Characterizing Small-Scale Irregularities in Sporadic E Layer using In-Situ Distributed Density Measurements

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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 main payload was equipped with a suite of instruments including a Sweeping Langmuir Probe (SLP), 6 individual multi-Needle Langmuir Probes (mNLP), and a Positive Ion Probe (PIP), as well as four ejectable subpayloads, each containing one PIP. This instrument package provided 5kHz distributed electron density measurements through a nighttime mid-latitude Sporadic-E layer. Both the main payload and ejectables measured small-scale irregularities within the main Es layer varying slightly in altitude. The power spectra of the measured density fluctuations are presented. Spectral characteristics are compared to previous in-situ data and the existence of instabilities at the Es layer boundaries are investigated.

Sporadic-E Layers

Sporadic E (Es) are thin layers of enhanced electron density that commonly form between 90-130km during the local 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, although this mechanism is not applicable universally and especially at very low or high latitudes.

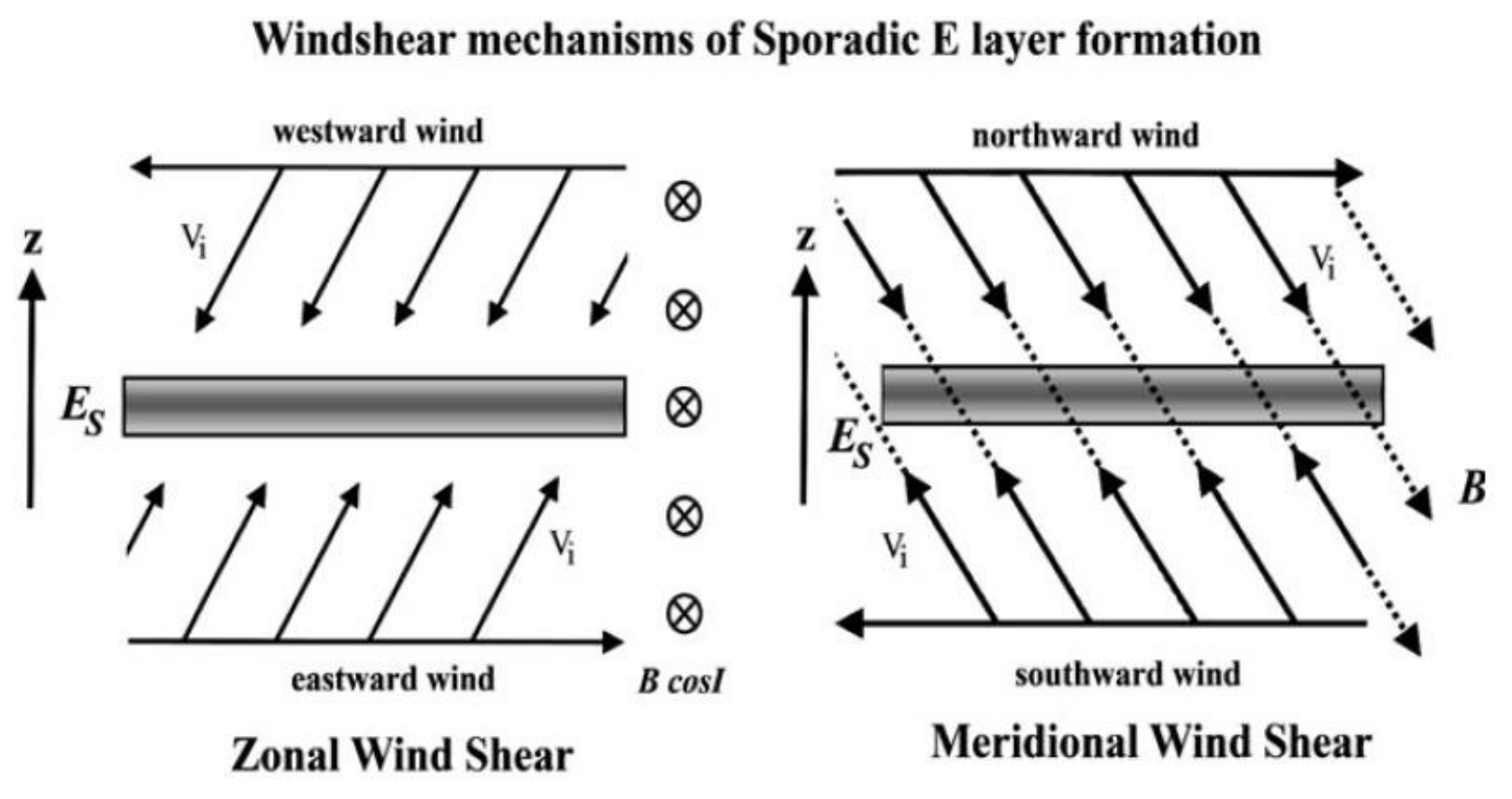
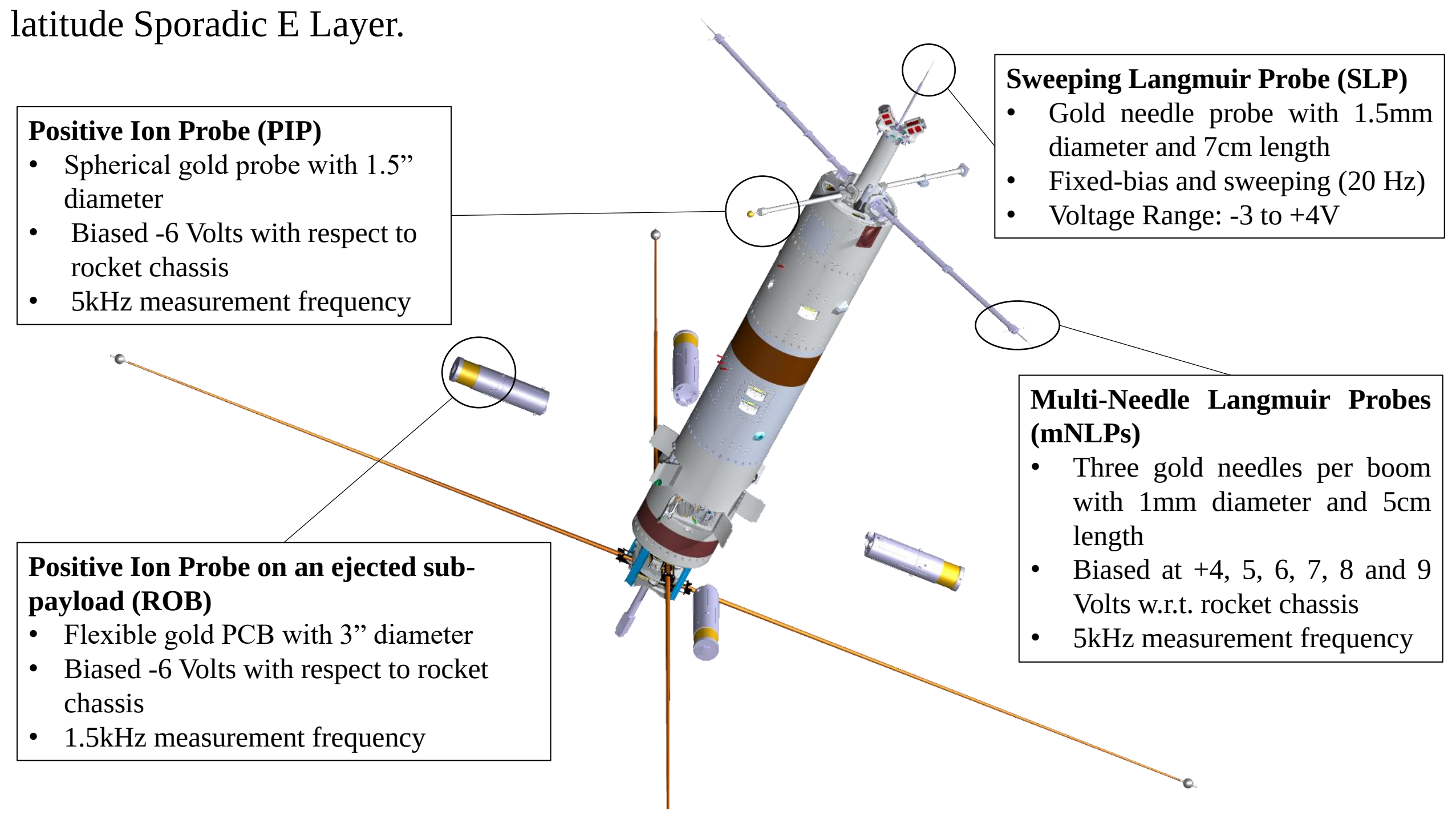


Figure 1: Sketches illustrating the zonal (*left*) and meridional (*right*) windshear theory mechanisms of sporadic *E* layer formation. [Haldoupis, 2011]

Sporadic-E ElectroDynamics Demonstration (SpEED Demon)

Sporadic-**E** **E**lectro**D**ynamics **Demon**stration – or SpEED Demon – was a sounding rocket mission launched from NASA's Wallops Flight Facility on August 23rd, 9:16 PM local time. The rocket's instrumentation suite was developed by Embry-Riddle Aeronautical University's Space and Atmospheric Instrumentation Laboratory (SAIL) with payload support and launch vehicle provided by NASA. The mission served as a technology demonstration flight for the upcoming SEED rocket campaign, scheduled to launch from Kwajalein in 2025. SpEED Demon was able to fly through and collected data from a mid-latitude Sporadic E Layer.



Positive Ion Probe (PIP)
- Spherical gold probe with 1.5" diameter
- Biased -6 Volts with respect to rocket chassis
- 5kHz measurement frequency

Sweeping Langmuir Probe (SLP)
- Gold needle probe with 1.5mm diameter and 7cm length
- Fixed-bias and sweeping (20 Hz)
- Voltage Range: -3 to +4V

Multi-Needle Langmuir Probes (mNLPs)
- Three gold needles per boom with 1mm diameter and 5cm length
- Biased at +4, 5, 6, 7, 8 and 9 Volts w.r.t. rocket chassis
- 5kHz measurement frequency

Positive Ion Probe on an ejected sub-payload (ROB)
- Flexible gold PCB with 3" diameter
- Biased -6 Volts with respect to rocket chassis
- 1.5kHz measurement frequency

SpEED Demon Langmuir Probes

The main payload carried a variety of Langmuir probes. This poster presents data from Positive Ion Probes (PIP) which is a Langmuir probe instrument that maintained a fixed-bias in the ion saturation region (Figure 2). That is, the probe is biased negative with respect to the plasma so that electrons are repelled, and positive charge is collected on the instrument's conductive surface. Analysis of the collected current allows for high-cadence *in-situ* measurements of relative change in ion density. The data are expressed in terms of absolute density only after measurements from other instruments have been considered. On the SpEED Demon rocket, there were 5 PIP instruments. One was installed on the main payload, mounted on a deployable boom and 4 were integrated into the ejectable subpayloads (called ROB). Figure 3 shows each instrument prior to integration.

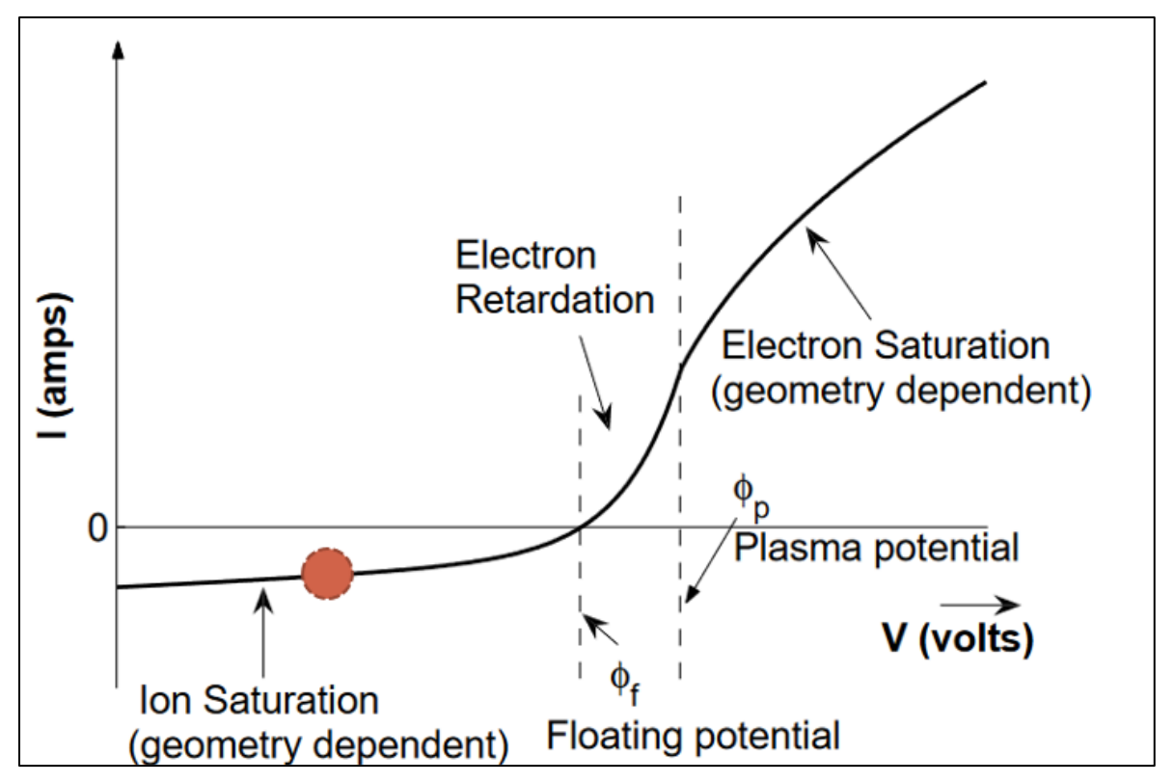


Figure 2: IV curve for a general Langmuir probe. PIP instruments are biased negative w.r.t plasma (orange dot) and collect ion current [1].

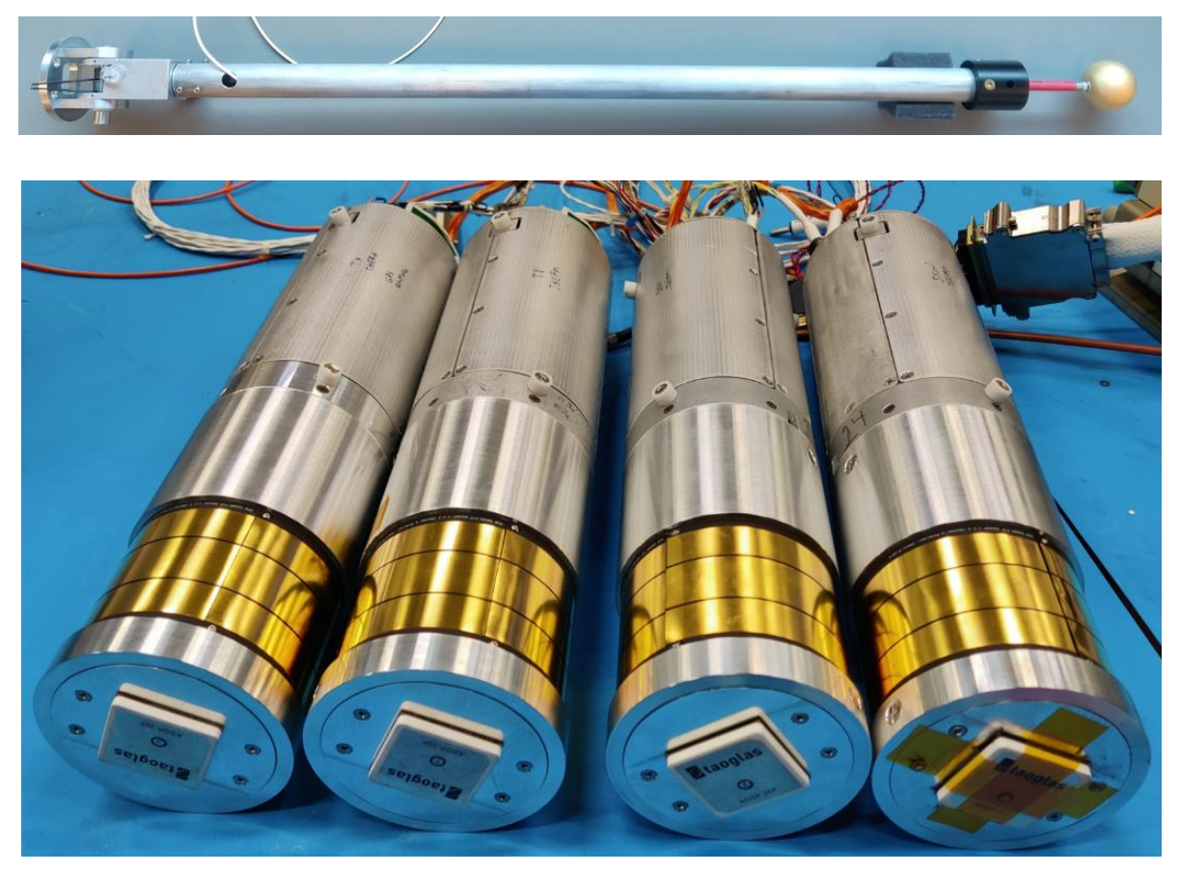


Figure 3: (Above) Main payload gold-plated, spherical PIP sensor on deployable boom. (Below) ROB ejectable subpayloads. Gold, cylindrical sensor.

SpEED Demon Density Measurements

The SpEED Demon payload passed through a Sporadic E layer near 102km on both the upleg and downleg of the flight. The absolute plasma densities derived from the mNLP main payload instrument are shown in Figure 4. The downleg layer is double-peaked and spans roughly 4 km.

The subpayload relative density measurements and relative locations in space are shown in Figure 5. As the subpayloads become more separated on the downleg, they measured different density structures and fluctuations. The subpayload pairs (1+2 and 3+4) are separated by over 2km during the downleg crossing

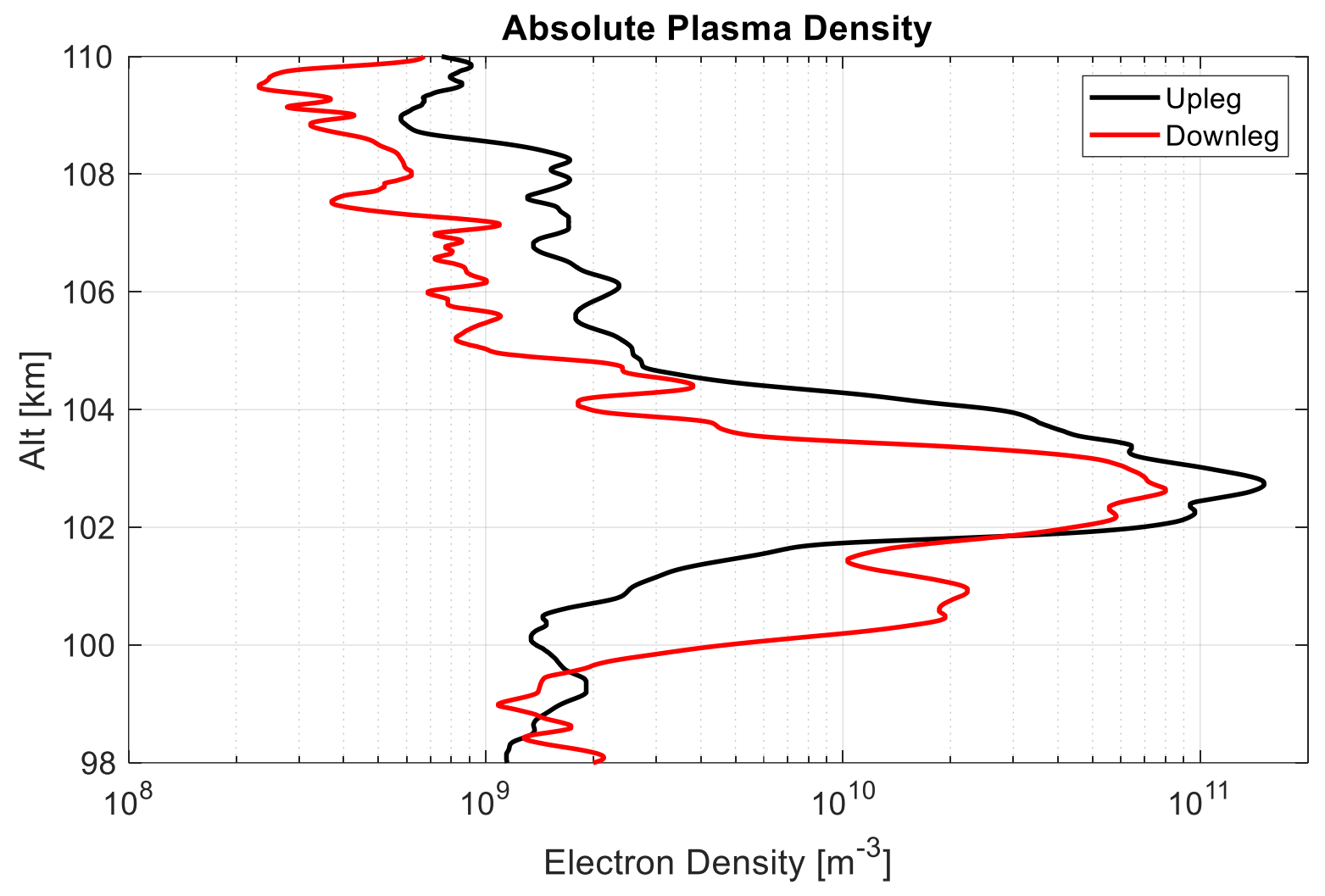


Figure 4: Derived plasma densities for both upleg (black) and downleg (red).

Upleg Sporadic E Layer Crossing

Downleg Sporadic E Layer Crossing

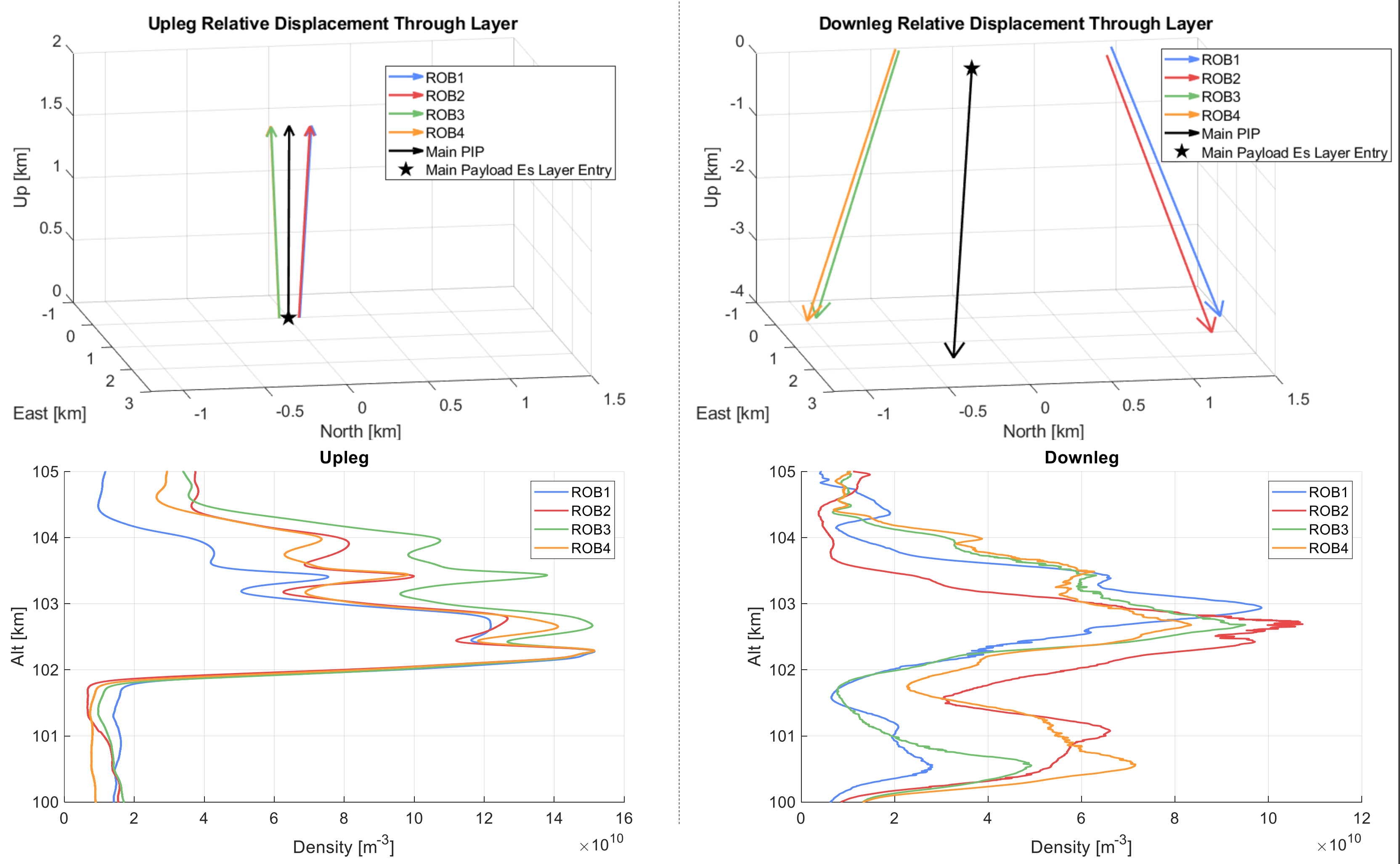


Figure 5: Relative displacement of both the subpayloads and main payload during Es layer crossing (top). Relative plasma densities measured by the four subpayloads during both the upleg (left) and downleg (right) Es layer crossing. Densities are normalized using the absolute plasma densities provided by the main payload mNLP instrument package.

Vertical Ion Drift Velocities and Es Layer Variation

If we assume a steady-state sporadic-E layer (constant, horizontally stratified neutral winds), we can estimate the vertical ion drift velocity required to maintain the layer against diffusion [Bernhardt, 2002; Miller 2005; Dalakishvili, 2020]. The ion continuity equation is given by,

$$\frac{\partial N}{\partial t} = Q - L - \frac{\partial}{\partial z}(NW) + \frac{\partial}{\partial z}\left(D\,\frac{\partial N}{\partial z}\right)$$

where $\frac{\partial N}{\partial t} = 0$, following our steady-state assumption. Since sporadic-E layers are primarily composed of long-lived metallic ions, Q and L are negligible. Therefore, the vertical ion drift velocity is

$$W = D\,\frac{\partial}{\partial z}(\ln N_m)$$

For simplicity, we assume the layer is composed of only metallic ions and therefore, refrain from calculating drift velocities at the boundaries where the metallic ion concentration rapidly falls off. The results are shown in Figure 6. It is important to emphasize that these values represent the **ion drift velocity required to maintain the layer from neutral wind shear alone.**

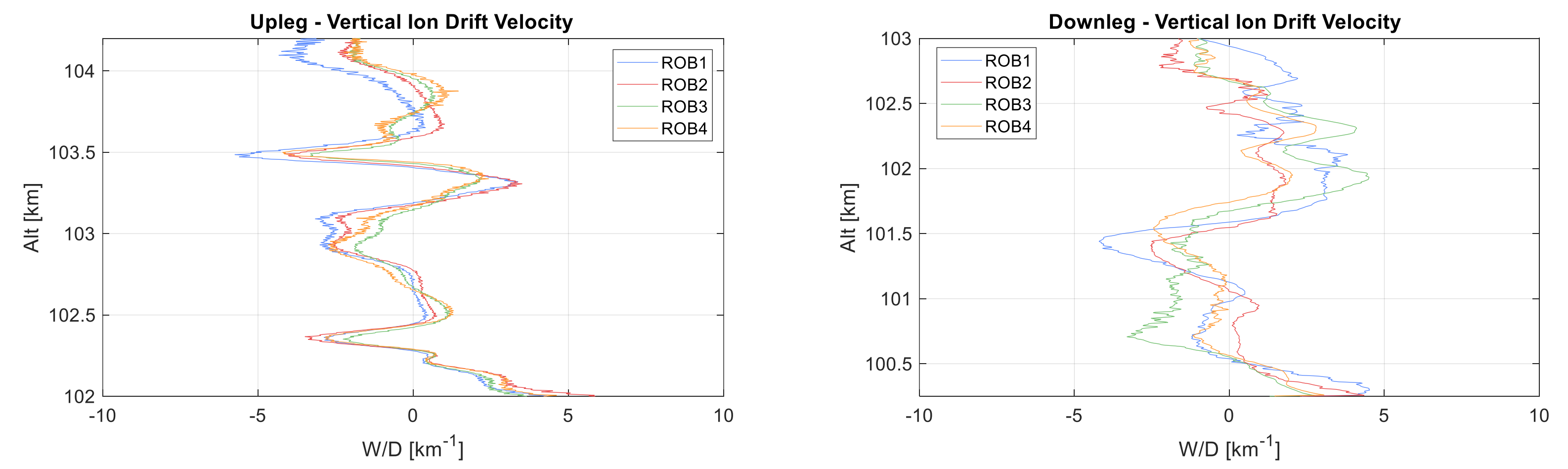


Figure 6: Vertical ion drift velocity (normalized by the ion diffusion coefficient) required to maintain the layer from neutral wind shear.

Horizontal Variations: During the upleg Es layer crossing all subpayloads are within hundreds of meters and see similar structure, particularly at the lower altitudes. The subpayloads' separation on the downleg results in differences in both magnitude and altitude, suggesting the layer is dynamic in the horizontal plane. The pairs of ROBs in similar regions of plasma (1+2 and 3 +4) continue to see similar structure throughout the layer.

Driving Mechanism: With more analysis, horizontal wind velocities can be derived assuming the layer is only driven by neutral winds and then compared to SpEED Demon's in-situ neutral wind measurements which are still being analyzed.

Takeaways

- SpEED Demon traversed a Sporadic E layer that is non-homogenous in the horizontal plane at kilometer scales.
- Small-scale irregularities are dominant on the topside and within the layer.
- **Following the combination of horizontal variation, steep spectral slopes, and either vertically or field aligned irregularities, we propose the layer is driven by an instability on the topside.**

Small-Scale Irregularities

Small-scale density irregularities are found both above and within the Es layer. During the downleg, all four subpayloads measure fluctuations at different locations within the layer, as shown in Figure 7, where the plots are arranged from the southernmost to northernmost subpayload. ROBs 1+4 are separated by roughly 1 km north/south.

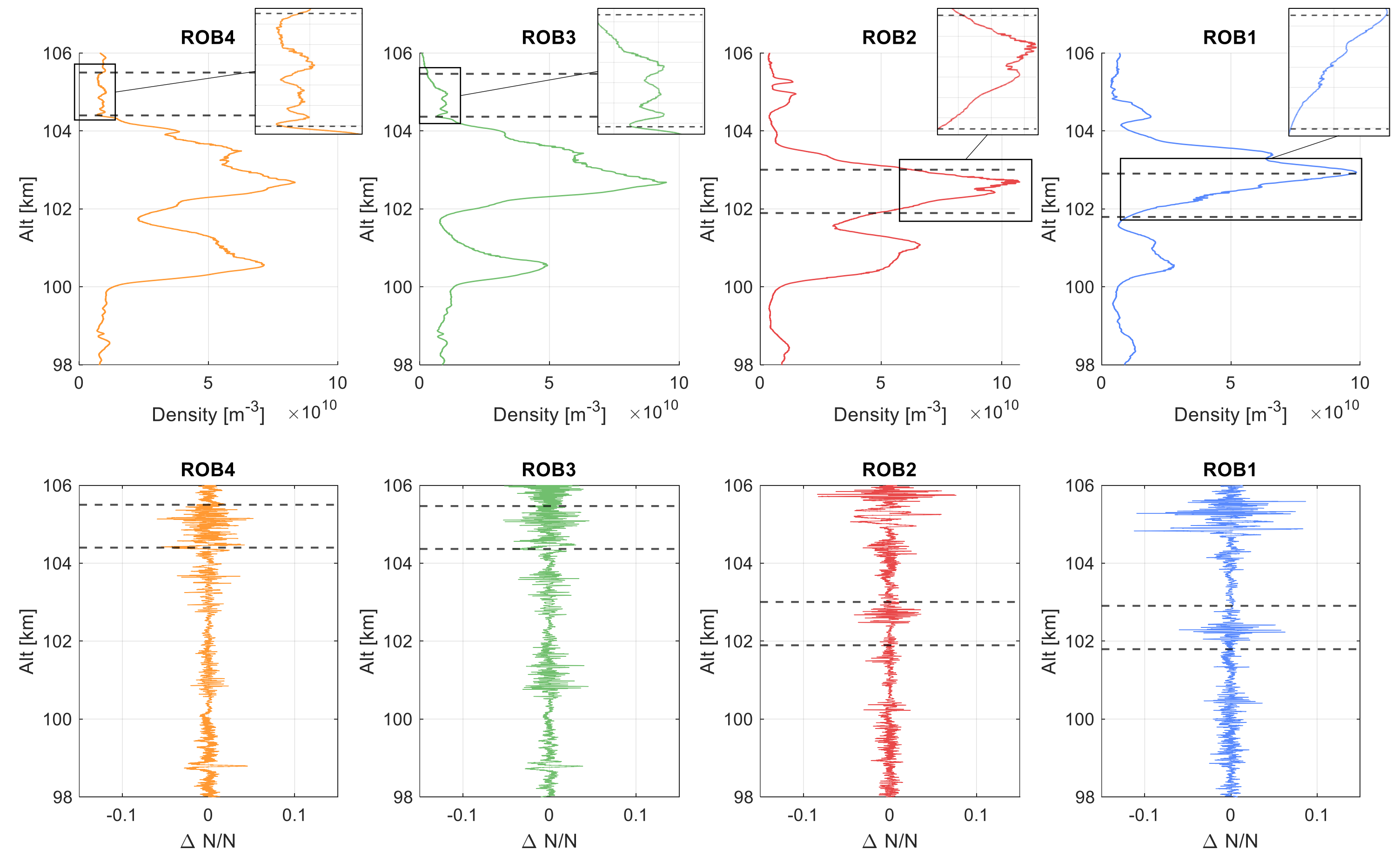


Figure 7: Subpayload relative density measurements during the downleg Es layer crossing (top) and their corresponding density fluctuations (bottom). Horizontal dashed lines represent magnetic field lines mapped from ROB4 if we neglect the east/west displacement.

The payloads see the Es layer peak at largely the same altitude and time, but measure density fluctuations at different points within and above the layer. We offer two possibilities

1. **Vertically propagating irregularities:** Ion drift profiles suggest the layer is non-homogenous in the horizontal plane. Since ROBS 1+2 are roughly 2km away from ROBs 3 + 4, there is a strong chance that turbulence and density irregularities occurred at different altitudes.
2. **Field-aligned irregularities:** The bands in Figure 7 represent regions mapped by magnetic fields assuming a magnetic dip angle of 63.737°. These calculations ignore the east/west payload displacements shown in Figure 8. The irregularities seen by ROB4 above the layer map to the regions within the layer for ROBs 1 and 2. This offers the possibility that the irregularities are field-aligned. This conclusion is supported by magnetic field scattering measured by VIPIR, shown in Figure 9, and suggests either the two-stream or gradient-drift instability [Haldoupis, 2011].

In both cases it is difficult to distinguish between spatial and temporal variations. In either case, the fluctuations above the layer are larger in magnitude and appear to dampen with descending altitude.

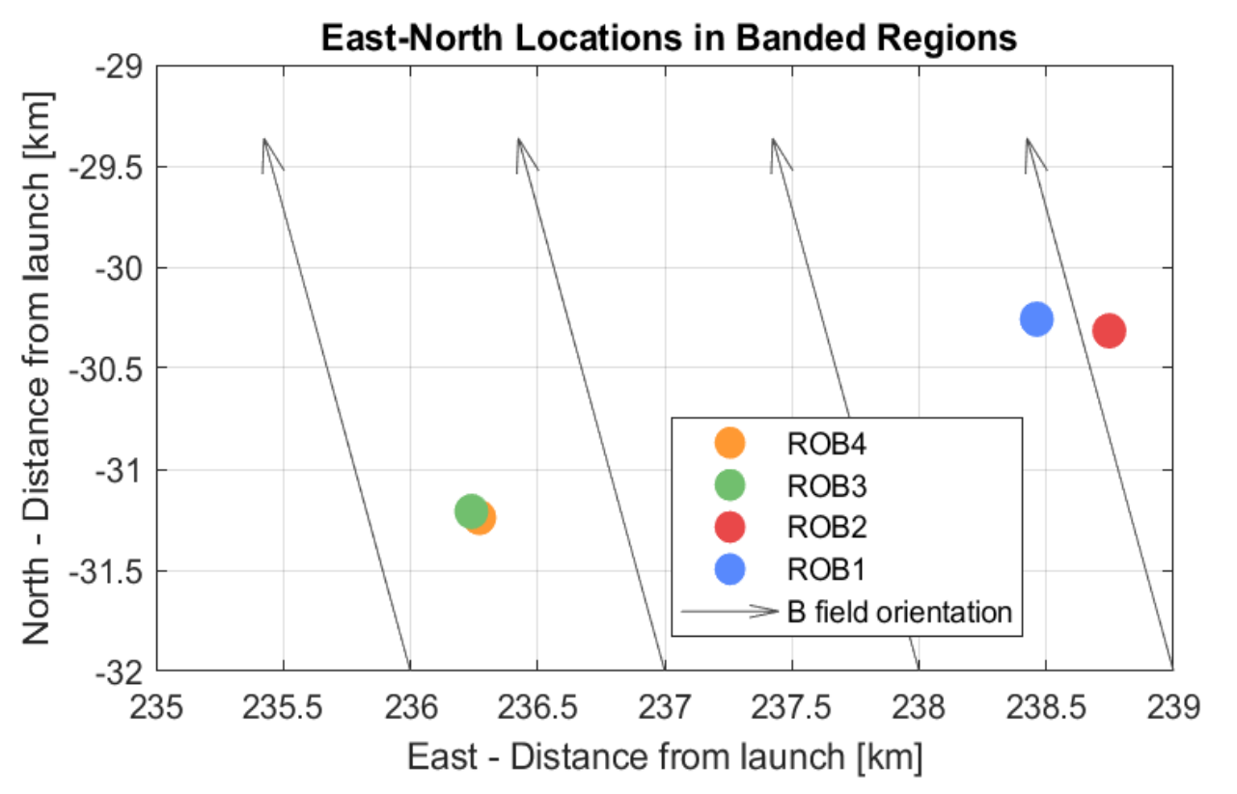


Figure 8: Locations of subpayloads within the banded regions of Figure 5 relative to the Wallops' launch site.

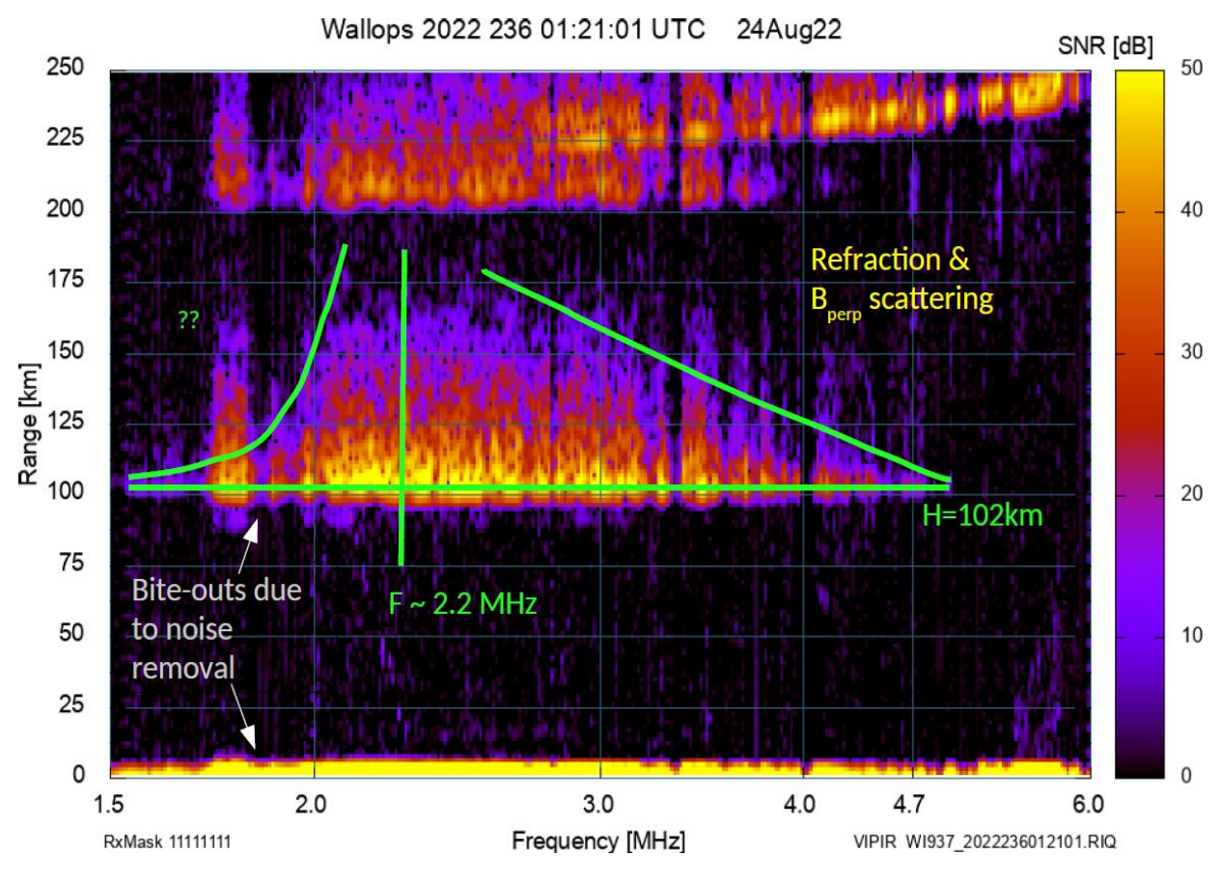


Figure 9: Vertical Incidence Pulsed Ionospheric Radar (VIPIR) data during the SpEED Demon flight.

Density Fluctuations Power Spectra

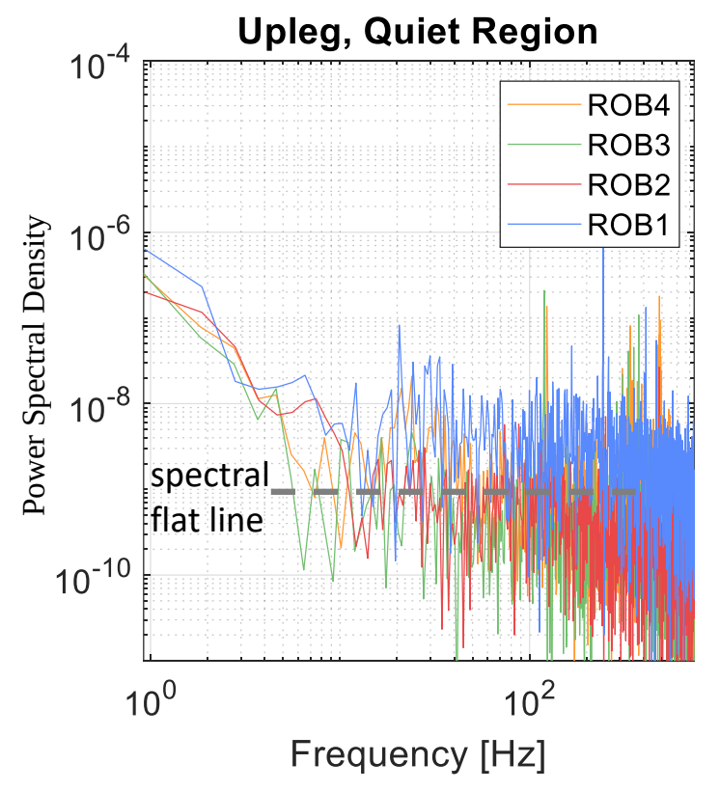


Figure 10: Power spectral density during quiet upleg regions.

Power spectral density plots are created for the banded altitude regions in Figure 7, both for the upleg and downleg. The upleg serves as a spectral comparison, where measured fluctuations are within 2% of the measured density. Results are shown in Figure 10. During quiet regions, the spectral flat line occurs at roughly 10Hz.

The downleg spectra are shown in Figure 11 for each subpayload. The spectral slopes are fit following the power law, $P = k^{-\alpha}$, where P is the power spectral density and k is wavenumber [Kyzyurov, 2000]. The spectral slope, α, contains information about how energy is dissipated throughout the layer and can relate to different instabilities [Giono, 2021]. All four measure spectral slopes between 2.3-2.6 and indicate spectral flat lines near 200Hz (~6 meters).

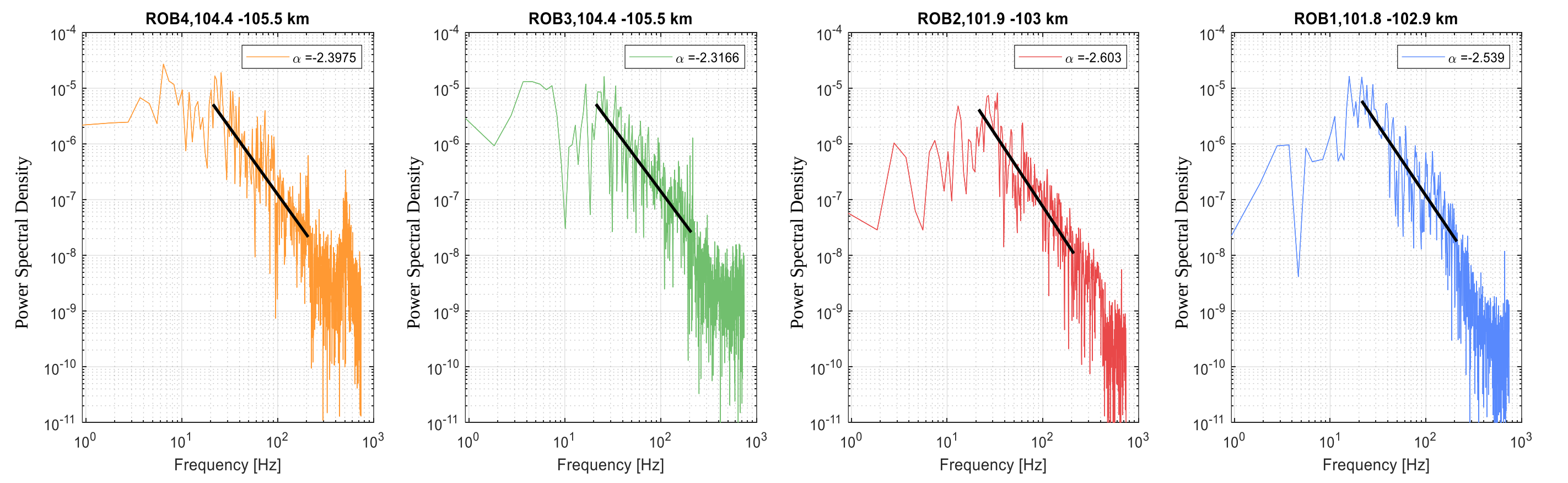


Figure 11: Power spectral density during active downleg regions indicated by the dashed lines in Figure 5.

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