Geophysical Research Abstracts
Vol. 15, EGU2013-6472, 2013
EGU General Assembly 2013

Vertically propagating acoustic waves launched by seismic waves visualized in ionograms

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After the magnitude 9.0 earthquake off the Pacific coast of Tohoku (near the east coast of Honshu, Japan), which occurred on 11 March 2011, an unusual multiple-cusp signature (MCS) was observed in ionograms at three ionosonde stations across Japan. Similar MCSs in ionograms were identified in 8 of 43 earthquakes with a seismic magnitude of 8.0 or greater for the period from 1957 to 2011. The appearance of MCSs at different epicentral distances exhibited traveling characteristics at a velocity of $\sim$4.0 km/s, which is in the range of Rayleigh waves. There was a $\sim$7 min offset in delay time at each epicentral distance in the travel-time diagram. This offset is consistent with the propagation time of acoustic waves from the ground to the ionosphere.

We analyzed vertical structure of electron density perturbation that caused MCSs. The ionosonde technique is essentially radar-based measurement of a reflection at a height where the plasma frequency is equal to the sounding radio frequency and it is possible to obtain an electron density profile by sweeping the frequency. However, this measured height is not a true height because radio waves do not propagate at the speed of light in the ionosphere. The group velocity of radio waves decreases just below the reflection height where the sounding frequency approaches the plasma frequency. The amount of delay is larger when this region is thicker. The vertically propagating acoustic waves modulate the electron density. The radio wave speed greatly delays and a cusp signature appears in the echo trace at a phase of the periodic perturbation of electron density where the density gradient is most gradual.

Simulations were conducted how large amplitude of density perturbation produces cusp signatures as observed. First, the real height density profile was obtained by converting the ionogram trace just before the arrival of coseismic disturbances. The electron density profile was then modified by adding a periodic perturbation and the virtual height at each frequency was calculated, which is a simulated ionogram. We considered two types of perturbation: one of sinusoidal shape with a period of 20 s and a density fluctuation of the background of $\pm$0.5% and another with a period of 40 s and density fluctuation of $\pm$2%. MCSs similar to the observations were reproduced in both the cases.

If the sweep time for the whole ionospheric echo trace is much shorter than the propagation time of acoustic waves, MCSs in ionograms provide a snapshot of vertical disturbances induced by a wave. The vertical scale of the disturbances thus determined for the 8 earthquakes was 10$\sim$30 km, which corresponded to an acoustic wave period of 20$\sim$50 s at ionospheric heights.