The Effects of Ionospheric Scintillation on Transit-Satellite Measurement of Total Electron Content

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Abstract

Ionospheric scintillation impacts not only satellite communications but also satellite measurements of the ionosphere, such as the measurements of total electron content (TEC) made by Transit-like signal transmissions. In this work, a numerical phase-screen propagation simulation is used to study the accuracy of the measurement of TEC made with Transit-like signals. To measure TEC, the phase from coherently related 150 and 400 MHz tones is combined to yield an estimate of the phase imparted to a propagating signal by transmission through the ionosphere. This phase is processed to remove ambiguities of 2p and converted to a relative value of TEC. However, scattering caused by ionospheric irregularities produces amplitude fading and phase variations that degrade the TEC measurement in several ways. Rapid phase variations that may be associated with deep fades can degrade the phase-ambiguity removal process. Fresnel filtering acts to convert to scintillation intrinsic ionospheric variations of size of the Fresnel zone and smaller. Receiver noise also acts to degrade the phase measurements and is especially important during the deepest fades. This paper considers the effects of all these processes and develops rule-of-thumb qualifiers to assure the accuracy of Transit-like measurements of TEC.

Transit TEC Measurement

Transit-like signals consist of narrow-band tones at transmission frequencies of 150 and 400 MHz. To measure TEC, the phase at each of the two transmission frequencies is recorded. With no scintillation, the phase is the sum of a contribution caused by satellite motion and a contribution due to the ionization traversed along the propagation path from satellite transmitter to ground-based receiver. The phase contribution from satellite motion is inversely proportional to wavelength and the contribution from ionization is proportional to wavelength. If the phase is measured simultaneously at both frequencies and is unwrapped and the 2-pi ambiguities removed, the two measurements yield two equations in two unknowns, namely the TEC and the range. With no scintillation and sampling sufficient to remove the 2 pi phase ambiguities, one can measure the change in TEC as the satellite moves in its trajectory above the ionosphere. Only relative TEC is available from this type of measurement unless additional information is available to provide a reference value of TEC at some location.

MPS simulation

The multiple-phase-screen (MPS) simulation technique is used to account for the RF propagation through the ionosphere. The MPS propagation simulation is quite general and is easily applied to problems involving numerous, separated, layers of ionization characterized by spatially varying electron density. MPS techniques can handle all levels of ionospheric disturbances from the least severe, where only minor phase fluctuations occur, to the most severe cases of Rayleigh fading, where the scintillation index is unity. A direct solution to the parabolic wave equation is obtained and the results are exact given the description of the propagation environment. In the calculations reported here, the ionization is assumed to consist of long striations, so that a two-dimensional model applies.

In the MPS simulation here, 524,288 points are used to represent a grid 6000 km in length. The propagation distance from the ionosphere to the receiver is 300 km. The ionosphere is modeled as a one-dimensional phase screen with a power spectral index of 2.7, corresponding to a 3-dimensional medium with spectral index of in situ electron density fluctuations of 3.7 (as predicted by PROPMOD/WBMOD). The outer scale is 1000 km and the inner scale is 1 m. We assume that the propagation distance is known exactly, so that only one of the Transit-like transmission frequencies need be considered. Additive noise in included to model the effects of receiver noise on the measurement of electric field. In addition, the simulation results are decimated to obtain the effect on the TEC measurement process of variations in the receiver sampling rate. Results are obtained for values of scintillation index ranging from 0.1 to 1.0.

Results

Examples of the TEC as a function of distance along the simulation grid are presented. These are obtained by reconstruction of the phase values (which are ambiguous on a 2 pi interval) obtained from the received electric field. Increasingly erroneous measurements of the TEC occur as the severity of the ionospheric degradation increases (as quantified by the value of scintillation index). The effect of variations in the sample spacing of the received signal are studied to understand the effect of variations in receiver sampling rate. Analysis of the simulation results indicates that the use of Transit-like signals for TEC measurement is adequate if the scintillation index is less than 0.75, the average signal-to-noise density ratio is greater than about 15 decibels, and the sample spacing is no greater than 0.75 times the decorrelation time of the received signal.