3-D structure of the high-latitude ionospheric irregularities: ground- and space-based GPS measurements during the 2015 St. Patrick's Day storm

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The most intense ionospheric irregularities in the high-latitude ionosphere are caused by plasma processes associated with auroral activities, attributed to auroral particle precipitation, and dynamical processes including high speed plasma convection. We present an analysis of ionospheric irregularities at high-latitudes during the 2015 St. Patrick's Day storm. The 2015 St. Patrick's Day storm occurred on March 17, 2015 and caused a dramatic response in the ionosphere-plasmasphere-magnetosphere system and to date is the strongest geomagnetic storm in current solar cycle. The strong disturbance of the geomagnetic field on March 17, 2015 led to intense particle precipitation and auroras were observed at different locations around the globe, even at mid-latitudes. The aim if this work is to determine the altitudinal range where the observed ionospheric irregularities occur and develop and estimate the physical mechanisms of their origin. Our study is based on measurements from ~2700 ground-based GPS stations and from GPS receivers onboard five Low Earth Orbit (LEO) satellites - Swarm A, B and C, GRACE and TerraSAR-X—that had close orbit altitudes of ~500 km, and the Swarm in situ plasma densities. The joint analysis of the ground-based observation of ionospheric gradients signatures in the GPS signal parameters characterized by the Rate of Total Electron Content Index (ROTI) together with the Swarm in situ plasma probe data and LEO GPS observations allowed us to estimate differences of features in ionospheric irregularities development in the ionospheric F2 layer and above 500 km altitude. The main features of the ionospheric storm effects in the high latitudes of the Northern and Southern hemispheres are revealed. We observed strong ionospheric irregularities in the high-latitude topside ionosphere during the storm's main phase that were associated with the storm enhanced density (SED) formation at mid-latitudes, and further evolution of the SED plume to the polar tongue of ionization (TOI). Analysis of the Swarm in situ plasma measurements revealed that, during the storm's main phase, all events with extremely enhanced plasma densities (> 10^6 el/cm^3) in the polar cap were observed in the Southern Hemisphere. When Swarm satellites crossed these enhancements, degradation of the GPS performance was observed, with a sudden decrease in the number of GPS satellites tracked. Our findings indicated that polar patches and TOI structures in the topside ionosphere were predominantly observed in the Southern Hemisphere, which had much higher plasma densities than the Northern Hemisphere, where SED/TOI structures have been already reported earlier, in particular by the Millstone Hill ISR. We should emphasize that ground-based GPS and LEO GPS data are consistent with these results and they represent unique and important data source for ionospheric research in the Southern Hemisphere auroral zone.