Swarm-E Observation of Ion Composition and Small (Decameter) Scale Plasma Density Irregularities: Variability over a Solar Cycle and Impact on Magnetosphere-Ionosphere-Thermosphere (MIT) Coupling in the Topside Ionosphere

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Summary

IRM data over 8 years reveal important features in magnetosphere-ionosphere-thermosphere (MIT) coupling in topside ionosphere (2013/10 – 2021/12; at 325-1500 km): e.g.

- Effects of atmospheric photoelectrons on spacecraft charging
- Molecular and nitrogen (N+) ion enhancements in active auroral ionosphere
- Decameter-scale structures at both high and low latitudes (i.e., aurora, equatorial plasma bubbles)

IRM Ion Time of Flight (TOF) Measurements

Swarm-E imaging and rapid-scanning ion mass spectrometer (IRM):

- Combines ion time-of-flight (TOF), hemispherical electrostatic analysis, and 2D positional imaging
- Resolves ion mass-per-charge (M/q), energy-per-charge (E/q), and incident direction
- Simultaneously measures incident plasma current at high (1-ms) cadence

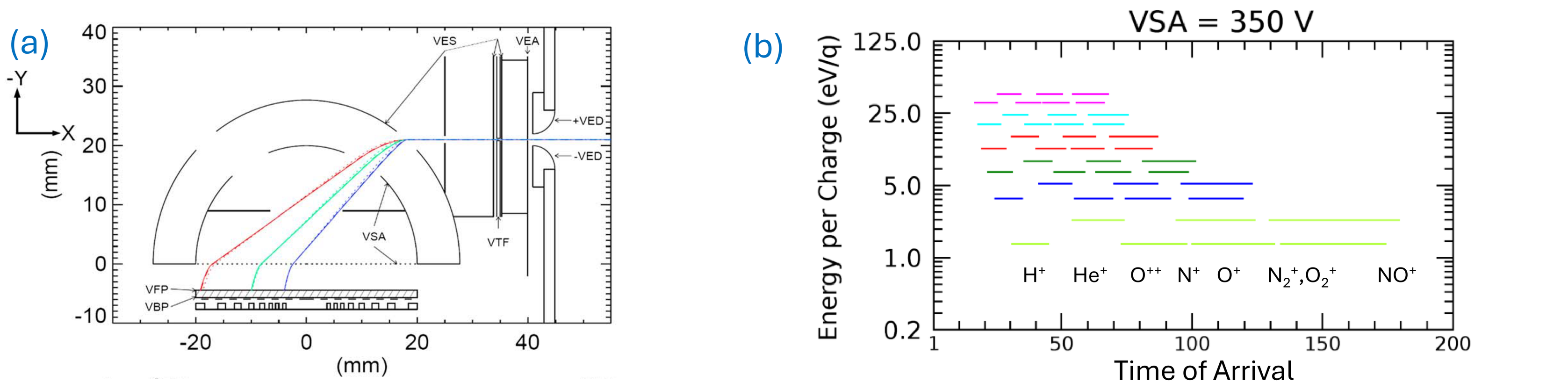


Figure 1: (a) schematic cross section of IRM sensor, showing simulated ion trajectories for V_{SA}= –174 V at E/q=1.3, 12.5 and 45.0 eV/q (cf. Yau and Howarth 2016) and (b) time of arrival (TOA) ranges for various ion species at V_{SA} = –350 V for the 6 lowest energy pixels

Spacecraft Potential and Ion Composition Analysis

Spacecraft Potential

- Significant effects of escaping atmospheric electrons in sunlit ionosphere above source altitude of atmospheric photoelectrons
- Other sources (than ambient electrons) of 'significant' negative (and positive) spacecraft potentials
- Small, non-negligible percentage of cases of highly negative potentials at low and high latitude

Method:

- Fit TOA distributions of measured ions in spacecraft ram at peak and adjacent pixels and V_{SA} (O+; other species where available).
- Infer spacecraft potential V_{SC} from measured ion velocity inside sheath v'(m) and corresponding velocity outside sheath v(m) (multi-species analysis) or spacecraft ram velocity v_{ram} (single-species analysis)

$$V_{SC} = \frac{-m}{2q}\left(v'(m)^2 - v(m)^2\right)$$

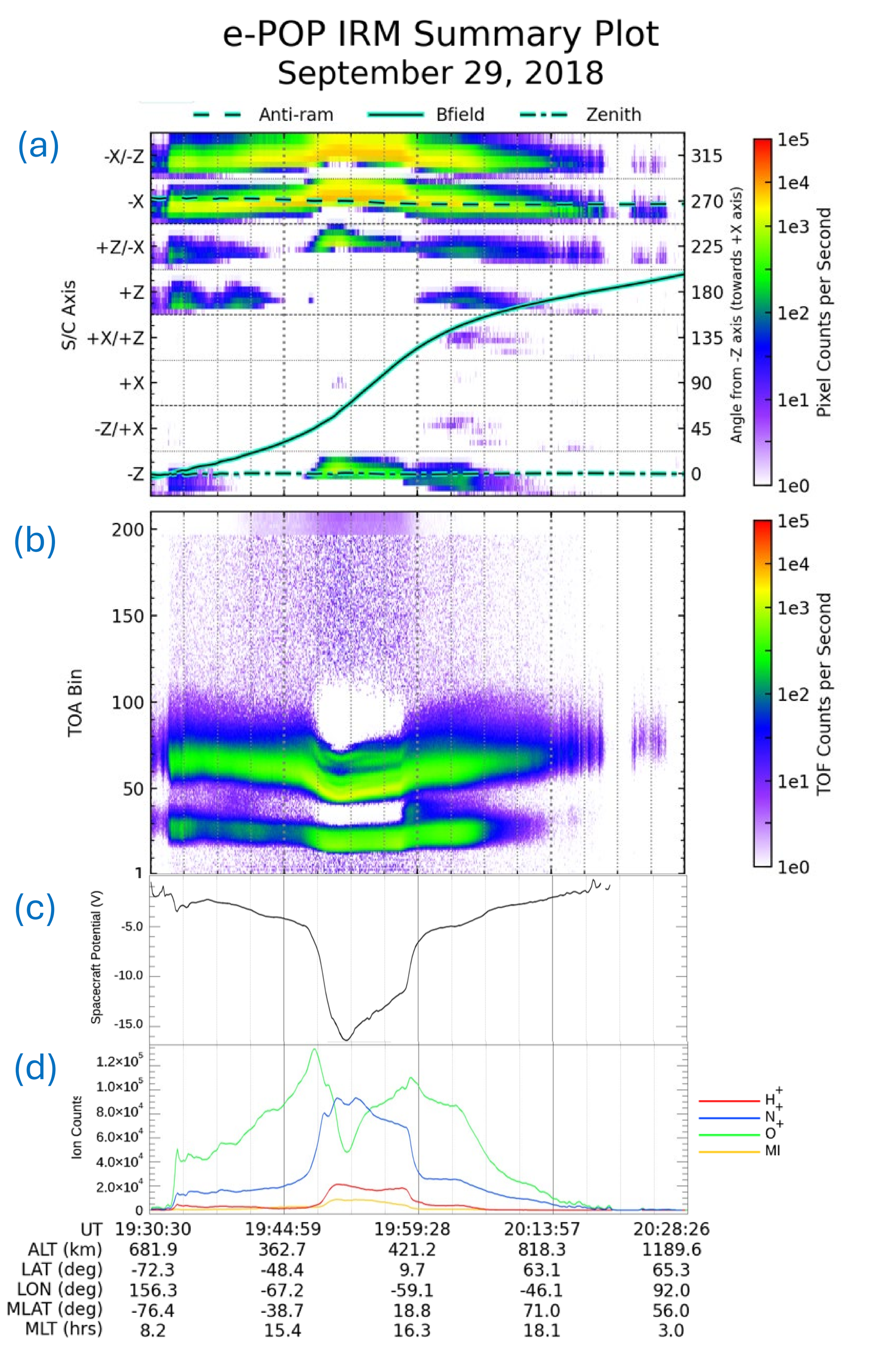


Figure 2: IRM summary plot showing (a) energy-time spectrograms at 8 angles and (b) time of flight spectrogram of measured ions, and (c) inferred spacecraft potential and (d) ion composition

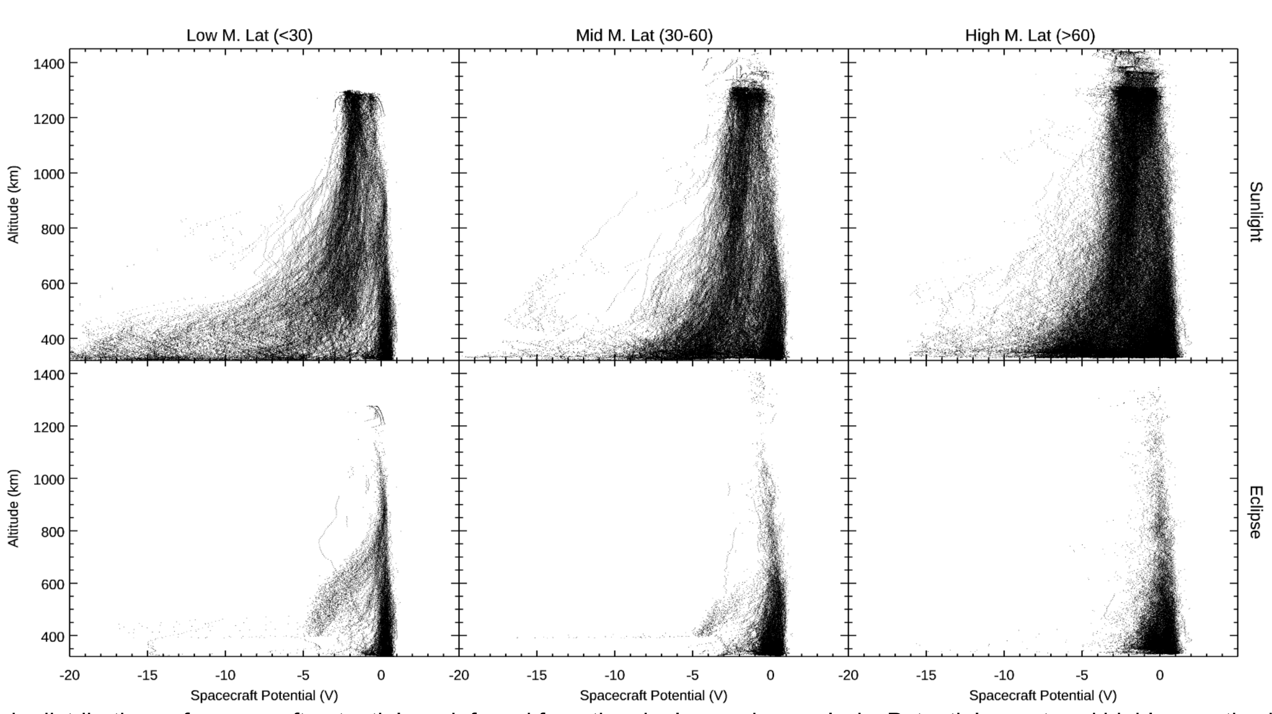
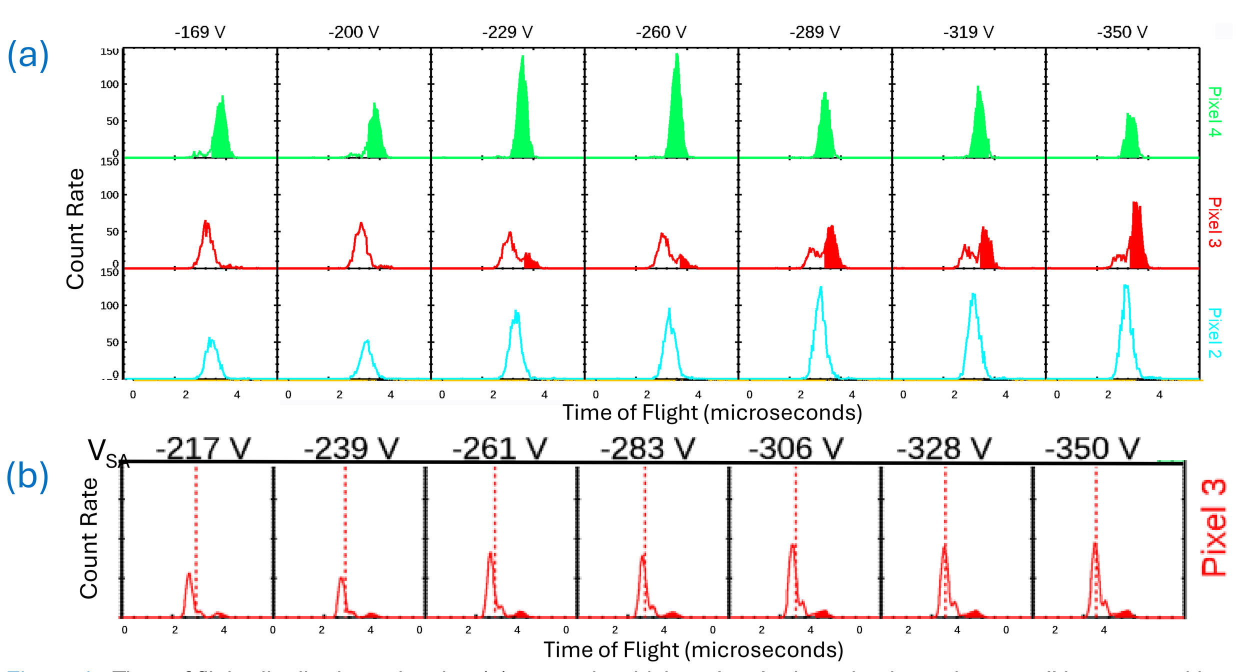


Figure 3: Altitude distributions of spacecraft potentials as inferred from the single-species analysis. Potentials can trend highly negative in the low-altitude and low-latitude sunlit ionosphere, reaching tens of volts on occasions.

Molecular and nitrogen (N^+) ions

- Challenge of measuring N^+
- Unique capability of IRM to separate N^+ from O^+ (and dependence of capability on S/C potential)
- Occurrence of molecular ions (MI): altitude distribution & interpretation
- Occurrence of N^+ enhancement: association with MI & interpretation
- Occurrence frequency of MI in topside ionosphere vs. above: interpretation & MIC implications



Unshaded: O^+
Shaded: Molecular Ions (N_2^+, NO^+, O_2^+)

$$\frac{\mathrm{MI}}{\mathrm{O}^+} > 1$$

Left of dashed line: **N+**
Right of line: **(N+, O+)**
Shaded: Moleculars (N_2^+, NO^+, O_2^+)

$$\frac{\mathrm{N}^+}{\mathrm{O}^+} > 1$$

Figure 4: Time of flight distributions showing (a) a case in which molecular ions dominate the overall ion composition and (b) a case where N^+ ions dominate, and a smaller molecular ion enhancement is present.

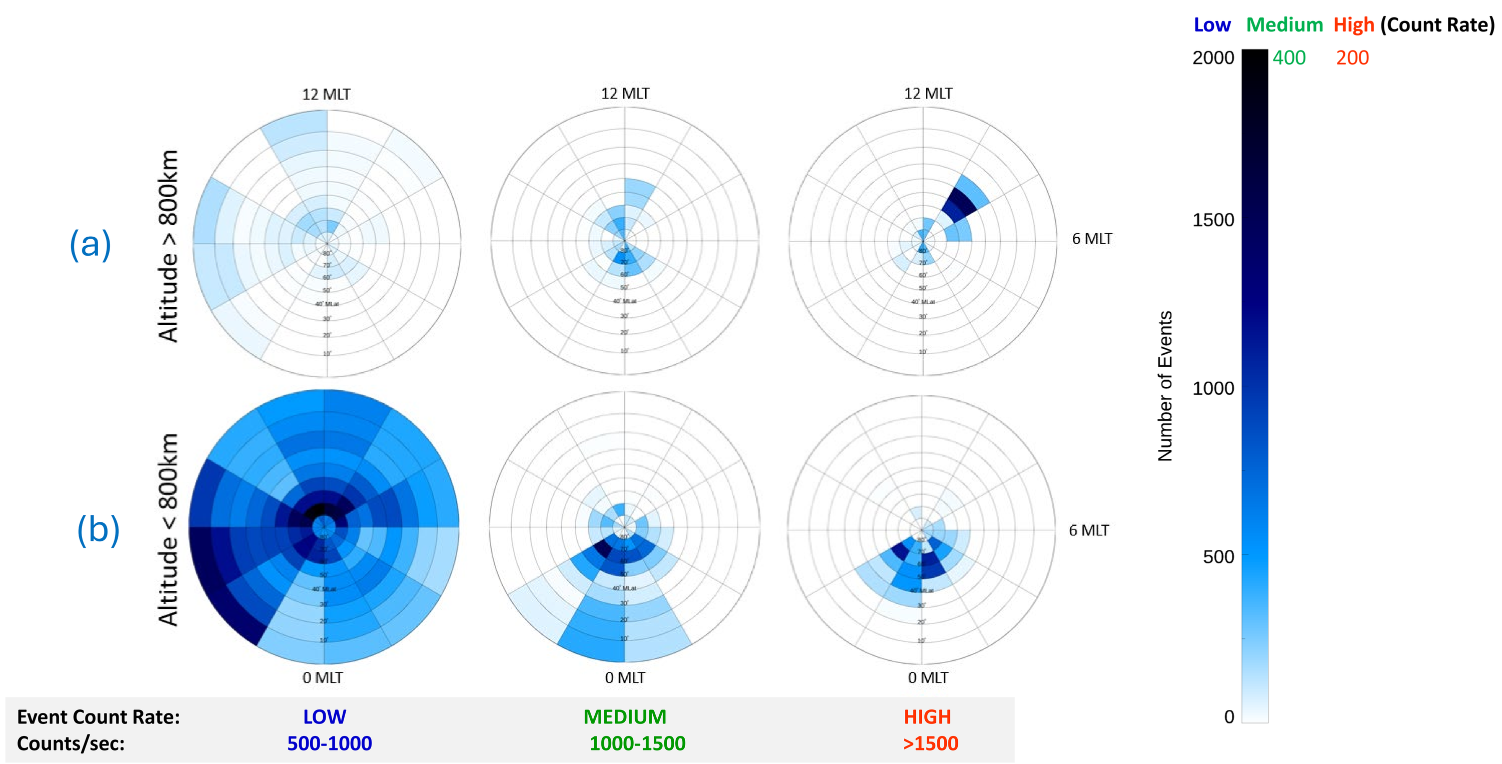


Figure 5: Occurrence distributions of molecular ions (a) above and (b) below 800km shown for events with high, medium, and low count rates. Observed distributions suggest more frequent occurrence of fast acceleration at low altitudes in the nightside auroral ionosphere compared with the dayside, and likely continuation of acceleration to higher altitudes in the dayside cleft.

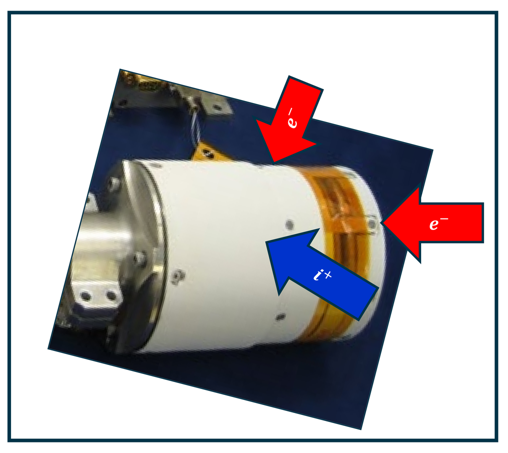
Small-scale plasma density irregularities

- Measured plasma current on sensor surface I_{SS} (typically) due to ambient electrons and ions, photoelectrons, and (primarily) auroral electrons and proportional to plasma density n_e.
- I_{SS} used as proxy for n_e : $\Delta I_{SS}/I_{SS}$ used to study density irregularities $\Delta n_e/n_e$ down to 10-m scale
- Statistically significant differences in morphological characteristics between:
  - current enhancement and current depletion structures,
  - positive and negative current structures,
  - large-scale and small-scale current structures
- Scale-dependent spectral index, with significant power down to 10's of meters: detailed analysis in progress

In general: $I_{SS} = I_{i,th} + I_{e,th} + I_{e,ph} + I_{e,au} + I_{e,sc}$

(a)

Plasma	Source	Current Polarity	$\propto n_e$?	Other Dependencies
Thermal ions	$I_{i,th}$	+	$\propto n_e$	↓ with positive $V_{S/C}$ (spacecraft potential)
Thermal electrons	$I_{e,th}$	–	$\propto n_e$	↓ with negative $V_{S/C}$
Atmospheric photoelectrons	$I_{e,ph}$	–	$\propto n_e$	Sunlit ionosphere (SZA ≤ 90° in F-region); altitude dependent; negligible at ≥1,000 km
'Auroral' electrons	$I_{e,au}$	–		'High latitude' ONLY: Auroral-activity (AE, KP, Dst) dependent
Spacecraft-gen. photoelectrons	$I_{e,sc}$	+		Sunlit spacecraft (SZA ≤ 90° at spacecraft); generally negligible at Swarm-E altitudes



Typically: $I_{SS} \cong I_{i,th} + I_{e,th} + I_{e,ph} \propto n_e$

$(|I_{e,au} + I_{e,sc}| \ll |I_{i,th} + I_{e,th} + I_{e,ph}|)$

$$\Rightarrow \quad \frac{\Delta n_e}{n_e} = \frac{\Delta I_{SS}}{I_{SS}}$$

(b)

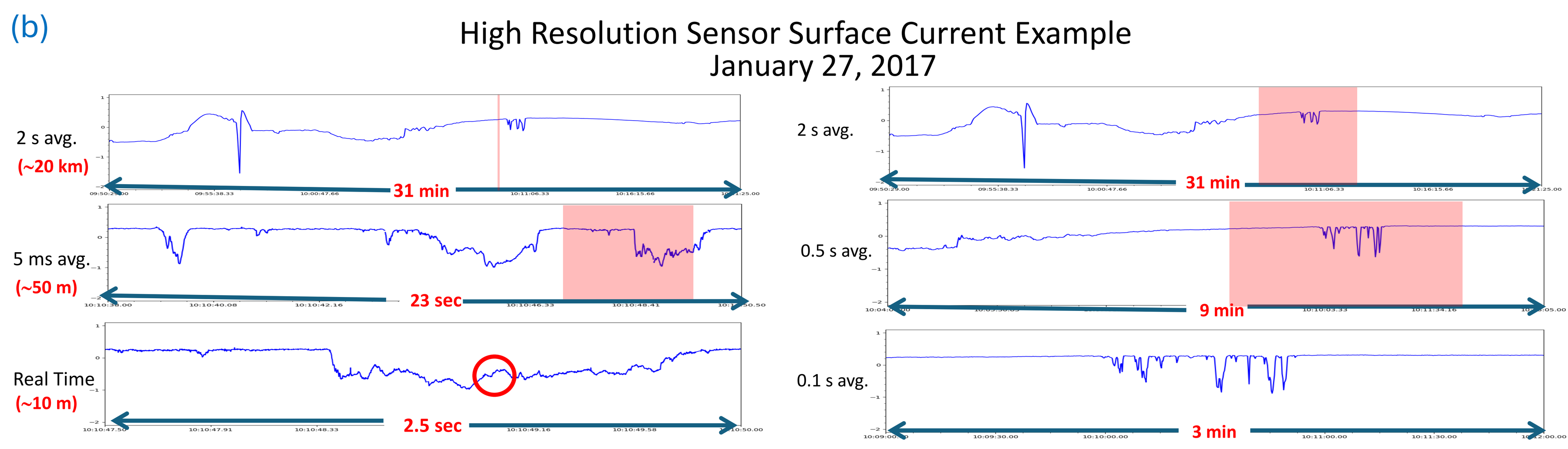


Figure 6: (a) Sources of measured plasma current I_{SS} on the sensor surface, (b) example of measured I_{SS} data at increasing resolution

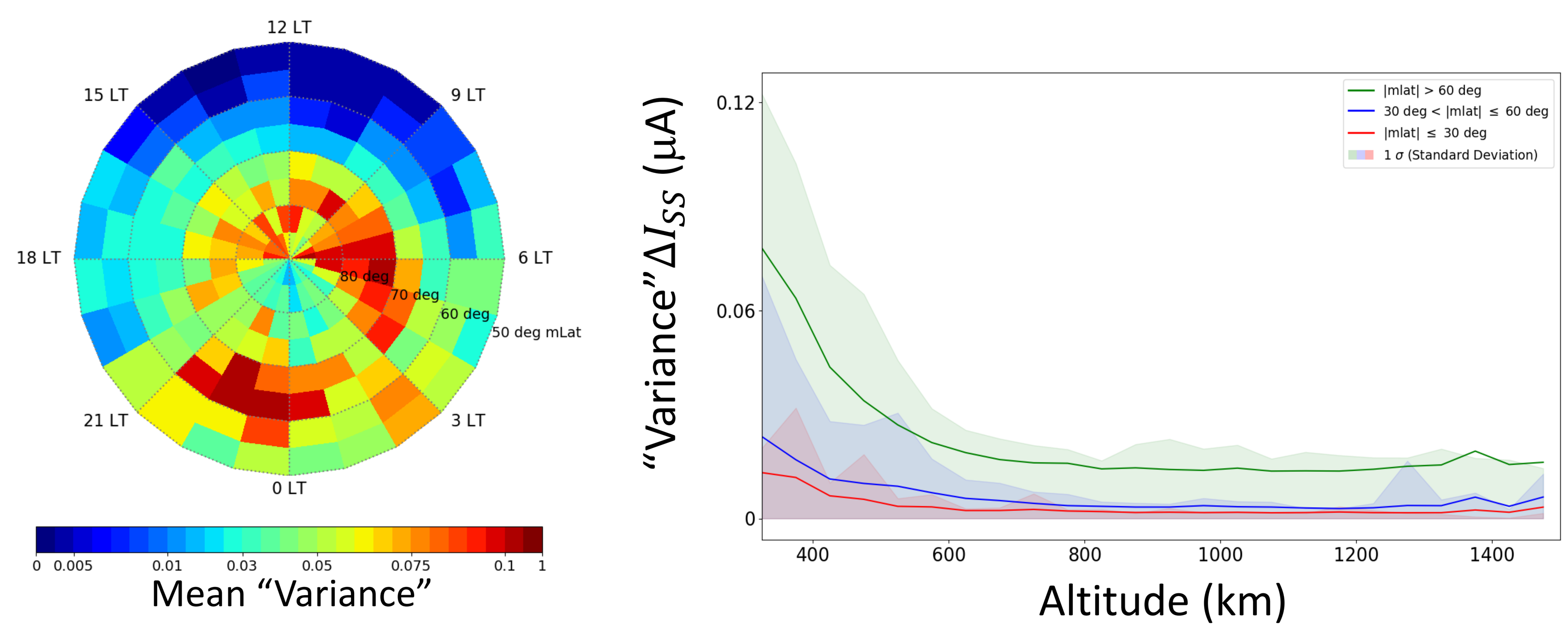


Figure 7: (a) Magnetic latitude-local time and (b) altitude distributions of "variance" ΔI_{SS} of measured sensor surface current I_{SS} as a proxy for Δn_e

Conclusions

- Swarm-E/CASSIOPE (e-POP) IRM:
  - 8 years of ion time-of-flight (TOF) & plasma current data spanning SC 24 & 25 (2014-2021)
  - Unique measurements for study of (under/unexplored) ion composition & small-scale irregularities
- Molecular ions
  - Much more abundant than model prediction
  - Enhanced events much more frequent than expected - both upward & downward ions
- N^+ enhancement
  - Frequent enhancement events; at times in association with molecular ions
- Spacecraft charging
  - S/C potential negative & >1 V (at times >>1 V) in magnitude in sunlit ionosphere
- Decameter-scale density structures; statistical differences in morphological characteristics between:
  - current enhancement and current depletion structures
  - positive and negative current structures
  - large-scale and small-scale current structures

Acknowledgments

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