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

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1 Tsunami ionospheric disturbances (TIDs) of the 26 December 2004 M8.9 Sumatra earthquake are detected by the total electron content (TEC) field 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.


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 (Gover, 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 waves 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 data from the earthquake and its aftershocks as the source, propagation of the tsunami waves has been computed (K. Satake, 2005, 66 http://staff.aist.go.jp/kenji.satake/Sumatra-E.html).

[4] Ionospheric disturbances triggered by the tsunami in the Indian 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° × 1° latitude by longitude. Solid blue and open pink stars denote epicenter and trial source, respectively.

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/usslavl/).

3. Discussion and Conclusion
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


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