Method of determining a coherence band and plotting coherence band maps for a transionospheric radio channel

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Abstract

Paper presents the findings of the research into the effects of second-order phase frequency dispersion in wideband transionospheric communication channels. We estimated dispersion distortions of the system characteristics using a coherence band calculated through the integral characteristics of an electron concentration profile. A method aimed at estimating coherence band with the use of data on total electron content was developed. Besides a method for plotting diagnostic maps of coherence bands for various regions of the Earth was developed. There is used data obtained from the receiving stations of the satellite navigation systems.

1. Introduction

Expanding frequency band of radio signals gives technical advantages for the UHF satellite communication and location systems. Thus, it attracts scientist and developers around the world. However, expanding a signal frequency band is a difficult task due to the frequency dispersion, which negatively influences on the performance of the communication systems. The general solution of the problem is associated with studying distortions of system characteristics of an equivalent linear system (LS): frequency response (FR) and impulse response (IR). In general case, IR and its Doppler frequencies spectrum, described by the channel scattering function (CSF) are studied to estimate dispersion distortions. CSF is a power delay profile (PDP) in the time domain. An instantaneous PDP is equal to the square of an IR envelope. It was shown [1, 2] that the distortions of a PDP can be estimated using a coherence band (CB) of a channel. CB characterizes the maximum possible frequency band for which dispersion distortions can be neglected. Thus, it is crucial to find relationship between the parameters of a transionospheric channel and a coherence band to study dispersion distortions of an IR. Dispersion parameters are functions of coordinates of a receiving point. Thus, we developed an algorithm and a software for plotting diagnostic maps of the coherence bands of the transionospheric radio channels. Algorithm uses data obtained from the GNSS and GPS satellite navigation systems and aimed at monitoring distortions of PDPs of wideband and ultra-wideband transionospheric radio channels.

The aim of the research was to develop method for determining CB and plotting diagnostic maps of coherence bands using experimental data obtained from the GNSS and GPS satellite navigation systems.

2. General framework of frequency phase dispersion

A spectral method and an equivalence principle are used to study distortions of wave packets when propagation of a signal through the ionosphere is considered as a propagation through an equivalent liner system which has the following FR [3]:

$$H_\omega \approx H_0(r,\omega)\cdot\exp[-j\varphi(r,\omega)] \qquad (1).$$

where $\omega = 2\pi f$ – wave frequency, r – distance to a receiver.
We studied the influence of dispersion on an impulse response of a channel within bandwidth B_{ch} from f_1 to f_2:

$$h(\tau) = \int_{f_1}^{f_2} H(f)\cdot\exp(if\tau)df \qquad (2).$$

Function $P(\tau) = |h(\tau)|^2$ according to the international classification is called the instantaneous power delay profile. In general, in a channel within a limited frequency band B_{ch} and a mid-band frequency (the “carrier”) $\bar{f} = (f_1+f_2)/2$, the phase frequency characteristic can be presented as follows:

$$\begin{aligned}\varphi(\omega) &= \varphi(\overline{\omega}) + \varphi'_\omega\cdot\Omega + \varphi''_\omega\cdot\frac{\Omega^2}{2!} + \\ &+\varphi'''_\omega\cdot\frac{\Omega^3}{3!} + \cdots \approx \varphi(\bar{f}) + \\ &+2\pi\tau_g\cdot(F) + \pi s\cdot(F)^2 + \frac{\pi}{3}v\cdot(F)^3\end{aligned} \qquad (3).$$

where $F \in [-\frac{B_{ch}}{2}, \frac{B_{ch}}{2}]$. In this case there is a phase dispersion of the 1st, 2nd and 3rd orders, where τ_g, s, v are dispersion parameters and $F = f - \bar{f}$.

Nonlinear phase dispersion causes dispersion distortions in a channel. Let us suppose that a channel has a frequency band $B_{ch} = f_2 - f_1$ and there is the second-order phase dispersion. We shall note that in the case of the second-order dispersion, there is a frequency band called coherence band. It is the frequency interval where the phase taper does not exceed 1 radian at the interval boundaries:

$$\pi s \cdot \left(\frac{B_k}{2}\right)^2 = 1, \qquad B_k = \frac{2}{\sqrt{\pi s}} \qquad (4).$$

In addition to a channel phase frequency characteristic (PFC), let us introduce a function $\tau(f)$, which is called a dispersion characteristic (DC) of a channel or a dispersion of a delay. It contains only the parameters of phase dispersion and is as follows:

$$\tau_g(F) = \frac{d\varphi}{d\omega} \approx \tau_g + s(F) + \frac{v}{2}(F)^2 \qquad (5).$$

PDP distortions are caused by nonlinear component of a PFC [4, 5]. According to (3), PFC consists of a linear and a nonlinear component:

$$\varphi(\bar{f}, F) = \varphi_{lin}(\bar{f}, F) + \varphi_{nlin}(\bar{f}, F) \qquad (6).$$

where $\varphi_{lin}(\bar{f}, F) = \varphi(f) + 2\pi\tau_g(F)$ – a liner component of a PFC, $\varphi_{nlin}(\bar{f}, F) = \pi s(F)^2 + \frac{\pi}{3}v(F)^3$ – a nonlinear component of a PFC.

3. Relationship between coherence band of transionospheric radio channels and TEC

The phase taper caused by the transionospheric propagation can be presented as follows [6]:

$$\begin{aligned}\varphi(\omega) &= \frac{1}{c}\int [\omega \cdot n(\omega, z)]dz \approx \\ &\approx \omega \int \frac{dz}{c} - [\frac{1}{f}\frac{\pi k}{\tilde{n}}\int N_e(z)dz + \\ &+ \frac{1}{f^3}\frac{\pi k^2}{4c}\int N_e^2(z)\,dz + \\ &+ \frac{1}{f^5}\frac{\pi k^3}{8c}\int N_e^3(z)\,dz] = \\ &= \omega \int \frac{dz}{c} - [\frac{\alpha_1}{f} + \frac{\alpha_2}{f^3} + \frac{\alpha_3}{f^5}]\end{aligned} \qquad (7).$$

where $k = 80.5$, $\int N_e(z)dz$ – total electron content of the ionosphere for high z values, N_t.

We took the first three derivatives of the phase function with respect to the frequency at a point $\bar{f}$ to obtain the characteristics of frequency dispersion:

$$\begin{aligned}\tau_g(f) &= \frac{d\varphi}{d\omega}(f) = \frac{1}{2\pi}[2\pi\int\frac{dz}{c} + \\ &+ \frac{\alpha_1}{f^2} + 3\frac{\alpha_2}{f^4} + 5\frac{\alpha_3}{f^6} + \cdots]\end{aligned} \qquad (8a).$$

$$\begin{aligned}s(f) &= \frac{d\tau_g}{df}(f) = -\frac{1}{\pi}[\frac{\alpha_1}{f^3} + \\ &+ 6\frac{\alpha_2}{f^6} + 15\frac{\alpha_3}{f^7} + \cdots]\end{aligned} \qquad (8b).$$

$$\begin{aligned}v(f) &= \frac{d^2\tau_g}{df^2}(f) = \frac{3}{\pi}[\frac{\alpha_1}{f^4} + \\ &+ 10\frac{\alpha_2}{f^6} + 35\frac{\alpha_3}{f^8} + \cdots]\end{aligned} \qquad (8c).$$

The values $\tau_g(\bar{f})$, $s(\bar{f})$, $v(\bar{f})$ are the parameters of the channel phase dispersion at a fixed frequency $f = \bar{f}$. Each equation (8a) - (8c) represents the sum of different approximations. Their significance is determined primarily by the value of the frequency. Optimization of the calculations requires to estimate the frequency ranges for which the individual approximations are important. It is clear that the first summand in (8a) does not depend on frequency and thus does not influence on signal distortions. The impact of the second summand will be significant at high frequencies. The impact of the third and fourth summands increases as frequency gets close to the ionosphere penetration frequency.

An analysis of the data presented in [7] showed that the first approximation is valid when $\hat{f} > 6$, the second approximation is valid when $6 > \hat{f} > 4.5$ and the third approximation is valid when $4.5 > \hat{f} > 3$.

The work [6] shows, that satisfying of inequality $\bar{f} > \sqrt[3]{\alpha_2}$ (high-frequency (HF) approximation) is sufficient to solve practical tasks for the space communication systems. Thus, the phase dispersion of the first $\tau_g(\bar{f})$, second $s(\bar{f})$ and third $v(\bar{f})$ order can be presented as follows:

$$\begin{aligned}\tau_g(f) &= \int\frac{dz}{c} + \frac{\alpha_1}{2\pi\bar{f}^2} = \\ &= \int\frac{dz}{c} + \frac{k}{2c\cdot\bar{f}^2}\cdot N_t\end{aligned} \qquad (9a).$$

$$s(f) = -\frac{1}{\pi}\frac{\alpha_1}{\bar{f}^3} = -\frac{k}{c\cdot\bar{f}^3}\cdot N_t \qquad (9b).$$

$$v(f) = \frac{3}{\pi}\frac{\alpha_1}{\bar{f}^4} = \frac{3k}{c\cdot\bar{f}^4}\cdot N_t] \qquad (9c).$$

The concept of a radio channel coherence band is introduced to estimate the significance of dispersion distortions. When a signal frequency band exceeds a coherence band, a channel phase frequency characteristic depends on frequency and one can judge the presence of dispersion distortions. According to (9b), the equation for coherence band of a transionospheric radio channel is as follows:

$$B_k = \frac{2}{\sqrt{\pi \cdot |s|}} = \sqrt{\frac{4c \cdot \bar{f}^3}{\pi k \cdot N_t}} \qquad (10).$$

Thus, the key parameters for calculating CB are a TEC value and an operating frequency of a space communication system.

4. Algorithm and software for plotting electronic diagnostic maps of coherence bands of transionospheric radio channels

The algorithm and software have been developed for automated plotting electronic diagnostic maps of the coherence bands. The input data of the algorithm are RINEX files obtained as a result of sounding of transionospheric radio channels with the use of GNSS/GPS signals. The algorithm includes the following steps:

1) Automated converting RINEX files to .dat files which contain data on the residual component of TEC ($N_{T,o}$) using AutoIt programming language as well as TecSuite and MapTec [8, 9] programs for data from the whole network of sounding stations. Recording information about files into a PostgreSQL database.

2) Then we obtain information about the regular component of TEC ($N_{T,r}$) according to the data of online resource IRI (International Reference Ionosphere) using the AutoIt programming language and the computer program Wget. Information is also recorded into the database.

3) Calculation of absolute TEC as a sum of the regular and residual components obtained in stages 1 and 2: $N_T = N_{T,r} + N_{T,o}$.

4) Calculation of a coherence band for selected communication channels with the use of equation (4). Calculated CB values are recorded into the database.

5) Plotting electronic diagnostic maps of coherence bands of transionospheric radio channels with the use of developed MapCreator program for selected sounding stations, date, time interval and step.

5. Experimental results

Figures 1-4 show, respectively, examples of CB maps for Moscow, South region, Republic of Tatarstan and Samara Region. The longitude is plotted along the X-axis, the latitude is plotted along the Y-axis, and the color points indicate the place in which the value of a coherence band was measured. Similar maps can be plotted for various region of the Earth, if there is appropriate data from receiving stations of GNSS/GPS systems. Coherence bands map is presented in the form of an animated image in the .gif format or a media file in the .mp4 format at which the points move dynamically over time and change the color depending on the value of the coherence band.

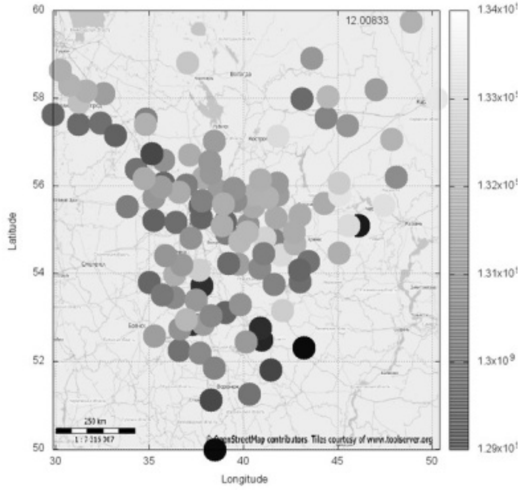

Figure 1. Example of CB map for Moscow

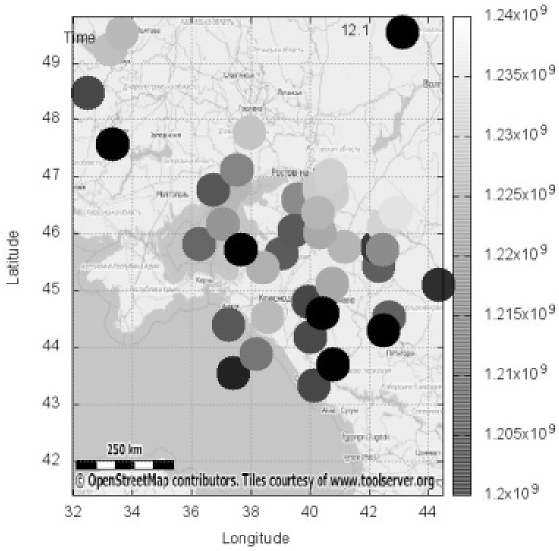

Figure 2. Example of CB map for South region

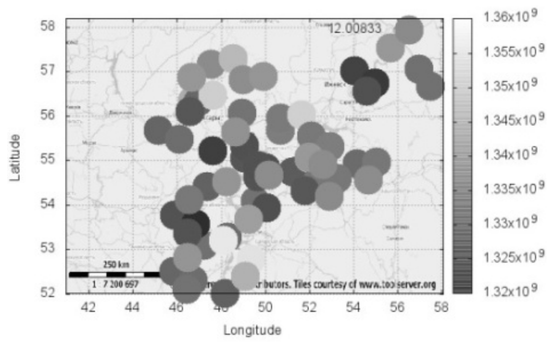

Figure 3. Example of CB map for Republic of Tatarstan

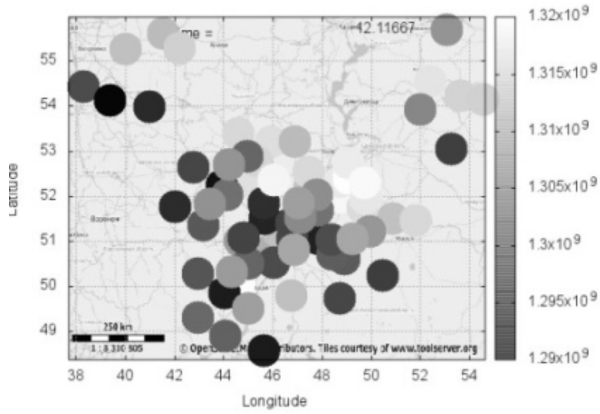

Figure 4. Example of CB map for Samara region

Verification of the developed software has shown that the time costs for an automated processing of sounding results are reduced to next lower order. Besides, the data obtained are systematized in the database and ready for further study.

6. Conclusions

A new method for determining and plotting coherence bands which limit signal frequency band under the influence of frequency dispersion has been proposed. We developed an algorithm and a software for plotting regional diagnostic maps using experimental data obtained from the GNSS and GPS satellite navigation systems. Experiments conducted in the European part of the Russian Federation showed high efficiency of the method.

7. Acknowledgements

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