Reconstruction of the frequency dependence of the complex reflection coefficient from data of the oblique LFM ionosonde

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Based on the analysis of analogous linear frequency modulated (chirp) signals propagation inside the ionosphere HF channel, a geometrical-optics technique for data processing at the output of LFM ionosonde compressor is proposed, allowing reconstruction of the frequency dependence of the complex reflection coefficient to the initial phase under multipath conditions. Use of the above technique will allow an increase of information capacity of the atmosphere remote LFM sensing.

Introduction

In recent years, chirp signals are widely used for the remote sensing of the atmosphere,[1–3] which allows the frequency dependence of the group-delay time to be determined for every propagation mode. The choice of chirp signals provides for a high delay-time resolution, interference protection, and a reduced radiation power in LFM sensing radio systems.

Besides, for an analogous chirp signal, there exists a linear relationship between the signal frequency f and radiation time t, therefore, the signal parameters at the output of a LFM ionosonde receiver at the time point t correlate with the reflection coefficient $H(f)$ at the frequency f.

The problem of determining the complex reflection coefficients of a single radio signal propagation path was solved in Ref. 4 within the geometrical optics method on the base of analogous chirp signal sensing. The reflection coefficient phase for every beam is determined by this method with the accuracy to a linear summand, which does not allow the total reflection coefficient of the whole multipath channel to be determined.

In this work, a technique is presented for measuring the frequency dependence of complex reflection coefficients for individual beams with the help of chirp signals.

The technique for determining the reflection coefficient for individual beams

The sensing transmitter radiates the analogous chirp signal $a_1(t)$, which can be represented in the form

$$a(t) = a_0 \exp[j(2\pi f_0 t + \pi \dot{f} t)^2)] t \in \left[-\frac{T}{2}, \frac{T}{2}\right], \qquad (1)$$

were f_0 is the initial radiation frequency; $\dot{f} = \frac{\mathrm{d}f}{\mathrm{d}t}$ is the frequency change rate; a_0 is the signal amplitude; T is the pulse duration.

The instantaneous cyclic frequency ω of this signal linearly varies with time: $\omega = 2\pi f_0 + 2\pi \dot{f} t$.

The processing of a received chirp signal in the receiver by the compression method in the frequency range consists in its multiplication by a heterodyne signal, complex-conjugated to the radiated signal, and analysis of the resulted difference-mode signal spectrum. The following mathematical relations correspond to these operations[5]:

$$A(t) = a_{\text{out}}(t) a^*(t);$$

$$S(\Omega) = \int_{-\infty}^{\infty} A(t) \mathrm{e}^{-j\Omega t} \mathrm{d}t, \qquad (2)$$

where * is the sign of complex conjugation; $A(t)$ is the difference-mode signal; $S(\Omega)$ is its spectrum; $a_{\text{out}}(t)$ is the signal at the output from ionosphere.

To find the difference-mode signal spectrum, the approach is used, based on the representation of propagation medium by a transfer function. Within the geometrical optics method, the reflection coefficient of an individual beam is associated with the transfer function of the propagation channel $H(\omega, t)$ [Ref. 6]:

$$H(\omega,t) = |H(\omega,t)| \exp[-j\varphi(\omega,t)] = \sum_{i=1}^{m} |H_i(\omega,t)| \exp[-j\varphi_i(\omega,t)], \qquad (3)$$

where $|H_i(\omega, t)|$ is the modulus of the path transfer function; $\varphi_i(\omega, t)$ is the path phase in ionosphere; m is the number of propagation modes.

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The chirp element occupies a certain band $\Delta f = \dot{f}T$ near the frequency f_0. Considering the signal as quasi-stationary for small time scales T, in the absence of frequency dispersion, we can expand the transfer function phase of an individual beam in the Taylor power series $\Delta\omega = 2\pi(f - f_0)$ and $\Delta t = t - t_0$, restricting to linear summands, and considering $|H_i(\omega, t)|$ as constant:

$$\varphi_i(\omega, t) \approx \varphi_{i0} + \varphi'_{i\omega}(\omega_0, t_0)\Delta\omega + \varphi'_{it}(\omega_0, t_0)\Delta t;$$

$$|H_i(\omega, t)| = |H_i(\omega_0, t_0)| = |H_{i0}| = \text{const}, \qquad (4)$$

where $\omega_0 = 2\pi f_0$; $\varphi_{i0} = \varphi_i(\omega_0, t_0)$.

As is known, the first phase derivative with respect to frequency equals to the group signal-delay time[6]:

$$\varphi'_{i\omega}(\omega_0) = \tau_i(\omega_0). \qquad (5)$$

The dependence $\varphi(t)$ is related with the Doppler frequency shift $F_{\partial i}$:

$$\varphi'_{it}(t_0) = -\omega_{\partial i} = -2\pi F_{\partial i}. \qquad (6)$$

Approximation (4) is valid when the inequalities

$$\frac{\Delta\omega\Delta t\partial F_{\partial i}}{\partial f} \ll 2\pi; \qquad (7)$$

$$\pi\frac{\partial F_{\partial i}}{\partial t}\Delta t^2 \ll 2\pi \qquad (8)$$

hold.

The Doppler frequency shift is directly proportional to the carrier signal frequency f_0, therefore, inequality (7) can be written as follows: $F_{\partial i}\Delta t \ll f_0 / \Delta f$.

For example, at $\Delta t = 1$ s, $f_0 = 10$ MHz, and $F_{\partial i} = 1$ Hz inequality (7) holds for $\Delta f \approx 1$ MHz, i.e., for the frequency band exceeding those using in HF communications.

The summand with the second time derivative describes nonstationarity of a single-path ionospheric channel. For middle latitudes and undisturbed ionosphere $\frac{\partial F_{\partial i}}{\partial t} \sim 0.01$ Hz/s [Ref. 5] and Equation (8) is valid at $\Delta t < 7$ s.

The absence of the frequency dispersion supposes a chirp signal to occupy the frequency band Δf, which is less than the channel coherence band (i.e., frequency range centered at the point f_0, at the edges of which the nonlinear phase component incursion due to frequency dispersion is equal in magnitude to 1 rad [Ref. 7]).

Hence, approximation (4) is fulfilled in the case, when chirp signals have $\Delta f \le 100$ kHz and duration $T \le 1$ s. When propagating in the ionosphere, $\tau_{0i} \sim 10^{-3}$–10^{-2} s and $T \gg \tau_{0i}$ [Ref. 5]. In this case, from Eqs. (2) and (4) we obtain

$$A(t) = \sum_{i=1}^{m} A_i(t) = \frac{a_0^2}{2\pi}\sum_{i=1}^{m}|H_{0i}|\exp j(\pi\dot{f}\tau_{0i}^2)\times$$

$$\times\exp\left[-j\left(\varphi_i(\omega_0; t_0) - 2\pi F_{\partial i}(t - t_0) + 2\pi\dot{f}\tau_{0i}t\right)\right]. \qquad (9)$$

At $2\pi\dot{f}t = \Delta\omega$

$$A(t) = \frac{a_0^2}{2\pi}\sum_{i=1}^{m}|H_{0i}|\exp j(\pi\dot{f}\tau_{0i}^2)\times$$

$$\times\exp\left[-j\left(\varphi_i(\omega_0; t_0) - 2\pi F_{\partial i}\Delta t + \tau_{0i}\Delta\omega(t)\right)\right]. \qquad (10)$$

As is seen from the comparison of Eq. (10) with Eqs. (3) and (4), the difference signal of i-mode coincides with the value of the transfer function for this mode to the scaling factor $a_0^2/2\pi$ and phase constant $\pi\dot{f}\tau_{0i}^2$. Knowing the signal parameters a_0 and $\dot{f}$ and measuring τ_{0i}, we can determine the value of ionosphere radiochannel transfer function in the frequency band

$$\left[f_0 - \frac{\Delta f}{2}; f_0 + \frac{\Delta f}{2}\right].$$

To determine the group delay, use the difference signal spectrum. As is seen from Eq. (10), the difference signal of T duration is a leg of harmonic oscillation. Taking this into account, $S(\Omega)$ can be written in the following form:

$$S(\Omega) = \sum_{i=1}^{m} S_i(\Omega) = \frac{a_0^2 T}{2\pi}\sum_{i=1}^{m}|H_{0i}|\exp[-j(\varphi_i(\omega_0; t_0) - \pi\dot{f}{\tau_{0i}}^2)]\times$$

$$\times\sin c\left(\frac{\Omega - 2\pi F_{\partial i} + 2\pi\dot{f}\tau_{0i}}{2}T\right), \qquad (11)$$

where $\sin c(x) = \sin x / x$.

The modulus $|S(\Omega)|$ has maxima at frequencies $\Omega_{0i} = 2\pi F_{\partial i} - 2\pi\dot{f}\tau_{0i}$. Since $\dot{f}\tau_{0i} \gg F_{\partial i}$, the group delay of individual propagation mode is determined by the equation $\tau_{0i} = |\Omega_{0i} / 2\pi\dot{f}|$.

Finally, for the transfer function of the multipath HF radiochannel with the frequency band $\left[f_0 - \frac{\Delta f}{2}; f_0 + \frac{\Delta f}{2}\right]$ write

$$H(\omega; t) = \sum_{i=1}^{m} H_i(2\pi f_0 + 2\pi\dot{f}t; t) =$$

$$= \frac{2\pi}{a_0^2}\sum_{i=1}^{m} A_i(t)\exp\left[-j\left(\frac{\Omega_{0i}^2}{4\pi\dot{f}}\right)\right]. \qquad (12)$$

The technique for determining the frequency dependence of reflection coefficient

Let several beams come to a receiving point with different delays τ_{0i}. Each of the beams is associated with its own difference frequency F (Fig. 1, where F_1 is the difference frequency of the bottom beam of the mode 1F2; F_2 — of the mode 2F2; F_3 — of the top beam of the mode 3F2; f_i and f_f are the initial and finite radiation frequencies; t_0 and t_f are the initial and finite radiation times).

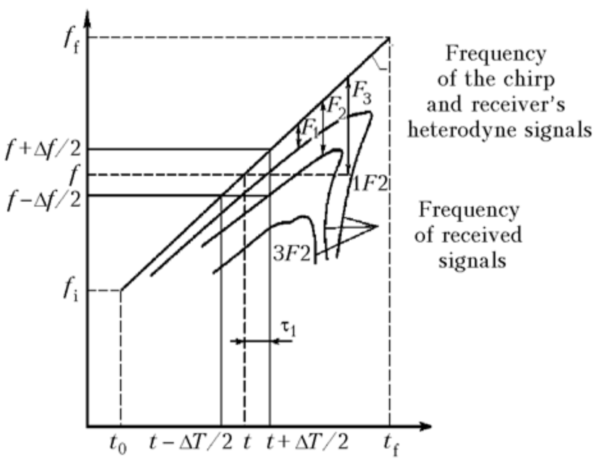

Fig. 1.

In this case, the frequency resolution δF is defined by the ratio $\delta F \approx 1/T$; from this, the delay resolution is[5]

$$\delta\tau \approx \delta F/\dot{f} \approx 1/\Delta f. \qquad (13)$$

For example, if a chirp element has the frequency range Δf = 100 kHz, potential resolution is 10 μs.

Received modes in the difference signal can be separated with bandpass filters agreed with signals of corresponding modes (Fig. 2). A difference signal, passing through the ith frequency filter Φ_i ($1 \le i \le m$), is multiplied by the complex multiplier $\frac{2\pi}{a_0^2}\exp\left[-j\left(\frac{\Omega_{0i}^2}{4\pi\dot{f}}\right)\right]$. Signal amplitude and phase at the adder output $A_\text{out}(t)$ at the moment t correspond to the amplitude and phase of the reflection coefficient at the frequency $f = f_\text{i} + \dot{f}t$.

Figure 3 shows the dependence $|A_\text{out}(t)|$ (gray) obtained from the simulation modeling of chirped signal (1) passing through a radiochannel with transfer function (4) at Δt = 1 s, $\dot{f}$ = 100 kHz/s and its processing according to the scheme from Fig. 2. The dashed line corresponds to the dependence $|H(t)|$.

Figure 3a shows the simulation results for a two mode propagation channel with parameters

$$\dot{f}\tau_{01} - F_{\partial 1} = 404 \text{ Hz}, \ \dot{f}\tau_{02} - F_{\partial 2} = 411 \text{ Hz},$$

$$|H_{01}| : |H_{02}| = 2 : 3.8.$$

Figures 3b and c show the simulation results for three- and four mode channels with the parameters of complementary modes

$$\dot{f}\tau_{03} - F_{\partial 3} = 407 \text{ Hz}, \ |H_{01}| : |H_{02}| : |H_{03}| = 2 : 3.8 : 1.5$$

and

$$\dot{f}\tau_{04} - F_{\partial 4} = 417 \text{ Hz},$$

$$|H_{01}| : |H_{02}| : |H_{03}| : |H_{04}| = 2 : 3.8 : 1.5 : 1.1,$$

respectively.

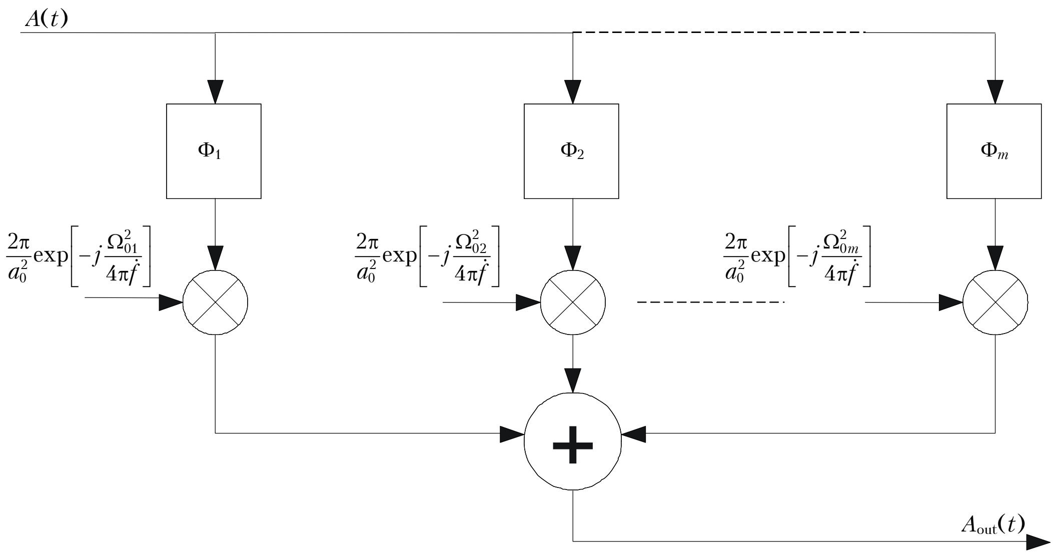

Fig. 2.

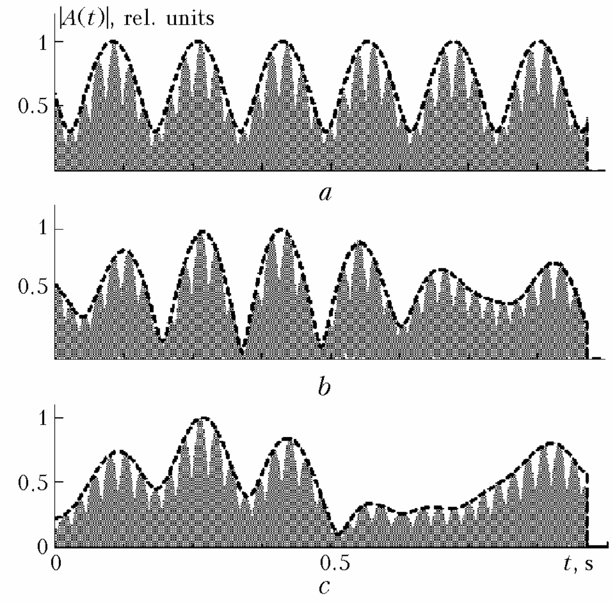

Fig. 3.

The envelope curve $A_{out}(t)$ is evidently in good agreement with $|H(t)|$, which points to the fact that both the phases of individual modes and the amplitudes are determined correctly.

Conclusion

The technique is presented for processing data of ionosphere sensing with analogous chirp signal, which allows definition of frequency dependences of both delay time and complex reflection coefficient for individual beams.

The use of the technique allows an enhancement of reliability and an increase of information capacity of ionosphere remote sensing with chirped signals.

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