High-Fidelity Spatial Characterization of Ionospheric Plasma Instabilities to Forecast a Quantifiable Uncertainty of GNSS PNT Solution

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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 operation ANACONDA in 2002.

End State

Develop a Langmuir Probe device capable of collecting in-situ data characterizing the environment in the E-region ionosphere. Integrate the Langmuir Probe as a scientific payload on a small satellite to ensure data measurements will have high horizontal spatial fidelity. The data will be used to develop a model forecasting the uncertainty of GNSS PNT solutions based on solar activity to provide civil and military leaders the necessary knowledge to make well informed decisions.

Introduction

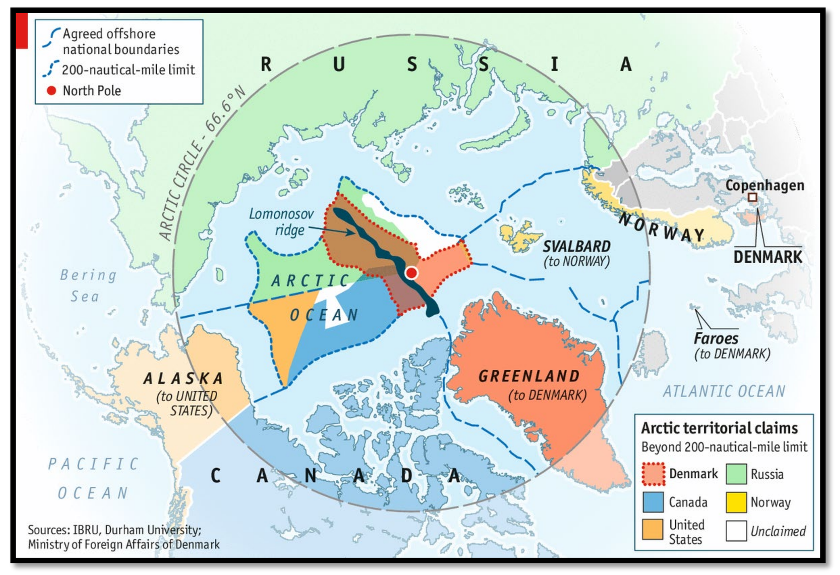

Figure 2: Map of territorial claims in the Arctic Region, The Economist 2014.

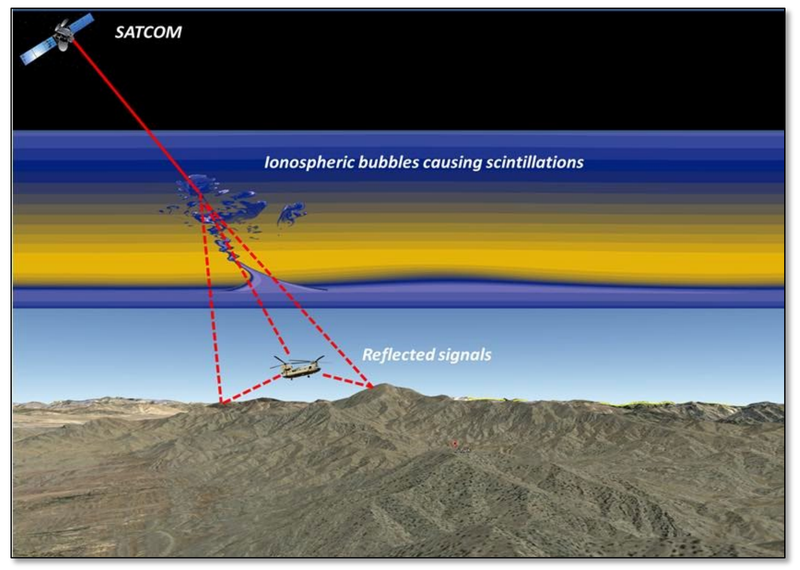

Figure 3: Plasma bubbles disrupting satellite communications analysis during the battle of Takur Ghar on March 4, 2002. JHU APL Space Weather Course, 2021.

- Precision of GNSS PNT signals such as the Global Positioning System (GPS) are susceptible to scintillation caused by solar influence on ionospheric plasma. While characterization of ionospheric plasma within the equatorial latitudes is an active region of study and generally understood, a quantifiable uncertainty described as a distance has yet to be forecasted.
- Global warming has caused new passages to open in the arctic, providing access to valuable resources, but also raising contention between several nations. The conditions influencing plasma perturbations in this region differ from those in the equatorial region due an increased flux of high energy particles raveling along Earth's magnetic field lines. Atmospheric turbulence, solar radiation induced ionization, and charged particle dynamics result in a highly dynamic environment in the polar ionosphere fostering scientific collaboration and debate amongst the space weather community

Ionosphere

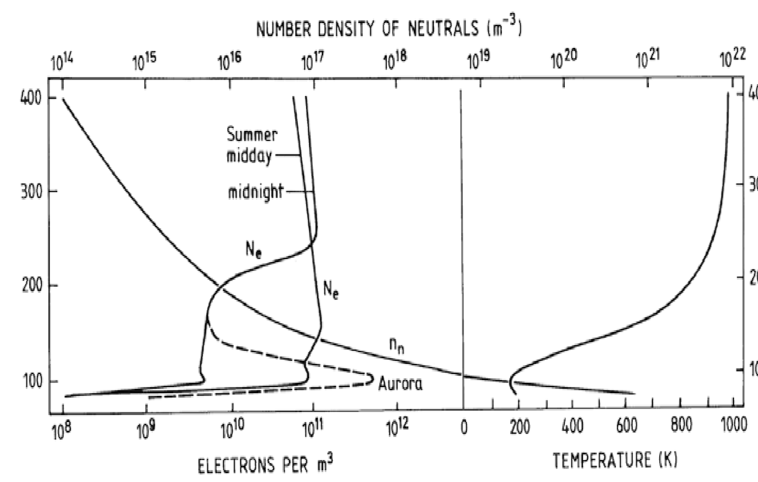

Figure 4: Electron density profiles representing average daytime and night-time conditions at high latitudes. Also indicated is a profile for auroral conditions and the background neutral density profile as the average neutral temperature profile. (*Physics of the Upper Atmosphere*, Brekke, 2013)

The ionosphere is a region of weekly ionized plasma nestled into thermosphere between 90 and 400 km in altitude. The behavior of the plasma is dependent upon varying factors to include time of day, solar activity, neutral atmosphere thermal fluctuations, and Pederson currents. 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 150 km. These characteristics are then utilized to characterize radio wave refraction through, absorption in, and diffraction around plasma irregularities in the ionosphere.

Langmuir Probe

A Langmuir probe (LP) is a passive device used to measure the internal parameters of a plasma. A potential is applied across an electrode, and the LP collects the resulting current due to free-flowing ions and electrons. This data is used to determine ion and electron temperatures and densities, which then characterize the refractive index of the plasma gradients. The structure of a particular LP is dependent on the plasma environment it is intended to measure. Different theories are applied to the current-voltage curves LPs produce to determine plasma parameters based on the LP's specific structure.

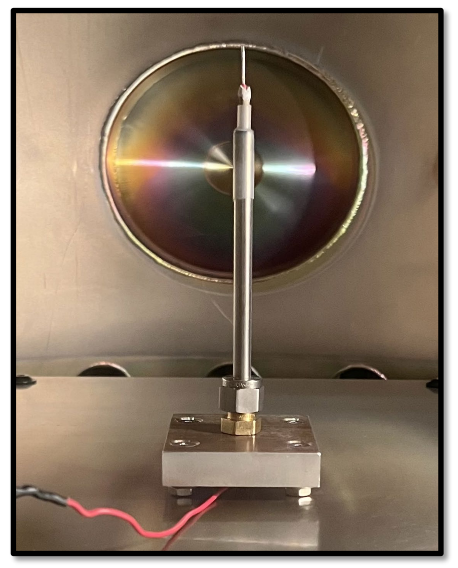

Figure 5: A cylindrical LP prototype constructed and vacuum chamber tested by USMA cadets at LASP in the Summer of 2023.

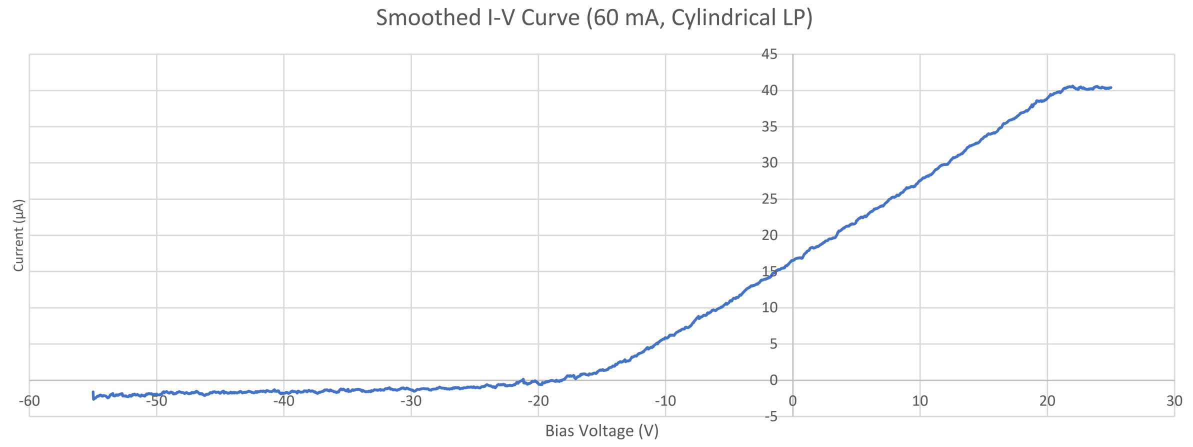

Figure 6: Vacuum Chamber data collected by LP prototype by USMA cadets at LASP in Summer of 2023.

Due to ease of construction, the cylindrical geometry was chosen. Cylindrical probes are often associated with Orbital Motion Limited (OML) LP Theory, which produces distinctly different IV Curves in the electron saturation region. For a cylindrical probe, this region will increase linearly, as opposed to exponentially. OML requires the probe radius be much smaller than the plasma Debye length, and the length to be of scale with or smaller than the probe sheath. Because the E-region ionosphere has a Debye length range of ~1.2 – 3.7 mm, the flight-ready probe tip will have a diameter of 0.05 mm, and ideally be 1.2 mm in length. However, the length can also be greater than the probe sheath and treated differently in analysis. As such, a length of 5 mm was also proposed. Vacuum chamber testing will determine the viability of the probe prior to launch.

Method

Ionospheric conditions are commonly measured actively with incoherent scatter radars (ISR) The active nature of the radar subtly changes the environment measured, and the ground-based technology is limited in scope and horizontal spatial resolution. To mitigate active influence of the ionosphere, passive, in-situ, measurements are typically measured aboard sounding rockets. However, sounding rockets pose several logistical issues and highly localized data. Current fidelity is roughly 20 km.

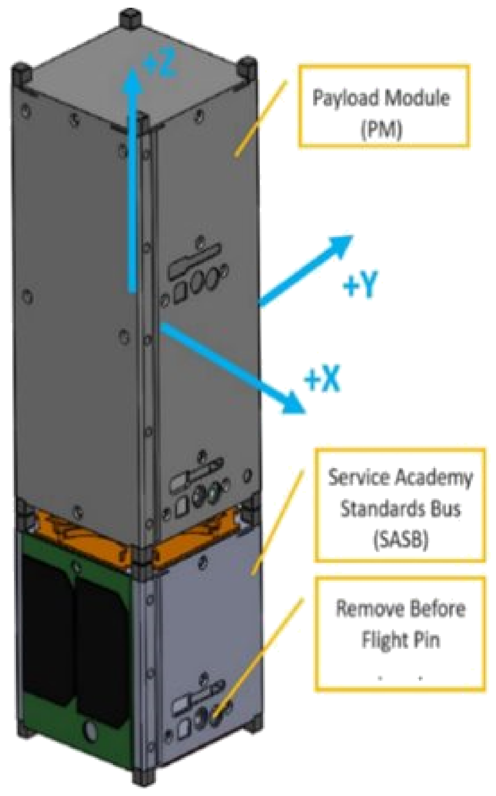

Figure 7: CubeSat Bus design utilized by USMA cadets, 2023.

Collecting non-localized in-situ measurements with a horizontal spatial resolution of just 10 m at the demand of solar temperament can only be achieved via satellite.

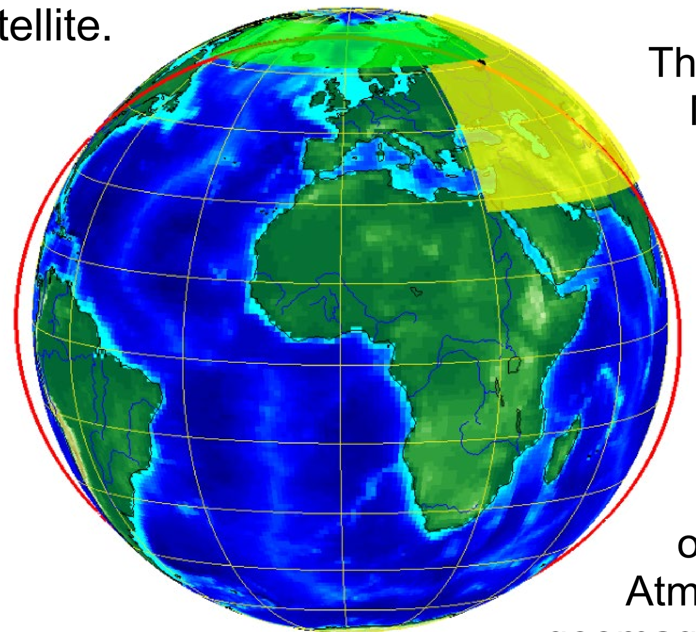

Figure 8: Orbital design for data collection allowing for 10,500 km of ionosphere to be measured.

The Polar Latitude Atmospheric Space Measurement & Analysis (PLASMA) research group is integrating the LP onto a very small satellite, known as a CubeSat. The orbital design allows for mostly horizontal data collection through the entire depth of the ionosphere and across both equatorial and polar latitudinal regions. Incorporating the probe on a CubeSat also allows the system to be "on demand", meaning data collection occurs when the National Oceanic and Atmospheric Agency (NOAA) forecasts a significant geomagnetic storm causing significant scintillation of radio wave propagation.

The CubeSat will be launched into a parking orbit of about 500 km inclined to roughly 70º and then transition into a data collection orbit when such a solar event occurs. Perigee of the data collection orbit is designed at an argument of about 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.

Data collected will be analyzed to characterize the plasma in the E-region ionosphere when affected by solar weather. This information will then be used to create an ionospheric model in Geometry and Tracking (GEANT4) modeling software to show how the environment affects radio wave propagation and the degree of error on space-based effects, such as GPS, experience due to scintillations caused by solar events.

Acknowledgements & References

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- Please ask presenter for a full list of references