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ORIGINAL PAPER

Vertical Profiling of Radio Refractivity and Associated Parameters Using Tethered Balloon Over New Delhi

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Abstract: Atmospheric radio refractivity and its vertical gradient affect electromagnetic (EM) wave propagation mostly in the lower troposphere. The vertical profiles of the radio refractivity over New Delhi are very limited that inspired us to study the same using tethered balloon facility. Here, we investigated radio refractivity and its gradient over New Delhi (28°38′10″N, 77°10′17″E) using radiosonde balloon observation for one week (February 21–27, 2014). Vaisala RS 80 radiosonde device used during this experiment comprised of the individually factory-calibrated temperature, pressure and humidity sensors. The resolution of temperature sensor, pressure sensor and humidity sensor is 0.1 °C, 0.1 hpa and 1% RH, respectively. The refractivity measured using radiosonde has been observed to be reduced by 8.6% at 930 masl (mean above sea level) relative to that of ground level (i.e., 230 masl) during up-leg observation (7:00–7:30 PM), while the same has been found to be increased by 10.8% at ground level relative to that of 930 masl during down-leg observation (3:30–4:00 AM). Though it is a small set of information pertaining to refractivity observations using tethered balloon, certainly it can provide micro-insights of the meteorological effects on radio wave propagation better than that of routine experiments. The present study could be crucial for understanding the probable effects on radio wave propagations within atmospheric boundary layer over the study region and would reduce the underlying uncertainties associated with such measurements.

Keywords: Refractivity; Tethered balloon; Gradient; Atmospheric boundary layer

1. Introduction

The electromagnetic (EM) propagation gets affected majorly due to the non-homogeneous nature of the lower troposphere [1]. The worst propagation conditions are generally observed due to the increased level of fading on the communication links and the decreased power levels at transmitter/receiver side [2, 3]. The most important parameter in the lower atmosphere is the radio refractive index (n) which determines the EM wave propagation and plays equally important role in radio communication link budget planning [4, 5]. The value of the radio refractive index is almost unity, and thus, even small changes are not much visible; so, a novel term has been adopted, i.e., radio refractivity, N in N units [6, 7]. Measurements of radio refractivity can be taken using LIDARs, radars and some other techniques which generally measure near-surface refractive index [8, 9]. LIDARs have been termed as an efficient instrument in finding various atmospheric parameters [10]. However, the widely used technique around the globe for the measurement of radio refractivity is still radiosonde that measures refractivity indirectly from meteorological parameters (temperature, pressure, humidity). Though the radiosonde is widely used for the determination of radio refractivity, these techniques still lack adequate temporal/spatial resolution to show a detailed description of the lowest part of the atmosphere. This is the limitation of the method used during this campaign. In case of radio occultation methods the Global Positioning System (GPS) signals are launched and subsequently measured by satellites, but the launched signals generally bend when they pass through the atmosphere [11, 12]. When using the satellites, it is always hard to measure the radio

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refractivity with sufficient time resolution. The measurement error is generally too high for the altitudes below ~ 1 km, i.e., the lower troposphere.

In the present study, a tethered balloon carrying Vaisala RS 80 radiosonde at CSIR-NPL was used to calculate refractivity indirectly from the observed meteorological parameters [13, 14]. The measured weather variables (air temperature, atmospheric pressure and relative humidity) were used to derive and analyze the radio refractivity, modified refractivity and refractivity gradient which are crucial in describing local radio signal propagation as recommended by the International Telecommunications Union.

Another important factor which determines the effects of the turbulence in the lower troposphere is the gradient of radio refractivity, G. There is a thorough need for studying the profiles of G values within atmospheric boundary layer (ABL) for the better understanding of the processes like super-refraction and ducting phenomenon and their allied impacts on communication links. The term G leads to a way of the bending of propagation direction of the EM wave [15]. If the value of G is negative, the signal bends downward. The EM wave propagation conditions (i.e., refractivity gradient value around $-40\ \mathrm{km}^{-1}$ up to one km above the Earth's surface above mean sea level) are considered to be the most representative one [16]. T, P and H values decrease exponentially as a function of height in a thoroughly mixed atmosphere [17]. For the study of communication link budget scenarios, the refractive index of air is almost frequency independent within EM spectrum lower than 300 GHz. Thus, the factor, radio refractivity or its gradient, can be well suited for application in different radio frequency bands [18]. However, there have been similar studies done elsewhere by some other researchers [11, 19, 20]. The uniqueness of the present study is the effect of variation in the local radio wave propagation conditions in ABL using tethered balloon specifically over New Delhi, India.

The variations in the refractive index structure constant over New Delhi were reported using the meteorological parameters on diurnal and seasonal basis [21]. In our previously published work [13], we have focused on the investigation of vertical variation in morphology, mineralogy and mixing state of atmospheric pollutants in the winter season. In this work, we tried to study the variations in the radio refractivity and refractivity gradient with height within ABL during the winter season over New Delhi, India.

2. Experimental Details

The radiosonde device attached to the tethered balloon was launched on daily basis from February 21 to 27, 2014, over New Delhi (28°38′10″N, 77°10′17″E). The complete details of the campaign have been given in the companion paper [13]. Vaisala RS 80 radiosonde device was used during this experiment. In this radiosonde, the temperature, pressure and humidity sensors were individually factory-calibrated. The resolutions of temperature, pressure and humidity sensors are 0.1 °C, 0.1 hpa and 1% RH, respectively. Every day, the payload comprising the radiosonde was lifted to a given altitude. The observations of meteorological parameters using radiosonde during the ascent of the balloon are termed as "up-leg measurement," while the same during the descent of the balloon is termed as "down-leg measurement." In this work, we used the vertical profiles of meteorological parameters observed during February 23 for the calculation of vertical profiles of radio refractivity, refractivity gradient and modified refractivity. This was the day when the balloon was lifted to the highest altitude [i.e., 700 m agl (above ground level) or 930 masl (mean above sea level)] during the campaign (Fig. 1).

The standard uncertainties associated with the instrument for meteorological parameters are shown in Table 1.

3. Calculation of Radio Refractivity and its Gradient

The radio refractive index (n) value is very close to unity, and the changes in n are relatively smaller during spatiotemporal variations in the atmosphere.

To make those changes more visible, the term of radio refractivity, N [1], was used:

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

where N is dimensionless and depends upon the meteorological parameters such as atmospheric pressure, P (mb), temperature, T (K), and partial water vapor pressure, e (mb) [1]. Following the approach by Bean and Dutton [1], calculation of e (water vapor content in air) was carried out using RH profile.

These parameters are related to N by:

$$N = \frac{77.6P}{T} + 3.73 \times 10^5 \frac{e}{T^2} \tag{2}$$

The radio refractivity gradient G [1] in upper air is calculated as:

$$G = \frac{N_1 - N_2}{h_1 - h_2} \tag{3}$$

where N_1 and N_2 are radio refractivity values at heights h_1 and h_2, respectively.

The G value usually determines the type of refraction that occurs within the ABL. The radio refractivity gradient which is measured in the lower part of ABL is said to be an important parameter for the estimation of propagation effects such as sub-refraction, super-refraction and ducting

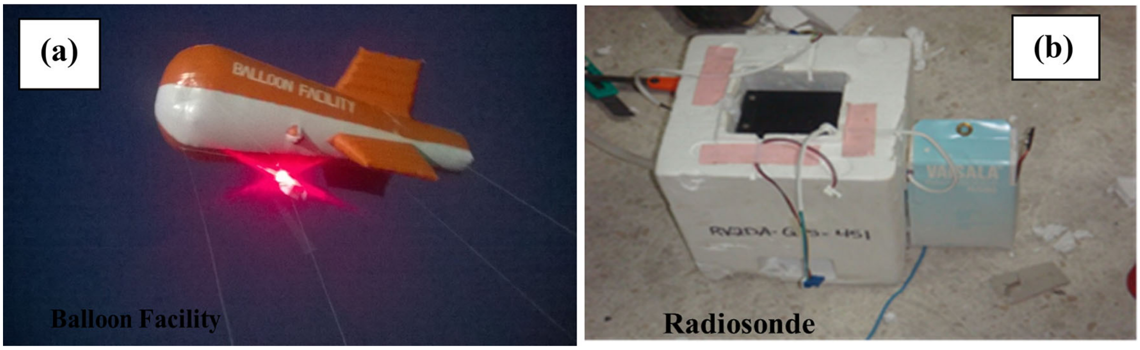

Fig. 1 **a** Tethered balloon facility **b** Vaisala RS 80 radiosonde for the measurement of meteorological parameters (temperature, pressure and humidity)

Table 1 Accuracy of the meteorological sensors in RS80 Vaisala radiosonde

Meteorological parameters	Standard uncertainty (accuracy)
Temperature	0.2 °C up to 50 hpa
	0.3 °C up to 50–150 hpa
Pressure	0.5 hpa
Relative humidity	± 2% RH

phenomenon [20]. More detailed classifications on the types of refraction that are found in the Earth's atmosphere are presented in [22]. It is noted that in most of the cases if N is constant for some height above the ground surface, then the EM wave is observed to be of non-refractive in nature. Generally, the temperature, pressure and relative humidity decrease with height above the ground surface leading to an overall decrease in N with altitude. It is noteworthy to mention here that the meteorological conditions can give rise to channels, or ducts, of cool air which looks like to be sandwiched between the two layers [20, 22].

The other parameter, modified refractivity, *M*, which is also of equal importance clearly indicates ducting conditions: If (a) $dM/dh < 0$, the rays are bent back to the earth, whereas if (b) $dM/dh = 0$, the rays travel parallel to the Earth's surface [23].

Modified refractivity M is given by:

$$M = N + 0.157h \quad (4)$$

where *h* is the height above the Earth's surface in km [23].

4. Results and Discussion

4.1. Vertical Profiles of Radio Refractivity

As mentioned in Sect. 2, "Experimental details," the atmospheric radio sensing was carried out for about a week in the winter season in New Delhi. Radio refractivity plays an important role in the study of radio wave propagation, EM wave propagation and in other communication-oriented phenomena like radar, microwave, etc. Figure 2 shows the radio refractivity profiles for up-leg case [7:00–7:30 PM] (Fig. 2a) and down-leg case [3:30–4:00 AM] (Fig. 2b). The radio refractivity has been observed to be reduced by 8.6% at 930 masl relative to that of ground level, i.e., 230 masl during up-leg observation, while the same has been found to increase by 10.8% at a ground level relative to that of 930 masl during down-leg observation. During this campaign, the temperature inversions have been observed at two different altitudes. Here, it is noteworthy to mention that the conditions for super-refraction and ducting are generally observed when there are inversions present in the ABL.

We observed inversions at two different altitudes: One defines the height of the ABL which is an important factor for the determination of the fate of air pollutants and to understand the transport process in the troposphere, while the second inversion can play an important role in describing the radio wave propagation conditions in the lower layers. The second inversion observed near the ground level could be possibly due to the presence of fog at very low altitudes in the winter season. This inversion has much significance in formulating the proper design of radio wave propagation and link budget.

4.2. Vertical Profiles of Modified Radio Refractivity

Figure 3 shows the modified radio refractivity, M, profiles for up-leg case (Fig. 3a) and down-leg case (Fig. 3b).

The ducting phenomena can be properly understood by calculating M which is a function of N as explained earlier. This parameter tells how much EM/radio wave bends by the curvature of the Earth or how much the refraction has been observed or how much the absorption phenomenon has taken place [24]. In Fig. 3, we find the minute changes in modified refractivity profile. The changes in the

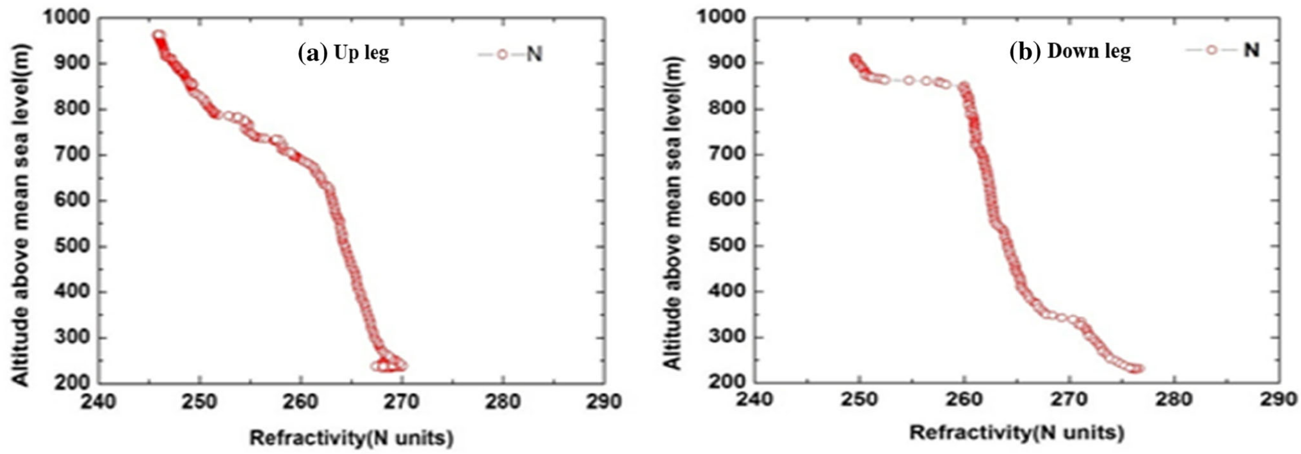

Fig. 2 Radio refractivity profiles for **a** up-leg case and **b** down-leg case

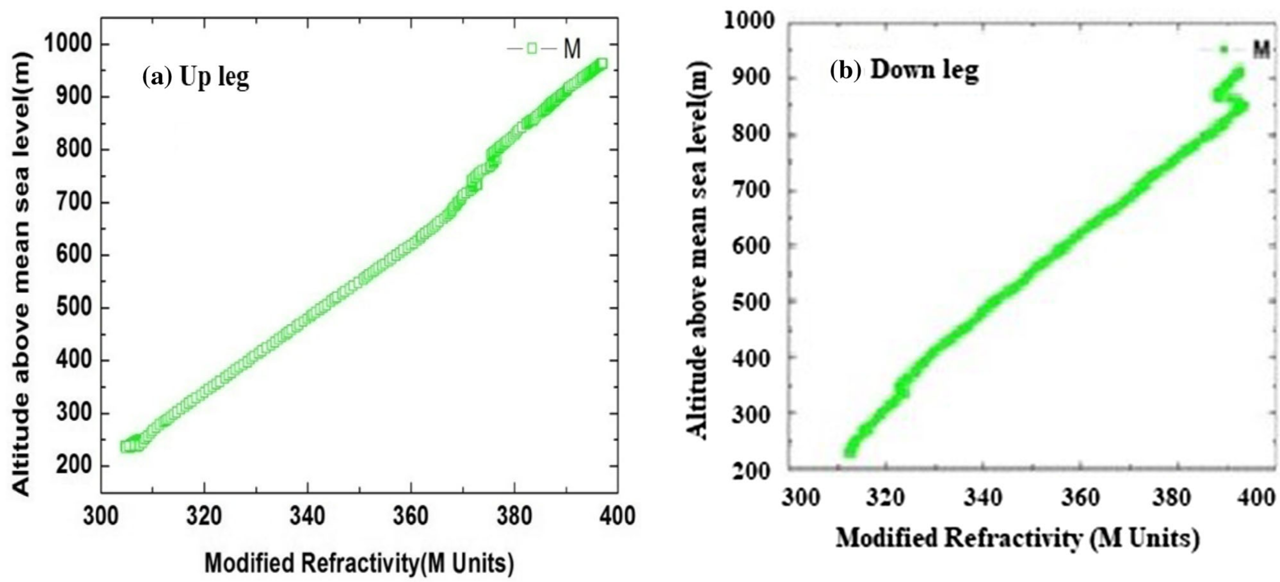

Fig. 3 Modified refractivity profiles for **a** up-leg case and **b** down-leg case

numerical values of M have been clearly observed in down-leg case (3:30–4:00 AM) compared to those of up-leg case (7:00–7:30 PM) due to the relatively strong inversion during down-leg. At lower level, the inversion is quite pronounced during down-leg compared to that of up-leg due to the occurrence of dominant fog in morning hours. Among all the cases (up-leg and down-leg), M was found to be maximum (i.e., 397 M units) during up-leg. The linear profile of M is perturbed due to inversions in the ABL. M also plays a vital role in designing radio wave communication, radar and microwave communication.

Table 2 describes the maximum values of refractivity and modified refractivity measured using different techniques over the world. These are results from the compilation of the present study data and previous ones [25–28]. Obtaining these values is of much importance as the maximum value of radio refractivity is always desired for designing the radio link budget. These values differ for different regions under different meteorological conditions.

4.3. Vertical Profiles of Radio Refractivity Gradient

Figure 4 shows the radio refractivity gradient profiles for up-leg case (Fig. 4a) and down-leg case (Fig. 4b).

The radio refractivity gradient, G, is considered to be an important parameter for the clear understanding of the effects of meteorological parameters on communication links. In Fig. 4, the conditions for positive increased refraction (super-refraction) have been observed in the layer starting from 100 m (330 masl) up to 500 m

Table 2 Maximum values of refractivity (*N*) and modified refractivity (*M*) in the present study and previous studies

Radio propagation parameters studies	Sampling sites	Maximum refractivity (*N*)	Maximum modified refractivity (*M*)
Louf et al. [25]; radar based	Niamey, Niger	380	NA
Ukhurebor and Azi [27]; portable weather monitoring station	Auchi, Edo, Nigeria	354	NA
Manjula et al. [26]; satellite based	Gadanki, India	352	414
Sarma [30]; aircraft based	Kanpur, India	268	NA
Kulshrestha and Srivastav [28]; radiosonde based	New Delhi, India	312	370
Johny et al. [31]; GPS occultation and radiosonde based	New Delhi, India	350	NA
[a]Ahlawat et al. present study	New Delhi, India	276	397

[a]The observation of radio parameters using tethered balloon experiment over New Delhi

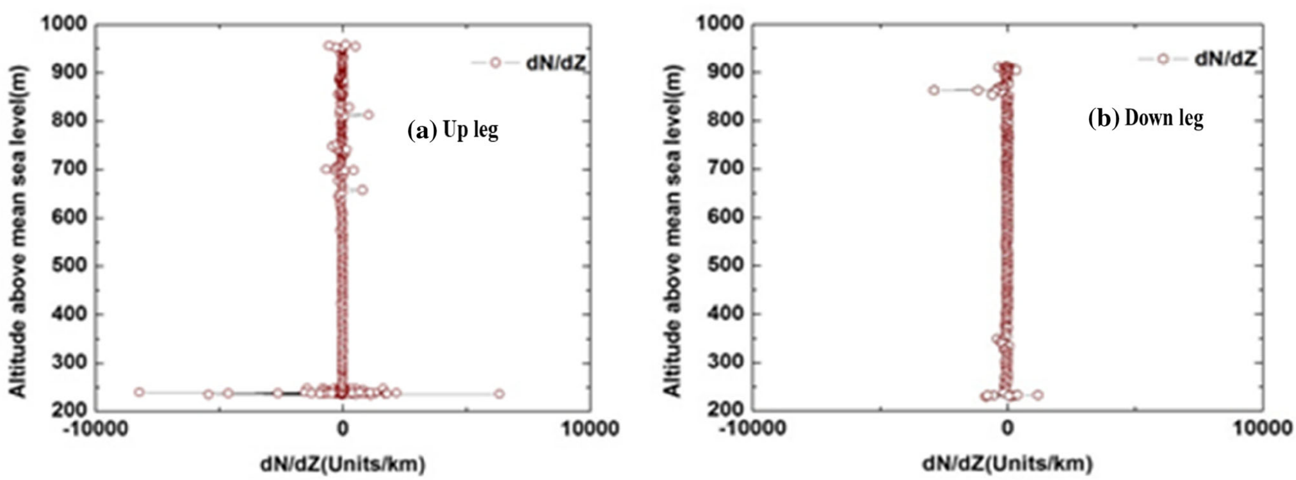

Fig. 4 Radio refractivity gradient profiles for **a** up-leg case and **b** down-leg case

(730 masl). The conditions for radio wave ducting have also been observed in the layer starting from 100 m (330 masl) to 200 m (430 masl). The conditions for radio wave surface duct have been found to be most prominent in the lowest layer of the troposphere, i.e., ground to 100 m (330 masl). Here, we find that the lowest layer of the troposphere (i.e., ground to 100 m) is playing a very critical role in governing EM propagation over the study site.

Based on the previous studies, there are three different classifications of the radio refraction, i.e., normal refraction (whenever $G = -40$ *N* units/km), super-refraction (whenever $-41 > G > -156.9$ *N* units/km) and ducting (whenever $G = -157$ *N* units/km) [29], whereas the sub-refraction criterion is presented in [20], i.e., $G > -40$ *N* units/km. The conditions of super-refraction occur when the propagating radio wave trajectory further bends toward the ground surface than that of the normal case. It is important to note here that the term ducting is also named as exceptional super-refraction, which is very much crucial for the communication purposes [19]. Apart from this, when we consider the case of positive critical refraction, then the trajectory of radio wave is found to be parallel to the ground surface.

5. Conclusion

In the present experiment, the vertical profiles of radio refractivity and associated parameters in the ABL have been studied. More scientific insights were explored for the parameters which can affect the broadcast signal strength within ABL. The information on refractivity profile over a region is very important for predicting the performance of radio link over a region. In New Delhi, the variations in radio refractivity in the winter season are majorly influenced by changes in air moisture and temperature. The radio refractivity and its vertical gradient have been found to be strongly affected in the cases of strong temperature inversions. The conditions for positive increased refraction (super-refraction) have been observed in the layer from 100 m (330 masl) to 500 m (730 masl). The conditions of positive increased refraction emerged for the layer spanning from the ground to 200 m (430 masl). Surface ducts have been found to be most prominent from ground level to 100 m (330 masl). It is noteworthy to mention here that the EM wave propagation faces super-refraction and ducting conditions during early morning hours over the study site. This type of observations will be of great importance for the communication link designers, where they know exactly about the atmospheric factors which strongly influence their system's performance. However, more such experimental observations are required to have statistically significant information of the studied radio parameters.

The statistically significant region-specific information of the radio parameters could be very important to ascertain the link budget over the region.

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