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Sensing Ionospheric Disturbances Using a Large GNSS Network

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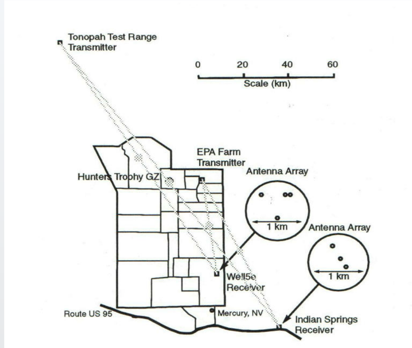
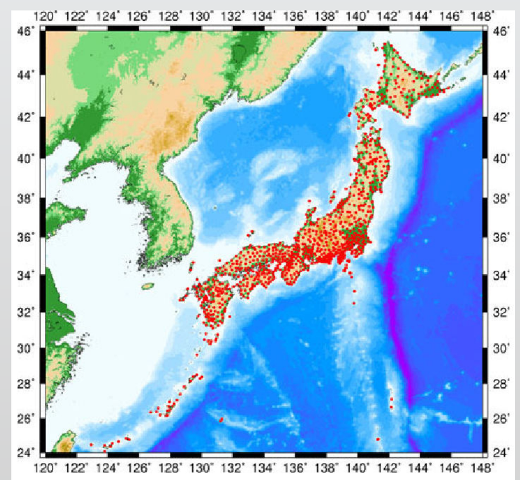
Background

- Seismic events induce disturbances in the ionosphere.
- Prior studies ([Blanc, 1984], [Fitzgerald,1994], [Krasnov, 1999], [Archambeau et al., 1992] have investigated the use of this phenomena for detecting underground weapons tests.
- Since the 2000's large, dense networks of dual-frequency GNSS stations have been deployed in various regions (e.g. Japan, California).
- Ionospheric corrections in dual frequency GPS measurements can be used to measure Ionosphere TEC.
- New time-frequency array processing methods can detect coherent disturbances and estimate speed and direction of propagation



Radar locations in the 1992 *Hunters Trophy* experiment [Fitzgerald, 1994]



GEONET GNSS Station Locations [Demyanov, et. al. 2011]

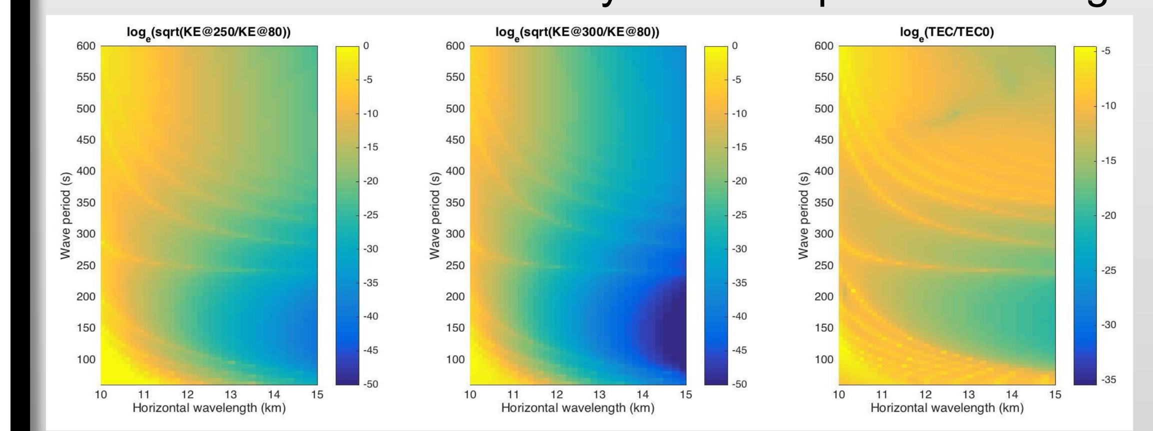
Acoustic-Gravity Waves from surface and underground nuclear tests can induce disturbances in the ionosphere. These disturbances can be observed as perturbations in Total Electron Content (TEC) time series obtained as a byproduct of dual frequency Global Positioning System (GPS) measurements made by ground based receivers. Large, dense networks of GNSS reference stations, such as Japan's GNSS Earth Observation Network System (GEONET) can be used for making locally dense measurements of the spatial and temporal variation in ionospheric TEC. These networks also allow identification of various disturbances propagating across the network.

By performing time-frequency analysis on TEC time series from multiple stations in dense GNSS networks and looking for common structures, potential candidates for TIDs can be identified. This approach is used to identify and track potential TIDs from underground nuclear tests. Candidate TIDs from North Korean UGTs are identified through a combination of wavelet analysis and cross correlation of TEC time series obtained from GEONET base stations in Japan. Ionospheric disturbances with periods ranging from 3 minutes to 5 minutes were identified in the case of UGTs conducted by the DPRK on 9 Oct 2006 and 25 May 2009. The authors have begun to look at identifying disturbances from the NK UGT on 9 Sep 2016 as well as finding similarities in the TEC time-frequency signatures of these events.

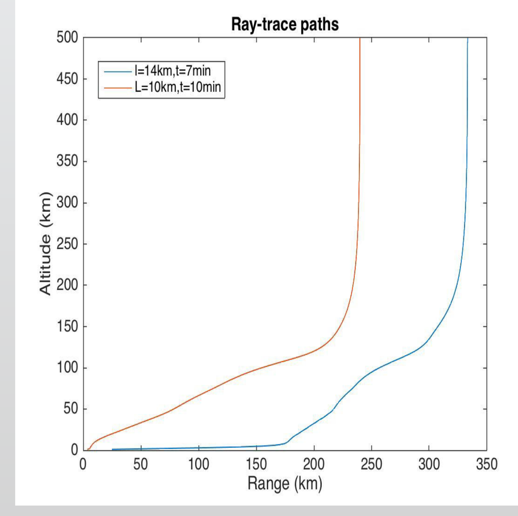
Model development, to assess the sensitivity of TEC time series to source strength and geography, complement these experimental observations.

Preliminary Modeling Results

- Spectral Full-Wave Model (SFWM)
- Numerical model for dispersion, including: non-isothermal atmosphere, height-dependent mean winds, Coriolis force, ion-drag, eddy and molecular diffusion of energy and momentum.
- Horizontal and vertical group velocity computed numerically and used for ray-trace
- Evaluate TEC sensitivity to wave spectrum through white noise disturbance



Ratio of kinetic energy at 250 km altitude to that at 80 km altitude (left panel), a similar plot with the upper altitude being 300 km (middle panel), and the amplitude of the relative perturbation in the total electron content (right panel) for waves having periods between 50 and 600 seconds, and horizontal wavelengths between 10 & 15 km.



Ray trace: 7 and 10 min periods.

Signal Processing

- TEC time series observed from multiple close stations: contains long period variation and traveling disturbances.
- Wavelet coherence (between two stations a, b) used to identify coherence signals in space and time

$$\left(R_{s1,s2}(a,b)\right)^2 = \frac{|W_{s1}(a,b)W_{s2}^*(a,b)|^2}{|W_{s1}(a,b)|^2|W_{s2}(a,b)|^2}$$

- Wavelet transform (VT) shows good results over multiple scales (in comparison with short-time Fourier transform (STFT)

$$W(a,b) = \int_{-\infty}^{\infty} TEC(t)\psi\left(\frac{t-b}{a}\right)dt$$

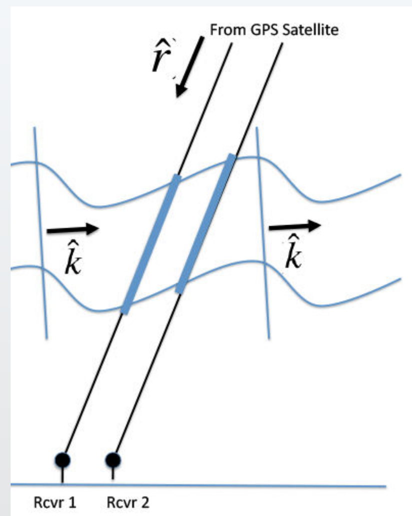
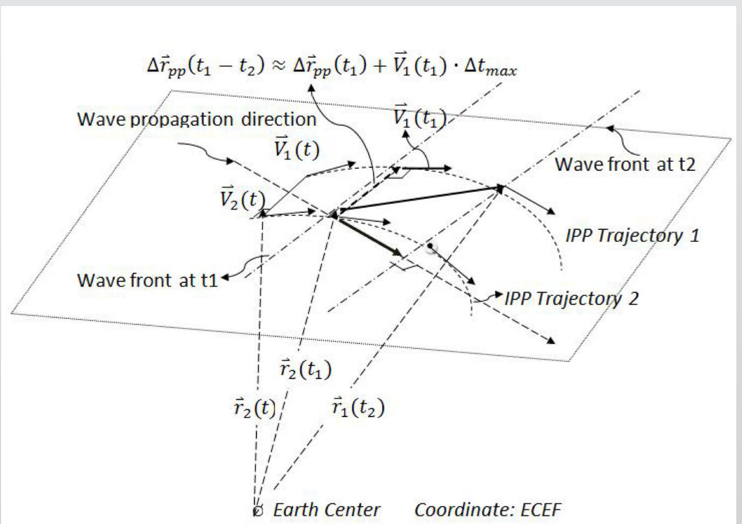


Illustration of coherent wave structure observed from two proximate stations

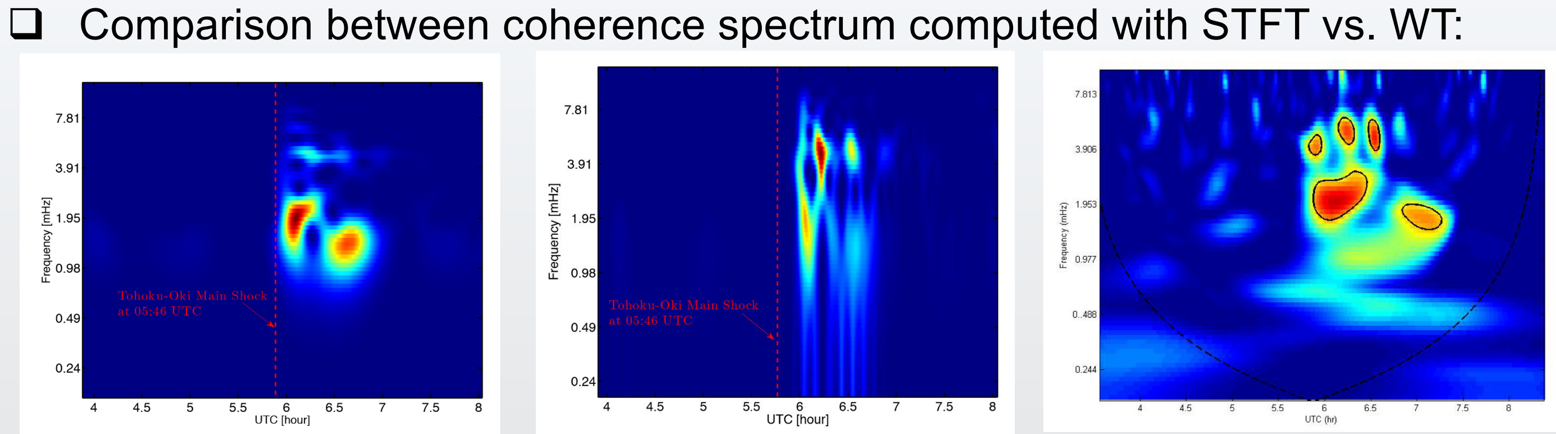
- Wavelet filter designed to isolate time and frequency with high coherence
- Cross-correlation estimates time of travel between ionospheric pierce points (IPP's)
- 2-D propagation can be estimated from travel time between multiple pairs of stations



Right: Relationship between travel time between two (2) IPP's and horizontal projection of wave propagation vector

Experimental Results

- Comparison between coherence spectrum computed with STFT vs. WT:



STFT (1024 s window): High freq. not resolved

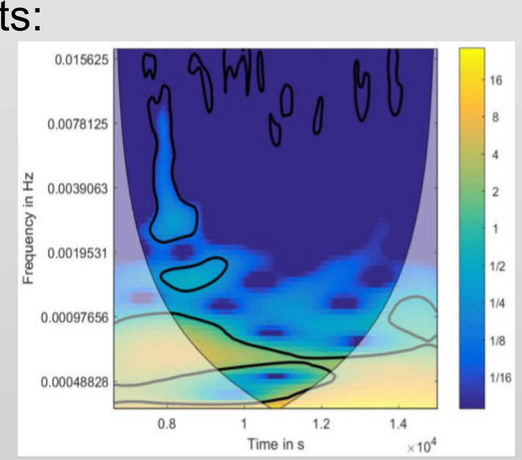
STFT (512 s window): Low freq. not resolved

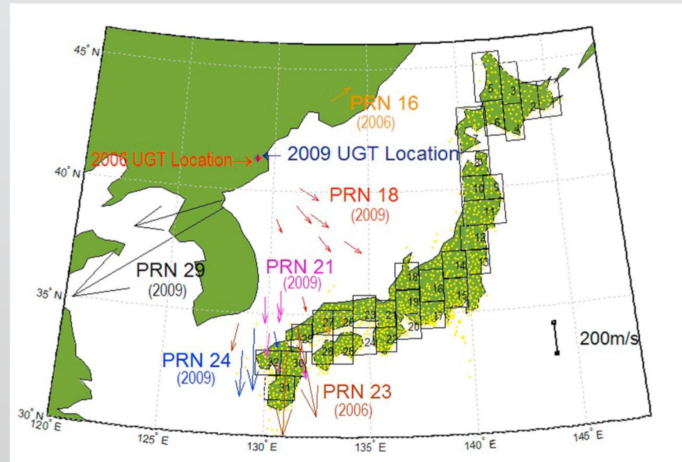
WT: Resolves both scales

(Data from 2011 Tohoku Earthquake and Tsunami [Yang, et al, in preparation])

- Results for 2006, 2009 and 2016 DPRK Tests:

Right: Preliminary results for 2016 event: PRN 28 substation 332 - some evidence of high coherence around 8000 sec





Propagation directions from 2006 & 2009. Sub-areas of GEONET are indicated on map [Yang, et al, 2012]

Conclusion and Future Work

- Preliminary results indicate TEC time series from large GNSS networks may contain unique signatures characteristic of underground nuclear tests.
- The wavelet coherence shows promise in detecting coherent structures at multiple scales in time and frequency
- Modeling activities have been initiated to better understand the atmospheric response to seismic inputs.
- Future work under DTRA funding:

2016-17:
- Application of SFWM and Time-Dependent Nonlinear Model (TDNM) for UGT sources
- Inter-comparison of SFWM with TDNM and sensitivity study
- Refinement of wavelet signal processing to improve isolation and filtering
- Literature review and theoretical derivation of feature recognition and pattern classification algorithm

2017-18:
- Validation and comparison of models with observations of 2006 and 2009 events
- Application of pattern classification to discriminate observation of UGTs from other sources

2018-19:
- Study of physical basis for observed signatures
- Model determination of minimum observable threshold
- Model investigation of sensitivity of observations to geometry and uncertainty in environmental conditions

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