Ionospheric GPS total electron content (TEC) disturbances triggered by the 26 December 2004 Indian Ocean tsunami

Jann-Yenq Liu,[1,2] Yi-Ben Tsai,[3] Kuo-Fong Ma,[3] Yuh-Ing Chen,[4] Ho-Fang Tsai,[5] Chien-Hung Lin,[1] Masashi Kamogawa,[6] and Chien-Ping Lee[3]

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[1] Tsunami ionospheric disturbances (TIDs) of the 26 December 2004 M_w 9.3 Sumatra earthquake are detected by the total electron content (TEC) of ground-based receivers of the global positioning system (GPS) in the Indian Ocean area. It is found that the tsunami waves triggered atmospheric disturbances near the sea surface, which then traveled upward with an average velocity of about 730 m/s (2700 km/hr) into the ionosphere and significantly disturbed the electron density within it. Results further show that the TIDs, which have maximum height of about 8.6–17.2 km, periods of 10–20 min, and horizontal wavelengths of 120–240 km, travel away from the epicenter with an average horizontal speed of about 700 km/hr (190 m/s) in the ionosphere.

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1. Introduction

[2] The ionosphere can be affected by a variety of disturbances including, for example, solar disturbances, geomagnetic storms, severe weather, volcanoes, and earthquakes [*Davies*, 1990]. Although the ionosphere is primarily affected by solar and magnetospheric activities, while solid Earth–related perturbations are generally small in comparison, there is considerable evidence observed by ionosondes and high-frequency (HF) Doppler sounding systems that transient disturbances occurred in the ionosphere as a result of earthquakes [*Bolt*, 1964; *Leonard and Barnes*, 1965; *Davies and Baker*, 1965; *Row*, 1966, 1967; *Yuen et al.*, 1969; *Najita et al.*, 1974; *Tanaka et al.*, 1984; *Artru et al.*, 2004]. Recently, scientists analyzing data recorded from numerous ground-based receivers of the global positioning system (GPS) have observed ionospheric disturbances of the total electron content (TEC) triggered by seismic surface waves [*Calais and Minster*, 1995; *Afraimovich et al.*, 2001; *Ducic et al.*, 2003] and by tsunami waves [*Artru et al.*, 2005]. In this paper, we report disturbances of the ionospheric GPS TEC triggered by the Indian Ocean tsunami of 26 December 2004.

[1]Institute of Space Science, National Central University, Chung-Li, Taiwan.
[2]Also at Center for Space and Remote Sensing Research, National Central University, Chung-Li, Taiwan.
[3]Institute of Geophysics, National Central University, Chung-Li, Taiwan.
[4]Institute of Statistics, National Central University, Chung-Li, Taiwan.
[5]Central Weather Bureau, Taipei, Taiwan.
[6]Department of Physics, Tokyo Gakugei University, Tokyo, Japan.

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2. Observation

[3] A preliminary report by the U.S. Geological Survey gives the earthquake origin time at 0058:53 UT; its epicenter was located at 3.31°N, 95.95°E off the west coast of northern Sumatra http://earthquake.usgs.gov/eqcenter/eqinthenews/2004/usslav/). The moment magnitude of 9.3 ranks it as the second largest earthquake in the world since 1900 and the largest one since the 1960 Chile earthquake [*Stein and Okal*, 2005]. Displacements of the adjacent seabed generated damaging tsunami waves that killed nearly 280,000 people http://earthquake.usgs.gov/eqcenter/eqinthenews/2004/usslav/) at countless coastal communities around the Indian Ocean. A maximum tsunami height of as much as 10 m was observed in several locations along the coast of the Indian Ocean, and a maximum height of about 70 cm was reported in the open sea [*Gower*, 2005]. The tsunami propagated as long waves in the ocean with average speeds of about 700–800 km/hr depending on the water depth. The rupture length of the earthquake is over 1150 km [*Kruger and Ohrnberger*, 2005] as inferred from the first arrival times of tsunami recorded by tide gauge stations at Vishakapatnam in India and Cocos Island of Australia (K. Satake, 2005, http://staff.aist.go.jp/kenji.satake/Sumatra-E.html). Using the earthquake and its aftershocks as the source, propagation of the tsunami waves has been computed (K. Satake, 2005, http://staff.aist.go.jp/kenji.satake/Sumatra-E.html).

[4] Ionospheric disturbances triggered by the tsunami in the India Ocean were also observed. Figure 1 sketches a cartoon showing the tsunami-induced acoustic gravity waves near the sea surface which travel vertically via the atmosphere then into the ionosphere and modify the electron density or TEC within it. The TEC along the slant paths from GPS satellites to a ground-based receiver can be employed to detect the tsunami ionospheric disturbances (TIDs). Taking the ionosphere as a thin spherical shell at a

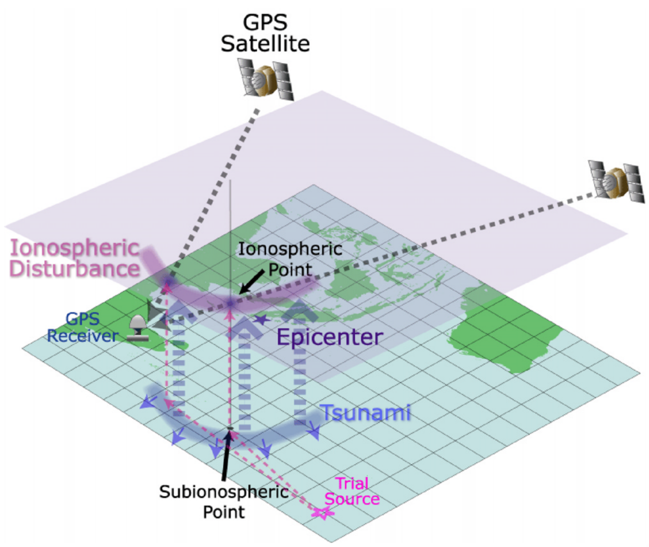

Figure 1. Tsunami activated by an earthquake travels away from the epicenter (blue star) along the ocean surface (blue curve) and launches atmospheric gravity waves (blue dashed arrows) which then propagate into the ionosphere and trigger tsunami ionospheric disturbances (TID) (purple curve). Slant total electron content (TEC) (grey dashed arrows) is the integration of electron density along path from a GPS satellite to a ground-based receiver. Vertical component of slant TEC at intercept (or ionospheric point) of slant path on ionospheric surface is termed a vertical TEC (grey line). Each ionospheric point acting as a monitoring station can be employed to detect TIDs. Footprint of monitoring station on Earth's surface is termed subionospheric point. Grid for ray-tracing method is $1^\circ \times 1^\circ$ latitude by longitude. Solid blue and open pink stars denote epicenter and trial source, respectively.

height of 350 km, then the intercept of the slant path on the ionospheric shell surface can serve as a monitoring station floating at an ionospheric point for observing the disturbances. Twelve monitoring stations projected from the coco, iisc, karr, dgar, and kerg ground receiving stations of the international GPS services http://igscb.jpl.nasa.gov/) have clearly detected the TIDs of differential TEC variations [*Liu et al.*, 2004] triggered by the tsunami of the Sumatra earthquake (Figure 2). Note that, the differential TEC is defined by subtracting each TEC from its previous 30-s value, which is a simple two-point differentiation. The TIDs observed by the monitoring stations near the epicenter, such as those around iisc, karr, dgar, and coco, have shorter periods of about 10–15 min. By contrast, the two monitoring stations around kerg at longer distances from the epicenter yield a longer period of about 20 min. The average horizontal speed of the TIDs derived from the arrival times observed at all the monitoring stations is approximately 688 km/hr (Figure 2). Meanwhile, the arrival times of the tsunami right under the 12 monitoring stations can be extracted from the published simulation data (K. Satake, 2005, http://staff.aist.go.jp/kenji.satake/Sumatra-E.html) and employed to derive the associated average horizontal speed. It is found that the two average horizontal speeds are nearly identical except that the TID lags behind the tsunami by about 8 min. From the ionospheric shell height of 350 km and the time lag, the average vertical speed of the acoustic gravity waves triggered by the tsunami traveling upward into the ionosphere is about 730 m/s, which is quite comparable to the previous observations of about 800 m/s of atmospheric gravity waves [*Davies*, 1990; *Liu et al.*, 2005] as well as the average values of acoustic waves of the previous simulations [*Artru et al.*, 2004, 2005].

[5] A simple ray-tracing technique [*Aki and Richards*, 2002] commonly used in seismology is employed herein to estimate the arrival times at the 12 monitoring stations for locating the earthquake source (or tsunami origin) as well as to find if the observed disturbances of the ionospheric GPS TEC is triggered by the tsunami. We first try to guess a location of the tsunami source; calculate travel time of the tsunami propagating horizontally away from the trial source and triggering the acoustic gravity wave which in turn propagates vertically to reach each monitoring station; and compute a standard deviation of the differences between the calculated and the observed arrival times. We repeat this procedure through the whole set of grid points (trial source locations) and then contour the computed standard deviations to find the minimum, which is then considered to be a possible source. Figure 3 shows that an average horizontal speed of 191 m/s (about 700 km/hr) and an average vertical speed of 730 m/s give an optimal induced time at 0106 UT±15 min and source location at -1°N, 93°E which is about 580 km southwest of the earthquake epicenter. Note that the average horizontal and vertical speeds generally agree with those directly estimated from the time delay (Figure 2). Meanwhile, the estimated tsunami source location and the induced time are close to the epicenter and origin time of the earthquake given by the U.S. Geological Survey http://earthquake.usgs.gov/eqcenter/eqinthenews/2004/usslav/).

3. Discussion and Conclusion

[6] The West Coast/Alaska Tsunami Warning Center http://wcatwc.arh.noaa.gov/IndianOSite/IndianO12-26-04.htm) reports that the tsunami yields the maximum peak-to-trough height of 42 cm while the current TID observations reveal that the maximum peak-to-trough value in the differential GPS TEC is about 0.16 TECU (total electron content units, 1 TECU = 10^{16} el m^{-2})/30 s (Figure 2). *Liu et al.* [2004, 2006] show that the differential TEC, which stands for the frequency deviation of the GPS signals, is well correlated to Doppler shift in signals transmitted by a colocated HF (5.262 MHz) Doppler sounding system. On the basis of their results we estimate 1 TECU/30 s corresponding to an ionospheric layer at about 200 km altitude moving 280 m/s vertically. Assume the TID to be a cosine wave with a maximum velocity of 45 (= 280 $\times$ 0.16) m/s and a period 10–20 min, we then obtain that the ionosphere has been uplifted by about 8.6–17.2 km around the Cocos Island of Australia. This generally agrees with *Liu et al.* [2005] and confirms that the amplification factor of the ionosphere relative to the near-Earth atmosphere is about 17,000–43,000, because of the exponential decrease of neutral density with height. The result also shows that the 10–20 min period TIDs (Figure 2) propagate with an average horizontal velocity of about 700 km/hr away from the source

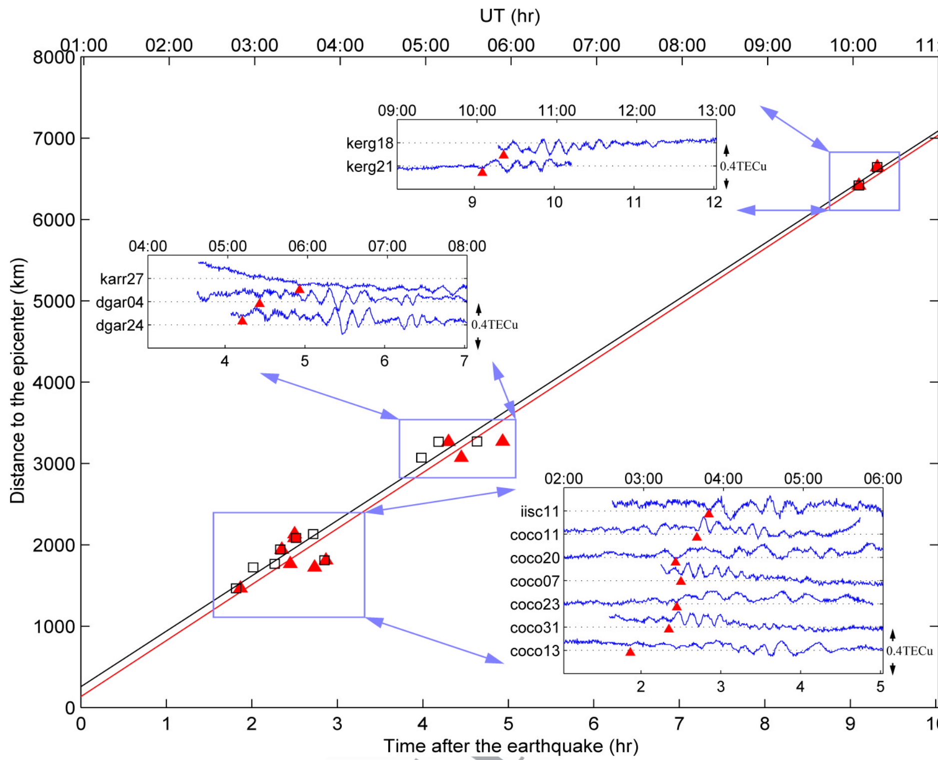

Figure 2. Average horizontal speeds of TIDs and tsunami are shown. Arrival times (red triangles) vs. distance from epicenter to each monitoring station are employed to compute average horizontal speed of TIDs (red line). Arrival times of tsunami (black squares) at footprints (subionospheric points) of monitoring stations, which are extracted from published simulation result, are used to find average horizontal speed of tsunami (black line). Average vertical speed of acoustic gravity waves is estimated from time lag between the two lines.

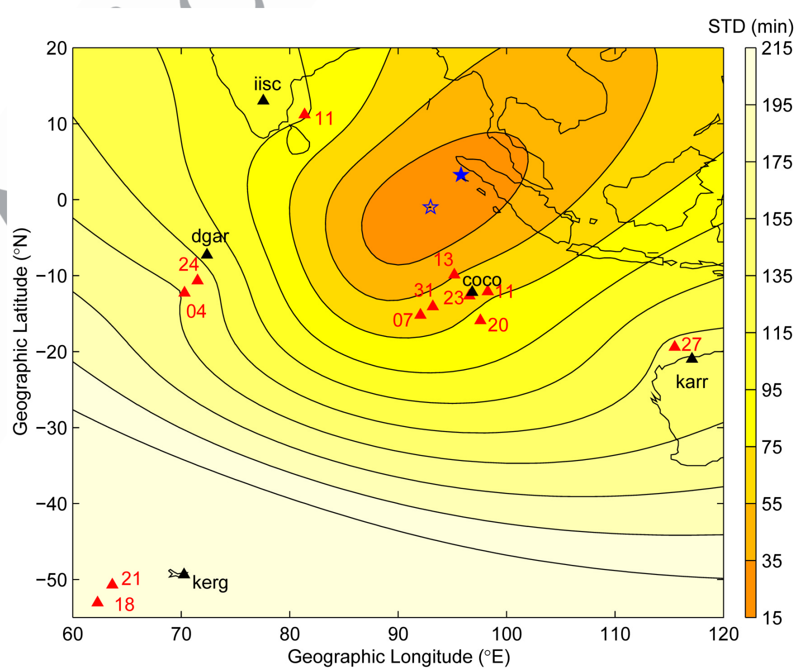

Figure 3. Contours of standard deviation of the differences between calculated and observed arrival times are shown. Locations of ground-based GPS receivers and associated monitoring stations are denoted by black triangles with station name and red triangles with GPS satellite number. Epicenter reported by U.S. Geological Survey and calculated source are denoted by solid and open blue stars, respectively.

(Figures 2 and 3). Simply on the basis that the speed of propagation equals the product of frequency and wavelength, we obtain the TID horizontal wavelength ranging from 117 to 233 km. Many geophysics factors could trigger fluctuations of the ionospheric TEC, for instance, traveling ionospheric disturbance, etc. To find whether the GPS TEC disturbances are related to the 26 December 2004 tsunami, we further apply the ray-tracing technique to locate the disturbance source. The agreement in the locations of the calculated source and reported epicenter confirms that the TIDs of the GPS TEC are indeed triggered by the tsunami.

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References

Afraimovich, E. L., N. P. Perevalova, A. V. Plotnikov, and A. M. Uralov (2001), The shock-acoustic waves generated by earthquakes, *Ann. Geophys.*, *19*, 395–409.

Aki, K., and P. G. Richards (2002), *Quantitative Seismology*, 2nd ed., Univ. Sci. Books, Sausalito, Calif.

Artru, J., T. Farges, and P. Lognonné (2004), Acoustic waves generated from seismic surface waves: Propagation properties determined from Doppler sounding observations and normal-mode modeling., *Geophys. J. Int.*, *158*, 1067–1077.

Artru, J., V. Ducic, H. Kanamori, P. Lognonné, and M. Murakami (2005), Ionospheric detection of gravity waves induced by tsunamis, *Geophys. J. Int.*, *160*, 840–848.

Bolt, B. A. (1964), Seismic air waves from the great 1964 Alaskan earthquake, *Nature*, *202*, 1094–1095.

Calais, E., and J. B. Minster (1995), GPS detection of ionospheric perturbations following the January 17, 1994, Northridge earthquake, *Geophys. Res. Lett.*, *22*, 1045–1048.

Davies, K. (1990), *Ionospheric Radio*, Peter Peregrinus, London.

Davies, K., and D. M. Baker (1965), Ionospheric effects observed around the time of the Alaskan earthquake of March 28, 1964, *J. Geophys. Res.*, *70*, 2251–2253.

Ducic, V., J. Artru, and P. Lognonné (2003), Ionospheric remote sensing of the Denali earthquake Rayleigh surface waves, *Geophys. Res. Lett.*, *30*, 1951–1954.

Gower, J. (2005), Jason 1 Detects the 26 December 2004 Tsunami, *Eos*, *86*, 37–38.

Kruger, F., and M. Ohrnberger (2005), Tracking the rupture of the M_w 9.3 Sumatra earthquake over 1150 km at teleseismic distance, *Nature*, *435*, 937–939.

Leonard, R. S., and R. A. Barnes Jr. (1965), Observation of ionospheric disturbances following the Alaska earthquake, *J. Geophys. Res.*, *70*, 1250–1253.

Liu, J. Y., C. H. Lin, H. F. Tsai, and Y. A. Liou (2004), Ionospheric solar flare effects monitored by the ground-based GPS receivers: Theory and observation, *J. Geophys. Res.*, *109*, A01307, doi:10.1029/2003JA009931.

Liu, J. Y., Y. B. Tsai, S. W. Chen, C. P. Lee, Y. C. Chen, H. Y. Yen, W. Y. Chang, and C. Liu (2005), Giant ionospheric disturbances excited by the *M* 9.3 Sumatra earthquake of 26 December 2004, *Geophys. Res. Lett.*, *33*, L02103, doi:10.1029/2005GL023963.

Liu, J. Y., C. H. Lin, Y. I. Chen, Y. C. Lin, T. W. Fang, and C. H. Chen (2006), Solar flare signatures of the ionospheric GPS TEC, *J. Geophys. Res.*, *111*, XXXXXX, doi:10.1029/2005JA011306.

Najita, K., P. F. Weaver, and P. C. Yuen (1974), A tsunami warning system using an ionospheric technique, *Proc. IEEE*, *62*, 563–567.

Row, R. V. (1966), Evidence of long-period acoustic-gravity waves launched into the *F*-region by the Alaskan earthquake of March 28, 1964, *J. Geophys. Res.*, *71*, 343–345.

Row, R. V. (1967), Acoustic-gravity waves in the upper atmosphere due to a nuclear detonation and an earthquake, *J. Geophys. Res.*, *72*, 1599–1610.

Stein, S., and E. A. Okal (2005), Speed and size of the Sumatra earthquake, *Nature*, *434*, 581–582.

Tanaka, T., T. Ichinose, T. Okuzawa, T. Shibata, Y. Sato, C. Nagasawa, and T. Ogawa (1984), HF-Doppler observations of acoustic waves excited by the Urakawa-Oki earthquake on 21 March 1982, *J. Atmos. Terr. Phys.*, *46*, 233–245.

Yuen, P. C., P. F. Weaver, R. K. Suzuki, and A. S. Furumoto (1969), Continuous traveling coupling between seismic waves and the ionosphere evident in May 1968 Japan earthquake data, *J. Geophys. Res.*, *74*, 2256–2264.

Y.-I. Chen, Institute of Statistics, National Central University, Chung-Li 32054, Taiwan.

M. Kamogawa, Department of Physics, Tokyo Gakugei University, 4-4-1 Nukuikita-machi, Koganei-shi, Tokyo 184-8501, Japan.

C.-P. Lee, K.-F. Ma, and Y.-B. Tsai, Institute of Geophysics, National Central University, Chung-Li 32054, Taiwan.

C.-H. Lin and J.-Y. Liu, Institute of Space Science, National Central University, Chung-Li 32054, Taiwan. (jyliu@jupiter.ss.ncu.edu.tw)

H.-F. Tsai, Central Weather Bureau, 64 Kung Yuan Road, Taipei 10039, Taiwan.