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New in the Ionospheric Seismology: Recent Advances in the Space Detection of Earthquakes, Tsunamis and Volcano Eruptions

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ABSTRACT

In this contribution we will first give a brief overview on the space detection of earthquakes, tsunamis and volcano eruptions. We will further proceed with recent developments in the ionospheric seismology, and we will discuss the possibility to use the ionospheric measurements for seismological applications, including ionospheric images of seismic faults, and first attempts of the inversion of the seismological parameters from ionospheric observational data.

Ionospheric seismology is a branch of geophysics that aims to study the ionospheric response to large earthquakes and seismic-like events, including earthquakes, tsunamis, volcano eruptions and explosions, and to investigate the main properties of such ionospheric disturbances. Earthquake-generated vertical displacements of the ground are known to produce infrasonic pressure waves in the atmosphere. Because of the coupling between neutral particles and electrons at ionospheric heights, these acoustic and gravity waves cause perturbations of the ionospheric electron density.

The first observations of co-seismic waves in the atmosphere and ionosphere were reported after the great Alaskan earthquake in 1964. The first instruments were Doppler sounders, whose location and non-continuous observations put limits on detection of coseismic ionospheric disturbances (CID) systematically. A new era has been opened with the launch of Global Positioning System (GPS) and installation of permanent ground-based GPS receivers, whose primary task was monitoring of the ground displacement. However, apart from the purely geological applications, from GPS measurements of the group and phase delays of signals, it is possible to retrieve the ionospheric total electron content (TEC) along the path between a satellite and a receiver. In 1995, Calais and Minster were the first to use GPS-measurements for detection of co-seismic perturbations in the TEC over California after the 1994 Northridge earthquake [4]. Later on, the GPS allowed better understanding of co-seismic phenomena. It is now shown that earthquakes with moment magnitudes Mw>6.8 are very much probable to cause CID. The near-field CID are usually N-shaped in response to propagation of compression-rarefaction wave launched from the ground (Figure 1a, on the example of the Illa earthquake of 16 September 2015 in Chile). Besides these primary waves generated directly by the co-seismic

crustal displacements, it is possible to observe multi-mode CID propagation, especially in places with good instrumental coverage. The multiple modes are triggered and correspond to the surface Rayleigh waves (3.0-3.5 km/s), free gravity waves, tsunami propagation, etc. When the observations take place directly over the seismic fault regions, ionospheric measurements can help to obtain information on the dimensions on seismic fault and its location, referred to as ionospheric images of seismic fault [1, 2].

Propagation of tsunamis, even of moderate height, can be seen in the ionosphere and can be detected by the GPS, as they generate gravity waves that propagate obliquely upward and reach the ionosphere ~45 min later [5].

Figure 1a. TEC response to the Illa earthquake of 16 September 2015. The time of the earthquake is shown by gray vertical line. Names of GPS-stations and the numbers of satellites are shown in italic next to each curve.

Volcano eruptions and explosions can generate both acoustic and gravity waves, so that the ionospheric response contains several components and often quasiperiodic (Figure 1b). Co-volcanic ionospheric disturbances, are so far less studied. Heki, 2006 [5] appeared to be the first to use the GPS-TEC measurements to study the ionospheric response to the Asama volcano explosion in Japan on September 1, 2004. From the GPS-TEC measurements it was also possible to estimate the energy of volcano explosions [5].

Thus, the global and local networks of ground-based GPS-receivers have made an extraordinary contribution in the space detection of earthquakes, tsunamis and volcano eruptions. Further, the development of the Russian GLONASS as well as the European Galileo systems allow nowadays the use of additional data to study the co-seismic, co-tsunamic and co-volcanic ionospheric TEC perturbations. Further, one of the most exciting recent results concerns ionospheric “imaging” of seismic fault that we have managed to perform on the example of the 11 March 2011 M9.0 Tohoku earthquake. By using high-resolution GPS-data from the Japanese network GEONET, we have analyzed the first arrivals of the co-seismic ionospheric perturbation above the seismic source area (Figure 2a-d). In this case, we consider the ionosphere as a thin shell at the height H=250 km, so that each colored point shows the ionospheric piercing point, i.e. the crossing point of a ray GPS receivers-GPS satellite and the thin layer ionosphere. One can see that the perturbation arrives in the ionosphere ~500 seconds after the beginning of the earthquake, and the ionospheric TEC shows the occurrence of two spots of TEC increases on the north east and on the south-east from the epicenter. The TEC perturbation further increases in amplitude and further propagates away from this initial source points. Comparison of these ionospheric source spots with the seismological models of the co-seismic crustal displacements (Fig. 2e) shows good agreement. This signifies that in certain conditions the ionospheric data can provide information on the seismic source.

Figure 1b. Ionospheric TEC response to the Calbuco volcano eruption on 22 April 2015**.**

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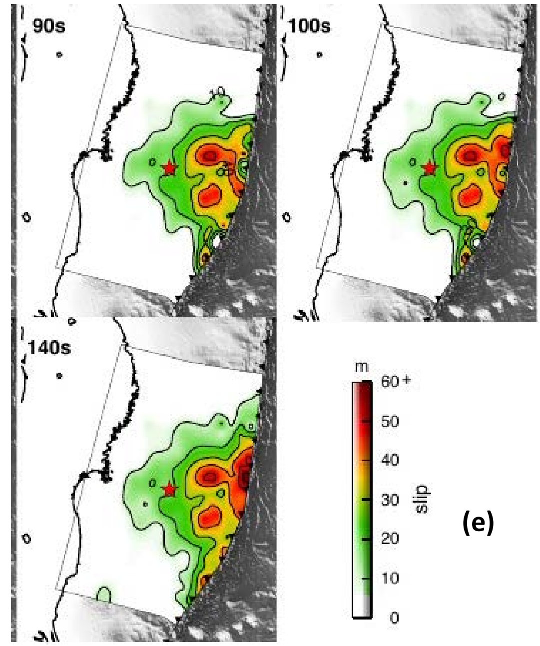

(e)

Figure 2. (a-d) Ten second snapshots of TEC perturbations above the near-epicentral region of the 11 March 2011 Tohoku-oki earthquake. Color indicates TEC value, and the color scale is shown on the right. Black star indicates the epicenter of the Tohoku-oki earthquake. Time in seconds after the quake are shown in the bottom right corner of each panel; **(e)** - seismological model of the co-seismic crustal motion. Color shows the amplitude of the coseismic-slip, red star – the epicenter. From [3]

Key words: Ionospheric seismology, GPS-TEC, natural hazards, space detection

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