Modeling and studying ionograms of oblique sounding of HF radio channels for radio links of various length using a digital ionosonde with USRP platform

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***Abstract* — The paper analyses the outcomes of numerical studies into the effect of phase dispersion on broadband elements of a FMCW signal with varying central spectrum frequencies corresponding to the central frequencies of radio channels. We used the International Reference Ionosphere (IRI) model as the background ionosphere, which takes into account the spatiotemporal variability of the radio channel. The data corresponding to the extreme values in the annual distribution of solar activity were selected for modeling ionograms. The effect of the second-order phase dispersion on power delay profile distortions was analyzed.**

Keywords — ionosphere, dispersion, FMCW signal, radio channel, power delay profile distortions

I. INTRODUCTION

Currently, one of the topical scientific missions is the development of radiophysical techniques aimed at processing and analyzing signals to improve the information efficiency of sounding broadband and ultra-broadband ionospheric HF radio channels using frequency modulated continuous wave (FMCW) and frequency modulated interrupted continuous wave (FMICW) signals. However, the dispersion caused by the extension of a signal bandwidth leads to a decrease in the correlation between the received complex signal with a replica of the transmitted signal. Besides, the wider the signal bandwidth the larger frequency dispersion. The aim of the research is to study the influence of nonlinear phase dispersion on the distortions of a FMCW signal with the different signal element bandwidth and different central spectrum frequency.

II. THE TECHNIQUE OF CHANGING THE FREQUENCY BANDWIDTH AND HOPPING THE CENTRAL SPECTRUM FREQUENCY OF A FMCW SIGNAL ELEMENT

In the case of using a FMCW signal and its compression in the receiver, increasing the signal bandwidth leads to the increase in the sample length. We proposed the method [1] of changing the signal element bandwidth and hopping the central

frequency by varying the sample length of a difference frequency signal and the origin of the samples. According to the proposed method, it is necessary to select a certain number of samples at the sounding time and the certain number of fast Fourier transform points in order to compute the difference frequency signal spectrum.

Fig. 1 illustrates the proposed processing method. At the left there is procedure of changing the spectrum bandwidth of an element of a FMCW signal. At the right - hopping the central spectrum frequency.

Let us analytically analyze the effect of dispersive propagation on broadband elements of a FMCW signal. We shall note that dispersion [1-2] depends on the frequency bandwidth of the signal element. Besides, it depends on the central spectrum frequency of the element. Thus, we are going to study dispersion distortions of the compressed signal element.

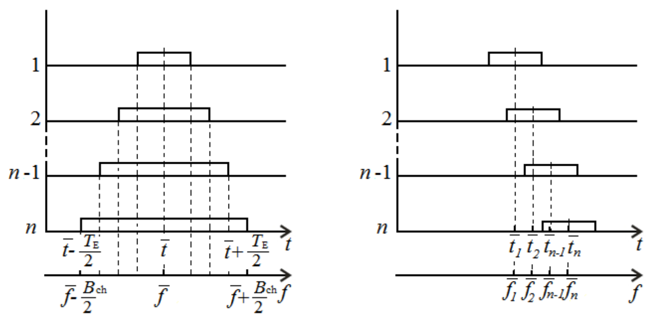

Fig. 1. Changing the frequency bandwidth and hopping the central spectrum frequency of a FMCW signal element

III. THEORETICAL ESTIMATION OF THE EFFECT UNDER RESEARCH

Analytic solution of the problem requires taking into account the second approximation for the phase function in order to study the effect of the phase dispersion on the propagation of a FMCW signal [1-2]. We shall note that matched filter processing gives the frequency difference between transmitted and received signals. For a FMCW signal, its frequency is linearly related to time. Thus, the signal phase is a complex function of "slow" time t, and the frequency is an intermediate variable.

When signal propagate in a dispersive medium, the phase acquires a nonlinear component, expressed by the second time derivative. The nonlinear component is the second-order frequency dispersion parameter, which for a random propagation mechanism (mode) can be express using difference frequency F_j or the parameters of the function $\tau_j(f) = F_j(f) / \dot{f}$:

$$\frac{d^2\varphi_j}{dt^2} = 2\pi\dot{f}\frac{dF_j}{dt} = 2\pi\dot{f}^2 s_j \tag{1}$$

where $\tau_j(f) = \dfrac{d\varphi_j}{2\pi\, df}$ - «fast» time, $s_j = \dfrac{d\tau_j(f)}{df}$ - second-order frequency dispersion parameter.

Thus, the phase expansion near the value of a "slow" time $\bar{t}$ in terms of the second approximation is as follows:

$$\varphi_j(t) = \varphi_j(\bar{t}_n) + 2\pi\dot{f}\tau_j \cdot (t - \bar{t}_n) + \pi\dot{f}^2 s_j \cdot (t - \bar{t}_n)^2 \tag{2}$$

The third summand determines the nonlinear component of the phase as a function of time, and, consequently, of frequency. In this case, due to the dispersion, the difference frequency signals acquire a linear frequency modulation with a frequency sweep rate:

$$\dot{F}_j = \dot{f}^2 \cdot s_j \tag{3}$$

As a result, on the sampling time T_{E}, the difference frequency signals, referring to different propagation modes, acquire a deviation:

$$\Delta F_j = \dot{f}^2 \cdot s_j(\bar{f}_n) \cdot T_E = \dot{f} \cdot s_j(\bar{f}_n) \cdot \Delta f_E \tag{4}$$

where $\Delta f_E = \dot{f} \cdot T_E$ – frequency bandwidth of an element of a FMCW signal.

It is clear [3], that the amplitude spectrum of the difference frequency signal has the form (5) in terms of the second approximation of the phase function:

$$|S(f)| = \sum_{j=1}^{m}|S_j(f)| = \frac{U_0^2\sqrt{T_E}}{2} \cdot \sum_{j=1}^{m}\frac{H_j(\bar{f}_n)}{\sqrt{2\Delta F_j}} \cdot \left[\{C(z_1)+C(z_2)\}^2 + \{S(z_1)+S(z_2)\}^2\right]^{0.5} \tag{5}$$

where $C(z), S(z)$ - Fresnel integrals,

$$z_1 = \sqrt{\frac{2T_E}{\Delta F_j}}(F - F_j(\bar{f}_n)) - 2\sqrt{\Delta F_j T_E}\,,\quad z_2 = \sqrt{\frac{2T_E}{\Delta F_j}}(F - F_j(\bar{f}_n))$$

Linear frequency modulation of the difference frequency signal causes the dispersion distortions of the shape of signal amplitude spectrum, which is similar to a channel impulse response (CIR).

Let us consider the occurrence of significant dispersion distortions. It is necessary to estimate variation in the nonlinear component of the phase function on the sample length of the difference frequency signal. Let us suppose that the critical sample length is the interval where the phase taper does not exceed 1 radian at the interval boundaries. The critical slope is an increment in the function $\tau_j(f)$ for which, the nonlinear component of the phase function does not exceed 1 radian.

According to (1), critical sample length and critical slope are calculated using the equation (6):

$$T_{crj} = 2 / \dot{f}\sqrt{\pi|s_j|}\,,\quad s_{crj} = \frac{4}{\pi} \cdot \frac{1}{\dot{f}(T_E)^2} \tag{6}$$

Simultaneously with the distortion of the CIR form in channels with frequency dispersion, there are impulse power losses, which can be estimated using the equation:

$$\eta = 20\lg\left[|h_M(\bar{f})| / |h_0(\bar{f})|\right] \tag{7}$$

where $|h_M(\bar{f})|$ and $|h_0(\bar{f})|$ - maximum values of the CIR module with dispersion and without dispersion, respectively.

Numerical studies showed that for a channel with a rectangular and Gaussian frequency response function (FRF) and the bandwidth $\Omega_{ch} = 2\Omega_S$, the losses in a channel with a second-order phase dispersion are calculated using equations (8) and (9):

$$\eta = -10\lg\left(\frac{C^2(1.3p_j) + S^2(1.3p_j)}{(1.3p_j)^2}\right) \tag{8}$$

$$\eta = -5\lg\left(1 + (0.7p_j)^4\right) \tag{9}$$

where $p_j = \sqrt{\dfrac{\pi |s_j(\bar{f})|}{4}} \cdot B_{ch} = \dfrac{B_{ch}}{B_{2c}}$ - frequency dispersion coefficient, $B_{ch} = \dfrac{\Omega_{ch}}{2\pi}$ - channel bandwidth, B_{2c} - coherence bandwidth.

The coherence bandwidth in the case of second-order dispersion is estimated using the equation (10):

$$B_{2c} = \sqrt{\frac{2}{\pi^2 |\varphi''(\bar{f})|}} = \sqrt{\frac{4}{\pi |s(\bar{f})|}} \tag{10}$$

It is clear that the coherence bandwidth decreases (the losses increase) with an increase in the second-order dispersion parameter.

Let us suppose that the allowable losses are $\eta = \eta_l = 0.5$ dB and the inequality $\eta \le \eta_l$ is satisfied at:

$$B_{ch} \le B_{2c} \tag{11}$$

Dispersion distortions estimates suggest that in the case of a third-order dispersion, the losses are allowable when the inequality (12) is satisfied:

$$B_{ch} \le 0.9 B_{3c} \tag{12}$$

It is clear that dispersion will lead to a decrease in the signal-to-noise ratio. It is estimated using the equation (13):

$$SNR = 10\lg \frac{S}{S_0}\frac{S_0}{N} = 10\frac{S_0}{N} + \eta = 10\lg \frac{S_0}{N} + 10\lg D + \eta \tag{13}$$

where N – noise power, S - peak power of a compressed distorted signal, S_0 - peak power of a compressed undistorted signal, $\hat{S}_0$ - peak power of an undistorted signal before compression in a receiver, D - signal base.

We shall note that the loss coefficient due to dispersion always has a negative value. Thus, when the signal bandwidth is expanded over the coherence bandwidth the dispersion leads to a decrease in the signal base and, consequently, in the signal-to-noise ratio.

IV. Modeling the Frequency Dependence of the Delay in a Medium at Vertical Incidence and Oblique Incidence

In the mission of modeling the frequency dependence of the delay in a medium for the case of vertical-incidence sounding (VIS) we used the equation (14) of an ordinary wave in the parabolic layer model [4]:

$$\tau_V(f) = \frac{2h_0}{c} + \frac{y_m}{c}\frac{f}{f_k}\ln\frac{f_k + f}{f_k - f} \tag{14}$$

where $f_k[kHz] = \sqrt{80.8 N_m} \approx 9\sqrt{N_m}$ – layer penetration frequency, N_m – electron concentration at the maximum of a layer, h_0 – height of the bottomside of a layer, y_m – half-thickness of a layer. The penetration frequency of the layer was calculated using the maximum value of the electron concentration specified in the IRI model.

The dependence for VIS was recalculated [5] for the case of oblique-incidence sounding (OIS) using the equation (15):

$$\tau_O = \left(\tau_V + \frac{2R_s}{c}\left(1 - \cos\frac{D}{2R_s}\right)\right)\sqrt{1 + \left[\frac{2R_s \sin\frac{D}{2R_s}}{c\tau_V + 2R_s\left(1 - \cos\frac{D}{2R_s}\right)}\right]^2} \tag{15}$$

where f_O – frequency for the equivalent OIS, τ_O – delay for the equivalent OIS, f_V – frequency for the VIS, τ_V – delay for the VIS, D – path length, c – light velocity, R_s – Earth radius.

We used the method of equal hops in order to calculate the frequency dependencies of the delay for the multiple hop modes. Fig. 2 and 3 show the examples of the frequency dependences of group delay for the 1F2, 2F2, 3F2 modes in case of OIS. They refer to different path lengths with a minimum level of solar activity.

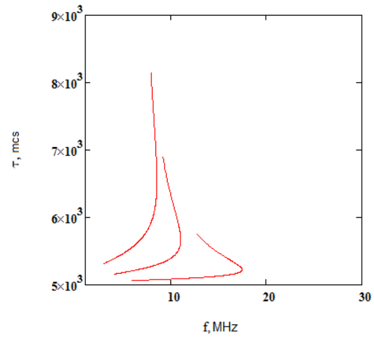

Fig. 2. Frequency dependence of group delay for OIS for the path length of 1500 km

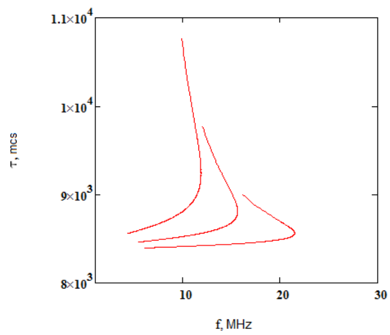

Fig. 3. Frequency dependence of group delay for OIS for the path length of 2500 km

V. Studying the Dispersion Distortions of the Sounding Signal

The technique described in [3,6] was used to synthesize the spectra of the difference frequency signal with hopping central frequencies considering the phase dispersion distortions. At first, the frequency dependence of the delay is synthesized for various propagation mechanisms (or modes) of a FMCW signal using the data specified in the IRI model at the sounding check point. Then the frequency bandwidth Δf of a sounding signal element and the frequency step are selected for one of the propagation mechanisms. The modules of the spectra of the difference frequency signal (in the logarithmic scale - amplitude values) are then calculated for potential operating frequencies and plotted on the plane $(f = \dot{f}\,t,\ \tau = F / \dot{f})$. A three-dimensional image of this dependence shows the dispersion distortions of the modes.

Fig. 4 shows examples of distorted modes of modeled ionograms for the paths 1500 km and 2500 km with a different channel bandwidth. Dispersion distortions increase with the rise in the number of hops. The width of the modes of the ionogram increases when the phase dispersion increases i.e. as frequency get close to the maximum usable frequency (MUF)

VI. Studying the Experimental Ionograms of Oblique-Incidence Sounding Obtained Using a Digital Ionosonde Based on the USRP Platform

In the above, we considered the technique for synthesizing the dispersion characteristic using modeled ionograms. Processing of experimental ionogram differs a lot from the modeled one. According to the theory presented in the monograph [7], the dispersion characteristic $\tau(f)$ of a radio channel has several components – regular $\overline{\tau}_r(f)$, irregular $\overline{\tau}_{ir}(f)$ and stochastic $\widetilde{\tau}(f)$. The regular component of the dispersion characteristic is required for studying dispersion distortions. Suitable algorithm and appropriate software based on LabVIEW were developed in order to obtain regular component from the experimental dispersion characteristic. The method is based on polynomial filtering of the experimental dispersion characteristic. The polynomial approximant is the regular component.

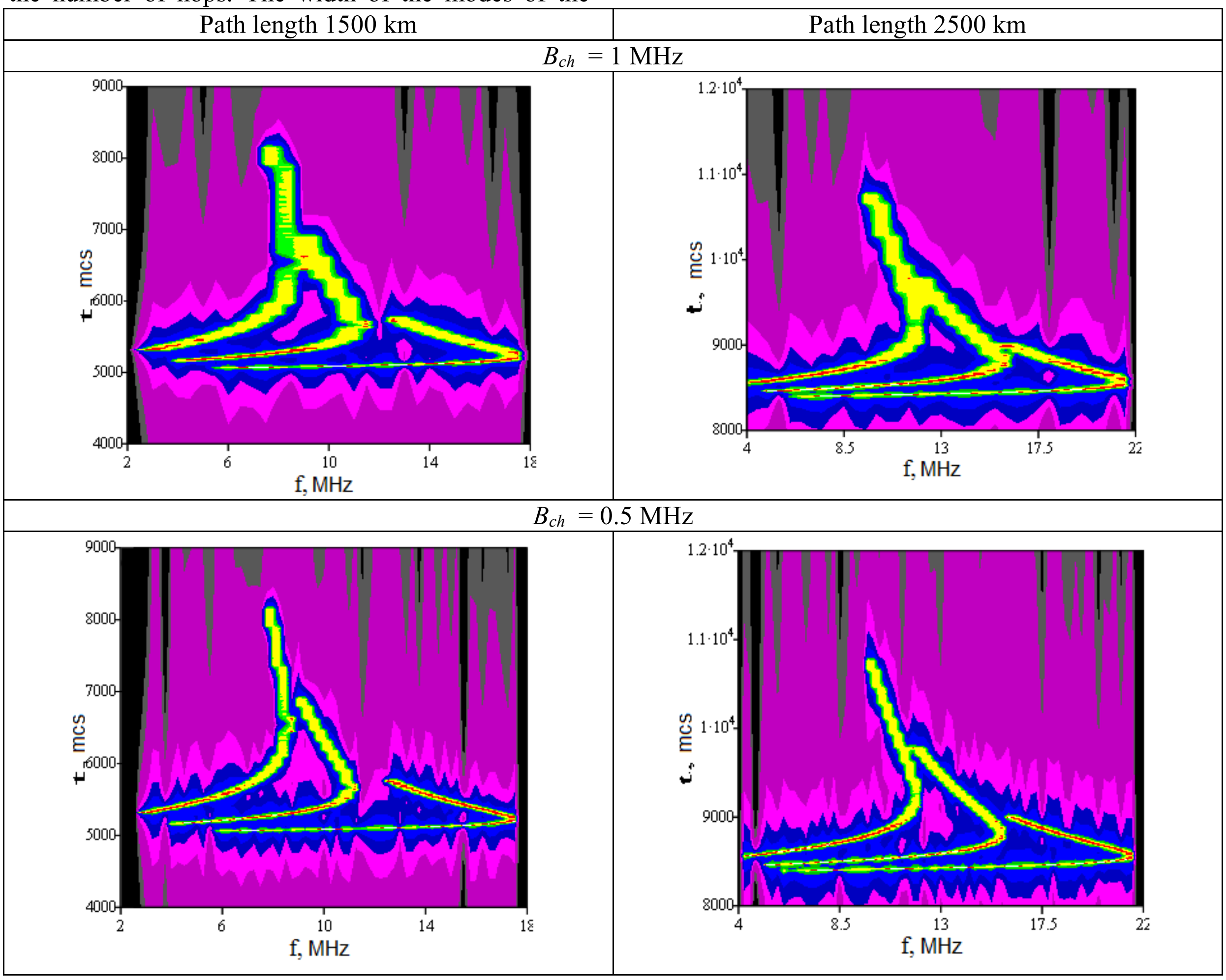

Fig. 4. Distored modes of modeled ionograms for paths 1500 km and 2500 km

The algorithm for obtaining a regular component has the following steps:

- the regions of a mode are selected for a given band B_{ch} and frequency step (Fig. 5);
- points (f_j, τ_j) with the largest signal-to-noise ratio are selected;
- the selected values are approximated by the polynomial of the second order.

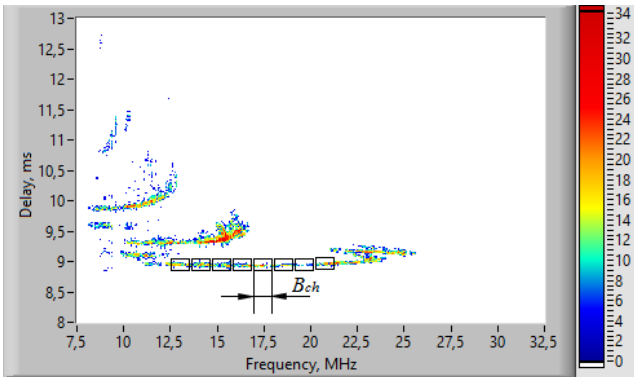

Fig. 5. Selecting the regions of the 1F2 mode for the approximation

The polynomial dispersion characteristic allowed us to determine the second- and third-order dispersion parameters (respectively, the slope s_j and the nonlinearity parameter v_j). This approach is aimed at studying the second- and third-order dispersion parameters over long-distance propagation paths (1000-3500 km). Table 1 presents the second- and third-order phase dispersion parameters for channels with a bandwidth of 1 MHz.

TABLE I. THE SECOND- AND THIRD-ORDER PHASE DISPERSION PARAMETERS FOR CHANNELS WITH A BANDWIDTH OF 1 MHZ

Path length (km)	**Time of day**	$\hat{f}$ **=0.5MUF**		$\hat{f}$ **=0.7MUF**		$\hat{f}$ **=0.9MUF**	
		Sj	***Vj***	***Sj***	***Vj***	***Sj***	***Vj***
1500	day	16	8	26	12	52	26
	night	37	30	62	47	126	114
2620	day	15	6	25	10	52	25
	night	33	25	51	38	104	106

VII. CONCLUSIONS

The effect of dispersion distortions of sounding signals on ionogram modes for various paths was numerically studied. The rise in number of hops leads to the increase in dispersion distortions. Dispersion increases as frequency gets close to the maximum usable frequency, which results in the increase in the modes width. Experimental research into the second- and the third-order frequency dispersion parameters for paths of different lengths showed that the second-order dispersion parameter does not depend on the path length at paths from 2000 km to 3500 km. The third-order parameter of frequency dispersion decreases with the increase in the path length and increases by the night time. The results presented indicate that the dispersion distortions, and, consequently, the losses in the pulse power increase with the decrease in the path length and they also increase by the night time.

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