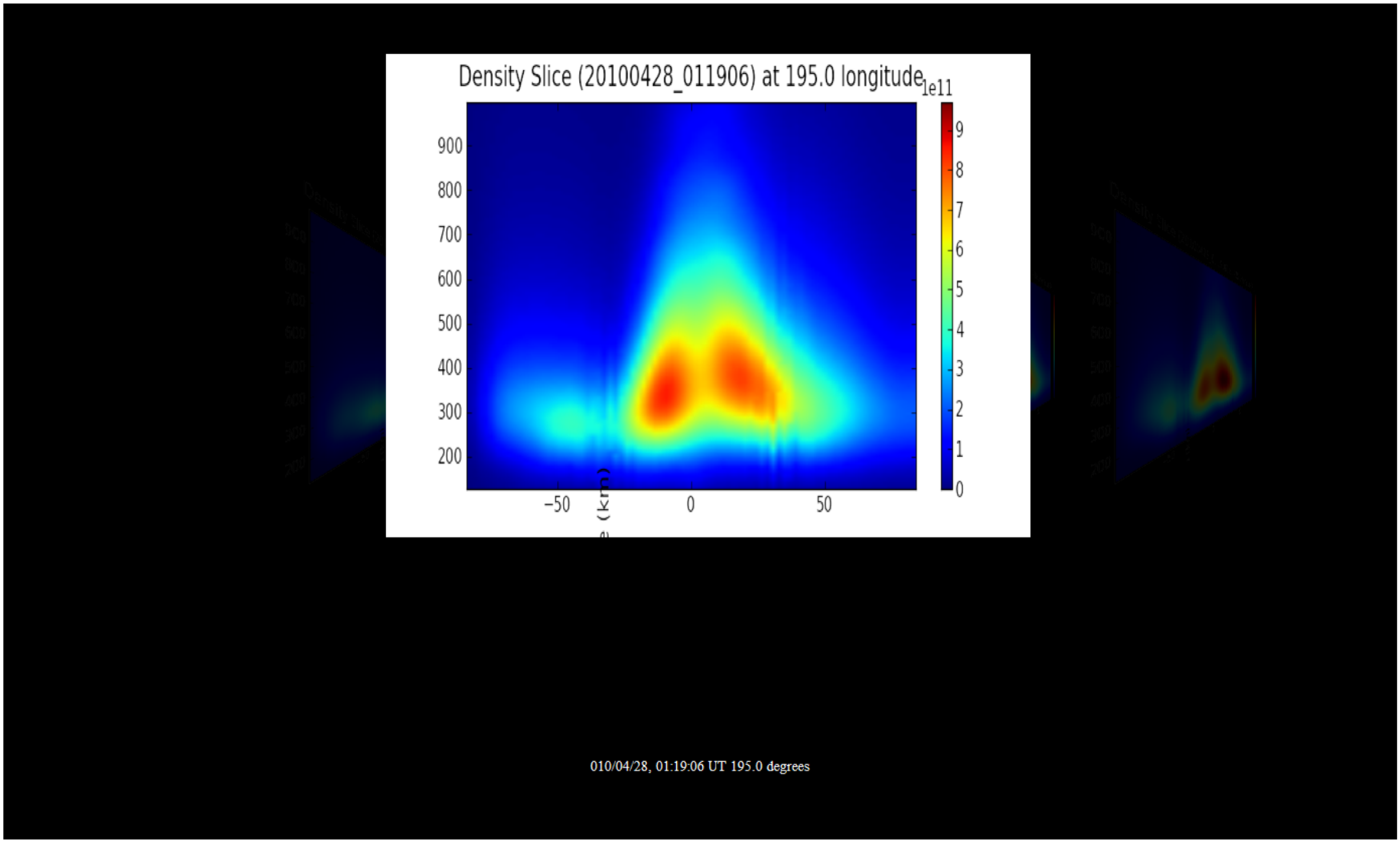




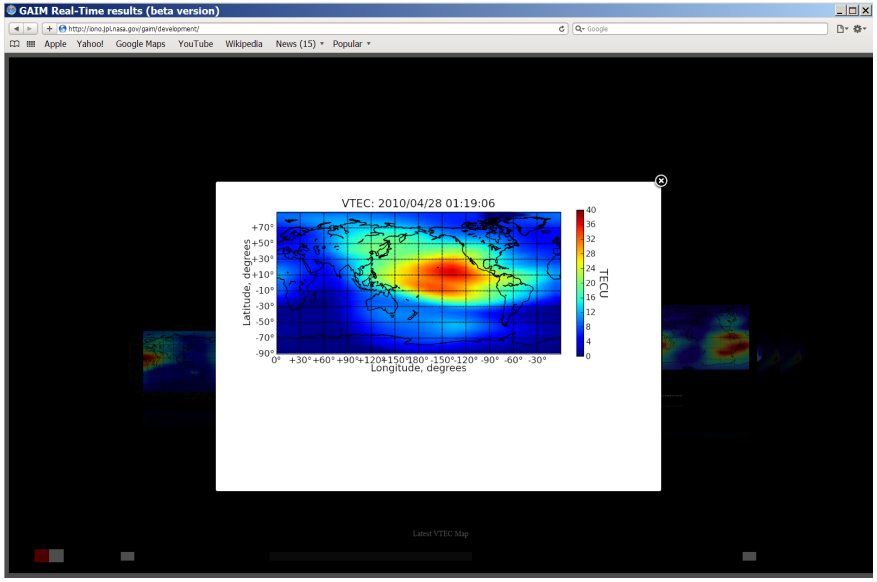
Global TEC Map Generated Every 5 Minutes

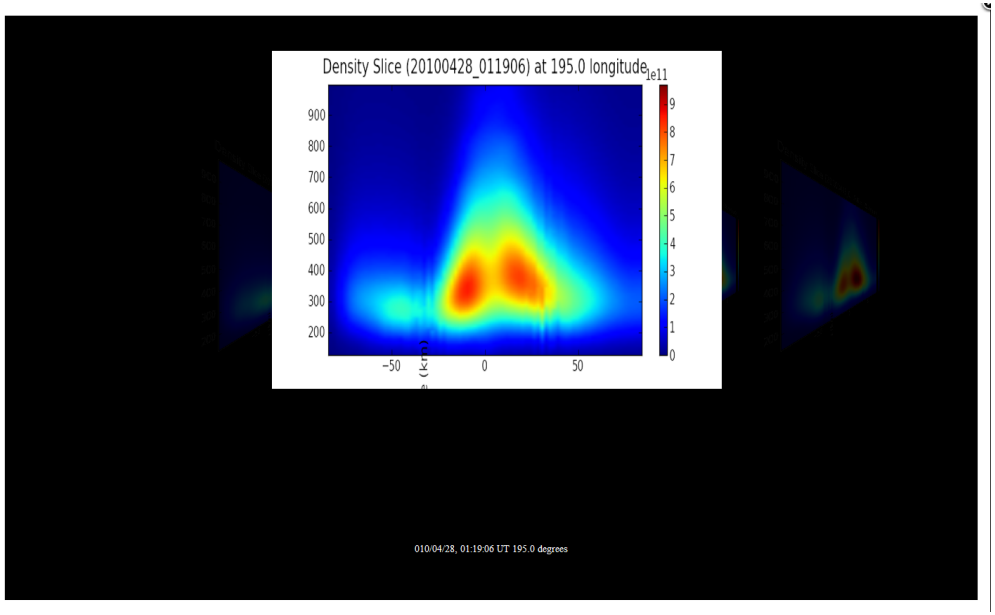


RTGAIM: Longitudinal Density Slice

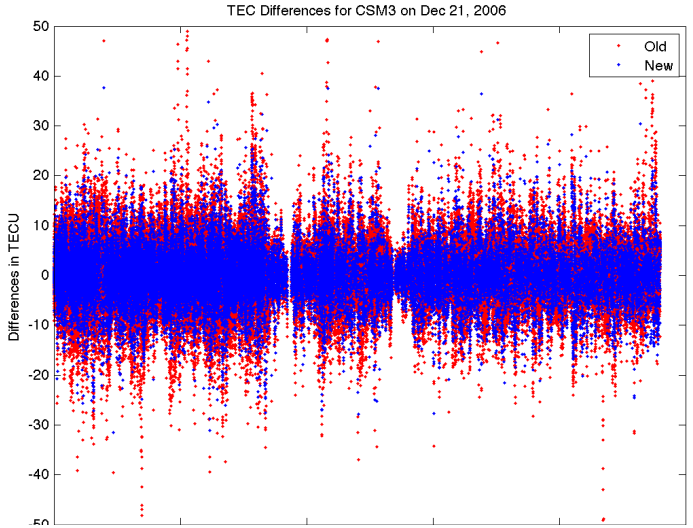


RTGAIM: Vertical TEC and Density Slice Maps

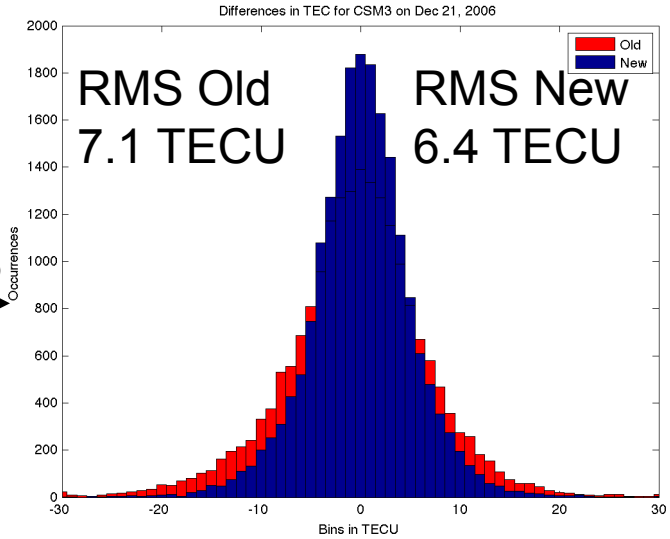


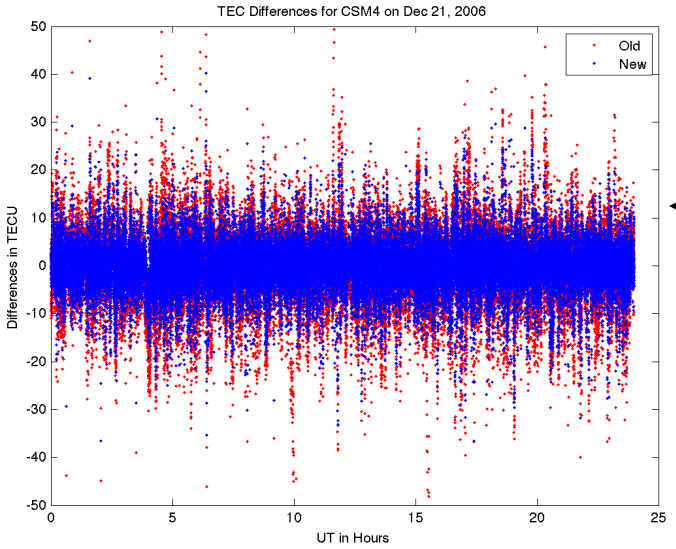


All CSM3 and CSM4 Residuals and Histogram for Dec 21, 2006

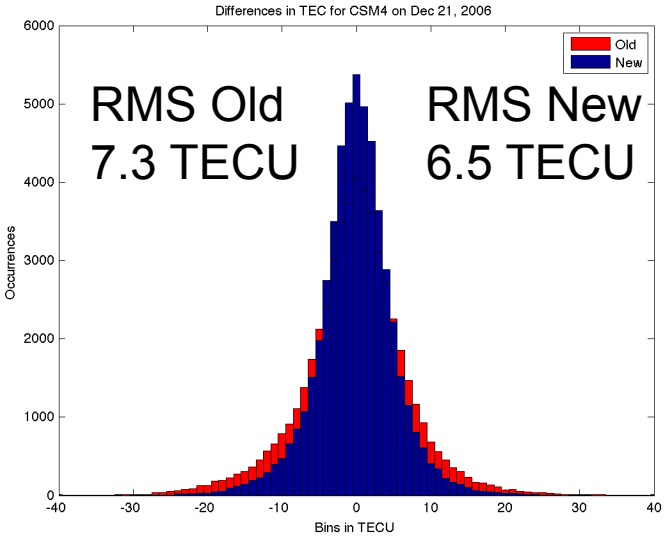


CSM3





CSM4



Real-Time GAIM Ground GPS Data Postfit Residuals