Analysis of Tropospheric Radio RefractivityoverJuliusNyerere International Airport, Dar es Salaam

Philbert M. Luhunga[1, 4, *], Edmund Mutayoba[2], Hazla Masoud[3], Ladislaus Chang'a[1], Aleksandar D. Prodanov[5]

[1]Tanzania Meteorological Agency, Research Section, P.O. BOX 3056, Dar es Salaam
[2]Mbeya University of Science and Technology, department of civil engineering
[3]Tanzania Meteorological Agency, International affairs Section, P.O. BOX 3056, Dar es Salaam
[4]University of Pretoria, Faculty of Natural and Agricultural Sciences, Department of Geography, Geoinformatics and Meteorology
[5]Hydrometeorological Service, street Skupi 28, Republic of Macedonia

Email address

philuhunga@yahoo.com (P. M. Luhunga),edmundmutayoba@yahoo.com (E.Mutayoba), aprodanov@meteo.gov.mk (D. Prodanov), changa60@hotmail.com(L. Chang'a), hazlaa@gmail.com (H. Masoud)

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Abstract

The characteristics of radio refractive index in the troposphere as they relate to meteorological parameters-is of fundamental importance in planning and advancing the understanding of radio wave propagation and wireless communication systems within the troposphere. The vertical profiles of radio refractivity gradient (G) within 1km above the earth's surface are important for the estimation of anomalous propagation (AP) of microwave radiation. Furthermore the effect of AP in weather radar measurements may be important as spurious echoes from distant ground targets may appear as precipitation leading to incorrect rainfall estimations. AP may also affect dramatically the quality of clear air radar observations. In this paper,we present the vertical and temporal variations of refractive index represented by refractivity (N-units) and refractivity gradient (G) (N-units km^{-1}) in the troposphere to evaluate the occurrence of AP over Julius Nyerere International Airport (JNIA), Dar es Salaam, Tanzania. Meteorological data of air temperature, relative humidity, and atmospheric pressure collected from radiosonde station at JNIA during January, February, August, 2012 and September, October, and November, 2013, were used to compute refractivity, refractive index and refractivity gradient. The percentage of occurrences of super-refraction, sub-refraction, normal-refraction and ducting conditions are presented. Results reveal that, the tropospheric radio wave propagation conditions over JNIA have varying degree of occurrence with normal-refraction conditions prevalent at all the levels except in February, 2012. During this month, super-refraction and normal-refraction conditions have prevailed at the altitude of 1km. The presented results in this paper indicate how the variation in meteorological parameters such as humidity and temperature in the lower troposphere can cause AP. These results can be used by air traffic controllers at:

Tanzania Civil Aviation Authority (TCAA) surveillance radar, which is located at JNIA and TMA weather radar, which is located 10km from JNIA, to improve performance of their radars to detect and eliminate false echoes from AP of the radar beam.

1. Introduction

The radio refractive index is defined as a ratio of the radio wave propagation velocity in the free space to its velocity in a specific medium (Tamosiunaite, et al., 2011). This parameter is very important in many applications. For example radio refractive index that occurs in the lower atmosphere significantly influences the performance of wireless communication systems (Valtr and Pechac, 2005). The vertical distribution of radio refractive index strongly influences the reliability, strength, direction and time of propagation of satellite and astronomical radio signals (Geodesy and Astronomy). One of the primary steps in the radio link system design is to estimate the atmospheric refractive index (Zilinskas, et al., 2012). In addition, the vertical distribution profiles of refractive index and ducts formed by the decrease in humidity with height, and increase in temperature with height or a combination of both can be used as a measure of atmospheric turbulence which have application in Numerical Weather Prediction (NWP) modelling and analysis of geodetic data (Tatarski,

1961). The variation of values of refractive index determines the propagation of radio, and radar-waves in the troposphere (Freeman, 2007, Aediji and Ajewole, 2008). On the other hand the variation of refractive index as the results of turbulent eddies can distort electromagnetic wave fronts (Roddier, 1981). The variation of refractive index along the trajectory of the radar beam can cause the radar beam to move along a path other than the line of sight path which results in Anomalous Propagation (AP) (sub-refractivity, super-refractivity and ducting) phenomena of the radar's beam. The anomalous propagation could cause problems for radars, because a variation of the refractive index can induce loss of radar coverage.

The detection of AP is very important in weather radar applications as spurious echoes from distant ground targets may appear as precipitation leading to incorrect rainfall estimations (Bech et al., 1998). Echoes as a result of AP can mislead the quantitative precipitation estimation as may not be filtered completely, even with modern Doppler radars, and are difficult to discriminate from real rainfall echoes when they appear simultaneously. Bech et al., (1998) indicated that AP may also affect dramatically the quality of clear air radar observations. The study by Tang et al., (2010) pointed out that a challenge for the quality control (QC) of AP echoes exists because the intensity and texture of AP returns are similar to those of strong and isolated convective cells.

Figure 1. Tanzania Civil Aviation Authority (TCAA) surveillance radar at JNIA

Figure 2. *TMA weather radar located at Bagule, 10 km from JNIA*
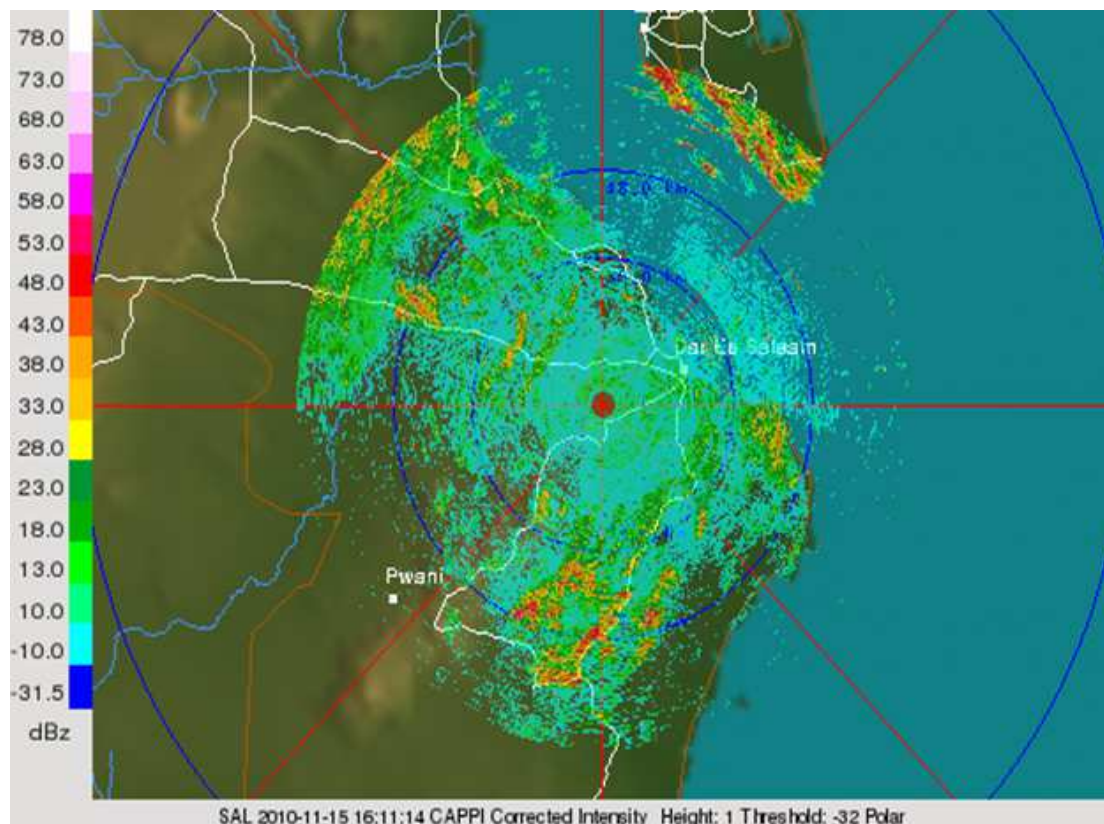

Figure 3. *The plane position indicator for Tanzania Meteorological Agency weather radar*

Figure 1 indicates the air surveillance radar used by TCAA. The radar is located at JNIA. Figure 2 indicates the TMA weather radar located 10 km from JNIA.

Figure 3 above indicates plane-position indicator of TMA weather radar, which is an S-band Doppler radar, located 10km form Julius Nyerere International Airport (JNIA). These types of radar are also affected by AP as detailed explained by Bech et al., (2003). The above figure shows both ground and sea clutter that forms when the radar beam encounter a backscattered signal from the ground targets and sea surface. The clutter appears in red (higher return) and can mislead the interpretation of thunderstorm cells because they are like isolated thunderstorm cells.

The aim of this study is to evaluate the occurrence of AP over Julius Nyerere International Airport (JNIA) and improves the working knowledge of extreme orographic blockage cases on the air surveillance radar used by TCAA located at JNIA and the Tanzania Meteorological Agency (TMA) weather radar located at Bagule, Pugu10km from JNIA.

2. Data and Methodology

2.1. Data

In this study, radiosonde observations are used to evaluate the conditions for weather radar beam propagation, especially the radar anomalous propagation (anaprop) conditions and their potential effects on the air surveillance radar used by TCAA located at JNIA and TMA weather radar network located in Pugu Hill, Dar es Salaam.

Pressure, temperature and relative humidity profiles collected from GPsondes, specified as M2K2- DC radiosonde station over JNIA(41.38 ° N, 2.12 ° E, and 94 m ASL) during 2012-2013 were used to calculate the refractivity and refractive index of the troposphere. The vertical resolution of standard radiosonde observations launched daily worldwide is given by the so-called standard levels, mandatory significant levels and additional levels, following World Meteorological Organization (WMO) regulations. Standard pressure levels are 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20 and 10 hPa. Significant levels relevant for this study (restricted to heights up to 4000 m) include the surface level and any level with certain strong gradients of temperature.

2.2. Methodology

The atmospheric radio refractive index, n, can be computed by the following formula:

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

, where:

N: radio refractivity expressed in terms of air temperature, atmospheric pressure, and water vapour pressure (Bean and Dutton, 1966; Valma et al., 2010) as

follows:

$$N = N_{dry} + N_{wet} = 77.6\frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2} \quad (2)$$

Where P is atmospheric pressure in hectopascal (hPa), e is water vapour pressure in (hPa) and T is absolute temperature in kelvin (K). According to ITU-R P.835 recommendations, the above expression may be used for all radio frequencies; for frequencies up to 100 GHz, the error is less than 0.5%.

The relationships between water vapour pressure e and relative humidity is given by:

$$e = \frac{RH \times e_s}{100} \qquad (3)$$

, where RH is the relative humidity, and e_s, is the saturated vapour pressure

The saturated vapour pressure is obtained using Clausius, (1850)-Clapeyron, (1834) equation:

$$e_s = 6.11 \times \exp\left(2.453 \times \frac{10^6}{461} \times \left(\frac{1}{273} - \frac{1}{T}\right)\right) \quad (4)$$

, where T is the absolute temperature (K).

When characterizing the radio propagation of the environment, it is usual to consider the vertical refractivity gradient G, of the air in the few kilometres above ground level which can be expressed as:

$$G = \frac{N_1 - N_2}{h_1 - h_2} \qquad (5)$$

, where N1 and N2 are the values of radio refractivity at heights h1 and h2 respectively

According to Bech et al. (2001) the gradients of refractivity are classified according to the following criteria:

Normal refraction occurs when $-79 \leq \frac{\partial N}{\partial Z} < 0\ N - units/km$

Sub-refraction occurs when $\frac{\partial N}{\partial Z} \geq 0\ N - units/km$, in this case refractivity increases with height and in this case (sub-refraction), the radio waves moves away from the earth's surface and the line of sight range and the range of propagation decrease accordingly.

Super-refraction occurs when $-157 \leq \frac{\partial N}{\partial Z} < -79\ N - units/km$, in this case refractivity decreases with height and the radio waves are bent downward to the earth. The degree of bend depends on the strength of super refraction condition. Since the radius of the ray path is smaller than earth's curvature, the rays leaving the transmitting aerial at small angles of elevation will undergo total internal reflection in the troposphere and it will return to the earth at some distance from the transmitter. On reaching the earth's surface and being reflected from it, the waves can skip large distances, thereby giving abnormally large ranges beyond the line of sight due to multiple reflections.

Ducting occurs when $\frac{\partial N}{\partial Z} \leq -157\ N - units/km$

During ducting phenomenon, the waves bend downwards with a curvature greater than that of the earth.

Radio energy bent downwards can become trapped between a boundary or layer in the troposphere and the surface of the earth or the sea (surface duct) or between two boundaries in the troposphere (elevated duct). In this wave guide-like propagation, very high signal strengths can be obtained at very long range (far beyond line-of-sight) and the signal strength may exceed its free-space value. In the case of positive critical refraction, the trajectory of a radio wave is parallel to the ground surface

3. Results and Discussion

The theory discussed in the previous section, allow the presentation of the following results: (1) dependence of air temperature and water vapour pressure at the height above the earth's surface, (2) dependence of refractivity and its vertical gradient on the height above the earth's surface and (3) the conditions for propagation of radar waves at1 to 4km in the troposphere over Julius Nyerere International Airport (JNIA).

Figure 4-6 illustrates the dependence of water vapour

pressure and air temperature in the troposphere in September, October, and November, 2013. It is found that the air temperature and vapour pressure are higher close to the ground and decrease with vertical height in the troposphere. Under normal condition, temperature and water vapour pressure tend to decrease steadily with height in the troposphere. However, in the presented results figure 4-6, there are small variations of air temperature and water vapour pressure at different levels. For example, in figure 4 there are constant values of air temperature at 1.5-2km. On the other hand, there is a sharp decrease of water vapour pressure at 0.05km- 0.1km and 2.5-3.15km, 5.8-6.7km. These small changes can affect the tropospheric refractivity and hence affect radar wave propagation. The radar wave can be refracted over the whole of the signal path and this may extend for many kilometers. Figure 5 depicts sharp decrease of water vapour pressure below 0.1km, 4-5km and at 5.8-6.7 km. This observation also suggests that the small variation in vapour pressure will affect the refractivity of the troposphere in the particular month period and hence affect the propagation of radar waves.
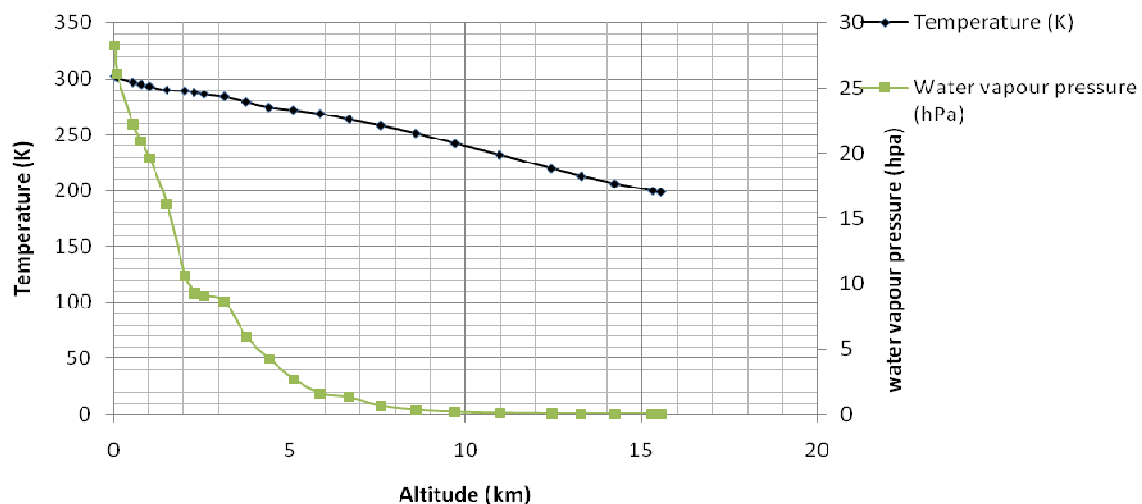

Figure 4. The dependence of average values of air temperature and water vapour pressure on the height above the earth-surface in September, 2013
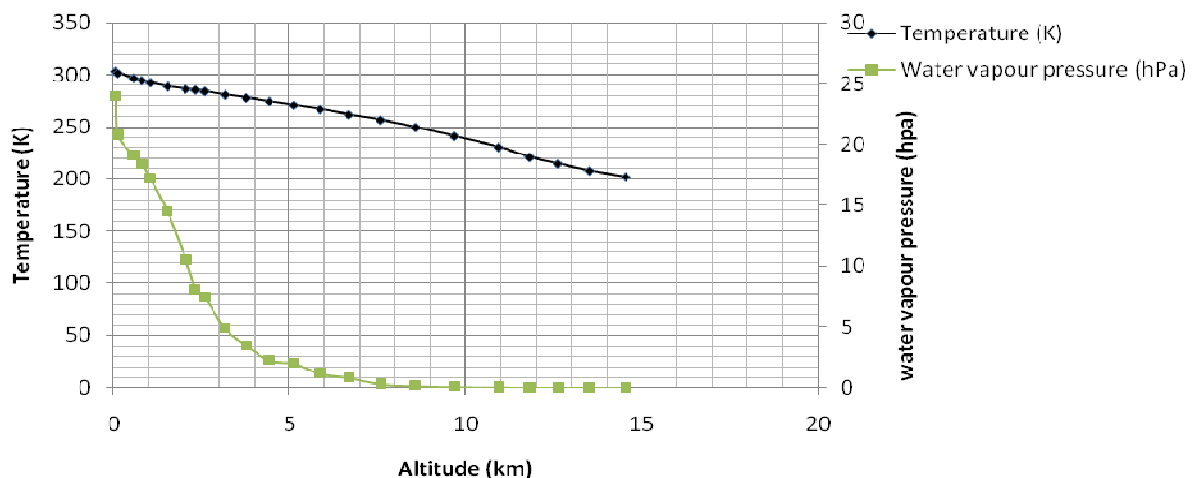

Figure 5. The dependence of average values of air temperature and water vapour pressure on the height above the earth-surface in October 2013
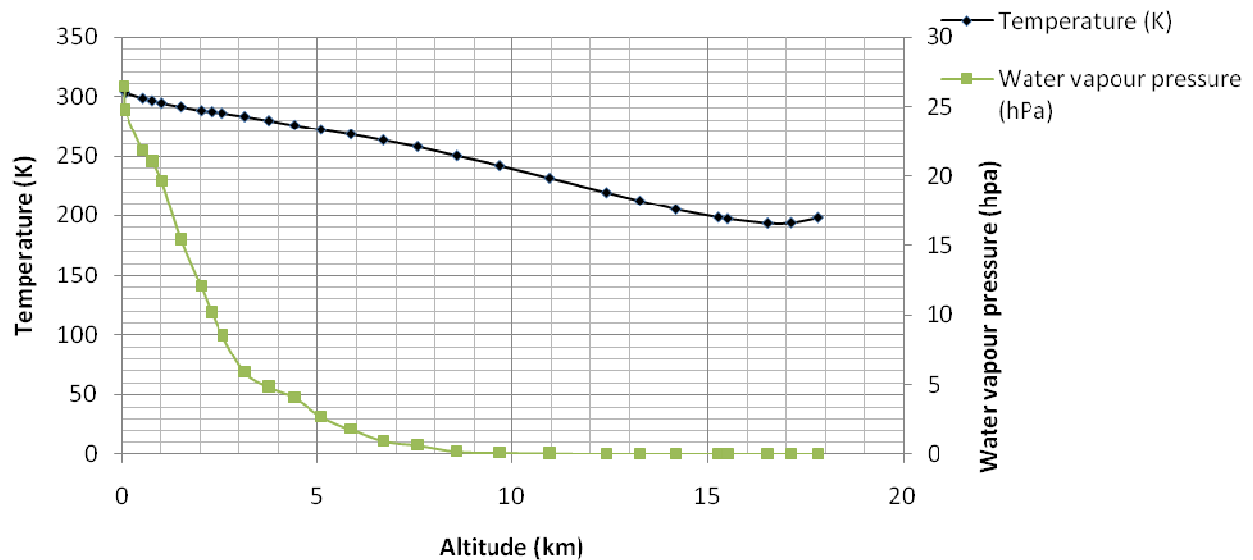
Figure 6. *The dependence of average values of air temperature and water vapour pressure on the height above the earth-surface in November 2013*

Shown in Figure7-9 are the dependence of refractivity and the gradient of refractivity on the height above the earth's surface in September, October and November, 2013. Figure 7-9 disclose that the refractivity (N) decrease while the gradient of refractivity increase with height in the troposphere. The decrease of refractivity with vertical height is not smooth, but there are small variations. This variation can influence the anomalous propagation of the radar wave in the troposphere for the particular month period. Figure 7 indicates the average values of both refractivity and its gradient in September 2013. It is clear from figure7 that the conditions of Anomalous Propagation of radar waves exist in September at lower level of the troposphere. For example, at 0.055km the gradient of refractivity is -172.92N/km which is the condition for ducting phenomenon. Also the conditions for super refraction of the radar waves exist below 0.1052km where the gradient of refractivity is in the range of -159 to -80N/km.

Figure 8 indicate the sharp increase of refractivity from 0.11km to 0.5km. This might have influenced by the variation of water vapour pressure and temperature (Fig. 5).It is evident from this figure that at lower level the Anomalous Propagation dominates at the particular month period. The dominant AP conditions are the super refraction, and ducting phenomena.
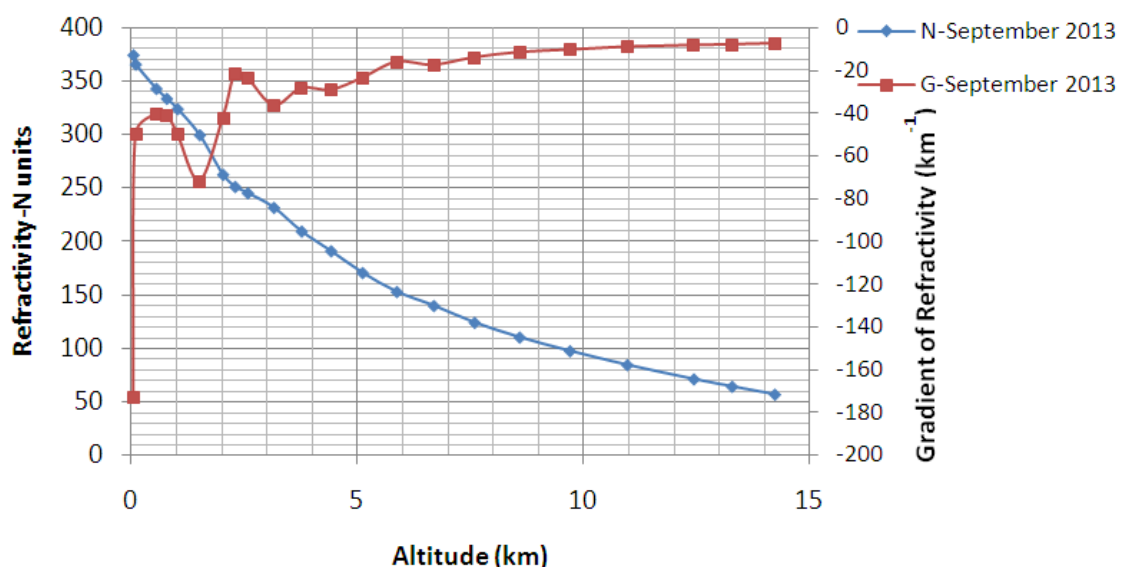

Figure 7. *The dependence of refractivity (N) and its vertical gradient (G) on the height above the earth's surface in September 2013*
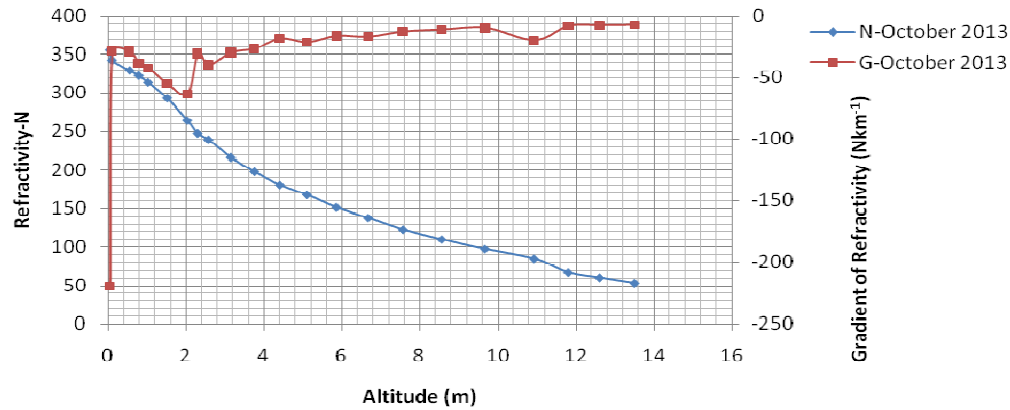
Figure 8. The dependence of refractivity (N) and its vertical gradient (G) on the height above the earth's surface in October 2013
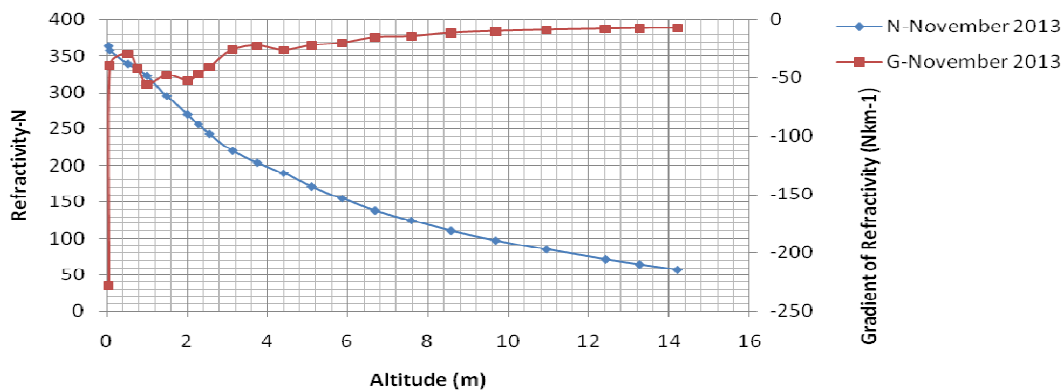

Figure 9. The dependence of refractivity (N) and its vertical gradient (G) on the height above the earth's surface in November 2013

Figure 10-15 show the monthly statistics of the occurrence of propagation conditions: Normal-refraction, sub-refraction, super-refraction and ducting over JNIA deduced fromgradients of refractivity calculated from equation 5 using datasets collected in January, February, August, 2012 and September, October, and November, 2013. The statistics show that the propagation conditions have varying degree of occurrence with normal-refraction conditions prevalent at all the levels except in February, 2012 where super-refraction and normal-refraction conditions have prevailed at the altitude of 1km (Figure 12).

Figure 10 indicates that normal-refraction conditions prevalent by 67-90% at all levels in August 2012. 90%, 77%, 75% and 67%of normal refraction conditions are prevalent at 4km, 1km, 3km and 2km respectively (Figure 10). 10% of sub-refraction conditions are observed at 4 km, and23% of Anomalous propagation conditions (12.3% for sub-refraction conditions, 5.4% for super-refraction conditions and 5.3% for ducting conditions) are observed at 1km. 25% of the Anomalous propagation conditions (14% for super-refraction, 7% for ducting and 4% for sub-refraction) are observed at 3km and 33% of Anomalous propagation conditions (14% for ducting conditions, 12% for super-refraction and 7% for sub-refraction) are observed at 2km.

Figure 11 depicts that normal-refraction conditions prevalent by 62-86% at all levels in January, 2012. 86%, 82%, 73% and 62% of normal refraction conditions are prevalent at 3km, 4km, 2km and 1km respectively (Figure 11). 14% of the anomalous propagation conditions (9% for sub-refraction and 5% for super refraction) are observed at 3km and 18% of anomalous propagation conditions (12% for sub-refraction, and 6% for super refraction) are observed at 4km.27% of Anomalous propagation conditions (12% for sub-refraction conditions, 12% for super-refraction conditions and 3% for ducting conditions) are observed at 2km and 38% of the Anomalous propagation conditions (18% for ducting conditions,16% for super-refraction and 4% for sub-refraction) are observed at 1km

Figure 12 depicts that normal-refraction conditions prevalent by 31-100% at all levels in February, 2012. 100% of normal refraction conditions is observed at 3 and 4km. 50% and 31% of normal refraction conditions are prevalent at 2km and 1km respectively (Figure 12). 50% of the anomalous propagation conditions (25% for sub-refraction and 25% for super refraction) are observed at 2km and 69% of anomalous propagation conditions (31% for super-refraction, 23% of ducting conditions and 15% for sub-refraction) are observed at 1km. These results suggest that radar waves are more affected by AP at 1km.

Figure 13 depicts that normal-refraction conditions

prevalent by 67-100% at all levels in November, 2013. 100%, 91%, 82% and 67% of the normal propagation condition are prevalent at 4km, 3km 1km and 2km respectively. 9% of the sub-refraction conditions are observed at 3km and 18% of anomalous propagation conditions (15% for ducting conditions, 3% for super-refraction conditions) are observed at 1km and 33% of anomalous propagation conditions (27% for super-refraction conditions, 6% for sub-refraction conditions). These results suggest that radar waves are more affected by AP at 2km.

Figure 14 indicates that normal-refraction conditions prevalent by 73-93% at all levels in October, 2013. 93%, 91%, 80% and 73% of the normal propagation conditions are prevalent at 3km, 4km, 1km and 2km respectively (Figure 14). 7% of the sub-refraction conditions are

observed at 3km and 9% of the sub-refraction conditions are observed at 4km. 20% of the anomalous propagation conditions (13% for ducting conditions and 7% for super-refraction) are observed at 1km and 27% of anomalous propagation conditions (25% for super-refraction, and 2% for ducting) are observed at 2km.

Figure 15 indicates that normal-refraction conditions prevalent by 70-100% at all levels in September, 2013. 100%, 90%, 80% and 70% of the normal propagation conditions are prevalent at 4km, 3km, 2km and 1km respectively (Figure 15). 10% of the sub-refraction conditions are observed at 3km and 20% of the anomalous conditions (13% for super refraction, and 7% for sub-refraction) are observed at 2km. 30% of the anomalous propagation conditions (17% for ducting conditions and 13% for super-refraction) are observed at 1km
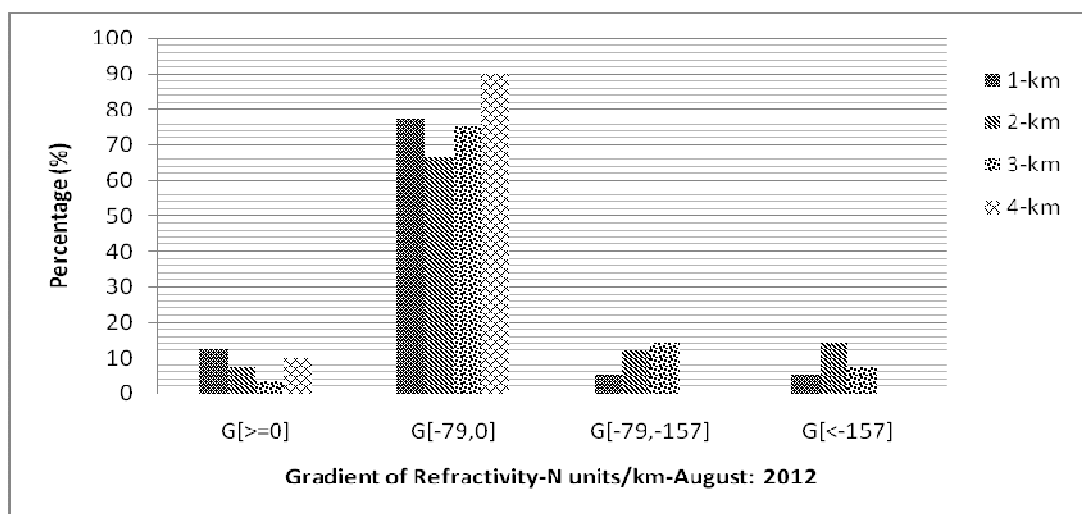

Figure 10. *Average variation of gradient of refractivity over JNIA for August: 2012*
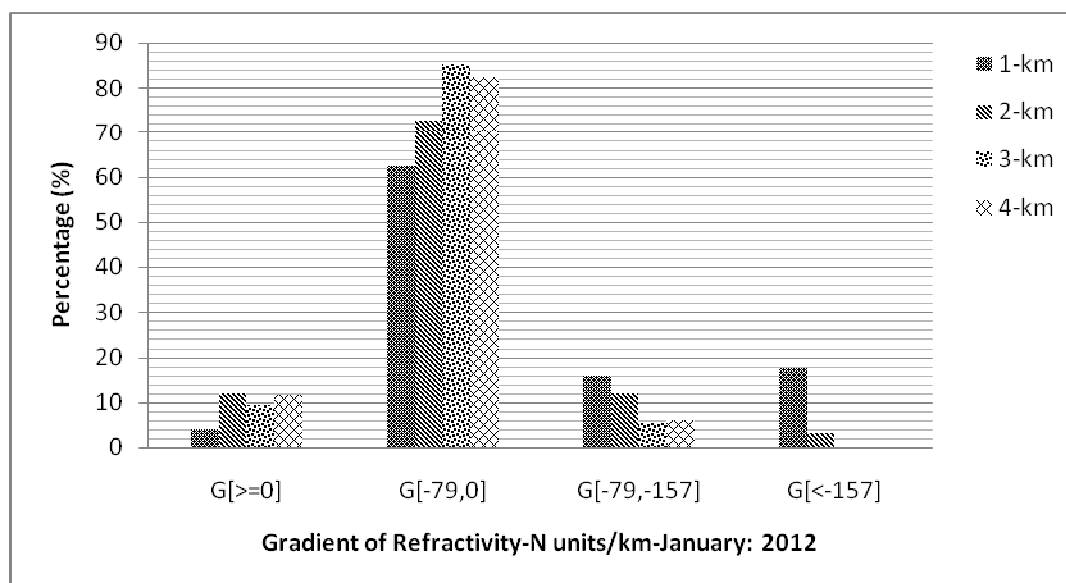

Figure 11. *Average variation of gradient of refractivity over JNIA for January: 2012*
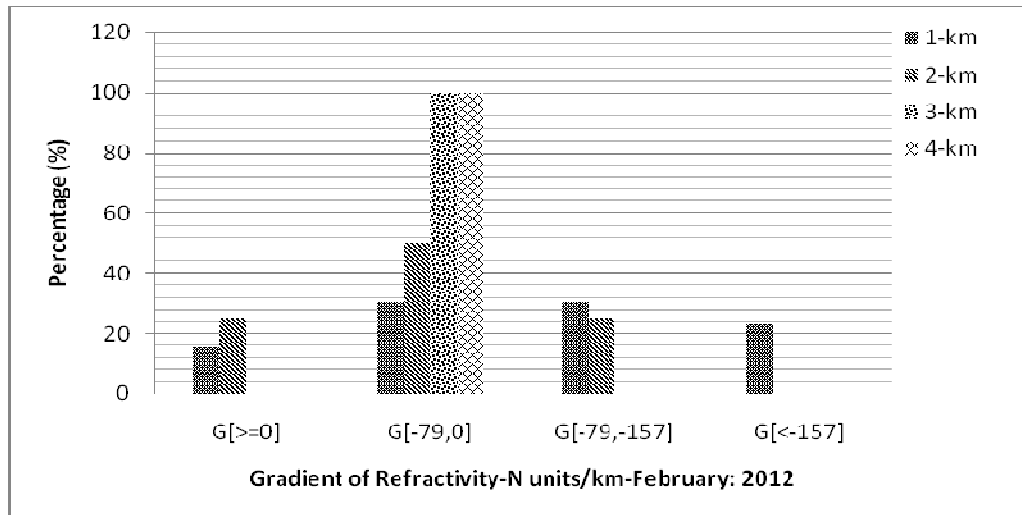
Figure 12. Average variation of gradient of refractivity over JNIA for February: 2012
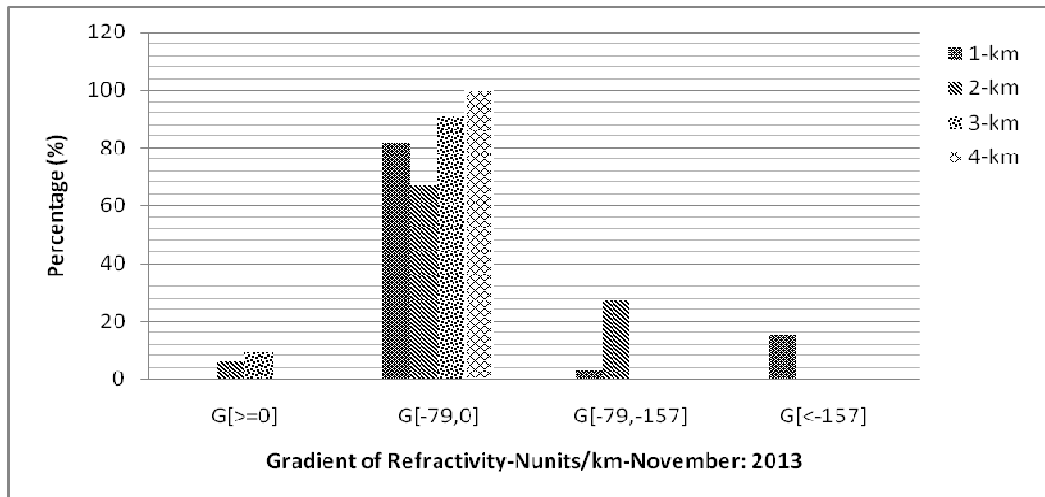

Figure 13. Average variation of gradient of refractivity over JNIA for November: 2013
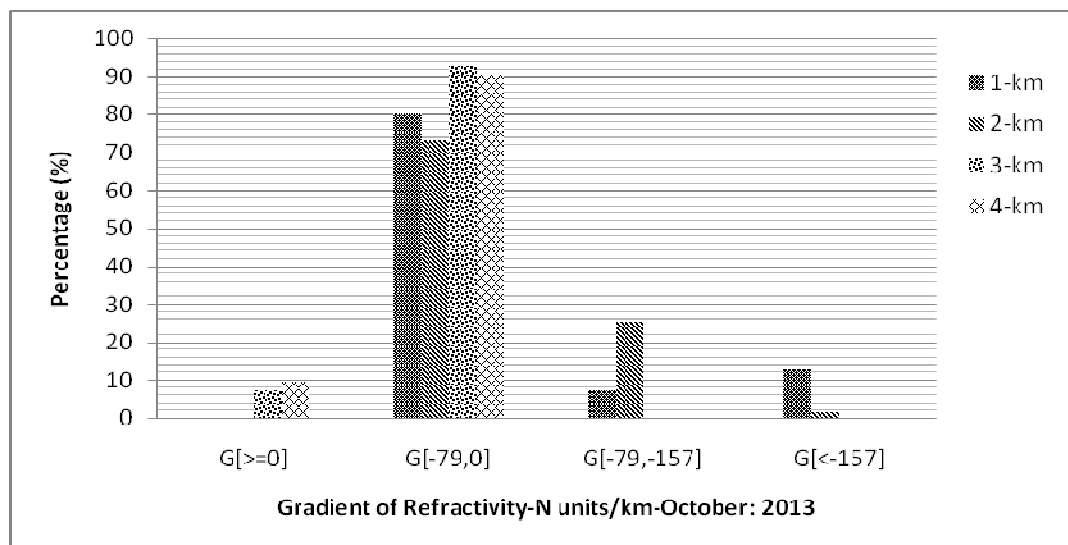

Figure 14. Average variation of gradient of refractivity over JNIA for October:2013
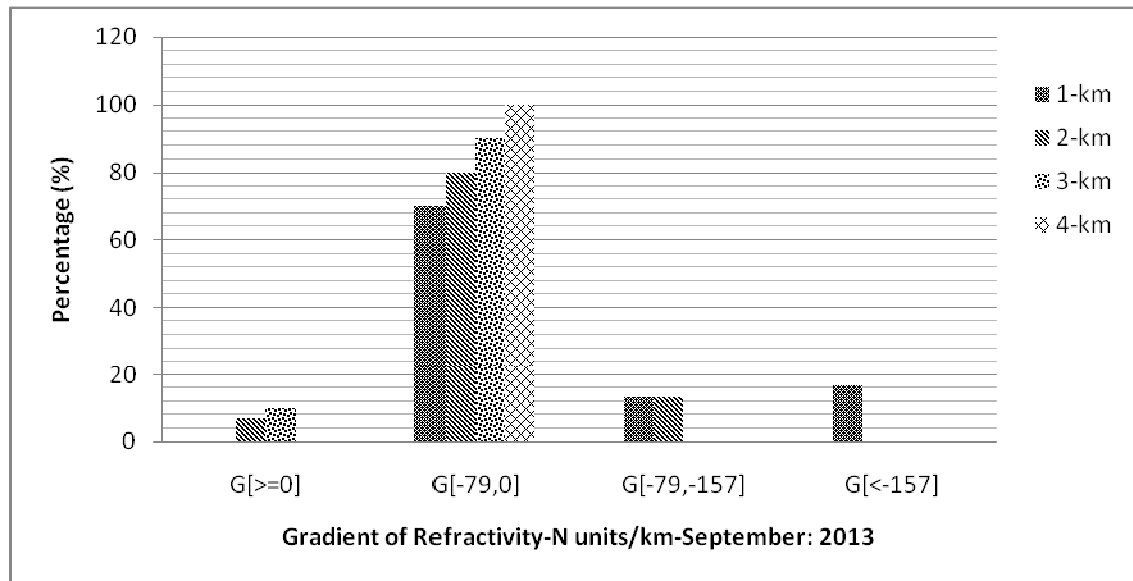
Figure 15. Average variation of gradient of refractivity over JNIA for September: 2013

4.Conclusion

Anticipating the occurrence of Anomalous Propagation (AP) may be an advantage for monitoring purposes of radar quality control or to obtain a deeper understanding of processes related to anomalous propagation.This study evaluated the dependence of air temperature and water vapour pressure on the height above the earth-surface, and the dependence of refractivity and its gradient on the height above the earth-surface over JNIA. Also the study evaluated the propagation conditions of radar waves in the troposphere over JNIA. Results indicate the following:

(1) The air temperature and vapour pressure are higher close to the ground and decrease unsteadily with vertical height over JNIA.

(2) The refractivity (N) decreases with vertical height unsteadily, this variation could influence the occurance of anomalous propagation of the radar wave in the troposphere for the particular month period. In all months evaluated in this study, there are smaller values of the gradient of refractivity than the value, which was recommended by ITU-R for standard atmosphere especially in lower levels.

(3) The conditions of Anomalous Propagation of radar waves exist in September at the lower level of the troposphere. For example, at 0.055km the gradient of refractivity is -172.92N/km which is the condition for ducting phenomenon. Also the conditions for super refraction of the radar waves exist below 0.1052km where the gradient of refractivity is in the range of -159 to -80N/km.

(4) Monthly statistics of the occurrence of propagation conditions deduced from gradients of refractivity shows that, the propagation conditions have varying degree of occurrence with normal-refraction conditions prevalent at all the levels except in February, 2012 where super-refraction and normal-refraction conditions have prevalent at the altitude of 1km

The above findings suggest that there is a possibility that both TCCA air surveillance radar located at JNIA and TMA weather radar which is located 10km from JNIA to be contaminated with the anomalous propagation especially in the lower levels below 0.11lkm. Otherwise the dominant propagation condition is a normal refraction condition.

Acknowledgment

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