Statistics of Radio Refractivity Derived from Prague Radiosounding Data

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Abstract. *Vertical gradient of radio refractivity in the lowest 100 m is derived from the meteorological radiosounding data of the Prague-Libus station. The data cover the measurements at the terms 00, 06, 12, and 18UTC, and the extent of data is 20 years. Diurnal, monthly, and annual distributions are presented and the relative role of the dry and wet components of the refractivity gradient is discussed. The* β_0 *values, expressing the percentage of the time with the refractivity gradient below -100 km*$^{-1}$*, are presented. This work should enable the effective radio-relay link design with respect to the radiowave bending.*

Keywords

Radio refractivity, meteorological radiosounding, probability of exceedance, diurnal variations, annual variations.

1. Introduction

Bending of the radio ray trajectory depends on the vertical distribution of radio refractive index *N* and is pronounced especially at longer ray path in the atmosphere. That is why the statistical properties of the vertical gradient of refractivity parameters can be useful information when the quality of radio-relay links and low-elevation satellite links is calculated. There are several studies of the statistical properties of radio refractivity. Much work in that field was done in the frame of COST 215 action [1], which finds a continuation in the running action COST 280, e.g. [2].

Based on the known refractive index *n*, the radio refractivity, *N*, is defined by:

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

In terms of meteorological quantities, the *N* can be expressed as [1, 3, 4]:

$$N = 77.6\frac{p}{T} + 3.73\times10^5\frac{e}{T^2} = N_d + N_w\ , \tag{2}$$

where *p* (hPa) is the air pressure, *T* (K) is the temperature, *e* (hPa) is water vapor pressure, and N_d (N_w) is so called dry (wet) component of *N*. The *e* can be calculated from the relative humidity and from the saturation water pressure e_s, the last depending only on the air temperature, *T*. In this paper we apply the relationship $e_s(T)$ from the ITU-R recommendation [4] published also in [3]. From (2) it is clear that to evaluate the long-term statistics of the reflectivity profiles we can rely on the long-term meteorological radiosounding measurements, which provide vertical profiles of air pressure, temperature, humidity, wind speed and wind direction. We can determine the vertical gradient of *N*, *dN/dz*, and consequently the *dn/dz* from the vertical profiles. The value of $dN/dz = -40$ km^{-1} corresponds to the standard atmosphere.

The last parameter, important in the studies of clear air propagation and interference, is the so-called β_0 parameter. It is defined as the percentage of time, for which the radio refractivity gradient *dN/dz* is below –100 km^{-1} in the lowest 100 meters above the ground, and it represents the probability that super-refracting "surface" layers occur at a given location (e.g. [1]).

In this study, we discuss the statistical characteristics of the gradient *dN/dz* in the lowest 100 m. We used the radiosounding data from the aerological station Prague Libus, operated by the Czech Hydrometeorological Institute (CHMI). The elevation of the station is 304 m a.s.l. and consequently, the *dN/dz* (km^{-1}) was calculated by:

$$dN/dz = 10[N(404) - N(304)], \tag{3}$$

where *N(z)* is radio refractivity in the height *z* (m a.s.l.). The *N*(404) values were determined by linear interpolation from the nearest radiosounding levels below and above the 404 m a.s.l. In accordance with (2) and (3), we also determined the dry component and wet component of the refractivity gradient, dN_d/dz and dN_w/dz, respectively.

This article is structured as follows. In Section 2, we introduce the input data and we show the basic statistical characteristics of *N* and *dN/dz*. The distribution of *dN/dz* is presented in Section 3 and the particular role of the wet and dry component is discussed in Section 4. Section 5 is devoted to the basic statistical properties of β_0 and *k*, Section 6 shows the practical use of the described phenomena and Section 7 summarizes the results and the outlook for the further work.

2. Input Data and Basic Processing

The results of radiosounding measurements from the aerological station Prague-Libus (304 m a.s.l.) were used as the input data set for this study. Meteorological sonds are launched four times a day, at 00, 06, 12, and 18UTC, and the resulting data cover vertical profiles of air pressure, temperature, dew point temperature, wind speed and wind direction. From the dew point values we calculated the actual water vapor pressure, *e* (hPa), taking into account the temperature dependence of saturation vapor pressure. We used the data from 20 years (1980 – 1991, 1994 -2001) and the structure of the input data set is shown in Tab. 1.

month / time	00 UTC	06 UTC	12 UTC	18 UTC	all
I	506	447	496	453	1902
II	469	414	464	403	1750
III	506	474	490	441	1911
IV	508	517	483	462	1970
V	515	497	458	434	1904
VI	461	460	434	405	1760
VII	453	475	416	405	1749
VIII	462	491	431	400	1784
IX	489	454	469	436	1848
X	553	503	526	482	2064
XI	517	520	500	490	2027
XII	526	520	523	508	2077
all	5965	5772	5690	5319	22746

Tab. 1. The number of radiosoundings in the input data set

month	N	dN/dz
I	304.9 (4.3)	-35.9 (11.2)
II	304.1 (5.2)	-37.6 (14.8)
III	304.4 (6.2)	-38.2 (19.7)
IV	304.8 (8.1)	-41.5 (26.5)
V	312.9 (11.0)	-49.0 (38.6)
VI	320.2 (12.1)	-51.2 (43.4)
VII	325.6 (11.9)	-54.1 (46.7)
VIII	325.8 (11.6)	-54.8 (48.6)
IX	321.3 (9.1)	-47.0 (38.4)
X	314.6 (8.5)	-40.1 (28.1)
XI	308.0 (5.4)	-37.7 (16.3)
XII	305.7 (4.8)	-36.7 (12.4)
year	312.4 (11.8)	-43.4 (31.9)

Tab. 2. Mean ground radio refractivity, *N*, and mean radio refractivity gradient, *dN/dz*, for all months and the year. Corresponding values of standard deviation are in parenthesis.

The *N* values were calculated according to (2) and the gradient values, *dN/dz,* in the lowest 100 m according to (3). Tab. 2 gives the monthly and annual mean values of *N*(304) and *dN/dz* together with corresponding standard deviations. The negative mean *dN/dz* values confirm the decrease of *N* with the height in average. The mean values of the refractivity gradient are shown in Fig. 1 for all terms considered. The dry component of the refractivity gradient and corresponding values of temperature gradient are also indicated. Fig. 1 shows the inverse proportion between the temperature gradient, *dt/dz*, and the dN_d/dz while the course of *dN/dz* differs due to the effect of the dN_w/dz. The daily change in the humidity disturbs the nearly regular daily course of temperature.

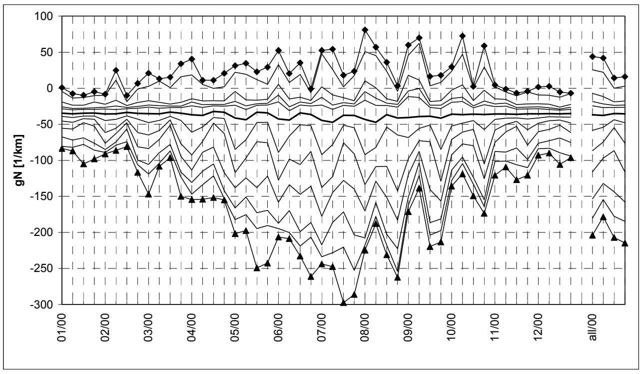

Fig. 1. Mean gradient of temperature *gt* (K/km), radio refractivity *gN* (1/km), and the dry component *gNd* (1/km) in dependence on the time during the year. The terms 00UTC are labeled on the horizontal axis for each month. The non-labeled terms 06, 12, and 18UTC follow.

3. Distribution of *dN/dz*

In contrast to Fig. 1 showing the time dependence of the mean *dN/dz*, Fig. 2 presents the quantile values corresponding to the *dN/dz* distribution. The extent of input data set allowed us to determine the individual distributions of *dN/dz* for each term and month during the year together with the overall monthly and annual distributions. Fig. 2 shows the annual course of *dN/dz* values given probability of exceedance. The large dispersion of the *dN/dz* distribution is obvious especially in summer. In Fig. 3 and Fig. 4, the curves depicting the probability of exceedance are shown to demonstrate the differences in monthly distributions (Fig. 3) and in the distributions relating to the time during the day (Fig. 4).

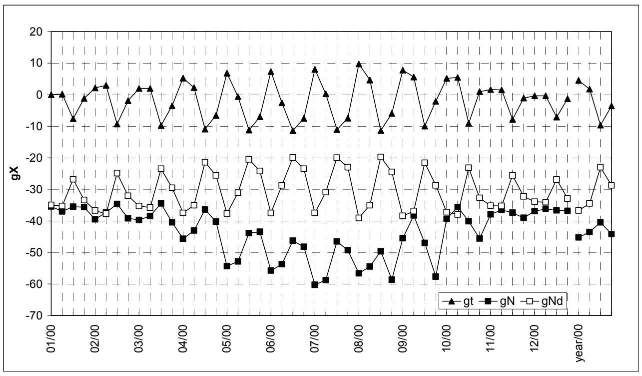

Fig. 2. Diurnal and annual changes of *dN/dz*. The curves correspond to the probability of exceedance 0.995 (triangles), 0.99, 0.98, 0.95, 0.90, 0.80, 0.50 (thick line), 0.15, 0.10, 0.05, 0.01, 0.005 (diamonds).

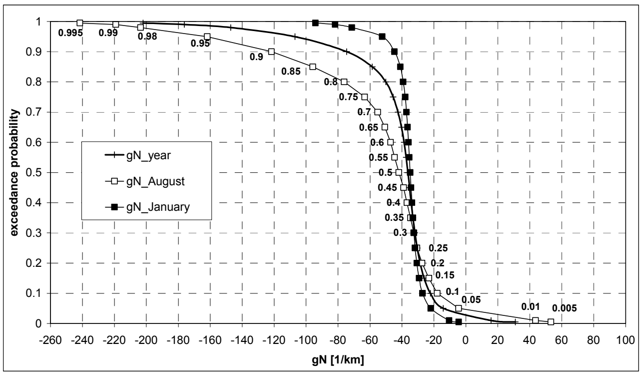

Fig. 3. Annual distribution of *dN/dz* (gN_year) and the monthly distributions in August (gN_August) and in January (gN_January). The January and August curves introduce an envelope for all monthly distributions.

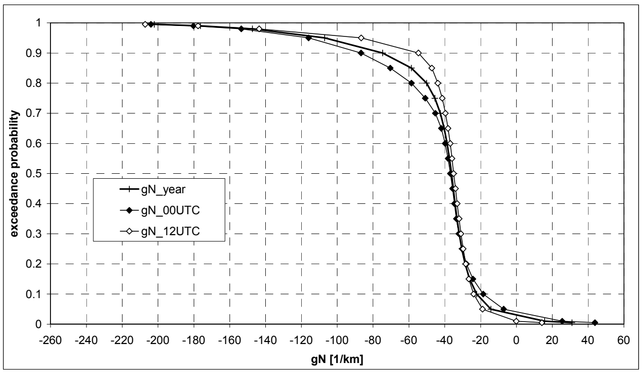

Fig. 4. The annual distribution for the terms 12UTC (gN_12UTC) and 00UTC (gN_00UTC) as compared with the total annual distribution (gN_year). The 12UTC and 00UTC curves introduce an envelope for the 06UTC and 18UTC distributions.

4. The Effect of Humidity on *dN/dz*

Fig. 1 indicates that the distribution of *dN/dz* can be affected not only by the temperature gradient but also by the vertical change in the atmospheric humidity. This can be demonstrated in terms of the separate distributions for the dry and wet gradient component shown in Fig. 5.

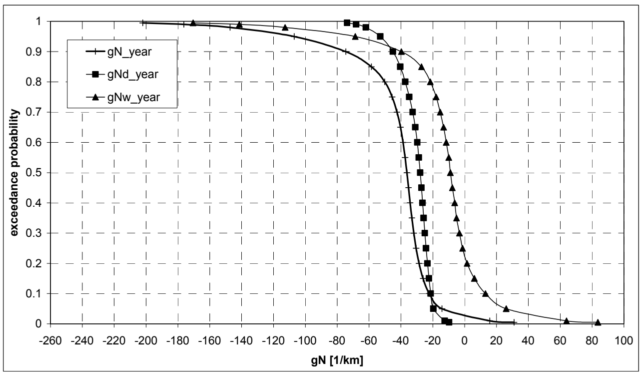

Fig. 5. Annual distribution of the gradient of dry component (gNd_year) and wet component (gNw_year) of *N* as compared with the annual *dN/dz* distribution (gN_year).

It is known that the wet part, N_w, represents a smaller portion of the *N* value than the N_d component. As an example, the mean monthly values N_w/N and N_d/N as well as the ratio N_d/N_w are shown in Fig. 6.

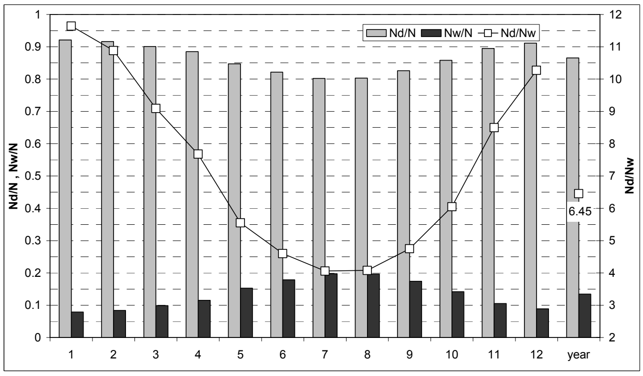

Fig. 6. The N_d and N_w components relative to the *N* value (left scale). The monthly and annual values are depicted by columns. The N_d/N_w ratio (right scale) is marked by the empty squares and the annual value is labeled.

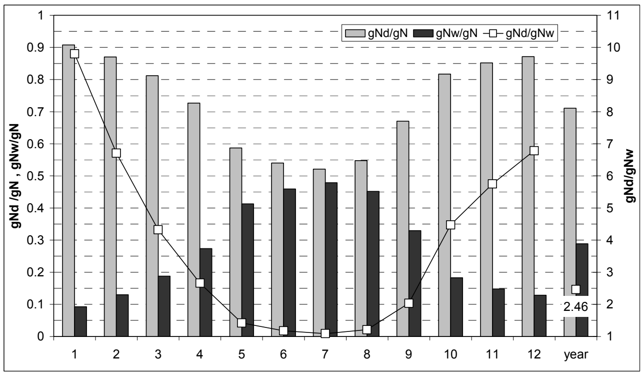

Fig. 7. The same as in **Fig. 6** but for the gradient values.

Fig. 6 shows that the largest N_w portion can be met in summer, however, its value does not exceed 20% of *N*. The same dependence of the gradient values (Fig. 7) shows a distinct picture with maximum relative dN_w/dz of 47%. Therefore, the humidity gradient in the lowest 100 m is of high relevance to the *dN/dz* values.

5. Distribution of β_0 and *k*

The β_0 values were expressed by the relative frequency of the occurrence of dN/dz<-100 km^{-1}. The resulting β_0 values (for 00, 06, 12, 18UTC) are given in Fig. 8, which also indicates the monthly and annual values. The graph shows that the maximum β_0 can be met in summer months with maximum value 0.17 in July at 00UTC.

The earth refractivity coefficient, *k*, is defined as the ratio of the effective earth radius R_e and the actual earth radius, *R*. It can be expressed by the relation:

$$k = \frac{R_e}{R} = \left(1 + R\frac{dN}{dz}10^{-6}\right)^{-1}, \tag{4}$$

where dN/dz is the vertical gradient of the radio refractive index, N. The annual distribution of the coefficient of earth refractivity k is shown in Fig. 9.

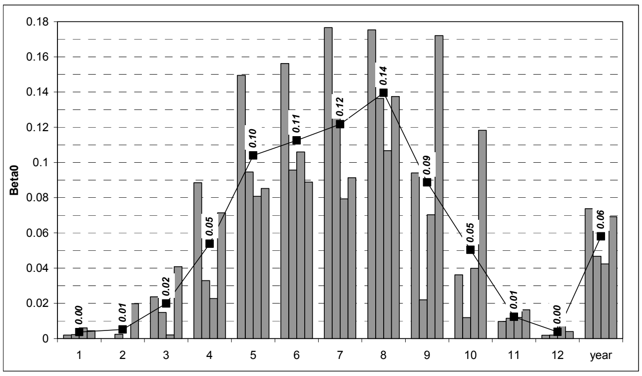

Fig. 8. The β0 (Beta0) values corresponding to the terms 00UTC, 06UTC, 12UTC, 18UTC for each month and for the whole year (columns). Monthly and annual Beta0 values are marked by the filled squares and labeled.

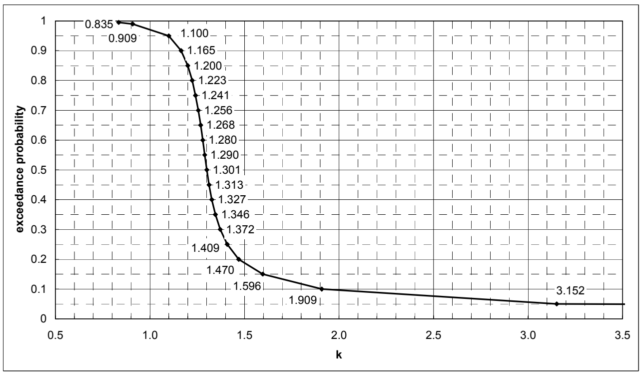

Fig. 9. Annual distribution of earth refractivity coefficient, k.

6. Use of k in Radio-Relay Calculation

Usually, the tropospheric refractivity index is not homogenous. That is why the radiowave trajectory, following the Fermat principle, is not linear. We can respect this fact by replacing the actual earth radius R by the effective radius, R_e, using the earth refractivity k given by (4). In such case we can approximately consider the refractivity index to be homogenous, and consequently, the radiowave trajectory to be linear. As $k>1$ for more than 96% of the time (see Fig. 9), the radiowave bending enables the trans- horizon propagation for more than 96% of the radiocommunication operation.

The correction respecting the bending of radiowave can be expressed by the term

$$\Delta = \frac{d^2}{2kR}, \tag{5}$$

where Δ represents the distance between the radiowave path (the tangent to the earth surface at the receiver position) and the earth surface at the distance d from the receiver (transmitter position). This correction respects the radiowave bending due to the variable k.

7. Conclusion

This study summarizes the first results of the processing the radiosounding data from Prague-Libus station to determine the radio refractivity vertical gradient dN/dz in the lowest 100 m. The distributions of dN/dz and of its components are discussed and the effect on the radio-relay links is shown. The results show that the maximum negative dN/dz values can be expected in summer months when the humidity can achieve the highest values. This last result also corresponds to the annual distribution of β_0. Again the highest β_0 frequency occurs in summer. The derived k distribution can be used in the calculation of both radio-relay and satellite links.

The results, presented in this study, deal with the first part of the discussion of dN/dz. At present, meteorological and practical aspects of dN/dz distribution are examined, which comprise e.g. the influence of temperature inversions and the dependence of dN/dz distribution on the large-scale meteorological pattern.

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