International Beacon Satellite Symposium BSS-2016
Trieste, Italy

Using Ionospheric Transients to Detect Multiple Natural Hazards: Measurements and Modeling Results

Attila Komjathy*, Yu-Ming Yang, Xing Meng, Olga Verkhoglyadova
and Anthony J. Mannucci
(Corresponding email address: <Attila.Komjathy@jpl.nasa.gov>)
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
Richard B. Langley
University of New Brunswick, Fredericton, NB, Canada

ABSTRACT

Natural hazards including earthquakes, volcanic eruptions and tsunamis have been significant threats to humans throughout recorded history. Global navigation satellite systems (GNSS; including the Global Positioning System (GPS)) receivers have become primary sensors to measure signatures associated with natural hazards. These signatures typically include GPS-derived seismic deformations measurements, co-seismic vertical displacements and real-time GPS-derived ocean buoy positioning estimates. Another way to use GPS observables is to compute the ionospheric total electron content (TEC) to measure, model and monitor post-seismic ionospheric disturbances caused by e.g., earthquakes, volcanic eruptions and tsunamis. In the presentation, we discuss new applications using examples of recent natural hazards that generated TEC perturbations. We present results for state-of-the-art imaging using ground and space-based ionospheric measurements and coupled atmosphere-ionosphere modeling of ionospheric TEC perturbations using recent events in 2015. Our study strongly suggests that both ground-based and spaceborne GPS remote sensing techniques could play a critical role in detection and imaging of the upper atmosphere signatures of natural hazards including earthquakes, tsunamis, and volcanic eruptions.

Key words: TEC, natural hazards, detection, early warning systems

Introduction

Following the original work by Hines [1972], a series of observations and modeling studies have been conducted in order to understand the physics of earthquake- and tsunami-driven acoustic-gravity waves (AGWs) in the ionosphere by analyzing TEC values retrieved from ionospheric Doppler sounding systems and dense GPS networks [e.g., Astafyeva et al., 2011; Galvan et al., 2012; Komjathy et al., 2012]. Recent research at NASA's Jet Propulsion Laboratory using ground- and space-based GPS measurements resulted in new and innovative GPS applications including the use of ionospheric measurements to detect small fluctuations in the GPS signals between the spacecraft and GPS receivers caused by natural hazards occurring on or near the Earth's surface. This continuing research is expected to provide early warning for tsunamis, volcanic eruptions and asteroid atmospheric impacts, for example, using real-time data from GPS and other global navigation satellite systems. In the research, we discuss new applications using examples of recent natural hazards that generated TEC perturbations. We present results for state-of-the-art imaging and coupled atmosphere-thermosphere-ionosphere modeling of ionospheric perturbations using ground and space-based ionospheric measurements. By studying the propagation properties of ionospheric perturbations generated by natural hazards along with applying sophisticated first-principles physics-based ionospheric modeling, we are on track to develop new ground- and space-based technologies that can potentially save human lives and minimize property damage.

Spaceborne Natural Hazard investigations and Analysis

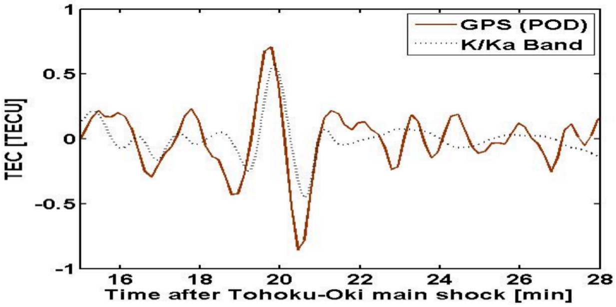

Figure 1. The TEC disturbances retrieved using a GRACE GPS receiver (POD) corresponding to GRACE tracks traveling through the same region (Alaska) during the event time.

The GRACE inter-satellite precise range measurements provide a new opportunity to analyze the interaction of atmospheric waves and ionospheric disturbances associated with the 2011 Tohoku-Oki earthquake. Here, we derived ionospheric TEC from measurements made from instruments on board the GRACE spacecraft. We examine and compare regional seismic measurements, infrasound signals, ground-based GPS network measurements, and GRACE Level 1-B observations a day before and after the earthquake event to detect co-seismic ionosphere-thermosphere perturbations. At the time of the Tohoku-Oki earthquake on March 11, 2011, the twin spacecraft were orbiting at an altitude of ~450 km over Alaska. Significant TEC fluctuations (up to 0.6 TEC units, as shown in Figure 1) were observed ~8 minutes after the arrival of seismic and infrasound waves on the ground in Alaska, ~20 minutes after the Tohoku-Oki main shock at 05:46:23 UTC. The results of three-dimensional ionosphere-thermosphere modeling and infrasound ray-tracing simulations are consistent with the arrival time and physical characteristics of the disturbances at GRACE. This is the first time that ionospheric disturbances associated with an earthquake are clearly attributable to perturbations at such high altitudes.

Model Simulations of Earthquake- and Tsunami-Ionosphere Coupling

In the talk, we summarize JPL's physics-based modeling of atmosphere-ionosphere coupling processes and demonstrate comparisons with space-based observations for the 2011 Tohoku-Oki earthquake. The model is built upon the Global Ionosphere Thermosphere Model (GITM) [Ridley et al., 2006] by implementing AGW perturbations at the lower boundary (100 km altitude) of GITM. Unlike other physics-based ionospheric models that use pressure-based coordinate systems, GITM applies an altitude-based grid and does not assume hydrostatic equilibrium, which makes the model uniquely qualified to capture the vertical dynamics more accurately than hydrostatic approaches.

Conclusions

Using ground- and space-based GPS measurements we demonstrated the observational evidence of atmosphere-ionosphere signatures associated with natural hazards including the 2011 Tohoku-Oki earthquake and tsunami. We found that the TEC perturbations are consistent with the arrival of infrasound signals and Tohoku-Oki earthquake-generated seismic waves. The frequency band appears to be in good agreement with the dominant periods of infrasound signals in the upper atmosphere (at the 445 km altitude of GRACE satellites at 06:07 UTC on March 11, 2011). Comparisons between ground infrasound waves and space-based observed neutral air density perturbations show a 9-minute time delay, which may be interpreted as the infrasound propagation time from the ground to the GRACE altitude. JPL's atmosphere-ionosphere coupling simulations indicate a good agreement with the observations. The new results provide additional arguments towards enhancing the GNSS ionosphere-based techniques for detection and imaging of natural hazards including earthquakes, tsunamis, and volcanic eruptions. In addition, the space-based remote-sensing platforms (such as GRACE and the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) spacecraft) are expected to provide even more accurate observations that could potentially be applied to verify the coupling between traveling ionospheric disturbances and acoustic-gravity waves.

Acknowledgements

The authors would like to thank NASA Headquarters, the Earth Science and Interior NASA ROSES Grant Program (NNH07ZDA001N-ESI). This research was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration. Copyright 2016. All rights reserved.

References

Astafyeva, E., P. Lognonné, and L. Rolland (2011), First ionospheric images of the seismic fault slip on the example of the Tohoku-oki earthquake, *Geophys. Res. Lett., 38*, L22104, doi: 10.1029/2011GL049623.

Galvan, D.A., A. Komjathy, M.P. Hickey, P. Stephens, J. Snively, Y. Tony Song, M.D. Butala, and A.J. Mannucci (2012), "Ionospheric signatures of Tohoku-Oki tsunami of March 11, 2011: Model comparisons near the epicenter", *Radio Science, 47,* RS4003, doi: 10. 1029/2012RS005023.

Hines, C.O. (1972), "Gravity waves in the atmosphere", *Nature*, *239*, 73–78, doi: 10.1038/239073a0.

Komjathy, A., D. A. Galvan, P. Stephens, M. D. Butala, V. Akopian, B. D. Wilson, O. Verkhoglyadova, A. J. Mannucci, and M. Hickey (2012), Detecting ionospheric TEC perturbations caused by natural hazards using a global network of GPS receivers: The Tohoku case study, *Earth Planets Space*, *64*, 1287–1294, doi: 10.5047/eps.2012.08.003.

Ridley, A. J., Y. Deng, and G. Toth (2006), The global ionosphere-thermosphere model, *J. Atmos. Solar Terr. Phys.*, *68*, 839–864, doi: 10.1016/j.jastp.2006.01.008.