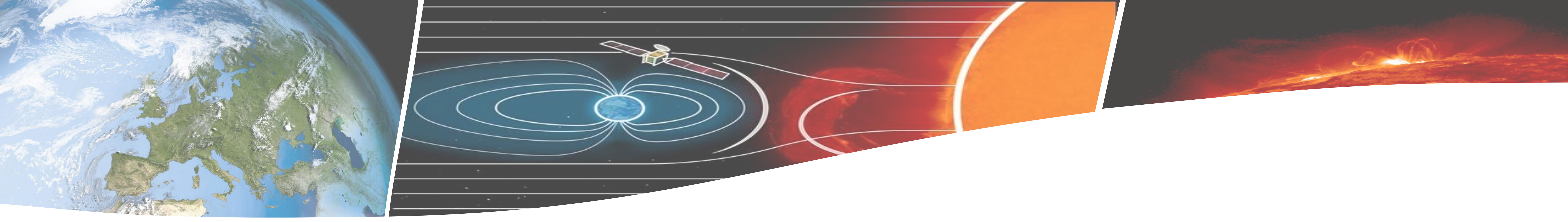

Phase gradient screen approach in modeling of ionospheric scintillation

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Motivation / Introduction

Multiple studies of scintillation events have shown that in certain situations the intense phase fluctuations of trans-ionospheric radio signals are associated with the scattering on strong electron density gradients. However, a theoretical understanding of this correlation is lacking. We propose a novel method of scintillation simulation that extends the conventional approach by including the next-order correction in the geometric-optics approximation for the propagating radio wave. In this way we are able to reproduce the patchy scintillation patterns due to refractive scattering at the edges of equatorial plasma bubbles, storm enhanced density regions, ionospheric trough boundaries, etc. In the current version of the algorithm we use the electron density gradient data from the Swarm satellite mission (NeGIX) to derive the empirical values of the ionospheric gradients.

Scintillation modeling

The conventional scintillation simulation techniques, such as split-step method and random phase screen approximation, are not able to reproduce the relationship between certain scintillation events and the presence of steep gradients in the ionosphere. This happens because these methods adopt approximative solutions for amplitude and phase of propagating radio-wave and neglect contributions of second-order smallness with respect to the fluctuating part of the medium refractive index. For example, such approach allows one to account for the random phase delay or advance due to the propagation in medium but discard such effects as random tilts of the wavefront. The latter effect however can be sufficiently large if the signal wave scatters on inhomogeneities with steep gradients of the refractive index.

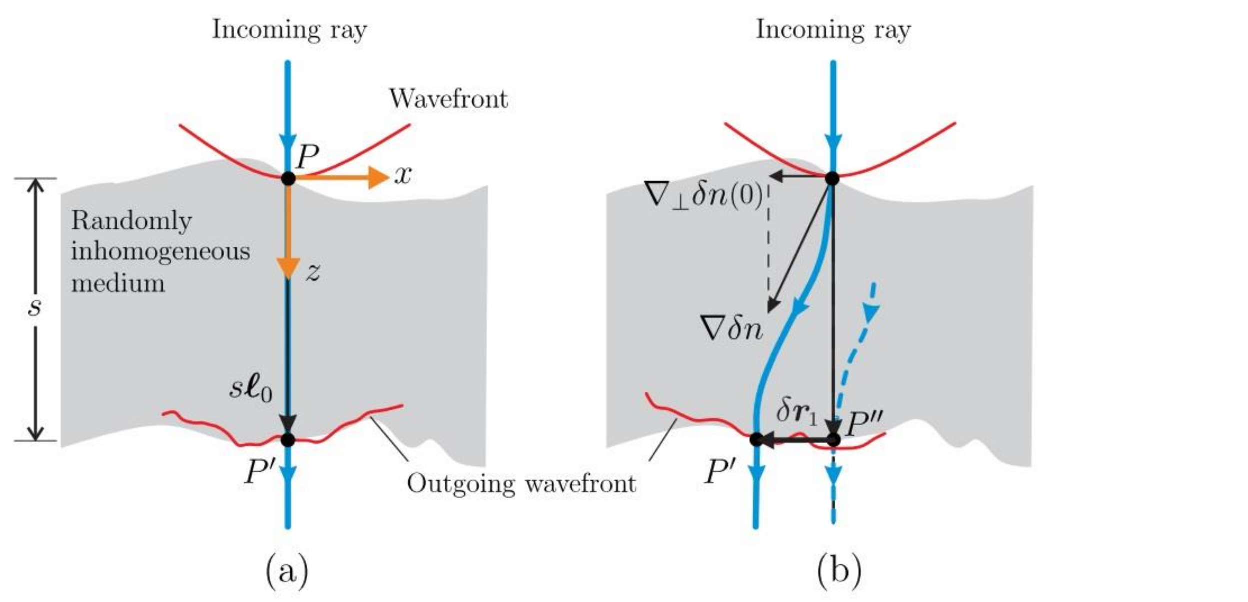
We extended the conventional random phase screen scintillation simulation algorithm with the aim to include second-order correction term derived within the formalism of geometrical optics. The resulting phase gradient screen realization is written as

$$\delta\varphi(s\,\vec{l}_0)= \delta\varphi\left(\left(s\,\vec{l}_0+\delta\vec{r}_1\right)-\delta\vec{r}_1\right)\approx \delta\varphi\left(s\,\vec{l}_0+\delta\vec{r}_1\right)-\delta\vec{r}_1\cdot\vec{\nabla}_{\perp}\delta\varphi\left(s\,\vec{l}_0+\delta\vec{r}_1\right).$$

Here $\delta\varphi\left(s\,\vec{l}_0\right)=\frac{2\pi}{\lambda}\int_0^s\delta n\left(\vec{r}_{\perp,P},z\right)dz=-\lambda\,r_e\int_0^s\delta N_e\left(\vec{r}_{\perp,P},z\right)dz$ is the realization of the conventional random phase screen, $\vec{l}_0$ is the initial propagation direction, s is the layer thickness, and

$$\delta\vec{r}_1\approx\frac{s^2}{2}\,\vec{\nabla}_{\perp}\delta n(0)=-\frac{r_e\,s^2\lambda^2}{4\pi}\,\vec{\nabla}_{\perp}\delta N_e(0)$$

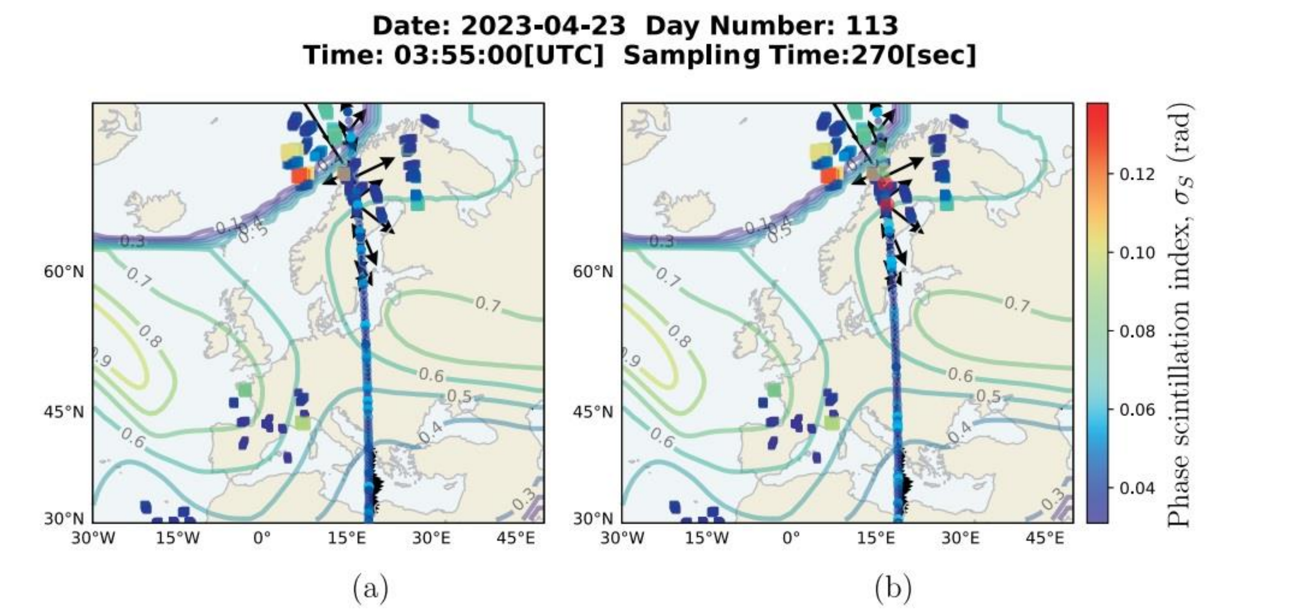
is the ray displacement vector that is proportional to the transversal gradient of the refractive index fluctuations $\vec{\nabla}_{\perp}\delta n$ (or the transversal gradient of the electron density fluctuations $\vec{\nabla}_{\perp}\delta N_e$). The displacement vector $\delta\vec{r}_1$ shows how strong the exiting wavefront is tilted, see figure below. One could also note that the term $\vec{\nabla}_{\perp}\delta\varphi$ can be rewritten in terms of the TEC gradient.



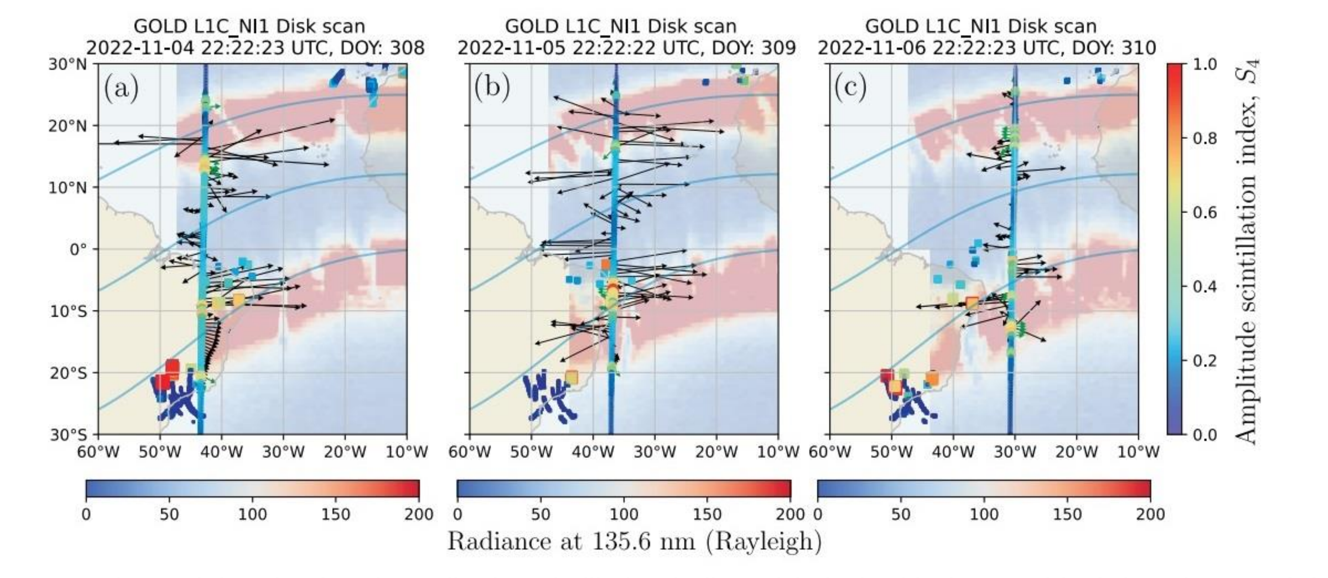
The conventional phase screen approach simulates the random corrugation of the incoming wavefront (a). The phase derivative screen adds the random refraction of the incoming signal ray (b).

Validation

For validation purposes, we use the NeGIX gradient index derived from electron density measurements on Swarm A and C satellites. The NeGIX provides the values for $\vec{\nabla}_{\perp}\delta N_e(0)$ in phase gradient screen simulation algorithm. The figures below show the results of the simulations (colored circles) superimposed on the distribution of the empirical indices (colored squares). By inferring the shape of equatorial plasma bubbles the GOLD mission images of atmospheric irradiance were used.



Comparison of simulated phase scintillation indices (colored circles along the orbit of the Swarm satellite) with the empirical values (colored squares) for L1 radio signals. Simulations are performed using the conventional random phase screen technique (a) and by using the phase gradient screens (b). The empirical values are obtained from several GNSS receivers located in Europe and their geographical locations are given by the position of their ionospheric piercing points. The black arrows correspond to the NeGIX vectors (arbitrary scale). For reference, the contours for the magnitude of the vertical TEC gradient (in units of mm/km on GPS L1) are also shown.



Comparison of the simulated amplitude scintillation indices (circles) with the empirical data (squares) for the low latitude region over Africa, the Atlantic Ocean, and South America. The scintillation data are obtained from GNSS receivers installed in San Paolo and Fortaleza (Brazil) and on the island of Teneriffa (Spain). As a reference to the possible plasma bubble shapes, the background image shows the atmospheric emission radiance obtained from the GOLD mission data. The green vectors represent the gradient values of the mask extracted from the GOLD images and the black vectors correspond to the Swarm NeGIX index.

Outlook / Conclusion

- We present the method of phase gradient screens for the simulation of the ionospheric scintillation phenomena. The method takes into account the 2nd order correction to the magnitude of a phase screen realization. It is able to account for the random wavefront shift due to refractive scattering on topside of the scintillation-producing irregular ionospheric layer. Such a correction term is proportional to the product of the TEC gradient and the electron density gradient.
- The correlation between the scintillation indices and the gradient-based indices, such as ROTI, RODI, DIX, AATR, etc., can be explained within the proposed approach
- We show that the phase gradient screen algorithm is able to reproduce patchy regions of enhanced scintillation associated with scattering on steep ionospheric gradients. The method performs well in high and low latitude regions.

References:

Vasylyev, D., Béniguel, Y., Wilken, V., Kriegel, M., Berdermann, J., Modeling of ionospheric scintillation, JSWSC, **12**, 16, 2022

Vasylyev, D., et al., Scintillation modeling with random phase gradient screens (in preparation)

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