SPACE SEISMOMETERS

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ABSTRACT

A major earthquake occurred (Mw7.6; 12.83°N, 88.79°W) off the coast of El Salvador about 110 km south-southeast of San Salvador at 17:33:29 UTC (11:33:29 AM local time (LT) in El Salvador), Jan 13, 2001. A network of five ground-based receivers of the global positioning system (GPS) detects ionospheric disturbances in the total electron content triggered by the earthquake. Due to the satellite constellations, the GPS network simultaneously register seismo-ionospheric disturbances at various latitudinal and longitudinal locations. We then apply standard seismology techniques on those seismo-ionospheric disturbances to locate the epicenter. Results show that the located epicenters are near the one reported by the U.S. Geological Survey (USGS). The agreement suggests that ionospheric GPS measurements could provide with an alternative way to locate the epicenter.

INTRODUCTION

When an earthquake occurred, the first question would be "where was it?" A network of seismometers securely mounted onto the surface of the Earth is used to monitor the motion of the ground and record earthquakes. Based on recorded seismograms, seismologists could accurately determine the epicenter, depth, and magnitude of an earthquake. Many space scientists also observed ionospheric disturbances in the space as the result of seismic waves [1-6] and estimate the speed of the seismo-ionospheric disturbances. Recently, geodetic scientists have investigated Earth’s surface deformation rates by using ground-based GPS networks [7]. While observing Earth’s surface deformation, the same GPS networks can be simultaneously employed to monitor the total electron content (TEC) of the ionosphere [8-9]. In this paper, we combine the existing seismic techniques and GPS applications to construct a network of space seismometers and for the first time to locate the epicenter and accurately determine the speed of ionospheric disturbances.

OBSERVATION

The ionosphere can be affected by a variety of disturbances. Natural sources include, for example, severe weather, volcanoes, and earthquakes. Near-surface sources causing large vertical near-field displacement of the Earth’s surface excite mechanical disturbances (infrasonic waves) in the neutral atmosphere, which propagate to the ionosphere where they couple into the ionized gas [2]. Since the atmospheric density decreases almost exponentially with altitude, energy conservations imply that the pulse amplitude increase upward as it propagates into the atmosphere. The amplification factor can reach 10^4 at the ionospheric heights, where the coupling between the natural and ionized atmosphere results in fluctuations of ionospheric electron density [6]. For example, a 10-cm vertical displacement of the Earth’s surface possible excites a 1-km vertical motion in the ionosphere. Many scientists applied electromagnetic soundings to observe ionospheric disturbances as the result of mechanical coupling between the solid earth and the atmosphere at certain frequencies that allow the energy to be transferred into the atmosphere by seismic waves (in particular the surfaces) as they travel away from the epicenters of strong earthquakes [1-6].

To have a better estimation of the earthquake hazard, a large amount and broad distribution of GPS stations recording for a long time period are usually needed. This simultaneously provides a chance without any extra cost to observe the ionospheric TEC. The center of mass (electron density) of the TEC is termed the ionospheric point. The greatest electron density in the ionosphere usually situates at about 300s km altitude, which contributes the heaviest weight in the TEC calculation. Based on the spirit of the center of mass, TEC temporal variations practically represent the ionospheric disturbances occurring at about 300s km altitude. That is a GPS TEC, which acts as a space detector floating at about 300s km above the Earth's surface to monitor ionospheric disturbances. From recorded GPS broadcast ephemeris, the latitudinal and longitudinal coordinates of each space detector (or the ionospheric point) are then precisely determined [10]. Since a ground-based receiver could tracks multiple GPS satellites, scientists could simultaneously derive the TEC variations of various satellites and monitor perturbations in a large area of the ionosphere [6].

A major earthquake occurred (Mw7.6; 12.83°N, 88.79°W; Depth: 39.0 km) off the coast of El Salvador about 110 km south-southeast of San Salvador at 17:33:29 UTC (11:33:29 AM LT in El Salvador), Jan 13, 2001. The main shock (as a normal faulting event appeared within the Caribbean plate above the subducting Cocos plate. The El Salvador epicenter is located around 5 permanent stations of the International GPS Service (IGS) (Fig. 1). Beacons from three GPS satellites #1, #13, and #19 are found to be suitable to derive the TEC, which results in a network of 11 space seismometers (detectors) floating at a height about 300s km (Fig. 1) to be employed to monitor ionospheric disturbances triggered by the earthquake. However, it is difficult to identify any obvious earthquake related disturbance on the temporal variations of the TEC (Fig. 2a). To enhance as well as to detect precisely and correctly the earthquake disturbances, we further deduce their rates of change dTEC/dt by subtracting each TEC from its previous value, i.e. a simple 2-point differentiation. Fig. 2b clearly shows that ionospheric disturbances in dTEC/dt, which are in deed very similar records of typical seismometers, appeared about 10s min after the El Salvador. In previous, ionospheric scientists would find the distance and the associated time delay of each observed ionospheric disturbance to the epicenter and occurrence time of an earthquake reported by seismologists, and then estimate the speed of seismo-induced wave traveling in the ionosphere [1-6]. The distances between the space seismometers and the epicenter (Fig. 1) and their associated time delays (Fig. 2b) suggest that the speeds of seismo-induced waves traveling in the ionosphere during the El Salvador earthquake lie between 400 and 600 m/s, which generally agrees with the previous results.

Since the ionospheric disturbances are similar to the seismic wave(s) recorded by traditional seismometers, we therefore apply two standard seismological techniques, beam forming and ray tracing, to locate the epicenter and together to precisely calculate the seismo-waves traveling in the ionosphere. In other words, we are going to locate the epicenter from Space by simultaneously analyzing the disturbance wavefront passes observed by the network 11 seismometers floating at 300s km altitude.

The beam forming technique is a quite simple approach to guess a possible epicenter location area by grid search technique [11]. It includes to calculate the mean and standard deviation of each guess location using the speeds of the seismo-waves traveling in the ionosphere from the distance between the guessed grid point and each space seismometer with the observed time delays at each space seismometer; and then repeat this procedure through the whole grid points. Then, we contour the calculated standard deviations to find the minimum, which is considered to be a detected epicenter.

Fig. 1. The black star shows the epicenter of El Salvador Earthquake on Jan. 13, 2001. The red triangles show the operating GPS receivers and the red dots show the associated ionospheric points.

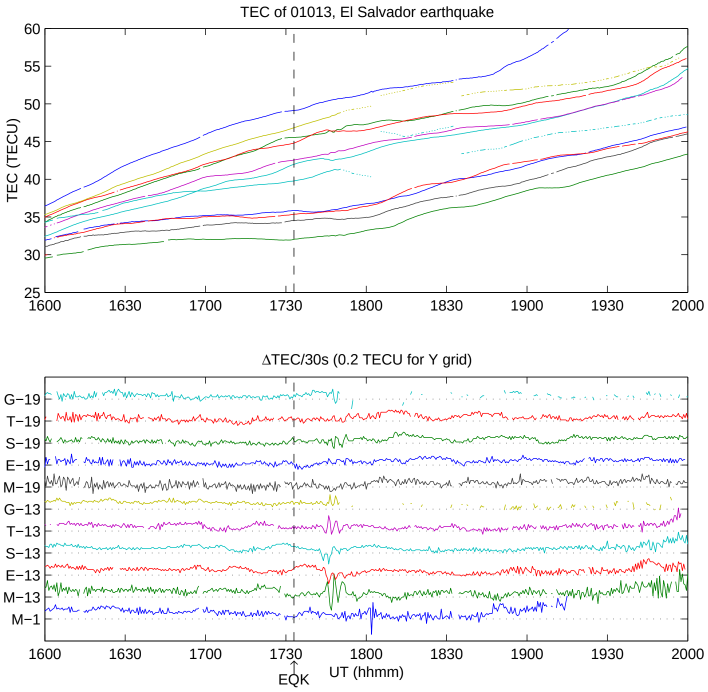

Fig. 2. TEC and its time rate of change of El Salvador Earthquake on Jan. 13, 2001. Dashed lines show the earthquake onset.

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, 266°E to 18°N, 276°E for each grid point. The contour in Fig. 3 shows that the mean velocity of seismic induced waves is 426±67 m/s, the epicenter detected from the GPS beam forming technique is at 13.8°N, 271.0°E, which is about 100 km north of the epicenter reported by the USGS.

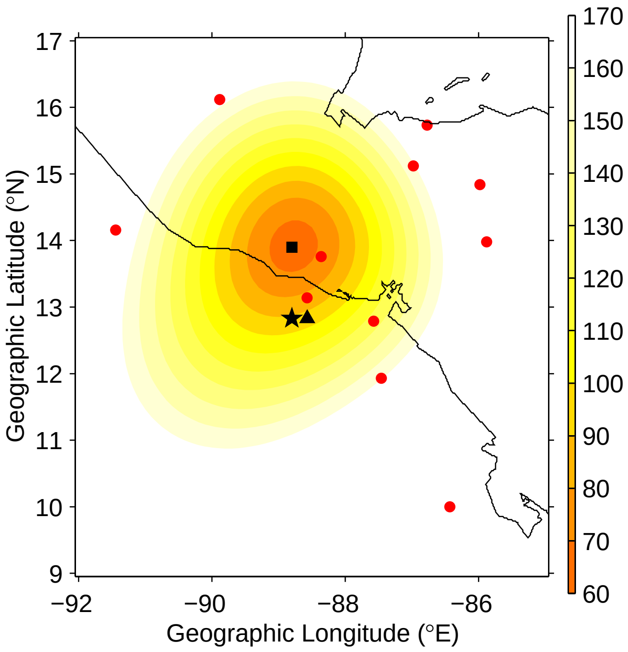

Fig. 3. The percent error of the seismic velocity detected by the ray tracing technique. The black star indicates the real epicenter. The black square and triangle indicate the detected epicenters by the ray tracing technique and the GPS beam forming technique, respectively.

Alternatively, the ray tracing technique is applied to deduce the epicenter location. The technique minimizes the differences between the observed and calculated travel times from the source to observatory stations (seismometers) by given a velocity model. To find the earthquake source, different locations and origin times are given to calculate the travel times from the guess source to stations, and eventually the optimum result will be obtained by minimizing the differences between the observed and calculated travel times through an inversion process. In general, the latitude and longitude of the earthquake focus and the time of occurrence of the earthquake can be determined if arrival times at three or more observatories are available. In this study, the arrivals of the 11 signals converted from seismic waves on the surface were picked to locate the epicenter of the El Salvador earthquake. Uncertainties of the arrivals were further given by different weights. For example, some signals with clear arrivals such as Station TEGU13 were given with the largest weight, but others such as Station TEGU19 were given by (a) smaller weight. A computer program, HYPO77 that is the most popular one for routinely locating earthquakes in the earth, was employed to locate the epicenter. Different velocities, ranging from 400 m/s to 800 m/s, were assumed for the propagation of earthquake-induced acoustic waves from surface to the atmosphere at several hundred kilometers. The optimum result with the smallest standard deviation of horizontal errors shows that the epicenter was located at 13.15°N, 88.57°W by given a velocity of 500 m/s for the propagation of earthquake-induced acoustic waves from surface to the atmosphere at 325 km. The relocated epicenter from signals of the ionospheric disturbance very closes to the epicenter (12.767°N, 88.827°N) reported by the USGS (Fig. 3).

DISCUSSION AND CONCLUSION

Seismometers have been long time used to locate the earthquake hypocenter, while GPS applications have been widely employed to study numerous geosciences. In this study, we combine existing techniques of these two to develop a new way for locating the earthquake epicenter and determining the speed of seismo-ionospheric waves simultaneously. It has been demonstrated that the epicenters deduced from the seismo-ionospheric waves detected by GPS receivers well agree with the one located by seismic waves recorded by seismometers. The agreement suggests that the speed of seismo-ionospheric waves triggered the 13 January 2001 El Salvador earthquake is about 500 m/s. 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. Note that there are more than thousands of permanent ground-based GPS receivers all over the world. Therefore, the method proposed herein should provide with an efficient alternative to locate disturbance sources and to have a better understanding on the propagation of the triggered waves.

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