

# Monte Carlo simulations of nanosecond electromagnetic pulse interaction with field-aligned ionospheric plasma density irregularities

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## Key Points:

- Monte Carlo model of nanosecond electromagnetic pulse propagation in ionospheric plasma with field-aligned density depletions is developed
- Frequency dispersion competes with pronounced pathlength dispersion for scattered waves at low frequencies.
- The effects of density depletions on electromagnetic pulse properties seem weak even for strong plasma density depletions of up to 50%.

## Abstract

We propose an approach to simulate ultra-wideband (UWB) electromagnetic pulse (EMP) propagation in ionosphere with magnetic field-aligned irregularities of plasma density based on Monte Carlo technique. This approach considers propagation of a nanosecond EMP by ray trajectories in frequency domain, which allows one to analyze the role of scattering effects for lower and higher harmonics of the pulse. Parameters of the irregularities used in the simulations are chosen close to those of artificial ionospheric turbulence (AIT) density striations stimulated by high-frequency (HF) heating facilities. The employed technique provides a possibility to compare the effects of dispersion and scattering on a waveform of bipolar nanosecond EMP for various parameters of ionospheric plasma and its disturbances. In the presence of 10-meter scale, 10-percent level density striations, we show that lower frequencies are most responsible for the EMP waveform transformation due to the plasma dispersion, and are scattered away from the initial propagation direction, while higher frequencies experience minor dispersion and are less scattered. The influence of AIT-type striations on the straightforward EMP delay and its broadening in time domain is analyzed compared to the EMP propagation in uniform plasma. Preliminary, the effects of AIT-type striations on EMP characteristics seem to be weak in the main part of its frequency spectrum, even for strong (non-realistic) plasma density depletions of up to 50%.

## 1 Introduction

Ultrawideband (UWB) electromagnetic pulses (EMPs) are signals with duration from tens of picoseconds to several nanoseconds. The frequency spectrum of such signals is very broad, from about 100 MHz to 10 GHz, since EMPs are as short as one cycle of oscillation of the electromagnetic field. The development of UWB technology in recent decades (Agee et al., 1998; Baum, 1992; Nekoogar, 2011) has led to discussion of the possibilities of UWB EMP use for sounding the ionosphere and building trans-ionospheric radio communication channels (see, for example, (Soldatov & Terekhin, 2016)). Recently, first experiment of trans-ionospheric propagation of a nanosecond EMP with its reception onboard a satellite was reported (Zhang et al., 2024).

In this regard, questions inevitably arise about the effect of ionospheric plasma on the waveform and frequency spectrum of UWB EMP, primarily the effects of dispersion and scattering on natural and artificial electron density irregularities along the EMP propagation path. The role of linear dispersion and linear absorption leading to the spreading of the UWB EMP and a decrease in its amplitude has been extensively studied (see (Arnush, 1975; Cartwright & Oughstun, 2009; Dvorak, et al, 1997) and references therein), as well as nonlinear effects for high-power EMPs (Golubev, et al, 2000). Laboratory simulations of UWB EMP propagation in ionosphere are also being developed under the support of analytical and numerical models (Es'kin, et al, 2023; Goykhman et al., 2022; Zudin et al., 2024). However, the effects of ionospheric irregularities on the propagation of UWB EMPs have not been explicitly studied yet, to our knowledge.

Generally, the effect of ionospheric irregularities on the propagation of very-high (VHF, 30 – 300 MHz), ultra-high (UHF, 300 MHz – 3 GHz), and super-high frequencies (SHF, 3 – 30 GHz) that overlap the UWB EMPs' frequency spectrum has been actively studied since the 1970s (Perkins, 1975). In recent years, interest in this problem is driven first of all by ensuring the high accuracy of Global Navigation Satellite Systems (GNSS) that use L-band transmission channels (see (Aol et al, 2020; Hong et al., 2020; Mrak et al, 2023; Wernik et al, 2003) and references therein). To date, models of diffraction and scattering on natural ionospheric irregularities with sizes from several kilometers to several meters have been developed that allow one to estimate the amplitude and phase scintillations of monochromatic or narrowband signals (Carrano et al, 2011; Deshpande et al, 2014; Galiègue et al 2017). These models, however, cannot be explicitly applied to analyze the waveforms of UWB EMPs propagating in disturbed ionosphere.

Artificial ionospheric irregularities (AIs) are a manifestation of artificial ionospheric turbulence (AIT) which develops in ionosphere exposed to powerful radio waves (see (Streltsov et al., 2018) and references therein). Generation of AIs and their effect on the propagation of VHF waves were discovered in early experiments on ionosphere modification (Fialer, 1974). Ground-based HF ionosphere heating facilities located at different geographic latitudes (SURA, Russia; HAARP, USA; EISCAT-Heating, Norway) (Streltsov et al., 2018) are capable of generating the AIs.

In scattering of high-frequency waves, the irregularities with scales from meters (and even decimeters) to kilometers provide dominating impact. Properties of such AIs were studied in sufficient detail from radar scattering after plasma modification by heating facilities, as well as from the characteristics of artificial radio emission from ionosphere (Dhillon & Robinson, 2005; L. Erukhimov et al, 1988; L. M. Erukhimov & Mityakov, 1989; Franz et al, 1999; Frolov et al, 1997; Grach et al, 2016). Direct measurements of AIs are complicated, however they were performed in rocket experiment (Kelley et al., 1995). A simplified model of AI system can be represented as multiple plasma density depletions up to 10-20% from the background (or "striations") oriented parallel to the geomagnetic field, (Franz et al., 1999; Kelley et al., 1995). Owing to the pronounced anisotropic mobility of electrons and ions in the geomagnetic field, AIs have nearly cylindrical shape. Axial AI scale  $l_{\parallel}$  is limited by the thickness of the turbulence area and can be as large as several tens of km. Transverse scale of the irregularities  $l_{\perp}$  can be about 10 m or even less. Aspect ratio of irregularities  $l_{\parallel}/l_{\perp}$  can be of the order of the ratio of frequency of electron collisions with neutral particles to electron gyrofrequency, which amounts  $10^{-4}$  in ionospheric F-layer (Robinson, 2002).

Our interest in the effect of AIs on the propagation of EMPs in the GHz frequency range is because such irregularities can be excited under controlled conditions and be quite small-scaled, i.e. of the order of 10 m or less causing considerable scattering of short (meter and decimeter) waves. Therefore, the developed models of UWB EMP scattering on ionospheric irregularities can in future be verified in active experiments with heating facilities. To date, AI-caused scintillation of L-band signals has been observed using HAARP (Mahmoudian et al., 2018) and EISCAT (Sato et al, 2021) heaters. Moreover, the possibility of generating AIs of very small transverse scales of the order of 10 cm, or so-called "super small-scale" (SSS) irregularities in the heating experiments is being discussed (Milikh et al, 2008). If density variations in SSS

irregularities reach 20-30% (Najmi et al., 2014), such AIs can in principle lead to strong scattering of GHz signals including UWB EMPs.

The frequencies of sub GHz and GHz waves significantly (by several orders of magnitude) exceed the plasma frequency of the F-layer which is typically below 10 MHz, and electron collision frequencies (Soldatov & Terekhin, 2016). This leads to a number of assumptions in a model of UWB EMP interaction with ionospheric irregularities: (1) approximation of collisionless plasma can be used; (2) the influence of geomagnetic field on the EMP dispersion can be neglected. Thus, plasma acts as a medium that is transparent to radiation and does not absorb electromagnetic energy, with an isotropic dielectric constant and a refractive index close to unity. The irregularities manifest themselves as refractive index variations (Hunsucker & Hargreaves, 2007), while scattering of GHz waves is determined by the geometry of irregularities exclusively, i.e. their depth and statistics. However, the three-dimensional geometry of striations turns out to be quite complex, which complicates achievement of analytical solutions.

To simulate the propagation of GHz waves in ionosphere in the presence of AIs numerically, a parabolic wave equation (PWE) is used in combination with a series of phase screens (PSs) that carry information about random distribution of refractive index along the propagation path. Note that similar numerical approach is widely used to assess the effects of atmospheric turbulence on electromagnetic wave propagation (Deshpande et al., 2014; Knepp, 2005). Given the limited performance of machine calculations in ionospheric research, two-dimensional PWE in combination with multiple one-dimensional PSs was previously used to estimate ionospheric scintillations (Carrano et al., 2011). Due to low dimensionality of the method, the interpretation and applicability of the results was limited. To represent a realistic geometry in the case when the EMP propagation path through the ionosphere is several hundred kilometers and the AIs are obviously three-dimensional, it was proposed to use a three-dimensional PWE in combination with a series of two-dimensional PSs (Galiègue et al., 2017), which made it possible to refine the solution at the cost of significant increase of the calculation time.

A good alternative are statistical numerical methods like Monte Carlo (MC) technique which are actively employed in the wave propagation and energy transport problems. Monte Carlo method is based on repeated simulation of random ray trajectories and subsequent statistical processing and analysis of the results obtained. This method is used in various fields of atmospheric (Marchuk et al., 2013) and ionospheric (Kim, Yoon, Lee, Pullen, & Weed, 2017; Mountcastle & Martin, 2002; Schlegel, 1973) physics, optics of ocean (Leathers et al, 2004; A. Luchinin & Kirillin, 2017) and biological tissues (Kirillin et al, 2014; Yan & Fang, 2020). When applied to the problems of propagation of electromagnetic waves in randomly inhomogeneous media, the Monte Carlo method allows one to estimate the characteristics of signal amplitudes and phases after their scattering and absorption in a volume with random dielectric irregularities. Random medium can be defined by a set of irregularities with known sizes and refractive index variations, as well as by spatially distributed statistical characteristics of scattering and absorption. Flexibility in setting the medium properties provides an advantage for MC technique compared to analytical and semi-analytical modeling that requires information about the spectral correlation characteristics of the medium which is often

available only empirically. Another important point is that MC technique is successfully used to solve problems of propagation of ultrashort (similarly, UWB) pulses in randomly inhomogeneous media (A. G. Luchinin et al, 2019; A. G. Luchinin & Kirillin, 2021; A. G. Luchinin et al, 2024; Sergeeva, Kirillin, & Priezzhev, 2006).

The aim of the current paper is to present a methodology based on the Monte Carlo technique for modeling the propagation of a nanosecond EMP in the ionospheric plasma allowing to account for both the dispersion of the EMP in plasma and the effects associated with scattering on small-scaled field-aligned ionospheric plasma irregularities.

## 2 Model description

### 2.1 UWB EMP and ionospheric plasma model

Let us consider a plane linearly polarized electromagnetic wave with an electric field  $E_0(\tau = t - z/c)$  which propagates downwards along vertical direction coinciding the  $z$  axis through a plasma layer of total thickness  $Z_{layer}$ , where  $c$  is the speed of light in vacuum. We assume the nanosecond EMP of duration  $\tau_0$  is generated at the top of the layer in the plane  $z = 0$  and has a bipolar shape (Soldatov & Terekhin, 2016):

$$E_0(\tau) = H(\eta)H(1 - \eta)\eta(\eta - 0.5)(\eta - 1) \quad (1)$$

where  $\eta = \tau/\tau_0$  and  $H(\eta)$  is the Heaviside step function. In frequency domain, the shape of the initial EMP is characterized by spectrum  $\tilde{E}_0(f)$ :

$$\tilde{E}_0(f) = \int_{-\infty}^{\infty} E_0(\tau) \exp(-j2\pi f\tau) d\tau. \quad (2)$$

Complex amplitude  $\tilde{E}(f, z)$  of the signal harmonic the with the frequency  $f$  depends on the pathlength  $z$  in uniform plasma as follows:

$$\tilde{E}(f, z) = \tilde{E}_0(f) \exp\left(j \frac{z}{c} (1 - n(f))\right), \quad (3)$$

where

$$n(f) = \sqrt{1 - f_p^2/f^2} \quad (4)$$

is the refractive index in plasma with linear plasma frequency  $f_p$ . The latter is defined in CGS metric system as  $f_p = \sqrt{\frac{\rho_e e^2}{\pi m_e}}$  where  $e$  and  $m_e$  are the electron charge and mass, respectively, and  $\rho_e$  is the electron density (number of electrons per  $\text{cm}^3$ ) in uniform plasma.

We suppose the frequency spectrum of a nanosecond EMP propagating in ionosphere belongs to the range from tens MHz to several GHz. For frequencies exceeding the plasma frequency of the F-layer, we neglect the effects of collisions and typical features of wave propagation in the ionosphere located in the geomagnetic field such as the splitting of the dielectric constant for O-mode and X-mode, reflection of waves and their thermal dissipation.

Figure 1 shows the evolution of EMP shape after its propagation in uniform plasma layer with thickness of  $Z_{layer} = 30$  km and plasma frequency  $f_p = 5$  MHz calculated using Eq. (3), as well as the its spectrum. Due to dispersion, the shape of UWB EMP undergoes significant changes including shape distortion and considerable center of mass displacement. Pulse center of mass delay  $\langle \tau \rangle$  and pulse width  $\Delta \tau$  can be estimated numerically as:

$$\langle \tau \rangle = \int_0^{\infty} E^2(\tau) \tau d\tau / \int_0^{\infty} E^2(\tau) d\tau, \quad (5)$$

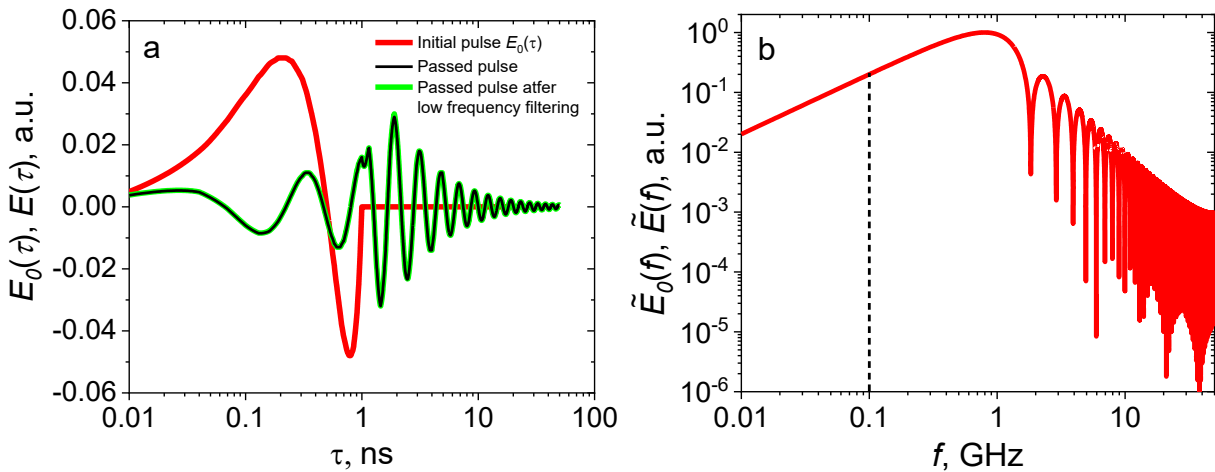
$$\Delta \tau = \sqrt{\int_0^{\infty} E^2(\tau) \tau^2 d\tau / \int_0^{\infty} E^2(\tau) d\tau - \langle \tau \rangle^2}. \quad (6)$$

For propagation in free space the pulse characteristics are  $\langle \tau \rangle = 0.5\tau_0$  and  $\Delta \tau \cong 0.29\tau_0$ . Note that even in the absence of Alls, dispersion along the path leads to an increase of the pulse delay and width by more than 10 times.

We consider the main effect of the pulse-plasma interaction associated with Alls and causing difference from propagation in uniform plasma consists in linear scattering of the harmonics as they pass through the refractive index irregularities. We characterize the Alls by reduced electron density  $\rho_{e, str} = \rho_e (1 - \delta)$ , where  $0 < \delta < 1$  is the relative density depletion within the irregularity. For each harmonic  $f$  of the EMP the refractive index  $n_{str}$  inside the irregularity can be achieved in the following form:

$$n_{str}(f) = \sqrt{1 - f_p^2(1 - \delta)/f^2}, \quad (7)$$

and meets the condition  $n(f) < n_{str}(f) < 1$ . Refractive index irregularities due to electron density depletion within Alls lead to the EMP scattering, and, consequently, to the additional modification of its shape which will be analyzed further within the framework of Monte Carlo simulation.



**Figure 1.** Shape of initial bipolar UWB EMP with duration of  $\tau_0 = 1$  ns calculated by Eq.(1) and its profile after propagation within a uniform plasma layer of the thickness of 30 km with plasma frequency  $f_p = 5$  MHz as well as the passed pulse profile after filtering the frequencies below 100 MHz (a); amplitudes of frequency spectrum of initial pulse (b).

## 2.2 Monte Carlo technique for modeling the UWB EMP propagation in ionospheric plasma with irregularities

Among methods that analyze propagation of electromagnetic radiation in a random medium, Monte Carlo technique implements the principle of wave-particle duality. A wave is presented as a bundle of rays where each ray defines propagation of a small section of the wave front. Random trajectory of each ray is simulated as a set of adjacent piecewise linear sections. The nodes at the connections of these sections are the points of the ray interaction with the scatterers. To consider the wave phenomena, each ray is assigned with the wave attributes, such as amplitude and phase, which vary depending on the particular ray trajectory in the medium.

### 2.2.1 Frequency domain approach

One of the advantages of Monte Carlo method in the problem of UWB EMP propagation in ionospheric plasma is its ability to evaluate the effect of AIs in a certain plasma layer on the scattering of the ray. In radiation transfer problems, Monte Carlo method can be implemented using one of the two most general schemes: (1) a classical scheme with random arrangement of scatterers when all scattering events are considered independent, and the position of each scatterer is determined at each step based on a priori given scattering and absorption parameters of the medium, and (2) a so-called “fixed particle Monte Carlo” (Xiong et al., 2005) in which the positions of the scatterers in the medium are defined in advance.

In the first scheme, the result of calculation is the average over various possible ensembles of scatterers, while the second scheme makes it possible to account for the characteristics of radiation propagation within the mean free path in a particular ensemble of scatterers. In this study, we used the first classical approach which allows one to obtain a result averaged over various ensembles leading to a more general solution compared to a particular solution obtained within the second approach.

Let us consider the implementation of Monte Carlo algorithm for modeling the ray trajectory of  $k$ -th harmonic  $f_k$  from the EMP spectrum defined by Eq. (2) in a layer of ionospheric plasma in the presence of AIs. Geomagnetic field aligned cylindrical striations (see Fig.2) are considered as a statistical ensemble of scatterers. For simplicity all irregularities are assumed to be of the same size but with a varying in-between distance. The input parameters for modeling are the harmonic frequency  $f_k$ , plasma frequency  $f_p$  corresponding to the average electron density value in the plasma layer, radius  $r$  of a single irregularity, mean ray free path (RFP)  $\langle l \rangle$  between two adjacent irregularities, depth  $\delta$  of relative electron density depletions within the irregularity, and thickness  $Z_{layer}$  of plasma layer containing striations. The properties of EMP after passing the plasma layer with striations are analyzed at the layer lower boundary

$z = Z_{layer}$ , which is called "detector plane". Detection area is divided into segments with center position  $(x_a, y_b)$  and size  $\Delta x \times \Delta y$  where  $\Delta x$  and  $\Delta y$  are dimensions along the corresponding axes.

Calculation is based on consequent tracking of  $N$  rays which travel from the origin through the plasma layer. Let  $i$ -th ray ( $i = 1...N$ ) corresponding to the harmonic with frequency  $f_k$  be assigned with a local scalar field:

$$E_{i,k}(x, y, z, \tau) = E_{0,k} \cos(2\pi f_k(\tau + z/c) + \varphi_{0,k} - \phi_{i,k}), \quad (8)$$

where  $E_{0,k}$  and  $\varphi_{0,k}$  are, respectively, the field amplitude and initial phase of the harmonic in the plane  $z = 0$ , and  $\phi_{i,k} = \phi_{i,k}(x, y, z)$  is the phase shift along the pathway in dependence on Cartesian coordinates. Local propagation direction is defined by three direction cosines  $(\gamma_x, \gamma_y, \gamma_z)$ . Random RFP between the two consecutive scattering events is calculated in accordance with semi-empirical concept of single scattering described by the Bouger-Lambert-Beer's law. It defines the average intensity  $I(z)$  of the non-scattered plane wave after passing the distance  $z$  in the scattering and non-absorbing medium as:

$$I(z) = I_0 \exp(-\mu_s z), \quad (9)$$

where  $I_0$  is the initial intensity and  $\mu_s$  is the scattering coefficient of the medium which is the inverse to the mean free path in the medium:  $\mu_s = 1/\langle l \rangle$ . In this connection, current RFP is calculated as follows:

$$l = -\ln(\xi)/\langle l \rangle, \quad (10)$$

where  $\xi$  is a random value uniformly distributed in the range  $(0,1]$ .

Interaction of the ray with each irregularity is considered within the framework of geometric optics approach under the assumption that the transverse size of the irregularity significantly exceeds the wavelength for all harmonics of a nanosecond EMP, which limits the lowest spectrum frequency. One iteration of a ray tracing cycle includes searching the intersection point of the ray trajectory with a cylinder, calculating reflection coefficient  $R_{ref}$  of the ray by the cylinder surface in accordance with the Fresnel law. Occurrence of reflection is defined by the condition:

$$\zeta < R_{ref}, \quad (11)$$

where  $\zeta$  is a random value uniformly distributed in the range  $(0,1]$ . If condition (11) is met, the ray direction changes in accordance with the reflection law, and a new RFP in the external medium is generated according to Eq. (10). If condition (11) is violated, refraction of the ray occurs. The ray changes its direction according to the Fresnel law and propagates through the irregularity to its far boundary, where the reflection test using condition (11) is performed again. Simulation of the ray propagation inside the irregularity is performed until a refraction event occurs at the cylinder-plasma boundary and the ray exits into the surrounding plasma. In this case, a new iteration begins by evaluation of the free path using Eq. (10). Iterations are repeated until the ray exits the boundaries of the medium or reaches the detector plane  $z = Z_{layer}$  which coincides with the lower boundary of the layer with irregularities. Output coordinates  $(x_i^{ex}, y_i^{ex})$  of the  $i$ -th ray in the detection plane are recorded together with the total phase shift  $\phi_{i,k}^{ex}$ :

$$\phi_{i,k}^{ex} = 2\pi f_k (n(f_k) L_{p,i} + n_{str}(f_k) L_{str,i}) / c, \quad (12)$$



where  $L_{p,i}$  is the total ray path in surrounding plasma and  $L_{str,i}$  is the total ray path inside irregularities.

At the final stage, averaging of field oscillations  $E_{i,k}(x^{ex}, y^{ex}, \tau) = \tilde{E}_{0,k}(f) \cos(2\pi f_k(\tau + Z_{layer}/c) + \varphi_{0,k} - \phi_{i,k}^{ex})$  of all rays reaching the detector plane  $z = Z_{layer}$  within the segment  $(x_a, y_b)$  is performed:

$$E_k^{ray}(x_a, y_b, \tau) = \sum_{i|x_a < x_i^{ex} < x_a + \Delta x, y_b < y_i^{ex} < y_b + \Delta y} E_{i,k}(x_i^{ex}, y_i^{ex}, Z_{layer}, \tau) / N. \quad (13)$$

It is assumed in Eq. (13) that the output direction of the ray does not change significantly with respect to the initial direction.

## 2.2.2 Frequency scattering map construction

To analyze the structure of the EMP in space and time, it is convenient to present the pulse by a discrete Fourier spectrum with a set of harmonics  $f_k = k/T$  ( $k = 1 \dots N_k$ ):

$$\tilde{E}_{0,k} = \frac{1}{T} \int_0^T E_0(\tau) \exp(-j2\pi f_k \tau) d\tau, \quad (14)$$

where  $T$  is the pulse record time. Previously described Monte Carlo simulation of ray propagation can be then performed for each harmonic  $f_k$  followed by summation for all harmonics within the detector segment  $(x_a, y_b)$ :

$$E^{pulse}(x_a, y_b, \tau) = \sum_k E_k^{ray}(x_a, y_b, \tau) = \sum_k \sum_{i|x_a < x_i^{ex} < x_a + \Delta x, y_b < y_i^{ex} < y_b + \Delta y} E_{0,i}^k \cos(2\pi f_k(\tau + Z_{layer}/c) + \varphi_{0,k} - \phi_{i,k}^{ex}). \quad (15)$$

For better visual representation of both effects of scattering and dispersion on the EMP propagation we propose to construct “frequency scattering maps” similar to construction of a point spread function. These maps illustrate the deviations of particular frequency harmonics from straight forward propagation due to scattering, and their arrival to a particular detector segment  $(x_a, y_b)$ . Such maps can provide a complete picture of the scattering role in ray deflecting from the straight forward propagation. We constructed the 2D map of minimal  $D_f^{min}$  and maximal  $D_f^{max}$  nonzero frequencies of the pulse discrete spectrum  $\tilde{E}$ :

$$D_f^{min}(x_a, y_b) = \min(f_k | \tilde{E}(x_a, y_b, f_k) > 0) \quad (16)$$

$$D_f^{max}(x_a, y_b) = \max(f_k | \tilde{E}(x_a, y_b, f_k) > 0) \quad (17)$$

To our knowledge, it is the first example of this approach in the analysis of spatial-spectral structure of EMPs in a plasma medium.

## 2.2.3 Simulation of plane wave

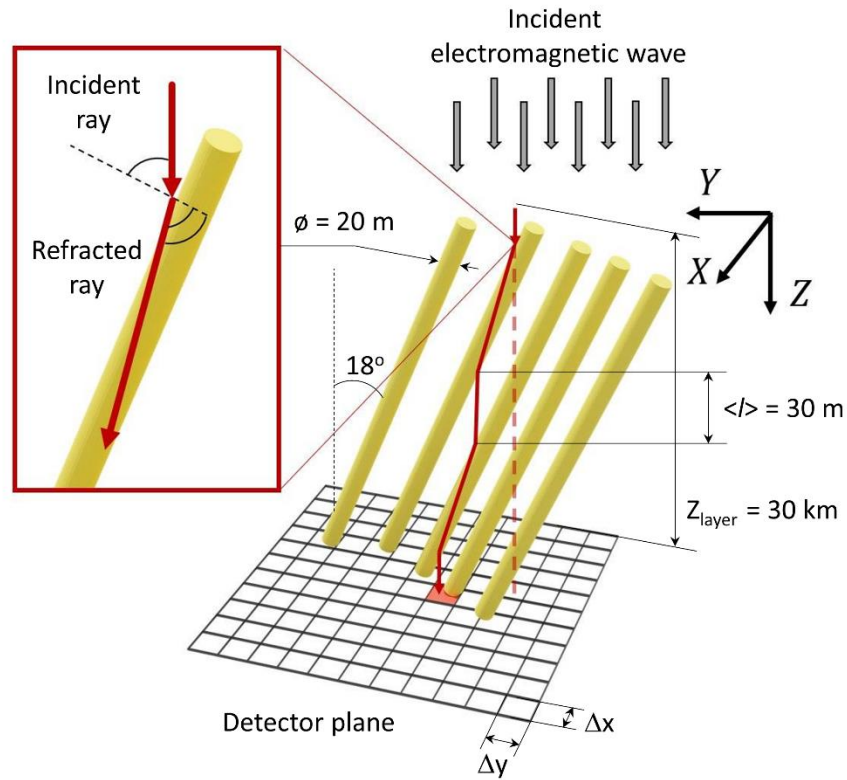
When the source is located at a fairly large distance from the ionospheric layer (significantly exceeding its thickness), the problem can be considered in the plane wave approximation. It means that electric field is transversely uniform in the plane of the layer boundary and the solution obtained for a single ray can be averaged over the detection plane. The solution for a plane wave can be obtained as follows:

$$\begin{aligned}
E^{planar}(\tau) &= \sum_{a,b} E^{pulse}(x_a, y_b, \tau) = \\
&= \sum_{a,b} \sum_k \sum_{i | \substack{x_a < x_i^{ex} < x_a + \Delta x, \\ y_b < y_i^{ex} < y_b + \Delta y}} E_{0,i}^k \cos(2\pi f_k(\tau + Z_{layer}/c) + \varphi_{0,k} - \phi_{i,k}^{ex}). \quad (18)
\end{aligned}$$

In the case of modeling a spherical wave, the effect of the shape of the spherical front can be accounted by modeling a set of rays with individual initial directions, initial phase shift and coordinates of the entry point into the layer based on an a priori given position of the source. Modeling with such initial parameters is carried out separately for each harmonic.

### 2.3 Problem statement

In this study, we considered propagation of an EMP in a layer of ionospheric plasma of thickness of  $Z_{layer} = 30$  km containing cylindrical irregularities with radius of  $r = 10$  m (Kelley et al., 1995) oriented at an angle of  $\alpha = 18^\circ$  relative to vertical direction which mimic striations formed under mid-latitude ionospheric heating conditions as in experiments with SURA heating facility. Average RFP between the irregularities was chosen as  $\langle l \rangle = 30$  m. Relative depth of electron density depletions within striations varied in the range of  $\delta = 5\% - 50\%$ . The largest values of  $\delta$  are hardly realistic, and used in simulations in demonstrative purposes only. Two values of electron density in unperturbed plasma were considered corresponding to plasma frequencies  $f_p = 5$  MHz and 10 MHz. The pulse duration  $\tau_0$  was assumed to be equal to 1 ns, its initial profile in the plane  $z = 0$  was given by Eq.(1). Typical trajectory of a ray propagating in the layer with the cylindrical irregularities is shown in Fig. 2. The number of random ray trajectories used in the simulations for individual harmonics varied in the range of  $N = 10^5 - 10^6$ . These values were chosen based on preliminary simulations and ensure the invariance of the key observables analyzed in this study, such as pulse delay or pulse width, with respect to the number of trajectories employed in simulations. Detector plane had the size of 4000 m in X direction and 160 m in Y direction, while the size of segments  $\Delta x$  and  $\Delta y$  are 1 m on default, and could be specified differently in separate cases.



**Figure. 2.** Schematic of the model: typical ray trajectory when scattering on ionospheric irregularities.

### 3 Simulation results

#### 3.1 Frequency spectrum of a nanosecond pulse in Monte Carlo simulations

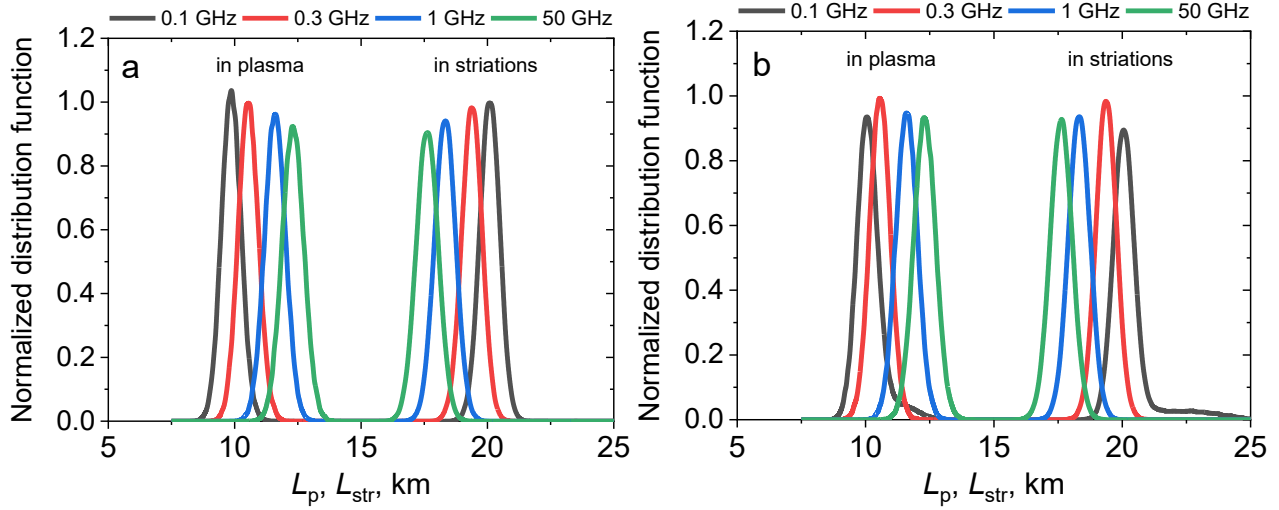
First, we have to define the number  $N_k$  of discrete Fourier spectrum harmonics employed in Monte Carlo simulations of UWB EMP propagating in plasma with striations according to Eq.(14). The shape of the initial 1-ns pulse given by Eq. (1) is shown in Fig.1 (a) while analytically calculated harmonic spectrum of the initial pulse and the pulse passing a layer of uniform plasma with plasma frequency  $f_p = 5$  MHz are shown in Fig.1(b). Lower frequency limit of 10 MHz is related to the pulse record time of 100 ns, while upper frequency limit of 50 GHz is caused by temporal resolution of the incident pulse which was taken as  $10^{-2}$  ns. Total number of counts used in analytical calculation is  $N_{\text{counts}} = 10^4$  yielding  $N_k = N_{\text{counts}}/2 = 5 \cdot 10^3$  harmonics required to compose the pulse.

In Monte Carlo modeling of the ray propagation in plasma with striations, several assumptions are made which put certain restrictions on the harmonic spectrum of the pulse. First, the transverse scale of striations is assumed large compared to the particular harmonic wavelength so that ray optics can be employed. In the case  $r = 10$  m this condition is met for frequencies not less than 100 MHz which means the first 10 harmonics in the range of 10-100

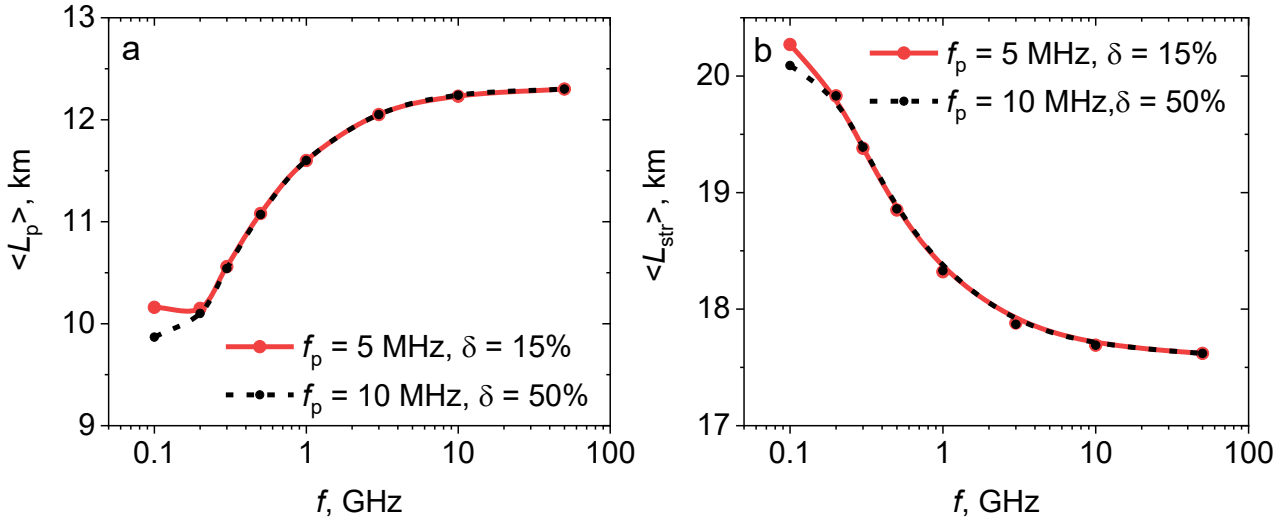
354 MHz should be withdrawn from the EMP spectrum. Fig.1(a) demonstrates the effect of low-  
 355 frequency filtering on the distortion of the passed pulse shape. The effect is rather minor and it  
 356 is almost negligible in the main body of the pulse in the range of 1-10 ns since the relative loss  
 357 of energy due to the withdrawn harmonics is below 0.2%. Another restriction comes from large  
 358 number of harmonics needed to be simulated for correct reconstruction of a scattered pulse  
 359 shape, which leads to intensive Monte Carlo modeling. In sub-GHz and GHz range the effect of  
 360 the ray refraction is mostly pronounced for lower harmonics while higher harmonics experience  
 361 less refraction. The question is in defining the domain of higher harmonics for which phase  
 362 delay can be evaluated analytically avoiding time-consuming Monte Carlo tracing.

### 363 3.2 Ray trajectories for different frequency harmonics

364 We considered tracing a single pulsed ray incident on a 30-km-thick layer of plasma in  
 365 the origin ( $x = 0, y = 0, z = 0$ ) and directed along Z axis. We simulated the ray propagation in the  
 366 plasma layer with plasma frequency  $f_p = 5$  MHz containing density irregularities with  $\delta = 15\%$   
 367 which corresponds to some observations (Kelley et al., 1995), as well as the layer with plasma  
 368 frequency  $f_p = 10$  MHz with the irregularities with  $\delta = 50\%$  which is beyond natural conditions  
 369 and is presented as a limiting case. Fig. 3 demonstrates normalized statistical distribution of ray  
 370 pathlengths in plasma ( $L_p$ ) and in striations ( $L_{str}$ ) registered in the whole detector plane  
 371  $z = Z_{layer}$  for four individual EPM harmonics with frequencies of 0.1 GHz, 0.3 GHz, 1 GHz and  
 372 50 GHz. In the case of small  $\delta$  (Fig. 3a) all distributions are Gaussian-shaped with peak position  
 373 and width depending on the harmonic frequency. Lower harmonics are characterized by  
 374 smaller pathlengths in plasma and larger pathlengths within irregularities, as well as by  
 375 narrower width of the distribution. In the case of large  $f_p$  and  $\delta$  (Fig. 3b) the pathlength  
 376 distribution function is asymmetric for lowest harmonics with noticeable contribution of large  
 377 pathlengths both in striations and in the surrounding plasma which describes wandering of the  
 378 ray due to multiple refractions. Dependence of average pathlengths  $\langle L_p \rangle$  and  $\langle L_{str} \rangle$  on the  
 379 frequency for both cases of  $(f_p, \delta)$  is plotted in Fig. 4 for eight harmonics within the range 0.1 –  
 380 50 GHz. Average pathlength increases in plasma with the harmonic frequency (Fig. 4a) while it  
 381 decreases within striations (Fig. 4b) thus showing the lowering effect of refraction in higher  
 382 harmonics. The curves  $\langle L_p \rangle$  and  $\langle L_{str} \rangle$  are almost identical for both cases of  $(f_p, \delta)$  except for  
 383 the region of smallest frequencies where the effect of large-path tail in the distribution for  $f_p =$   
 384 10 MHz and  $\delta = 50\%$  is evident. Asymptotic average pathlength at high frequencies is almost  
 385 the same for weak and strong electron density depletions and amounts about  $\langle L_p \rangle = 12.4$  km  
 386 and  $\langle L_{str} \rangle = 17.6$  km while their sum is equal to the layer thickness  $Z_{layer} = 30$  km.



**Figure 3.** Normalized distributions of total pathlength within plasma and striations of the EMP harmonics with the indicated frequencies for the parameters  $f_p = 5$  MHz,  $\delta = 15\%$  (a) and  $f_p = 10$  MHz,  $\delta = 50\%$  (b).

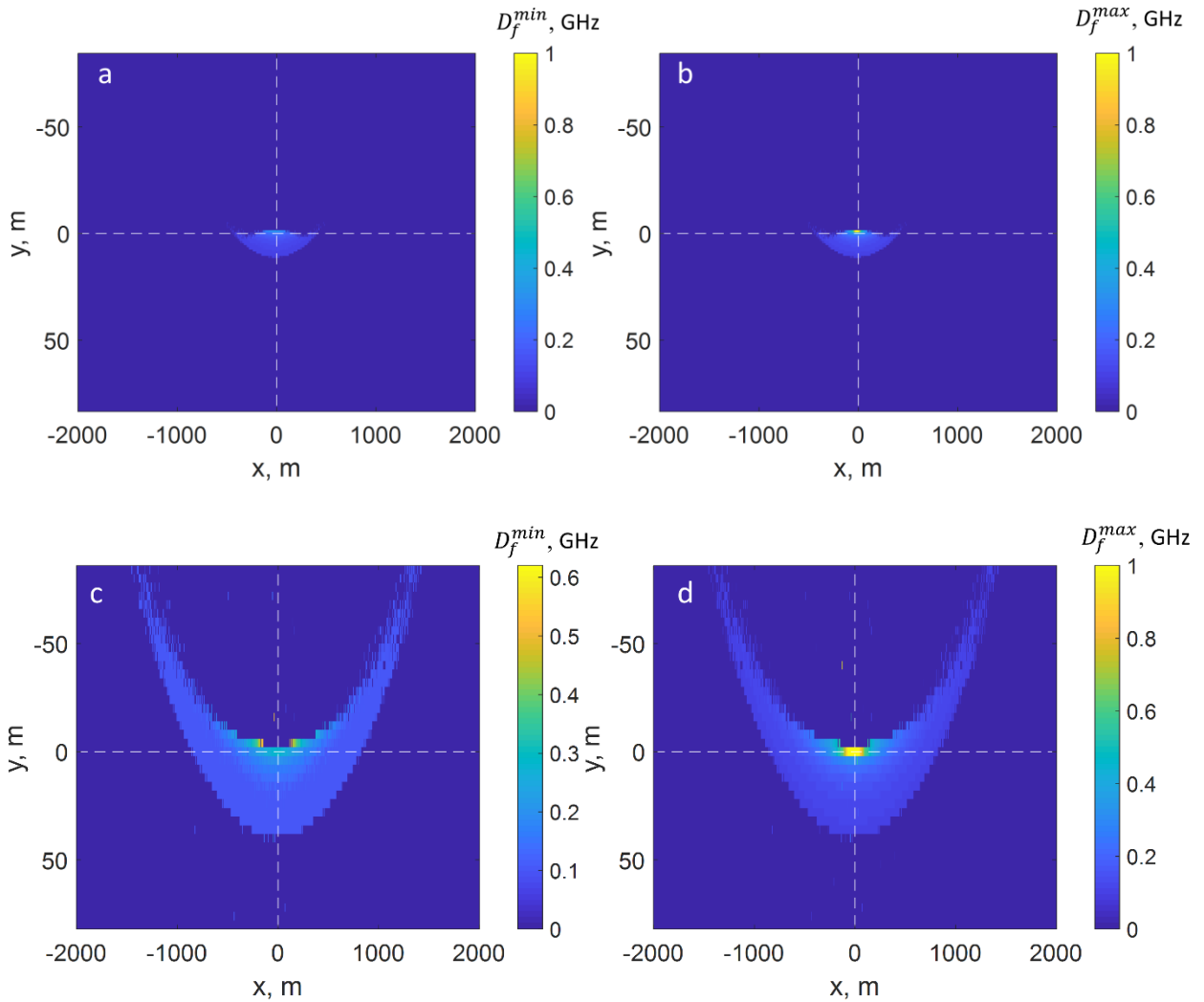


**Figure 4.** Average pathlength within background plasma (a) and striations (b) versus frequency for the parameters  $f_p = 5$  MHz,  $\delta = 15\%$  (a) and  $f_p = 10$  MHz,  $\delta = 50\%$  (b).

In Fig. 5 scattering maps of minimum  $D_f^{min}$  (Fig. 5a) and maximum  $D_f^{max}$  (Fig. 3b) frequencies from the UWB EMP discrete spectrum are shown. Spatial resolution in the maps is  $\Delta x = \Delta y = 1$  m both in the direction parallel to the projection of the cylinder axis onto the detector plane (Y axis), and orthogonal to it (X axis). The brightest spot in both maps covers central segment around  $(0, 0, Z_{layer})$  point of the detector plane in which all the harmonics of the non-refracted pulse should be observed. In the case of random refraction, lower frequencies deviate from straightforward propagation. The largest shift takes place for smallest

frequencies in the spectrum which is related to the maximum difference in the refractive indices  $n$  and  $n_{str}$  (see Eq.(4) and Eq.(7)). The anisotropy of the frequency distribution is due to the inclination of the irregularities at the angle of  $\alpha = 18^\circ$  with respect to vertical direction. Non-uniform displacement is observed along Y axis, i.e., in the direction parallel to the projection of the cylinder onto the detector plane, while in the orthogonal direction (along X) the distribution is symmetric due to random positions of the striations relative to the initial beam direction.

The  $D_f^{min}$  map (Fig. 5a) shows that all harmonics with frequencies less than 0.3 GHz experience a shift in Y direction, and, hence, the signal in the central segment of the detector, associated with the part of the pulse which passes through the medium without scattering, is composed of higher harmonics. The entire scattering region for all harmonics covers the range of  $\pm 500$  m along X-axis and less than 20 m along Y-axis. According to Fig. 5b, the highest harmonics deviate within the limits of one segment along Y direction with size of 1 m, and within  $\pm 20$  m along X axis.



**Figure 5.** Scattering maps of minimum  $D_f^{min}$  (a,c) and maximum  $D_f^{max}$  (b,d) nonzero harmonics of EMP discrete spectrum detected after propagation within 30-km-thick plasma layer with plasma frequency of  $f_p = 5$  MHz containing Alls with variation of electron density  $\delta = 15\%$  (a,b) and  $\delta = 50\%$  (c,d).

An increase of electron density depletions depth leads to the increased scattering of EMP. Figures 3c,d show frequency scattering maps for the case of  $\delta = 50\%$  corresponding to intense irregularities. Typical size of the scattering region increases up to 120 m along Y direction, and up to  $\pm 3000$  m in X direction.  $D_f^{min}$  map (Fig.5c) shows that higher harmonics (up to 0.6 GHz) experience stronger deviation compared to the case of weaker irregularities,  $\delta = 15\%$ , (Fig. 5a) where deviation was observed for frequencies below 0.32 GHz only.

Detailed analysis of zoomed-in central parts of  $D_f^{max}$  maps (Figs.5b and 5d) shows that maximum frequencies which deviate from the central detector segment of the size  $1 \times 1$  m<sup>2</sup> are below 10 GHz. This allows limiting the modeling of propagation of different harmonics by frequencies in the range of 100 MHz - 10 GHz with the step of 10 MHz. Phase delay of higher harmonics with frequencies in the range 10-50 GHz propagating in plasma with striations will can be estimated using asymptotic average path lengths  $\langle L_p \rangle$  and  $\langle L_{str} \rangle$  and asymptotic dispersion relation used in high-frequency approximation (Soldatov & Terekhin, 2016):

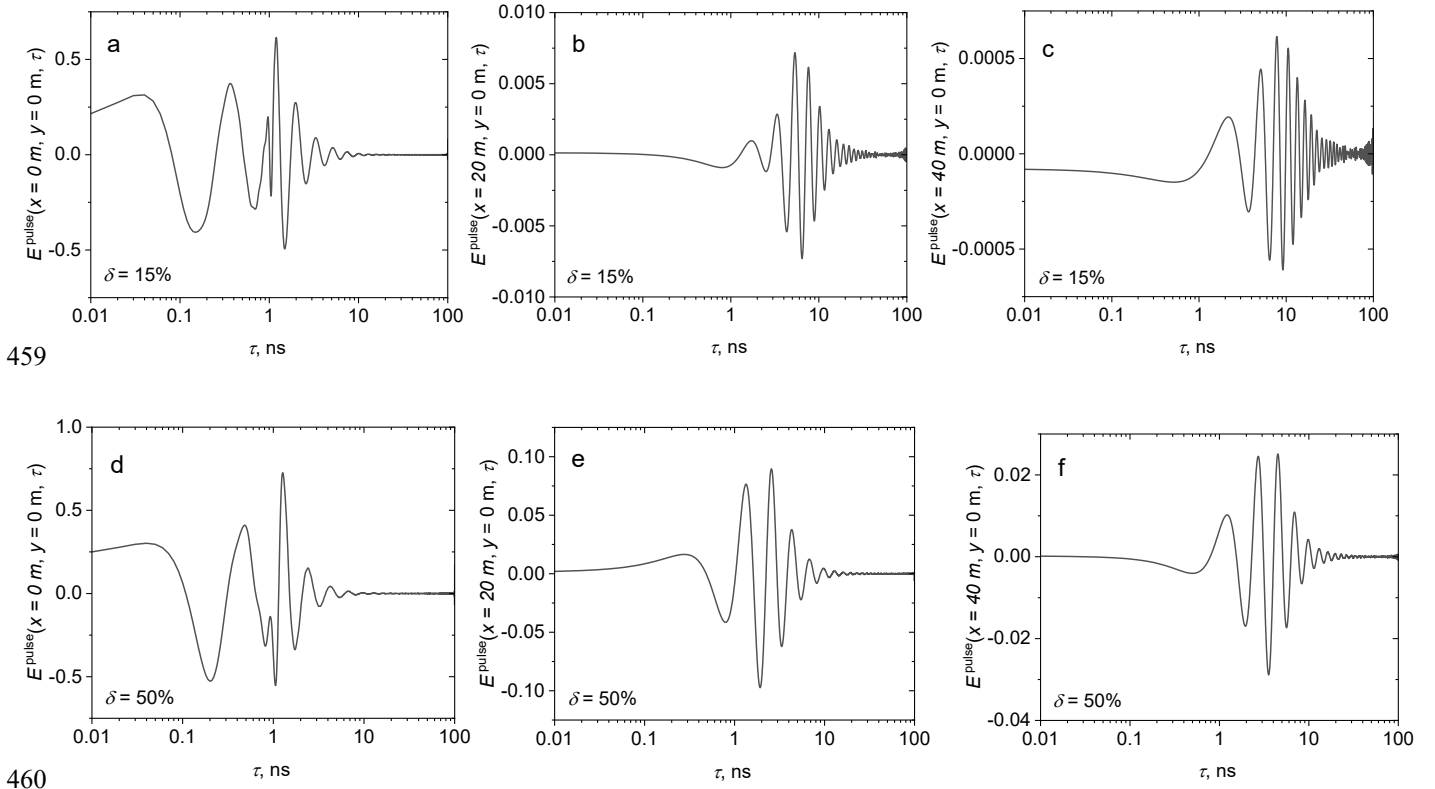
$$\phi_k^{ex} \cong \frac{2\pi f_k}{c} \left( Z_{layer} - \frac{f_p^2}{2f_k^2} (\langle L_p \rangle + (1 - \delta) \langle L_{str} \rangle) \right) \quad (19)$$

The number of harmonics in MC simulations can be thus 5 times reduced, from 5000 to less than 1000.

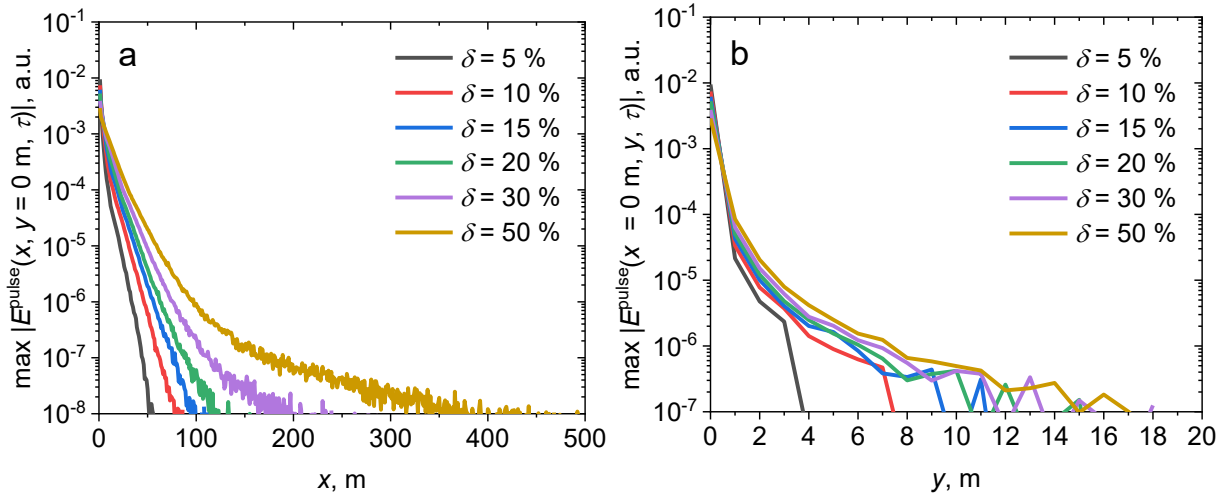
### 3.3 Scattered pulse profiles and characteristics

Figure 6 shows the waveforms of partial pulsed signals  $E^{pulse}(x, y, \tau)$  detected by different segments of the plane  $z = Z_{layer}$ . For weaker scattering with  $\delta = 15\%$  the detector segments have size  $1 \times 1$  m<sup>2</sup> (Fig. 6a-c); for stronger scattering with  $\delta = 50\%$  the segment size is  $4 \times 4$  m<sup>2</sup> (Fig. 6d-f). The waveforms are presented in a central segment of the detector plane (Fig.6a, d) and size  $1 \times 1$  m<sup>2</sup> (Fig. 4a) and  $4 \times 4$  m<sup>2</sup> (Fig. 6d) which fully collects the pulse in the case of uniform plasma, as well as by the segments of the same size shifted along X axis at distances of 20 m (Fig. 6b, e) and 40 m (Fig. 6c, f). The waveforms of partial pulses are composed according to Eq.(15) with account for all harmonics arriving at a defined detection segment, and are plotted versus the time variable  $\tau = t - Z_{layer}/c$ . The figure demonstrates that the pulse waveform detected in the central segment and therefore composed of a large number of harmonics differs considerably from that in the shifted segments where the signal is formed by scattered harmonics at low frequencies predominantly. An attenuation of the signal amplitude as well as the delay of the pulse center of mass are observed with the increase of the transverse shift. Figure 7 presents dependences of the scattered pulse amplitudes  $\max(|E^{pulse}(x, y, \tau)|)$  versus the shift along X axis (Fig. 5a) and Y axis (Fig. 7b) for three different values of  $\delta = 15, 30$ , and  $50\%$ . Amplitude decays nearly exponentially in X direction for up to 100 m (Fig. 7a) with the decay rates that decrease with the increase of  $\delta$ . Slow decay at

large distances is most pronounced for high  $\delta$  and is apparently related to deflection due to strong multiple refraction.



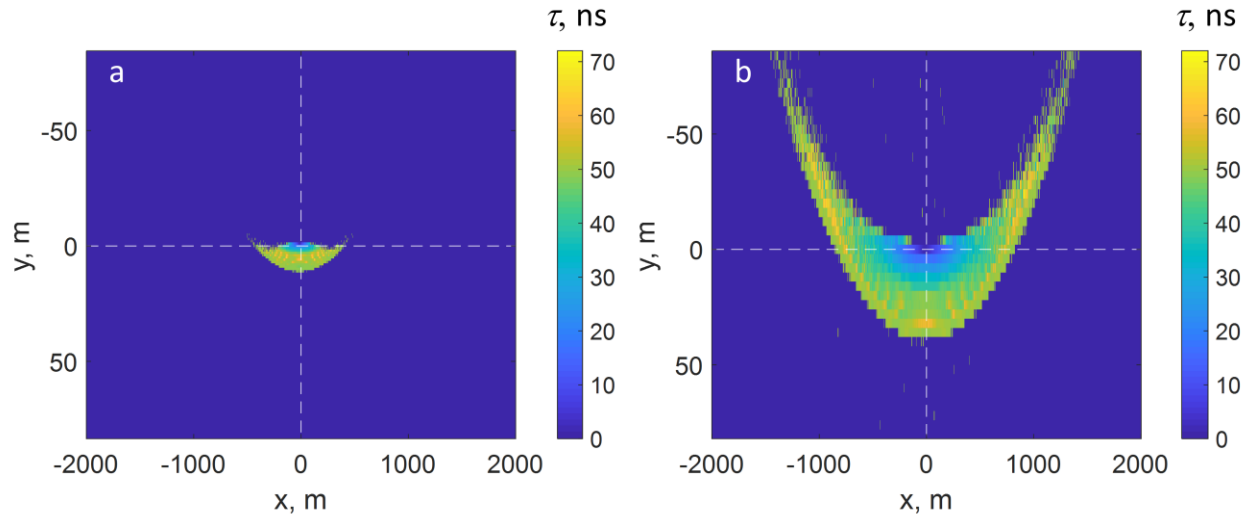
**Figure 6.** Partial pulses  $E^{\text{pulse}}(x, y, \tau)$  detected within the central segment (a,d) and segments shifted along X axis for 20 m (b,e) and 40 m (c,f) after the ray propagation in a 30-km-thick plasma layer with plasma frequency  $f_p = 5$  MHz in the presence of AIs with  $\delta = 15\%$  (a-c) and  $\delta = 50\%$  (d-f).





**Figure 7.** Dependence of the scattered pulse amplitude  $\max(|E^{pulse}(x, y, \tau)|)$  on transversal shift along X axis (a) and Y axis (b) after propagation in a 30-km-thick plasma layer with plasma frequency  $f_p = 5$  MHz in the presence of AIs for various values of electron density depletion  $\delta$ .

Study of average delays of the detected partial pulses is of particular interest. In Fig. 6 maps of average delay of partial pulsed signals  $E^{pulse}(x, y, \tau)$  calculated by Eq.(5) are presented for the cases of  $\delta = 15\%$  (Fig. 8a) and  $\delta = 50\%$  (Fig. 8b). Note that in the central part of the detection plane the case of  $\delta = 15\%$  (Fig. 8a) is characterized by larger delay values compared to the case of  $\delta = 50\%$  (Fig. 8b) for a given shift of the detection segment despite stronger scattering in the latter case with larger spreading of detected rays. It should be noted that typical delays are of few ns in the segments close to the central one, and can reach 72 ns at the periphery. A detailed interpretation of this phenomenon will be given in the next section devoted to the simulation of a plane wave propagation.



**Figure 8.** Delay maps of detected partial pulses after the ray propagation in a 30-km-thick plasma layer with plasma frequency  $f_p = 5$  MHz in the presence of AIs with values of electron density fluctuations  $\delta = 15\%$  (a) and  $\delta = 50\%$  (b).

### 3.4 Simulation of the propagation of a nanosecond pulse in the plane wave approximation

To expand the presented results on the case of plane-wave EMP propagation we employ the approach described by Eq.(18). For each harmonic, the electric fields detected within the whole detector plane  $z = Z_{layer}$  are summarized and then all harmonics are converted into a pulse. This simplified approach does not account for the effect of polarization change when calculating the net field. Such an assumption was previously made in (Soldatov & Terekhin, 2016) in a high-frequency limit. Being convenient, it yields an approximate pulse structure with overestimated net amplitudes of the harmonics. In our study, the influence of polarization change at the boundaries of striations may be significant for lower frequencies. However,

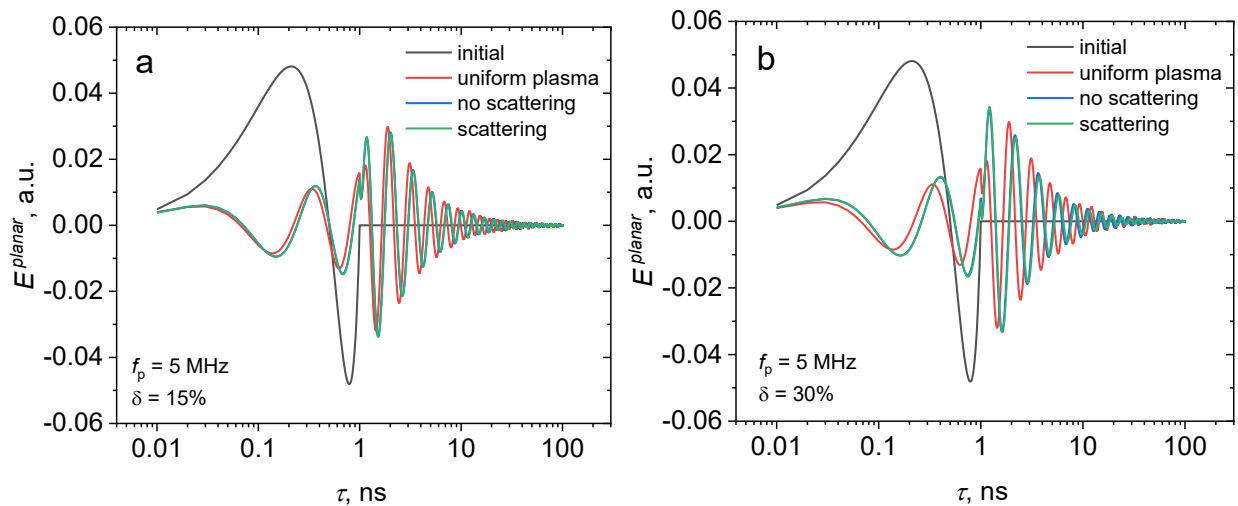
preliminary analysis in the frames of geometrical optics shows that depolarization of radiation (polarization vector rotation for linearly polarized field) due to scattering on irregularities is of the same order as the angular spread of wave vectors  $\theta_k$  of the rays arriving to the observation point. This statement can be easily verified by considering the incidence of a beam on a flat boundary of two isotropic media. The greatest angle of rotation of the electric field intensity vector will be observed in the case of a TM wave, and it will be equal to the angle of rotation of the wave vector. In the case of a TE wave, the electric field vector will not rotate at all. The magnitude  $\theta_k$ , in its turn, can be evaluated from scattering maps (Fig.5) as  $\Omega_k \approx 0.05 - 0.1$  for lower harmonics. Therefore, the effect of polarization change can be omitted at the current step, while the results obtained under the stated assumption can be considered as a reference for future detailed findings.

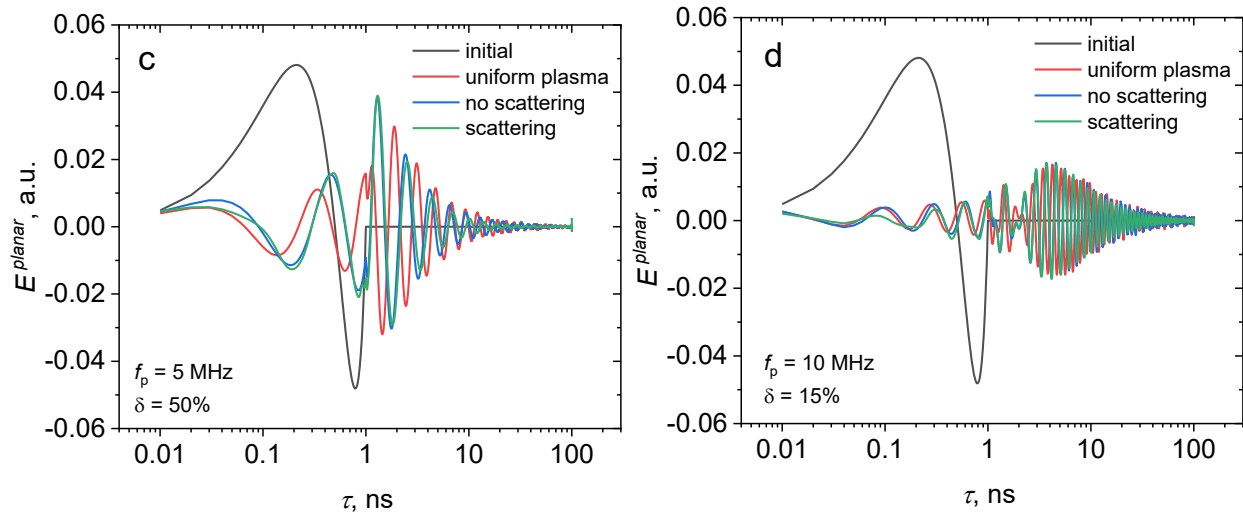
To demonstrate the effect of random striations on the pulse waveform, we compared two models of electron density distribution with depletion. First model is attributed as “no scattering” where plasma is considered as a uniform medium with an effective refractive index:

$$n_{eff}(f) = \frac{\langle L_p \rangle n(f) + \langle L_{str} \rangle n_{str}(f)}{Z_{layer}} = \frac{1.24n(f) + 1.76n_{str}(f)}{3} \quad (20)$$

Propagation of all the harmonics in such medium is considered straight-forward with the phase shift calculated in accordance with Eq. 15. Another model is attributed as “scattering”, and describes the pulse propagation in plasma with cylindrical irregularities simulated by Monte Carlo technique in accordance with Section 2.2.4.

The results of modeling the pulse transformation in the plane wave approximation are presented in Fig. 9a-c for background plasma frequency  $f_p = 5$  MHz and different values of  $\delta$ . For reference, the waveforms of the EMP propagating in uniform plasma (attributed as “uniform plasma”) are shown. The presence of irregularities leads to the distortion of the EMP waveform which becomes stronger with the increase of  $\delta$ . It is worth noting that the pulse waveforms in uniform plasma differ from those in plasma with density distortions both for “no scattering” and “scattering” cases. The difference between the latter two cases also grows with the increase of  $\delta$  value, which is most clearly seen from Fig. 9c for  $\delta = 50\%$ .





**Figure 9.** Waveforms of a plane wave EMP  $E^{planar}(\tau)$  after propagation in a 30-km-thick plasma layer with background plasma frequency  $f_p = 5$  MHz for uniform plasma (“uniform plasma”), in a medium with effective refractive index depending on electron density fluctuations (“no scattering”), and in plasma with AIs (“scattering”) for electron density fluctuations  $\delta = 15\%$  (a),  $30\%$  (b),  $50\%$  (c), and  $\delta = 15\%$  with  $f_p = 10$  MHz (d). Initial EMP waveform is given as a reference.

Figure 9d shows the results of the EMP waveform simulations for the case of high background plasma frequency  $f_p = 10$  MHz when the refractive index dispersion is more pronounced. This case is manifested by larger overall delays of the pulse body compared to the case of  $f_p = 5$  MHz. As it seen from comparison of the EMP waveforms in Fig.9a and Fig.9d for the same  $\delta$  but different  $f_p$  values, dispersion has greater impact on the pulse shape compared to scattering effects.

The results of calculating the delays of the EMP center of mass by Eq.(5) are presented in Fig. 10a. Starting point of the plot is a relative delay for a pulse in uniform plasma given as a reference and indicated as “ $\delta = 0$ ”. The figure shows data for both models of density distributions (“no scattering” and “scattering” cases). In “no scattering” model, a delay of the EMP center of mass decreases with the increase of  $\delta$ , which is explained by the fact that refractive index  $n_{str}$  tends to 1 with the growth of  $\delta$ . As a result, average refractive index of the medium also becomes closer to 1 resulting in smaller effect of dispersion. What is worth noting is that the presence of scattering additionally reduces the EMP delay. This is expectable for a plasma-type medium with a refractive index below unity since larger propagation paths of scattered waves give an additional phase delay. As a result, larger propagation paths partly compensate the dispersion. This effect is especially pronounced for smaller frequencies, for which the refractive index  $n$  is smaller, however, scattering is also stronger. Moreover, scattering seems to play a more significant role in dispersion compensation for larger  $\delta$  as compared to “no scattering” case. The effect of scattering can also be illustrated by the delay maps (Fig. 8) which show angular spreading due to scattering. Curves for  $f_p = 5$  MHz and  $f_p = 10$  MHz demonstrate similar systematic decrease of  $\langle \tau \rangle$  in the presence of irregularities compared

to the case of EMP propagation in a uniform plasma with effective refractive index. For higher value of  $f_p$  a decrease in  $\langle \tau \rangle$  is more apparent.

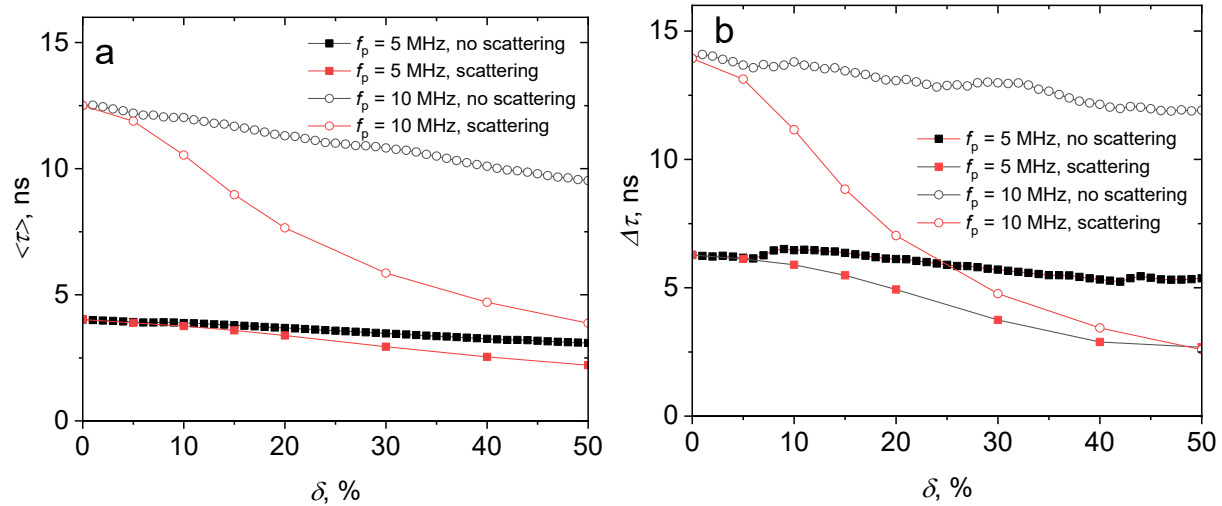


Fig. 10. Center of mass delay with respect to EMP propagation in free space (a) and pulse width of the pulsed plane wave (b) scattered in a 30-km-thick plasma layer with background plasma frequencies  $f_p = 5$  and 10 MHz in the presence of Alls with different values of  $\delta$ : cases of uniform plasma with effective refractive index (no scattering) and plasma with random cylindrical irregularities (scattering).

Dependences of the pulse width  $\Delta \tau$  versus the value of  $\delta$  calculated by Eq.(6) are shown in Fig. 10b for both low and high plasma frequencies and demonstrate trends similar to those observed for  $\langle \tau \rangle$ . This figure also confirms that the presence of the refractive index irregularities can partly compensate dispersion effects and diminish pulse widening. As density depletions become deeper with the growth of  $\delta$ , scattering plays more significant role in compensation of EMP broadening due to the dispersion.

#### 4 Discussion and Conclusions

In this study, a methodology based on the Monte Carlo technique was developed for modeling the linear propagation of a nanosecond electromagnetic pulse (EMP) in ionospheric plasma in the presence of field-aligned depleted density irregularities, which are similar to well-known striations stimulated by HF heating experiments. By employing individual ray tracing approach, this technique allowed to analyze the effect of scattering by the irregularities on lower and higher frequency harmonics of the EMP for different electron densities corresponding to typical plasma frequencies from 5 MHz to 10 MHz. Due to the specific orientation of the irregularities the scattering is anisotropic and is elongated in the direction transversal to irregularities axis projection on the lower boundary of the layer with density irregularities. The harmonics below 0.3 GHz deviate from the initial direction for more than 1 m within a 30-km path, while harmonics above 10 GHz experience almost no deviation. Simulation

of a plane wave propagation demonstrated two competing phenomena affecting the structure of the outgoing EMP. On the one hand, the scattering leads to energy loss in the straightforward pulse. On the other hand, average refractive index of the medium with the irregularities increases with respect to that of basic plasma leading to partial compensation of dispersion. The pulse delay and its width decrease with the increase of the electron density variation within irregularity indicating stronger role of the former phenomenon.

The results obtained are valid within the framework of the simplifying assumptions made, which should be recalled.

First, the approximation of a collisionless and cold background plasma in a uniform magnetic field on a scale of about 30 km is used, which seems to be valid for the conditions of propagation of GHz-range signals (including bipolar nanosecond EMPs) in F2-layer of mid-latitude ionosphere. Plasma frequencies (5 – 10 MHz) and corresponding background plasma densities chosen for simulations ( $\rho_e = 3 \times 10^5 - 10^6 \text{ cm}^{-3}$ ) are quite typical for F2-layer near its maximum.

Second, the ionospheric irregularities are represented by a system of randomly located, field-aligned, cylindrical plasma depletions with sharp boundaries, having the same diameter (20 m) and the same level of perturbation of the electron density relative to the background value (from 5 to 50 percent). In fact, we are considering irregularities of the smallest diameter (according to (Kelly et al., 1995)), the level of density perturbations in which varies from those measured in the experiment (approximately 10 percent) to unrealistically high values. The length of irregularities (30 km in vertical projection) is chosen to be the maximum possible under the conditions of the ionospheric heating experiment. Such irregularity parameters should correspond to the strongest scattering effects for GHz-range radiation.

Third, the propagation of an EMP in the form of a quasi-plane electromagnetic wave at an angle of 18 degrees to the magnetic field direction, which corresponds to vertical ionospheric propagation in mid-latitudes, i.e. around the geographical location of the SURA heater. The aperture at which the EMP shape is reconstructed in the presence of density irregularities is of the order of several kilometers, which is sufficient to collect the overwhelming majority of signals scattered by the irregularities in forward direction. Taking into account the spherical shape of the EMP front propagating from a finite-sized source may yield additional effects, but their discussion is beyond the scope of this paper and will be conducted separately.

Forth, when simulating the pulse shape after interaction with the irregularities we calculate the phases of separate rays and frequency harmonics, but without taking their polarization into account.

When considering the EMP shape for scattering by irregularities, we excluded frequency harmonics below 100 MHz from the analysis. For these harmonics (specifically, from 10 to 100 MHz), scattering by density striations is no longer described by the geometric optics approximation. At the same time, these harmonics might be strongly scattered by irregularities and the plasma is transparent for them, therefore, additional grounds are needed to exclude them from analysis. Here, on the one hand, it is necessary to point out once again their

extremely small share in the full spectrum of the pulse: less than 0.2 percent in energy. The second significant reason for excluding these harmonics from consideration is the properties of radio wave propagation in the ionosphere with a realistic (non-uniform in height) profile. Indeed, when propagating from the EMP source in the direction of increasing plasma density in the F-layer, spectral harmonics whose frequency is only a few times higher than the maximum plasma frequency will experience strong refraction. Even without irregularities, low-frequency harmonics will drift away from the main high-frequency rays for any finite angle of the ray direction other than strictly vertical propagation. Each act of scattering by an irregularity should lead to a significant deviation of the ray path from the original direction. Furthermore, such harmonics will also experience more pronounced backscattering on irregularities than high-frequency ones. As a result, in addition to their low spectral weight, these harmonics will be further filtered out due to the properties of electromagnetic waves' propagation in ionosphere. As a result, the exclusion of harmonics in the 10-100 MHz range from the analysis of EMPs has, in our opinion, significant physical grounds.

Of course, real density striations in heating experiments are characterized by complex statistics, i.e. they have a spread in length, transverse dimensions, depth, as well as various features of spatial distribution, including clustering. At the same time, from elementary geometric-optical analysis it is obvious that the wider the irregularities and the greater the distance between them, the lesser the scattering effects and their influence on the EMP shape. In this sense, the parameters we selected correspond to the narrowest (~10 m) and deepest density irregularities that can be realized, which lead to the strongest scattering effects. We believe that accounting for the spread of irregularities in transverse dimensions or space positions will only further weaken the influence of irregularities on pulse characteristics, which is already small.

In general, field-aligned density depletions from 10% (a realistic estimate) to 50% (an overestimate) from the background value and a diameter of about 10 m do not have a significant effect on the EMP shape, which is distorted to a much greater extent due to frequency dispersion. Of course, this result requires clarification in further studies – both in terms of taking into account the effects of radiation depolarization on irregularities, and in terms of taking into account the finite radius of curvature of EMP wave front. However, at this stage it is clear that in the approximation of a plane wave of small amplitude propagating in a cold collisionless plasma, one should not expect a significant influence of scattering effects on the amplitude-temporal and spectral characteristics of EMP in the frequency band of about 1 GHz and above.

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## Data Availability Statement

The simulations data are available at <https://doi.org/10.5281/zenodo.16687403> [Kirillin 2025].

## Conflict of Interest

The authors have no conflicts to disclose.

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