Technical Physics Letters, 2022, Vol. 48, No. 11

11.1

Radio-physical method for studying the deformation of ultra-wideband pulses during propagation in the atmosphere

© *V.V. Bukin*[1], *T.V. Dolmatov*[1], *M.V. Efanov*[2], *E.F. Lebedev*[2], *V.E. Ostashev*[2], *A.V. Ulyanov*[2], *V.M. Fedorov*[2], *M.A. Shurupov*[2]

[1] Prokhorov Institute of General Physics, Russian Academy of Sciences, Moscow, Russia
[2] Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia
E-mail: lebedev@ihed.ras.ru

Received July 21, 2022
Revised September 28, 2022
Accepted September 29, 2022

Field experiments have been carried out to measure ultra-wide-band subnanosecond radiation pulses in the time domain, taking into account the influence of reflection from the Earth's surface. Received results allow us to prepare experiments in a free atmosphere on real ranges of 10 kilometers or more in length. The optimal technical solution in terms of weight and size characteristics and elevation to heights up to 1000 meters is the using a single-channel ultra-wideband radiator with a pulse duration of about 50 ps and a specially designed measuring antenna in the form of a passive antenna array with high sensitivity.

Keywords: ultra-wideband pulses, propagation through atmosphere, reflected signal influence.

DOI: 10.21883/TPL.2022.11.54892.19318

The studies into nanosecond switches of high-power current pulses have advanced considerably in recent years through the efforts of engineers and researchers (in particular, electrophysicists from St. Petersburg and Tomsk) [1–8]. The commercial production of a wide range of generators of high-voltage pulses with a rise time varying from several tens of picoseconds to several nanoseconds [5] facilitates wider application of these advanced switches for feeding of lasers and ultra-wideband (UWB) radiating antennas.

The primary aim of the present study is to perform field experiments on propagation of UWB signals in real media over short distances (up to 100 m) with account for the influence of signals reflected off the surface of the Earth and compare the obtained data with those provided by a calculation model.

The mass of a radiating UWB module constructed based on modern voltage generators (together with a horn antenna, an accumulator for 1200 s of self-sufficient operation, and a control unit) is approximately 10 kg. Such weight parameters of UWB radiators make it possible to mount them on lightweight carriers for various kinds of experiments. The key data on constructed UWB radiators and devices being designed (including radiators combined into synchronized active antenna arrays) are given in [8,9].

These instruments may be used to construct a radiating UWB module with a pulse duration of approximately 50 ps that is needed to verify the results of calculation works [10], where a significant deformation of UWB pulses in the atmosphere was found to occur at pulse durations shorter than 50 ps and propagation distances longer than 10 km. The deformation effect is attributable to the presence of a resonance absorption frequency at around 22 GHz. However, this requires verification, since such components in the spectrum of UWB signals above 10–12 GHz are very weak at a pulse duration of 50 ps.

At the same time, exactly these pulse durations (50 ps and shorter) are of interest for practical applications (specifically, for high-altitude ice and soil sounding) due to the smallness of apertures of radiating antennas. Direct experiments on propagation of such UWB pulses in the atmosphere have not been performed.

It is rather hard and costly to plan and carry out such experiments in the atmosphere over distances of many kilometers. This is due to the need to exclude (or suppress to the extent reasonably practical) the influence of the surface of the Earth and its irregularities on the detected signals. Thus, one needs to lift the instruments and operators to a height of several tens of meters (or even several hundred meters) above ground.

The primary technical problems arising in the design of such equipment were solved in [9]. Synchronized assemblies of UWB modules in the form of active antenna arrays with a dimension of 1×1 (single module, 10 kg), 2×2 (four modules, 50 kg), and 3×3 (nine modules, 100 kg) and a specialized measurement quasi-horn with its sensitivity being two orders of magnitude higher than the sensitivity of a well-known [6] strip-line measurement transducer (SLMT) were constructed for atmospheric and ionospheric experiments. This equipment allows one to examine signal propagation over a distance of 100 km (or even longer distances).

In view of the vertical stratification of parameters of the atmosphere of the Earth, it seems rational to perform the initial studies for a trajectory going along the surface of the Earth with near-uniform atmospheric parameters. Several scenarios of kilometer-range experiments are feasible:

propagation from one mountain to another (an expedition needs to be organized); propagation between tall buildings (permission to use a radiator in an urban area needs to be obtained); and propagation from one air balloon flying over a sparsely populated area to another (this scenario was the one selected for further development).

The need to launch a radiator and a detector to considerable elevations, where the influence of the surface of the Earth would be virtually excluded, on two balloons simultaneously introduces additional difficulties associated with the mutual adjustment of direction pattern of the radiator and the detector. However, this scenario is the minimum-cost one and provides an opportunity to perform a clean experiment unaffected by the surface of the Earth. The latter advantage is key for making a correct comparison between calculated and experimental data.

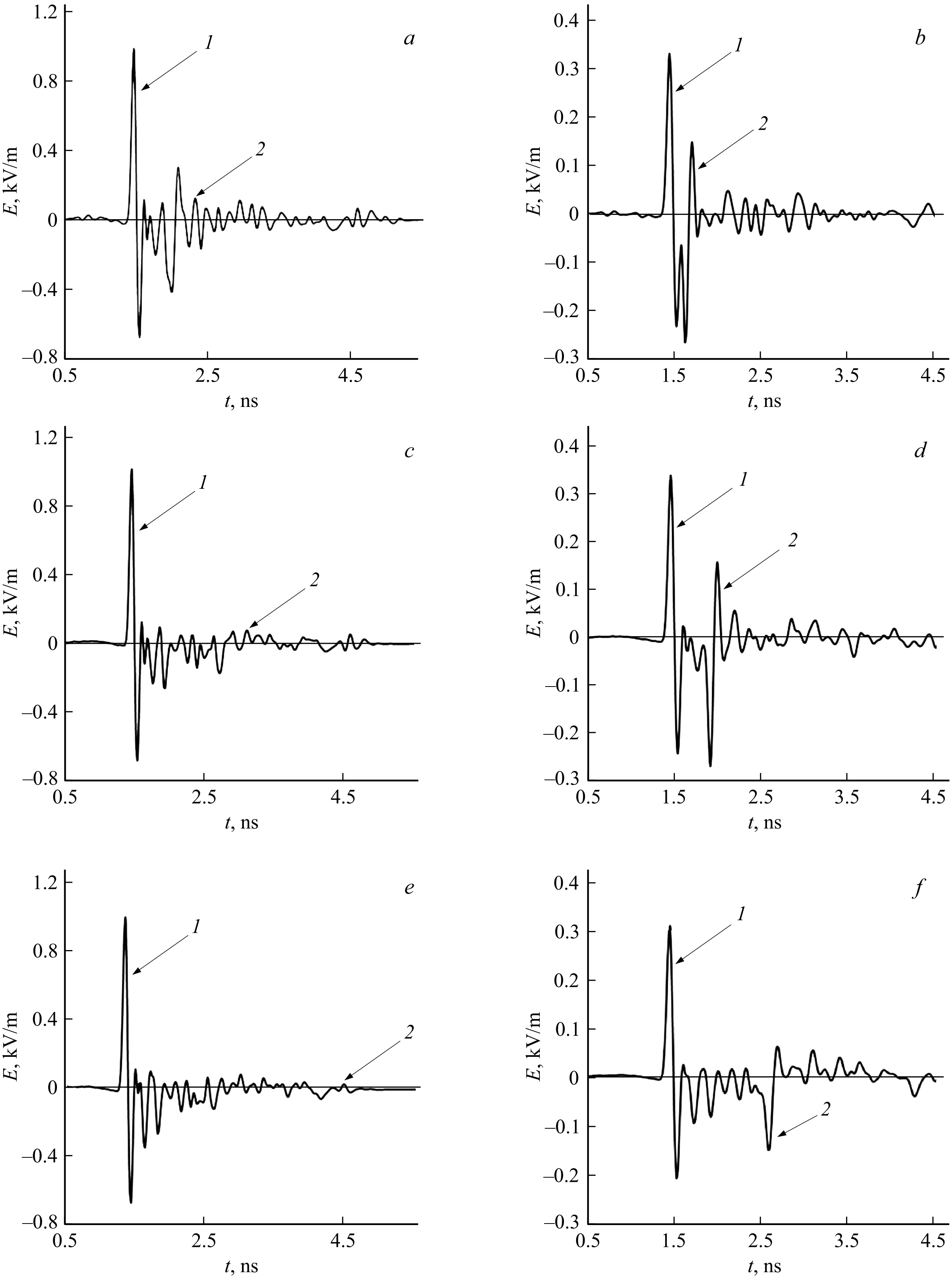
The goal of field experiments, which are presented below, was to examine the influence of the surface of the Earth on detected signals under varying parameters (distance, elevation of elements, tilt angles, etc.) of geometry of the experiment. These experiments constitute a preliminary stage before the ones planned for a propagation distance of 10 km, which require additional substantiation of experimental arrangements due to the presence not only of obstacles positioned along the signal path (forest, buildings), but also of the curved surface of the Earth. In the context of comparison with calculated data, only a field experiment may offer a definitive answer to the question as to how accurately he actual conditions matched the conditions of propagation of UWB pulses in a free atmosphere. While the distances did not exceed 100 m, the reported field experiments performed in immediate proximity to the ground still provided useful information, since it was relatively easy to alter the tilt of longitudinal axes of the sensing element and the radiator with respect to the horizon and adjust the distance between elements and their elevation. Experiments were carried out on a level field with sparse grass no taller than 0.2 m. The distance varied from 20.0 ± 0.1 to 60.0 ± 0.1 m in 10 m increments with alignment of the axes of direction patterns of the radiator and the sensing element. The angle of elevation above horizon of the radiator varied from 0.036 ± 0.002 rad at a distance of 60.0 ± 0.1 m to 0.107 ± 0.002 rad at 20.0 ± 0.1 m. The spectral characteristics of radiation pulses and their dependence on the experimental conditions were calculated based on the obtained oscilloscope records of signals.

A comparison between the oscilloscope records of UWB radiation pulses in various geometries of the experiment (specifically, at equal elevations of the radiator and the sensing element: 1.0 ± 0.1 m (maximum ground influence) and 3.0 ± 0.1 m (minimum ground influence)) is presented in the figure. The calculated position of a signal reflected off the ground (see panels *a*, *c*, *e*) was determined using a two-dimensional code developed by Ostashev [11]. This code is designed for estimation of the key parameters and characteristics of UWB radiation generated by planar apertures with non-uniform and non-synchronous excitation (multielement synchronized antenna arrays included). The code was augmented by a module needed to perform radiation calculations with account for reflection off planar underlying surfaces with above-unity permittivity values. This module factors in the specifics of formation of reflected UWB signals and provides an opportunity to estimate their influence on signals detected on the axis of the UWB radiation pattern.

An ALMT-type sensor with a sensitivity of $0.38 \pm 0.01\,\mathrm{V/(kV \cdot m)}$ was used as a primary detector to obtain oscilloscope records, which were averaged over 1000 captures. The oscilloscope record in panel *a* of the figure, which presents the data for a distance of 20.0 ± 0.1 m, demonstrates that a negative-polarity signal reflected off the ground has an amplitude of about 40% of the direct signal amplitude. According to the results of calculations, the reflected signal also lags 1 ns behind the direct one. As the distance increases further, the reflected pulse „catches up“ the leading edge of the pulse, first amplifying the negative half-wave relative to the positive one and then reducing the amplitude of the positive half-wave (see panel *b*). At an elevation angle of approximately 0.107 ± 0.002 rad in experiments performed over a distance of 20 m (see panel *c*), the radiator direction pattern is positioned sufficiently high above the ground, and the signal is almost free of reflected data (two negative spikes with a delay of 0.5 and 1 ns and amplitudes of 20 and 10%). The amplitudes of direct signals transmitted over a distance 20 m are almost the same in all three modes: 1.00 ± 0.05 kV/m. The calculated spectra of signals differ insignificantly.

When the propagation distance increased to 60.0 ± 0.1 m (see panels *b, d, f*), the signal amplitude naturally dropped to 0.30 ± 0.05 kV/m. At an elevation angle of 0.036 ± 0.002 rad set for this distance (see panel *d*), the reflected signal amplitude increases to 80%, but this signal does not interfere with the detection of the direct one, since it lags approximately 0.2 ns behind. At the same time, when the radiator and the sensing element were positioned at an elevation of 1.0 ± 0.1 m (see panel *b*), the reflected signal started to distort the direct one and interfere with correct detection. In the case of signal propagation at an elevation of 3.0 ± 0.1 m, the time lag between reflected and direct signals is 0.5 ns.

Although the primary UWB signal pulse may be detected without any significant distortion, the discussed configuration has a considerable effect on the spectral characteristics of detected pulses. Even a weak reflected signal (30−40% of the maximum amplitude) transforms the spectrum from an ultra-wideband to a band-line one. High-frequency (6−9 GHz) spectral components start to form in propagation at an elevation of 1.0 ± 0.1 m. At an elevation of 3.0 ± 0.1 m, up to ten bands form (each with a width of approximately 500 MHz). This provides evidence of the emergence of a separate reflected signal on the time axis, which, as was already noted, transforms the spectrum from a continuous to a band one. The distance between spectral



Electric-field intensity pulses recorded over a distance of 20 (*a, c, e*) and 60 m (*b, d, f*) at the following elevations of radiator h_R and sensing element h_S: *a, b* — $h_R = h_S = 1$ m; *c, d* — $h_R = 1$ m, $h_S = 3$ m; *e, f* — $h_R = h_S = 3$ m. *1* — direct signal, *2* — reflected signal (at a distance of 20 m, the position is calculated).

lines is inversely proportional to their period in the time domain.

The obtained data bode well for 10-km field experiments and should help adjust the geometry of these longer-range endeavors (specifically, the positioning of the radiator and the sensing element and the elevation of the radiator–sensor system) and minimize the influence of the signal reflected off the ground. The ground influence is suppressed considerably at an elevation angle of at least 0.1 rad. In practice, this may be achieved by lifting the radiator to a height of 1000 m above the surface of the Earth. Natural surface relief will also affect the results of long-range experiments. All this will need to be accounted for and reconfirmed in field experiments.

Funding

This study was supported financially by grant No. 075-15-2020-790 from the Ministry of Science and Higher Education of the Russian Federation.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] I.V. Grekhov, G.A. Mesyats, Phys. Usp., **48** (7), 703 (2005). DOI: 10.1070/PU2005v048n07ABEH002471.
[2] I.V. Grekhov, A.F. Kardo-Sysoev, Sov. Tech. Phys. Lett., **5** (8), 395 (1979).
[3] G.A. Mesyats, S.N. Rukin, V.G. Shpak, M.I. Yalandin, in *Ultra-wideband, short-pulse electromagnetics 4*, ed. by E. Heyman, B. Mandelbaum, J. Shiloh (Plenum, N.Y., 1999), p. 1.
[4] W.D. Prather, C.E. Baum, R.J. Torres, F. Sabath, D. Nitsch, IEEE Trans. Electromagn. Compat., **46** (3), 335 (2004). DOI: 10.1109/TEMC.2004.831826
[5] V.M. Efanov, in *Proc. on 14th IEEE Int. Pulsed Power Conf.* (Dallas, TX, USA, 2003), p. 100.
[6] K.Yu. Sakharov, *Izluchateli sverkhkorotkikh elektromagnitnykh impul'sov i metody izmerenii ikh parametrov* (MIEM, M., 2006) (in Russian).
[7] V.I. Koshelev, V.P. Gubanov, A.M. Efremov, S.D. Korovin, B.M. Kovalchuk, V.V. Plisko, A.S. Stepchenko, K.N. Sukhushinin, in *Proc. of 13th Int. Symp. on high current electronics* (Tomsk, Russia, 2004), p. 258.
[8] V.M. Fedorov, M.V. Efanov, V.Ye. Ostashev, V.P. Tarakanov, A.V. Ul'yanov, Electronics, **10** (9), 1011 (2021). DOI: 10.3390/electronics10091011
[9] M.V. Efanov, E.F. Lebedev, A.V. Ul'yanov, V.M. Fedorov, M.A. Shurupov, Teplofiz. Vys. Temp., **59** (6), 877 (2021) (in Russian). DOI: 10.31857/S0040364421060028
[10] A.M. Stadnik, G.V. Ermakov, Radiotekh. Elektron., **40** (7), 1009 (1995) (in Russian).
[11] V.E. Ostashev, A.V. Ul'yanov, V.M. Fedorov, J. Commun. Technol. Electron., **65**, 234 (2020). DOI: 10.1134/S1064226920030134.