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A.A. KOLCHEV, PhD, associate professor, MarSU, Yoshkar-Ola, Russia;
A.E. NEDOPEKIN, PhD, MarSU, Yoshkar-Ola, Russia;
V.V. SHUMAEV, PhD, senior researcher, "ADASIS" Ltd., Yoshkar-Ola, Russia

SIMULTANEOUS DETERMINE OF DOPPLER SHIFT AND GROUP DELAY TIME USING AMPLITUDE MODULATED CHIRP-SIGNAL

New method of the simultaneous measurement of the frequency dependencies of Doppler shift and group delay time of separate ionosphere modes by means of amplitude modulated chirp signal is presented in this paper. The algorithms of data processing are presented.

Keywords: ionosphere, chirp-sounder, phase, Doppler shift.

Formulation of the problem. LFM ionosonde powerful tool for monitoring the state of the ionosphere. Recently chirp sensing capabilities expand [1]. One of the main parameter of radio channel is differential Doppler shift between rays, which effect to reliability and noise-immunity of radio systems work. References 0 shows method of simultaneous determine of dependences group delay time and Doppler shift from radiation frequency of separately HF-signal propagation separate modes by means periodical frequency-modulated wave. Large time measuring on some frequency and large step of frequency are deficiencies of this method.

Analysis of the literature. Method of simultaneous definition group delay and Doppler shift of separate ionosphere modes, based on three-element frequency-modulated wave described in reference 0. Usage of phase measuring allow to reduce measuring time at same frequency channel, but measuring are realized discrete at channels defined previously, using three time-displaced signals with push-type parameters.

Reference 0 suggest way of simultaneous determine group delay and Doppler shift for each mode, using two continuous frequency-modulated wave (FMCW), but it's straightforward realization require two identical transmitters and two identical receivers.

Purpose of the article. This work describe methodic for realization of last way, using single transmitter and single receivers. It is more useful than straightforward realization.

Main equations. Let transmitter radiate continuous amplitude-modulated FMCW, which is expressed in the following way:

$$a_I(t) = a_0 \exp[j(2\pi \cdot f_M (t - t_0))] \times \exp[j(2\pi \cdot f_H (t - t_0) + \pi \cdot df \left(t - t_0\right)^2)], \quad t \in [t_0, t_0 + t_{\text{K}}], \tag{1}$$

where f_M is the modulate frequency; $df = df/dt$ is the chirp frequency change rate; f_H is initial radiation frequency; a_0 is the signal amplitude; t_0 is the time of radiation start; t_K is the radiation duration.

Amplitude-modulated signal may be represented as sum of two signals:

$$a_I(t) = a_0 \exp[j(2\pi(f_H + f_M)(t - t_0) + \pi \cdot df(t - t_0)^2)] + \\ + a_0 \exp[j(2\pi(f - f_M)(t - t_0) + \pi \cdot df(t - t_0)^2)],\ t \in [t_0, t_0 + t_K] \quad (2)$$

Processing of accepted chirp signal in the receiver using compression method in the frequency range is multiplication of chirp signal by the heterodyne signal, complex-conjugated to the signal being radiated, and in analysis of the accepted difference signal spectrum. For second term of (2): $a_2(t) = a_0 \exp[j(2\pi(f - f_M)(t - t_0) + \pi \cdot df(t - t_0)^2)],\ t \in [t_0, t_0 + t_K]$ following mathematical ratios correspond to those operations:

$$A_2(t) = a_{2\text{out}}(t)a^*(t)$$
$$S_2(\Omega) = \int_{-\infty}^{\infty} A_2(t)e^{-j\Omega t}dt, \quad (3)$$

where * is the sign of complex conjugation; $A_2(t)$ is the differential signal corresponding to $a_2(t)$; $S_2(\Omega)$ is its spectrum; $a_{2\text{out}}(t)$ is the signal at the output from ionosphere (at the input of the receiver).

To determine group delay time of separate ionosphere modes of propagation, SW signal of differential frequency is divided into N elements being T_E long at a distance between elements T and for each element Fourier transformation is calculated. Since $\Delta f_E = df \cdot T_E << f$ (f is a current frequency), each element of differential signal is referred to the central frequency of element Δf_E. Accordingly, spectrum of the signal element also can be referred to this frequency.

In case of multi-beam non-stationary channel of propagation a transfer function can be expressed in the following way:

$$H(\omega, t) = |H\ (\omega, t)| \cdot \exp j\,\varphi(\omega, t) = \sum_{i=1}^{m} |H_i(\omega, t)| \cdot \exp j\,\varphi_i(\omega, t), \quad (4)$$

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

The chirp element occupies a certain band of $\Delta f_E = df \cdot T_E$ near the frequency f_0. Considering the signal to be quasi-stationary for small scales of time $\Delta t = t - t_0$, in the absence of frequency dispersion, we can expand the transfer function phase of the individual beam in the Taylor power series $\Delta\omega = 2\pi \cdot (f - f_0)$ and Δt, having been restricted by linear summands, and considering $\left|H_i(\omega,t)\right| \cdot$ as constant:

$$\begin{aligned} &\varphi_i(\omega,t) \approx \varphi_i(\omega_0,t_0) + \varphi'_{it}(\omega_0,t_0)\Delta t + \varphi'_{i\omega}(\omega_0,t_0)\Delta\omega; \\ &\left|H_i(\omega,t)\right| = \left|H_{0i}\right| = const \end{aligned} \qquad (5)$$

The first phase derivative considering frequency equals to the group signal-delay time τ :

$$\varphi'_{i\omega}(\omega_0;t_0) = \tau_i(\omega_0;t_0) \qquad (6)$$

The first phase derivate considering time equals the Doppler frequency shift:

$$\varphi'_{it}(\omega_0;t_0) = -\omega_{\partial i}(\omega_0;t_0) = -2\pi F_{\partial i}(\omega_0;t_0) \qquad (7)$$

The absence of the frequency dispersion and quasi-stationary imply that within frequency band of signal element during its length time values $\tau_i(\omega;t)$ and $F_{\partial i}(\omega;t)$ do not change, i.e.:

$$\tau_i(\omega;t) = \tau_i(\omega_0;t_0) = \tau_{0i} = const$$

and

$$F_{\partial i}(\omega;t) = F_{\partial i}(\omega_0;t_0) = F_{\partial i0} = const\ .$$

When propagating in the ionosphere, $T_{\mathrm{E}} >> \tau_{0i}$. In this case, from Eq. (3), we obtain:

$$A_2(t) = a_0{}^2 \sum_{i=1}^{m} \left|H_{0i}\right| \exp[j(\psi_i(\omega_0,t_0) + 2\pi(t-t_0)f_{0i}], \qquad (8)$$

where

$$\begin{aligned} &\psi_i(\omega_0,t_0) = \varphi_i(\omega_0,t_0) - \tau_{0i}\cdot\omega_0 + 2\pi\,\mathrm{f_H}\tau_{0i} - 2\pi f_M\tau_{0i} - \pi\cdot df\cdot\tau_{0i}{}^2, \\ &\omega_0 = 2\pi(f_{\mathrm{H}} - f_M);\ f_{0i} = df\tau_{0i} + f_M - F_{\partial i0} \end{aligned} \qquad (9)$$

It can be seen from Eq. (8), a separate element of the differential signal in the course of T_{E} is a section of harmonic fluctuation. In this case we can obtain $S_2(\Omega)$ in the following way:

$$\begin{aligned} &S_2(\Omega) = a_0{}^2 T_{\mathrm{E}} \sum_{i=1}^{m} \left|H_{0i}\right| \exp[j\psi_i(\omega_0,t_0)] \times \\ &\times \sin c\left(\frac{\Omega - 2\pi(df\tau_{0i} - F_{\partial i0} + \mathrm{f}_M)}{2} T_{\mathrm{E}}\right) \end{aligned} \qquad (10)$$

where $\sin c(x) = \dfrac{\sin x}{x}$.

Methodic of data treatment. Individual modes are distinguished according to the procedures described in [6]. In element wise treatment of FMCW every *k*-th element of differential signal corresponding to time t_0 we denoted as $A_I(t)$, and every *(k+1)*-th element correspond to time $t_0 + T$ we denoted as $A_{II}(t)$. Time displacement of *(k+1)*-th element from *k*-th element defined in the following way:

$$T = \frac{2f_M}{df} \qquad (11)$$

In spectrum of differential signal for each propagation mode we can see two spectrum components with difference of frequency $2f_M$ because signal has amplitude modulation. The second spectrum component for *i*-th mode of *k*-th element of differential signal is defined as $S_{Ii,2}(\Omega)$ and illustrated in Fig. 1a). It corresponds to Eq. (10). The first spectrum component for *i*-th mode of *(k+1)*-th element of differential signal is defined as $S_{IIi,2}(\Omega)$ and illustrated in Fig. 1b).

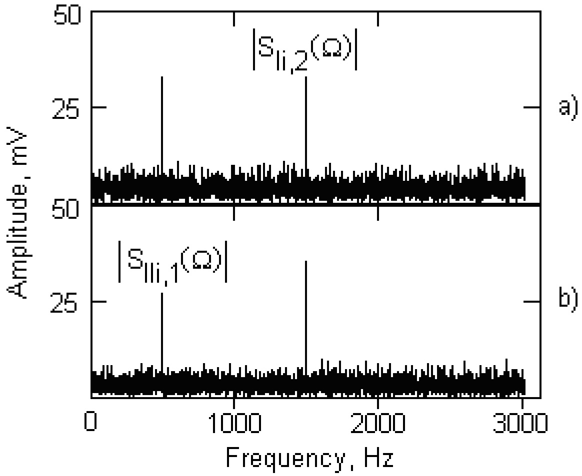

Fig.1 Spectrums of differential signal elements: a) *k*-th element of l signal; b) *(k+1)*-th element of signal

In equation of radiating signal first summand of Eq. (2) correspond to this spectrum component. Subject to time displacement T this summand is:

$$a_{II,1}(t) = a_0 \exp[j(2\pi(f - f_M)(t - t_0) - f_{\text{H}}T - f_M T + \\ + \pi \cdot df(t - t_0)^2 + \pi \cdot dfT^2)], \ t \in [t_0 + T, t_0 + t_K + T]. \qquad (12)$$

For differential signal of *(k+1)*-th element we obtained:

$$S_{II,1}(\Omega) = a_0{}^2 T_{\mathrm{E}} \sum_{i=1}^{m} |H_{0i}| \exp[j\psi_i(\omega_0, t_0 + T)] \times \sin c\left(\frac{\Omega - 2\pi(df\tau_{0i} - F_{\partial i0} - \mathrm{f_M})}{2} T_{\mathrm{E}}\right). \quad (13)$$

where

$$\psi_i(\omega_0, t_0 + T) = \varphi_i(\omega_0, t_0 + T) - \tau_{0i} \cdot \omega_0 + 2\pi f_{\mathrm{H}} \tau_{0i} - -2\pi f_M \tau_{0i} - \pi \cdot df \cdot \tau_{0i}{}^2 + 2\pi \cdot f_M T + 2\pi \cdot TF_{\partial i0}. \quad (14)$$

We see that both expressions for spectrums Eq. (10) and Eq. (13) have same amplitudes and different phases. Obviously phases differ on two summands. Equation (14) contains terms $2\pi F_{\partial i0} \cdot T$ and $2\pi \cdot f_M T$, therefore for define of Doppler shift we must change f_M and T so that product $f_M \cdot T$ become an integer number. For instance, if time displacement between signal elements T equals 0.01 s and f_M =500 Hz, then value of $2\pi \cdot f_M T$ is 20π — whole number of phase rotations.

If $\Delta\psi_i$ is difference between phases of spectral components $S_{Ii,2}(\Omega)$ and $S_{IIi,1}(\Omega)$, then with condition of Eq. (7) we have:

$$\Delta\psi_i = \varphi_i(\omega_0, t_0 + T) - \varphi_i(\omega_0, t_0) = 2\pi F_{\partial i0} \cdot T \quad (15)$$

There is necessity to change displacement T so that $|\Delta\psi_i| = |2\pi F_{\partial i0} T| \in (0;\pi)$. At the same time we have condition $T \in \left(0; \frac{1}{2|F_{\partial i0}|}\right)$. Usually in case of ionospheric propagation for short waves Doppler shift satisfy the condition $F_{\partial i0} < 10\,\mathrm{Hz}$, hence we can change value of data treatment displacement T < 0.05 s and amplitude modulation frequency 1000 Hz for good visibility of spectral components.

Making such treatment, we obtain two sequences of complex spectral samples for each element of differential signal.

If φ_{Iik} and φ_{IIik} are phases of spectral components for the *k*-th and the *(k+1)*-th elements of differential signal, then Doppler shift for element of the signal each *i*-th mode with central frequency $f_{0k} = f_{\mathrm{H}} + \dot{f} \cdot T\,(k - 1/2)$ can be defined in the following way:

$$F_{\partial ik} = \frac{\varphi_{IIik} - \varphi_{Iik}}{2\pi T}. \quad (16)$$

Registering variations of position for maximums of modulus of differential signal spectrum from element to element when operating frequency varies within the range of from f_{H} to f_{K}, we get frequency dependency for group delay $\tau_{ki}(f_{0k})$. Computing on Eq. (16) values of $F_{\partial ik}$ for each signal element, we obtain frequency dependency for Doppler shift $F_{\partial ik} = F_{\partial i}(f_{0k})$.

To define group delay, amplitude spectrum $S_{Ii,2}(\Omega)$ of differential signal $A_I(t)$ is used. For instance, modules $|S_{Ii,2}(\Omega)|$ have maximums on frequencies $\Omega_{I,2_{ki}} = 2\pi(df\tau_{ki} + f_M - F_{\partial ik})$.

In conditions of ionospheric propagation Doppler shift $F_{\partial ik}$ far less than product $df \cdot \tau_{ki}$, therefore group delay for central frequency $f_{0k} = f_{\text{H}} + df \cdot T(k - 1/2)$ is:

$$\tau_{ki} \approx \frac{\Omega_{I,2_{ki}} - 2\pi \cdot f_M}{2\pi \cdot df} \qquad (17)$$

Thus we obtain frequency dependency group delay for separate modes.

Conclusion. This methodic permit make straight forward element wise measurements of group delay time and Doppler shift by means phase values, without great averaging in great time interval. This advantage gives facility for Doppler-gram tracing with high temporal resolution. Methodic not requires many technical consumptions and wants only one transmitter and one receiver. Methodic usage in work of systems for FMCW radio sounding of ionosphere can give resource for define frequency dependences Doppler shift and propagation time of radio signal in ionospheric channel for whole decameter range. It will refine possibility of chirp-sounder as estimations tool for non-stationary short-wave channel.

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Представлено новий метод одночасного вимірювання частотних залежностей допплерівського зсуву і часу групової затримки окремих іоносферних мод з використанням безперервного ЛЧМ сигналу з амплітудною модуляцією. Наведено порядок обробки даних під час вимірювання.

Ключові слова: іоносфера, ЛЧМ іонозонд, фаза, допплерівській зсув.

Представлен новый метод одновременного измерения частотных зависимостей доплеровского сдвига и времени групповой задержки отдельных ионосферных мод с использованием непрерывного ЛЧМ сигнала с амплитудной модуляцией. Приведен порядок обработки данных при измерении.

Ключевые слова: ионосфера, ЛЧМ ионозонд, фаза, доплеровский сдвиг.