

Precise Calculation of Faraday Rotation in Uplink Propagation to Low Earth Orbit

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This paper introduces an advanced method for accurately measuring the Faraday Rotation Angle (FRA) of electromagnetic (EM) waves as they traverse the ionosphere. Faraday rotation, resulting from interactions between EM waves, ionospheric electron density, and the Earth's geomagnetic field, alters the polarization of these waves, leading to potential disruptions in satellite communications and space surveillance radar systems. Such disruptions are particularly severe during periods of intense solar activity and geomagnetic storms, where the ionosphere undergoes dynamic changes. Existing methods, including the ITU-R recommendations and the quasi-longitudinal (QL) approximation, often rely on oversimplified assumptions, resulting in reduced accuracy, particularly in the low Earth orbit (LEO) environment where precise measurements are essential.

To address these challenges, the proposed method integrates three-dimensional electron density data from the IRI-2016 model with geomagnetic field vectors from the IGRF-13 model. Unlike traditional approaches, it employs the Appleton-Hartree equation, a vector-based formulation derived from Maxwell's equations, to compute refractive indices for ordinary and extraordinary waves. This enables the method to capture the complex interactions within the ionosphere. Additionally, ray tracing techniques are used to simulate the paths of refracted waves and calculate the FRA along these trajectories, accounting for directional factors such as the varying angles between wave vectors and geomagnetic field vectors. This comprehensive approach ensures accurate modeling of ionospheric interactions across altitudes ranging from 90 to 1000 km, offering a more precise alternative to conventional methods. Simulations across multiple frequency bands confirm that FRA decreases with increasing frequency, becoming negligible at higher frequencies. The proposed method demonstrates marked accuracy improvements over the QL approximation, which tends to overestimate FRA values, and the ITU-R method, which fails to account for directional variations in quasi-transverse propagation scenarios. By addressing these limitations, the new technique provides more reliable measurements, especially in scenarios where traditional assumptions fail to capture the ionosphere's complexity.

Another significant advantage of this approach is its ability to reduce polarization mismatch losses, thereby enhancing the reliability and efficiency of communication systems. The method's computational efficiency, with each FRA calculation taking only a few seconds, makes it suitable for real-time applications. This is particularly critical for satellite communication and space surveillance systems, which require responsive adjustments to ionospheric conditions that can change rapidly during heightened solar and geomagnetic activity.

In conclusion, this innovative methodology greatly enhances the precision of FRA calculations by accurately accounting for the ionosphere's directional and dynamic variations. These advancements are especially critical during periods of intense solar and geomagnetic activity, ensuring consistent and dependable performance in challenging ionospheric environments.

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