Meteorology and Atmospheric Physics (2021) 133:1545–1554
https://doi.org/10.1007/s00703-021-00827-9

ORIGINAL PAPER

Comparative assessment of radio occultation-based refractivity measurements from the COSMIC mission and in-situ atmospheric measurements in equatorial Africa

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Received: 24 February 2021 / Accepted: 13 August 2021 / Published online: 19 August 2021

Abstract
The growing technological needs for multi-instrument datasets require proper understanding of the behaviour of the datasets relative to each other. This paper presents the first results of analysis on the relationship between in-situ ground refractivity measurements and Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) refractivity measurements in the African equatorial region. In-situ measurements of surface refractivity obtained from four atmospheric ground stations in the region are compared with COSMIC-1 refractivity measurements at 1 km altitude. The in-situ datasets cover the periods from years 2007 to 2014, and corresponding COSMIC-1 datasets over the same period was used. Datasets from the recently launched COSMIC-2 mission (October 2019–September 2020) were utilized to show that the typical differences between refractivity values measured at 0 and 1 km altitudes are about 48 N-units. Interestingly, time-coincident measurements from COSMIC-1 (at 1 km altitude) and from ground in-situ measurements indicate that there is a similar typical difference (about 52 N-units) between refractivity values at the two altitudes. The reason for using COSMIC-2 measurements is that the altitudes covered by COSMIC-1 measurements start from a minimum of 0.1 km, and even at this altitude, the COSMIC-1 measurements are very scanty that there are no coincident observations with the in-situ ground stations. This is why it became imperative to first use COSMIC-2 measurements which cover altitudes from as low as 0 km. The reason is to validate that the difference between COSMIC measurements at 0 and 1 km altitudes are equivalent/comparable to difference between in-situ ground measurements and COSMIC measurements at 1 km. These results indicate that the COSMIC measurements at 0 km are comparable to the in-situ ground measurements.

1 Introduction

Most of the refractivity studies in equatorial Africa have concentrated on deriving refractivity from atmospheric parameters such as temperature, pressure and humidity (Ayantunji et al. 2011; Adediji et al. 2014; Yusuf et al. 2019; Agbo et al. 2020a). In recent times however, there is rapid acquisition of satellite-based refractivity measurements, e.g., from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission using the radio occultation (RO) technique. There is very scanty research in the African equatorial region making use of such datasets, and there has been no research on a comparative analysis of RO-based refractivity measurements from COSMIC-1 mission and in-situ ground refractivity measurements computed from atmospheric parameters. We clarify here that whenever we refer to "in-situ ground refractivity" measurements, we mean the refractivity values computed using atmospheric parameters measured by in-situ ground equipment. This

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study presents the first comparative assessment of COSMIC RO refractivity and in-situ ground refractivity computed from atmospheric parameters. It is important to explain at this point that whenever we refer to the term "COSMIC" measurements (without specifying whether it is COSMIC-1 or COSMIC-2), we are using the generic term that covers both COSMIC-1 and COSMIC-2 measurements. This is because it is the same principles/techniques that are used by both COSMIC-1 and COSMIC-2 constellations, and we are actually referring to the measurements made by these principles/techniques, rather than just either of the constellations.

RO is a remote sensing technique which has been applied for measurement of the physical properties (such as refractivity) of atmosphere. With the combination of global coverage, high vertical resolution, and all-weather capability, Global Navigation Satellite System (GNSS) RO is an emerging satellite remote sensing technique that can probe the atmosphere on a global scale (Xie et al. 2010). GNSS RO also has the advantage of providing high vertical resolution measurements of the atmosphere. Most meteorological refractivity studies in equatorial Africa are limited to refractivity measurements carried out at altitudes below 100 m of the mean sea level (Ayantunji et al. 2011; Yusuf et al. 2019; Agbo et al. 2020a). This is mainly a problem of required equipment/facility to make measurements beyond that altitude. The COSMIC mission therefore presents excellent opportunity to obtain refractivity measurements at different altitudes in the atmosphere.

The refractive index (n) of a medium is expressed as in Eq. (1).

$$n = \frac{c}{v}, \tag{1}$$

where c is the speed of propagation of electromagnetic wave in a vacuum and v is the speed of propagation in the medium. When the electromagnetic wave in the atmosphere propagates just slightly slower than in vacuum, the refractive index is more conveniently expressed by the term refractivity (N) as shown in Eq. (2).

$$N = 10^6(n - 1). \tag{2}$$

Refractivity is usually derived using Eq. (3) (Smith and Weintraub 1953).

$$N = k_1\frac{P_\mathrm{d}}{T} + k_2\frac{e}{T} + k_3\frac{e}{T^2}. \tag{3}$$

where P_d is the partial pressure due to dry gases, including CO_2. e is partial pressure of water vapour which is directly proportional to humidity, and the K_is are constants whose values have been empirically determined in laboratory as $k_1 = 77.6848$; $k_2 = 71.2952$ and $k_3 = 375{,}463$ (Bevis et al. 1994; Olasoji 2016).

Radio refractivity measurements can be obtained through many processes, e.g., from terrestrial atmospheric measurements of temperature, pressure and humidity, from radiosonde soundings, GNSS RO, etc. The growing technological needs for multi-instrument datasets require proper understanding of the behaviour of the datasets relative to each other. In this study, the first results of analysis on the relationship between in-situ ground refractivity measurements and COSMIC GNSS RO measurements in the African equatorial region are presented.

2 Data and methods

In-situ ground measurements of temperature, pressure and humidity were obtained from the Tropospheric Data Acquisition Network (TRODAN) project of the Centre for Atmospheric Research (CAR), National Space Research and Development Agency (NASRDA). TRODAN data used in this work are for four stations: Abuja (8.9° N, 7.4° E), Lagos (6.5° N, 3.4° E), Nsukka (6.8° N, 7.4° E), and Port Harcourt (4.8° N, 7.0° E). The locations of these stations on a map of Africa are shown in Fig. 1. The thick continuous line in Fig. 1 represents the geomagnetic equator while the dash lines represent boundaries at ± 10° from the geomagnetic equator.

Equations (1)–(3) were used to compute corresponding surface refractivity values from these atmospheric parameters. Available TRODAN data for the four stations cover the periods from years 2007 to 2014. All available data for the four stations were used in this study.

Refractivity data were also obtained from the COSMIC mission. The COSMIC data are refractivity measurements obtained by GNSS RO technique. Data from both COSMIC-1 and COSMIC-2 missions were used. The COSMIC-1 data used for the study span the same period as for the TRODAN data (years 2007–2014), while the COSMIC-2 data span the period from October 2019 to September 2020. The data were obtained from the UCAR (University Corporation for Atmospheric Research) COSMIC website (https://data.cosmic.ucar.edu/). Data from the site were obtained as Tape Archive (TAR) files containing second level (wetPrf and wetPf2) files of the COSMIC data system. The files are in NetCDF (Network Common Data Form) format. The TAR files were uncompressed, and the program of Nzeagwu et al. (2020) was used to extract the refractivity (and other atmospheric parameter) data from the NetCDF files into text files. The NetCDF files contain badness flags that indicate whether each of the data profiles passed or flunked quality control checks. The program extracts only data profiles that passed the quality control checks. Only measurements obtained within the Nigerian region (latitudes 4°–14° N and longitudes 2°–15° E) were used. The COSMIC-1

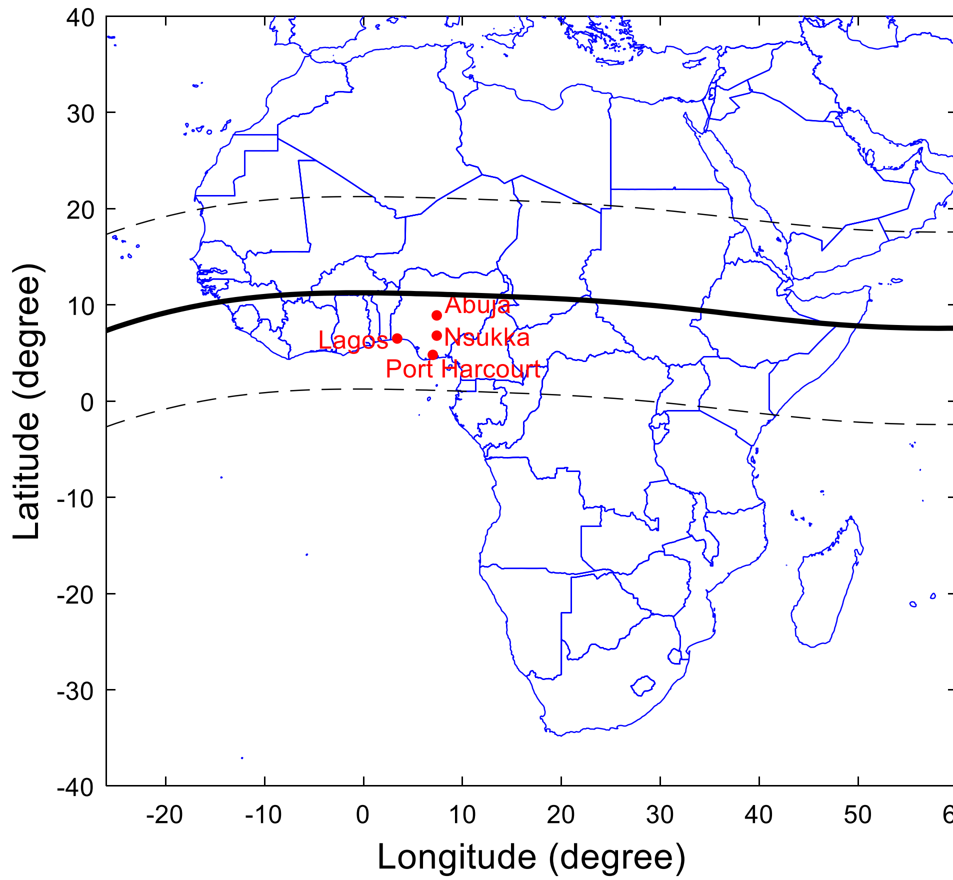


Fig. 1 Map of Africa showing locations of the four ground stations from which in-situ measurements are used in this work. The thick continuous line represents the geomagnetic equator while the dash lines represent boundaries at ± 10° from the geomagnetic equator

measurements cover altitudes from a minimum of 0.1 km, and measurements at this altitude are very scanty that there are not coincident observations with the TRODAN stations. This is why it became imperative to include COSMIC-2 measurements which cover altitudes from as low as 0 km.

COSMIC-2 measurements were used in this study to investigate typical differences between surface refractivity and refractivity at 1 km altitude. COSMIC-1 refractivity measurements (at 1 km altitude) were then compared with corresponding ground refractivity measurements obtained from the TRODAN stations to investigate typical differences between refractivity measured by two systems on ground and at 1 km altitude. The measurements from both system were binned and averaged in 1 h interval. If the difference between COSMIC measurements at 0 and 1 km is similar/comparable to the difference between in-situ ground measurements and COSMIC measurements at 1 km, then inference can be made that the COSMIC measurements at 0 km are similar/comparable to the in-situ ground measurements. The premise for this inference is based on the idea that if $x0 - x1 = c$, and $y0 - x1 = c$, then $x0$ is equivalent to $y0$. In this analogy, $x0$ represents COSMIC measurements at 0 km, $x1$ represents COSMIC measurements at 1 km, $y0$ represents the in-situ ground measurements, and c is the similar difference obtained in each case.

3 Results and discussion

3.1 COSMIC-2 surface refractivity versus COSMIC-2 refractivity at 1 km altitude

To investigate the relationship between surface refractivity values and refractivity values at 1 km altitude, we first look for COSMIC-2 data in which there are measurements for both 0 and 1 km. Surface measurements of refractivity are only available for some measurements recorded by the recently launched COSMIC-2 mission (that is during the 1-year period from October 2019 to September 2020). We obtained a total of 38 COSMIC-2 RO profiles within the region in which there are refractivity measurements for both 0 and 1 km. The results are shown in Fig. 2. Figure 2a shows plots of the surface refractivity measurements (refractivity_{c0}) against corresponding refractivity values at 1 km altitude (refractivity_{c1}). To ascertain the level of correlation between the two set of measurements, we computed the correlation coefficient between them. The value of correlation coefficient for the two set of measurements is $r = 0.4$, which indicates that there is correlation between the measurements at the two different altitudes, but that this correlation is not very strong. To give an idea of the magnitude of refractivity variation between the two altitudes, we compute the

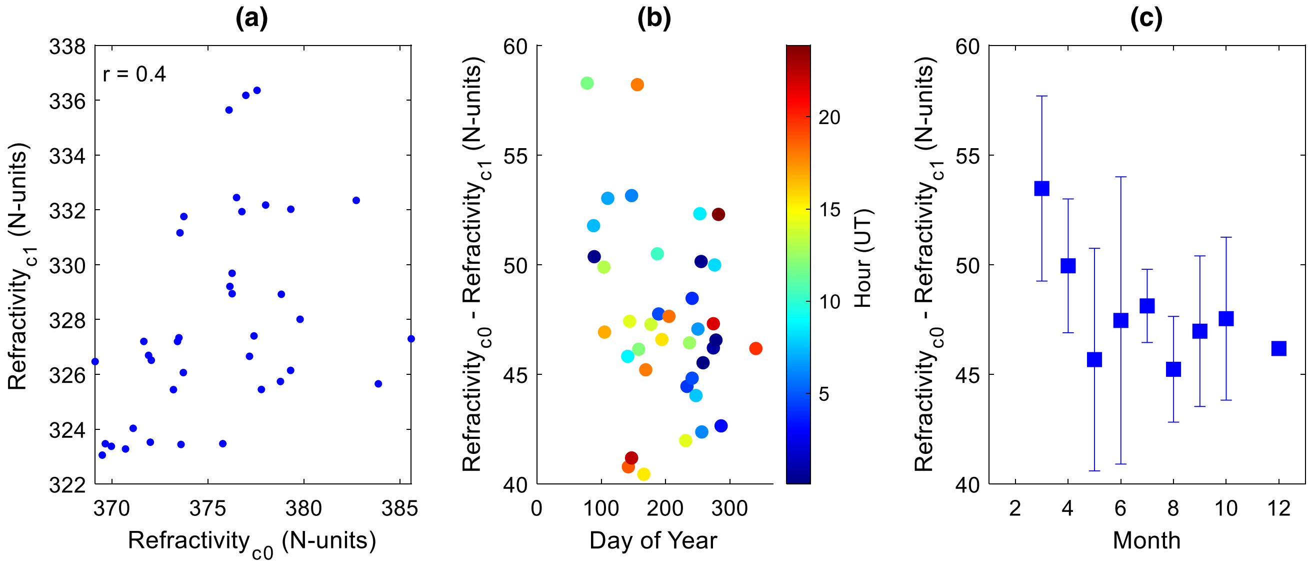


Fig. 2 **a** COSMIC-2 surface refractivity measurements versus corresponding COSMIC-2 refractivity measurements for 1 km altitude. **b** Differences between COSMIC-2 surface refractivity measurements and COSMIC-2 refractivity measurements at 1 km altitude, plotted as functions of the day of the year and the UT hour of the day. The points are illustrated in colours that indicate the UT hour of the day in which the measurements were done. **c** Monthly means of the differences between COSMIC-2 surface refractivity measurements and COSMIC-2 refractivity measurements at 1 km. The lengths of the error bars indicate corresponding standard deviations of the differences binned monthly

differences (refractivity$_{c0}$ – refractivity$_{c1}$) between refractivity measurements for the two altitudes. Figure 2b illustrates variations of the differences (refractivity$_{c0}$ – refractivity$_{c1}$) as functions of day of the year and hour of the day (in universal time, UT). The points are illustrated in colours that indicate the UT hour of the day in which the measurements were done. In Fig. 2c, the differences are binned monthly. The filled square points indicate monthly means of the differences, while the lengths of the error bars indicate the corresponding standard deviations.

Figure 2b does not reveal a clear pattern of seasonal or diurnal variations of the differences. It is however observed that lower values of the differences are recorded during the evening and night time hours: around 16:00 UT–05:00 UT (17:00 LT–06:00 UT). It is not rational to discuss about the seasonal variation of the differences since the coincident measurements do not span a complete year. Figure 2c however reveals that the differences are greatest in the months of February and March, where the values reach ~ 50 N-units and greater. Statistically, and in overall, the differences are in the range of about 40–60 N-units. The mean of the differences is 47.56 N-units, and the standard deviation is 4.22 N-units. Using atmospheric parameter measurements from the archive of the Climate Monitoring Satellite Application Facility (CM-SAF), Abimbola et al. (2020) obtained a similar refractivity gradient of about 46.48 N-units/km for the same West African region. In a related research, Fashade et al. (2019) used meteorological data from satellite sounding instrument by National Aeronautics and Space Administration (NASA) to obtain values of 40.2 N-units, 40.3 N-units, 47.0 N-units, and 43.0 N-units respectively for Abuja, Enugu, Lagos, and Port-Harcourt, which are in the same region as the present study. This shows that there is agreement and similarity between the datasets, thereby validating that the COSMIC measurements are good candidates for refractivity studies in the region.

3.2 In-situ surface refractivity versus COSMIC-1 refractivity at 1 km altitude

Surface refractivity data derived from in-situ TRODAN stations were also compared to COSMIC-1 refractivity measurements at 1 km altitude. All available data from the four atmospheric stations (Abuja, Lagos, Nsukka, and Port Harcourt) were used. For each of the four atmospheric stations, the COSMIC-1 database is searched for overlapping COSMIC-1 measurements using a computer program. We define overlapping COSMIC-1 measurements as measurements obtained within 1° spatial radius (~ 111 km) of the station and within a time interval of 1 h. The mean of such measurements are computed and considered as the corresponding COSMIC-1 measurements. We obtained a total of 120 pair of observations for the four stations. Figure 3 illustrates the results.

Figure 3a shows plots of the in-situ surface refractivity measurements (refractivity$_{s0}$) against

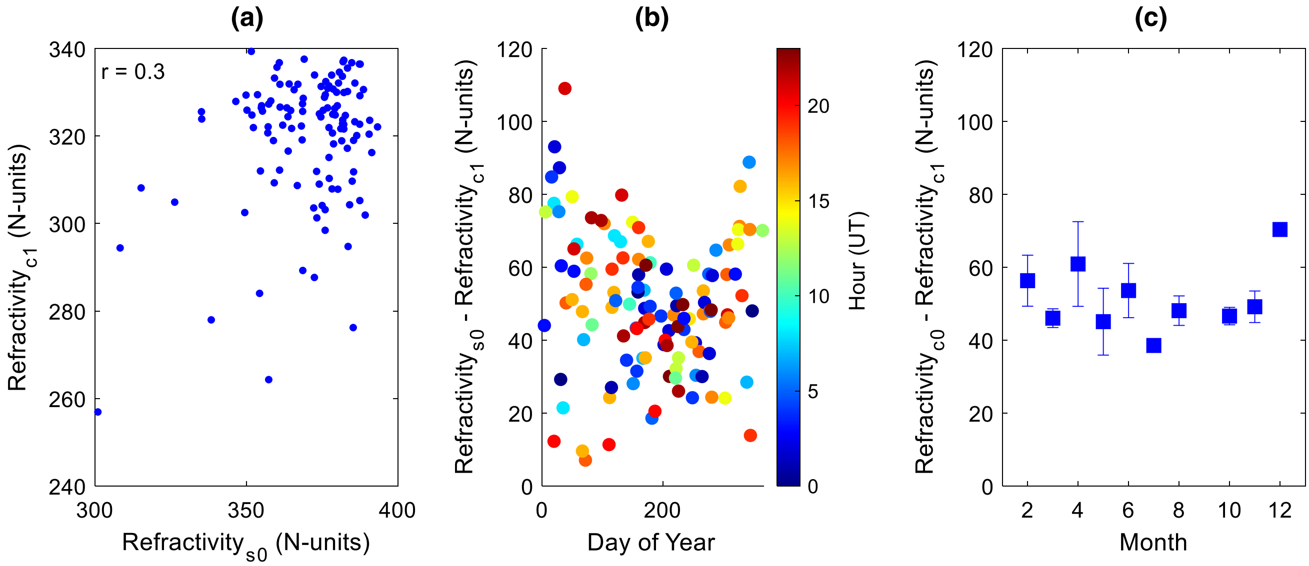


Fig. 3 **a** In-situ surface refractivity measurements versus corresponding COSMIC-1 refractivity measurements for 1 km altitude. **b** Differences between in-situ surface refractivity measurements and COSMIC-1 refractivity measurements at 1 km altitude, plotted as functions of the day of the year and the UT hour of the day. The points are illustrated in colours that indicate the UT hour of the day in which the measurements were done. **c** Monthly means of the differences between in-situ surface refractivity measurements and COSMIC-1 refractivity measurements at 1 km. The lengths of the error bars indicate corresponding standard deviations of the differences binned monthly

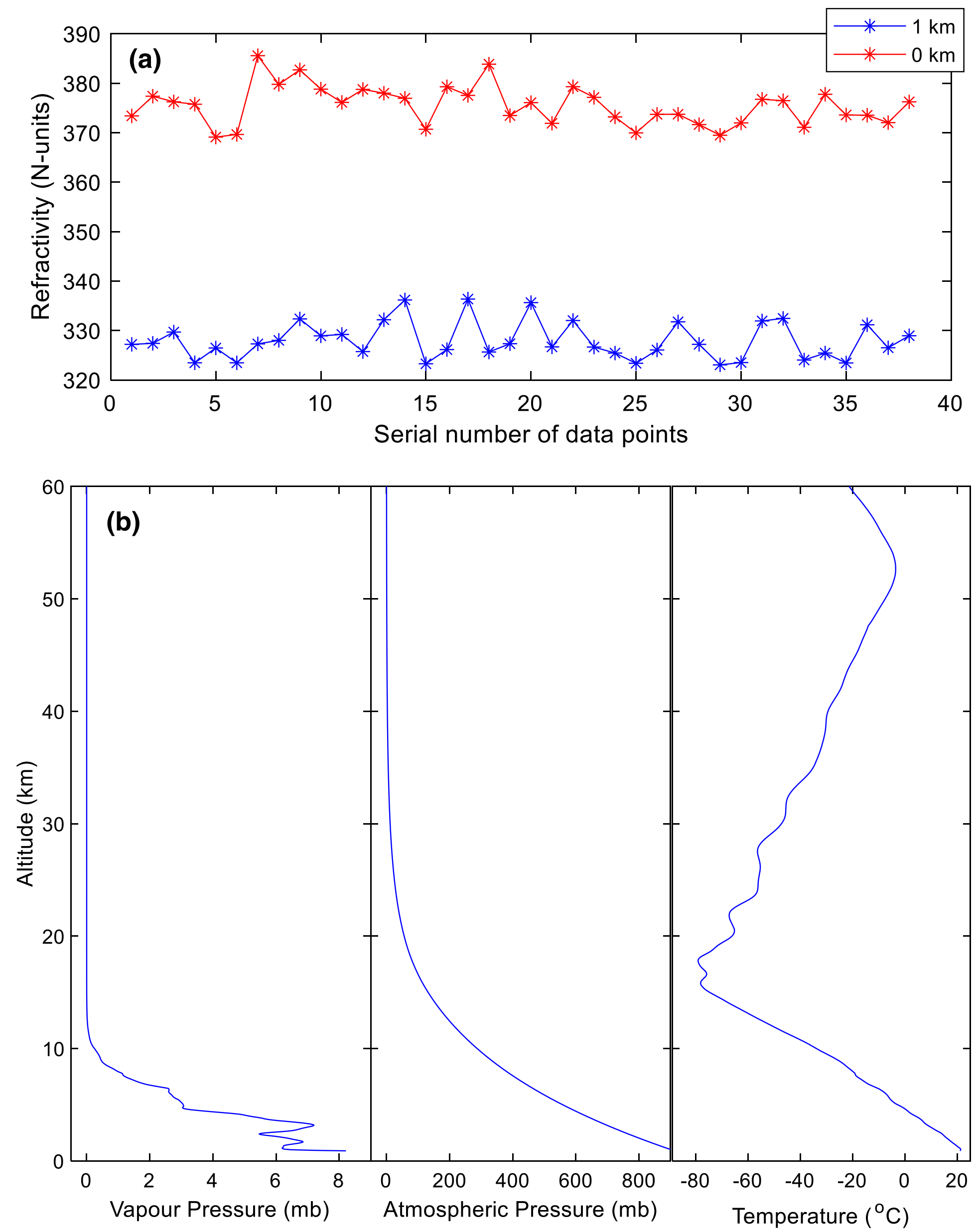
corresponding COSMIC-1 refractivity values at 1 km altitude (refractivity$_{c1}$). The value of correlation coefficient for the two set of measurements is $r = 0.3$, which is similar to the 0.4 value obtained for the case of the refractivity$_{c1}$ versus refractivity$_{c0}$ measurements. Figure 3b illustrates variations of the differences (refractivity$_{s0}$ – refractivity$_{c1}$) as functions of day of the year and hour of the day (in universal time, UT). The points are similarly illustrated in colours that indicate the UT hour of the day in which the measurements were done. In Fig. 3c, the differences are binned monthly. The filled square points indicate monthly means of the differences, while the lengths of the error bars indicate the corresponding standard deviations.

At first glance, it appears intuitive to expect high values of correlation between refractivity values at 0 and 1 km altitudes. We investigated possible reasons for the observed values of correlation coefficients, which appear lower than intuitively expected. First, we present in Fig. 4a, some examples of simultaneous COSMIC-2 measurements of refractivity at 0 and 1 km. The figure clearly shows that the correlation between the refractivity measurements at the two altitudes is not very high. This is because the figure shows that an increase in refractivity at 0 km does not necessarily correspond to an increase in refractivity at 1 km, and vice versa.

To further investigate this scenario, we took a more in-depth look at the altitudinal variation of atmospheric parameters that determine refractivity (e.g., temperature, pressure, and vapour pressure/humidity). The altitudinal profiles of these parameters (obtained from COSMIC-2 measurements for 03:53 UT on 1 January 2020) are shown in Fig. 4b. The figure reveals two reasons why the values of correlation coefficient between measurements at the two altitudes may not be high. First, the vapour pressure demonstrates an irregular pattern of altitudinal variation at ~ 0 to 4 km. This is understandably due to cloud conditions, which occur in an irregular pattern. This irregular variation of the vapour pressure at the two altitudes could influence the value of correlation coefficient for refractivity values measured at the two altitudes. Secondly, Fig. 4b reveals that the three parameters generally show a trend of decreasing values with increasing altitude (especially between 0 and 10 km). It is however known that refractivity has a direct variation with both atmospheric and vapour pressures, and an inverse variation with temperature (see Eq. 3). The consequence is that the atmospheric and vapour pressures drive the refractivity in one direction, while the temperature drives it in the opposite direction. Depending on magnitudes of the three parameters at 0 and 1 km, the same variation pattern of refractivity may not be obtained at the two altitudes, implying that the value of correlation coefficient may not be necessarily high.

Figure 3b reveals a scenario in which the widths of the differences appear smaller during the core of the rainy season (around May–October) and greater during the core of the dry season (around December–February). This is replicated in Fig. 3c. This implies that there is more variation of the refractivity during the dry season than during the rainy

Fig. 4 **a** Some examples of simultaneous COSMIC-2 measurements of refractivity at 0 and 1 km, **b** Altitudinal variations of the vapour pressure, atmospheric pressure, and temperature, obtained from COSMIC-2 for 03:53 UT on 1 January 2020



season. This same implication is corroborated by the results of Fig. 5a where the more variations of surface refractivity are seen during the dry seasons than during the rainy seasons.

Similar to Fig. 2b, lower values of the differences are recorded during the evening and night time hours. Statistically, the differences are in the range of about 5–110 N-units between in-situ surface refractivity and the COSMIC-1 refractivity at 1 km altitude. This range is wider when compared the 40 to 60 N-units obtained for the case of the refractivity$_{c1}$ versus refractivity$_{c0}$. Reasons for the disparity may come from the calibration techniques used to derive the refractivity values for the in-situ and COSMIC systems. Another reason could stem from the design of matching in-situ data for the station to COSMIC-1 data obtained in the neighbourhood of about 111 km radius of the station. Although small differences are expected at such spatial scale, such differences can contribute to the observed difference. Also, there are many more data point used in this case as compared to the fewer number of data points used for the case of the refractivity$_{c1}$ versus refractivity$_{c0}$. The increased number of data points connote an increased likelihood of obtaining data points that are outside of a given probability space. The mean of the differences is 51.92 N-units, which is about 4 N-units greater than the 47.56 N-units obtained for the case of the refractivity$_{c1}$ versus refractivity$_{c0}$. This slight difference may imply that the in-situ surface refractivity values are typically greater than the COSMIC-2 surface

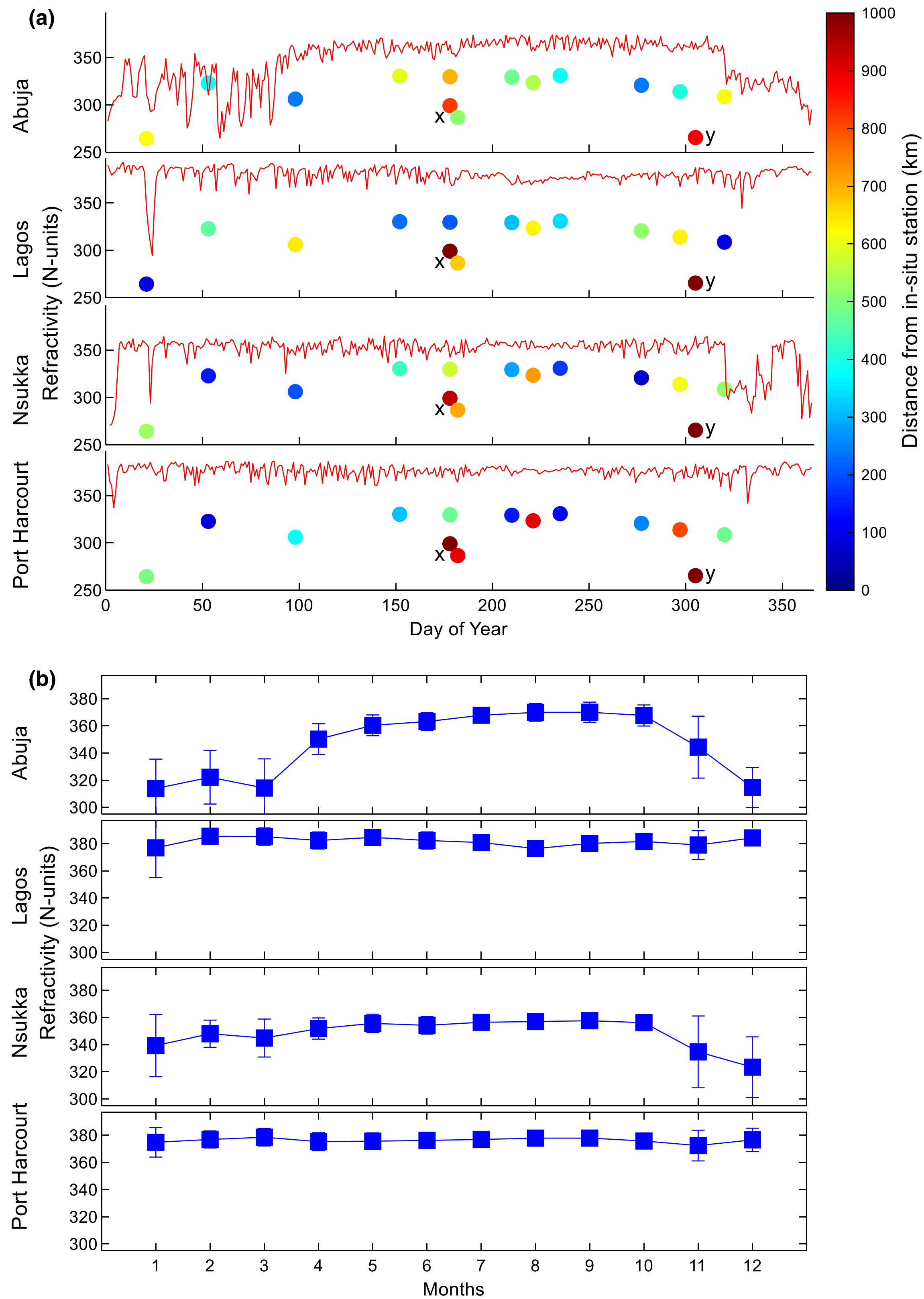


Fig. 5 **a** Seasonal variations of surface refractivity (in-situ measurements represented by lines) and refractivity at 1 km altitude (COSMIC-1 measurements represented by dots). Data for the hour of 03:00 UT for each day of year 2009 is illustrated. The dots are shown in colours that indicate spatial distances of the measurements from each of the four stations. **b** Monthly means of the in-situ surface refractivity measurements. The lengths of the error bars indicate corresponding standard deviations binned monthly

refractivity values by about 4 N-units. The higher value of standard deviation (which is 9.33 N-units) however indicates that there is more spread in the present case than in the case of the refractivity$_{c1}$ versus refractivity$_{c0}$. This is also corroborated by the wider range of values obtained in the present case than in the case of the refractivity$_{c1}$ versus refractivity$_{c0}$.

3.3 Seasonal and diurnal variations of refractivity

To investigate seasonal variations of refractivity across the region, we constructed plots of the refractivity versus day of the year for each of the four stations used for illustration in this study. Data for year 2009 are illustrated because this is the year in which there is consistently the greatest number of data points for the four stations. Figure 5a shows the results. In Fig. 5a, the line plots represent refractivity variations obtained from the in-situ measurements while the dotted plots represent refractivity variations obtained from the COSMIC-1 measurements. For each day, only measurements recorded within the hour of 03:00 UT are represented. The hour of 03:00 UT was chosen because that was the hour in which there is greatest number of COSMIC-1 measurements throughout the year for the region. The COSMIC-1 data points are plotted in colours that indicate spatial distances of the measurements from the respective in-situ stations. In Fig. 5b, the in-situ surface refractivity measurements are binned monthly. The filled square points indicate the monthly means, while the lengths of the error bars indicate the corresponding standard deviations.

Figure 5a shows that the refractivity values are typically greater during the rainy season (around March–October) than during the dry season (around November–February). This is also clearly evident in Fig. 5b. The greater values of refractivity during the rainy season is mainly due to the greater air humidity values observed in the region during the rainy season (Adediji and Ajewole 2008; Nzeagwu et al. 2021). It is obvious from Eq. (3) that refractivity increases with increasing air humidity. In Fig. 5a, this same pattern is replicated by the COSMIC-1 measurements, except for few points (e.g., marked 'x' and 'y') which are at great distances from the stations. This further gives credence to the practice of defining a spatial limit within which COSMIC-1 measurements are associated to particular in-situ stations. The results therefore indicate that the COSMIC measurements, just like in-situ measurements, can be used for refractivity studies in the region.

Figure 6 additionally shows patterns of the seasonal variations in each of the four stations throughout the year during the day time [from sunrise (06:00 LT) to sunset (18:00 LT)] and night time (before sunrise and after sunset). The plots represent surface refractivity variations constructed using the in-situ measurements for all hours and days of year 2009. The plots reveal a pattern in which the refractivity values are greater during the day than at nights, especially during the rainy season. During the dry season however, the refractivity values are typically greater at nights than during

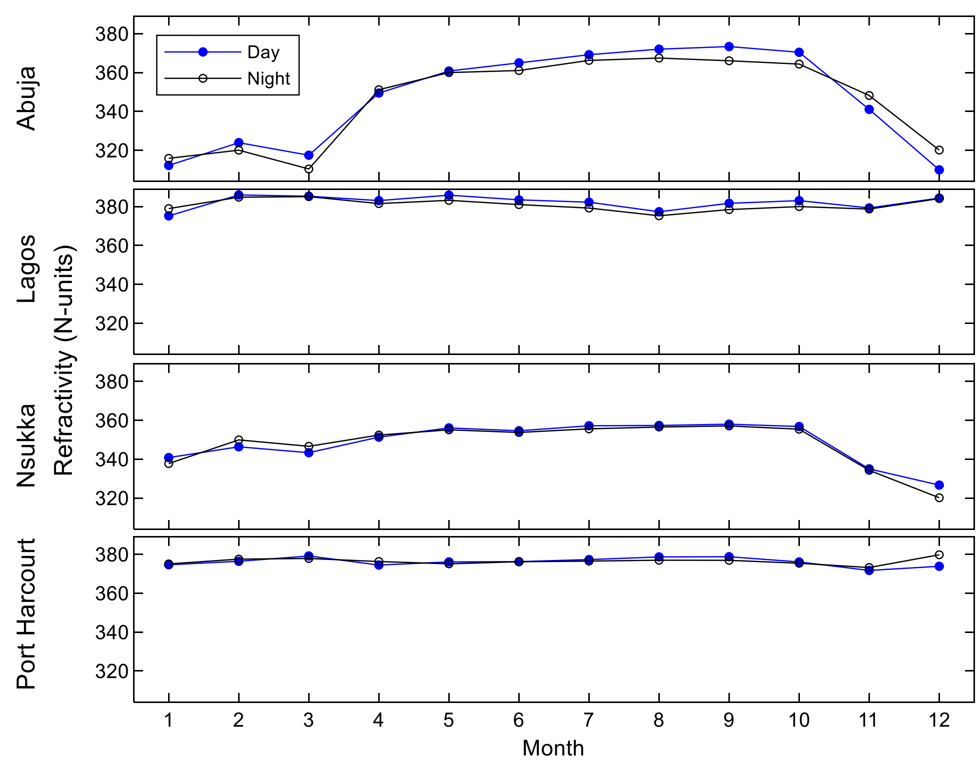


Fig. 6 Seasonal variations of the surface refractivity at Abuja, Lagos, Nsukka, and Port Harcourt, using in-situ measurements during the day time (06:00–18:00 LT) and night time (before 06:00 and after 18:00 LT)

the local daytimes. The dry season refractivity is lower during the day than at night because of the higher temperature and lower humidity values experienced during the day (see Bawa et al. 2017; Agbo et al. 2020b). Equation (3) shows that refractivity has an inverse relation with temperature, and so the refractivity values are lower during the daytime than at night. During the rainy season however, the diurnal temperatures do not vary as much as during the dry season, and the diurnal refractivity variations are controlled more by diurnal atmospheric pressure variations. The rainy season atmospheric pressures are greater during the day than at night (Bawa et al. 2017). Equation (3) shows that refractivity has direct relation with atmospheric pressure, and therefore the rainy season refractivity values are greater during the day than at night. Similar results are expressed by Agbo et al. (2020a) in which the refractivity values are lower in the daytimes of the dry season than in the nighttimes for Yola station (9.20° N, 12.50° E) which is also in equatorial Africa. Also, the results of Adediji et al. (2014) show that the refractivity values were higher in the daytimes of June and July (rainy season) than in the nighttimes for Akure station (7.15° N, 5.12° E) which is also in equatorial Africa. Seasonally, the results of Fig. 6 corroborate the same results of Fig. 5a in which the refractivity values are greater during the rainy season than during the dry season. Of particular interest in this work is that the COSMIC-1 measurements (Fig. 5a) replicate the same seasonal pattern in refractivity as the in-situ measurements. This shows that the COSMIC measurements are similar and also suitable for refractivity studies in the region.

4 Conclusion

In-situ measurements of surface refractivity obtained from four atmospheric ground stations in the Equatorial African region are compared with COSMIC-1 refractivity measurements at 1 km altitude. The in-situ surface refractivity was found to be higher than COSMIC-1 refractivity at 1 km irrespective of the season and time of the day. This supports the fact that refractivity decreases with increasing altitude.

The time-coincident measurements from COSMIC-1 (at 1 km altitude) and from ground in-situ measurements indicate that there is a typical difference of about 52 N-units between refractivity measurements at the two altitudes (using the two different systems of measurement). This is similar to about 48 N-units obtained using only the COSMIC-2 dataset, and also similar to the 46.48 N-units previously obtained by Abimbola et al. (2020) using CM-SAF dataset. The seasonal patterns revealed by both COSMIC-1 and in-situ datasets are also similar. These results indicate that the COSMIC dataset is similar and comparable to in-situ ground dataset which has been popularly used for research in the region.

The in-situ equipment has the advantage of providing continuous measurements over particular stations where they are installed. The COSMIC satellites however have the advantage of providing wider coverage of the measurements, and additionally providing high resolution altitude profiles of refractivity over the wide area covered. Developing a 3-D space and time model of the COSMIC measurements will therefore be useful resource for obtaining continuous refractivity profiles at any given space location and time.

Acknowledgements The results presented in this paper rely on TRODAN data collected and managed by the Centre for Atmospheric Research, National Space Research and Development Agency, Federal Ministry of Science and Technology, Anyigba, Nigeria. We thank the Centre for Atmospheric Research and their partners for promoting high standards of atmospheric observatory practice as well as the Federal Government of Nigeria for continuous funding of the Nigerian Space programme (http://www.carnasrda.com). We also appreciate the University Corporation for Atmospheric Research (UCAR) and the COSMIC team for making COSMIC GNSS radio occultation data used in this work available at the website (https://data.cosmic.ucar.edu/).

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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