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On traveling ionospheric disturbances induced by underground nuclear explosions and earthquakes: case study

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Abstract

The ionosphere responds to earthquakes, tsunamis, tropical storms, chemical explosions, underground explosions, and other geophysical activities. These phenomena can generate disturbances in the ionosphere, referred to as traveling ionospheric disturbances (TIDs). The TID can be extracted from the ionospheric delay of GNSS signals by eliminating the dominant trend from the solar diurnal variation. The aim of this study is to discriminate the specific TID wave generated by the underground nuclear explosion from other events, such as earthquakes. This study focuses on the TIDs induced by an earthquake and underground nuclear explosion (UNE), and the unique characteristics of the waveforms created by these two types of events are demonstrated.

To discriminate the waveforms of TID induced by UNEs from those generated by earthquakes, the North Korean UNEs, detonated in 2006 and 2009 were compared to the TIDs from the earthquake of 2011 that occurred in Tohoku, Japan. For each event, the GPS data from the vicinity permanently tracking stations were collected. Using the dual frequency GPS signals, the ionospheric delay was extracted that was converted to the total electron content (TEC) to observe the TID. The small fluctuations in the regional trend of the TEC, caused by the specific local events, were extracted by taking the numerical third order horizontal 3-point derivatives. The significant derivative peaks were considered as the TID waveforms. In addition, the coordinates of the epicenter of the event were determined by the detected TIDs at multiple stations with varying distances from the event.

This study focused on exploring the characteristics of the TID waveforms. The TIDs detected by the 3-point derivatives of the TEC signal were independently verified by a wavelet de-noising technique. The correlation coefficients (CC) between the TID signals of the UNEs of 2009 and 2006 were significantly higher than their CCs with the TIDs from the Japanese earthquake. In addition, the related power spectra revealed that the TID waveforms from the earthquake had significantly lower frequency components than the UNE-induced TIDs. The results of this case study indicate that TIDs induced by different events can be readily discriminated based on their distinctive spectral properties.

1. Traveling Ionospheric Disturbance (TID) and GNSS TEC

- TID can be excited by acoustic/gravity waves from a point, geomagnetic storms, tsunamis, tropical storms etc.
- GNSS Total Electron Content (TEC) is calculated from ionospheric delay along the GNSS signal path between the satellite and the receiver on the ground: Slant TEC (STEC)
- By taking the numerical third order horizontal 3-point derivatives of STEC, simply referred to as STEC derivatives, the fluctuations due to the TID are revealed (Park et al., 2011)

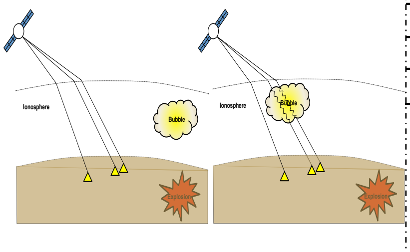

Figure 1: TID generated due to the explosion (left) and detected by GNSS stations (right)

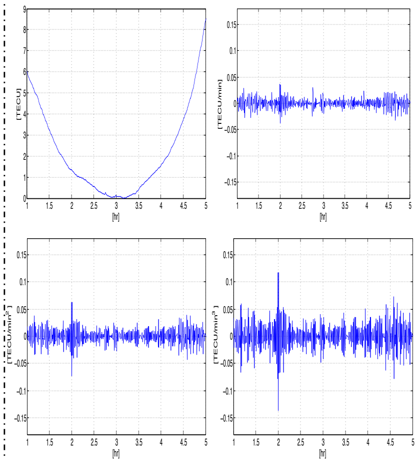

Figure 2: An example of the STEC and its derivatives observed at station CHAN, 25 May, 2009 – (a) relative STEC in the top left, (b) 1st order numerical derivatives in the top right, (c) 2nd order numerical derivatives in the bottom left, and (d) 3rd order numerical derivatives in the bottom right

2. Auto-detection using Cross-Covariance method

- From the STEC derivatives in Figure 2, several significant peaks are found that would be candidates of the TID induced by a specific event
- Through the automatic detection algorithm, 1) the wave property for the specific event can be distinguished and 2) the TID waves hidden by the surrounding noise can be automatically sensed
- The auto-detection uses the correlative properties between the wave packets: Cross-covariance across the STEC derivatives data span using the reference wave packet, which can be (1) manually selected from the current event, or (2) selected from example wave packets saved in a database, to represent the TID induced by certain types of events
- The wave packet of the maximum covariance, which is the most correlated with the reference wave, is considered as TID

3.Case Study: Underground Nuclear Explosion (UNE) and Earthquake

Table 1: Event description of the 2006 and 2009 North Korean UNE, and 2011 Tohoku, Japan Earthquake

	2006 UNE	2009 UNE	2011 Earthquake
Geographic Location (lat/long)	41.2867/129.0902 [deg] (±1 km)	41.293/129.066 [deg] (±1 km)	38.297/142.372 (±13.5 km)
Date, time	2006/10/09 01:35:27.8 UTC (±0.2 sec)	2009/5/25 00:54:42.8 UTC (±0.3 sec)	2011/3/11 05:46:24 UTC
Depth	0.2 km (±0.2 km)	0.6 (±0.4 km)	30 km
Explosion Yield	0.34 – 5.6 kT	2.2 – 4.8 kT	N/A
Event Mangnitude	4.1 – 4.2 mb	4.5 – 4.7 mb	M 9.0

- STEC derivatives of the three events were computed and compared to the signature of the TID of each event
- The duration of UNE waves is about 4 min while the duration of the earthquake wave is about 15 min
- Figure 3 illustrates STEC derivatives with the detected wave packets by auto-detection highlighted in red (left plot) and the corresponding wavelet de-noised plots (right plot)

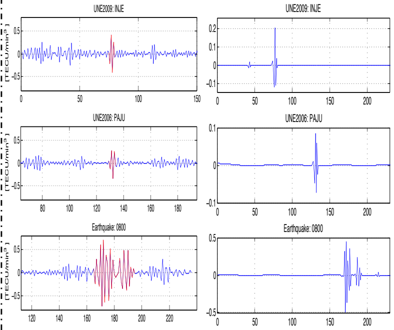

Figure 3: STEC derivatives (left plots) and their denoised counterparts (right plots) from station INJE, 2009 UNE (top), from PAJU, 2006 UNE (middle), and from 0800, 2011 Japanese earthquake (bottom). The red waves are distinct signals regarded as TIDs

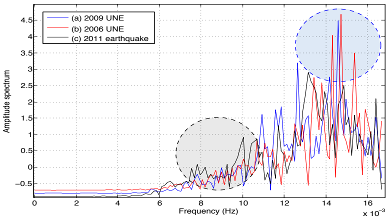

Figure 4: Comparison of the normalized amplitude spectra of the representative STEC derivatives from (a) INJE for the 2009 UNE (blue), (b) PAJU for the 2006 UNE (red), and (c) 0800 (black) for the 2011 earthquake. Black and blue dashed circles indicate the local maxima of the earthquake and the UNEs, respectively

- The CC was computed for all possible pairs with 11 TIDs of 2009 UNE, 3 TIDs of 2006 UNE, and 83 TIDs of 2011 Earthquake, as shown in Table 2

	2009UNE	2006UNE	Earthquake
2009 UNE	1 (N/A)	0.891 (0.067)	-0.009 (0.609)
2006 UNE	0.891 (0.067)	1 (N/A)	0.030 (0.626)
Earthquake	-0.009 (0.609)	0.030 (0.626)	1 (N/A)

Table 2: Mean and the standard deviation (in parentheses) of the correlation coefficients (CC) between TID signatures of 2009 UNE, 2006 UNE, and the 2011 Japanese earthquake using 4 min window

4. Conclusions

- The TID waveforms were correlated to investigate their ability to discriminate different types of underlying events
- The results of this case study indicate that TIDs induced by different events can be readily discriminated based on their distinctive spectral properties
- Well-concealed UNE may be undetected by some of the International Monitoring System (IMS) sensors (e.g., Radionuclide network)
  - GNSS-based method may provide a viable augmentation to IMS using the existing GNSS ground infrastructure

References

Park, J., R. R. B. von Frese, D. A. Grejner-Brzezinska, Y. Morton, and L. R. Gaya-Pique (2011), Ionospheric detection of the 25 May 2009 North Korean underground nuclear test, *Geophys. Res. Lett.*, 38, L22802, doi: 10.1029/2011GL049430