17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023.

SpaceOps-2023, ID # 397

Seasonal Variation of the GNSS Ionospheric Delay Observed Over the UAE

Hind Yousif Alhammadi[a], Noor A. Almahri[a], Shaikha Alzaabi[a], Halima Obaid Alnaqbi[a],
Shaima Ibrahim Rafi[a], Abdollah Masoud Darya[a]*, Sultan Suhail[a], Ilias Fernini[a]

[a] *SAASST, University of Sharjah, Sharjah, United Arab Emirates*
* Corresponding Author, adarya@sharjah.ac.ae

Abstract

The ionosphere is the largest source of error for single-frequency Global Navigation Satellite Systems users. This work studies the seasonal variations of the ionospheric delay as observed over the United Arab Emirates during a solar minimum period using observations from the GPS, Galileo, and BeiDou constellations. The highest ionospheric delay was observed at the equinoxes during the afternoon (up to 10 meters), while the lowest ionospheric delay was observed during the summer solstice (up to 7.5 meters). The observed ionospheric delay was higher for GPS signals and lowest for Galileo signals. In future work, these observations will be combined with observations from high solar activity periods to develop a regional ionospheric model.

Keywords: Ionosphere, GPS, Galileo, BeiDou.

1. Introduction

The use of Global Navigation Satellite Systems (GNSS) as the primary source for positional, navigational, and timing (PNT) solutions has seen exponential growth during the last two decades. In 2011, the European Commission estimated that 6–7% of the Gross Domestic Product (GDP) in western countries is dependent on the availability of GNSS [1], labeling it as a matter of national security. This is primarily due to the ubiquity and affordability of single-frequency GNSS receivers and their usage in many critical infrastructure sectors. However, unlike their dual-frequency counterparts, the positioning solutions obtained by single-frequency GNSS receivers are greatly influenced by ionospheric delay. In fact, the ionospheric delay is widely considered to be the largest source of single-frequency positioning errors [2].

The ionosphere is the ionized region of the Earth's upper atmosphere ranging from 50 to 1000 km above sea level. It contains free electrons and electrically charged ions created by the collision of solar radiation, in the form of extreme ultraviolet (EUV) and X-rays, with neutral air molecules. Since the ionosphere is a dispersive medium, it causes the GNSS electromagnetic signals to refract, thus inducing an error measured in meters, defined as the ionospheric delay. The ionospheric delay is proportional to the ionosphere's total electron content (TEC) and inversely proportional to the carrier frequency squared. Therefore, the ionospheric delay can be calculated by measuring the TEC of the ionosphere, which is the total number of electrons present along the path of propagation of the GNSS signal. The TEC, and consequently the ionospheric delay, are influenced by the geographical location of the receiver, solar activity, time of day, and seasons.

The ionospheric delay can be compensated by two different methods [3]. The first method involves mapping the ionosphere in real time and transmitting the corrections from Space-Based Augmentation Systems (SBAS). Unfortunately, the United Arab Emirates (UAE) is not covered by any SBAS system as of the time of writing this paper. The second method involves utilizing global ionospheric models such as the International Reference Ionosphere (IRI) model [4]. Since the ionosphere is highly dynamic and subject to regional perturbations, global ionospheric models may not represent regional ionospheric variations accurately. For this case, a regional ionospheric model is preferable. Developing a regional ionospheric model involves combining observations from ground-based reference GNSS stations and Low Earth Orbit (LEO) radio occultation measurements [5]. Additionally, observations during high and low solar activity are required.

This work presents ionospheric delay observations from a reference GNSS receiver at Sharjah, UAE, during a low solar activity period. It is hoped that these observations along with observations during a high solar activity period would enable us to develop a regional ionospheric model for the UAE.

2. Methodology

The ionospheric delay (I in meters) induced into the L1 signal (f_{L1}) at 1575.42 MHz is represented by [6]

$$\mathrm{I} = \frac{40.3\ \mathrm{STEC}}{f_{\mathrm{L1}}^2}$$

where the Slant TEC (STEC) represents the TEC along the propagation path of the signal and can be found through [7]

$$\mathrm{STEC} = \frac{1}{40.3}\frac{f_{\mathrm{L1}}^2 f_{\mathrm{L2}}^2}{f_{\mathrm{L1}}^2 - f_{\mathrm{L2}}^2}(P_1 - P_2) + b_r + b_s$$

where P_1 and P_2 represent the pseudoranges derived from the L1 and L2 signals respectively, b_r represents receiver biases, and b_s represents satellite biases.

This work presents our analysis of the seasonal and diurnal variations of ionospheric delays observed by a multi-constellation reference GNSS receiver at Sharjah (25.283N, 55.462E), United Arab Emirates (UAE), during a solar-minimum period. Our analysis includes three GNSS constellations: GPS, Galileo, and BeiDou; and was conducted for a period of two years, i.e., 2019 and 2020, corresponding to the solar-minimum period connecting solar cycles 24 and 25. The data was also filtered to exclude observations coinciding with geomagnetic storms, as they may offset the mean values we are trying to compare. As such, a threshold was implemented that excluded observations with a Disturbance Storm Time (Dst) index ≤ -30 or Kp index ≥ 5 [8].

We have divided the data into four seasons to study the seasonal variation of the ionospheric delay induced into the L1 (1575.42 MHz) signal for each constellation. These four seasons correspond to 30 days centered around the vernal equinox (21st of March), summer solstice (21st of June), autumnal equinox (21st of September), and winter solstice (21st of December). To account for the ionospheric delays induced by the different elevation values, we also divided the data into three categories: low elevation (5° < elevation ≤ 30°), medium elevation (30° < elevation ≤ 60°), and high elevation (60° < elevation ≤ 90°). All observations under 5° of elevation were excluded to avoid multipath effects.

3. Observations & Discussion

The seasonal ionospheric delay trends observed over the UAE are presented in Figs. 1–4, in terms of the ionospheric delay (I in meters), versus local time.

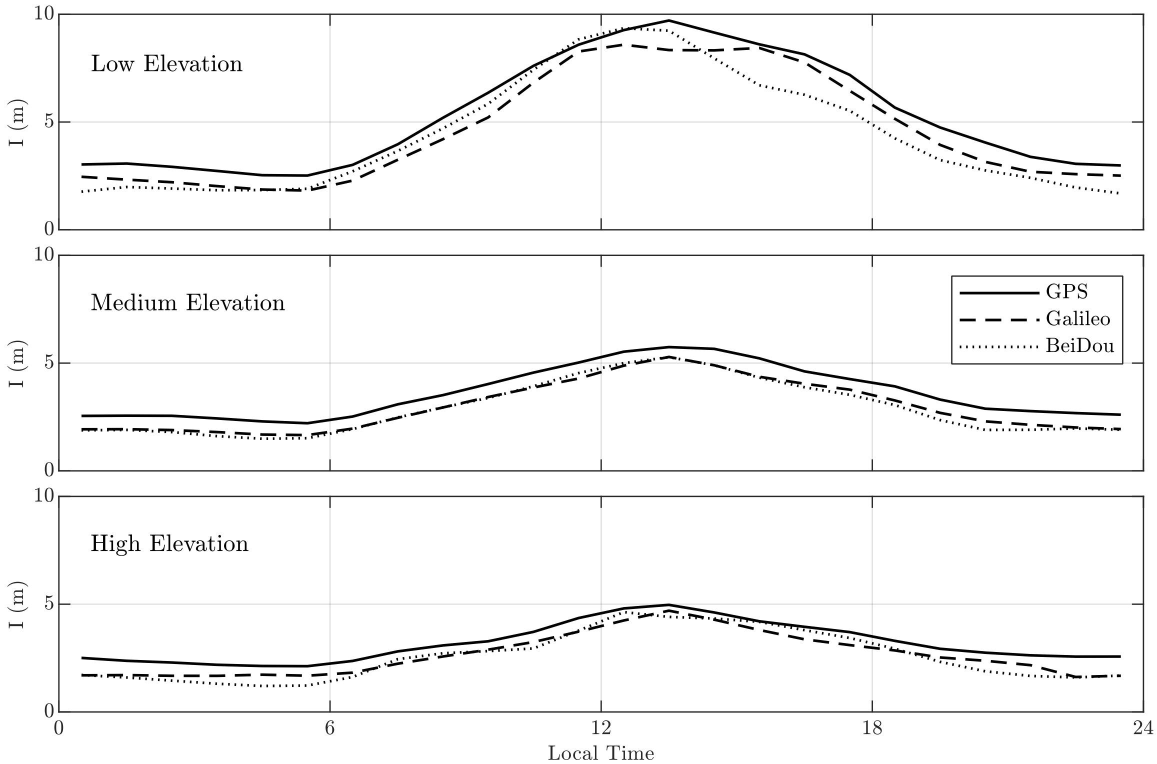

Fig. 1. Vernal equinox ionospheric delay

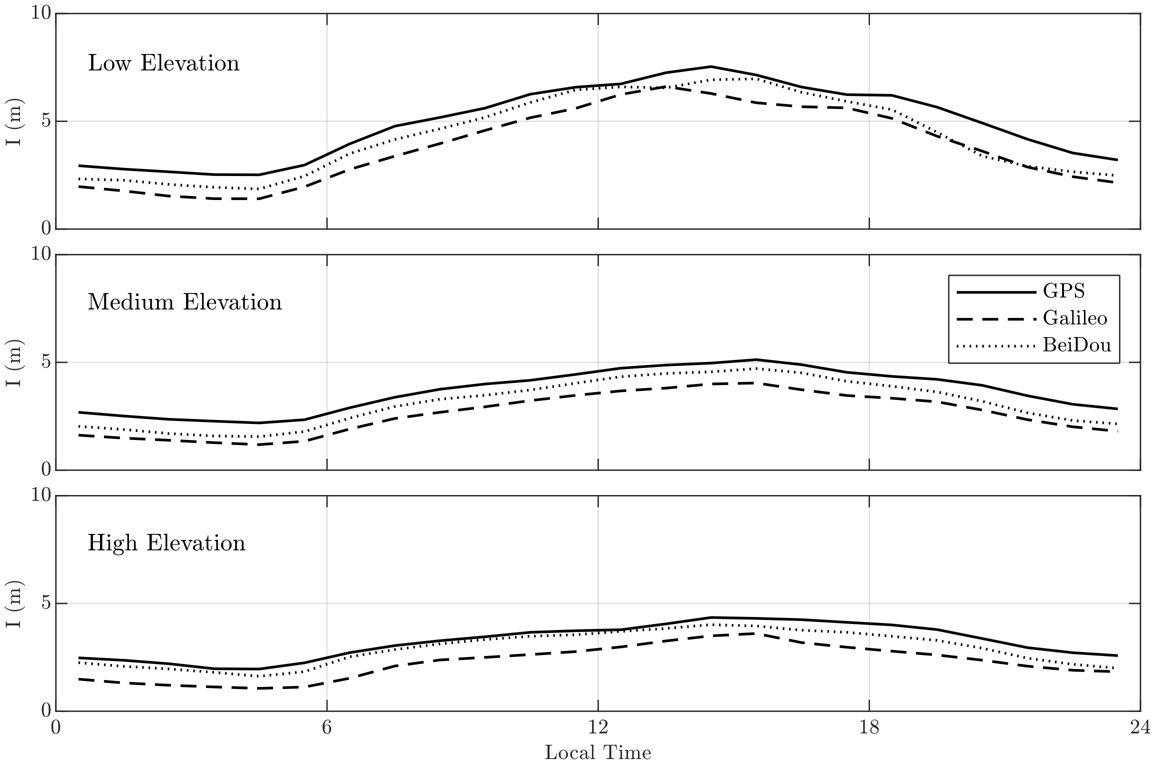

Fig. 2. Summer solstice ionospheric delay

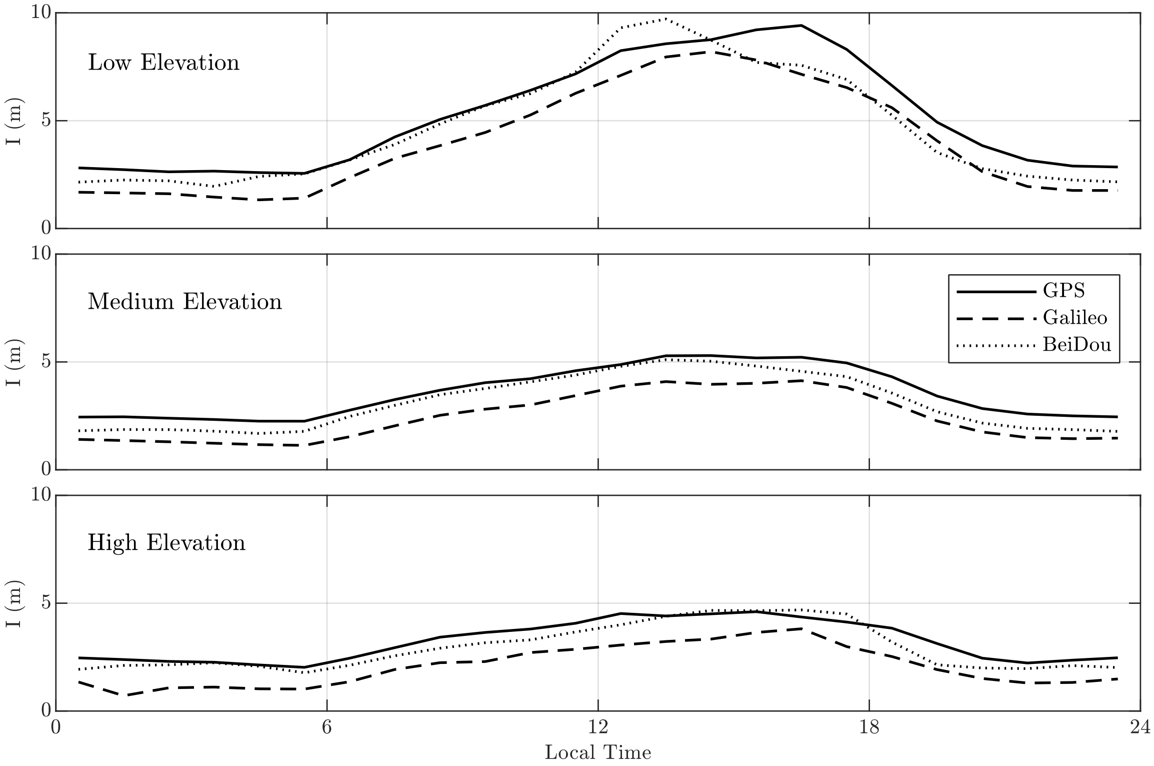

Fig. 3. Autumnal equinox ionospheric delay

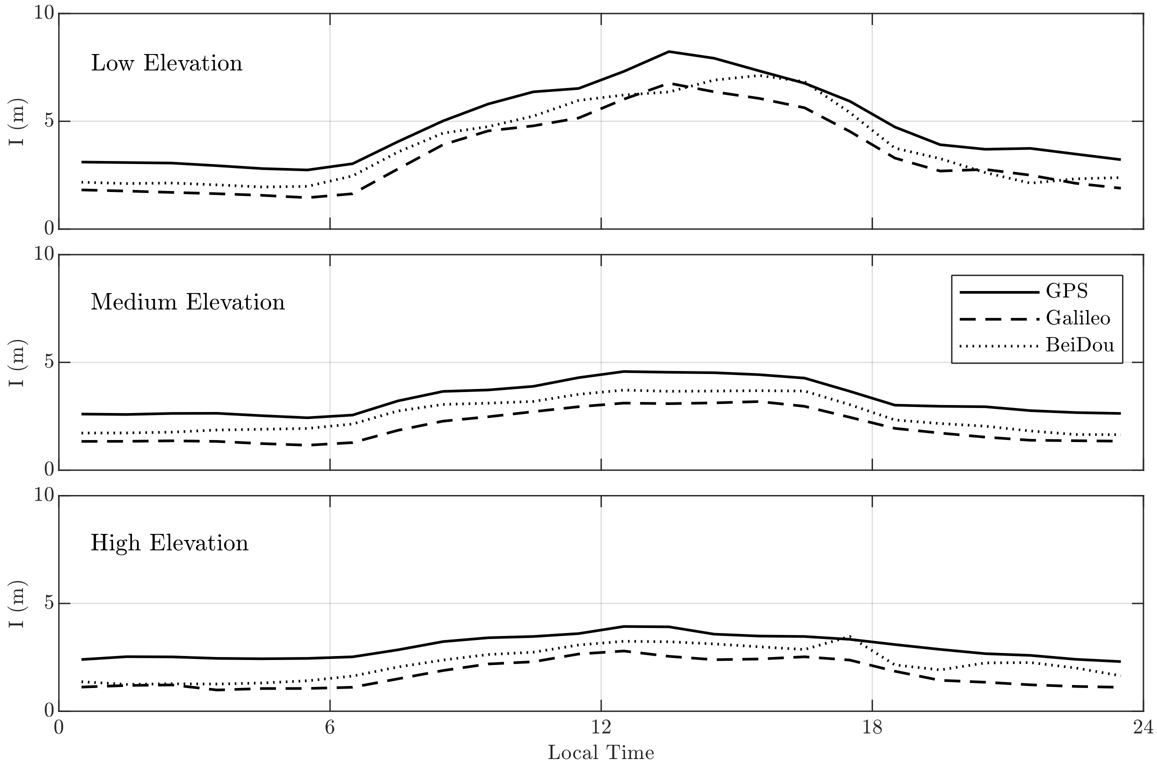

Fig. 4. Winter solstice ionospheric delay

It is important to note that GNSS signals transmitted from low-elevation satellites pass through more of the ionosphere compared to signals transmitted from satellites at higher elevations. As a result, the ionospheric delay induced by GNSS signals transmitted at low elevation was on average 1.5–2.5 times more than the ionospheric delay induced by GNSS signals transmitted by high-elevation satellites. This was the case during all seasons and for all constellations.

The maximum ionospheric delay was observed from noon to afternoon (12:00 – 17:00 local time) during the vernal and autumnal equinoxes, reaching up to 10 meters. Furthermore, the minimum ionospheric delay was observed from midnight to early morning (00:00 – 05:00 local time), reaching up to 3 meters. For most of the time, the ionospheric delay was largest for GPS and least for Galileo, while the ionospheric delay for BeiDou was somewhere in between.

An interesting feature that was observed was that the maximum ionospheric delay during the winter solstice (8.23 meters) was greater than that of the summer solstice (7.53 meters), even though the days around the summer solstice are the longest of the year while the days around the winter solstice are the shortest of the year. This feature was defined in previous work as the winter TEC anomaly [9]. The reason behind this feature is that the density ratio of atomic oxygen to molecular nitrogen O/N_2 is greater in winter compared to summer, causing the peak electron density of the ionosphere's F_2 layer (N_mF_2) to be higher during the winter as compared to summer.

4. Conclusion

The seasonal variations of the ionospheric delay observed over the UAE were studied in this work. The highest ionospheric delay was observed at the equinoxes during the afternoon, while the lowest ionospheric delay was observed during the summer solstice. The observed ionospheric delay was higher for GPS signals and lowest for Galileo signals.

As the UAE plans to establish its own regional space-based GNSS augmentation system and a regional navigation satellite system, it is important to account for and model ionospheric delays. Therefore, the importance of this study cannot be overstated, and we aim to extend it by including observations from the upcoming 25th solar cycle peak. We also aim to develop a regional ionospheric model for the Arabian Peninsula and compare it to global ionospheric models such as the Klobuchar, NeQuick2, and IRI-2016 models.

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