A study of equatorial plasma bubble structure using VHF radar and GNSS scintillations over the low-latitude regions

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Abstract

Ionospheric irregularities can cause detrimental effects on the global navigation satellite system (GNSS) signals, often in the form of rapid fluctuations in both amplitude and phase. Over the low-latitude regions, the equatorial plasma bubble (EPB) frequently arises after sunset, leading to GNSS scintillations since the signals propagate through ionospheric irregularities. The relationship between amplitude ionospheric scintillations (S4 index) on GNSS signals and EPB characteristics is presented. We investigate the geometrical relationship between backscatter echoes associated with the EPB and the multi-constellation and multi-frequency scintillations, specifically, GPS and Galileo constellations with L1/E1 and L5/E5a signals. By analyzing the GNSS scintillations along the GNSS signal paths, the GNSS ionospheric pierce points (IPPs) are mapped with S4 index at different altitudes and projected along the magnetic field line together with the backscatter echoes at the equatorial atmosphere radar (EAR), West Sumatra, Indonesia. Our results are obtained for moderate scintillation cases due to limited data available for this study. The results show the EPB impact ionospheric scintillations. The S4 index on the L5/E5a signal is more susceptible to scintillations than the L1/E1 signal. Moreover, we found a high correlation between EAR backscatter echoes and S4 values on both L1/E1 and L5/E5a at an altitude between 250 and 350 km, indicating that the EPB occurs on the bottomside of the ionosphere.

Keywords Ionospheric effects on radio waves · Equatorial plasma bubble · Amplitude scintillation index · VHF radar

Introduction

In the low-latitude regions, the irregularities of the electron density in the ionosphere, namely equatorial plasma bubbles (EPB), are frequently observed after sunset (Abadi et al. 2014; Kil 2015), especially during equinoctial months. The phenomenon is often explained by Rayleigh–Taylor (R–T) instability at the bottomside of the ionosphere (Sultan et al. 1996; Kelly 2009).

Ionospheric scintillations phenomena are caused by small-scale irregularities (Yeh and Liu 1982; Worthington et al. 1999; Cesaroni et al. 2015). The signal fluctuation results in GNSS signal amplitude scintillation (S4 index) propagating through the irregularity areas. The amplitude scintillations are caused by the first Fresnel diffraction ($D_F$) due to the ionospheric irregularities ($D_F = \sqrt{2\lambda h}$, where $\lambda$ is the wavelength of the signals (meter) and $h$ is the height of the irregularities in meter). At the altitude of 350 km, the first Fresnel radius is approximately 300–400 m for GNSS signals (Pi et al. 1997). As GNSS is widely used in many applications, multi-constellation and multi-frequency (MC/
MF) will be available for air navigation shortly, in addition to GPS L1 and Galileo E1 signals. Even if the ionospheric delay effects can be eliminated by the dual-frequency combination, the scintillation can still affect satellite signals, possibly causing loss of tracking signal or loss-of-lock (Pullen et al. 1998; Caamano et al. 2016). Scintillation effects on GNSS have been studied mainly for the GPS L1 C/A signal, but few works analyze the effects on “new” signals such as GPS L5 or Galileo E5a signals. He et al. (2016) have investigated the ionospheric scintillation effects on the B1I signal of the BeiDou system, and the simulation results show that the strong scintillations cause the pseudorange error are more than 4 m; moreover, the positioning errors could be more than 6 m. Moreover, Hlubek et al. (2014) have analyzed the statistics of scintillation events on GPS L1, L2C, and L5, GLONASS L1, L2, and Galileo E1 and E5a. Similarly, Salles et al. (2021) have studied the modernized L2C and L5 signals affected by scintillations in comparison with the L1 GPS signals. They found that the L2C and L5 signals are more susceptible to intense scintillations because their wavelengths are longer than that of the L1 signals.

Furthermore, although previous research addresses the scintillations and EPB characteristics, the scintillation effects on MC/MF GNSS satellites and how they relate to the structures of EPBs are not well studied. The EPBs are three-dimensional ionospheric structures. By understanding what part of EPBs are effective in causing scintillations on GNSS signals and what part is not so important, we would be able to evaluate the impacts on scintillations associated with EPBs on GNSS. Hence, we aim to better understand the EPB effects on the GPS and Galileo satellites on L1/E1 and L5/E5a signals by analyzing the amplitude scintillation index and comparing them with the EPB structure.

From previous works, there are various observations to monitor the EPB as well as its initiation, including ionosonde (Wei et al. 2021), all-sky airglow imager (Nakata et al. 2018), GNSS receivers (Haridas et al. 2021), beacon receivers (Watthanasangmechai et al. 2016), in situ satellites (Wernik et al. 2007), and very high frequency (VHF) radar stations such as in Sanya, China (Li et al. 2012), and equatorial atmosphere radar or EAR, Indonesia (Otsuka et al. 2009). In general, the EPB structure with various sizes, from meters to hundreds of meters can cause severe scintillation on GNSS signals passing through the EPB phenomenon.

EAR is a powerful radar system to detect irregularities in the troposphere and ionosphere over equatorial regions. It observes the field-align irregularity (FAI) with the spatial scale size of half the radar wavelength associated with EPB (about 3 m scale irregularity). The detection is based on the Bragg scattering from the ionospheric plasma density perturbation along the geomagnetic field lines (Tsunoda 1980). The ionospheric irregularities with spatial scale sizes of half the wavelength of the radar wave, associated with EPBs have been detected by EAR, whereby multi-beam observations can reveal the spatial structures of EPBs. The effectiveness of EPB monitoring via EAR clearly shows the precise shape, direction, and size of the irregularities (Fukao et al. 2003, 2004; Saito et al. 2008).

We employ an MC/MF scintillation receiver which is installed at the EAR site and relate the results with the 2-dimensional plasma bubbles observed from EAR. In this work, the relationship between F-region field-aligned irregularities related to the EPB characteristics and ionospheric scintillations are analyzed from EAR data as well as the S4 index during ionospheric disturbance days in 2019, a total of 22 events. The relationship between scintillation intensity and EAR echo power at ionospheric pierce points (IPPs) of GNSS satellites mapped at different altitudes along the magnetic field line will be highlighted. The observational results show the morphology of scintillations which concurrently occur as the EAR detects the backscatter echo power.

We describe the available data and the research methodology first. Next, the relationships between the ionospheric scintillations and the EAR echoing regions are shown. It can be separated into 3 parts; the first part is the morphology of scintillation study, the second part is EAR backscatter echoing regions, and third, the association between MC/MF scintillations and 2-dimensional plasma bubbles from EAR. Moreover, the discussions are made in this section. Finally, conclusions are provided.

**Data and methodology**

In this section, the amplitude scintillation or S4 index is utilized together with the backscatter echo power of Equatorial Atmosphere Radar (EAR) to associate the scintillation occurrences with the Equatorial Plasma Bubbles (EPBs) characteristics over low-latitude regions. The amplitude scintillation data are obtained from the multi-constellation and multi-frequency (MC/MF) GNSS scintillation receiver (Septentrio PolarRxS), which is located at Kototabang, namely KTTB station, West Sumatra, Indonesia (geographic; 0.20S, 100.32E, magnetic: 9.1S). We use the L1 and L5 signals of global positioning system (GPS) satellite at the L1 band (1575.42 MHz) and L5 band (1176.45 MHz), respectively, and E1 and E5a signals from Galileo constellations at the L1 and L5 bands, respectively. The satellite elevation angle cutoff at 30 degrees is chosen to refrain from the multipath effects. The S4 indices are estimated in the receiver at every 60-s interval.

The EAR, which is located at the same site as the GNSS receiver, is a phased-array pulsed Doppler radar operated at a frequency of 47.0 MHz (Fukao et al. 2003). It can detect coherent backscatter echoes from ionospheric irregularities with the scale size corresponding to half a radar wavelength,
which is about 3 m, known as the Bragg scattering. Since
the ionospheric irregularities are developed along the earth’s
magnetic field lines, strong backscatter echoes are obtained
only when the beam is perpendicular to the magnetic field.
By electronically switching the radar beam directions, the
cross sections of EPBs can be obtained. The range resolution
is 2.4 km. Table 1 shows the directions of 16 beams used in
the experiment. These 16 beams are divided into two sets of
8 radar beams. In each set of beam directions, beam direc-
tions are switched one after the other on a pulse-to-pulse
basis. After completion of a scan of one set of beams, obser-
vation with the other set of beams is conducted. By combin-
ing the echo powers of the two sets of scans, we can obtain
two-dimensional maps of the backscatter echoes (Saito et al.
2008). A two-dimensional echo power is obtained every 2
to 4 min. The interval between the scans may vary because
other observations of the E region, the troposphere, and the
stratosphere are conducted between the scans.

The GNSS data corresponding to the enhanced scintilla-
tion events are selected to compare with the backscatter echo
power of EAR on the same day. To compare the EPB struc-
tures obtained by the EAR with the scintillation activities,
S4 indices are compared with the EAR echo power along
the path of the GNSS signals. The criteria for choosing the
events are based on the 3 following conditions. First, the
echo power should be more than 30 dB, so that the EPB
shapes can be clearly observed by EAR after sunset. Sec-
ond, the enhancement of S4 index from GNSS satellites that
broadcast both L1/E1 and L5/E5a is considered since we aim
to analyze the relationship between EPB structures and MC/
MF GNSS scintillations. Finally, the GNSS signal paths,
which see enhanced S4 values, must simultaneously pass
through the (radar) echoing region to analyze the correla-
tion between the S4 index on L1/E1 and L5/E5a with the
echo power at the echoing regions at the same time. Unfor-
unately, based on available measurement data from 2019
to 2020, only moderate scintillation events with clear EAR
echoing regions exist. That is why we focus the study on the
moderate condition. One of the reasons is that the period of
2019–2020 entails the lowest SSN of solar cycle 24. Simul-
taneous occurrences of EAR echoing region observed after
sunset and strong scintillations (S4 index > 0.5) from GNSS
satellites under the condition #3 could not be found either.

To analyze these data together, the block diagram of map-
ning GNSS IPPs representing the GNSS signal path and
backscatter echo powers as EAR echoing regions is shown in
Fig. 1.

The enhanced S4 events for each satellite vehicle (SV)
as obtained from all satellites in view are selected, and then
the EPB structures are reconstructed by the EAR backscatter
echo powers at that time. The IPPs of the GNSS signal paths
at three reference altitudes of 250, 350, and 450 km are cal-
culated to represent the GNSS signal path. To compare the
EPB structures and scintillation activities, the GNSS signal
path and two-dimensional EAR echoing regions are pro-
jected to the horizontal plane at an altitude of 350 km along
the magnetic field line, because EPB develops along the
magnetic field line due to high electric conductivity along
that line (Tsunoda et al. 1980; Takahashi et al. 2018). This
reduces the complexity to a simple two-dimensional image.

Because of high electric conductivity along the mag-
netic field, ionospheric plasma structures dominated by the
electric field develop along the magnetic field line, and the
EPB cross sections observed by the EAR are mapped along
the magnetic field line (Otsuka et al., 2004). To analyze the
three-dimensional relationship between the GNSS signal
paths and the echoing regions, it is useful to project both of
them to a reference altitude, which is 350 km in this study.
Projections along the magnetic field lines are done by using
the International Geomagnetic Reference Field (IGRF)
model (Thébault et al. 2015). An illustration of a projected
satellite path is displayed in Fig. 2. For the signal path pro-
jection, the calculated IPPs at 250 and 450 km are projected
to an altitude of 350 km by tracing along the magnetic field.
Then, the echoing regions are plotted together with IPPs on
the geographic map as a horizontal plane.

Figure 2 illustrates the concept of a 3-D geometrical
relationship between an EPB which is developed along the
magnetic field line and the satellite-receiver paths. The sat-
ellite IPPs at the altitudes of 250 km, 350 km, and 450 km
along the signal path are shown as the star marks, labeled
with the point X, Y, and Z, respectively, then the satellite-
receiver path is obtained by referring to those 3 IPPs. The

| Table 1 | EAR beam directions and parameters |
|--------|-----------------------------------|
| Beam set | Beam number | Beam direction (degree) | Azimuth | Zenith |
| 1 | 1 | 125 | 34.88 |
| 2 | 137 | 28.54 |
| 3 | 151 | 24.47 |
| 4 | 165 | 22.45 |
| 5 | 180 | 21.85 |
| 6 | 195 | 22.68 |
| 7 | 209 | 24.99 |
| 8 | 223 | 29.54 |
| 9 | 130 | 31.80 |
| 10 | 144 | 26.18 |
| 11 | 158 | 23.26 |
| 12 | 172 | 21.99 |
| 13 | 188 | 22.11 |
| 14 | 202 | 23.62 |
| 15 | 216 | 26.90 |
| 16 | 230 | 33.19 |
IPPs at the altitudes of 250 and 450 km are then projected to the altitude of 350 km by tracing the magnetic field line \( \mathbf{B} \) by using the IGRF model. The projection of the GNSS signal path to the altitude of 350 km along the magnetic field line is represented as a blue line. The point \( X \) is projected (traced) down along the magnetic field line to the altitude of 350 km as denoted by \( X' \), however, the point \( Z \) is projected (traced) up along the magnetic field line to the altitude of 350 km as denoted by \( Z' \), in addition, the point \( Y' \) is already at the altitude of 350 km. Hence, it is the same point as \( Y \).

The backscatter echo distributions are also projected to the same horizontal plane at the altitude of 350 km by tracing the magnetic field line. As we aim to analyze the relationship between the S4 index and the EAR echoing region, we compare those values at the same altitude of 350 km, which is referred to the bottomside of the ionosphere.

Figure 3 shows the projection of both the GNSS signal paths and the EAR echoing region on the same horizontal plane. The solid lines indicate the radar beam directions of the total 16 beams and the projected GNSS signal path with IPPs at different altitudes. The echo powers corresponding to the IPPs at different altitudes can be retrieved from the nearest EAR echo power IPP every time the two-dimensional echo map is obtained.

### Observational results and discussions

In this section, we show the results of the relationship between ionospheric scintillations (S4) and EAR echoing regions. S4 indices have been obtained from MC/MF GNSS scintillation receiver, model of Septentrio PolarRxS. The scintillation data are estimated by the receiver every minute. The backscatter echo power of very high-frequency radar is derived from Equatorial Atmosphere Radar (EAR)
every 2 to 4 min. The interval between the scans may vary because other observation of the atmosphere is conducted between the scans. The equipment is located at Kototabang (KTTB station), Indonesia. Table 2 summarizes the details of data used in the total of 22 events in 2019. The relationship between those results will be clarified in this part. The results are separated into 3 parts.

(A) Morphological study of scintillations

Figure 4 shows the time series of amplitude scintillations or S4 indices which are obtained at every 1 min from all satellites in view on L1/E1 and L5/E5a signals on March 18, 2019, at KTTB station, Indonesia. The different colors indicate the S4 indices from different satellites.

As shown in Fig. 4, the enhanced S4 values can be obviously seen at the time around 21.40 to 00.30 local time (LT). The local time is 7 h ahead of universal time (UT). The number of satellites with enhanced S4 values is shown in Table 3. The letters $G_{xx}$ and $E_{xx}$ mean GPS and Galileo PRN-$xx$ satellites, respectively. The highest S4 values shown in the top panel are from GPS PRN13 (G13) satellite, but this satellite does not transmit the L5 signal, nor do GPS satellites G02, G05, G19 and G28 in Table 3. Hence, the satellites that transmit L1/E1 and L5/E5a frequencies are employed to analyze.

| Date               | Event number | SV number | Frequency bands | Duration (LT) |
|--------------------|--------------|-----------|----------------|---------------|
| 26 February        | 1            | E 01      | E1/E5a         | 18.48–23.50   |
|                    | 2            | E 04      | E1/E5a         | 22.50–4.00    |
| 28 February        | 3            | E 02      | E1/E5a         | 20.24–01.12   |
| 6 March            | 4            | E 07      | E1/E5a         | 22.44–03.53   |
|                    | 5            | E 30      | E1/E5a         | 18.40–23.42   |
| 18 March           | 6            | E 01      | E1/E5a         | 17.29–22.29   |
|                    | 7            | E 04      | E1/E5a         | 21.29–02.39   |
|                    | 8            | E 31      | E1/E5a         | 19.38–00.15   |
| 25 March           | 9            | E 01      | E1/E5a         | 18.42–23.30   |
|                    | 10           | E 04      | E1/E5a         | 22.48–03.42   |
|                    | 11           | E 19      | E1/E5a         | 20.45–01.31   |
|                    | 12           | E 21      | E1/E5a         | 16.36–21.33   |
| 3 April            | 13           | E 09      | E1/E5a         | 19.16–00.13   |
|                    | 14           | E 24      | E1/E5a         | 17.12–22.12   |
| 6 April            | 15           | E 03      | E1/E5a         | 21.33–02.33   |
|                    | 16           | E 05      | E1/E5a         | 19.24–00.30   |
| 11 September       | 17           | G 10      | L1/L5          | 18.22–22.18   |
|                    | 18           | E 24      | E1/E5a         | 17.28–22.30   |
| 18 September       | 19           | G 26      | L1/L5          | 18.55–23.10   |
|                    | 20           | E 09      | E1/E5a         | 20.42–01.49   |
|                    | 21           | E 24      | E1/E5a         | 18.43–23.31   |
|                    | 22           | E 31      | E1/E5a         | 16.36–21.36   |
The comparison of S4 indices on the quiet and disturbed days on March 8 and 18, 2019, respectively, is shown in Fig. 5 (top left to bottom right). The blue dots represent the S4 indices on quiet days and the red dots represent the S4 indices on disturbed days as a function of LT. The enhancement of S4 values on March 18, 2019 (red color) can be clearly observed at the time around 22.00 LT, compared to the S4 values that were not enhanced on March 8, 2019 (blue color). The comparison of S4 indices between disturbed and quiet days of E1 and E5a signals of the Galileo PRN01 (E01) satellite are shown on the top row. The highest S4 values of E1 and E5a signals, i.e., in L1 and L5 bands, are 0.23 and 0.35, respectively, at 22.06 LT. For more examples, the S4 indices from the E04 and E31 satellites are presented on the middle and bottom row, respectively. The highest S4 values of E04 satellite for E1 and E5a signals are 0.22 and 0.32, at 22.39 LT. Lastly, for E31 satellite, the S4 values appear to be at the highest levels of 0.23 (for E1 signal) at 22.41 LT and 0.35 (for E5a signal). From the top left to bottom right panels, the results apparently show that the obtained S4 indices in the L5 band are larger than those in the L1 band.

In subsection A), the E04 satellite is used as an example of the results to be discussed in detail since the E04 satellite broadcast the signals on both L1 and L5 bands. Then the geometrical relationship of the signal path and the EAR backscatter echoing regions is investigated.

Figure 5 (middle row) shows the S4 values from E04 satellite on March 8, 2019 (blue color), and March 18, 2019 (red color) of E1 and E5a signals, respectively. The highest S4 values of the E04 satellite can be obviously seen at 22.39 LT, whereas the highest S4 values on E1 and E5a signals are 0.2 and 0.31, respectively. Table 4 shows the number of visible GNSS satellites at 22.39 LT. The gray shade in this table highlights the results of E04 satellite.

(B) EAR backscatter echoes

The backscatter echo powers which were observed on March 18, 2019, are shown in Fig. 6 in the range-time-intensity (RTI) format for each beam. The enhancements of echo power which indicates the existence of 3 m scale irregularities associated with EPBs are detected from 21.00 to 23.30 LT.

Figure 6 shows the echo power in signal-to-noise ratio (SNR) as observed by each of 16 beams. The horizontal axes indicate time in LT and the vertical axes indicate the range from the radar in kilometers. Intense echoes are observed at the slant range about 250 km up to 450 km. The cluster of echo power enhancements, as seen in the figure, indicates a series of EPB occurrences. The EPBs are detected by EAR from approximately 20.50 to 00.00 LT. The first EPB is observed around 21.00 LT, the second EPB starts to be observed around 22.00 LT and it can be seen until 23.50 LT later when the EPB is going out of the radar field of view (FOV). With the procedure shown in Fig. 2, we discuss the scintillation and radar echoes projected on a horizontal plane at an altitude of 350 km. The echo powers of the 16 beams are combined and plotted in the fan-shaped format projected to an altitude of 350 km along the magnetic field lines.

Figure 7 shows the series of two-dimensional echo maps from 21.00 to 22.40 LT, whereby the horizontal and vertical axes represent the geographic longitude and latitude, respectively. The areas of enhanced SNRs indicate the shape of the detected EPBs. The EPBs (labeled as “A” and “B” in Fig. 7) appear in sequential order. The first EPB as indicated by cluster A at 21.00 LT is shown in top left panel. At 20 min later, cluster A moves eastward to the center of the EAR FOV as presented in the top right and middle left panels. The second EPB denoted by cluster B moves into the radar FOV from 22.01 to 22.21 LT, while the first EPB is moving out of the EAR FOV. The bottom right panel shows the second EPB only.
while the first detected EPB is already out of the EAR FOV. We can evidently see that the EPBs are moving eastward.

**(C) Analysis of scintillations and EAR echoing region**

In Fig. 8, the IPPs at 22.39 LT are plotted together with echoing regions projected at the altitude of 350 km on the geographic plane. The dot size of each IPP indicates the levels of S4 values. Larger dots indicate higher S4 values than the smaller ones. The top panel shows that the IPPs of G05, E04, and E31 satellites are inside the echoing regions. On the bottom panel, IPPs of satellites E04 and E31 are inside the echoing regions. The IPPs of G17, G19, and E19 are outside the radar FOV. It is clear from this figure that, at some IPPs are not in the echoing region, the S4 levels can be high as well. This leads to further investigation.

Because the GNSS signals may pass through the EPBs at altitudes other than 350 km, the signal paths are represented by the IPPs at 250, 350, and 450 km are projected along the magnetic field line to the horizontal plane at the altitude of 350 km as shown in Fig. 9. The example of the results at 22.39 LT on March 18, 2019, is displayed. The top and bottom panels show that the derived signal paths of L1/E1 and L5/E5a are mapped together with the EAR backscatter echo power associated with the EPB. The black, red, and blue circles represent the projected IPPs from the altitudes of 250, 350, and 450 km to a certain altitude of 350 km, respectively. Hence, the GNSS signal paths at 350 km can be obtained by connecting the three IPPs as shown by the dashed lines. The red dashed lines and gray dotted lines indicate that the signal paths are inside and outside the EPB, respectively. From the observational results, the dot sizes of the IPPs outside the EPB are smaller than those inside the EPB. For G13 satellite in Fig. 8 (top panel), the size of IPP is bigger than those of G17, G19, and E19 which are outside the EPB because the satellite path passes through the EPB at the altitude of about 250 km.

In Fig. 9, GNSS the signal paths and the echoing regions are shown together. For instance, the E1 and E5a signals of E04 satellite show enhancements in the S4 index. It can be clearly seen that the signal paths at the altitude of 250 to 350 km are inside the EPB. But the signal path of satellite from the altitude of 350 to 450 km is outside the EPB.
Fig. 6  Range time-intensity (RTI) on March 18, 2019, from EAR. The different subfigures represent obtained RTI from different radar beams. These 16 beams are separated into two sets of 8 radar beams, as mentioned in Table 1. The disturbances are detected by higher-numbered beams (such as beam #16) earlier than lower-numbered beams (such as beam #1).
Hence, the signal path of E04 satellite penetrates through the bottom side of the EPB.

To relate the satellite paths with the echoing regions, the time series of S4 values derived from L1/E1 and L5/E5a signals are plotted against the SNRs for backscatter echoing regions at the IPPs at different altitudes as shown in Fig. 10. The S4 values which are derived from E1 and E5a of E04 satellite are displayed in panels a1 and b1. The echo powers observed on March 18, 2019, at the IPP at the altitudes of 250 km (black color), 350 km (red color), and 450 km (blue color) are shown in panels c1 to e1, respectively, as a function of time in LT. The peak of the echo power at the IPP at an altitude of 250 km is slightly before the peak of the S4 index while the peak of the echo power at the IPP at an altitude of 350 km is slightly after the peak of the S4 index. The peak of the echo power at the IPP at the altitude of 450 km is obviously after the peak of the S4 index. The results of E04 satellite in panels a1 to e1 indicate that the best correlation between the S4 index and EAR echo power would be obtained at altitudes between 250 and 350 km.

The correlation coefficients between S4 indices and the SNR at different altitudes are calculated to see the relationship quantitatively. The highest correlation coefficients for E1 and E5a signals of the E04 satellite are 0.713 at altitude of 250 km and 0.76 at altitude of 350 km.
In Fig. 10, a2 to e2 and a3 to e3 panels show the relationship between the S4 index and EAR backscatter echo power for E01 and E31 satellites, respectively, in the same way as panels a1 to e1. In the panels a2 and b2, the enhancement of S4 indices can be observed from around 21.20–22.30 LT. The echo power IPPs at the altitude of 250 shows a clear peak slightly before the peak of the S4 index as shown in panel c2. On the other hand, no clear enhancement in the echo power at IPPs at the altitudes of 350 and 450 km are observed as in panels d2 and e2, respectively. While the IPPs at an altitude of 250 km are still inside the EAR field of view (FOV), those at 350 and 450 km are outside the EPB. From panel e2, the echo power at the IPPs at the altitude of 450 km is observed only for 7 min because they are outside the EAR FOV for most of the time. In this case, the altitude which is most effective for scintillation is not clear, although the correlation between the S4 index and the echo power at IPPs at the altitude of 250 km is high. For E31 satellite, the results are shown in panels a3 to e3, the best correlation between the S4 index and the echo power is obtained at the altitude of 350 km, which is 0.594 for E1, and 0.686 for E5a.

To investigate the correlation between the S4 index and the EAR echo power more extensively, 22 events in 2019 are analyzed. In these events, the enhancements in the S4 index and EAR echo power enhancements are simultaneously observed. Furthermore, the signal paths are in the EAR FOV at least one of the three altitudes of 250, 250, and 450 km. Table 5 (in appendix) summarizes the correlation coefficients between EAR echo power at the different altitudes and the S4 indices of L1/E1 and L5/E5a signals. The gray shading boxes indicate the highest correlation coefficients which are calculated for each event. For example, on February 26, 2019, for the E01 satellite, the highest correlation coefficients for E1 and E5a signals are 0.469 at an altitude of 250 km and 0.372 at an altitude of 250 km, respectively. From these results, the S4 variations from the frequencies of L1/E1 and L5/E5a are highly correlated with the EAR echoes at altitudes between 250 and 350 km.

The correlation coefficients show that the highest correlation between enhanced S4 indices and high SNR echoing regions is happening at altitudes between 250 and 350 km, indicating irregularities at altitudes around or slightly lower than the F region peak more effective in causing scintillations on GNSS signals. It can be concluded that we simultaneously observed the different scale sizes of the irregularities (about 3 m scale and about 300 m scale irregularities) in the ionosphere. These results demonstrate that the ionospheric scintillations are affected by EPB at altitudes from 250 to 350 km, which are the bottomside of the ionosphere rather than around the peak of the ionospheric F region. Tsunoda (1981) showed that the west wall of EPBs is susceptible to a wind-driven interchange instability and tends to be more irregular. In addition to the altitudinal variation of the effectiveness of irregularities to scintillation, variation of scintillation intensity across the EPB from east to west needs to be studied.

It should be noted that the observed S4 indices are generally higher for L5/E5a signals than those of L1/E1 signals for all three cases shown in Fig. 10. This could be explained
in the following way: Because the frequency is lower for L5/E5a signals, the corresponding Fresnel scale is larger than that of L1/E1 signals. This means that larger irregular scale sizes (L5/E5a) are more common than smaller scale sizes (L1/E1). Generally speaking, the spatial spectra of ionospheric irregularities obey a power law, where irregularities with a larger spatial scale have larger amplitudes. Thus, the scintillation of L5/E5a signals tends to be more intense than L1/E1 signals. However, the differences in signal characteristics, including their transmitted power and coding schemes, may have additional effects. But it is beyond the scope of this paper and left for our future studies.

Figure 11 shows the correlation coefficients between echo power levels and S4 values on L1/E1 (top) and L5/E5a (bottom). The different colors of the bars represent the different altitudes of IPP, black color refers to 250 km, red color refers to 350 km, and blue color refers to 450 km. The horizontal and the vertical planes indicate the total of 22 events according to Table 5 (see appendix) and the correlation coefficient between the S4 indices and the echo power at each altitude, respectively. The bar graph results clearly show that the irregularities observed from EAR highly correlate with the ionosphere at an altitude between 250 and 350 km. Moreover, in Fig. 12 top and bottom panels show the boxplot of correlation coefficients between echo power levels (at each altitude) and S4 values on L1/E1 and L5/E5a, respectively. The physical explanation of the irregular altitudes is as follows. Since the irregularity amplitude is proportional to the background density, it would be stronger around the F region peak at the altitudes around 350 km. The vertical density gradient at the bottomside of the ionosphere would also enhance irregularities. Thus, the irregularities may be concentrated around and below the F region peak.

Our results are obtained for moderate scintillation cases because of limited data available for this study. Additional studies are necessary to understand if our results apply to the strong scintillation case by using data obtained in the near future with increased solar activity.

Conclusions

The relationship between MC/MF GNSS scintillations and the EPB characteristics has been studied by analyzing the amplitude scintillation or S4 index together with the EAR backscatter echo power at Kototabang (KTTB station), Indonesia, for moderate scintillation cases. In the data on disturbance days in 2019, a total of 22 events are used. EAR observations of backscatter echo power clearly show the EPB occurrences, and simultaneously, the S4 indices are enhanced for satellites of which propagation paths go through the EPBs.
The results show the high correlations between EAR backscatter echoing regions and amplitude scintillations, even though they are different scale size irregularities. Large-scale irregularities embedded in hundred-meter scales have been observed simultaneously with the small-scale irregularity in meter-scale by using EAR. These results demonstrate that the ionospheric scintillations are affected by EPB. The S4 indices on the signals on L5/E5a are generally higher than those on L1/E1. The peak of backscatter echo power at the altitude of 250 and 350 km are highly correlated to the S4 indices enhancements. This means that scintillations are mainly caused by irregularities in the relatively lower part of EPBs. Future studies are necessary to understand if our results apply to strong scintillation cases by using data obtained in the future as solar activity increases.

Appendix 1: (Table 5)
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Data availability The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

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Table 5 Correlation coefficients between echo power levels (at each altitude) and S4 values on L1/E1 and L5/E5a

| Date       | Event number | SV number | Alt. 250 km | Correlation coefficients | Alt. 350 km | Correlation coefficients | Alt. 450 km | Correlation coefficients |
|------------|--------------|-----------|-------------|--------------------------|-------------|--------------------------|-------------|--------------------------|
|            |              |           | Alt. 250 km | L1/E1                    |             | L5/E5a                   | L1/E1       | L5/E5a                   |
|            |              |           |             |                          |             |                          |             |                          |
| 26/02/2019 | 1            | E 01      | 0.469       | 0.372                    | −0.004      | −0.0144                  | −0.095      | −0.107                   |
| 2          | E 04         | 0.335     | 0.275       | 0.1                       | 0.161       | 0.11                     | 12          |
| 28/02/2019 | 3            | E 02      | 0.333       | 0.377                    | 0.432       | 0.542                    | −0.23       | −0.205                   |
| 06/03/2019 | 4            | E 07      | 0.574       | 0.707                    | 0.215       | 0.349                    | −0.15       | −0.097                   |
|            |              | E 30      | 0.161       | 0.132                    | −0.002      | −0.174                   | 0.051       | 0.026                    |
| 18/03/2019 | 6            | E 01      | 0.18        | 0.32                     | 0.071       | 0.045                    | Out of field of radar view |
| 7          | E 04         | 0.713     | 0.657       | 0.683                    | 0.76        | 0.106                    | 0.059       |
| 8          | E 31         | 0.192     | 0.243       | 0.594                    | 0.686       | 0.196                    | 0.197       |
| 25/03/2019 | 9            | E 01      | −0.217      | −0.039                   | 0.251       | 0.548                    | 0.066       | 0.019                    |
| 10         | E 04         | 0.366     | 0.367       | 0.584                    | 0.589       | −0.073                   | −0.036      |
| 11         | E 19         | 0.659     | 0.637       | −0.366                   | −0.268      | −0.099                   | −0.013      |
| 12         | E 21         | 0.45      | 0.606       | −0.131                   | 0.157       | −0.067                   | 0.049       |
| 03/04/2019 | 13           | E 09      | 0.388       | 0.485                    | 0.67        | 0.7                      | −0.189      | −0.175                   |
| 14         | E 24         | 0.568     | 0.627       | −0.055                   | 0.072       | 0.01                      | 0           |
| 06/04/2019 | 15           | E 03      | 0.384       | 0.375                    | 0.77        | 0.837                    | 0.056       | −0.043                   |
| 16         | E 05         | 0.689     | 0.207       | 0.802                    | 0.784       | −0.102                   | −0.051      |
| 11/09/2019 | 17           | G 10      | −0.049      | −0.014                   | 0.667       | 0.745                    | 0.48        | 0.447                    |
| 18         | E 24         | 0.321     | 0.437       | 0.645                    | 0.694       | 0.242                    | 0.24        |
| 18/09/2019 | 19           | G 26      | −0.111      | −0.009                   | 0.197       | 0.217                    | −0.074      | −0.129                   |
| 20         | E 09         | Out of field of radar view | 0.19 | 0.055 | 0.421 | 0.286 |
| 21         | E 24         | 0.512     | 0.538       | 0.191                    | 0.172       | −0.171                   | −0.187      |
| 22         | E 31         | Out of field of radar view | 0.576 | 0.529 | 0.132 | 0.158 |

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