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Filling the Void in Ionosphere and Space Weather Monitoring with Unconventional GNSS Data

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Monitoring the ionosphere and space weather is vital for safeguarding technology, infrastructure, human health, and scientific progress in our contemporary society. Global Navigation Satellite System (GNSS) is one of the critical technologies that relies on extremely low power signals traversing the ionosphere to reach users on the Earth surface. Space weather activities are among the most impactful nuisance factors that hinder GNSS measurement accuracy and availability. Because of their sensitivity to ionosphere and space weather, GNSS receivers are among the dominant contributors to ionospheric and space weather monitoring and research. However, there are large data voids over the oceans, polar regions, and geographically and politically challenging terrains that prevent the deployment of ground GNSS receivers. Until recently, spaceborne GNSS receivers onboard low Earth Orbiting (LEO) satellites performing radio occultation (RO) and satellite precise orbit determination (POD) have offered limited relief due to their relatively small numbers, orbit inclinations, and low horizontal resolutions.

The last few years have seen exciting advancement in both ground and spaceborne GNSS receiver technologies that hold the promise of closing the data gaps. Research and implementation on low-cost ground-based GNSS receivers are blossoming especially in developing world where high-end GNSS receivers are too costly to acquire and ground stations are challenging to maintain. At the end of 2024, Google reported the successful mapping of ionosphere total electron content (TEC) using millions of Android cell phone data worldwide. These cell-phone generated ionosphere TEC maps captured storm-enhanced plasma density structures, equatorial plasma bubbles, mid-latitude trough, and even the shadows of a solar eclipse. Their coverage is especially impressive in regions such as Central Asia, Eastern Europe, Africa, and part of South America where dedicated ground-based GNSS receiver networks are sparse and where ionospheric anomaly effects are intense and frequent.

In polar regions and over the oceans, spaceborne GNSS reflectometry (GNSS-R) have demonstrated feasibility in mapping ionospheric TEC and scintillation by utilizing signals reflected from the Earth surface and received by side- or downward-looking antennas on board low-cost CubeSats. These types of GNSS-R tracks are particularly dense over polar regions where the surface is covered with ice and over equatorial oceans where wind speeds are relatively low, as these surfaces are excellent reflectors of the GNSS signals. Unlike ground-based GNSS observations where the space and time variations of the ionospheric effects are convoluted, the rapid scan velocity of the GNSS-R rays across the ionosphere offers a “frozen-in time” view of ionospheric structures. In addition, strong specular reflected GNSS signals have high spatial resolution determined by the Fresnel radius in the order of hundreds of meters to a few kms, depending on the signal elevation. The high spatial resolution and rapid scan across vast space over oceans and polar areas made GNSS-R measurements an attractive new data source to fill data gaps where it is not possible to have ground-based ionosphere monitoring systems. In addition, low-cost CubeSats launched and operated by commercial small satellite companies are also ramping up in numbers and quality to produce more densely populated GNSS-RO and POD measurements, poised to further close the gap over oceans and land, enabling and improving 3D imaging of the ionosphere.

These new developments come with their challenges. Low-cost sensors require additional filtering and processing to ensure quality of measurements. Handling of large volume of near real time data demands sophisticated computing resource allocation. The ever-increasing presence of jamming and spoofing of GNSS signals poses threats to the integrity and utility of GNSS signals received on the ground and in space. Overcoming these challenges hold the key to unlock the tremendously power presented by our latest technology advancement.

This presentation will discuss the progress made in recent years in both ground and spaceborne GNSS technologies for ionosphere and space weather monitoring. The challenges we are facing, strategies to overcome the challenges, and new applications enabled by the technology advancement will be highlighted.