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PROBABILITY OF ERRONEOUS RECEPTION OF NAVIGATIONAL RADIO SIGNALS UNDER IONOSPHERIC DISTURBANCES

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Abstract: The work deals with the issues of the determination of the probability of frequency-selective fading (FSF) of navigational radio signals in satellite radio navigation systems under artificial ionosphere disturbances. The connection between the coherence band of the trans-ionospheric channel and the conditional size of ionospheric inhomogeneities is established. Based on the results of computer simulation, the threshold values of the Mean square deviation (MSD) of fluctuations of the total electron content in the inclined radio-line are determined, in which the probability of frequency-selective fading is high. This study will enable improving the operation of the developed information system of the ionosphere monitoring.

Keywords: satellite radio navigation systems; size of ionospheric inhomogeneities; artificial disturbances of the ionosphere; the probability of arising the frequency-selective fading; coherence band of the transionospheric channel.

I. INTRODUCTION

It is known that ionosphere heating by high-power short-wave radiation can lead to the emergence of an artificial ionospheric formation (AIF).A characteristic feature of the AIF is the appearance of intense irregularities in the electron concentration (EC) of various scales. Frequency-selective fading (FSF) of navigation signals arises in the case of ionospheric disturbances (for example, AIF), accompanied by increasing of the EC fluctuations $(\Delta N(h_m) \cong \Delta N_m)$ of small-scale irregularities at the height of the ionization maximum $h = h_m$. It causes an increase in the fluctuations of the total electron content (TEC) in the ionosphere $\Delta N_T : \Delta N_m$ on the propagation path of radio waves from the navigational space vehicle(NSV) throughthe AIF to the ground receiver.It causes the narrowing of the coherence band $(\Delta F_k \sim \frac{1}{\Delta N_T})$ of the transionospheric communication channel, caused by the scattering properties of ionospheric irregularities. Modern satellite radio navigation systems (SRNS) use broadband navigation radio signals with a spectrum width $\Delta F_0 = 10$ MHz

.Therefore, the narrowing of the coherence band of the TRANS-ionospheric communication channel to values less than the width of the signal spectrum ($\Delta F_k < \Delta F_0 =$ 10 MHz) will result in FSF of the navigation radio signals (NRS). [1-4]

It is known [5] that the positioning accuracy in the SRNS can decrease significantly (by orders of magnitude) if the FSFarises in at least one of the four navigation radio lines measuring pseudoranges. Consequently, the issue of determining the probability of the FSF arising in the radio links of the SRNS is very relevant.

II. OBJECTIVE

The goal of the article is to determine if the frequency selective fading of navigation radio signals can ariseunder ionospheric disturbances that are accompanied by an increase in small-scale fluctuations of the total electronic content in an artificial ionospheric formation on the propagation path of radio waves.

III. PROBLEM STATEMENT

Let us suppose that a local AIF region appears in the F-layer of the ionosphere, where an increase in the mean-square deviation ($\sigma_{\Delta N}$) of the fluctuations of the EC(ΔN_m) in small-scale irregularities is observed. The size of the emerging small-scale irregularities in the AIF is a random variable characterized by a minimum (L_m) and a maximum (L_0) scale. The zenith angle of the navigational space vehicle (NSV) assumes values at the range $\Theta = 0^0 ... 85^0$. It is required to determine if the mean square deviation (MSD) of small-scale AIF fluctuations can exceed its threshold value ($\sigma_{\Delta N} \geq \sigma_{\Delta N_T}^{thr}$), which characterizes the probability of the FSFarising in the satellite radio link.

IV. EXPERIMENTAL PARAMETERS OF IONOSPHERIC DISTURBANCES

The following states of the ionosphere can be distinguished [5-7]:

- normal ($\sigma_{\Delta N} = 2 \cdot 10^9 \div 2 \cdot 10^{10}$ el/m^3);
- slightly disturbed ($\sigma_{\Delta N} \leq 2 \cdot 10^{11}$ el/m^3);
- medium-disturbed ($\sigma_{\Delta N} \leq 2 \cdot 10^{12}$ el/m^3);
- strongly disturbed($\sigma_{\Delta N} > 2 \cdot 10^{12}$ el/m^3).

There is a technique and equipment [8] that allows using the navigation equipment “NovAtel GPS-6” to measure the fluctuations of the TEC in the inclined radio link ($\Delta N_T : \Delta N(h_m)$) and calculate their RMS ($\sigma_{\Delta N_T}$) directly on the signal propagation path. The value $\sigma_{\Delta N_T}$ is defined as [9,10]:

$$\sigma_{\Delta N_T} = \sigma_{\Delta N} \sqrt{\left(L_0 L_m\right)^{1/2} h_E \sec \Theta \Gamma(p/2 - 1\big/2)\sqrt{\pi}\ \Gamma(p/2 - 1)}\ , \qquad (1)$$

where L_0, L_m are the minimal and maximal scales of the ionosphericirregularities; h_E is the equivalent thickness of the ionosphere ; Θ is the NSV zenith angle; p is the phase spectrum index; Γ(x) is the gamma function.

The expression (1) includes the conditional size of ionospheric irregularities ($L_U = \sqrt{L_o L_m}$) which is a random variable. According to [11- 13], the minimum size of ionospheric irregularities can take on values 10 m ≤ L_m ≤ 100 m; the maximum size (L_o) can vary from a few hundred meters to a dozen kilometers. The conducted computer simulation enables stating that the conditional size of ionospheric irregularities at the above values L_m and L_o changes within the limits of $50\text{ м} \leq L_U \leq 880\text{ м}$.

The coherence band of the transionospheric communication channel (ΔF_k) is related to the RMS ($\sigma_{\Delta N_T}$) by inversely proportional dependence [5,9]

$$\Delta F_k = \frac{2\ f_0^2 c}{80.8\pi\sigma_{\Delta N_T}\sqrt{2(1 + d_1^2\ / 2)}} \qquad (2)$$

where f_0 –frequency NRS in [Hz]; c–propagation velocity(3.10^8 M/C); 80.8 – coefficient with dimension [m3/s2]; d_1^2 – a parameter that takes into account the increase of diffraction effects in the wave front as it propagates on the z path inside the ionosphere (with equivalent thickness) and behind it in the free space to the receiver at vertical propagation (~600 km)

$$d_1^2 = \left(3z^2 3zh_E + h_E^2\right)c^2 \sec^2 \Theta \big/ 192\pi^2 f_0^2 L_U^4\ . \qquad (3)$$

According to [5], the specified condition of the lack of FSF impact on reaching the permissible probability of erroneous reception of signals in satellite radio systems ($P_{er} = 10^{-5}$) looks like $\Delta F_0 \big/ \Delta F_k \leq 0.1$. Thus, it is possible to find from the expression (2) the threshold value of the fluctuation RMS of the ionospheric EC in the inclined radio link ($\sigma_{\Delta N_T}^{thr}$)for $\Delta F_k = \Delta F_0 \big/ 0.1$, at which the FSF of the received signal:

$$\sigma_{\Delta N_T}^{thr} = \frac{0.2\ f_0^2 c}{80.8\pi\Delta F_0\sqrt{2(1 + d_1^2\ / 2)}}\ . \qquad (4)$$

The coefficient d_1^2in (4) depends on the zenith angle (Θ) in addition to the value of L_U.According to (4), computer simulation was conducted and dependences $\sigma_{\Delta N_T}^{thr}$ on the conditional size of the ionospheric irregularities L_U were obtained. The analysis of these dependences show that when ionospheric disturbances arise, the average RMS value of EC fluctuations in the ionosphere in an oblique radio link ($\sigma_{\Delta N_T}$) reaches its threshold values faster in cases where the conditional size of ionospheric discontinuities (LU) is minimum and it is tens of meters. At the same time,for a zenith and near-horizon NFA,the threshold value $\sigma_{\Delta N_T}^{thr}$ when the size of ionospheric irregularities $L_U = 50\text{м}$ differ by an order of magnitude: $\sigma_{\Delta N_T}^{thr} \approx 1.7 \cdot 10^{16}\ el/m^2$ for a zenith NSV ($\Theta = 0^0$) and $\sigma_{\Delta N_T}^{thr} \approx 2.3 \cdot 10^{15}\ el/m^2$ for a near-horizon ($\Theta = 85^0$) NSV.

This difference decreases and it is practically absent with an increase in the size of ionospheric irregularities, when the value L_U reaches values $L_U \geq 300$ m, and the threshold value becomes $\sigma_{\Delta N_T}^{thr} \approx 2.1 \cdot 10^{15}\ el/m^2$.

The greatest danger in terms of arising the FSF navigation radio signals in the SRNS will be small-scale ionospheric irregularities of small size (of the order of tens of meters). Computer simulation data enable stating that for navigational radio signals that have the spectrum width equal to $\Delta F_0 = 10\,\text{МГц}$, the threshold value $\sigma_{\Delta N_T}^{thr}$, when the FSF arises, lies within the range of $2.3 \cdot 10^{15} \leq \sigma_{\Delta N_T}^{thr} \leq 2.1 \cdot 10^{16}\ el/m^2$.

Due to the conducted study, it can be stated that in the case where the signal enters the AIF from the zenith NSV, the FSF can arise only with strong IP. If the signal enters the AIF from the horizontal NSV, the value $\sigma_{\Delta N}$ can reach and exceed its threshold value $\sigma_{\Delta N_T}^{thr}$ already under ionospheric disturbances of medium intensity. Let us determine the probability of this event.

Probability of frequency - selective fading. Ionospheric disturbances may be sudden. Such disturbances arise when pulsed sources are applied to the ionosphere. This may be due to both natural (sudden flare on the Sun) and artificial causes (man-made accidents, rocket launches, explosions, etc.). The duration [12 – 14] of ionospheric disturbances due to these processes can be several minutes, and their amplitude can exceed the background level by several orders of magnitude. The mean-square deviation of TEC fluctuations can increase by 3 orders of magnitude and reach the values $\sigma_{\Delta N_T} : 100\ TECU = 10^{18}\ el/m^2$ with a highly perturbed ionosphere in the AIF, which can lead to the FSF arising. Therefore, the determination of the probability of the FSF arising in the case of ionospheric disturbances in the AIF is an important task.

According to [5], the value of TEC fluctuations in the oblique radio link ΔN_T is a random variable distributed according to the normal law with mathematical expectation $m(\Delta N_T) = 0$ and RMS $\sigma_{\Delta N_T}$.The above threshold value of the mean-square deviation of TEC fluctuations in the ionosphere in an oblique radio link ($\sigma_{\Delta N_T}^{thr}$) is a numerical characteristic of a random variable at which the FSF of the received NRS can arise.

Let us determine the probability of exceeding the random value ΔN_T the threshold values, $\Delta N_T^{thr} \approx \sigma_{\Delta N_T}^{thr}$, at which the FSF of the accepted RNS can arise at various degrees of ionospheric disturbances. A computer simulation was carried out simulating the arising of medium and strong ionospheric disturbances. The value of the conditional size of irregularities was taken to be L_U = 50; 100; 400; 1000 m.

The fluctuation value of the integral EC in the oblique radio link (ΔN_T) is distributed according to the normal law with the expectation $m(\Delta N_T) = 0$ and the following values of the standard deviation:

- for $\Theta = 0^0$ and strong disturbances $\sigma_{\Delta N_T} = \left[6 \cdot 10^{15}; 8 \cdot 10^{15}; 1.7 \cdot 10^{16}; 3 \cdot 10^{16}\right] el/m^2$;
- for $\Theta = 85^0$ and medium disturbance $\sigma_{\Delta N_T} = \left[1.2 \cdot 10^{16}; 1.8 \cdot 10^{16}; 3 \cdot 10^{16}; 4 \cdot 10^{16}\right] el/m^2$;
- for $\Theta = 85^0$ and strong disturbances $\sigma_{\Delta N_T} = \left[4.3 \cdot 10^{16}; 5.2 \cdot 10^{16}; 7 \cdot 10^{16}; 9.2 \cdot 10^{16}\right] el/m^2$.

If the value ΔN_T exceeds the threshold value $\Delta N_T \geq \Delta N_T^{thr}$ ($\Delta N_T^{thr} = \sigma_{\Delta N_T}^{thr}$), the FSF arises in the radio link. The probability of the FSF arising is determined by the expression

$$P(\Delta N_T \geq \Delta N_T^{thr}) = 1 - P(\Delta N_T \leq \Delta N_T^{thr}) = 1 - \frac{1}{2} F\left(\frac{\Delta N_T^{thr} - m(\Delta N_T)}{\sigma_{\Delta N_T} \geq \sqrt{2}}\right), \tag{5}$$

where F(x) is the Laplace function.

The results of computer simulation are presented in Fig.1, 2 and 3.The threshold values, ΔN_T^{thr}, are plotted on the horizontal axis in accordance with the data of Figure 2. The value of the threshold value varies within $\Delta N_T^{thr} = 8.8 \cdot 10^{15} \ldots 2.1 \cdot 10^{16}\ el/m^2$ for zenith satellite (Fig.1) and $\Delta N_T^{thr} = 8.4 \cdot 10^{14} \ldots 2.1 \cdot 10^{16}\ el/m^2$ for near-horizon satellite (Fig.2 and 3). The vertical axis represents the value of the probability $P(\Delta N_T \geq \Delta N_T^{thr})$ of exceeding a randomly generated value over the corresponding threshold value ΔN_T, calculated in accordance with (4), at which the FSF of radio signals can arise. The FSF can arise only with strong ionospheric disturbances in the case when a signal from a zenith satellite ($\Theta = 0^0$) passes through the disturbed ionosphere. At the same time, the probability of their arising is sufficiently large and takes the values

$P(\Delta N_T \geq \Delta N_T^{thr}) = 0.45...0.8$ for $\sigma_{\Delta \mathrm{N_T}} = 3.10^{16}\ el/m^2$ and $P(\Delta N_T \geq \Delta N_T^{thr}) = 0.2...0.6$ for $\sigma_{\Delta \mathrm{N_T}} = 1.7 \cdot 10^{16} el/m^2$ (Fig.1).

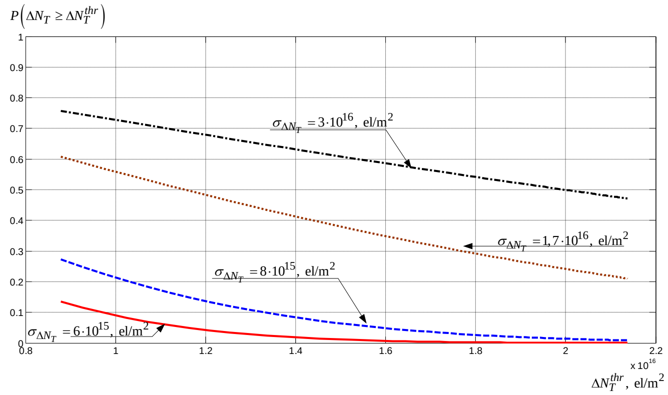

Figure1. The probability of exceeding the threshold value of TEC fluctuations in a highly perturbed ionosphere with vertical propagation ($\Theta = 0^0$)

The probability of arising does not exceed the value $P(\Delta N_T \geq \Delta N_T^{thr}) \leq 0.3$ at lower values $\sigma_{\Delta \mathrm{N_T}} = [6.10 \cdot 10^{15}; 8.10 \cdot 10^{15}] el/m^2$. The probability of arising FSF is insignificant and does not exceed the values $P(\Delta N_T \geq \Delta N_T^{thr}) \approx 10^{-2}$ under ionospheric disturbances of average intensity (not shown in Fig. 1).

The FSF can arise even with medium ionospheric disturbances in the case of near-horizontal propagation of RNS ($\Theta = 85^0$) (Fig. 2).

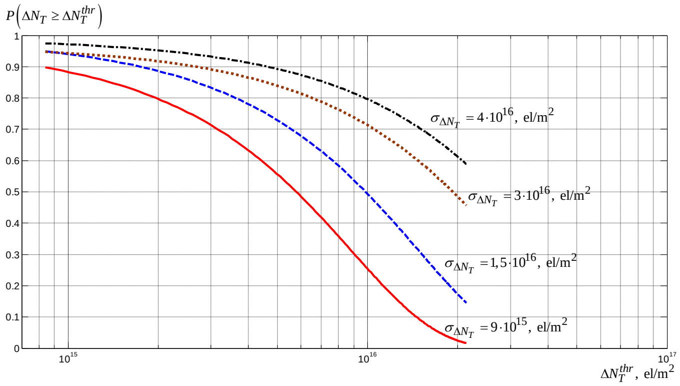

Figure 2. The probability of exceeding the threshold value of TEC fluctuations in medium perturbed ionosphere and near-horizontal distribution of RNS ($\Theta = 85^0$)

In this case, the probability of FSF can reach values $P(\Delta N_T \geq \Delta N_T^{thr}) = 0.5 \ldots 0.98$ with $\sigma_{\Delta \mathrm{N_T}} = \left[1.5 \cdot 10^{15};\ 3 \cdot 10^{16};\ 4 \cdot 10^{16}\right] el/m^2$ and small sizes of irregularities ($\mathrm{L_U} \leq 100$ m), when the threshold value $\Delta N_T^{thr} \leq 10^{16}\ el/m^2$.

The probability of arising FSF is also high for small sizes of irregularities ($\mathrm{L_U} \leq 80$ m) in the case where the value $\sigma_{\Delta \mathrm{N_T}} < 10^{16}$el/m^2, when the threshold value $\Delta N_T^{thr} \leq 6 \cdot 10^{16}\ el/m^2$. Then the value of the probability of FAF arising decreases dramatically and reaches values close to zero with the conditional size of irregularities$\mathrm{L_U} \geq$ 300 m.

The probability of FSF arising is very high and exceeds the value $P(\Delta N_T \geq \Delta N_T^{thr}) > 0.6$ for any size of ionospheric irregularities with strong ionospheric disturbances and near-the-horizon propagation of a radio signal (Fig.3).

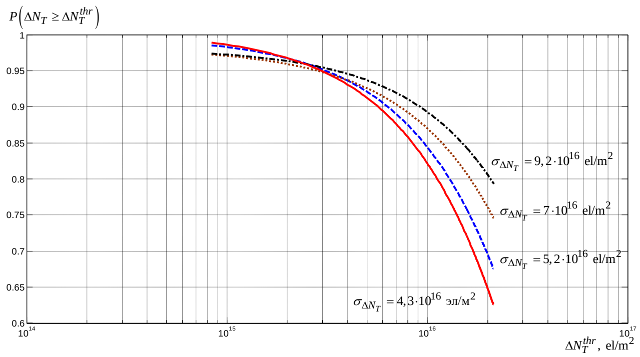

Figure 3. The probability of exceeding the threshold value of TEC fluctuations in highly perturbed ionosphere and near-horizon distribution of RNS ($\Theta = 85^0$)

The probability of FSF arising is close to unit $P(\Delta N_T \geq \Delta N_T^{thr}) = 0.83 \ldots 0.99$ with small sizes of irregularities ($\mathrm{L_U} \leq 100$ m).

V. DISCUSSION

The study shows that determining the threshold values of TEC fluctuations in an oblique radio link will make it possible to select "suspicious" radio signals from the entire set of NRSs in the case of an AIF, and to measure the coherence band (ΔF_k) within these radio linksonly. The results obtained in this work enable specifying the algorithm of the information system of monitoring the ionosphere which has been proposed in [4].

VI. CONCLUSION

The following conclusions can be drawn from the study. If ionospheric irregularities of small-scale (tens of meters) arise in the ionosphere, then the mean-square deviation of TEC fluctuations in the ionosphere in an inclined radio link reaches its threshold value ($\sigma_{\Delta N_T}^{thr}$) faster than in case of ionospheric irregularities with dimensions ~102 m. The probability of FSF arising in a radio link is determined by the probability of exceeding the value of TEC fluctuations of its threshold value $P(\Delta N_T \geq \Delta N_T^{thr})$ at which the coherence band can narrow to the value $\Delta F_k = \Delta F_0 / 0.1$. In this case, the threshold value $\Delta N_T^{thr} = \sigma_{\Delta N_T}^{thr}$. The probability of FSF arising is close to zero in the case of the weakly perturbed ionosphere. FSF can arise in near-horizontal NSV in the case of medium ionospheric disturbances. In the case of strong ionospheric disturbances, FSF can arise with a high degree of probability for any conditional sizes of ionospheric irregularities and for all values of the zenith angle.

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