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Research Article

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On the direction of the velocity and magnetic field fluctuations in undisturbed solar wind

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Abstract: Measurements of velocity and magnetic field in near-Earth heliosphere is analized in order to investigate systematical deflection from transversality of the velocity and magnetic field fluctuations in undisturbed solar wind. Fluctuations occurred in the meridional plain of heliosphere (RN plain of the RTN reference system) are transversal with respect to mean magnetic field during periods of high solar activity, but they become non-transversal close to solar cycle minima. This phenomenon is investigated focusing on a role of Alfvén waves. It is shown that deflections from transversality is mostly expressed by fluctuations in slow solar wind streams with low contribution of Alfvén waves, whereas strongly Alfvénic turbulence undergo such deflection in a less degree. In addition, we consider orientation of velocity fluctuations in the azimuthal (RT) plain of heliosphere, which also indicates some interesting features.

Keywords: solar wind, velocity, fluctuations

1 Introduction

It has been found by a number of investigators that fluctuation of magnetic field and velocity in undisturbed solar wind (SW) mainly are transversal with respect to mean magnetic field (see Bruno and Carbone 2013) and references therein). This fact is explained, at least in part, by presence of large-amplitude Alfvén waves propagating along mean magnetic field. However, there were reports about systematical deflections from transversality of magnetic and velocity fluctuations, probably did not associated with interplanetary disturbances. So, Lyatsky *et al.* (2003) have found that radial and vertical components of interplanetary magnetic field, B_x and B_z (in GSE reference system), significantly correlate during periods of low solar activity, and sign of the correlation coefficient depends on both direction of mean magnetic field (*i.e.*, polarity of magnetic sector) and direction of polar magnetic field of the Sun. Results by Lyatsky *et al.* (2003) were verified by Youssef *et al.* (2012). Erofeev (2019a) who used RTN coordinate system has found that correlation between radial B_R and normal B_N components of magnetic field exists in cycle minima within wide range of periods of fluctuations, at least from several minutes to a day, and it slowly decreases with decreasing period (or increasing frequency). On the other hand, correlation between tangential and normal components of magnetic field, B_T and B_N, is very weak or absent during solar cycle minima. As also has been shown by Erofeev (2019a), the above properties are characteristic of velocity fluctuations, but only of those with periods shorter than about 5 hr.

Thus, magnetic and velocity fluctuations become non-transversal close to solar cycle minima, and deflection from transversality occurs in the meridional plain of heliosphere. It is reasonable to suppose that such deflection is caused by large-scale latitudinal gradients of plasma parameters, which are characteristic of heliosphere during minimum phase of solar cycle (Smith 2008; McComas *et al.* 2000). Lyatsky *et al.* (2003) expained non-transversality of magnetic fluctuations during cycle minima by refraction of Alfvén waves due to latitudinal gradient of plasma density. Another explanation (Erofeev 2019b) consists in deformation of any transversal fluctuations, both Alfvénic and not, by action of latitudinal gradient of SW velocity. A possible way to choose from the two explanations is to clear up whether deflection from transversality exclusively is characteristic of Alfvén waves or not. In such a way, one need to make comparative analysis of velocity and magnetic fluctuations occurred in the meridional plain of heliosphere (RN plain of the RTN reference system). This reason was a main cause to launch the present investigation. In addition, we intent to clear up a cause of disagreement between behaviour of magnetic and velocity fluctuations at low frequencies. For this purpose, we analyse velocity and magnetic fluctuations occurred in the azimuthal plain of heliosphere (RT plain of the RTN reference system).

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2 Data and methods of investigation

We use for investigation measurements of velocity, **V**, proton density, N_P, and magnetic field, **B** made in near-Earth heliosphere by WIND spacecraft in years 1995-2020. The data are averaged over 92 s. In the source data set, vector parameters are expressed in GSE coordinate system, but we transformed they to RTN reference system that undergoes less influence of Earth's orbital motion. The RTN system is defined as follows: the radial axis R is directed along the line connecting center of the Sun and the spacecraft, the tangential axis T is parallel to $\Omega \times R$ where Ω is vector of Sun's rotation, and the normal axis $N = R \times T$. In addition to the WIND data, we use hourly-averaged parameters of SW collected in OMNI2 data base. We selected for analysis only time intervals when no significant disturbances of SW were observed. In addition to sporadic events, we treat as disturbances such long-lived structures as interaction regions between low-speed and high-speed flows and sector boundaries including their vicinities (see Erofeev 2019a for details). Note that removal of the sector boundaries means that the data obtained near the heliospheric current sheet are not used. Selected measurements were marked by two indices, one of them indicates sort of SW stream, slow or fast, and another indicates polarity of magnetic sector, +1 or −1. As a result of the data selection, we obtain a number of continuous time series with different lengths from several days up to about 10 days. For our purpose, it is convenient to use time series with approximately constant length of about 1.5 days. Therefore, selected data were devided to more short time series whose lengths varied within interval from 1.5 to 2 day, with average value of 1.7 day. Each of the short data series was standardized by means of substraction of average values and linear trends from measurements of velocity and magnetic field. Thus, long-term variations were eliminated from the data. In addition, we calculated normalized cross-helicity σ_C for each of the short data series to use this parameter as a measure of alfvénicity (*i.e.*, contribution of Alfvén waves to SW turbulence).

Let V_i and B_i be components of velocity and magnetic field vectors expressed in the RTN reference system, while δV_i and δB_i be their fluctuation parts. For any vector, say velocity **V**, one can determine second-order statistical moments in the form $\langle \delta V_i \cdot \delta V_j \rangle$, where angular brackets mean averaging over time. Analysis of the set of the second-order moments is a usual method to estimate preferable direction of fluctuations in SW. For the reasons given in Section 1, we intent to investigate separately fluctuations occurred in different planes of heliospere, using projection of the vectors to one of the coordinate planes, RN or RT, of the RTN reference system. Thus, one can esimate three second-order moments of velocity fluctuations for each of the coordinate planes. It shoul be noted that we need to take into account dependency of the second-order moments on several parameters, such as phase of solar cycle, polarity of magnetic sector, frequency of fluctuations, sort of SW stream (slow or fast), and alfvénicity. In order to minimize the number of parameters under investigation, it is reasonable to reduce three second-order moments to one parameter, coefficient of correlation r^V_{ij} between pairs of vector components, δV_i and $\delta V_j (i \neq j)$. Coefficient of correlation r^B_{ij} for magnetic fluctuations may be determined in the same way. We consider in Section 3.1 the yearly-averaged coefficients of correlation, $r^V_{ij}(t)$ and r^B_{ij}, as functions of time.

A more convenient tool for our investigation is frequency-dependent coefficient of correlation $C^V_{ij}(f)$ estimated as follows:

$$C^V_{ij}(f) = \mathrm{Re}[\Gamma^{\mathrm{V}}_{\mathrm{ij}}(\mathrm{f})], \tag{1}$$

where $\Gamma^V_{ij}(f)$ is complex-valued function of coherency:

$$\Gamma^V_{ij}(f) = \frac{\langle F[\delta V_i] \cdot F[\delta V_j]^* \rangle}{\sqrt{\langle |F[\delta V_i]|^2 \rangle \langle |F[\delta V_j]|^2 \rangle}}, \tag{2}$$

$F[\delta V_i]$ denotes Fourier transform of $\delta V_i(t)$, asterick stands for complex conjugation, and angular brackets mean averaging over ensemble of realizations. In practice, the ensemble of realizations was presented by a large number of 1.7-day data series selected as described above. In addition to averaging over the realizations, we applied averaging within small sliding interval of frequency in order to reduce statistical errors of estimations. Coefficients of correlation for magnetic fluctuations, $C^B_{ij}(f)$, may be calculated in the same manner by using vector components δB_i.

One of the aims of the present investigation is to estimate a role of Alfvénic fluctuations. To do this, we apply two methods based on well-known relationship between velocity and magnetic field for Alfvén wave propagating in direction **k**:

$$\delta \mathbf{V} = -\frac{\delta \mathbf{B}}{\sqrt{\mu_0 \rho}} sign(\mathbf{k} \cdot \mathbf{B_0}) \tag{3}$$

where ρ is plasma density, $\mathbf{B_0}$ is constant magnetic field. First of the methods is comparison between SW flows with low and high alfvénicity. Usually applied measure of alfvénicity is absolute value of normalized cross-helicity σ_C:

$$\sigma_C = \frac{2\langle \delta \mathbf{V} \cdot \delta \mathbf{b} \rangle}{\langle \delta \mathbf{V}^2 \rangle + \langle \delta \mathbf{b}^2 \rangle}, \tag{4}$$

where $\mathbf{b} = \mathbf{B} / \sqrt{\mu_0 \rho}$ is magnetic field expressed in Alfvén units. Second method regards cross-correlations between projections of velocity and magnetic field vectors on different coordinate axis, δB_i and $\delta V_j (i \neq j)$. We determine the cross-correlation coefficient in the symmetrized form:

$$C^S_{ij}(f) = \mathrm{Re}[\Gamma^{\mathrm{BV}}_{\mathrm{ij}}(\mathrm{f}) + \Gamma^{\mathrm{VB}}_{\mathrm{ij}}(\mathrm{f})]/2, \quad (5)$$

where Γ^{BV}_{ij} is function of coherence of δB_i and δV_j, while Γ^{VB}_{ij} is function of coherency of δV_i and δB_j. Empasize that C^S_{ij} is cross-correlation between projections of $\delta \mathbf{V}$ and $\delta \mathbf{B}$ on *different* coordinate axis, unlike cross-helicity; so, $\sigma_c \neq 0$ does not mean that $C^S_{ij} \neq 0$.

3 Results

3.1 Meridional (RN) plain

As follows from reports by Lyatsky *et al.* (2003) and by Erofeev (2019a), components of magnetic field δB_R and δB_N significantly correlate during periods of low solar activity, and sign of the correlation coefficient depends on both direction of mean magnetic field B_0 (*i.e.*, polarity of magnetic sector) and direction of polar magnetic field of the Sun, B_P. This dependency may be expressed by the 'sign rule':

$$\mathrm{sign}(r^B_{RN}) = \mathrm{sign}(B_O) \cdot \mathrm{sign}(B_P). \quad (6)$$

Erofeev (2019a) has found that the same properties are characteristic of velocity fluctuations with periods shorter than about 5 hr. The statements given above are exhibited by Figure 1 where we show coefficients of correlation r^B_{RN} and r^V_{RN} calculated as functions of time by using OMNI2 data set (in calculating, we eliminate variations of velocity with periods larger than 5 hr). Notice the similarity in behaviour of $r^B_{RN}(t)$ and $r^V_{RN}(t)$. In Figure 2a–2b we show how preferable direction of magnetic fluctuations with periods shorter than 5 hr varied in going from solar activity maximum to the minimum. One can see in these graphs that axis of maximum variance was directed approximately parallel to N axis during period of large solar activity, but it became strongly tilted to the N axis in the activity minimum. Figure 2c–2d shows the same for fluctuations of velocity.

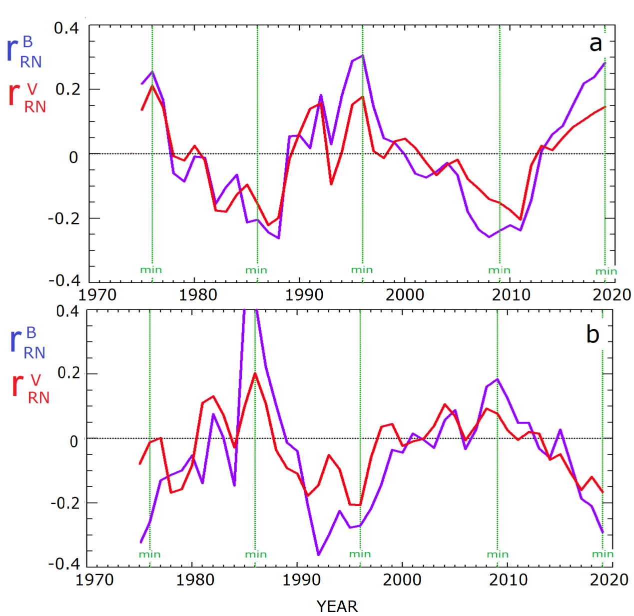

Figure 1. Correlation between radial (R) and normal (N) components of magnetic field (*blue line*) and velocity (*red line*) as functions of time, (a) – for positive magnetic sector, (b) – for negative magnetic sector. Vertical green lines mark minima of solar activity

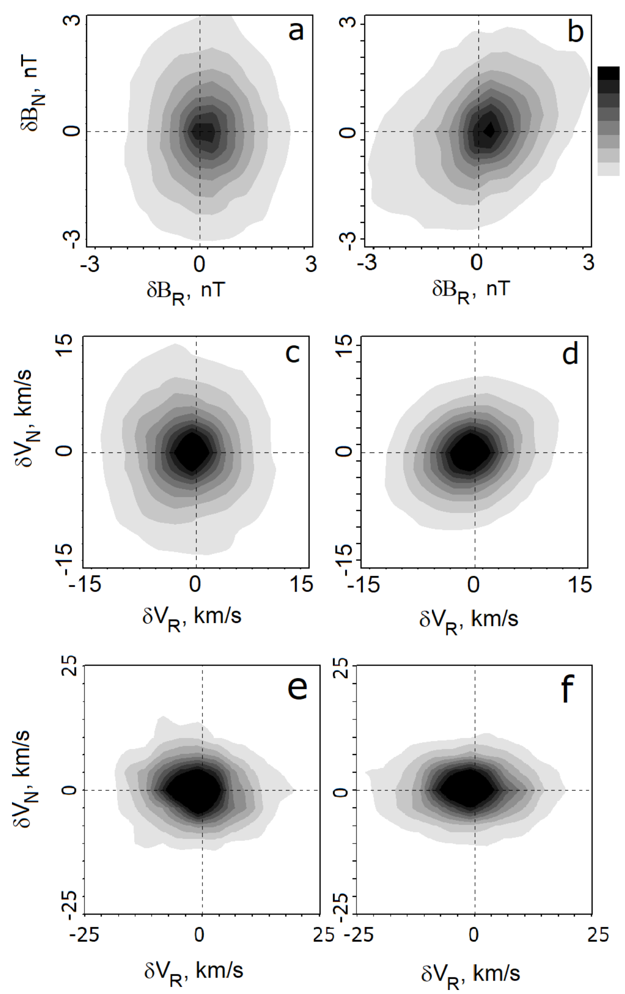

Figure 2. (a) 2D distribution of radial (R) and normal (N) components of magnetic fluctuations occurred in positive magnetic sector during period of high solar activity in years 2012–2015. (b) the same for period of solar cycle minimum (years 2018–2020). (c) and (d) show the same as in (a) and (b), but for fluctuations of velocity with periods <5 hr. Parts (e) and (f) indicate the same as in (c) and (d), but for velocity fluctuations with periods >5 hr

Thus, both magnetic and velocity fluctuations preferably are transversal with respect to mean magnetic field during periods of large solar activity, but they become non-transversal close to solar cycle minima. In order to investigate this phenomenon in more detail, we selected data obtained by WIND spacecraft during three minima of solar cycle, in years 1995–1997, 2008–2010, and 2018–2020. Note that high-speed SW streams are rare in cycle minima, therefore we mainly analyse data of slow SW. When calculated frequency-dependent correlation coefficients, we multiplied normal (N) components of velocity and magnetic field by the factor $\mathrm{sign}(B_0) \cdot \mathrm{sign}(B_P)$ in order to avoid the long-term variations occurred in accordance with the 'sign rule' (Eq. (6)). This allows us to make averaging over three cycle minima and over two magnetic sectors. Figure 3 exhibits correlation coefficients of magnetic field, C^B_{RN}, and velocity, C^V_{RN}, as fuctions of frequency. Statistical errors of the estimation ≈ 0.016, and frequency resolution $\approx 3 \cdot 10^{-5}$ Hz. The graphs in Figure 3 show that behaviour of $C^V_{RN}(f)$ is similar to that of $C^B_{RN}(f)$ at frequencies $f > 5 \cdot 10^{-5}$ Hz (periods of fluctuations < 5 hr), although correlation of velocity is smaller by a factor ≈ 0.7 as compared to that of magnetic field. At frequencies $f < 5 \cdot 10^{-5}$ Hz, C^V_{RN} falls down, unlike correlation of magnetic fluctuations, C^B_{RN}. A cause of such difference probably is large-scale inhomogeneity of SW flow (see Section 3.2).

As has been mentioned in Section 1, two physical processes were suggested as a possible cause of deflection from transversality in meridional plain exhibited by SW fluctiations close to cycle minima. One of the suggestions (Lyatsky *et al.* 2003) assigns an exclusive role to Alfvén waves, while the second one (Erofeev 2019b) does not. Therefore, it is of interest to assess a role of Alfvén waves in the deflection from transversality of SW fluctuations. For this purpose, we first consider coefficient of cross-correlation between velocity and magnetic field determined in Section 2. If correlation between δB_R and δB_N, as well as correlation between δV_R and δV_N, are caused by Alfvén waves, one may expect existence of cross-correlation between radial velocity, δV_R, and normal magnetic field, δB_N, as well as existence of cross-correlation between δV_N and δB_R (this follows from (Eq. (3))). Also, signs of the cross-correlations should be dependent of polarity of magnetic sector, so coefficient of correlation C^S_{RN} should follow the relationship: $\mathrm{sign}(C^S_{RN}) = -\mathrm{sign}(C^B_{RN}) \cdot \mathrm{sign}(B_0)$. Therefore, we show in Figure 3 cross-correlation $C^S_{RN}(f)$ calculated separately for positive and negative magnetic sectors. As can be seen in Figure 3, velocity and magetic field exhibit weak (but statistically significant) cross-correlation, and the cross-correlation coefficient $C^S_{RN}(f)$ has different signs in magnetic sectors of different polarities, as it has been expected. This means that Alfvénic fluctuations do undergo deflection from transversality in the meridional (RN) plain. However, cross-correlation C^S_{RN} is smaller in absolute value than C^V_{RN} by a factor of about 0.7, and it approximately half as large as C^B_{RN}. This evidences that deflection from transvertality also is characteristic of SW fluctuations other than Alfvénic ones.

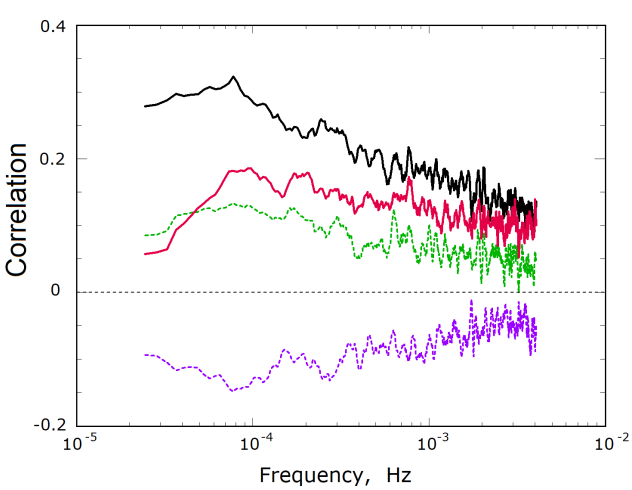

Figure 3. Correlation between radial (R) and normal (N) components of magnetic field (*black solid line*) and velocity (*red solid line*) as functions of frequency, for minima of solar activity. *Blue* and *green* dashed lines exhibit cross-correlation of velocity and magnetic fluctuations in positive and negative magnetic sectors, correspondently (*see text for details*)

Another way to evaluate a role of Alfvén waves is comparison between SW streams with low and high alfvénicity. Separation of the data with low alfvénicity may be done for slow SW, since fast SW is strongly Alfvénic. Figure 4a-b exhibits coefficients of correlation calculated with using data of slow SW, separately for $|\sigma_c| < 0.4$ and $|\sigma_c| > 0.4$. Figure 4c shows coefficients of correlation for fast SW, which

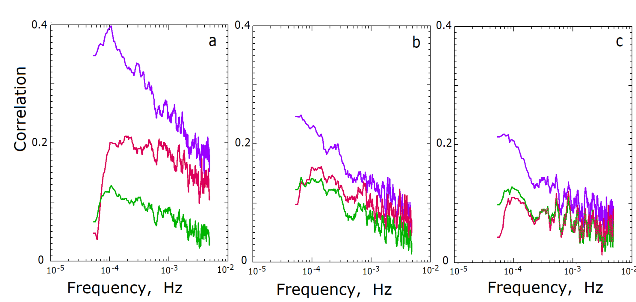

Figure 4. Correlation between radial (R) and normal (N) components of magnetic field (*blue line*) and velocity (*red line*) as functions of frequency, for minima of solar activity. *Green line* exhibit cross-correlation of velocity and magnetic fluctuations. (a) – slow solar wind, low alfvénicity; (b) – slow solar wind, large alfvénicity; (c) – fast solar wind (*see text for details*)

is strongly Alfvénic. In these graphs we also present cross-correlation $C^S_{RN}(f)$ obtained by averaging over two magnetic sectors (to eliminate dependence on sector polarity, we multiplied $C^S_{RN}(f)$ by the factor $-\text{sign}(B_O)$). The comparison of the graphs in Figure 4 shows that the correlation coefficients C^B_{RN} and C^V_{RN} both indicate maximal values in SW streams with lowest alfvénicity, and they substantially decrease with increasing $|\sigma_C|$. On the other hand, cross-correlation C^S_{RN} exhibits little or no dependency of $|\sigma_C|$, so C^S_{RN} is significantly smaller than C^V_{RN} at $|\sigma_C| < 0.4$, but it become approximately equal to C^V_{RN} at high alfvénicity. Thus, two methods applied by us indicate that deflection from transversality in RN-plain is not an exclusive property of Alfvén waves; on the contrary, the deflection is more expressed in SW flows with low alfvénicity.

As already has been mentioned, agreement between directions of magnetic and velocity fluctuations in the RN-plain takes place for periods <5 hr. In Figure 2(e-f) we show 2D distributions of δV_R and δV_N for fluctuations with periods larger than 5 hr. One can see that these large-scale fluctuations of velocity mainly are directed along the R axis, especially during minimum phase of solar cycle. More strictly speaking, Figure 2(e-f) indicates that preferred direction of the large-scale velocity fluctuatios lies in the azimuthal (RT) plane.

3.2 Azimuthal (RT) plain

When investigated fluctuations occurred in the meridional (RN) plain, we pointed out that agreement between behavior of velocity and magnetic fluctuations violates at frequencies smaller than about $5 \cdot 10^{-5}$ Hz. This disagreement arises due to that the large-scale variations of velocity tend to be directed radially, so they are rather inhomogeneity of SW flow than turbulence. However, the large-scale velocity variations indicate some systematical deviation from the radial direction in the azimuthal (RT) plain. In fact, calculation shows that fluctuations of radial velocity, δV_R, correlate with those of tangential velocity, δV_T, and the correlation coefficient is negative independently of phase of solar cycle and polarity of magnetic sector. Note that in the case if velocity fluctuation be directed radially, the correlation coefficient should be equal to zero. On the other hand, in case if the velocity fluctuations be transversal wih respect to the mean magnetic field $\mathbf{B_0}$, like Alfvén waves, the correlation coefficient should be positive (this follows from the fact that $\mathbf{B_0}$ is inclined to radial direction at angles of about $-45°$ or $135°$). Negative correlation means that preferred direction of velocity fluctuations deflects from the radial direction R in the same manner as the mean magnetic field.

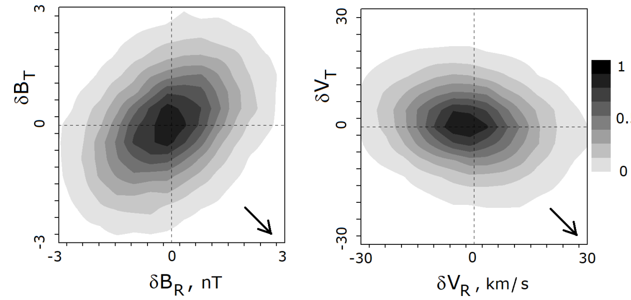

Figure 5. 2D distribution of radial δB_R and tangential δB_T components of magnetic fluctuations (*left panel*) and distribution of radial δV_R and tangential δV_T components of velocity fluctuations (*right panel*). Arrow indicates approximate direction of mean magnetic field

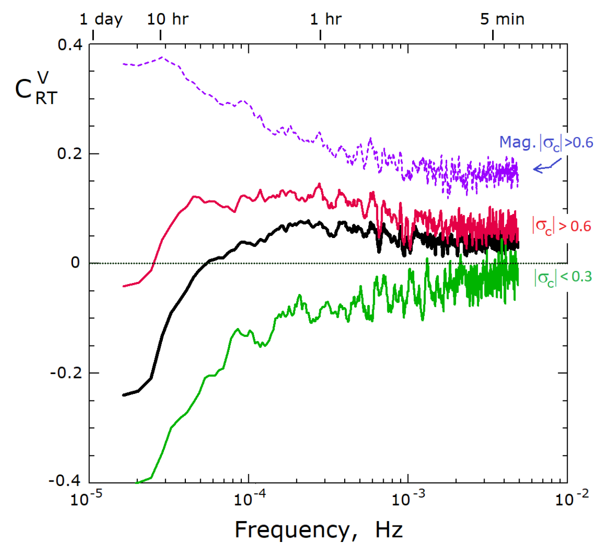

Figure 6. Correlation between radial (R) and tangential (T) components of velocity is shown with *black line*. *Green* and *red lines* exhibit the same, but calculated separately for time intervals with small and high alfvénicity; *blue dashed line* indicates for comparison correlation between R- and T-component of magnetic fluctuations

In Figure 5, we show 2D distribution of velocity components δV_R and δV_T in comparison with distribution of magnetic field components, δB_R and δB_T. The graph in the left panel of Figure 5 shows that preferred direction of the magnetic fluctuations is approximately orthogonal to the mean magnetic field (whose direction is indicated with arrow), as it may be expected for Alfvénic turbulence. Axis of maximum variance of velocity fluctuations, on the contrary, is inclined to radial direction in the same manner as mean magnetic field, but at smaller angle. Calculation yields value of the inclination angle of about $-21°$. Such a 'quasi-longitudinal' orientation mainly is characteristic of large-scale fluctuations of velocity. This follows from the fact that frequency-dependent correlation coefficient

$C^V_{RT}(f)$ (shown with blck line in Figure 6) indicates negative correlation between δV_R and δV_T only at lowest frequencies, whereas fluctuations with periods shorter than about 5 hr exhibit no correlation or low positive correlation. However, comparison between SW flows with low and high alfvénicity (see Figure 6) indicates that behaviour of the correlation coefficient $C^V_{RT}(f)$ substantially depends on contribution of Alfvénic fluctuations. So, SW flows with high alfvénicity ($|\sigma_c| > 0.6$) indicate no negative correlation between δV_R and δV_T even at lowest frequencies, whereas SW flows with low alfvénicity ($|\sigma_c| < 0.3$) indicate $C^V_{RT}(f) < 0$ within a wide range of frequency extended up to 10^{-3} Hz. This evidences that 'quasi-longitudinal' fluctuations with small scales also exist, but they are comparatively weak and usually are masked by intensive Alfvénic turbulence.

4 Conclusion

We investigated fluctuations of velocity and magnetic field in undisturbed SW. We analysed separately fluctuations occurred in meridional and azimuthal planes of heliosphere, since the two sorts of fluctuations exhibit different temporal befaviour as well as different dependency on frequency. Also, we took into account dependence of the SW fluctuations on phase of solar cycle, polarity of mean magnetic field, and alfvénicity.

When anlysed SW fluctuations in the meridional plain of heliosphere, we found that both magnetic and velocity fluctuations preferably are transversal with respect to mean magnetic field during periods of large solar activity, but they become non-transversal close to solar cycle minima, and deflection from transversality has variable direction in dependency of polarity of magnetic sector and orientation of polar magnetic field of the Sun. These conclusions confirm results of previous investigations by Lyatsky *et al.* (2003); Youssef *et al.* (2012), and Erofeev (2019a). A new result is evaluation of the role of Alfvénic fluctuations in deflection from transversality of SW fluctuations. Our analysis indicates that although Alfvénic fluctuations undergo such deflection to a certain degree, a mostly expressed deflection takes place in SW flows with low alfvénicity. For this reason, explanation of deflection from transversality of SW fluctuations based on action of latitudinal gradient of velocity (Erofeev 2019a) seems to be more preferable as compared to explanation based on refraction of Alfvén waves suggested by Lyatsky *et al.* (2003). Note however that the different behavior of SW fluctuation during time intervals with low and high alfvénicity may in part be caused by difference in physical conditions between highly Alfvénic and weakly Alfvénic SW flows (for example, different latitudinal gradients of velocity). Difference in physical conditions between Alfvénic and non-Alfvénic flows in slow SW was reported by D'Amicis *et al.* (2019).

Although magnetic fluctuations exhibit the above described behaviour of polarization within wide range of periods extended up to 1 day, fluctiations of velocity with periods larger then about 5 hr tend to be oriented close to radial direction. Analysis indicates that preferable direction of the large-scale velocity fluctuations is not radial, but it deviate from the radial direction in the meridional (RT) plain at angle of about −20°. We suppose that such large-scale fluctiations of velocity are rather inhomogeneties of SW flow than turbulence, and that deviation from radial direction occurs due to interaction of flows with slightly different velocity. We also found that polarization of this sort is not an exclusive property of the large-scale velocity variations, but it is exhibited by smaller scale fluctiations in SW streams with low alfvénicity. Presence of intensive Alfvénic turbulence usually masks such small-scale fluctuations of velocity.

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References

Bruno R, Carbone V. 2013. The Solar Wind as a Turbulence Laboratory. Living Rev Sol Phys. 10:2.
D'Amicis R, Matteini L, Bruno R. 2019. On the slow solar wind with high Alfvénicity: from composition and microphysics to spectral properties. Mon Not R Astron Soc. 483:4665.
Erofeev D. 2019a. Correlation of the Radial and Meridional Components of IMF and the Solar Wind Velocity: Dependence on the Time and the Fluctuation Frequency. Geomagn Aeron. 59(1):7–15.
Erofeev D. 2019b. Effect of large-scale inhomogeneity of solar wind velocity on distribution of directions of interplanetary magnetic field vector. Solar-Terrestrial Physics. 5(3):42–53.

Lyatsky W, Tan A, Lyatskaya S. 2003. Effect of Sun's magnetic field polarity on interplanetary magnetic field *B z*. Geophys Res Lett.30(24):L2258.

McComas D, Barraclough B, Funsten H, Gosling JT, Santiago-Muñoz E, Skoug RM, et al. 2000. Solar wind observations over Ulysses' first full polar orbit. J Geophys Res. 105 A5:10,419–10433.

Smith E. 2008. The global heliospheric magnetic field. in: The Heliosphere through the Solar Activity Cycle. Balogh A, Lanzerotti LJ, Suess ST, editors. Berlin, Heidelberg: Springer; 2008. p. 79.

Youssef M, Mahrous A, Mawad R, Ghamry E, Shaltout M, El-Nawawy M, et al. 2012. The effects of the solar magnetic polarity and the solar wind velocity on Bz-component of the interplanetary magnetic field. Adv Space Res. 49(7):1198–1202.