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REFLECTION OF THE ULTRA-WIDEBAND SIGNALS FROM PLASMA LAYERS

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This paper is concerned with the temporal distortion caused by the dispersion of ultra-wideband signals reflecting from linear and parabolic plasma layers. The magnitudes of the expected effects have been estimated for the various parameters of the plasma layers and sounding ultra-wideband signals. The ultra-wideband signal distortions are calculated for reflection from the ionospheric plasma layers and their features are described.

1. Introduction

In the 90s of the 20th century, the ultra-wideband (UWB) signals introduced in the 50–60s by Kennaugh, Moffatt, and Kosgriff began to find increasingly wide application to different areas of science and engineering.

For example, the UWB signals could be used for remote radio sensing snow and ice covers, the radiolocation of subsurface targets, the communication with immersed submarines, for super fast data traffic in computer networks, etc.

The application of such signals to radiolocation allows a range resolution of 0.1 m to be attained for a pulse duration of $\tau \approx 10^{-9}$ s, the detection of targets with a special antiradar cover, e.g., manufactured by using the "Stealth" technology, to be accomplished, and the data on non-coordinate information on the target (form, size, etc.) to be inferred [1].

The UWB signals were suggested to apply to remote radio sensing near-earth space in the middle of the 90s of the 20th century [2].

The plasma environments, in particular the Earth's ionosphere and magnetosphere, were expected to exert the main negative effect on UWB radio wave propagation due to the dispersion. The features and magnitudes of these distortions due to the phase velocity dispersion, as well as the absorption and attenuation dispersions, are considered in detail in [3] for different models of the UWB signals.

The radar equation necessary for calculating the parameters of radio systems was updated for the case of UWB signal applications [4].

2. Simulation of Reflection

The sounding signals are described by six simple analytical UWB signal models in the time-domain, which have been suggested in [3].

The reflected signals in the time domain are represented by the relation

$$E_r(t) = \int\limits_{-\infty}^{\infty} \dot{S}(f) \exp\left(i4\pi \frac{f}{c} z_r(f) \overline{n}(f) + i2\pi ft - i\frac{\pi}{2} \right) \times Q(f)\, df \quad (1)$$

where $\dot{S}(f)$ is the spectral density of the sounding signal given by the complex function

$$\dot{S}(f) = \int\limits_{-\infty}^{\infty} E_0(t) \exp(-i2\pi ft)\, dt,$$

f is the frequency, t is time, c is the speed of light in free space, $z_r(f)$ is the altitude of reflection of the harmonic with frequency f, which is determined from the condition

$$n(f, z_r(f)) = 0,$$

$n(f,z)$ is the index of refraction;

$$\overline{n}(f) = \frac{1}{z_r(f)} \int\limits_0^{z_r(f)} n(f,z)\, dz,$$

$$Q(f) = \begin{cases} 1, & f \le f_{pm} \\ 0, & f > f_{pm} \end{cases}, \quad (2)$$

and where f_{pm} is the maximum plasma frequency of the medium. The relation (2) expresses the fact that the spectral components with $f > f_{pm}$ are not reflected from the plasma layer.

The index of refraction of the medium is given by

$$n^2(f) = 1 - \frac{f_p^2}{f^2}.$$

The linear and parabolic plasma layers were selected for describing the medium because they are most frequently used for approximating the actual profiles of the Earth's ionospheric electron density. They are given by the following expressions.

For the piece-wise *linear* layer

$$f_p^2 = f_p^2(z) = f_{pm}^2 \frac{z}{z_m},$$
$$z \in [0, z_m], \quad f \in [0, f_{pm}],$$

where z_m is the altitude of the piece-wise linear layer maximum.

For the *parabolic* layer

$$f_p^2(z) = f_p^2(z_{\max})\left(1 - \left(\frac{z_{\max} - z}{z_{\max} - z_{\min}}\right)^2\right),$$
$$z \in [z_{\min}, z_{\max}], \quad f \in [0, f_p(z_{\max})],$$

where $z_{\min}$ is the height of the parabolic layer beginning, $z_{\max}$ is the height of the peak density. In our case, it is convenient to set $z_{\min} = 0$, and to designate $z_{\max} = z_m$, $f_p(z_{\max}) = f_{pm}$.

It is convenient to introduce the dimensionless variables

$$T = \frac{t}{\tau_0}, \quad F = f\tau_0, \quad Z = \frac{z}{c\tau_0}, \quad F_p = f_p\tau_0,$$

which are dimensionless time, frequency, distance, and plasma frequency, respectively, and τ_0 is the finite time duration of the UWB signal.

The signal reflected from the piece-wise linear layer can be represented as

$$E_r(T) = \int_{-\infty}^{\infty} \dot{S}(F) \exp\left(i\frac{8\pi}{3} Z_m \frac{F^3}{F_p^2(Z_m)} + i2\pi FT - i\frac{\pi}{2}\right) Q(F)\, dF. \quad (3)$$

The signal reflected from the parabolic layer is given by

$$E_r(T) = \int_{-\infty}^{\infty} \dot{S}(F) \exp\left(i\pi F Z_m \left(2 + \frac{F_p^2(Z_m) - F^2}{F F_p(Z_m)} \times \ln\frac{F_p(Z_m) - F}{F_p(Z_m) + F}\right) + i2\pi FT - i\frac{\pi}{2}\right) Q(F)\, dF. \quad (4)$$

The integrals (3) and (4) are evaluated by numerical methods.

To model the actual ionospheric plasma layer, we set $f_p(z_m) = 10$ MHz for the daytime ionosphere and $f_p(z_m) = \sqrt{10}$ MHz for the nighttime ionosphere, and $z_m = 200$ km in both cases.

3. Results of Model Calculations

In reflecting the UWB signal from a linear or parabolic plasma layer with a given maximum plasma frequency $F_{pm} \equiv F_p(Z_m)$, two different situations are possible.

In the first of them, the condition $F_{\max} \le F_{pm}$ is satisfied ($F_{\max}$ is the maximum frequency of the UWB signal spectral density), i.e., all spectral components of the probing signal are reflected and returned back. Then, if all of them are reflected at the same range from the source, i.e. from the boundary of the plasma layer ($Z_{\min} = Z_{\max}$), the signal changes insignificantly due to the phase changes of the complex spectrum of the signal by $\pi/2$ in the process of reflection. Such a situation is shown in Fig. 1 for $F_{pm} = 80$. It can be seen that a bi-lobe signal pattern ($\mu \to 2$) has transformed into a tri-lobe one ($\mu \approx 1,33$). However, the reflected signal remains ultra-wideband.

In the second situation, $F_{\max} > F_{pm}$, part of the UWB signal spectrum is not reflected from the plasma layer, and does not return. As a result, the more there are such components, the narrower the signal spectrum becomes, and therefore, the more reflected signal lobes occurs, the smaller the wide-band index μ becomes, and the faster the reflected signal ceases to be a UWB signal. In Fig. 1, this process can be seen as F_{pm} decreases.

Therefore, in practical applications of UWB signals to remotely sounding the ionosphere, the signals with $F_{\max} \le F_{pm}$ should be selected. It is beneficial both from the point of view of decreasing the distortion in reflected signals, and from the point of view of energy conservation, since for $F_{\max} > F_{pm}$ part of signal energy is wasted.

Consider separately the effect of dispersion distortion of the sounding signal arising exclusively because of the fact that the different signal spectral components are reflected at different ranges from the source of the signal, i.e., the condition $F_{\max} \le F_{pm}$ satisfied.

In Fig. 2, the dispersion distortions in the UWB sounding signals are shown when it is reflected from the model parabolic plasma layer. It is established that the greater spectral component frequency is, the greater path it travels up to the level of reflection and back. Provided F_{pm} is a constant, this results in an increase in the dispersion distortion of the reflected signal as Z_m increases; in dimensional variables, this corresponds to an increase in z_m if $f_p(z_m)$ and τ_0 remain constant. The distortion is displayed in the ap-

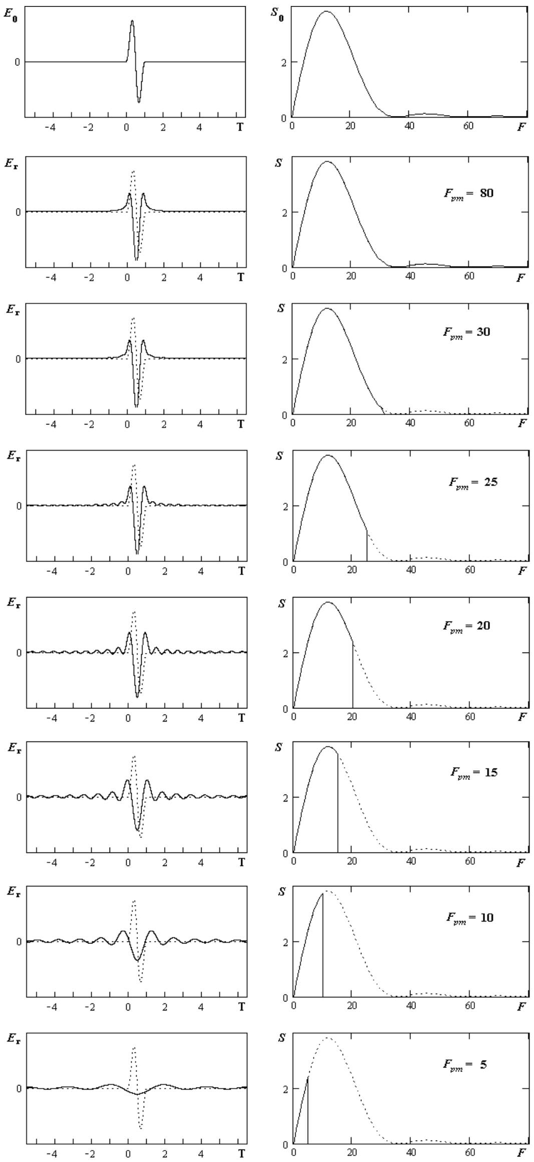

Fig. 1. *Probing signal in the time-domain ($E_0(T)$) and in the frequency domain ($S_0(F)$), and the reflected signal in the time domain ($E_r(T)$) and in the frequency domain ($S_r(F)$) for different values of the peak plasma frequency F_{pm}*

pearance of new lobes in the UWB signal, which reduces its wideband index; therefore, the signal gradually ceases to be ultra-wideband. The temporal duration of the signal also increases with increasing Z_m.

As distinct from the dispersion distortions of UWB signals arising during their propagation in the dispersive plasma environments, in particular, in the Earth's ionosphere [3], when, as the signal disperses, the high frequency components propagate to the rising edge of the signal and the low frequency to the falling edge of the signal, at reflection the opposite picture is observed. Here the lower frequency components appear closer to the signal rising edge and those with the higher frequency to the falling edge.

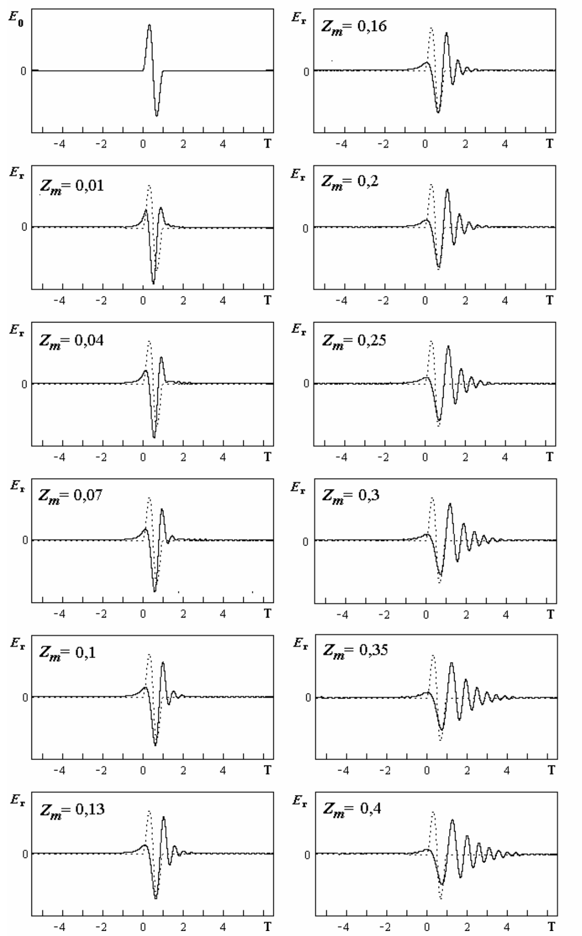

Fig. 2. *Dispersive distortion of the probing UWB signals (model 5) reflecting from the parabolic plasma layer with various layer peak heights Z_m. The layer peak plasma frequency $F_{pm} = F_{\max} = 50$*

We shall now consider the reflection of UWB signals from a real ionospheric layer, for which the parabolic plasma layer model is used with the mentioned above parameters. It is convenient to introduce the parameter r that is equal to the ratio of the maximum frequency, $f_{\max}$, in the UWB sounding signal spectral density to the plasma frequency at parabolic layer peak

$$r = \frac{f_{\max}}{f_p(z_m)} = \frac{F_{\max}}{F_{pm}}.$$

The dispersive distortions depend on the value of this parameter: the greater this parameter r is, the greater distortions are.

The range $0 < r \leq 1$ corresponds to the reflection of all spectral components from the plasma

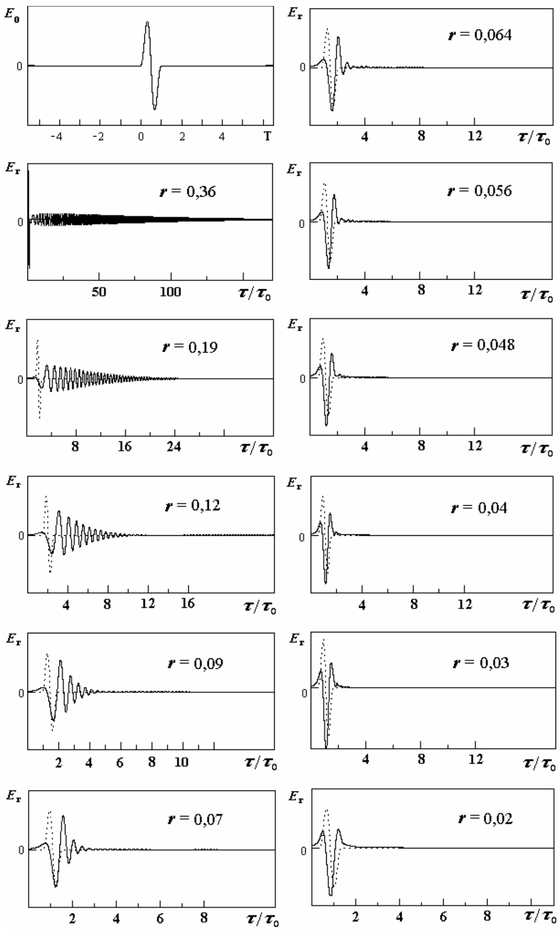

Fig. 3. *Dispersive distortion of the sounding UWB signals reflecting from the parabolic ionospheric layer with various values of* r *and for* $\tau_0 = 5 \cdot 10^{-4}$ *s,* $f_{pm} = 10$ *MHz,* $z_m = 200$ *km*

layer, and for $r > 1$, part of them does not reflect, and consequently, does not return to the source of the sounding signal. The number of such components grows with increasing r.

As a quantitative property of the distortion, we shall use the relative signal lengthening τ / τ_0 where τ is the echo time duration. It is established that the dispersive distortion of the sounding UWB signals used for remotely radio sensing the Earth's ionosphere is essential.

When the UWB signal with $\tau_0 = 5 \cdot 10^{-4}$ s is reflected from the ionospheric plasma layer with $z_m = 200$ km and $f_{pm} = 10$ MHz, which corresponds to the daytime ionosphere, $\tau / \tau_0 \sim 1 \div 1000$ when $r = 0.01 \div 0.60$. The features of the distortion is shown in Fig. 3.

Use of the same UWB sounding signals in the nighttime ionosphere, $f_{pm} = \sqrt{10}$ MHz, results in $\tau / \tau_0 \sim 1 \div 225$ when $r = 0.05 \div 0.60$. Similar results are also obtained with other ionospheric models. Therefore, the effects are virtually independent of UWB signal model.

4. Conclusions

1. As the UWB signals are reflected from the ionospheric plasma layers, significant dispersive distortion arises.
2. The features of this distortion differ from those occurring during UWB signal propagation in the Earth's ionosphere and magnetosphere.

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ОТРАЖЕНИЕ СВЕРХШИРОКОПОЛОСНЫХ СИГНАЛОВ ОТ ПЛАЗМЕННЫХ СЛОЕВ

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Рассмотрены дисперсионные искажения, которые возникают при отражении сверхширокополосных сигналов от линейного и параболического плазменных слоев. Оценены величины наблюдаемых эффектов при различных соотношениях параметров плазменного слоя и зондирующего сверхширокополосного сигнала. Рассчитаны величины и описан характер дисперсионных отражений сверхширокополосных сигналов при отражении от ионосферных плазменных слоев.

ВІДБИТТЯ НАДШИРОКОСМУГОВИХ СИГНАЛІВ ВІД ПЛАЗМОВИХ ШАРІВ

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Розглянуто дисперсійні спотворення, що виникають при відбитті надширокосмугових сигналів від лінійного та параболічного плазмових шарів. Оцінено величини ефектів, що спостерігаються, при різних співвідношеннях параметрів плазмового шару та зондуючого надширокосмугового сигналу. Розраховано величини та описано характер дисперсійних спотворень надширокосмугових сигналів при відбитті від іоносферних плазмових шарів.