TURBULENCE IN THE SOLAR WIND: 3D MEASUREMENTS OF WAVENUMBER SPECTRA USING THE K-FILTERING TECHNIQUE

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Magnetic turbulence in the solar wind has been studied for many years. Most of the observational work have been focused on the large (MHD) scales, i.e. the so-called inertial range with a Kolmogorov scaling $k^{-5/3}$ [e.g.,1,2]. The inertial range is widely believed to form by strong nonlinear interaction of Alfvén waves. However, the anisotropy of the turbulence (in wavenumber space) is still hotly debated [e.g., 3]. From single spacecraft data, inferring the wavenumber spectra from the temporal measured ones onboard the satellite can be achieved only by using the Taylor frozen-in assumption $\omega_{sat} \sim \mathbf{k.V}_{SW}$. This means that all the phase speeds of the waves need to be smaller than the solar wind speed V_{SW}. While this assumption is generally valid at MHD scales (because the Alfvén speed $V_A << V_{SW}$), it breaks down at the sub-ion (and electron) scales where whistler modes may exit. Moreover, even when the Taylor assumption is justified it can yield *only one component of the wavenumber spectra*: along the flow V_{SW} [4-6]. The two other directions perpendicular to V_{SW} are thus missing unless additional assumptions, such as isotropy, are used. Therefore multispacraft data and appropriate space-correlations methods are necessary in order to fully determine the 3D wavenumber spectra of space turbulence. This can be achieved by applying the *k*-filtering technique on the four Cluster spacecraft data.

Cluster is an ESA mission launched in year 2000 and will be operational until 2014 [7]. There are 4 Cluster spacecraft, each of them carrying identical plasma wave and particles instrumentation. The magnetic wave form is measured continuously by the three-axis flux gate magnetometers (FGM instrument) up to several Hz and the three-axis search coils (STAFF- SC instrument) up to ~200Hz in Burst mode (1.5 in normal mode). Thus magnetic waveform is accessible from DC to ~200Hz with a redundancy around 1Hz.

The k-filtering technique (known also as the wave telescope) makes use of the full 12x12 correlation matrix of the magnetic (and/or electric) field data (3 components x 4 satellites) to estimate the 4D spectral energy density $P(\omega,\mathbf{k})$ of the measured field fluctuations. By applying this technique to interplanetary magnetic field data, it has been possible to accomplish real progress in understating turbulence, reconnection and wave-particle interaction in various regions in space: magnetosheath [8-11], in the foreshock [12] in the cusp region [13], in the magnetotail [14], an in the solar wind [15,16]. These applications have however revealed several technical problems that need to be fully considered and understood in order to safely interpret spacecraft observations [17]. Here we will show results of application of the *k*-filtering technique to MHD simulations data in the inertial range. Several questions will be addressed such as the role of the Doppler shift in producing asymmetrical spectra in the wavenumber domain, and the role of the Cluster tetrahedron geometrical factors in affecting the spatial anisotropy of the inferred wavenumber spectra. Comparison with real Cluster data in the solar wind will also be performed.

References:

1. Matthaeus, W. H., and M. L. Goldstein (1982), Measurement of the Rugged Invariants of Magnetohydrodynamic Turbulence in the Solar Wind, *J. Geophys. Res.*, 87(A8), 6011–6028, doi:10.1029/JA087iA08p06011.
2. Marsch, E., and C. .-Y. Tu (1990), On the Radial Evolution of MHD Turbulence in the Inner Heliosphere, *J. Geophys. Res.*, 95(A6), 8211–8229, doi:10.1029/JA095iA06p08211.

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3. Grappin, R. and Müller, W-C. (2010), Scaling and anisotropy in magnetohydrodynamic turbulence in a strong mean magnetic field, *Phys. Rev.*, E 82, 026406.
4. Osman, K. T., and T. S. Horbury (2009), Quantitative estimates of the slab and 2-D power in solar wind turbulence using multispacecraft data, *J. Geophys. Res.*, 114, A06103, doi:10.1029/2008JA014036.
5. Chen, C. H. K.; Horbury, T. S.; Schekochihin, A. A.; Wicks, R. T.; Alexandrova, O.; Mitchell, J. (2010), Anisotropy of Solar Wind Turbulence between Ion and Electron Scales, *Phys. Rev. Lett.*, 104, 255002.
6. Podesta, J.J., Self-similar stochastic processes in solar wind turbulence, *Advances in Space Research*, Volume 41, Issue 1, 2008, Pages 148-152, ISSN 0273-1177, DOI: 10.1016/j.asr.2007.07.008.
7. Escoubet C.P., Schmidt R. and Goldstein M.L. (1997), CLUSTER – SCIENCE AND MISSION OVERVIEW, *Space Science Reviews*, Volume 79, Numbers 1-2, 11-32, DOI: 10.1023/A:1004923124586.
8. Sahraoui, F., et al. (2003), ULF wave identification in the magnetosheath: The k-filtering technique applied to Cluster II data, *J. Geophys. Res.*, 108(A9), 1335, doi:10.1029/2002JA009587.
9. Sahraoui, F., et al. (2004a), Correction to "ULF wave identification in the magnetosheath: The k-filtering technique applied to Cluster II data", *J. Geophys. Res.*, 109, A04222, doi:10.1029/2004JA010469.
10. Sahraoui, F., et al. (2004b), Magnetic turbulent spectra in the magnetosheath: new insights, Ann. Geophys., 22, 2283-2288, doi:10.5194/angeo-22-2283-2004.
11. Tjulin, A., J.-L. Pinçon, F. Sahraoui, M. André, and N. Cornilleau-Wehrlin (2005), The k-filtering technique applied to wave electric and magnetic field measurements from the Cluster satellites, *J. Geophys. Res.*, 110, A11224, doi:10.1029/2005JA011125.
12. Narita, Y.; Glassmeier, K.-H.; Treumann, R. A. (2006), Wave-Number Spectra and Intermittency in the Terrestrial Foreshock Region, *Phys. Rev. Lett.,* 97, 191101 .
13. Grison, B., et al. (2005), Wave particle interactions in the high-altitude polar cusp : A Cluster case study, *Annales Geophysicae*, Vol. 23, pp 3699-3713.
14. Huang, S. Y. et al. (2010), Wave properties in the magnetic reconnection diffusion region with high β: Application of the *k*-filtering method to Cluster multispacecraft data, *J. Geophys. Res.*, 115, A12211, doi:10.1029/2010JA015335.
15. Sahraoui, F., Goldstein, ML., Belmont, G., Canu, P., Rezeau (2010b), L., Three Dimensional Anisotropic k Spectra of Turbulence at Subproton Scales in the Solar Wind, *Phys. Rev. Lett.*, 105, 131101
16. Narita, Y., F. Sahraoui, M. L. Goldstein, and K.-H. Glassmeier (2010), Magnetic energy distribution in the four-dimensional frequency and wave vector domain in the solar wind, *J. Geophys. Res.*, 115, A04101, doi:10.1029/2009JA014742.
17. Sahraoui, F., G. Belmont, M. L. Goldstein, and L. Rezeau (2010a), Limitations of multispacecraft data techniques in measuring wave number spectra of space plasma turbulence, *J. Geophys. Res.*, 115, A04206, doi:10.1029/2009JA014724.