SPATIO-TEMPORAL PROGNOSIS OF CHANGEABILITY OF INDEX OF REFRACTION OF TROPOSPHERE ON WAY OF SHIP

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ABSTRACT

In the article possibility of prognosis of changeability is reasonable and distribution of index of refraction of troposphere on certain temporal and spatial intervals on the way of motion of ship.

Keywords: *index of refraction, troposphere, prognosis, statistical method, quadratic equalization, coefficient of correlation, nomogram, meteorological parameters, water content and density of the aerosol.*

ანოტაცია

სტატიაში დასაბუთებულია გემის მსვლელობის გზაზე გარკვეულ დროით და სივრცულ ინტერვალებში ტროპოსფეროს გარდატეხის მაჩვენებლის ცვალებადობისა და განაწილების პროგნოზირების შესაძლებლობა.

საკვანძო სიტყვები: *გარდატეხის მაჩვენებელი, ტროპოსფერო, პროგნოზი, სტატისტიკური მეთოდი, კვადრატული განტოლება, კორელაციის კოეფიციენტი, ნომოგრამა, მეტეოროლოგიური პარამეტრები, აეროზოლის წყლიანობა და სიმკვრივე.*

General statement of the problem. Getting information about the conditions of propagation of electromagnetic wave emitted by the antenna marine radar is an important problem today, solution of which increases the safety of navigation. When an electromagnetic wave is propagating through the troposphere, bending of its path occurs as a result of refraction, which occurs due to inhomogeneities of the refractive index and its vertical gradient. Radio waves propagating in the troposphere set water vapor molecules in oscillatory motion, which affects the degree of radiorefraction. In the troposphere, the temporal and spatial variation of refractive index with height is conditioned by changes in the distribution of pressure, temperature and humidity.

It is known [1], that the troposphere refractive index N is a function of temperature T, pressure P, mass fraction of water vapor s, water content w and density ρ of aerosol

$$N = f(T, P, s, w, \rho), \qquad (1)$$

which are measured in Hydrometeorological Service network and published in the meteorological and upper-air yearbooks.

The refractive index is determined in accordance with a known relationship:

$$N = 1 + \left[\frac{78{,}5\,P}{T} \left(1 + 7{,}717\,\frac{s}{T} \right) \right] \cdot 10^{-6} + \frac{3\,w}{\rho} \left| \frac{m^2 - 1}{m^2 + 2} \right| , \tag{2}$$

where m is a complex index of electromagnetic wave refraction by a substance of tropospheric aerosol and is defined by the following expression

$$m = n - j\,l\, , \tag{3}$$

where n is a real part called the refractive index of aerosol substance, and l is an imaginary part called the absorption index.

For cloudless troposphere in the range of radio waves used by marine radars, the refractive index is a real value and there is a relation $m = n$ and the expression (2) can be represented in the following way:

$$N = 1 + \left[\frac{78{,}5\,P}{T} \left(1 + 7{,}717\,\frac{s}{T} \right) \right] \cdot 10^{-6} + \frac{3\,w}{\rho} \left| \frac{n^2 - 1}{n^2 + 2} \right| . \tag{4}$$

For dry cloudless troposphere the third summand can be neglected, and then the equation (3) takes the following form:

$$N = 1 + \left[\frac{78{,}5\,P}{T} \left(1 + 7{,}717\,\frac{s}{T} \right) \right] \cdot 10^{-6} . \tag{5}$$

Above the ocean surface a transfer of salt water occurs in the direction of the ocean-troposphere. Such transfer causes appearance in the troposphere of dissolved salts being water aerosol, the water content and density of which is determined by the state of the ocean water surface [2]. The main source of entering salt aerosols in the troposphere is the rupture of gas bubbles on the surface of the wave crests. When rupturing salt bubbles the droplets are formed of 1 *µm* to 100 *µm*, which are released into the troposphere to a height of 1 cm and up to several kilometers depending on their size. 1-20 *µm* droplets form ocean aerosol, the density of which at the near-surface layer is 300 *µg/m*^{3} and in the distant layer at the height of 2-2.5 *km* – 0.5*µg/m*^{3}. The total average concentration of salt aerosol according to [1] is estimated at 36 *µg/m*^{3}. Bulk concentration $c_k = 2 \cdot 10^{-10}$. The specified aerosol parameters over the ocean surface, depending on the troposphere parameters may vary from 2 to 4 orders of magnitude. The attenuation of electromagnetic waves in salt aerosols reaches 2.72 *dB/km*.

In the formula (2), the module characterizes the influence of the salt aerosol's state of aggregation on the refractive index. Salty water aerosols can be considered as a random lattice and in accordance with [3] $m = \sqrt{\varepsilon_k}$, where ε_k is a complex permittivity of the salt aerosol related to the reflection coefficient by the following relationship:

$$\varepsilon_k = \frac{1 - \sqrt{R}}{1 + \sqrt{R}} , \tag{6}$$

a

$$R = \left(\frac{1 - n}{1 + n} \right)^2 + \left(\frac{l}{1 + n} \right)^2 . \tag{7}$$

Then, taking into account (6) and (7) the equation (2) is represented in the following way:

$$N = 1 + \left[\frac{78{,}5\,P}{T} \left(1 + 7{,}717\,\frac{s}{T} \right) \right] \cdot 10^{-6} + \frac{3\,w}{\rho} \left| \frac{m^2 - 1}{m^2 + 2} \right| \cdot \frac{1 - \sqrt{\left(\frac{1 - n}{1 + n} \right)^2 + \left(\frac{l}{1 + n} \right)^2} - 1}{1 + \sqrt{\left(\frac{1 - n}{1 + n} \right)^2 + \left(\frac{l}{1 + n} \right)^2} + 2} . \tag{8}$$

Total energy reflected by dipoles does not exceed the right-hand side of formula (7). In predicting the radar detection range of the electromagnetic wave propagation over the sea on the way of ship movement it is expedient to determine its path by the refractive index profile. The refractive index profile is characterized by systematic and small-scale changes that lead to deviation of ray propagation from the normal rectilinear propagation, as well as to formation of false object echoes on the marine radar display devices.

On the ship movement route, up to the present time there is no statistically secured data on the distribution and variation of the refractive index of the troposphere at certain time and space intervals, therefore an important task is to predict the refractive index variation with a certain lead time, which is the objective of this article.

Statement of the base material. Let's set the problem of the refractive index operative prediction for the propagation path of electromagnetic wave emitted by the antenna marine radar at point D by the value of refractive index at point C with a lead time τ (*h*) with a distance between the points C and D, equal to R (*km*). We will solve the problem using probabilistic and statistical method.

In solving the problem we assume that the distribution of values N, as a random variable follows the normal law [4] and for the prediction we can use linear regression equation, assuming at the initial stage of calculation $\tau = 0$, i.e. we take into account only the spatial variability of the troposphere refractive index. The most probable value of the refractive index at the point D of the troposphere is determined by its known value at the point C using the following equation [4]:

$$N'_D(R, 0) = \overline{N}_D + \frac{\sigma_{N_D}}{\sigma_{N_C}} K_N(R)\left[N(0) - \overline{N}_C\right], \qquad (9)$$

where $\overline{N}_C$ and N_D are average values of the refractive index at the points C and D;

σ_{N_C} and σ_{N_D} are mean-square deviations of the refractive index values at the points C and D;

$K_N(R)$ is correlation coefficient.

These statistical characteristics of the troposphere refractive index have to be obtained for the same time averaging interval – hour, day, month, season. On the assumption of process stationarity the variation N over a uniform underlying (water) surface can be equated with the average values of the refractive index and its mean-square deviations, i.e.

$$\overline{N}_D = \overline{N}_C = \overline{N}, \qquad (10)$$

$$\sigma_{N_D} = \sigma_{N_C} = \sigma_N. \qquad (11)$$

Taking into account (10) and (11) the equation (7) is represented in the following way:

$$N'_D(R, 0) = \overline{N}_C + K_N(R)\left[N_C(0) - \overline{N}_C\right]. \qquad (12)$$

Using regression equation the most probable value of the refractive index at the point C at a time interval τ after measurement is determined in the following way:

$$N'_C(0, \tau) = \overline{N}_C + K_N(\tau)\left[N_C(0) - \overline{N}_C\right]. \qquad (13)$$

The equation (13) takes into account temporal variability of the refractive index N at the point C.

By replacing $N_C(0)$ with $N'_C(0, \tau)$ in the formula (13), we will obtain a formula for determining the most probable value N at the point D at a time interval τ after measurement N at the point C, i.e.

$$N'_D(R, \tau) = \overline{N} + K_N(R) K_N(\tau)\left[N_C(0) - \overline{N}\right]. \qquad (14)$$

Mean-square deviation of various refractive index values N from its most probable value is determined from the following condition:

$$\sigma_N(R,\tau) = \sigma_N\sqrt{1-[K_N(R)\,K_N(\tau)]^2}\ . \qquad (15)$$

For various target values $N_C(\tau)$ taking into account various combinations of R and τ a set of values $N'(R,\tau)$ and $\sigma_N(R,\tau)$ is pre-calculated and a nomogram is plotted, which provides the necessary expeditiousness of spatio-temporal prediction of the troposphere refractive index at the point D on the way of ship.

For the calculation of refractive index statistical characteristics used to plot a predictive nomogram, it is necessary to calculate the statistical characteristics of the temperature at a certain height with a known air pressure.

Consider the path of ship movement n the Atlantic Ocean, for which it is necessary to make a prediction of the refractive index at the averaged point of path. For this purpose, we use the statistical characteristics of temperature on the surface 1000 *hPa*, taken from [5] and [6], and presented in Table 1.

Table 1

Statistical characteristics of the temperature at a height of 1,000 *hPa* in the tropical zone of the Atlantic Ocean

P, *hPa*	$\overline{T}$ °K	σ_T	$\overline{q}$	σ_q	$K_T(6)$	$K_T(12)$	$K_T(18)$
1000	297.2	1.6	15.7	1.7	0.75	0.64	0.62

According to Table 1 the following is calculated:

1) average value $\overline{N}$ from the formula [7]:

$$\overline{N} = A\frac{\overline{P}}{\overline{T}} + B\frac{\overline{P}\,\overline{q}}{\overline{T}^2} = 370{,}7N_{\text{ед}}\ , \qquad (16)$$

where $A = 77{,}6$; $B = 6\cdot10^2$;

mean-square deviation σ_N :

$$\sigma_N = \frac{\overline{P}}{\overline{T}^2}\left[\left(A+2B\frac{\overline{q}}{\overline{T}}\right)\sigma_T - B\,\sigma_q\right] = 8{,}95\ N_{\text{ед}}. \qquad (17)$$

In the absence of values $K_N(\tau)$ and $K_N(R)$ we can use the following equations obtained in [8]

$$K_N(\tau) = K_T(\tau) = K_q(\tau)\ , \qquad (18)$$

$$K_N(R) = K_T(R) = K_q(R)\ . \qquad (19)$$

Taking into account (17) and (18), the relations (13) and (14) have the following form:

$$N'_D(R,\tau) = \overline{N} + K_T(R)\,K_T(\tau)\left[N_C(0) - \overline{N}\right], \qquad (20)$$

$$\sigma_{N_D}(R,\tau) = \sigma_N\sqrt{1-[K_T(R)\,K_T(\tau)]^2}\ . \qquad (21)$$

The paper [8] defines the relationship between the spatial and temporal structural functions of temperature $D_T(R) = 2{,}5\cdot10^{-5}R$ (*m²/s²*) and $D_T(\tau) = 2{,}1\cdot10^{-4}\tau$ (*deg²/s²*), whereby $K_T(R) = K_T(\tau)$. Equating the right-hand sides of the spatial and temporal functions we obtain the same temperature variations through 8.4 *m* of distance and through 1 *s* of time, or respectively $K_T(\tau = 1\,ч) = K_T$ (R=30*km*).

Based on the variability of $K_T(\tau)$ and $K_T(R)$, $[K_T(R)\cdot K_T(\tau)]$ are calculated and then a calculation of $N'_D(R,\tau)$ and $\sigma_N(R,\tau)$ is carried out for a set of values $N(0)$ and $[K_T(R)\cdot K_T(\tau)]$ from which a predictive nomogram is plotted for determining the refractive index at the point D .

Conclusions.

1. The method of predicting the spatio-temporal variability of the refractive index at any point of the troposphere from the known values of meteorological parameters at the reference poin is substantiated.

2. A spatio-temporal relationship between the values of the troposphere refractive index at two points is established.

3. The findings of theoretical research will be further used in the plotting of the nomogram for predicting the most probable value of the troposphere refractive index at any point along the path of ship movement.

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