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Incredibly distant ionospheric responses to earthquake

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Attempts to observe ionospheric responses to the earthquake has been going on for decades. In recent years, the greatest progress in the study of this question have GPS-measurements with simultaneous HF-measurements. The use of a dense network of GPS-receivers and getting with it sufficiently detailed two-dimensional maps of the total electron content (TEC) greatly clarified the nature of the ionospheric response to strong earthquakes.
For ionospheric responses observation, that are remote more than 1000 km from the strong earthquakes epicentres, it is necessary to applying more sensitive methods than GPS. The most experience in the observation of the ionospheric responses to earthquakes accumulated with Doppler sounding. Using these measurements, ionospheric disturbances characteristic features (signature) have been allocated, which associated with the passage of Rayleigh waves on the surface. Particular, this Rayleigh wave signatures allocation is implemented in the Nostradamus coherent backscatter radar. The authors of this method suggest using radar techniques like a sensitive "ionospheric seismometer."
The most productive allocation and studying of the vertical structure ionospheric responses could be ionosonde observations. However, their typical 15 minute sounding rate is quite sufficient for observing the regular ionosphere, but it is not enough for studying the ionospheric responses to earthquakes, because ionospheric responses is often seen only in one ionogram and it is absent in adjacent.
The decisive factor in establishing the striking ionospheric response to the earthquake was the Tohoku earthquake in 2011, when there was three ionosondes distant at 870-2000 km from the epicentre. These ionosondes simultaneously showed distortion of the F1-layer traces as its multiple stratification (multiple-cusp signature - MCS), which generated by Rayleigh wave. Note that there was another fourth Japanese ionosonde. It is located a little further near boundaries area of medium-scale wave (387 km), which ionograms showed F-spread rather than MCS. Obviously, this is due to the vertical structure of the disturbance in the near zone. Another interesting feature associated with the vertical structure is a 1-2 minute advance of the appearance MCS in ionograms in relation to the advent of large-scale TEC disturbance. Naturally, such appearance time comparison can only be in such distances, when there are large-scale TEC disturbances (<1000-1200 km). Only MCS and Doppler shifts are observing at large distances.
Look-back analysis of Japanese ionograms showed only eight cases of ionogram MCS observation from 43 strongest earthquakes (magnitude> 8) during the period from 1957-2011. This indirectly explains why it had to wait 50 years to recognize the MCS as a response to the earthquake. Previously performed statistical analyses showed that the MCS appear mainly from 9 to 15 LT and the epicentre distances range is the 800-6000 km. The MCS signatures at distances removing from earthquake epicentre more than 6000 km seen in ionosondes in Kazan, Kaliningrad and Sodankyla. These MCS in Kazan (as well in Kaliningrad, in Sodankyla) observed during the daytime from 9 to 15 LT. At this time, the height electron concentration gradient is significantly reducing in the F1-layer. This leads to the fact that a small disturbance of this gradient distorts some area of electron density profile and it reduces the value of the local gradient to zero (or even negative) values.
Observations in our ionosonde first showed that the ionospheric response to the strong earthquakes (magnitude more than 8) could be observing at distances more than 15,000 km. In the daytime such responses appearance distort the form of the electron density profile of the F-layer, which is appearing in the ionograms as a multiple trace stratification of F1-layer.