



Comparison of ionospheric irregularities observed by the COSMIC satellites with ground-based scintillation observations over the low latitude African Region

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Abstract

This study compared the ionospheric irregularities as observed using two different techniques, namely; the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) satellites and the scintillation intensity index (S4) data measured by the Scintillation Network and Decision Aid (SCINDA) receiver which operated at Nairobi University (geog lon 36.8° E, geog lat 1.3° S, dip lat -24.1°), Kenya. The data compared were those of the years 2009 (low solar activity) and 2011 (ascending phase of solar cycle 24), for both quiet ($K_p < 3$) and disturbed ($K_p \geq 5$) geomagnetic conditions. For the cases of Global Positioning System (GPS) satellites with elevation angle $< 0^\circ$ as observed by the COSMIC satellites, a geo-location of the COSMIC S4 data associated with the link between GPS and COSMIC satellites was proposed at the tangent point. The COSMIC S4 data whose geo-locations fall in the vicinity of Nairobi were compared with the S4 data measured by the SCINDA receiver. The coefficient of determination which represents the percentage of the variation in COSMIC S4 data associated with the variation in SCINDA S4 was 50 %. The two data sets depict that scintillation occurs mostly in the seasons of March and September equinoxes of high solar activity conditions. However, there was a moderate positive correlation (Pearson correlation coefficient, $r = 0.52$ on quiet days) between COSMIC and SCINDA S4 data. The results presented signify that the COSMIC S4 could be analyzed to study ionospheric irregularities (which cause scintillations) over locations such as deserts and oceans where it is usually difficult to deploy equipment.

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Keywords: Ionospheric irregularities; Scintillation; radio occultation; low latitude ionosphere

1. Introduction

The night-time low latitude ionospheric F-region often contains plasma density irregularities. The irregularities have scale sizes in the range of hundreds of kilometers to

a few meters (Aarons et al., 1996; Mungufeni et al., 2015; Olwendo et al., 2013). The small-scale ionospheric irregularities may cause scintillations, loss of locks and cycle slips usually observed as sudden phase jumps in Global Navigation Satellite System (GNSS) signals. From simultaneous observations of amplitude scintillation at Very High Frequency (VHF) and L-band frequencies, Olwendo et al. (2013) observed over Kenya that scintillation activity were

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greater during the post sunset hours of equinox months than at the solstice. Moreover, [Olwendo et al. \(2013\)](#) noted that there were practically no signatures of the L-band scintillation in solstice months (June, July, December, and January) and after midnight. The observed irregularities exist within plasma bubble, which are localized electron density depletions. The plasma bubbles are generated through the Rayleigh–Taylor Instability (RTI) ([Kelley, 2009](#)) that occurs when the ionosphere over the magnetic equator, under the nearly horizontal geomagnetic field, is uplifted up by the pre-reversal enhancement (PRE) of the zonal electric field.

The patterns of ionospheric irregularity occurrences during quiet geomagnetic conditions over the low latitude regions of African analyzed by [Mungufeni et al. \(2016a\)](#) revealed that the strengths of ionospheric irregularities in March equinox were mostly higher than those during September equinox over East Africa. The variation trend observed over West Africa was in opposite sense. The asymmetries were linked to the direction of the meridional winds over the different stations during the equinox months. Moreover, [Mungufeni et al. \(2016a\)](#) observed that the severity of ionospheric irregularity reduced from West Africa towards the East Africa. They associated this observation to the decreasing of the geomagnetic field strength in east–west direction. [Aol et al. \(2020\)](#) presented ionospheric irregularities as observed by Langmuir probes on the Swarm satellites. The observations were compared with amplitude scintillation events (S4) recorded by the Global Positioning System (GPS) Scintillation Network and Decision Aid (SCINDA) receiver installed in Mbarara, Uganda (more details on SCINDA receivers are provided in subSection 2.1). It was revealed that the ground-based amplitude scintillations were enhanced when Swarm registered ionospheric irregularities for a large number of passes. Using ground based International GNSS Service (IGS) for geodynamics receivers and one dedicated SCINDA receiver, [Olwendo et al. \(2019\)](#) examined the correlations of SCINDA S4 with Swarm satellite observed electron density variations (the Rate of Density Index (RODI)) for cases when the Swarm satellites orbital tracks on the ground traverse coincidental locations to the SCINDA station. This result implies that RODI could be used to detect irregularities usually observed using ground-based SCINDA system.

[Azzouzi et al. \(2015\)](#) presented the Rate of change of Total Electron Content (TEC) Index (ROTI) (proxy of the scintillation index) over middle and low latitudes in European African longitude sector during the transient variations of the Earth's magnetic field associated to the impacts of solar events during October 2013. Their report indicated that in some cases, scintillations occur, while in others, they are inhibited over the whole Africa. The ionospheric irregularities during geomagnetic storms in the low-latitude regions might be associated to the ring current (usually quantified using the Disturbance storm time (Dst) index), prompt penetration and disturbed dynamo

electric fields. [Aarons \(1991\)](#) suggested that when the peak of Dst excursion occurs during 18:00 – 22:00 LT, 00:00 – 06:00 LT, and 10:00 – 16:00 LT, occurrence of ionospheric irregularities might (i) not be influenced that night, (ii) be inhibited on the following night, (iii) exist at the same time, respectively. When the main phase of a geomagnetic storm occurs, dawn-to-dusk electric fields penetrate to the equatorial regions. These east wards electric field increase the growth rate of the Rayleigh–Taylor instability (RTI). The RTI is usually considered to be responsible for the generation of ionospheric irregularities. The daytime westward directed disturbed dynamo electric fields on disturbed geomagnetic days reduce vertical plasma drifts ([Aarons, 1991; Fejer and Scherliess, 1999](#)). This usually inhibits occurrence of ionospheric irregularities.

The above discussions demonstrate that occurrence of ionospheric irregularities over the African low latitude regions have been characterized based on both ground- and space-based observations. The benefit of space-based observations is that it can cover locations over the seas and deserts where deployment of instrument might be challenging. For instance, the three dimensional global morphology and seasonal variations of scintillation index (S4 index) measured by the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) satellites presented by [Brahmanandam et al. \(2012, 2016\)](#) revealed that high values of the S4 index confined around ± 30 magnetic latitudes start occurring around 19:00 MLT. The high values often persist till 03:00 MLT and they exist at altitudes ranging 150–350 km, during equinox and northern winter seasons.

It seems that the S4 data along the links between the satellites of GPS and COSMIC, referred to as COSMIC S4 has not been explored properly. Therefore, this study proposed a novel approach for geo-locating the COSMIC S4 data. Moreover, the study compared the COSMIC S4 data whose geo-locations fall within Nairobi, Kenya with the S4 data observed by the SCINDA receiver deployed at the station. Such a preliminary assessment paves way for wide usage of COSMIC S4 for studying scintillation caused by ionospheric irregularities.

The data sources and the methods of data analysis, results, and discussions of this study are presented in Sections 2–4, respectively.

2. The data sources and the methods of analysis

2.1. Data sources

As already mentioned in the introduction, this study used S4 data observed by the COSMIC satellites, also known as FORMOSAT satellite 3 which consists of six identical micro-satellites operated by Taiwan's National Space Organization. The satellites were launched on April 15, 2006 into a circular, 72° orbital inclination, and 512 km altitude. During the first 17 months following launch, the satellites were gradually dispersed into their final orbits at

~800 km (Brahmanandam et al., 2012). The science data products of COSMIC are generated by the University Corporation for Atmospheric Research (Yue et al., 2014) and archived at the COSMIC Data Analysis and Archive Center (CDAAC). Therefore, the S4 data observed by the GPS receiver onboard the COSMIC satellites were obtained from the scnLv1 files archived at CDAAC. At CDAAC ground processing, the GPS L1 raw 50 Hz measurements of signal-to-noise intensity are used to compute amplitude scintillations at a rate of 1 Hz. Instead of utilizing the maximum values of S4 index and their tangent point coordinates available in scnLv1 files to study the global morphology of scintillation without standardizing the maximum S4 values as in Brahmanandam et al. (2012, 2016) used the ionospheric layer thickness of 1 km and the length of the tangent line to standardize the maximum S4 index values.

Instead of using maximum S4 index values (Brahmanandam et al., 2012; Liu et al., 2016), this study used all the S4 index values during the tracking of a particular GPS satellite by the receiver onboard COSMIC satellite. The S4 index values were assigned to ground locations as described in subSection 2.2. The COSMIC S4 data whose ground locations were close to that of Nairobi (geog lon 36.8° E, geog lat 1.3° S, dip lat -24.1°), Kenya were validated with the S4 data measured by the SCINDA receiver that operated at Nairobi. The SCINDA is a network of ground-based GPS receivers established by the Air Force Research Laboratory (AFRL) to monitor scintillations at L-band frequencies in the equatorial ionosphere. The main aim of SCINDA is to provide regional specification and short-term forecasts of scintillation to operational users in real time (Groves et al., 1997). Using high rate GPS measurements, the SCINDA software provides measurements of S4, TEC, and ROTI, as well as receiver position.

Specifically, the COSMIC S4 data were validated during the years 2009 and 2011, representing low and high solar activity conditions, respectively. Actually, the mean F10.7 flux in the years 2009 and 2011 were 70.6 and 113.4 sfu, respectively. The frequency of occurrence of ionospheric irregularities is expected to increase with increase in solar activity. It should be noted that the S4 data considered were those on geomagnetically quiet ($K_p < 3$) and disturbed days which might have experienced significant ionospheric disturbance for which $K_p \geq 5$. The K_p data provided by GFZ Potsdam (<ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap/>) were used in this study. The total of days in the years 2009 and 2011 with SCINDA S4 data were 365 and 325, respectively. The total of geomagnetically disturbed and quiet days in 2009 were 4 and 342, respectively, while in 2011, the totals were 34 and 291, respectively.

2.2. Methods of Data Analysis

Under the COSMIC-2 Cal/Val program, Carrano et al. (2022) developed a product to geolocate irregularities that

produce scintillation of GPS and GLONASS signals. They reported that only those plasma bubbles intersected by the ray-paths at F-region altitudes were detected. Moreover, they found that scintillation mostly occur due to plasma bubble near the tangent point and the plasma bubbles can exist up to 200 km above the tangent point. Based on these ideas, we proposed a typical geometry for geolocating COSMIC S4 data as shown in Fig. 1. In the figure, positions of the center of the Earth (O), COSMIC (L) and GPS (G) satellites are indicated.

The links between the COSMIC and GPS satellites considered were those with negative GPS satellite elevation angle (E) as observed by the COSMIC satellite. The tangent point (P) is where the link between the COSMIC and GPS satellites is closest to the Earth's surface. Since the Cartesian coordinates of the GPS and COSMIC satellites are known from the scnLv1 files, distances, OL, OG, and LG can easily be calculated. The scnLv1 files also provide the elevation angles E of the GPS satellites. It is important to mention that the coordinates of O were considered as (0,0,0). Based on these known distances and elevation angles of the GPS satellites, the Cartesian coordinates of the points P were determined and then used to compute the longitude and latitude of the points as in Hofmann-Wellenhof et al. (2007). Following Polyanin and Manzhirov (2007) the Cartesian coordinates of the point P(XP, YP, ZP) were determined as in Eqs. (1)–(3).

$$XP = \frac{XL \times GP + XG \times LP}{LG}, \quad (1)$$

$$YP = \frac{YL \times PG + YG \times LP}{LG}, \quad (2)$$

$$ZP = \frac{ZL \times PG + ZG \times LP}{LG}. \quad (3)$$

The distance LP was computed as in Eq. 4,

$$LP = OL \times \cos(90 - E) \quad (4)$$

Therefore, $PG = LG - LP$.

After determining the geo-locations of the COSMIC S4 data (longitude and latitude of P), validations of the data with S4 data obtained from the SCINDA receiver that

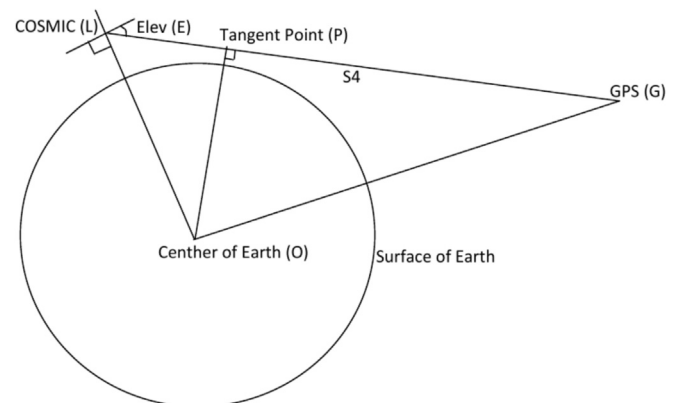


Fig. 1. Typical COSMIC S4 observation geometry.

operated in Nairobi, Kenya was performed. In order to minimize the multipath effects on SCINDA S4, the data associated with satellites with elevation angle $> 30^\circ$ were considered. The COSMIC S4 data for which the geographic longitude and latitude of point P differed from that of Nairobi by 5 and 5 degrees, respectively, were considered. This grid cell would contain pierce points of all ground-based S4 observations at 30° elevation.

3. Results and discussions

3.1. Observations of COSMIC S4

Since the electron densities above the COSMIC satellite altitudes (> 800 km) are much lower than that below the satellites, the frequency of occurrence of ionospheric irregularities (as measured by the COSMIC S4 index) above the satellite is expected to be lower compared to that below the satellite. This is clearly demonstrated in Fig. 2. The figure presents COSMIC S4 data on the vertical axis and the corresponding elevation angles on the horizontal axis. Panels in rows (a) and (b) of Fig. 2 present the data during the years 2009 and 2011, respectively. Moreover, panels in columns (i) and (ii) present the data for quiet and disturbed geomagnetic conditions, respectively. The magenta horizontal lines in Fig. 2 and later in Figs. 5, 6 and 8 mark the estimated background level. The S4 data presented in Fig. 2 are those observed within the vicinity of Nairobi, Kenya during 18:00–24:00 LT when low latitude iono-

spheric irregularities are expected to occur. Aarons (1980) stated that the most intense irregularities are from 225 to 450 km in altitude, although irregularities are found as high as 1000 km.

As expected, all the panels in Fig. 2 show that majority of high COSMIC S4 values occur at negative elevation angles where high electron densities exist. Specifically, during quiet and disturbed geomagnetic conditions in the year 2011 the elevation angles associated with high frequency of high S4 values appears to be $< -2^\circ$ and $< -6^\circ$, respectively. This observation implies that the altitudes for occurrence of irregularities during disturbed geomagnetic days is lower than that on quiet days. The electric fields in the disturbed days were not examined, but the observed phenomenon is consistent with the effects of westward disturbed dynamo electric fields, which can influence the growth rate of the Rayleigh–Taylor instability (Fejer and Scherliess, 1999). Therefore, the altitude extension of the plasma bubble is suppressed compared to that during quiet geomagnetic conditions. Generally, in the year 2009 the altitudes for observing high values of COSMIC S4 are lower than those in the year 2011. These high values of S4 at lower altitudes in the year 2009 might be associated with lower atmospheric effects as explained in the next paragraph.

Based on the S4 data presented in Fig. 2, a background value of ~ 0.25 of COSMIC S4 data can be deduced. The S4 data above this background value might be associated with occurrence of ionospheric irregularities. Fig. 2 depicts common occurrence of high values of COSMIC S4 at ele-

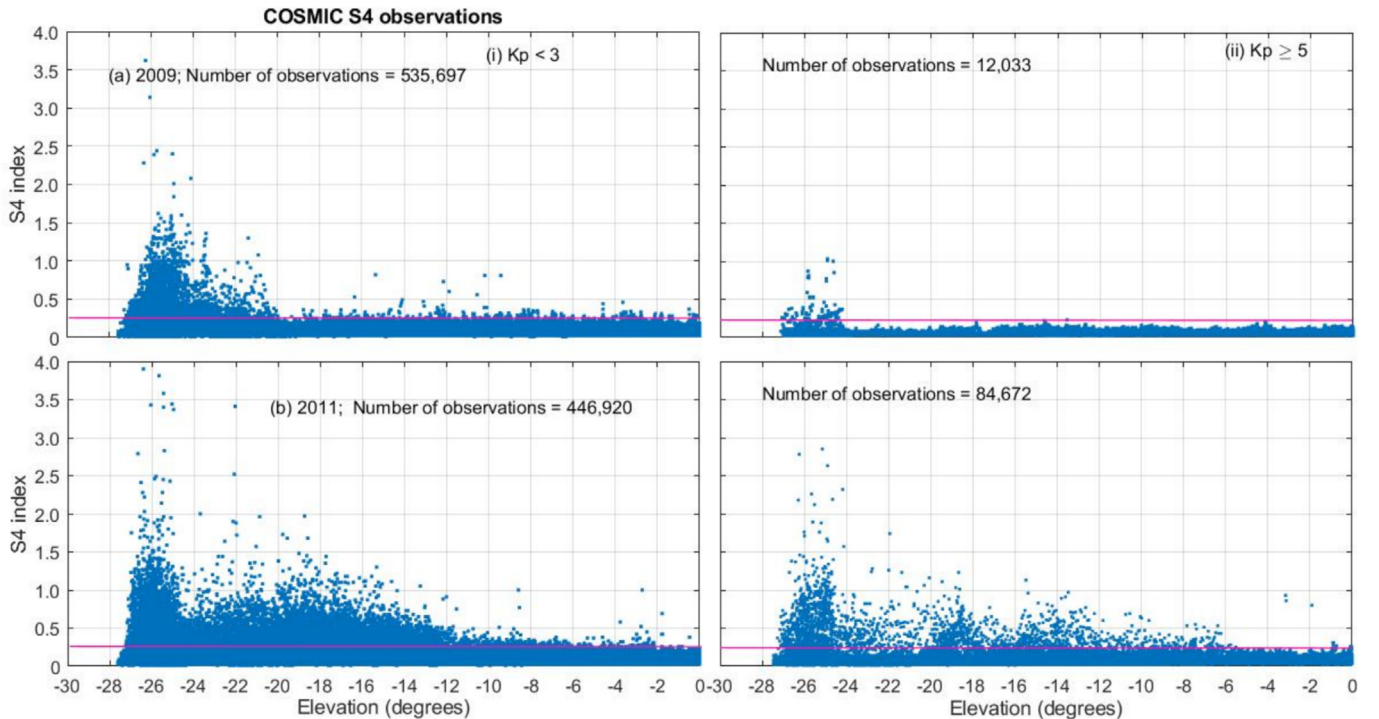


Fig. 2. Variation of COSMIC S4 as a function of elevation angle. Panels in rows (a) and (b) present the data for the years 2009 and 2011, respectively while panels in columns (i) and (ii) present the data during quiet and disturbed geomagnetic conditions. The magenta horizontal line marks the estimated background level.

vation angles $< -24^\circ$. This observation might correspond to the lower atmospheric effects at E-region altitude. Specifically, signals that pass through sporadic E. In fact, if one considers $OP = RE + 120$ and $OL = RE + 800$, where $RE = 6371$ km is the radius of the Earth, the angle E in Fig. 1 would be computed as $\sim 25^\circ$. Therefore, while analyzing the data presented in Figs. 3, 5, and 6, the distance OP was restricted above E region altitude in order to eliminate the lower atmospheric effects on COSMIC S4. That is, $OP \geq (RE + 120)$ km. In the next subsection, we present the correlation between COSMIC S4 and coincident SCINDA S4.

3.2. Correlation between COSMIC and SCINDA S4

Since scintillations rarely occur in a low solar activity year such as 2009, we present in Fig. 3 scatter plots for COSMIC S4 versus coincident SCINDA S4 during the year 2011. Panels in rows (a) and (b) present the data for quiet and disturbed geomagnetic conditions, respectively. Moreover, panels in columns (i) - (iv) present the data during December solstice, June solstice, September equinox and March equinox, respectively. The data presented in Fig. 3 are hourly mean COSMIC and SCINDA S4 which were separately determined during 18:00–24:00 LT.

The number of COSMIC S4 data which were coincidental with SCINDA S4 data, Pearson's correlation coefficient, r and the coefficient of determination R-squared for the various geomagnetic and solar activity conditions are indicated on Fig. 3. It can be deduced from Fig. 3 that during disturbed geomagnetic conditions (panels in row (b)), mostly very low ($r < 0.35$) correlation exists between

COSMIC and SCINDA S4. This observation is consistent with the low (< 0.2) S4 values seen during disturbed geomagnetic conditions. However, in September equinox corresponding to disturbed geomagnetic conditions, the S4 values are high, yielding moderate correlation ($r = 0.51$) between COSMIC and SCINDA S4. The observations during disturbed geomagnetic conditions might be associated with the fact that the ionospheric irregularities may occur (September equinox) or get inhibited (other seasons) during such a condition as already discussed in Section 1.

It can be deduced from panels in row (a) of Fig. 3 that during quiet geomagnetic conditions in equinox seasons, moderate positive correlation ($r \geq 0.46$) exists between COSMIC and SCINDA S4. The R-squared value which represents the percentage of COSMIC S4 variation associated with the variation of SCINDA S4 during quiet conditions in September equinox was 50 %. Moreover, in solstice seasons low positive correlation ($r \leq 0.38$) exists. The low correlation in solstice seasons is consistent with the low S4 values observed in the seasons. We attribute the moderate correlation coefficients in equinox seasons to differences in observation geometry and resolutions of data sets used. The COSMIC S4 data is provided by the CDAAC at 1 s resolution while the SCINDA S4 data has 1 min resolution. As scintillation is a measure of amplitude fluctuations, a 1-min window signal might experience more fluctuations than that of 1 s. It should be noted that although this study utilized the COSMIC S4 data processed by the CDAAC at 1 s resolution, the atmospheric occultation data (opnGPS files) in a simple custom binary format containing high rate data could be obtained (<https://data.cosmic.ucar.edu/gnss-ro/cosmic1/repro2021/level1a>) and used to compute S4

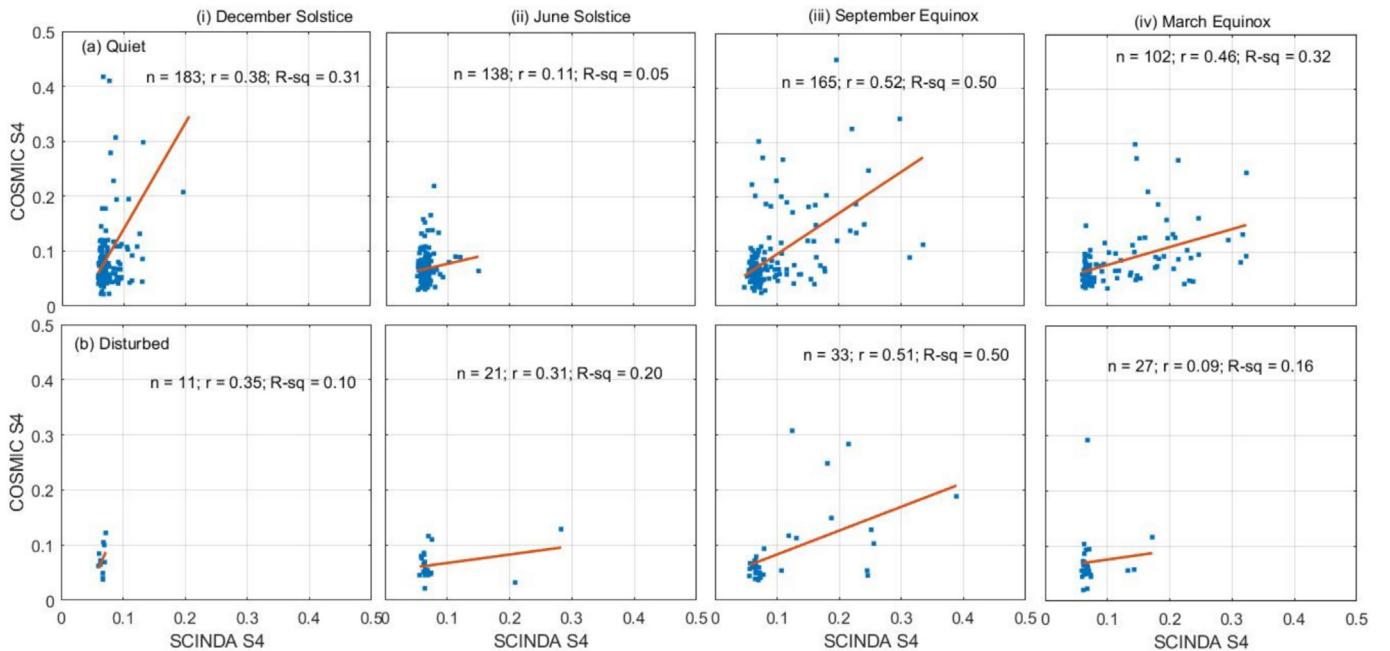


Fig. 3. Scatter plots of COSMIC S4 against SCINDA S4 observed in the year 2011. Panels in rows (a) and (b) are for quiet and disturbed geomagnetic conditions, respectively. Panels in columns (i) – (iv) are for December solstice, June solstice, September equinox and March equinox, respectively.

data at 1 min resolution. Unfortunately, the opnGPS files do not contain the coordinates of the LEO and GNSS satellites tracked. The accuracy of geolocating the COSMIC S4 data processed from opnGPS files would be reduced if the observation times in the files are not well synchronized with those in files which provide satellite coordinates.

The fact that ionospheric irregularities are not uniformly distributed over a particular location might have resulted in the moderate correlations in equinox seasons. For example, all satellites observed by a ground receiver might not experience scintillation when there are patches of irregularities above the receiver. Similarly, the links between GPS and COSMIC satellites might pass through ionospheric irregularities and experience scintillation while the signals observed by the SCINDA receiver might not pass the irregularities. The opposite might be experienced in some cases. Fig. 4 illustrates that though the locations of COSMIC and SCINDA observations are around the same locality, the Ionospheric Pierce points (IPPs) associated with the two observations are not always at same point. The data presented in the figure were for September equinox. Instead of averaging the data within 1 h interval (as presented in Fig. 3), the coordinates of the IPPs of the data were extracted and presented in Fig. 4. Panels (a) - (d) in Fig. 4 present IPPs during 18:00–18:59, 19:00–19:59, 20:00–20:59, and 21:00–21:59 LT, respectively. The blue dots in the figure present the locations of COSMIC S4 data while the magenta asterisks are for those of SCINDA data. The black plus symbol indicates the location of Nairobi

SCINDA station. Clearly, Fig. 4 demonstrates that the IPPs of COSMIC and SCINDA S4 data are not always at the same point. Moreover, the figure shows that sufficient data were used to obtain hourly averaged S4 data.

It is noteworthy to consider that the nature of ionospheric irregularities within the Equatorial Plasma Bubbles (EPB) is geomagnetic field-aligned. Thus, the scintillation strength observed by COSMIC satellites may escalate when the propagation path from the satellite to the receiver aligns parallel to the geomagnetic field line (Anderson and Straus, 2005; Abadi et al., 2014; Abadi et al., 2017; Sousasantos et al., 2022).

The moderate correlation coefficient ($r \geq 0.46$) between COSMIC and SCINDA S4 obtained in this study are similar to that obtained by Aol et al. (2020) when they analyzed the SCINDA S4 obtained from a station located in Mbarara, Uganda and electron density perturbations associated with plasma bubbles observed by the Swarm satellites. Fig. 8 in Aol et al. (2020) revealed a linear dependence between S4 and electron density perturbations with moderate positive correlation coefficients ranging between 0.48 to 0.55. Olwendo et al. (2019) also obtained a moderate probability (~ 0.45) when they expressed the total number of agreements between irregularities observed by Swarm satellites and SCINDA receiver at Nairobi, Kenya as a percentage of the total number of coincident measurements done by the two instruments. An agreement was considered to have occurred when either RODI index was > 0.02 and S4 index was > 0.2 or RODI index < 0.02 and S4 index was < 0.2 .

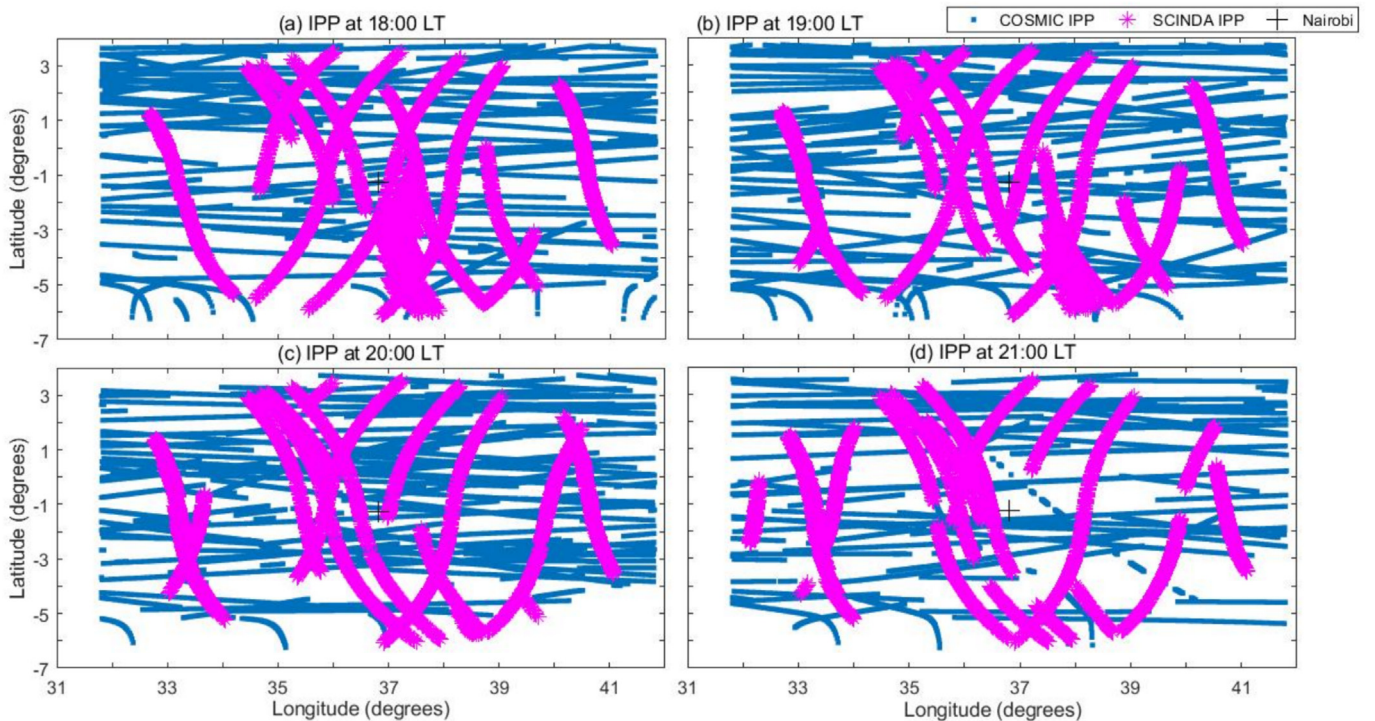


Fig. 4. Panels (a) - (d) present the IPPs at 18:00, 19:00, 20:00 and 21:00 LT, respectively. The blue dots represent locations of COSMIC S4 data while the magenta asterisks represent those of SCINDA S4. The black plus symbol indicates the location of Nairobi SCINDA station.

Based on the results obtained in this study and the above discussions, the scintillation activity (S4 index) in the F region ionosphere observed by the COSMIC satellites correlates moderately with that recorded by the SCINDA ground-receiver. This implies that COSMIC S4 indices can be used to supplement SCINDA data. Due to the few number of coincident COSMIC and SCINDA S4 during disturbed days, the analysis of local time, seasonal and solar activity variations of ionospheric irregularities were performed during quiet geomagnetic conditions.

3.3. Local Time, Seasonal and Solar Activity variations of Ionospheric Irregularities

In order to appreciate the appropriateness of COSMIC S4 to represent occurrence of ionospheric irregularities, we present in Figs. 5 and 6 the data for the months of January - December 2011 and the corresponding SCINDA S4 data in these months. Figs. 5 (a) - (f) present the COSMIC S4 data against Local Time for the months of January - June 2011, respectively, while Figs. 5 (g) - (l) are for SCINDA S4 data against Local Time in the corresponding months. Fig. 6 is similar to 5, but for the months of July - December.

As expected, Figs. 5 and 6 show that the values of SCINDA S4 > 0.2 (background value) mainly exist after sunset and before mid-night in equinox months of March, April, August, September, and October. Moreover, the SCINDA S4 data depicts significant occurrence of ionospheric irregularities during the stated local time period in November. The COSMIC S4 data in Figs. 5 and 6 depict

that the local time and seasonal patterns of occurrence of the majority of the cases of COSMIC S4 data greater than or equal to the background value are similar to that of SCINDA data already mentioned.

The night-time occurrence of ionospheric irregularities are usually associated with the Pre-Reversal vertical drift velocity Enhancements (PRE) under which the depleted plasma of the lower heights rise up to the topside ionosphere in the form of plasma bubbles or ionospheric irregularities (Fejer and Scherliess, 1999; Li et al., 2008; Basu et al., 1999). The occurrence of ionospheric irregularities in equinox months depicted in Figs. 5 and 6 might be due to the fact that zonal electric field at the evening terminator, so-called PRE, is larger at equinox. This is because the solar terminator is close to being aligned with the magnetic meridian, and thus the intense zonal electric field is generated in the E region (Tsunoda, 1985). Moreover, in equinox months, the increased intensity of the ionizing radiation due to high elevation of the sun (Hargreaves, 1992) in such months increases electron density gradients required for generation of ionospheric irregularities (Rastogi, 1980). In fact the significant cases of ionospheric irregularities in November that were mentioned before might be associated with increased electron density gradients in this month. Actually, Fig. 3(d) and 8(d) in Mungufeni (2020) reveal high values of TEC over the African low latitude regions in December solstice.

Figs. 5 and 6 show isolated cases of high SCINDA S4, particularly in the months of March, August - December. Since the COSMIC S4 was limited to altitudes above E region, daytime high values are not common in the data.

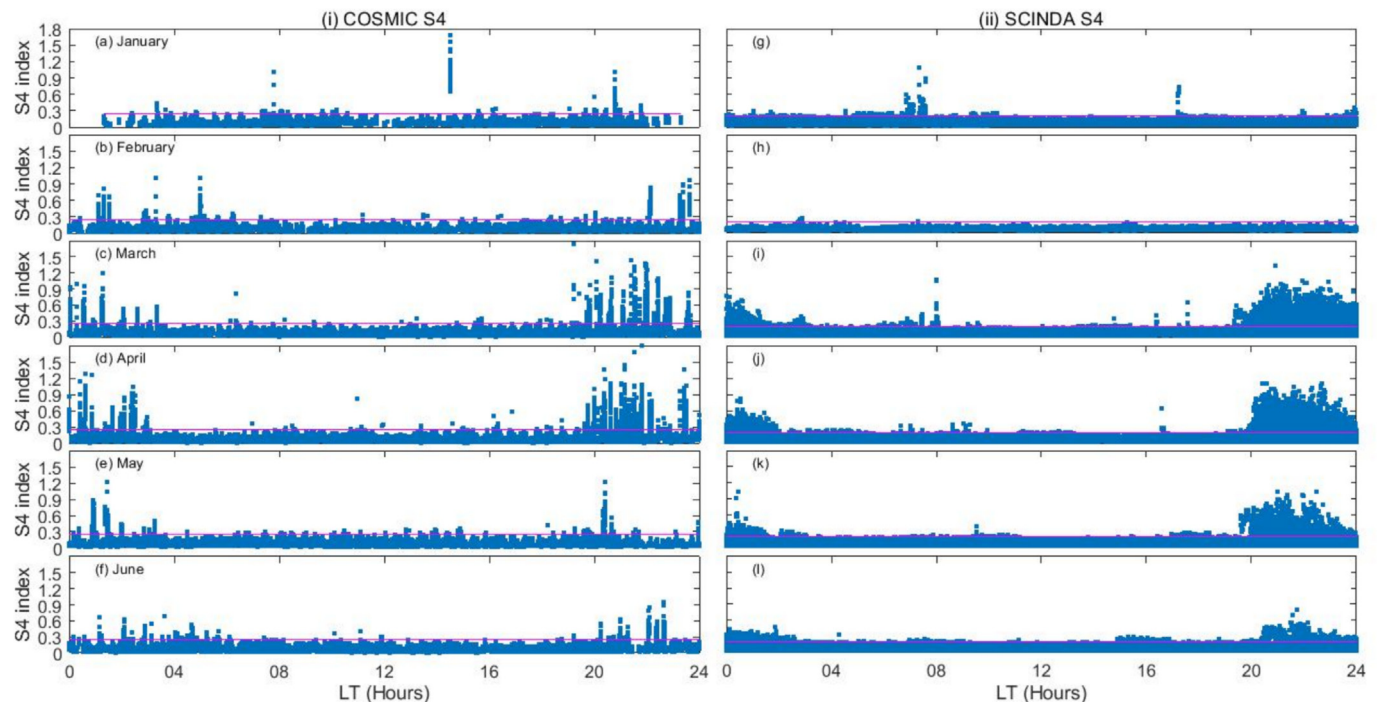


Fig. 5. Panels (a) – (f) present COSMIC S4 against Local Time during January - June 2011, respectively, while panels (g) - (l) present SCINDA S4 against Local Time during these months, respectively. The magenta horizontal line marks the estimated background level.

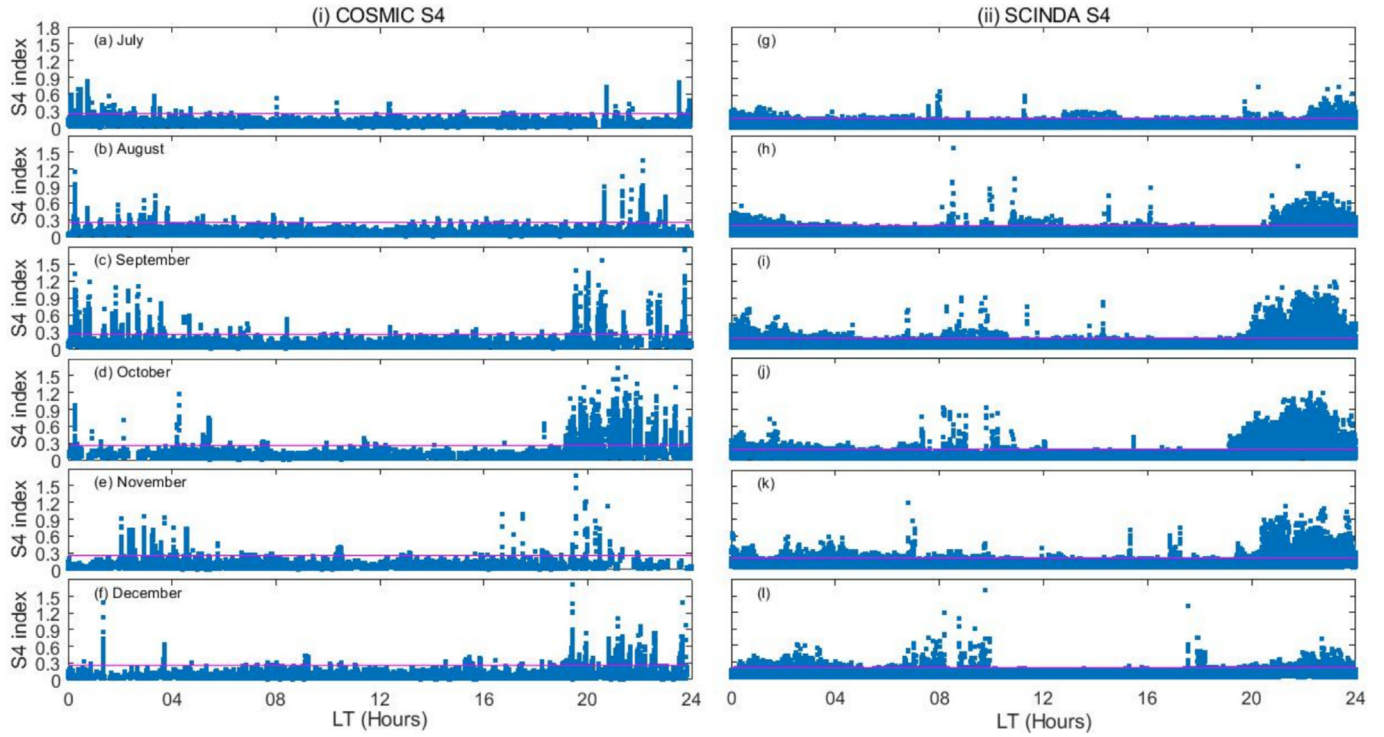


Fig. 6. Similar to Fig. 5, but for months of July -- December 2011.

Therefore, the isolated cases of high SCINDA S4 might be associated with sporadic E. The number of observed ionospheric irregularities presented simultaneously with the average foF2 observed over Japan by Mungufeni (2021) showed that day-time irregularities might be associated with Es-layer. Day-time Es occurrences have been previously reported by Atulkar et al. (2017, 2019).

Using the data plotted in Figs. 5 and 6, we determined the number of observations during time intervals, representing mid-night to morning, morning to noon, afternoon to before sunset and after sunset to mid-night. The results are shown in Fig. 7. The blue, black, green and red bars in the figure indicate the number of observations during time intervals 0–6:00, 6:01–12:00, 12:01–18:00, 18:01–24:00, respectively. Clearly, most time intervals show that the amount of data exceeds 1000 observations, except SCINDA observations in February which are slightly > 1500. These observations give confidence in relying on the deductions made from Figs. 5 and 6.

Since Figs. 5 and 6 demonstrate that scintillations mainly occur during March and September equinoxes, we used data of September and October 2009 and 2011 to study the solar activity variation patterns of both COSMIC and SCINDA S4. Fig. 8, top row panels (a) and (b) present COSMIC and SCINDA S4, respectively in the month of September, 2009. Moreover, panels (c) and (d) present the corresponding data for the month of October. Bottom row panels are similar to that of top, except for the year 2011. Clearly, the post-sunset scintillations observed by both COSMIC and SCINDA are commonly seen in the

high solar activity year 2011, but not in the low solar activity year 2009. The occurrence of ionospheric irregularities that cause scintillation during high solar activity conditions is usually attributed to the existence of sufficient background electron density created during such conditions.

3.4. Scintillation Occurrence rates

Following the local time trends of scintillation observed in previous section, we computed the occurrence rates from the data plotted in Figs. 5, 6 and 8 at two intervals. The first interval corresponds to the time during 0:00–18:00 LT (mid-night to before sunset) while the second corresponds to the time during 18:00–24:00 LT (after sunset to mid-night). For purposes of showing seasonal scintillation occurrence rates, the percentage in a month was computed using the Eq. 5,

Scintillation Occurrence

$$= \frac{\text{total number of S4} > \text{Bg in a time interval}}{\text{total number of S4 data in that time interval}} \times 100. \quad (5)$$

In Eq. 5, Bg is the background S4 value (0.2 for SCINDA and 0.25 for COSMIC). Figs. 9 and 10 present the results. Fig. 9 presents in panels (a) and (b) the scintillation percentages obtained from COSMIC and SCINDA S4 data, respectively. The blue and black bars in the figure and later in Fig. 10 represent the percentages during 0:00–18:00 LT and 18:00–24:00 LT, respectively. As expected, Fig. 9 shows that the scintillation occurrence rate during 18:00–24:00 LT in most cases exceeds those during 0:00–

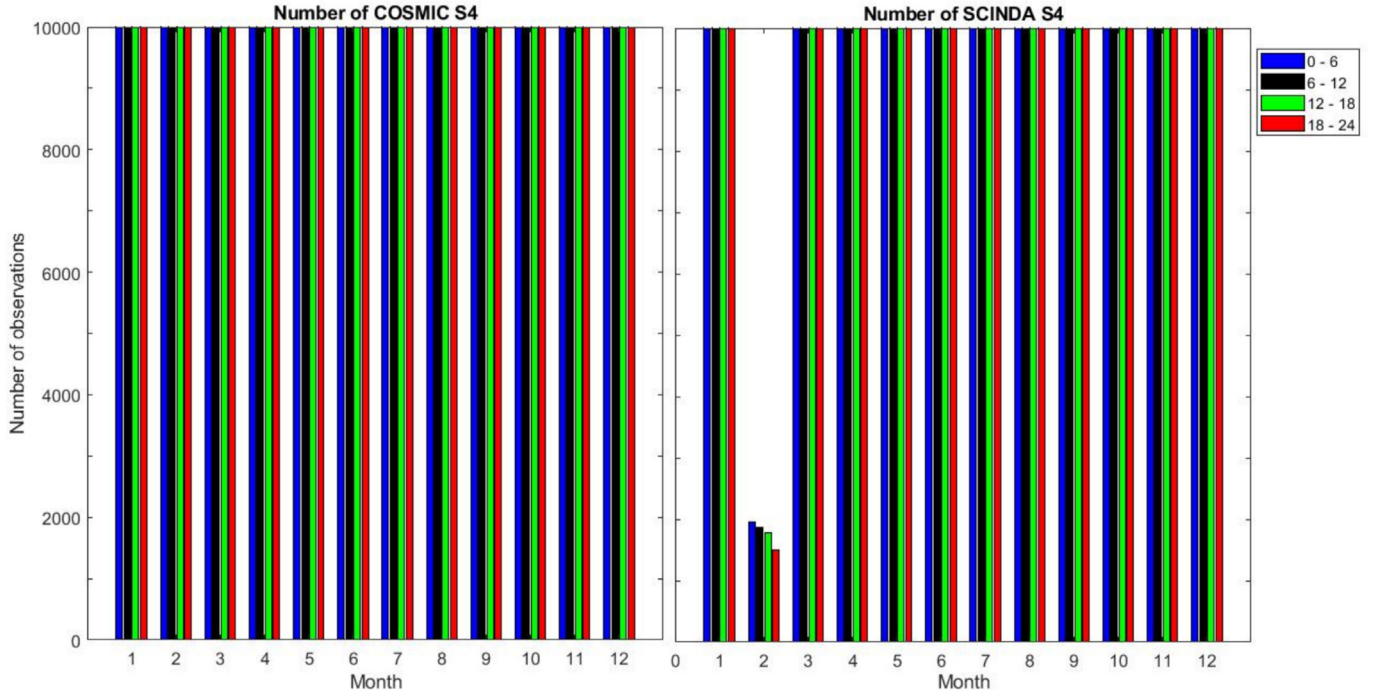


Fig. 7. Number of data points associated with the data presented in Figs. 5 and 6. Panels (a) and (b) show number of COSMIC and SCINDA S4 data points, respectively. The blue, black, green and red bars represent the number of data points during time intervals 0–6:00, 6:01–12:00, 12:01–18:00, 18:01–24:00, respectively.

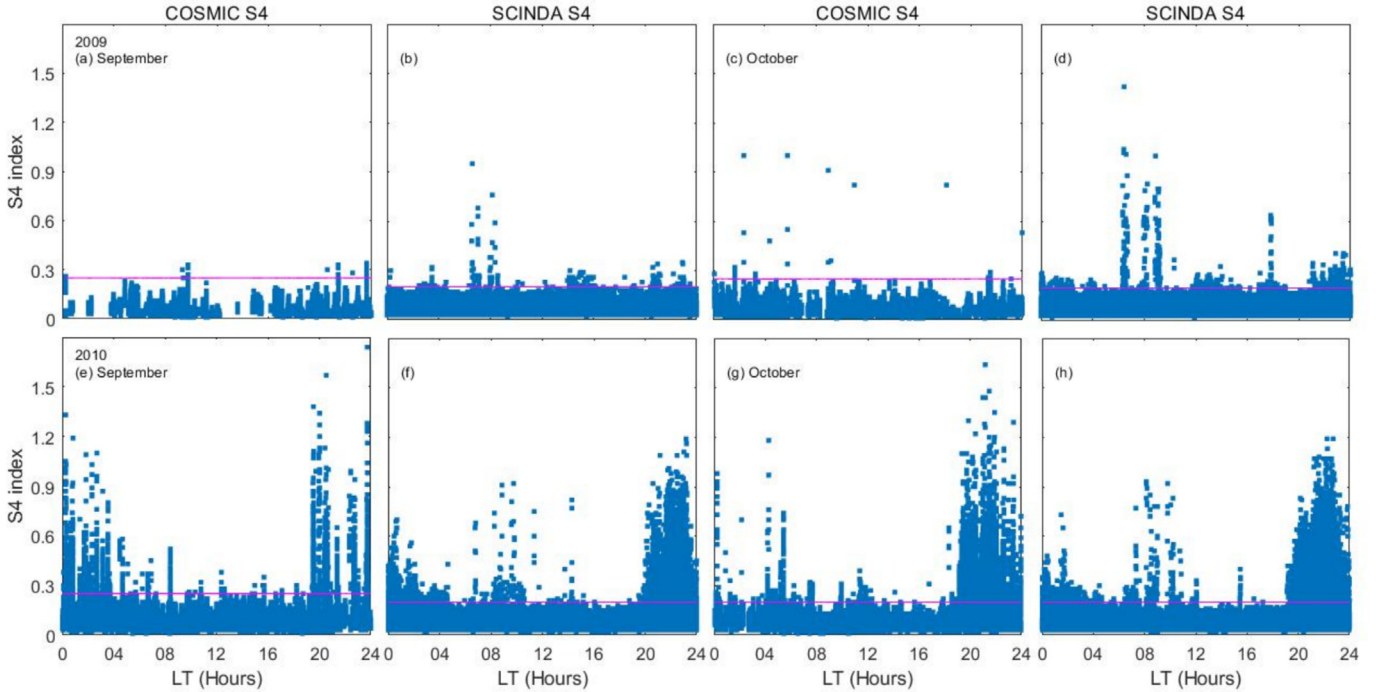


Fig. 8. Panels (a) and (b) in the top row present COSMIC and SCINDA S4 data, respectively in September 2009, while panels (c) and (d) present COSMIC and SCINDA S4 data, respectively in October 2009. Panels in the bottom row are similar to that in the top row, except for the year 2010. The magenta horizontal line marks the estimated background level.

18:00 LT. Actually, the maximum scintillation occurrence rate during 18:00–24:00 LT exceeded 15% in the months of October and April (see panel (b)). On the other hand,

the maximum scintillation occurrence rate during 0:00–18:00 LT did not exceed 1%. Moreover, the scintillation occurrence rates during equinox months (March, April,

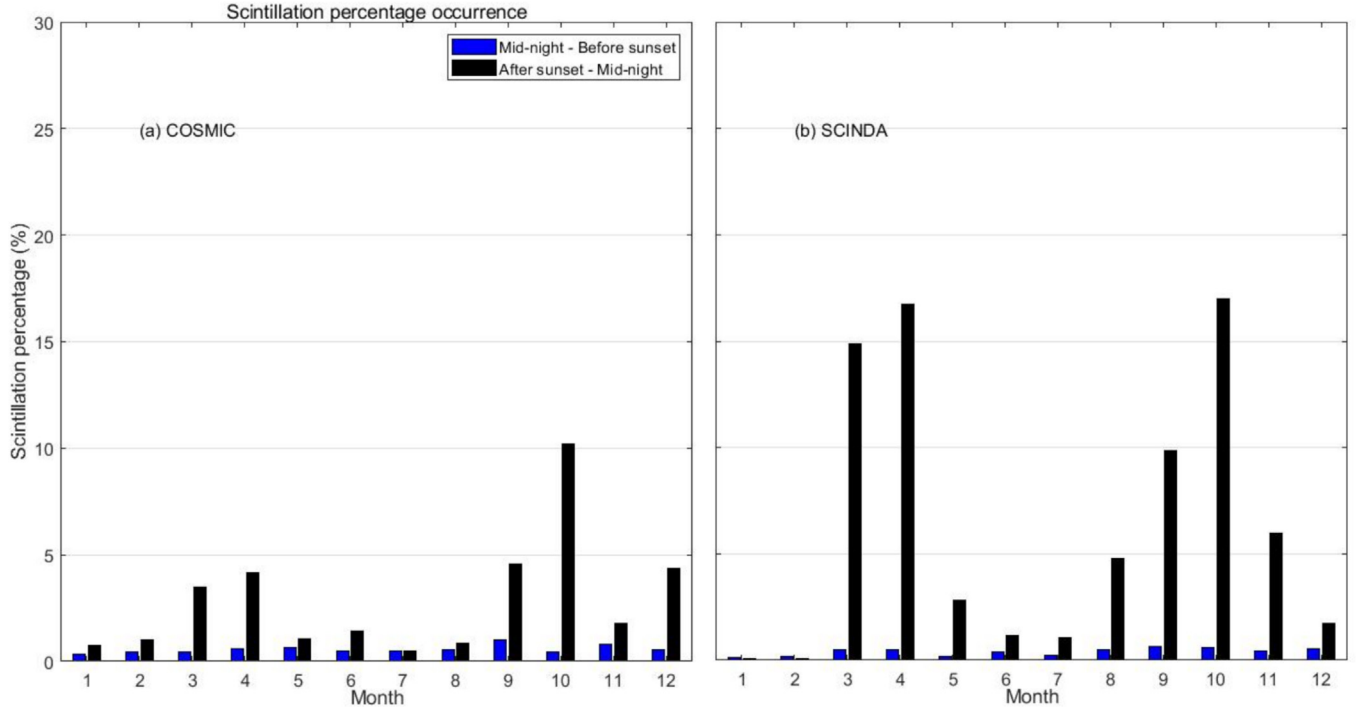


Fig. 9. Panels (a) and (b) present scintillation percentage obtained from COSMIC and SCINDA S4 data, respectively. The S4 data used are for the year 2011. Blue and black bars indicate the percentage during 0:00–18:00 LT and 18:00–24:00 LT, respectively.

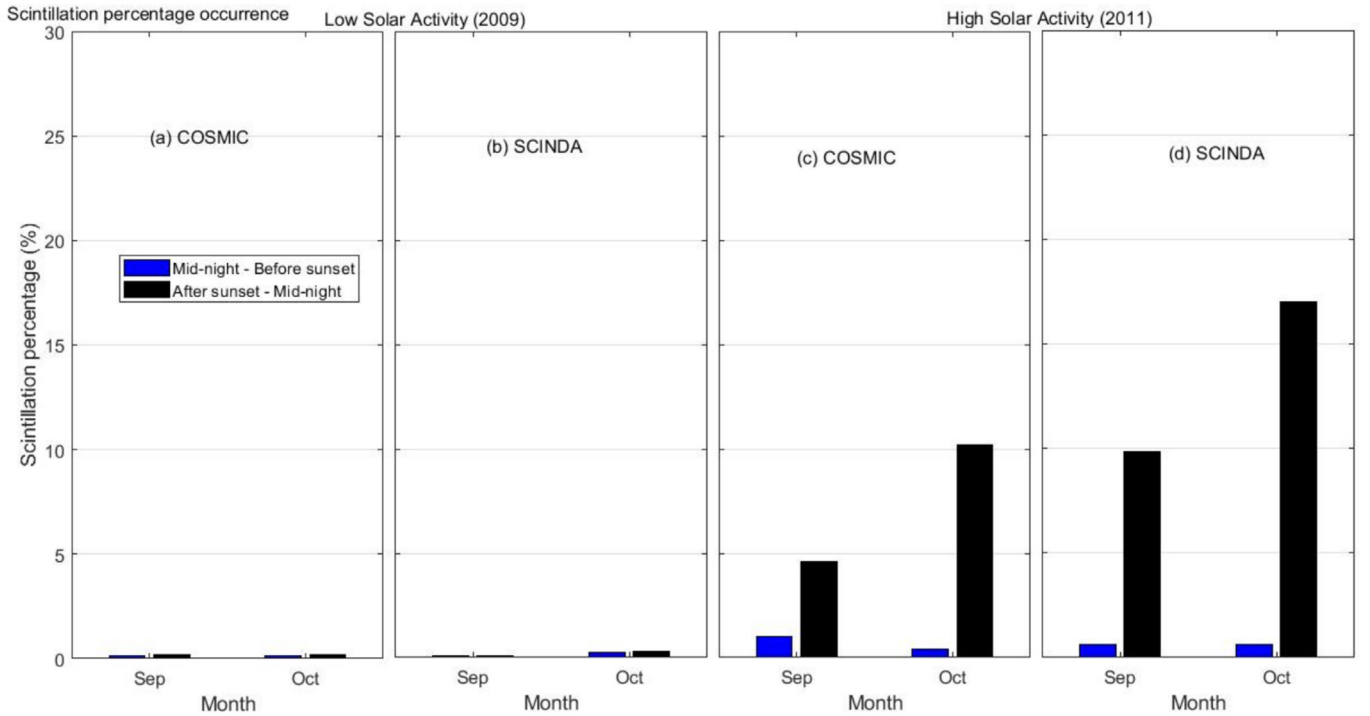


Fig. 10. Panels (a) and (b) present scintillation percentages for COSMIC and SCINDA S4, respectively during low solar activity year 2009. The corresponding panels (c) and (d) present the data during high solar activity year 2011. The color bars are described as in the caption of Fig. 9.

September, and October) mostly are greater than those during solstice months (June, July, November, and December). Indeed these results confirm the earlier ones

deduced from Figs. 5, 6 where it was observed that scintillation mostly occur during 18:00–24:00 LT in the equinox months.

Fig. 10 presents in panels (a) and (b) the scintillation percentages for COSMIC and SCINDA S4, respectively during low solar activity conditions. The corresponding panels (c) and (d) are for high solar activity year. The data presented in the Fig. 10 are for the same months indicated in Fig. 8. Similarly to the observation made from Fig. 9, it can be observed from Fig. 10 that the scintillation occurrence rate during 18:00–24:00 LT mostly exceeds that during 0:00–18:00 LT. The key observation that should be noted from Fig. 10 is that scintillation occurrence rate during high solar activity conditions exceeds that during low solar activity. Actually, the scintillation occurrence percentage in high solar activity year reached >15% (see panel (d)), while the highest scintillation occurrence during low solar activity was ~1 %. These results quantify the earlier observation made from Fig. 8. Generally, Figs. 9 and 10 demonstrate that the patterns of variation of scintillations associated with local time, season and solar activity in COSMIC and SCINDA S4 are similar.

4. Conclusions

The COSMIC S4 data during quiet ($K_p < 3$) and disturbed ($K_p \geq 5$) geomagnetic days of the years 2009 and 2011 were compared with the SCINDA S4 data measured by the SCINDA receiver which operated at Nairobi University, Kenya. For the cases of GPS satellites having < 0 degrees elevation angle as observed by the COSMIC satellites, a geo-location of the COSMIC S4 data associated with the link was proposed at the tangent point. Specifically, the data considered were those whose tangent points are in F-region. The COSMIC S4 data whose geo-locations fall in the vicinity of Nairobi were compared with the S4 data measured by the SCINDA receiver. The coefficient of determination which represents the percentage of the variation in COSMIC S4 data associated with the variation in SCINDA S4 was 50%. Both COSMIC and SCINDA S4 data sets depict that scintillation occurs mostly in the seasons of March and September equinoxes compared to June and December solstices. Moreover, both COSMIC and SCINDA show that scintillations occur mostly during high solar activity conditions. However, there was a moderate positive correlation ($r = 0.52$) between COSMIC and SCINDA S4 data. Therefore, COSMIC S4 can be used to supplement SCINDA S4 data. For instance, the COSMIC S4 could be analysed to study F-region ionospheric irregularities (which cause scintillations) over locations such as deserts and oceans where it is usually difficult to deploy ground-based GPS SCINDA receiver.

Data Availability

The data of GPS-SCINDA system used in this study are protected. Access can be obtained on request from one of the authors, Dr. George Omondi (omondigeok@yahoo.com). The K_p data was obtained from: <https://wdc.kugi.kyoto-u.ac.jp/kp/index.html>. The scnLv1 files which yielded COSMIC S4 data were obtained from: <https://data.cosmic.ucar.edu/gnss-ro/cosmic1/repro2013/level1b>. The F10.7 flux values were obtained from: <https://www.space-weather.gc.ca/forecast-prevision/solar-solaire/solarflux/sx-5-mavg-en.php>.

kyoto-u.ac.jp/kp/index.html. The scnLv1 files which yielded COSMIC S4 data were obtained from: <https://data.cosmic.ucar.edu/gnss-ro/cosmic1/repro2013/level1b>. The F10.7 flux values were obtained from: <https://www.space-weather.gc.ca/forecast-prevision/solar-solaire/solarflux/sx-5-mavg-en.php>.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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