INTERPLANETARY SCINTILLATION AND SPACE WEATHER MONITORING

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ABSTRACT

Interplanetary scintillation (IPS) is a technique that allows us to remotely sense the plasma number density in the inner heliosphere. Thus, using IPS, we can track density structures propagating out from the Sun and should be able to predict their time of arrival at the Earth. Since these structures carry the enhanced fluxes of momentum and energy that drive geomagnetic activity, IPS measurements are potentially an important space weather activity that can help to predict the onset of geomagnetic activity. However, in practice, IPS has proved disappointing as a means of predicting geomagnetic activity. In this paper, we briefly review results obtained from the Cambridge IPS array during 1990-93 with a focus on those results that are particularly relevant to space weather. We also discuss some of the limitations that have made IPS so disappointing and suggest ways in which these limitations might be overcome in a future IPS system.

INTRODUCTION

The amplitude of a radio signal passing through the inner heliosphere is modulated by the motion of solar-wind plasma irregularities across the line of sight. This modulation, which may be observed with a suitable radio telescope, is termed *interplanetary scintillation.* The scintillation amplitude, ΔS, is proportional to the amplitude of the fluctuations in plasma density, but many workers (e.g. Ref. 2) have suggested that the amplitude of these fluctuations (and hence ΔS) is proportional to the absolute plasma density, N. Thus measurements of ΔS can be used to monitor N.

In this paper we focus on the IPS data that were recorded during 1990-93 by the 81.5 MHz IPS array at Cambridge, UK (Ref. 1). This system made daily measurements of ΔS for a large number of natural radio sources outside the solar system. Each source was measured as it crossed the local meridian plane. In this manner a daily skymap of scintillation could be built up similar to that shown in Figure 1. To detect temporal changes in ΔS (and, by implication, changes in the plasma density) the actual skymap shows $g_I = \Delta S_I/\langle\Delta S_I\rangle$ where ΔS_I is the measured scintillation amplitude for source I and $\langle\Delta S_I\rangle$ is the expected amplitude for that source (based on a long-term average of the measurements).

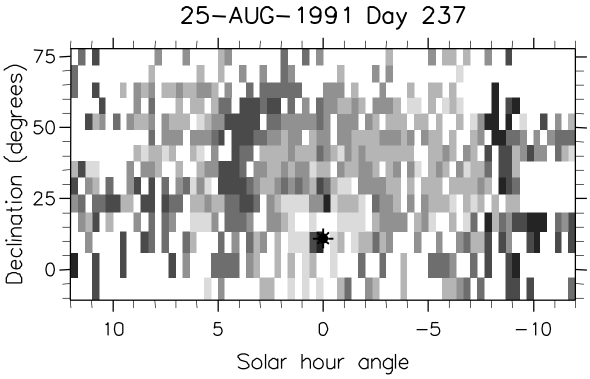

Figure 1. IPS scintillation levels displayed on a grid of declination and solar hour angle. Black indicates high scintillation levels, light grey indicates low scintillation levels and white pixels contain no suitable sources. The IPS event appears as a coherent patch of high scintillation to the left of the Sun (indicated on the zero solar hour angle line).

In the rest of the paper we first discuss the relationship between IPS and geomagnetic activity (as revealed by analysis of the Cambridge IPS data) - and hence the ability of such IPS observations to help in predicting that activity (which is an important aspect of space weather forecasting). We then discuss a number of factors that constrain the use of existing IPS data in space weather forecasting. We suggest ways in which these constraints might be overcome. These suggestions complement those already published by Hewish and Duffett-Smith (Ref. 5) - see their section 3.

Note that, given the limited space available, our aim throughout this paper has been to outline the key issues concerning the use of IPS in space weather activities. Wherever possible, we have not discussed technical detail but, instead, have given references to published papers where these details are discussed.

IPS AND GEOMAGNETIC ACTIVITY

Figure 1 shows a good case where the observation of a coherent patch of enhanced scintillation was followed by enhanced magnetic activity (Ref. 9). This is typical of a number of good cases that can be found in the 1990-93 data and in previous IPS studies. For example, Hewish and Duffett-Smith (Ref. 5), using data from a 14-month period near the peak of Solar Cycle 21, reported that all 16 storms (peak Ap ≥ 40) during that period were preceded (1 to 7 days) by observations of enhanced scintillation. These results, together with the example shown in Figure 1, are suggestive of a relationship between enhanced scintillation and geomagnetic activity. However, much further work is required to determine a substantive relationship such that we can use IPS as a predictor of geomagnetic activity. In particular two issues need attention:

1. Are there observations of enhanced scintillation that are not followed by enhanced geomagnetic activity? That is, IPS events that would yield false alerts of geomagnetic storms. We shall show below that such events are common.
2. Is there a statistically significant correlation between enhanced scintillation and geomagnetic activity?

These issues have been considered in a number of papers. For example, Lucek and Clark (Ref. 7) manually examined a series of 1235 daily skymaps taken by the Cambridge array. They used each skymap, together with maps recorded on previous days, to predict geomagnetic activity on that day or the two following days. These forecasts were considered successful if either (a) a sudden storm commencement or a sudden impulse, or (b) geomagnetic activity with Ap ≥ 30, were observed during the period covered by the prediction. Even with these broad criteria for success they found that there was a very high rate of false alarms, which occurred about twice as frequently as real events. Given this high level of false alarms, they concluded that IPS data cannot be used alone to produce reliable forecasts of geomagnetic activity. Lucek and Clark also noted that the temporal and spatial resolution of the data was insufficient to allow estimation of the speed and direction of features seen in skymaps. This may account for a substantial number of the false alarms.

Another approach to these issues is to find a more quantitative method of analysing sky maps. Several workers have devised IPS indices that are sensitive to systematic changes in skymaps. One such index is the I_{35} index devised by Harrison et al. (Ref. 4), which is calculated for selected portions of a skymap, e.g. all sources in a given elongation range from the Sun. The I_{35} index ranges from -1 to +1; positive values indicate a systematic enhancement of scintillation while negative values indicate a corresponding reduction. Harrison et al used this index to show that the correlation between IPS and the geomagnetic activity index Ap takes the form of a triangular distribution (see example in Figure 2 below). For any value of I_{35}, Ap can take any value between zero and some maximum, where that maximum increases with increasing I_{35}.

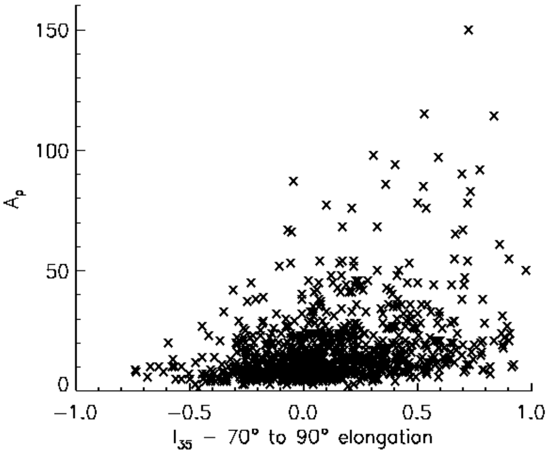

Figure 2. Scatter plot of Ap against I35 measured one day ahead.

Hapgood and Harrison (Ref. 3) investigated this triangular distribution in detail. They showed that (a) I_{35} is well-correlated with the plasma number density measured in the near-Earth solar wind - with the peak correlation occurring when the density is measured on the same day as I_{35}, (b) that the correlation between Ap and I_{35}, as shown in Figure 2, is best when Ap is measured on the day after I_{35} was measured, and (c) the scatter of Ap values within the triangular distribution shows a trend such that higher Ap values are associated with a more southward interplanetary magnetic field. They concluded that the triangular distribution was the result of two factors:

1. The momentum and energy flux in the solar wind, which sets the maximum possible level of geomagnetic activity. This is largely determined by the density of solar wind, which is correlated with I_{35}. The upper envelope of the triangular distribution reflects this correlation.
2. The coupling between the solar wind and the magnetosphere. This is determined by factors, such as the orientation of the interplanetary magnetic field (IMF), which are not correlated with I_{35}. The scatter within the triangular distribution reflects this lack of correlation.

They concluded that IPS can contribute to predictions of geomagnetic activity by providing an estimate of the maximum potential activity. However, other independent sources of information are required to determine how much of this potential is realised.

A broader study of the correlation between IPS indices and geomagnetic activity has been undertaken by Lucek and Clark (Ref. 8). They started with the I_{35} index, as defined by Harrison et al (Ref. 4), and developed several modified versions to try to increase the correlation between Ap and the IPS index. They found that some of these modified indices gave small but statistically significant improvements in the correlation. They emphasised the importance of comparing Ap with the IPS index measured one or more days earlier - in order to provide a basis for predicting Ap. However, in this case the maximum correlation coefficient between Ap and the IPS index was about 0.45. This left 80% of the variance in Ap unexplained by the correlation. Thus they concluded that the measured correlation was well below the value that would allow IPS data to act as a reliable predictor for geomagnetic activity.

LIMITATIONS OF THE IPS TECHNIQUE

Our experience of using the IPS data has allowed us to identify a number of factors that can limit the use of these data to predict geomagnetic activity:

Density structures that miss the Earth. The IPS technique is best suited to detecting density structures at some elongation from the direction of the Sun. (The elongation depends on the frequency of the telescope used to collect IPS data. For the Cambridge array it is elongations of 30° to 110°.) Thus IPS detects structures that are propagating at an angle to the Earth-Sun line. However, these structures are thought to have angular extents of order 45° as seen from the Sun. Thus many, but not all, structures detected by IPS will intercept the Earth. However, we should expect that a significant fraction of the density structures detected by IPS will miss the Earth. Thus this factor leads to a class of IPS events that will not be associated with enhanced geomagnetic activity. However, it is possible that further analysis of skymaps may help us to estimate which density structures will intercept the Earth. This is an important topic for future IPS studies. In particular, it would be interesting to compare IPS observations of density structures with spacecraft observations of coronal mass ejections (CMEs) - such as those made by the LASCO instrument on SOHO. Unfortunately, as yet, there is little or no overlap between IPS datasets and spacecraft observations of CMEs.

IMF orientation. It is very well known that this factor, in particular the IMF north-south component B_z, controls the flow of energy and momentum from the solar wind into the magnetosphere. Thus only density structures associated with southward IMF will be effective in generating geomagnetic activity. Since IPS detects density structures but has no correlation with B_z (Ref. 3), we may expect that a significant fraction of IPS events will not be associated with enhanced geomagnetic activity. In any prediction scheme based on IPS data, the IMF orientation is an additional independent factor that must be taken into account.

Ionospheric scintillation. The motion of plasma irregularities in the Earth's ionosphere is also a source of scintillation in natural radio signals. This ionospheric scintillation is an additional signal that can confuse our interpretation of IPS results. Unfortunately, ionospheric scintillation can be triggered by enhanced geomagnetic activity - and therefore is likely to occur in conjunction with the IPS events that could help to predict enhanced geomagnetic activity. Several papers have reported apparent enhancements of IPS that may actually be ionospheric scintillation. For example, Lucek and Clark (Ref. 8) found that the highest correlation between scintillation levels and Ap occurred between IPS data in the 90° to 110° elongation band and the Ap value recorded the same day (rather than the IPS index being measured one day before Ap). They attributed this marked increase to the effects of ionospheric scintillation. Lucek and Rodger (Ref. 6) made a more detailed study of the effect of ionospheric scintillation. They used data from the ionosonde at Slough, 90 km south-west of Cambridge, to identify days when there were plasma irregularities in the ionosphere. By excluding such days they were able to obtain a significant increase in the correlation between Ap and IPS indices measured one day before Ap. They concluded that contamination by ionospheric scintillation is a major problem in the interpretation of IPS data. However, there could be methods to monitor and reduce the impact of ionospheric scintillation on IPS. Their development is an important issue for the future development of IPS as a practical tool for space weather activities.

Seasonal effects. As noted above, IPS detects density structures when they lie at an angle to the Earth-Sun line, i.e. within a cone of solid angle centred on the Sun. However, only a fraction of that solid angle is viewable from a particular site on a particular day. This fraction exhibits marked seasonal variations. This is illustrated in the table below that shows the solid angle, between 30° and 90° from the Sun, which, in principle, could be viewed from Cambridge (52° N) in different seasons. We also show this as a fraction of the total solid angle in that cone (5.4 steradians). These figures assume that IPS can be measured down to a minimum elevation of 5° above the local horizon.

Season	Solid angle - steradians	Fraction
Summer	4.7	86%
Equinox	4.0	74%
Winter	3.6	66%

These figures show that, even for an optimum system, there are significant variations in the solid angle (and hence the volume of the heliosphere) sampled each day. As one would expect, this sampling is worse in winter. At a technical level the solution to this sampling problem would be straightforward. We would simply require an additional IPS array in the southern hemisphere, so that the seasonal variations at the two sites will cancel out. Of course, the implementation of this solution poses significant financial and operational problems.

Non-optimum sampling The Cambridge IPS array was operated as part of a radio astronomy observatory and thus, quite reasonably, was optimised for astronomical applications. In particular, the array sampled radio sources only over a limited range of declination (-8° to + 75°) and only when those declinations were south of the celestial pole. This further reduced the solid angle that was viewed as shown in the table below (using the same format as the table above).

Season	Solid angle - steradians	Fraction
Summer	3.3	61%
Equinox	2.9	53%
Winter	2.6	48%

In winter the Cambridge IPS array sampled less than half of the solid angle in which we may expect to IPS events. Thus there is a considerable possibility that many IPS events were not observed by the array.

SUMMARY

If a future IPS system were built specifically for space weather applications, it would be important to optimise its design for that application. For example:

1. Use of several arrays giving: improved coverage of inner heliosphere, reduced seasonal variations in that coverage, better time resolution, cross-comparison to identify sources of interference and improve statistics.
2. Sampling over a greater range of declination to improve coverage. However, sampling at lower elevations may bring the risk of increased interference from man-made sources. This might be less of an issue if future IPS observations were made at remote locations with low levels of man-made radio noise.
3. Observations on several different meridians by each array giving better time resolution.
4. Observations over a range of frequencies giving: observations over a wider range of elongations, overlap between elongation ranges at different frequencies to help identify interference, use of higher frequencies less susceptible to ionospheric interference.

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