

USE OF THE SWARM IONOSPHERIC GRADIENT PRODUCT TO MODEL SCINTILLATION AT HIGH LATITUDES

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Vienna, Austria
24 June 2025



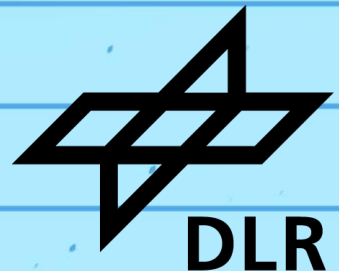
DLR Neustrelitz
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Space WeatherImpact Department



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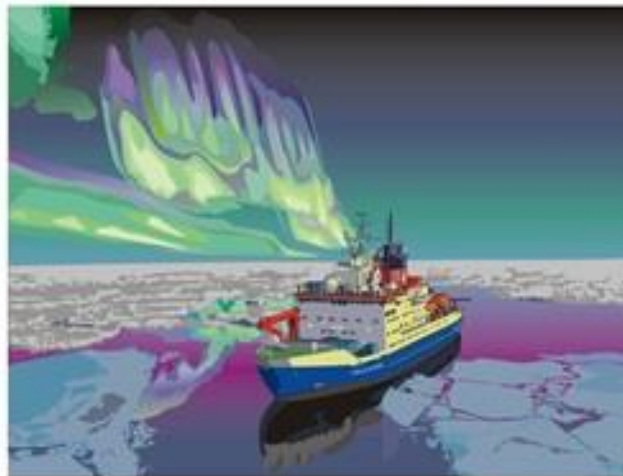
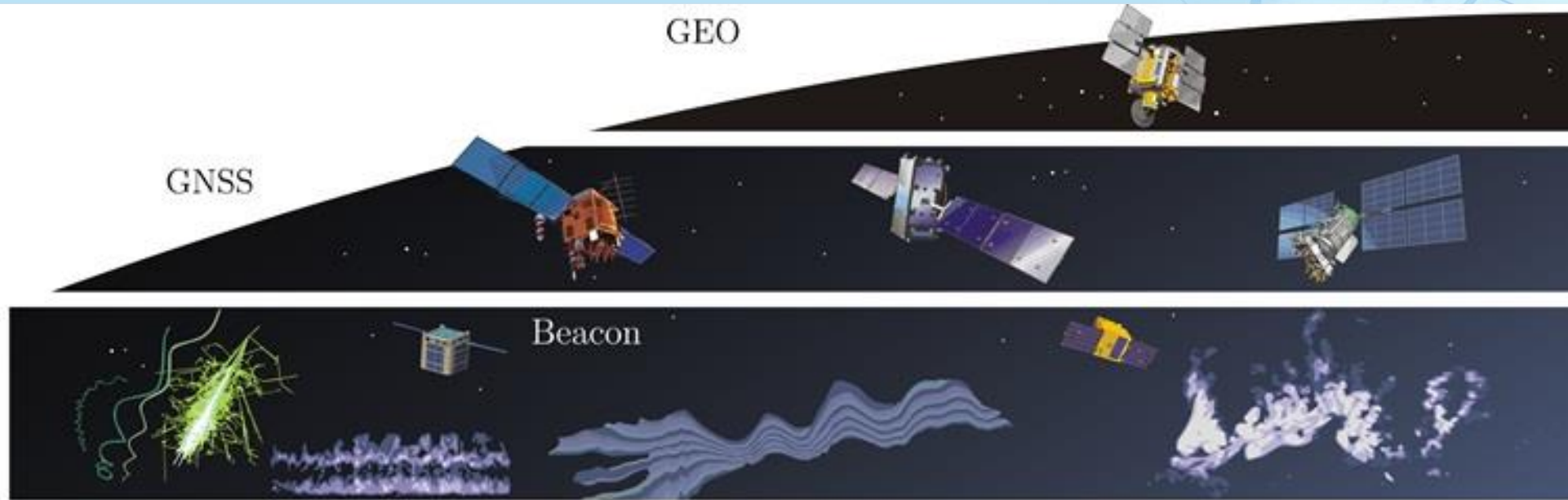
J. A. Cahuasqui,
M. Hoque,
M. Kriegel,
J. Berdermann



A diagram illustrating the Earth's magnetosphere and a satellite. The Earth is shown as a small blue and white sphere in the center. Concentric white lines represent the magnetic field lines, forming a teardrop shape on the left (facing the Sun) and a larger, more elongated shape on the right. A satellite, depicted as a small yellow cube with solar panels and a dish, is shown in orbit around the Earth. To the left of the Earth, a large, glowing orange and red sphere represents the Sun. White curved lines indicate the solar wind flowing from the Sun towards the Earth. The background is a dark blue space with small white stars.

INTRODUCTION: NEW METHOD OF SCINTILLATION MODELING

Ionospheric irregularities



Remote sensing

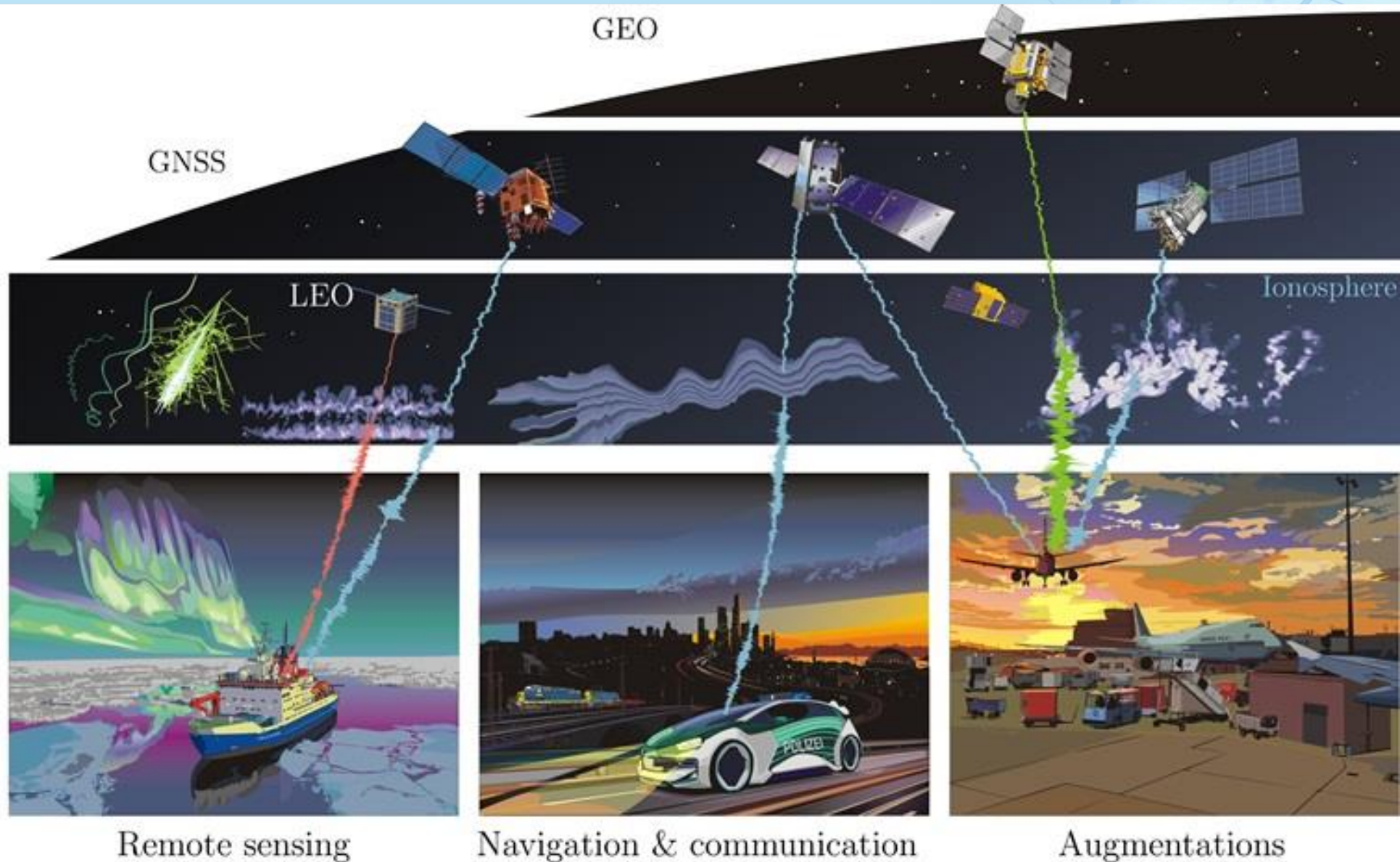


Navigation & communication



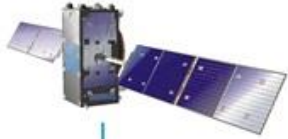
Augmentations

Ionospheric scintillation



Phase screen model for estimation of scintillation strength

Transmitter



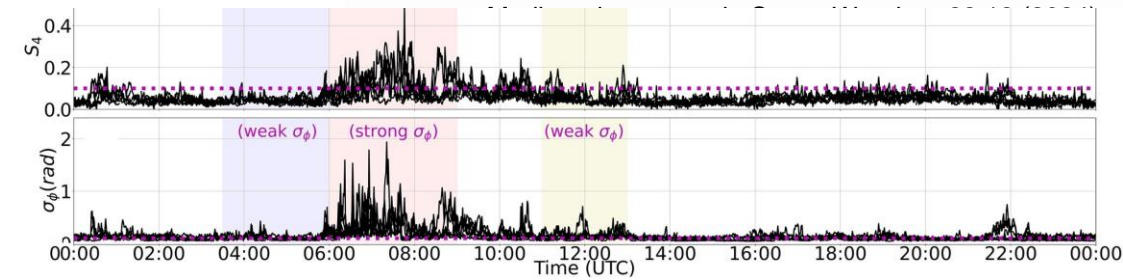
SCINTILLATION INDICES:

- Amplitude fluctuations δA :

$$S_4^2 = \frac{\langle |\delta A(0)|^4 \rangle - \langle |\delta A(0)|^2 \rangle^2}{\langle |\delta A(0)|^2 \rangle^2}$$

- Phase fluctuations δS :

$$\sigma_{\delta S} = \sqrt{\langle \delta S(0)^2 \rangle}$$



Phase screen realization:

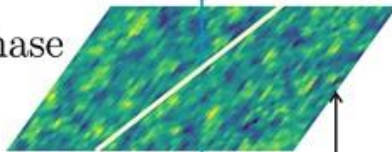
$$\delta\varphi(\mathbf{r}_\perp) = -r_e \lambda \int \delta N_e(\mathbf{r}) dz = -r_e \lambda \delta N_{\text{TEC}}(\mathbf{r}_\perp)$$

Statistical properties of the screen are related to those of the electron density fluctuations.

C. Rino, Radio Sci., 14, 6 (1979)

Ordinary phase screen

$$\delta\varphi \sim \delta N_{\text{TEC}}$$



z

$\left. \begin{matrix} \delta A \\ \delta S \end{matrix} \right\}$



Receiver

$$\delta A = \frac{ik}{2\pi z} \int A_0(\mathbf{r}'_\perp) \left(e^{-i\delta\varphi(\mathbf{r}'_\perp)} - 1 \right) \overbrace{e^{-i\frac{k}{2z}|\mathbf{r}_\perp - \mathbf{r}'_\perp|^2}}^{\text{Fresnel filtering}} d^2\mathbf{r}'_\perp$$

$$\delta S \approx \delta\varphi$$

Fresnel filtering

Phase screen model for estimation of scintillation strength

Transmitter

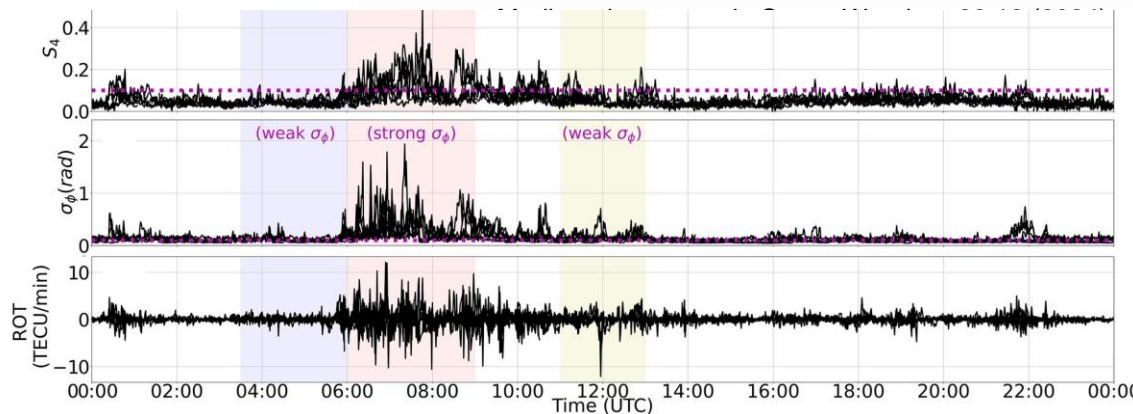
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$\sim \delta \mathbf{r}_1$
($\sim \nabla_{\perp} \delta N_e$)

$\nabla_{\perp} \delta N_{\text{TEC}}$

$\delta \varphi \sim \delta N_{\text{TEC}}$

Phase gradient screen realization:

$$\delta \varphi(\mathbf{r}_{\perp}) = -r_e \lambda \delta N_{\text{TEC}} + r_e \lambda \delta \mathbf{r}_1 \cdot \nabla_{\perp} \delta N_{\text{TEC}}$$

Statistical properties of the screen are related to those of the electron density fluctuations.

D. Vasylyev et al., JSWSC, 14, 29 (2024)

$\left. \begin{matrix} \delta A \\ \delta S \end{matrix} \right\}$

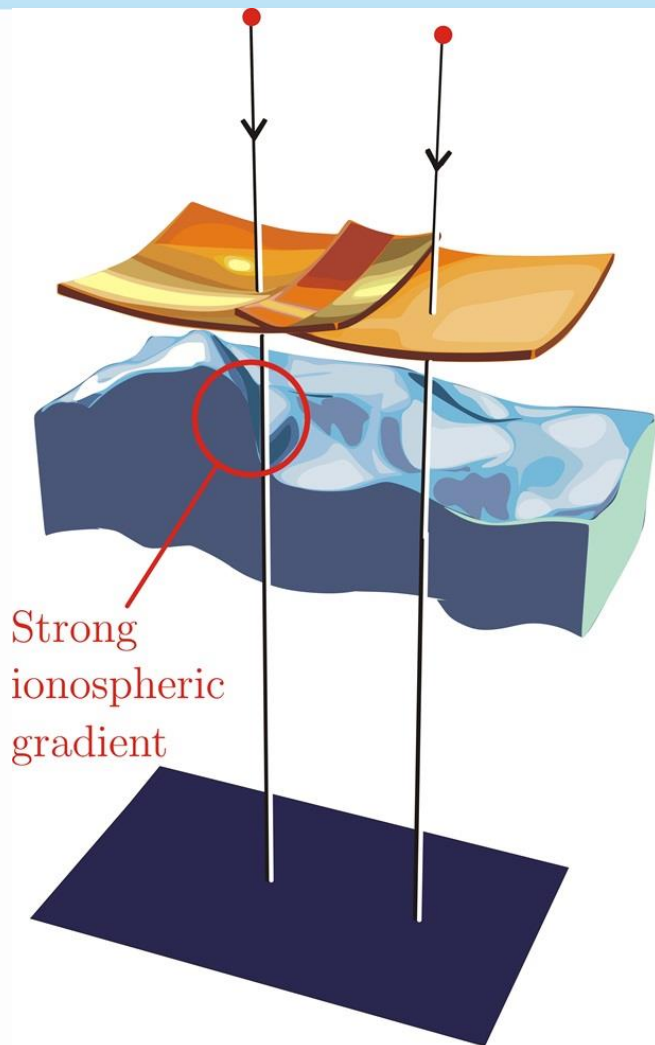
Receiver

$$\delta A = \frac{ik}{2\pi z} \int A_0(\mathbf{r}'_{\perp}) \left(e^{-i\delta \varphi(\mathbf{r}'_{\perp})} - 1 \right) \overbrace{e^{-i\frac{k}{2z} |\mathbf{r}_{\perp} - \mathbf{r}'_{\perp}|^2}}^{\text{Fresnel filtering}} d^2 \mathbf{r}'_{\perp}$$

$$\delta S \approx \delta \varphi$$

Physics behind the gradient dependent correction

Random Diffraction



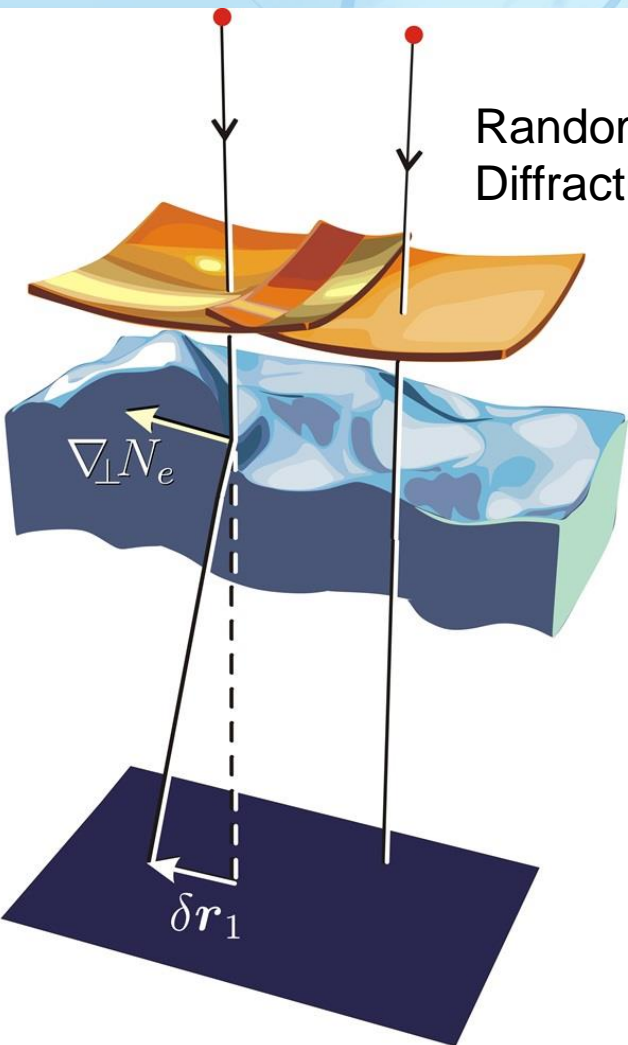
Ignoring wavefront tilt

Incoming wavefronts

Random medium

Receiver plane

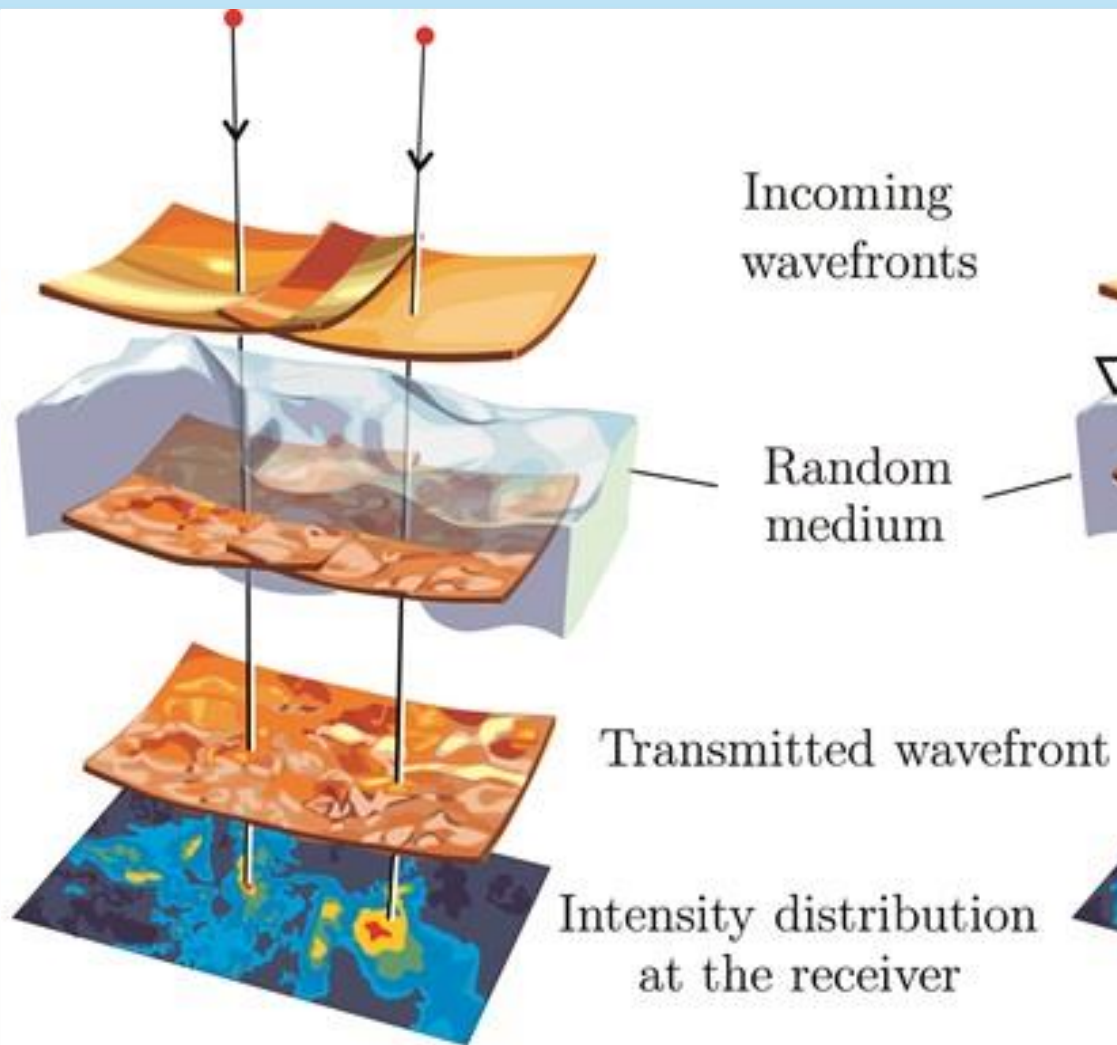
Random Diffraction+Refraction



Taking wavefront tilt into account

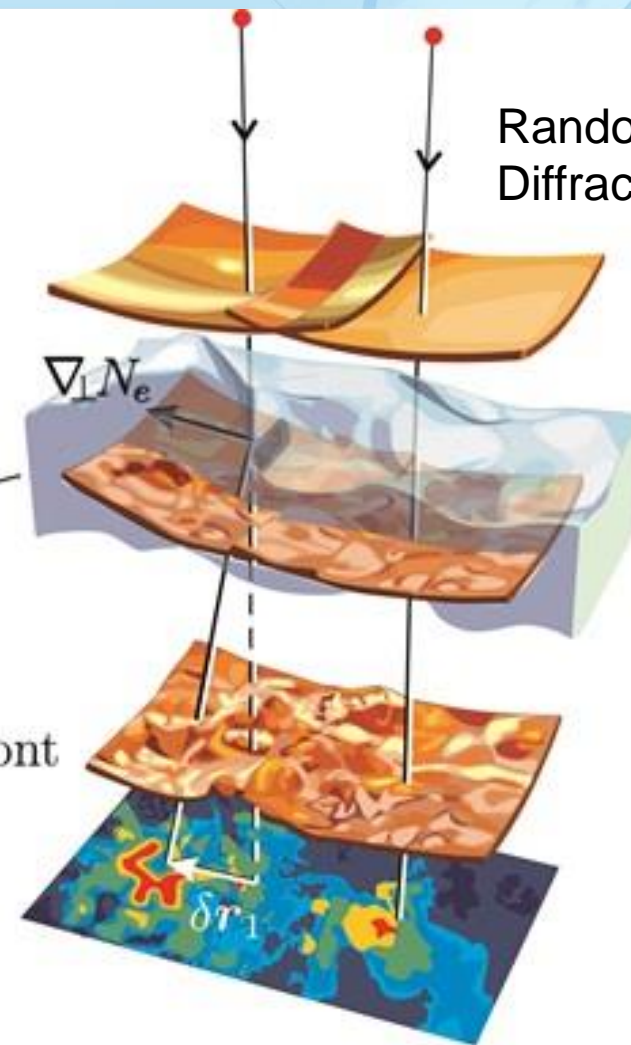
Physics behind the gradient dependent correction

Random
Diffraction



Ignoring wavefront tilt

Random
Diffraction+Refraction



Taking wavefront
tilt into account

A diagram illustrating the Earth's magnetosphere and a satellite in orbit. The Earth is shown as a small blue and white sphere in the center. Concentric white lines represent the magnetic field lines, which are compressed on the left side (facing the Sun) and stretched out on the right side. A satellite, depicted as a small yellow cube with solar panels and a dish, is shown in orbit around the Earth. The background is a dark blue space with white stars. On the left, a large, glowing orange and red sphere represents the Sun. White lines connect the Sun to the magnetosphere, indicating the flow of solar wind. A dark blue horizontal bar is at the bottom, containing the title text.

GRADIENT-BASED INDICES AND SCINTILLATION

1st component: Total Electron Content gradient (related to ROTI)

$$ROTI = \sqrt{\frac{\sum_i^n (ROTI_i)^2}{n} - \left(\frac{\sum_i^n ROTI_i}{n}\right)^2}$$

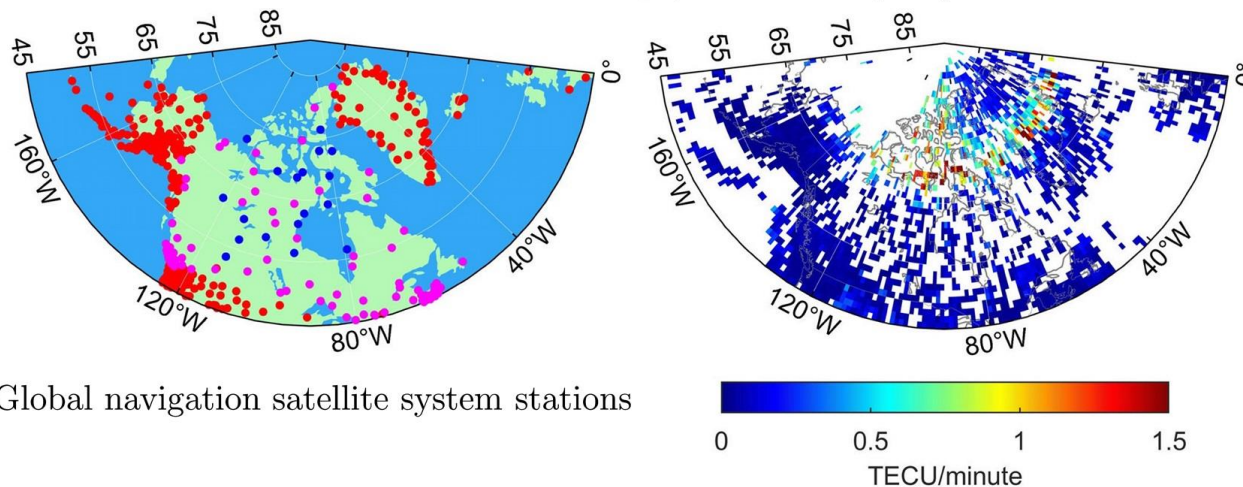
$$ROTI_i \equiv \frac{TEC\left(t + (i - n/2)\delta t\right) - TEC\left(t + (i - n/2 - 1)\delta t\right)}{\delta t}$$

TEC gradient derived from ROTI:

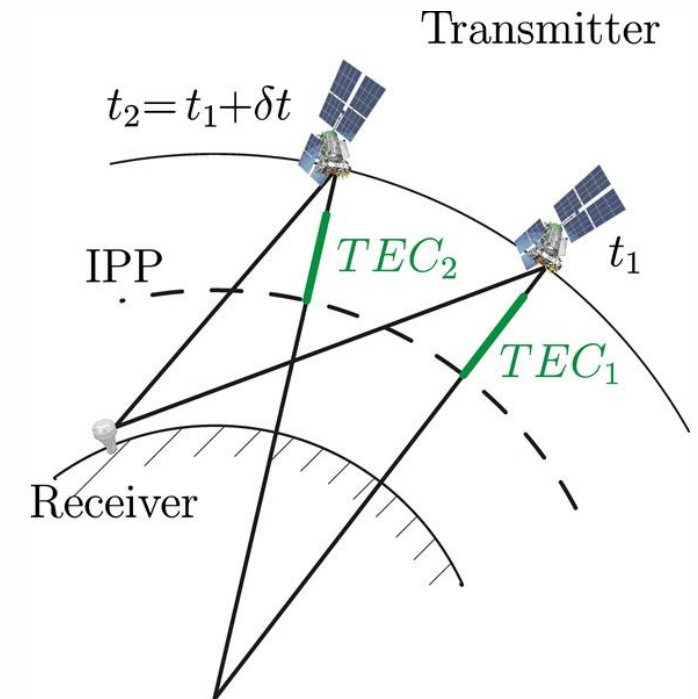
$$\nabla TEC = \frac{\overline{V_{drift}}}{(\overline{V_{drift}})^2} ROTI,$$

where $\overline{V_{drift}}$ is the plasma drift velocity averaged over the time $n\delta t$.

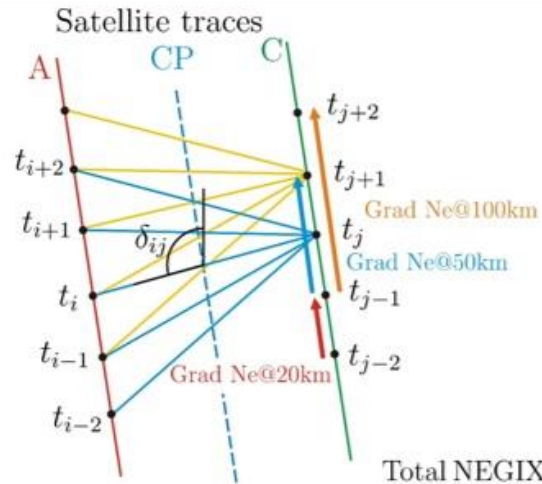
L.Liu, Y. Morton, Y. Liu, Geophys. Res. Lett. (2021)



Pi et al., Geophys. Res. Lett. 24, 2283 (1997)



2nd component: Electron density gradient index NeGIX (SWARM)



$$\langle \nabla N_{e_x} \rangle = \frac{1}{N_D} \sum^{N_D} \nabla N_{e_{ij}} \sin \delta_{ij} = \text{NeGIX}_x$$

$$\langle \nabla N_{e_y} \rangle = \frac{1}{N_D} \sum^{N_D} \nabla N_{e_{ij}} \cos \delta_{ij} = \text{NeGIX}_y$$

$$\text{NeGIX} = \sqrt{\langle \nabla N_{e_x} \rangle^2 + \langle \nabla N_{e_y} \rangle^2}$$

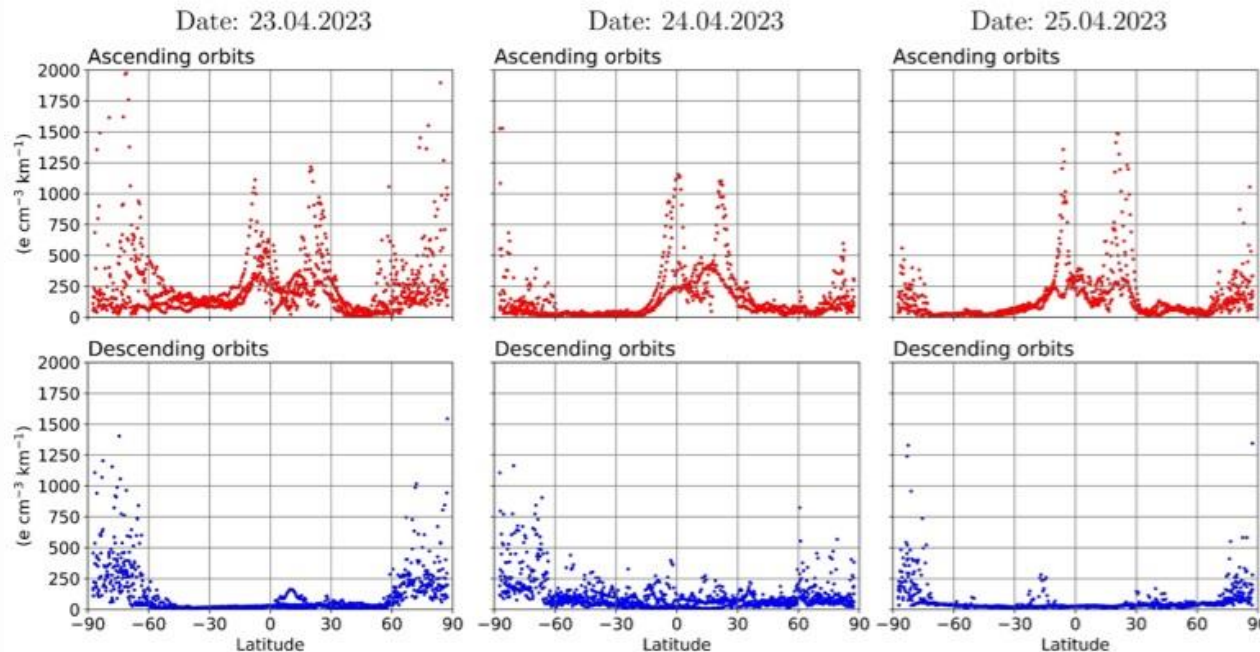
Total NEGIX (-30° – 50° longitude sector)

SWARM
DISC

Project:

**Monitoring of Ionospheric
Gradients At Swarm (MIGRAS)**

J. A. Cahuasqui, et al., “New Swarm products NeGIX and TEGIX for monitoring ionospheric gradients”, submitted to JSWSC



1st component: Model for TEC gradient/ROTI

EOF model by Y. Jin et al., Space Weather (2023)

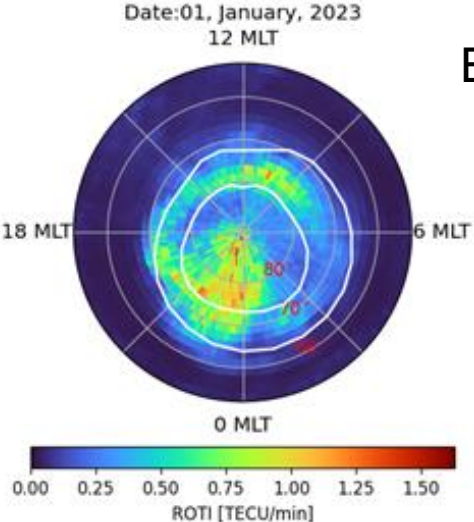
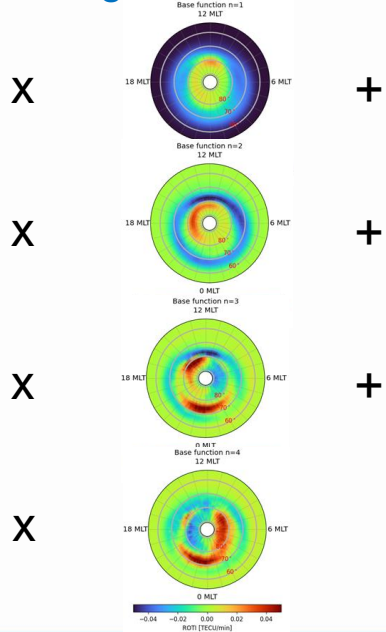
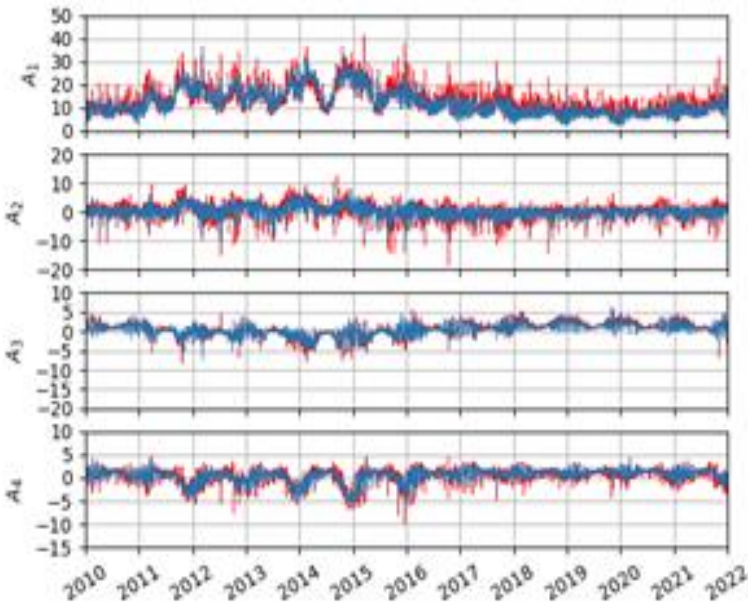
Geophysical parameters: $F_{10.7}$, K_p , IMF , ...

$$ROTI = \sum_i^4 \text{coefficients}_i \cdot \text{functions}_i$$

(red:truth
blue:model)

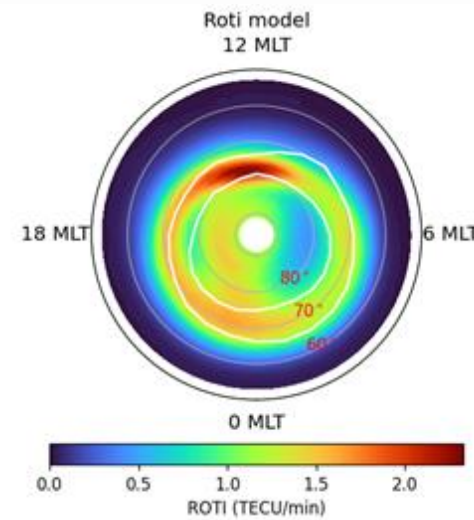
coefficients

orthogonal functions

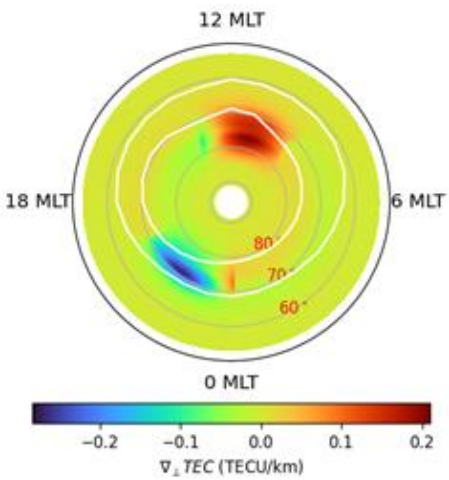


Empirical ROTI

Model ROTI



Gradient TEC
E-W component

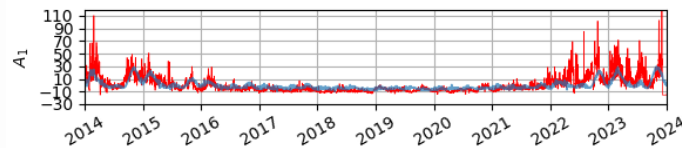


2nd component: Model for SWARM NeGIX

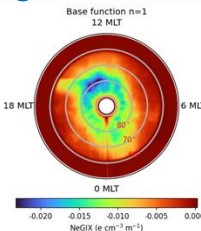
Geophysical parameters: $F_{10.7}$, K_p , IMF , ...

$$NeGIX = \text{coefficient} \cdot \text{function}$$

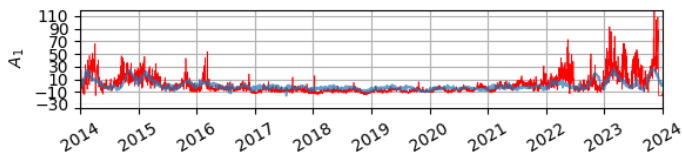
Negative component of NeGIX_x
(red:truth, blue:model) **coefficient** **orthogonal function**



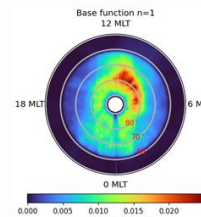
X



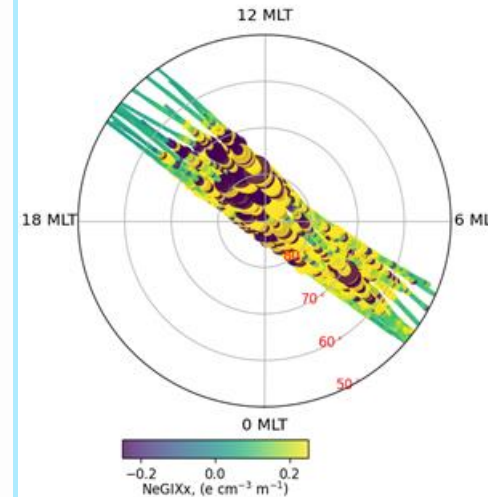
Positive component of NeGIX_x



X



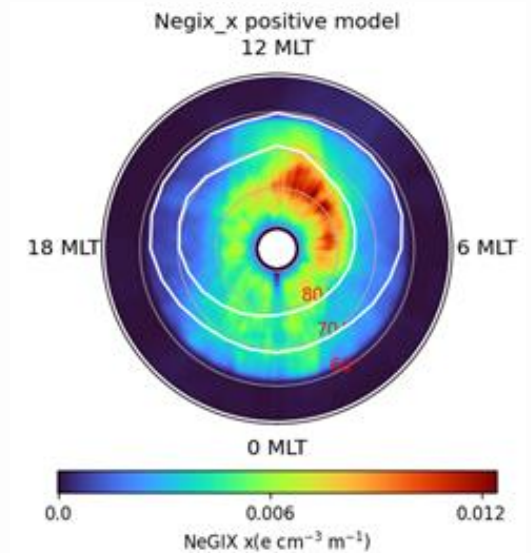
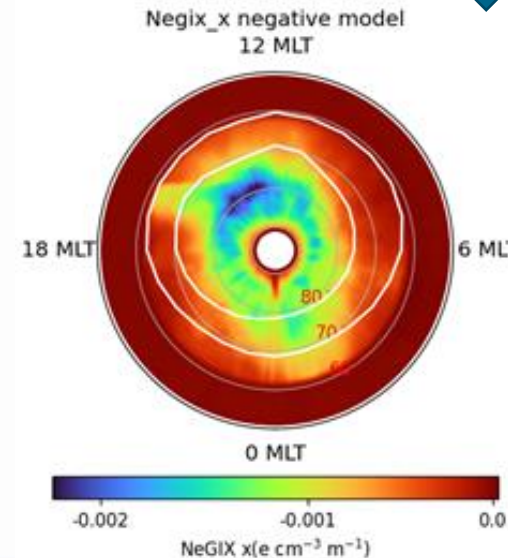
NeGIXx, asc/descending orbit: 2023.01.01.



Empirical NeGIX_x
(East-West component of gradient)



Model NeGIX_x
(negative & positive components)



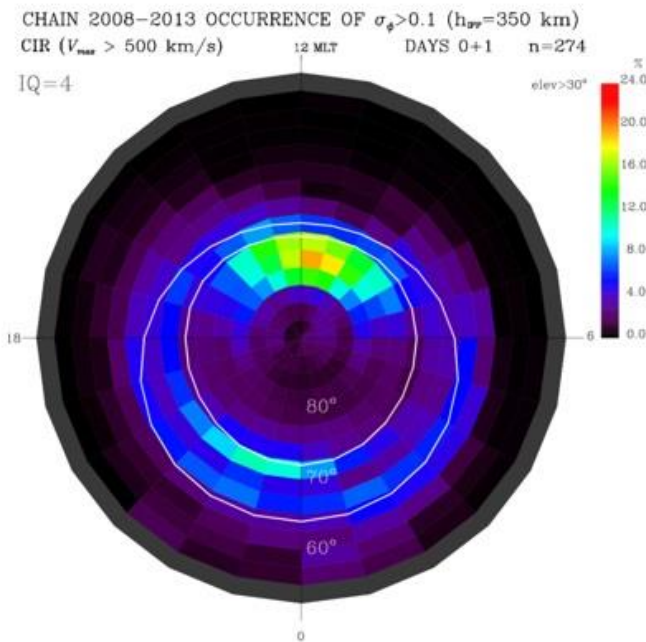


The diagram illustrates the Earth's magnetosphere and a satellite in orbit. On the left, a large, glowing orange and red sphere represents the Sun. White lines represent the solar wind flowing from the Sun towards the Earth. The Earth is shown as a small blue and white sphere in the center. White lines around the Earth represent the magnetic field lines, which are compressed on the left side (facing the Sun) and stretched out on the right side. A satellite is shown in orbit around the Earth, with a white body and two long, thin solar panel arrays. The background is a dark blue space with small white stars.

SCINTILLATION MODELING FOR HIGH-LATITUDE REGION

High-latitude scintillation model for GISM

Empirical probability of occurrence
of $\sigma_\phi > 0.1$

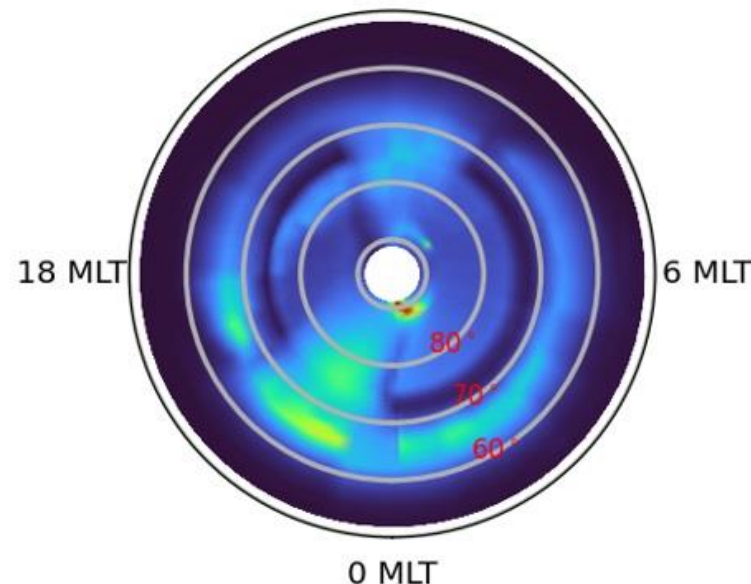


Prikryl et al., Ann. Geophys. 33, 531 (2015)

Example of scintillation map
realisation with $\sigma_\phi > 0.1$

WBMOD

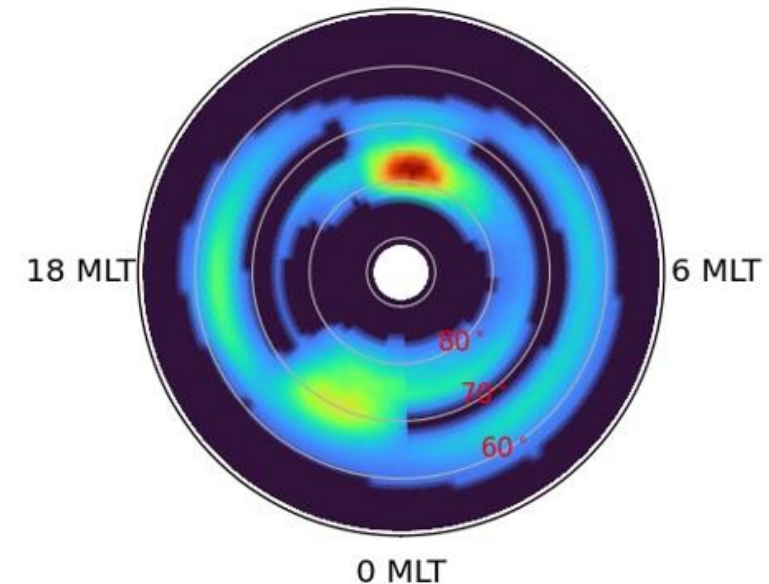
Date: 2015.12.1, Kp=3.4, sunspot nr=186.0
12 MLT



Diffraction scintillation

GISM

Phase scintillation index
12 MLT



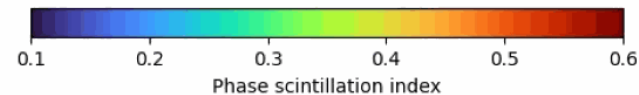
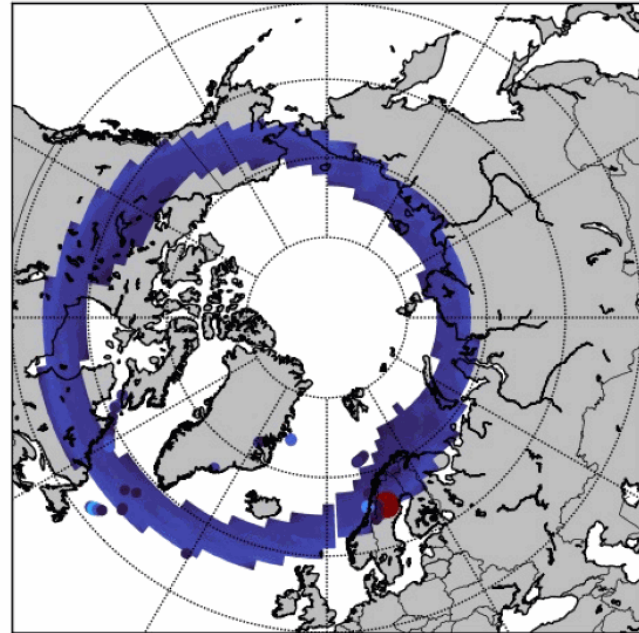
Diffraction+ refractive scintillation

High-latitude scintillation model for GISM

Empirical scintillation from CHAIN and DLR stations: points
Current model: colored area

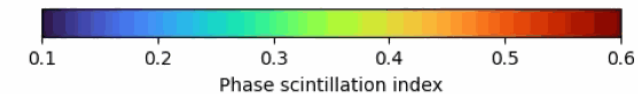
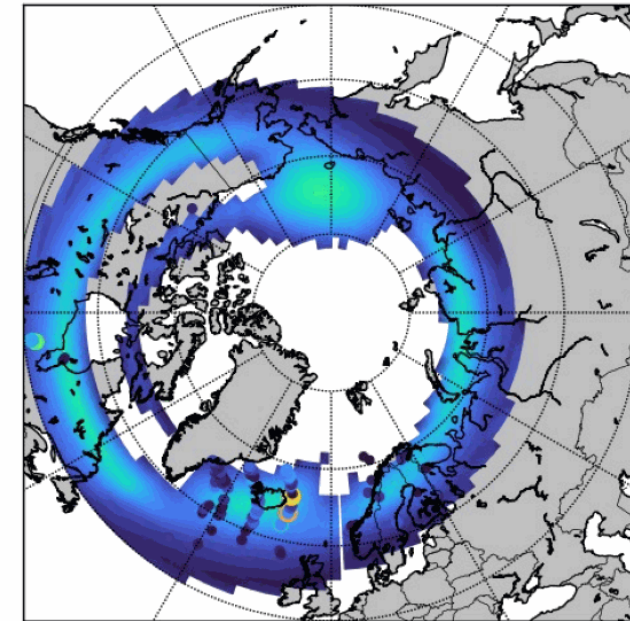
Quite geomagnetic conditions

Date: 2024-01-03 07:30, Kp=1.0, sunspot=59, freq=1565 MHz



Disturbed geomagnetic conditions

Date: 2024-05-10 11:30, Kp=2.0, sunspot=172, freq=1565 MHz





- Strong ionospheric gradients may cause intense refractive scintillation (primarily phase scintillation)
- Phase gradient screen approach is bale to incorporate such type of scintillation
- Electron density gradients derived from SWARM (NeGIX) products along with ROTI are valuable input for scintillation modeling
- Climatological model for NeGIX has been constructed by using empirical orthogonal function in similar footing as it was done for ROTI
- The resulting high-latitude scintillation model is capable to explain the enchanced scintillation activity at magnetic noon sector.