Ionospheric observations of Underground nuclear explosions using GPS

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Education and Research interests

- Studied in Geodetic science from The Ohio State University, Columbus, Ohio, USA

- Research interests: GPS algorithms, focusing on GPS positioning and GPS remote sensing that includes troposphere and ionosphere observation and modeling with GPS

Research Experiences

- Development of the **network based GPS** processing programs
  1. Point positioning and network RTK processing
  2. TEC computation for local GPS network stations: TEC map of the local area
  3. Testing various tropospheric models for the precise positioning in network RTK

- Development of the **Traveling Ionospheric Disturbance (TID) detection** program

- CALIBRA project (current)
Recent study

- Ionospheric detection of underground nuclear explosions
  - **Detection** of traveling ionospheric disturbances (**TID**) from the GPS ionospheric observation, GPS TEC
  - **Determination of the epicenter** using the detected TIDs by the least squares adjustment theory
  - **Validation** of the TID waves associated to the specific event using 1) statistical approach 2) verification from the other technique, i.e., Radio astronomical observation
  - **Discrimination** between different types of events using the properties of the TID waves
Problem statements

- Traveling ionospheric disturbance (TID) can be generated by various sources, such as geomagnetic storms, tsunamis, earthquakes, volcanic eruptions, underground nuclear explosions (UNEs), surface explosions, etc.

- Independent recent studies (Park et al., 2011; Yang et al., 2012) observed the North Korean UNE of 2009 using slant Total Electron Content (STEC) extracted from ground-based GPS observations.

- The discrimination between the characteristics of TIDs originating from different sources may allow for detection and understanding of the source of ionospheric disturbance: case study for UNE and earthquake.

- Very Large Array (VLA), a radio frequency interferometer located in New Mexico, observes STEC along the line of sight to a cosmic source.

- Both methods are sensitive to local ionospheric disturbances.

- This study compares the TID observations of the same event, US UNE of 1992, using both techniques.
Worldwide nuclear tests

- In five decades (1945 - 1996), over 2000 nuclear tests were conducted.

<table>
<thead>
<tr>
<th>Country</th>
<th># tests</th>
<th>year</th>
</tr>
</thead>
<tbody>
<tr>
<td>The United States</td>
<td>1032</td>
<td>1945 - 1992</td>
</tr>
<tr>
<td>The Soviet Union</td>
<td>715</td>
<td>1949 - 1990</td>
</tr>
<tr>
<td>The United Kingdom</td>
<td>45</td>
<td>1952 - 1991</td>
</tr>
<tr>
<td>France</td>
<td>210</td>
<td>1960 - 1996</td>
</tr>
<tr>
<td>China</td>
<td>45</td>
<td>1964 - 1996</td>
</tr>
</tbody>
</table>

- Comprehensive Nuclear-Test-Ban Treaty was open for signature in September, 1996; since then, seven tests have been conducted.

<table>
<thead>
<tr>
<th>Country</th>
<th># tests</th>
<th>year</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>2</td>
<td>1998</td>
</tr>
<tr>
<td>Pakistan</td>
<td>2</td>
<td>1998</td>
</tr>
</tbody>
</table>
International Monitoring System (IMS)

- International Monitoring System (IMS) established by the CTBTO uses Seismic, Hydroacoustic, Infrasound, and Radionuclides technologies to monitor and detect nuclear explosions (Medalia, 2010)
  - A **seismic** network monitors for terrestrial shock waves from nuclear explosions
  - A **hydroacoustic** network scans the oceans for nuclear explosion generated sound waves
  - An **infrasound** network of acoustic pressure sensors identifies and locates atmospheric nuclear explosions
  - A **radionuclide** network detects radioactive particulates and gas (e.g., xenon) that are by-products of nuclear explosions
International Monitoring System Sensors

- **Seismic** – detect explosions underground
  - Earthquake vs. explosion - complicated travel paths
  - Ineffective if explosion is decoupled from the ground

- **Hydro-acoustic** – detect explosions in oceans/coastal areas
  - Explosion needs to be close to ocean

- **Infrasound** – detect explosions in atmosphere
  - Susceptible to atmospheric noise and disturbances

- **Radionuclide** – detect radioactive particles and noble gases
  - Definitive identification of nuclear event
International Monitoring System of the CTBTO

Σ = 337

www.ctbto.org/map/#ims
The International GNSS Service (IGS) Tracking Network: 439

Possible new global UNE/earthquake/blast/etc. tracking tool?
Observing traveling ionospheric disturbance excited by an UNE

**Definitions:***
- **GNSS**: Global Navigation Satellite System
- **IPP**: Ionospheric Pierce Point
- **UNE**: Underground Nuclear Explosion
Diagram of determination for UNE epicenter

Unknown: coordinates of UNE, \((\phi, \lambda)\); three components of TID velocity \(v_T\), \(v_N\), and \(v_E\)

Observation: the time after the event \(t_i\) and coordinates of IPP, \((x_i, y_i, z_i)\) at \(t_i\)

Related terms: slant distance between IPP and UNE, \(s_i\); horizontal distance between UNE epicenter and the station coordinates, \(d_i\); azimuth and the elevation angle of IPP as seen from the UNE, \(\alpha_i\) and \(\epsilon_i\), respectively
Detection of TID: Slant TEC (STEC) derivatives

- STEC is strongly affected by the Sun’s diurnal cycle and changing geometry of GNSS satellites: these forces drive the main trends of GNSS STEC measurements, which typically are low frequency and high amplitude.

- Any unresolved bias/error in GNSS geometry-free observations should be removed.

- The numerical third order horizontal 3-point derivatives, or simply STEC derivatives, is applied to suppress the STEC trend and bias, and to reveal small, local fluctuations.
Comparison of the TID waveforms

2009 UNE: 3.5 – 7.5 mHz (Yang et al., 2012)

Frequency band for the Seismic region: 0.2 – 1.667 mHz (Freybourger et al., 1997)

MSTID like TID induced by UNEs: less than 1 km/s (200 m/s or more) (Francis, 1974)

TID propagation speed studied by Liu et al. (2011): 0.3 – 1.5 km/s

<table>
<thead>
<tr>
<th></th>
<th>UNE 2006</th>
<th>Earthquake2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>4 min</td>
<td>15 min</td>
</tr>
<tr>
<td>Frequency of the wave packet</td>
<td>4 mHz (1/4 min)</td>
<td>1 mHz (1/16 min)</td>
</tr>
<tr>
<td>Amplitude (peak to peak)</td>
<td>0.8 TECU/min</td>
<td>1.4 TECU/min³</td>
</tr>
<tr>
<td>Propagation speed</td>
<td>375.8 m/s</td>
<td>1.27 km/s</td>
</tr>
</tbody>
</table>
**Correlation coefficient between the UNEs and the earthquake**

<table>
<thead>
<tr>
<th></th>
<th>2009 UNE</th>
<th>2006 UNE</th>
<th>2011 Earthquake</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2009 UNE</strong></td>
<td>1 (N/A)</td>
<td>0.891 (0.067)</td>
<td>-0.009 (0.609)</td>
</tr>
<tr>
<td><strong>2006 UNE</strong></td>
<td>0.891 (0.067)</td>
<td>1 (N/A)</td>
<td>0.030 (0.626)</td>
</tr>
<tr>
<td><strong>2011 Earthquake</strong></td>
<td>-0.009 (0.609)</td>
<td>0.030 (0.626)</td>
<td>1 (N/A)</td>
</tr>
</tbody>
</table>

- Mean and the standard deviation (in parentheses) of the correlation coefficients (CC) between TID signatures of the 2009 UNE, 2006 UNE, and the 2011 Japanese earthquake using a 4 [min] window

- The number of extracted TIDs for the 2009 UNE, 2006 UNE, and 2011 earthquake were 11, 4, and 51, respectively. Consequently, the total number of pairs of correlation coefficients (CC) computed was 44 between the 2009 UNE, and the 2006 UNE, 561 between the 2009 UNE and the 2011 earthquake, and 204 between the 2006 UNE and the 2011 earthquake

- CCs between the UNEs were close to 0.9 (extremely high correlation), while those between the UNE and the earthquake were close to zero

- It supports the fact that the TID waves induced by the same type of events should be highly correlated, a fact that can be used to detect source of TIDs in future events
## UNEs conducted by USA at Nevada Test Site (NTS) in 1992

<table>
<thead>
<tr>
<th>Country</th>
<th>USA (South Nevada)</th>
<th>USA (Yucca Flat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Hunters Trophy</td>
<td>Divider</td>
</tr>
<tr>
<td>Source Type</td>
<td>Underground</td>
<td>Underground</td>
</tr>
<tr>
<td>Data Time [UTC]</td>
<td>1992/09/18 17:00:0.080</td>
<td>1992/09/23 15:04:0.0</td>
</tr>
<tr>
<td>Latitude/Longitude [deg]</td>
<td>37.207/-116.211</td>
<td>37.021/-115.989</td>
</tr>
<tr>
<td>Depth [km]</td>
<td>0.385</td>
<td>0.34</td>
</tr>
<tr>
<td>Yield [kT]</td>
<td>&lt;= 20</td>
<td>&lt;= 20</td>
</tr>
<tr>
<td>mb</td>
<td>4.3</td>
<td>4.3</td>
</tr>
</tbody>
</table>

### Maps

- **Hunters Trophy**
- **Divider**
GPS detection result: Travel time-distance model of the UNE induced TID observations

The travel time and the travel distance of each event are highly correlated, with correlation coefficients of 0.93 and 0.81 for the Hunters Trophy and the Divider, respectively.

The propagation velocity is about 573 m/s with std. 85 m/s and 740 m/s with std. 135 m/s, respectively, for both events.
VLA radio telescope observation

- The Very Large Array (VLA) is a radio-frequency interferometer located in New Mexico (34°04’43.5”N, 107°37’05.8”W)

- Operated as an interferometer, the VLA measures the correlation of complex voltages from each unique pair of antennas, or “baseline,” producing what are referred to as visibilities

- Each antenna’s line of sight passes through a different part of the ionosphere, and thus the measured visibilities have an extra phase term added as a consequence of the difference in ionospheric delays
  - This extra phase term is proportional to the difference in the TEC along the lines of sight of the two telescopes
  - The interferometer is sensitive to the TEC gradient rather than the TEC itself, which renders it capable of sensing both temporal and spatial fluctuations in TEC
VLA detection result: Hunters Trophy

Spectral amplitude (left) and peak temporal frequency (right) of VLA observation during the time of the Hunters Trophy

- The STEC derivatives detailed the propagation of TIDs from the UNE as acoustic-gravity waves with velocities ranging over 570 – 710 m/s
Summary & Conclusions

- TIDs induced by the different events tend to have unique wave properties and manifest strong correlations with other TIDs of the same type of underlying event.

- This study presented the result of independent detection of the TID induced by the 1992 US UNEs using GPS and VLA observations.

- GPS and VLA detected the TID of the same event with the same range of propagation velocity:
  - GPS detected the TID induced by the Hunters Trophy and the Divider, with their propagation velocities of about 573 m/s and 740 m/s, respectively.
  - VLA detected the TID induced by the Hunters Trophy with the propagation velocity of about 570 – 710 m/s.

- Global availability of GNSS tracking networks combined with further algorithmic improvement of this method and new low-frequency (VHF) radio telescopes may offer in the future a method which could complement International Monitoring System (IMS).
References

Thank you!

Q&A
Backup slides
Traveling Ionospheric Disturbance (TID)

- TID can be excited by **Acoustic Gravity Wave (AGW)** from a point source, such as surface/underground explosions, geomagnetic storms, earthquakes, tsunamis, tropical storms etc.
  - When nuclear weapon detonates (or another high energy explosion occurs), an electromagnetic pulse (EMP) is generated that rapidly changes the electric fields and the magnetic fields that may result in ionospheric disturbances.

- Can be classified as Large Scale TID (LSTID) and Medium Scale TID (MSTID) based on their periods, regardless of the generation mechanism.
  - The velocity of MSTIDs ranges from several hundreds of meters per second to less than a kilometer per second, while LSTID’s velocities are more than a kilometer per second.
  - LSTIDs mostly occur as a result of geophysical events, such as geomagnetic storms, which can be indicated by global Kp indices, while MSTIDs are not related to any high score Kp indices.
Determination of UNE epicenter and TID velocity by Gauss-Helmert (GH) model

\[ s_i = v_i \times t_i \quad \text{(1)} \]

Where

- \( s_i \) is the slant distance between IPP and UNE,
- \( t_i \) is the arrival time of TID,
- \( v_i \) is the apparent velocity of TID with the subscript \( i \) for the \( i^{th} \) station

(1) is rewritten as

\[ NED = \sqrt{v_{TID,N}^2 + v_{TID,E}^2} \times \sec \varepsilon_i \times t_i \]

- With the slant distance, \( NED = \sqrt{N_i^2 + E_i^2 + D_i^2} \)

\( s_i \):

- Decomposing the apparent velocity to the TID velocity and the wind velocity:

  \[ v_{TID,N} = (v_T \cos \alpha_i + v_N) \quad v_{TID,E} = (v_T \sin \alpha_i + v_E) \]

  with the slant propagation, \( \sec \varepsilon_i \)

- AND the observation \( t_i \) from the TID auto-detection output