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Total square Root Electron Content: a Measurement of the Ionospheric Plasma from Extremely Low Frequency Whistlers Detected by Swarm Satellites

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Powerful lightning strikes generate broadband electromagnetic signals. At Extremely Low Frequencies (ELF), the signal partly leaks into the ionosphere and produces whistlers that can be detected by satellites. Indeed, the satellites Alpha (~450 km) and Bravo (~510 km) of the Swarm mission can detect those signals during 250 Hz burst-mode acquisition campaigns of their Absolute Scalar Magnetometers (ASM).

The time of propagation of these whistlers depends on their propagation path and the distribution of ionization in the ionosphere crossed along that path. Based on the founding work of Stix [1], we led a theoretical development in the ELF band to study the propagation of such waves in the ionosphere. It suggests a proportionality relationship between the group delay of the whistler and the integral of the square root of the electron density along the propagation path of the wave. We name this quantity the Total square Root Electron Content (TREC) by analogy with the Total Electron Content.

An *a priori* estimation of the propagation path is obtained with ray tracing through an ionosphere based on the International Reference Ionosphere 2016 (IRI), using a local dipolar approximation of the magnetic field derived from IGRF-13. In conjunction with the whistler analysis from the Swarm data, we are able to calculate the TREC for any whistler along its propagation path.

This method has been tested on 378 whistlers that occurred between April 2020 and December 2022, within 500 km of one of three active ionosondes in the American sector: Ramey, Boa-Vista and Santa-Maria. Swarm TREC have been compared against predicted TREC computed by integration of the ionospheric profiles from climatological IRI and from experimental ionosondes. A topside correction was applied to the latter, taking advantage of *in situ* measurements of the plasma density by the Swarm Langmuir probes. The Swarm-derived TREC is well correlated with the predicted TREC, validating the possibility of obtaining new ionospheric measurements from whistler parameters [2].

As an example of possible applications, the TREC measured on longitudinal streaks of whistlers is used to investigate ionospheric structures. These are of particular interest in regions with limited GNSS-TEC coverage. The potential uses of the TREC and its recovery method will be discussed.

[1] T. H. Stix, “Waves in Plasma”. *American Institute of Physics*, 1992, pp. 15-46, isbn:978-0-88318-859-0.

[2] M. Jenner, P. Coïsson, G. Hulot, D. Buresova, L. Chauvet and V. Truhlik, “Total Root Electron Content: A New Metric for the Ionosphere Below Low Earth Orbiting Satellites”. *Geophysical Review Letters*, in review.