TAO, Vol. 17, No. 2, 345-351, June 2006

Ionospheric Disturbances Triggered by the M_w 7.6 Earthquake off the Coast of El Salvador on 13 January 2001

Ting-Kuo Jung[1], Jann-Yenq Liu[1, 2, *], Ho-Fang Tsai[3], Bor-Shouh Huang[4], and Cheng-Horng Lin[4], Shui-Beih Yu[4], and Yih-Shiung Yeh[4]

(Manuscript received 8 April 2005, in final form 27 April 2006)

ABSTRACT

A network of five ground-based receivers of the global positioning system (GPS) was use to detect seismo-ionospheric disturbances in the total electron content (TEC) triggered by the 13 January 2001 El Salvador M_w 7.6 earthquake. We apply least square fitted analysis as well as beam forming and ray tracing methods to analyze the GPS TECs. Results show that the average speeds of the seismo-ionospheric disturbances traveling in the upper atmosphere and ionosphere lie between 360 and 570 $m\ s^{-1}$, and the disturbance origins on the ground derived by the two methods are near the epicenter reported by the U.S. Geological Survey (USGS).

(Key words: Ionosphere, GPS TEC, Space seismometer, Beam forming method, Ray tracing method)

1. INTRODUCTION

The ionosphere has sensitive responses to a variety of disturbances, including natural and manmade sources; for example, sever weather, volcanoes, earthquakes as well as nuclear detonations (Davies 1990). Many scientists by using HF (high frequency) Doppler sounding systems or ionosondes have observed ionospheric disturbances triggered by strong earthquakes (see papers listed in, Davies 1990; and Liu et al. 2005). Near-surface earthquakes causing large vertical near-field displacement of the Earth's surface excite mechanical disturbances in the neutral atmosphere, which propagate to the ionosphere where they couple into the ionized

[1] Institute of Space Science, National Central University, Chung-Li, Taiwan, ROC
[2] Center for Space and Remote Sensing Research, Chung-Li, Taiwan, ROC
[3] Center Weather Bureau, Taipei, Taiwan, ROC
[4] Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, ROC
* *Corresponding author address:* Prof. Prof. Jann-Yenq Liu, Institute of Space Science, Chung-Li, National Central University, Taiwan, ROC; E-mail: jyliu@jupiter.ss.ncu.edu.tw

gas (Blanc 1985). Since atmospheric density decreases almost exponentially with altitude, energy conservation implies that pulse amplitude increases upward as it propagates into the atmosphere and ionosphere. The amplification factor can reach tens to hundreds of thousands at ionospheric heights (Calais and Minster 1995). For example, a 10-cm vertical displacement of the Earth's surface possibly excites a 10-km vertical motion in the ionosphere. Scientists find that short period (< 1 min) waves are due to Rayleigh waves, while long period (few min to hrs) acoustic gravity waves have propagation speeds ranging from 300 to 800 $m\ s^{-1}$ (Davies 1989).

Recently, geodetic scientists investigated Earth's surface deformation rates using ground-based GPS networks (e.g., see Calais and Amarjargal 2000). While observing deformation, the same networks can be simultaneously employed to monitor total electron content (TEC) (Liu et al. 1996; Liu et al. 2001). The TEC is defined as the sum (or integration) of ionospheric electron density along line-of-sight from a ground-based receiver to the associated GPS satellite at an orbital altitude of about 22000 km (for detail, see Liu et al. 1996). The greatest electron density in the ionosphere usually situates at about a 300-km altitude, which contributes to the heaviest weight in the slant TEC calculation. Based on the spirit of the center of mass, the center of the TEC at about a 350-km altitude is termed the ionospheric point. Therefore, a GPS TEC acts as a space seismometer floating at about 350 km above the Earth's surface to monitor ionospheric disturbances. From recorded GPS broadcast ephemeris, the latitudinal and longitudinal coordinates of each space seismometer are obtained. Since a ground-based receiver tracks multiple GPS satellites, scientists can simultaneously monitor ionospheric TEC disturbances in a large area. In this paper, we apply a least square fitted analysis as well as the beam-forming and ray-tracing methods analyzing GPS TEC observations to locate the origin and compute average propagation speeds of seismo-ionospheric disturbances triggered by the 13 January 2001 El Salvador $M_w 7.6$ earthquake.

2. OBSERVATIONS AND RESULTS

A major earthquake occurred ($M_w 7.6$; 12.8°N, 88.8°W) off the coast of El Salvador about 110 km south-southeast of San Salvador at 17:33:29 UT (11:33:29 AM local time (LT) in El Salvador), 13 January 2001. The main shock is determined to be a normal faulting event within the Caribbean plate above the subducting Cocos plate. The El Salvador epicenter is located around 5 tracking stations (ground based GPS receivers) of the International GPS Service (IGS) (Fig. 1). Beacons from three GPS satellites #1, #13, and #19 to the five receivers consist of a network of 11 space seismometers floating at a height of about 350 km to monitor ionospheric disturbances triggered by the earthquake.

Figure 2 displays that the seismo-ionospheric disturbances in the time rate of change of total electron content every 30 seconds, rTEC, (Liu et al. 2004) appeared about 12 min after the earthquake's onset. It can be seen that space seismometer S-13, locating at 350 km altitude right above the epicenter (Fig. 1), detects the seismo-ionospheric disturbance in rTEC at 07:43 UT, which is about 571 seconds (17:33 - 17:43UT) after the earthquake's onset. We then roughly estimate the average vertical speed of the seismo-ionospheric disturbance of 570 $m\ s^{-1}$

Fig. 1. The epicenter, GPS tracking stations, and the associated space seismometers. The black star shows the epicenter of El Salvador Earthquake on 13 January, 2001. The red triangles show the operating GPS receivers and the red dots show the associated ionospheric points of the space seismometers. For example, S-13 denotes the space seismometer of the slant TEC from SLOR station to the GPS satellite #13.

with the distance of 350 km divided by the time delay of 571 seconds (Fig. 2).

A least square fitted method proposed by Ducic et al. (2003) can be employed to calculate the average horizontal and vertical speeds of the seismo-ionospheric disturbances. Figure 3 illustrates the time rate of TEC changes observed by each space seismometer and the distance from the associated space seismometer to the epicenter versus the time delay (or travel time). Two parallel slopes, one being the least square fitted of the 11 seismo-ionospheric disturbances (also shown at 17:45 UT in Fig. 2) and the other going through the earthquake-onset time, indicate that the average horizontal speed is about 1.7 ± 0.3 $km\ s^{-1}$. Meanwhile, the time difference between the two slopes is due to the time delay of vertical propagations. Thus, the average vertical speed of the vertical propagation 486 ± 80 $m\ s^{-1}$ can be derived by the alti-

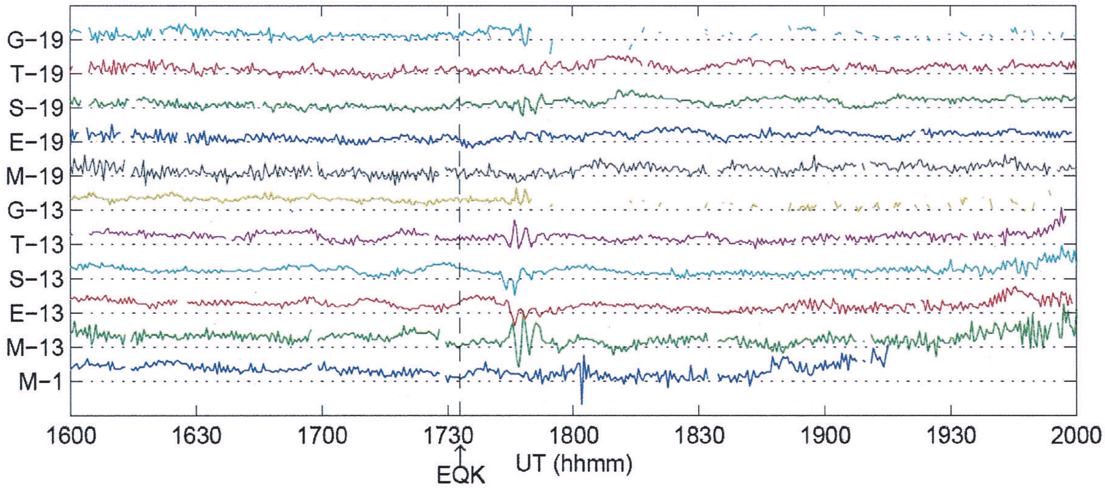

Fig. 2. The time rate of TEC changes triggered by the El Salvador Earthquake on 13 January 2001. The dashed line denotes the earthquake onset. The time rate of TEC change, rTEC (= ΔTEC/Δt, where TEC is in TECu, 1 TECu = 10^{16} el m^{-3} and Δt = 30 sec). The vertical grid denotes in 0.1 TECu 30 sec^{-1}.

tude of space seismometers at 350 km divided by the time difference of about 12 minutes.

Alternatively, we apply two standard seismological methods, beam-forming (Huang et al. 1999) and ray tracing (Lee and Lahr 1972) to locate the origin of the disturbances on the ground and together to calculate the average speeds of the disturbance propagations. For simplicity, we assume that the seismo-ionospheric disturbances travel away from the earthquake source in a radial direction.

The beam forming method is a quite simple approach to guessing a possible origin location area by applying a grid search. It calculates the mean and standard deviation of the speeds of the seismo-ionospheric disturbances at each trial point by dividing the distance between the trial grid point and each space seismometer by the observed time delay, and repeating this procedure with all grid points. Then, we contour the calculated standard deviations finding the minimum, which is considered to be a detected origin of the seismo-ionospheric disturbance. Here, we take 0.1° as the grid interval in both latitudinal and longitudinal directions, and calculate the mean and associated standard deviations from 8°N, 92°W to 17°N, 85°W for each grid point. The contour in Fig. 4 shows that the average velocity of seismo-ionospheric disturbances is 426 ± 67 m s^{-1}, and the calculated origin is at 13.8°N, 89.0°W, which is about 100 km north of the epicenter reported by the US geological Survey (USGS).

Meanwhile, the ray-tracing method is applied to deduce origin location. This method

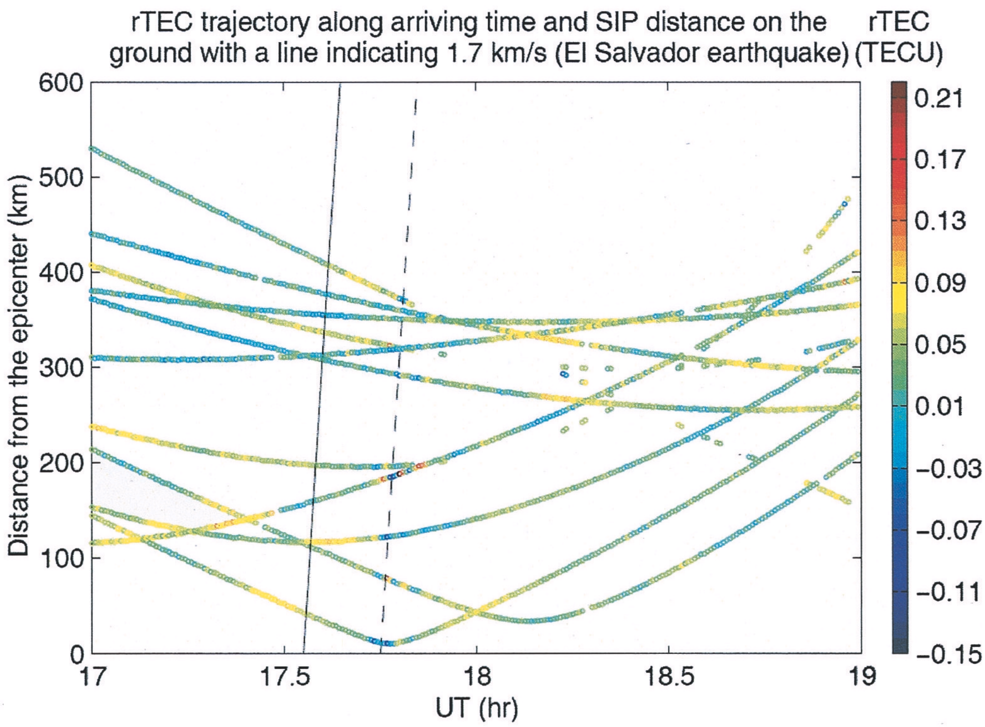

Fig. 3. The distance-time-rTEC plot. This plot denotes the distance from each space seismometer to the epicenter, the time period after the earthquake onset, and the time rate of TEC changes rTEC. The dashed and solid lines denote the least square fitted of the arrival times of the eleven seismo-ionospheric disturbances and parallel slope through the earthquake onset time.

requires a velocity model. Based on previous observations (Davies 1989), a suitable velocity model has the seismo-ionospheric disturbance traveling radially from its origin with a velocity ranging from 300 to 800 $\mathrm{m\ s^{-1}}$. By trying a velocity within the model range, we calculate travel times, and then minimize the differences between the observed and calculated travel times from the trial origin to the space seismometers. In general, the latitude and longitude of the earthquake focus and its onset time can be determined if arrival times at three or more observatories are available. Here, the arrival times of the 11 disturbed signatures shown in Fig. 2 are picked to locate the disturbance origin. For example, the signature with a clear arrival time at the space seismometer T-13 is given with a larger weight, but that at T-19 is given by a smaller weight. The optimum result with the smallest standard deviation shows that the origin is located at 13.2°N, 88.6°W, given a velocity of about 500 $\mathrm{m\ s^{-1}}$ for the seismi-ionospheric disturbance traveling radially from Earth's surface to the ionosphere at 350 km. Note that the located origin is very close to the epicenter (12.8°N, 88.8°W) reported by the USGS (Fig. 4).

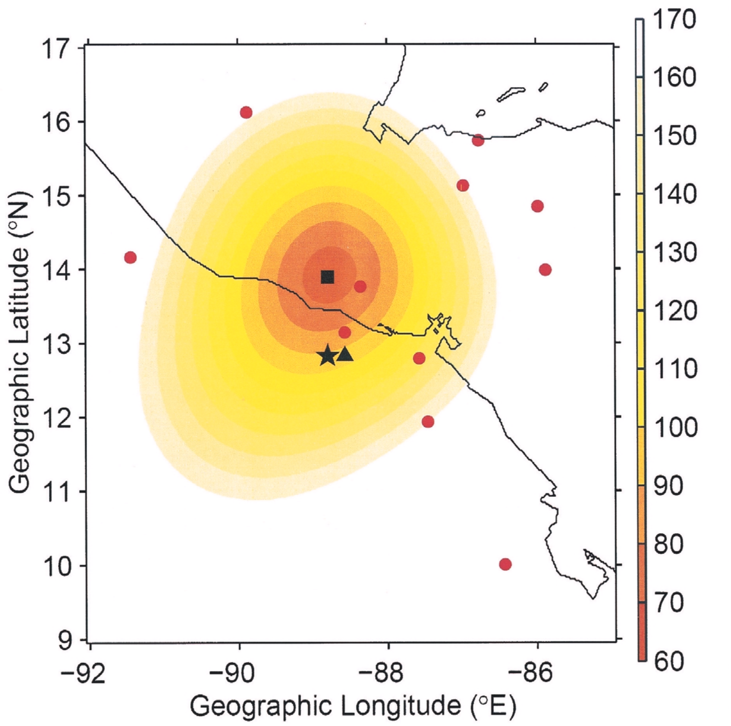

Fig. 4. Locations of the USGS epicenter and detected epicenters by the beam forming and the ray tracing methods. The contour is the percent error of the seismic velocity derived from the beam forming method. The black star, square, and triangle indicate epicenters reported by the USGS, as well as origins calculated by the beam forming and the ray tracing methods, respectively. The red dots are the location of the ground projection of the 11 space seismometers.

3. SUMMARY AND CONCLUSION

Seismometers have long been used to locate earthquake hypocenters, while GPS applications have been widely employed to study numerous earth sciences problems. In this study, we combine the two techniques to locate the origin and find the average speed of seismo-ionospheric disturbance simultaneously. A direct estimation from an overhead observation shows that the averaged vertical speed of the seismo-ionospheric disturbance observed is about 570 $m\ s^{-1}$, while the least square fitted method reveals that the averaged horizontal and vertical speeds of the disturbance are 1.7 ± 0.3 $km\ s^{-1}$ and 486 ± 80 $m\ s^{-1}$, respectively. Although the horizontal speed is less than the Rayleigh surface waves of about 3.5 $km\ s^{-1}$, the two average vertical velocities generally yield good agreement. Meanwhile, the average radial speeds derived from the beam-forming and ray-tracing methods are 426 ± 67 $m\ s^{-1}$ and 500 $m\ s^{-1}$, respectively. It can be seen that the two vertical and two radial average speeds are within the acoustic gravity waves of 300 - 800 m s^{-1} traveling in the atmosphere and ionosphere. The agreement between the calculated origins and the reported epicenter further confirms that the seismo-ionospheric disturbance was triggered by the 13 January 2001 El Salvador earthquake. There are thousands of permanent ground-based GPS receivers all over the world. The methods proposed herein provide an efficient alternative to locating disturbance origin and to having a better understanding of the propagation of seismo-ionospheric disturbances.

Acknowledgements This study was initiated when J. Y. Liu and H. F. Tsai visited Academia Sinica in Taiwan during January-April, 2000. This research was partially supported by the Ministry of Education under Grand 91-N-FA07-7-4 for the iSTEP project of the National Central University.

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