Predicting interplanetary magnetic field (IMF) propagation delay times using the minimum variance technique

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[1] It has been known that the fluctuations in the interplanetary magnetic field (IMF) may be oriented in approximately planar structures that are tilted with respect to the solar wind propagation direction along the Sun-Earth line. This tilting causes the IMF propagating from a point of measurement to arrive at other locations with a timing that may be significantly different from what would be expected. The differences between expected and actual arrival times may exceed an hour, and the tilt angles and subsequent delays may have substantial changes in just a few minutes. A consequence of the tilting of phase planes is that predictions of the effects of the IMF at the Earth, on the basis of IMF measurements far upstream in the solar wind, will suffer from reduced accuracy in the timing of events. It has recently been shown how the tilt angles may be determined using multiple satellite measurements. However, since the multiple satellite technique cannot be used with real-time data from a single sentry satellite, then an alternative method is required to derive the phase front angles, which can then be used for more accurate predictions. In this paper we show that the minimum variance analysis (MVA) technique can be used to adequately determine the variable tilt of the plane of propagation. The number of points that is required to compute the variance matrix has been found to be much higher than expected, corresponding to a time period in the range of 7 to 30 min. The optimal parameters for the MVA were determined by a comparison of simultaneous IMF measurements from four satellites. With use of the optimized parameters it is shown that the MVA method performs reasonably well for predicting the actual time lags in the propagation between multiple spacecraft, as well as to the Earth. Application of this technique can correct for errors, on the order of 30 min or more, in the timing of predictions of geomagnetic effects on the ground. *INDEX TERMS:* 2194 Interplanetary Physics: Instruments and techniques; 2134 Interplanetary Physics: Interplanetary magnetic fields; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2722 Magnetospheric Physics: Forecasting; *KEYWORDS:* Interplanetary magnetic field, IMF, space weather, forecasting, techniques, minimum variance

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1. Introduction

[2] Ever since there have been more than one instrumented satellite in the interplanetary magnetic field (IMF), there have been comparison studies of simultaneous, multipoint measurements of the IMF. With an increasing emphasis on "space weather" effects and prediction capability, these type of studies have become more important. Measurements of the IMF taken at an "upstream" solar wind position, the so-called first Lagrangian (L_1) position ($\sim$230 R_E from the Earth toward the Sun), are used extensively for research into the effects of the IMF on the near-Earth space environment, and for predicting these effects. These predictions rely on the approximately one-hour propagation delay time, at the solar wind velocity, between the measurement at L1 (with essentially no delay in radio data transmission) and the arrival of the same IMF at the Earth's magnetosphere.

[3] For some time it had been recognized that the variations in the IMF may be contained in approximately planar structures that are tilted with respect to the solar wind propagation vector along the Sun-Earth line. This tilted propagation may cause the IMF that is measured at one location to arrive at another location with a time delay that is different from what would be calculated by assuming a non-tilted orientation of the IMF variations. For example,

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Russell et al. [1980] had compared correlation coefficients and lags using IMF measurements from both ISEE-1 and ISEE-3 for 3 hour intervals. They found that the average lags matched the expected corotation delay, but there were very large departures from this value, suggesting "that the normals to the planes separating fields of different orientation often make large angles to the ecliptic plane." Looking at plasma velocity and density structure in the solar wind from three spacecraft, *Richardson and Paularena* [1998] found that the average orientation of plasma fronts is roughly halfway between perpendicular to the solar wind and the Parker spiral direction. *Ridley* [2000] discusses propagation timing errors associated with differing tilt angle assumptions, including a flat plane propagation with no tilt at all, or using the orientation of the Parker spiral. He found that, among the more simple methods, using the total magnetic field vector to determine the front plane gave the lowest average error, and that the minimum variance method could be used to further reduce uncertainty in propagation times.

[4] Additional summary of other, previous multisatellite IMF/solar wind comparisons is given in a recent paper by *Weimer et al.* [2002], and references therein. A new and novel result reported by *Weimer et al.* [2002] was the ability to ascertain the time delay between four different satellites as a continuously variable function of time, and thereby deduce the three-dimensional orientation of the planes of constant phase, also as a continuously variable function of time. The results had indicated that a significant tilt, on the order of 45° or more, is the norm rather than exception, and that the tilt angle may often have substantial variations of several tens of degrees in just a few minutes or less. Likewise, there could be considerable differences between the expected and actual time delays between satellites, on the order of 30 to 60 min, and these delays could change very quickly.

[5] Due to the tilting of the IMF phase planes, the propagation time delay calculations for both research and predictive applications will not be accurate unless the tilting is taken into consideration. If a spacecraft could be placed precisely on the Earth-Sun line, then the tilt angle would have little effect on the time delays to the Earth. However, due to engineering considerations, a "halo" orbit of about 40 R_E around the L_1 location is more practicable. This leads to a dilemma, as the technique of using multiple satellites can only be done at rare instances and not in real time. Thus a technique is required for determining the orientation of the tilt angle of the IMF phase front, using only the measurements from one satellite.

[6] We have found that the "minimum variance analysis" technique [*Sonnerup and Scheible*, 1998] can be used to obtain a good estimate for the tilt angle of the phase plane. This technique had originally been devised for an analysis of data from satellite passes through a discontinuity at the magnetopause boundary [*Sonnerup and Cahill*, 1967]. The technique had also been used by *Farrugia et al.* [1990] for one event to deduce the orientation of the phase front in the IMF. As mentioned earlier, *Ridley* [2000] had found that the minimum variance method could be used to reduce uncertainty in IMF propagation times, particularly for tangential discontinuity events. Surprisingly, *Horbury et al.* [2001] had found that for tangential discontinuities the minimum variance technique had a very poor performance, and that better results were obtained with a cross-product of the magnetic field vectors on both sides of the discontinuity. *Horbury et al.* [2001] had used 60 s of IMF data on both sides of the discontinuities for their minimum variance calculations; it will be shown later that this number may have some influence on their results.

[7] The purpose of this paper is to show the results of our investigation into using minimum variance in order to be able to improve upon the accuracy of the IMF propagation time delay when only one satellite in the solar wind is available for prediction or analysis. One very important criteria is that it is desired to have a method that could be used routinely and continuously to predict the IMF tilt angles and time delays, rather than a technique that is usable only with distinctive discontinuity events. We make the distinction here that the term "phase front" is not synonymous with discontinuity. The previous observational results reported by *Weimer et al.* [2002] showed that there is always a tilted and varying plane of constant phase present in the IMF, even at times when no there are no obvious discontinuities present. However, it was also observed that the variations in the IMF vector tended to lie within the same three-dimensional phase plane that was derived from the time delay calculations. As the maximum IMF variations appeared to lie mostly within or near the phase plane, then it seemed that the maximum/minimum variance technique should be usable for deriving the orientation of these phase planes.

2. The Minimum Variance Technique

[8] To quote from *Sonnerup and Scheible* [1998], "the main purpose of minimum or maximum variance analysis (MVA) is to find, from single-spacecraft data, an estimator for the direction normal to a one-dimensional or approximately one-dimensional current layer, wave front, or other transition layer in a plasma." Without dwelling on the theory of the technique, which can be found in the references, it is useful to give a summation of the basic equations. With the elements of a symmetric, 3 by 3 "magnetic variance matrix" defined as

$$M^B_{\mu\nu} \equiv \langle B_\mu B_\nu \rangle - \langle B_\mu \rangle \langle B_\nu \rangle, \quad (1)$$

the fundamental MVA equation can be written in matrix form as

$$\sum_{\nu=1}^{3} M^B_{\mu\nu} n_\nu = \lambda n_\mu, \quad (2)$$

In these equations the brackets represent the mean values from any number of magnetic field measurements during a traversal or interval, having the vector components B_μ and B_ν. The subscripts μ, ν = 1,2,3 are the row and column indices of the variance matrix $M_{\mu\nu}$, and they also denote Cartesian components *X, Y,* and *Z* in the chosen system. The n_μ and n_ν represent the components of a unit vector. The λ are scalar values. Again quoting *Sonnerup and Scheible* [1998], "the allowed values of λ are the eigenvalues λ_1, λ_2, λ_3 of (the matrix) $M^B_{\mu\nu}$ ...the corresponding eigenvectors,

x_1, x_2, and x_3, are orthogonal. The three eigenvectors represent the directions of maximum, intermediate, and minimum variation of the field components along each vector'' [*Sonnerup and Scheible*, 1998]. The eigenvector that corresponds to the smallest eigenvalue is in the direction of minimum variance. This vector is normal to the plane that contains the maximum variance, which is assumed to be the plane of the IMF phase front. Often the ratio of the intermediate to minimum eigenvalues is used as an indicator of the quality of the result. If these eigenvalues are approximately equal, so that this ratio is near unity, then the solution is said to be degenerate.

[9] The MVA is prone to some uncertainty, and the accuracy can depend on arbitrary choices of both how many data points to use in computing the variance matrix and the criteria for rejecting degenerate cases. No definitive numbers are given in the references, although ratios in the range of 5 to 10 are often used as the requirement for a good, non-degenerate solution. *Lepping and Behannon* [2001] have also analyzed minimum variance results on the basis of a ''composite eigenvalue ratio'' for the specific case of directional discontinuities. However, as mentioned earlier, we wish to be able to use the technique on the typical IMF at all times, comprising a mixture of rotational and tangential discontinuities as well as nearly steady intervals.

3. Results From the MVA Method With Multiple Satellites

[10] By using a comparison of IMF measurements from multiple satellites it is possible to test how well the MVA technique works on data from a single satellite, and to determine the optimal MVA parameters for routine use. We needed to find the time interval duration, or number of points, to use in each ''variance matrix'' calculation, and the minimum allowable value for the eigenvalue ratio. If N points are to be used for each variance matrix calculation, then in order to apply the technique to a continuous stream of IMF measurements, rather than one distinct magnetopause or discontinuity event, the MVA computation process would start with the first N points from the time period, compute the variance matrix from these N vector measurements, and then test the matrix eigenvalues for degeneracy. If the intermediate/minimum eigenvalue ratio is greater than some value, r_{min}, then the minimum variance eigenvector is used for the phase plane normal direction for the time at the center of the N-point interval. The center point is more conveniently computed if N is odd. The computation then steps forward in time by adding one new IMF vector to the variance calculation and dropping the oldest one, then repeating. If the eigenvalue ratio fails the degeneracy test, then the last known ''good'' normal vector is used for each time step up until a new, non-degenerate eigenvector is found.

[11] In order to derive the best parameters for both the number of points to use in the MVA and the r_{min} ratio, four different time intervals having simultaneous IMF measurements from four satellites (ACE, Wind, IMP-8, and Geotail) have been used. The intervals and spacecraft positions at the center of the intervals are listed in Table 1. ACE is the only satellite at the L_1 location. Since the major focus of this investigation has been to evaluate the reliability of the L_1 data for making predictions, only the ACE IMF data were used for the MVA calculations. The magnetometer instrumentation on ACE is described by *Smith et al.* [1998]. The averages of the solar wind velocity for each interval are also included in Table 1, indicating that they were a little higher than normal, in the range of 490 to 600 km/sec, but not extremely so.

Table 1. Positions of the Satellites for the Four Test Cases

Date Time	SW Vel., km/s	Spacecraft	GSE Position, R_E		
			X	Y	Z
Oct. 21, 1998 0–24 UT	541	ACE	228.8	−36.8	−7.8
		Wind	74.8	35.1	6.6
		IMP-8	32.9	1.5	−7.5
		Geotail	15.8	−25.1	−1.1
April 29, 1999 12–24 UT	490	ACE	224.5	−23.1	−16.3
		Wind	53.0	−19.9	−9.1
		IMP-8	18.3	28.1	−25.5
		Geotail	13.8	10.9	−2.7
April 30, 1999 0–24 UT	603	ACE	224.3	−22.1	−16.8
		Wind	51.5	−17.0	−18.2
		IMP-8	7.0	31.9	−27.6
		Geotail	3.0	27.6	−2.5
July 7, 1999 03–19 UT	604	ACE	236.8	38.7	−1.3
		Wind	208.3	−22.6	−0.5
		IMP-8	9.9	33.5	−16.1
		Geotail	23.2	19.6	−1.4

[12] After computing the minimum variance directions in the IMF at the ACE location as a function of time, the predicted propagation delay time (Δt) from ACE to each of the other three satellites is computed with the formula:

$$\Delta t = \hat{\mathbf{n}} \cdot (\overline{\mathbf{P}}_T - \overline{\mathbf{P}}_A)/\hat{\mathbf{n}} \cdot \overline{\mathbf{V}}_{SW} \quad (3)$$

given the vector positions of each ''target'' satellite ($\mathbf{P}_T$) and ACE ($\mathbf{P}_A$), the solar wind velocity vector ($\mathbf{V}_{SW}$), and the minimum variance eigenvector (the phase plane's normal direction), $\hat{\mathbf{n}}$. All three components of the solar wind velocity are used in (3) for calculating the proper delay time. Even though the X component is by far the most important, the other two components of the velocity vector were found by *Weimer et al.* [2002] to have subtle contributions as well. It is also worth repeating that the spacecraft at the L_1 orbit share with the Earth an orbital motion around the Sun, and this creates an aberrated component to the solar wind velocity in the +Y direction that is seen in the spacecraft velocity measurements. This aberration is routinely removed in the processing of these velocity measurements, so that the data are transformed to the reference frame of the Sun. When these data are given in GSE coordinates, the angular rotation to this coordinate system is often done without the translation of the velocities to the Earth-centered reference frame. For the purpose of calculating the delay times in three dimensions the aberration needs to be put back in, which amounts to adding 29.8 km/s to the Y component. Over the course of an hour this correction changes the Y position by about 17 R_E, or almost half the radius of the ACE libration orbit around L_1. In the case of the real time data from ACE, currently only the X component of the velocity is supplied, so that the Y component should be given an assumed value of 29.8 km/s rather than zero.

[13] For our tests the next step after the delay calculation is to propagate the IMF that was measured at ACE to the locations of each of the other satellites, by adding the

computed delay times to the time of each vector sample. Due to the continuously variable delay times, the data that were originally sampled at an even cadence become compressed and expanded in time, so they are resampled by interpolation to the same time-tags as at each target satellite (similar sample frequencies are used on all). After the delay propagation, some ACE measurements may appear to arrive at the other satellites out of order, so before interpolation it is necessary to remove the time delayed data samples which would arrive at the target at times earlier than previous samples.

[14] This process is done for each complete interval, after which we have obtained the time delayed ACE IMF data at the same times as each of the other three satellites. Next, a figure-of-merit test score is derived by computing the total squared deviation of the MVA-predicted magnetic field from the magnetic field at the three independent spacecraft (those not used in the MVA). This deviation is computed using all three components of the IMF vectors, at every point in the interval. The optimal values of N and r_{min} to use then, are those that reduce the error and therefore minimize this score. Our tests have indicated that there are no magic numbers, as there were variations between the different cases on what worked the best. One firm conclusion was that the quality of the results depends primarily on the duration of the time interval that is used for each variance matrix computation. The number of points to use is then determined by the sampling period of the IMF measurements.

[15] For example, the best score for the entire four-day period was obtained with a duration of about 28 min for each MVA calculation. Using our highest resolution ACE IMF data, which are sampled at a cadence of 16 s, then the number N that works is approximately 105 samples. But since the real-time data from ACE that are posted by the NOAA Space Environment Laboratory (SEL) are given at 1 min intervals, then the comparisons were also tried with similar data, using a 4-sample moving box average to resample the 16 s measurements at 64 s intervals. At this temporal resolution the number of points that worked best was about 30.

[16] The test score increases, becoming much worse, for a lower number of points and shorter durations, particularly below 7 min. These results were not what was originally expected, as initially it had been assumed that the time period used for the MVA should span only seconds, or a minute or two at the most. This may very well be the case for the magnetopause crossings for which this technique had been developed.

[17] The test results are not as sensitive to the choice of r_{min} as they are for the time duration. In general, as the number of data points N increases, the optimal value of r_{min} decreases, as the variance matrix eigenvalues are typically smaller. If too high of a value is chosen for the r_{min} ratio, then a number of perfectly valid points are eliminated as well as the degenerate cases. The overall temporal resolution of the process is thereby reduced, as the angle stays fixed for a longer time at the last known good normal vector. However, if the minimum ratio r_{min} is chosen to be too low, then a few indeterminate vectors, often oriented 90° from the intended result, may pass through the rejection filter, causing spurious spikes to appear in the time delay calculations.

Table 2. Optimal Parameters for the MVA Technique Using Two Simultaneous Intervals

IMF Sample Period	Number of Points	Minimum Eigenvalue Ratios
16 s	29, 105	10., 2.
32 s	17, 69	12., 2.
64 s	11, 31	15., 2.

[18] Another criteria that can be used to reject possibly "bad" orientations is that the normal vector should not be tilted more than 70° from the GSE X direction. This use of a "limiting angle" follows from *Ridley* [2000], who had used a 45° limit. Our 70° limit was found by trial-and-error to work the best for the test cases.

[19] As mentioned previously, with all four days taken together the best MVA interval to use was about 28 min, but at some times a shorter interval would seem better. As the IMF contains structures with a mixture of scale-sizes, then it became apparent that a better approach would be to simultaneously compute the variance matrix for intervals of different length. After some experimentation it was found that only two values of N are needed to obtain satisfactory results. Using a lower value of N helps to find phase-plane transitions within the rapidly varying regions of the IMF, but it would not find good normal vectors at times with a more slowly varying IMF. If the short period fails the degeneracy test, then the process looks at the result of the MVA using the next, higher N. In order to determine what two pairs of N and r_{min} works best for the MVA calculations, a computer program was used to do a reiterative search for the first, lower N and the associated value of r_{min} that produced a locale minimum in the error from the multiple satellite test. The program next searched for the next N-r_{min} pair that further reduced the score to another minimum, while still using the first pair for the initial MVA computation.

[20] The results from this process are listed in Table 2. The results are given for IMF measurements having three different temporal resolutions. The "Level 2" IMF data from the ACE satellite are provided with a sample interval of 16 s, the lowest given in Table 2. The other sample intervals of 32 and 64 s were derived from this data by a moving-box average. In these tests the magnetic data from the other three satellites were always filtered so that their temporal resolution matched that of the ACE data. The 64 s time step is very close to that of the IMF data from the ACE satellite that are provided in real time by the SEL, so the parameters in the third row of Table 2 are appropriate for use with these data. The numbers in this table are not invariable, as the differences in the errors at neighboring values generally were not large. However, as mentioned before, the errors do increase as the lowest value of N is decreased.

[21] An astute reader may question how the minimum variance technique may work during intervals with "steady IMF." At these times the direction of maximum variance that is found is the same as the steady IMF vector, which may be along the direction of the Parker spiral. The small fluctuations that are superimposed on this steady background, though not nearly distinct enough to be labeled as discontinuities, define the direction of intermediate variance, and the minimum variance is perpendicular to these two.

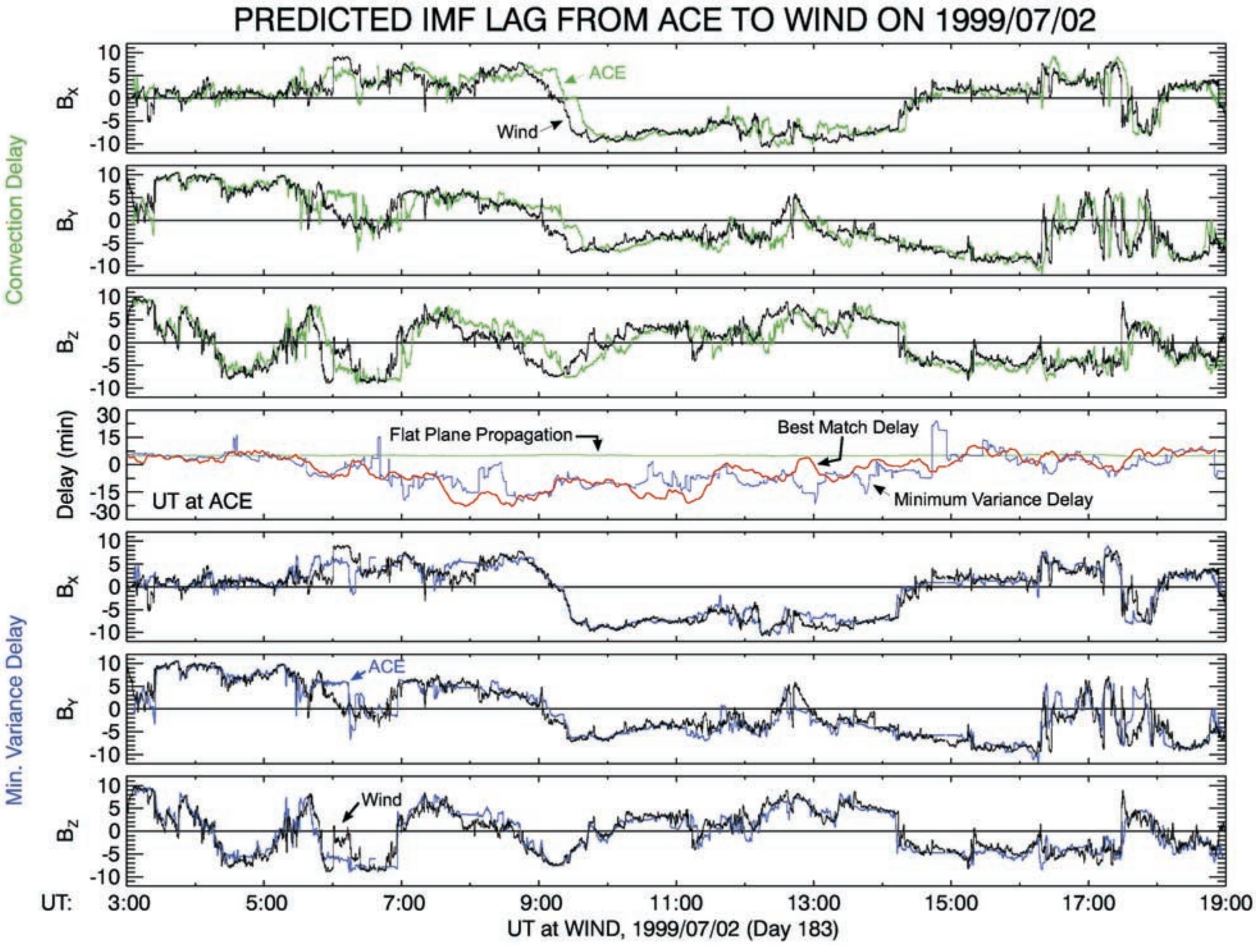

Figure 1. Comparison of the IMF measurements from both the Wind and ACE satellites, taken on July 2, 1999. The top three panels show the three components of the IMF measured at Wind in black, while the green lines show the ACE measurements, after first shifting these data in time according to a flat plane propagation at the solar wind velocity. The horizontal axes shows the UT at Wind. The delay time that was used is shown as the green line in the middle plot, plotted as a function of the UT at ACE. The bottom three panels show the same Wind data (black), but this time the ACE measurements (blue) have been shifted in time according to the tilt angles from the minimum variance technique. The value of these time shifts are shown in blue in the middle panel. For comparison, the time delay curve that was found to give the best match between the measurements is shown in red.

[22] In order to demonstrate how well the MVA technique works at actually predicting propagation delay times when used with the optimal parameters in the process described above, Figure 1 shows a comparison of IMF measurements from ACE and Wind. The format of this graph is nearly the same as those that were presented by *Weimer et al.* [2002], except that the horizontal axis for the UT corresponds to that of the Wind spacecraft rather than ACE. The upper three panels in Figure 1 show the three components of the IMF measured at Wind in black on the original time line of these measurements at the Wind location. The green lines in these plots show a superposition of the same measurements at ACE, shifted in time to the Wind position according to the solar wind velocity and separation distance, and assuming a flat, non-tilted propagation. These data have a temporal resolution of 16 s. The nearly flat, green line in the middle panel shows the amount of this time shift, the solar wind ‘‘advection time delay,’’ as a function of UT at ACE. At the start of this time interval ACE was at coordinates (236.6, 38.8, −1.6) R_E GSE and Wind was at (208.5, −22.6, −0.7). As the separation between the two spacecraft in the X distance was small, the expected time delay is only a few minutes, yet there are times when features in the IMF measured with ACE arrived at Wind much earlier than expected. For example, around 0900 UT the Wind data in the upper three graphs (black) are obviously shifted in time ahead of the convected ACE data (black) results by approximately 20 min. Due to the effects of the tilted phase planes, certain transitions in the IMF actually reached Wind before they reached ACE, even though the Wind satellite was farther ‘‘downstream.’’

[23] Using the complete MVA process that is described above to compute the variable phase front tilt angles, the resulting time delays from ACE to Wind are shown as the blue line in the middle panel of Figure 1. The parameters in the top row of Table 2 were used for the ACE data with 16 s

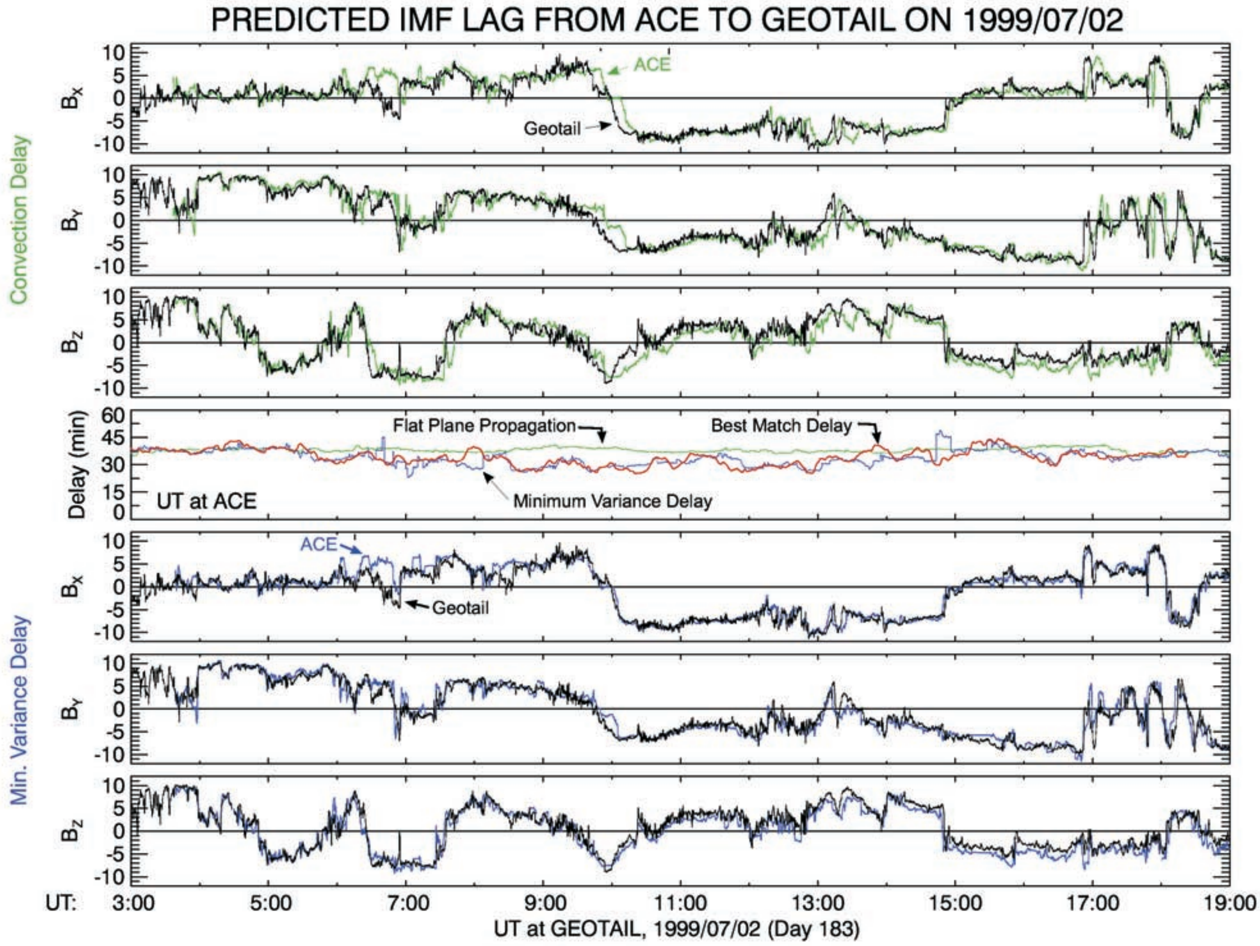

Figure 2. Comparison of the IMF measurements from both the Geotail and ACE satellites for the same case on July 2, 1999. The format is the same as in Figure 1, but with the black lines representing the Geotail measurements. The data are plotted as a function of UT at Geotail, with the exception of the middle panel which shows the time delays at ACE.

resolution. Finally, the blue lines in the bottom three panels show the ACE IMF measurements shifted in time according to the MVA calculations, overlaid on the same reference Wind measurements in black. Transition features in the IMF that did not line up before now come together quite nicely, demonstrating that the MVA calculation of the time delays is far superior to using a non-tilted model. It is the square of the differences between these curves in the bottom three panels that was used in the calculation of the figure-of-merit that was discussed previously.

[24] For purpose of comparison, the red line in the middle of Figure 1 shows the time delay from ACE to Wind that was computed by the same technique that is described in detail by *Weimer et al.* [2002]. It is not a predicted time delay, but a "measured" time delay, being that which achieved the best match between all three components of the IMF. As described in the prior publication, the process that computed this measured delay was inhibited from making too sudden transitions in the delay function, so the result does not have as much fine structure as from the MVA computations.

[25] Another comparison is shown in Figure 2, which exhibits both the Geotail and ACE measurements for the same time period as in Figure 1. (Geotail was in the solar wind during this interval, even though its orbit was designed to keep it primarily in the geomagnetic tail.) The format is the same as in Figure 1, except in this case the UT time line and black lines correspond to the measurements at Geotail instead of the Wind spacecraft. Again, the MVA calculation produces a better match between the two spacecraft measurements. The differences between the tilted and flat-plane convection delays are not as great in this case, and the data also agree more closely even though Geotail is much farther downstream from ACE and Wind, demonstrating that the separation in the GSE Y-Z direction is more important than the separation along the Sun-Earth (X) line. In this particular case the IMP-8 spacecraft showed very little difference between the tilted and non-tilted calculations and measurements, since IMP-8 had an even better alignment with ACE.

4. Tilt Angles Compared With Other Technique

[26] Figure 3 exhibits what the three-dimensional tilt angle of the IMF phase plane is actually doing during the time period shown in the previous Figures. The three stacked plots show the orientation of the phase plane normal vector (or minimum variance direction) as a function of time at the ACE

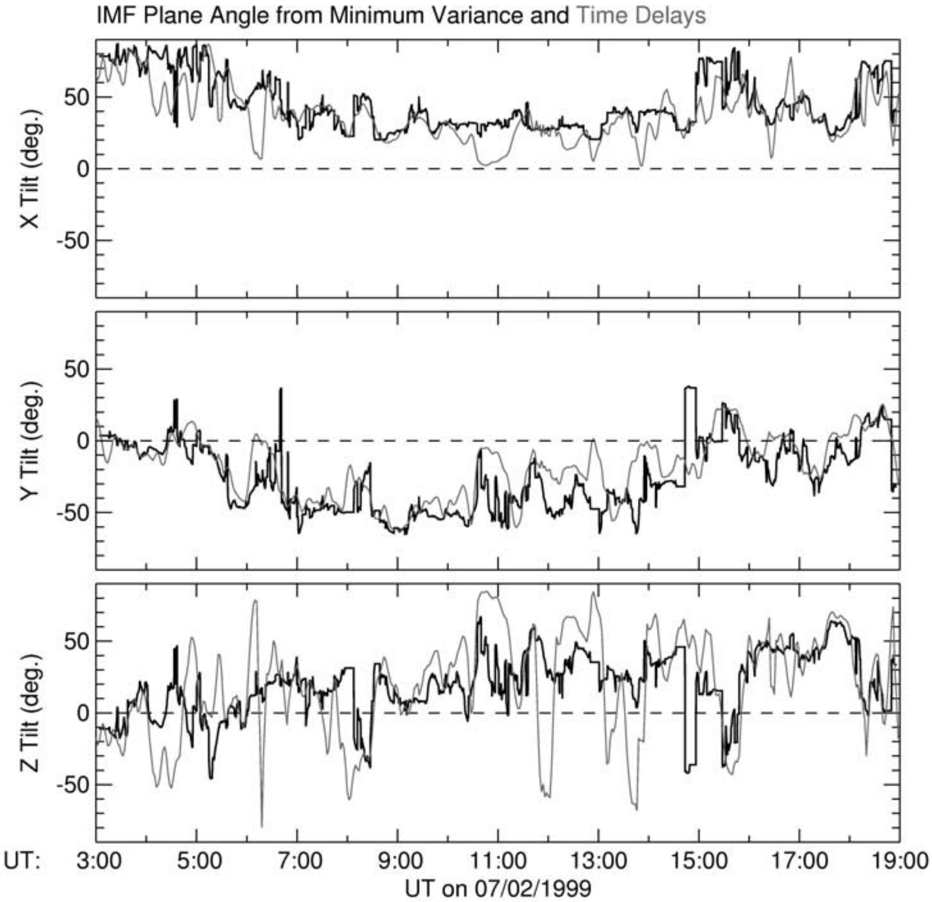

Figure 3. Computed IMF tilt angles as a function of time on July 2, 1999. The lighter gray lines show the results from using the propagation time delays between four satellites, and the dark black lines are the results obtained with the minimum variance method. The graphs show the angle between the tilt plane's normal vector and the three GSE coordinate axes.

spacecraft. What are plotted are the inverse sines, in degrees, of the normalized vectors' *X*, *Y*, and *Z* components in GSE coordinates. As the normal vectors that are calculated have arbitrary signs, then each vector was multiplied by -1 if the *X* component were negative. Where the phase plane is not tilted at all, i.e. perpendicular to the Earth-Sun line and lying within the *Y-Z* plane, then the "X tilt" on the graph is 90° and both the *Y* and *Z* tilt angles are zero. Alternatively, if the "Y tilt" increases in the positive direction, then it means that the normal vector is moving from the +X direction toward the +Y axis, and vice versa. The thick, black lines show the tilt angles obtained from the MVA technique at the 16 s sample rate. Because the ACE and Wind spacecraft are separated by 61.4 R_E in the *Y* direction, and little in the *Z* direction, the time delays in Figure 1 follow the *Y* tilt angle shown in Figure 3 very closely.

[27] The light grey lines in Figure 3 show for comparison the results from using the multispacecraft time delay technique to calculate the tilt angles, with points computed at two minute intervals. This technique used the "measured" delays between ACE and the other three spacecraft, and then used these results, as well as locations, to obtain the orientation of the phase plane. The results from the two methods usually follow each other quite closely, and in places have nearly perfect alignment. Another case where the MVA-derived tilt angle is compared with the time delay technique is given in Figure 4, with results very similar to those in Figure 3.

[28] Overall, the results that are obtained by the two different methods, while not in perfect agreement, do match reasonably well. The overlaid tilt angle graphs show that the same general trends are present; the results from the time delay method resemble a low-pass filtered version of the MVA results. Additionally, there are often sudden changes in the IMF phase plane tilt angle which are found using both techniques. These results can be taken as a confirmation that the minimum variance method, when used with these parameters, does give a reasonably accurate measurement of the IMF phase plane tilt angle as a function of time. Conversely, the MVA results can be construed as a validation of the technique that was used to construct the time delays between satellites, and the subsequent interpretation of these variable delays as due to nearly planar fronts of constant phase that are tilted with respect to the direction of propagation.

5. Satellite-to-Ground Propagation Test

[29] Next it seems prudent to ask whether or not the tilted phase planes can have any significant influence on actual

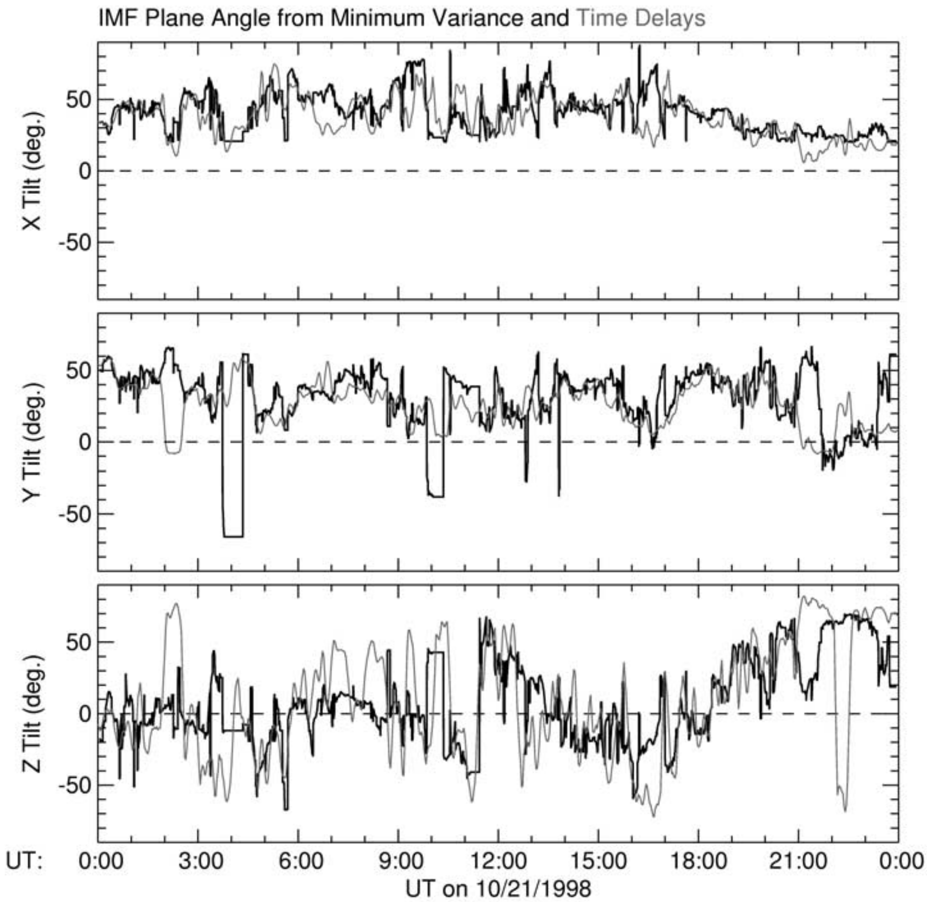

Figure 4. Computed IMF tilt angles as a function of time on October 21, 1998. The format is the same as in Figure 3.

space weather predictions, since ACE's separation from the Earth-Sun line, about 40 R_E, is not as great as from Wind in the extreme example cases. And can the single-satellite MVA technique be successfully applied to making predictions? The answer is found by performing the MVA and delay calculations with the ACE data for a number of different days. The result obtained is that, in general, the differences in the delay times between tilted and non-tilted propagation to the Earth are not as great as demonstrated with some multiple satellite comparisons [*Weimer et al.*, 2002]. For a given perpendicular separation distance, $d_\perp$, the typical delay differences are $d_\perp/V_{SW}$, or about 0.25 min/R_E [*Collier et al.*, 1998], giving about 10 min at 40 R_E separation. Yet it is still not uncommon for there to be found cases with differences on the order of 30 to 40 min. An example is shown in Figure 5, where the bottom three panels show the predicted tilt angles in the same format as in the previous figures. For the purpose of this test, the real-time data from ACE are mimicked using 64 s resolution data (derived from the 16 s data), and applying the MVA parameters in the third row of Table 2. An additional panel on top of Figure 5 shows the computed time delays from ACE to Earth using both the MVA technique, shown as the heavy black line, and the flat plane calculation, shown as the lighter gray line. For this calculation the position of the target satellite in (3) was replaced by a location on the Earth's magnetopause near the Northern cusp, at (8, 0, 4) R_E.

[30] This case in Figure 5 from June 6, 2001 is one of several found in an examination of very recent ACE data during Northern summer months where there was both a significant difference between the two delay calculations and a distinct transition feature in the IMF which would be detectable by the response of high-latitude magnetometers on the ground. The objective was to test the MVA technique with an actual "space weather" prediction without using any other IMF data from a second spacecraft. In Figure 6 are shown the *Y* and *Z* components of the IMF, from 10 to 14 UT, as a function of the predicted times of impact on the magnetopause. The light gray lines show the result using the non-tilted delay calculation and the heavy black lines use the MVA results. There is an approximately 30 min time difference in the arrival of the transition where the *Y* component of the IMF goes briefly positive, while the *Z* component oscillates from positive to negative. Both lines have the same tempoaral resolution. As the MVA time delays are not constant, some features of the IMF are not only shifted in time but have their temporal profile altered as well.

[31] In Figure 7 are shown both the northern and vertical components of the magnetic perturbations measured from five northern stations in the "Greenland Chain" that is maintained by the Danish Meteorological Institute. The

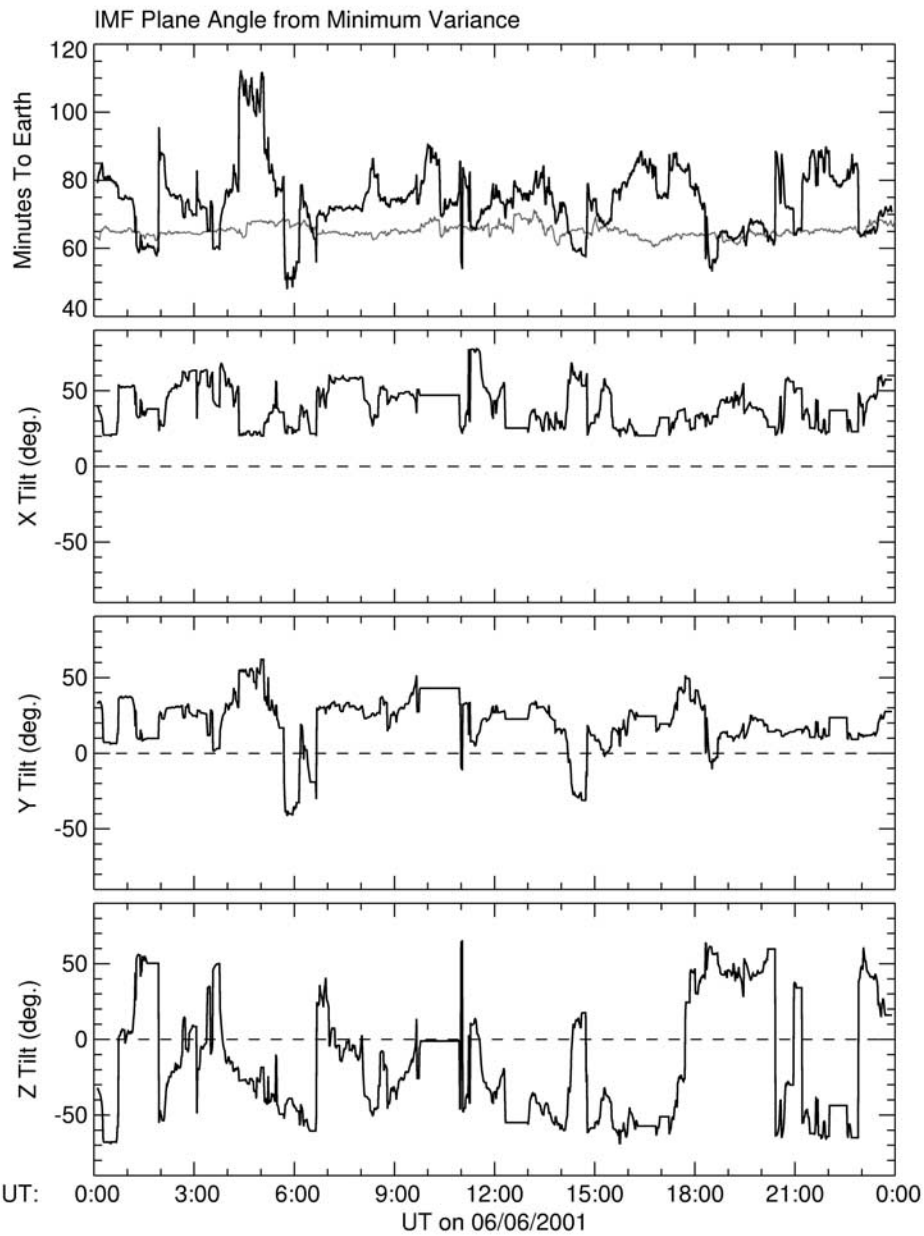

Figure 5. Computed IMF tilt angles as a function of time on June 6, 2001. The format is the same as in Figure 3, only in this case the results are shown from the minimum variance technique only, using measurements from ACE. Additionally, the top panel shows the propagation delay time, from ACE to Earth, that is obtained by using these tilt angles. For comparison, the lighter gray lines show the time delay that is obtained without using any tilt.

corrected geomagnetic latitudes of these stations are in the range of 75.8 to 83.5°. The actual magnetometer data are shown as the light gray lines in both rows, at a temporal resolution of 1 min. It is not intuitively obvious what the effects should be from the IMF shown in Figure 6, so in order to facilitate a comparison, the measurements from ACE have been passed through a mathematical model that can predict magnetic perturbations solely on the basis of the IMF, solar wind velocity, and the dipole tilt angle (which includes the seasonal effects). The heavy black lines in Figure 7 show the model-derived magnetic perturbations, with the bottom row using the IMF timing from the non-tilted plane propagation and the top row using the tilted phase fronts from the MVA technique. The model perturbations are calculated at 2 min. intervals, using propagated IMF values that have been smoothed with a 15 min. moving average. It is evident that the timing of the comparison is better in the top row, with the MVA technique, than in the bottom row where the predicted effects of the IMF occur about a half-hour before they actually do.

[32] The prediction of these geomagnetic effects were derived from an interim version of the empirical field-

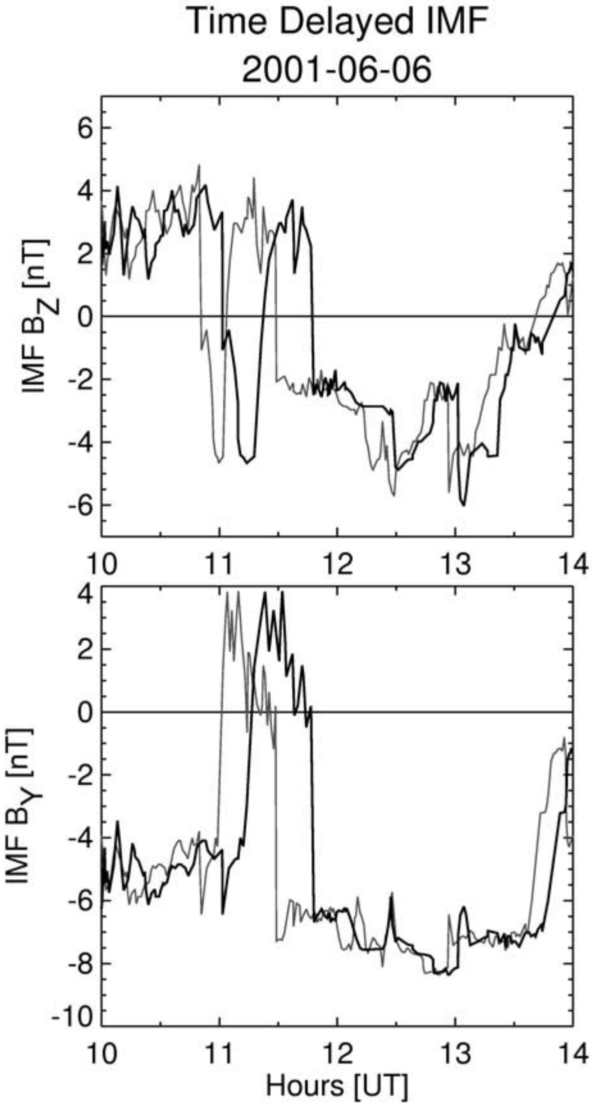

Figure 6. The Y and Z components of the IMF that were measured by ACE on June 6, 2001. These measurements have been shifted in time by using the two different delay values that were plotted in Figure 5, thus giving two different predictions for the IMF variations at the Earth. The darker lines show the results from using the minimum variance calculations.

aligned current model described by *Weimer* [2001]. The exact details of how the geomagnetic prediction is accomplished with this particular model is beyond the scope of this paper and will be described in more detail in a future publication. Suffice it to say, the technique is akin to the reverse of the well-known magnetometer inversion process to derive the field-aligned currents [*Richmond*, 1992]. How well the values from this model agree or do not agree are not as important here as the timing of the characteristic signature that is associated with this particular flip in the IMF.

[33] Thus the tilting of the phase planes is demonstrated to have a measurable influence on the propagation of the IMF from their measurement at the L_1 location to the Earth, and it would be advantageous to always use an MVA calculation when these time delays are required, for both research purposes and actual forecast predictions. Although the technique is not 100% accurate and foolproof, the overall results should be more accurate than not doing any correction at all for the tilted propagation.

6. Discussion and Summary

[34] Previously it had been found that the propagation time of the IMF from an upstream monitor at L_1 to other satellites and to the magnetosphere may be significantly different from what would be expected by using a simple, flat plane propagation in the GSE *X* direction at the solar wind velocity. The differences can be accounted for by tilted phase planes in the IMF. A consequence of these tilted phase planes is that predictions of the effects of the IMF at the Earth on the basis of the L_1 measurements may suffer from reduced accuracy in the timing of events. A technique for measuring the actual delay times between multiple satellites was used by *Weimer et al.* [2002] to determine the angle of tilt and how it varies with time, and it was found that the angle of tilt can vary significantly within only a couple of minutes. As this technique can not be used with real-time data from a single satellite at L_1, then an alternative method is required to derive the phase front angles for more accurate space weather predictions.

[35] In this paper we have demonstrated that the minimum variance analysis technique can be used successfully with single-satellite IMF measurements to determine the variable tilt of the plane of propagation. While the MVA technique was developed for application to satellite crossings of the magnetopause, it can work with the IMF provided that sufficiently long intervals are used for each calculation of the variance matrix. The optimal parameters for the MVA were determined by employing simultaneous measurements of the IMF with multiple spacecraft, and comparing the predicted IMF that is propagated from one satellite with the actual measurements at the other satellites. The best justification that can be given for using the minimum variance technique with the IMF is simply that it works. Exactly why it works is left to future experimental and theoretical studies of the three-dimensional structure of the solar wind and is beyond the scope of this Technique Report.

[36] The number of points that is required to compute the variance matrix had been found to be much higher than we originally expected, corresponding to time periods in the range of 7 to 30 min. The quality of the results drops very sharply as the number of data points that are used goes below a total duration of 7 min. This finding is consistent with the negative result regarding the value of the MVA technique experienced by *Horbury et al.* [2001], as they had used a sample interval of only 2 min. For an analysis of events which are clearly tangential discontinuities, the cross-product method described by *Horbury et al.* [2001] may very well be more suitable. But for more general use, where the tilt angles are required as a continuous function of time, the application of the MVA technique as described here can be used to advantage.

[37] It had been found that the best results are obtained when two different time periods are used simultaneously for

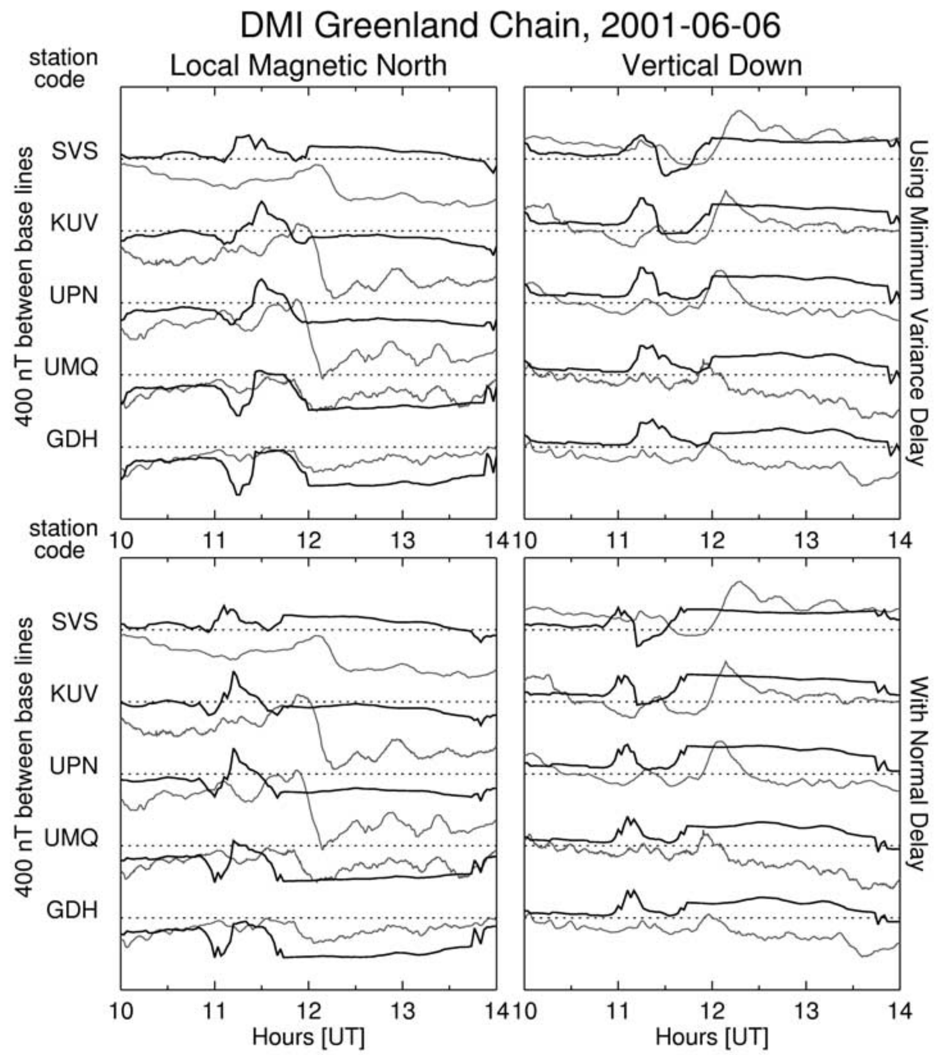

Figure 7. A comparison of measured magnetic perturbations and model predictions for 10 to 14 UT on June 6, 2001. The northern and vertical components of the magnetic perturbations are shown for five northern stations in the Greenland Chain, using the light gray lines. The darker black lines show the results from predicting these variations with an empirical model, using the IMF data that are shown in Figure 6 as the input. The upper row uses the IMF that were shifted in time according to the minimum variance tilt angles, while the bottom row uses the flat plane propagation.

the MVA calculation, using the calculation from the shorter period where the results are favorable, and resorting to the results from the longer period otherwise. The 7 to 30 min range for the optimal time period to use with the MVA is most likely is related to a characteristic scale size of the solar wind IMF, and this time range is not expected to be valid for other applications of the minimum variance technique, such as at magnetopause crossings. Note that at a nominal solar wind speed of 4 Earth radii per minute, this range of periods corresponds to dimensions of 28 to 120 R_E. This result agrees with the scale sizes found by *Crooker et al.* [1982] and *Collier et al.* [2000], who describe the IMF as the "two length scale medium." It had been found that there is a "short scale length of the order of many 10s of R_E representing correlation decay along a parcel." If there is dynamical evolution of the IMF, then perfect predictions are not to be expected for structures smaller than this. There also may be smaller scale structure in the IMF that does not share the same orientation. *Collier et al.* [2000] interpreted the larger scale size, on the order of 100 R_E, as geometric in nature. In any case, what we refer to as a "planar phase front" is only an approximation to large scale, turbulent structure in the IMF that appears to be relatively flat within a range of several 10s of R_E.

[38] With use of the optimized parameters it has been shown that the MVA method, using the ACE data alone, performs reasonably well for predicting the actual time lags in the propagation between ACE and other spacecraft, as well as to the Earth. It has been shown that this technique can correct for errors, on the order of 30 min, in the timing of predictions of geomagnetic effects on the ground using an empirical model. In every case that we have examined so far the IMF delays between multiple spacecraft can be explained by the planar phase plane model, and the MVA

technique gives a good estimate for the front orientation. It does not appear that it is necessary for the IMF to have any special characteristics for this technique to work. There is not a requirement that the IMF have the property of a compressed "planar magnetic structure" [*Nakagawa et al.*, 1989] or a "corotating interaction region" [*Clack et al.*, 2000].

[39] *Maynard et al.* [2001] had found that the tilted phase planes will interact with the northern and southern hemisphere merging regions on the magnetopause at different times, and the effects in one hemisphere are later seen in the ionosphere of the other. Perhaps the empirical models could eventually be made more sophisticated in order to mimic this "double source" response. We note that the MVA technique should also be usable for improving the performance of MHD simulations. Although it is recognized that there is considerable complexity involved in implementing a variable tilt IMF phase front at the "front end" of such models, eventually it should be done in order for the simulations to show how the tilted IMF planes interact with the magnetosphere.

[40] The technique for the MVA calculations that is presented here most likely could be improved upon in the future. Until then, it is useful to have available now a method to predict time delays from the L_1 position as a continuous function of time, without requiring multiple satellites. The technique also portents to a greater appreciation and understanding of the three-dimensional structure of the IMF variations and their measurable effects.

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