SURVEY OF LOCALIZED SOLAR FLARE SIGNATURES IN THE IONOSPHERE WITH GNSS, VLF, AND GOES OBSERVATIONS

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Introduction
Global navigation satellite system (GNSS) phase measurements of the total electron content (TEC) and ionospheric delay are sensitive to sudden increases in electron density in the layers of the Earth’s ionosphere. These sudden ionospheric disturbances or SIDs, are due to enhanced X-ray and extreme ultraviolet radiation from a solar flare that drastically increases the electron density in localized regions. SIDs are solar flare signatures in the Earth’s ionosphere and can be observed with very low frequency (VLF; 3-30 kHz) monitors and dual-frequency (L1 = 1575.42 MHz, L2 = 1227.60 MHz) receivers that probe lower (D-region) to upper (F-region) ionospheric layers, respectively.

Data
Data from over 500 solar flare events, spanning April 2010 to July 2017, including GOES-C, -M, and -X solar flares at various intensities, were collected from the Space and Weather Database Of Notifications, Knowledge, Information (DONKI), developed at the NASA Goddard Space Flight Center (GSFC) Community Coordinated Modeling Center (CCMC). Historical GOES solar flux (SOAS) X-ray flux (NASA GSFC CCMC integrated Space Weather Analysis system (iSWA)), and VLF SID (Stanford University Solar Sid Spellman Monitor program) time series data are available for all solar flare events of the sample set. The GNSS daily data archived at the NASA GSFC Crustal Dynamics Data Information System (CDDIS) are used to character F-region reactions to increased ionization, complementing ground-based D-region (VLF) and space-based X-ray observations (GOES). CDDIS provides GNSS data with continuous 24-hour coverage from multiple satellites, at a temporal resolution of 30 seconds from over 400 stations.

Results
The ionospheric delay “pulse” was discovered in 36% of the case study GNSS observation files (o-files), appearing typically at the time of the solar flare event, 08:00 - 08:15 UTC. The pulse appears for GPS satellites only; none appear to be present in GLONASS satellite observations. Specific GPS satellites will pick up the pulse characteristics for various GPS satellite observations, specifically.

Acknowledgements

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Figures
Figure 1: Earth’s ionosphere is ionized by radiation from the Sun; here the ionospheric layers are illustrated during both night (left) and day (right).
Figure 2: GOES X-ray flare X6.9 from August 9, 2011 around 08:05 UTC.
Figure 3: GOES-15 x-ray flux over the time of the solar flare event shown in Figure 1 (above) illustrate the pulse feature discovered in the LEI (left) during the solar flare event.
Figure 4: Very low frequency (VLF) wave diagram illustrating smooth carrier phase advance (green) data are plotted on top, following each subplot (blue, red, and orange) showing smooth carrier phase advance (green) data are plotted on top, following each subplot (blue, red, and orange).
Figure 5: Very low frequency (VLF) wave diagram illustrating smooth carrier phase advance (green) data are plotted on top, following each subplot (blue, red, and orange).
Figure 6: GPS carrier phase estimates of ionospheric delay plotted with the two dashed lines; characteristically smooth carrier phase advance (green) data are plotted on top, following each subplot (blue, red, and orange).
Figure 7: 2011-08-09 ionospheric delay plots with time from the solar flare event. The solid red line indicates the two dashed lines; characteristically smooth carrier phase advance (green) data are plotted on top, following each subplot (blue, red, and orange).
Figure 8: GOES-15 Solar X-ray flux from August 9, 2011 around 08:05 UTC.
Figure 9: GOES-15 Solar X-ray flux from August 9, 2011 around 08:05 UTC.
Figure 10: World map with satellites tracking GNSS receiver stations with 50% pulse presence in observation, and great circles marking those with a delay pulse present.