Magnetosphere response to a spatially non-uniform solar wind stream

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1. Motivation

Recent investigations, using multiple upstream monitors, revealed that properties of the solar wind are often non-uniform on spatial scales comparable to the size of the Earth's magnetosphere. Here, we perform a critical investigation of a case study (2013 July 8 ≈00:00–05:00 UT) in which a particular solar wind mesoscale structure, in the form of a periodic density structure (PDS), shows coherence on a limited extent of the Earth's upstream region. *Di Matteo et al. (2024)* reported high coherence between Wind and ARTEMIS-P1 (hereafter, P1) observations of solar wind density (N_{SW}) and total magnetic field (B_{IMF}). We present new considerations adding information from the ACE spacecraft and magnetospheric satellites.

2. 2013 July 8 event overview

During the event in analysis, P1 is the most aligned to the Sun-Earth line, followed by ACE and then Wind (panel A in Figure 1). P1 and ACE data are time shifted to match the Wind time assuming radial propagation of the solar wind at an average speed of ≈297 km/s.

At P1, N_{SW} is locally different from that at Wind (panel B), likely due to instrument biases (Blüthner et al., 2026). As for the speed (panel C), P1 shows values significantly lower than those of Wind and ACE (remarkably, in good agreement with each other). The B_{IMF} intensity and direction show an overall agreement (panel D–F) and reveal the **presence of Heliospheric Current Sheet (HCS) crossings**.

During the interval of high coherence (confirmed via cross-wavelet analysis and delimited by vertical dotted lines in Figure 1) the cross-correlation for N_{SW} and B_{IMF} between Wind and P1 shows high values (≈0.8) and no delay while the one obtained for B_{IMF} between Wind and ACE (Figure 2) reveals lower maximum values (≈0.52) and a delay anticipated by ≈5 min with respect to the 16 min delay expected based on the solar wind speed.

This time delay is remarkably similar to the one among HCS crossings by the three spacecraft. In panel E, the Wind and the time shifted P1 measurements observed the same crossing of the HCS (red arrow in panel E) at ≈00:50–00:53 UT, **indicating that the structure has not changed from Wind to P1.** The ACE spacecraft instead sees the HCS crossings at ≈00:57–00:59 UT consistent with the ≈5 min delay expected from cross-correlation. This **suggests that the different observations at ACE are due to a spatial rather than temporal deformation of the HCS.**

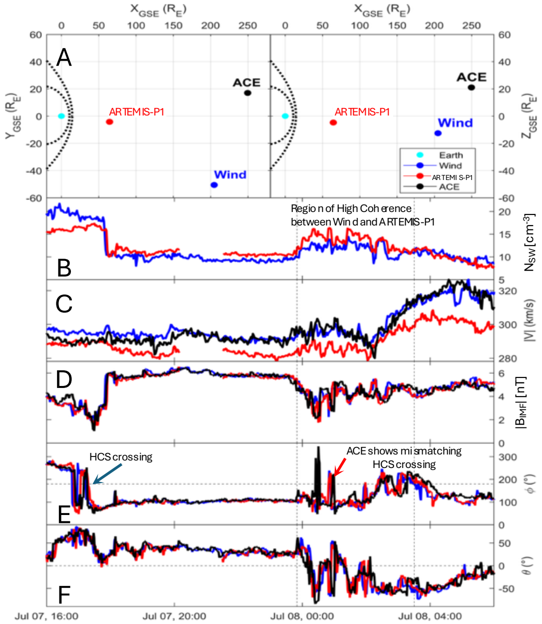


Figure 1. Overview of time shifted Wind (reference time), ACE (+16.0 min), and P1 (-50.1 min) location and measured solar wind plasma (density and bulk speed) and magnetic field (intensity and direction) properties.

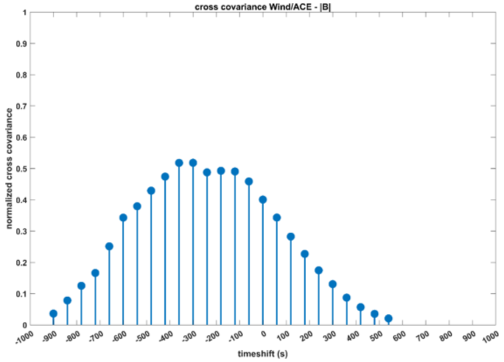


Figure 2. The cross-correlation between the $|B_{IMF}|$ at Wind and ACE reveals maximum values (≈ 0.52) for an additional delay of ≈ 5 min.

3. Magnetosphere response

In the magnetosphere the GOES 13 and GOES 15 geostationary satellites cover the dusk to midnight sector during the impact of the solar wind parcel under investigation (Figure 3A). The measured total magnetic field, |B|, shows simultaneous oscillations at both satellites matching the profile of the solar wind density in the dusk region (Figure 3B). As the satellites move deeper in the nightside region, tail phenomena dominate the |B| variations.

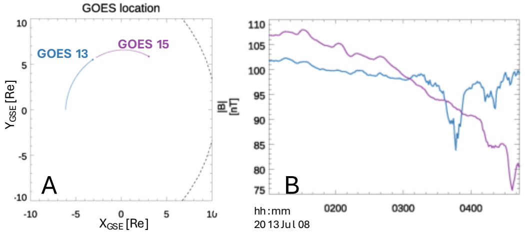


Figure 3. GOES 13 and 15 location (black lines indicate the magnetopause, panel A) and measured |B| (panel B).

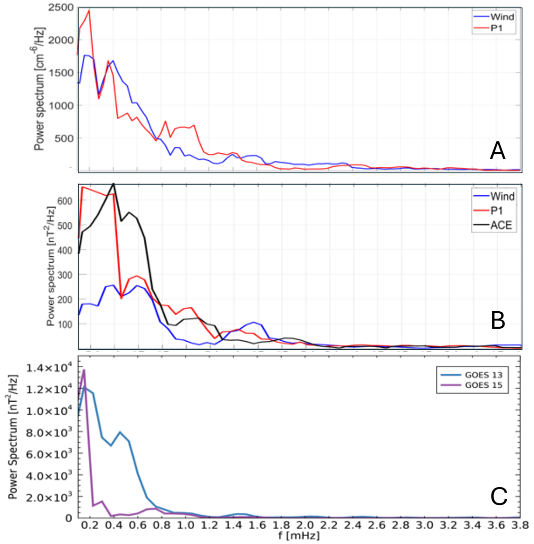


Figure 4. Multitaper spectral analysis results for N_{SW} and $|B_{IMF}|$ at upstream monitors and |B| at the geostationary orbit.

4. Spectral analysis results

- Figure 4A compares the N_{SW} spectra resulting from Wind and P1 observations, obtained with the Multitaper method. As can be seen (see also Table 1), the power spectra show clear common spectral peaks and/or spectral enhancements.
- A similar analysis for $|B_{IMF}|$ (figure 4B and Table 1), confirms the correspondence between the Wind and P1 observations. In contrast, the spectrum resulting from the ACE measurements shows an agreement with Wind and P1 at ≈0.39 mHz while other spectral enhancements occur at different values at higher frequencies.
- The GOES satellites, despite being located in the dusk sector and more aligned with the ACE satellite, show power spectral enchacements consistent with the one observed for N_{SW} and $|B_{IMF}|$ at Wind and P1.
- Given the likely spatial organization of the upstream driver, the discrepancy of the ACE observations might be related to its location above the ecliptic (Z_{GSE}≈21.0 R_E, Figure 1A) rather than due to the azimuthal separation with respect to Wind (Z_{GSE}≈-12.6 R_E) and P1 (Z_{GSE}≈-4.7 R_E) located closer and below the ecliptic.

Table 1. Frequency at which power spectrum enhancements are observed in observations of N_{SW} and $|B_{IMF}|$ at upstream monitors and |B| at GOES satellites.

Spc.	Var.	frequency [mHz]								
Wind	N_{SW}	0.16 - 0.20	0.40			0.92		1.40 - 1.60		(2.31)
P1	N_{SW}	0.20	0.36			0.84 - 1.08		1.40		(2.47)
Wind	$|B_{IMF}|$	0.13 - 0.20	0.39		0.60			1.56		
P1	$|B_{IMF}|$	0.13	0.39		0.60	1.04		1.43 - 1.56		
ACE	$|B_{IMF}|$		0.39	0.52			1.11		1.82	
G13	|B|	0.15	0.45					1.43	(2.03)	(2.48)
G15	|B|	0.15				0.75 - 0.90		1.50		

5. Conclusions

1. Analysis of a solar wind parcel in the proximity of the HCS by three interplanetary monitors revealed the presence of **a spatially non-uniform stream**.
2. The power spectrum properties of ARTEMIS-P1, just upstream of Earth close to the Sun-Earth line, remain consistent with the ones at Wind even though their separation in the YZ_{GSE} plane is larger (ΔY_{GSE}≈46 Re, ΔZ_{GSE}≈7.9 Re) than the one with ACE (ΔY_{GSE}≈21 Re, ΔZ_{GSE}≈26 Re) at which significant differences are observed.
3. Preliminary analysis of the magnetospheric response shows magnetospheric field fluctuations consistent with direct driving by solar wind density variation at Wind/P1 despite the non-uniform solar wind front.

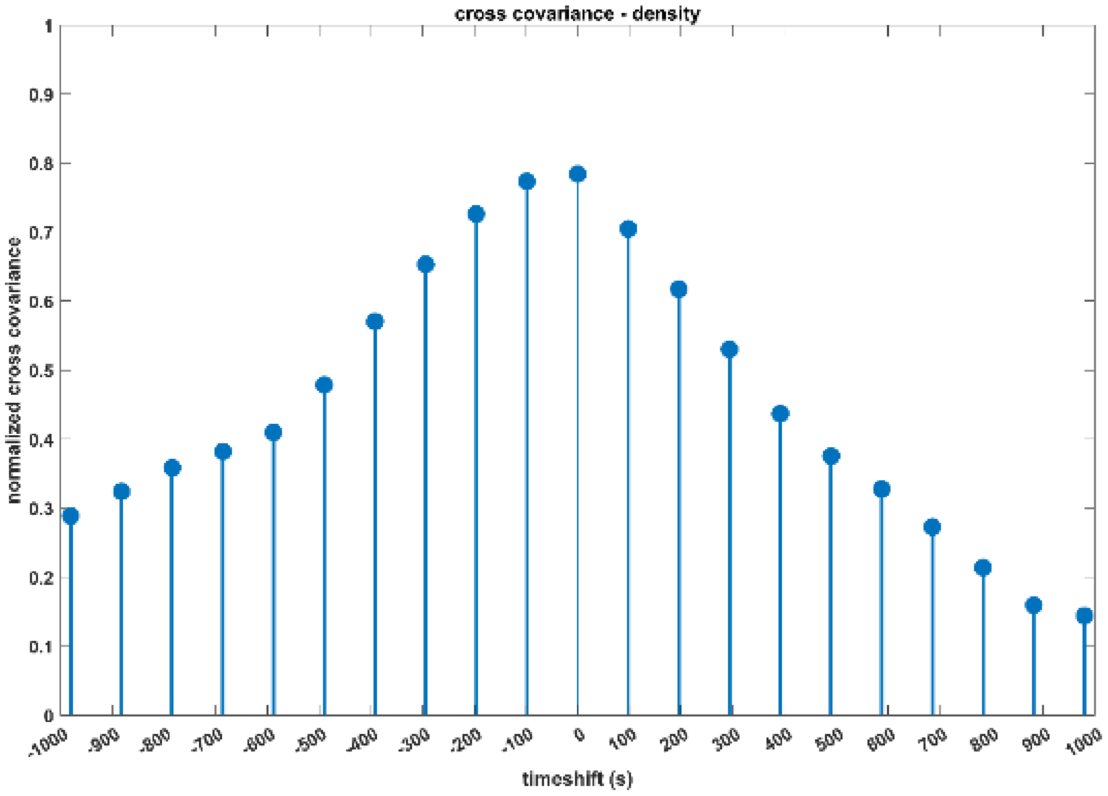
References

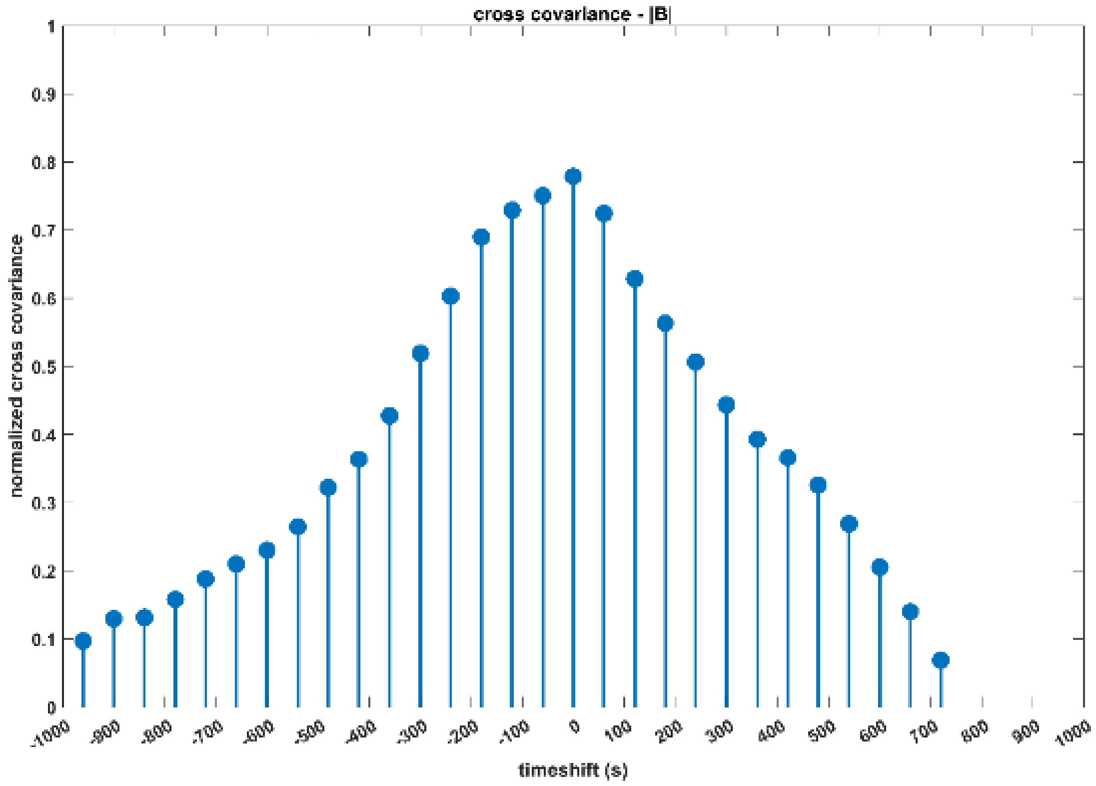
Di Matteo, S., Katsavrias, C., Kepko, L., and Viall, N. M (2024), ApJ, ***969****, 67. doi:10.3847/1538-4357/ad479e*

Blüthner, G. H., et al. (2026). JGR: Space Physics, 131, e2025JA034781. doi:10.1029/2025JA034781

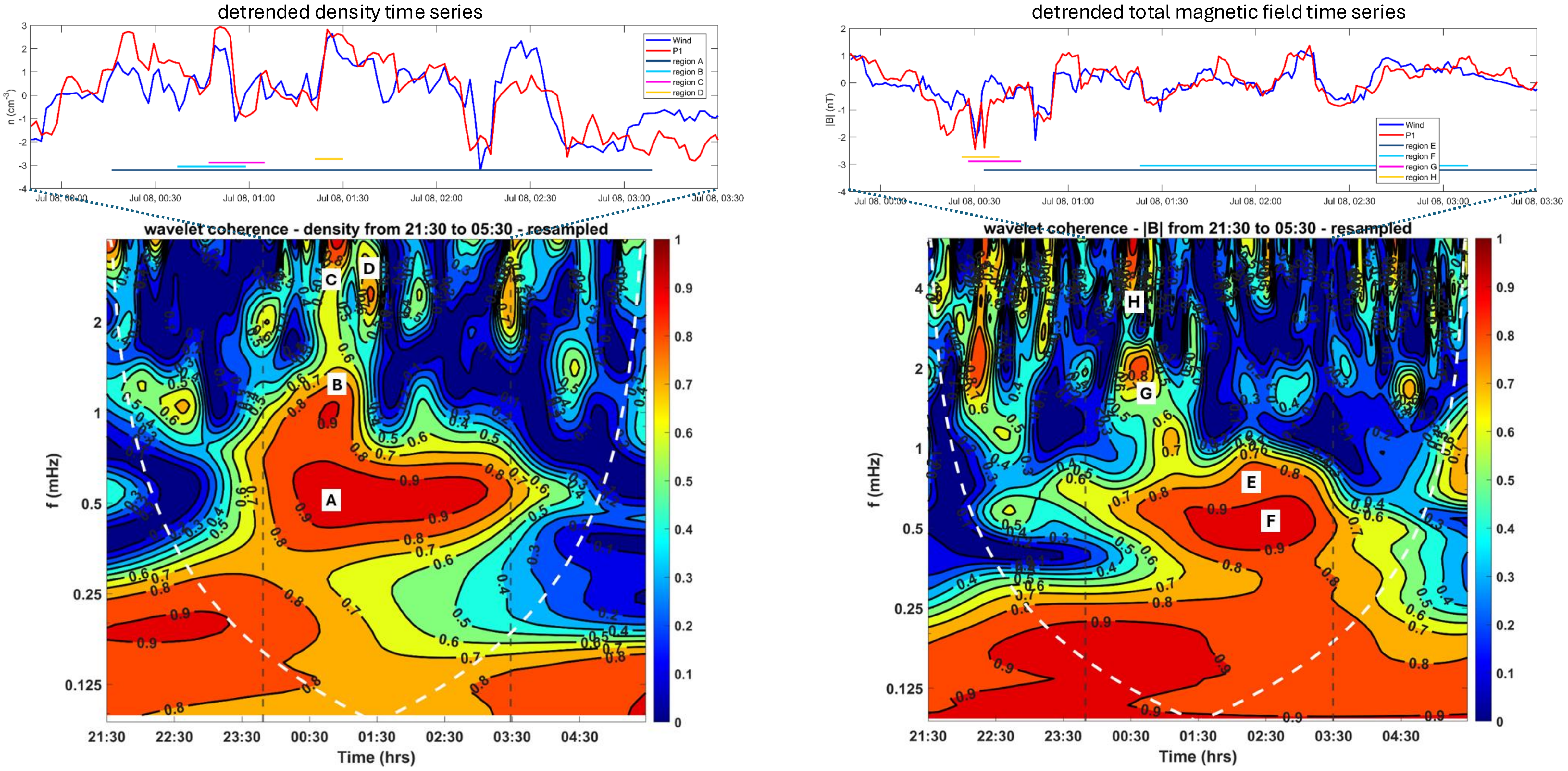
Supplementary Material

The cross-correlation between Wind and P1 density and total magnetic field shows high values (≈0.8) and no additional delay

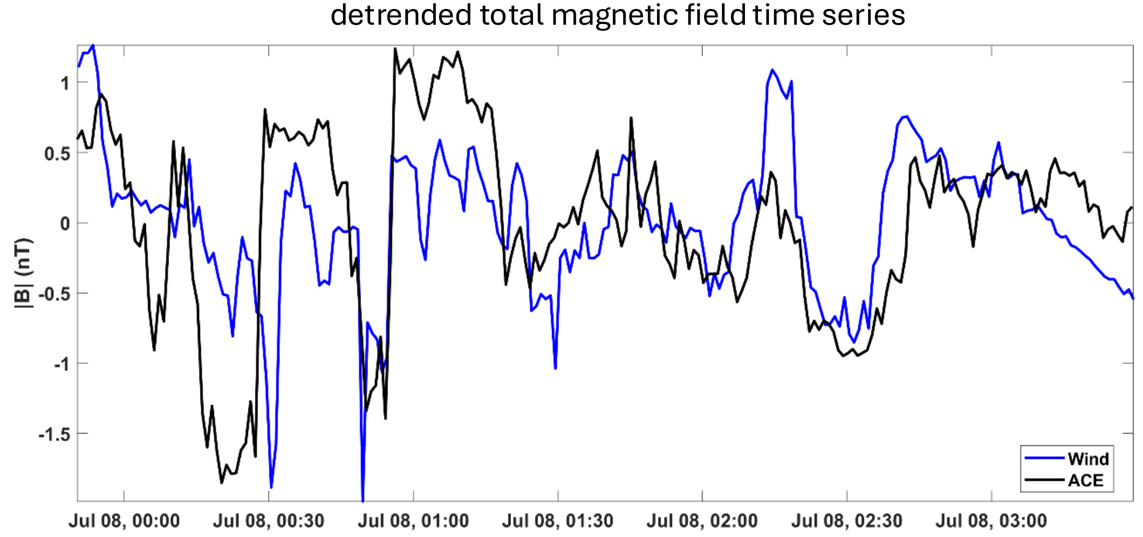


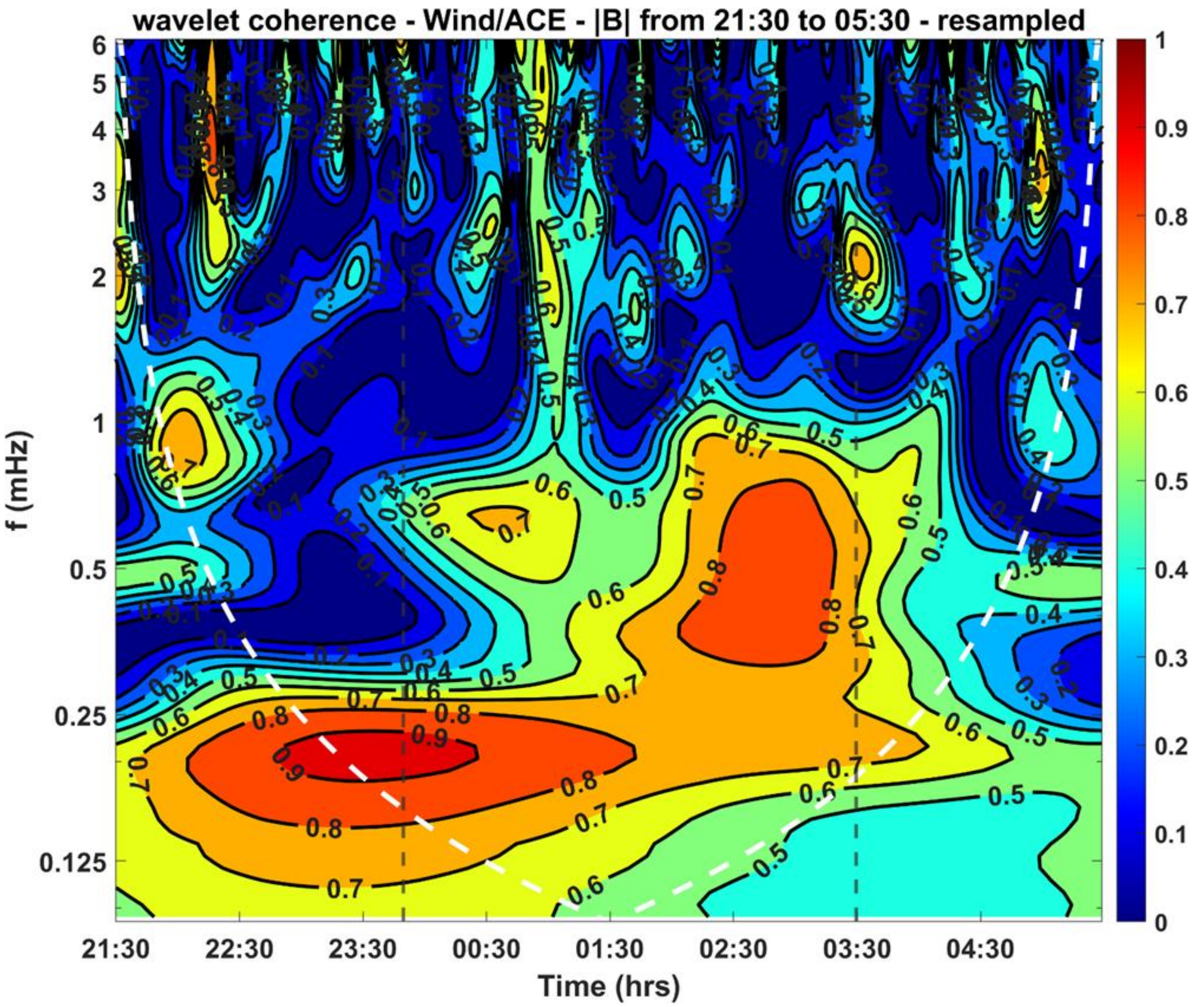


High coherence between Wind and ARTEMIS-P1 density and total magnetic field observations



Low coherence between Wind and ACE total magnetic field observations





The comparison of the time series shows notable delays between Wind and ACE observations. The analysis of the HCS crossings timing suggests that these discrepancies are due to spatial deformation of the HCS.