Constructing Optical Flow Vorticity Spectra of a Discrete Auroral Arc Using Ground-Based All-Sky Imagers

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Motivation

- The aurora exhibits characteristic motion on both MHD and kinetic scales.
- Both Alfvenic and quasi-static (QS) arcs exhibit characteristic cross-scale motion driven by differing electrodynamics in the auroral acceleration region.
- We aim to quantify this motion by constructing optical flow vorticity spectra using all-sky imagers (ASIs).
- Vorticity spectra scaling relations allow us to probe regimes of QS and Alfvenic acceleration and can serve as a proxy for plasma density in the auroral acceleration region (AAR).
- Allows us to indirectly observe the underlying magnetic field fluctuations driving auroral motion, which can be quantified using in-situ B field data from the GREECE sounding rocket mission.

Important Points

- Chaston (2024) showed optical flow is correlated with perpendicular plasma flow in the acceleration region.
- The spectral break wavenumber between quasi-static and Alfvenic power laws gives us a rough estimate of the electron inertial length (λ_e) at the base of the auroral acceleration region.
  - We make these estimates in cases where the transition is defined by a single clean spectral break.

Methodology

- We performed the vorticity analysis on data recorded by the medium-field (FOV~47°) all-sky camera in Venetie, AK, during the overnight flight of GREECE on 03 Mar 2014.
  - We cropped and performed a gamma correction on the ASI images with $\gamma = 1.5$ ($I(x,y) = I_{raw}^{\gamma}(x,y)$).
- We determine optical flow velocity fields using 2d wavelet cross-correlation with a Paul wavelet of order 4 on the spatial derivative of the gamma-corrected successive even-numbered ASI frames.
- We compute optical flow vorticity fields from the optical flow field using 6th order finite-differencing.
- We determine the vorticity spectrum by averaging the vorticity magnitudes of all points within the 90% confidence interval over 15 frames.
  - Error bars determined by the standard deviation of the vorticity distribution.
- We truncate the spectrum at the optical smearing limit due to the finite lifetime of the auroral green line ($\tau = 0.7s$).
  - $k_{\perp,max} = \frac{2\pi}{v_{ch}\tau}$, where v_{ch} is the characteristic speed of optical flow determined by averaging the velocity fields.
- We perform a rolling exponential fit to determine the spectral index of the vorticity spectrum.
- Additionally, we take the ratio of right-handed to left-handed motion within the 90% confidence interval to determine how the average polarization varies with scale.
  - We aim to investigate if any characteristic motion is present with spectral breaks in the vorticity spectrum.
- We construct vorticity spectra on 2-second intervals with a 6-second cadence between them to investigate statistical trends in auroral motion.

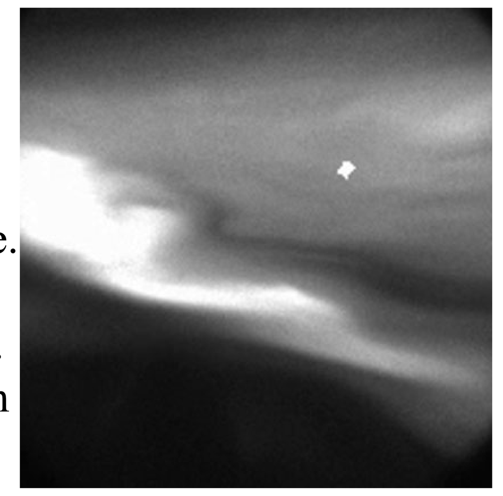

Figure 2: cropped ASI frame at T+359s.

Vorticity Spectra

- We observe a spectral break at the transition between quasi-static and Alfvenic behavior at $k_{\perp} \sim 0.0002 m^{-1}$ in figure 3.
- Spectral break is correlated with enhancement of LH vorticity for this event
- From the QS-Alfvenic transition, we estimate $\lambda_e \sim 5km$.
  - This value implies $n_e \sim 1.1\ cm^{-3}$, consistent with the typical values in the acceleration region ($n_e \sim 0.1 - 10\ cm^{-3}$, Strangeway et al. 1998).
- Figure 4 shows a broadened QS-Alfvenic transition, spanning $k_{\perp} \approx 0.0002m^{-1} - 0.0004m^{-1}$
- There is also a LH enhancement at the QS spectral break at $k_{\perp} \approx 0.0003m^{-1}$

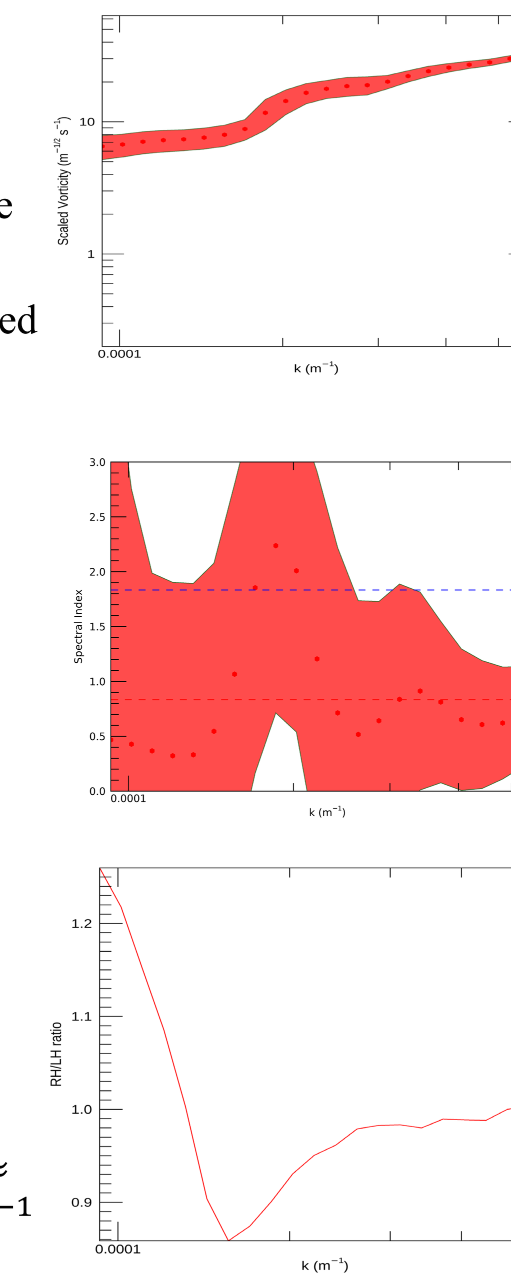

Figure 3: (top) vorticity spectrum for an event at T+359s. (middle) Vorticity spectral index determined by a rolling exponential fit. (bottom) RH-LH ratio.

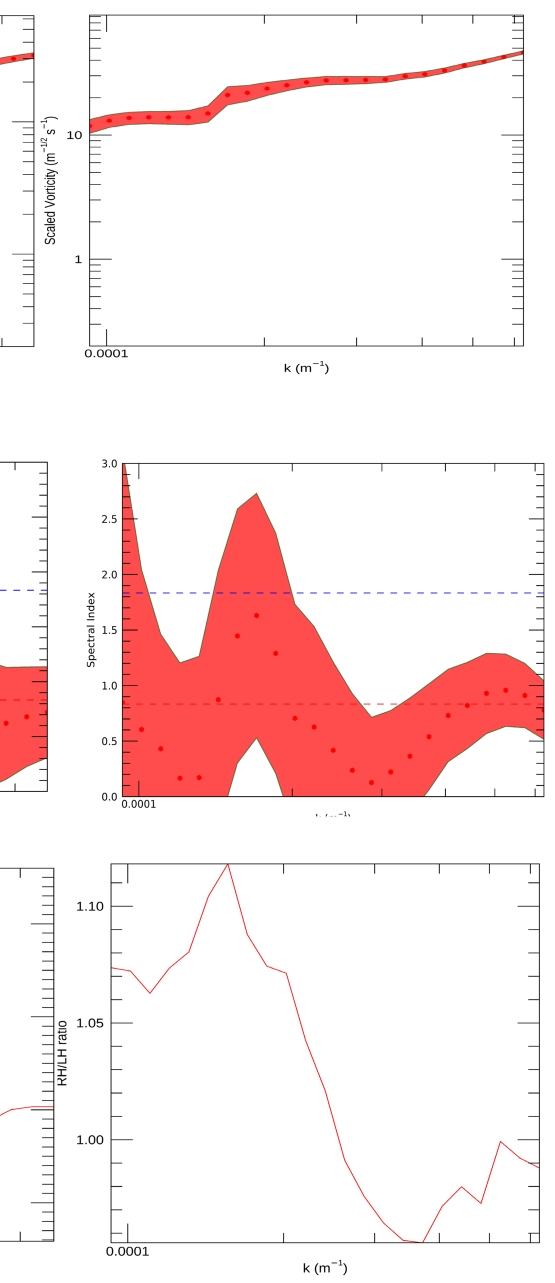

Figure 4: (top) vorticity spectrum for an event at T+311s. (middle) Vorticity spectral index determined by a rolling exponential fit. (bottom) RH-LH ratio.

Observations

- We observe the predicted vorticity scaling for both Alfvenic and quasi-static arcs in all-sky imagery.
  - Some events display a sharp spectral break between QS and Alfvenic regimes (figure 3).
  - A few events display a broadened/messy transition; we do not estimate λ_e for these events (figure 4) since the transition is not tied to a single key length scale.

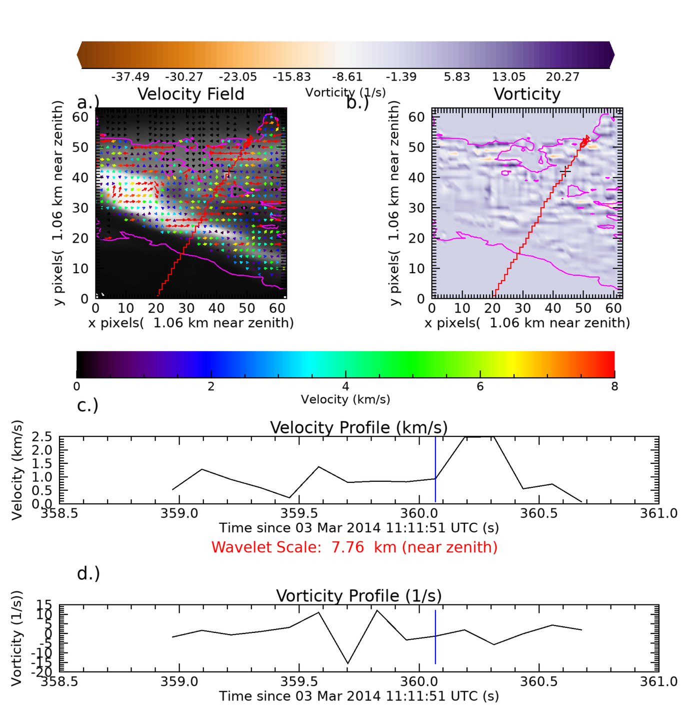

Figure 1: Optical flow (left) and vorticity field (right) with 90% confidence interval (pink contour) for an event at T+359s.

Parameter Comparison

- Chaston, Seki et al. (2010) derived two limits for ion dynamics: Alfvenic and quasi-static.
  - In these limits, normalized vorticity scaled as follows:

$$|\Omega_{\parallel}(k_{\perp})| \big/ \Delta k_{\perp}^{1/2} \approx \frac{C^{1/2} k_{\perp}^{-1/6} V_A \sqrt{1 + k_{\perp}^2 \lambda_e^2 (1 + i\nu/\omega)}}{B_o} \quad |\Omega_{\parallel}(k_{\perp})| \big/ \Delta k_{\perp}^{1/2} \approx C^{1/2} \frac{k_{\perp}^{-1/6}}{\mu_o B_o \Sigma_P} (1 + k_{\perp}^2 \lambda_{M-I}^2)$$

- The following relations predict $k_{\perp}^{5/6}$ and $k_{\perp}^{11/6}$ power law behaviors for Alfvenic and quasi-static arcs, respectively.
- Transition point between quasi-static and Alfvenic behavior occurs roughly at $k_{\perp}\lambda_e = 1$.
- We observe a spectral break between Alfvenic and quasi-static around $k_{\perp} \sim 0.0002m^{-1}$, implying $\lambda_e \sim 5km$ (figure 3).

Important point

- Measurements at the largest scales (where wavelet scales approach scale of auroral arc or grid size respectively) are less reliable due to COI effects.
- This sometimes manifests as an artificial inflation of vorticity at the largest scales.

Conclusions

- The QS-Alfvenic spectral break sometimes displayed a sharp transition, set by a spectral break corresponding to $k_{\perp}\lambda_e \approx 1$ and was sometimes a broadened transition.
- We could estimate the electron inertial length in cases where the transition was sharp using $k_{\perp}\lambda_e \approx 1$.
- We could not estimate the electron inertial length in broadened transitions, since there was not a definitive length scale governing the transition.
- Lastly, there was no significant correlation between LH enhancements and spectral breaks (<50% of events).

Key point

Future work should incorporate in-situ GREECE data to quantify how auroral motion is correlated with ionospheric electrodynamics.

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