Ionospheric disturbances driven by seismic tsunami-excited gravity waves

1. Introduction

Big earthquakes and tsunamis can excite acoustic resonance between the earth or ocean surface and the lower atmosphere. Owing to the wave amplitude increase against the decrease of the atmosphere density and makes the upper atmosphere a good medium to propagate the gravity waves. Some of the resonance waves leaks upward into the ionosphere and trigger ionospheric anomalies which can be observed as traveling ionospheric disturbances (TIDs). These TIDs generated by ocean waves was first established by Daniels and the theory was developed by Hines. There are different methods to detect these TIDs, including radar altimeter, incoherent scatter radar, ground-based GPS network. In addition, the ionospheric data from radio occultation which is performed between a GPS satellite and a Low Earth Orbit (LEO) satellite was applied to detect the ionospheric disturbances following the 11 March 2011 earthquake and tsunami off coast of Tohoku by Piedavide et al (2014). The gravity waves were also detected in neutral atmosphere by the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellite with low orbiting altitude of 250km [Carcia et al., 2014].

The Global Positioning System (GPS) is a powerful tool to analyze the atmospheric or ionospheric response to the earthquakes and tsunamis especially for regions with dense GPS continuous operating stations. There are delays caused by the tropospheric and ionospheric refraction when the GPS signals path through the atmosphere of Earth. The delays include lengthening of the geometric path and variation of signal's group velocity and phase velocity. The differences between dual-frequency carrier phase (L1 and L2) observations contain the information of ionosphere including TEC. When signal travelling through the atmosphere or ionosphere, the frequency of the signal will be affected by the neutral gas and ionospheric plasma. GPS-TEC was first used as a sensor to analysis the solid Earth [Calais and Minster,1995]. Later GPS-TEC was applied into earthquake and tsunami study. For instance, 2008 Wenchuan earthquake and 2011 Japan earthquake and tsunami were studied and a detailed method of GPS-TEC was introduced by Shuanggen Jin et al (2015).

The ionospheric anomalies after the earthquakes or tsunamis were widely analyzed based on GPS-TEC, firstly the TEC anomalies following the earthquake were widely known as a N-shape disturbance [Heki et al. 2006]. Later the TEC disturbances following earthquakes and tsunamis were found to be more complicated and have different modes with different features. Heki et al. reported that the seismic ionospheric disturbance following the great Sumatra earthquake in 2004 was mainly related to the direct acoustic wave from the focal area, tsunami induced gravity wave and secondary acoustic wave exited by the Rayleigh wave in the far field. The results of the 2011 Tohoku earthquake in Japan also showed three modes with different propagation velocities, which include tsunami generated gravity waves (0.1-0.3 km/s), acoustic waves (0.3-1.5 km/s) and seismic Rayleigh waves (2-3 km/s).

The features including velocities, propagating direction, amplitude and so on of TEC anomalies were widely studied by researchers in the last decade. And then more attention was paid to understanding the coupling mechanism between the tsunami and ionosphere. Three-dimensional model of ocean-wave disturbances triggered by earthquakes and tsunamis, the one-dimensional model of atmospheric gravity wave propagation and the one-dimensional model of ionospheric response to the earthquakes and tsunamis are combined by Occhipinti et al (2006) to simulate the ionospheric disturbances following the 2004 Sumatra tsunami. And the perturbation results were compared with the TEC observations obtained from Jason-1 and Topex-Position satellites and there were good agreement between the model simulations and satellite observations. However, the influence of atmospheric viscosity on the propagation of gravity waves is not considered in the simulation, which makes the velocity of disturbance not consistent with the fact, and the vertical and horizontal wind fields perturb the velocity to 600 m /s. Occhipinti et al (2008) simulated the ionospheric response to heavy waves at different latitudes. And their results demonstrate that the coupling of neutral and ionospheric ions in low latitudes was significantly stronger than that in mid-latitudes.

The coupling between the tsunamis and ionosphere is complicated and there are many factors should not be ignored. Hickey et al proposed that the influence of Coriolis force, atmospheric viscosity and background wind field should be taken into consideration when simulating the tsunami-induced interaction of gravity waves with the ionosphere. The ionospheric disturbances of the gravity waves generated by Japan’s tsunami in 2011, and they found that different wave propagation directions and horizontal wind fields related to the depth of the ocean also contribute to the upward propagation of the gravity waves. Therefore, the simulation of the ionospheric disturbances triggered by tsunami-induced atmospheric gravity waves should take full account of atmospheric viscosity and background wind and other natural physical processes, as well as wave propagation direction and geomagnetic properties.

It can be seen that the current research on the ionospheric disturbances caused by the gravity wave include observation data analysis and numerical simulation. Scientists compare the simulated data with observed data to help understand the actual propagation of gravity waves and their perturbations in the ionosphere. Galvan et al (2016) used the coupled model of atmosphere and ionosphere and the Song model to simulate the ionospheric disturbance caused by the atmospheric gravity wave triggered by the Japan tsunami in 2011. And combined the modeling results with the TEC perturbation time series from GPS observation data of Japan's GEONET network. It is found that the maximum disturbance caused by the Japanese tsunami in the ionosphere is 1.5 TECU in the southeast direction.

Although researchers made many progress in this field, the core scientific problems regarding the nature of the coupling between the ocean and ionosphere are still not sufficiently understood and let alone the accurate tsunami warning. The tsunamis can cause great damage to human beings, about 20 thousand people died because of the 2011 tsunami of Japan. Dense scientific observation network is equipped in Japan, while the present tsunami forecasting systems are not effective. Traditional forecasting system based on the long-period waves cost too much time to calculate the accurate information of the rapture area and it is hard to predict the near-field tsunami. And density network of offshore monitoring for tsunami using GPS buoys and ocean-pressure gauges required a large budget and human power. While the TEC disturbances could be detected about 10-20 min after the main shock and the high speed of the development of GPS network which make ground-GPS observations processed in real-time may have the potential to enhance the current system by independently providing the tsunami speeds and amplitude.

1. Theory and Methods

TEC can be easily derived from GPS dual-frequency observations. The GPS equation of carrier phase and code observations are as follows (Shuanggen Jin et al,2015):



in which k=1,2 represent dual-frequency carrier phase. L is the carrier phase measurement, P is the code measurement, is the true distance between the GPS satellite and receiver, and  are ionospheric delay and tropspheric delay respectively, c is the speed of light in a vacuum, is the clock error, b is the phase advance of instrument bias, d is the code delay of instrument bias, N is the ambiguity of the carrier phase, and is residuals in the GPS measurement.

The delay when GPS signals travel through the ionosphere is

and the TEC is expressed as:

The difference of the dual-frequency phase and code observations contain the information of the ionospheric delay, and the TEC can be calculated by the following equation(Shuanggen Jin et al,2015):



or

Before estimating the STEC, the cycle slips must be detected and repaired to get clean GPS observations, here we use a second-order and time-difference phase ionospheric residual(STPIR) algorithm (Cai et al., 2013). Besides we consider the instrument bias, ambiguity of the carrier phase and residuals as constants for one continuous arc and can be ignored because that we pay more attention to the disturbance of TEC instead of the absolute TEC. After obtaining the TEC series, the variations of TEC series can be derived by smoothing the original TEC series or calculating the gradient of the TEC series. In our work, the four-order zero-phase Butterworth band-pass filter with cutoffs at 3mHz and 8 mHz was applied to isolate the acoustic component of TEC perturbation(Thomas Dautermann et a., 2008).

1. Initial results and Discussion
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* 1. Haida Gwaii, Canada earthquake

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* 1. Maule, Chile earthquake







1. Coupling and Modeling
2. Summary

Reference