METHOD FOR FORECASTING OF INTERFERENCE IMMUNITY OF LOW FREQUENCY SATELLITE COMMUNICATION SYSTEMS

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Abstract: This article describes analysis of interference immunity of low frequency satellite communication systems under conditions of ionosphere disturbances accompanied by formation of small-scale irregularities of electron concentration. The model of electron concentration distribution in disturbed ionosphere and the model of transionospheric communication channel have been developed allowing to determine probability of erroneous signal reception as a function of root-mean-square deviation of small-scale fluctuations of total electron content. In order to determine them by GPS sounding, dual frequency receiver GPStation-6 of satellite navigation systems has been modified expanding significantly its capabilities. It is exemplified by modification of interference immunity of Gonets-D1M satellite communication system upon increasing fluctuations of total electron content during formation of regions with small-scale irregularities of electron concentration in ionosphere. The obtained results allow to develop practical recommendations for improvement of interference immunity of satellite communication radio systems under ionosphere disturbances on the basis of GPS sounding.

Keywords: dual frequency receiver, GPS sounding, interference immunity, ionosphere disturbance, satellite communication systems, satellite navigation systems, small-scale irregularities, total electron content.

1 Introduction

It is known [1, 2] that in the regions of equatorial and polar latitudes, natural disturbances of ionosphere are observed which cause interference fading (scintillations) of received signals upon transionospheric radio wave propagation (RWP) in satellite communication systems (SCS). In addition, impacts on ionosphere by powerful heating facilities, injection of easily ionized chemical substances, and other artificial factors can cause frequency selective fading and intersymbol interference of received SCS signals [3, 4]. Under such conditions, interference immunity of satellite radio systems drops significantly (by several orders of magnitude).

Analysis of reasons of ionospheric scintillations in SCS demonstrates as follows [5, 6]. Natural and artificial phenomena in the regions of equatorial and polar latitudes can result in occurrence of specific ionospheric formations. They are comprised of small-scale irregularities of electron concentration (ΔN_i) with regard to average (background) value ($\overline{N}$). These small-scale irregularities are expanded along the Earth magnetic field, their transversal dimensions are $l_i = 10...1000$ m. The small-scale irregularities of electron concentration stipulate small-scale fluctuations of total electron content (TEC) in ionosphere $\Delta N_{Ti} \sim \Delta N_i z_e$ with equivalent thickness z_e with regard to average TEC ($\overline{N_T} \sim \overline{N} z_e$) along RWP route from transmitter (XMTR) of spacecraft (SC) to on land receiver (RCVR) of SCS. Under conditions of ionosphere disturbances and occurrence of ionospheric formations, the small-scale TEC fluctuations ($\Delta N_{Ti} \sim \Delta N_i z_e$) can increase by 1–3 orders of magnitude and higher in comparison with normal (nondisturbed) ionosphere. Therefore, RWP under such conditions is accompanied by dissipation of radio waves on small-scale irregularities, occurrence of multipath propagation and fading of received signals [1-6]. Moreover, with increase in small-scale TEC fluctuations and decrease in carrier frequency (f_0) of SCS, relative phase ($\Delta\varphi_i \sim \Delta N_{Ti}/f_0$) and time ($\Delta\tau_i \sim \Delta N_{Ti}/f_0^2$) lagging of incoming beams will increase. As a consequence of interference of incoming beams, the average signal power at SCS receiver input will be comprised of regular and fluctuation constituents $\overline{P}_r = P_{reg} + P_{fl}$, their ratio depends on $\Delta\varphi_i$ and determines the parameters of Rician fading and scintillation index of received signals:

$$\gamma^2 = P_{reg}/P_{fl} \sim 1/\Delta\varphi_i \, ; \, S_4^2 \sim P_{reg}/\overline{P_r} \sim \Delta\varphi_i \, . \qquad (1), (2)$$

The mentioned parameters γ^2 and S_4^2 characterize the depth of general (that is, nonselective, smooth) fading of received signals. However, with the increase in phase ($\Delta\varphi_i \sim \Delta N_{Ti}/f_0$) and time ($\Delta\tau_i \sim \Delta N_{Ti}/f_0^2$) shifts of incoming beams, there occurs narrowing of the coherence bandwidth of incoming beams (that is, the interval of frequency correlation) of transionospheric communication channel $F_c = 1/\Delta\tau_i \sim f_0^2/\Delta N_{Ti}$, which can lead to occurrence of frequency selective fading (FSF) $F_0 / F_c \geq 1$ and intersymbol interference (ISI) $\Delta\tau_i \approx 1/F_c \geq T_S$ upon transmitting signals with wide spectrum band F_0 and low duration T_s [5, 6]. Existence of general fading, FSF and ISI in transionospheric communication channel leads to significant decrease in SCS interference immunity.

It is obvious that the most significant influence of the mentioned RWP factors via disturbed ionosphere is exerted on SCS interference immunity with low orbit SC upon operation at relatively low carrier frequencies ($f_0 = 137...138$MHz and $f_0 = 387...390$ MHz) [7]. Further on, such SCS will be referred to as low frequency.

Therefore, under conditions of ionosphere disturbances and occurrence of ionospheric formations with small-scale irregularities, the SCS interference immunity (characterized by probability of erroneous signal receiving $P_{err} = \psi(h^2)$ as a function of signal/noise ratio h^2) will depend on TEC fluctuations (ΔN_{Ti}) and selection of the frequency and time parameters of signals (f_0, F_0, T_S): $P_{err} = \psi(h^2, \gamma^2, F_c) = \psi(h^2, \Delta N_{Ti}, f_0, F_0, T_S)$.

SCS interference immunity under conditions of occurrence of ionospheric formations with small-scale irregularities can be improved on the basis of monitoring of TEC fluctuations of ionosphere (ΔN_{Ti}) and adaptation of the frequency and time parameters of transmitted signals (f_0, F_0, T_S).

Thus, an urgent scientific problem exists comprised of development of analysis of interference immunity of low frequency SCS and recommendations on its improvement under conditions of ionospheric disturbances resulting in occurrence of ionospheric formations with small-scale irregularities on the basis of monitoring of TEC fluctuations of ionosphere.

This problem can be solved on the basis of implementation of the following projects:

1) model of TEC variation (N_T) in ionospheric formations with small-scale irregularities;

2) models of transionospheric communication channel with fading of various types allowing to determine fading parameters as a function of root-mean-square deviation (RMSD) of small-scale TEC fluctuations ($\sigma_{\Delta N_T} = \left(\overline{\Delta N_{Ti}^2}\right)^{0,5}$) of ionosphere:

$$\left\{\gamma^2, S_4^2, F_\kappa\right\} = \psi\left(\sigma_{\Delta N_T}\right); \qquad (3)$$

3) analysis of SCS interference immunity allowing to determine error probability as a function of RMSD of TEC fluctuations of ionosphere, parameters of transmitted signals and factor of their diverted reception (n_{div}):

$$P_{err} = \psi\left(h^2, \sigma_{\Delta N_T}, f_0, F_0, T_S, n_{div}\right); \qquad (4)$$

4) RMSD monitoring of TEC fluctuations ($\sigma_{\Delta N_T}$) of ionosphere on the basis of GPStation-6 dual frequency receiver (GISTM class);
5) recommendations on improvement of operation quality of low frequency SCS on the basis of monitoring of ionospheric formations with small-scale irregularities.

2 Methods

2.1 Model of variation of total electron content in ionized formation with small-scale irregularities

It is known [6, 8] that variation of electron concentration in ionospheric formations with small-scale irregularities along the height (z) and space ($\rho = x, y$) is described as follows:

$$N(z,\rho) = \overline{N}(z) + \Delta N(z,\rho), \qquad (5)$$

where $\Delta N(z,\rho)$ is the small-scale fluctuations of electron concentration with regard to variation along height of average (background) electron concentration $\overline{N}(z)$ in ionosphere (Figure 1a). According to Eq. (5), spatial variations of TEC upon vertical transionospheric RWP from SC (at the height of z_{Es}) to on land SCS receiver are determined as follows:

$$N_T(\rho) = \int_0^{z_{Es}} N(z,\rho)dz = \int_0^{z_{Es}} \overline{N}(z) + \Delta N(z,\rho)dz = \overline{N}_T + \Delta N_T(\rho) \equiv \overline{N}_T + \Delta N_{Ti}, \qquad (6)$$

where $\overline{N}_T = \int_0^{z_{Es}} \overline{N}(z)dz = \overline{N}_m z_e$ is the average TEC of ionosphere; $\overline{N}_m = \overline{N}(z_m)$ is the maximum average electron concentration in ionosphere at the height of $z = z_m$ (Figure 1a); z_e is the equivalent thickness of homogeneous atmosphere with electron concentration $\overline{N}_m$ (at normal ionosphere $\overline{N}_m \approx 10^{12}\, el/m^3$); $\Delta N_T(\rho) = \int_0^{z_{Es}} \Delta N(z,\rho)dz \equiv \Delta N_T(\rho_i) \equiv \Delta N_{Ti}$ is the spatial small-scale TEC fluctuations in ionosphere with small-scale irregularities of electron concentration $\Delta N(z,\rho)$.

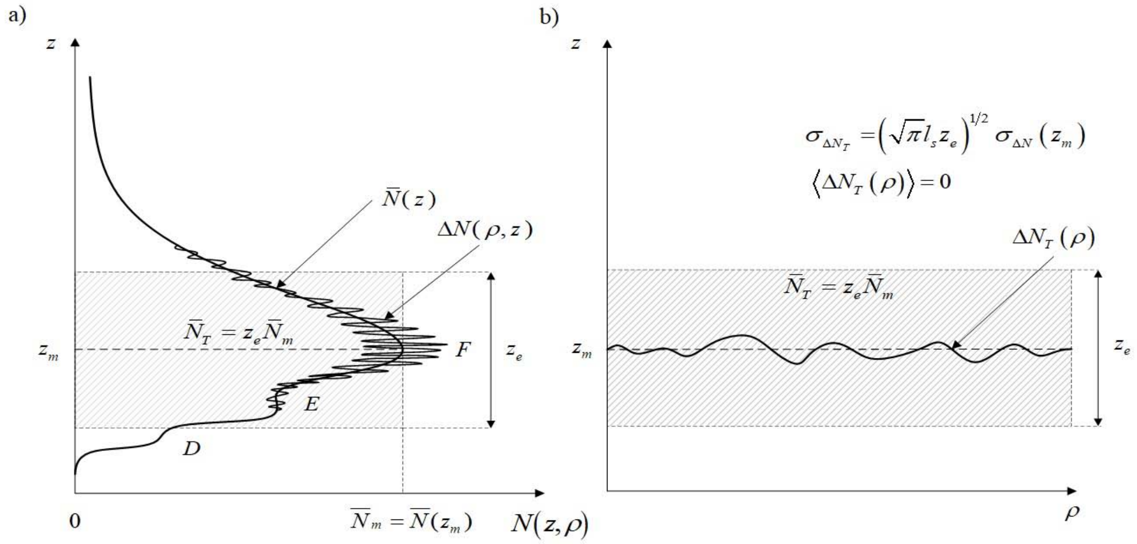

Figure 1. a) variation of electron concentration in ionosphere formation by small-scale irregularities along the height (z) and space ($\rho = x, y$); b) model of ionosphere in the form of thick homogeneous layer and thin layer of TEC irregularities.

Statistical properties of small-scale TEC fluctuations are described by zero average $\overline{\Delta N_T(\rho)} = 0$ and RMSD, which at Gauss spectrum of irregularities with characteristic (average) scale l_s is determined as [6, 8]:

$$\sigma_{\Delta N_T э} = \left[\overline{\Delta N_T(\rho)^2}\right]^{0,5} = \left(\sqrt{\pi} l_s z\right)^{0,5} \sigma_{\Delta}(z), \qquad (7)$$

where $\sigma_{\Delta N}(z_m)$ is the RMSD fluctuations of electron concentration at the height z_m of maximum ionization of ionosphere.

According to Figure 1a and Eqs. (5, 6), the mathematical model of ionosphere containing ionospheric formation with small-scale irregularities can be presented in the form of combination (Figure 1b) of: 1) thick homogeneous layer with the thickness z_e characterized by average TEC $\overline{N}_T = \overline{N}_m z_э$; 2) thin layer of irregularities positioned at the height of ionization maximum z_m and characterized by average $\overline{\Delta N_T(\rho)} = 0$ and RMSD (7) $\sigma_{\Delta N_T} \sim \sigma_{\Delta N}(z_m)$.

2.2 Models of transionospheric communication channel with fading of various types

On the basis of ionosphere model (Figure 1b), two models of transionospheric RWP were developed (Figure 2) [6, 8, 9]. The first model (Figure 2a) is based on the concept of multiple beams formed on the surface of thin layer of TEC irregularities (phase screen) $\Delta N_T(\rho) \equiv \Delta N_T(\rho_i)$ and coming to the receiver point with relative phase shifts $\Delta\varphi_i \sim \Delta N_T(\rho_i)/f_0$.

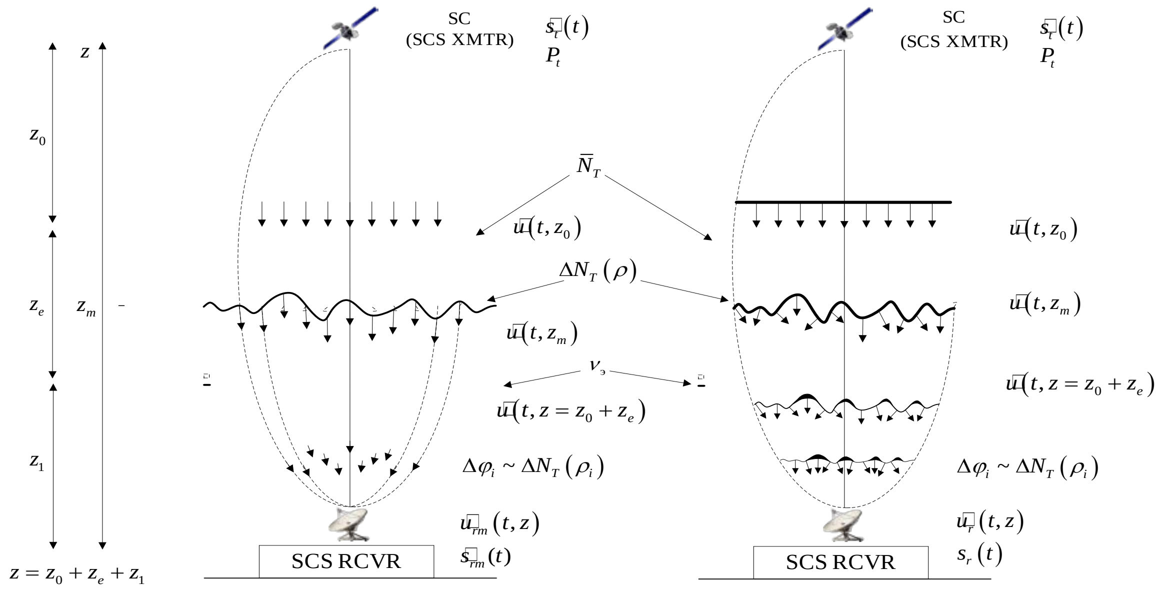

Figure 2. Models of transionospheric RWP based on concepts of multipath propagation (a) and diffraction (b) of wave on ionosphere irregularities.

On this basis equations were derived for complex signal at receiver input $\dot{s}_{r\text{M}}(t,z)$ and average power of received signal [6, 8, 9]:

$$\overline{P}_r = P_t K_{\text{att}} \overline{|\dot{R}_{fl}|^2} = P_{\text{div}} + P_{\text{fl}} = \alpha_{reg}^2 P_t K_{att} + 2\sigma^2 P_t K_{\text{att}}, \quad (8)$$

where K_{att} was the coefficient of power attenuation of transmitted signal P_t in transionospheric communication channel without irregularities and multipath propagation (that is, with accounting for attenuation in free space and absorption in ionosphere). Dispersion of module of normalized transmittance factor of transionospheric multipath communication channel is described as follows:

$$\overline{|\dot{R}_{fl}|^2} = \overline{\left|\sum_{i=1}^{M}\exp(-j\Delta\varphi_i)\right|^2} = \overline{\left|\sum_{i=1}^{M}\exp(-j80{,}8\pi\Delta N_T(\rho_i)/cf_0)\right|^2} = \alpha_{reg}^2 + 2\sigma^2 . \quad (9)$$

Analysis of Eq. (9) demonstrates that the regular α_{reg}^2 and fluctuation $2\sigma_{в}^2$ constituents of the transmittance factor of transionospheric multipath communication channel depend on small-scale TEC fluctuations of ionosphere $\Delta N_T(\rho_i)$. However, in the frames of development of multipath models of transionospheric communication channel it is impossible to obtain analytical expressions of the constituents $\alpha_{reg}^2 = \psi(\sigma_{\Delta N_T}/f_0)$ and $2\sigma_{в}^2 = \psi(\sigma_{\Delta N_T}/f_0)$ of normalized transmittance factor as a function of RMSD small-scale TEC fluctuations of ionosphere (7) $\sigma_{\Delta N_T} = \left[\overline{\Delta N_T(\rho)^2}\right]^{0,5}$ and selection of carrier frequency in SCS (f_0) from Eq. (9) for $\overline{|\dot{R}_{fl}|^2}$. This problem can be solved by the methods of statistical radio physics describing wave diffraction on irregularities of ionosphere in addition to transionospheric RWP (Figure 2b).

The method of phase screen is the simplest, it determines average intensity ($\overline{I}_r = I_{\text{reg}} + I_{\text{fl}}$) of wave field at input of receiving antenna $\dot{u}_{r\text{M}}(t,z)$ as well as its regular (I_{reg}) and fluctuation (I_{fl}) constituents according to Eqs. [6, 8, 9]:

$$\overline{I}_r(z) = I_{\text{reg}}(z) + I_{\text{fl}}(z) = A_0^2(z)\exp(-\sigma_\varphi^2) + A_0^2(z)\left[1-\exp(-\sigma_\varphi^2)\right] = A_0^2(z) = P_t K_{\text{att}}(z), \quad (10)$$

where $A_0(z) = \sqrt{P_t K_{\text{att}}(z)}$ is the amplitude in the front of received wave without scintillations determined by the coefficient of power attenuation of transmitted signal of emitted wave $K_{\text{att}}(z)$ in free space and due to absorption in ionosphere; σ_φ is the RMSD fluctuations of phase $\Delta\varphi(z_m,\rho_i) = \Delta\varphi_i$ in the wave front at outlet of heterogeneous ionospheric layer (phase screen) determined by RMSD $\sigma_{\Delta N_T}$ TEC fluctuations $\Delta N_T(\rho)$ of ionosphere as [6]:

$$\sigma_\varphi = \left(\overline{\Delta\varphi_i^2}\right)^{0,5} = 80{,}8\pi\left[\overline{\Delta N_T(\rho)^2}\right]^{0,5}/cf_0 = 80{,}8\pi\sigma_{\Delta N_T}/cf_0 . \quad (11)$$

According to Eq. (10), the average signal power at the outlet of receiving antenna (that is, at inlet of SCS receiver) is determined as:

$$\overline{P}_r = P_{\text{div}} + P_{\text{fl}} = \alpha_{reg}^2 P_t K_{\text{att}} + 2\sigma^2 P K_{\text{att}} = \exp(-\sigma_\varphi^2) P K_{\text{att}} + \left[1-\exp(-\sigma_\varphi^2)\right] P K_{\text{att}} = P K_{\text{att}} . \quad (12)$$

Comparative analysis of Eqs. (8) and (12) for average signal power ($\overline{P}_r$) at outlet of SCS receiver obtained by multipath and radio physical methods confirms their identity. Hence, it is possible to write equations for regular α_{reg}^2 and fluctuation $2\sigma_{в}^2$ constituents of transmittance coefficient of transionospheric communication channel in the form of [6, 8, 9]:

$$\alpha_{reg}^2 = \exp(-\sigma_\varphi^2); \quad 2\sigma_{в}^2 = \left[1-\exp(-\sigma_\varphi^2)\right] \quad (13), (14)$$

as a function of RMSD small-scale TEC fluctuations of ionosphere $\sigma_{\Delta N_T}$ in terms of RMSD fluctuations of phase at outlet of ionospheric phase screen (11) $\sigma_\varphi = 80.8\pi\sigma_{\Delta N_T}/cf_0$.

According to Eqs. (2, 12-14), the required Eq. (6) $\gamma^2 = \psi(\sigma_{\Delta N_T})$ of parameter of Rician distribution of fading as a function of RMSD small-scale TEC fluctuations is as follows:

$$\gamma^2 = P_{\text{reg}}/P_{\text{fl}} = \alpha_{reg}^2/2\sigma_{\text{fl}}^2 = 1/\left[\exp(\sigma_\varphi^2)-1\right] = \left[\exp(80.8\pi\sigma_{\Delta N_T}/cf_0)^2 - 1\right]^{-1} . \quad (15)$$

Index of ionospheric scintillations S_4 is related with $\sigma_{\Delta N_T}$ as follows [10]:

$$S_4^2 = 1-\left[\alpha_{reg}^2\Big/\left(\alpha_{reg}^2 + 2\sigma_{в}^2\right)\right]^2 = 1-\left(\alpha_{reg}^2\right)^2 = 1-\left[\exp\left(-\sigma_\varphi^2\right)\right]^2 =$$
$$= 1-\exp\left(-2\sigma_\varphi^2\right) = 1-\exp\left[-2\left(80.8\pi\sigma_{\Delta N_T}/cf_0\right)^2\right]. \quad (16)$$

According to Eqs. (15) and (16), increase in RMSD TEC fluctuations ($\sigma_{\Delta N_T}$) upon transionospheric RWP leads to increase in RMSD fluctuations of phase in wave front at outlet of phase screen (11) $\sigma_\varphi \sim \sigma_{\Delta N_T} / f_0$ and increase in the fading depth of received signals: $\gamma^2 = P_{\text{reg}}/P_{\text{fl}} \to 0$, $S_4^2 \to 1$.

Moreover, the increase in $\sigma_\varphi \sim \sigma_{\Delta N_T} / f_0$ stipulates narrowing of coherence band of transionospheric communication channel as follows [9]:

$$F_{\text{c}} \approx f_0 \big/ \sqrt{2}\sigma_\varphi = f_0 \big/ \sqrt{2}\sigma_\varphi = cf_0^2 \big/ 80.8\pi\sqrt{2}\sigma_{\Delta N_T} . \quad (17)$$

According to Eq. (17), increase in RMSD TEC fluctuations upon transionospheric RWP $(\sigma_{\Delta N_T})$ and fluctuations of phase in wave front at outlet of phase screen (18) $\sigma_\varphi \sim \sigma_{\Delta N_T} / f_0$ leads to decrease in coherence band $F_{\text{c}} \sim f_0^2 / \sigma_{\Delta N_T}$ of fading in transionospheric communication channel.

It should be mentioned that Eqs. (15-17) were obtained for the case of vertical ($\theta_0 = 0$) transionospheric RWP (Figure 2). In the case of inclined RWP via ionosphere at the angle $\theta_0 > 0$, the equivalent thickness of ionosphere z_e and the distance to reception point (z, z_m, z_1) increase to $z'_{\text{e}} = z_{\text{e}} \sec\theta_0$; $z' = z \sec\theta_0$; $z'_m = z_m \sec\theta_0$; $z'_1 = z_1 \sec\theta_0$, and RMSD fluctuations of phase in the screen increase to $\sigma_\varphi = 80{,}8\pi\sigma_{\Delta N_T} \sqrt{\sec\theta_0} / cf_0$.

Therefore, the required Eq. (3) $\{\gamma^2, S_4^2, F_c\} = \psi(\sigma_{\Delta N_T})$ of parameters of signal fading in transionospheric communication channel as a function of RMSD small-scale TEC fluctuations of ionosphere is obtained in the form of analytical expressions (15-17).

2.3 Analysis of SCS interference immunity under conditions of ionospheric formations with small-scale irregularities

The generalized expression is known [6] for estimation of interference immunity of noncoherent reception of orthogonal signals in transionospheric communication channels with various depth of overall fading and degree of FSF and ISI:

$$P_{err} = 0.25(P_{111} + P_{110} + P_{011} + P_{010}), \quad (18)$$

where P_{a1c} is the partial value of probability of erroneous reception of symbol 1 upon transmittance of the sequence of data symbols $a1c$ (where $a, c = 0$ or 1, that is, 111, 110, 011, 010) via symmetric communication channel with fading determined as follows:

$$P_{a1c} = \frac{\gamma^2 + 1}{W_{a1c} + 2(\gamma^2 + 1)} \exp\left[-\frac{\gamma^2 W_{a1c}}{W_{a1c} + 2(\gamma^2 + 1)} \right], \quad (19)$$

where γ^2 is the Rician parameter, W_{a1c} is the average signal/noise ratio at output of noncoherent reception system upon recording of central symbol 1 determined for each sequence of the transmitted symbols $a1c$. For transionospheric communication channel, the dependence $\gamma^2 = \psi(\sigma_{\Delta N_T} / f_0)$ is determined by Eq. (15), and $W_{a1c} = \psi(h^2, \eta_{\text{f}}, \eta_{\text{is}})$ depends on inlet signal/noise ratio (h^2) and coefficient of energy loss upon processing of signals from FSF (η_{f}) and ISI (η_{is}):

$$W_{111} = h^2\eta_{\text{d}}\eta_{\text{f}}; \quad W_{110} = W_{011} = \frac{h^2\eta_{\text{d}}\eta_{\text{f}} - h^2\eta_{\text{d}}\eta_{\text{is}}}{1 + h^2\eta_{\text{d}}\eta_{\text{is}}}; \quad W_{010} = \frac{h^2\eta_{\text{d}}\eta_{\text{f}} - 2h^2\eta_{\text{d}}\eta_{\text{is}}}{1 + 2h^2\eta_{\text{d}}\eta_{\text{is}}}. \quad (20), (21), (22)$$

These losses depend on the degree of FSF ($\eta_{\text{f}} = \psi(F_0/F_{\text{c}})$ and ISI ($\eta_{\text{is}} = \Psi(1/T_s F_{\text{c}})$ of received signals as follows:

$$\eta_{\text{f}} = \left[1 + \frac{1}{2\pi^2}\left(\frac{F_0}{F_{\text{c}}}\right)^2 \right] \text{erf}\left(\frac{\pi F_{\text{c}}}{F_0}\right) - \frac{1}{\pi\sqrt{\pi}}\left(\frac{F_0}{F_{\text{c}}}\right)\left\{ 2 - \exp\left[-\left(\frac{\pi F_{\text{c}}}{F_0}\right)^2 \right] \right\} \le 1; \quad (23)$$

$$\eta_{\text{is}} = \frac{1}{2\pi^2}\left(\frac{1}{T_S F_{\text{c}}}\right)^2 \text{erf}\left(\pi T_S F_{\text{c}}\right) - \frac{1}{\pi\sqrt{\pi}}\left(\frac{1}{T_S F_{\text{c}}}\right) \exp\left[-\left(\pi T_S F_{\text{c}}\right)^2 \right] \ge 0, \quad (24)$$

where the coherence band of transionospheric communication channel depends on RMSD TEC of ionosphere according to Eq. (17): $F_{\text{c}} \sim f_0^2 / \sigma_{\Delta N_T}$.

According to Eqs. (18–24), Figure 3 illustrates estimations of interference immunity of signal reception ($P_{err} = \psi(h^2)$ in Gonets-D1M low frequency SCS (for $f_0 = 387$ MHz, $F_0 = 1024$ kHz, $R_T = 1024$ Kbit/s, $\theta_0 = 60^\circ$) during increase in RMSD TEC from $\sigma_{\Delta N_T} = 10^{13}\text{el/m}^2$ in normal ionosphere to $\sigma_{\Delta N_T} = 10^{16}\text{el/m}^2$ in ionospheric formation with small-scale irregularities.

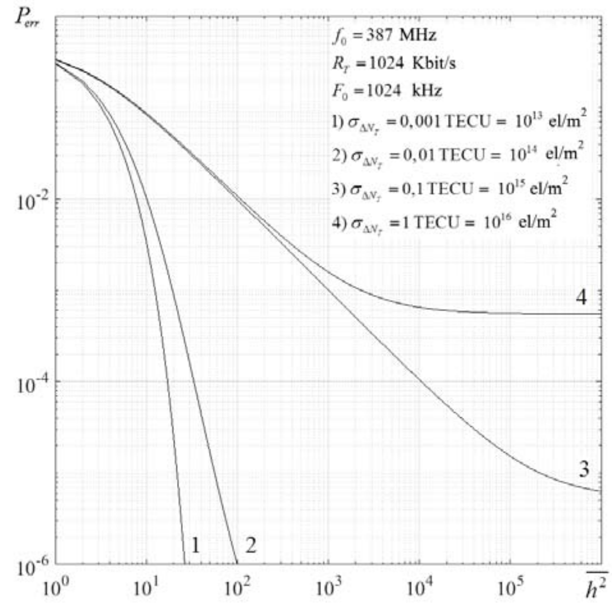

Figure 3. Estimation of interference immunity of Gonets-D1M SCS upon growth of TEC fluctuations in ionospheric formation with small-scale irregularities.

While preventing fading in SCS using conventional methods of diverted reception by several (n) branches, the probability of error $P_{err}(n) = P_{err(n)}$ can be determined irrespectively of diversion type using the known [11] approximated expression (at $h^2 >> 1$ and without fading correlation in diversion branches) as follows:

$$P_{err(n)} \approx C_{2n-1}^{n} P_{err(1)}^{n} = \left[(2n-1)!/n!(n-1)!\right] P_{err(1)}^{n}, \quad (25)$$

where $P_{err(1)} = P_{err}$ is the probability of erroneous signal reception in one diversion branch determined in this case by Eqs. (18-24). It should be mentioned that the signal/noise ratio at receiver inlet h^2 in each of n diversion branches depends on their total number and diversion type as follows [11]: $\overline{h^2}(n) = \overline{h^2}/n^{\alpha}$. In this case the coefficient α characterizes receiver power distribution between parallel channels and is $\alpha = 0$ upon spatial diverted reception, $\alpha = 1$ upon time diversion, and $1 < \alpha < 2$ upon frequency diversion. Then the equations for estimation of partial signal/noise ratio, Eqs. (20-22), W_{a1c} at outlet of noncoherent circuit of signal processing in each of n diversion branches are as follows:

$$W_{111} = h^2 \eta_f \eta_d / n^{\alpha}; \quad W_{110} = W_{011} = \frac{\left(h^2 \eta_f \eta_d - h^2 \eta_{is} \eta_d\right)}{\left(n^{\alpha} + h^2 \eta_{is} \eta_d\right)}; \quad W_{010} = \frac{\left(h^2 \eta_f \eta_d - 2h^2 \eta_{is} \eta_d\right)}{\left(n^{\alpha} + 2h^2 \eta_{is} \eta_d\right)}. \quad (26)$$

Therefore, the required Eq. (4) of SCS quality as a function of RMSD TEC fluctuations of ionosphere and parameters of transmitted signals $P_{err} = \psi(h^2, \sigma_{\Delta N_T}, f_0, F_0, T_S, n_{div})$ are obtained in the form of analytical Eqs. (18–24) upon conventional single reception of signals $(n \equiv n_{div} = 1)$ and in form of Eqs. (18-26) at arbitrary order ($n \equiv n_{div} \geq 2$) and type ($\alpha = 0...2$) of diversion.

2.4 Monitoring of TEC fluctuations of ionosphere based on improved GPStation-6 receiver (GISTM class)

At present the most perfect receiver of satellite navigation systems (SNS) of GISTM class is the receiver of GPStation-6 which facilitates monitoring of current TEC of ionosphere N_T [12]. The monitoring method of TEC of ionosphere implemented in the GPStation-6 receiver is illustrated in Figure 4. Its essence is as follows. Navigation spacecraft (NSC) transmits navigation signals simultaneously at two carrier frequencies: $f_1 \approx 1.6$ GHz and $f_2 \approx 1.2$ GHz. Upon RWP via ionosphere with small-scale irregularities and fluctuations of TEC determined by Eq. (6) $N_T = \overline{N_T} + \Delta N_T$, the delay in time (pseudo-delay) and phase (pseudo-phase) of signals at receiver inlet will be random and depend on frequency [13]:

$$\tau_1 \sim \left(\overline{N_T} + \Delta N_T\right) / f_1^2; \quad \tau_2 \sim \left(\overline{N_T} + \Delta N_T\right) / f_2^2; \quad (27)$$

$$\varphi_1 \sim \left(\overline{N_T} + \Delta N_T\right) / f_1; \quad \varphi_2 \sim \left(\overline{N_T} + \Delta N_T\right) / f_2. \quad (28)$$

In GPStation-6 dual frequency receiver, GISTM class, on the basis of code measurements (that is, pseudo-delays τ_1 and τ_2) and solution of Eq. (27), the TEC is determined in radio line from NSC to dual-frequency receiver [11]:

$$N_T = \psi(\tau_1, \tau_2) = \overline{N_T} + \Delta N_T + \delta_{\text{inst}}. \quad (29)$$

where δ_{inst} is the instrumental noise error of TEC measurements.

The main disadvantages of the GPStation-6 dual-frequency receiver upon standard operation mode are as follows:
1) TEC of ionosphere is determined on the basis of dual-frequency code measurements (27), hence, it contains noise instrumental error equaling to $\delta_{\text{inst}} >> \Delta N_T$ (stipulating noise pollution of small-scale TEC fluctuations);
2) discretization frequency of detection of TEC of ionosphere by GPStation-6 receiver is 1 Hz which facilitates detection of RMSD TEC fluctuations stipulated by irregularities of electron concentration with minimum average sizes $l_s \approx 1500$ m (whereas signal fading in satellite radio systems is caused by small-scale irregularities with the sizes of not higher than 200…400 m).

In order to eliminate the instrumental error δ_{inst}, it is required to modify the monitoring method of TEC of ionosphere implemented in GPStation-6 receiver by adding the following units (indicated by dashed lines in Figure 4): detection of TEC by code measurements; detection of TEC by phase measurements; their combinations; determination of statistic properties of TEC fluctuations.

Combinations of code $N_T = \psi(\tau_1, \tau_2)$ and phase $N_T = \psi(\varphi_1, \varphi_2)$ measurements of TEC makes it possible to eliminate both instrumental error (δ_{inst}) and peculiar for phase measurements uncertainty ($\overline{\delta N_T}$) of average TEC ($N_T = \psi(\varphi_1, \varphi_2) = \overline{N_T} + \overline{\delta N_T} + \Delta N_T$) [13]. Therefore, the results of combination of TEC in radio line from NSC to dual-frequency RCVR will be as follows:

$$N_T = \psi(\tau_1, \tau_2, \phi_1, \phi_2) = \overline{N_T} + \Delta N_T. \quad (30)$$

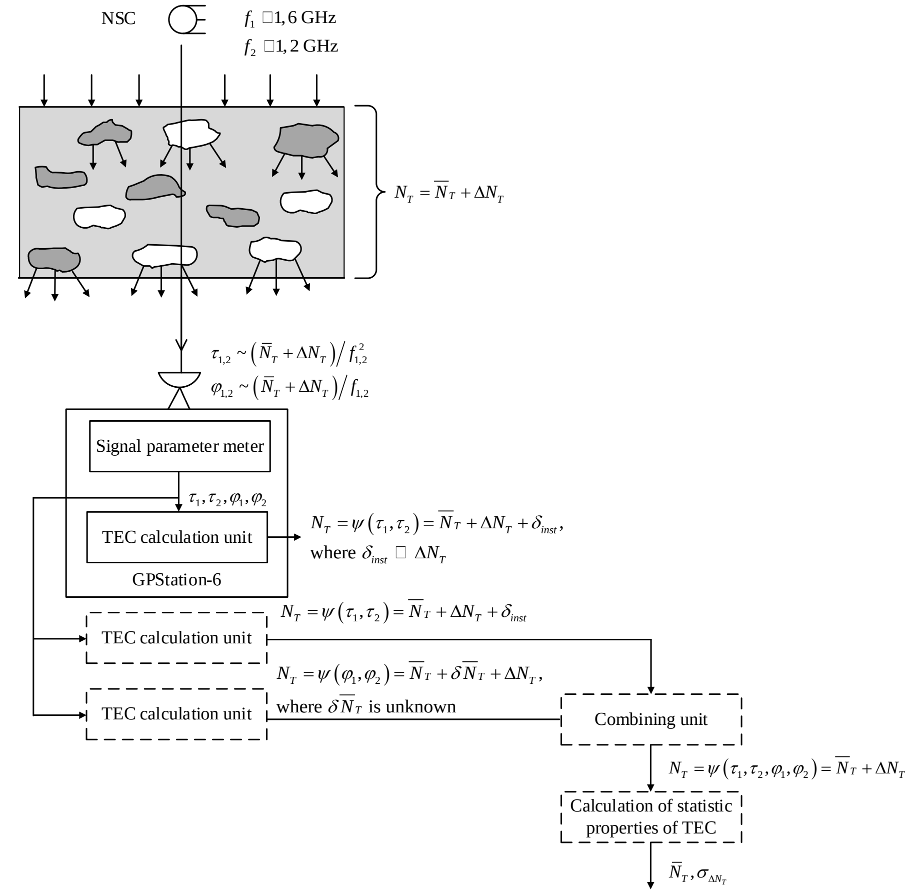

Figure 4. GPS monitoring of ionospheric TEC implemented in GPStation-6 receiver and its modification (dashed line).

In order to highlight small-scale TEC fluctuations (ΔN_T) with the required sizes ($l_s \approx 10...400$ m) and to separate them from medium range fluctuations ($l_s > 400$ m) and noises, it is necessary [14, 15]:

1) to increase discretization frequency of TEC detection from 1 Hz to 50 Hz which would allow to determine RMSD small-scale TEC fluctuations (stipulated by irregularities of electron concentration with the average sizes of $l_s \approx 30...300$ m);

2) to develop procedure of separation of small-scale TEC fluctuations from medium scale fluctuations (included in $\overline{N}_T$) and noises.

In order to solve the aforementioned problems, the algorithm was developed for determination of RMSD small-scale TEC fluctuations upon occurrence of ionospheric formations with small-scale irregularities [13-15]. At the first stage TEC is determined by dual frequency code ($N_T = \psi(\tau_1, \tau_2)$ and phase ($N_T = \psi(\varphi_1, \varphi_2)$ measurements with the discretization frequency of 50 Hz. This is aided by the fact that the GPStation-6 receiver is capable to measure parameters of navigation radio signals (pseudo-distances $\tau_{1,2}$ and pseudo-phases $\varphi_{1,2}$) with the discretization frequency of $f_\text{d} = 50$ Hz. However, the software of this receiver provides messages in ISMRAWTEC format with minimum discretization frequency of only $f_\text{d} = 1$ Hz. At the same time, the GPStation-6 receiver is capable to use messages in RANGE format, which facilitates measurements of pseudo-distance and pseudo-phase by signals of all visible NSC with minimum discretization frequency of $f_\text{d} = 50$ Hz. Then these data can be applied to detection of TEC of ionosphere by code $N_T = \psi(\tau_1, \tau_2)$ and phase $N_T = \psi(\varphi_1, \varphi_2)$ measurements. At the second stage, using combination of $N_T = \psi(\tau_1, \tau_2)$ and $N_T = \psi(\varphi_1, \varphi_2)$, TEC is detected with the discretization frequency of 50 Hz by Eq. (30) $N_T = \psi(\tau_1, \tau_2, \varphi_1, \varphi_2) = \overline{N}_T + \Delta N_T$. At the third stage, in order to separate small-scale TEC fluctuations (ΔN_T) from its average (background) value TEC ($\overline{N}_T$), the Butterworth filter of the 6th order is applied [15, 16]. At the fourth stage the obtained results of ΔN_T detection are used for prediction of RMSD small-scale TEC fluctuations $\sigma_{\Delta N_T}$.

3 Results

The Figure 5 illustrates the principle of SCS, which improves operation quality under ionospheric disturbances based on monitoring of RMSD small-scale TEC fluctuations in ionospheric formations with small-scale irregularities and adaptation of transmitted signals.

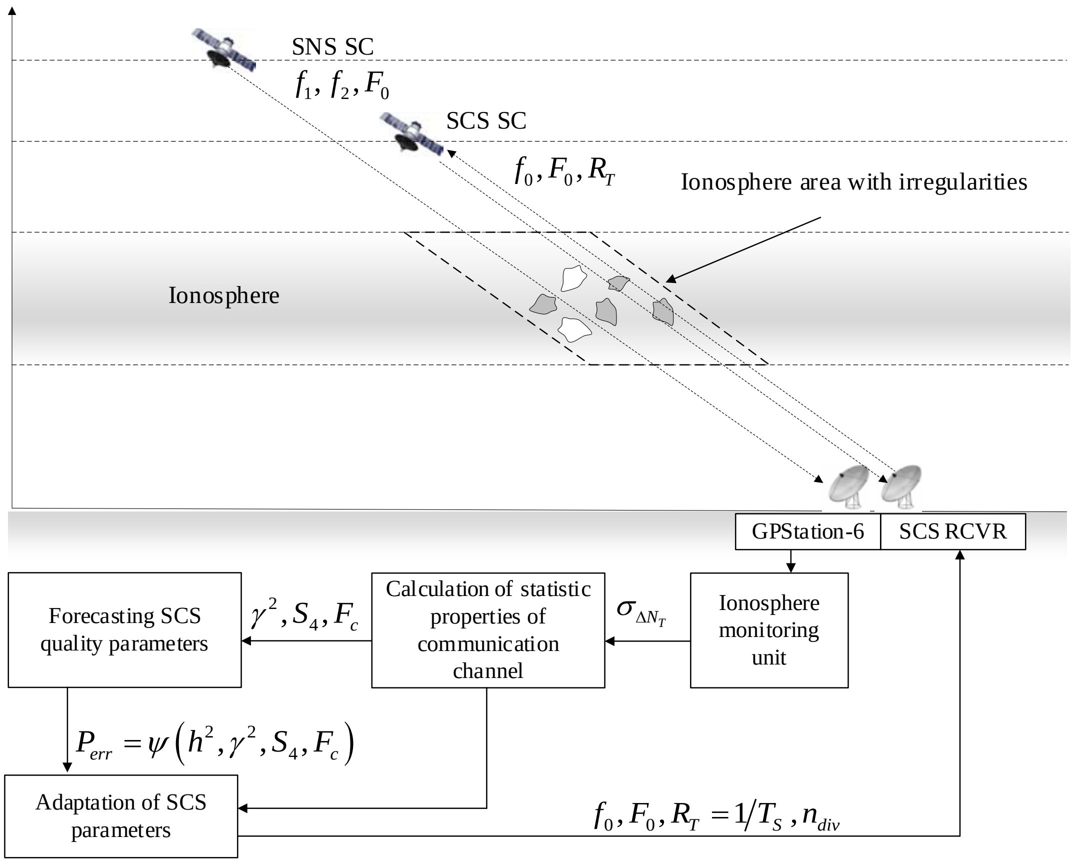

Figure 5. SCS development on the basis of GPS monitoring of TEC fluctuations in ionospheric formation with small-scale irregularities and adaptation of transmitted signals.

The main recommendations on improvement of SCS operation quality under conditions of ionospheric formations with small-scale irregularities are as follows:

1. Prior to satellite communication session, it is necessary to monitor ionosphere using modified dual-frequency SSN receiver with evaluator of RMSD small-scale TEC fluctuations ($\sigma_{\Delta N_T}$) in SCS radio line according to the developed algorithm.

2. On the basis of monitoring results $\sigma_{\Delta N_T}$, the evaluator of statistical properties of fading calculates parameters of fading depth (γ^2, S_4^2) and coherence band (F_κ) of transionospheric communication channel at preset frequency and time parameters ($f_0, F_0, R_T = 1/T_S$) of transmitted signals according to Eqs. (15-17).

3. The unit of predictions of SCS quality estimates probability of erroneous reception ($P_{err} = \psi(h^2, \sigma_{\Delta N_T}, f_0, F_0, T_S, n_{div})$) at preset signal/noise ratio (h^2), fading parameters (γ^2, S_4^2, F_c), and diversity factor (n_{div}) according to Eqs. (18-26).

4. If the error probability is at least the allowable value ($P_{err} \leq P_{err\ all}$), then it is possible to start satellite communication. Otherwise, ($P_{err} > P_{err\ all}$), it is required to start adaptation of satellite communication.

5. In the unit of adaptation of SCS parameters on the basis of $P_{err} = \psi(h^2, \sigma_{\Delta N_T}, f_0, F_0, T_S, n_{div})$, the signal parameters (f_0, F_0, T) and diversity factor (n_{div}) are selected providing the required communication quality ($P_{err} \leq P_{err\ all}$) upon increase in $\sigma_{\Delta N_T}$ under conditions of ionospheric formations with small-scale irregularities.

6. Transmit/receive facility of on land SCS station transmits data on adaptation of parameters of transmitted signals f_0, F_0, T to SCS SC and necessity to apply diverted reception with the required order (n_{div}).

Figure 6 exemplifies possibility to increase interference immunity of Gonets-D1M low frequency SCS under conditions of ionospheric formations with small-scale irregularities on the basis of adaptation of transmittance rate, spectrum bandwidth of transmitted signals and their diverted reception with the factor $n_{div} = 4;6;8$ according to Eqs. (18-26) [16].

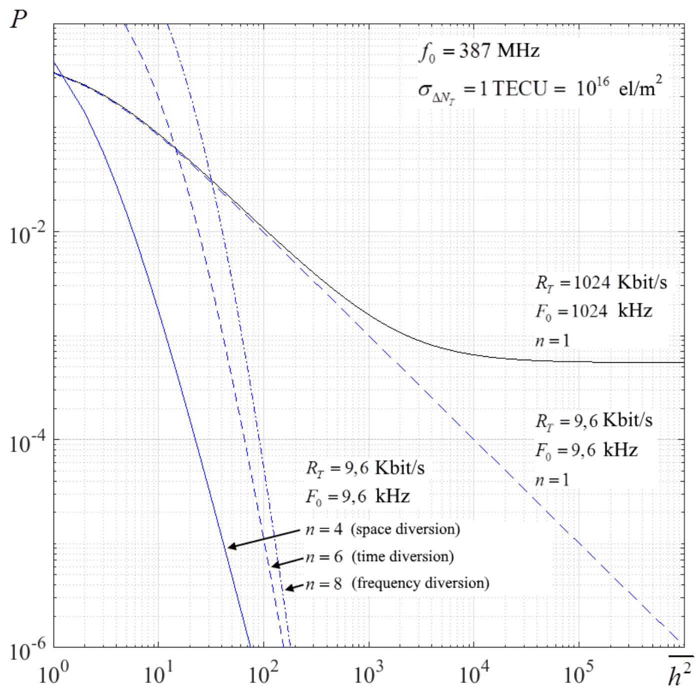

Figure 6. Improvement of SCS interference immunity under conditions of ionospheric formations with small-scale irregularities based on adaptation of transmittance rate, signal spectrum width, and their diversity reception with the factor of $n_{div} = 4,6,8$.

Comparative analysis of the plots in Figures 3 and 6 demonstrates possibility to provide allowable interference immunity in Gonets-D1M low frequency SCSA ($P_{err} \le P_{err\ all} = 10^{-5}$ at achieved maximum signal/noise ratio $h^2 = 200 = 23$ dB) under conditions of strong disturbances (increase in RMSD TEC fluctuations in ionospheric formation with small-scale irregularities to $\sigma_{\Delta N_T} = 10^{16}$ el / m^2) in two stages: 1) elimination of ISI and FSF by decrease in transmittance rate (from $R_T = 1/T_S = 1024$ KBit/s to 9.6 Kbit/s) and band width to $F_0 = 9.6$ kHz); 2) application of diverted reception of signal with the factor of $n_{div} = 4$ (space diversion), or $n_{div} = 6$ (time diversion), or $n_{div} = 8$ (frequency diversion).

4 Conclusion

The method of analysis of interference immunity of low frequency SCS has been developed under the conditions of ionospheric disturbances causing occurrence of ionospheric formations with small-scale irregularities. On the basis of determination of RMSD small-scale TEC fluctuations of ionosphere ($\sigma_{\Delta N_T}$), and using modified dual-frequency receiver of GPStation-6 satellite navigation system, it allows to estimate error probability $P_{err} = \psi(h^2, \sigma_{\Delta N_T}, f_0, F_0, T_S, n_{div})$ upon noncoherent reception of signals with preset frequency and time parameters (f_0, F_0, T_S) and diversity order (n_{div}) as well as to present recommendations on improvement of SCS interference immunity to allowable levels ($P_{err\ all} = 10^{-5}$ at signal/noise ratio equaling to $h^2 = 23$ dB).

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