

INTERPLANETARY MAGNETIC FIELD CALCULATED FROM PHOTOSPHERIC MEASUREMENTS

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ABSTRACT

The difficulties of calculating the parameters of the interplanetary magnetic field (IMF) from solar magnetic data are discussed. It is shown that the measured solar parameters are underrated due to the signal saturation of the magnetographs. A correction is needed both for the observation heliocentric latitude and for the phase of the cycle. The proposed correction method ensures a good agreement between the calculated and observed parameters. Empirical numerical models are suggested that allow calculation of the solar wind velocity, IMF intensity, and IMF longitudinal and B_z components using solar magnetic measurements. It is shown that, under quiet or weakly disturbed conditions, the solar magnetic observations can be used as a basis for the advance forecast of the geomagnetic activity index A_p for 3 days. Such a forecast proves to be more reliable than the forecasts based on the traditional methods.

1. INTRODUCTION

A continuous gas flow leaving the Sun at a speed from 500 to 1500 km/s was mentioned for the first time by Biermann (1951, 1957) in the early 1950s. Parker (1958) developed this idea using the mathematical tools. In the case of a quiet flow, the radial solar magnetic field in interplanetary space had to decrease as r^{-2} . However, as the quantity and quality of the data available increased (in particular, with the advent of geophysical satellites), it became clear that the relationship between the solar magnetic fields and solar wind parameters was much more complicated and depended significantly on time.

The further progress in calculating the interplanetary magnetic field (IMF) from the solar field parameters was associated with the use of the so-called source surface (Altschuler and Newkirk, 1969; Schatten et al., 1969; Hoeksema and Scherrer, 1986; Wang and Sheeley, 1992, 2000). An attempt was made to proceed to direct calculations based on real magnetographic observations of the photospheric magnetic field, and rather promising results were obtained. The sign of the IMF radial component B_x in the Earth's environment proved to agree fairly well with the sign of the source-surface magnetic field B_{ss} (taking into account the transport time equal to 4 days). However, B_{xc} calculated

on the basis of the standard expansion law r^{-2} was much smaller than the measured value (Obridko et al., 1996). Obridko et al. (2004) tried to account for this discrepancy by introducing the expansion law with an index somewhat smaller than 2.

In this paper, we describe the correction procedure, which ensures a good agreement between the calculated and observed IMF values.

2. REDUCTION OF PHOTOSPHERIC MEASUREMENTS

It is well known that observations carried out in different spectral lines (or even in the same line, but at different observatories) may differ significantly. This effect is mainly attributed to the fine structure of the solar magnetic fields. The use of the spectral lines with high magnetic sensitivity leads to the signal saturation. As a result, the magnetograph underrates the real magnetic field several times. Such a line is the widely used (in particular, at the John Wilcox Observatory) line FeI $\lambda 525.02$ nm.

Nonlinearity of the magnetographic signal is quite a simple phenomenon calculated from the theory of line formation in the magnetic field (Obridko, 1985). It could be easily taken into account but for the resolution of the telescopes, which is much worse than needed to resolve the fine-structure elements. In fact, the majority of the magnetographs have resolution no better than a few thousand km in the photosphere, and the standard resolution of WSO observations is 3 arc. min. Therefore, tens to hundreds of elements with their own magnetic field and (still more important) their own temperature, pressure, and geometry are averaged in the field of view of the magnetograph. It additionally complicates the interpretation of observations in the FeI $\lambda 525.02$ nm line, whose excessive sensitivity not only to the magnetic field, but also to temperature (the lower level excitation potential $\chi_l = 0.12$ eV) leads to various distortions of the line contour in the regions with different physical conditions.

Howard and Stenflo were the first to call attention to this problem (Howard and Stenflo, 1972; Stenflo, 1973). They arrived at the conclusion that the field intensities measured in FeI $\lambda 525.02$ nm should be multiplied by a factor $K = 0.48 + 1.33\mu$, where $\mu = \cos\theta$ and θ is the

heliocentric angle. The same inference was made by Frazier and Stenflo (1972) and Gopasyuk et al. (1973). Later on, Svalgaard et al. (1978) found out that the factor K was constant all over the disk and was equal to 1.8. As shown by Ulrich (1992), K depends significantly both on the heliocentric distance and spatial resolution. This result was used by Snodgrass et al. (2000) for plotting synoptic maps of polar magnetic fields and by Wang and Sheeley (2000) for calculating the interplanetary magnetic field. The correction was introduced in the form:

$$K=4,5.-2.5\sin^2\varphi. \quad (1)$$

For comparison, the correction proposed in (Howard and Stenflo, 1972) and (Stenflo, 1973) in this system has the form:

$$K=3.0.-0.5\sin^2\varphi. \quad (2)$$

In general, the most adequate method is to find a matrix for transition between the measuring systems for all coefficients of the expansion in Legendre polynomials. This method was applied in (Obridko and Shelting, 19996). It makes allowance for different contribution of the fields of different spatial scales. However, the method requires the stability and uniformity of both measuring systems, as well as the constancy of the transition matrix and its independence of the cycle phase, which, obviously, cannot be originally warranted.

Though, sometimes, the use of a formal factor related to the heliocentric distance is not clearly justified from heliophysical viewpoint and provokes objections (Demidov, 1998a, 1998b, 2002), there is no other way to match the calculated values of the interplanetary magnetic field and galactic cosmic ray variations. In particular, the calculated and measured fields averaged over a rotation were reduced to a single scale by introducing the Ulrich correction (Eq. 1) (Wang and Sheeley, 1995, 2000). Note, however, that the agreement, though fairly good on the whole, is violated in some phases of the cycle. It suggests that the correction may change during a cycle.

3. CALCULATION OF THE ROTATION-MEAN INTERPLANETARY MAGNETIC FIELD

Now, we can proceed directly to calculating the interplanetary magnetic fields. To begin with, we calculate the r.m.s. solar magnetic field at the source surface B_{SS} . This value is the square root of the squared source-surface magnetic field averaged over the sphere. It was derived from the synoptic charts for each Carrington rotation. Calculations were made with different corrections for saturation. The polar correction introduced earlier (Hoeksema and Scherrer, 1986) to take into account underestimation of the polar observations was used in all cases.

Since the calculations were based on the synoptic charts comprising observations at the center of the solar disc, we could avoid taking into account the complicated and poorly understood dependence of saturation on the position angle. Thus, we assumed that the latitudinal dependence was enough to introduce the correction for saturation. The procedure was as follows. All values on the synoptic map were multiplied by a correction factor depending on latitude. Then, the expansion coefficients g_l^m, h_l^m were calculated and were used to find the source-surface field. Then, the B_{SS} values obtained were used to calculate B_{xc} by the formula:

$$B_{xc}=B_{SS}(R_{SS}/R_E)^2=0.141B_{SS} \quad (3)$$

Here, R_E is equal to one astronomic unit, and R_{SS} is the source-surface radius equal to 2.5 solar radii. It is taken into account that B_{SS} is measured in μT and the interplanetary magnetic field at the Earth's orbit, in nT. The B_{xc} values obtained were compared with the absolute values of the IMF B_x -component averaged over one rotation as a function of time without allowance for saturation (Fig. 1). One can see that the correlation is rather good (0.67), but the calculated values are much lower than the measured ones (Obridko et al., 2004).

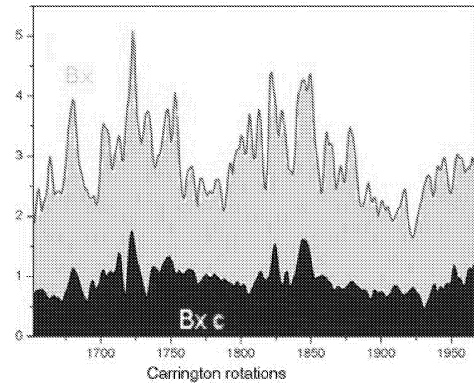


Figure 1. Comparison of the measured values B_x (heavy curve) and the values calculated without correction for saturation B_{xc} (lower curve)

In Fig. 2, B_{xc} is compared with the absolute values of B_x using the Ulrich correction (Eq. 1). The curves obtained have similar mean scales and the correlation coefficient equal to 0.74. This result was obtained earlier by Wang and Sheeley (1995, 2000). However, the agreement is insufficient at the maximum of the cycles. Now, the calculated B_{xc} values are much greater than the measured ones. The Ulrich equation, apparently, “overestimates” the contribution of local fields at the cycle maximum owing to excessive correction. It seems, that a more reasonable correction to use at the cycle maximum would be that proposed by Stenflo (Eq. 2).

We have calculated B_{xc} using Eq. 2 for the years close to the cycle maximum (1980-1982, 1989-1991, and 1999-

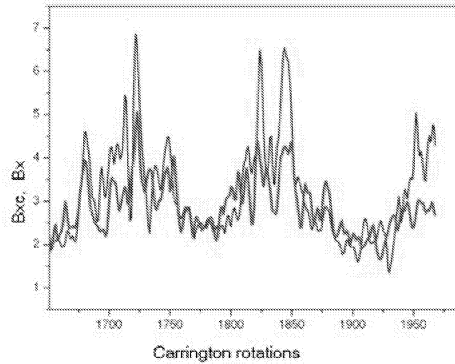


Figure 2 Comparison of B_x (heavy curve) and B_{xc} obtained using the Ulrich correction (Eq. 1).

2000) and Eq. 1 for the other years. Fig. 3 illustrates the comparison of B_{xc} and B_x . We have used the r.m.s. B_{SS} value in Eq. 3. The curves display similar scales and high correlation coefficients (0.75). Using the mean absolute value of the source-surface magnetic field at the Earth's helioprojection point, we obtain correlation as high as 0.84 (Obridko et al, 2005).

4. CALCULATION OF THE DAILY MEAN INTERPLANETARY MAGNETIC FIELD

Now, the solar magnetic field B_S at the Earth's projection onto the solar-wind source surface was calculated for each day over the time interval from 1976 to 2004 using the correction method described above.

The solar magnetic data were compared with the daily mean solar wind velocities and IMF parameters taken from the OMNI database (<http://nssdc.gsfc.nasa.gov/omniweb/ow.html>). As a result, we had at our disposal the data for a period more than 28 years (from May 1976 to September 2004). However, not all those data could serve for finding quantitative relations.

To develop the model, we have used data that satisfy the following criteria:

1. Solar wind velocity was measured 24 hours a day.
2. We have introduced a simple quality index: the number of the days of Stanford measurements available for the 27-day interval centered at a given day. The more rigorous quality criterion was applied the better were the results. The best result was obtained with the fullest data (27 days of measurements per rotation).
3. We have excluded the days when interplanetary shock waves producing sudden storm commencements (SSC) were recorded at the Earth. A shock wave often follows a CME, and interplanetary conditions are far from quasi-stationary for a few days. Therefore, besides the SSC day, we had to exclude the following three days. Note that this limitation attenuates the ejection effect significantly and does not influence much the

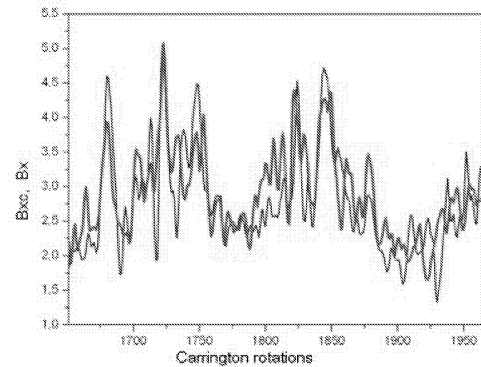


Figure 3. Comparison of B_x and B_{xc} obtained from Eq. 3 using both corrections

effects associated with coronal holes, since the arrival of high-speed solar wind streams from the latter is not usually accompanied by interplanetary shock waves.

4. Then, we excluded the days of very large and severe magnetic storms, when the maximum three-hour Kp -index was equal to or exceeded 8-. Such magnetic storms are always associated with CME events, and this limitation has even smaller influence on the coronal-hole effects than the previous one.

5. We have additionally filtered out the days with increased solar wind density N_{SW} and intensity B of the interplanetary magnetic field. At the strictest selection, all days with the daily mean values $N_{SW} < 10$ particles cm^{-3} and $B_{IMF} < 10$ nT were kept in.

The above-mentioned criteria of data filtration often duplicate one another and, on the whole, only one third of the days were excluded. Thus, the approach under discussion, in spite of its obvious limitation, is applicable to most situations in near-Earth space and to about two thirds of the days.

5. RESULTS

5.1. Time delay

Our model of the solar wind velocity was used to study the effect of the time delay. The smallest dispersion of the measured and calculated velocities was observed for the delay $\tau=4$ days, somewhat greater for 5 days, and much greater for the other delay times. By setting the delay time of 4 or 5 days for the whole sample, we obtain quite satisfactory results. They will be even better if we use solar wind observations V_{SW} and assume that $\tau=R_E/V_{SW}$ ($R_E=1$ a.e.). The value of τ determined by this expression and rounded to an integer number of days was used in all models discussed below.

5.2. Simulation of solar wind velocity

Wang and Sheeley (1990, 1991) introduced a parameter characterizing the divergence of the field lines. In our earlier work (Obridko et al., 1996), we introduced another parameter inverse in magnitude to that of Wang

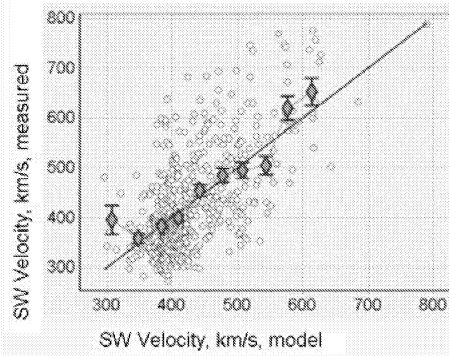


Figure 4. Correlation between the experimental and calculated daily mean solar-wind velocities.

and Sheeley. In doing so, we assumed the radius of the source surface to be equal to 2.5 solar radii. It is obvious that $W_s=1.0$ if the field lines are strictly radial and $W_s<1.0$ in all other cases.

$$W_s = 6.25 \left(\frac{B_s}{B_r} \right)^2 \quad (4)$$

First, we checked the agreement between the SW velocity and the Wang-Sheeley parameter W_s for the sampled daily means. Taking into account the relation between the solar wind velocity and density, we did not restrict the solar wind density N_{SW} in the V_{SW} models, but used all other limitations discussed above. The correlation coefficient between W_s and V_{SW} was found to be $\rho=0.49$ with the mean-square residual $\sigma=91.3$ km/s. Such a high correlation between the daily mean unsmoothed values is promising. However, this isn't the best possible one-parameter model. The correlation between $|B_s|$ and V_{SW} proved to be even better with the correlation coefficient of 0.53 and the mean-square residual of 88.7 km/s. It is surprising that the modulus of B_s is more closely connected with the solar wind velocity than the parameter specially developed to estimate the latter. Of course, it does not matter which parameter gives higher correlation. Much more important is that $|B_s|$ can be combined with W_s in a two-parameter velocity model and that both parameters fortunately complement one another. Some additional, statistically significant improvement of the model can

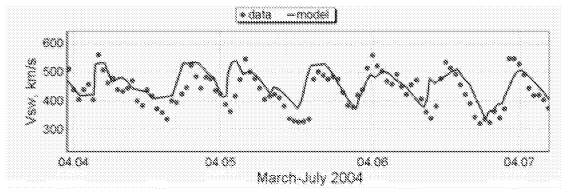


Figure 5. Behaviour of the experimental and calculated daily mean solar-wind velocities in 2004.

be ensured by introducing the modulus of the photospheric field $|B_p|$ as the third parameter. Choosing the coefficients by the least-square method, we obtain the following velocity model:

$$V_{SW}(t) = (393.2 \pm 7.6) + (192.9 \pm 40.0)W_s + (3.94 \pm 0.35)|B_s| - (0.019 \pm 0.004)|B_p|, \quad (5)$$

where B_s and B_p are measured in μT and $V_{SW}(t)$, in km/s. All solar parameters from here on are determined at a time $t-\tau$.

Fig. 4 demonstrates a fairly good agreement ($\rho=0.64$, $\sigma=81.2$ km/s) between the measured and calculated velocities for the model under discussion. As shown by the mean values determined for various intervals of velocity variation, the relation is close to linear.

Because of many gaps in data, it is not easy to compare the expected and real behaviour of V_{SW} . In Fig. 5, the expected velocities over several months in 2004 were calculated by Eq. 4 not only for the days corresponding to all criteria of data selection, but virtually for all days when solar magnetic data were available. One can see that such a deliberately roughened model represents adequately the alternation of high- and low-speed solar-wind streams at the Earth.

5.3. Simulation of the IMF longitudinal component

Let us compare the radial component of the interplanetary magnetic field B_{xe} at the Earth with B_s measured τ days earlier (Fig. 6). In doing so, we shall use only the days without gaps in data and all limitations discussed above: no large magnetic storms, SSC absent on the day under examination and three following days, $B_{IMF}<10$ nT, and $N_{SW}<10$ particles $^{-1}\text{cm}^{-3}$.

Fig. 6 illustrates the coupling between B_s and B_{xe} . For 84% of the days, the sign of B_s coincides with the IMF polarity. At large $|B_s|$ values, the polarities coincide almost completely. On the other hand, the situation is far from ideal. The relation between B_s and B_{xe} is obviously nonlinear, and at small $|B_s|$, the polarities are often mixed. One can readily see that the magnetic field intensity close to zero is more frequently observed at the source surface than at the Earth's orbit.

As noted earlier (Obridko et al., 2004), the spherical source surface with strictly radial magnetic field at all points is a mere abstraction. The real magnetic field cannot be radial all over the sphere. It expands below the source surface and, in some regions (e.g., over the coronal holes), above it. In the process, the weak fields are replaced by stronger ones, which do not always conserve the initial polarity. To take it into account, we have introduced the polarity index p_s of the source-surface magnetic field, which is determined as follows: $p_s=1$ or -1 at $B_s>B_u$ or $B_s<-B_u$, respectively, and for the other, intermediate values, $p_s= B_s/B_u$. It turned out that

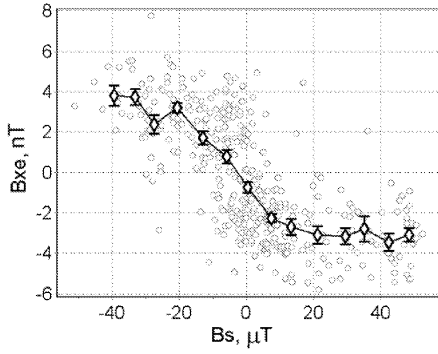


Figure 6. Coupling between the daily mean magnetic field B_S (Earth's projection onto the source surface) and IMF radial component at the Earth.

the median value of the modulus of B_S could be successfully used as the critical value of B_u . For our sample, $B_u = \text{med}(|B_S|) = 9.08 \mu\text{T}$.

In the absence of interplanetary interactions, the radial field B_S at the Earth's orbit must be transformed into the field directed along the helical field line at an angle $\psi = \arctg(\Omega R_E / V_{SW})$ to the radius, where Ω is the solar rotation rate. Let us calculate such an IMF component at the Earth aligned with the expected field line: $B_L = B_{XE} \cos(\psi) + B_{YE} \sin(\psi)$, where B_{XE} and B_{YE} are the field components in the ecliptic plane. The signs in the last expression are taken such that positive B_L corresponds to the direction from the Sun. The linear regression model

$$B_L(t) = (0.44 \pm 0.13) + (3.42 \pm 0.35)p_S(t-\tau) + (0.039 \pm 0.012)B_S(t-\tau) - (0.00030 \pm 0.00011)B_P(t-\tau), \quad (6)$$

makes it possible to determine the IMF longitudinal component with the correlation coefficient $\rho = 0.79$ and the mean-square standard deviation $\sigma = 2.4 \text{ nT}$ (Fig. 7).

As seen from Fig. 8 plotted for several months of 2004, our model describes the sector structure and other features of the IMF behaviour fairly well. Because of gaps in the data, we have plotted Fig. 8, as before, applying the model based on strictly selected data for the entire period (1976-2004) to all data available in a limited time interval. However, the model, though deliberately degraded, works and yields useful results. An additional analysis shows that the discrepancy between the model and experiment is most significant in

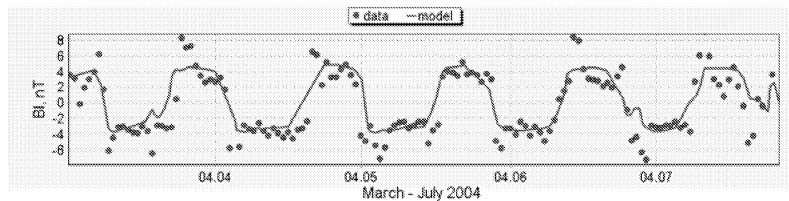


Figure 8. Behaviour of the experimental and calculated daily mean values of the IMF longitudinal component at the Earth during March-July 2004.

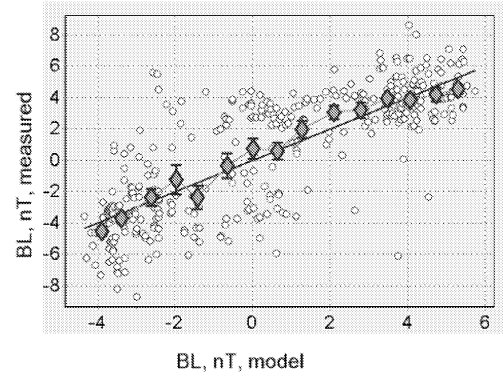


Figure 7. Correlation between the experimental and calculated daily mean values of the IMF longitudinal component at the Earth.

the periods of interplanetary disturbances associated with sporadic events in the Sun.

Using $|B_S|$ (with a small contribution of $|B_P|$), we obtain a model for the IMF absolute value:

$$B(t) = (5.06 \pm 0.14) + (0.0428 \pm 0.0056)|B_S|(t-\tau) + (0.00010 \pm 0.00007)|B_P|(t-\tau), \quad (7)$$

which agrees with observations with a mean-square deviation $\sigma = 1.5 \text{ nT}$.

5.4. Simulation of the Ap-index of geomagnetic activity

We have seen that the source-surface magnetic field B_S can be used to estimate the absolute value and various components of the interplanetary magnetic field and the solar-wind velocity at the Earth's orbit, i.e., almost all main geoeffective parameters of the solar wind.

Preliminary calculations show also a good agreement with the Akasofu index (1980) with a correlation coefficient as high as 0.81. Thus, we combine the parameters determining V_{SW} , B , and B_{zm} in a single linear regression model for A_p .

$$A_p = (7.1 \pm 0.6) + (22.0 \pm 3.5)W_S + (0.15 \pm 0.03)|B_S| - (0.19 \pm 0.03)B_S \sin(2\pi/T) + (0.05 \pm 0.03)B_S \cos(2\pi/T), \quad (10)$$

The A_p values obtained with such a model correlate with the observed A_p -indices with the coefficient $\rho = 0.52$ (Fig. 9).

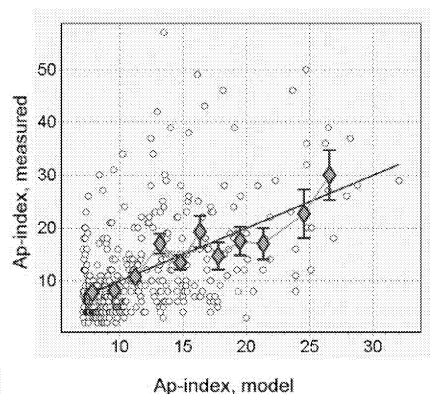


Figure 9. Correlation between the experimental and calculated daily mean A_p -indices of geomagnetic activity.

This correlation must be considered satisfactory. The fact is that Eq. 7 allows a forecast of the A_p -index, on the average, for 4 days. At present, none of the prognostic centers can ensure a reliable forecast of geomagnetic activity for such a long period. Thus, for example, the three-day forecasts of the daily mean A_p -index issued by NOAA/SEC and the Australian Prognostic Agency (IPS) for 1999-2004 were justified with a correlation coefficient of 0.26-0.28 (Oraevsky et al., 2002, Belov et al., 2005). It means that the available prediction methods give half as good agreement with observations as the model under discussion.

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