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BRIEF RESEARCH REPORT
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The Triple Dusk-Dawn Aberration of the Solar Wind at Earth

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In this Brief Report it is pointed out that there are three dusk-dawn aberrations of the solar-wind plasma and magnetic structure approaching Earth and the magnitudes of these aberrations are estimated for various solar-wind types monitored from L1. Solar-wind monitors closer to the Earth than L1 would have superior performances.

Keywords: solar wind, magnetosphere, solar wind monitor, solar wind magnetosphere coupling, space weather

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The solar-wind plasma and its magnetic structure that hit an L1 monitor on the Sun-Earth line will on average pass duskward of the Earth's magnetosphere. This is depicted in **Figure 1** with L1 at the top of the sketch and with the shape of the magnetosphere drawn in blue using the Lin et al. (2010) magnetopause model (eq. (3) of Lin et al. (2010) with r_o = 10.8 R_E, m = 0.1, and $\beta = -1.1$).

The solar-wind velocity vector at 1 AU varies with time by about ±5° in both the dawn-dusk and north-south directions (cf. Borovsky 2012; Borovsky, 2018). With L1 being 235 R_E upstream from the Earth (cf. **Figure 1**), the ±5° time variation of the flow vector corresponds to a ±20.5 R_E time variation in the location at Earth of a flow streamline passing through an L1 monitor. The timescales of these velocity-vector changes can be slow (e.g., the days-long variations about stream interfaces discussed below) or fast [e.g., the 98 km/s change in the solar-wind velocity vector over 3 s shown in Fig. 6b of Borovsky (2020a)].

In addition to this variation in the streamline location at Earth, there is a systematic triple aberration (shift) in the dawn-dusk direction. The plasma flow of the solar wind experiences the first two aberrations and the magnetic structure of the solar wind experiences all three aberrations. The origins of the triple aberration are as follows.

(1) The motion of the Earth around the Sun. The 29.8 km/s dawnward motion of the Earth in its orbit (black arrow in **Figure 1**) means that for a perfectly radial solar-wind flow with a speed v_{sw} hitting L1 at the Sun-Earth line will have a streamline that passes the Earth on the dusk side by a distance of (235 R_E) (29.8/v_{sw}) (e.g., Fairfield, 1993). For v_{sw} = 350 km/s this distance is 20 R_E and for v_{sw} = 650 km/s this distance is 10.8 R_E (cf. **Table 1**). In Borovsky (2018) the variability of this first aberration owing to the variability of the solar-wind flow vector is examined in comparison with the typical structure sizes of the solar wind magnetic field (10's of R_E to 100 R_E): cf. Fig. 5 of Borovsky (2018).

(2) The non-radial average flow vector of the solar wind. Using multiple spacecraft at 1 AU, Nemecek et al., (2020a) found a systematic nonradial component to the proton-solar-wind flow that tends to be in the direction of the solar rotation [see also Pizzo et al., (1983) and Finlay et al., (2019)]. As noted in **Table 1**, this systematic flow is ~10 km/s dawnward for slow solar wind and is ~5 km/s duskward for mid-range solar-wind speed. Note that there are also very large ~40 km/s dawn-dusk flows at Earth associated with stream interfaces (Gosling et al., 1978): for slow-to-fast (leading-edge) stream interfaces the solar-wind flow is strongly dawnward on the day before the interface passes the Earth and the flow is strongly duskward on the day after the passage of the interface [cf. Fig. 4b of Borovsky and Denton (2010)] and for fast-to-slow (trailing-edge) stream interfaces the solar-wind flow is systematically duskward for about 3 days prior to the interface passage and the flow is systematically dawnward for about 3 days after the interface passage [cf. Fig. 14b of Borovsky and

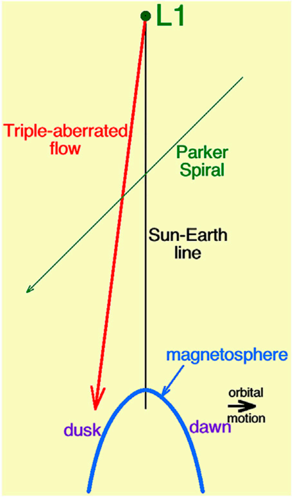

FIGURE 1 | A sketch of a net duskward aberration (red arrow) from a monitor at L1 (green).

Denton (2016)]. As noted in **Table 1**, the Nemecek et al., (2020a) 10 km/s dawnward velocity in a 350 km/s wind yields an offset of 6.7 R_E for the streamline at Earth.

(3) The magnetic structure of the heliosphere moves out from the Sun along the Parker spiral faster than the proton flow. In the Alfvenic fast wind and in the Alfvenic slow wind, the magnetic structure of the heliosphere moves outward from the Sun at a speed of about 0.7 v_A along the Parker-spiral direction relative to the proton flow (Borovsky, 2020b; Nemecek et al., 2020b). [Alfvénic wind has strong temporal correlations between the flow vector $\mathbf{v}(t)$ and the magnetic-field vector $\mathbf{B}(t)$.] A nominal 45° Parker-spiral orientation is sketched as the green arrow in **Figure 1**. For v_{sw} in the range 500–650 km/s, the mean Alfven speed in the OMNI2 data set (King and Papitashvili, 2005) is $v_A = 73$ km/s. Accounting for the angle of the Parker spiral from the Sun-Earth line (39° for 500 km/s and 32° for 650 km/s) the aberration of the magnetic structure is estimated to be 31.7 km/s duskward for 500 km/s Alfvenic solar wind and 27.1 km/s for 650 km/s Alfvenic solar wind (cf. **Table 1**). These aberrations yield "streamline" duskward displacements of 14.9 R_E and 9.8 R_E. Note that the alpha particles of the solar wind are approximately at rest in the reference frame moving with the magnetic structure (Nemecek et al., 2020b), so the alpha-particle flow has the same aberration as the magnetic structure. Also note that at 1 AU the instantaneous magnetic-field direction varies by about ±45° with respect to the calculated Parker-spiral direction [cf. Table 1 of Borovsky (2010)], but the magnetic structure moves in the mean-field direction which is the calculated Parker-spiral direction.

These aberrations are on the order of the 10s-of-R_E magnetic structure sizes in the background Parker-spiral solar wind at 1 AU (Borovsky, 2008; 2018).

Assuming a radial proton flow, the magnitude of the first aberration is straightforward to calculate with the formula ($29.8/v_{sw}$): if the flow is not radial the correction to the first aberration is very small. The second aberration (caused by the non-radial flow) is very variable with time: with a ±5° variation in the flow vector this is a ~ ±20-R_E variation at Earth. The variability of the third aberration has yet to be explored: the Parker-spiral direction varies according to the known formula ($405/v_{sw}$) however the statistics of the magnetic-structure velocity vector with respect to the Parker-spiral direction have not been studied.

TABLE 1 | Estimates of the dusk-dawn aberrations of the proton plasma and the magnetic structure for typical solar wind types.

Solar wind	Aberration 1	Aberration 2	Aberration 3	Total Aberration
350 km/s non-Alfvenic	Duskward 29.8 km/s 20.0 R_E	dawnward 10 km/s 6.7 R_E	0 km/s 0 R_E	duskward 13.3 R_E
500 km/s non-Alfvenic	Duskward 29.8 km/s 14.0 R_E	duskward 5 km/s 2.4 R_E	0 km/s 0 R_E	duskward 16.4 R_E
500 km/s Alfvenic	Duskward 29.8 km/s 14.0 R_E	Duskward 5 km/s 2.4 R_E	duskward 31.7 km/s 14.9 R_E	duskward 31.3 R_E
650 km/s Alfvenic	Duskward 29.8 km/s 10.8 R_E	?	duskward 27.1 km/s 9.8 R_E	duskward 20.6 R_E

The aberration problem from L1 gets better or worse depending on the location of the solar-wind monitor about the L1 point. And during the systematic large deflections of the solar wind in the days around the passages of stream interfaces, the aberration problem gets worse.

There have been a number of recent criticisms of using L1 monitoring for solar-wind/magnetosphere coupling studies (Sandahl et al., 1996; Ashour-Abdalla et al., 2008; Borovsky, 2018, 2020a; Walsh et al., 2019; Burkholder et al., 2020) and several estimates of the solar-wind errors between L1 and Earth (Crooker et al., 1982; Ridley, 2000; Weimer et al., 2002; Mailyan et al., 2008; Case and Wild, 2012). These criticisms and error calculations were based on the temporal flow deviations of the solar wind, the magnetic-structure scalesizes in the solar wind, and cross correlations between L1 measurements and near-Earth measurements.

In studying the driving of the Earth by the solar wind, recent work indicates that errors in the solar-wind values make it difficult to uncover or confirm the physics of the driving. In particular in data-analysis studies the "best fit" formulas obtained by optimizing correlations change depend on the amount of noise in the solar wind measurements (Borovsky, 2022; Sivadas et al., 2022).

To make needed progress in understanding solar-wind/magnetosphere interaction, a call is made for solar-wind monitors much closer to the Earth than L1. A study to optimize the monitor mission is needed. One suggestion would be multiple spacecraft in IMP-type circular orbits (r ~ 30 R_E) wherein one of the spacecraft would always be in the upstream solar wind.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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REFERENCES

Ashour-Abdalla, M., Walker, R. J., Peroomian, V., and El-Alaoui, M. (2008). On the Importance of Accurate Solar Wind Measurements for Studying Magnetospheric Dynamics. *J. Geophys. Res.* 113, A08204. doi:10.1029/2007ja012785

Borovsky, J. E., and Denton, M. H. (2010). Solar-wind Turbulence and Shear: A Superposed-Epoch Analysis of Corotating Interaction Regions at 1 AU. *J. Geophys. Res.* 115, A10101. doi:10.1029/2009ja014966

Borovsky, J. E., and Denton, M. H. (2016). The Trailing Edges of High-Speed Streams at 1 AU. *J. Geophys. Res. Space Phys.* 121, 6107–6140. doi:10.1002/2016ja022863

Borovsky, J. E. (2022). Noise, Regression Dilution Bias, and Solar-Wind/magnetosphere Coupling Studies. *Front. Astron. Space Sci.* 9, 867282. doi:10.3389/fspas.2022.867282

Borovsky, J. E. (2020b). On the Motion of the Heliospheric Magnetic Structure through the Solar Wind Plasma. *J. Geophys. Res. Space Phys.* 125, e2019JA027377. doi:10.1029/2019JA027377

Borovsky, J. E. (2010). On the Variations of the Solar Wind Magnetic Field about the Parker Spiral Direction. *J. Geophys. Res.* 115, A09101. doi:10.1029/2009ja015040

Borovsky, J. E. (2012). The Effect of Sudden Wind Shear on the Earth's Magnetosphere: Statistics of Wind-Shear Events and CCMC Simulations of Magnetotail Disconnections. *J. Geophys. Res.* 117, A06224. doi:10.1029/2012ja017623

Borovsky, J. E. (2008). The Flux-Tube Texture of the Solar Wind: Strands of the Magnetic Carpet at 1 AU? *J. Geophys. Res.* 113, A08110. doi:10.1029/2007ja012684

Borovsky, J. E. (2018). The Spatial Structure of the Oncoming Solar Wind at Earth and the Shortcomings of a Solar-Wind Monitor at L1. *J. Atmos. Solar-Terrestrial Phys.* 177, 2–11. doi:10.1016/j.jastp.2017.03.014

Borovsky, J. E. (2020a). What Magnetospheric and Ionospheric Researchers Should Know about the Solar Wind. *J. Atmos. Solar-Terrestrial Phys.* 204, 105271. doi:10.1016/j.jastp.2020.105271

Burkholder, B. L., Nykyri, K., and Ma, X. (2020). A Multispacecraft Solar Wind Monitor. *J. Geophys. Res.* 125, e2020JA027978. doi:10.1029/2020ja027978

Case, N. A., and Wild, J. A. (2012). A Statistical Comparison of Solar Wind Propagation Delays Derived from Multispacecraft Techniques. *J. Geophys. Res.* 117, A02101. doi:10.1029/2011ja016946

Crooker, N. U., Siscoe, G. L., Russell, C. T., and Smith, E. J. (1982). Factors Controlling Degree of Correlation between ISEE 1 and ISEE 3 Interplanetary Magnetic Field Measurements. *J. Geophys. Res.* 87, 2224–2230. doi:10.1029/ja087ia04p02224

Fairfield, D. H. (1993). Solar Wind Control of the Distant Magnetotail: ISEE 3. *J. Geophys. Res.* 21265, 21276.

Finlay, A. J., Hewitt, A. L., Matt, S. P., Owens, M., Pinto, R. F., and Reville, V. (2019). Direct Detection of Solar Angular Momentum Loss with the Wind Spacecraft. *Astrophys. J. Lett.* 885, L30.

Gosling, J. T., Asbridge, J. R., Bame, S. J., and Feldman, W. C. (1978). Solar Wind Stream Interfaces. *J. Geophys. Res.* 83, 1401. doi:10.1029/ja083ia04p01401

King, J. H., and Papitashvili, N. E. (2005). Solar Wind Spatial Scales in and Comparisons of Hourly Wind and ACE Plasma and Magnetic Field Data. *J. Geophys. Res.* 110, 2104. doi:10.1029/2004ja010649

Lin, R. L., Zhang, X. X., Liu, S. Q., Wang, Y. L., and Gong, J. C. (2010). A Three-Dimensional Asymmetric Magnetopause Model. *J. Geophys. Res.* 115, A04207. doi:10.1029/2009ja014235

Mailyan, B., Munteanu, C., and Haaland, S. (2008). What Is the Best Method to Calculate the Solar Wind Propagation Delay? *Ann. Geophys.* 26, 2383–2394. doi:10.5194/angeo-26-2383-2008

Nemecek, Z., Durovcova, T., Safrankova, J., Nemec, F., Matteini, L., StansbyJantizek, D. N., et al. (2020b). What Is the Solar Wind Frame of Reference? *Astrophys. J.* 889, 163.

Nemecek, Z., Durovcova, T., Safrankova, J., Richardson, J. D., Simunek, J., and Stevens, M. L. (2020a). (Non)radial Solar Wind Propagation through the Heliosphere. *Astrophys. J. Lett.* 897, L39.

Pizzo, V., Schwenn, R., Marsch, E., RosenbauerMuhlhauser, H., Muehlhaeuser, K.-H., and Neubauer, F. M. (1983). Determination of the Solar Wind Angular Momentum Flux from the HELIOS Data - an Observational Test of the Weber and Davis Theory. *ApJ* 271, 335–354. doi:10.1086/161200

Ridley, A. J. (2000). Estimations of the Uncertainty in Timing the Relationship between Magnetospheric and Solar Wind Processes. *J. Atmos. Solar-Terrestrial Phys.* 62, 757–771. doi:10.1016/s1364-6826(00)00057-2

Sandahl, I., Lundstedt, H., Koskinen, H., and Glassmeir, K.-H. (1996). On the Need for Slar Wind Monitoring Close to the Magnetosphere. *Asp. Conf. Ser.* 95, 300.

Sivadas, N., Sibeck, D., Subramanyan, V., Wlach, M.-T., Murphy, K., and Halford, A. (2022). *Uncertainty in Solar Wind Forcing Explains Polar Cap Potential Saturation*. Cornell University, Ithaca New York, United States: arXiv:2201.0217v1. doi:10.48550/arXiv.2201.02137

Walsh, B. M., Bhakyapaibul, T., and Zou, Y. (2019). Quantifying the Uncertainty of Using Solar Wind Measurements for Geospace Inputs. *J. Geophys. Res. Space Phys.* 124, 3291–3302. doi:10.1029/2019ja026507

Weimer, D. R., Ober, D. M., Maynard, N. C., Burke, W. J., Collier, M. R., McComas, D. J., et al. (2002). Variable Time Delays in the Propagation of the Interplanetary Magnetic Field. *J. Geophys. Res.* 107, 1210. doi:10.1029/2001ja009102