Recent Developments in Understanding Natural-Hazards-Generated TEC Perturbations: Measurements and Modeling Results

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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 deformation 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 this paper, 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. Our study strongly suggests that both ground-based and space-borne 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. The GNSS-based remote sensing of natural-hazard induced ionospheric disturbances could potentially be applied to operational tsunami and earthquake 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., Artru et al., 2001; 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, earthquakes, volcanic eruptions and asteroid atmospheric impacts, for example, using real-time data from GPS and other global navigation satellite systems. In the research reported in this paper, 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.

METHOD OF GENERATING TEC MEASUREMENTS

The ionosphere is a dispersive medium for GNSS signals. The refractive index for a radio wave of frequency f (to the 1st order) is $n_p \approx 1 - 40.3N_e/f^2$, where n_p is the phase refractive index and N_e is the electron density. As a radio wave travels through the ionosphere, one can calculate the excess phase delay $\delta\tau_p$ (in meters) from the refractive index n_p as:

$$\delta\tau_p = -40.3 \cdot TEC/f^2. \qquad [1]$$

GPS measurements from Gravity Recovery and Climate Experiment (GRACE) dual-satellite precise orbit determination (POD) receivers are used to calculate GPS-derived TEC time series from the carrier phase (Φ_1 and Φ_2) and pseudorange data (P_1 and P_2). Furthermore, the GPS-derived TEC is given as

$$TEC = \frac{f_1^2 f_2^2}{40.3(f_1^2 - f_2^2)}(B - (\Phi_2 - \Phi_1)) , \qquad [2]$$

where f_1 and f_2 are the GPS L1 and L2 frequencies, Φ is the carrier phase measurement, and B is the ambiguity term defined, e.g., in Mannucci et al. [1993]. In addition, this approach also applies to the retrieval of the change of the TEC time series (ΔTEC(t)) from GRACE K/Ka band ranging signals, which is defined as

$$\Delta TEC(t) = dR(t) \cdot f_{ka}^2/40.3, \qquad [3]$$

where $f_{ka} = 32$ GHz.

NATURAL HAZARD INVESTIGATIONS AND ANALYSIS

In this section, we summarize recent processing results for selected natural-hazard events including the 2011 Tohoku-Oki earthquake and tsunami and the 2013 Chelyabinsk asteroid impact on the atmosphere.

2011 Tohoku-Oki Earthquake and Tsunami. On March 11, 2011, a large (Mw = 9.0) earthquake occurred off the Pacific coast of Tohoku, Japan (38.103°N, 142.861°E) at

05:46:23 UTC. It triggered a powerful tsunami with destructive run-up waves up to 10 meters in wave height. Concurrent GPS-based remote-sensing results indicate that the co-seismic traveling ionospheric disturbances (TIDs) may be characterized with horizontal propagation speeds of 3 km/s, 1 km/s, and 200 m/s that were found to be in agreement with the propagation speeds of Rayleigh waves (3.3 km/s), acoustic waves (1 km/s at altitude of 300 km in the ionosphere), and gravity waves triggered by a fault slip and its following tsunami (200 m/s) respectively [Galvan et al., 2012]. It has been demonstrated that large and dense GPS networks provide new opportunities to detect ionospheric signatures of large earthquakes such as the Tohoku-Oki earthquake and the resulting tsunami-induced ionospheric responses. However, TEC measurements from GPS satellites to ground-based receivers are often affected by measurement biases due to "phase cancelation effects." Phase cancelation effects, prominent in integrated measurements of signals from satellites (such as TEC), were introduced by Georges and Hooke [1970].

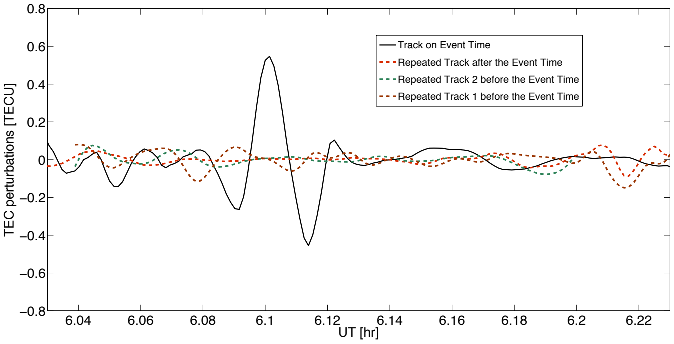

Figure 1. The TEC perturbations (black line) that correspond to different GRACE tracks passing through the region close to the event time. Significant TEC disturbances are observed about 20 minutes after the Tohoku-Oki main shock in Alaska. Other TEC waveforms (dashed lines) present the observations corresponding to repeated tracks traveling the same area (Alaska) at the same UTC on days before and after the event day. Results indicate that no significant TEC perturbations were observed one day before and after the track corresponding to the event time.

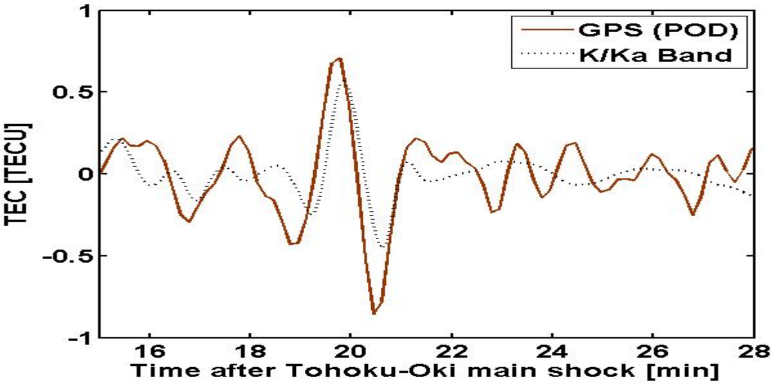

Figure 2. The TEC disturbances retrieved using a GRACE GPS receiver (POD) corresponding to GRACE tracks traveling through the same region (Alaska) during the event time.

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 and Figure 2) 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 [Yang et al., 2014b].

The Chelyabinsk Asteroid Event. A recent natural hazard event of high interest – the Chelyabinsk asteroid and resulting meteor, the largest since 1908 – entered the Earth's atmosphere with an estimated speed of approximately 18.6 km/s and impacted Chelyabinsk, Russia, on February 15, 2013 [Borovička et al., 2013; Popova et al., 2013]. The estimated effective diameter of the asteroid was about 20 meters, with a mass of about 10,000 metric tons, and the estimated total kinetic energy before the atmospheric impact was equivalent to 410 kilotons of TNT. Due to the shallow atmospheric entry angle of the asteroid, the Earth's atmosphere absorbed most of the energy from the generated explosions, shock waves and heat. The hypersonic bolide generated powerful shock waves while acoustic perturbations in the atmosphere led to the upward propagation of acoustic and gravity waves into the ionosphere. In our research, we applied two different techniques to detect ionospheric disturbances in dual-frequency GPS measurements during the asteroid impact event. The data were collected from near-field GPS networks in Russia, GEONET in Japan, and Plate Boundary Observatory (PBO) stations in the coterminous U.S. Using a novel wavelet coherence detection technique [Yang el al., 2012], we were able to identify three different wave trains in the measurements collected from the nearest GPS station to the impact site, with frequencies of approximately 4.0 - 7.8 mHz, 1.0 - 2.5 mHz, and 2.7 – 11 mHz at 03:30 UTC. We estimated the speed and direction of arrival of the TEC disturbances by cross-correlating TEC time series for every pair of stations in several areas of the GEONET and PBO networks. The results may be characterized as three different types of traveling ionospheric disturbances. First, the higher frequency (4.0 - 7.8 mHz) disturbances were observed around the station ARTU in Arti, Russia (56.43º N, 58.56º E), with an estimated mean propagation speed of about 862 ± 65 m/s (with 95% confidence interval). Another type of TID disturbance related to the wave trains was identified in the lower frequency band (1.0 - 2.5 mHz), propagating with a mean speed of 362 ± 23 m/s. The lower frequency ionospheric perturbations were observed at distances of 300-1500 km away from Chelyabinsk. The third type of TID wave train was identified using the PBO stations in the relative short period range of 1.5 - 6 minutes (2.7 – 11 mHz) with a mean propagation speed of 733 ± 36 m/s. The observed short-period ionospheric perturbations in the U.S. region is, to the best of our knowledge, the first observational evidence of the coincident long-range meteor-generated infrasound signals propagating in the ionosphere, as shown in Figure 3 [Yang et al., 2014a].

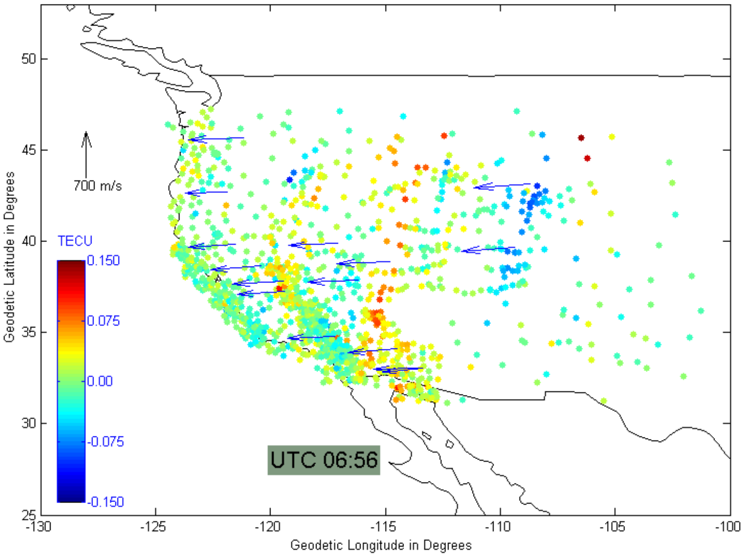

Figure 3. Snapshot of TEC perturbations following the asteroid atmospheric impact at 06:56 UTC. Color-scaled points represent the TEC perturbation magnitudes at each ionospheric pierce point (in geodetic longitude and latitude) corresponding to each line of sight station-to-satellite pair for the coterminous GPS stations to PRN 8 and PRN 17. Blue arrows and the black vector represent the estimated TID propagation velocities and a reference velocity vector, respectively. The starting points of the blue arrows represent the ionospheric-pierce-point locations with maximum TEC perturbations in a subarea [Yang et al., 2012].

MODEL SIMULATIONS OF EARTHQUAKE- AND TSUNAMI-IONOSPHERE COUPLING

In this section, 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 [Ridley et al., 2006].

In this research, we apply the model to simulate the ionospheric perturbations after the Tohoku-Oki earthquake. The simulation domain covers 50°N to 66°N in geodetic latitude, 159°W to 167°W in geodetic longitude, and up to 600 km in altitude. To model the earthquake-generated perturbations, we perturb the simulated east wind at the lower boundary of GITM starting at the arrival of infrasound and seismic waves (05:57:30 UTC) in the region. The perturbation is a cosine wave with a duration of 90 seconds, a period of 1 minute and pressure amplitude of 2 Pa. These parameters are obtained from the co-seismic infrasound waves observed by IMS I53US. The simulation results seem to support the conclusion that the infrasound waves will take about 8 minutes to propagate from the Earth's surface to the height of the GRACE satellites. They generate up to 4% amplitude density perturbations (against the ambient air-density background) as shown in Figure 4. The results of JPL's three-dimensional atmosphere-ionosphere modeling seem consistent with the arrival time and physical characteristics of the disturbances at GRACE.

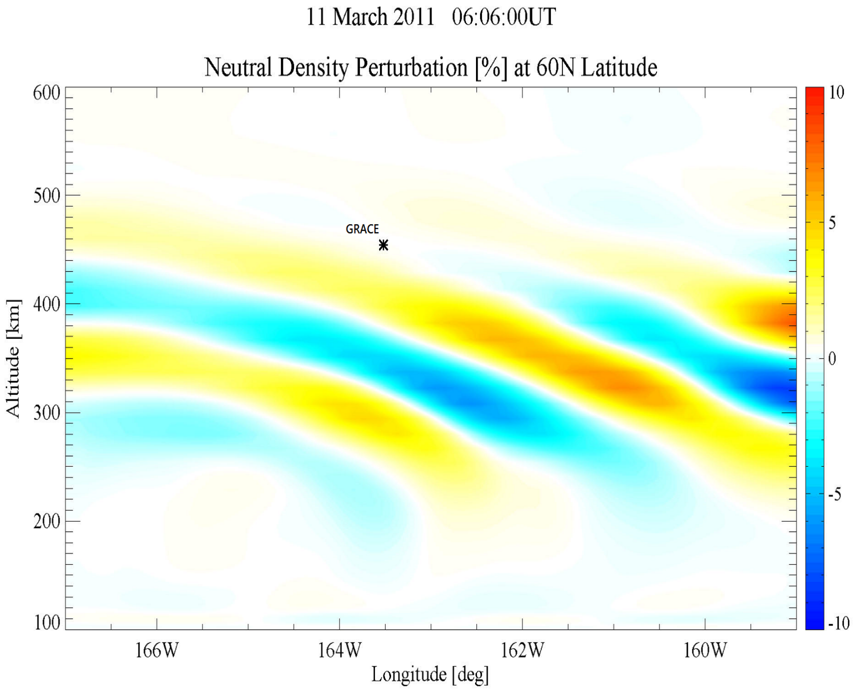

Figure 4. Snapshot of GITM-simulated neutral density perturbation 20 minutes after the main shock with approximate GRACE location (denoted by asterisk).

CONCLUSIONS

Using ground- and space-based GPS measurements we demonstrated the observational evidence of atmosphere-ionosphere signatures associated with natural hazards including the 2013 Chelyabinsk asteroid impact and the 2011 Tohoku-Oki earthquake and tsunami. We found that the TEC perturbations are consistent with the arrival of meteor infrasound signals and Tohoku-Oki earthquake-generated seismic waves. For the Tohoku-Oki event, 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.

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