A Study of Daytime L-Band Scintillation in Association With Sporadic E Along the Magnetic Dip Equator

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Abstract In this paper, we present a comprehensive study of occurrence of L-band scintillation in association with the appearance of sporadic E (Es) along the magnetic dip equator during daytime in 2013. The presence of L-band scintillation was determined from signals collected with GNSS (Global Navigation Satellite Systems) ground-based Scintillation Network Decision Aid receivers from five stations situated at the magnetic dip equator. The detection and analysis of Es layers were obtained from GNSS FORMOSAT-3/Constellation Observing System for Meteorology, Ionosphere, and Climate (F3/C) radio occultation (RO) data. Combining ground-based data with the limb-viewing geometry from space provides a unique opportunity to retrieve complementary information about scintillation and association with equatorial E region irregularities (i.e., Es) during daytime. Results for the first time show that daytime scintillation does occur at the magnetic dip equator and the occurrence is associated with the appearance of Es observed using GNSS F3/C RO data.

1. Introduction

Sporadic E (Es) irregularities can cause disruptions on trans-ionospheric radio signals because of their strong vertical electron density gradients. Affected signals include L-band radio transmissions of GNSS (Global Navigation Satellite Systems) resulting in a form of scintillation. Es can occur during daytime and nighttime. The occurrence of daytime Es can result in strong ionospheric scintillations (Aarons, 1982) even in the frequency range of gigahertz (GHz) (Kumar, Kishore, & Ramachandran, 2007; Seif et al., 2015; Zou, 2011; Zou & Wang, 2009). That is, during daytime, scintillation-producing irregularities are requiring a steep gradient associated with the background plasma-density profile, and a current driven by a neutral wind, where the Es layer is presumed to provide the exceptionally steep gradient particularly in the midlatitude. The most common theoretical explanation of the formation of Es layers is the wind shear theory. This theory has proven to work well in the midlatitude, where the inclination angle (I) is steep enough to produce Es layers (Whitehead, 1970, 1989). Evidence regarding the midlatitude (Hajkowicz, 1977, 1978; Hajkowicz & Minakoshi, 2003; Ogawa, Suzuki, & Kunitake, 1989), low latitude, and equatorial regions (Alfonsi et al., 2013; Huang, 1978; Kumar et al., 2007; Patel et al., 2007, 2009; Seif et al., 2011, 2012, 2015, 2016; Zou & Wang, 2009; Zou, 2011) have shown correlation between the occurrence of daytime scintillation and the Es layer. Nevertheless, thus far, very little is known about the nature of daytime L-band scintillations and characteristics of Es at the magnetic dip equator, where wind shear theory fails to operate. Therefore, the observations presented in this paper are important to understanding the detailed properties of L-band scintillations and their relationship to Es at the magnetic dip equator around the Earth during daytime.

Over the past decades, the identification of Es layers has been distinguished mostly from ground-based measurements including ionosondes (Whitehead, 1970, 1989). Recently, techniques for Es observations have remarkably enhanced. The GNSS radio occultation (RO) observation (satellite-to-satellite communication links) provides an ideal geometry with a significantly improved spatial and temporal vertical resolution, which has been used to study the Es layer structure (e.g., Arras et al., 2008; Chen et al., 2017; Liu et al., 2016; Wickert et al., 2004; Wu et al., 2005; Yue et al., 2015; Zeng & Sokolovskiy, 2010). On the other hand, ground-based Global Positioning Systems (GPS) receivers provide an adequate technique to observe the scintillation of radio waves in Earth’s ionosphere (Pi et al., 1997). Therefore, an ideal limb-viewing geometry from space...
provides a unique opportunity to retrieve complementary information about the characteristics of L-band scintillation and extract Es information from the signal fluctuations in satellite RO measurements during daytime at the magnetic dip equator.

In this study, we present the presence of L-band scintillation determined from signals collected from Scintillation Network Decision Aid (SCINDA) network (Groves et al., 1997) of ground-based stations situated at the magnetic dip equator during daytime in 2013. The SCINDA site locations cover longitude from the Pacific to the American sectors, which is particularly beneficial for this study. To identify the occurrence of Es at the magnetic dip equator at these stations, we use the GNSS FORMOSAT-3/Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) (F3/C) RO data. Ultimately, we show that the presence of daytime L-band scintillation is consistent with the occurrence of Es at the magnetic dip equator.

2. Observation and Interpretation

The experimental results contain data from two GNSS data sets using different geometry from ground and in space, which are (1) five SCINDA ground-based stations and (2) F3/COSMIC RO. The data acquired from these two data sets are restricted at the magnetic dip equator during daytime in 2013, which is characterized as a solar maximum period. We aim to (1) investigate the characteristics of scintillation at the magnetic dip equator, (2) study the appearance of Es, and (3) verify whether the distributions of scintillation are consistent with Es layers.

2.1. GNSS SCINDA Ground-Based Network Station

GNSS ground-based observations extracted from five SCINDA stations (Groves et al., 1997) analyzed during daytime in 2013 were employed in this study. Network of ground-based stations was managed by the U.S. Air Force Research Laboratory. Figure 1 shows the location of these five SCINDA stations, spanning the longitude from the Pacific to the American regions situated at the magnetic dip equator. The locations of each station are shown by triangles. The locations on each station are listed in Table 1. These stations provide amplitude scintillation data (S4 index) on GPS links at the L1 frequency. To minimize the effects of multipath on our observations, we set a threshold value of greater than 30° elevation angle for a GPS satellite (e.g., Carter et al., 2016) when S4 index ≥0.2. The analysis is further limited to the measurements of amplitude scintillation activity recorded during daytime from 06:00 to 18:00 LT.
To investigate characteristics of daytime scintillation at the magnetic dip equator around the Earth, we examine the amplitude scintillation (S4 index) for all GPS satellite pseudo-random noises (PRNs) observed at five SCINDA ground-based stations. Figure 2 shows amplitude daytime L-band scintillation activities for all GPS PRN satellites observed at Ancon Dua (AN2), Dakar (DKR), Addis Ababa (ADD), Tirunelveli (TIR), and Kwajalein (KWA) stations in 2013. Daytime L-band scintillation represented by red points and nighttime scintillation are represented by blue points. To detect the occurrence of daytime amplitude scintillation activity, S4 measurements from the GPS satellites must exceed a value of 0.2 from 0600 to 1800 LT at each station. SCINDA S4 values are generated every 1 min.

The main features to be noted from Figure 2 are the following: (1) Occurrence of daytime L-band scintillation, from the global point of view, at the magnetic dip equator is intermittent. (2) The diurnal occurrence of daytime scintillation observed at AN2, ADD, TIR, and KWA shows a peak in the morning hours followed by a secondary peak in the late afternoon hours. (3) The occurrence of daytime L-band scintillation observed at AN2 situated in the American sector is low. Apparent 1.5–2 h shift in the DKR peak compared to other

<table>
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<tr>
<th>Station</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Dip latitude</th>
<th>Local time (h)</th>
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</thead>
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<tr>
<td>Ancon Dua (AN2)</td>
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<td>UT</td>
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<tr>
<td>Addis Ababa (ADD)</td>
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<td>38.77°E</td>
<td>1°N</td>
<td>UT + 3</td>
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<tr>
<td>Tirunelveli (TIR)</td>
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<td>77.81°E</td>
<td>0.3°N</td>
<td>UT + 5.5</td>
</tr>
<tr>
<td>Kwajalein (KWA)</td>
<td>9.40°N</td>
<td>167.47°E</td>
<td>4.4°N</td>
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</tbody>
</table>

Figure 2. Variations of daytime amplitude scintillation (S4 index) activities observed at five GNSS SCINDA stations (i.e., from above panel, AN2, DKR, ADD, TIR, and KWA) situated at the magnetic dip equator. The red points represent scintillation during daytime, and the blue points show nighttime scintillation.
stations and that it is not clear what causes this shift. However, the latitudinal dependence may be the reason why activity is higher at DKR.

### 2.2. GNSS FORMOSAT-3/COSMIC Radio Occultation

The space-based data set analyzed in this study was collected by the F3/COSMIC satellites in 2013. The COSMIC Data Analysis and Archive Centre (CDAAC) provide the time series of amplitude scintillation (S4 index) for each RO event. The 1 Hz S4 index is used to represent the occurrence of the ionospheric irregularities in the E region. In this study, we use the “S4max9s” parameter from global data to limit the number of our observation of ionospheric irregularities within a specific altitude range. S4max9s parameter is the 9 s average of the S4 values surrounding the time that S4max values were recorded in the RO event. The tangent point altitude, latitude, and longitude must be employed carefully and accounted for properly in order to interpret the RO results. The tangent point location used in this study are the “alttp S4max,” “lcttp S4max,” “lattp S4max,” and “lontp S4max” parameters that represent the altitude, local time, latitude, and longitude, respectively, of the RO tangent point at the time when the maximum S4 was measured.

To represent the boundaries of the Es characteristics for the RO data set, the occurrence statistics in terms of the threshold scintillation level and the altitude range must be examined. Figure 3 shows the percentage occurrence of scintillation events with different thresholds, (i.e., S4max9s ≥ 0.1, 0.3, 0.6, and 0.7) that occurred at altitudes of 0–800 km. It is clear that for S4max9s thresholds of 0.3 and above, the peak occurrence within the E region is at ~110 km. The sharp increases toward 110 km are due to the Es detections. It can be concluded from Figure 3 that the altitude ranges of 90–120 km and the S4max9s threshold of 0.3 are an appropriate description of the vast majority of E region scintillation events.

To study the altitude-temporal characteristics of Es using RO data, we present scintillation as a function of the tangent point altitude for all RO events occurred in 2013. Figure 4a presents the S4max9s data in different

![Figure 3](image-url)

**Figure 3.** The percentage occurrence of scintillation events versus tangent point altitude using different scintillation threshold event, i.e., S4max9s ≥ 0.1, 0.3, 0.6, and 0.7 depicted by different colors.

![Figure 4](image-url)

**Figure 4.** Amplitude scintillation statistics measured by FORMOSAT-3/COSMIC satellites in 2013. (a) Distributions of the S4max as a function of altitude. (b) Distributions of the S4max versus LT occurred at altitudes below 150 km (represented by red dots). (c) Distributions of the S4max versus LT occurred at altitude above 150 km (represented by blue dots). The black (magenta) curve displays the percentage occurrence of S4max9s ≥ 0.3 in an altitude range below (above) 150 km.
tangent point altitude. The scintillation RO events are remarked by red (altitudes below 150 km) and blue points (altitudes above 150 km), where each point represents one RO event. It can be seen in Figure 4a that the $S4_{\text{max9}} \geq 0.3$ cluster into two groups of points: (1) altitudes below 150 km with a sharp high scintillation activity as denoted by red points and (2) altitudes above 150 km with moderate to strong scintillation activity presented by blue points. The first group of RO events corresponds to the ionospheric irregularities in the $E$ region, which is the primary focus in this study, and the second group of RO events attributed to the $F$ region ionospheric irregularities.

Figure 4b displays the distribution of the first group of data ($S4_{\text{max9}}$ in altitude below 150 km) as a function of LT. The black curve shows rapid rise in the $S4_{\text{max9}}$ values during daytime attributed to the $E$ region (altitude above 150 km) particularly in the early morning and in the late afternoon. The black curve also displays that the Es can appear during both daytime and nighttime. It is interesting to note that the nighttime maximum in the Es rate exceeds the one occurring during daytime. The reason is that the occurrence of nighttime Es can add to the effects of spread $F$ irregularities on ionospheric scintillations (Aarons, 1982). In this regards, Rastogi (1983) found that intense VHF equatorial scintillations caused by nighttime Es even during complete absence of spread $F$.

Figure 4c presents distributions of the second group of data (altitude above 150 km) versus LT. The most significant feature is nonoccurrence of $S4_{\text{max9}}$ values during daytime of 0600–1800 LT at altitude above 150 km, where ionospheric irregularities correspond to the $F$ region. Therefore, it can be concluded from Figure 4b that $S4_{\text{max9}} \geq 0.3$ in altitude range below 150 km during daytime are an appropriate description of $E$ region scintillation event, which are produced by irregularities that are embedded in the $E$ region (i.e., Es).

### 2.3. Comparative Study

Further analyses were conducted to verify the relationship between scintillation and Es. To study the correlation between scintillation and the Es layer during the daytime at each station, we statistically examine the percentage occurrence of scintillation and appearance of thin layer Es. The Es percentage occurrence was detected by the F3/COSMIC satellites and computed for each SCINDA ground-based station within $\pm 6^\circ$ in latitude and longitude with $S4_{\text{max9}} \geq 0.3$ between 0600 and 1800 LT. The occurrence of daytime scintillation is calculated by the ratio of the number of scintillation events ($S4$ index above threshold) and to the total number of data points during the days of available data. The comparison of scintillation using combined data sets is interesting because of the location of the stations, which enables us to study scintillation in accordance with Es at the magnetic dip equator around the Earth using different geometry. In fact, we use the distribution of $S4$ index as the distribution of irregularity strength. We are interpreting this observation using different geometry in terms of changes in the propagation path length through an Es layer, that is, horizontally stratified and uniformly filled with scintillation-producing irregularities.

Figure 5 displays statistics of scintillation observed from five GNSS SCINDA stations in accordance with the appearance of Es from GNSS RO measurements. In Figure 5, it can be noted that Es does exist at the magnetic dip equator and the occurrence of it appears to be associated with the appearance of scintillation at each station during daytime. Interestingly, it can be noted that the most significant Es occurrence peak is observed at TIR corresponding to the Asian sector. This Es occurrence feature is quite similar to that shown in the occurrence of scintillations recorded by ground-based SCINDA station at TIR. Similarly, the lowest occurrence rate of scintillation and Es observed in both data sets at AN2 station is situated in the American sector. These results suggest that scintillation and Es significantly depend on longitude.

It can be seen in Figure 5 that the Es occurrence rate is significantly higher for RO compared to SCINDA ground-based measurements. This implies that GNSS RO is more sensitive to the Es layer occurrence. In this regard, Carrano et al. (2011) used RO simulator tool to propagate waves in an RO geometry and space-to-ground geometry and showed the expected difference in sensitivity. The main reason is the geometry with respect to the plasma irregularities, and the propagation path length through an Es layer is
substantially different. This suggests that path length is important. This finding is consistent with the idea that scintillation-producing irregularities are embedded in a relatively thin layer, and longer path lengths through irregularities are necessary to produce significant scintillations. In fact, the Es layer is thin vertically, so path length through scintillation is shorter vertically (GPS) than horizontally (RO). That could be why RO is more sensitive. Also, the scattering process might be different. RO may be more sensitive to strong diffractive effects, such as scattering from sharp edges. GPS may just look at weak perturbations distributed horizontally across the Es phase screen.

3. Discussion and Conclusion

This paper presents some of the unique worldwide characteristics of daytime L-band scintillation and its association with Es layers at the magnetic dip equator, where little or no previous information existed and where the new results have obvious utility for further understanding the nature of daytime L-band scintillation and relationship with Es layers. A close investigation of the characteristics of scintillation during daytime at the magnetic dip equator from ground and in space was analyzed. Detailed characteristics of RO scintillation data at the magnetic dip equator were presented. Finally, a comparative study of the characteristics of scintillation in association with Es from five SCINDA ground-based stations simultaneously with RO data was examined.

Each of these aspects is discussed in detail below.

Observations from GNSS ground-based SCINDA stations (see Figure 2) show that scintillation during daytime hours occurs intermittently at the magnetic dip equator suggesting the appearance of Es, which is not expected based on prevailing models and theories. According to the Tsunoda model (Tsunoda, 2008; Seif et al., 2015), Es can sometimes occur near the magnetic dip equator under favorable conditions. Such favorable conditions arise when the electric field is small; that is, the zonal wind shear produces the convergence of metallic ions to an altitude where the upward and downward forces are close to zero. In the absence of an electric field, the meridional winds may transport the Es sheet equatorward. This is particularly evident in RO results as shown in Figure 5, where appearance of Es is correlated with the occurrence of scintillation at each station.

The overall Es occurrence statistics revealed in this study using RO data are in a good agreement with previous studies that have investigated and identified the Es occurrence (e.g. Arras et al., 2008; Wu et al., 2005; Yue et al., 2015; Zeng & Sokolovskiy, 2010). Supporting the notion that the GNSS RO technique is well suited for Es studies. Particularly, characteristics of F3/COSMIC RO scintillation data in Figures 4 and 4a clearly show that distribution of RO scintillation events during daytime corresponds to the ionospheric irregularities in the E region (altitude 90–120 km). This is consistent with the results obtained from GNSS RO data as reported by Zeng and Sokolovskiy (2010), Arras et al. (2008), and Carter et al. (2013), who demonstrated that enhanced S4 was measured in the E region, are attributed to the presence of Es.

The finding that there are no scintillation producing irregularities in the daytime F layer is shown in Figure 4b. This is another piece of information that positively supports the idea that L-band scintillation during daytime is produced by irregularities that are embedded in Es layer. In fact, theoretically, the polarization electric field cannot survive in the daytime, when there is a highly conducting E layer. This electric field is shorted out by the closure of current in the E layer. Therefore, we have a theoretical basis for expecting the absence of daytime F region irregularities, and we have no theoretical basis to speculate on the presence of daytime F region irregularities. This is particularly evident in our RO results as shown in Figure 4.

Figure 5 shows that occurrences of L-band scintillation observed at five GNSS SCINDA stations are consistent with the appearance of Es as denoted by RO data at the magnetic dip equator during daytime. We found that the correlation of scintillation and Es during daytime at the magnetic dip equator is much more frequent at TIR situated in the Asian region than is evident at AN2 located in the American zone. This implies the abundance of Es over Asian region compared to its scarcity over American sector at the magnetic dip equator. This result is consistent with the results that were obtained by Knecht and McDuffie (1962) and Cohen and Bowles (1963), who showed that the occurrence of Es is higher in the Indian sector and is considerably lower in the American sector. According to Whitehead (1970, 1989), the increased production of metal ions may explain the geographical distribution of Es around the Earth. He discussed the abundance of Es over Asia, which is 10 times greater than other regions and is due to the greater magnetic field component $B_0$. This suggests that Es varies approximately as the square of $B_0$. This means that over Asian sector, the wind pushes the ions and...
particulate together more than than over America since the horizontal component of the Earth’s magnetic field is greater. Thus, the rate of metal ion production is greater over Asia and Es production is greater. The effect of few more ions can lead to more abundant Es.

In conclusion, a comprehensive comparison between the five GNSS ground-based scintillation observation around the Earth and the simultaneous occurrence of Es measurements of L1 C/A code at 50 Hz sampling rate obtained from RO indicates that irregularities during daytime at the magnetic dip equator are consistent with thin layer Es and thus support interpretation that thin layer Es is responsible for producing scintillation.

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References


