Determining experimental plasma wave dispersion relations in the solar wind

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Introduction

- The solar wind hosts short and intense coherent magnetic field fluctuations at multiple scales up to 10% of the time [1, 2] :
  - → what type of waves are they?
  - → under what conditions do they form?
- Solar Orbiter and Solar Probe Plus will be able to answer these questions for the first time in the inner heliosphere
- Here we look at waves between ion and electron scales at 1AU as a case study

[1] Lacombe et. al. (2014) ApJ doi:10.1088/0004-637X/796/1/5
[2] Jian et. al. (2014) ApJ doi:10.1088/0004-637X/786/2/123

Measuring dispersion relations

- To experimentally derive a dispersion relation, need to measure frequency (ω) and wave-vector ($\underline{k}$)
- ω directly from $\underline{B}$ waveform
- $\hat{\underline{k}}$ from minimum variance on $\underline{B}$ waveform and direction of $\delta\underline{E} \times \delta\underline{B}$
- $|\underline{k}|$ from $\frac{\omega}{|\underline{k}|} = \frac{|\delta E_{\perp}|}{|\delta B|}$
- This method works with elliptically polarised monochromatic waves (eg. ion cyclotron, whistler waves)

With both $\underline{E}$ **and** $\underline{B}$ waveforms, possible to calculate plasma frame frequencies, wavenumbers, and an experimental **dispersion relation**.

Electric field processing

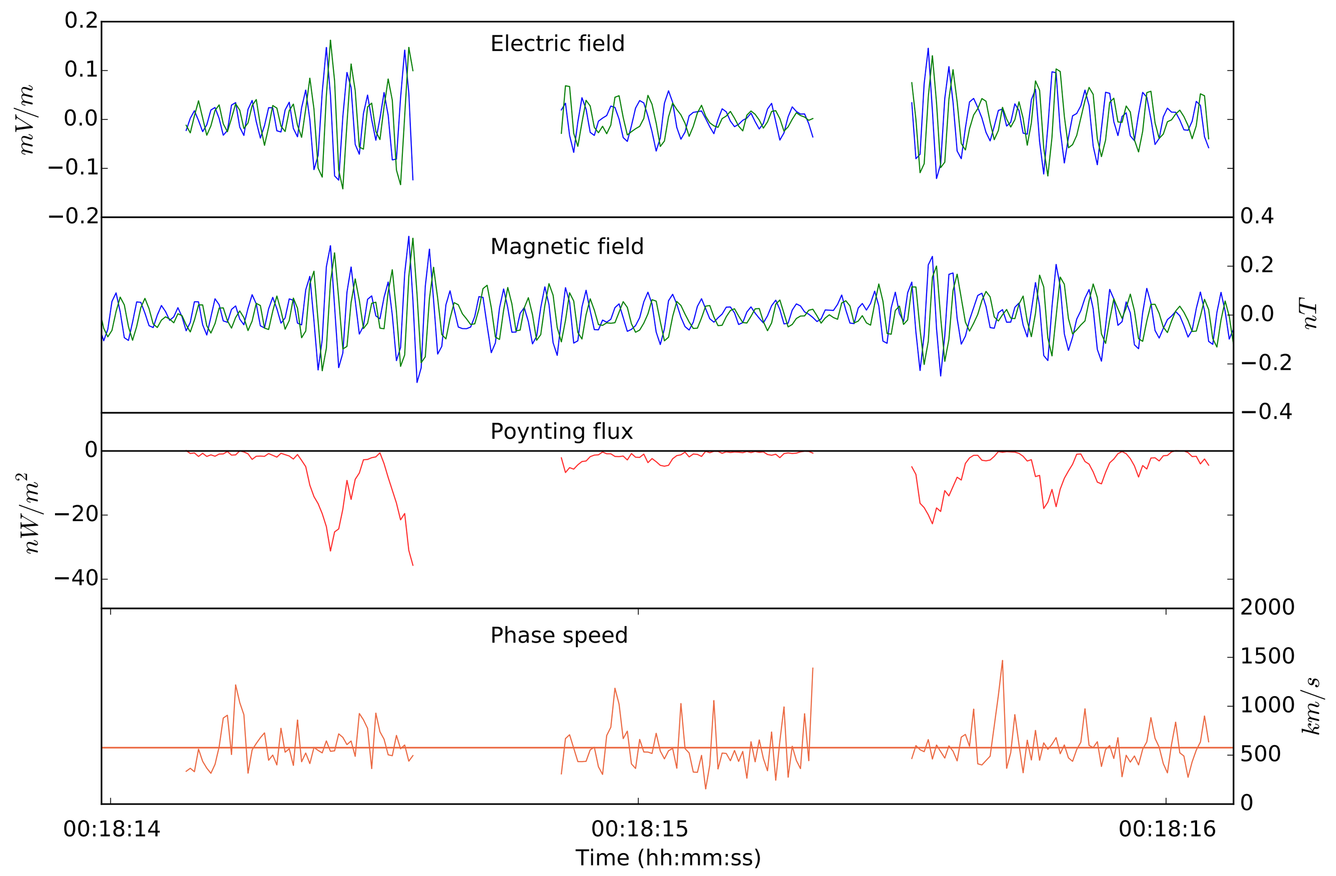
- Using electric field measurements taken in the solar wind is challenging due to spacecraft wake effects and spin tones
- A new method has been developed to remove these effects from Electric Field Instrument measurements on ARTEMIS

Remove large amplitude wake spikes in spinning probe frame
↓
Transform data into de-spun frame
↓
Subtract spin period waveform to remove smaller scale wake effects
↓
Remove advected $\underline{v}_{sw} \times \underline{B}$ field

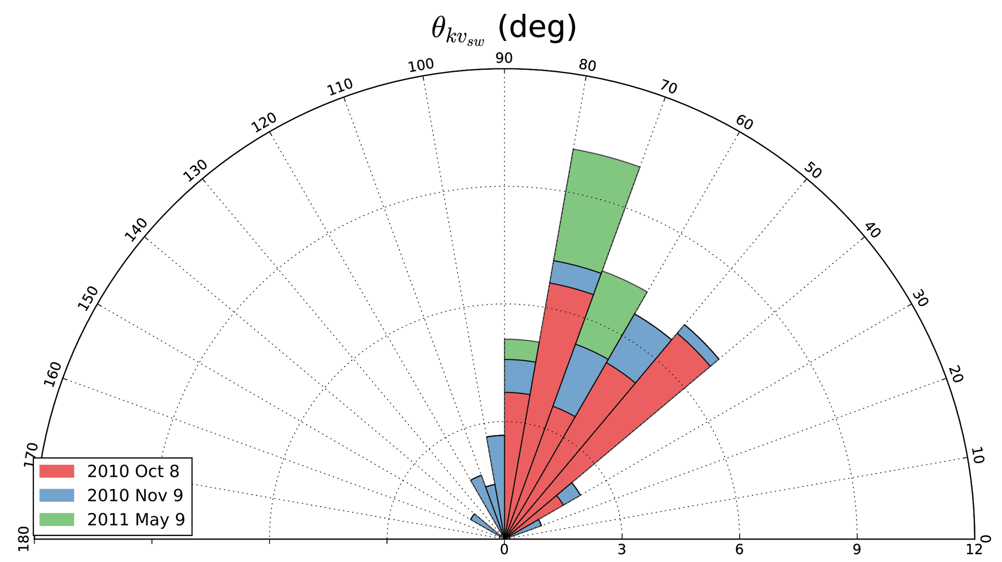
- This is used to extract high frequency (128 samples/s) 2D spin plane electric field waveforms

Wave packet observations

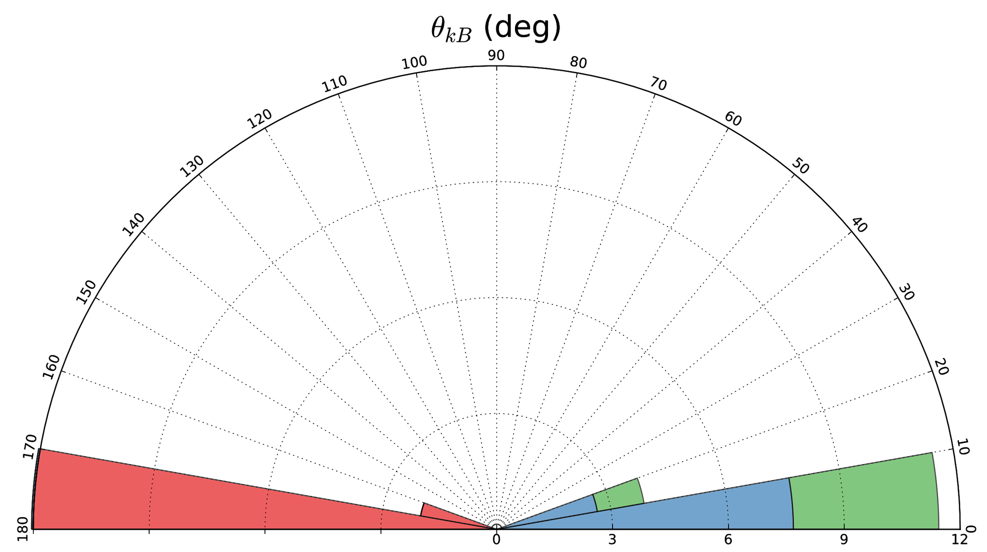
- 2.5 years of ARTEMIS data in solar wind (2009 - mid 2011)
- Burst mode data at 128 samples/s with strong magnetic fluctuation power in the range [4, 64]Hz selected
- Automatically detect wave packets



- 289 wave packets with reliable data detected over three separate days
- > 95% are **RH circularly polarised**

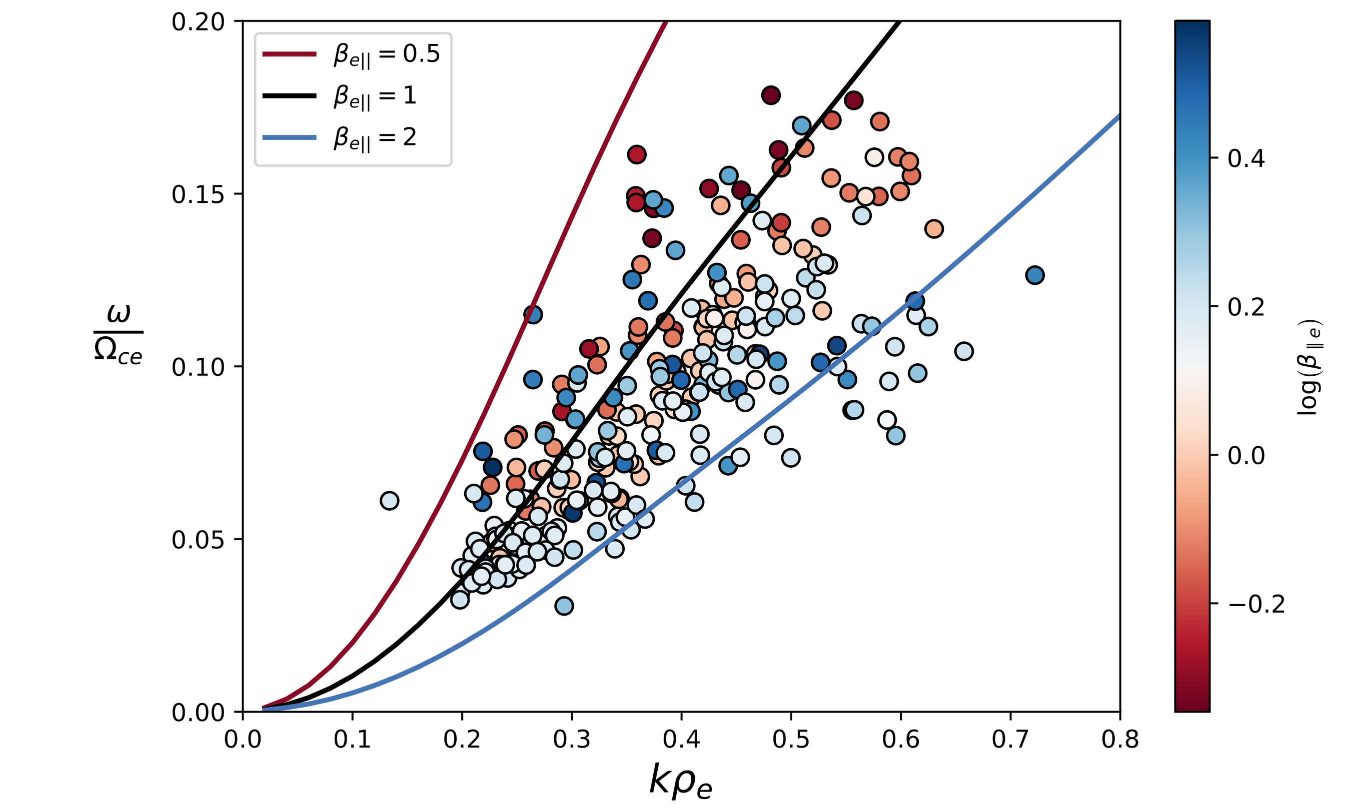


Travel predominantly **anti-sunward**



Travel **along** $\mathbf{B}_0$

Experimental dispersion relation



- Agreement with warm dispersion relation and RH polarisation
  - → These are electron whistler waves
- Systematic variability in dispersion relation with local $\beta_{\|e}$
  - → Agrees qualitatively with bi-Maxwellian dispersion relations

Conclusions

- Developed a new method to isolate high frequency component of solar wind electric field data
- For the first time have experimentally measured dispersion relation of whistler waves at electron scales in the solar wind
- Warm plasma effects play a significant role in whistler wave dispersion
- These whistler waves are travelling anti-sunward → **cannot** undergo linear wave-particle interaction to scatter electron strahl

Further work

- Combine experimental dispersion relations with theoretical predictions derived from in-situ particle measurements
- Apply method to fluctuations near ion scales

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