In-Situ Rocket Investigation of a Mid-Latitude Sporadic-E Layer

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Abstract

In August 2022, the Space and Atmospheric Instrumentation Laboratory launched SpEED Demon, a tech demo sounding rocket from Wallops Flight Facility. The rocket payload was equipped with a suite of instruments capable of measuring both relative and absolute plasma densities. The main payload carried a Sweeping Langmuir Probe (SLP), 6 individual multi-Needle Langmuir Probes (mNLP), and a Planar Ion Probe (PIP). This instrument package provided 5kHz electron density measurements through a Sporadic-E layer. This work presents plasma density, electron temperature, and relative spacecraft charging. These in-situ measurements are supported by ground-based data from both Wallops' VIPIR Ionosonde and MIT Haystack Observatory's Incoherent Scatter Radar at Millstone Hill. Anomalies during the flight are also presented. Effects due to magnetic field alignment and surface contamination are included.

Langmuir Probes in Earth's Ionosphere

Langmuir probes are used to measure plasma densities and temperatures in both Earth's ionosphere as well as interplanetary space. In the case of a Sweeping Langmuir Probe (SLP), a voltage is swept across both negative and positive potentials with respect to the spacecraft chassis, and the resulting current is measured. Each current-voltage (IV) curve, shown in Figure 1, gives a single measurement of electron and ion density, electron temperature, and can even provide insight into spacecraft charging.

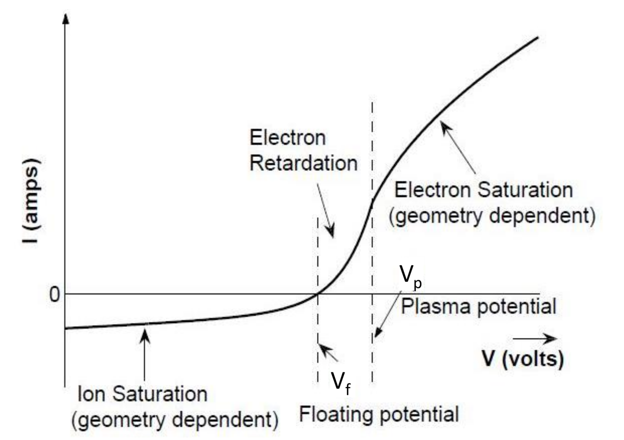


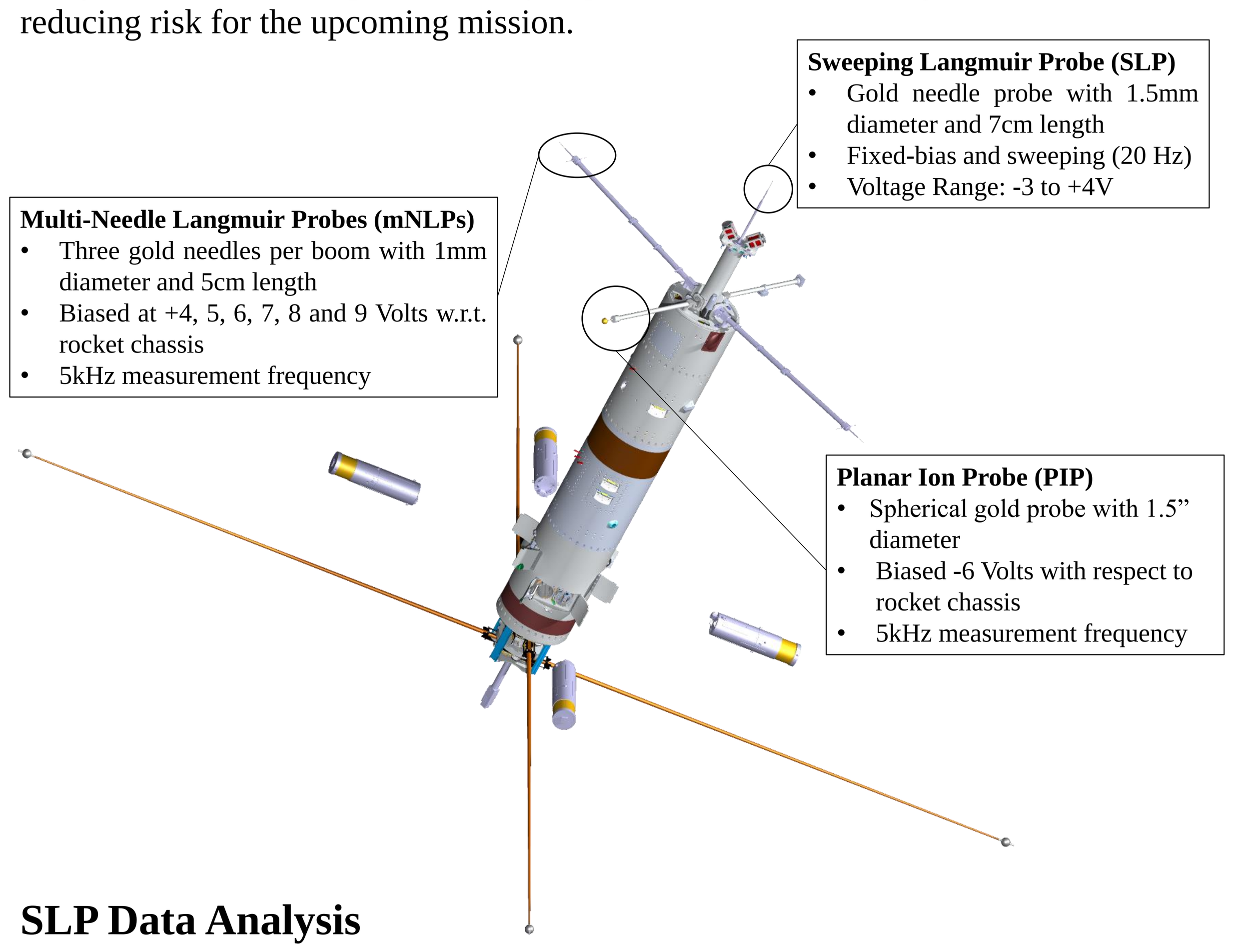
Figure 1: General IV curve showing the three main collection regions. Ion saturation current is amplified for ease of viewing. Figure from Barjatya [2007].

Sporadic-E Layers

Sporadic E (Es) are thin layers of enhanced electron density that commonly form between 90-130km during the summer months. These high density layers reflect radio waves at significantly higher frequencies than normal and therefore, have implications on radio wave propagation. They are generally understood to be formed by vertical shears in the neutral wind that result in heavy ion accumulation within the sporadic-E layer.

Sporadic-E ElectroDynamics Demonstration (SpEED Demon)

SpEED Demon was a NASA technology demonstration mission for the SEED campaign that will launch two rockets into low latitude Es layers from Kwajalein Atoll in Summer 2024. The payload was equipped with a suite of instruments designed to measure Sporadic-E layer patchiness and field-aligned currents, while reducing risk for the upcoming mission.



SLP Data Analysis

The SLP IV curves provide plasma densities, payload floating potentials, and electron temperature measurements at a rate of 23 Hz. The data products from the SLP are used to seed least-squares fitting routines for the 6 mNLP fixed bias points allowing for absolute plasma densities at 5kHz sampling frequency.

Both SLP and mNLP fit the electron saturation region using a nonlinear least-squares routine following Orbital Motion Limited (OML) theory. When the signal to noise ratio is sufficiently large, the SLP retardation region can be fit for electron temperature, again following OML theory. Relevant equations are given below.

Electron Retardation, when $V < V_p$:

$$I_e(V) = I_{th_e} exp(-|\frac{e(V-V_p)}{k_B T_e}|)$$

$$I_i(V) = -I_{th_i}\left(1-\frac{e(V-V_p)}{k_B T_i}\right)^{\beta}$$

$$I_{ram}(V) = -eN_i A_{ram} v_{ram}$$

Electron Saturation, when $V > V_p$:

$$I_e(V) = I_{th_e}\left(1+\frac{e(V-V_p)}{k_B T_e}\right)^{\beta}$$

Where $I_{th,j} = N_j eA\sqrt{(k_B T_j/(2\pi M m_j)}$ is the random thermal current to the probe, e is electron charge, k_B is Boltzmann's constant, $m_{i,e}$ is ion/electron mass, V is the voltage applied to the probe, and V_p is the plasma potential.

Ground Based Support: VIPIR Ionosonde and Wallops Digisonde

The Vertical Incidence Pulsed Ionospheric Radar (VIPIR) at NASA Wallops provided ground-based measurements of the Sporadic E Layer. Figure 2 shows VIPIR data while Figure 3 shows Digisonde data on August 24th, 2022 at 1:20 UTC, four minutes after launch. The Es lower boundary is identified at 102km and the layer's critical frequency (ω_p) at roughly 2.9MHz. The plasma frequency can be used find the peak electron density using the following relation:

$$N = (\varepsilon_o\, m\, \omega_p^2/e^2)^{1/2}$$

Es peak density: 1.05e11/m³

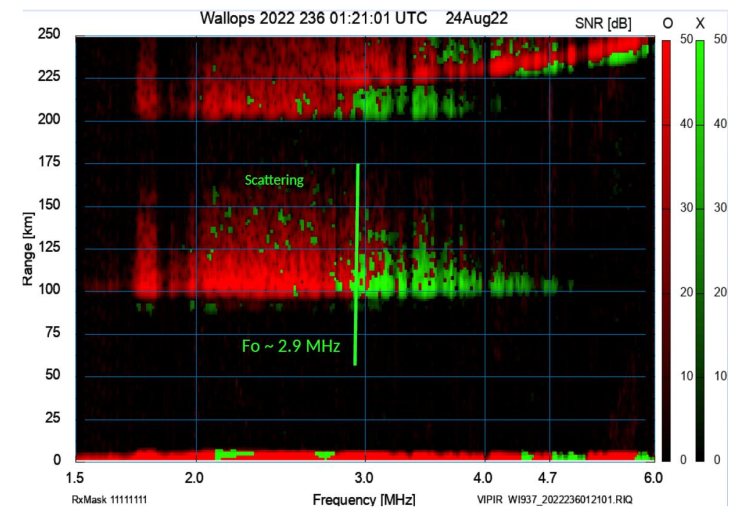


Figure 2: VIPIR plot showing both O (red) and X traces (green). Critical frequency is identified at 2.9MHz.

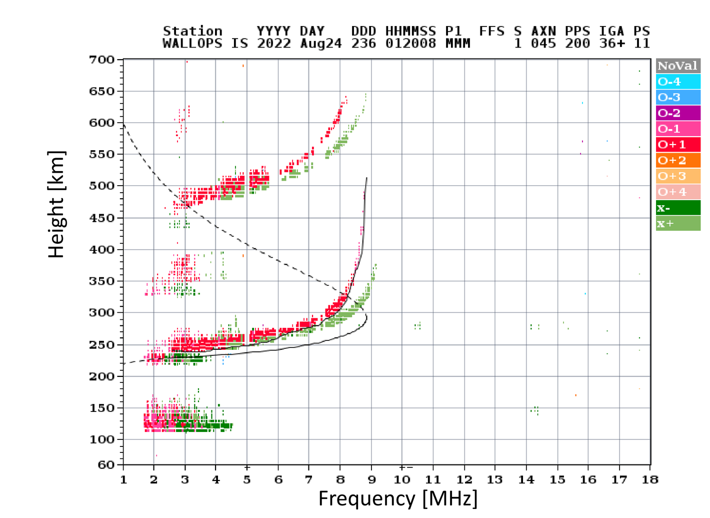


Figure 3: Digisonde data showing both O (red) and X (green) traces.

Ground Based Support: MIT Haystack Observatory's Incoherent Scatter Radar (ISR)

SpEED Demon was also supported by MIT Haystack's Millstone Hill ISR. Figure 4 shows both density and corresponding error for a 10 hour window surrounding launch at 08-24 1:16 UTC. The steerable antenna is pointed with an elevation of 16° and an azimuth of -163°. It is important to note that although ISR is pointed in the direction of Wallops, it is nearly 800km northeast. Therefore, lower altitude measurements may see significant variation.

ISR data shows densities near 1e10/m³ at 180km at the time of launch with notable error at lower altitudes. It also identifies the F2 peak at roughly 8e11/m³ at the time of launch.

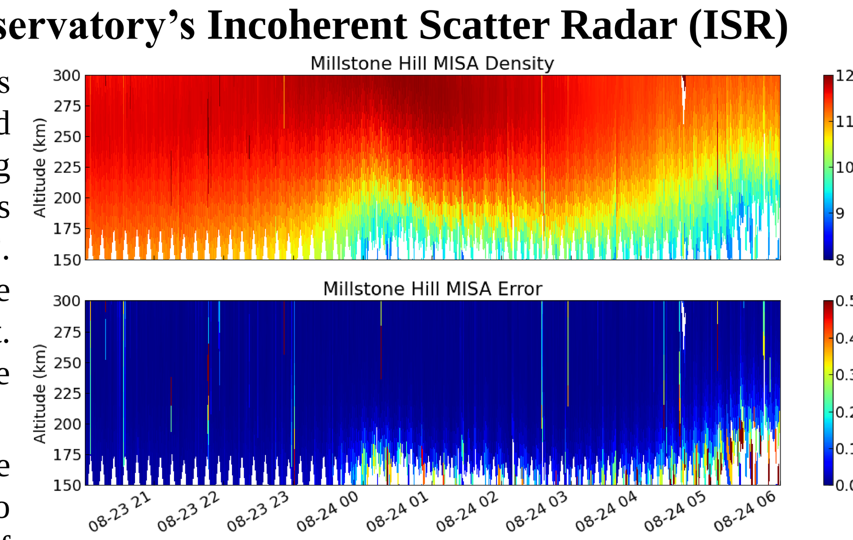


Figure 4: Plasma density and associated error measured by MIT Haystack's ISR. Launch occurred on 08-24 at 1:16 UTC.

In-Situ Preliminary Results

Figure 5 shows derived densities from both the SLP and mNLP. Both instruments identify strong enhancements in density between 102-104km on the upleg and 100-104km on the downleg. SLP and mNLP measure upleg peak densities of 1.55e11/m3 and 1.7e11/m3, respectively. These show some agreement with VIPIR's Es peak considering the measurements are separated in both time and space. SLP and mNLP show some disagreement at higher altitudes.

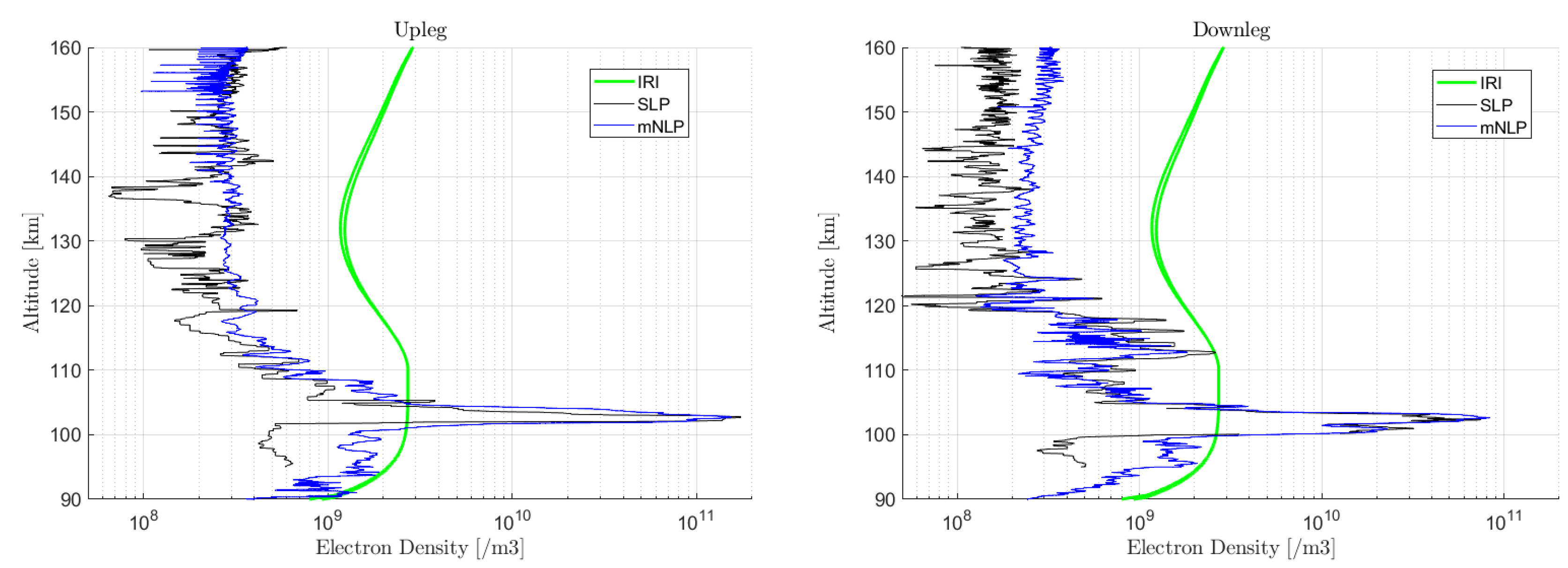


Figure 5: Derived densities for both upleg (left) and downleg (right). SLP results are given in black, mNLP in blue, and modeled IRI in green.

In regions of high SNR, electron temperature derivations are made possible by fitting the electron retardation region. Figure 6 shows SLP derived densities and preliminary temperatures within the downleg Es layer. Electron temperature appears to have a positive correlation with density inside the layer. However, magnetic field effects in the electron saturation region warrant further analysis and investigation into associated error.

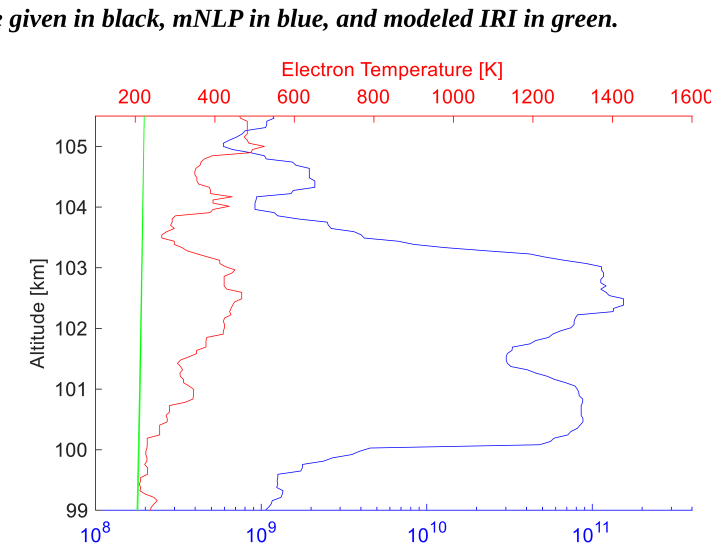


Figure 6: Derived densities, electron temperatures, and IRI temperature model within the downleg Es layer.

Figure 7 shows SLP's relative payload charging measurements. The payload potential drops over a volt negative within the Es layer but remains relatively stable with fluctuations at higher altitudes. Similar charging was experienced by the Sudden Atom Layer payload, a 1998 sounding rocket mission from Puerto Rico. Barjatya and Swenson [2] attribute the behavior to triboelectric charging associated with the Es layer's metal concentration.

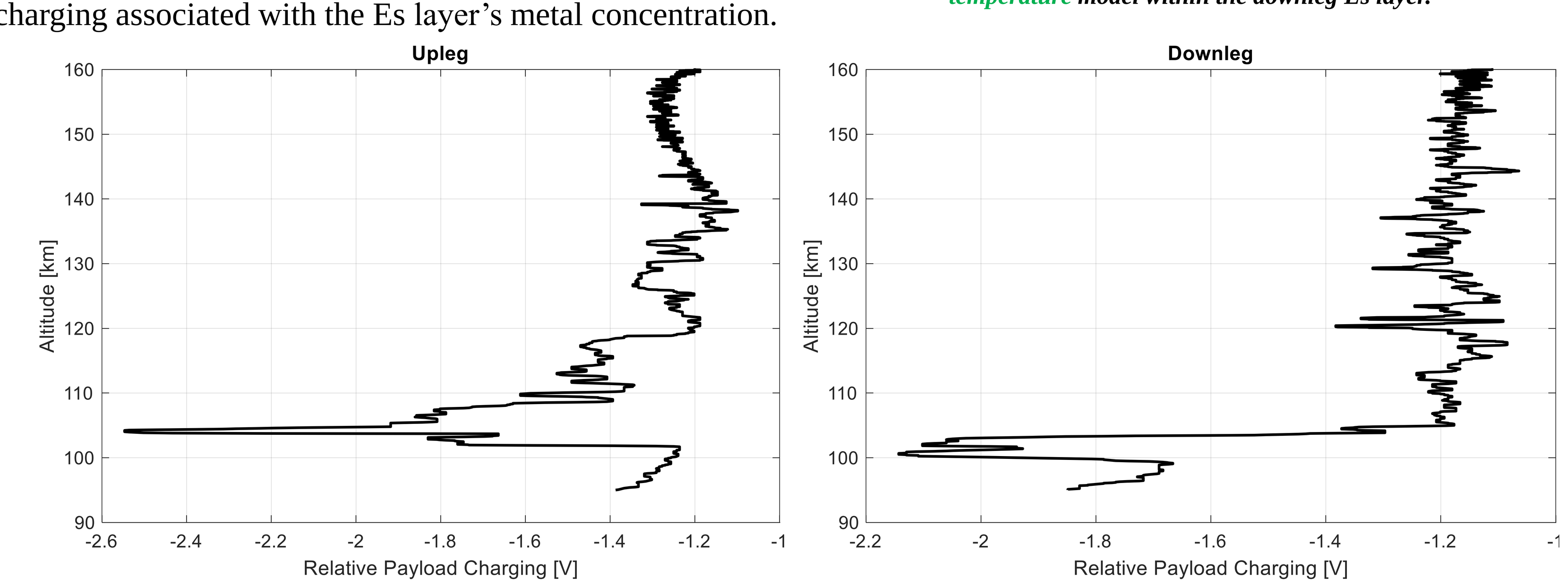


Figure 7: Relative payload charging measured by the SLP for both upleg (left) and downleg (right).

Anomalies During Flight – Magnetic Field Alignment

Magnetic field alignment has been shown to cause a negative current characteristic in the electron saturation region [3]. In the presence of a sufficiently strong magnetic field and large Debye length, electrons gyrate within the probe's sheath. As the voltage applied to the probe increases, the sheath expands and the number of electrons lost to the plasma exceeds those collected by the probe. This results in a sudden drop in current collection.

The SpEED Demon payload saw a range of orientations relative to the magnetic field as a result of ACS issues during the upleg. The payload's angle to B is shown in Figure 8.

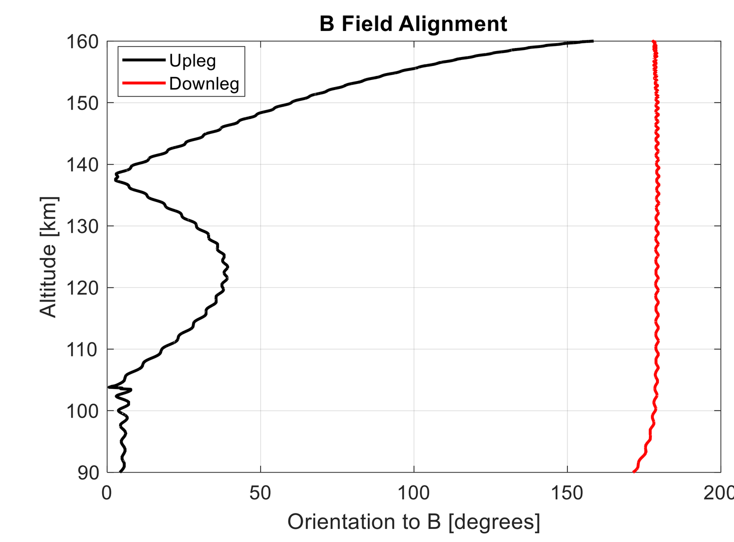


Figure 8: Departure from B field alignment for upleg (black) and downleg (red).

This negative characteristic is apparent when SpEED Demon's SLP is aligned to the magnetic field. Figure 9 shows IV curves from both the upleg and downleg in similar regions of background plasma but differing B field orientations. The upleg is 24° from parallel while the downleg is 1.2°. The downleg electron saturation region is dominated by magnetic field effects.

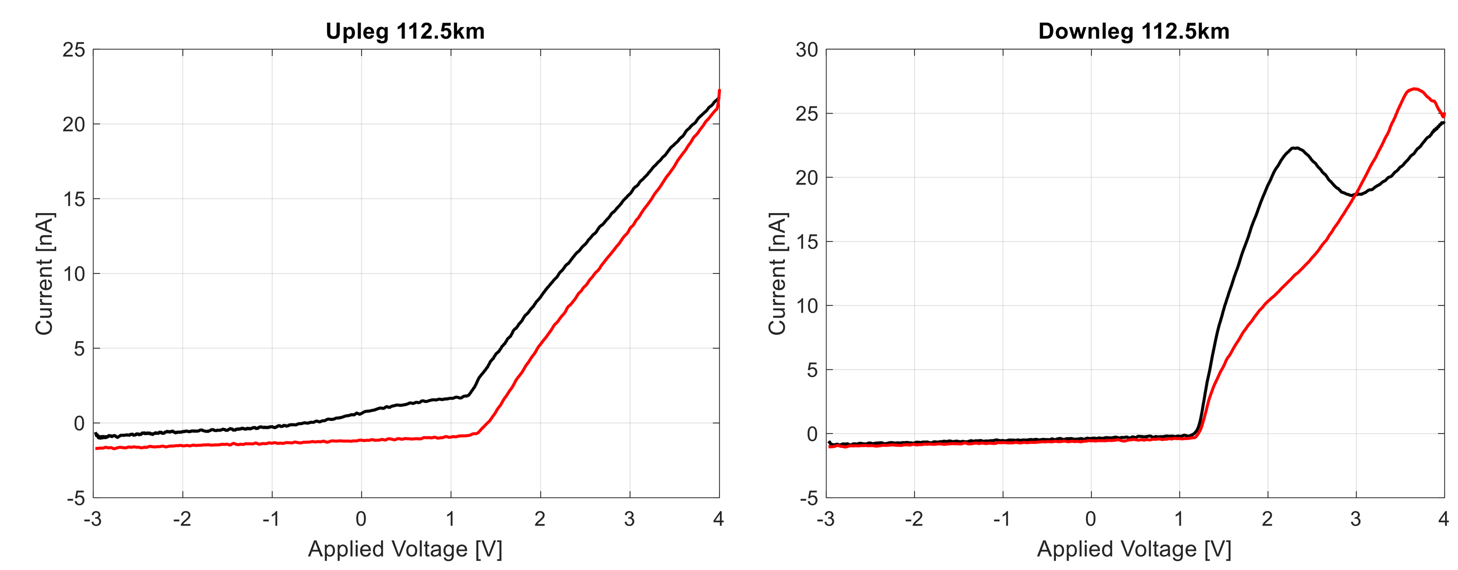


Figure 9: SLP IV curve at 112.5 km during the upleg (left) and downleg (right). Upsweep and downsweep are shown in black and red, respectively. The spin axis is 24 ° from the magnetic field vector during the upleg, while the downleg is 1.2 °.

Figure 10 shows IV curves from both the upleg and downleg in similar regions of background plasma and B field orientations. The spin axis is within 3° of the magnetic field in both cases and both see B field effects.

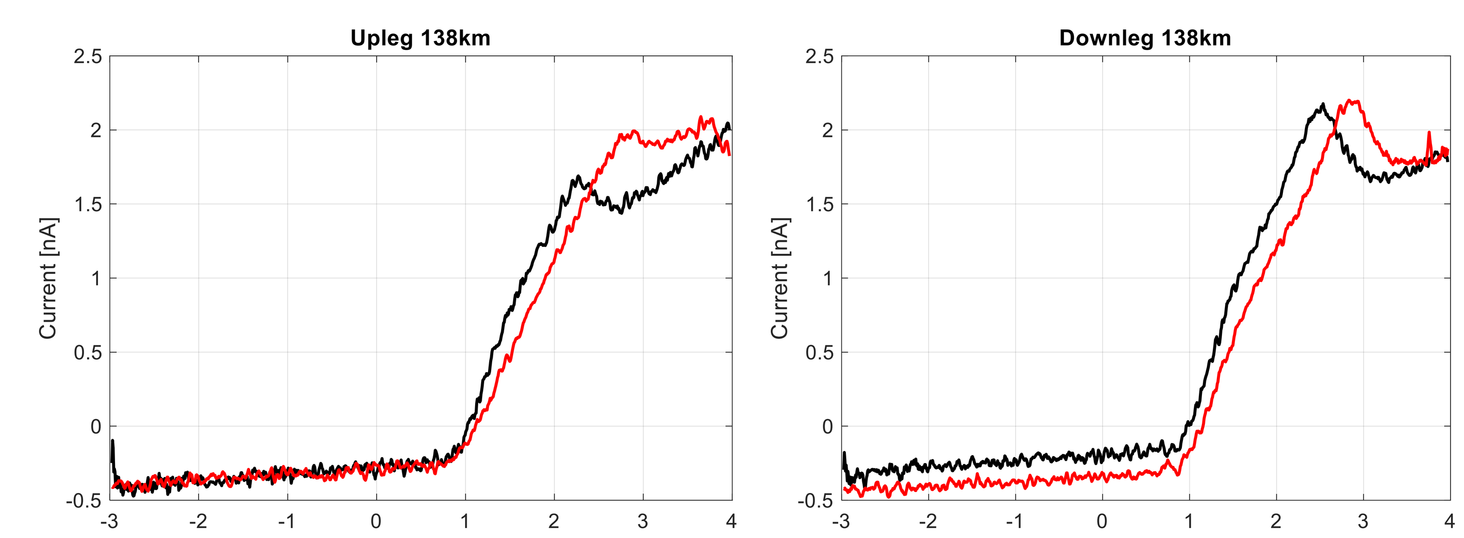


Figure 10: SLP IV curve at 138 km during the upleg (left) and downleg (right). The spin axis is 3° from the magnetic field vector during the upleg, while the downleg is 0.5 °. Upsweep and downsweep are shown in black and red, respectively.

The negative characteristic presents in different shapes and sizes over the duration of the flight as shown in Figure 11. It is not present within the Es layer where smaller Debye lengths occur. The disagreement between the SLP and mNLP in Figure 5 can likely be attributed to magnetic field effects resulting in lower SLP measured densities.

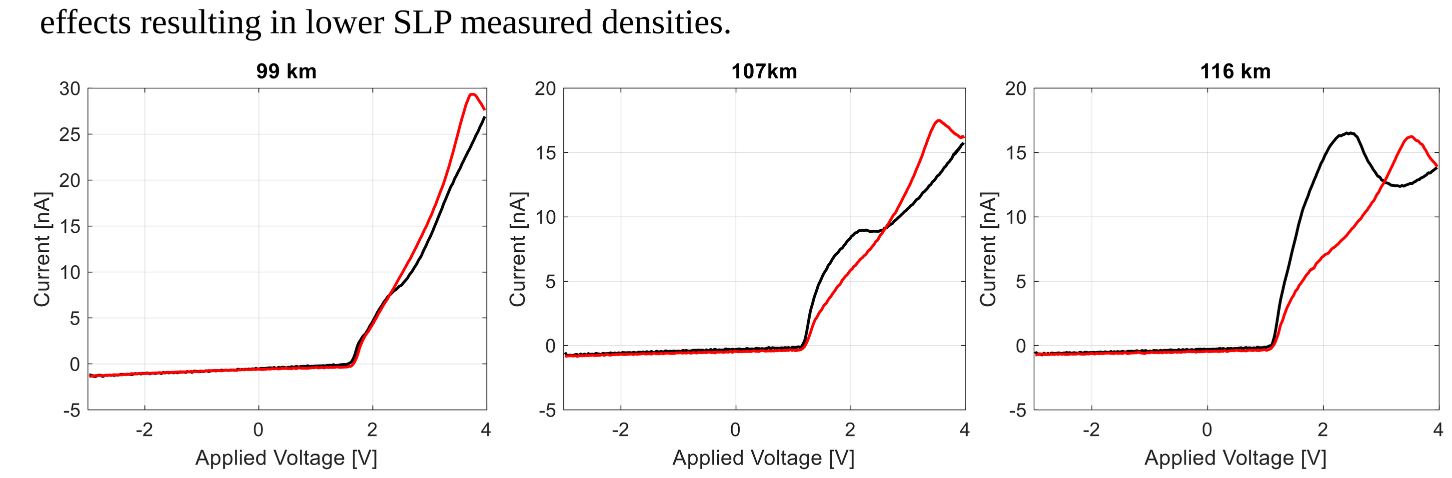


Figure 11: IV curves at various altitudes during the downleg. Upsweep and downsweep are shown in black and red, respectively.

Takeaways

- SpEED Demon made plasma density, electron temperature, and relative payload charging measurements through a Sporadic E Layer with 1.5e11/m3 peak density.
- Preliminary results show temperature enhancements and a positive correlation with plasma density inside the Es layer.
- Payload saw a more charging within the Es layer.
- Cylindrical sweeping probes aligned to the magnetic field fall victim to magnetic field effects that dominate the electron saturation region and result in lower derived densities.

References

[1] Barjatya, A., *Langmuir Probe Measurements in the Ionosphere*, PhD thesis, Utah State University, 2007.
[2] Barjatya, A., and Swenson, C. M. (2006), Observations of triboelectric charging effects on Langmuir-type probes in dusty plasma, *J. Geophys. Res.*, 111, A10302, doi:10.1029/2006JA011806.
[3] Dote, T. and Amemiya, H., "Negative Characteristic of a Cylindrical Probe in a Magnetic Field", *Journal of the Physical Society of Japan*, vol. 19, no. 10, pp. 1915–1924, 1964. doi:10.1143/JPSJ.19.1915.