Real-Time Detection of Tsunami Ionospheric Disturbances Using a VARION Approach: Results for the 2011 Tohoku-Oki and 2012 Queen Charlotte Island (Haida Gwaii) Events

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Abstract

It is well known that strong earthquakes and tsunamis can produce acoustic and gravity waves that propagate up to the ionosphere, disturbing the electron density in the F region. These ionospheric disturbances can be studied in detail estimating the ionospheric total electron content (TEC) through continuously operating ground-based receivers from the Global Navigation Satellite Systems (GNSS). Modeling efforts have shown atmospheric gravity waves caused by tsunamis may be detected as traveling ionospheric disturbances (TIDs) [1]. If TEC variations are estimated and geolocated in real-time, there is a potential to provide the tsunami speed and amplitude, in order to develop an operational tsunami early warning systems [3]. Thanks to the intrinsic real-time operating feature of VADASE (Variometric Approach for Displacements Analysis Standalone Engine), the algorithm was successfully applied to estimate ground velocities and displacements induced by an earthquake [2]. The algorithm was modified and applied to geometry-free combination of GPS carrier-phase measurements for estimating TEC variations. This new algorithm, named VARION (Variometric Approach for Real-time Ionosphere Observation), was designed in 2015 by University of Rome "La Sapienza", Department of Civil, Building and Environmental Engineering, and subsequently in 2016 further developed and validated in collaboration with the Ionospheric and Atmospheric Remote Sensing Group, Jet Propulsion Laboratory. The approach is based on single time differences of geometry-free combination of GPS carrier-phase measurements, using a standalone GPS receiver and standard GPS broadcast products (orbits and clocks corrections) that are available in real-time. Hence, one receiver works in standalone mode and the TEC variations between two consecutive epochs are estimated (Eqn. 1).

$$\delta TEC(t+1,t) = \frac{{f_1}^2 {f_2}^2}{A({f_1}^2 - {f_2}^2)} \left[L_{4R}^S(t+1) - L_{4R}^S(t) \right] \tag{1}$$

Subsequently, the TEC variations are integrated over the time interval during which the tsunami event occurred to retrieve tsunami ionospheric disturbances (Eqn. 2).

$$TEC(t_f, t_0) = \int_{t_0}^{t_f} \delta TEC(t) \tag{2}$$

We applied this new algorithm to the 2011 Tohoku-Oki and 2012 Haida Gwaii earthquake events, comparing the results with JPL's PyIono algorithm and we found a good agreement, as shown in Figure 1. The differences in amplitude between the two time series are due to the different data filtering methods applied. The VARION results were filtered by computing the ionospheric carrier-phase residuals using an 8^{th} order polynomial fit while the PyIono algorithm uses a band-pass filter (corresponding to waves with frequencies between 0.5 and 5 mHz) [6]. Concerning the geolocation of the TEC mea-

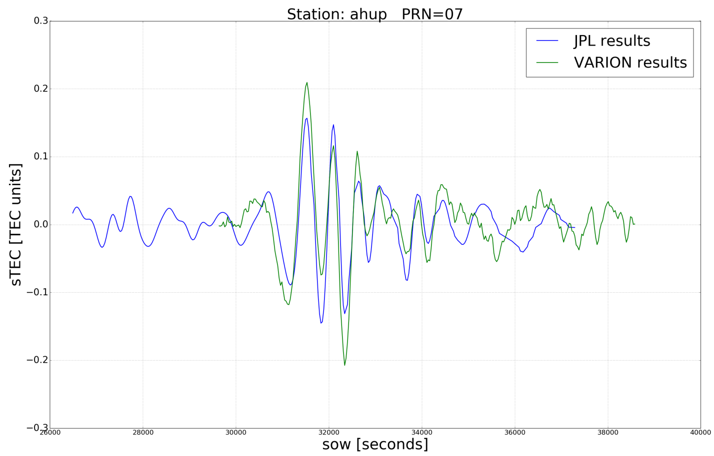

Figure 1. Comparison between the two different data processing techniques for GPS satellite 07 and AHUP station for TIDs associated with the tsunami.

surements, the VARION algorithm uses the Klobuchar broadcast ionospheric model that approximates ionospheric thin shell [4] in order to compute the coordinates of the sub-ionospheric points in real-time. A magnitude 9.0 earthquake occurred on March 11, 2011 at 05:46:23 Universal Time (UT) off the coast of Japan. The earthquake generated a major tsunami resulting destruction along the coast. Using the VARION algorithm the TEC variations has been computed from station MIZU (Mizusawa, 140 km from the epicenter), collecting high-rate GPS data (1 Hz). At 03:04:08 Universal Time (UT) on 28 October 2012, a magnitude 7.8 earthquake occurred 202 km SSW of Prince Rupert, Canada. The earthquake produced an ocean tsunami that arrived at the Hawaii Islands about 5 hours later. Using the VARION algorithm the TEC variations were computed with 46 GPS receivers on the Hawaii Island. We observed TEC perturbations with typical amplitudes of up to 0.2 TEC units for this event. Figure 2 shows that the estimated speed of the tsunami ionospheric disturbances (TIDs) is about 270 m/s and it is in good agreement with a typical speed of the gravity waves.

In addition, we compared the TEC observations with the real-time tsunami MOST (Method of Splitting Tsunami) model produced by the NOAA (National Oceanic and Atmospheric Administration) indicating wavefront positions both for the ocean waves and ionosphere TEC variations. We observed variations in TEC that correlated in time, space, with wave properties of the tsunami waves.

There exists the potential to apply this data processing using all the GNSS constellations, in order to have a better coverage that may be useful for real-time early warning systems. In fact, the GNSS is a powerful tool not only for monitoring crustal deformations but also detecting seismic ionospheric variations, especially for regions with dense GNSS coverage using continuous operating stations. GNSS provides us a new opportunity to monitor the detail of fault rupture with high spatial-temporal resolution. Moreover, it will give us a new perspective to understand the earthquake effect with seismic ionospheric disturbances.

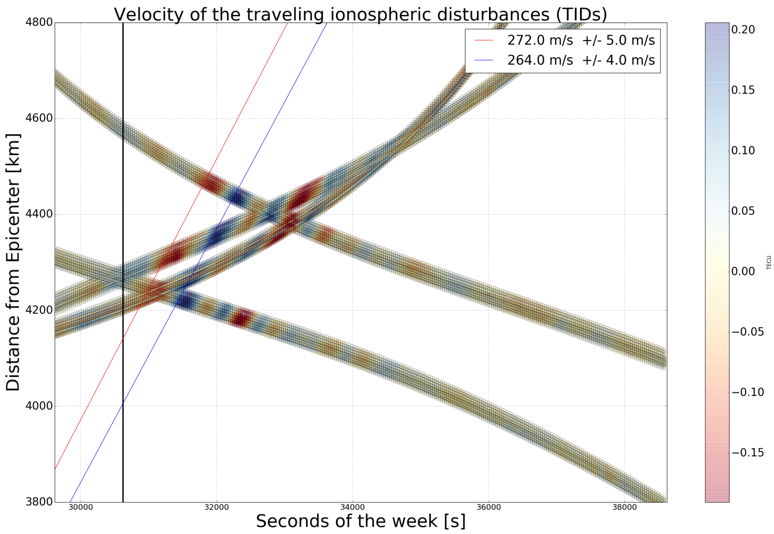

Figure 2. TEC derived using 4 satellites in view from 46 GPS stations. We used a least-squares regression line to fit the measutements. The slopes of the lines may be interpreted as the velocity of the TID disturbances.

Key words: Ionospheric disturbance, Ionospheric seismology, GNSS early warning system, TEC

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