GNSS Multi-scale studies of the ionosphere and plasmasphere

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Outline

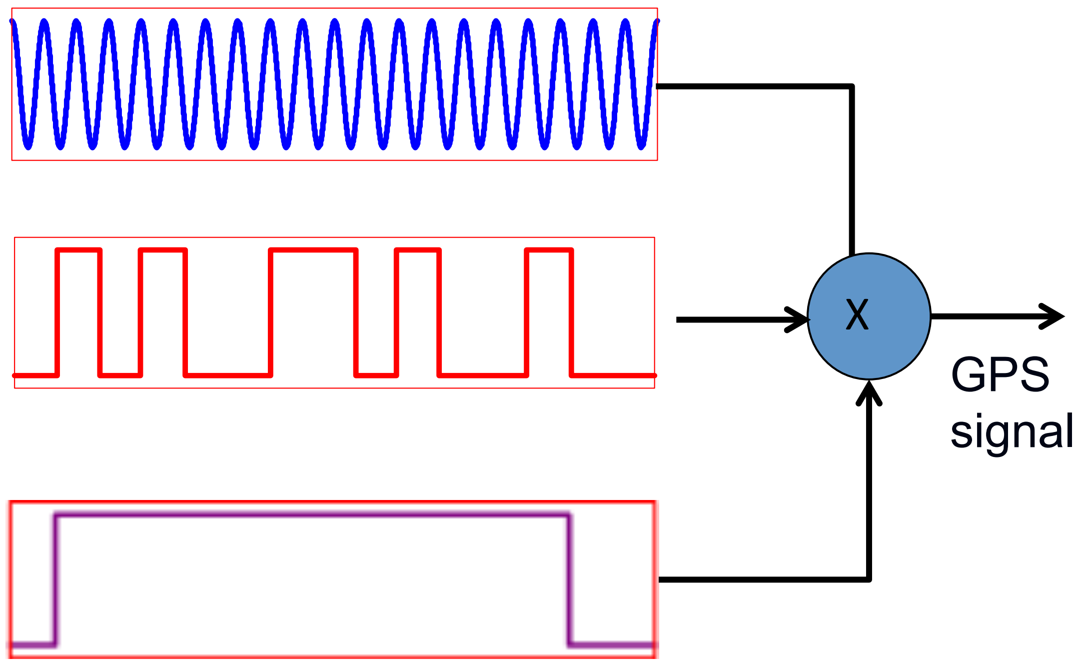
- GPS Signal Structure
- Other GNSS Constellations
- GPS Ionospheric Observations
- TEC Based Scientific Studies of the Ionosphere and Plasmasphere
- Scintillation Based Scientific Studies of the Ionosphere
- Summary

GPS Satellite Signal Structure

Carrier:
- Doppler
- Range

Code modulation:
- Identifies SV
- Spread power
- Range

Navigation data
- SV orbit
- Error correction
- SV health



Range Measurements

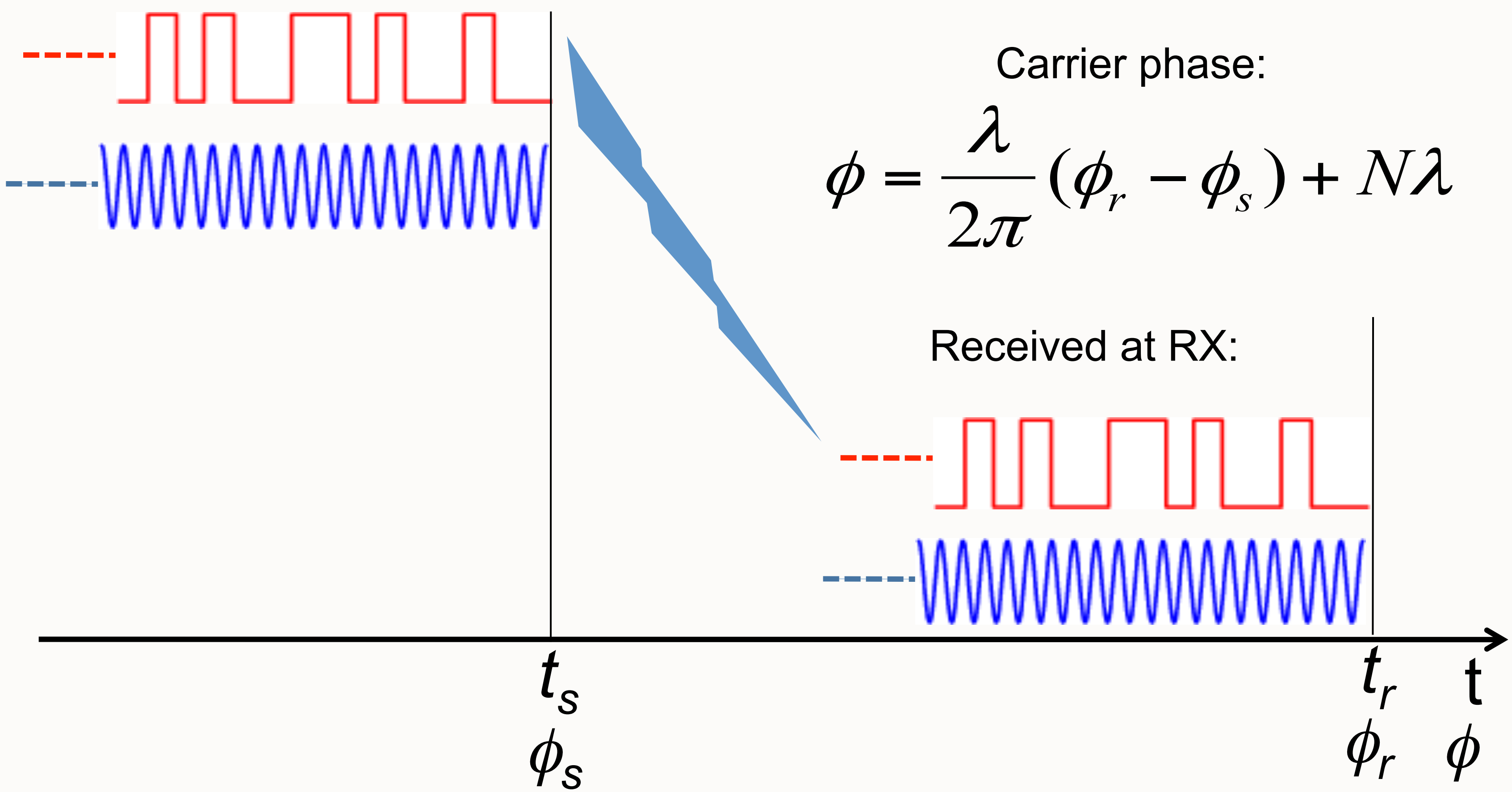
Pseudorange:

$$\rho = c(t_r - t_s)$$

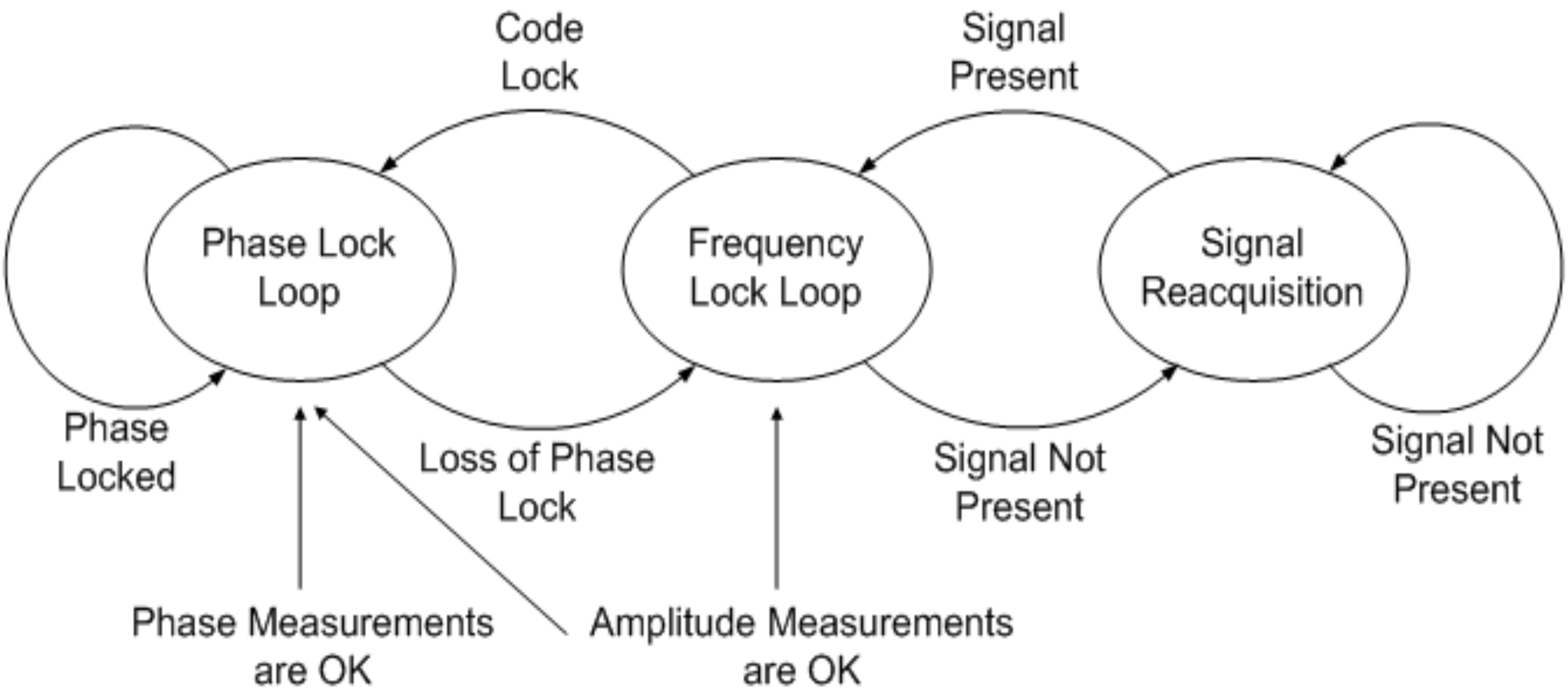
Carrier phase:

$$\phi = \frac{\lambda}{2\pi}(\phi_r - \phi_s) + N\lambda$$

Transmitted at SV:



Signal Tracking State Diagram



- Not necessarily implemented in all receivers

Ionospheric Range Correction

$$n \approx \left(1 - \frac{\omega_N^2}{\omega^2}\right)^{\frac{1}{2}} \approx 1 - \frac{\omega_N^2}{2\omega^2} \approx 1 - \frac{AN_e}{f^2}$$

$$\Delta R_{ion}(meters) = \frac{40.3}{f^2} \int_0^R N_e \, dr$$

$$TEC_{Si,Rj}(range) = \frac{f^2 \Delta R_{ion}^{ij}(meters)}{40.3} + \varepsilon_{range} + (SB_i + RB_j)$$

Constellations - Signals

GPS

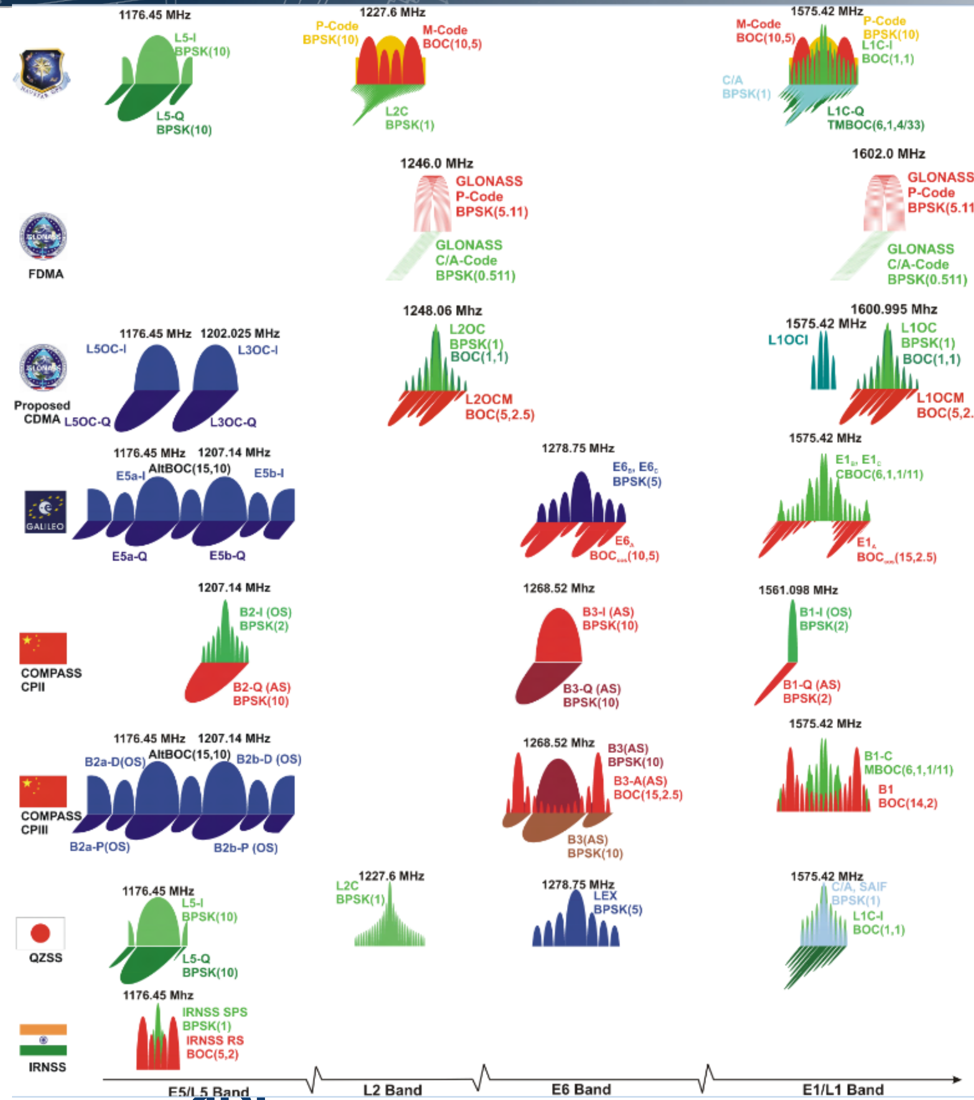
Glonass

Galileo

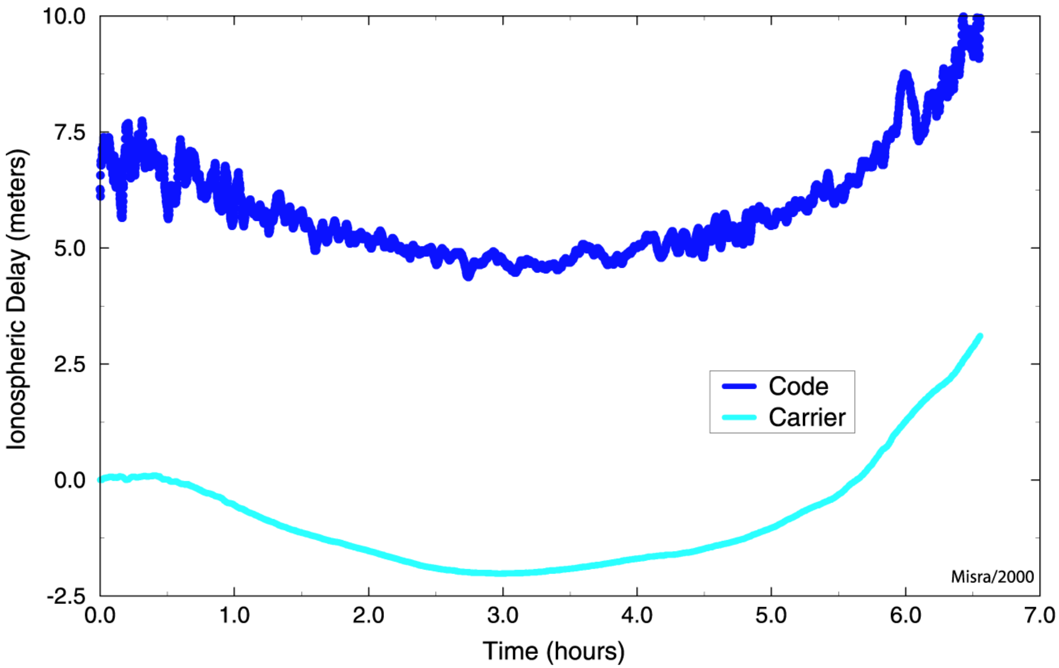
Compass

QZSS-Japan

IRNSS - India



Total Electron Content (TEC) Dual-Frequency Measurements: Processing Issues



Example: Open GNSS Processing Codes: GPSTK (ARL:UT)

<u>Processing Problem 1:</u>

- The pseudo-range TEC observation is noisy. Several to 10's of TECU (10^{16} el/m^2) The phase TEC is precise (~0.05 TECU) but there is an unknown phase ambiguity for each satellite-receiver pair

<u>Solution: Phase averaging</u>

- Average the phase (carrier) against the range (code) to resolve unknown phase ambiguity
- Implies need for continuous phase arcs over the time period --NO cycle slips

<u>Processing Problem 2:</u>

- Detect and fix phase cycle slips
- If cannot fix, then flag
- ***This must be done for any precise TEC investigation***
- Not easy – several different methods

<u>Processing Problem 3:</u>

- Satellite and Receiver Biases

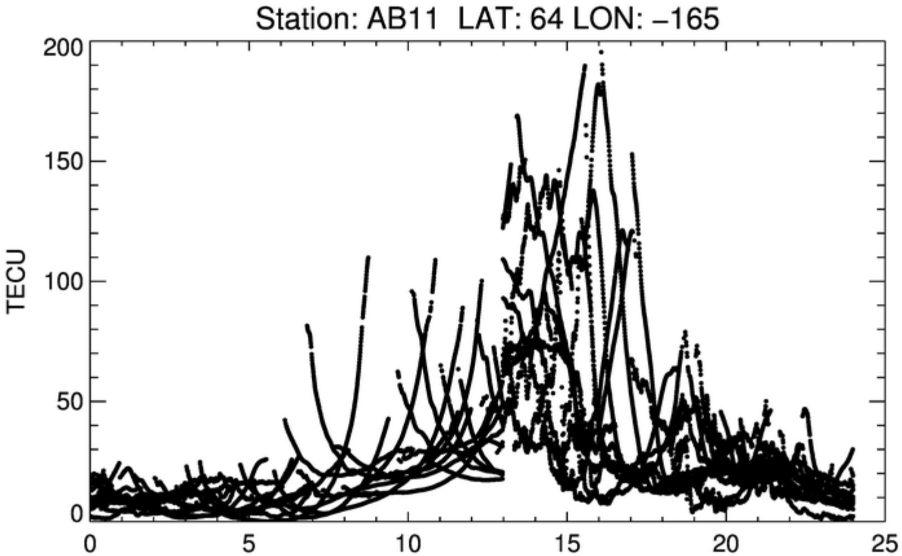
Problem 3: GPS Biases

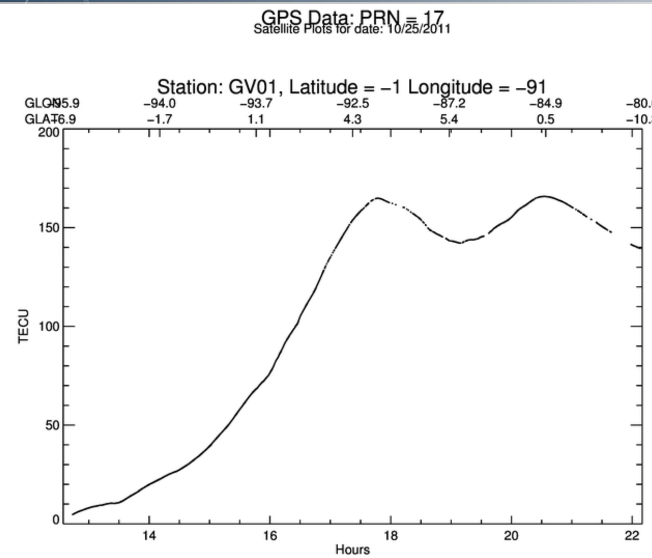
- GPS delay difference between two frequencies provides TEC
- Delay differences are also introduced by the satellite and receiver
- Satellite biases are determined by IGS community and are fairly stable
- Receiver biases are determined by individual user and most users estimate one bias over a 24 - hour period.

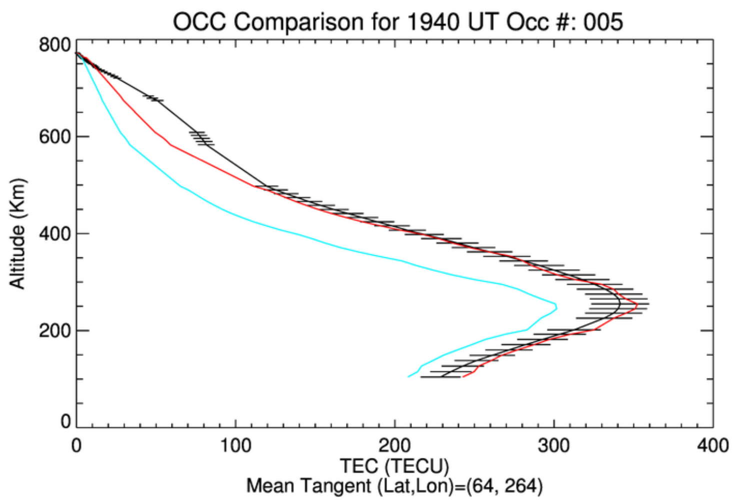
TEC Based Studies of the Ionosphere and Plasmasphere

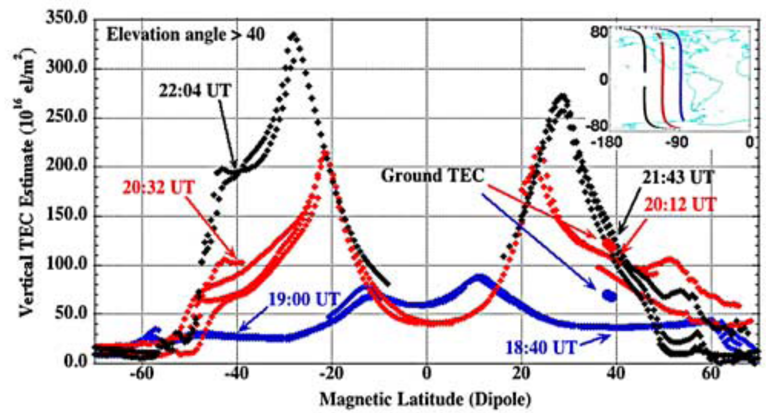
- Observations
  - Ground GPS slant TEC
  - Satellite based GPS radio occultations (RO) TEC
  - Satellite based GPS slant zenith (positive elevation angle) RO TEC
- Methods
  - Single receiver studies
  - Vertical TEC maps
  - GNSS tomographic imaging
  - Ionospheric data assimilation
  - Plasmaspheric imaging
  - Filter the TEC to look for waves and perturbations- Traveling ionospheric disturbances (TIDS)
- Scientific Studies
  - Global ionospheric storms
  - Polar cap patches
  - Storm enhanced density
  - MI coupling
  - Sudden stratospheric warming
  - TIDS
    - Tsunamis
    - MSTIDS
  - Equatorial plumes
  - E-region equatorial densities and conductances – equatorial spread-F
  - Auroral E-region densities and conductances – electrodynamics
  - Sharp density gradients during storms
  - Using TEC to estimate other state variables and drivers

TEC Observation Types

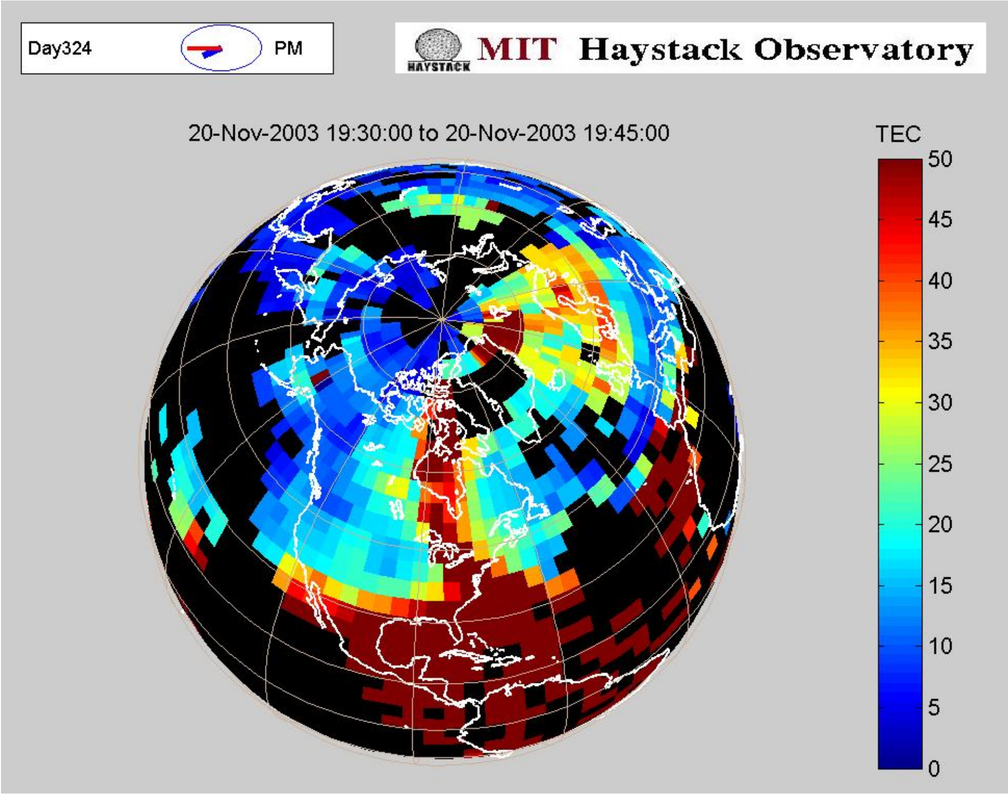




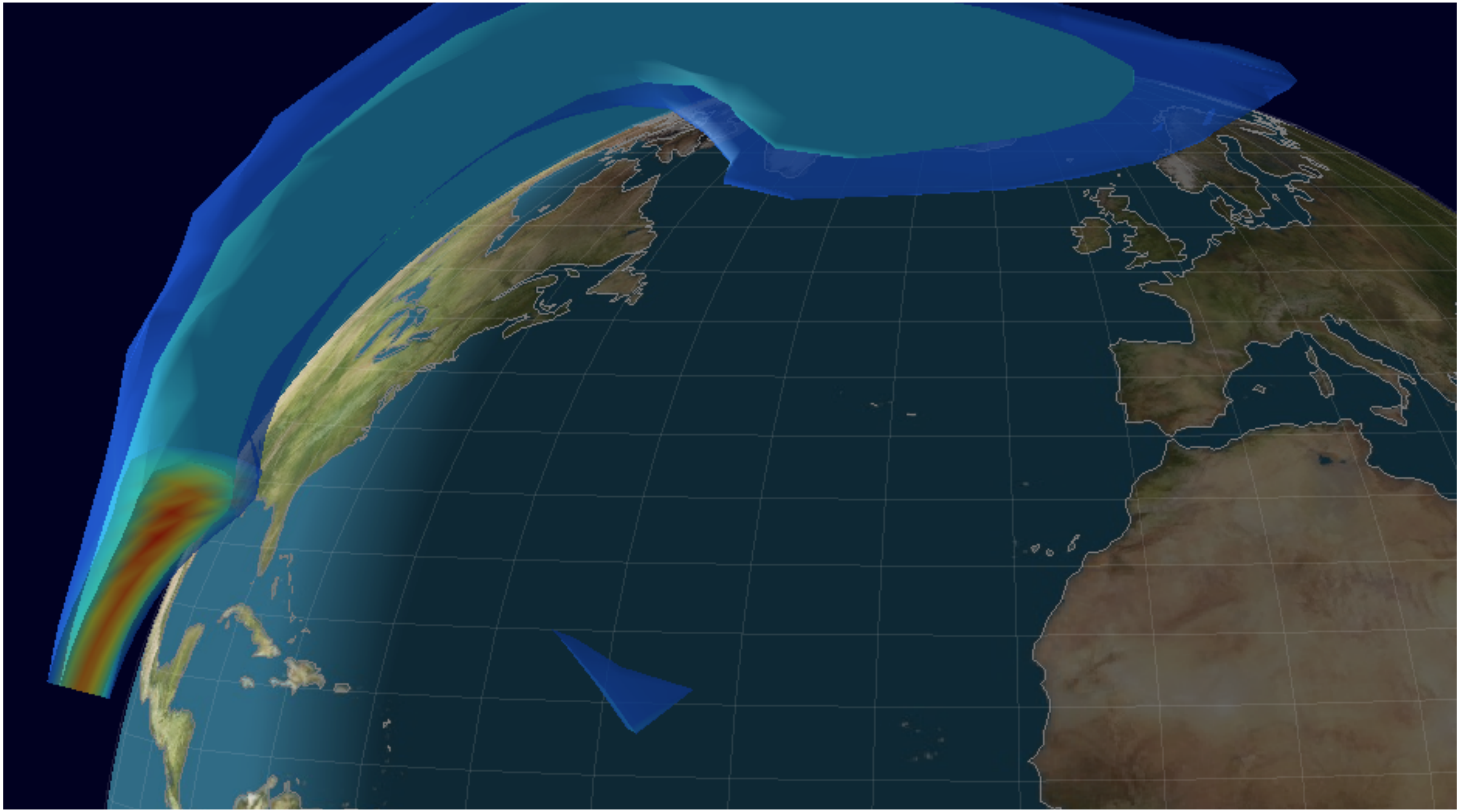




Vertical TEC Maps

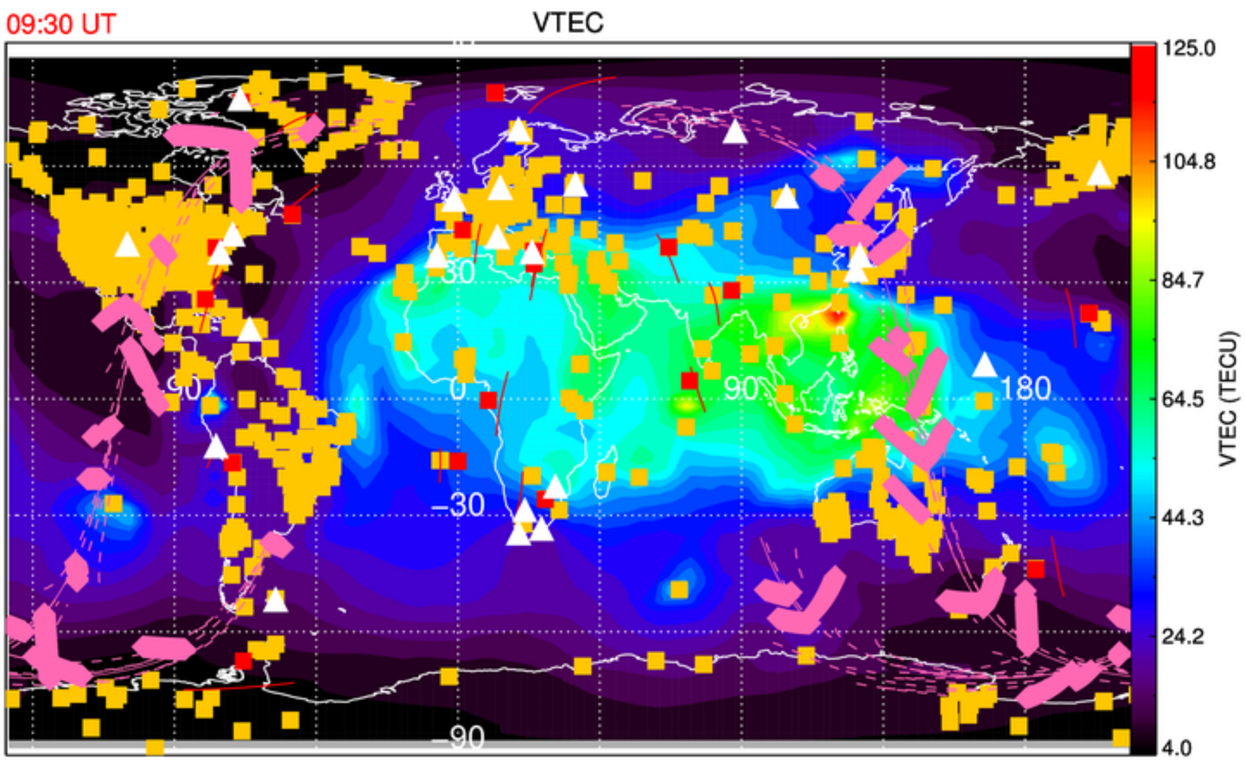


Tomographic Imaging

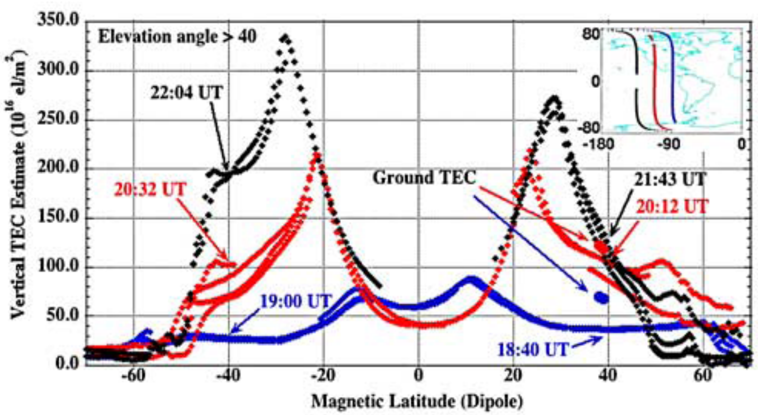


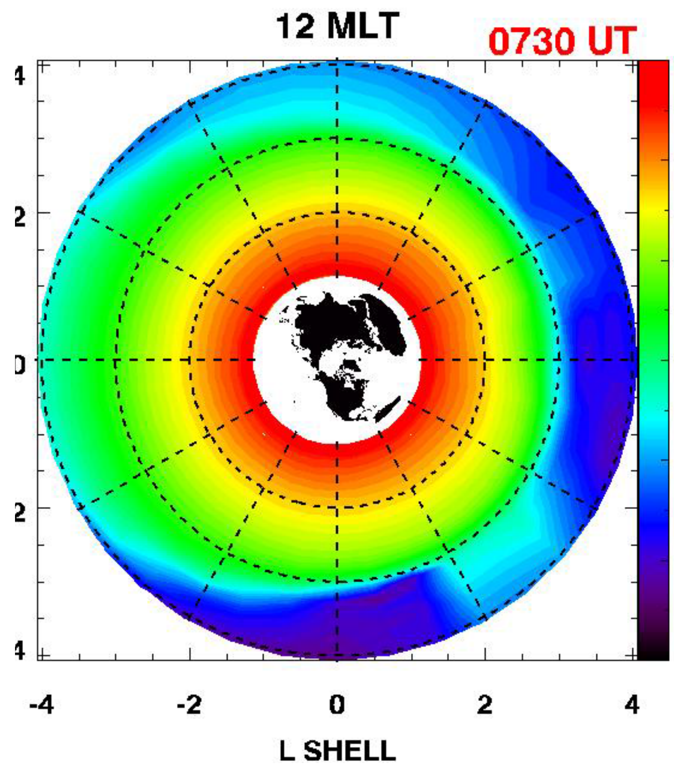
Data Assimilation: Coverage

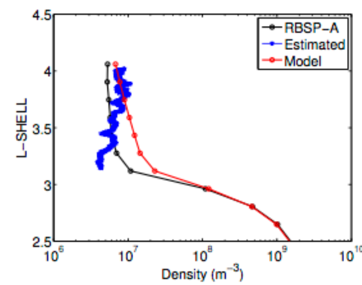
- Ionospheric Data Assimilation Four Dimensional (IDA4D)
- 2012 day 69
  - 1 hour of coverage
- Orange – GPS receiver sites
- Pink diamonds – GPS occulations
- Pink dashes GPS slant zenith TEC

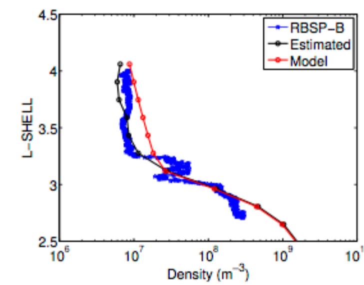


Plasmaspheric Imaging

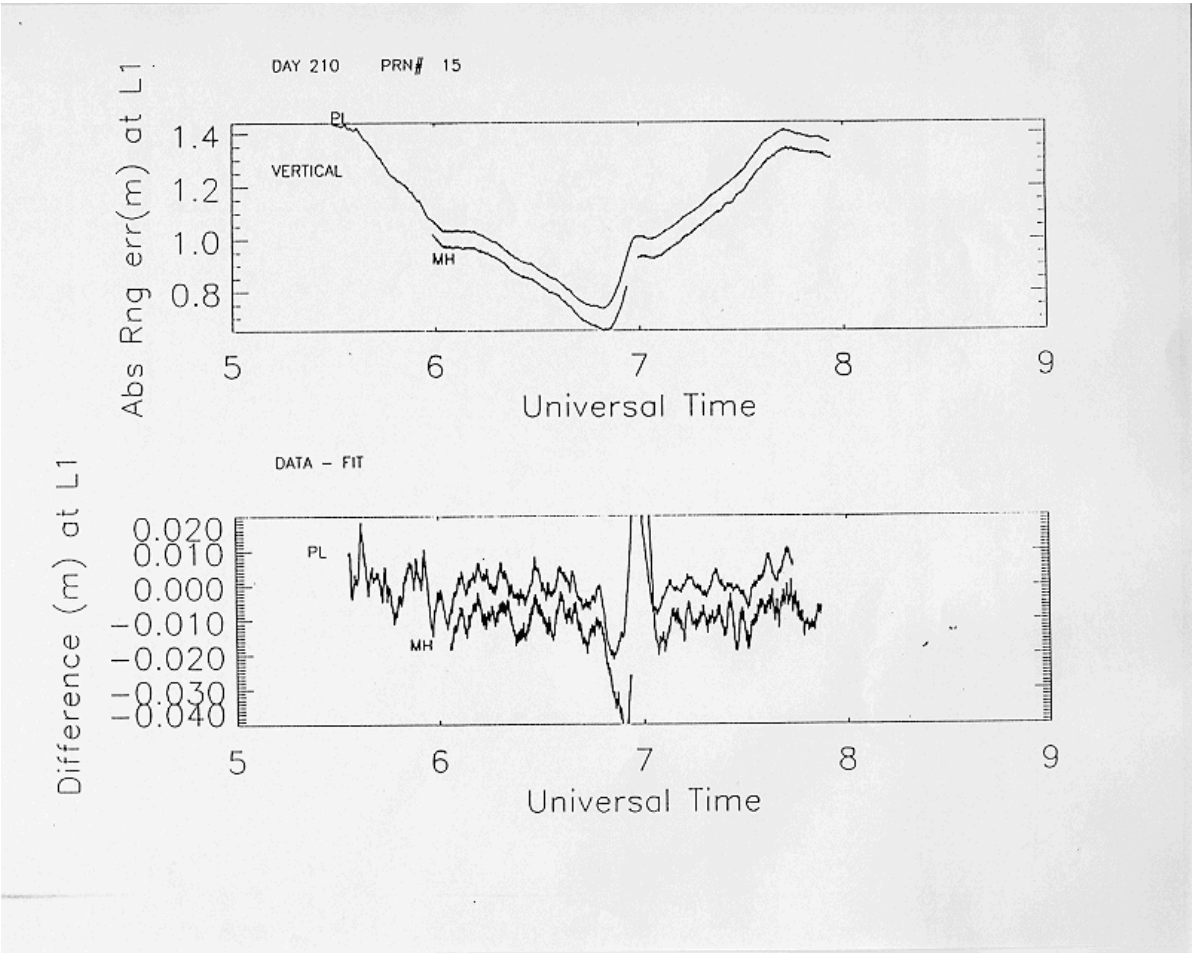








Traveling Ionospheric Disturbances (TIDS): Historical TID Data 29 July 1991



Two TI 4100 receivers separated ~ 25 km in MA P. Doherty and A. Coster

TIDS: Interferomety Imaging

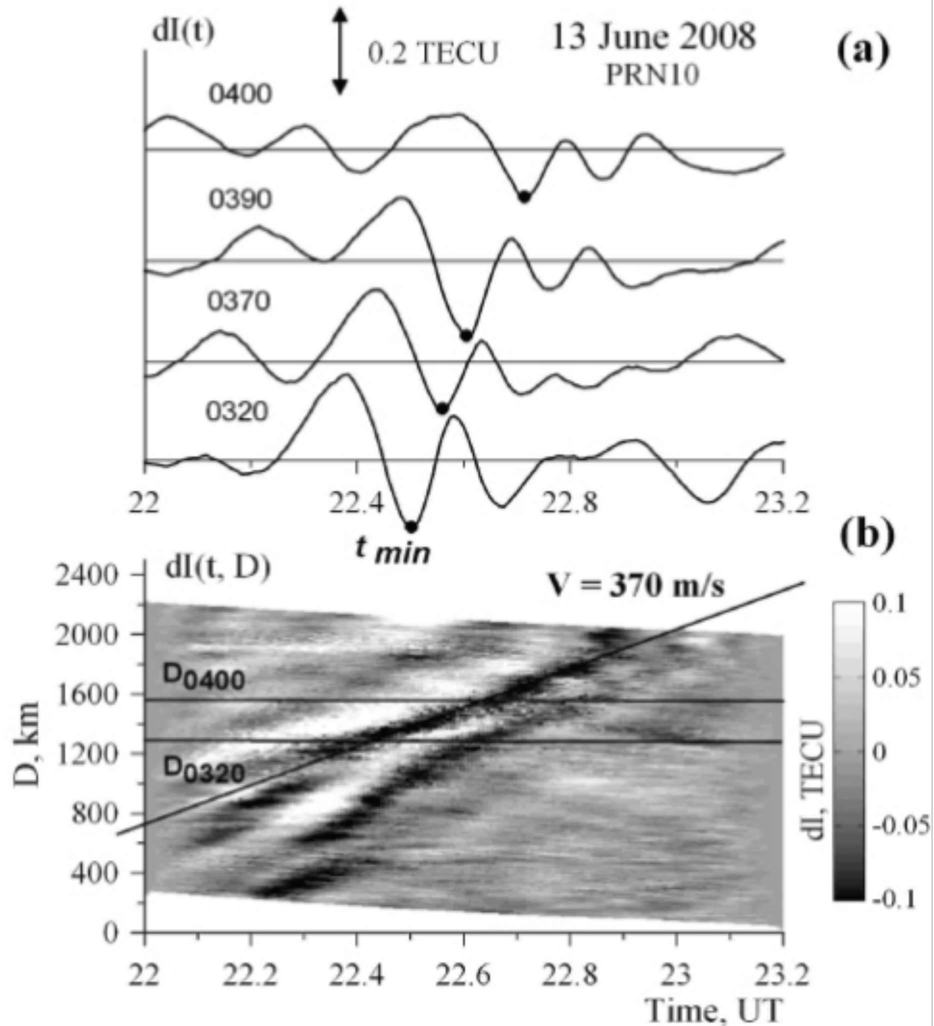
Afraimovich, 2009

4 GPS stations
Separated by ~ 100 km
Time delays between them
Model as 2D waves
Spatial wave numbers, period

IMPT: Filtering GPS TEC can
Lead to false waves due to satellite
Motion ~50-100 m/s

At low enough elevation angles static
Spatial gradients can look like waves

Need to use a high enough elevation
cutoff and perhaps background data
assimilation or tomographic imaging to
understand the larger scales



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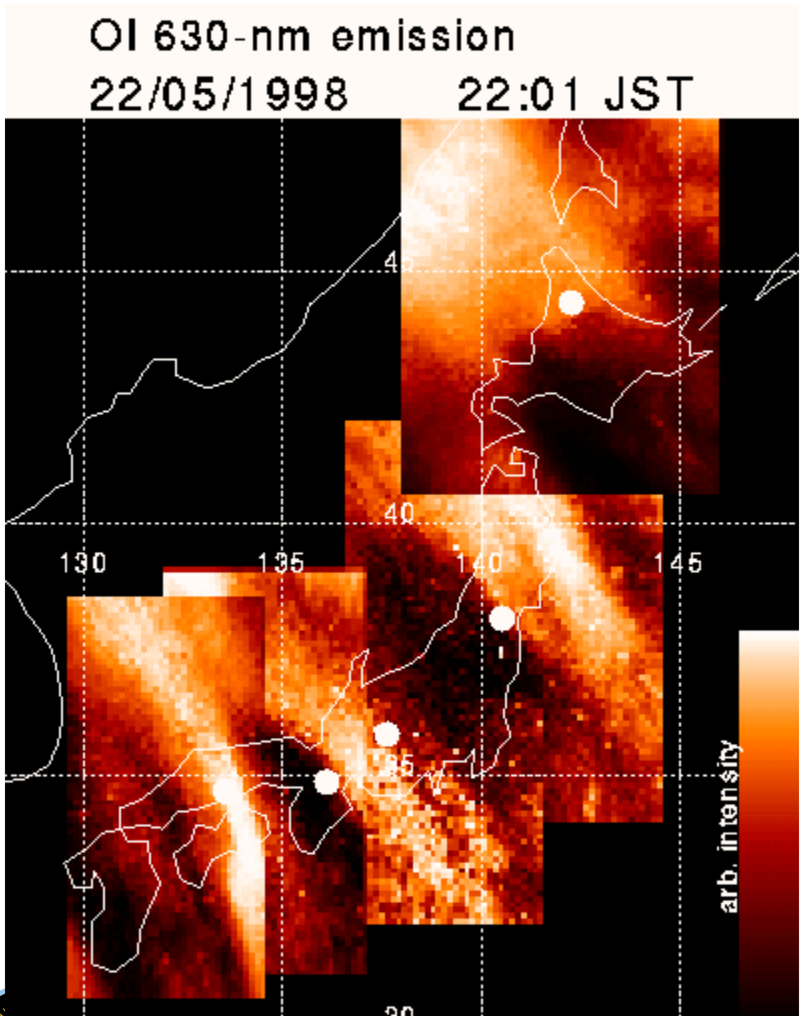
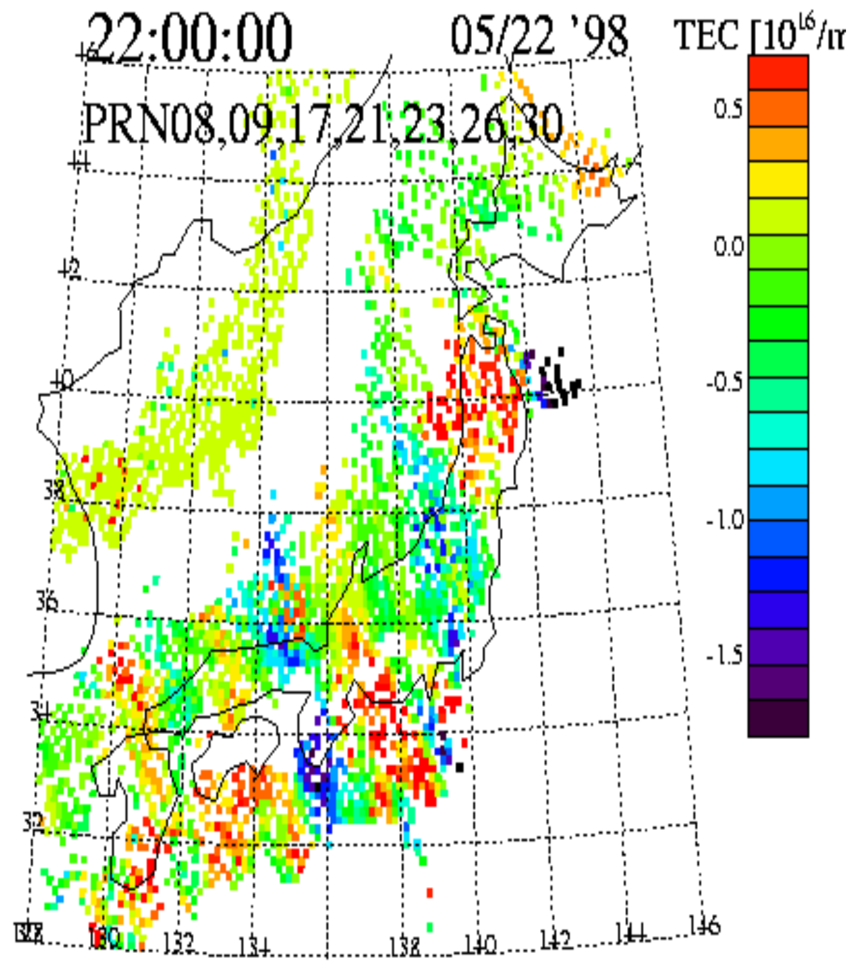
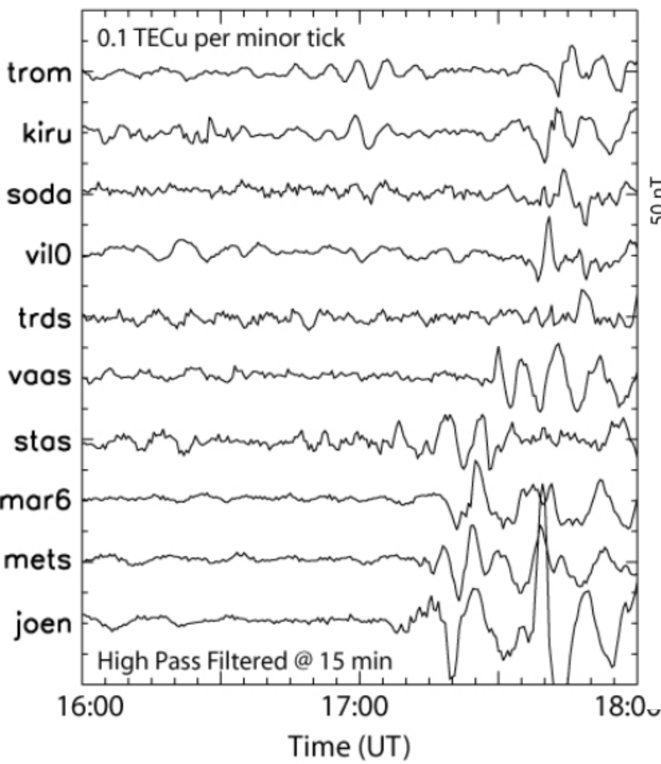
Nighttime MSTID Observations (TEC, Airglow)

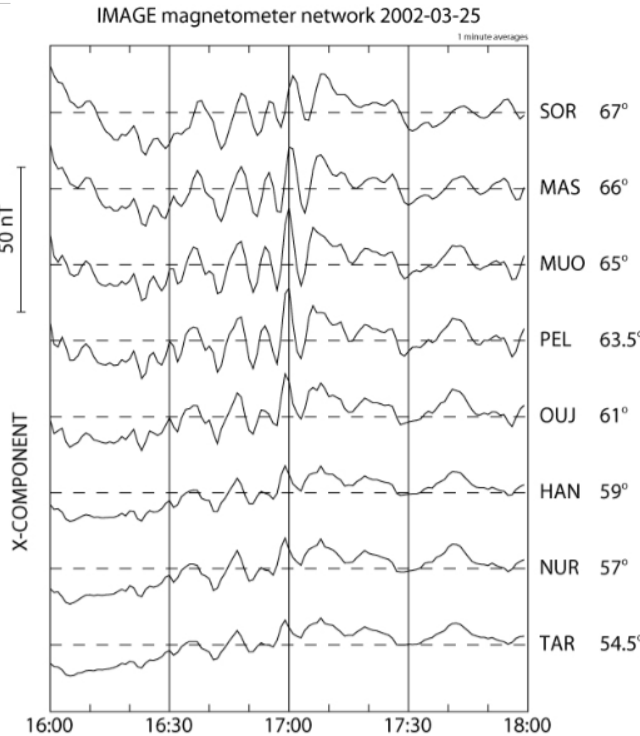
[*Saito et al.*, 2001]

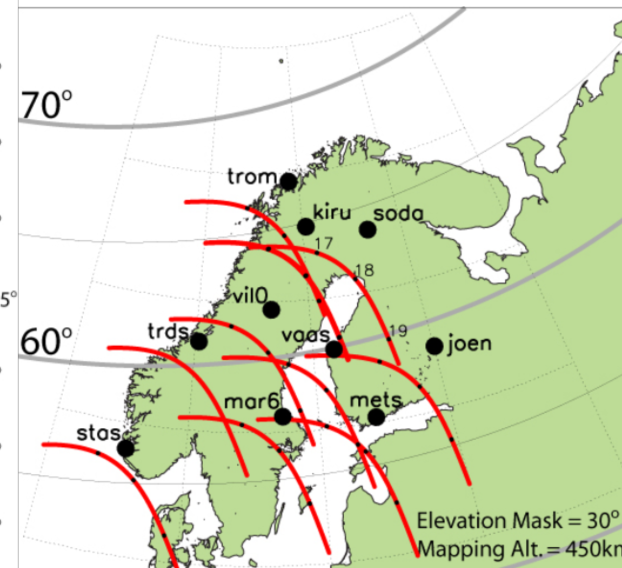




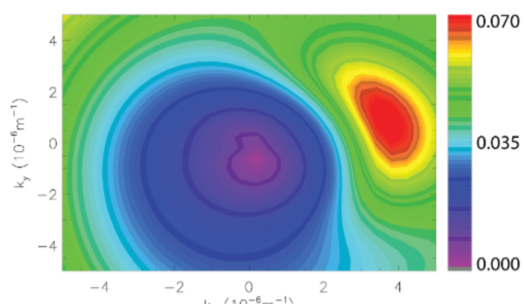
GPS ULF Waves: D. Murr, M. Engebretson, V. Pilipenko Augsburg College, USA







Several authors have used increasingly sophisticated models of the ULF wave fields in the ionosphere to explain and predict the impact on GPS signals (e.g., *Poole and Sutcliffe*, 1987; *Pilipenko and Fedorov*, 1995; *Waters and Cox*, 2009)



Percent change in TEC from a 15mHz ULF wave with ULF wave mix of 80% shear Alfven mode at 1000 km, as a function of the ULF wave spatial scale size. (from Figure 5 of *Waters and Cox*, 2009)

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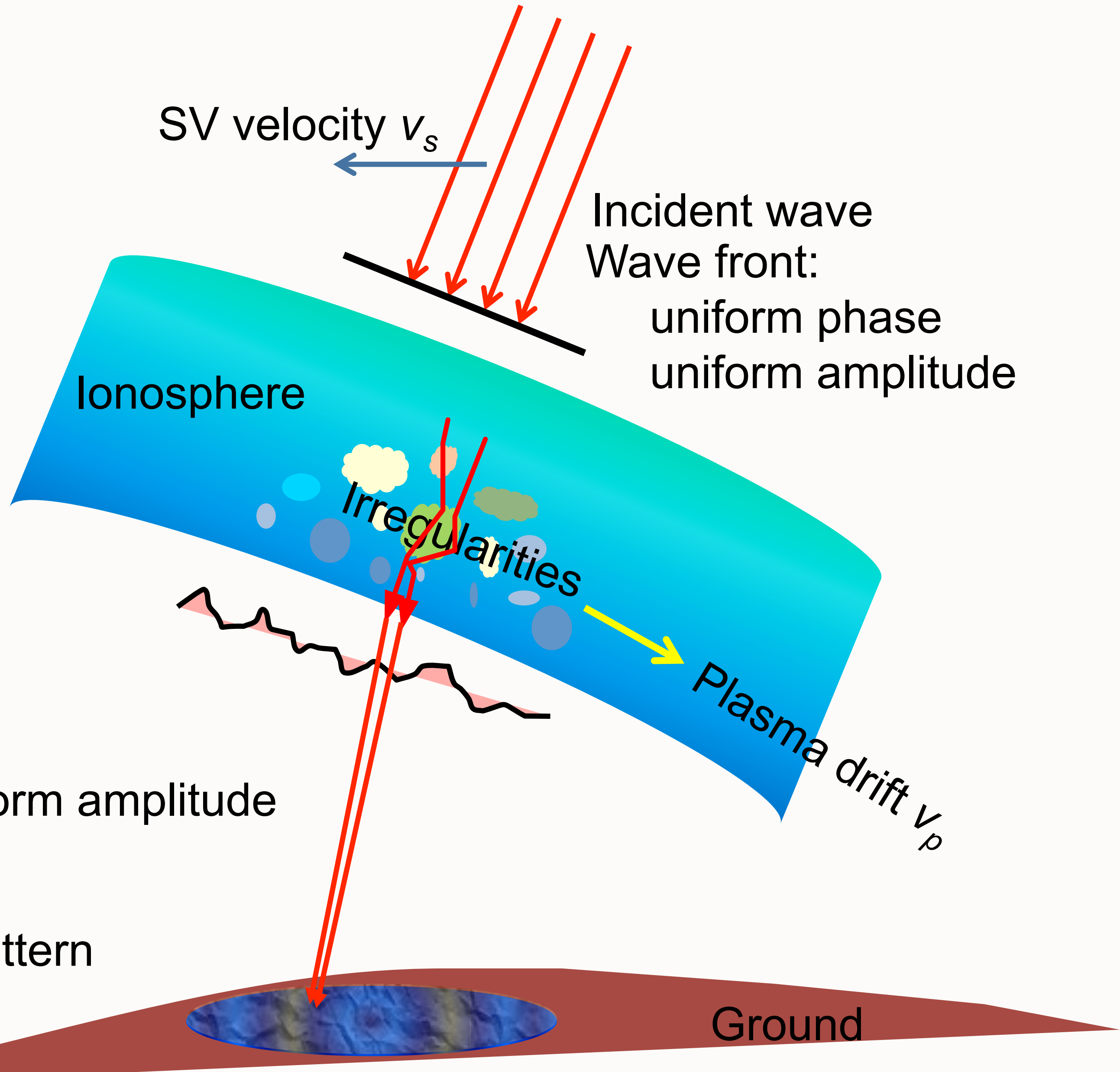
NSS

Scintillation Based Studies of the Ionosphere

- Observations
  - Ground GPS statistical parameters of phase (σ_ϕ) and amplitude (S_4)
  - Ground GPS high-rate (50-100 Hz) observations of phase and amplitude
  - Satellite based GPS radio occultations (RO) statistical and high rate observations
- Methods
  - All high rate observations (and statistical parameters derived from them) must be carefully filtered
  - Must have continuous phase over time period being filtered
  - Filter out satellite motion effect and low frequency refraction
  - High pass filtering
  - For phase scintillations need to have a low noise clock (oven controlled crystal oscillators OXCO)
  - Or need to find a satellite that is not scintillating and subtract it off (remove common receiver clock errors)
- Scientific Studies
  - Equatorial Spread F / Bubbles
  - Occurrence statistics
  - Geographical location, intensity
  - Duration
  - Physics of irregularities that cause scintillations
- High latitudes
  - Relation to auroral processes all sky imagers
  - MI coupling
  - Patches / Structuring
  - Understanding of physical processes the produce scintillations

Space Weather - Scintillation

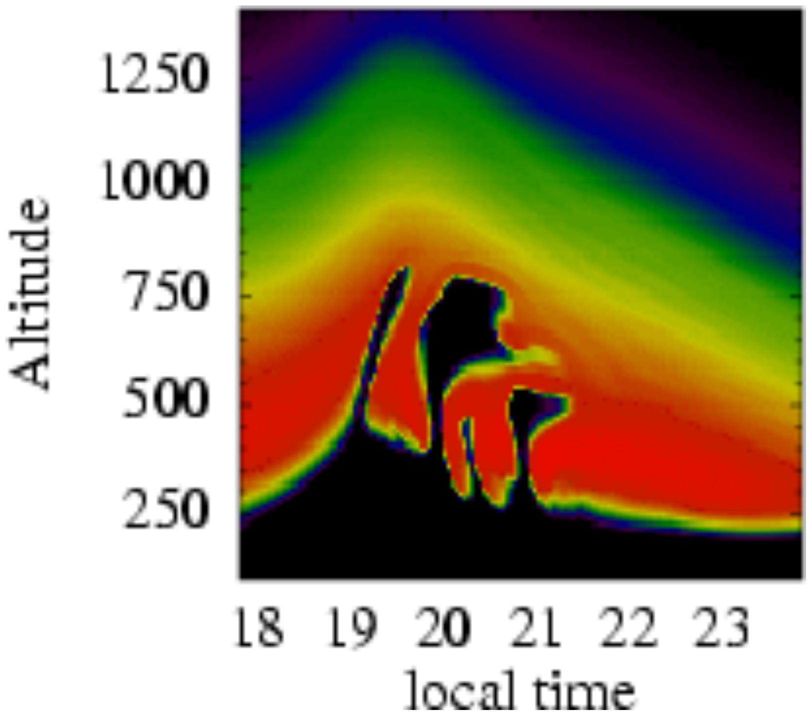


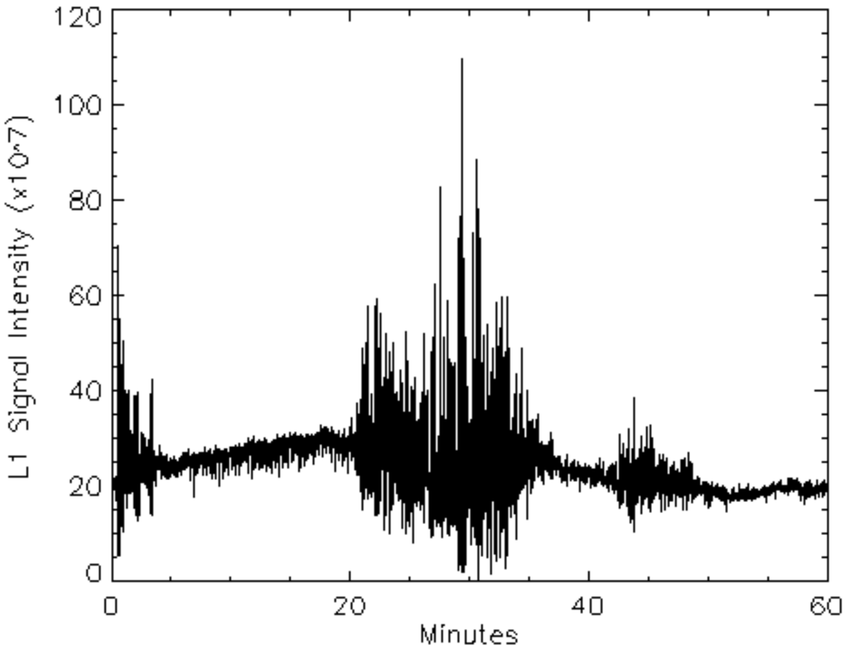
Wave emerging from below irregularities:

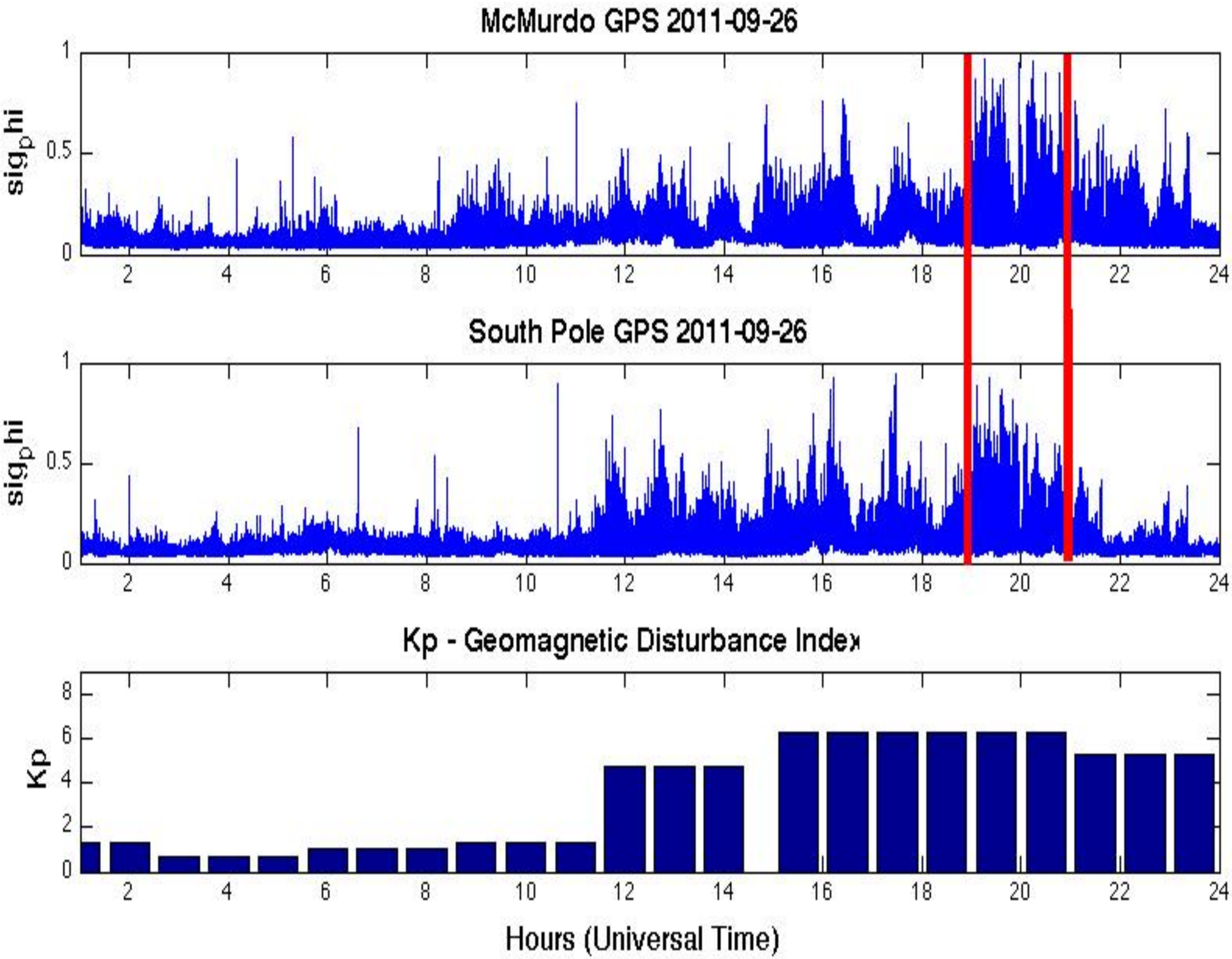
- non-uniform phase
- quasi-uniform/non-uniform amplitude

Diffraction/interference pattern

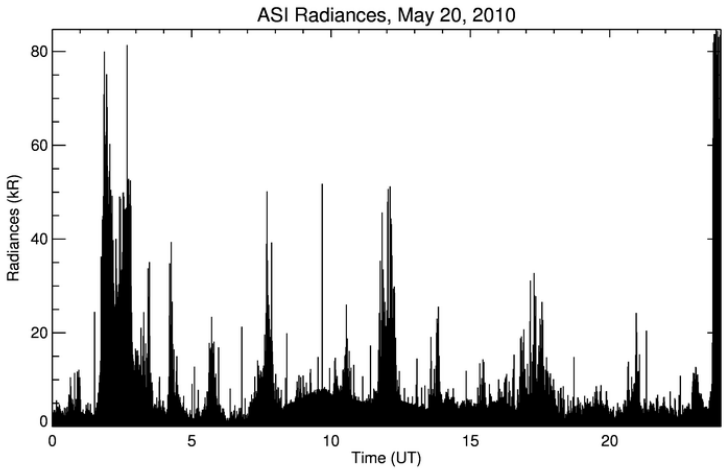
Space Weather - Scintillation

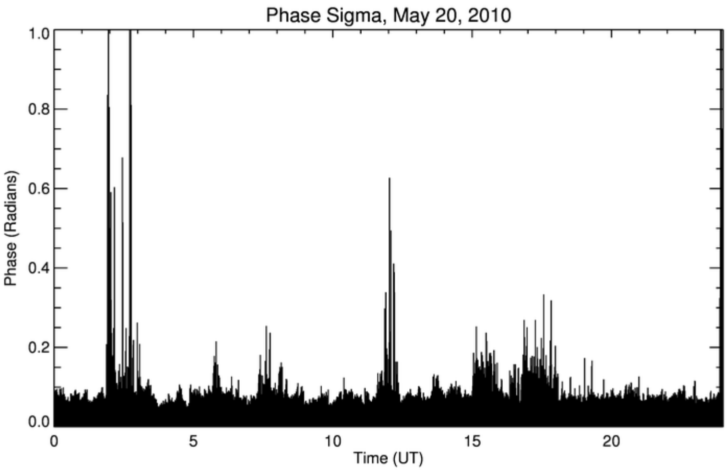




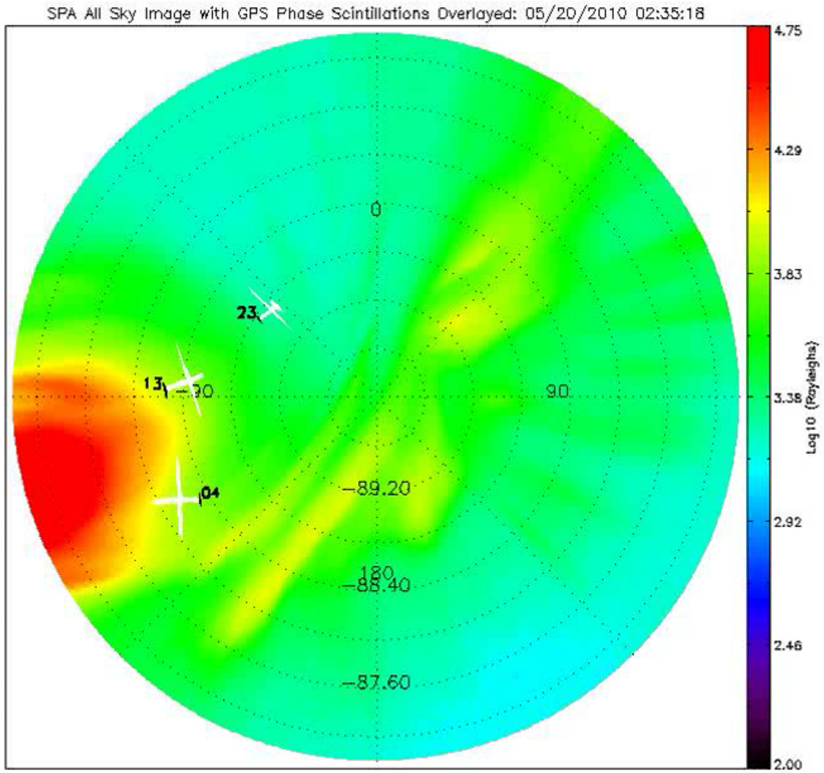

McMurdo GPS 2011-09-26
sig_p hi
1
0.5
0
2 4 6 8 10 12 14 16 18 20 22 24
South Pole GPS 2011-09-26
sig_p hi
1
0.5
0
2 4 6 8 10 12 14 16 18 20 22 24
Kp - Geomagnetic Disturbance Index
Kp
8
6
4
2
0
2 4 6 8 10 12 14 16 18 20 22 24
Hours (Universal Time)

Study of GPS phase scintillations and ASI May 20, 2010

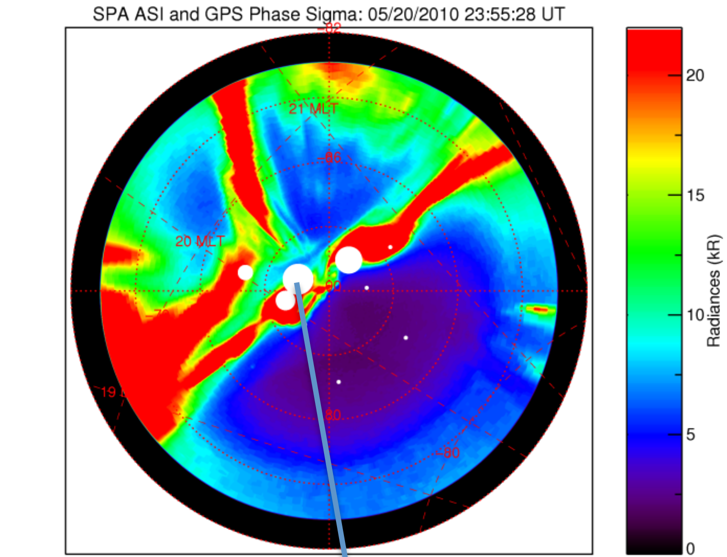


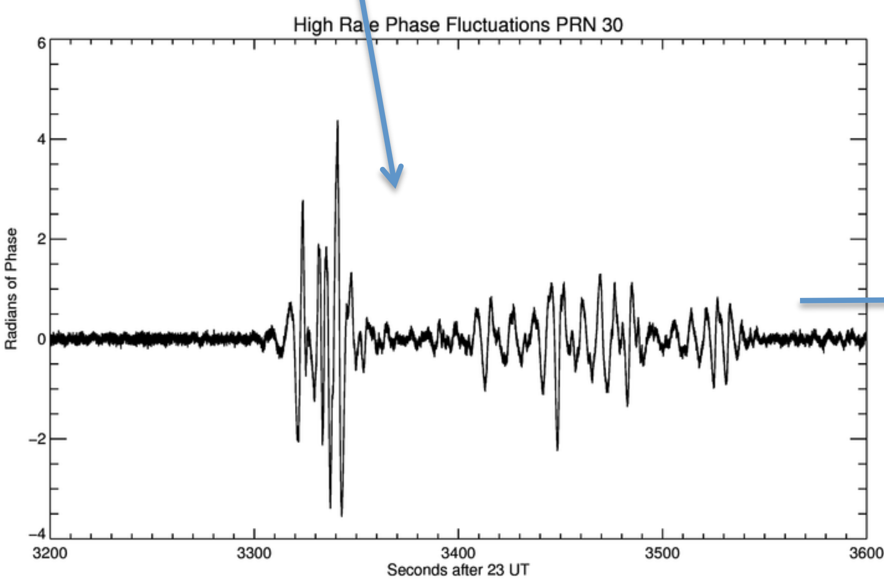


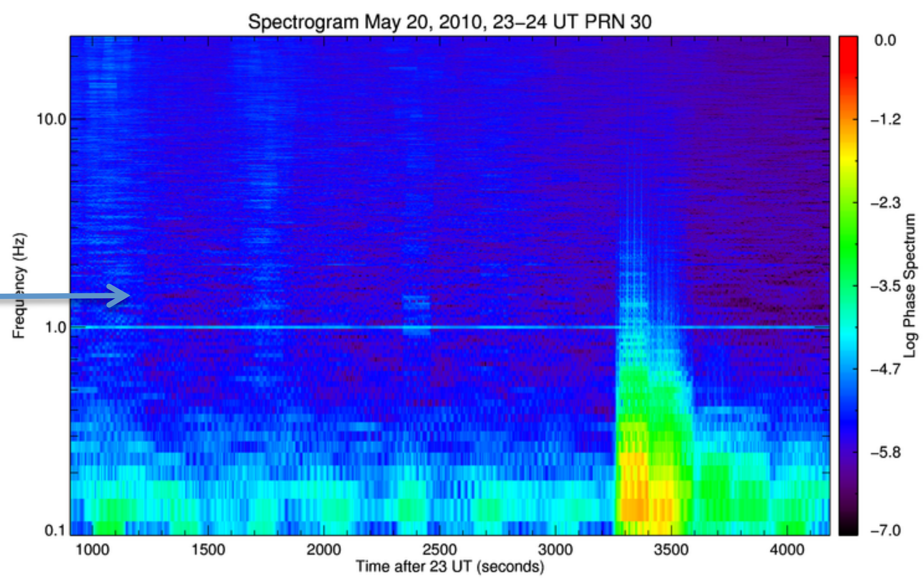
ASI and phase scintillations 02:35 – 02:50 May 20, 2010



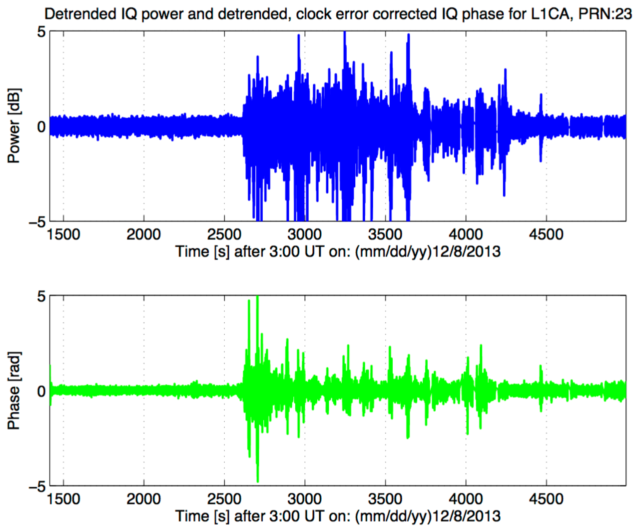
Detailed Comparison of PRN 30 Fluctuations at ~ 24 UT

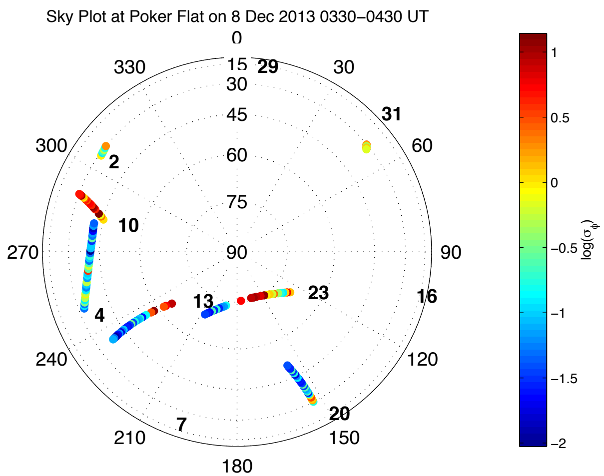


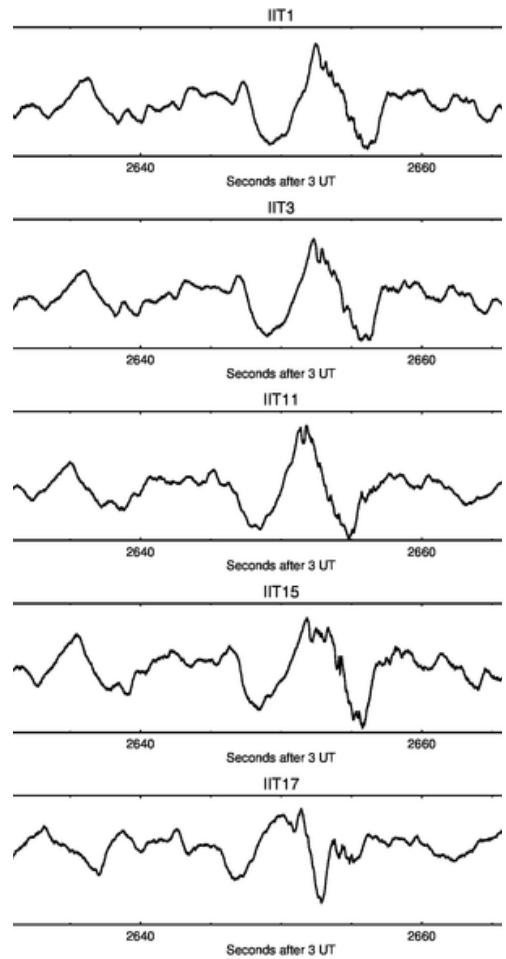




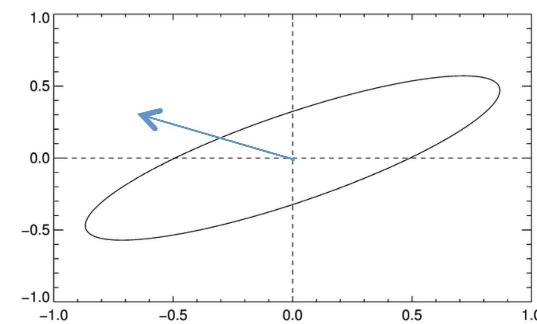
Poker Array: 7 CASES GPS Scintillation Receivers: December 8, 2013: 2620-2680 seconds after 3 UT







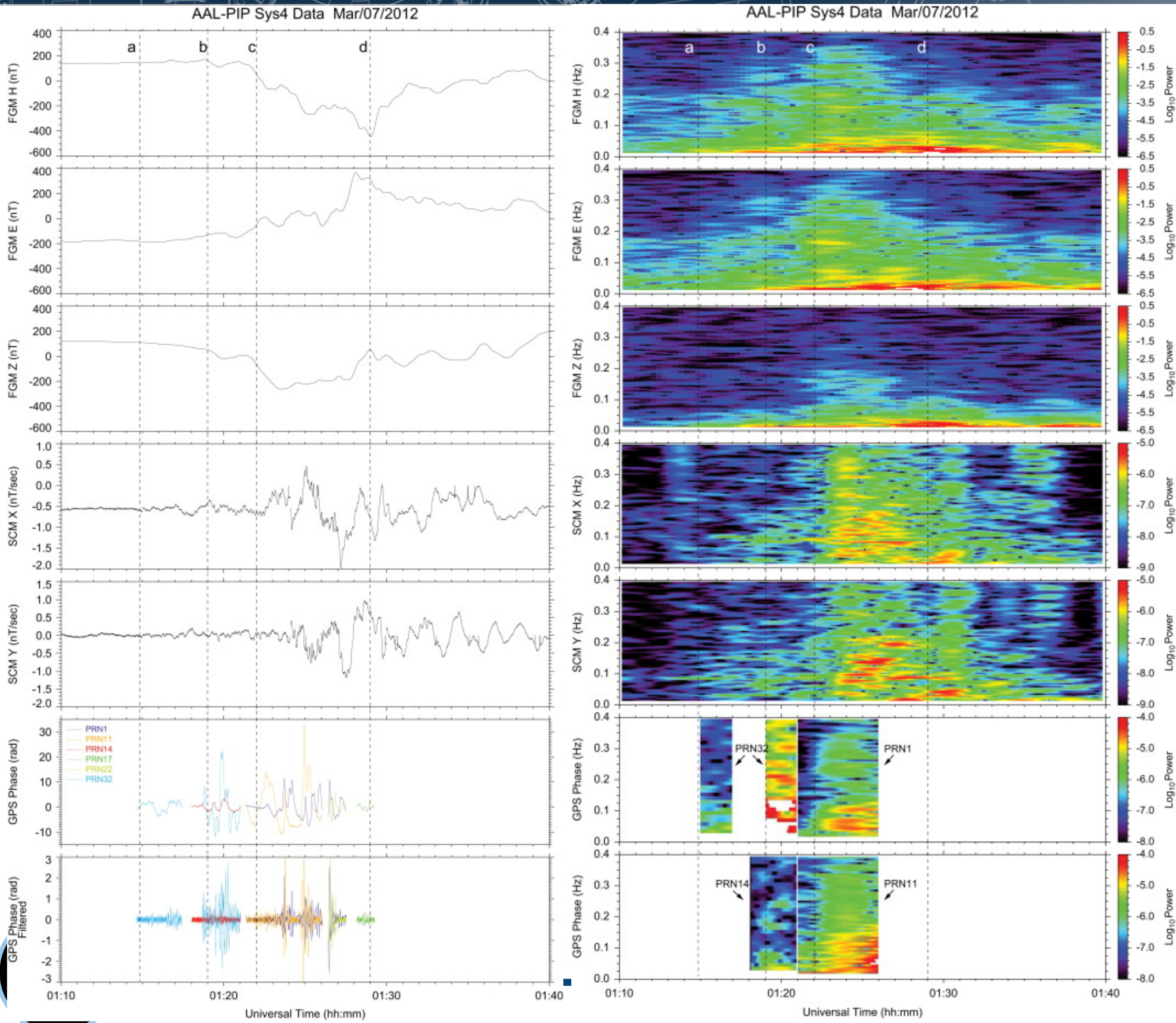
- Velocity Estimation (on ground geographic East-North
  - Magnitude = 1,184 m/s
  - Direction = 160 degrees
- Ellipse of ground diffraction pattern
  - Ratio of major / minor axis: 3.3
  - Angle of ellipse from East: 32



Basu et al., Interplanetary magnetic field control of drifts and anisotropy of high-latitude irregularities, *Radio Sci.*, V 26 (4), 1991

Ionospheric irregularities during a substorm event: Observations of ULF pulsations and GPS scintillations

H. Kim, C.R.Clauer, K.Deshpande, M.R.Lessard, A.T.Weatherwax, G.S.Bust, G. Crowley, T.E.Humphreys



Summary

- GNSS observations can be used in a variety of ways to probe the ionosphere and plasmasphere
- Both ground-based and space-based receivers are useful
- Processing the raw GPS signals to either TEC or Scintillation observations is not trivial
  - Need to use good established techniques
  - Be careful, check for quality
  - Are results sensible
- GNSS satellite and receiver biases are still an issue
  - Magic Number: Get absolute Vertical TEC < 1 TECU
- Biggest issue for GNSS tomography or data assimilation is lack of satellite coverage
  - Typical receiver only sees 10-12
  - All receivers in a region ~ 100-200 km wide see the same satellites
  - Lack of high latitude coverage
  - New constellations will help
  - New methods / receivers / arrays that can obtain observations from all constellations
- Still a lot of “undiscovered country”
  - Scientific uses
  - Combining with other IT data sources
  - Dense arrays – what is the best way to analyze the data