Determining the repetition period of transionospheric radio channel sounding to retrain a facility of correction for dispersion distortions

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Abstract. Correction for dispersion distortions in the transionospheric radio channel poses a topical problem of determining the appropriate repetition period of sounding. Research focused on studying the variations of the sounding repetition period to increase the efficiency of correction for dispersion distortions in the channel. There is proposed a method for experimental studying the diurnal variations of the coherence time (“lifetime”) of the transionospheric channel. The method is supported by the derived equations that establish relations between the channel lifetime and the time derivative of the total electron content of the ionosphere. Research findings allowed to determine the appropriate repetition period of channel sounding to retrain the facility of correction for dispersion distortions in the transionospheric radio channels.

1. Introduction
Previous research [1-4] into the effect of frequency dispersion of the transionospheric radio communication channels allowed to state the concept of increasing the efficiency of space communication systems by means of dispersion correction. The variability of the medium poses challenges that are related to the variability of the transionospheric radio channel parameters. It means that the channel parameters are priori unknown. Therefore, the corrected channel after a certain amount of time will become mismatched to the receiver. In this regard, dispersion distortions corrector should involve a training procedure to update correction functions with a period equal to the communication channel coherence time also termed to as channel “lifetime”. The key parameter influencing dispersion is the total electron content (TEC) of the ionosphere above the terminal of reception of satellite communication signals. Therefore, it is crucial to periodically update information on the TEC in accordance with the channel lifetime to retrain channel corrector. Currently, the problem of determining the appropriate period of retraining the channel corrector is poorly studied and topical.

2. Training method and the algorithm for estimating channel lifetime
The important step in creating an adaptive corrector is the development of training mode. Figure 1 illustrates a general scheme of training procedure. The concept is based on the sounding data gathered with the use of GLONASS / GPS signals.

The primary processing circuit transforms raw data into the RINEX format and calculates pseudorange by phase and code measurements. The combination of these two steps allows to calculate the absolute values of the total electron content of the ionosphere [5]. Then, data on TEC are fed into
the secondary processing circuit. It evaluates the phase functions that allows to compensate for the nonlinear dispersion that occurs within a wide channel bandwidth. According to the calculated dispersion parameters, phase functions are derived taking into account linear and nonlinear components. The nonlinear dispersion parameters vary depending on the changes in the TEC over slow (geophysical) time. For this reason, we faced the problem of determining the appropriate repetition period of channel sounding. Tackling the problem, we estimated the lifetime of the corrected channel.

To solve the problem, we selected a channel model with the frequency response \( H(j\omega,t) \) varying over slow time \( t \) [6, 7]:

\[
H(j\omega,t)=H(\omega,t)\exp[-j\omega.t]
\]

where \( H(\omega,t) \) is the amplitude-frequency response (AFR) of the channel; \( \phi(\omega,t) \) - phase-frequency response (PFR) of the channel.

Since the influence of amplitude dispersion is modest, i.e. \( H(\omega,t)\approx \text{const} \), and the major cause of distortions is the phase dispersion, we assumed that for a channel with mid-band frequency \( \bar{\omega}=(\omega_1+\omega_2)/2 \) and bandwidth \( \Omega_{ch} \), the PFR can be expressed as a power series [8, 9]:

\[
\phi(\bar{\omega},t)\approx\phi(\bar{\omega},t)+\phi'(\bar{\omega},t)\cdot\Omega+\phi''(\bar{\omega},t)\cdot\frac{\Omega^2}{2!}
\]

\[
=\phi(\tilde{\omega},t)+2\pi\varphi_{nl}(\tilde{\omega},t)\cdot F + \pi\varphi(\tilde{\omega},t)\cdot F^2 = \phi(\tilde{\omega},t) + \varphi_{nl}(\tilde{\omega},t),
\]

where \( F=f-\tilde{f} \), \( \Omega=\omega-\bar{\omega} \) - difference (beat-note) frequencies; \( \Omega=2\pi\cdot F \), \( F\in[-B_{ch}/2,B_{ch}/2] \), \( \varphi_{nl}(\tilde{\omega},t) = \varphi(\tilde{\omega},t)+2\pi\varphi_{nl}(\tilde{\omega},t)\cdot F \) - linear component of the PFR; \( \varphi(\tilde{\omega},t) = \pi\varphi(\tilde{\omega},t)\cdot F^2 \) - nonlinear component of the PFR; \( \tau_g = d\varphi/dF \) - dispersion characteristic (DC) of the channel; \( s=d\tau_g/dF \) - DC slope.

Further, we assumed that the inverse filtering method is optimal to correct for phase dispersion. In that case, we considered that the linear component \( \varphi(\tilde{\omega},t) \) of the phase response does not contribute signal distortions, but only results in a delay shift. So, inverse filtering is carried out by multiplying the frequency response by the following function:

\[
G(f,t) = \exp[j\varphi_{nl}(\tilde{\omega},t)].
\]

The nonlinear phase component is responsible for distortions in the transionospheric radio channel and can be represented as follows [9, 10]:

\[
\varphi_{nl}(\tilde{\omega},t) = \pi\varphi(\tilde{\omega},t)\cdot F^2 = \frac{\pi k N_i F^2}{c},
\]

where \( k=80.5[m^3/c^2] \); \( c \) - speed of light, \( N_i = \int N_e(z)dz \) - total electron content.
We shall note that the values of the dispersion characteristic slope \( s(\hat{f},t) \), and accordingly the phase \( \varphi(\hat{f},t) \) are calculated for the certain frequencies. In that case, the operating frequency of a random \( i \)-th channel will be synthesized according to the following equation: 
\[
\hat{f}_i = \hat{f}_i + i \cdot \Delta B_{ch} \quad (i = 0,1, ... N; N - number of channels; \Delta B_{ch} - sub-channel bandwidth).
\]

To estimate the channel lifetime, one should estimate the nonlinear phase dispersion \( \varphi_{n\ell_0} \) by sounding the transionospheric radio channel. After sounding, at the time point \( t=t_0 \), compensation for the nonlinear dispersion was carried out, i.e. the condition was satisfied: 
\[
\varphi_{n\ell}(\hat{f},t) = \varphi_{n\ell_0}(\hat{f},t_0).
\]
The equality is breaking with time \( t \), i.e. the difference between the values of \( \varphi_{n\ell} \) and \( \varphi_{n\ell_0} \) increases, and after the channel lifetime period \( \Delta t=t-t_0 = T_i \) the difference can't be neglected.

Let us estimate the difference in the phase function values at time increments \( \Delta t=t-t_0 = T_i \):
\[
\Delta \varphi_{n\ell}(\hat{f},t) = \varphi_{n\ell}(\hat{f},t) - \varphi_{n\ell_0}(\hat{f},t_0) \approx \frac{d\varphi_{n\ell}}{dt}(t-t_0) = \pi \cdot F^2 \frac{ds(\hat{f},t)}{dt}(t-t_0). \tag{5}
\]

We assumed that for \( F = B_{ch}/2 \) phase increment within the time \( t-t_0 \) does not exceed 1 radian, i.e. the value \( \Delta s = \frac{ds(\hat{f},t)}{dt}(t-t_0) \) does not exceed the critical value \( s_k \) (see Figure 2) (where \( s_k = \frac{4}{\pi} \cdot \frac{1}{B_{ch}} \)).

We employed the equality of these quantities to estimate the lifetime \( \frac{d\varphi_{n\ell}(\hat{f},t)}{dt} \cdot T_i = s_k \).
\[
T_i = s_k / |s'| = \frac{4}{\pi \cdot B_{ch}^2 \left| \frac{ds(\hat{f},t)}{dt} \right|} = \frac{4c \hat{f}^3}{\pi \cdot B_{ch}^2 \left| \frac{dN}{dt} \right|} = \frac{c \hat{f}^3}{63 \cdot (B_{ch})^2 \left| \frac{dN}{dt} \right|} = \frac{c f_0}{63 \cdot \eta_f \left| N_t' \right|}, \tag{6}
\]

where \( \hat{f} = f/f_0 \) - relative frequency; \( \eta_f = B_{ch}/f_0 \) - fractional bandwidth (for conversion to different frequencies it can be represented as follows \( \eta_f = B_{ch}/(\hat{f} \cdot f_0) \); \( f_0 \) - reference frequency; \( N_t' = dN_t/|t| \) - rate of change of total electron content.

According to (6), one can conclude that the time interval between sounding sessions (repetition period) depends on the channel bandwidth, the relative mid-band frequency of the channel and the TEC change rate.

Figure 2 illustrates the method of estimating the sounding repetition period. We shall note that the communication channel exhibit degradation when the function loses linearity within a time period \( \Delta t=t-t_0 = T_i \), i.e. the tangent line does not fit with the curve.
3. Technique and conditions of the experiment

To carry out experimental studies, we upgraded the hardware software complex to perform sounding the transionospheric channel by the navigation signals of the GLONASS / GPS systems (figure 3). The complex consists of the Leica GR10 navigation receiver included in the SmartNet reference network of HEXAGON GEOSYSTEMS RUS [https://geosystems.ru/solutions/bazovyestantsii/] and a personal computer.

![Hardware software complex employed in studies](image1)

**Figure 3.** Hardware software complex employed in studies

First of all, TEC measurements were carried out with the use of phase and code measurements. Data were collected at the YOSH station (Yoshkar-Ola) and are related to the mid-latitude ionosphere. We selected the days of the spring and autumn equinox, as well as the days of the summer and winter solstices for 2018/2019 years. Software module, on the basis of the obtained analytical model, produces diurnal variations of the transionospheric channel lifetime and performs forecasting. At the same time, a frequency of 1 GHz with a channel bandwidth of 500 MHz was chosen as the operating one.

4. Results and discussions

The derived equation (6) for estimating the channel lifetime includes time derivative of the TEC. Thus, in order to plot the diurnal variations of the sounding repetition period, it is crucial to estimate the TEC above the signal reception point. We shall note that TEC values obtained from experimental data may exhibit short-term fluctuations due to the measurement errors, manifested in the TEC random components. Hence, there is a need for their filtration. During the experiment, a moving average filter was used to smooth the values. In that case, the arithmetic mean within the time interval of 60 minutes was calculated.

Figure 4(a) presents the experimental diurnal variations of smoothed TEC values for the studied periods. To verify the measurement results, we compared the TEC variations with the ones obtained with the use of the IRI model (figure 4b).

![Diurnal TEC variations](image2)

**Figure 4.** Diurnal TEC variations: a - according to the Yosh station data, b - according to the IRI model
Obtained results allowed to estimate the rate of change of TEC and determine the appropriate repetition periods of sounding the communication channels. In our studies we used the method of analysis of the variational series of sounding repetition periods. Figure 5 presents research findings. The application of that method is reasonable because it allows to calculate the probability of a certain variant, related to the series size, showing the variants which do not exceed it.

![Variational series for the sounding repetition periods at the frequency of 1 GHz obtained with the use of the IRI model (blue curve) and with the use of experimental data collected at Yoshkar-Ola station](image)

**Figure 5.** Variational series for the sounding repetition periods at the frequency of 1 GHz obtained with the use of the IRI model (blue curve) and with the use of experimental data collected at Yoshkar-Ola station (Yoshkar-Ola)

Research results allowed to conclude that the repetition period of sounding and consequently the period of retraining corrector estimated according to the experimental data is greater than the one estimated with the use of the IRI model. So, the repetition period obtained with the use of the IRI model at the probability of 0.5 did not exceed 150 minutes for March, September, December and 200 minutes for June. Experimentally obtained repetition period did not exceed 300, 180, 320, 250 minutes, respectively. In addition to this, measurements with the use of the IRI model showed that there are cases when the repetition period is less than an hour. For instance, such repetition period was observed for 10% of variants in March and September, and for 20% in December. According to the experimental data appropriate repetition period exceeded an hour for almost all variants. Typically, the minimum values of the period were observed during the dusk/dawn time when the TEC change rate increases. Large values of the period were observed in 25% of cases in December at night, in 18% of cases in June and September, and in 14% of cases in March. They proved the feasibility of long time operation of the radio channel.

The obtained results showed that the channel lifetime exhibited different variations depending on the season, channel bandwidth and time of day, as well. In this regard, there is a need to predict that parameter. At the same time, in order to train the corrector, one should select the period of updating the correction coefficients according to the minimum value of the channel lifetime, either update coefficients when the channel becomes mismatched according to the predictions.

5. Conclusion

There is proposed a method for estimating the appropriate repetition period of channel sounding. The method is supported by the approach of determining the TEC change rate. The developed method allowed to experimentally obtain the period of updating the phase correction coefficients to train the
facility of correction for dispersion distortions in the transionospheric radio channel. The major advantage of the method is its implementation on the basis of sounding the transionospheric channel by the signals of navigation satellite systems that allow to estimate the absolute values of TEC with high accuracy. Experimental studies carried out for the carrier frequency of 1 GHz with a channel bandwidth of 500 MHz allowed to determine the appropriate period of retraining the adaptive corrector and to analyze its temporal (daily and seasonal) variations.

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