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Statistical Analysis of Refractivity Gradient And β_0 Parameter In The Gulf Region

Abdulhadi AbouAlmal, Raed A. Abd-Alhameed, Kifah Al-Ansari, Hussein AlAhmad, James M Noras, Chan H See and Steve MR Jones

Abstract — **In this paper, nine years of local radiosonde meteorological data, from 1997 to 2005, have been used to calculate the vertical refractivity gradient, ΔN, in the lowest atmospheric layer above the ground surface. The values obtained are used to estimate the parameter β_0, which represents the probability of non-standard propagation. Hourly, monthly and yearly distributions of ΔN in the first 100 meters above the ground are given. Monthly and yearly variations of the mean of ΔN and β_0 are provided and the β_0 values are compared with the ITU maps.**

Index Terms – **Atmospheric refraction, Refractivity gradient, Anomalous propagation, β_0.**

I. INTRODUCTION

Electromagnetic waves propagating through the lower layers of the atmosphere follow curved paths as a result of the variation of refractive index with height. The refractive index of air is dependent on temperature, pressure and humidity and thus varies with height. As a reference point, the ITU has defined a negative exponential "standard atmosphere" and published maps showing variations in refractive index at the Earth's surface [1]. The gradient of refractive index in N-units versus height (in km) at the surface is known as the surface lapse rate ΔN. ITU maps [1] also provide ΔN data at specified altitudes. Anomalous propagation may occur due to nonstandard variation of vertical refractivity through different atmospheric layers. Several studies related to the refractivity analysis are available [2-7]. Only a few studies are available for the Gulf region although it is likely to experience abnormal conditions due to its special climate which is hot and humid, most of the year. Initial results of the statistical analysis of surface refractivity, ΔN in the first kilometer, *k*-factor and point refractivity gradient in United Arab Emirates (UAE) have been discussed previously in [8, 9]. The UAE is situated on the northeastern part of the Gulf, along the tropic of Cancer. Abu Dhabi, capital of UAE, is a coastal city located at 24.52º N latitude and 54.98º E longitude, with an altitude of 27 m above sea level. Its climate is subtropical and arid due to its location within the Northern desert belt, which is warm and sunny throughout the year. From May to September, the temperature and humidity are high with an average temperature above 40 °C and sandstorms occur intermittently. Winter can be windy with brief and irregular rainfall.

Long-term radiosonde data recorded with good resolution from two daily ascents, nominally at 00:00 and 12:00 UT, have been used for the analysis corresponding to 4:00 am and 4:00 pm local time. A radiosonde is an airborne weather station coupled with a radio transmitter which makes measurements of temperature, air pressure, humidity, and wind speed and direction, and transmits the measurements back to the ground. A Vaisala RS92 Radiosonde, which offers high level performance of meteorological measurements and GPS capabilities with a reliable telemetry link, has been used for gathering the meteorological data.

This study was conducted to investigate ΔN in the lowest part of the atmosphere, and to derive β_0 values for Abu Dhabi. The β_0 statistics are derived from the cumulative distributions of the vertical ΔN. Hourly, seasonally and yearly distributions of ΔN and β_0 variations are presented. The results obtained are compared with the β_0 values derived from ITU maps [1, 10], which are provided for different geographical locations where reliable local data are not available.

A. Refractivity Gradient in the Lowest Atmospheric Layer

ΔN statistics of the first 100 m from the surface may be used to estimate the occurrence probability of ducting and multipath conditions [1]. They have to be considered when studying the system performance of terrestrial line of sight communication. The atmospheric radio refractivity, N, is calculated by the following well known formula [1, 11]:

$$N = N_{dry} + N_{wet} = \frac{77.6}{T}\left(P + 4810\frac{e}{T}\right) \quad \text{(N-Units)} \qquad (1)$$

where *P* is the total atmospheric pressure (hPa), *e* is the water vapor pressure (hPa) and *T* is the absolute temperature (K). The dry component of refractivity is the most important; it

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contributes around 60 to 80 % of the overall value [5]. The atmospheric pressure and temperature are directly sensed during the radiosonde balloon ascents, while the vapor pressure is derived from the dewpoint as follows [12]:

$$e = 6.11 \times 10^{(7.5T_d / 237.7 + T_d)} \qquad \text{(hPa)} \qquad (2)$$

where T_d is the dewpoint temperature measured in degrees Celsius.

ΔN can be obtained from two refractivity values, N_s, surface refractivity, and N_1, refractivity at any height h_1 within the 1 km layer above the ground level h_s, using the following linear equation [13]:

$$\Delta N = (N_s - N_1)/(h_s - h_1) \qquad \text{(N/km)} \qquad (3)$$

Other works have been conducted to study the feasibility of estimating the vertical refractivity gradient near the ground from measurements of electromagnetic wave strength and diffraction losses [14, 15], in particular when upper air data are not available. An exponential model can also be used for quick, approximate estimates of refractivity gradient near the Earth's surface [1]. In the standard atmosphere, N decreases with altitude since the total pressure drops off rapidly while temperature decreases with height [16]. Consequently, the vertical refractivity gradient usually has a negative value causing rays to bend towards the earth and obtaining propagation beyond the geometric horizon. If the gradient is more (i.e. less negative) than usual, or even positive, sub-refraction occurs, where the ray bends less than usual towards the earth, even bending upwards in the case of a positive gradient and the range reduces. Sub-refraction occurs when warm moist air flows over a cool ocean surface or over a cooler air mass just above the ocean surface [2, 17].

If the gradient is less than in a standard atmosphere (i.e. more negative), super-refraction takes place, with rays bending more than usual towards the earth and propagating further than in standard conditions. Super-refraction occurs when temperature increases with height and/or water vapor content decreases with height, where the signal propagates between the normal and critical gradient conditions. At a critical gradient value, ΔN = -157 N/km, the radius of curvature of the ray becomes equal to the Earth radius. The wave path approaches the Earth curvature and consequently the signal moves parallel to its surface [17]. Gradients more negative than this critical value lead to ducting, in which the signal becomes trapped in the boundary layer, propagating well beyond its usual range. Table 1 summarizes the limits considered for the refractive conditions in this study.

B. *β_0 Statistics*

β_0 is an important parameter in studies of clear air propagation and interference since it is commonly used to indicate the relative incidence of anomalous propagation. β_0 represents the percentage of time in which the value of ΔN is less than or equal to -100 N/km [1, 2, 5]. It is derived from ΔN statistics in the lowest 100 m of the atmosphere. The normal range of ΔN in the surface layer is between 0 and -100 N/km. In this paper, "anomalous propagation" is defined as that occurring outside this normal range. Note that other references consider different values, such as -79 N/km, for the limit between the normal and non-standard propagation [17]. β_0 might relate, with reasonable accuracy, to the presence of ducting phenomenon where ΔN values do not exceed -157 N/km. It was observed [2] that β_0 is correlated to the latitude of the area under consideration, showing higher values in equatorial regions and lower toward the poles. In this work, β_0 is calculated from the occurrence probability of both super-refraction and ducting conditions.

TABLE 1: SUMMARY OF REFRACTIVE PROPAGATION CONDITIONS

Refractive Conditions	**Gradients (N/km)**
Sub-refraction	Positive Gradients
No Refraction	0
Normal Refraction	0 to -100
Super-refraction	-100 to -157
Trapping or Ducting	-157 to -∞

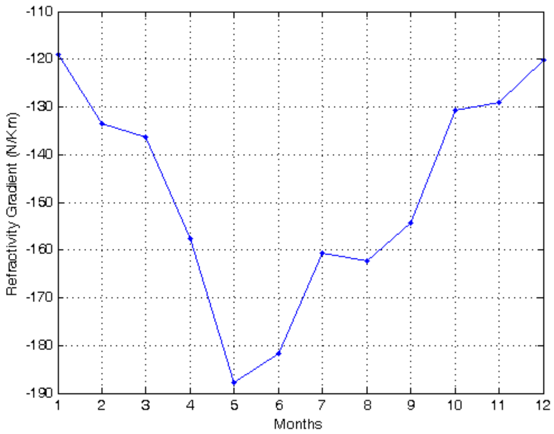

Fig. 1. Mean monthly variations of the refractivity gradient, ΔN, at 100 m (1997 to 2005)

II. RESULTS AND ANALYSIS

Nine years of high resolution meteorological data from 1997 to 2005 have been analyzed in this study. Data are available for 5,391 radiosonde ascents. Due to low quality or incomplete ascents, data for June 1998, April 2000 and November 2005 are not available. A small number of abnormal values have been excluded owing to faulty readings from the instrument.

A. Refractivity Gradient calculations in the first 100 meters

The refractivity gradient, ΔN, has been evaluated using (3). h_1 is selected to be the nearest point to 100 m height, which was found to be 103 m since data at the exact height were not available. In Figs. 1 and 2, the average seasonal and yearly variations of ΔN over the whole period of study are shown. The monthly variations are significant. Values oscillate between approximately -118 and -186 N/km, with a range of 68 units. The gradient values are lower (i.e. more negative) during summer months, May and June, than winter months, January and December. This can be attributed to the decreasing vapor content and pressure and to the increasing temperature with height. Such ΔN trends explain the frequent interference cases even across national borders, which are most commonly experienced during the summer months in the Gulf region. All monthly means do not exceed -100 N/km, which relates to the incidence of anomalous propagation as explained in section I. B above.

Year to year variations of the mean refractivity gradients with a span of 70 units, are given in Fig. 2. It has been observed that the mean ΔN values have increased for the four years 2002, 2003, 2004 and 2005, with some exceptional values in the years 2003 and 2004. Whether or not this yearly increment is part of some short or longer-term climate cycle cannot be reliably inferred from nine years' measurements, but may indicate an increasing probability of anomalous propagation occurrence in the Gulf region.

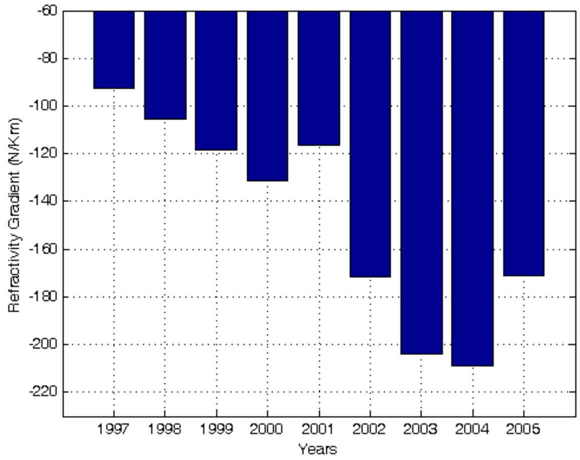

Fig. 2. Mean yearly variations of the refractivity gradient, ΔN, at 100 m (1997 to 2005)

Cumulative distributions of ΔN over this period for different times of day are shown in Fig. 3. The range of ΔN varied between approximately -1160 and 990 N/km, however for clarity only values between -1000 and 600 N/km are displayed. The long-term mean value of ΔN is -128.6 N/km, whereas the mean values at 00:00 and 12:00 UT are found to be -148.5 N/km and -113.9 N/km, respectively. The gradient values are less (i.e. more negative) during the morning. Meteorological phenomena following sunset, could be responsible for such a trend [5].

In a previous study [9], the vertical refractivity gradient was evaluated in Abu Dhabi for the first kilometer of atmosphere and found to vary between -200 and 63 N/km. The ITU proposes a standard value of -40 N/km as the reference for the vertical refractivity gradient in the first kilometer [18]. The range of gradients in the lowest 100 m layer is rather below this value, which indicates that anomalous propagation is frequent in this critical atmospheric layer where most terrestrial wireless links operate.

The long-term probabilities of super-refraction and sub-refraction phenomena during the course of the year can be obtained from the "0 & 12H" curve as in Fig. 3. These two refractive conditions correspond to range of gradients given in Table I, which are -100 to -157 N/km and positive gradient above 0 N/km respectively. The probabilities of super-refraction and sub-refraction conditions have been found to be around 23% and 9%, respectively.

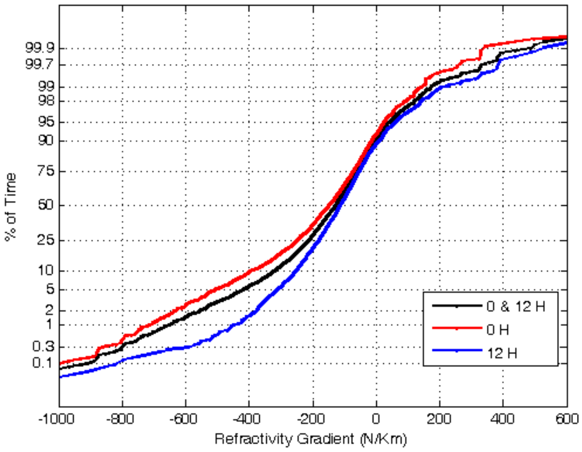

Fig. 3. Cumulative distributions of refractivity gradient at 100 m

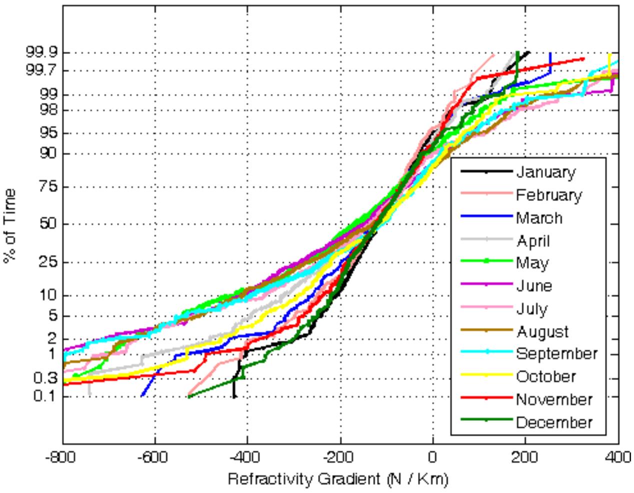

Fig. 4. Monthly cumulative distributions of the refractivity gradient at 100 m

Monthly and yearly cumulative distributions of Δ*N* are given in Figs. 4 and 5. The cumulative distribution of each month is drawn in Fig. 4 from all the data gathered for that calendar month during the entire period.

In Fig. 5, it is evident that the yearly cumulative distributions have a fairly consistent form, however, the median value of Δ*N* increases systematically from year to year. The probability of anomalous propagation where Δ*N* do not exceed -100 N/km also increases annually. However, there is a clear variation in the values during the course of the year as displayed in Fig. 4. Summer months are more critical where the gradient varies over a wider range than in winter. Gradients with lower values have been obtained during the summer for higher percentages of time. Similar observations have been reported in [5, 6]. The monthly distribution curves converge around gradients between -50 and -90 N/km, and the time percentages change between 60 to 75% accordingly. It can be noticed that the probability of gradients less than or equal to -157 N/km, which indicates ducting occurrence, varies from 29% in January to 52% in May.

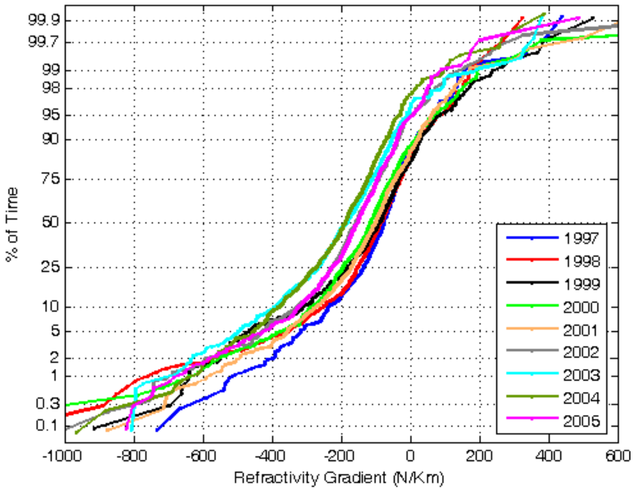

Fig. 5. Yearly cumulative distributions of the refractivity gradient at 100 m

B. β_0 Calculations

Hourly, monthly and yearly variations of the β_0 parameter have been derived from cumulative distributions of Δ*N* at the lowest 100 m of the atmosphere. It corresponds to the probability at which the value of Δ*N* is less than or equal to -100 N/km, causing the incidence of non-standard conditions such as super-refraction and ducting. The long-term value of β_0 has been found to be 60.8% from the "0 & 12H" curve in Fig. 3. This means that the value of refractivity gradient is expected to be less than or equal to -100 N/km for around 60% of the time. The values of β_0 obtained at 00:00 and 12:00 UT are 65.6% and 55.5% respectively, which indicate higher probability of anomalous propagation occurrence in the early morning. This can explain the operational experience of intermittent outage due to high signal fading for some of the microwave links operating in UAE during the morning, mostly within the summer season.

Fig. 6 shows monthly variations of β_0 obtained from the monthly cumulative distributions of the refractivity gradients in Fig. 4. The value of β_0 fluctuates between 53% and 68%, with the highest value occurring in May. Generally, the summer months show higher probabilities of anomalous propagation than others.

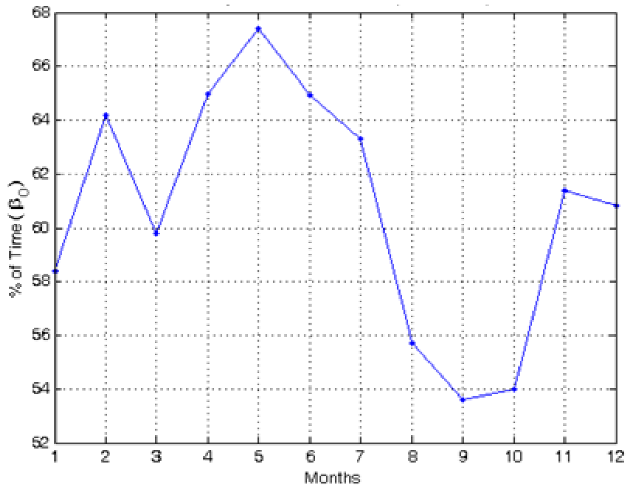

Fig. 6. Monthly variations of β_0

TABLE 2: VALUES OF β_0 COMPARED WITH ITU MAPS

Months	**ITU Values (%)**	**Obtained Values (%)**
February	30	64
May	75	67
August	75	56
November	40	61

The results obtained for the monthly variations of β_0 are compared with ITU maps [1] in Table 2. It is seen that the ITU values are not in good agreement with the results obtained in this study. The estimated ITU values are below those calculated in the case of February and November with differences of 34% and 21%, respectively, while they are overestimated for the months of May and August, with differences of 7% and 19%. This can be attributed to the fact that the ITU maps [1] were interpolated from radiosonde data from only 99 sites worldwide between 1955 and 1959. Differences have also been observed in other countries [5]. In addition, ITU curves and maps are usually derived from measurements performed largely in temperate regions of the world such as Europe, North America and Japan [19], which have different climatic conditions from the Gulf region. This would also suggest the necessity to revise these maps based on recently gathered long-term local meteorological data from more radiosonde sites, since they are being widely used for microwave link design.

The annual variations of β_0 are given in Fig. 7, obtained from the yearly cumulative distributions of the refractivity gradients in Fig. 5. The variation is significant where the percentages are increasing year by year; with a peak value shown for 2004.

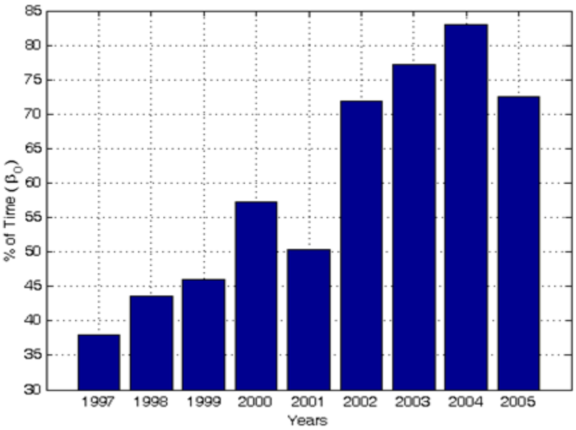

Fig. 7. Year to year variations of β_0

III. CONCLUSIONS

Local radiosonde data were used to obtain the refractivity gradient in the first hundred meters above the ground surface. The β_0 parameter has been calculated to indicate the probability of anomalous propagation such as ducting and multipath in Abu Dhabi. The results obtained for the long-term mean value of ΔN and β_0 were -128.6 N/km and 60.8%, respectively. The monthly results of β_0 were not in good agreement with the values provided by the ITU maps.

Monthly values of β_0 averaged over the nine years of this study showed the ITU values to be somewhat conservative during the summer months, but to significantly underestimate the severity during the winter months. However, year-to-year variations showed that in two out of the nine years, the annual average value of β_0 exceeded the ITU figure for the worst month. This is consistent with operational observations of the received signal strength, fading occurrence and interference cases for some of the microwave links operating in the UAE, which confirmed the high probability of anomalous phenomena over the course of the year, exceeding 50% even during the winter, and in particular during the early morning time.

Since local data are now available for the UAE region, it is strongly recommended that link designs for this region take account of the annual and seasonal variations reported here. This will enable better prediction of performance and reliability in the design and deployment of wireless communication systems working in this region.

There is perhaps an opportunity to revise the ITU maps using the now abundant long-term local meteorological data which have been collected recently all over the world. Work will continue to report the fading occurrence based on real signal strength measurements and to study the occurrence of different ducting classes in UAE.

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