The vertical profile of the refraction coefficient for microwave radiation in the troposphere and its variability

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Abstract. On the basis of data from 8 aerological stations: St. Petersburg, Tallinn, Sukhinichi, Bologoye, Velikiye Luki, Smolensk, Ryazan and Dolgoprudny, the variability of the refractive index vertical profile in the troposphere is shown. It is noted that the presence in the troposphere of inversions of the altitudinal temperature profile and narrow zones with increased and decreased water vapor content leads to sharp changes in the index refractive index gradient and determines the type of radio wave refraction.

Introduction
Among the various factors affecting the operation of microwave radar stations (radars), including Doppler meteorological radars (DMR), the spatial and temporal variability of the radio meteorological characteristics of the atmosphere should be noted. This variability is associated with variations in the temperature and humidity profiles, which, in turn, affect the spatial and temporal variability of the vertical profile of the refractive index and its gradient. All of this affects the efficiency of the radar station, as well as the reliability of detecting meteorological formations using the DMR [1, 2].

When assessing the efficiency of a particular locator, one should proceed from the features of refraction in the troposphere above the given locator location. In turn, the type of refraction depends on the meteorological conditions, which are determined, among other things, by the local conditions of the territory.

The work is devoted to the study of the spatio-temporal variability of the refractive index vertical structure based on the use of data from vertical sounding of the atmosphere at 8 aerological stations.

Research methodology
The refraction coefficient n (RC) of radio waves for the microwave range in the troposphere is usually determined using the semiempirical formula [3-6]:

\[ n = 1 + \left( \frac{78.5}{T} \left( p + \frac{4800e}{T} \right) \right) \cdot 10^{-6} = 1 + N \cdot 10^{-6}. \] (1)
The value $N = (n - 1)10^6$ is called the refraction coefficient (IRC).

Local changes in pressure, as well as temperature inversions, lead to fluctuations in the refractive index near the earth's surface $n = 1.00026 - 1.00046$. Above 10 km, $n = \text{const} = 1.00011$ is assumed.

- **Influence of meteorological parameters on the refractive index**

In the real atmosphere, due to changes in temperature, pressure and humidity, complex spatio-temporal changes in the refractive index occur. To assess the influence of meteorological parameters on the IRC dynamics, partial derivatives of equation (1) were determined:

$$
\frac{dN}{dT} = \left[ \frac{78.5p}{T^2} + \frac{2 \cdot 4800e}{T^3} \right],
$$

$$
\frac{dN}{de} = \frac{78.5 \cdot 4800}{T^2},
$$

$$
\frac{dN}{dp} = \frac{78.5}{T}.
$$

The quantitative values of the IRC sensitivity to temperature, humidity and pressure are presented in the form of a diagram in Fig. 1. Colored rectangles show the factors of influence, the size of the rectangle reflects the IRC change "rate" when substituting the characteristic real values of temperature, humidity and pressure at three heights in the atmosphere: 0 km, 3 km and 6 km.

![Diagram of characteristic values dN/dT, dN/de and dN/dp](image)

**Figure 1.** Diagram of the distribution of characteristic values $dN/dT$, $dN/de$ and $dN/dp$ for three heights: 0 km, 3 km and 6 km.

From the analysis of figure 1 it follows that the greatest influence on changes in the IRC value is exerted by variations in humidity (green rectangle). This influence insignificantly increases with height. At the lower level, when the partial pressure of water vapor changes by 1 hPa, the IRC will change by 5 $N$-units, while the temperature and pressure have values typical for a given height. At an altitude of 6 km, the change in IRC will be about 7 $N$-units.

The red and blue rectangles represent the effect of atmospheric pressure and temperature, respectively. The change in the refractive index due to the pressure drop is the smallest, and it practically does not change with height, amounting to about 0.3 $N$-units. A decrease in temperature with height causes a slight...
decrease in the refractive index from 1 \( N\)-unit at sea level up to 0.7 \( N\)-units.

- **Seasonal analysis variability of the gradient of the refraction coefficient index**
  The gradient of the refraction coefficient Index (GIRC) values experience seasonal and diurnal changes. Seasonal changes are mainly due to the annual variation of humidity with a maximum in the warm half-year period. In the annual time series of GIRC values calculated from the results of upper-air sounding at Voeikovo station in St. Petersburg for the period of 2019 (more than 700 soundings), it was possible to find three periods - with a constant or slowly changing trend, with an increasing and decreasing trend. Seasonal changes are shown in figure 2 in the form of trends – linear polynomials. The dotted line corresponds to the nighttime trends, the solid lines - to the daytime ones. Linear equations next to some of the trends are shown.

  In the GIRC annual change, the maximum prevails in the winter period, and the minimum - in the summer period (see figure 2).

![Figure 2. Seasonal variation of GIRC according to data from the aero logical station St. Petersburg (Voeikovo)](image)

- **Refraction types vertical distribution in the troposphere**
  The distribution of water vapor in the troposphere is highly variable and layered. The authors of [7, 8] point to the typical presence of thin layers with sharp drops in humidity in the atmosphere. In such layers the profile of the gradient of the refraction coefficient index will also experience oscillations, and the trajectory of propagation of radar pulses will change its direction.

  The existence of temperature inversion layers as well as layers with a sharp drop in temperature is accompanied by an increased value of turbulent energy, which also affects the GIRC. The greatest change in refraction is mainly associated with the "deformation" of the meteorological elements altitude distribution in the clouds [6]. The degree of cloudiness influence on refraction depends on the cloud height and its depth. The lower the cloud base and the greater its depth, the greater this influence.

  Fluctuations of the GIRC profiles altitude variation shown in figure 3, were constructed according to aerological sounding data at the stations of St. Petersburg, Tallinn, Sukhinichi, Bologoye, Velikiye Luki, Smolensk, Ryazan, and Dolgoprudny.
Figure 3. Examples of GIRC vertical profiles for 8 stations of upper-air sounding of the atmosphere

The greatest changes in GIRC take place in the lower three-kilometer layer of the atmosphere, which is due to large changes in temperature and humidity in this layer. Sharp fluctuations in GIRC are especially noticeable on the vertical profiles of St. Petersburg and Tallinn, apparently due to the proximity of sea areas. The inhomogeneity of the earth's surface, which has an additional effect on the fluctuations of the
GIRC, leads to horizontal gradients of the refractive index. The possibility of the presence of strong horizontal gradients of the refractive index up to 2 $N$-units /100 m is noted in [8-10]. The horizontal variability of the GIRC has an additional effect on the slant range fluctuations measured by the radar.

Corrections for the radio beam curvature are introduced relative to the standard radio atmosphere, where the GIRC average value is $-4 \times 10^{-8}$ 1/m. Refraction with such gradient is called normal. However, the GIRC average value in the entire troposphere does not reflect the diversity of the GIRC types vertical distribution in this region of the atmosphere. This is perfectly illustrated by the curves in figure 3.

In this work based on the results of aerological sounding at Voeikovo station in St. Petersburg for the period of 2019 (more than 700 soundings) the frequency of vertical layers occurrence with different types of refraction is calculated. Thus, during one sounding, a large number of different types of refraction were observed. According to the results of the analysis, the number of normal refraction cases at different heights was less than 0.02%. The distribution of other cases is shown in table 1.

| Refraction type             | GIRC                  | Number of cases | Frequency of cases, % |
|-----------------------------|-----------------------|-----------------|-----------------------|
| Negative                    | > 0                   | 909             | 2.4                   |
| Positive substandard        | < 0 and $> -4 \times 10^{-8}$ | 37019           | 95.8                  |
| Standard                    | $-4 \times 10^{-8}$   | 7               | 0.02                  |
| Positive superstandard      | $< -4 \times 10^{-8}$ and $> -15.7 \times 10^{-8}$ | 510             | 1.3                   |
| Critical                    | $-15.7 \times 10^{-8}$ | 0               | 0                     |
| Superrefraction             | $< -15.7 \times 10^{-8}$ | 140             | 0.4                   |

The vast majority of measurements (about 95.8%) correspond to positive substandard refraction. In these layers the radar pulse trajectory from the radar will bend less compared to standard refraction.

About 1.3% of the GIRC values correspond to the presence of layers with positive superstandard refraction (with a greater convexity of the radar beam); in 0.4% of cases the presence of layers with superrefraction is observed. In 2.4% of cases the presence of layers in the atmosphere with negative refraction was detected.

Thus in a real atmosphere the narrow beam trajectory will often have a different shape compared to standard refraction. In this case using the parameters of standard rather than real refraction will lead to an error in calculating the height and slant range to the radar target [6]. Of course, it is necessary to take into account the change in the vertical cross-section of the pulse as it moves away from the radar (for doppler weather radar already at a distance of 50 km this cross-section is about 1 km), which leads to a “natural” smoothing of the GIRC vertical profile. Such smoothing with a variable vertical size will decrease the GIRC profile fluctuations and reduce their influence on the ray trajectory.

- **Conclusion**

The presence of sharp fluctuations in the values of the IRC and GIRC vertical profiles in the lower troposphere associated with the spatio-temporal variability of the temperature, humidity and pressure vertical profiles is shown.

Based on the use of more than 700 data from upper-air sounding of the atmosphere in St. Petersburg (2019), the distribution of the frequency of atmosphere layers occurrence with different types of refraction was analyzed, and the seasonal variability of the GIRC average value was investigated. It was shown that
normal refraction was observed only in 0.02% of cases. The latter indicates that the replacement of real refraction by normal refraction will lead to errors in measuring the slant range and height of the object.

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