Comment on "A new interpretation of Weimer et al.'s solar wind propagation delay technique" by Bargatze et al.

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[1] In a recent article, Bargatze et al. (2005) have identified why the implementation of the minimum variance analysis (MVAB) by Weimer et al. (2003), even though based on an erroneous variance matrix, has been successful in estimating the orientation of the "phase fronts" and the resulting propagation delays of the interplanetary magnetic field (IMF). They recommend further testing of the Weimer analysis as a space weather forecasting tool. In this comment we stress that the Weimer et al. implementation of MVAB closely mimics the results of a well-known version of MVAB that is constrained by the condition that the average field along the phase front normals is zero. This version of MVAB starts from the correct variance matrix, whereas the Weimer analysis is based on an unphysical matrix resulting from a programming error. We recommend that the constrained MVAB, originally developed by Sonnerup and Cahill (1968) and later recast into a more convenient form by A.V. Khrabrov be used instead. The Khrabrov method, which we refer to as MVAB-0, has been tested at the Earth's magnetopause by Sonnerup and Scheible (1998) and more recently by Haaland et al. (2004) and Sonnerup et al. (2004).

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1. Introduction

[2] Estimating the propagation delay of solar wind and interplanetary magnetic field (IMF) variations between their observation at a solar wind monitor and their arrival at the front of Earth's magnetosphere is an important element of all studies trying to establish the coupling of magnetospheric processes with the solar wind. The standard approach is to compute the time delay simply as x/V_{sw}, where x and V_{sw} are the difference in GSE x position between monitor and target and the solar wind speed, respectively. The problem with this method is that the IMF variations often appear to occur along surfaces, referred to as "phase fronts," that can be tilted at large angles with respect to the solar wind direction. As a result, the simple approach can be quite wrong if the monitor and the target locations are not connected by a solar wind stream line. Using multiple-spacecraft observations, *Weimer et al.* [2002] determined the tilts required to match the IMF variations at Wind, Geotail, and IMP with those recorded by ACE in an optimum way. The resulting delays showed large and rapid variations that differed substantially from the simple x/V_{sw} results. This approach cannot be used routinely, however, because such multiple spacecraft configurations in the solar wind rarely occur. Thus a technique is needed that relies only on measurements from a single satellite.

[3] In a subsequent publication, *Weimer et al.* [2003] described a method, reportedly based on minimum variance analysis (MVAB) of the vector magnetic field data measured at ACE, to estimate the orientation of these fronts and showed that the arrival at Earth-orbiting satellites in the solar wind could be predicted quite well. However, it was subsequently discovered that *Weimer et al.* [2003] had used an erroneous formulation of the MVAB technique, as reported in a correction paper by *Weimer* [2004] and then discussed in detail in a paper by *Bargatze et al.* [2005]. According to these papers, the *Weimer et al.* [2003] analysis was based on finding the eigensolutions of the matrix

$$M_{ij}^{w} = \langle B_i B_j \rangle - N \langle B_i \rangle \langle B_j \rangle, \qquad (1)$$

where B_i and B_j are the vector components of the magnetic field, N is the number of magnetic field measurements in the chosen data window, and the brackets $\langle\ \rangle$ denote averages of the N data samples. In contrast, the correct (covariance) matrix is

$$M_{ij} = \langle B_i B_j \rangle - \langle B_i \rangle \langle B_j \rangle. \qquad (2)$$

[4] The fundamental question that arises immediately is why the erroneously modified MVAB used by *Weimer et al.* [2003] could lead to such good predictions. In order to answer this question, *Bargatze et al.* [2005] evaluated in

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detail what happens if one does the eigenanalysis on the matrix in equation (1) rather than that in equation (2), and they were able to clarify why Weimer et al.'s mistake actually results in an effective method.

[5] *Bargatze et al.* [2005] first noticed that the *Weimer et al.* [2003] "modified" MVAB (henceforth referred to as MVAB-W), is based on a matrix that is not a variance matrix because, in the GSE coordinate system, its diagonal elements are all negative, which violates the requirement that the trace of the variance matrix must equal the sum of three positive eigenvalues (variances). They pointed out that the analysis gives one eigenvalue that is large and negative and that by considering only its absolute value, Weimer et al. turned it from the smallest to the largest eigenvalue. The smaller of the remaining two eigenvalues then automatically became the minimum eigenvalue, and the associated eigenvector became Weimer et al.'s predictor for the normal, $\hat{\mathbf{n}}$, of the "phase fronts."

[6] A key to the *Bargatze et al.* [2005] interpretation of the *Weimer et al.* [2003] results is their finding that the eigenvector belonging to the large (negative) eigenvalue is directed nearly along the mean magnetic field, $\langle \mathbf{B} \rangle$, and that the two other eigenvectors must therefore lie in a plane nearly perpendicular to $\langle \mathbf{B} \rangle$. They demonstrated that this property is a direct consequence of Weimer et al.'s inadvertent amplification of the second term in equation (2) by a factor N.

[7] The purpose of this comment is to stress that the results of the *Weimer et al.* [2003] method are close to those of a version of MVAB that is constrained by the condition that the average field along the phase plane normal, $\langle \mathbf{B} \rangle \cdot \hat{\mathbf{n}}$, is zero. *Bargatze et al.* [2005] argue that testing the Weimer method as a space-weather forecasting tool "is clearly motivated." We suggest that the constrained MVAB be used instead because it is based on the correct variance matrix and not on an unphysical matrix resulting from a programming error.

2. Constrained MVAB

[8] For planar magnetic field structures in which the average field component $\langle \mathbf{B} \rangle \cdot \hat{\mathbf{n}}$ along the normal to that plane is zero (or nearly zero), reliable normals can be obtained by implementing MVAB under the constraint that $\langle \mathbf{B} \rangle \cdot \hat{\mathbf{n}} = 0$. This MVAB variant was first used by *Sonnerup and Cahill* [1968] for analysis of Explorer-12 magnetopause crossings. More recently it has been discussed and applied in papers by *Sonnerup and Scheible* [1998], *Sonnerup et al.* [2004], and *Haaland et al.* [2004].

[9] Choosing $\hat{\mathbf{n}}$ such that the variations along it are minimized under the constraint that $\langle \mathbf{B} \rangle \cdot \hat{\mathbf{n}} = 0$ requires geometrically that $\hat{\mathbf{n}}$ lies in the plane perpendicular to $\langle \mathbf{B} \rangle$. The intersection of the variance ellipsoid with that plane is an ellipse, the minor axis of which is used as the predictor for $\hat{\mathbf{n}}$.

[10] As described by *Sonnerup and Scheible* [1998] and *Sonnerup et al.* [2004], the simplest implementation of the constrained MVAB, henceforth referred to as MVAB-0, consists of multiplying the M_{ij} matrix (equation (2)) from the left and from the right by the projection matrix $P_{ij} = \delta_{ij} - \hat{e}_i \hat{e}_j$, where δ_{ij} is the Kronecker δ and the unit vector $\hat{\mathbf{e}}$ is defined by $\hat{\mathbf{e}} = \langle \mathbf{B} \rangle / B$, and then finding eigenvalues and eigenvectors of the resulting matrix, $Q_{nk} = P_{ni} M_{ij} P_{jk}$ (the summation convention is used here). The matrix P describes projection of a vector onto the plane perpendicular to $\hat{\mathbf{e}}$. The smallest eigenvalue of the Q matrix is exactly zero and the corresponding eigenvector is precisely along $\langle \mathbf{B} \rangle$. The eigenvector corresponding to the intermediate eigenvalue now serves as the predictor for $\hat{\mathbf{n}}$. Accordingly, the ratio between the maximum and intermediate eigenvalues, λ_1/λ_2, becomes a measure for the quality of the normal determination. For later reference we note that under the projection the second term in equation (2) vanishes identically because $P_{ni}\langle B_i \rangle$ and $\langle B_j \rangle P_{jk}$ are both zero. Note also that use of the projection matrix, which was introduced by A.V. Khrabrov [see *Sonnerup and Scheible*, 1998], replaces the earlier, more cumbersome method used by *Sonnerup and Cahill* [1968].

[11] As noted by *Bargatze et al.* [2005], in the MVAB-W method one of the the eigenvectors, namely the one belonging to the large (negative) eigenvalue, also points nearly, but not exactly, along the mean magnetic field. The other two eigenvalues in the *Weimer et al.* [2003] analysis nearly describe the variances in the plane nearly perpendicular to the mean field. As Bargatze et al. have shown, the reason for this behavior is that the matrix $-N\langle B_i \rangle \langle B_j \rangle$ in equation (1), erroneously magnified by the factor N, has one eigenvector exactly along $\langle \mathbf{B} \rangle$ with corresponding eigenvalue equal to $-N\langle \mathbf{B} \rangle^2$. It is degenerate in the plane perpendicular to $\langle \mathbf{B} \rangle$ where both eigenvalues are zero. For sufficiently large N values, the second term in equation (1) therefore nearly determines one eigenvector of the full Weimer et al. matrix to be nearly along $\langle \mathbf{B} \rangle$, whereas the first term nearly determines the other two. This is why the results of the Weimer et al. method are similar, but not identical, to those from the MVAB-0 method.

[12] As noted by *Bargatze et al.* [2005], normals similar to those from MVAB-W are obtained from the method (MVAB-S) developed by *Siscoe et al.* [1968] for finding the normal to a tangential discontinuity. The close similarity between MVAB-0 and MVAB-S for cases with small actual normal field components was already demonstrated by *Sonnerup and Scheible* [1998, p. 195].

[13] The MVAB-S method is based on the eigenanalysis of a variance matrix constructed solely from the first term on the right-hand side of equations (2) and (1), $M^s_{ij} = \langle B_i B_j \rangle$, which is equivalent to minimizing the sum of the squares of the normal field components. As a result, $\hat{\mathbf{n}}$ is obtained from minimization of $\langle (\mathbf{B} \cdot \hat{\mathbf{n}})^2 \rangle$, subject to the constraint $|\hat{\mathbf{n}}|^2 = 1$. Because the second term in equation (2) vanishes under the projection operation described above, MVAB-0 also deals with the first term only, but $\hat{\mathbf{n}}$ is obtained by minimization of the variance of the set $\langle (\mathbf{B} \cdot \hat{\mathbf{n}})^2 \rangle$ when the constraint $\langle (\mathbf{B}) \cdot \hat{\mathbf{n}} = 0$ has been applied [see *Sonnerup and Scheible*, 1998, p. 195]. Thus its is clear that when $\langle \mathbf{B} \rangle \cdot \hat{\mathbf{n}}$ is small, MVAB-S and MVAB-0 give similar but not identical normal vectors. If the constraint $\langle \mathbf{B} \rangle \cdot \hat{\mathbf{n}} = 0$ is implemented in each of the three methods (MVAB, MVA-S, and MVA-W), they give identical results, namely those of MVAB-0.

3. Benchmark Case

[14] To illustrate our point, we have run the various MVAB methods on the same 105-point interval (0000:01

Table 1. Eigenvalues, λ_i, Eigenvectors, $\mathbf{X}_i$, and $\langle \mathbf{B} \rangle \cdot \mathbf{n}$ From the Different MVAB Methods, for the Benchmark Interval on 2 July 1999[a]

Method	λ_i $[nT^2]$	X_i			$\langle B \rangle \cdot n$
Weimer et al.'s minimum variance (MVAB-W)	−1400.2	*0.6747*	*−0.6567*	*0.3368*	
	1.4619	**0.7266**	**0.6711**	**−0.1470**	0.0021
	12.377	−0.1295	0.3439	0.9300	
Constrained minimum variance (MVAB-0)	0	*0.6744*	*−0.6573*	*0.3364*	
	1.4615	**0.7270**	**0.6708**	**−0.1468**	0.0000
	12.377	−0.1291	0.3435	0.9302	
Siscoe et al's minimum variance (MVAB-S)	1.4171	**0.7637**	**0.6337**	**−0.1236**	0.9426
	12.165	0.0348	0.1507	0.9880	
	15.365	*0.6447*	*−0.7588*	*0.0930*	
Standard minimum variance (MVAB)	0.7379	**0.9845**	**0.0595**	**0.1648**	−2.4978
	2.2935	0.0114	0.9169	−0.3990	
	12.436	−0.1748	0.3947	0.9020	
Unit magnetic field vector		*0.6744*	*−0.6573*	*0.3364*	

[a]Eigenvectors that are estimators of normals are shown in bold face. Eigenvector alignment with $\langle \mathbf{B} \rangle$ can be judged from comparing the vectors shown in italics with the mean magnetic field unit vector shown at the bottom.

to 0027:45 UT on 2 July 1999) of "level-2" IMF data from ACE with 16-s cadence studied by *Bargatze et al.* [2005]. Table 1 shows the the eigenvalues, λ_i, and eigenvectors, $\mathbf{X}_i$, obtained for *Weimer et al.*'s [2003] MVAB-W, the constrained MVAB (MVAB-0), for the *Siscoe et al.* [1968] method (MVA-S), and finally for the standard MVAB. The eigenvectors that represent the estimators for the normals are indicated in bold face. The rightmost column shows the component of the magnetic field along those normals, which for the MVAB-0 method is exactly zero by definition. The extent to which one of the eigenvectors is aligned with mean magnetic field can be judged from a comparison between the vectors shown in italics, with the mean magnetic field unit vector shown at the bottom.

[15] Our results for MVAB-W and MVAB agree precisely with those presented in Tables 2 and 3 of *Bargatze et al.* [2005], respectively, except that we have followed the convention in the work of *Weimer et al.* [2003] that assures that the normals always have positive x-components. We have also ordered the eigenvalues, and associated eigenvectors, such that the smallest eigenvalue, λ_3, is always at the top, and we kept the minus sign for the largest eigenvalue in MVAB-W.

[16] Table 1 demonstrates that for $N = 105$ the method (MVAB-W) investigated by *Bargatze et al.* [2005] and the constrained MVAB (MVAB-0) method advocated here, give very nearly the same results, as claimed. We have extended the comparison to the full 24-hour interval on 2 July 1999 that is used by *Bargatze et al.* and found very close agreement throughout. In a plot of the tilt angles of the normals (not shown), as shown in Figure 4 in the work of *Bargatze et al.* [2005], the two methods are indistinguishable. However, in contrast with the MVAB-W method, MVAB-0 has one axis (the eigenvector $\mathbf{X}_1$) aligned precisely with the mean magnetic field so that the plane formed by ($\mathbf{X}_1$, $\mathbf{X}_3$) is exactly the plane of the phase front and $\mathbf{X}_2$ points along the plane's normal. Note that the discrepancy between the results from MVAB-W and those from MVAB-0 increases as N decreases, although, as noted by *Bargatze et al.* [2005], the alignment of one of the MVAB-W eigenvectors with the mean field remains surprisingly good, even for values as low as $N = 3$.

[17] As Table 1 shows, *Siscoe et al.*'s [1968] method (MVAB-S) gives normals similar to MVAB-0, but the eigenvector, $\mathbf{X}_3$ belonging to the maximum eigenvalue is only approximately along the mean magnetic field. By contrast, the standard MVAB gives a very different normal, with a correspondingly fairly large normal component, B_n. This is true for much of the 2 July 1999 interval. As is well-established by now, proper use of MVAB involves more than just checking for eigenvalue ratios: it requires inspection of the magnetic field hodograms as well as the use of nested time intervals [e.g., *Sonnerup and Scheible*, 1998]. For eigenvalue ratios as low as 3 (see Table 1), results of MVAB should be viewed with suspicion. However, even for ratios as high as 10 or more, there are circumstances where MVAB gives misleading results [e.g., *Haaland et al.*, 2004]. Standard MVAB is thus not suited for the application discussed here, namely a continuous determination of the normal directions for long time series of IMF data. It is ironic that the *Weimer et al.* [2003] approach to predict the time delays of the IMF phase fronts would have failed had they used the correct implementation of MVAB.

4. Summary

[18] *Bargatze et al.* [2005] have analyzed in detail why the minimum variance analysis implementation, here called MVAB-W, by *Weimer et al.* [2003] does lead to good estimates of the orientation of the "phase fronts" of the IMF, as evidenced by *Weimer at al.*'s [2003] success in predicting IMF propagation delays, even though that implementation is based on an erroneous "variance" matrix, and the results differ strongly from the results obtained with *Bargatze et al.*'s [2005] own correct implementation of the minimum variance method (MVAB). What *Bargatze et al.* [2005] found is that *Weimer at al.*'s [2003] matrix leads to one eigenvector that is directed nearly along the mean magnetic field and that their normal vector estimate corresponds to the direction belonging to the smallest eigenvalue in a plane that is almost perpendicular to the mean field. Because of the imperfect alignment, there is a nonzero, albeit usually very small, component of the magnetic field along the obtained normal.

[19] In our comment we have pointed out that there exists a minimum variance method, here called MVAB-0 [*Sonnerup and Cahill*, 1968] that is based on the correct variance matrix but differs from standard MVAB in that the normal, $\hat{\mathbf{n}}$, is

determined under the constraint that the mean field has no normal component, i.e., $\langle \mathbf{B} \rangle \cdot \hat{\mathbf{n}} = 0$ [see also *Sonnerup and Scheible*, 1998; *Haaland et al.*, 2004]. This constraint ensures that one axis (the eigenvector $\mathbf{X}_1$) is precisely along the mean magnetic field, and thus the normal is determined by minimizing the variance in the plane exactly perpendicular to the mean field. The assumption underlying the constrained MVAB method, namely that $\langle \mathbf{B} \rangle \cdot \hat{\mathbf{n}} = 0$, is strictly valid only if the IMF variations have the character of tangential discontinuities. However, it will work quite well for cases with finite normal components as long as those components are small. The good match [*Weimer et al.*, 2003] obtained between the predicted and measured magnetic fields suggests that the IMF variations were indeed predominantly tangential or nearly tangential.

[20] *Bargatze et al.* [2005] have also determined that the minimum variance method developed by *Siscoe et al.* [1968], here called MVAB-S, gives results that are quite similar to the *Weimer et al.* [2003] results and thus by implication to our constrained MVAB-0 results as well, even though *Siscoe et al.* [1968] use only the first term of the variance matrix. Here we point out that the similarity of the results from MVAB-S and MVAB-0, as well as the reasons for it, have been discussed earlier [*Sonnerup and Scheible*, 1998].

[21] In order to calculate the time delays between the IMF variations observed at the upstream monitor and their arrival at some target position, the IMF ''phase fronts'' are assumed to move with speed $\mathbf{V}_{\mathbf{sw}} \cdot \hat{\mathbf{n}}$ [see *Weimer et al.*, 2003]. As *Bargatze et al.* [2005] point out, this is strictly true only if those fronts have the character of tangential discontinuities. In contrast, rotational discontinuities move relative to the solar wind at a speed given by the Alfvén speed based on the normal magnetic field component, $V_n = B_n(\mu_0\rho)^{-0.5}$, where ρ is the solar wind mass density. For $B_n = 1$ nT and a solar wind number density of 5 protons per cm^3, for example, $V_n \sim 10$ km s^{-1}, which is small compared with the usual solar wind speed. The situation is quite different if an IMF change is caused by the passage of a shock. A perpendicular, or nearly perpendicular, planar shock has a magnetic field component along its normal that is zero, or nearly zero, so that MVAB-0 will give a good normal direction. However, such a shock can move with large speed relative to the solar wind. Thus except for changes induced by shocks, use of $\mathbf{V}_{\mathbf{sw}} \cdot \hat{\mathbf{n}}$ to describe the phase-front motion is justified.

[22] Another comment concerns the standard MVAB. That this technique does not provide valid normals, neither for the benchmark case nor for the full 2 July 1999 data set, directly follows from the failure of standard MVAB to reproduce the *Weimer et al.* [2003] phase plane orientations, which in turn provided successful forecasts of the IMF propagation delays. This is just clear evidence that MVAB is not suited for an application where long magnetic field time series are analyzed blindly, with attention paid only to the eigenvalue ratios.

[23] After reading Bargatze et al.'s response to our comment, we acknowledge that Table 4 of the *Bargatze et al.* [2005] paper does indeed give results, obtained by applying MVAB to only the field components orthogonal to the mean field, that are identical to those from our MVAB-0 calculation, a fact that we had missed. Here we point out that use of the $\langle \mathbf{B} \rangle \cdot \hat{\mathbf{n}} = 0$ constraint is by no means new, a fact that cannot be gleaned from the article by *Bargatze et al.* [2005]. There are now at least three different ways to implement this constraint: (1) Use of a Lagrange multiplier [*Sonnerup and Cahill*, 1968; *Sonnerup and Scheible*, 1998]; (2) Use of Khrabrov's projection matrix as described in our comment [*Sonnerup and Scheible*, 1998; *Haaland et al.*, 2004; *Sonnerup et al.*, 2004]; (3) Use of the field components orthogonal to the mean field, as presented in *Bargatze et al.* [2005]. All three methods give identical results and all can be denoted by MVAB-0. In our view, the Khrabrov approach is the most transparent and most easily implemented of these techniques. It is also easily adaptable to other types of constraints [*Sonnerup et al.*, 2004].

[24] The main point of our comment is that further use of Weimer's matrix is not justified, whereas further testing of the MVAB-0 method as a forecasting tool is.

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