Modeling Ionospheric E-Region Plasma Density Distribution Gradients with Geometry and Tracking (GEANT4) Software

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Problem Statement

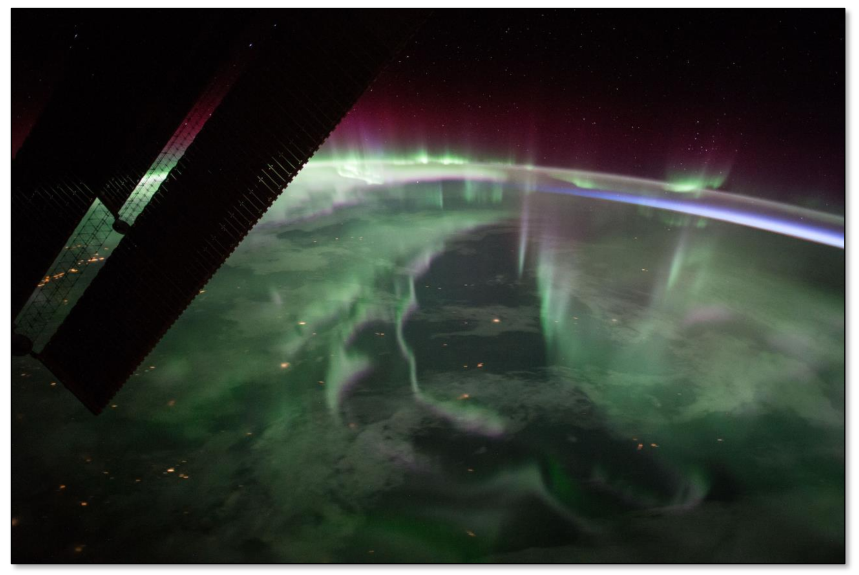

Figure 1: Aurora Borealis over northern Canada taken by Expedition 53 of the ISS, NASA, 2017.

Space weather effects on the upper atmosphere impacts radio wave propagation. Many space-enabled devices such as radar, satellite communications, terrestrial radio communications and Global Navigation Satellite System (GNSS) position, navigation and timing (PNT) signals are affected by solar-induced plasma irregularities which have resulted in temporary communication loss with satellites or failed operations, such as

End State

Create a model forecasting the unreliability of a GPS' location based on solar activity in order to provide commanders with the necessary knowledge to make well informed decisions for their military operations. The model will be developed based on high fidelity data collected through a passive, in-situ measurement device to avoid disrupting the measured environment.

Introduction

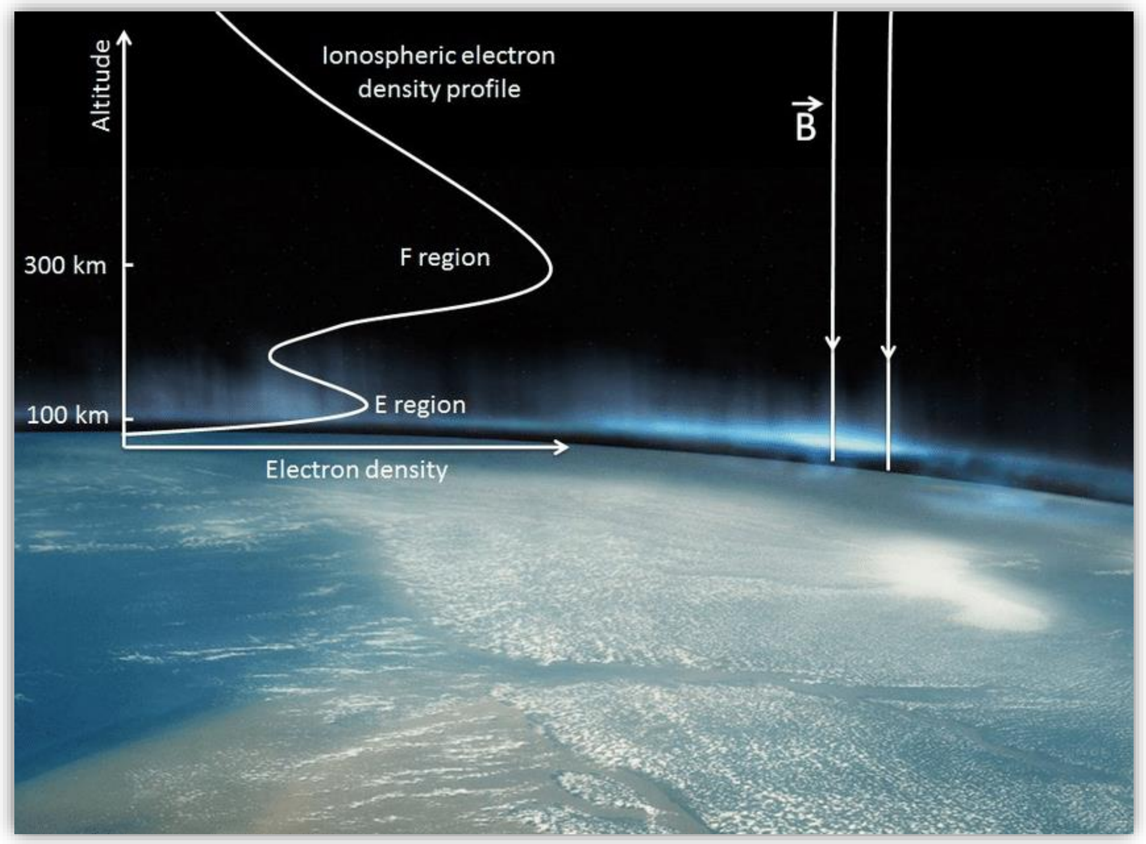

Figure 2: The Earth's Auroral region, Akbari 2015.

- In order to achieve the PLASMA (Polar Latitude Atmospheric Space Measurement and Analysis) team's primary end state, our project's objective will focus on modeling the E-region of the Ionosphere in GEANT4 in order to provide our team with the specifications necessary to design our probe and validate the results of our in-situ data.
- Current tools are limited in scope and horizontal fidelity. The PLASMA team at West Point is currently working on developing a model; however, the focus of this project is to construct a model that we can compare results from PLASMA's Langmuir Probe and verify our data. Our model will have experiment specific events that will simulate the planned orbit of our probe for finer comparison. This model will be our baseline for our work to come.

Environment

The ionosphere is a region of weekly ionized plasma nestled into thermosphere between 100 and 400 km in altitude. The charts below illustrate the dynamic relationship between plasma characteristics and temperature we expect to measure with the Langmuir probe.

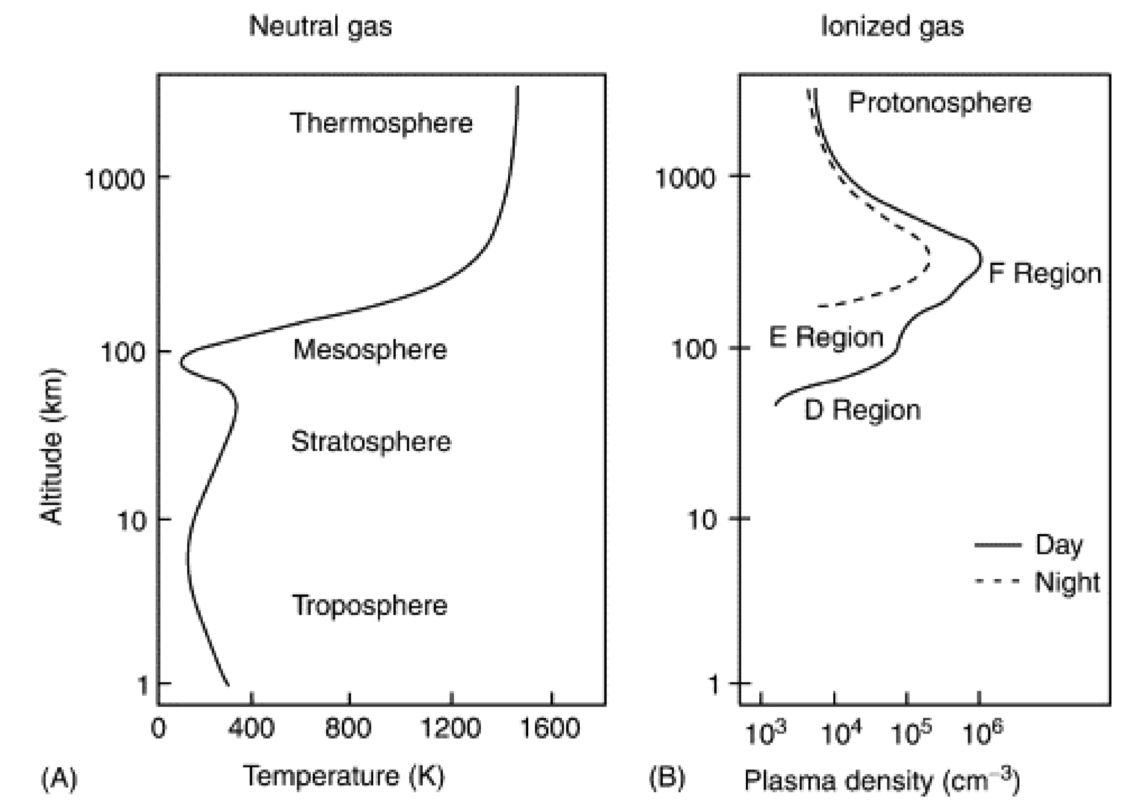

Figure 3: Typical profiles of neutral atmospheric temperature, Kelley 2003.

Our research will benefit from collecting data with more fidelity on the plasma under conditions where scintillation occurs, specifically the E-region between 90 and 140 km. For this project, we want to be able to represent the E-region of the Ionosphere with specific constituent ions in suspense: N_2, NO, and O_2. Furthermore, we need only to classify and characterize the polar latitudes.

Method

GEANT4 is a simulation toolkit that models the passage of particles through matter. A Langmuir Probe functions by creating an electric potential within a body of plasma and producing a current from which data can be gathered. With GEANT4, we want to simulate the passage of a probe through polar latitudes. The E-region of the ionosphere has specific characteristics which we need to include in our model. First and foremost, the environment itself needs to be created, which we've already identified from 90-140km into the Earth's atmosphere from 60°N to $90^{\circ}N$. With the environment now established, we must populate it with our constituents of interest, N_2, NO, and O_2. With these constituents in place, we need to create our detector and detector geometry representative of a Langmuir probe. Our detector geometry can and will be changed, as the specifications of our Langmuir Probe have not been solidified but will be in the near future.

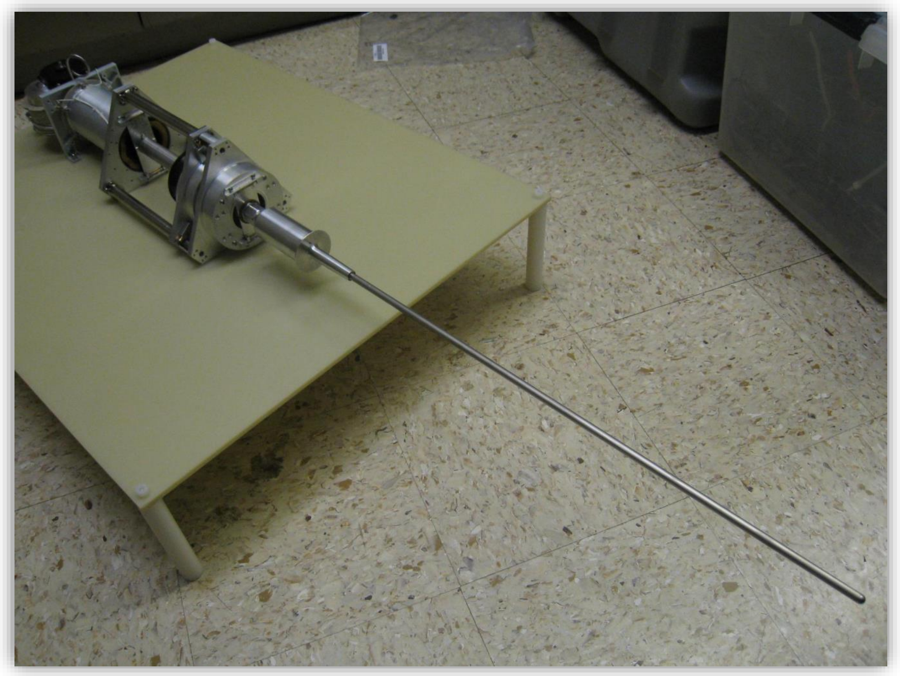

Figure 4: Mars MAVEN Langmuir Probe, LASP Colorado 2012.

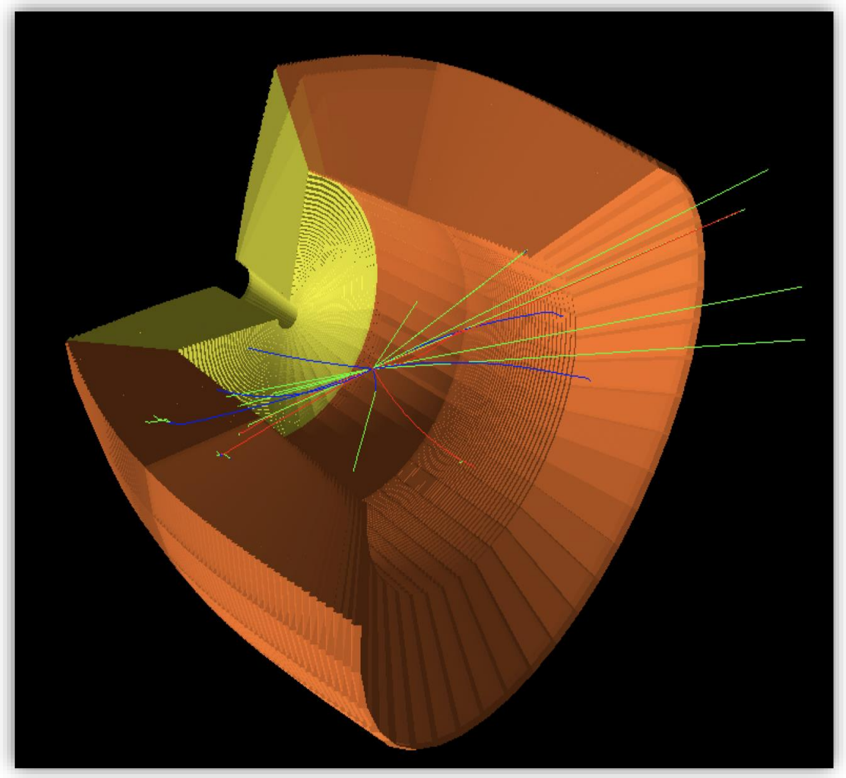

Figure 5 GEANT4 Simulation and Geometry Example, CERN 2022.

One of the main challenges of using GEANT4 to create a model to compare real world results to is getting the model to match the real-world environment. Within our project, our Langmuir Probe will sit on a CubeSat with its own geometry. For the purpose of data collection, the CubeSat will exist in a parking orbit of 500km at an inclination of 70°. Once an auroral event of interest with a Planetary K index of at least 5 is identified, the CubeSat will move into a data collection orbit with an argument of 105º and an altitude just above 92 km, resulting in a max orbital speed just above 8 km/s and sampling rate of 800 Hz for the LP.

With these parameters identified, we can run the simulation and create a Current-Voltage Curve from our results, providing us with a comprehensive understanding of the plasma's behavior when viewed through the lens of a Langmuir probe, enabling precise characterization in order to accurately compare to our real-world results.

Once the data from our Langmuir probe is verified, we can then incorporate it into our ionospheric model, from which we can show how the environment cause GNSS scintillation and provide a model capable of forecasting uncertainties in GPS PNT (Position, Navigation, and Timing) data.

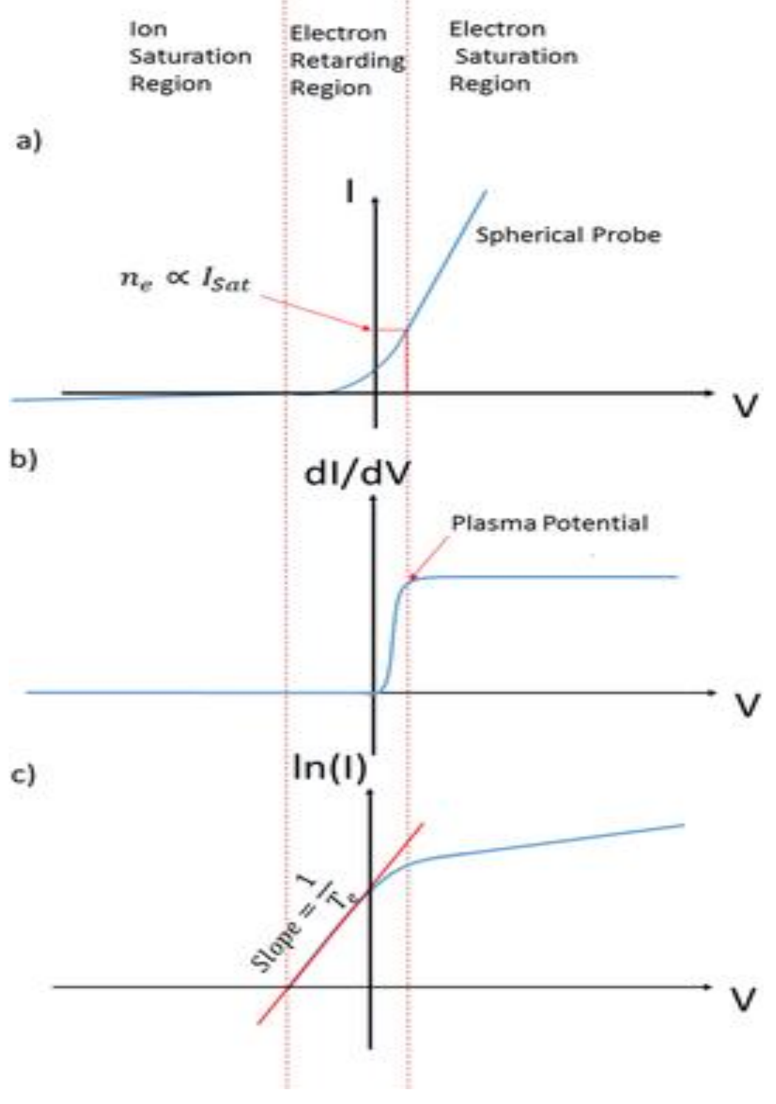

Figure 6 Ideal I-V curve labeling the ion saturation region, electron retarding region, and electron saturation region of a spherical Langmuir Probe, Samaniego 2019.

Acknowledgements & References

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- Please ask presenter for a full list of references