Ionospheric Tomography Using GNSS Reflections

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Abstract—In this paper, we report a preliminary analysis of the impact of Global Navigation Satellite System Reflections (GNSS-R) data on ionospheric monitoring over the oceans. The focus will be on a single polar Low Earth Orbiter (LEO) mission exploiting GNSS-R as well as Navigation (GNSS-N) and Occultation (GNSS-O) total electron content (TEC) measurements. In order to assess impact of the data, we have simulated GNSS-R/O/N TEC data as would be measured from the LEO and from International Geodetic Service (IGS) ground stations, with an electron density (ED) field generated using a climatic ionospheric model. We have also developed a new tomographic approach inspired by the physics of the hydrogen atom and used it to effectively retrieve the ED field from the simulated TEC data near the orbital plane. The tomographic inversion results demonstrate the significant impact of GNSS-R: three-dimensional ionospheric ED fields are retrieved over the oceans quite accurately, even as, in the spirit of this initial study, the simulation and inversion approaches avoided intensive computation and sophisticated algorithmic elements (such as spatio-temporal smoothing). We conclude that GNSS-R data over the oceans can contribute significantly to a Global/GNSS Ionospheric Observation System (GIOS).


I. INTRODUCTION

IONOSPHERIC electron content measurements provide an important element for space weather research and operations. Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation and electric power distribution grids, leading to a variety of socio-economic losses. Knowledge of ionospheric electron content is also very important for the operation of space radar systems [e.g., space altimetry, including Global Navigation Satellite System Reflections (GNSS-R)]. The initial focus of this paper will be on better coverage of data-void or data-sparse regions (e.g., data over the oceans, complementary data). Little data on ionospheric electron content is presently available over the oceans, although this situation will be mitigated by global positioning system (GPS) occultation measurements (e.g., from CHAMP and COSMIC, the U.S./Taiwan constellation), and the vertical character of GNSS-R soundings together with their availability over water (and perhaps ice and land) covered areas will be able to fill these gaps.

It is well known that the atmosphere affects the propagation of radio signals. The neutral troposphere and the ionosphere have an impact on ranging measurements from radar systems, and both have been an object of intense research exploiting the fact that GPS (L-band) signals are susceptible to the atmospheric gas composition and plasma distribution. This, tied to the high precision of the GPS system, has opened a wide door to study atmospheric phenomena. In fact, it has been an important goal for the GNSS research community to test the limits of the geophysical measurement techniques derived from this technology.

Both GPS and the forthcoming European Galileo are designed for precise navigation as multifrequency systems: the ionospheric contribution to the delay can then be measured and removed by making use of its dispersive nature.

Because of the existence of ionized free electrons, the ionosphere adds a delay of a few meters to the GNSS signal (L-band). The exact amount depends on the electron density along the ray link path and on which of the GNSS available frequencies is considered (e.g., in GPS, $f_1 = 1.57542 \, \text{GHz}$ and $f_2 = 1.2276 \, \text{GHz}$). As mentioned, the dispersive nature of this phenomenon is exploited to measure the integrated free electron content delay accurately, and, if needed, to remove it from the measurements (as in dual frequency GPS, for example). Consider a signal traveling at time $t$, between a given satellite and receiver, and let $I = \int_{-\infty}^{\infty} \rho(\tau) d\tau$ be the integrated electron density or total electron content (TEC) along the ray traversed by the signal (in electrons per square meter). Then the delay at frequency $f_2$ is modeled by

$$D_2 = D_0 (t) + I \rho f_2^2 + T + c_{sat}^2 + c_{rec}^2 + \text{noise} + (D^2 - D_0)$$ (1)

where $\rho = 40.30 \, \text{m}^3/\text{s}^2$, $D^2$ is the geometric length of the real ray, $D_0$ is the length of the ray if it traveled in a straight line (in the vacuum), $T$ models other frequency-independent terms, and $c_{sat}^2$ and $c_{rec}^2$ are the instrumental biases (which are assumed to remain constant in relatively long timescales). The last term is the difference between the length of the real ray and the length of the ray if it propagated in the vacuum and is also small for nongrazing geometries.

Ionospheric delay on GPS is usually expressed in electrons per square meter divided by $10^{16}$ (TEC units or TECU). Electron density (ED) is usually expressed by the number of free electrons per cubic meter. Typical peak values of ED are of the order of $10^{12}$ electrons per cubic meter (i.e., Tera electrons/m$^3$) and are found around 300 km of altitude.

A standard approach for 3-D tomography of the ionosphere is based on the voxel basis representation [7]. As with other approaches, an important problem in voxel tomography is that it is in general an ill-determined problem: the data available for inversion are typically not sufficient to uniquely specify a solution to the resolution desired. This problem is compounded...
used for the ED field generation with PIM. To these unknowns, the emitter–receiver biases (one per GPS satellite and GPS receivers) also need to be added (although we did not include them in our simulation for simplicity).

V. CONCLUSION

In this study, GNSS-R/O/N LEO and ground data were simulated based on the current GNSS-R code-ranging error budget, and a new 3-D tomographic representation used to study the impact of GNSS-R data for ionospheric ED tomography near a single LEO orbital ring.

The representation, which we call the H-representation, uses solutions similar to those of the hydrogen atom Schrödinger equation and provides an efficient way to represent the solution space. With as little as 55 coefficients ($n = 5$), a fit of 7 TECU was produced under the LEO track, using only LEO data, while the addition of IGS ground data gave a fit of about 13 TECU. Using more coefficients, and adding smoothing constraints, the solutions become more accurate, as expected.

The main point of this study is the demonstration that GNSS-R data improves the ED results in the LEO orbital ring area. It can be concluded from this study that the addition of GNSS-R data can cover an important gap over the oceans supporting occultation measurements, where ground data are not available. Future work is needed for more realistic simulations, to further improve GNSS-R error budgets and to understand ionospheric phase behavior—ideally through a GNSS-R mission to collect data from space in addition to further simulation, analysis, and air/ground experiments.

ACKNOWLEDGMENT

All Starlab authors have contributed significantly. The Starlab author list has been ordered randomly.

REFERENCES


Josep Marco Pallarés was born in Barcelona, Spain, in 1978. He received the degree in physics from the University of Barcelona, Barcelona, in 2000, and the M.S. degree in neuroscience in 2002. He is currently pursuing the Ph.D. degree in neuroscience at the University of Barcelona. He is currently with Starlab, Barcelona, focusing on new mathematical tools in order to increase the spatial resolution of tomography (EEG and GNSS-R).

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