Simulating Ionospheric Effects on GPS Signals in Space

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The Global Positioning System (GPS) is extensively used for navigation and positioning in static or kinematic condition in a large number of applications, such as Air Traffic Control. The ionosphere affects the propagation of the signal GPS and can reduce the accuracy of positioning by tens of meters particularly in the equatorial and low-latitude regions. Auxiliary systems have been developed to meet the safety requirements of aviation. For example, Ground Based Augmentation Systems (GBAS) provide higher accuracy for differential corrections. The propagation and degradation of signals in space due to ionospheric effects are important and are the focus of this work, which describes a simulation model of the GPS observables for future GBAS applications. For completeness, non ionospheric effects will also be considered.

For each active communication channel between satellite *i* and receiver *j*, the following expressions apply for the pseudorange $PR_{(i,j)}$, carrier phase $\phi_{(i,j)}$, and received power $C_{(i,j)}$ of the GPS L1 signals:

$$PR_{(i,j)} = \rho_{(i,j)} + c\left[\Delta t_{r(j)} - \Delta t_{s(i)}\right] + I_{(i,j)} + T_{(i,j)} + m_{\mathrm{PR}(i,j)} + v_{\mathrm{PR}(i,j)}$$

$$\phi_{(i,j)} = \rho_{(i,j)} + c\left[\Delta t_{r(j)} - \Delta t_{s(i)}\right] - I_{(i,j)} + T_{(i,j)} + m_{\phi(i,j)} + \lambda_{L1} N_{(i,j)} + \phi_{Iscint(i,j)} + v_{\phi(i,j)}$$

$$C_{(i,j)} = EIRP_{(i)} + \mathrm{G}_{(i)} + L_{(i,j)} + G_{(j)} + m_{\mathrm{C}(i,j)} + 20\log\left[a_{Iscint(i,j)}\right]$$

where $\rho_{(i,j)}$ is the geometric range; $\Delta t_{r(j)}$ and $\Delta t_{s(i)}$ are the receiver and satellite clock errors, respectively; $I_{(i,j)}$ and $T_{(i,j)}$ represent the ionospheric and tropospheric delays, respectively; $m_{PR,\phi,C(i,j)}$ are associated with multipath effects on the pseudorange, carrier phase, and power, respectively; $v_{PR,\phi(i,j)}$ represents random errors in the pseudorange and carrier phase, respectively; $\lambda_{L1} = c/f_{L1}$ is the L1 wavelength, c is the velocity of light in free space, and f_{L1} is the L1 frequency; $N_{(i,j)}$ is an integer number representing the cycle ambiguity, which considers effects from cycle-slips; $\phi_{Iscint(i,j)}$ and $a_{Iscint(i,j)}$ represent phase and amplitude ionospheric scintillation effects; $EIRP_{(i)}$ is the effective isotropic radiated power of each satellite transmitter; $G_{(i)}$ and $G_{(j)}$ are the gains of the satellite and receiver antennas in the pertinent directions, respectively; and $L_{(i,j)}$ is the free-space path loss, represented by:

$$L_{(i,j)} = -27.55 + 20\,log\left(f_{L1,MHz}\right) + 20\log\left[\rho_{(i,j)}\right]$$

To simulate the ionospheric delay $I_{(i,j)}$, the variability of the estimated vertical Total Electron Content (vTEC) at associated 400-km ionospheric pierce points (IPP) [1] has been characterized through a statistical analysis of dual-frequency GPS data from the Rede Brasileira de Monitoramento Contínuo (RBMC), as well as of their residuals relative to the ones provided by the latest version of the International Reference Ionosphere (IRI). This study considered different combinations of ranges of the following geophysical parameters: (i) solar activity, represented by the F10.7 index; (ii) geomagnetic activity, represented by the Kp index; (iii) geomagnetic latitude; (iv) local time; and (v) season. This residual is represented by:

$$vTEC^{res}_{IPP(i,j)} = vTEC^{RBMC}_{IPP(i,j)} - vTEC^{IRI}_{IPP(i,j)}$$

where $vTEC^{RBMC}_{IPP(i,j)}$ has been estimated from original RINEX files recorded by the RBMC network and $vTEC^{IRI}_{IPP(i,j)}$ has been estimated from the IRI model at the same IPP.

Considering the limitations of S_4 index alone in the characterization of amplitude scintillation, this work assumes that the α-μ distribution models the signal intensity [2]-[4]. Thus, to represent the amplitude scintillation term $a_{Iscint(i,j)}$ for each satellite–receiver pair (*i*, *j*), with multiplicative effects on the signal power, a random value for the S_4 index will be initially sorted, according to the probability distribution estimated [4] for the receiver of CIGALA/CALIBRA network that is closest to the geomagnetic latitude of the associated IPP. Then, for each S_4 value, the associated value for α will be selected according to empirical distributions presented in the same reference. A well-known relationship $\mu(S_4, \alpha)$ [2] provides the missing parameter of the α-μ distribution, allowing the generation of multiple values of $a_{Iscint(i,j)}$. Similarly, it is possible to generate successive samples of $\phi_{Iscint(i,j)}$, with additive effects on the signal phase, according to empirical relationships between the sorted values of S_4 and σ_ϕ (the standard deviation of phase fluctuations), combined with zero-mean Gaussian cumulative distribution functions [3].

Finally, this contribution will present and discuss results from the above formulation for different combinations of geophysical parameters and configurations of interest.

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References

[1] Ma, G.; Maruyama, T. Derivation of TEC and estimation of instrumental biases from GEONET in Japan. Annales Geophysicae, vol. 21, pp. 2083-2093, 2003.
[2] Moraes, A. O.; Costa, E.; de Paula, E. R.; Perella, W. J.; Galera, J. F. Extended ionospheric amplitude scintillation model for GPS receivers. Radio Science, vol. 49(5), pp. 315-329, 2014.
[3] Moraes, A. O.; Costa, E.; Abdu, M. A.; Rodrigues, F.; de Paula, E. R.; Oliveira, K.; Perella, W. J. The variability of low-latitude ionospheric amplitude and phase scintillation detected by a triple-frequency GPS receiver. Radio Science, vol. 52(4), pp. 439-460, 2017.
[4] Moraes, A. O.; Vani, B. C.; Costa, E.; Sousasantos, J.; Abdu, M. A.; Rodrigues, F.; Gladek Y. C.; de Oliveira, C. B.; Monico, J. F. G. Ionospheric scintillation fading coefficients for the GPS L1, L2, and L5 frequencies. Radio Science, vol. 53(9), pp. 1165-1174, 2018.