Modeling the Ionosphere with a novel Nuclear Perspective using GEANT4

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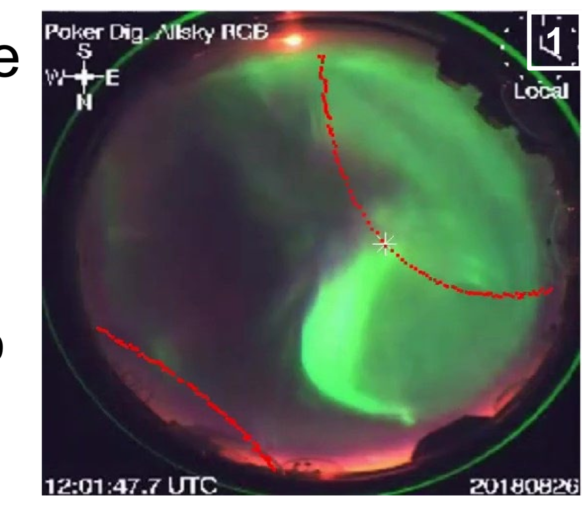
Problem Statement

Overarching Science Question: What impact does particle interaction in the auroral E region of the ionosphere have on GPS signal distortion?
Research Question: How can we develop a model for the auroral E region using a nuclear code platform with a focus on particle interactions?

Background

GPS signal distortion is a frequent occurrence within the high-latitude ionosphere with known contributions in the auroral E region. There are few models that can recreate plasma density with the resolution required to understand these disturbances.



Literature Review

Altitude vs Ionization Rate: the higher the energy of the electron flux, the deeper into the atmosphere it penetrates [2].

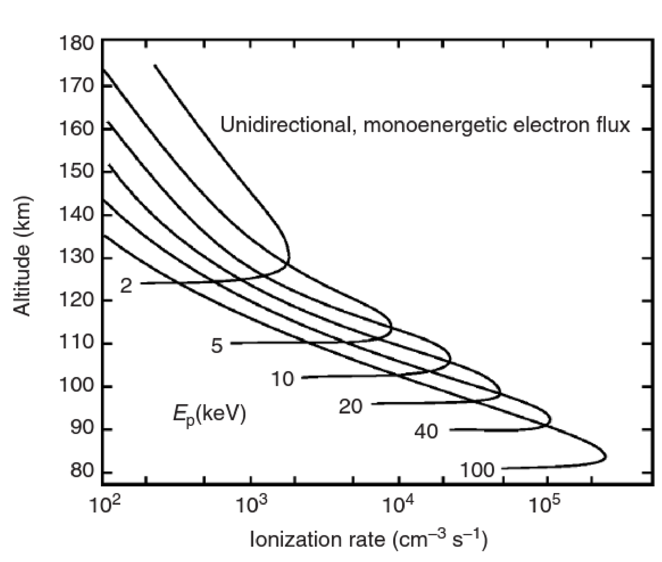
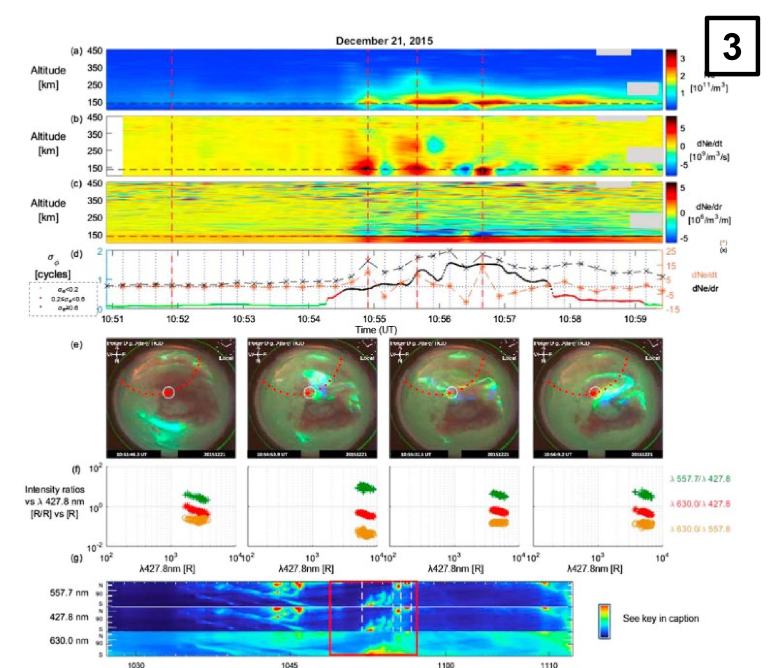
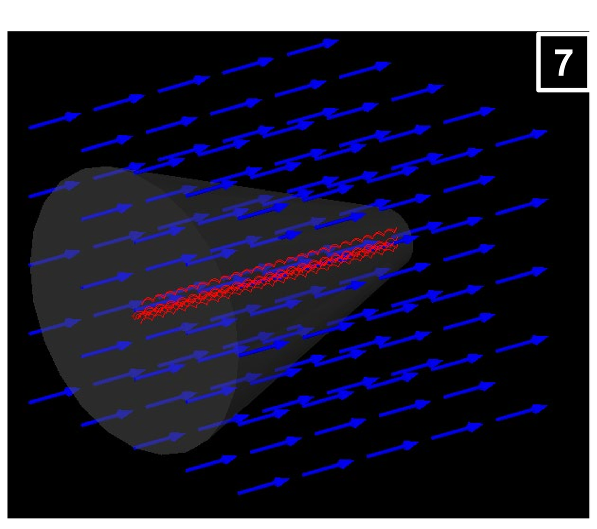


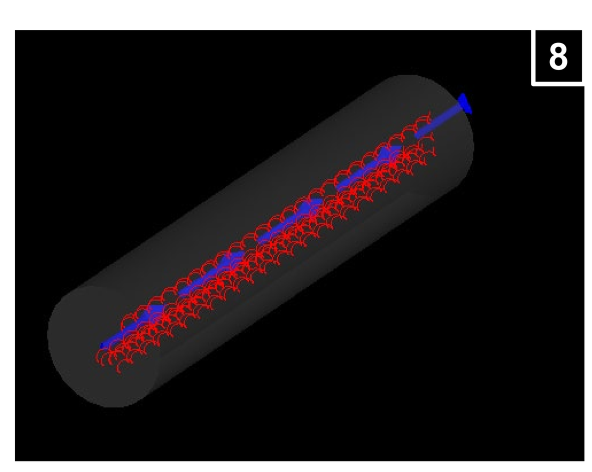
Figure 9.7 Calculated electron–ion pair production rates for monoenergetic electron fluxes of 10^8 electrons cm^{-2} s^{-1} precipitating into the terrestrial atmosphere.[22]



Gradients likely cause is impact ionization from auroral particle precipitation with energies between 1 and 4keV. [3] Electron density peaks are around 120-150km, lines up with electron-ion pair production rate profiles [2].

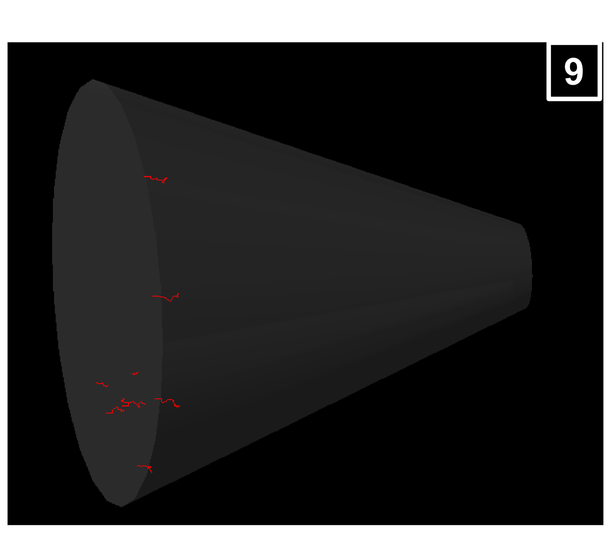
Method





Figures 7 & 8, demonstrate the helix electron trajectory as the electrons move within a cone and cylinder, respectively. Blue, shows magnetic field lines, and red shows electron path. Final model will be tested with a visual comparison (DASC) and, more accurately, a numerical comparison.

Results



10 Electrons shot in total with the same energy and angle entry, at random entry points.

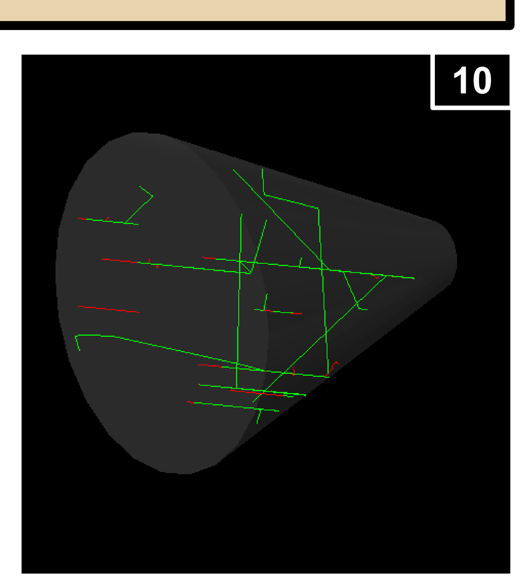


Figure 9, depicts a purely O_2 atmosphere, with a uniform magnetic field magnitude equal to $25 \times 10^{-6}\ T$, and an electron angle entry of 77.1° and energy 5 keV. Electrons eventually lose all momentum within volume.
Figure 10, depicts a purely O_2 atmosphere, with a uniform magnetic field magnitude equal to $25 \times 10^{-6}\ T$, and an electron angle entry of 77.1° and energy 5 GeV. Emphasizing electron penetration depth.

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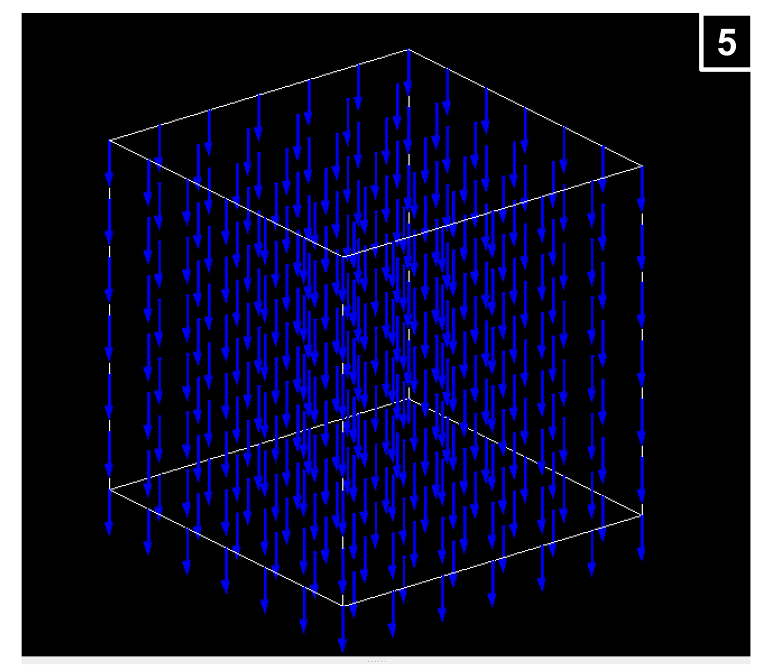
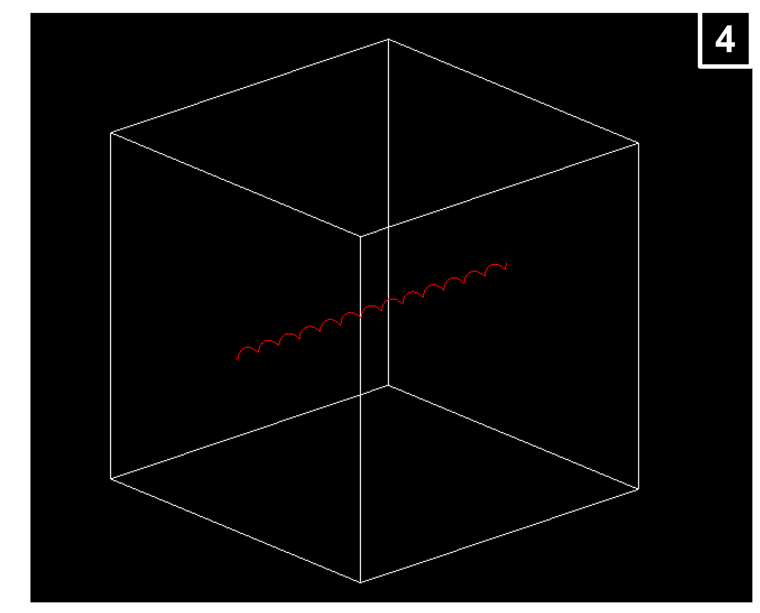
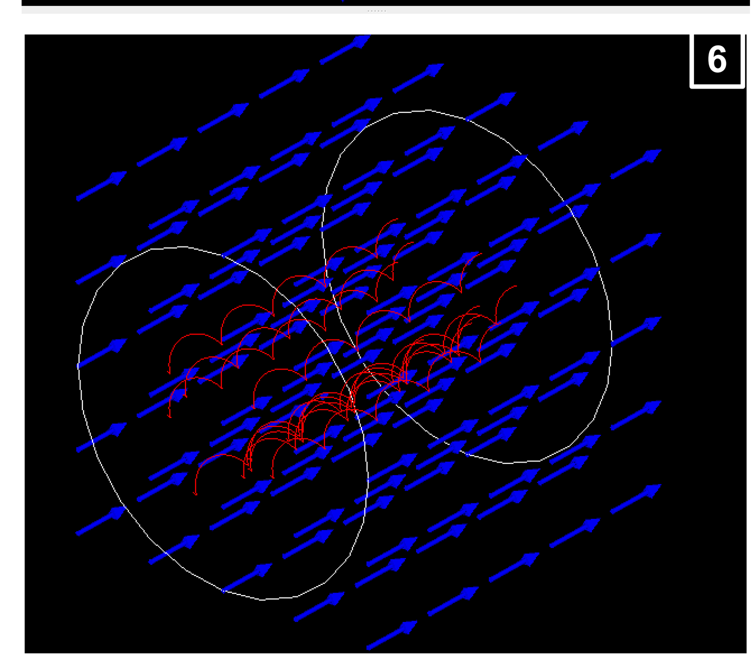
Theory







Development is iterative, with focus on three details; atmospheric composition, scale, and particle energies. Cube first used to develop uniform magnetic field and test archetypal helix electron trajectory. Cylinder, preferred, to articulate electron penetration. Goal is to model the conical radar volume the PFISR covers. Particle precipitation energies taken from PFISR, to match entry location with energy and a focus on the E region.

Figure 4, , models a 1 m^3 vacuum cube with a uniform magnetic field through the volume in the negative z-axis direction, and a single electron in a helix trajectory with an entry angle of 45° and energy 5 keV.
Figure 5, models a 1 m^3 cube with a uniform magnetic field through the volume in the negative z-axis direction.
Figure 6, models a vacuum cylinder with a uniform magnetic field through the volume, and 10 electrons in a helix trajectory with an entry angle of 45° and energy 5 keV.

Conclusions

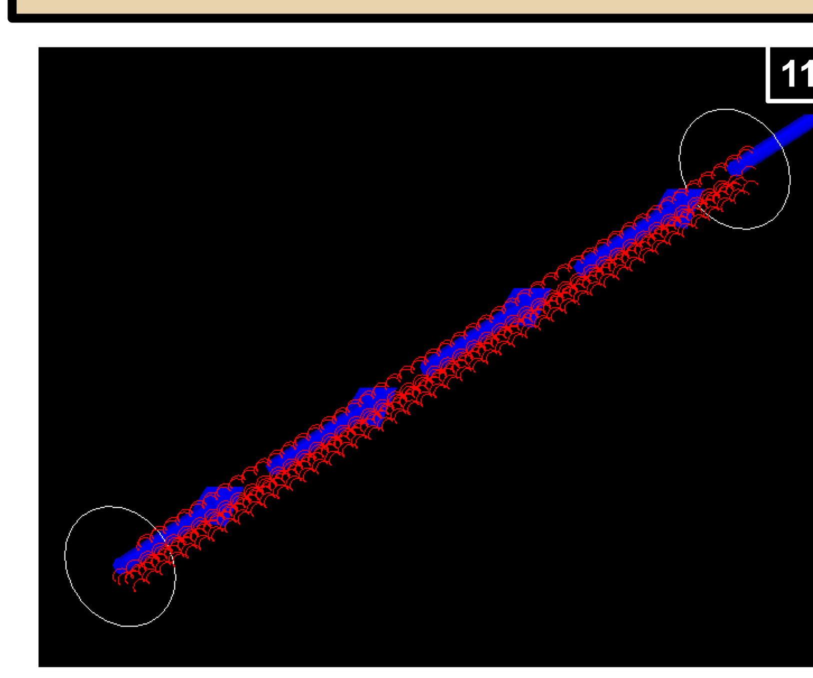


Figure 11, depicts a purely O_2 atmosphere, with a uniform magnetic field magnitude equal to $25 \times 10^{-2}\ T$, and an electron angle entry of 45° and energy 5 keV. This model had a diameter equal to 1 m and a depth/height equal to 10 m. Demonstrating the difficulty of matching true dimensions.

A layered model would now need to be created to simulate varying atmospheric compositions at various altitudes. With atmospheric compositions acquired through further literature review. However, dimensions do not need to match only scale, as models matching in dimension are unnecessarily large to visualize. Numerical data, such as electron densities can be extracted if the model is developed to a certain extent.

Abbreviated References* & Acknowledgements

[1] Loucks, D. (2017). "High-latitude GPS phase scintillation from E region electron density gradients during the 20-21 December 2015 geomagnetic storm" *Journal of Geophysical Research: Space Physics.*
[2] Schunk, Robert, Nagy (2009). *Ionospheres: Physics, Plasma Physics and Chemistry.* Cambridge University Press
[3] Rees, M.H. (1974) "Auroral electron energy derived from ratio of spectroscopic emissions 1. Model computations." *Geophysical Research.*
[4] GEANT4. Version 11.1, CERN, 09 Dec. 2022.
*Full reference table available upon request

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