Removing Obliquity Error from the Estimation of Ionospheric Total Electron Content

Lawrence Sparks,

Jet Propulsion Laboratory, California Institute of Technology

For more than twenty-five years, measurements of radio signals emitted by global navigation satellite systems (GNSS) such as the Global Positioning System (GPS) have been used to monitor the state of the ionosphere and, in particular, to generate maps of ionospheric total electron content (TEC). Standard methods for estimating vertical TEC invariably adopt simplified models of the spatial distribution of charged-particles in the ionosphere, the most popular being the *thin-shell model* where the electron density is considered to be collapsed into an infinitesimally thin layer located near the peak of the actual density profile. The thin-shell model is used internationally, for example, in all current satellite-based augmentation systems rendering GNSS safe for aircraft navigation. Adopting the thin-shell approximation serves two very useful purposes: (1) it associates each signal raypath with an *ionospheric pierce point* (IPP) where the raypath intersects the ionospheric shell, and (2) it provides a means of converting a slant TEC measurement to an estimate of the vertical TEC at the IPP using a simple geometrical conversion factor. It is well-known, however, that under disturbed conditions or at low latitude where ionospheric structure is complex, such crude model approximations can become significant sources of estimation error. The error associated with the slant-to-vertical conversion is designated *obliquity error*. This paper addresses TEC estimation algorithms designed to reduce or eliminate obliquity error as a source of estimation inaccuracy.

Previous work at the Jet Propulsion Laboratory has introduced two such TEC estimation algorithms: *conical domain estimation* [1] and *multi-cone estimation* [2][3]. Conical domain estimation avoids the thin-shell approximation by restricting each fit of GNSS measurements to a spatial domain encompassing signal raypaths that converge at a single point. As a stand-alone algorithm, it is useful to estimate slant TEC along a raypath that originates at a given GNSS satellite. The conical domain approach to ionospheric delay estimation is being considered a candidate algorithm for the Korea Augmentation Satellite System (KASS) currently under development for the Korean Peninsula [4].

To estimate vertical TEC above earth grid points (EGPs) used to define the region covered by an ionospheric TEC map, *multi-cone estimation* first uses the conical domain approach to estimate TEC along raypaths, designated *pseudo-observations*, that connect the EGPs to each of the GNSS satellites that are locally visible. The orientation of the conical domain estimation is then inverted and applied to spatial domains each restricted to pseudo-observations whose raypaths intersect the earth at a single EGP, that is, the vertex of the conical fit domain now resides on the surface of the earth rather than at a satellite. Multi-cone estimation can be readily extended in a similar fashion to TEC estimation along any arbitrary raypath.

Previous analyses in a limited number of test cases have verified that conical domain and multi-cone estimation can improve the accuracy of ionospheric TEC estimation over that of conventional methods which rely on the thin-shell model of the ionosphere. This paper extends these analyses, examining the dependence of this improvement on the elevation angle of the observation whose delay is estimated. Optimization of estimation parameters is performed for receiver networks that cover various geographic regions with varying densities of receiver sites. The results of this work are of potential benefit to any project interested in reducing the error associated with the estimation of signal propagation delays through the ionosphere, such as, for example, spacecraft tracking and radio astronomy (the calibration of such delays is a significant error source for low frequency radio arrays, particularly for absolute astrometric measurements). The results also have implications for improving the accuracy of vertical TEC maps.

Acknowledgements

The research described in this paper has been performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

[1] Sparks, L., Komjathy, A., Mannucci, A.J., "Estimating SBAS Ionospheric Delays Without Grids: The Conical Domain Approach," *Proceedings of the 2004 National Technical Meeting of The Institute of Navigation*, San Diego, CA, January 2004, pp. 530-541.

[2] Sparks, L., A. Komjathy, A., and Mannucci, A.J., "Estimating ionospheric slant delay without resorting to the thin shell approximation," in *Proceedings of the IEEE Position, Location, and Navigation Symposium*, San Diego, CA, April 25-27, 2006.

[3] Sparks, L., "Eliminating Obliquity Error from the Estimation of Ionospheric Delay in a Satellite-based Augmentation System," *Proceedings of the ION 2013 Pacific PNT Meeting*, Honolulu, Hawaii, April 2013, pp. 307-318.

[4] Donguk Kim, Deokhwa Han, Changdon Kee, "Preliminary Test Results of RTK-aided Conical Domain Model for SBAS Ionospheric Correction," *Proceedings of the ION 2019 Pacific PNT Meeting*, Honolulu, Hawaii, April 2019.