Method of diagnosing frequency dispersion parameters for transionospheric propagation of wideband signals using GLONASS/GPS technologies

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Abstract. To solve the problem of adaptive correction for dispersion distortions of the characteristics of a wideband transionospheric channel, we developed a method of diagnosing frequency dispersion parameters using satellite data on the total electron content (TEC) of the ionosphere developed. It also considers TEC measurement stochastic error. For this reason, we performed an analysis of the limitation of the communication signal bandwidth for the case of dispersion correction with an error. It was found that the TEC measurement error that typically exists in practice allows us to spread signal bandwidth by up to three times.

1 Introduction

In order to increase the operation efficiency (noise immunity, channel capacity) and decrease transmission power of a satellite wideband systems that operate under the negative influence of frequency dispersion, it is crucial to figure out how to overcome the problem of correction of wideband channel frequency response [1]. The variability of the propagation medium requires the development and study of the corrector training mode by means of data on sounding throughout the transionospheric radio channel. Previous research [2–4] showed that the frequency dispersion parameters, and, consequently, the transionospheric radio channel characteristics, depend on the total electron content (TEC) of the ionosphere. Since experimental estimates contain stochastic errors, it is crucial to perform an analysis of the influence of this factor on the correction performance.

In this paper, we present the results of the studies into the problems in question carried out with the use of analytical and experimental methods supported by the sounding data on a transionospheric radio channel gathered in Yoshkar-Ola by GLONASS / GPS signals.

2 Subject matter of the research and experimental technique

Studies were focused on the problems of satellite communications and transionospheric sounding of the ionized part of the Earth's upper atmosphere.

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The problem of spreading the bandwidth of such systems, that is posed by the negative effect of the frequency dispersion of the propagation medium, was addressed.

The aim of the research was to develop a method of diagnosing frequency dispersion parameters in transionospheric radio communication channels and an algorithm for training adaptive dispersion distortion corrector, that uses TEC data to compensate for frequency dependence of the phase in the spectrum of the received wideband signal.

To meet the goal, we tackled the following tasks:

1) deriving analytical expressions for calculating the dispersion parameters and expressions for implementing the method of adaptive correction for phase dispersion in the transionospheric radio channel;

2) verification of measuring instruments and equipment for carrying out experiment;

3) carrying out experimental studies into the variations in the parameters of the nonlinear second-order frequency dispersion as well as coherent bandwidths of transionospheric radio channels;

4) synchronization of the obtained data with the training mode and determining corrector coefficients update period.

3 Computational-experimental method of diagnosing frequency dispersion parameters

We developed a computational-experimental method for predicting the parameters of frequency dispersion. It includes the following main steps (Fig. 1):

- computation of the TEC absolute values with the use of GLONASS / GPS navigation systems. The approach is based on experimental data of code and phase measurements obtained from the navigation receivers of the HEXAGON network of reference base stations;
- measuring dispersion characteristic (DC). For the high-frequency approximation, the theoretically obtained analytical expression of the DC is represented as follows [3]:

$$\tau(\bar{f},t) = \int_Z \frac{dz}{c} + 2\pi\tau_g(\bar{f},t) + 2\pi s(\bar{f},t)\cdot[f-\bar{f}] \tag{1}$$

Considering the expansion of the phase excursion in the medium

$$\varphi(\omega) = \omega\int_s \frac{dz}{c} - \left[\frac{\alpha_1}{f} + \frac{\alpha_2}{f^3} + \frac{\alpha_3}{f^5}\right], \tag{2}$$

where – $\alpha_1 = k\cdot\int_s N_e^1(z)dz\cdot\frac{\pi}{c}$, $\alpha_2 = \frac{k^2}{4}\cdot\int_s N_e^2(z)dz\cdot\frac{\pi}{c}$, $\alpha_2 = \frac{k^3}{8}\cdot\int_s N_e^3(z)dz\times\frac{\pi}{c}$;

$k = 80{,}5[c^2/m^3]$, N_t – total electron content .

for transionospheric propagation in the case of high-frequency approximation, (1) can be represented as follows:

$$\tau_g(\bar{f}) = \int_s \frac{dz}{c} + \frac{\alpha_1}{2\pi\bar{f}^2} = \int_s \frac{dz}{c} + \frac{k}{2\cdot c\cdot\bar{f}^2}\cdot N_t \tag{3}$$

- determination of the second-order dispersion parameter (slope of DC) [3]:

$$s(\bar{f},t) = -\frac{k \cdot N_t}{c \cdot \bar{f}^3}; \tag{4}$$

and third-order parameter (concave of DC):

$$v(\bar{f}) = \frac{3 \cdot k}{c \cdot \bar{f}^4} \cdot N_t \tag{5}$$

- estimation of the limited bandwidth of a wideband system (coherent bandwidth) for the case of operation of a communication system in a dispersive channel [5, 6];

$$B_k = \sqrt{4 \cdot c \cdot \bar{f}^3 / \pi \cdot k \cdot \overline{N}_t} \tag{6}$$

- estimation of stochastic error in measuring TEC $-\ \Delta N_t$.

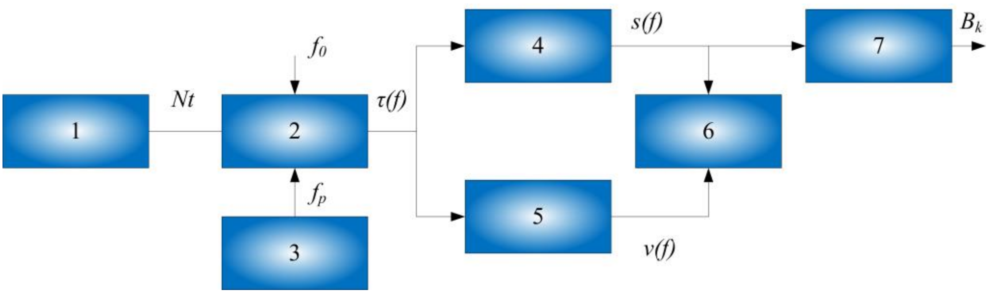

Fig. 1. Block scheme of the method for computing dispersion parameters and coherent bandwidth: 1 – TEC computation circuit; 2 – DC computation circuit; 3 – plasma frequency computation circuit; 4 – second-order dispersion parameter computation circuit; 5 - third-order dispersion parameter computation circuit; 6 - dispersion parameters plotting circuit; 7 - coherent bandwidth computation circuit.

Effect of frequency dispersion cannot be completely eliminated if TEC is measured with an error. When measuring TEC based on data from navigation satellites [7], stochastic errors occur. As a result, the measured TEC value can be written as follows:

$$N_t = \overline{N}_t \pm \Delta N_t \Rightarrow \overline{N}_t = N_t \mp \Delta N_t, \tag{7}$$

where ΔN_t – stochastic error *TEC*.

For practical applications, one can perform calculations for the selected frequency $\bar{f}_1$, which we term to as reference frequency, and then recalculate the result at a given frequency $\bar{f}$. In this case, let us introduce the relative frequency $\hat{f} = \bar{f} / \bar{f}_1$, then the equations for dispersion parameters and coherent bandwidth can be represented as follows:

$$\tau(\hat{f}) = \int_s \frac{dz}{c} + \frac{k \cdot N_t}{2 \cdot c \cdot \bar{f}_1^2} \cdot \frac{1}{\hat{f}^2} = \int_s \frac{dz}{c} + \frac{\tau_k}{\hat{f}^2} \tag{8}$$

$$s(\hat{f}) = -\frac{k \cdot N_t}{c \cdot \bar{f}_1^3} \cdot \frac{1}{\hat{f}^3} = \frac{s_k}{\hat{f}^3}; \tag{9}$$

$$\nu(\hat{f}) = \frac{3 \cdot k \cdot N_t}{c \cdot \bar{f}_1^4} \cdot \frac{1}{\hat{f}^4} = \frac{\nu_k}{\hat{f}^4}; \quad (10)$$

$$B_k = \sqrt{\frac{4 \cdot c \cdot \bar{f}^3}{\pi \cdot k \cdot \bar{N}_t} \cdot \frac{\bar{f}_1^3}{\bar{f}_1^3}} = \sqrt{\frac{4 \cdot c \cdot \bar{f}_1^3}{\pi \cdot k \cdot \bar{N}_t}} \cdot \hat{f}^3 = B_{k1} \cdot (\hat{f})^{1.5} \quad (11)$$

where $\hat{f}=\bar{f}/\bar{f}_1$ – relative frequency; $\bar{f}_1$ – reference frequency (1 GHz was used in the research); τ_k – dispersion characteristic at a reference frequency; s_k – second-order dispersion parameter at the reference frequency; ν_k – third-order dispersion parameter at the reference frequency; B_{k1} – coherent bandwidth at the reference frequency.

Thus, the usage of relative frequencies allows to distinct the influence of two factors: geophysical, associated with the variations in the total electron content of the ionosphere, and system factor (operating frequency).

4 Full-scale experiments on studying frequency dispersion parameters

Full-scale experiments on estiamting TEC were carried out with the use of a network of receivers of signals from GLONASS / GPS navigation systems. Data were provided by HEXAGON company. In our studies we selected ten days for the summer (June) and winter (December) periods in 2018. That periods are characterised with a quiet ionosphere conditions (Kp index <3, without solar flares). At first, diurnal TEC variations and the corresponding confidence intervals (solid line, Fig. 2) were produced and plotted using the average values for ten days in each period.

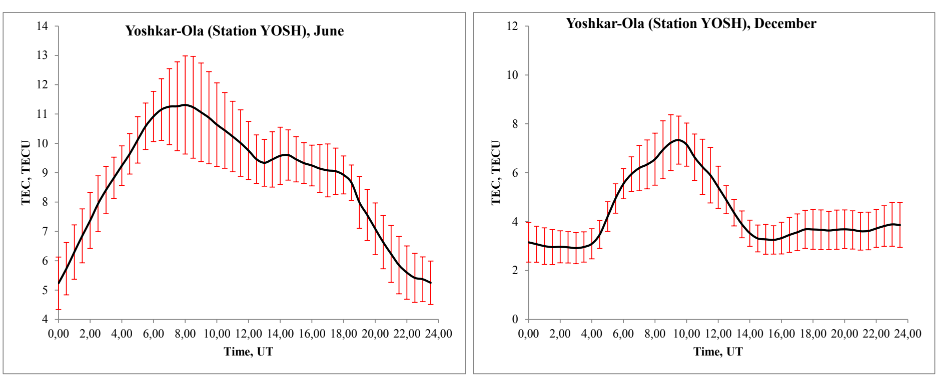

Fig. 2. TEC diurnal variations for the summer and winter periods.

So, the average TEC value was 11.2 TECU in June and 7.3 TECU in December (1 TECU = 10^{16} m^{-2}). The average error in measuring TEC by proposed method was 7.8%. It was found that with a relative error $\Delta N_t = 0.1$, the signal bandwidth can be increased by almost 3 times. These data allows to estimate the effect of improving the characteristics of satellite communications. For instance, taking into account the relation of the channel bandwidth with the channel capacity $\Delta B_{ch} = (3 \div 3.5) \cdot C$, it can be shown that the channel capacity C can be also increased by 3 times.

In fact, the variability of the transionospheric channel due to geophysical factors negatively influences the magnitude of the TEC measurement error. Solving this problem in the correction objective requires to periodically update (training mode) data on the dispersion parameters. It was found that the update period should not exceed 5 minutes. Thus, we suggested that the channel sounding, TEC measurement and its errors estimation should be performed every 5 minutes.

Besides, in the experiments, we obtained data on variations in frequency dispersion parameter (Fig. 3) and coherent bandwidth (Fig. 4).

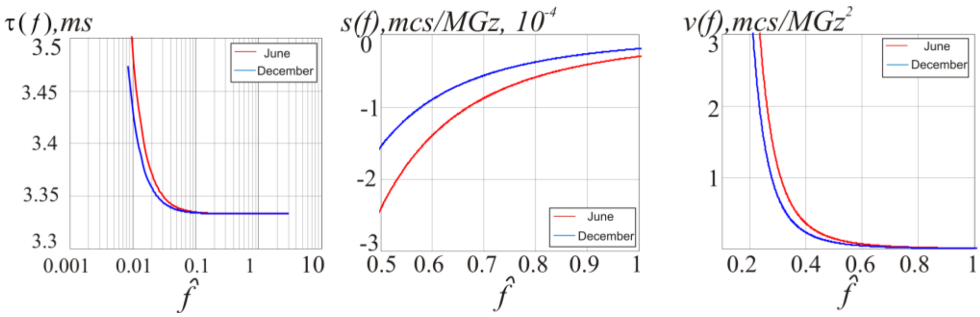

Fig. 3. Dispersion parameter variations in a transionospheric radio channel estimated with the use of sounding data obtained by means of GPS / GLONASS system signals (Yoshkar-Ola, 2018).

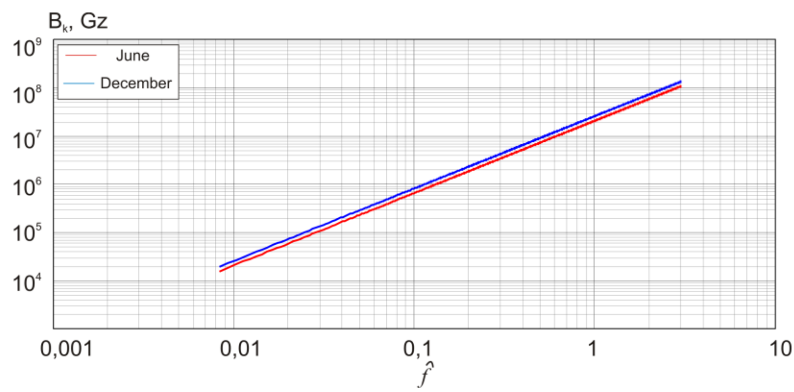

Fig. 4. Frequency dependences of coherent bandwidths for the summer and winter periods (Yoshkar-Ola, 2018).

Findings are interpreted for relative frequencies, that allows to estimate dispersion parameters and coherent bandwidth for any frequencies, using only the reference one. Furthermore, TEC variations affect only the measurements performed at the reference frequency. An increase in the TEC value leads to a rise in the values of the dispersion parameters and to a decrease in the coherent bandwidth.

5 Conclusion

A method for diagnosing frequency dispersion parameters in a transionospheric radio communication channel is presented. It is based on the measurement of the total electron content of the ionosphere with the use of data of GLONASS / GPS navigation systems. The usage of relative frequency allowed to distinct the influence of two factors: geophysical (TEC) and system factor (operating frequency). It was shown that diagnosing frequency dispersion parameters by means on satellite navigation data allows to solve the problems of dispersion distortions correction and ensures processing gain in the following characteristics of wideband communication systems: noise immunity, channel capacity, reducing transmission power. It was experimentally proved that, increasing the channel capacity is limited by up to 3 times due to the errors in measuring TEC.

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