THE QUALITY OF ESTIMATION OF PARAMETERS OF A BROADBAND SIGNAL WITH NON-OPTIMAL RECEPTION UNDER CONDITIONS OF DISPERSION DISTORTIONS IN THE EARTH'S IONOSPHERE

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In the article, analytical expressions are obtained that make it possible to calculate the variance of the estimates of the initial phase, frequency and delay of the signal, as well as the covariance functions of pairs of estimates under the conditions of dispersion distortions. At the same time, the evaluating device does not know exactly or does not know the level of dispersion distortions at all and does not try to evaluate them. Therefore, the estimation of the parameters is carried out by a non-optimal algorithm. The described conditions arise in practice, for example, when trying to estimate the above parameters of a broadband signal by a classical estimator that does not take into account dispersion distortions. The described conditions also occur when the true value of the slope of the dispersion characteristic of the channel deviates from the previously measured value over time or due to the use of inaccurate measurement results or an inaccurate prediction of the value of the slope of the dispersion characteristic of the channel. The article presents analytically obtained graphs for the root-mean-square deviations of the obtained phase, delay and frequency estimates for the case of complete absence of dispersion distortion compensation and the case of incomplete dispersion distortion compensation. In particular, it is shown that the degradation of the quality of delay estimation is due to two factors: a value decrease and an expansion of the correlation peak. In terms of energy, this degradation exceeds the acquisition or demodulation loss. The results of the obtained calculations are confirmed by simulation modeling.

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Introduction

In the modern world, high-frequency (HF) communication systems are actively used to organize radio links in remote and hard-to-reach regions of the world, including the Arctic and Antarctic. The relevance of the use of HF radio communication systems in these areas is due to the fact that such systems can offer reliable and low-cost solutions with minimal infrastructure that have proven themselves for decades.

The development of high-frequency communication systems is currently aimed at increasing the speed of information transmission by increasing the frequency band. As a rule, HF communication systems operate in a frequency band not exceeding 100 kHz. In this case, the frequency dispersion of the dielectric permittivity coefficient of the Earth's ionosphere plasma, do not significantly affect the communication quality. However, these dispersion distortions, taking into account the nonstationarity of the Earth's ionosphere, are a significant obstacle to expanding the spectrum of used signals above 100 kHz.

Therefore, an important task is to study the quality of estimating the parameters of a signal distorted by the frequency dispersion of the ionospheric channel. In this article, we study the effect of ignoring dispersion distortions by a receiving device on the quality of estimating other signal parameters.

Problem formulation

A received complex signal distorted by the ionospheric channel can be written as

$$\dot{y}(t)=\dot{x}(t,\varphi,\tau,f_d,s)+\dot{n}(t)=e^{-j\varphi}e^{j2\pi f_d(t-\tau)}\dot{x}(t-\tau,s)+\dot{n}(t),\quad t=-T_s/2\div T_s/2 \tag{1}$$

where $\dot{x}(t,s)=\dot{x}(t)*\dot{h}(t,s)$ is a complex signal distorted by frequency dispersion of the ionospheric channel, $\dot{h}(t,s)$ – impulse response (IR) of the ionospheric channel, $\dot{x}(t)$ is a transmitted complex signal, f_d is a frequency shift, τ is a delay, s is a slope of the dispersion characteristic (the slope of DC) which characterize dispersion distortions, φ is an initial phase, $\dot{n}(t)$ – white gaussian noise with zero expected value and dispersion $\sigma_{ш}^2$, T_s is a signal duration.

Notice that f_d, τ, s, φ are unknown, not random parameters of the received signal.

The model of the ionospheric channel with a linear dependence of the signal group delay on the center frequency was chosen [1-8] due to the reason that this model contains certain parameter characterizing dispersion distortions – s. The frequency response (FR) of the ionospheric channel in the absence of multipath signal propagation defined as

$$H(j2\pi f)=e^{-j\pi s f^2},\quad f\in[-\Delta f/2;\Delta f/2] \tag{2}$$

where Δf – a width of FR of the ionospheric channel. The phase response of the channel is described by a quadratic dependence on frequency, and the group propagation delay is linear with a slope of S μs/MHz.

Further, we offer to consider the case of non-optimal reception, when the signal at the input of the receiver differs from the reference signal. The signal (1) is a received signal, as indicated above, however, the signal to which the receiving device is tuned has the form:

$$\tilde{u}(t,\hat{f}_d,\hat{\tau},\hat{s},\hat{\varphi})=e^{-j\hat{\varphi}}e^{j2\pi\hat{f}_d(t-\hat{\tau})}\dot{x}(t-\hat{\tau},\hat{s}). \tag{3}$$

This means that the receiver has some inaccurate information about the slope of the DC $\hat{s}\neq s$ or knows nothing about dispersion distortions $\hat{s}=0$ and does not try to estimate / refine the value of $\hat{s}=0$.

According to the maximum likelihood method (ML), the coherent estimation of the unknown parameters f_d, τ, φ is calculated as the absolute maximum of following expression:

$$\left[\hat{f}_{d,ML},\hat{\tau}_{ML},\hat{\varphi}_{ML}\right]=\arg\max_{\hat{f}_d,\hat{\tau},\hat{\varphi}}\times$$
$$\times\left(\rho^2\,\mathrm{Re}\left[\dot{S}_\Delta\left(f_d,\hat{f}_d,\tau,\hat{\tau},s,\hat{s},\varphi,\hat{\varphi}\right)\right]+\rho\,\mathrm{Re}\left[\dot{N}_\Delta\left(\hat{f}_d,\hat{\tau},\hat{s},\hat{\varphi}\right)\right]\right), \tag{4}$$

where

$$\dot{S}_\Delta\left(f_d,\hat{f}_d,\tau,\hat{\tau},s,\hat{s},\varphi,\hat{\varphi}\right)=\frac{1}{\sigma_{ш}^2}\int_{-T_s/2}^{T_s/2}\dot{x}(t,\varphi,\tau,f_d,s)\tilde{u}^*\left(t,\hat{f}_d,\hat{\tau},\hat{s},\hat{\varphi}\right)dt$$

is the signal component of the logarithm of the likelihood function,

$$\dot{N}_\Delta\left(\hat{f}_d,\hat{\tau},\hat{s},\hat{\varphi}\right)=\frac{1}{\sigma_{ш}^2}\int_{-T_s/2}^{T_s/2}\dot{n}(t)\tilde{u}^*\left(t,\hat{f}_d,\hat{\tau},\hat{s},\hat{\varphi}\right)dt$$

is the interference component of the logarithm of the likelihood function, $\hat{f}_{d,ML}$ – the ML estimation of the frequency shift, $\hat{\tau}_{ML}$ – the ML estimation of the delay, $\hat{\varphi}_{ML}$ – the ML estimation of the initial phase, $\tilde{u}(t,\hat{f}_d,\hat{\tau},\hat{s},\hat{\varphi})$ is a complex reference signal formed on the basis of a priori information about the transmitted signal and unknown estimated parameters, $\hat{f}_d\in\Delta_{f_d}$ – a current estimation of the frequency shift, $\hat{\tau}\in\Delta_\tau$ – a current estimation of the delay, $\hat{\varphi}\in[0;2\pi]$ – a current estimation of the initial phase, * – complex conjugate symbol, Δ_{f_d} – domain of unknown frequency shift, Δ_τ – domain of unknown delay, $\rho_\Delta^2=\frac{\tilde{E}_s}{\sigma_{ш}^2}$ is a signal-to-noise ratio (SNR) for non-optimal reception, $\tilde{E}_s=\left|S_\Delta\left(f_d,f_d,\tau,\tau,s,\hat{s},\varphi,\varphi\right)\right|$, $\hat{s}\neq s$.

Then, substituting (1) and (3) into expression (4), we obtain that the signal component of the logarithm of the likelihood function in case of non-optimal reception described as:

$$\dot{S}_\Delta\left(f_d,\hat{f}_d,\tau,\hat{\tau},s,\hat{s},\varphi,\hat{\varphi}\right)=e^{-j(\varphi-\hat{\varphi})}e^{-j2\pi f_d\tau}e^{j2\pi\hat{f}_d\hat{\tau}}\frac{1}{\tilde{E}_s}\times$$
$$\times\int_{-\infty}^{\infty}\dot{x}(t-\tau,s)\dot{x}^*(t-\hat{\tau},\hat{s})e^{j2\pi t\left(f_d-\hat{f}_d\right)}dt \quad (5)$$

By calculation, it can be shown that, with non-optimal reception, a shift in the phase estimate occurs due to incomplete or absent compensation of dispersion distortions.

The phase shift value can be calculated by the formula:

$$\psi(s,\hat{s})=\operatorname{arctg}\frac{\operatorname{Im}\left[\dot{S}_\Delta\left(f_d,f_d,\tau,\tau,s,\hat{s},\varphi,\varphi\right)\right]}{\operatorname{Re}\left[\dot{S}_\Delta\left(f_d,f_d,\tau,\tau,s,\hat{s},\varphi,\varphi\right)\right]}=$$
$$=\operatorname{arctg}\frac{\operatorname{Im}\left[\int_{-\infty}^{\infty}\dot{x}(t-\tau,s)\dot{x}^*(t-\tau,\hat{s})dt\right]}{\operatorname{Re}\left[\int_{-\infty}^{\infty}\dot{x}(t-\tau,s)\dot{x}^*(t-\tau,\hat{s})dt\right]} \quad (6)$$

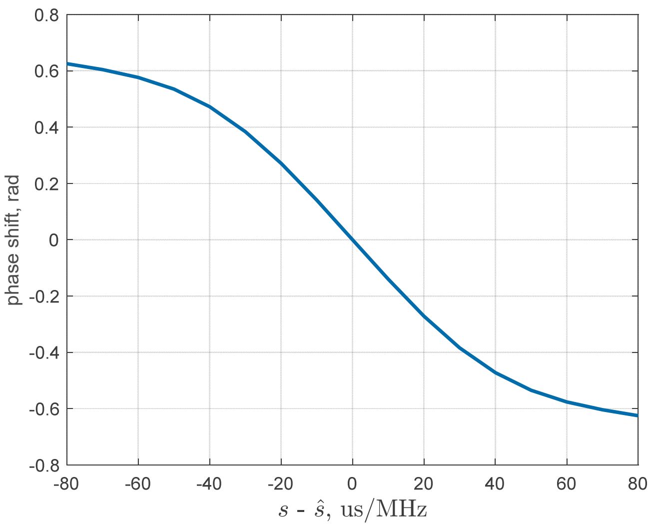

Figure 1. Phase shift $\psi(s,\hat{s})$ at non-optimal reception

The analysis of the variance of the obtained estimates is carried out near the global maximum of the likelihood ratio. Therefore, for further theoretical calculations, the phase shift should be eliminated analytically. For further analysis, we introduce a function:

$$S_\Delta\left(f_d,\hat{f}_d,\tau,\hat{\tau},s,\hat{s},\varphi,\hat{\varphi}\right)=\operatorname{Re}\left[\dot{S}_\Delta\left(f_d,\hat{f}_d,\tau,\hat{\tau},s,\hat{s},\varphi,\hat{\varphi}\right)e^{-j\psi(s,\hat{s})}\right]$$

The correlation function of estimations of the studied non-energy parameters in the first approximation is calculated as [9]

$$K_{jp}\left(\hat{\boldsymbol{\theta}}_{MП}/\boldsymbol{\theta}\right)=\frac{1}{\rho_\Delta^4\hat{\Omega}^2}\sum_{q=1}^{\mu}\sum_{\nu=1}^{\mu}\hat{A}_{j\nu}\hat{A}_{pq}\left.\frac{\rho^2\partial^2 S_N\left(\boldsymbol{\theta}_1,\boldsymbol{\theta}_2\right)}{\partial\theta_{1\nu}\partial\theta_{2q}}\right|_{\hat{\boldsymbol{\theta}}\to\boldsymbol{\theta}},$$
$$j=1\div\mu,\ p=1\div\mu. \quad (7)$$

where $\hat{\Omega}$ – Fisher matrix determinant W_Δ, $\hat{A}_{jp}$ – are cofactors of the matrix W_Δ, $S_N\left(\boldsymbol{\theta}_1,\boldsymbol{\theta}_2\right)=M\left[N_\Delta\left(\boldsymbol{\theta}_1\right)N_\Delta\left(\boldsymbol{\theta}_2\right)\right]$ is a correlation function of interference components of the logarithm of the likelihood function, equal to the signal component at points $\boldsymbol{\theta}_1$, $\boldsymbol{\theta}_2$ (non-optimal reception).

Since the estimated parameters are not energy ones, then

$$\theta_{11},\ \theta_{21}-\hat{f}_d,\ \theta_{12},\ \theta_{22}-\hat{\tau},\ \theta_{13},\ \theta_{23}-\hat{\varphi};$$

the matrix W_Δ is described as

$$W_\Delta=-\left.\begin{pmatrix}\frac{\partial^2 S_\Delta}{\partial\hat{f}_d^2} & \frac{\partial^2 S_\Delta}{\partial\hat{f}_d\partial\hat{\tau}} & \frac{\partial S_\Delta}{\partial\hat{f}_d\partial\hat{\varphi}}\\ \frac{\partial^2 S_\Delta}{\partial\hat{f}_d\partial\hat{\tau}} & \frac{\partial^2 S_\Delta}{\partial\hat{\tau}^2} & \frac{\partial S_\Delta}{\partial\hat{\tau}\partial\hat{\varphi}}\\ \frac{\partial^2 S_\Delta}{\partial\hat{f}_d\partial\hat{\varphi}} & \frac{\partial^2 S_\Delta}{\partial\hat{\tau}\partial\hat{\varphi}} & \frac{\partial S_\Delta}{\partial\hat{\varphi}^2}\end{pmatrix}\right|_{\substack{\hat{f}_d\to f_d\\ \hat{\tau}\to\tau\\ \hat{\varphi}\to\varphi}}, \quad (8)$$

where S_Δ is a shortened notation of $S_\Delta\left(f_d,\hat{f}_d,\tau,\hat{\tau},s,\hat{s},\varphi,\hat{\varphi}\right)$,

$$\left.\frac{\partial^2 S_\Delta}{\partial\hat{f}_d^2}\right|_{\substack{\hat{f}_d\to f_d\\ \hat{\tau}\to\tau\\ \hat{\varphi}\to\varphi}}=-\frac{4\pi^2}{E_s}\operatorname{Re}\left(\int_{-\infty}^{\infty}(t-\tau)^2\dot{x}(t-\tau,s)\dot{x}^*(t-\tau,\hat{s})dt\right),$$

$$\left.\frac{\partial^2 S_\Delta}{\partial\hat{\tau}^2}\right|_{\substack{\hat{f}_d\to f_d\\ \hat{\tau}\to\tau\\ \hat{\varphi}\to\varphi}}=-4\pi^2\operatorname{Re}\left(\frac{1}{E_s}\int_{-\infty}^{\infty}\left(f+f_d\right)^2\left|\dot{X}(j2\pi f)\right|^2e^{-j\pi f^2(s-\hat{s})}df\right),$$

$$\left.\frac{\partial^2 S_\Delta}{\partial\hat{\varphi}^2}\right|_{\substack{\hat{f}_d\to f_d\\ \hat{\tau}\to\tau\\ s\hat{\varphi}\to\varphi}}=-\operatorname{Re}\left(\frac{1}{E_s}\int_{-\infty}^{\infty}\dot{x}(t-\tau,s)\dot{x}^*(t-\tau,\hat{s})dt\right),$$

$$\left.\frac{\partial^2 S_\Delta}{\partial\hat{f}_d\partial\hat{\tau}}\right|_{\substack{\hat{f}_d\to f_d\\ \hat{\tau}\to\tau\\ \hat{\varphi}\to\varphi}}=\operatorname{Re}\left(j2\pi\frac{1}{E_s}\int_{-\infty}^{\infty}(t-\tau)\dot{x}(t-\tau,s)\frac{\partial\dot{x}^*(t-\tau,\hat{s})}{\partial t}dt+\right.$$
$$\left.+4\pi^2 f_d\frac{1}{E_s}\int_{-\infty}^{\infty}(t-\tau)\dot{x}(t-\tau,s)\dot{x}^*(t-\tau,\hat{s})dt+j2\pi\frac{1}{E_s}\int_{-\infty}^{\infty}\dot{x}(t-\tau,s)\dot{x}^*(t-\tau,\hat{s})dt\right)$$

$$\left.\frac{\partial^2 S_\Delta}{\partial\hat{f}_d\partial\hat{\varphi}}\right|_{\substack{\hat{f}_d\to f_d\\ \hat{\tau}\to\tau\\ \hat{\varphi}\to\varphi}}=\operatorname{Re}\left(2\pi\frac{1}{E_s}\int_{-\infty}^{\infty}(t-\tau)\dot{x}(t-\tau,s)\dot{x}^*(t-\tau,\hat{s})dt\right),$$

$$\left.\frac{\partial^2 S_\Delta}{\partial\hat{\tau}\partial\hat{\varphi}}\right|_{\substack{\hat{f}_d\to f_d\\ \hat{\tau}\to\tau\\ \hat{\varphi}\to\varphi}}=-2\pi\operatorname{Re}\left(\frac{1}{E_s}\int_{-\infty}^{\infty}\left(f+f_d\right)\left|\dot{X}(j2\pi f)\right|^2e^{-j\pi f^2(s-\hat{s})}df\right),$$

$$\frac{\partial^2 S_N\left(\boldsymbol{\theta}_1,\boldsymbol{\theta}_2\right)}{\partial\theta_{1\nu}\partial\theta_{2q}}=-\frac{\partial^2 S_N\left(\boldsymbol{\theta}-\hat{\boldsymbol{\theta}}\right)}{\partial\hat{\theta}_\nu\partial\hat{\theta}_q},$$
$$S_N\left(\boldsymbol{\theta}-\hat{\boldsymbol{\theta}}\right)=S_N\left(f_d,\hat{f}_d,\tau,\hat{\tau},\hat{s},\hat{s},\varphi,\hat{\varphi}\right)=$$
$$=\operatorname{Re}\left[\begin{array}{l}e^{-j(\varphi-\hat{\varphi})}e^{-j2\pi f_d\tau}e^{j2\pi\hat{f}_d\hat{\tau}}\frac{1}{E_s}\times\\ \times\int_{-\infty}^{\infty}\dot{x}(t-\tau,\hat{s})\dot{x}^*(t-\hat{\tau},\hat{s})e^{j2\pi t\left(f_d-\hat{f}_d\right)}dt\end{array}\right]. \quad (9)$$

It can be said that $S_N\left(f_d,\hat{f}_d,\tau,\hat{\tau},\hat{s},\hat{s},\varphi,\hat{\varphi}\right)$ represents the signal component of the logarithm of the likelihood function at optimal signal reception with fully known dispersion distortions (i.e., if $\hat{s} \neq 0$ is known) or without dispersion distortions (with $\hat{s} = 0$) $\dot{y}(t) = \dot{x}(t, \varphi, \tau, f_d, \hat{s}) + \dot{n}(t)$, $t = -T_s/2 \div T_s/2$.

All necessary derivatives of $S_N\left(f_d, \hat{f}_d, \tau, \hat{\tau}, \hat{s}, \hat{s}, \varphi, \hat{\varphi}\right)$ are given below:

$$\left.\frac{\partial^2 S_N}{\partial \hat{f}_d^2}\right|_{\substack{\hat{f}_d \to f_d \\ \hat{\tau} \to \tau \\ \hat{\varphi} \to \varphi}} = -4\pi^2 T^2_{эфф}(\hat{s}),$$

$$\left.\frac{\partial^2 S_N}{\partial \hat{\tau}^2}\right|_{\substack{\hat{f}_d \to f_d \\ \hat{\tau} \to \tau \\ \hat{\varphi} \to \varphi}} = -4\pi^2\left(F^2_{эфф} + f_d^2\right),$$

$$\left.\frac{\partial^2 S_N}{\partial \hat{\varphi}^2}\right|_{\substack{\hat{f}_d \to f_d \\ \hat{\tau} \to \tau \\ \hat{\varphi} \to \varphi}} = -1,$$

$$\left.\frac{\partial^2 S_N}{\partial \hat{f}_d \partial \hat{\tau}}\right|_{\substack{\hat{f}_d \to f_d \\ \hat{\tau} \to \tau \\ \hat{\varphi} \to \varphi}} = 4\pi^2 F_{эфф} T_{эфф}(\hat{s}) \rho_{\tau f}(\hat{s}),$$

$$\left.\frac{\partial^2 S_N}{\partial \hat{f}_d \partial \hat{\varphi}}\right|_{\substack{\hat{f}_d \to f_d \\ \hat{\tau} \to \tau \\ \hat{\varphi} \to \varphi}} = 0, \quad \left.\frac{\partial^2 S_N}{\partial \hat{\tau} \partial \hat{\varphi}}\right|_{\substack{\hat{f}_d \to f_d \\ \hat{\tau} \to \tau \\ \hat{\varphi} \to \varphi}} = -2\pi f_d,$$

S_N is a shortened notation of $S_N\left(f_d, \hat{f}_d, \tau, \hat{\tau}, \hat{s}, \hat{s}, \varphi, \hat{\varphi}\right)$,

$$\rho_{\tau f}(\hat{s}) = \frac{\int_{-\infty}^{\infty} t\, f_s(t,\hat{s}) \left|\dot{x}(t,\hat{s})\right|^2 dt}{F_{эфф} T_{эфф}(\hat{s}) \int_{-\infty}^{\infty} \left|\dot{x}(t,\hat{s})\right|^2 dt}$$

– a time-frequency coefficient; $f_s(t,\hat{s}) = \dfrac{1}{2\pi}\dfrac{\partial \gamma(t,\hat{s})}{\partial t}$; $\gamma(t,\hat{s}) = \arg\left[\dot{x}(t,\hat{s})\right]$ – angle modulation; $F_{эфф} = \sqrt{\dfrac{\int_{-\infty}^{\infty} f^2 \left|\dot{X}(j2\pi f)\right|^2 df}{\int_{-\infty}^{\infty} \left|\dot{X}(j2\pi f)\right|^2 df}}$ – an effective width of signal spectrum; $T_{эфф}(\hat{s}) = \sqrt{\dfrac{\int_{-\infty}^{\infty} (t-\tau)^2 \left|\dot{x}(t-\tau,\hat{s})\right|^2 dt}{\int_{-\infty}^{\infty} \left|\dot{x}(t-\tau,\hat{s})\right|^2 dt}}$ is an effective signal duration; $\eta(\hat{s}) = \dfrac{1}{E_s}\int_{-\infty}^{\infty} t \dfrac{\partial \gamma(t,\hat{s})}{\partial \hat{s}} \left|\dot{x}(t,\hat{s})\right|^2 dt$;

$$\overline{f^4} = \frac{\int_{-\infty}^{\infty} f^4 \left|\dot{X}(j2\pi f)\right|^2 df}{\int_{-\infty}^{\infty} \left|\dot{X}(j2\pi f)\right|^2 df};$$

$\dot{X}(j2\pi f)$ is a signal $\dot{x}(t)$ spectral density.

This article does not contain direct expressions of the quality characteristics of the estimation as the correlation functions and variance of estimations because of their cumbersome form. It is proposed to calculate the quality characteristics of the estimation directly by expression (7), using the obtained expressions for the derivatives of $S_N\left(f_d, \hat{f}_d, \tau, \hat{\tau}, \hat{s}, \hat{s}, \varphi, \hat{\varphi}\right)$ (9) and calculating cofactors and the determinant of the matrix (8) using simulation systems.

Simulation was carried out to analyze the effect of the absence of an estimation of S on the estimation of f_d, τ, φ. The model used a signal modulated by a binary phase-shift keying (BPSK). The sequence of rectangular pulses is formed on the basis of a maximum length sequence with a length of 2047. The true value of the slope of DC was chosen to be $s = 80$ μs/MHz, the frequency shift was $f_d = 12.5$ Hz, and the delay was $\tau = 5.0$ μs. The reference signal is formed in accordance with expression (3). It means that the receiver is not configured to receive a signal with a frequency dispersion of the ionospheric channel. Figures 2-7 show the theoretical (obtained from the expressions above) and experimental dependences of the standard deviation (SD), correlations and correlation coefficients of the studied estimations on the SNR for three cases:

1. The signal is not distorted by the frequency dispersion of the ionospheric channel, therefore, it contains only three unknown parameters: frequency shift, delay and phase, which are estimated.
2. The signal is distorted by the frequency dispersion of the ionospheric channel, therefore, it contains four unknown parameters: frequency shift, delay, phase and slope of DC, however, the reference signal of the receiver does not contain information about the ionospheric channel (all parameters are estimated except for the slope of DC).
3. The signal is distorted by the frequency dispersion of the ionospheric channel, therefore, it contains four unknown parameters: frequency shift, delay, phase and slope of DC; all unknown parameters are estimated [10-13].

From the analysis of the results from figures 2-7, we can conclude that if the effect of the frequency dispersion of the ionospheric channel is not taken into account in the receiver, then this significantly reduces the quality of the estimation of other unknown signal parameters. For example, at SNR of 10 dB, the SD of the delay estimation increases by about 6 times, the SD of the frequency shift estimation by 1.5 times, the SD of the phase estimation by 1.33 times.

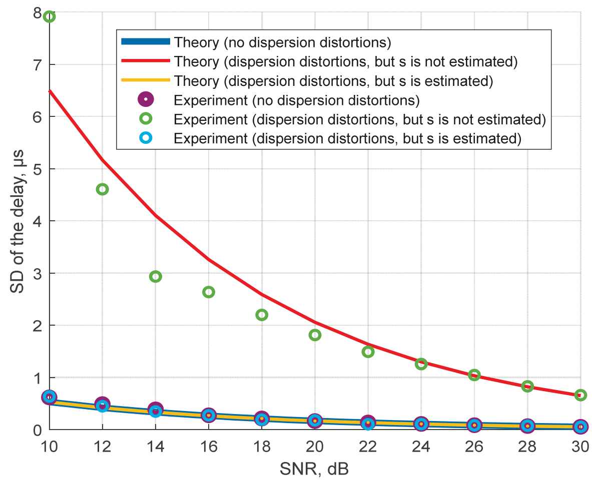

Figure 2. The SD of the delay versus SNR

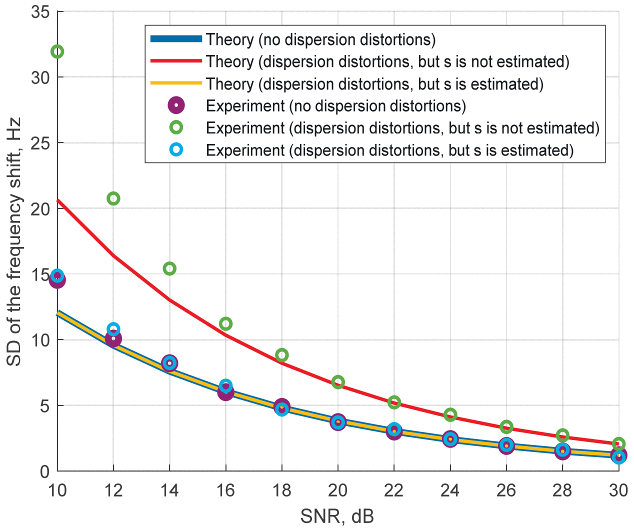

Figure 3. The SD of the frequency shift versus SNR

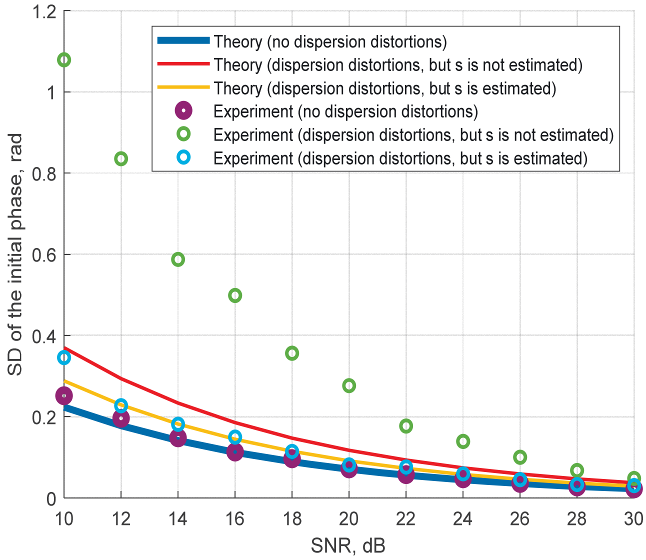

Figure 4. The SD of the initial phase versus SNR

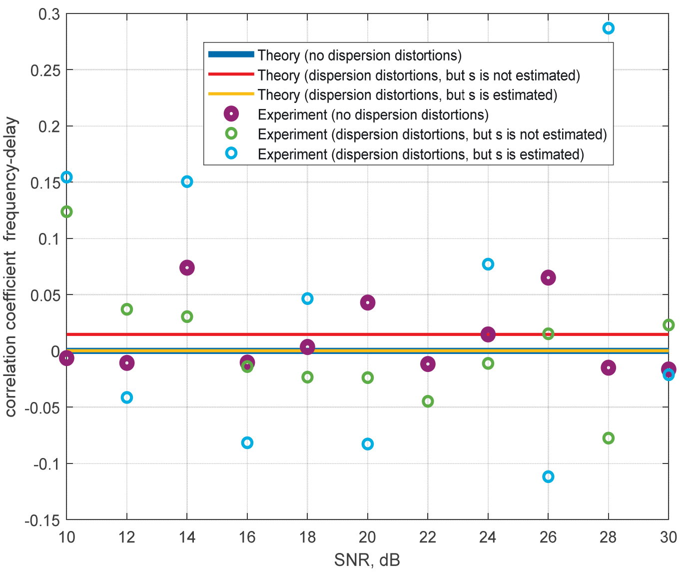

Figure 5. Correlation coefficient frequency-delay versus SNR

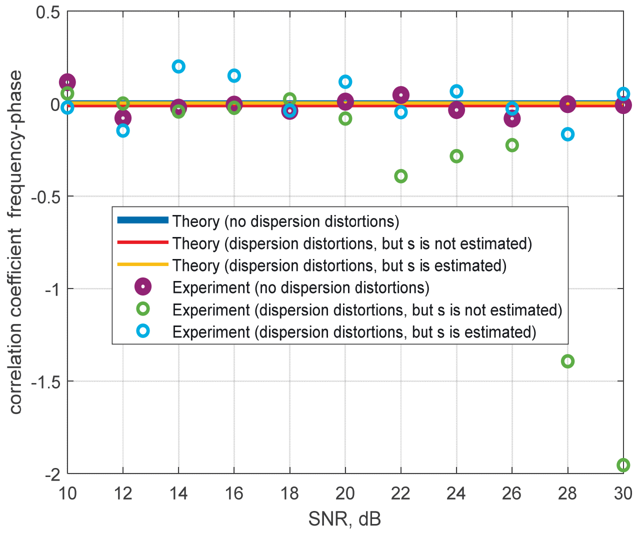

Figure 6. Correlation coefficient frequency-phase versus SNR

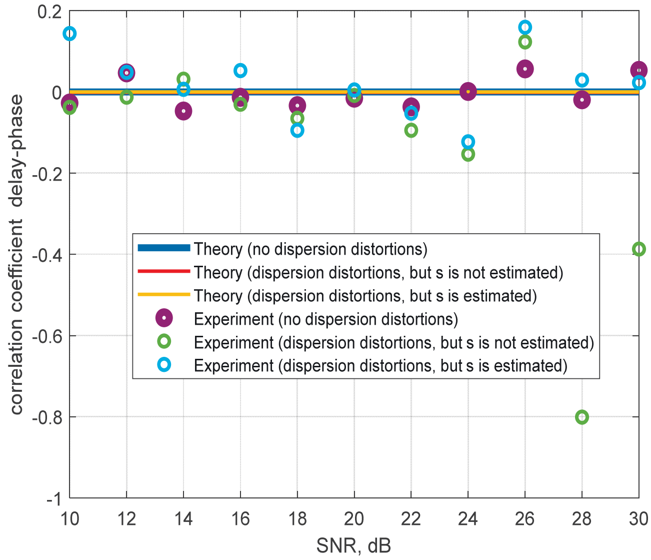

Figure 7. Correlation coefficient delay-phase versus SNR

Degradation of the quality of delay estimation is due to two factors: a value decrease and an expansion of the correlation peak. In terms of energy loss, this degradation (about 20 dB) exceeds the acquisition or demodulation loss (about 4.5 dB for this signal for s = 80 $\mu s / MHz$ [4, 6]).

The effect of incomplete compensation of dispersion distortions was investigated. In the simulation we have used an outdated estimation value that was does not coincide with ML estimation of S. This means that the estimation of S was not refined. The parameters of the simulation have stayed the same. The outdated value of the estimation was chosen close to the real value of S: $\hat{s} = 60$ µs/MHz, $\hat{s} \neq \hat{s}_{ML}$. In real systems $\hat{s}$ may be derived from predictions, or may be an outdated estimation that does not correspond to the present channel condition. Figures 8-10 shows the theoretical and experimental SD versus SNR for this case. It is obvious and can be easily seen from the illustrations that using inaccurate information about frequency dispersion is better than the absence of any information. For example, at an SNR of 10 dB, the SD of the delay estimation increases by about 1.2 times compared to the case when S is estimated, the SD of the frequency shift estimation has changed insignificantly, the SD of the phase estimation is better without refining the estimation of S. The figure 11 was built to explain the behaviour of the SD of the initial phase. The figure shows the SD of phase estimation in the problem of estimating three parameters without dispersion distortions, with dispersion distortions under conditions of their incomplete compensation, and in the problem of estimating four parameters, including the slope of DC.

It was clearly shown that the estimation of the slope of DC increases the SD of the phase estimation due to the close correlation with it (see blue and yellow plots). In some cases, even with non-optimal reception and small residual dispersion distortions (when the difference between the true slope of the DC and its estimate used for adjusting the compensator), the SD of the phase estimation may turn out to be less (see red graph).

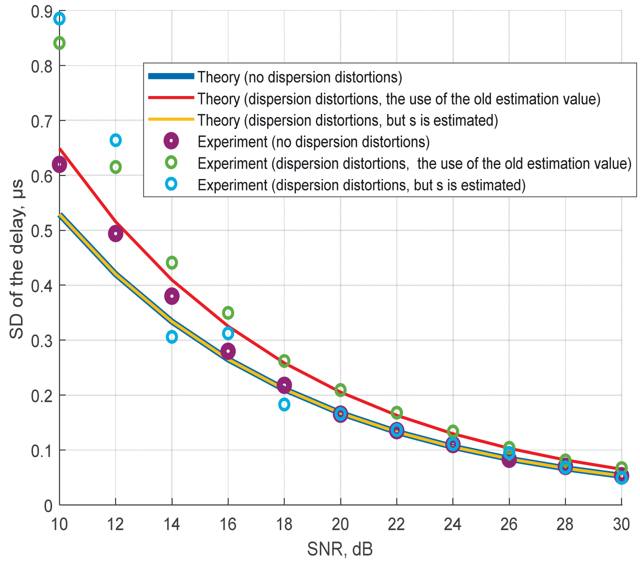

Figure 8. The SD of the delay versus SNR (incomplete compensation)

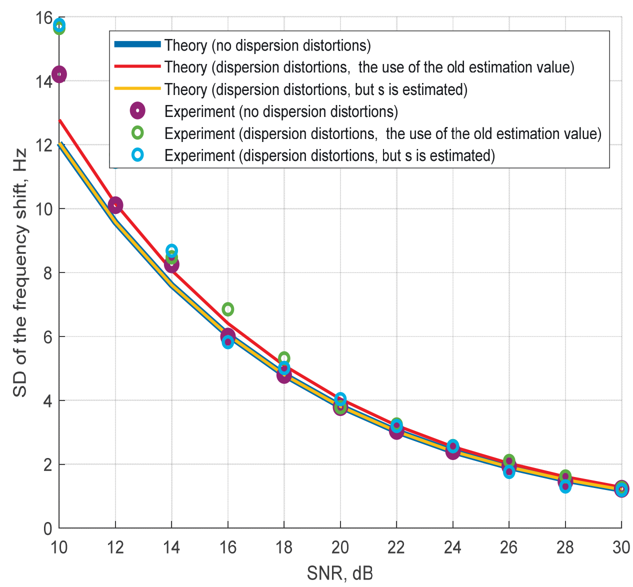

Figure 9. The SD of the frequency shift versus SNR (incomplete compensation)

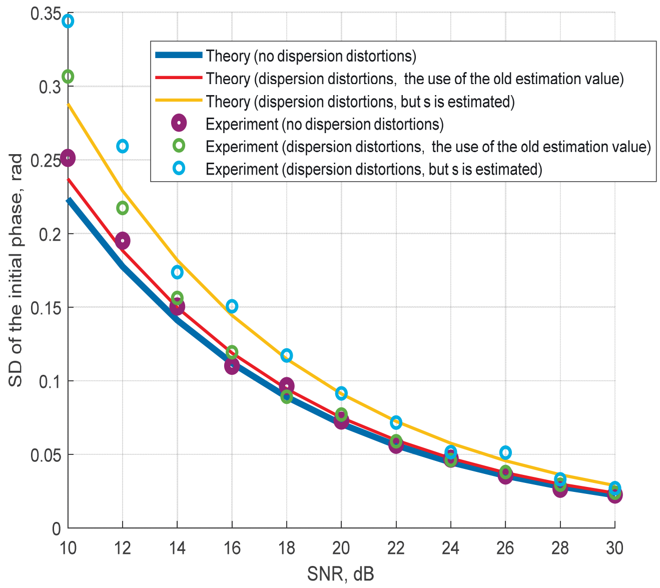

Figure 10. The SD of the initial phase versus SNR (incomplete compensation)

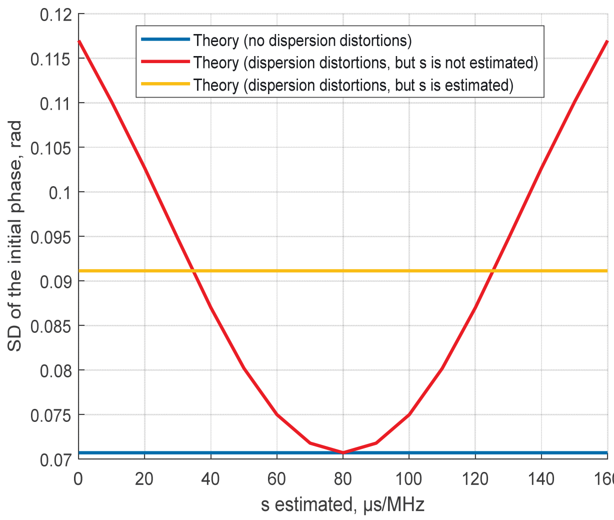

Figure 11. The SD of the initial phase versus the value of estimation of S

Conclusion

The article demonstrated the contribution of the estimation of the slope of DC to the quality of the estimation of other unknown parameters of the signal: delay, frequency shift and initial phase. For this, expressions were obtained that characterize the quality of the estimation of the frequency shift, delay, and phase for non-optimal reception. That is, receiver does not estimate the slope of DC or uses outdated information about dispersion distortions.

The analysis of the theoretical and simulation results showed that if the effect of the frequency dispersion of the ionospheric channel is not taken into account in the receiver, then this significantly reduces the quality of the estimation of other unknown signal parameters. For example, at SNR of 10 dB, the SD of the delay estimation increases by about 6 times, the SD of the frequency shift estimation by 1.5 times, the SD of the phase estimation by 1.33 times. If outdated information on dispersion distortions are used, then the accuracy of estimating other parameters depends on the degree of closeness of the outdated estimation to the real value of the parameter. If $s - \hat{s} = 80 - 60 = 20$ µs/MHz than at SNR of 10 dB, the SD of the delay estimation increases by about 1.2 times compared to the case when *s* is estimated, the SD of the frequency shift estimation has changed insignificantly. In some cases, even with non-optimal reception and small residual dispersion distortions (when the difference between the true slope of the DC and its estimate used for adjusting the compensator), the SD of the phase estimation may turn out to be less, which is demonstrated in the article.

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КАЧЕСТВО ОЦЕНИВАНИЯ ПАРАМЕТРОВ ШИРОКОПОЛОСНОГО СИГНАЛА ПРИ НЕОПТИМАЛЬНОМ ПРИЕМЕ В УСЛОВИЯХ ДИСПЕРСИОННЫХ ИСКАЖЕНИЙ В ИОНОСФЕРЕ ЗЕМЛИ

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Аннотация
В статье получены аналитические выражения элементов матрицы Фишера, позволяющие вычислить дисперсию оценки начальной фазы, частоты и задержки сигнала, а также ковариационных функций пар оценок в условиях дисперсионных искажений. При этом оценивающее устройство не точно знает или вовсе не знает уровень дисперсионных искажений и не пытается их оценить. Поэтому оценивание параметров сигнала осуществляется неоптимальным алгоритмом. Описанные условия на практике возникают, например, при попытке оценить указанные выше параметры широкополосного сигнала классическим оценщиком, не учитывающим дисперсионные искажения. Также описанные условия возникают при отклонении истинного значения наклона дисперсионной характеристики канала от измеренной ранее с течением времени или из-за использования неточных результатов измерений или неточного прогноза значения наклона дисперсионной характеристики канала. В статье приведены полученные аналитически графики для среднеквадратичных отклонения получаемых оценок фазы, задержки и частоты для случая полного отсутствия компенсации дисперсионных искажений и случая не полной компенсации дисперсионных искажений. В частности показано, что ухудшение качества оценивания задержки обусловлено двумя факторами: уменьшением и расширением корреляционного пика. В энергетическом эквиваленте указанное ухудшение превышает потери при обнаружении или демодуляции сигнала. Результаты полученных расчетов подтверждены имитационным моделированием.

Ключевые слова: *оценивание параметров, дисперсия оценки, максимум правдоподобия, ионосферный канал, широкополосный сигнал.*

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