# Daily JPL Processing of 1000+ Ground-Based GPS Receivers to Estimate Interfrequency Biases and Other Practical Applications

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# Introduction

- GPS has became one of the most powerful research tools to study the temporal and spatial variability of global ionospheric TEC even though it was not originally designed as scientific observing system.
- GPS does not provide us with direct measurement of TEC:
  - We need to estimate satellite and receiver biases “corrupting” the GPS TEC measurements;
  - We need more powerful algorithms to estimate TEC, process and quality check the large amount of GPS data currently available on a daily basis.
- In the last 10 years, the number of GPS ground receivers has increased by as much as an order of magnitude:
  - Currently we have access to amount 2000 GPS receiver worldwide.
- The talk focuses on a different technique to estimate biases for all available stations. The biases are then used to generate daily 1000-site VTEC maps/movies.

# Outline

- GIM versus Bias-Fixing Method
- An automated tool to estimate 1000+ interfrequency receiver biases that could help the following applications:
  - Provide receiver interfrequency biases for second-order ionospheric correction
  - Investigate quiet vs storm-time ionospheric behavior for WAAS and other scientific studies
  - Help detect seismic ionospheric signatures during large earthquakes or tsunami event such as on Dec 26, 2004

# The Single vs. Multi-Shell Model: Observation Equation

For single shell, our model is

$$TEC = M(h,E)\sum_i C_i B_i(lat,lon) + b_r + b_s$$

For three shells, our model is

$$TEC = M(h_1,E)\sum_i C_{1i} B_i(lat,lon) + M(h_2,E)\sum_i C_{2i} B_i(lat,lon) + M(h_3,E)\sum_i C_{3i} B_i(lat,lon) + b_r + b_s$$

where

$TEC$ is the slant TEC;

$M(h_1,E)$ is the thin shell mapping function for shell 1, etc;

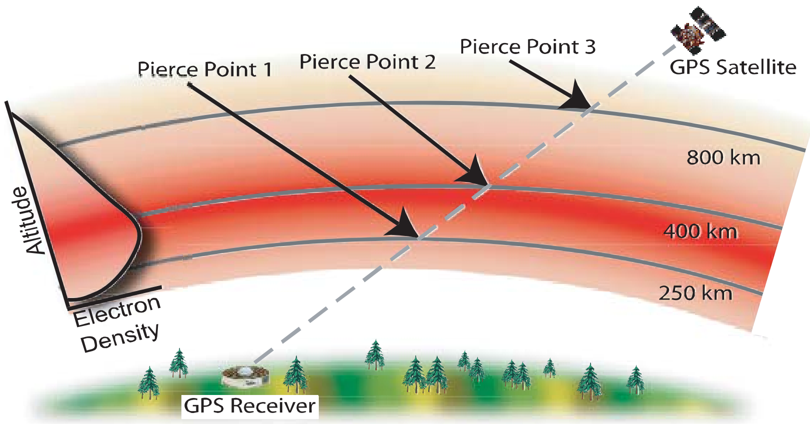
$B_i(lat,lon)$ is the horizontal basis function ($C^2$, TRIN, etc);

$C_{1i}$ are the basis function coefficients solved for in the filter, indexed by horizontal (i) and vertical (1,2,3 for three shells) indices;

$b_r, b_s$ are the satellite and receiver instrumental biases.

# Single Vs. Three-Shell Model Limitations

The concept of multi-shell GIM:

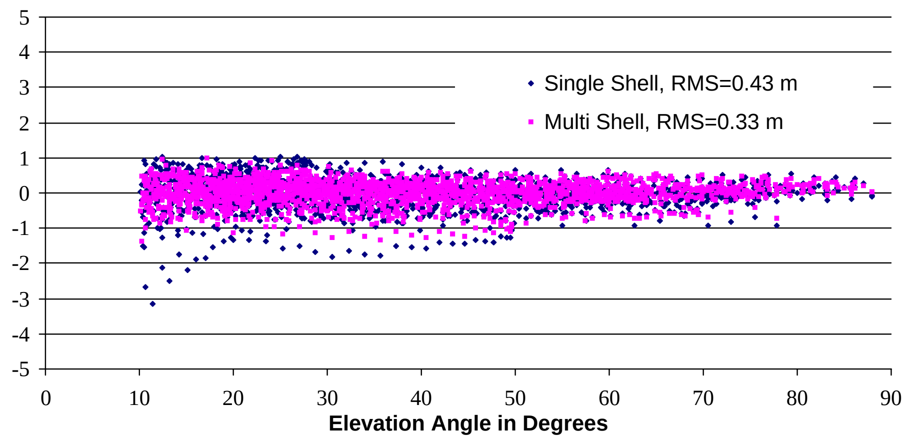



Single-shell 2-D maps

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

Does not capture small-scale variations in the ionosphere

Multi-shell is more realistic and accurate than the single-shell approximation



# New: All-Site GPS Data Processing Algorithm

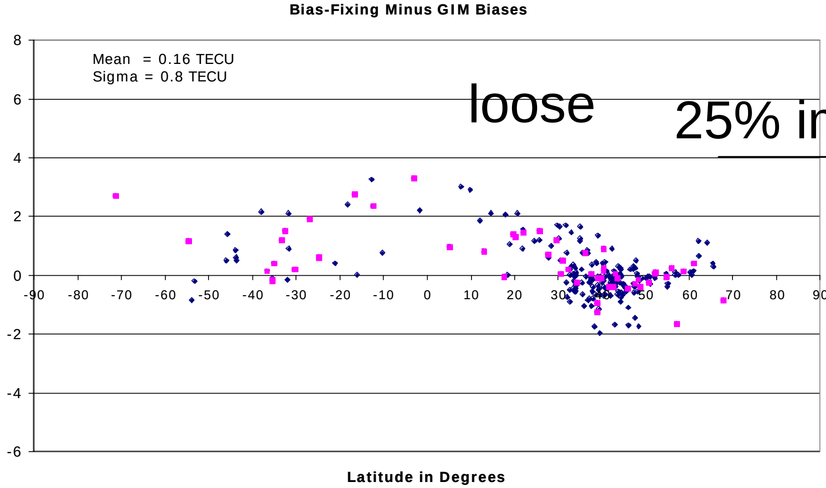
Bias Fixing Algorithm using all available GPS stations worldwide:

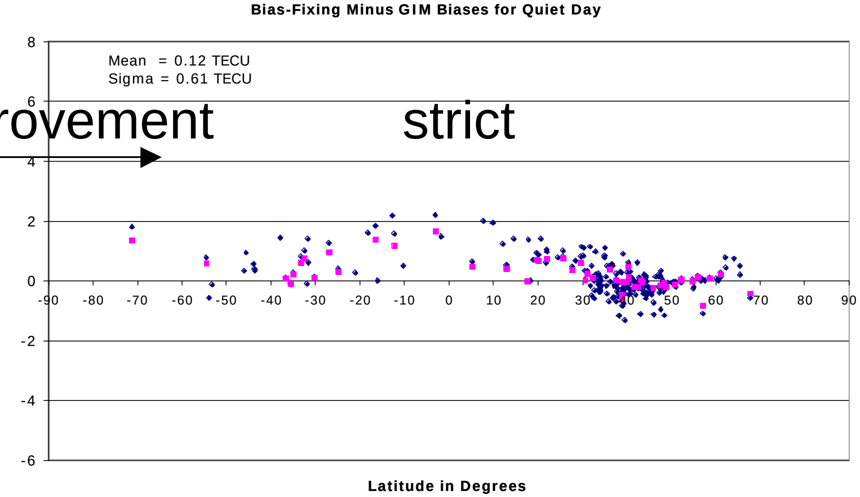
$$\underbrace{b_r = TEC}_{\text{Biased TEC observation}} - \underbrace{M(h,E)\sum_i C_i B_i(lat,lon)}_{\text{GIM TEC prediction}} - \underbrace{b_s}_{\text{GIM satellite bias estimate}}$$

| | |
|---|---|
| $TEC$ | is the biased phase-levelled ionospheric observable |
| $M(h_1,E)$ | is the thin shell mapping function for shell 1, etc; |
| $B_i(lat,lon)$ | is the horizontal basis function ($C^2$, TRIN, etc); |
| $C_{1i}$ | are the basis function coefficients solved for in the filter, indexed by horizontal (i) and vertical (1,2,3 for three shells) indices; |
| $b_r, b_s$ | are the satellite and receiver instrumental biases. |

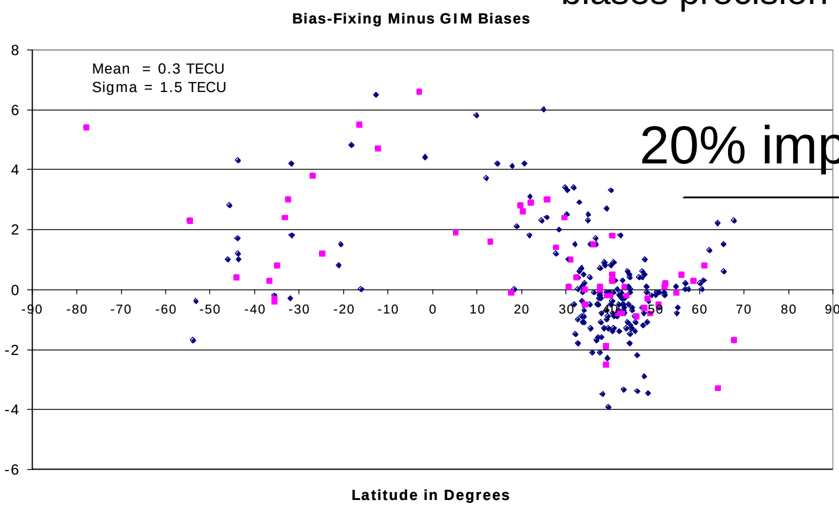
# Receiver Bias Estimation Precision

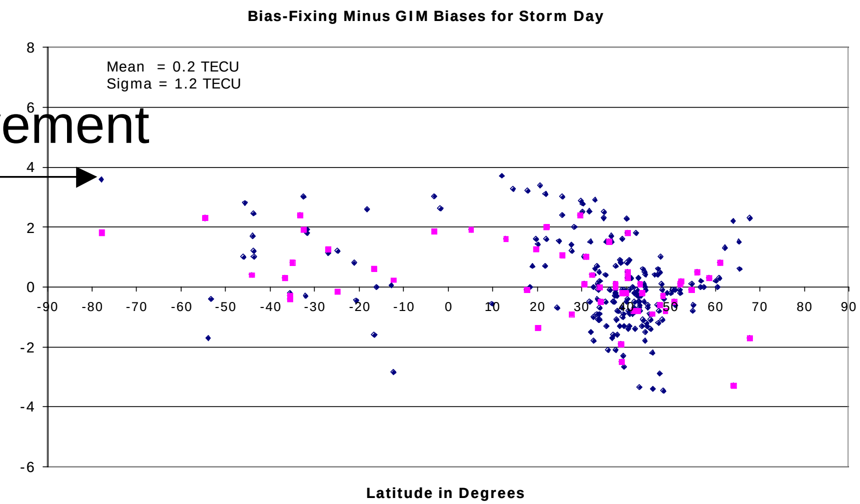
biases precision - quiet day (April 26, 2004)



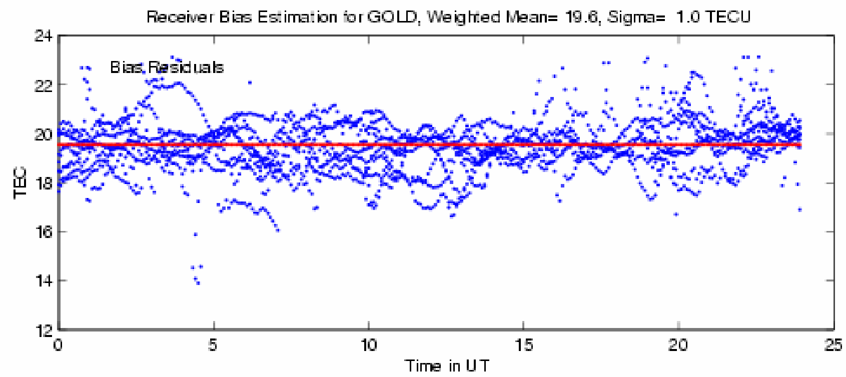




biases precision - storm day (July 15, 2000)

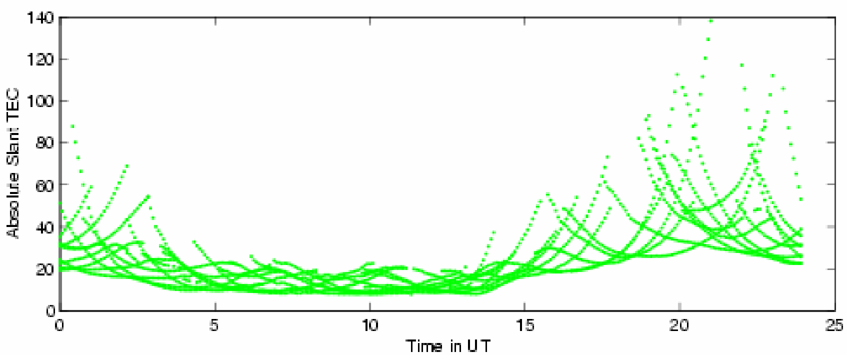


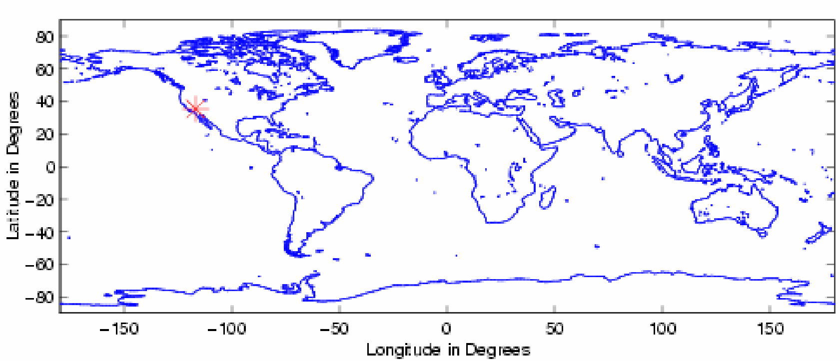
# Slant TEC Bias-Fixing Method




Estimated bias time series: errors caused by GIM, multipath, noise, sub-daily bias drift

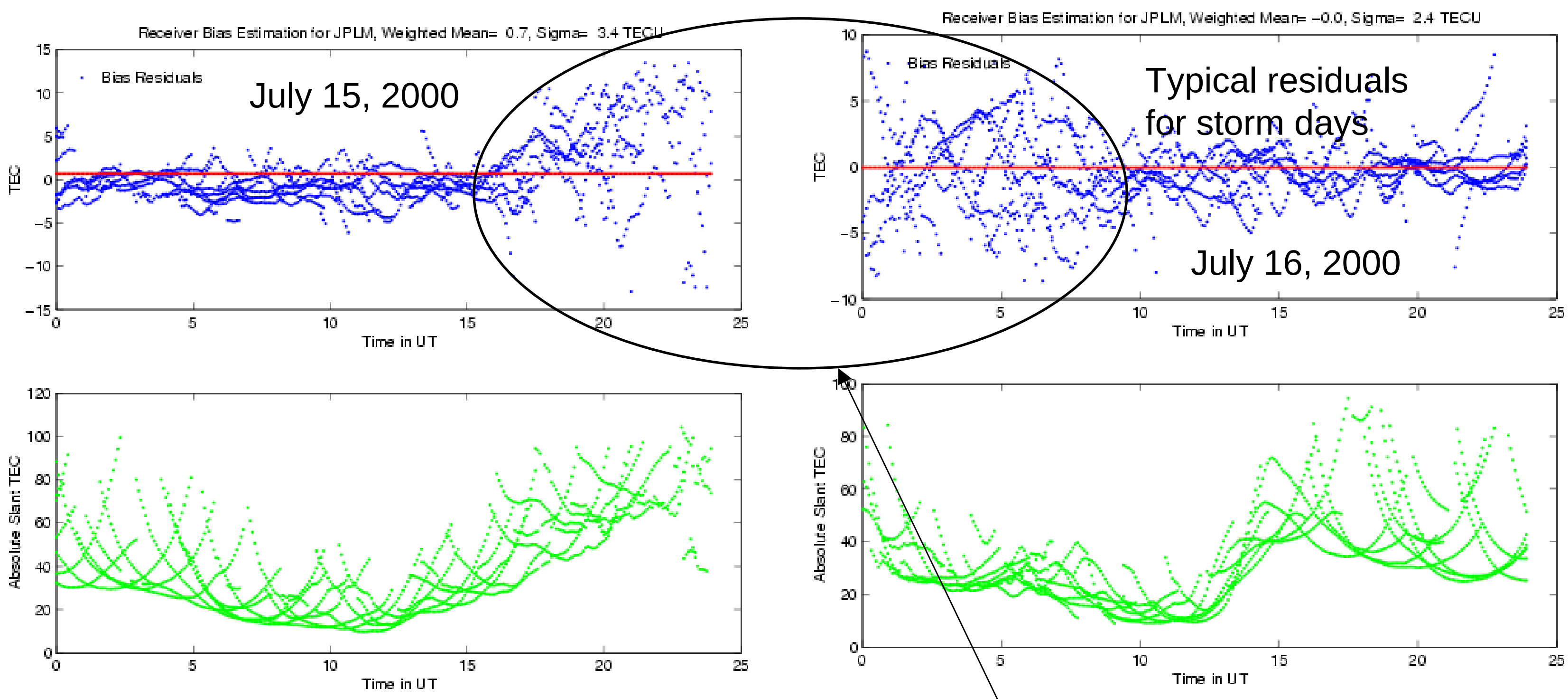


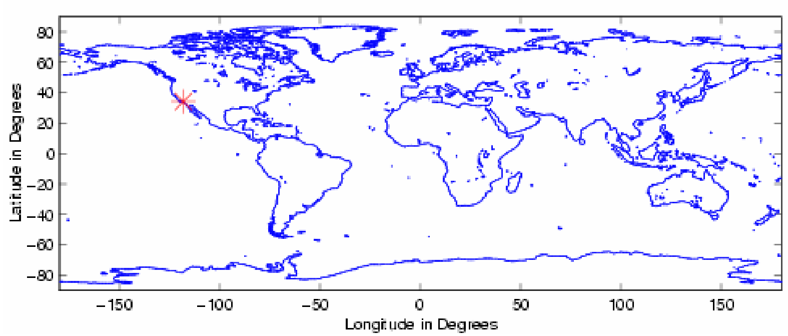

Bias-removed slant TEC




Location of station

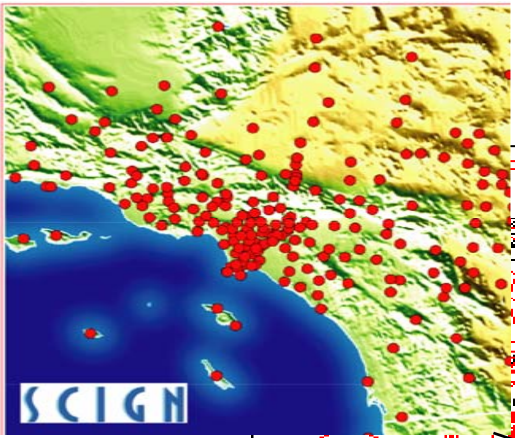
# Storm-Time Biases: Repeatibility and Uncertainty Increase



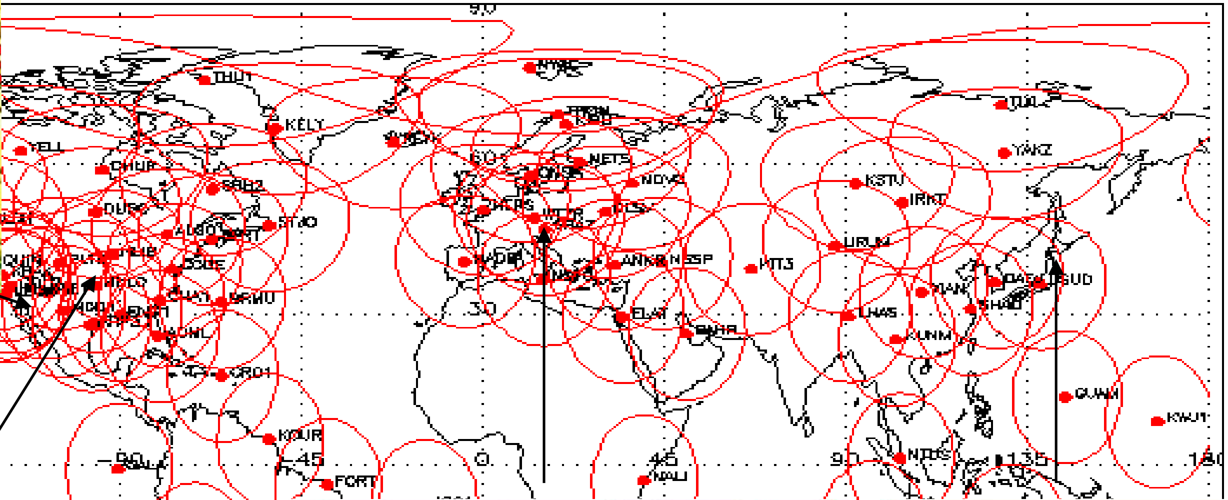



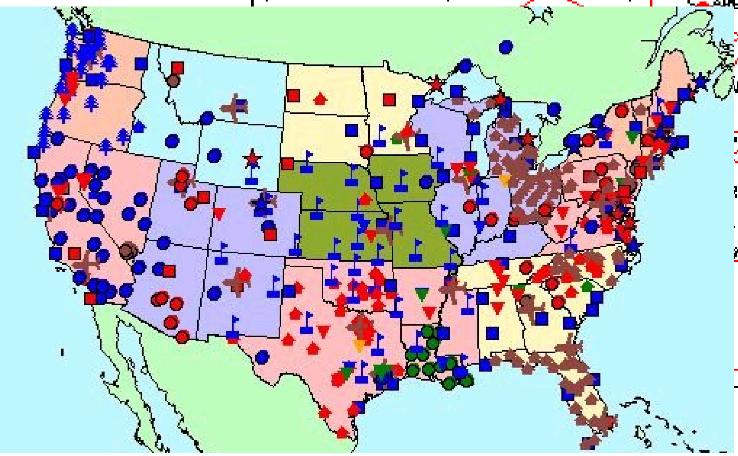

Estimating biases are more challenging for storm-time

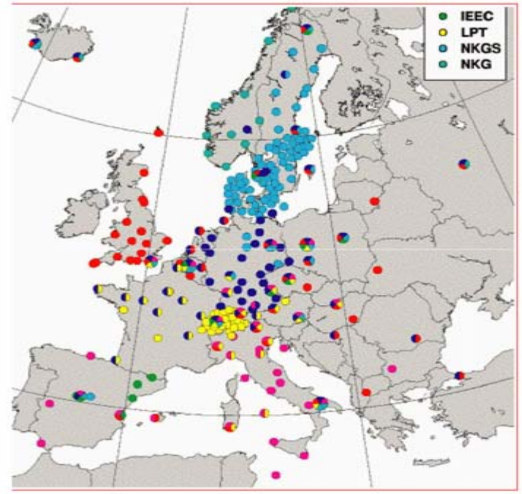
# Coverage of Daily IGS Network and Regional Networks

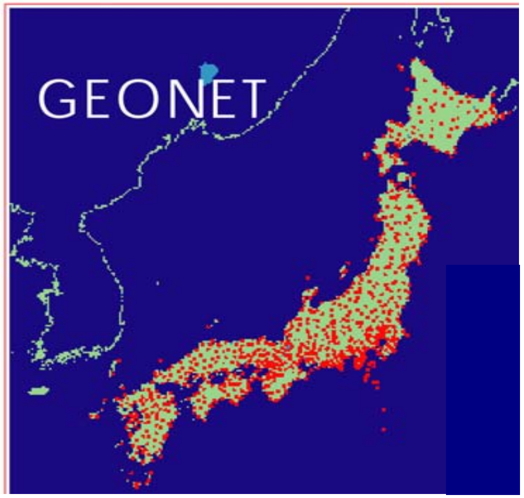



(10 degree elevation mask; 450 km shell height)



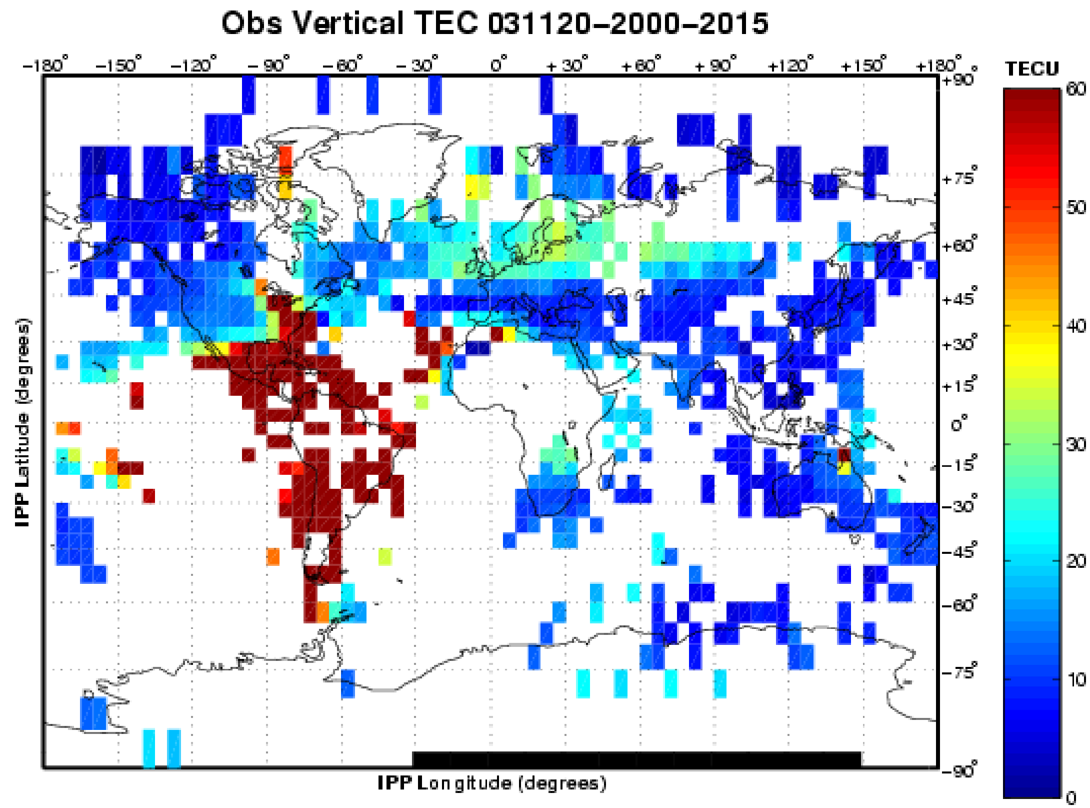





# An Example of 1000-Site Storm-Time VTEC Movie

- Frames every 15 minutes
- 2 degree by 2 degree pixels
- Mean of VTEC within each pixel computed
- No interpolation: strictly data driven
- Slant TEC mapped to vertical with biases removed
- Available on a daily basis



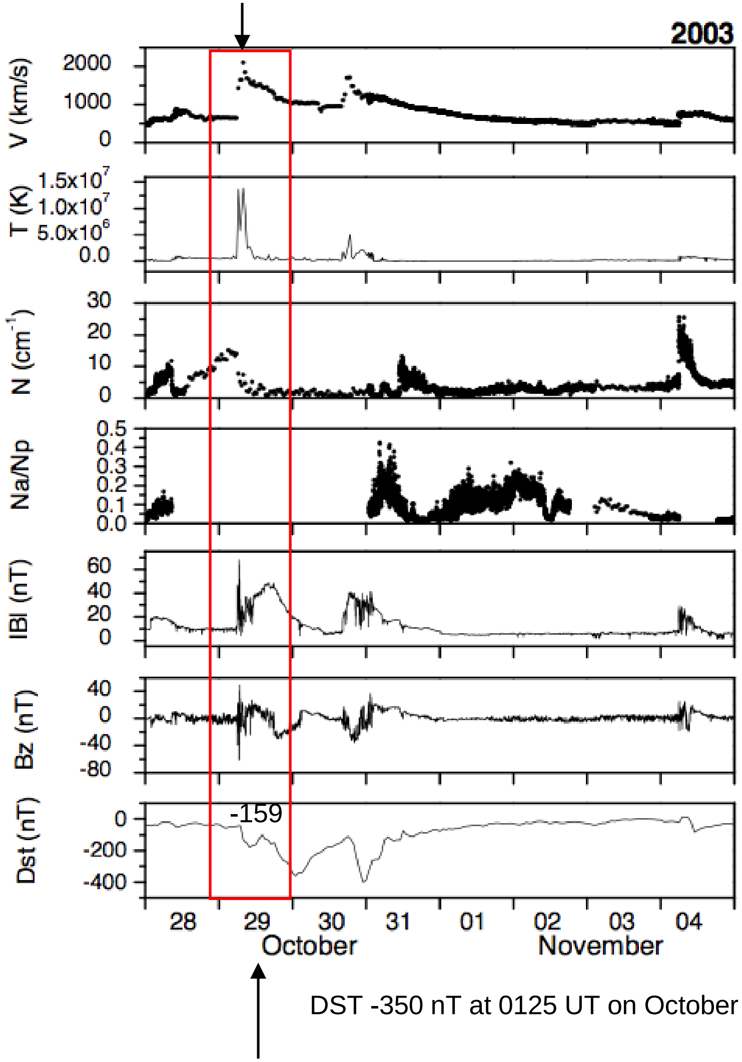

All movies available at

ftp://sideshow.jpl.nasa.gov/pub/axk/allsites

# October 29, 2003

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

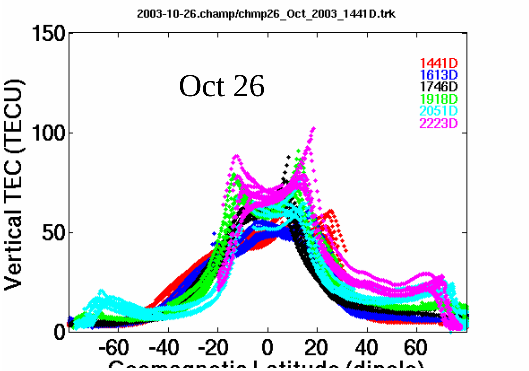
1st Interplanetary Coronal Mass Ejection

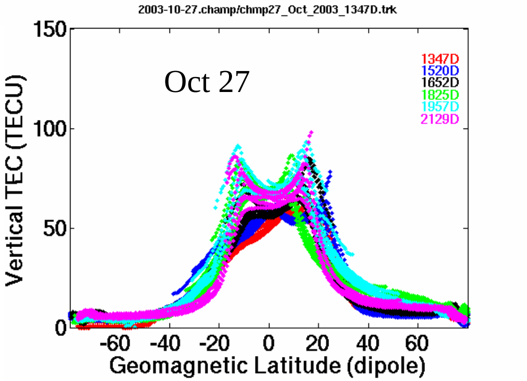


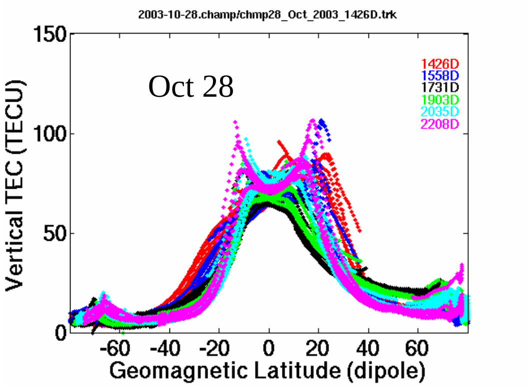

DST -350 nT at 0125 UT on October 30

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

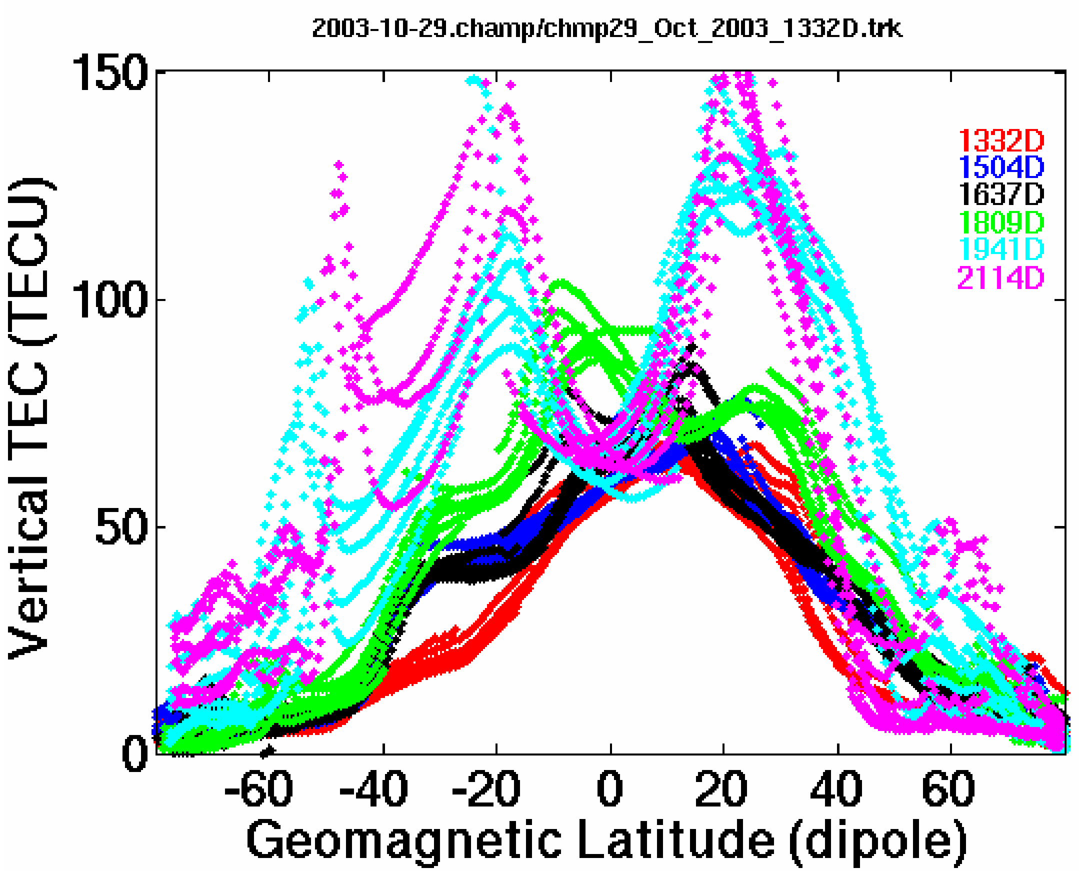
# October 29, 2003




Event Time: 17:30 UT Local Time: 13:00

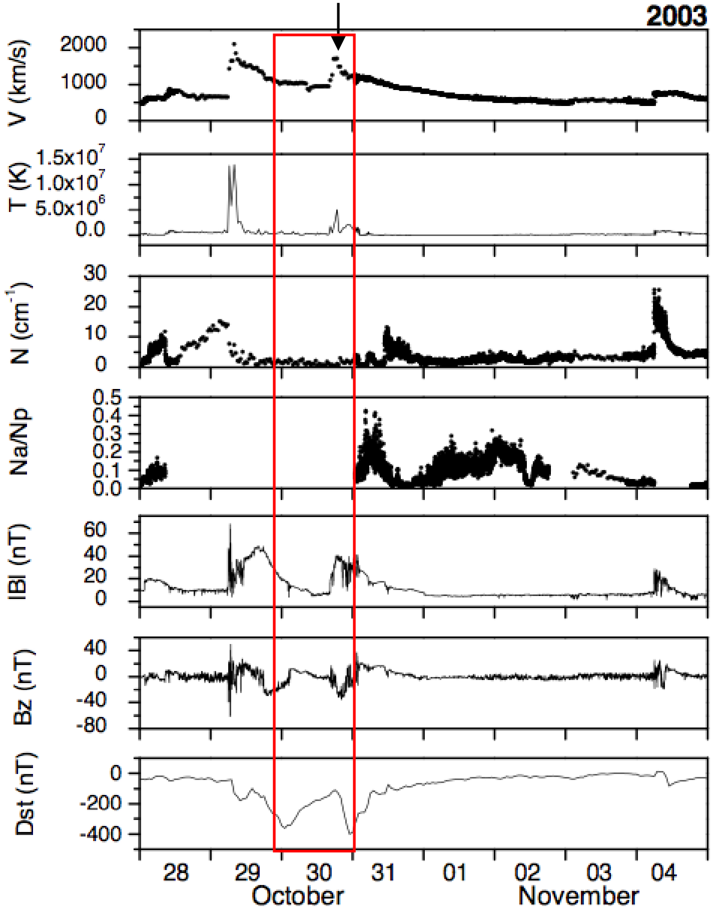


# October 30, 2003

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

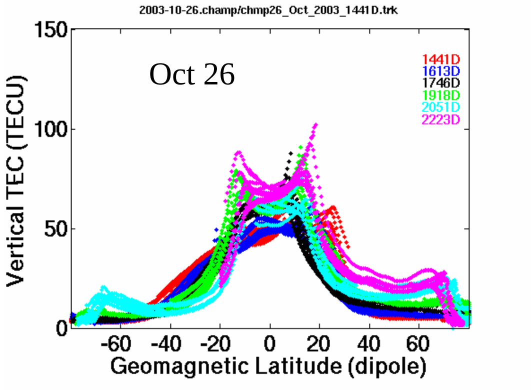
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

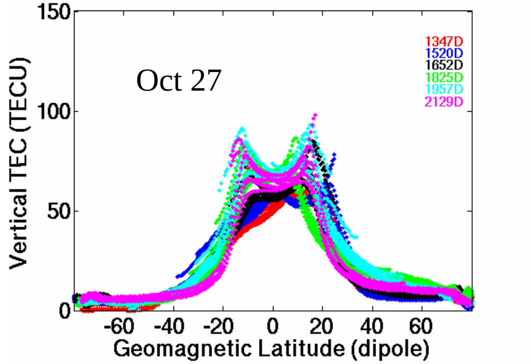
2nd Interplanetary Coronal Mass Ejection

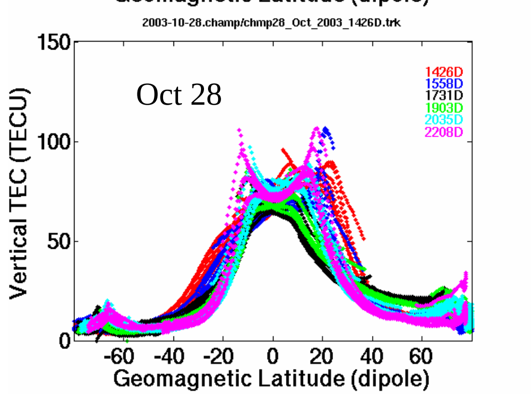



DST -390 nT at 2315 UT on October 30

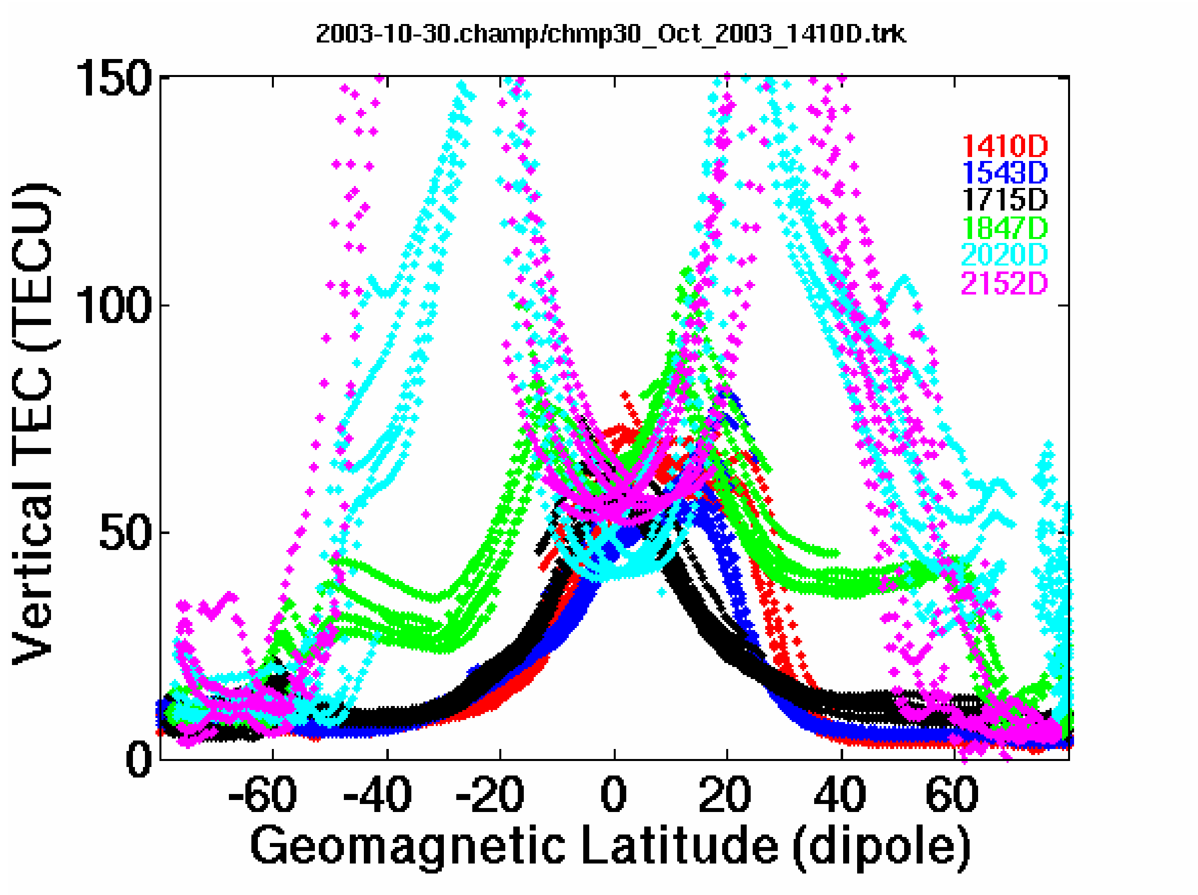
# October 30, 2003




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



# November 20, 2003 Storm

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Details are difficult to interpret

5-day average of quiet ionosphere removed: structures are easier to detect

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Quiet ionosphere following the storm

# November 20, 2003 Storm

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

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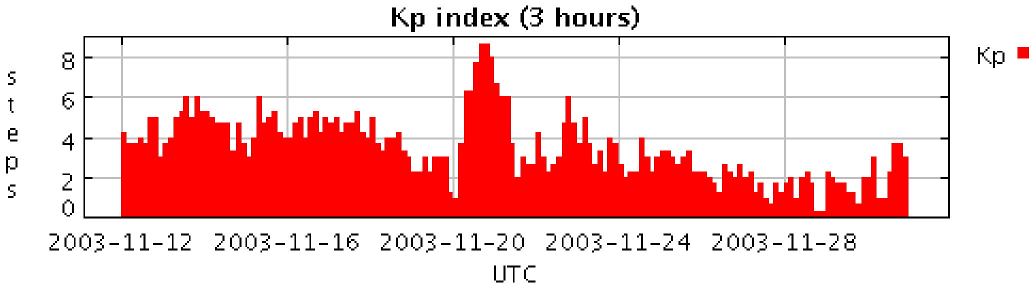
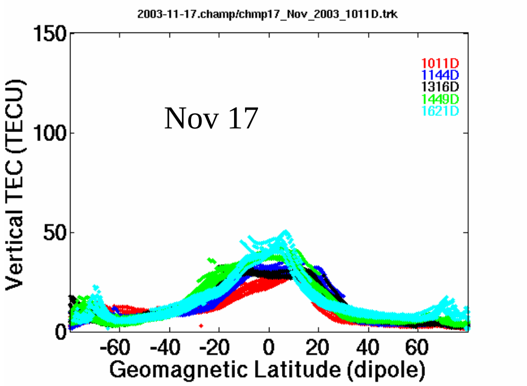
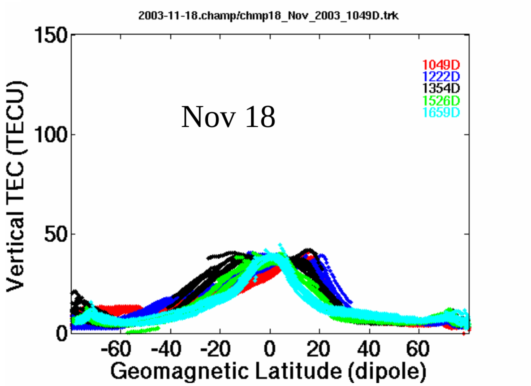
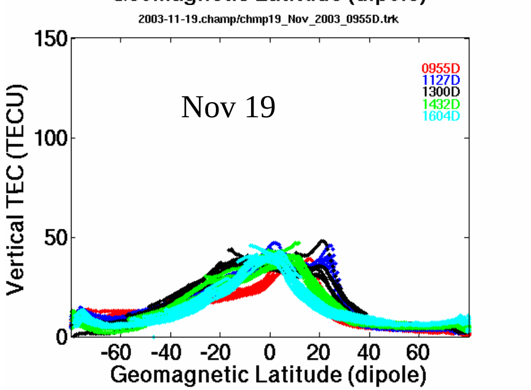
YUV420 codec decompressor
are needed to see this picture.



# November 20, 2003

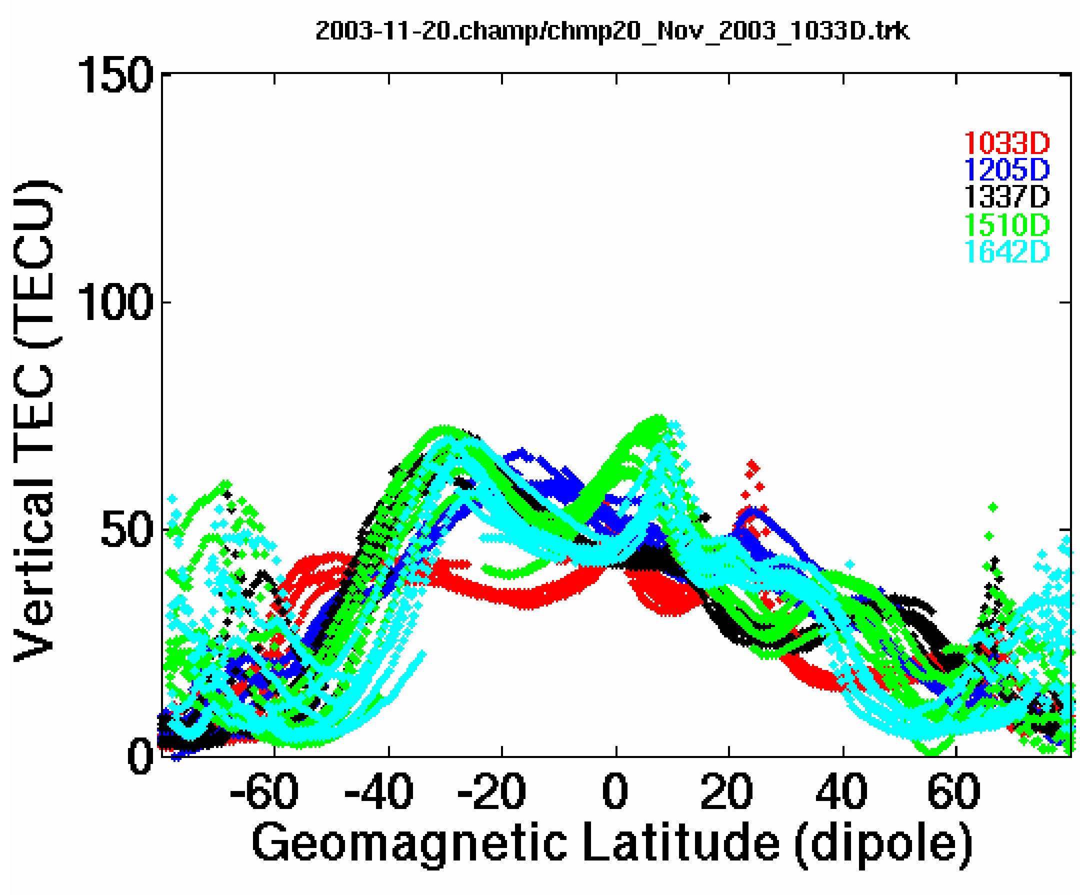



Event Time: 13:20 UT

Local Time: 11:00



# Application: Detecting Seismic-Ionospheric Signatures

- Recently there have been several claims made by researchers indicating
  - 20-30 (!) TECU level changes in the ionosphere following the Dec 26, 2004 devastating Sumatra Earthquake;
  - large changes lingering for several hours and they can be seen at GPS stations separated by thousands of miles.

- Scientific literature indicates the largest TEC changes following an earthquake or tsunami generated by a large earthquake event is up to 0.5 TECU.

- **There appears to be a disconnect between recent claims and earlier published results.**

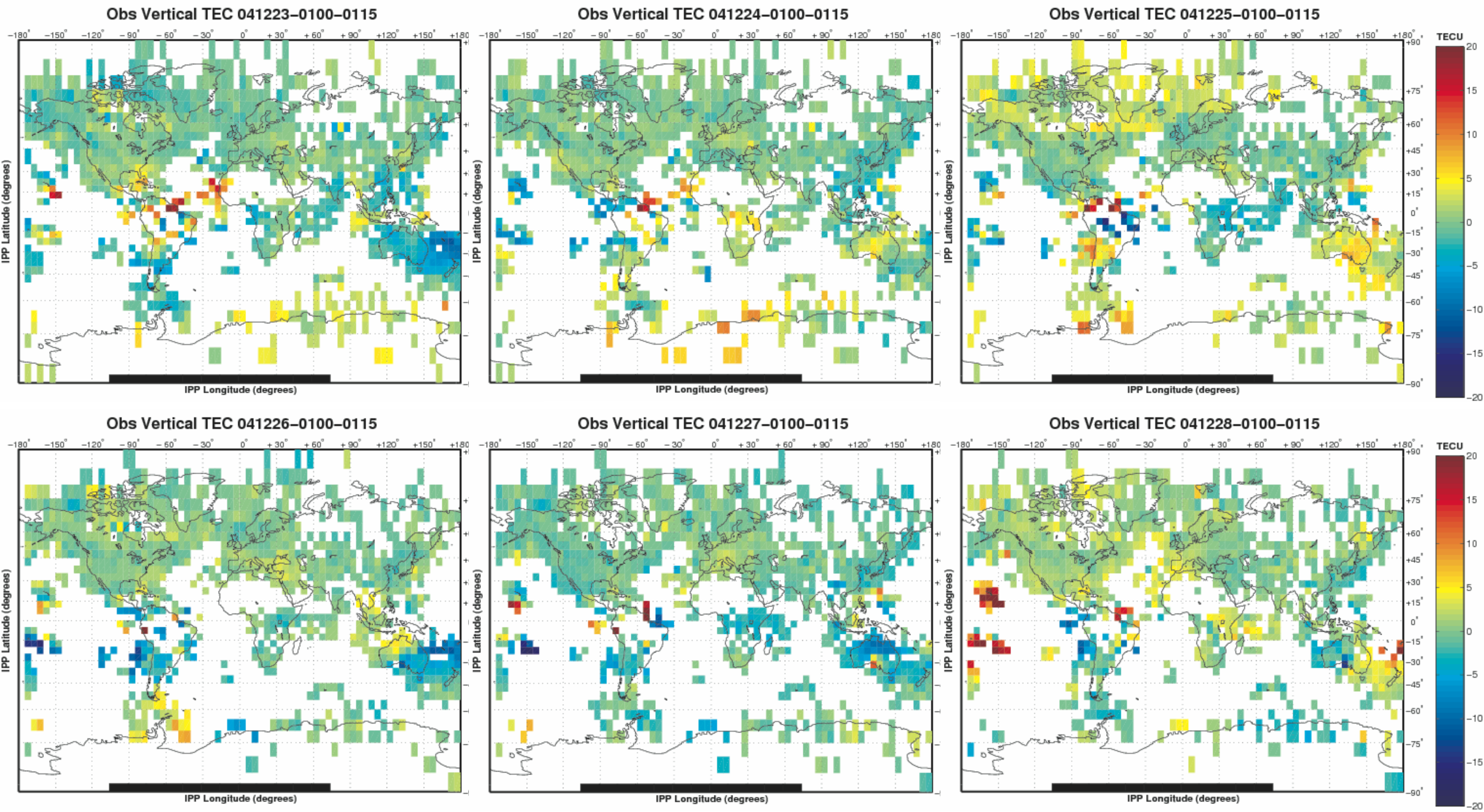
# Software Development

- We developed a comprehensive package to process individual GPS stations to extract ionospheric perturbations caused by TID:
  - Software estimates receiver and satellite interfrequency biases using 1000+ site bias-fixing method
  - Removes background ionospheric signature and forms the ionospheric residual as primary observable
  - It uses the supertruth processing technology developed for WAAS to form high-precision individual phase-connected arcs using tecdump files
  - Uses band-pass filter to extract perturbations starting at the 0.1 TECU level
  - Plots TID signatures using multiple satellites on a station-by-station basis.

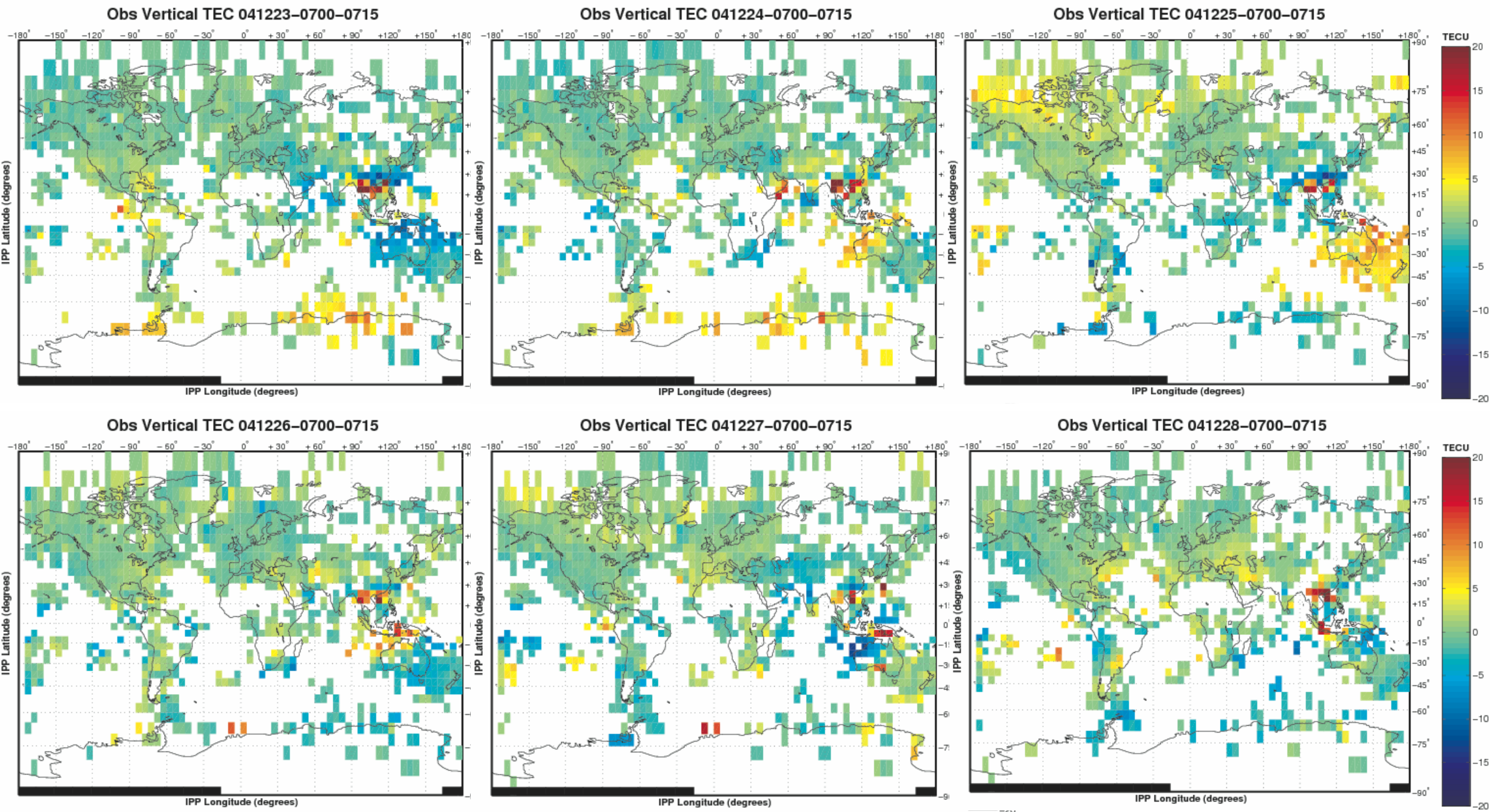
# Approach

- We looked at 1100 GPS stations/per day for six days surrounding the Dec 26, 2004 Tsunami event (Dec 23-28)
  - Investigated absolute TEC with background ionosphere (6-day averaged) removed
- We investigated TEC at individual GPS stations nearest in distance to Sumatra
  - Absolute TEC computed at individual stations between subsequent days
- Finally, we band-pass filtered the phase TEC data to see the variation possibly caused by the earthquake-generated tsunami

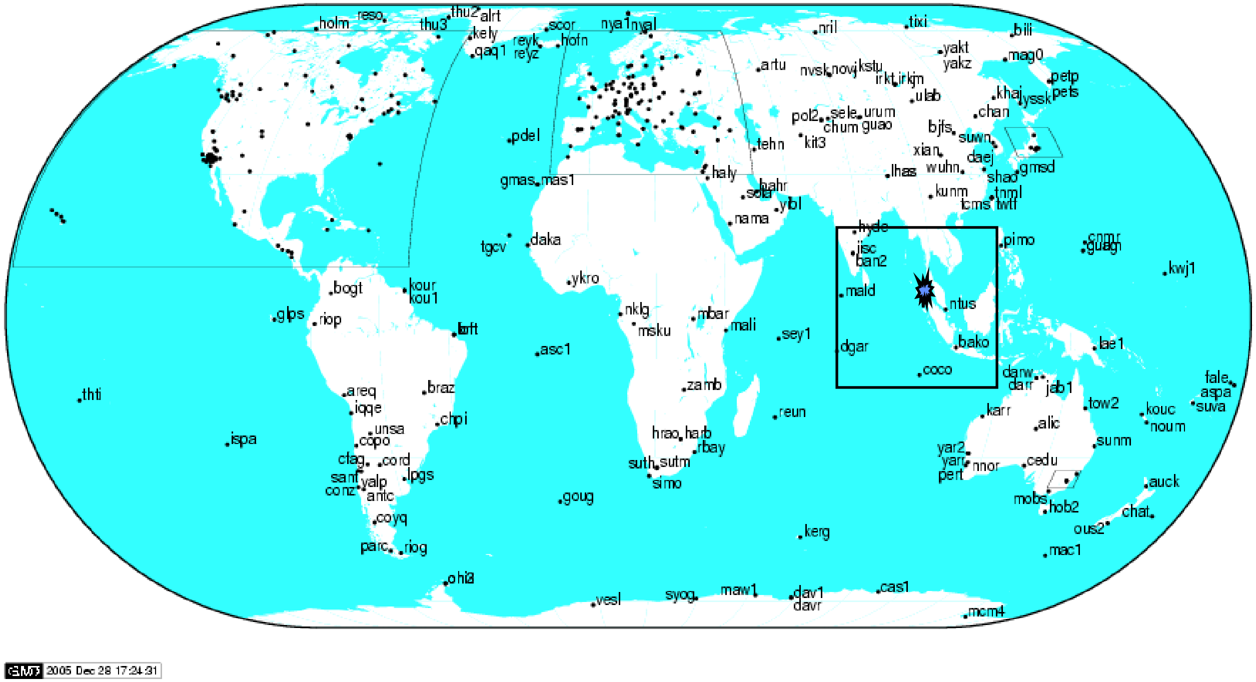
# Dec 23-28, 2004 Vertical TEC for UT 0100-0115

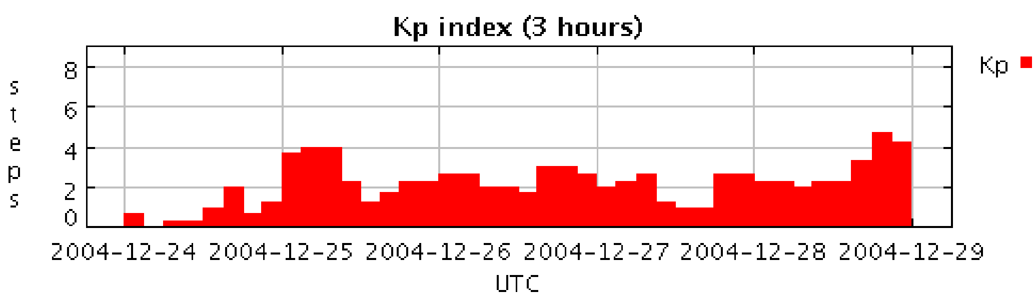


# Dec 23-28, 2004 Vertical TEC for UT 0700-0715



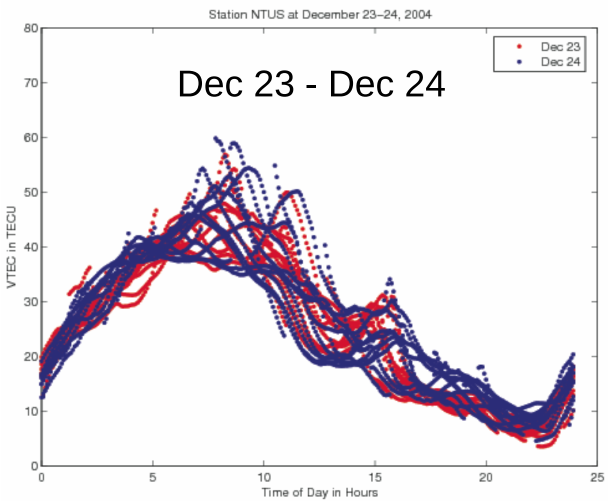
# GPS Stations Near Sumatra and Geomagnetic Activity

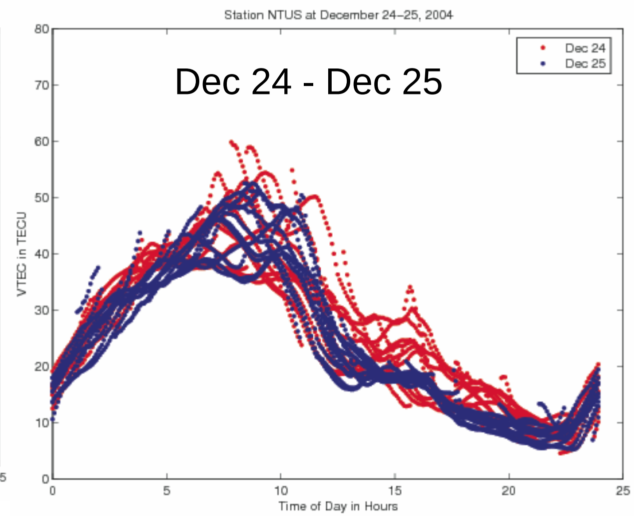


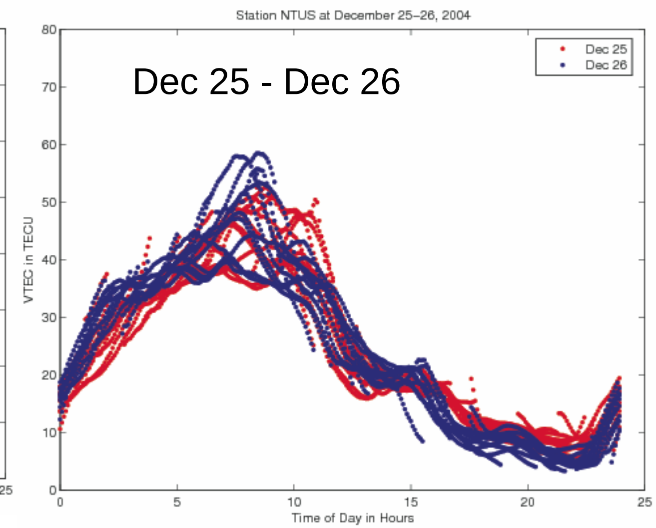



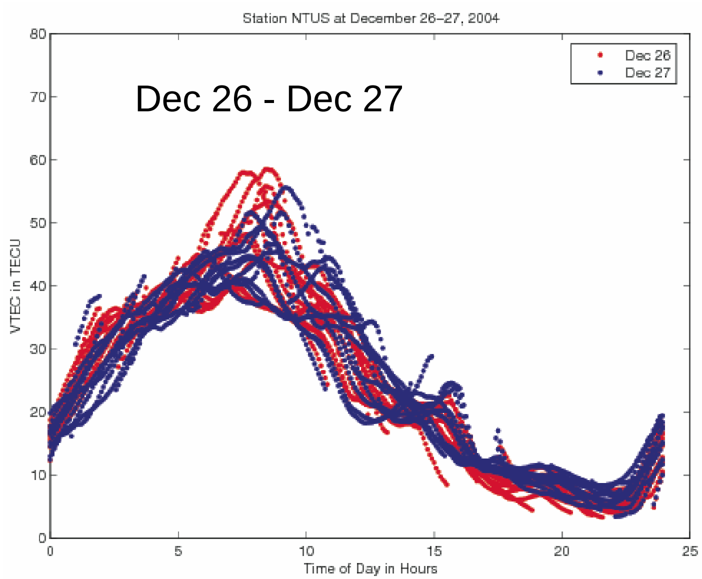

Geomagnetic Kp activity around the Sumatra event

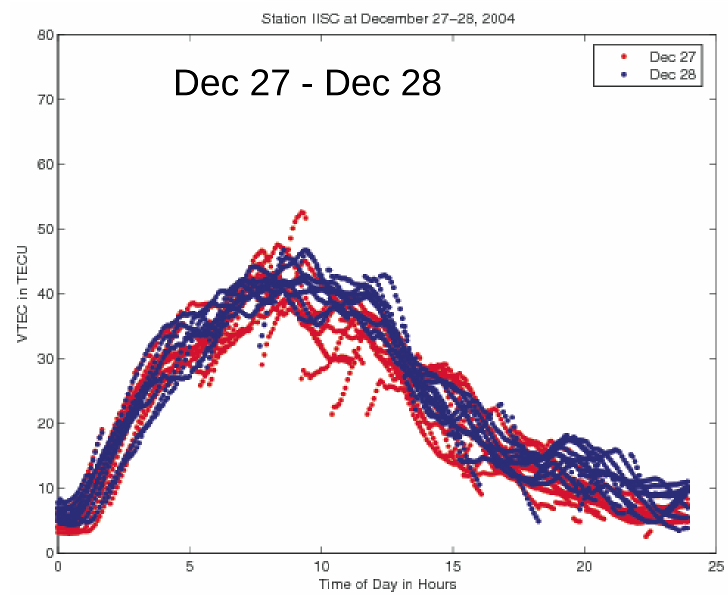
# IGS Station NTUS, Singapore



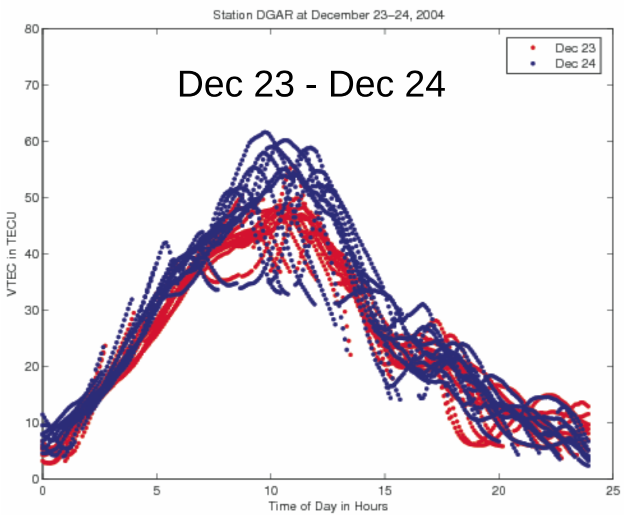



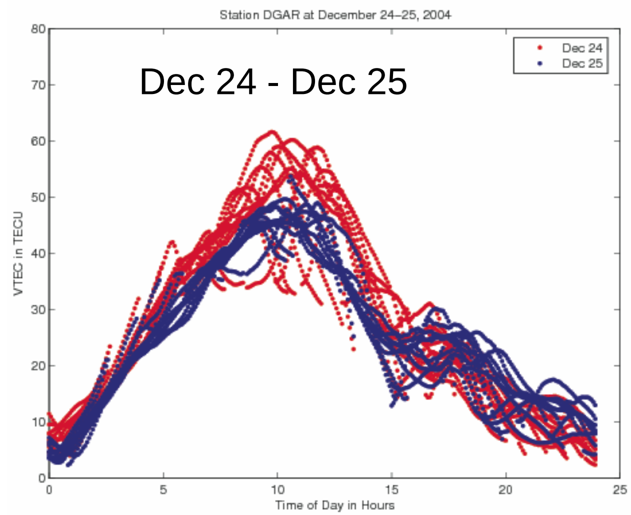



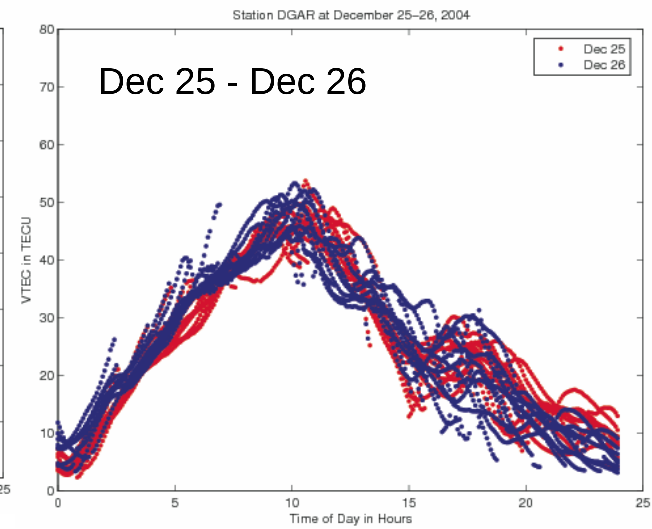



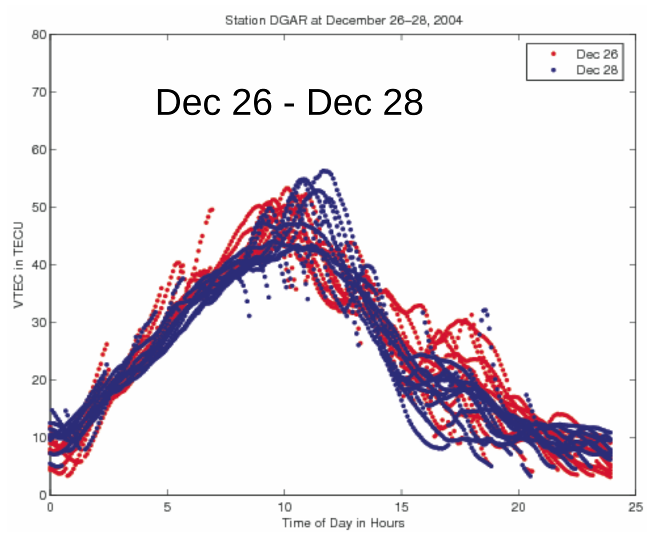



# IGS Station DGAR, Diego Garcia Island

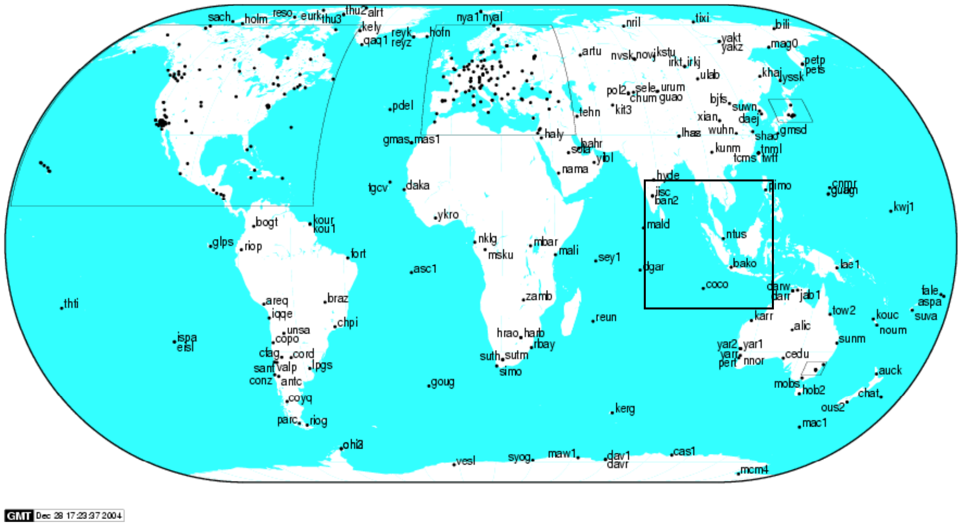


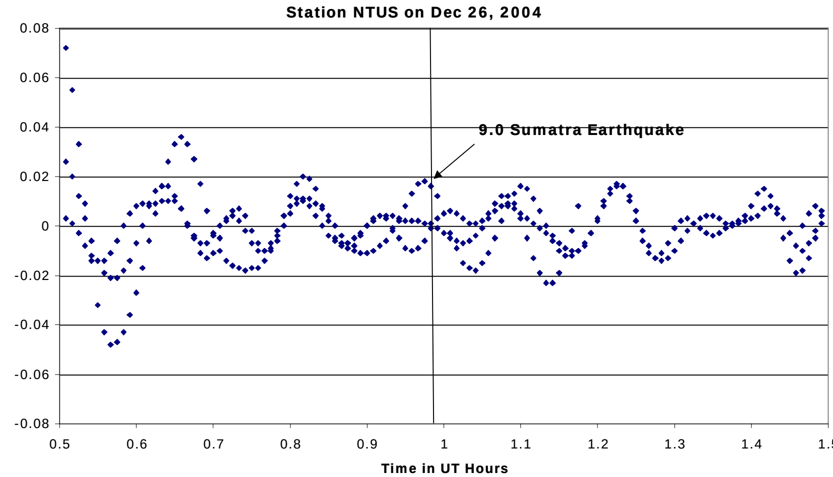



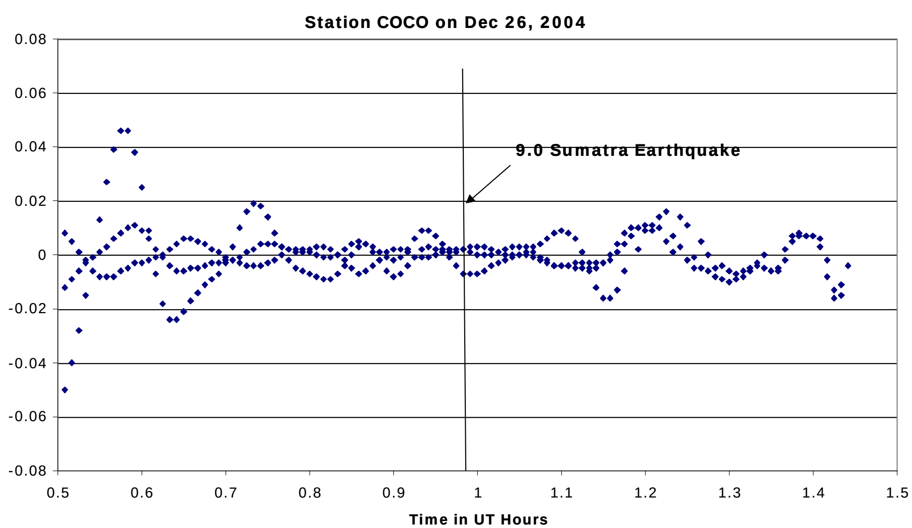



# Band-Pass Filtering Using 30-Second RINEX Data

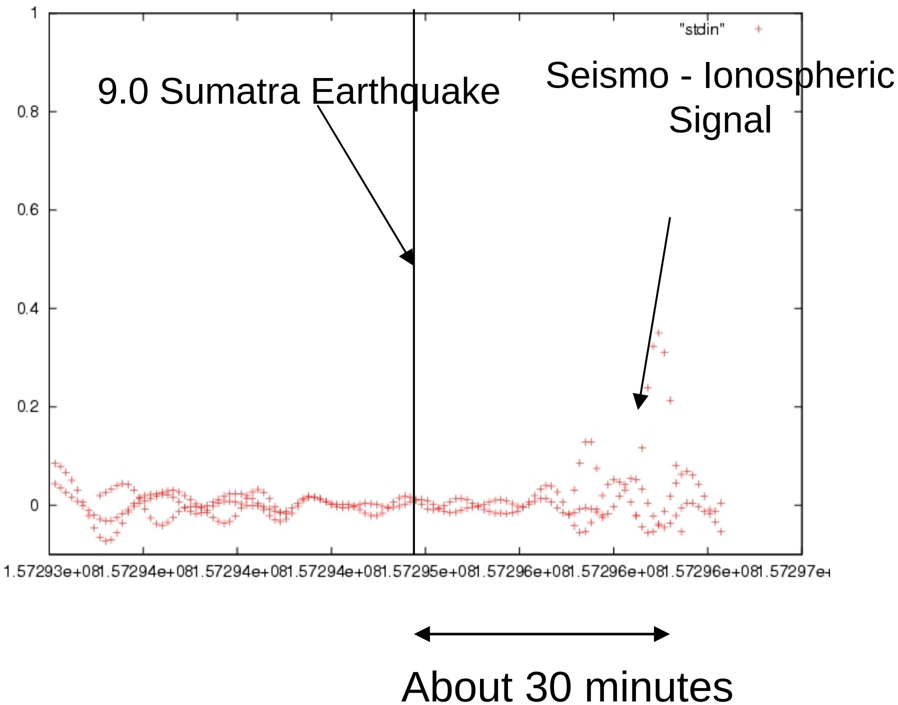





- Initially 30-sec RINEX-data from IGS stations used for development
- Dec 26, 2004 Sumatra Earthquake used to test algorithm
- Two stations processed above, separated by about 1500 km.
- No seismo-ionospheric signature found due to the low (30-sec) sampling rate
- Multiple satellites plotted at higher than 50 degrees elevation angles to minimize multipath effect

# Band-Pass Filtered GPS TEC Data at 1-Second Sampling Rate




- We found 1-second data at station DGAR near the Sumatra Earthquake
- We applied the same algorithm and obtained the time series shown on the left
- Three satellites plotted at higher than 50 degrees elevation angle
- Lag between earthquake and disturbance in the ionosphere is what we would expect using propagation velocity of the waves in the atmosphere based on Afraimovich paper [2003].
- Amplitude of disturbance is also what we would expect (0.2 to 0.4 TECU).

# Summary

- We estimate receiver daily biases using this routine 1000-site biases estimation technique.
- For storm-time VTEC mapping, we estimate biases using surrounding quiet days; We now routinely remove background ionosphere to highlight fine structures.
- As a product, we generate 1000-site daily VTEC data sets, bias estimates and animations. Daily global 1000-site representation of VTEC available at: ftp://sideshow.jpl.nasa.gov/pub/axk/allsites
- We showed the following potential applications:
  - Providing receiver interfrequency biases for 2nd order ionospheric correction
  - Performing storm-time studies for e.g., WAAS
  - Help detect seismic-ionospheric signatures
- Do you have any suggestions for other interesting applications?

Acknowledgement:

- The research was performed at JPL/Caltech under contract to the National Aeronautics and Space Administration