RADIO SCINTILLATION OBSERVATIONS OF THE SOLAR WIND - RECENT RESULTS FROM EISCAT AND PROPOSALS FOR A NEW-GENERATION SYSTEM

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ABSTRACT

Measurements of radio scintillation which use the motion of ~100 km scale size density irregularities as flow tracers for solar wind speed (the technique of *Interplanetary Scintillation* or *IPS*) have been used to study the solar wind for many years. Recently improvements to analysis methods have transformed the capabilities of this technique and it has emerged as a powerful tool for probing regions of the solar wind which are hard to study by other means - particularly the region from ~25 solar radii (R) out to ~100 R. As this is the region in which interaction between streams of solar wind and between mass ejections and the background wind determine the solar wind structure seen at Earth orbit good measurements of this region are of great importance. We present some recent results and show that these measurements can be used to trace the evolution of solar wind structures.

Over the next 10-15 years a new generation of space-based instruments will deploy to study the corona and solar wind, including STEREO and Solar Orbiter. We have identified a need for an instrument capable of producing scintillation-level and velocity maps of the solar wind from ~40 R to ~180 R with good spatial and temporal resolution to complement these missions. Such an instrument would be invaluable for placing in-situ measurements in their large-scale context, and would also be very suitable for monitoring space weather. We discuss the requirements for such a system and present a possible design.

1. INTERPLANETARY SCINTILLATION (IPS)

If a distant, compact radio source is observed when it lies close to the Sun in the sky then density irregularities in the solar wind will introduce phase changes in the radio waves from the source. As the waves continue towards the antennas these phase variations are progressively converted to fluctuations in amplitude by the normal processes of interference [1]. As the density irregularities are moving outwards in the solar wind the effect is to cast a drifting diffraction pattern across the antennas, and the rate of drift of this pattern can be used to determine the solar wind outflow speed.

Velocities can be estimated in two ways - either from the spectral shape measured by a single antenna [2, 3] or – with greater accuracy, from the form of the cross-spectra of the scintillation patterns measured at two widely-separated sites at a time when the raypaths from source to antennas lie in a plane radial to the Sun [4, 5]. Single antenna systems can make many more observations but velocities derived from multi-site systems allow more accurate estimates of velocity [6].

IPS measurements contain contributions from the whole of the extended ray-path through the solar atmosphere from the distant source to the receiving antenna(s). In earlier studies the inability to distinguish between contributions from different regions of the solar wind led to a "blurred" view of solar wind structure. Significant technical advances in the last 10 years have significantly reduced this problem.

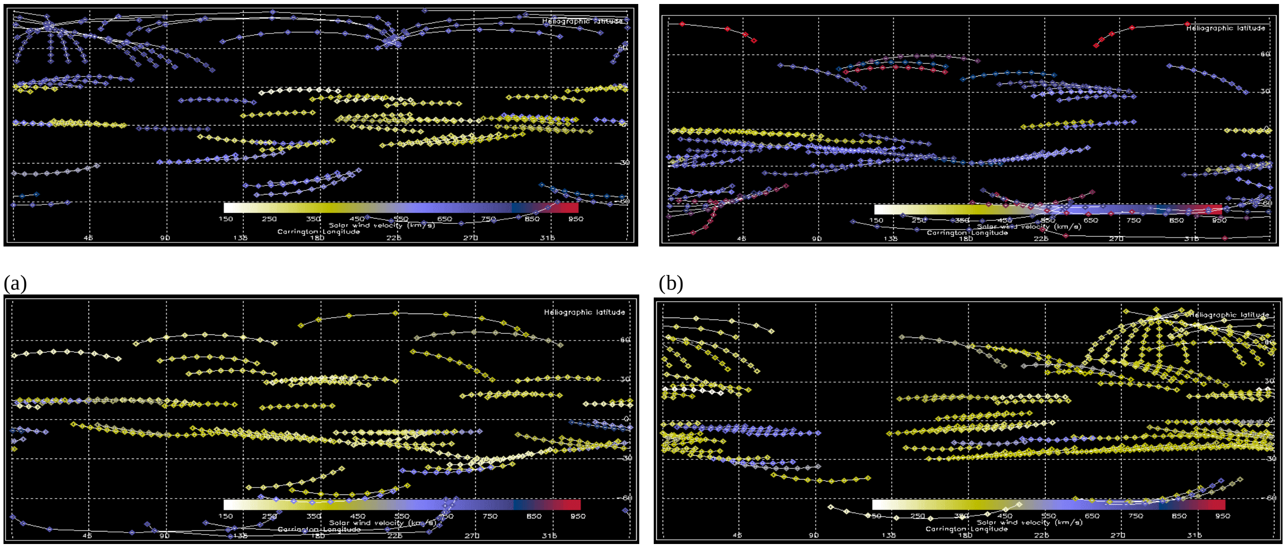
1.1 Long-baseline 2-site IPS

The accuracy to which the outflow speed can be determined improves as the baseline between the sites increases, as does the ability to resolve fast and slow streams when both are present in the scattering region. By fitting the observed auto- and cross-spectra with a bi-velocity 2D weak scattering model it is possible to determine the velocities of separate streams of solar wind with good accuracy [7, 8]. Comparison of IPS results with coronal data and in-situ measurements of solar wind speed confirmed a clear association between fast flow seen by IPS and in-situ instruments and outflow from coronal holes, allowing coronal white-light maps to be used to determine which regions of IPS ray-paths are immersed in fast and which in slow flow [8]. The method is robust and allows regions of different solar wind speed to be identified from single observations lasting 15-30 minutes.

At present the EISCAT facility is the only system to make large numbers (typically 5-8 measurements/day over two months each year) of long-baseline measurements on a regular basis, although other systems such as the VLBA normally make a smaller number of observations each year.

1.2 Heliospheric tomography using IPS

An alternative approach is to make large numbers of overlapping IPS measurements use tomographic reconstruction codes to recover the details of solar wind structure from measurements taken over a solar



(a) (b)

(c) (d)

Figure 1.

IPS velocities from EISCAT observations made in (a) 1996, (b) 1998, (c) 1999 and (d) 2000 projected ballistically to a reference surface at 215 solar radii (1 AU) and plotted against heliographic latitude and Carrington longitude. Observations from 1999 indicate that the northern polar fast stream was either undetectably small or absent but a large southern polar fast stream was still present. This southern stream had either contracted or vanished by 2000.

rotation [9, 10]. This method works very well at solar minimum but can encounter difficulties towards solar maximum when the distribution of fast and slow streams can change dramatically over the course of a solar rotation. Fully time-dependent tomographic codes have been developed in recent years to address these difficulties and these have proved capable of recovering details of dramatic events, but they do require a large number of observations for best results.

2. RECENT RESULTS OF EISCAT IPS

At solar minimum (from 1992 to mid-1998 during cycles 22 and 23) EISCAT and Toyokawa IPS measurements showed a solar wind dominated by fast flow above the polar regions and slow flow above the narrow, bright streamer belt seen in white light data. Co-rotating interaction regions were found above equatorial extensions of coronal holes and were clearly detectable in observations as close to the Sun as 40 solar radii. As solar activity increased over 1998 the streamer belt became wider and more convoluted, and by 1999 the northern polar fast stream was no longer detectable. The southern polar fast stream remained detectable into 2000, suggesting that there may be an asymmetry between the northern and southern hemispheres of the Sun (consistent with results from the Toyokawa IPS system and with magnetic field measurements from Ulysses, recently reported by Kojima in 2000 and Forsyth in 2001 respectively). The change in solar wind velocity distribution seen at high latitudes in 1998-99 was very rapid, with a sharp change to a slow-wind dominated heliosphere. The change from a solar minimum to a solar maximum wind was much more abrupt than the change from maximum to minimum-type wind in the declining phase of cycle 22.

Intensive programmes of measurements from the LASCO instruments on SoHO, from EISCAT and from the Wind and Ulysses spacecraft during the second Ulysses orbit have revealed significant changes in the longitudinal structure of the solar wind between 25-60 solar radii (IPS measurements) and the orbits of the spacecraft (at 1 AU and 1.25-4.5 AU respectively). Velocities measured by IPS were generally consistent with those seen in-situ, except in cases when large longitudinal gradients in solar wind speed were seen in the in-situ data - in these cases the IPS results suggested that solar wind velocities varied much more near the Sun than they did at the spacecraft. The degree of "self-smoothing" in solar wind velocity increased with distance from the Sun, so that velocities seen at 4.5 AU (960 solar radii) by Ulysses were much more uniform than those seen by Wind at 1 AU (215 solar radii), which were in turn less variable than those seen at 25-65 solar radii by EISCAT [11]. We propose that the underlying mechanism is stream-stream interaction between narrow regions of solar wind with different velocities and suggest that this is important in converting the highly non-uniform slow wind seen in the corona to the more uniform with at 1 AU.

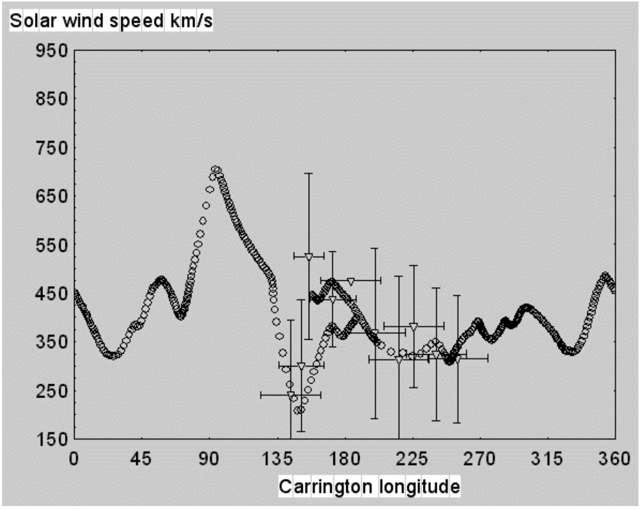


Figure 2.

Ulysses in-situ speed measurements (circles) and EISCAT IPS speeds (triangles) from within ±10º of the latitude of Ulysses during its fast equatorial scan in Carrington rotation 1976 (May 2001), mapped to a uniform heliocentric distance of 30 R. The large vertical bars in the EISCAT data points represent an upper bound on the variation in solar wind speed across the width of the stream observed and are not estimates of statistical error.

The evolution and propagation of coronal mass ejections (CMEs) has been studied using a combination of ultra-violet and white-light measurements from the EIT and LASCO instruments on the SoHO spacecraft and EISCAT IPS measurements. The results of this study demonstrate that it is possible to identify common features in LASCO white-light data and IPS observations and trace the evolution of the velocity of the event out into interplanetary space. The case studies carried out to date suggest that most CMEs tend towards the background solar wind velocity within 30-50 solar radii of the Sun and that interaction between different regions of CMEs may be an important mechanism in their evolution.

3. FHIRN: A NEW-GENERATION IPS SYSTEM

3.1 Scientific requirements

A system is required which will provide information on the large-scale structure of the solar wind, and particularly on the interaction regions between streams of fast and slow solar wind and between coronal mass ejections and the background solar wind. A large number of observations/day are required for this. The heliospheric white-light imagers on SMEI and STEREO will provide density information over a large region of the inner heliosphere, but the greater sensitivity of IPS measurements to variations in electron density, together with the ability to measure velocity, can provide an overlapping dataset which would be the ideal complement to the white-light data.

The main scientific aims that a next-generation IPS facility could address are therefore:

- To provide context for high-resolution IPS (EISCAT, MERLIN, VLBA) and in-situ measurements, by revealing the large-scale structure of the solar wind at intermediate distances from the Sun. The results would be especially valuable in providing context for Solar Probe measurements.
- In conjunction with SMEI/STEREO white-light data, to provide information for 3D tomographic reconstruction of the solar wind
- To provide density and velocity information for solar wind and space weather modelling.

The system would also provide information suitable for operational space weather monitoring.

3.2 Observational requirements

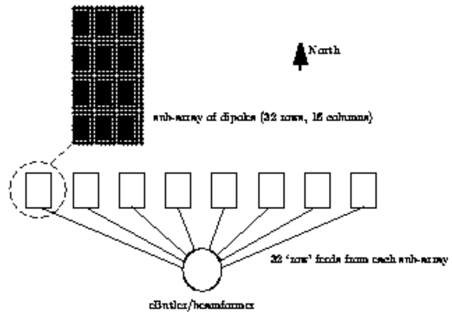
In order to meet these scientific aims, a next-generation IPS system would need to be able to:

- Observe enough sources to create daily maps of solar wind 'G-value' (density proxy) and velocity
- Observe enough sources to detect transient events on a daily basis
- Make more than 100 15-minute source-observations 3 times a day - 300 daily observations
- Observe a significant sub-set of observations with 2 sites, to provide cross-spectrum velocity measurements which can be used to cross-check and confirm the single-site velocity estimates
- Make ~20-30 15-minute sources-observations/day with two sites

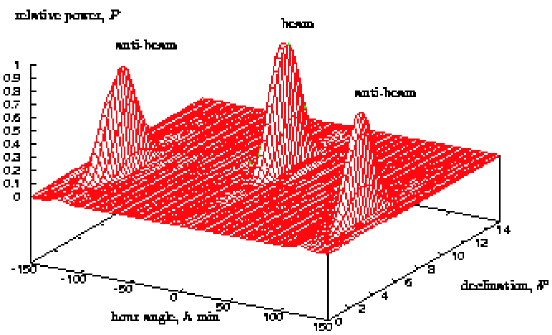
In addition, the system must be affordable to build and to run. The first militates against the use 2-D phase-steered arrays, while the second rules out mechanically-steered antennas.

The instrument should be capable of unattended operation, automatically selecting sources to be observed, taking the data and performing routine analysis. The daily output of the system should therefore be maps of scintillation level ("g"-maps) and velocity ("v"-maps) [2, 3]. Monthly output could include synoptic maps generated using a tomographic approach [9, 10] or full 3-D tomographic reconstructions similar to those performed by B.V. Jackson using Toyokawa data. Raw data would be stored to allow more detailed analysis later, but automating routine analysis would allow the system to function as a resource for the space physics and space weather communities, without requiring a great deal of effort and time. The intention is to avoid data overload.

The single-site measurements would be analysed using the method developed by Woan [3], while the velocities would be determined from the two-site measurements using the UCSD analysis method, as used for EISCAT data [7, 8, 11].



(a)



(b)

Figure 3.

(a) Proposed layout of the primary 5000 m^2 antenna, showing the 8 sub-arrays - each consisting of 32 rows and 16 columns of Yagi antennas - linked through the "eButler" hierarchical matrix.

(b) The power response of a typical beam (beam 6) of the main 5000 m^2 antenna as a function of declination and hour angle with both the "main beam" and "anti-beams" shown. The two "anti-beams" are located at hour angles of ±2 hours and at slightly lower declination than the main beam.

3.3 Proposed design

The system should consist of three sites, laid out in a rough triangle with baselines N-S and E-W. The main antenna should have a total collecting area of ~5000 m^2 and the satellite antennas ~2000 m^2. The sites should ideally lie some 300-400 km apart. The frequency of operation favoured is 327 MHz, a protected radio band and thus unlikely to experience serious interference and ideally suited to observing the solar wind between ~40 and 200 R.

The proposed antenna design is a novel combination of the traditional transit instrument and modern phase-steered techniques. It produces 32 simultaneous beams generated in a hierarchical matrix (the "eButler") which steer together in right ascension. The beams can be phased to generate either a single "main beam" or two simultaneous "anti-beams" straddling the meridian and positioned approximately half-way between the grating responses of the row - thus allowing most sources to be observed three times in a day.

4. CONCLUSIONS

Over the last 10 years there have been great advances in using IPS observations to study the solar wind. In particular - we are no longer presented with a "blurred" view of the solar wind. Recent results studying the three-dimensional evolution of the solar wind point the way to the use of IPS as an integral link in any programme intended to trace the expansion of the solar atmosphere into interplanetary space. We suggest that a new-generation IPS system is required to take full advantage of upcoming solar-observing spacecraft. Ideally, this should be a multi-site system with antennas 300-400 km apart and with high sensitivity, allowing both long-baseline and tomographic methods to be used. An observing frequency band centred on 327 MHz would give the best view of the solar wind inside 1 AU. Such a system would also be of great utility in space weather monitoring.

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