Dear Professor Song,

The authors are grateful to the Reviewers for their careful examination of our manuscript and valuable comments enabled us to significantly improve its quality. We especially appreciate the methodology improvement suggestions, which stimulated us to completely rearrange the manuscript figures.
Please, find below the response to the Reviewers' comments. The original text of the referees' comments is marked as **bold**.
Corresponding changes in the manuscript are labeled with yellow color.

Reviewer #1 (Formal Review for Authors (shown to authors)):

The manuscript "Monte Carlo simulations of nanosecond electromagnetic pulse interaction with field-aligned ionospheric plasma density irregularities" by M. Kirillin et al. presents the results of statistical modeling of the ultra-wideband electromagnetic pulse propagation in ionosphere with magnetic field-aligned irregularities of plasma density. The modeling methodology is mainly based on the concepts of ray optics, which is to a certain extent justified based on the considered relationships between the wavelengths of the harmonics that form the pulse and the characteristic size of the inhomogeneities. A feature of the modeled ionospheric layer is its essentially anisotropic nature, due to the same tilt angles of the model striations with respect to the vertical direction. This feature leads to the formation of symmetrical spatial distributions of the simulated electromagnetic field ("scattering maps") in the detection plane. In my opinion, the results obtained may be of significant interest to the community of researchers and engineers specializing in the field of ionospheric radiophysics. The analysis of key works related to the subject, carried out in the introduction, is of an appropriately high level and allows readers to easily immerse themselves in the problem. In general, the submitted manuscript, in terms of its focus, the scientific level of the conducted research, and the novelty of the obtained results, meets the criteria for publication in the "JGR Space Physics". However, there are some comments that, if taken into account, will improve the quality of the publication.

We thank the reviewer for positive evaluation of our work.

1. Please carefully check the notations of physical quantities to avoid ambiguities. So, for example, in line 159, η is the dimensionless time in Eq. 1, and in lines 256-257, η is a uniformly distributed random variable.

We agree that using the same symbol for different values introduces ambiguities to the manuscript text. We have replaced the symbol for random variable to another Greek letter.

2. A small comment should be added to Eq. 12 to explain the effect of the electron density depletion in the inhomogeneity on its refractive index. It is clear to a specialist that the square of the plasma frequency is proportional to the electron density, but for a reader who is not familiar with the topic, the appearance of the factor (1 - δ) may raise questions. Also, the value of δ must be defined immediately after Eq. 12.

The following paragraph with the details on irregularities' parameters is added into Section 2.1. Equation 12 has been shifted into this section with the renumbering.

We consider the main effect of the pulse-plasma interaction associated with AIIs 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 AIIs by reduced electron density $\rho_{e,str} = \rho_e$ (1-δ) 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 AIIs 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.

3. It is recommended that the discussion of the results will contain an additional paragraph with a qualitative analysis of how the spread of the structural characteristics of inhomogeneities (their tilt angles and transverse dimension) will affect the obtained results (for example, scattering maps).

Definitely, real ionospheric irregularities vary greatly in size, depth, and other characteristics. Variations in the tilt (or inclination) of irregularities are not expected, since all irregularities, especially small-scale ones, should be oriented along the local magnetic field. Regarding transverse dimensions, in general, the wider the irregularities and the greater the distance between them, the lesser the scattering effects and their influence on the pulse shape. In this sense, the selected parameters correspond to the narrowest (~10 m) and deepest (20-50%) irregularities that can be realized according to direct measurement data (see, for example, Kelly et al., 1995), which lead to the strongest scattering effects. We suppose that the variations in the irregularities transverse scale will only weaken the observed effect on the pulse characteristics which is already small. Since the question posed is quite important, and it has been also raised by the second reviewer, we have added the relevant paragraph of the manuscript into the "Discussion" section.

Reviewer #2 (Formal Review for Authors (shown to authors)):

This work develops a Monte-Carlo, frequency-domain ray-tracing model for the propagation of a 1-ns ultra-wideband electromagnetic pulse through an ionospheric layer containing field-aligned density depletions (AIT-like striations). The authors reconstruct the time-domain pulse after scattering and compare it to propagation in uniform plasma and in an effective-index "no scattering" approximation. They find that scattering is strongly frequency-dependent (dominant at sub-GHz), anisotropic, and that for realistic AIT parameters, its net effect on the main pulse body is weak relative to dispersion.

The paper is publishable in the Journal of Geophysical Research - Space Physics. It is well written and methodologically engaging. The approach is novel for the ns-UWB + FAIs scenario, the implementation is clearly grounded in prior radiation-transfer MC practice, and the main physical conclusions are plausible. Improving the conclusion section by providing context and a validity-dominating statement will enrich the presentation of this work.

We thank the reviewer for positive evaluation of our work.

My primary concerns about this method are :
1. The geometric-optics restriction may remove the most strongly scattered part of the spectrum. The ray model requires striation radius (\gg \lambda), so the first 10 harmonics (10-100 MHz) are excluded. The authors argue that energy loss from this filtering is < 0.2% and negligible for the main pulse body. However, low frequencies are precisely where their results show the most significant scattering and path-length dispersion. Excluding them may underestimate:

a) The full delay spread / late-time coda,
b) Off-axis spectral redistribution,
c) Any low-frequency observational signatures relevant to diagnostics.
Even if total energy is tiny, phase-sensitive metrics can be affected. This limitation is fundamental and should be highlighted more strongly in the conclusions (and perhaps quantified with a sensitivity test).

Indeed, based on spectral analysis, we have excluded frequencies in the plasma transparency band ranging from the critical frequency (~10 MHz) to the lower limit at which the geometric optics approximation is valid for density depletions with a transverse scale of 10 m (~100 MHz). On a qualitative level, the reviewer is certainly correct. Exclusion of this part of the spectrum can be considered as a necessary limitation within the framework of the ray optics approximation used. We have included the relevant comments and clarifications in the revised version of the article.

At the same time, the small energy contribution of low-frequency components in the full spectrum is not the only reason for excluding this portion of the pulse spectrum from consideration. The fact is that, given a realistic ionospheric profile, smoothly nonuniform in altitude, in this frequency range (at frequencies only a few times higher than the maximum critical frequency), low-frequency harmonics will experience strong refraction and drift away from the pulse body. Furthermore, such components will also experience more pronounced backscattering on irregularities than high-frequency components. As a result, in addition to their low spectral weight, these harmonics will, in our opinion, be further filtered out due to the properties of the ionosphere. Additional estimates of the pulse delay and width in the absence of low frequencies showed the discrepancy of decimal of percent and units of percent, respectively, compared to full-spectrum case. Detailed comments on the matter have been added to the text.

2. Idealised irregularity and tailor-made ensemble (single-scale cylinders, Poisson spacing, constant Z_{layer} and <l>). All striations have identical radii and depletion depths, with random spacings drawn from a mean-free-path distribution. Real FAIs/AIT exhibit a spectrum of transverse scales and depths, intermittency, and sometimes clustering. A single-scale Poisson model might bias scattering low at higher frequencies if smaller-scale gradients exist. I suggest adding a short discussion estimating how a multi-scale spectrum (e.g., power-law transverse sizes) could shift the scattering-vs-frequency boundary. Additionally, what are the effects on the result of the variation of the Z_{layer} and <l>?

Similar comment has been discussed partially within the response to the first reviewer. Of course, real ionospheric irregularities vary greatly in size, depth and other characteristics. Regarding transverse dimensions, in general, the wider the irregularities and the greater the distance between them, the lesser the scattering effects and their influence on the pulse shape. In this sense, the parameters we have selected correspond to the narrowest (~10 m) and deepest (20-50%) irregularities that can be realized according to direct measurement data (see, for example, Kelly et al., 1995), which lead to the strongest scattering effects. We suppose that variations of the irregularities transverse scale will additionally weaken the influence of irregularities on the pulse characteristics, which is already small.

One-parameter Poisson spacing between the cylinders mimics the distribution of a free path in a classic problem of scattering within the frames of radiative transfer theory modeled by Monte Carlo approach. The spacing parameter refers to the mean free path between scattering events which, in its turn is a statistical parameter of scatterers spatial distribution that can be arbitrary complex.

We have added the relevant paragraph of text to the "Discussion and Conclusions" section.

3. Regarding the Open Research section, there is a link to the data used in the plots, but no software is available.

Unfortunately, we are unable to upload the software as it is not officially licensed, and our organizational policy prohibits this. We are happy to provide calculation results upon any reasonable request and hope that the lack of software will not prevent publication of this article. We hope that the description of the methodology in the manuscript is detailed enough to be implemented by other researchers using available instruments.

There are also two minor comments and presentation issues.

1. Clarify the robustness of Monte-Carlo convergence, stating explicitly whether key observables (e.g., central-segment delay, width) were checked for stability vs. N for at least one harmonic set.

The key observables were checked for stability vs N for the basic properties δ = 15%, f_{pl} = 5 MHz. The dependences of the resulting values of central-segment delay and width on the number of rays used for simulations are shown below. One can see that the chosen number of ray trajectories provides the key observables values invariant with respect to the number of trajectories in this range.

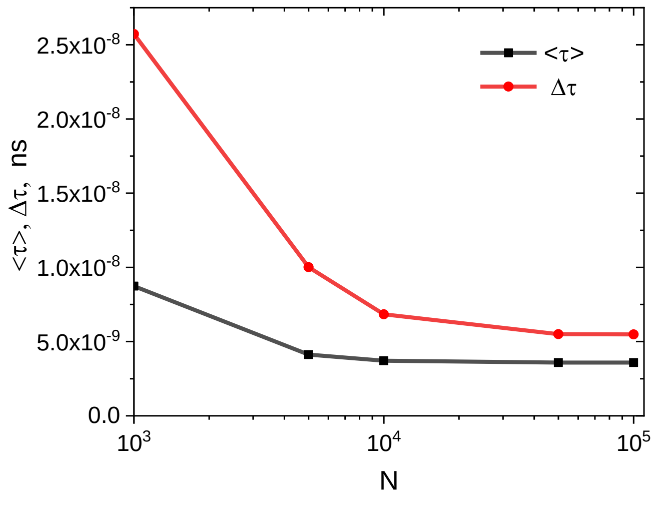

Figure R1. Dependence of the central-segment delay and pulse width of the number of ray trajectories employed in simulations.

The following clarification was added to the Materials and methods section:

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.

2. Provide a compact "validity domain" paragraph. The mentioned limitations are scattered throughout

Section 3.1 and later. A summary of frequency and geometry validity would be helpful to readers.

The results obtained are valid for a bipolar EMP of nanosecond duration, taking into account a number of model approximations, including: (a) the approximation of a collisionless, cold, quasi-uniform plasma in a uniform magnetic field on a scale of 30 km, (b) propagation of an EMP in the form of a quasi-plane wave at an angle of 18 degrees to the magnetic field, which corresponds to vertical ionospheric propagation in mid-latitudes; (c) the presence of a system of randomly located, field-aligned, cylindrical plasma depletions with sharp boundaries, having the same diameter (10 m) and the same level of perturbation of the electron density relative to the background value (5-50%). The problem of finding the pulse shape after interaction with the irregularities is solved in the geometric optics approximation taking into account phase effects, but without taking into account the polarization of frequency harmonics. Sub 100 MHz harmonics are neglected due to their high potential to be back-refracted from the major direction of the pulse which allowed to implement geometric optics approximation. Under the assumptions made, the selected parameters of the model correspond to the regime of EMP interaction with the smallest-scale and most intense striations that can occur during heating experiments, demonstrating the case where the effects of scattering and transformation of the EMP shape can be most pronounced.

The extended discussion of the validity domain clarifying in details all the point of the summary above is added to the revised manuscript to the "Discussion and conclusions" section.

This paper is novel and likely publishable with only modest changes. The main physical conclusion-dispersion dominates ns-EMP distortion, and realistic AIT striations weakly affect the GHz-band pulse-is acceptable within the stated assumptions, which should be stressed. Strengthening the discussion of geometric-optics cutoff, irregularity statistics, and polarisation neglect would substantially improve transparency and the paper's long-term value as a model.

We sincerely hope, that the introduced changes address all the comments and questions raised by the referees. We have also introduced additional changes to manuscript text that, we believe, improved its quality.

With kind regards,

Authors