Revelation of early detection of coseismic ionospheric perturbations in GPS-TEC from realistic modelling approach: Case studies

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During an earthquake, the energy released by sudden crust displacement disturbs the surrounding atmosphere. The resultant atmospheric disturbances propagate upward in the region of decreasing ambient neutral density and essentially manifest as acoustic-gravity waves. The amplitude of upward propagating wave disturbances increases with altitudes to compensate with the decreasing background neutral density. In general the acoustic-gravity waves as induced by the uplift/subsidence around the epicentre require ≥10 minutes to arrive at the maximum ionospheric electron density altitudes (hmF2). Once these waves arrive at ionospheric altitudes, they redistribute the background electron density and generate the perturbations called as co-seismic ionospheric perturbations (CIP).

Global Position System (GPS)-Total Electron Content (TEC) has been emerged as one of the powerful techniques to study the spatio-temporal evolution of the seismic induced ionospheric perturbations. However, GPS measured TEC is an integrated quantity along the satellite line of sight (LOS) hence it is difficult to determine the detection altitude of ionospheric perturbation in TEC. Knowing the fact that TEC is weighted by the maximum ionospheric density, the corresponding altitude (hmF2) is, generally, assumed as the perturbation detection altitude. This assumption is not always accurate.

To investigate the validity of this assumption in detail, we conduct an accurate analysis of the GPS-TEC measured early ionospheric signatures (<<10 minutes) related to the vertical surface displacement of the Mw 7.4 Sanriku-Oki earthquake (Sanriku-Oki Tohoku foreshock). We demonstrate that the early detection of the foreshock CIP at ionospheric altitudes is linked to the interaction of the seismo-acoustic wave with satellite line of sight (LOS) at altitudes lower than that of the maximum electron density (hmF2). We determine that the signatures can be detected at altitudes up to ~130km below the hmF2. Quantification of the observed early detection time is supported by a 3D acoustic ray tracing model involving the interaction between the upward propagating seismo-acoustic wave (in space and time) and satellite LOS (Figure 1).

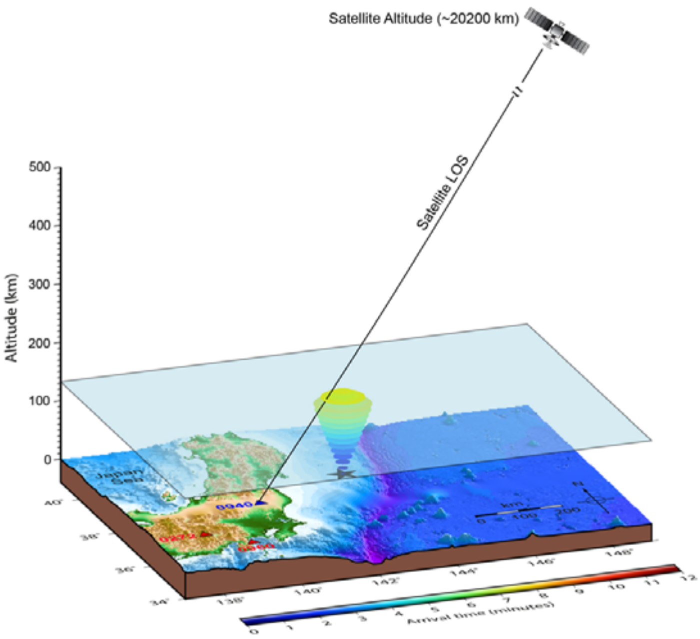

Figure 1. Proposed model containing the seismo-acoustic rays in 3D space and satellite LOS to explain the early CIP detection during the Sanriku-Oki Tohoku foreshock. The seismo-acoustic rays are computed in space and time by considering the maximum uplift as the source. The first interaction between the seismo-acoustic rays and PRN 07 LOS from GPS station 0940 is shown. PRN 07 LOS is plotted at the time of observed CIP onset. The altitude of the first interaction between the seismo-acoustic wave and the satellite LOS is highlighted with a transparent 3D plane. The maximum uplift location is denoted by the black star. The GPS station 0940 is located at a distance of ~251 km from this source. The elevation angle for PRN 07 at the time of CIP onset is ~30.5°. The conceptual orbiting plane of satellite PRN 07 is also shown.

The significance of GPS station locations during the early CIP detection is analysed. To validate the proposed simple model, we reconstruct the CIP by integrating electron density perturbations modelled on a 3D spherical grid along the LOS, taking the ambient geomagnetic field and satellite motion into account. The synthetic slant TEC waveforms reproduce reasonably well the observed CIP onset and this suggests that the detected onsets are directly linked to the evolution of the acoustic wave in space and time. After determining the detection altitudes of GPS-TEC measured CIP over the epicentral region, we extend our method analysis to estimate the detection altitude of Rayleigh wave induced ionospheric signatures.