Magnetic Pulsations as a Probe of the Interplanetary Magnetic Field: A Test of the Borok B Index

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A magnetic pulsation index based on the periods of Pc 2-4 pulsations as recorded in earth current measurements at the Borok Geophysical Observatory has been claimed to be a measure of the interplanetary field. Tests of this index for the period 1972 to June 1974 show only a 27% success rate. However, a simple recalibration of the index improves the success rate to 51%. The success of the index indicates that the source of many terrestrial magnetic pulsations is external to the magnetosphere.

INTRODUCTION

Magnetic pulsations observed in ground records may have sources internal to the magnetosphere (endogenic) or external to the magnetosphere transmitted through the magnetopause (exogenic). There are many possible endogenic sources. The most popular sources involve instabilities associated with resonances with the cyclotron, bounce, and drift motion of energetic particles in the magnetosphere together with particle distribution functions which have certain anisotropies which lead to wave growth. Free energy for wave growth may also be supplied in pressure gradients and velocity shears. Further, rapid changes in the configuration of the magnetosphere can cause field line resonances to be excited or ring. For details of these mechanisms the interested reader is referred to the recent reviews by Hasegawa [1971, 1974], Southwood [1974], Fredricks [1975a, b], and Gendrin [1975]. In short, there is no dearth of possible endogenic sources.

On the other hand, there are only two candidate exogenic sources: the Kelvin-Helmholtz instability excited by the flow of the magnetosheath plasma along the flanks of the magnetosphere [cf. Southwood, 1968] and the bow shock associated wave phenomena [Greenstadt, 1976], the most extensively studied being the upstream wave phenomena associated with particles reflected and/or accelerated by the bow shock [Fairfield, 1969; Russell et al., 1971]. The former mechanism excites surface waves on the magnetopause which can couple into different modes in the interior of the magnetosphere [cf. Chen and Hasegawa, 1974]; the latter waves must be convected and propagate through the magnetosheath and impact the magnetopause before they can couple into resonant modes interior to the magnetospheric cavity.

Although waves may propagate in the magnetosphere over a wide range of frequencies, we expect to see the largest wave amplitudes when the wave frequency matches a field line resonance, i.e., when a standing wave along the field is produced. Since the resonant frequency is a function of position [cf. Cummings et al., 1969], a given frequency will excite field lines only over a narrow range of L values. Conversely, in the 10- to 300-s range there is little difficulty in exciting a field line resonance somewhere. The signature of such resonances on the ground should be a narrow banded signal, as Pc 2-4 pulsations usually are, and the amplitude should be a function of latitude, peaking under the resonant field line. If there are multiple sources, each exciting a different field line, we would expect to detect each of these resonant frequencies at a ground station, but the observed amplitude of each of these should be a function of the distance of both the site from the resonant field line and the strength of the source.

The costs of installing and maintaining a ground magnetometer site are small in comparison to the cost of obtaining in situ magnetospheric and extramagnetospheric data. Thus it is of considerable interest to be able to monitor the properties of magnetic pulsations in an attempt to infer the properties of their sources. However, in view of the multiplicity of possible sources and the different factors affecting the observed wave amplitudes, this task is difficult.

Since exogenic sources are possible and since solar wind parameters are easier to monitor than magnetospheric parameters, which vary rapidly with position and time, it is natural that some of the earliest correlatative studies were with solar wind parameters. In particular, the period of Pc 2-4 pulsations was compared with the solar wind velocity [Troitskaya and Gul'yel'mi, 1967; Gul'yel'mi et al., 1973], the plasma density [Gringauz et al., 1971], and the interplanetary field strength [Troitskaya et al., 1971; Gul'yel'mi and Bol'shakova, 1973; Gul'yel'mi et al., 1973]. In view of the complexities described above it is somewhat surprising that any correlation was observed at all. However, not only were there correlations between the wave periods and the solar wind conditions, but also some of these correlations were quite large. For example, the correlation coefficient between the log of the average interplanetary field strength and the log of the pulsation period in the Pc 2-4 range was found to be 84% [Gul'yel'mi et al., 1973]. Furthermore, the amplitude of the waves was found to be controlled by the direction of the interplanetary magnetic field. Initially, it was believed that these waves were generated when the interplanetary field lay along the Parker spiral [Bol'shakova and Troitskaya, 1968], and it was suggested that the field direction modulated the stability of the Kelvin-Helmholtz instability. However, later work revealed that the angular dependence of the wave occurrence on the interplanetary field direction was similar to the dependence of the occurrence of upstream waves on the direction of the interplanetary field [Plyasova-Bakunina, 1972]. Further, simultaneous measurements of upstream waves and ground pulsations revealed similar periods. In short, these studies indicate that upstream waves are, in fact, the source of at least a large fraction of the observed Pc 2-4 magnetic pulsations.

Perhaps owing to the brevity of the above-mentioned reports and the limited data sets used these results have not gained wide acceptance outside the Soviet Union. On the other
Fig. 1. (Top) Percent occurrence of Borok $B$ indices and (bottom) the interplanetary field strength in the nominal intervals of the $B$ index. Data used are the 3232 hourly averages of simultaneous interplanetary field data, as given on the National Space Science Data Center tape, and Borok $B$ indices during the period January 1972 to June 1974.

Fig. 3. Dependence of interplanetary field strength on the Borok $B$ index. Inner bars give probable error of mean; outer bars give standard deviation.

derived from the period of Pc 2–4 pulsations observed in earth current measurements at the Borok Geophysical Observatory (58°02'N latitude, 38°58'E longitude).

The Borok $B$ Index

The Borok $B$ index consists of five levels (one through five) which represent field strengths of $<2.5$, 2.5–4, 4–6, 6–8, and $>8$ $\gamma$ [Gul'iev and Bol'shakova, 1973]. The procedure for measuring pulsation periods or choosing between multiple

Fig. 2. Annual and diurnal variation of average interplanetary field strength and Borok $B$ index. Only simultaneous data were used.

Fig. 4. Histograms of the occurrence rate of interplanetary field strengths for the nominal bins of the Borok $B$ index for each index value separately.
signals is not given. The index is published once an hour for the 6 hours 0600–1200 UT (± 3 hours of local noon) beginning in 1972 in the publication 'Kosmichesky Danny' (cosmic data) and may be obtained from the World Data Center A for Solar-Terrestrial Physics. Prior to 1975, no formula was given for deriving the index. Beginning in 1975 the index apparently changed. The index was retitled 'intensity of interplanetary magnetic field' from 'B micropulsion index,' and the following formula was given: \( B = 0.7 + 0.15F + 0.16Kp \), where \( B \) is in gammas, \( F \) is the hourly mean frequency of pulsations in millihertz, and \( Kp \) is the familiar 3-hour geomagnetic index. However, we do not use any 1975 data in this report because the requisite interplanetary data are not yet available.

**Testing the Index**

The means of testing the index is to compare the \( B \) index predictions with the simultaneously measured interplanetary magnetic field. To do this, we will use the 3323 hourly averages of the strength of the magnetic field for the period 1972 to June 1974 compiled by King [1975] for which an index value was published and a field value available. We will examine the average properties of the index first, then test the rate of success of the index, and finally propose an improved index based on the existing \( B \) index.

**Properties of the \( B \) Index**

Figure 1 shows the distribution of \( B \) indices and the distribution of interplanetary magnetic field values sorted into the nominal bins of the index. They are quite different. Although they have the same general shape, the interplanetary field has a sharp peak from 4 to 6 \( \gamma \) (corresponding to a \( B \) index of 3) and almost no occurrences of values below 2.5 \( \gamma \), whereas the \( B \) index has a peak at a value of 2 and an occurrence rate of 22% for its lowest interval.

Figure 2 shows the annual and diurnal variation of the interplanetary field and the \( B \) index, again chosen only for simultaneous occurrences. As would be expected, there is no obvious diurnal or annual variation in the interplanetary field strength. Similarly, the \( B \) index seems little affected by seasonal or diurnal effects. Thus while Figure 1 suggests that the index is not very successful in reproducing the interplanetary magnetic field, the index may still be dominantly controlled by the interplanetary field as claimed.

**Comparison With the Interplanetary Field**

Figure 3 shows a plot of the average field strength for each level of the \( B \) index, and the dominant control by the interplanetary field is clearly evident. The outer bars give the standard deviations and the inner bars the probable error in the mean about each of these averages. The relationship is not linear, however, and there is a great deal of overlap between adjacent standard deviations, especially for indices 2 and 3.

Figure 4 shows the distribution of the field values for each one of the indices both as number of occurrences and as percent occurrence. We see that each of the first three indices has a peak occurrence for 4–6 \( \gamma \) rather than for its nominal value. Furthermore, the distributions for \( B = 2 \) and 3 are nearly indistinguishable.

If we count occurrences of field strengths equal to the nominal field strength for a bin as successes and all other occurrences as failures, Figure 4 contains 875 successful predictions for a 27% success rate. However, if the group of interplanetary field strengths corresponding to each \( B \) index value simply reproduced the overall field distribution, i.e., if every histogram on the right of Figure 4 were the same as that at the bottom of Figure 1, there would be no correlation at all, but we would obtain a success rate of 20%. This rate is three fourths of our actual success rate, and so we must conclude that despite the clear control of the index exhibited in Figures 3 and 4, the present index is not much better than random. Furthermore, a better strategy would be simply to ignore the micropulsion data entirely and pick an index of 3 for all time because the observed field strength is between 4 and 6 \( \gamma \) 42% of the time.

Clearly, a better index can be devised than was published. Part of the low success rate is due to the spread in the data. In particular, the distributions for \( B = 2 \) and 3 are very similar. However, it is obvious from Figure 3, in particular, that the index has been miscalibrated. If the calibration were correct, the best fit straight line should pass close to the origin.

**Recalibration of the Index**

Figure 5 repeats the distributions of Figure 4 using a finer bin size (1 \( \gamma \)). Again the control of the index by the interplanetary field is evident, as is the miscalibration. For \( B = 1 \) the occurrence rate peaks from 3 to 5 \( \gamma \); for \( B = 2 \) and 3 the peak is around 5 \( \gamma \); for \( B = 4 \) it is close to 7 \( \gamma \); and for \( B = 5 \) there is no clear peak and a long tail on the distribution. To recalibrate the index, we wish to maximize the area under each histogram that falls in the proper bin. As an aid in this recalibration, Figure 6 shows the cumulative distributions for \( B = 1, 2, 3, 4, \) and 5 corresponding to the distributions in Figure 5. We have combined \( B = 2 \) and 3 into one curve because these indices exhibit much overlap.

The rules for the recalibration are as follows: we wish to equalize as much as possible the probability of any index being correct, while achieving the maximum success rate. We also

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**Figure 5.** Histograms of the occurrence rate of interplanetary field strength for 1-\( \gamma \) bins.
wish to retain as many levels in the index, i.e., resolution, as reasonable, and we wish the index to be bounded at 1- or 1-γ levels, not some arbitrary number.

If we choose \( B = 1 \) to represent fields less than 4.5 \( γ \) and \( B = 5 \) to represent fields greater than 9 \( γ \), we obtain roughly a 50% success rate in each case. This leaves one interindex boundary to choose. Choosing 6.5 \( γ \) as this boundary also results in roughly a 50% success rate for \( B = 2/3 \) and \( B = 4 \). Table 1 gives the occurrence matrix for the recalibrated index. The success rate for this index is 51% compared to the random rate of 34% obtained in the previous section by using the observed distribution of interplanetary field strengths and the given distribution of the index. We note that the strategy of ignoring the micropulsation data entirely and always predicting a field strength of 4.5-6.5 \( γ \) has a success rate of 42% and is now less desirable than using the micropulsation data.

**Discussion**

The Borok \( B \) index is a very important index despite its apparent success rate of only 27%, or one third better than random, over the 23-year test period. First, it attests what no other geomagnetic index presently attempts, i.e., to make a quantitative assessment of an extraterrestrial parameter, and it does so with some success. The only other geomagnetic index which approaches this goal is the A/C or A/T index [Stvalgaard, 1972; Wilcox et al., 1975; Russell et al., 1975a], which is only a qualitative (i.e., polarity) indicator of the interplanetary field, albeit more accurate.

Second, the index can be recalibrated without recourse to the original data to provide a four-level index which is accurate 51% of the time compared to a random rate of 34% and a best strategy in the absence of pulsation data of 42%. This success rate could improve forecasts of geomagnetic activity.

**Table 1.** Occurrence Rate of Interplanetary Field Strengths: Recalibrated Bins

<table>
<thead>
<tr>
<th>( B ) Index</th>
<th>Occurrences</th>
<th>(&lt;4.5\gamma)</th>
<th>(4.5-6.5\gamma)</th>
<th>(6.5-9\gamma)</th>
<th>(&gt;9\gamma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>707</td>
<td>376</td>
<td>220</td>
<td>75</td>
<td>36</td>
</tr>
<tr>
<td>2/3</td>
<td>1865</td>
<td>377</td>
<td>991</td>
<td>378</td>
<td>119</td>
</tr>
<tr>
<td>4</td>
<td>423</td>
<td>34</td>
<td>121</td>
<td>182</td>
<td>86</td>
</tr>
<tr>
<td>5</td>
<td>237</td>
<td>10</td>
<td>42</td>
<td>72</td>
<td>113</td>
</tr>
</tbody>
</table>

**Table 2.** Occurrence Rate of Interplanetary Field Strengths: Random Occurrences

<table>
<thead>
<tr>
<th>( B ) Index</th>
<th>Occurrences</th>
<th>(&lt;4.5\gamma)</th>
<th>(4.5-6.5\gamma)</th>
<th>(6.5-9\gamma)</th>
<th>(&gt;9\gamma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>707</td>
<td>175</td>
<td>300</td>
<td>155</td>
<td>78</td>
</tr>
<tr>
<td>2/3</td>
<td>1865</td>
<td>461</td>
<td>793</td>
<td>408</td>
<td>205</td>
</tr>
<tr>
<td>4</td>
<td>423</td>
<td>104</td>
<td>180</td>
<td>93</td>
<td>47</td>
</tr>
<tr>
<td>5</td>
<td>237</td>
<td>59</td>
<td>101</td>
<td>52</td>
<td>26</td>
</tr>
</tbody>
</table>

Since such activity is proportional to both the magnitude and the direction of the interplanetary field [cf. Burton et al., 1975]. If sufficiently long an interval of pulsation data were available for analysis, this index could provide some valuable data on the variation of the strength of the interplanetary field despite its limitations in much the same way that the A/C classification permitted the identification of the 22-year cycle in interplanetary magnetic polarity data despite imperfections in the historical record [Fougere, 1974; Russell et al., 1975b].

Third, the success of the index indicates that the major source of Pc 2-4 pulsations in the 6-hour period centered around local noon is exogenic and that internal magnetospheric sources provide only a minor component, since none of the endogenic sources cited above are controlled by the interplanetary field. This claim may seem quite rash, since a 51% success rate appears to allow 49% of the waves to be generated in the magnetosphere. However, Tables 2 and 3 show this is not so. Table 2 gives the expected occurrence of indices and field strength given that they have their observed distributions but occur independently. Table 3 is the ratio of Tables 1 and 2. It illustrates that the recalibrated \( B \) index is good at picking extreme values. For example, the \( B = 1 \) index is correct 2.15 times random. Also the recalibrated index very seldom has extreme failures. For example, the interplanetary field is less than 4.5 \( γ \) only 17% of the time when \( B = 5 \). Thus any source of pulsations not dependent on the interplanetary field must be small, less than 20% for periods associated with the \( B = 5 \) level (\( \leq 15 \) s) and ranging up to less than 50% for periods associated with the \( B = 1 \) level (\( \geq 70 \) s), where periods have been assigned according to the work of Gul' yel'mi and Bol'shakova [1973]. To further emphasize this point, we note that if we made a bilevel index to determine whether the interplanetary field was greater than or less than 9 \( γ \), it would be correct 89% of the time.

Although the index is an important index and a promising tool for remote probing of the interplanetary magnetic field, it needs further refinement. Part of this refinement could be simply improved techniques of data analysis to define more accurately the period of these pulsations or techniques to separate endogenic from exogenic waves, e.g., by their longitudinal extent. Part of this refinement could be in understanding

**Table 3.** Ratio of Observed to Random Occurrences

<table>
<thead>
<tr>
<th>( B ) Index</th>
<th>Occurrences</th>
<th>(&lt;4.5\gamma)</th>
<th>(4.5-6.5\gamma)</th>
<th>(6.5-9\gamma)</th>
<th>(&gt;9\gamma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>707</td>
<td>2.15</td>
<td>0.73</td>
<td>0.48</td>
<td>0.46</td>
</tr>
<tr>
<td>2/3</td>
<td>1865</td>
<td>0.82</td>
<td>1.25</td>
<td>0.93</td>
<td>0.58</td>
</tr>
<tr>
<td>4</td>
<td>423</td>
<td>0.33</td>
<td>0.67</td>
<td>1.96</td>
<td>1.83</td>
</tr>
<tr>
<td>5</td>
<td>237</td>
<td>0.17</td>
<td>0.42</td>
<td>1.38</td>
<td>4.35</td>
</tr>
</tbody>
</table>
more fully the process of generation of bow shock and up-
stream waves and the dependence of their periods on solar
wind parameters in addition to the dependence on field
strength. Part of this refinement could come from the use of
wave amplitude information, since the wave amplitudes are
apparently controlled by the direction of the interplanetary
field. Perhaps there are times when it is not prudent to predict
the interplanetary field. When such refinements are made, this
index could fully justify its calculation on a worldwide basis to
provide 24-hour-a-day coverage and could be an important
addition to our present techniques for inferring the long-term
behavior of the solar wind from geomagnetic records [cf.
Russell, 1975].

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magnetic field data by J. H. King of the National Space Science Data
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