New Methods of Characterizing Traveling Ionospheric Disturbances using GNSS Measurements

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Outline

- Hooke TID Model
  - Hooke TEC analytical derivation
  - Analysis of satellite motion distortion
- Issues with standard GNSS TID estimation methods
- New spectral methods
  - Simulation
  - Actual Data
- General sensitivity of results to satellite motion
- Summary

Derivation of Hooke AGW TID Model

- Electron density TID due to AGW
- Ad-hoc saturation and decay with altitude
- Ad-hoc horizontal windowing function
- Vertical wavelength obtained from dispersion relation
- Parameters required: kx,ky, f, ub at reference altitude, phase, vertical neutral scale height

$$\delta N(z \leq z_T) = Re\left\{\left(\frac{u_b \sin(I)}{\omega}\right)\frac{N(z)}{L_N(z)}\, e^{\frac{(z-z_*)}{2H}} e^{i\left[\omega(t-t_0)-\vec{k}\cdot\vec{r}+\frac{\pi}{2}+\phi_0-\Phi_N(z)\right]}\right\} W_S(\vec{\rho},t)$$

$$\delta N(z > z_T) = Re\left\{\left(\frac{u_b \sin(I)}{\omega}\right)\frac{N(z)}{L_N(z)}\, e^{\frac{-(z-z_T)}{2H_T}} e^{i\left[\omega(t-t_0)-\vec{k}\cdot\vec{r}+\frac{\pi}{2}+\phi_0-\Phi_N(z)\right]}\right\} W_S(\vec{\rho},t)$$

$$\frac{1}{L_N(z)} = \left[\left(\frac{1}{H_N(z)}+\frac{1}{2H}\right)^2 + \frac{k_{br}^2}{\sin^2(I)}\right]^{\frac{1}{2}}$$

$$\Phi_N(z) = \tan^{-1}\left[\frac{k_{br}}{sin(I)}\left(\frac{1}{H_N(z)}+\frac{1}{2H}\right)^{-1}\right]$$

Derivation of Hooke TEC – with satellite distortion

$$\delta T(x_r, y_r, \theta_r(t), \alpha_r(t), t) = \int ds\,\delta N$$

$$x = x_r + \cot(\theta_r)\sin(\alpha_r)\,z$$
$$y = y_r + \cot(\theta_r)\cos(\alpha_r)z$$
$$z = \sin(\theta_r)\,S$$

Slant integral of TID gives perturbed TEC:

- Approximate geometry as local Cartesian coordinates at “center of wave
- Use location of station, elevation and azimuth to go from slant to vertical integration
- Note: ignore horizontal gradients in background density

$$\delta T(x_r, y_r, \theta_r(t), \alpha_r(t), t) = \left(\frac{u_b \sin(I)}{\omega}\right) Re\left[\langle N(t)\rangle e^{i\left(\omega(t-t_0)-k_x x_r - k_y y_r + \frac{\pi}{2} - \phi_0\right)}\right] W_S(\vec{\rho}, t)$$

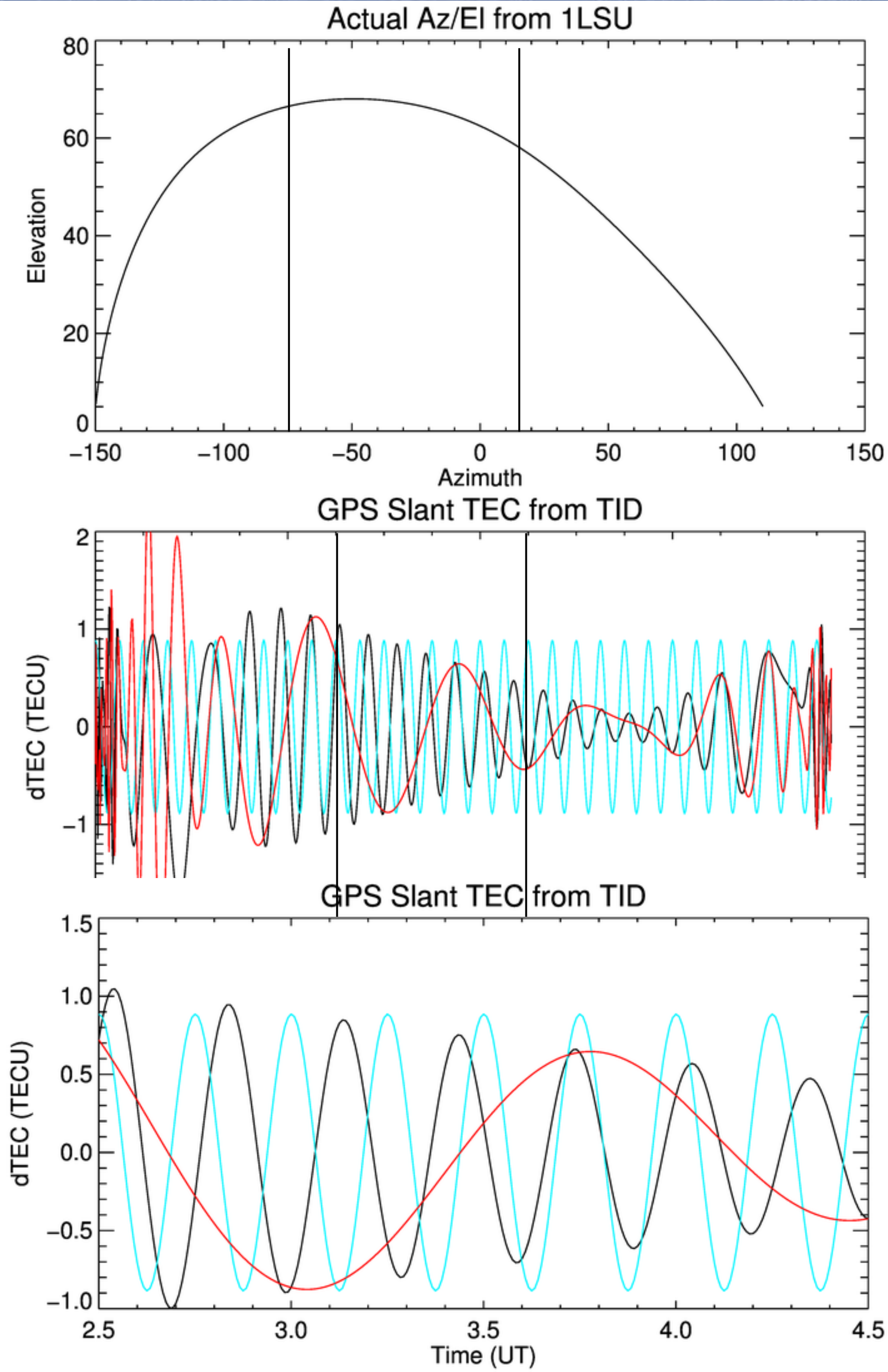
$$\langle N\rangle = \frac{1}{\sin(\theta_r)}\int dz \frac{N(z)}{L_N(z)} E(z) e^{-i\{[(k_x \sin(\alpha_r) + k_y \cos(\alpha_r))\cot(\theta_r) + k_z]z + \Phi_N(z)\}}$$

$$E(z) = e^{\frac{(z-z_*)}{2H}}(z \le z_T) = e^{\frac{-(z-z_T)}{2H}}(z > z_T)$$

- Effect of satellite motion
- Multiplied by altitude
- Thus altitude distribution very important

- No simple thin shell

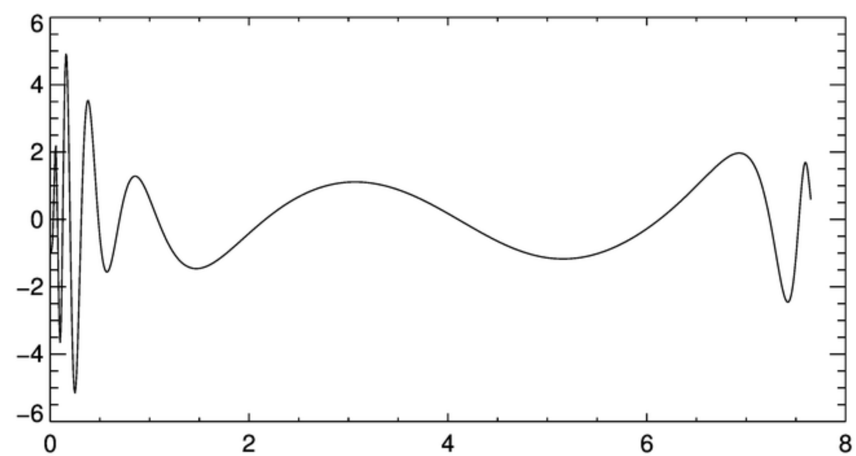
Modeled TEC from TID – impact of satellite motion



GPS Station 1LSU

- Actual elevations and azimuths from one PRN over 6 hours
- Ground station located at 300km east from central location and 200km north from central location
- Blue curves are what a ground station would see from fixed non moving satellite.
- Red curve is the motion only due to the satellite
- Black curve is what the GPS receiver would see.

Static Bkgd w/ 1000 km horizontal scales



Previous Methods of Estimating TIDS from GNSS

- **Closely clustered sets of receivers**
- **Receiver distances < wavelength of TID**
  - **Don't know wavelengths ahead of time, cannot always guarantee**
- **Need to choose ionospheric pierce point altitude**
  - **Separation between receivers**
  - **Velocity of pierce point**
  - **Period very sensitive to pierce point altitude and IPP velocity**
- **Fundamental problem is TIDs are not thin shells.**
  - **Extended in altitude over 100+ km**
  - **Thus, velocity, period very sensitive to altitude effects**
  - **Cannot use one shell**
  - **Particularly case when speeds are close to GPS IPP speeds**

A new technique: Spectral Methods

- Use as many GPS receivers as possible over as many different possible baselines pairs
  - Range from very small separation to largest as possible separation
  - Still need high elevation angles
- Cross correlation estimator
  - For each PRN take all baselines between pairs of receivers. For example, 60 receivers gives 1770 baselines
  - Compute cross correlations for each baseline pair

$$C_{i,j}\left(\tau,\Delta\vec{\rho}_{i,j}\right) \cong \cos\left(\left(\omega-\vec{k}\cdot\vec{v}_j\right)\tau-\vec{k}\cdot\Delta\vec{\rho}_{i,j}\right)$$

- Spectrum estimator
  - Take the zero time delay – this avoids any reference to frequency or velocity since:
- Then the Spectrum is Fourier Transform of the spatial correlation (the above with zero time delay)
- When we have 100s – 1000s of correlation pairs, we can approximate that integral as a sum over all correlations:

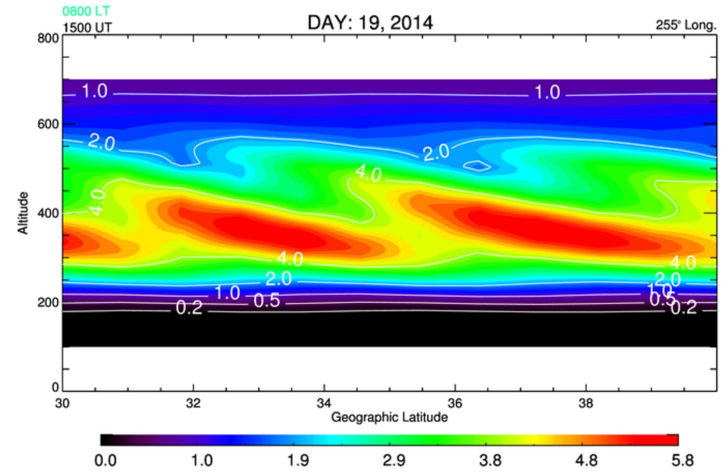
$$S\left(k_x,k_y\right) \approx \sum_n C\left(\Delta\vec{\rho}_n\right)e^{i\left(\vec{k}\cdot\Delta\vec{\rho}_n\right)}$$

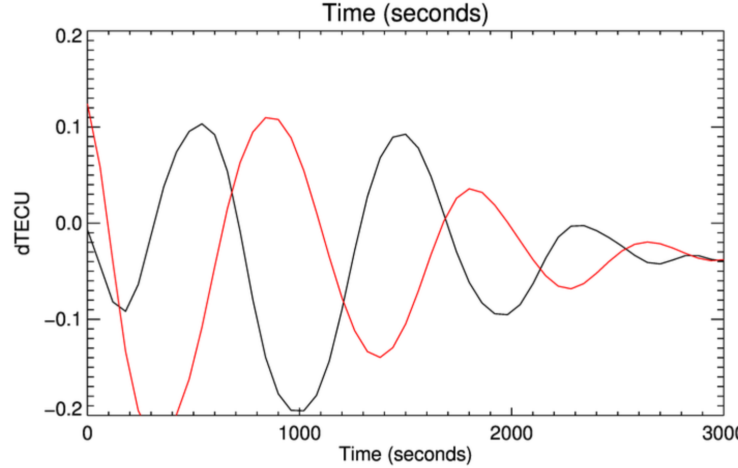
- Since the correlation is hopefully almost a pure single mode (or maybe just a few), the spectrum should be ~ a delta function at the mode.
- Thus, we can look for maxima in the spectrum
- There are better methods for calculating spectrum than a FFT sum – we are looking into

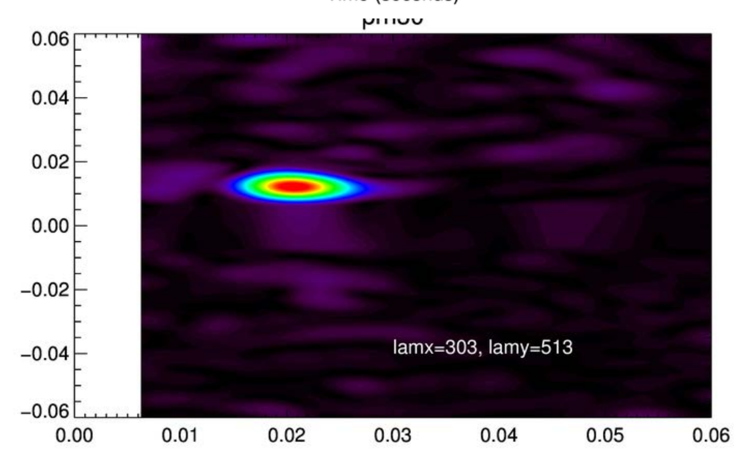
GNSS TID Estimator

- New Mexico Region
- All GPS stations within 500 km
- Chapman background profile
- Hooke TID
- Actual integration along slant paths
  - Real ephemeris for the day
  - 1 minute time intervals
  - 2 hours of simulation

- Results
  - Ran this case for a TID simulation of :
    - 300 km in longitude 500 km in latitude, 15 minute period
    - 75 km scale height 10 m/s at 120 km altitude
    - Saturated it at ~350 km
    - So a large easy to see wave.
- Upper right – example of simulated TID
- middle right – example of filtered TEC from two receivers
- Figure on lower right is spectra for PRN 30



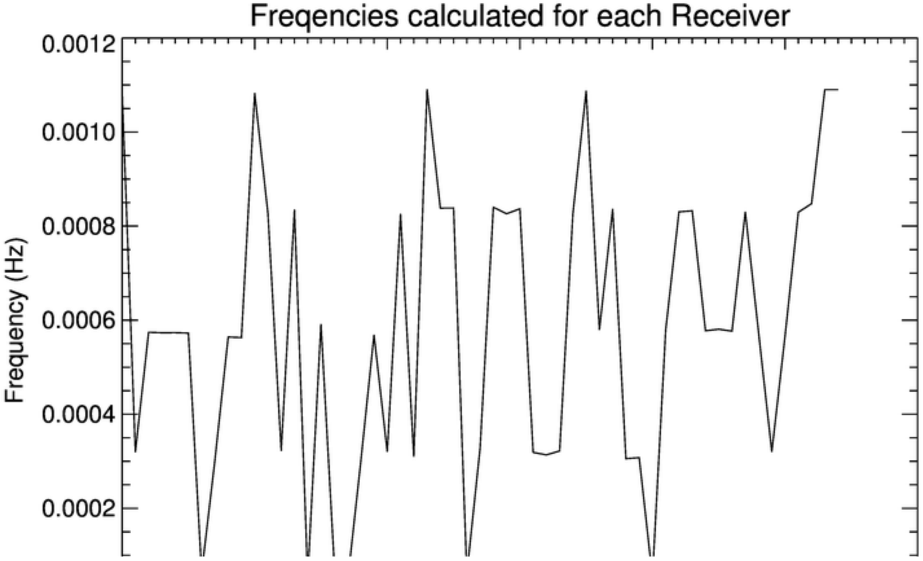




Try methodology on Real GPS Data

- **January 19, 2014 White Sands NM**
- **~147 Standard GPS stations**
- **15:75-17:75 UT**
- **New issues with actual data**
  - **Observations can have gaps in the data**
  - **Can have cycle slips**
  - **Need to perform QC**
    - **Minimum acceptable signal strength (0 or > 6)**
    - **Los of lock flag mod 2 = 0**
  - **Need to have long enough continuous time series to filter, see full periods of waves, and compute correlations**
- **Sample case with ~57 receivers preliminary analysis**

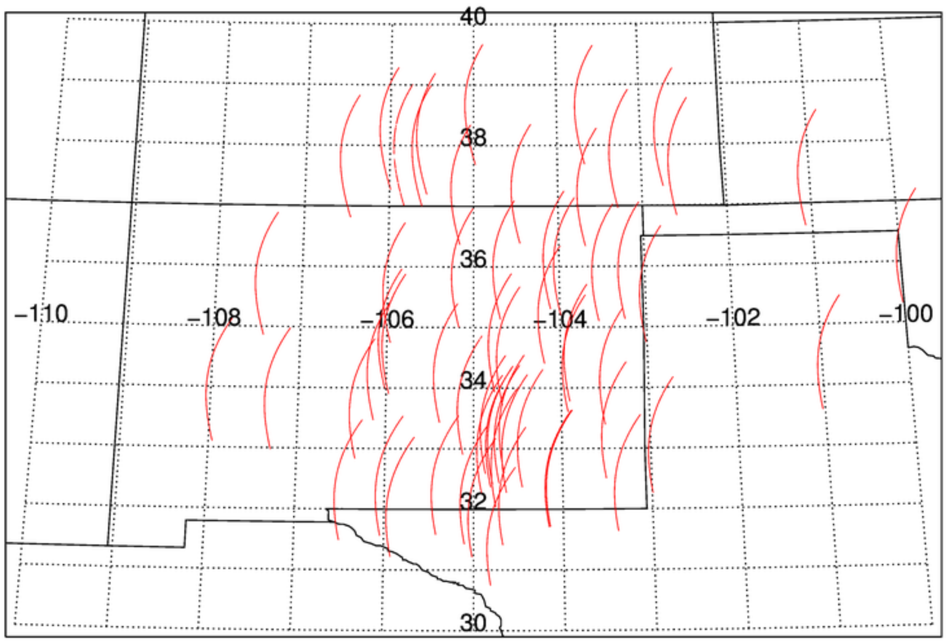
Analysis of PRN 14

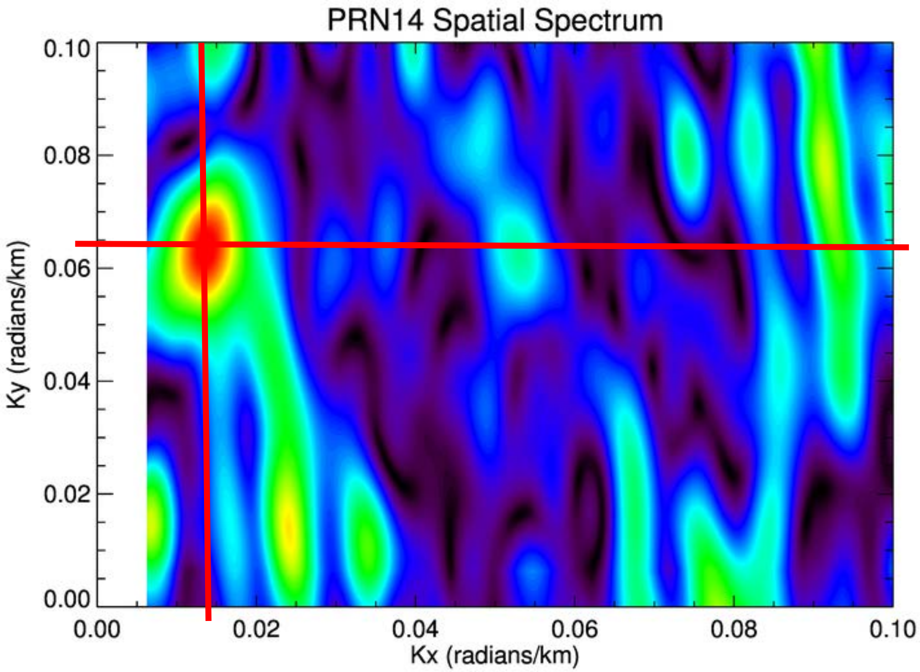


Mean Frequency: 5.83E-4 Hz
Mean Period: 1714 Seconds

Kx = 0.0135
Ky = 0.0635
X-(longitude) wavelength: 465 km
Y-(latitude) wavelength: 99 km

Direction: South and West





Hooke TEC again

- When estimating periods from GPS data, we have to take account of satellite motion
- Standard: ionospheric pierce point (IPP) for the GPS motion through the ionosphere
- This clearly still provides an error but how big and what does it depend on?
- If we start with a Hooke model of TIDS

$$\delta T(x_r, y_r, \theta_r(t), \alpha_r(t), t) = \left(\frac{u_b \sin(I)}{\omega}\right) Re\left[\langle N(t)\rangle e^{i\left(\omega(t-t_0)-k_x x_r - k_y y_r + \frac{\pi}{2} - \phi_0\right)}\right] W_S(\vec{\rho}, t)$$

$$\langle N\rangle = \frac{1}{\sin(\theta_r)} \int dz \frac{N(z)}{L_N(z)} E(z) e^{-i\{[(k_x \sin(\alpha_r) + k_y \cos(\alpha_r))\cot(\theta_r) + k_z]z + \Phi_N(z)\}}$$

$$E(z) = e^{\frac{(z-z_*)}{2H}}(z \le z_T) = e^{\frac{-(z-z_T)}{2H}}(z > z_T)$$

Space-time correlations:

$$|\delta T(x_1, y_1, \theta_1(t), \alpha_1(t), t)\delta T(x_2, y_2, \theta_2(t'), \alpha_2(t'), t')|$$

$$= \left(\frac{u_b \sin(I)}{\omega}\right)^2 \{\langle|N_{1,2}(t,\tau)|\rangle \exp[i(\omega\tau_{1,2} - k_x \Delta x_{1,2} - k_y \Delta y_{1,2})]\}$$

$$\langle|N_{1,2}(t,\tau)|\rangle =$$

$$\int dz F(z) \int d\Delta z\, F(z+\Delta z) \langle e^{-i\{[k_x \delta\hat{x}_{1,2}(t,\tau) + k_y \delta\hat{y}_{1,2}(t,\tau)]z\}} e^{-i\{[k_x \delta\hat{x}_2(t+\tau) + k_y \hat{y}_2(t+\tau)]\Delta z\}}\rangle_t$$

Use of Hooke TEC to Estimate Frequency

- **If we ignore the explicit frequency (omega) in the TEC model**
  - **Then the variation in time is ONLY DUE TO THE SATELLITE MOTION**
  - **Further, that variation has no approximation due to an IPP height**
- **IF we consider the satellite motion and the frequency motion as two function then we can write**

$$F(\omega)=\int d\omega' G(\omega')H(\omega-\omega')$$

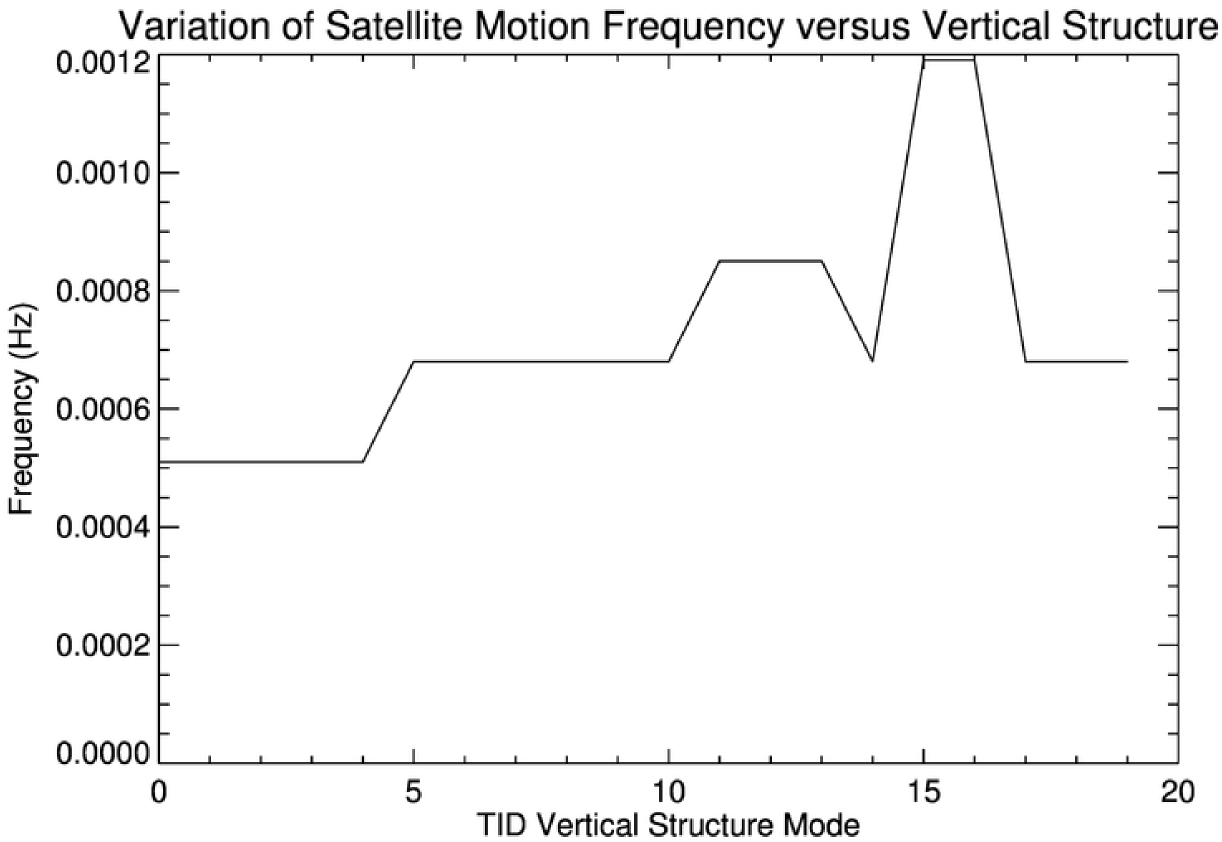
$$G(\omega)\approx\delta(\omega'-\omega_*)$$

$$F(\omega)\approx H(\omega-\omega_*)$$

- **Where, G represents the F.T. of the pure wave, and H is the F.T of the satellite motion effect. Since the pure wave is a delta function in frequency space, we can get that the entire F.T should at omega should be equal to the satellite motion at omega – the "true frequency"**
- **Thus we can compute F from GPS delta TEC data.**
- **We can then compute H from the Hooke TEC model with zero frequency**
- **We can compute the maximums of each, difference the frequency and get the intrinsic frequency WITHOUT ANY IPP approximation**

Results

- **20 variations in Hooke TEC altitudes**
  - **Vary 5 scale heights HD = (30, 50, 77, 100, 125)**
  - **Vary 4 height maximums ZT = (250,300,400,500)**
- **Satellite motion frequency more than doubles**
- **Mainly dependent on saturation altitude**
- **Frequency variation is right in the20-40 minute period**
- **Large effect!!!**



Conclusion

- **Issue:**
  - The satellite motion frequency varies A LOT based on the exact vertical profile shape of the TID
  - The same effect occurs for estimating spatial spectrum or velocities, or any combination
  - There is no correct IPP point to take, no preferred altitude.
  - The finite thickness of the TIDS – which can extend well over 100 km or so creates an error for any kind of 2D correlation method.
  - Effect is minimized for shorter period / longer wavelength / faster speed waves
- **Solution/Way Forward**
  - Use GNSS satellites at GEO – no satellite motion
  - Use very high elevations
  - Have to know the vertical distribution
    - If known, possible to iteratively improve estimation in 2D
  - Direct 3D+time imaging of TIDS using GPS
  - Other data sets to help with vertical distribution
  - Parameterization and estimation

Summary

- We have modeled that analytical form of slant TEC from a Hooke model of TIDS
- We have shown the importance of satellite motion upon the TID estimation process
- To overcome limitations of closely clustered receivers and 2D correlations we have
  - Used as many GNSS receivers as possible over ~ 500 km baselines around the region of interest
  - introduced a spectral estimation process for the horizontal wavenumbers, periods, velocity
  - Demonstrated on simulated data
  - Estimated parameters on actual data from New Mexico
- Despite the generalization, and removal of some limitations of the new method we find:
- The satellite motion produces a significant intrinsic error that cannot be removed by an 2D processing / analysis method
  - The 3D extended nature of the TID combined with the satellite motion produces an error that cannot be removed
  - The effect is worst for velocities ~ the GPS ionospheric speed
  - But always there
- The satellite motion in GPS combined with non-linear propagation in HF implies that we should not expect an apples to apples comparison – it is premature to say GPS TIDS and HF bottomside TIDS do not see same waves
- Full 3D methods need to be developed