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Application of the "Minimum Correlation Technique" to the Correction of the Magnetic Field Measured by Magnetometers on Spacecraft

F. Mariani

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APPLICATION OF THE "MINIMUM CORRELATION TECHNIQUE" TO THE CORRECTION OF THE MAGNETIC FIELD MEASURED BY MAGNETOMETERS ON SPACECRAFT

F. Mariani
Laboratory for Extraterrestrial Physics*
NASA-Goddard Space Flight Center
Greenbelt, MD 20771

*On leave from Istituto Astrofisica, Universita L'Aquila, Italy 67100
Now at Istituto Fisica, Universita Roma, Italy 00185

1. INTRODUCTION

One experimental difficulty in measuring the low magnetic fields existing in the interplanetary medium is that of having precise, absolute determination of the field vector. In the ideal case of a magnetically clean spacecraft and no zero-offsets in the instruments, the problem does not exist. In the case of a real S/C, there is always the possibility of a spurious field which includes the spacecraft residual field and/or a possible field from the sensors, due to both electronic drifts or changes of the magnetic properties of the sensor core (these latter effects may occur during the storage of the sensors prior to launching and/or in-flight).

It is the purpose of this report to discuss some aspects of the problem and to test the reliability of a method originally devised by Hedgecock (1975). No mention will be given here about other methods which are described in the literature (see Davis and Smith (1968), Ness (1970), Ness et al. (1971), Rosenberg (1971), Belcher (1972), Neubauer and Schatten (1974).

2. A BRIEF OUTLINE OF THE METHOD

The basic postulate of the Hedgecock technique is that there should be no correlation between changes in measured field magnitude and changes in the measured inclination of the field with respect to anyone of three fixed cartesian component directions. By means of simple algebraic relationships between the field magnitude variation ΔB between successive measurements and the associated direction variation $\Delta\theta$, one can show (Hedgecock, 1975) that the covariance function $V_{(c)}$ between ΔB and $\Delta\theta$

for a given small spurious field correction c in the direction of a monoaxial sensor, is just proportional to the product c sin θ.

This implies that a given field component, possibly affected by an unknown error c, can be simply corrected by searching for the value -c which makes the covariance function zero. In some experimental conditions it may not be so easy to find the zero crossing, due to the dependence of $V_{(c)}$ upon the term sin θ: when θ is small, it is possible that statistical fluctuations lead to more than one zero crossing, within the explored range of corrections. This ambiguity can be avoided by setting a minimum possible value for θ reasonably larger than 0° (Hedgecock takes 30° and we do the same).

There are a number of effects which may influence the numerical value of the covariance function and hence the correction field, in a very complicated and practically unpredictable way. One source of error is the quantization of the experimental data. Another source may be identified when the set of data, or even part of it, used for the computation of $V_{(c)}$ is biased by a systematic correlation of ΔB and $\Delta\theta$: it may happen for example that superimposed on a random variation there is a trend of B to increase during the period and of θ to increase (or decrease). In some cases, when the technique is iteratively in succession for the three axes a bad determination of, for example the y axis, can mathematically lead to a significant second order correction which may well be physically meaningless. Some other sources are discussed later.

In general, a few hundreds to a few thousands of data points prove sufficient for a good estimate of the correction, so that the method

are smaller for shorter sampling times. Small variations of the spin rate do not significantly affect these conclusions. If data points are missing when averages are computed, a new source of noise occurs, whose effect is difficult to estimate if the pattern of missing data is not known. The simplest way to reduce this source of noise is to avoid using intervals with too many missing data points.

4. APPLICATION OF THE MINIMUM CORRELATION TECHNIQUE

4.1 A Simulation

We took a field vector whose intensity F and direction θ and ϕ where randomly variable around an average defined by certain values F_0, θ_0, ϕ_0 ; we superimposed a spurious field defined by three orthogonal components c_1, c_2, c_3 on $\underset{\sim}{F}$; and the minimum correlation technique was then used to determine the corrections. Table 2 shows some typical results. We used the same averaging intervals considered above (Δt = 5 and 6 sec), together with 6 different sets of given corrections c_1, c_2, c_3. The table shows that when Δt = 6 the computed corrections are always within $\pm 0.2\gamma$ of the specified corrections. When Δt = 5 sec, the discrepancy is small at the highest sampling rate, but at lower sampling rates the discrepancies are large. These discrepancies are drastically increased when the absolute values of c_1, c_2, c_3 are increased by a factor of two, which means that the method is very sensitive to the magnitude of the corrections.

The occurrence of large computed corrections when Δt = 5 sec requires an explanation. The basic reason is that using an averaging time which is not a common integer multiple of the spin period and the sampling

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period introduces an artificial long-period modulation on the succession of $\delta F'_x$ and $\delta F'_y$ superimposed on its random part. This biases the covariance function, and as a consequence erroneous "corrections" are computed. Once a wrong value is found, its effect propagates to the following computations; in general, the process does not necessarily converge to any good value of the corrections.

4.2 Application to (IMP-8) Data

An independent check of the merits of the minimum correlation technique has been made by applying it to the data of Explorer 50 (IMP-8), which are known to be very reliable (no spurious field in excess of 0.1 - 0.2γ). Three separate time intervals of approximately one week were selected with no special care except to be sure that interplanetary field was being measured. In one of these intervals the field happened to be highly variable.

Determination of the zero offsets was made for sets of 1440 consecutive 15.36-sec-averages (treated as individual data). No significant difference was found between the three intervals, so the entire set of 72 zero-offset corrections was finally taken as a single set and statistically studied.

The absolute value of the field correction on the X axis was found to be less than 0.2γ in 44 cases and less than 0.3γ in 58 cases, corresponding figures for the Y axis were $<0.2\gamma$ in 55 cases and $<0.3\gamma$ in 66 cases. As regards to the Z axis, i.e. the spin axis, a slightly negative average field corrections of about -0.1γ was found. The results are summarized in Table 3 where average values and statistical

errors are shown, along with the linear best fit parameters (versus time).

The results of Table 3 give us confidence that for real data the minimum correlation technique gives good estimates of the corrections c_1, c_2, c_3, the only requirement being that data do not show a systematic correlation of ΔF and $\Delta\theta$.

4.3 Application to Helios 1 Data

In this case the individual data points that we used for the analysis are 5 sec averages. Early examination of the quick-look data showed some anomaly in the in-flight offsets as compared to those measured in the pre-flight tests on the ground. This was at least partially due to some local spurious field from the spacecraft.

Individual offset determinations have been made over each consecutive two-hour time interval. As an illustration of the results, we show in Fig. 2 a plot of the values of the field corrections versus time, together with the corresponding plot representing the flipper position. A striking anticorrelation shows up between the offset of the spin component and the flipper position. A simple interpretation is that there is a combination of both a S/C field and a sensor-associated drift. Individual contributions of the two sources must be determined by means of some additional considerations. To this purpose, let us consider the situation illustrated in Fig. 3. By means of a flipper mechanism the sensors D1 and D3 are periodically rotated by 90° from the S/C spin direction to lie on the equatorial plane and vice-versa. The reference system X, Z is rigidly fixed on the S/C and rotates with it.

Let us also assume that the spurious fields c_1 and c_3 can be

decomposed in two parts C_1, C_3 from the sensors package and S_x, S_z from the S/C.

In the position (a) the correction on z is expected to be

$$C' = C_3 + S_z \tag{3}$$

As regards the equatorial component x, one can say that if the offset determined by standard techniques happens to be different from the nominal pre-flight value by an amount D' then

$$D' = C_1 + S_x \tag{4}$$

Similarly for the configuration (b) one gets

$$C'' = S_z - C_1 \tag{5}$$

$$D'' = S_x + C_3 \tag{6}$$

The above 4 equations then lead to the desired solutions

$$\begin{aligned} C_1 &= \frac{C' - C'' + (D' - D'')}{2} \qquad S_x = \frac{(C'' - C') + (D' + D'')}{2} \\ C_3 &= \frac{C' - C'' - (D' - D'')}{2} \qquad S_z = \frac{C' + C'' + (D' - D'')}{2} \end{aligned} \tag{7}$$

which define completely both the S/C spurious field and the field perturbation to be attributed to the mechanical system which is rigidly rotating with the sensor itself.

As an example we take from Fig. 2, $C' = -0.3\gamma$ and $C'' = +2.5\gamma$. If the pre-flight determination of the sensors' offsets are compared with the actual flight determinations (see Villante and Mariani, 1977), we have for the time interval under consideration $D' = 0.7\gamma$ and $D'' = 2.1\gamma$, and equations (7) lead to

$$C_1 = -2.1\gamma \qquad S_x = 2.8\gamma$$

$$C_3 = -0.7\gamma \qquad S_z = 0.4\gamma$$

The fact that $D' \neq 0$ and $D'' \neq 0$ means that some change occurred before launching or in flight, or both. One possibility is that the change occurred in the sensors. Another possibility is that at some stage of the post-test assembly of the S/C some magnetic component was used near our sensor. The only way to get $C_1 = C_3 = 0$ would be $C' = C''$ and $D' = D'$, in which case we would also have $S_x = S_z = D'/2$. On the other hand, the condition of no S/C field, $S_x = S_z = 0$, can be satisfied by a variety of situations, under the restrictions $D' + C'' = 0$ and $D'' - C' = 0$, which simply imply that $C_1 = -C''$ and $C_3 = C'$. In conclusion, it seems reasonable to believe that the corrections are due to the combination of a S/C field and a sensor package effect.

In a later phase of the Helios 1 flight the corrections C' and C" changed significantly to become $C' = 1.8\gamma$ and $C'' = 2\gamma$ which, combined with $D' = 1.3\gamma$ and $D'' = 1.0\gamma$, leads to

$C_1 = 0.05\gamma$ $\qquad$ $C_3 = -0.2\gamma$

$S_x = 1.2\gamma$ $\qquad$ $S_z = 2.1\gamma$

This is indicative of a temporal drift of both sources of spurious field, S/C and sensor package.

It is important to point out that our analysis is limited to the D1 and D3 sensors. Whether or not a drift of the sensor D2 and a S/C field component parallel to it exist cannot be stated. The only indication of a combined effect can be derived by the shift (if any) of the D2 offset from its nominal value, but there is no way to decide which is the relative amount to be attributed to the two possible sources.

5. CONCLUSIONS

The minimum correlation technique is generally appropriate for determination of the zero offset corrections of triaxial magnetometers, as investigated with S/C data taken at $\leq$ 1 AU by IMP-8 and Helios 1-2.

In general a number on the order of 1000 consecutive data points is sufficient for a good determination.

The time separation between consecutive zero determinations can be as low as a few tens of minutes. However some care has to be exercised when individual measured points (rather than averages over appropriate time intervals) are taken, due to the possible unrecoverable effect of spurious field components perpendicular to the spin axis. The best way to avoid the difficulty is that of using as individual points for the correlation averages over a time interval which is an integer multiple of the spin period and the sampling period. Use of simple algebraic relationships allows separation of the contributions due to the S/C

and the sensor system on those experiments with flippers.

6. ACKNOWLEDGEMENTS

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TABLE 1

THE MAXIMUM VALUES OF AVERAGE δF_x AND δF_y (IN γ) WHEN Δt=5 SEC AND Δt=6 SEC, FOR DIFFERENT SAMPLING PERIODS $T_{SAMPL.}$

AVERAGING INTERVAL	"CORRECTIONS"	SPIN (SEC)	SAMPLING TIME 0.1875 (SEC)	0.3750 (SEC)	0.75 (SEC)	1.50 (SEC)
Δt=5 SEC	$\lvert c_1\rvert = \lvert c_2\rvert = 2$	1.00	0.06	0.14	0.66	0.67
		1.01	0.10	0.13	0.64	0.93
		1.02	0.13	0.15	0.60	0.91
	$\lvert c_1\rvert = 2 \lvert c_2\rvert = 0$	1.00	0.05	0.10	0.33	0.67
		1.01	0.07	0.09	0.45	0.66
		1.02	0.09	0.11	0.43	0.93
Δt=6 SEC	$\lvert c_1\rvert = \lvert c_2\rvert = 2$	1.00	0.00	0.00	0.00	0.00
		1.01	0.03	0.04	0.09	0.13
		1.02	0.06	0.07	0.17	0.26
	$\lvert c_1\rvert = 2 \lvert c_2\rvert = 0$	1.00	0.00	0.00	0.00	0.00
		1.01	0.02	0.02	0.06	0.09
		1.02	0.04	0.05	0.12	0.18

TABLE 2

Computed offsets for six different sets of given c_1, c_2 and c_3. An asterisk indicates that no value was computed due to the reduced number of points taken into account in the computation of the covariance function (because of small angle to the sensor, too small field, etc). Numbers in parentheses indicate values computed for T_{spin}=1.00 sec; the others computed with T_{spin}=1.01 sec.

Assumed offsets (γ)			Averaging time = 6 sec				Averaging time = 5 sec			
			T_{samp}=0.1875	0.3750	.75	1.5	0.1875	0.375	0.75	1.5
c_3	0	Z_{OFF}	0.02(-0.02)	0.11 (0.11)	-0.08(-0.08)	-0.01(0.01)	0.01(-0.10)	0.14 (0.04)	0.23(0.15)	0.17(-0.06)
c_1	0	X_{OFF}	-0.08(-0.08)	-0.05(-0.05)	* (*)	* (*)	-0.07(*)	-0.06(-0.08)	-0.10(*)	-0.05(*)
c_2	0	Y_{OFF}	-0.09(-0.09)	-0.19(-0.19)	* (*)	* (*)	-0.11(*)	-0.15(-0.11)	-0.12(*)	-0.26(*)
c_3	2	Z_{OFF}	2.08 (2.11)	1.96 (1.95)	2.13 (2.12)	1.82 (1.88)	2.12 (2.09)	2.16 (2.01)	-2.10(-2.18)	-2.19(-2.11)
c_1	2	X_{OFF}	-0.02(-0.06)	-0.03(-0.03)	-0.09(-0.09)	* (-0.06)	0.00(-0.02)	* (*)	* (*)	* (*)
c_2	0	Y_{OFF}	-0.06(-0.13)	-0.05(-0.05)	-0.07(-0.07)	* (-0.15)	-0.29(0.23)	* (*)	* (*)	* (*)
c_3	0	Z_{OFF}	0.04 (0.07)	0.09 (0.08)	0.02(-0.03)	0.27 (0.08)	0.27 (0.21)	1.61 (1.69)	* (*)	* (*)
c_1	-2	X_{OFF}	-0.06(-0.09)	-0.08(-0.08)	-0.06(-0.06)	-0.08(*)	-0.24(-0.26)	-0.55(-0.58)	* (*)	* (*)
c_2	2	Y_{OFF}	0.03(-0.05)	-0.08(-0.09)	-0.21(-0.20)	-0.26(*)	0.31 (0.35)	0.49 (0.51)	* (*)	* (*)
c_3	-2	Z_{OFF}	-2.07(-1.93)	-1.98(-1.93)	-1.84(-2.03)	-1.94(1.77)	-1.84(-1.68)	-0.11(-0.55)	* (*)	* (*)
c_1	2	X_{OFF}	* (0.09)	-0.09(-0.07)	-0.06(-0.05)	* (-0.08)	-0.23(*)	-0.58(-0.53)	* (*)	* (*)
c_2	-2	Y_{OFF}	* (-0.05)	-0.08(-0.09)	-0.24(-0.20)	* (-0.25)	0.31(*)	0.52 (0.53)	* (*)	* (*)
c_3	0	Z_{OFF}	0.06 (0.02)	0.01 (0.11)	-0.04(-0.08)	0.16 (0.03)	2.29 (1.79)	4.32 (4.14)	-3.45(-3.51)	* (*)
c_1	2	X_{OFF}	* (-0.08)	-0.04(-0.05)	* (*)	-0.09(*)	0.22 (0.14)	0.49 (0.39)	* (*)	* (*)
c_2	2	Y_{OFF}	* (-0.10)	-0.04(-0.20)	* (*)	-0.23(*)	-0.61(-0.58)	-1.46(-1.40)	* (*)	* (*)
c_3	2	Z_{OFF}	2.06 (2.06)	2.07 (2.07)	1.97 (1.97)	2.23(2.23)	1.98 (1.98)	2.01 (2.01)	2.09 (2.09)	2.06(2.06)
c_1	0	X_{OFF}	-0.09(-0.09)	-0.07(-0.07)	-0.06(-0.06)	-0.08(-0.08)	-0.10(-0.10)	-0.06(-0.06)	-0.07(-0.07)	-0.05(-0.05)
c_2	0	Y_{OFF}	-0.05(-0.05)	-0.09(-0.09)	-0.21(-0.21)	-0.25(-0.25)	-0.05(-0.05)	-0.09(-0.09)	-0.24(-0.24)	-0.24(-0.24)

TABLE 3

Results of the best linear fit $c_i = a_i t + b$ of the temporal variation of the correction on the X, Y, Z direction as computed from IMP-8 data.

	Statistics on Algebraic Values		
	a_i (γ/day)	b_i (γ)	σ (γ)
c_1	-.00025 ± .00343	-0.0183 ± 0.0301	0.25
c_2	-.00088 ± .00264	-0.0298 ± .0231	0.19
c_3	-.00677 ± .00325	-0.109 ± 0.028	0.24
	Statistics on Absolute Values		
c_1	-.00079 ± .00218	0.191 ± 0.0191	0.16
c_2	-.00218 ± .00178	0.142 ± 0.0156	0.13
c_3	.00186 ± 0.00198	0.222 ± 0.0173	0.14

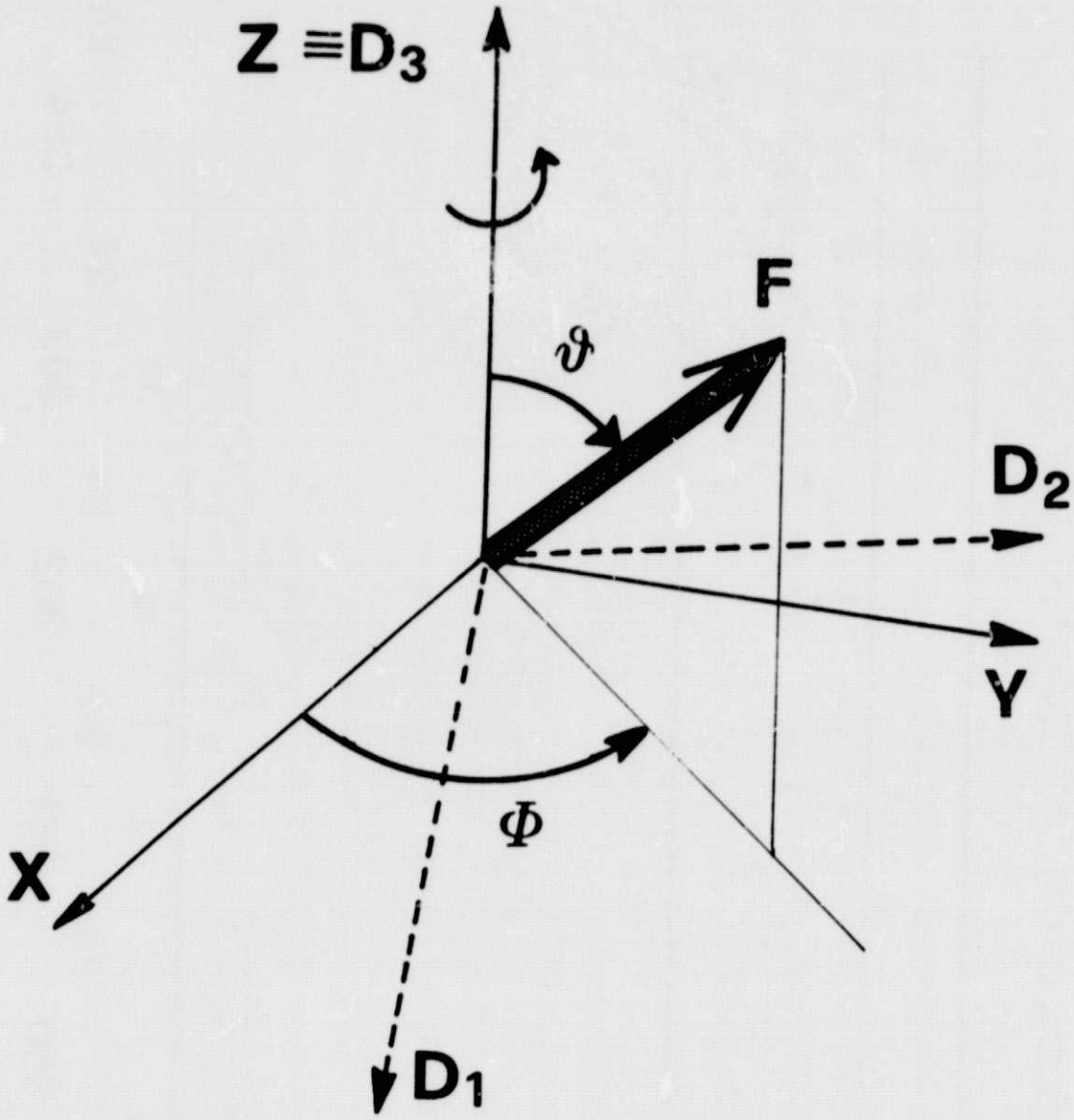

FIG. 1

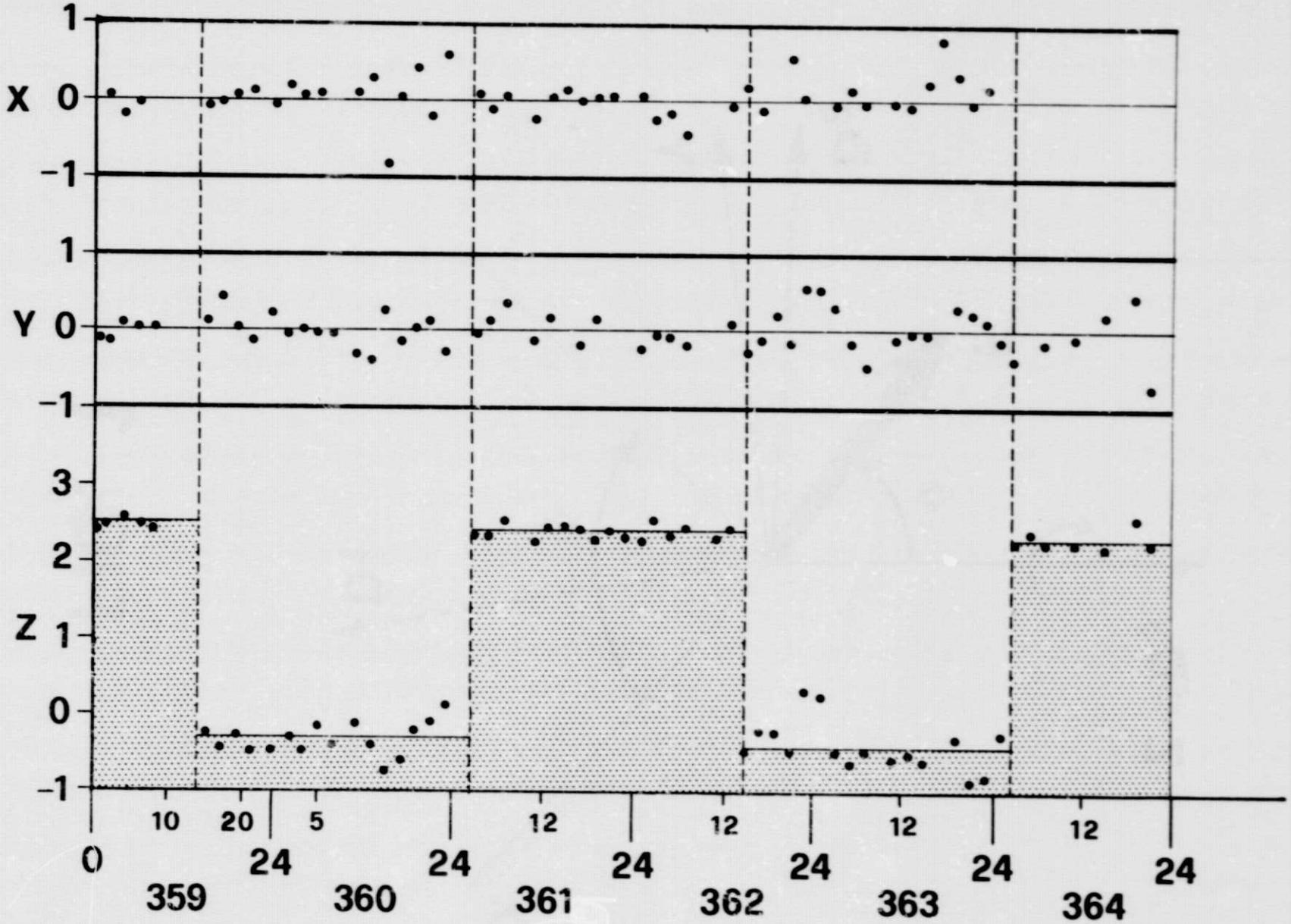

FIG. 2

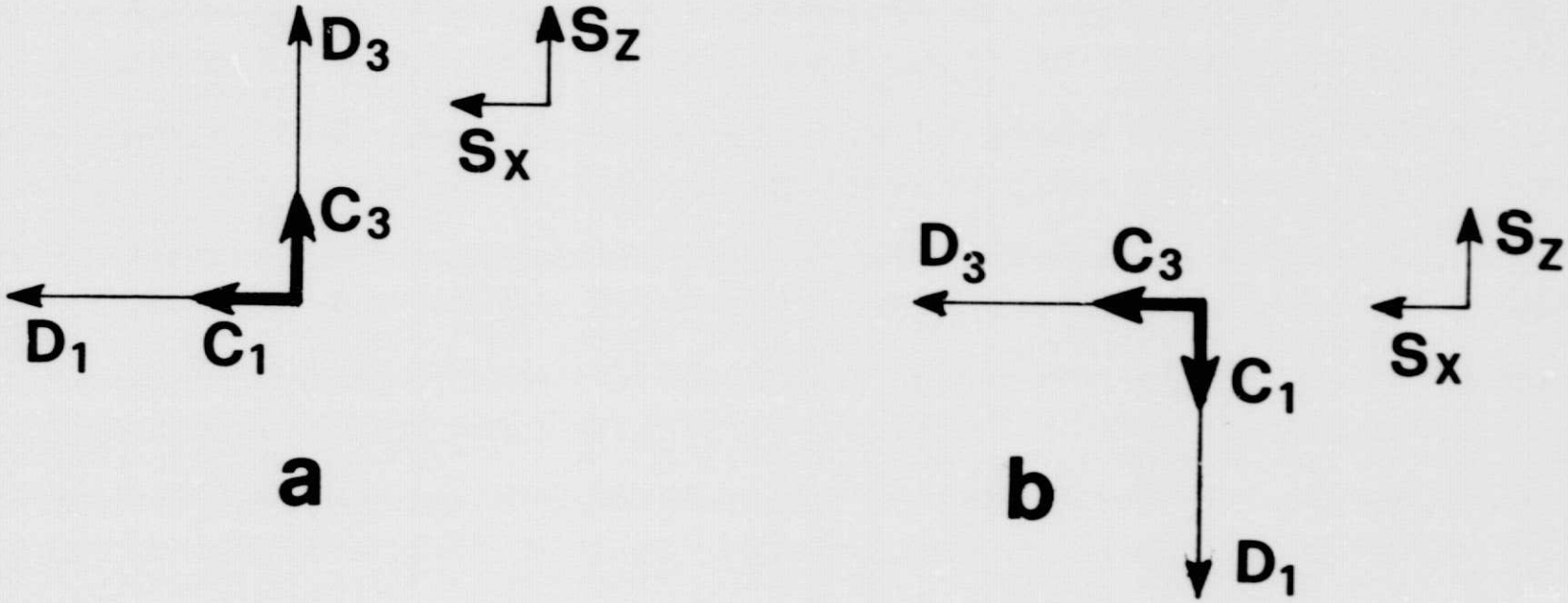

FIG. 3

1. INTRODUCTION

One experimental difficulty in measuring the low magnetic fields existing in the interplanetary medium is that of having precise, absolute determination of the field vector. In the ideal case of a magnetically clean spacecraft and no zero-offsets in the instruments, the problem does not exist. In the case of a real S/C, there is always the possibility of a spurious field which includes the spacecraft residual field and/or a possible field from the sensors, due to both electronic drifts or changes of the magnetic properties of the sensor core (these latter effects may occur during the storage of the sensors prior to launching and/or in-flight).

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