Solar wind propagation delay: Comment on “Minimum variance analysis-based propagation of the solar wind observations: Application to real-time global magnetohydrodynamic simulations” by A. Pulkkinen and L. Raststätter

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1. Introduction

[1] Many space weather phenomena, like geomagnetic storms, aurora etc., are typically associated with disturbances in the solar wind, in particular directional changes in the interplanetary magnetic field (IMF). A southward directed IMF interacts with the geomagnetic field at the dayside magnetopause and causes enhanced energy and momentum transfer from the solar wind to the magnetosphere. The subsequent entry of this energy into the terrestrial ionosphere can lead to disturbances in radio communication, navigation systems and power grids. The ability to predict such consequences is therefore a central topic for space weather applications.

[2] Since actual measurements of the solar wind and IMF are typically taken at large distances from the Earth, e.g., from the Advanced Composition Explorer (ACE) spacecraft orbiting the L1 libration point some 1.5 * 10^8 km upstream of the Earth, any measurements need to be time shifted to be representative for the conditions near the upstream magnetopause where the interaction takes place. The propagation time depends on both solar wind velocity, orientation of the IMF and the location of the solar wind monitor.

[3] A lot of effort has therefore been made to be able to predict the propagation time of solar wind disturbances between a monitor and a target position. One of the most successful methods in terms of prediction accuracy is the phase front model introduced by Weimer et al. [2003, hereafter W03] and later benchmarked by, e.g., Weimer and King [2008] and Mailyan et al. [2008].

[4] W03 noted that variations in the IMF primarily occur within surfaces that can be arbitrarily tilted with respect to the IMF orientation. They use the term phase front normal (PFN) to describe the orientation of these surfaces, and use minimum variance analysis on sliding time segments of IMF measurements to determine the PFNs. In many aspects, the analyzed time segments are thus treated as discontinuities, although IMF variations within a time segment usually do not fulfill more formal classifications of a discontinuity suggested by, e.g., Tsurutani and Smith [1979] and Lepping and Behannon [1986].

[5] As pointed out by Pulkkinen and Raststätter [2009, hereafter PR09], one problem with the W03 method arises from the use of quality criteria imposed on the minimum variance analysis. Failure to satisfy these quality criteria can lead to “locking” to certain orientations of the phase fronts, and therefore an erroneous propagation time estimation. To circumvent this problem, PR09 suggested a modification which does not rely on these quality criteria, and which prevents abrupt changes in the phase front orientation. In this comment we point out some undesirable effects of the PR09 approach, and present an alternative solution.

[6] The outline of this paper is as follows. In section 2 we give a brief review of the W03 method and the alterations and optimizations proposed by PR09. In section 3 we point
In the W03 method, illustrated in Figure 1, the \( B \cdot \vec{n} = 0 \) property (or MVABC, where the C is for constrained) is the average solar wind bulk flow velocity \( v_{sw} \), the maximum cone angle \( \theta \) between the boundary normal \( \vec{n} \) and the phase front orientation. Mathematically, MVAB involves diagonalization of the magnetic covariance matrix to obtain the normal. MVAB implies finding a new coordinate system organized according to the variance of the magnetic field. The direction of minimum variance serves as an estimator of the boundary normal, the smallest eigenvalue ratio between the three eigenvalues. Well separated eigenvalues, \( \lambda_{max} \gg \lambda_{int} \gg \lambda_{min} \), typically indicate well defined eigenvectors [Sonnerup and Scheible, 1998]. For the constrained MVAB0 analysis, the only sensible ratio is \( \lambda_{max}/\lambda_{int} \), the ratio between the largest and the intermediate eigenvalue (the smallest eigenvalue will by definition be zero). W03 put certain minimum requirements on the eigenvalue ratio, and in a comprehensive benchmarking, Weimer and King [2008] found that optimal results were achieved if the eigenvalue ratio \( \lambda_{max}/\lambda_{int} \) was above 7.8. In addition to this eigenvalue threshold, they also required that the cone angle between the boundary normal and the solar wind bulk speed was below 75° (see Figure 1). For time segments where these criteria were not fulfilled, the previous valid phase front normal was used in the time delay calculation.

As pointed out by PR09, a undesirable effect of the eigenvalue threshold was that the normal could remain “locked” in certain directions if the MVAB results did not provide eigenvalue ratios above this threshold. This locking can in theory also occur if the IMF phase planes change their orientation. A plausible explanation for poor MVA results is the presence of fluctuations caused by small-scale structures in the solar wind. PR09 therefore devised a method which did not utilize any eigenvalue thresholds at all, but instead uses a weight function to get smooth variations of the boundary normal:

\[
\vec{n}(t_{j+1}) = \vec{n}(t_j) + \frac{2}{m} (\vec{n}^* - \vec{n}(t_j)) \Delta t
\]

where \( \vec{n}^* \) is the phase front normal obtained from the W03 method, \( m \) is a weight factor and \( \Delta t \) is the sampling time of the IMF. This scheme is effectively a low-pass filtering of the IMF phase plane orientation. The weight factor \( m \) determines the degree of “smoothing.” Unlike the W03


In the W03 method, illustrated in Figure 1, the orientation of an IMF phase front, represented by its boundary normal, \( \vec{n} \), is essential. The propagation time, \( \tau \), of a solar wind phase front from the monitor to a target is given by

\[
\tau = \frac{(\vec{r}_{mon} - \vec{r}_{tar}) \cdot \vec{n}}{(\vec{v}_{sw}) \cdot \vec{n}} \tag{1}
\]

where \( \vec{v} \) is the average solar wind bulk flow velocity within the sliding time segment.

W03 uses minimum variance analysis of the magnetic field (MVAB) to obtain the normal. MVAB implies finding a new coordinate system organized according to the variance of the magnetic field. The direction of minimum variance serves as an estimator of the boundary normal of a structure. Mathematically, MVAB involves diagonalization of the magnetic covariance matrix to obtain a set of eigenvalues and eigenvectors which defines the new coordinate system [e.g., Sonnerup and Scheible, 1998].

Although not explicitly apparent from the original W03 paper, the covariance matrix they used gave a normal direction almost (but not perfectly) perpendicular to the average magnetic field. Bargatze et al. [2005] and Haaland et al. [2006] pointed out that this property can be perfectly satisfied either by performing the MVA on a data set with the average B field subtracted, or by projecting the covariance matrix from both sides with a projection matrix containing averages. As demonstrated by PR09, these two approaches are mathematically equivalent. In the literature, this form for minimum variance is sometimes referred to as MVAB0 (where the 0 is used to indicate the \( B \cdot \vec{n} = 0 \) property) or MVABC, (where the C is for constrained (where the constrain may also be formulated to satisfy other properties) [see Sonnerup et al., 2004, 2006]). Among others, the MVAB0 method is routinely used to generate time shifted solar wind data in the OMNI data set available from CDAWEB (http://cdaweb.gsfc.nasa.gov/istp_public/).

Physically, the \( B \cdot \vec{n} = 0 \) condition implies that the IMF phase fronts have the nature of tangential discontinuities (TDs); that is, there is no magnetic field along the normal and no flow of plasma through the discontinuity. Recent studies by, e.g., Knetter et al. [2004] seem to indicate that this assumption is valid, in particular for discontinuities in the solar wind, but also for time periods without any distinct discontinuities [Weimer and King, 2008; Mailyan et al., 2008].
method, the above approach provides a forward prediction of the orientation which may be of advantage for real time computations. The PR09 method also reduces the issue of one phase front overtaking another.

3. Implications of the Alterations Proposed by Pulkkinen and Raststätter [2009]

While the alterations proposed by PR09 removes the locking in issue, two undesirable implications arise with this approach; First, the proposed modifications do not preserve the \((\vec{B} \cdot \vec{n}) = 0\) condition that is the underlying assumption in the W03 model, and which is the key to the success of the phase front method [Bargatze et al., 2005]. Also, since the proposed modifications effectively acts as a low-pass filter, no sharp changes in the IMF phase plane orientation can occur. To our knowledge, however, no mechanisms preventing such sharp changes exist in nature.

To demonstrate our concern, we refer to Figure 2, which shows the magnitude of the IMF and the normal component of B (\((\vec{B} \cdot \vec{n})\) (red line)) resulting from application of the modification in the work by Pulkkinen and Raststätter [2009]. During some periods, the normal component constitutes a significant fraction of the total IMF.

Physically, a significant normal component in the magnetic field can be taken as an indication of ongoing reconnection, and hence transfer of plasma from one side to the other side of the phase plane surface. For a rotational discontinuity and any planar Alfvén wave, the plasma flow is proportional to the normal component [Paschmann and Sonnerup, 2008]. In theory, an independent check of to determine whether a structure is of Alfvénic nature can be done by consulting the plasma data, and performing the so-called Walén test [Khrabrov and Sonnerup, 1998a; Paschmann and Sonnerup, 2008]. However, due to the high flow speed of the solar wind, combined with the limited time resolution of present generation plasma instrumentation, one can at best only resolve structures with scale sizes of a few 1000 km. In the case of ACE, plasma data are routinely available at 64 s resolution [McComas et al., 1998], corresponding to spatial resolutions of several 10,000 km.

We should here strongly emphasize that we do not claim that the rotational discontinuities cannot exist in the solar wind (see, e.g., Gosling et al. [2009, and references therein] for an updated discussion about Alfvén fluctuations and reconnection in the solar wind). For this particular purpose, however, and given the insignificant improvement provided by the PR09 method, the assumption that the phase planes are TDs seem to be more justified. We therefore suggest that any improvements of the phase plane method should take this into account.

4. Proposal for an Alternative Method to Improve Boundary Normal Determination

As pointed out, the PR09 modification is effectively a low-pass filtering of the phase front normal direction to exclude the effect of small-scale fluctuations in the IMF. Rather than using this approach, we propose that filtering should be performed on the input data to the MVAB, i.e., a filtering of the B field measurements. Also, instead of a
filtering in the frequency domain, we suggest to do the filtering in amplitude domain.

[18] A drawback with frequency filtering (averaging, low-pass filtering, using spin averages etc.) is that any sharp transitions in the data disappear. In particular for solar wind applications, the high solar wind bulk velocity cause shock fronts and discontinuities to be smeared out unless the time resolution of the measurements is sufficiently high. Furthermore, since MVAB is a statistical method, any reduction of the number of data points also increases the statistical uncertainty and thus error bounds for the variance analysis [Khrabrov and Sonnerup, 1998b; Sonnerup and Scheible, 1998].

[19] A method which has proven to yield better results is wavelet denoising. The original signal (the measured IMF) is then transformed into wavelet domain, which effectively decomposes the signal into a finite number of frequency and amplitude bins. The part of the signal that represents “noise” (in this case the low-amplitude fluctuations and wave activity) are then removed. Thereafter, the signal is transformed back into time domain again. If the signal in question is a vector, each component is treated individually.

[20] Any localized function, h(t), can be used as a basis for wavelet transforms as long as it satisfies the admissibility criteria:

\[ \int_{-\infty}^{\infty} h(t) = 0; \quad \int_{-\infty}^{\infty} |h(t)|^2 < \infty \]  

For more information about wavelets types and wavelet denoising in general, we refer to papers by, e.g., Donoho [1992], Graps [1995], Daubechies [1992], and Torrence and Compo [1998, and references therein].

[21] Wavelet denoising, using Morlet wavelets, was tested out on magnetic field measurements obtained by the AMPTE IRM and UKS experiments during a series of magnetopause crossings by Haaland and Paschmann [2001]. The purpose of that study was to establish accurate boundary normals of the terrestrial magnetopause. Wavelet filtering of the input signal prior to MVAB gave an improvement of the eigenvalue ratio in 28 of 30 cases investigated.

[22] In Figure 3 we show some results from this technique applied to the IMF during the period 0500-0700 UT on 2 July 1997 (same event as discussed above, and also used for benchmarking by Weimer and King [2008] and PR09). The first three panels show the three GSE components of the IMF for this day. Black lines are the original measurements and the red lines show the “denoised” signal. In the wavelet domain, we have here removed (i.e., set to zero) all coefficients representing amplitudes below 2% of the total dynamic range of the signal, and then transformed back to the time domain. The large-scale variations, and in particular the fast rotations seen, e.g., in By component around 0612 UT are retained.

[23] It should be pointed out that we did not try any optimization at all on the wavelet filtering. The 2% threshold mentioned above is the same as that used by Haaland and Paschmann [2001]. Further improvements can be achieved by adjusting the wavelet threshold and/or trying different data segment lengths.

[24] If we now use the denoised signal as input for the Weimer model, we obtain the eigenvalue ratios shown in the fourth panel of Figure 3. The average (i.e., both mean and median) eigenvalue ratio is now significantly improved. For the 2 h time interval (i.e., 480 samples with 15 s resolution) shown here, 165 samples fail to meet the eigenvalue ratio of 7.8 when using the unmodified measurements. For the denoised signal, only 64 samples fail to meet this threshold. For the full 24 h period as shown in Figure 2 of PR09, the corresponding numbers are 2192 and 796, respectively. Much of the arguments for the PR09 modifications are thus resolved.

[25] Alternatively, if phase front locking is not an issue, the use of wavelet denoised signals as inputs to the minimum variance allows for higher eigenvalue quality thresholds for the W03 method.

5. Summary

[26] In this paper, we have pointed out some undesirable effects of the MVA based propagation delay calculation presented by PR09. In particular, the sometimes dominant normal magnetic field component and the fact that no sharp changes in IMF are allowed, contradict our present understanding of solar wind phase planes and directional discontinuities in the solar wind. Although the sole purpose of the modifications suggested by PR09 was to improve the arrival prediction of solar wind phase fronts, we suggest that any tools and methods should be based on known physical properties of the solar wind.

[27] While we recognize that small-scale structures and fluctuations in the IMF can distort or invalidate minimum variance based normal determination, we suggest that any attempt to remove effects of such structures should be done in the input data. One way to achieve this is to use a wavelet based denoising technique for removal of such fluctuations. As demonstrated, the use of this technique largely reduces the issue which was the motivation for the modifications by PR09. Wavelet toolboxes are readily available for many software packages, so the implementation and application are not necessarily more complicated than the modification suggested by PR09. The required calculations are not very computer intensive, so near real-time denoising should also be possible.

[28] We have not tested how our alternate method performs for the MHD simulation by PR09 or any other real-time applications for that case. Given the insignificant improvement the PR09 method provided, and the number of other sources of complications for real-time space weather predictions, we remain somewhat sceptical. However, we plan to test out the denoising technique extensively on the data set discussed by Mailian et al. [2008] to address this issue.

[29] The PR09 results demonstrate how important accurate solar wind input data can be for modeling pos-
Figure 3. Time segment with results from the proposed wavelet denoising technique. First three panels show GSE components of the IMF at ACE. Solid black lines show the original ACE measurements but resampled to 15 s resolution as in the work by Weimer et al. [2003] and Pulkkinen and Rastätter [2009]. Red lines are the corresponding denoised signal. Sharp transitions are retained, but small amplitude variations are removed. Fourth panel shows eigenvalue ratio $\lambda_{\text{max}}/\lambda_{\text{int}}$. The black line shows the ratio for the standard W03 method, and the red line shows the corresponding ratio for the denoised signal. The eigenvalue ratio for the denoised signal is significantly higher, and a few periods fail the eigenvalue threshold of 7.8, marked with a dashed line in the fourth panel.
sible consequences of space weather. Accurate propagation delay calculations and methods are therefore essential elements for space weather forecasts.

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References

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