Mapping of S4 Over the Arabian Peninsula During Solar Minimum

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Abstract—In this letter, we study the temporal and spatial variability of ionospheric irregularities by generating high-resolution maps of the observed amplitude scintillation index (S4) using data from a multiconstellation and multifrequency global navigation satellite system (GNSS) receiver. The study is located in the Arabian Peninsula region, which falls under the northern crest of the equatorial ionization anomaly (EIA). Even though the study was conducted during a solar minimum period, considerable pre-sunset scintillation occurrences have been observed between 15 and 17 local time (LT), particularly during the winter solstices. While most scintillation occurrences have been observed at low elevation (20°–25°), a considerable number of scintillation causing ionospheric irregularities have been observed toward the north, east, and southeast of the receiver location, for elevation ranging from 40° to 60°. Out of all the GNSS constellations with medium-earth-orbit (MEO) satellites, GPS was the most impacted by amplitude scintillation, while BeiDou and Galileo satellites were the least affected. It is anticipated that the patches of ionospheric irregularities reported in this work will be further enhanced, as solar activity increases in the coming years. Therefore, this work can serve as a reference for future studies during periods of increased geomagnetic activity.

Index Terms—BeiDou, Galileo, GLONASS, GPS, scintillation.

I. INTRODUCTION

THE presence of ionospheric irregularities severely affects global navigation satellite systems (GNSSs) quality of service. These irregularities are typically caused by heightened geomagnetic activity and induce frequent fluctuations in signal intensity (SI). The fluctuations in the SI are referred to as amplitude scintillation [1]. The occurrence of ionospheric scintillation depends on various spatial and temporal factors, including time of day, season, and geographical location [2]. Ionospheric irregularities may be detected either by continuously monitoring GNSS signals using ground-based receivers or by radars, such as the ionosonde or multistatic high-frequency radars [3]–[5].

Jiang et al. [4] used GNSS and ionosonde data to detect large-scale ionospheric irregularities. They generated maps that detected ionospheric irregularities originating from the equator at low- and mid-latitude stations. Wu et al. [5] detected daytime ionospheric irregularities in the E and lower F regions around midday using a multistatic high-frequency radar. This is significant as ionospheric irregularities primarily occur during the post-sunset to midnight period.

II. DATA AND METHODOLOGY

Amplitude scintillation is typically observed through the S4 index. The total S4 index (S4total) can be defined as the

Harsha et al. [6] generated 5-min amplitude scintillation index (S4) maps for India during a severe geomagnetic storm. The maps were generated using the Kriging method and had a resolution of 2° by 2°. These maps successfully captured the features of the equatorial ionization anomaly (EIA) over the Indian region, which is a neighboring region to the one considered in this letter. Following a similar methodology, Geng et al. [7] generated 30-min S4 maps over southern China for a high solar activity period. The Kriging method had been used in both cases to interpolate for missing values. However, in this letter, we rely purely on data retrieved from observations in our work, and no attempt was made to interpolate for missing data. This should allow for a more accurate representation of the local ionosphere, particularly as we generate higher resolution maps as compared with previous work [6], [7]. Additionally, both [6] and [7] generated maps for high solar activity periods using only GPS data.

In this letter, we study the spatial and temporal variations of amplitude scintillation during a solar minimum period. The data were obtained from a multiconstellation and multifrequency GNSS receiver with scintillation monitoring capabilities (Septentrio PolaRx5S). The study region is the Arabian Peninsula (25.2827°N, 55.4621°E), which falls under the northern crest of the EIA. The presence of pre-sunset scintillation for the Arabian Peninsula region has been previously highlighted in [8] and [9]. This is a feature that has previously been only observed in low-latitude/equatorial regions [10], [11]. In this letter, we expand on the analysis performed in previous work by generating maps with a resolution of 0.2° latitude and 0.5° longitude to study the spatial distribution of the observed S4. Thus, our main objective is to identify the regions around the Arabian Peninsula that are consistently influenced by the presence of amplitude scintillation on GNSS signals. We also compare the S4 observed on different orbits of the BeiDou GNSS constellation and observations from the GPS, GLONASS, and Galileo constellations. As this study was conducted during a solar minimum, this work can serve as a reference for future studies during periods of increased geomagnetic activity.

The outline of this work is as follows. First, in Section II, the methodology and techniques used in this letter are presented. Then, the results and discussion are given in Section III. Finally, the conclusions and future work are in Section IV.
standard deviation of the 50-Hz SI normalized to the average S1 over 60 s. The corrected S4 index eliminates ambient noise (S4\_noise) from the total S4 index and is represented as [12]

\[
S4 = \sqrt{S4_{\text{total}} - S4_{\text{noise}}}
\]

\[
S4 = \sqrt{\frac{(SI)^2 - (SI_{\text{L4}})^2}{(SI_{\text{L4}})^2} - \frac{100}{\text{SNR}} \left[ 1 + \frac{500}{19 \text{ SNR}} \right]}
\]

(1)

where SNR is the signal-to-noise ratio of the signal. Note that for some instances, particularly for low total S4 values, the corrected S4 value was negative. These negative values were set to zero.

This work utilizes S4 data generated by a PolaRxSS multi-constellation and multifrequency GNSS receiver at the Sharjah Academy for Astronomy, Space Sciences and Technology (geographic coordinates: 25.2827°N, 55.4621°E; geomagnetic coordinates: 19.19°N, 131.06°E), Sharjah, United Arab Emirates. The location is of particular interest as it falls within the northern crest of the EIA. In this work, S4 data from three different signals are obtained from each of the GPS, Galileo, and BeiDou constellations, while only two signals are observed from the GLONASS constellation (see Table I). While the space segments of GPS, GLONASS, and Galileo, consist exclusively of satellites orbiting at medium-earth-orbit (MEO), BeiDou combines satellites at MEO, geostationary orbits (GEO), and inclined geostationary orbits (IGSO) [13]. A wider coverage area can be obtained by combining observations from these different constellations. To mitigate the multipath effects on the observations, the following steps were taken: 1) placing a choke ring antenna (PolaNt Choke Ring) in a position where all potential sources of multipath fall under 2° of elevation and 2) excluding observations under 20° of elevation.

The study period includes the summer, winter, and equinox seasons of 2019 and 2020, as well as the winter solstice of 2018 and the vernal equinox and summer solstice of 2021. Each season is taken as 90 days centered around their respective start dates, and the data for the equinoxes of 2019 and 2020 have been combined.

To map the observed S4 value to a particular geographical location, we use the thin shell ionospheric model (TSM) simplification [14]. We consider a perfectly spherical Earth with a radius equal to 6371 km and the TSM to be 350 km above the surface of the Earth [14].

Once the S4 values have been mapped to a geographical location, we divide the regional map ranging from 22° to 28° latitude with a resolution of 0.2° and from 45° to 65° longitude with a resolution of 0.5°. Thus, each pixel would be of size 0.2° latitude and 0.5° longitude. Then, the S4 values of 5 min over 90 days centered around the start date of each season are projected onto the map, and the mean S4 value for each pixel is taken by considering all observations that fall within the pixel during the specified time. Data from these 5-min maps will be used in the following figures. Considering that the period analyzed is that of a solar minimum, three different categories for amplitude scintillation have been used, weak scintillation corresponding to 0.1 \( \leq S4 < 0.2 \), moderate scintillation corresponding to 0.2 \( \leq S4 < 0.3 \), and high scintillation corresponding to \( S4 \geq 0.3 \).

### III. Results and Discussion

Fig. 1 presents the seasonal trends based on the total number of occurrences of \( S4 \geq 0.1 \). The number of occurrences was obtained from the 5-min maps for each season, respectively. The black, blue, and red lines correspond to signals 1, 2, and 3, respectively (see Table I).
The most noticeable feature that can be seen in Fig. 1 is the daytime enhancement in S4 values around 15–17 local time (LT), particularly during the winter solstices. This peak reached its maximum point at 16 LT and was more prominent during 2018 and 2020. This feature was previously reported in [8] and [9], and during the last solar cycle minimum at low-latitude/equatorial regions [10], [11]. It is important to note that, unlike previous works, no enhancement of S4 was observed during the post-sunset to midnight (17–24 LT) period [7], [11]. This feature may be attributed to the winter anomaly [15], where the ionization level during the winter season is higher than that of the summer season. It may also be attributed to the irregularities in the E region of the ionosphere, called sporadic-E (Es) [16]. Based on these observations, the winter solstices were chosen to be the focus of this work, particularly during 15–17 LT.

Fig. 2 shows signal 1 S4 maps for the 2018, 2019, and 2020 winter solstices around 15–17 LT. Each subplot represents 30 min, starting from 15 LT, and was obtained by taking the maximum of six consecutive 5-min maps. The intensity of the S4 values can be seen to increase from 15 LT, peaking around 16 LT, and then gradually decreasing. The majority of high and moderate scintillation occurrences can be seen around the edges of the map. During 2018, S4 observations from the eastern and western edges of the map showed considerable amounts of ionospheric irregularities, from 47° to 50°, and from 60° to 63° longitude. However, during 2019 and 2020, the eastern edge (60° to 65° longitude) was considerably more active than the west. Moderate and high S4 values were also observed around the receiver location, mostly through the 2018 and 2020 winter solstices from 15:30 LT to 16:30 LT. During this period, many pixels within the map can be seen to exceed an S4 value of 0.1. This is very significant for a solar minimum period. We note that these maps are a result of averaged S4 over 5 min for 90 days. This means that the S4 activity seen here was persistent for the entire season, i.e., over a total period of 90 days.

To better understand the data from the receiver’s viewpoint and provide a different perspective on the spatial distribution of S4 values, we present the polar plots in Fig. 3. Similar to Fig. 2, Fig. 3 presents signal 1 S4 data for the winter solstices of the study period from 15 to 17 LT for 90 days. However, the data are not represented in terms of the ionospheric pierce point location; instead, the azimuth and elevation of the line-of-sight between the receiver and satellites were considered. Each polar map has been divided into cells of size 30° azimuth and 5° elevation. The total number of occurrences of S4 in each cell has been counted and divided by the total number of occurrences for the entire slice of 30° azimuth and 5° elevation. The percentage occurrence is calculated for each cell. This should help us independently analyze each 30° azimuth segment and understand the relationship between among, elevation, and S4 activity.

The majority of S4 occurrences can be seen at 20°–25° elevation during all three years. A patch of considerable occurrences of weak, moderate, and high scintillation can be seen toward the north (330°–30° azimuth), ranging between 35° and 60° elevation for all years but more prominent in terms of coverage during 2019. This can be attributed to the data gap seen toward the north in Fig. 2. An additional feature that can be seen is the existence of a small patch ranging between 45° and 60° elevation, toward the south to southeast direction (120°–180° azimuth), with scintillation occurrence ranging...
Fig. 3. S4 polar plots (in terms of azimuth and elevation) during 15–17 LT for the winter solstices of 2018 (top row), 2019 (middle row), and 2020 (bottom row). The columns correspond to (from the left) $0.1 \leq S4 < 0.2$ (weak scintillation), $0.2 \leq S4 < 0.3$ (moderate scintillation), and $S4 \geq 0.3$ (high scintillation), respectively. The color bar corresponds to the percentage of occurrences. This percentage is found by dividing the number of occurrences in each cell by the total occurrences per 30° azimuth.

from 10% to 50%. For all years, the occurrence of scintillation toward the west to south direction (180°–270° azimuth) at mid (30°–60°) elevation is minimal, ranging from 0% to 10%, unlike the east, where various patches of 10%–50% occurrence can be seen. The reason behind these features will be explored in the next paragraphs.

To better understand the amplitude scintillation observed by each constellation separately, we present Fig. 4. In Fig. 4 (left), the winter solstice S4 peak around 15–17 LT is observed from all satellite constellations and signals. It is important to note that not all satellites of the four constellations transmit at all frequencies; therefore, different signals for each constellation are expected to have different numbers of occurrences. Expanding on the analysis of Fig. 1, most of the occurrences can be seen from signal 1 of GPS, followed by signals 1 and 2 from GLONASS. For GLONASS, both signals have similar numbers of occurrences, a feature that is also shared by all three Galileo signals as they are transmitted by all satellites within the constellation.

While the space segment of the four major GNSS constellations consists mainly of MEO satellites, BeiDou incorporates GEO and IGSO satellites as well. The bar chart in Fig. 4 presents the percentage occurrence of amplitude scintillation on signal 1 for the winter solstices of 2018, 2019, and 2020 at 15–17 LT. The BeiDou GEO and MEO satellites, as well as the Galileo MEO satellites, displayed similar percentage occurrences, unlike the BeiDou IGSO satellites, which had higher percentage occurrences due to their relatively low elevation. On the other hand, the GPS satellites had the maximum percentage occurrence for all scintillation categories, followed by GLONASS. Due to the availability of IGSO and GEO BeiDou observations (see the polar plot in Fig. 4), more scintillation occurrences were observed from the regions in the south to southeast of the receiver, as seen in Fig. 3. From the polar plot in Fig. 4, we can deduce that the patches of ionospheric irregularities seen toward the north in Fig. 3 were not covered by the GEO and IGSO BeiDou satellite observations and instead were a result of the lack of MEO satellite observations in the low elevation segment toward the north, leading to higher occurrences in the mid to high elevation segment. Similarly, the increased intensities of scintillation toward the mid-elevation southern and southeastern segments, as observed in Figs. 2 and 3, were caused by the additional BeiDou GEO and IGSO satellite observations, on top of the MEO GPS, GLONASS, BeiDou, and Galileo observations. These observations from Fig. 3 point toward an interesting feature of the GEO and IGSO satellites as part of a GNSS system. Further investigation of the BeiDou GEO and IGSO satellites would provide more interesting features and confirm the observations presented in this work.
We found the values of $S_4$ peaking at 15–17 LT during the winter solstice, particularly during the 2018 and 2020 winter solstices, and to a lesser extent, during the equinoxes at the same time.

2) The pre-sunset enhancement of $S_4$ during the winter solstice was observed by all constellations, but in greater effect in GPS, and GLONASS signals, and less so for BeiDou and Galileo satellites.

3) A patch of ionospheric scintillation occurrences has been observed in Fig. 3 toward the north of the GNSS station between 45° and 60° elevation.

4) Patches of ionospheric scintillation observed toward the south to southeast of the receiver in Fig. 3 are the result of the additional GEO BeiDou satellite observations.

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