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A simple method for determining the local inclination of the ‘interplanetary current sheet

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Abstract. A method which allows to determine the local inclination of the Interplanetary Current Sheet has been developed. The method uses magnetic field measurements acquired during current sheet crossings. In GSE coordinates, the temporal variation of these components for an "ideal" crossing, i.e.: that with the current sheet on the ZX plane, has been work out. Assuming that the measured magnetic field has the same structure but rotated respect to the "ideal" crossing, an estimation of its local inclination has been obtained.

1 Introduction

Since Sonnerup and Cahill paper about the magnetopause structure (Sonnerup and Cahill, 1967), the main tool used for estimating the Interplanetary Current Sheet (ICS) local orientation has been the Minimum Variance Analysis (MVA). This method allows us to estimate a normal vector, **n**, to the plane which contains the ICS. From **n** is possible to calculate the azimutal (ϕ_N) and latitudinal (θ_N) angles in GSE coordinates. This pair of angles determine the ICS local inclination. The MVA is well defined when the medium and minimum eigenvalue ratio is greater than or equal to 2, $\lambda_2/\lambda_3 \geq 2$ (Lepping and Behannon, 1980).

It is accepted that when the current sheet is nearly perpendicular to the spacecraft path along to the ecliptic plane, the MVA gives local inclination consistent with the observed inclination on the solar Corona. However, if the current sheet is nearly parallel, the MVA can not estimate the ICS local inclination correctly (Behannon et al., 1983).

In this communication, we present an alternative method to the MVA for estimating ICS local inclination. Our preliminary results seems to show that this method can estimate correctly both perpendicular and parallel ICS.

2 Instrumentation and data selection

Magnetic field key parameters from the Magnetic Field Instrument (MFI) on board of WIND spacecraft have been used. These key parameters are 46 and 92-s averages.

Using these key parameters, a compilation of magnetic field polarity reversals has been done from January 1, 1995 to January 31, 1997. A sample of 76 magnetic field inversions has been compiled.

After this, a selection criteria for a current sheet crossing detection has been established:

The magnetic field polarity is conserved for several hours, the angle ω between the local interplanetary magnetic fields before crossing, $\mathbf{B_1}$, and after crossing, $\mathbf{B_2}$, is greater than 120º and finally, data were available during the crossing interval.

Finally, a sample with 30 current sheet crossing has been compiled.

3 The method

A set of magnetic field component equations for an "ideal" current sheet crossing is proposed. This set must be adapted for being used to fit experimental data. Equations system is:

$$B_x = B_{0x} tanh\left[\frac{t-t_0}{T}\right]$$
$$B_y = B_{0y} \qquad (1)$$
$$B_z = B_{0z}$$

where B_{0x}, B_{0y}, B_{0z} are the magnetic field components out of the crossing region, t_0 is the crossing middle point and

2T is the temporal width of the crossing.

The magnetic field components measure into the current sheet should follow the "ideal" field form but rotated with respect to this "ideal" field by an azimutal ϕ_R, and latitudinal θ_R, angles.

So if this rotation is included in (1), it is obtained:

$$B_x = B_{0x} tanh\left[\frac{t-t_0}{T}\right] cos\, f_R + B_{0y} sin\, f_R$$

$$B_y = \left(-B_{0y} tanh\left[\frac{t-t_0}{T}\right] sin\, f_R + B_{0y}\, cos\, f_R\right) cos\, q_R + B_{0z} sin\, q_R$$

$$B_z = -\left(-B_{0x} tanh\left[\frac{t-t_0}{T}\right] sin\, f_R + B_{0y}\, cos\, f_R\right) sin\, q_R + B_{0z}\, cos\, q_R \quad (2)$$

where ϕ_R and θ_R are the rotated angles with respect to an ideal current sheet, placed on Sun-Earth line connection, and vertical to the ecliptic plane. We have called this fit method, hyperbolic tangent rotation (HTR) method.

4 Data analysis

When the previous criterion described in point 2 is obeyed, the MVA and the HTR are applied to all the current sheet crossings detected. The ϕ_N, θ_N, ϕ_R and θ_R are calculated. In each case the MVA was performed on a time series of length Δt, where Δt was always less than or equal to the temporal width of the individual current sheet crossings. In the other hand, the HTR method was performed on time series greater than the temporal width of the individual current sheet crossings.

In this point, it is important to note that our ideal current sheet has been chosen so that the latitude angle module, $|\theta_R|$, coincides with the latitude angle module of a normal vector to the current sheet plane in the GSE system, while the azimutal angle ϕ_R, is the angular difference between the current sheet and the theoretical current sheet. So, keeping this in mind, it is easy to note that ϕ_R and ϕ_N can not be compared directly.

During the data analysis we have noted that the MVA is very dependent of the selected measure sample while the HTR method requires only that the magnetic field component were stable on the current sheet crossing border.

5 Results

The data analysis explained above has been applied to a current sheet selection detected by MFI instrument between 1st January, 1995 and 31st January 1997. The sample is composed by thirty events. All of them have been included into the table 1. In table 1, it has been calculated and tabulated the date of crossing, the time in the centre of the crossing (t_0). The angle ω through which the magnetic field rotated in the plane of the sheet. The λ_2/λ_3 ratio and ϕ_N, θ_N, ϕ_R and θ_R angles.

With the aim to compare MVA with HTR method an arbitrary criteria for current sheet crossing classification in quasi-perpendicular, intermediate and quasi-parallel crossings has been introduced. This criteria is:

- If $\theta \leq 20^o$ quasi-perpendicular case.
- If $20^o < \theta < 50^o$ intermediate case.
- If $\theta \geq 50^o$ quasi-parallel case.

In table 1, it can be observed that there are eight cases with θ_N and $\theta_R \leq 20^o$ simultaneously. Seven of them present a very similar values for the current sheet orientation.

Table 1. Selected current sheet crossings.

	Date	t_o	ω	λ_2/λ_3	ϕ_N	$\|\theta_N\|$	ϕ_R	$\|\theta_R\|$
1	01/02/96	2.184	161	14	45	22	58	30
2	01/08/95	8.028	133	13	228	63	205	11
3	01/09/95	9.91	143	8	110	13	173	53
4	01/28/95	28.949	129	3	32	54	53	10
5	02/05/95	36.066	133	74	331	71	27	11
6	02/05/95	36.906	161	7	52	6	34	2
7	02/06/95	37.215	122	5	231	39	221	3
8	03/09/95	68.107	133	3	47	5	45	18
9	03/09/95	68.466	144	4	38	6	52	5
10	05/02/95	122.342	175	42	232	14	234	35
11	05/23/95	143.513	146	6	236	57	197	29
12	05/23/95	143.553	164	2.5	8	66	24	61
13	05/30/95	150.181	148	3	52	5	43	25
14	06/07/95	158.397	136	7	188	52	217	77
15	06/07/95	158.774	160	2	59	16	38	11
16	06/25/95	176.521	155	80	53	15	40	12
17	07/31/95	212.857	172	78	219	12	232	10
18	10/26/95	299.596	166	9	358	49	233	52
19	10/26/95	299.643	161	9	32	12	56	55
20	12/09/95	343.041	121	2.5	225	36	224	17
21	12/24/95	358.074	157	3	141	77	225	11
22	01/19/96	19.573	138	63	249	9	206	9
23	01/20/96	20.498	160	2.2	56	30	43	25
24	06/13/96	165.304	143	23	215	9	242	47
25	07/11/96	193.96	168	13	38	38	40	6
26	09/04/96	248.375	169	7.5	34	14	47	25
27	12/21/96	356.188	143	43	41	16	45	11
28	12/25/96	360.486	121	3.5	29	3	56	33
29	12/29/96	364.4	149	32	12	48	49	34
30	01/22/97	22.686	156	500	250	27	204	52

The seventh case, number 22, looks to have a discrepancy in the azimutal angle estimation, but it must be noted than ϕ_R is the angular distance between the real current sheet plane and our ideal current sheet plane, and ϕ_N is the azimutal angle of a normal vector to the current sheet plane. So to compare both angles it is necessary to apply the next operation: 360-(ϕ_R+90). Then it is obtained 244º. This value is very similar to ϕ_N=249º.

This seems to indicate that both method obtain reliable values for quasi-perpendicular crossings.

There are three cases with θ_N and $\theta_R \geq 50$º. All of them have different values for the angles calculated for each method. However, preliminary comparison with the source surface plots (Hoeksema et al., 1983) from Wilcox Observatory shows a better fit with the estimated inclination using the HTR method.

Finally, there are six cases which can be catalogued as intermediate crossing using both methods. In three of them a good agreement was found between the two methods.

In summary, in the 56% of cases analysed, both methods classify them into the same group. However, the discrepancy between the two methods is enhanced with the latitude angle. This could indicate that the HTR method works better than MVA for estimating local current sheet inclination, when the sheet is parallel or nearly parallel to the ecliptic plane.

In figure 1, the distribution in the ICS local inclination is presented. On the top of this figure θ_N angle is depicted and at the bottom the θ_R is represented. In this figure is possible to observe that there is a major occurrence for quasi-perpendicular crossings. This result could be due to the chosen selection criterion.

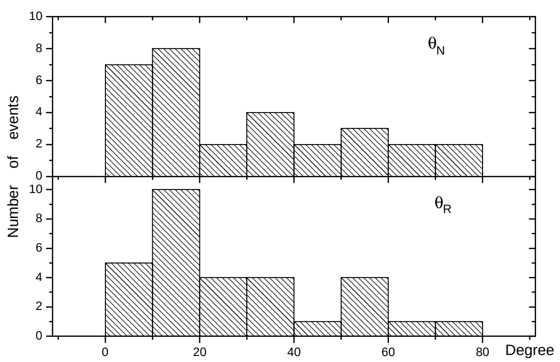

Fig. 1. Histogram for $|\theta_N|$ (top of panel) and $|\theta_R|$ (bottom of panel) angles estimated with the MVA and HTR methods respectively.

Quasi-perpendicular, intermediate, and quasi-parallel current sheet crossings are depicted in figures 2, 3 and 4 respectively. In these figures, the result of the HTR fit is presented. In all cases, the solid line is the fit curve for each case.

In figure 2, a quasi-perpendicular current sheet crossing happened in December 21st, 1996 is plotted. In this crossing, the estimated local current sheet inclination on the ecliptic plane with MVA was 74º. Using our fit method we obtained 79º. This is a very favourable case because the crossing was isolated enough and the values estimated with the two methods were very similar.

In figure 3, an intermediate current sheet crossing happened in December 29th, 1996 is presented. In this crossing, the estimated local current sheet inclination on the ecliptic plane by MVA was 42º. With HTR fit method we obtained 56º. A very low azimutal angle is obtained with MVA (12º). In solar wind conditions there was nothing that it could explain this value. Nevertheless, a most reliable angle (49º) is obtain with the HTR method.

A quasi-parallel current sheet is plotted in figure 4. This crossing was detecting in June 7th, 1995. The current sheet local inclination calculated for this crossing with the MVA was 38º while with the HTR method this estimated inclination was 13º. In this case, we have compared these results with the current sheet inclination calculated with the source-surface model. We have found a better agreement between source-surface model and the HTR than MVA method.

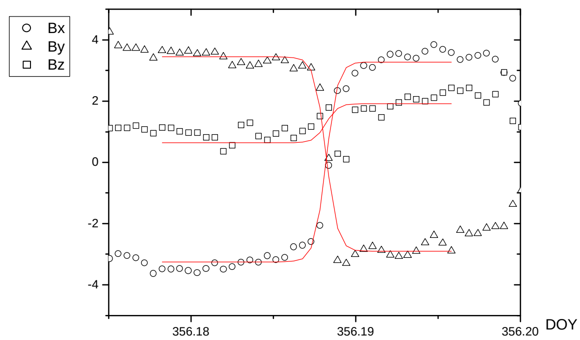

Fig. 2. Quasi-perpendicular current sheet crossing in December, 1996. Magnetic field component in nT are plotted. The solid lines are the fit lines from equation (2).

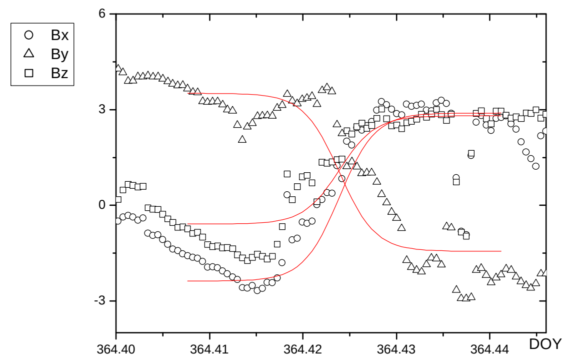

Fig. 3. Intermediate current sheet crossing in December, 1996. Magnetic field component in nT are plotted. The solid lines are the fit lines from equation (2).

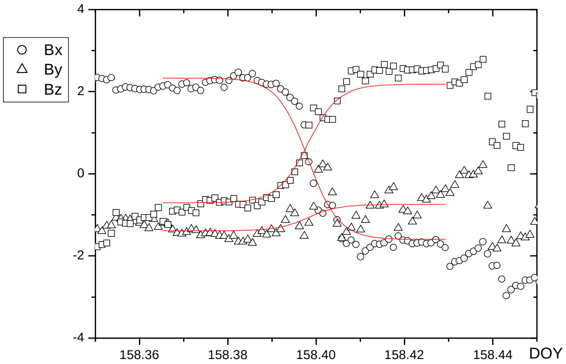

Fig. 4. Quasi-parallel current sheet crossing in June, 1995. Magnetic field component in nT are plotted. The solid lines are the fit lines from equation (2).

6 Conclusions

An alternative method to the MVA for estimating the ICS local inclination during a current sheet crossing has been developed.
This method is based on the supposition that the magnetic field components measured during a current sheet crossing is a rotated form of an "ideal" magnetic field across the current sheet.
We have called to this preliminary method Hyperbolic Tangent Rotation method.
On a 30 current sheet sample, a comparison between the MVA and the HTR method has been carry out. The conclusions were:

- Each method uses different temporal intervals for estimating the current sheet local inclination. The MVA needs points into the crossing, while the HTR method uses measures out of the current sheet crossing border.
- In a 56% of crossings, both methods classify them into the same group of current sheets.
- Discrepancy between the estimated angles enhances when the ICS is nearly parallel to the ecliptic plane.
- Both methods can estimate quite well the local inclination when the current sheet is nearly perpendicular to the ecliptic plane.
- Comparison with source-surface plots seems to indicate that the HTR method is capable of estimating local inclinations when the current sheet is nearly parallel to the ecliptic plane.

Finally, we want to emphasize that this fit method is a preliminary form. The result validity is pending of subsequent tests.

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