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SOLAR WIND AND CME STUDIES OF THE INNER HELIOSPHERE USING IPS DATA FROM STELAB, ORT, AND EISCAT

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Interplanetary scintillation (IPS) observations provide views of the solar wind at all heliographic latitudes from near 1 A.U. down to fields of view covered by coronagraphs. These observations can be used to study the propagation of the solar wind and solar transients out into interplanetary space, and also measure the inner-heliospheric response to co-rotating solar structures and coronal mass ejections (CMEs). We use a three-dimensional (3D) reconstruction technique that obtains perspective views from solar co-rotating plasma and outward-flowing solar wind as observed from the Earth by iteratively fitting a kinematic solar wind model to IPS data from various observing systems. Here we use the model with both Solar Terrestrial Environment Laboratory (STELab), Japan, and Ootacamund (Ooty) Radio Telescope (ORT), India, IPS observations. This 3D modeling technique permits reconstructions of the density and velocity structures of CMEs and other interplanetary transients at a relatively coarse resolution for STELab and better for Ooty; and is dependent upon the number of observations. We present 3D reconstructions of CME events around 4-8 November 2004 from Ooty IPS observations and some preliminary reconstructions of STELab IPS observations around the Whole Heliospheric Interval (WHI). We also present some preliminary results of a CME observation by both the European Incoherent SCATter (EISCAT) radar IPS observations and those made by the Solar TErrestrial RElations Observatory (STEREO) of a CME in May 2007.

1. Introduction

Interplanetary scintillation (IPS) observations of the solar wind, solar wind transients, and the inner-heliosphere have now been used for around 45 years e.g. Refs. 1–6. IPS is seen as a powerful tool to probe the interplanetary medium. It is the rapid variation in signal received by radio antennas on Earth arising from the diffraction of radio waves from a distant, compact, natural radio source due to density variations within the outwardly-propagating solar wind. IPS observations allow the solar wind speed to be inferred over all heliographic latitudes and a wide range of heliocentric distances (dependent upon source strength and observing frequency, and also the location of observable sources in the sky), e.g. Refs. [1, 7–10]. Using the scintillation-level converted to g-level as a proxy, the solar wind density can also be inferred from such IPS observations, e.g. Refs. [6, 11–13]. See Equation 1 later.

The sources of IPS data discussed in this paper were taken from observations made by three different IPS systems around the World. These are the radio arrays of the Solar Terrestrial Environment Laboratory

(STELab),[14] University of Nagoya, Japan; the Ootacamund (Ooty) Radio Telescope (ORT),[15–17] India; and the mainland radio telescopes of the European Incoherent SCATter (EISCAT)[18–20] radar in Northern Scandinavia (Norway, Sweden, and Finland). The two Asia-based systems (STELab and Ooty) operate at an observing frequency of 327 MHz where STELab typically observes 20-40+ radio sources per day, and Ooty is currently capable of observing up to 1000 radio sources per day. EISCAT (based in Europe) however, currently operates in IPS mode on a campaign basis only at frequencies of either 928.5 MHz or 1420 MHz and is capable of observing up to a dozen sources per day at best.

As fully described by Ref. [12], the scintillation-level measurements have been available from the STELab radio antenna at Kiso, Japan, from 1997 to the present, and more recently from mid-2002 from the STELab radio antenna at Fuji. The New Toyokawa site will also be used for these measurements when it is fully operational. Another STELab antenna is located at Sugadaira, making four antenna sites in total with geographic distances between sites ranging from 98 km to 207 km. Ooty has been providing scintillation-level measurements on a similar time span as that of STELab. Unfortunately, the EISCAT system presently does not provide a scintillation-level measurement. The 3D velocity reconstructions are based directly on the IPS velocity observations; for 3D density reconstructions the g-level provides a proxy for density. This requires a "conversion" from IPS scintillation level, expressed as g-level, to density. The resulting reconstructions are of an inner-heliosphere region typically ranging from 15 solar radii ($R_\odot$) out to approximately 3 astronomical units (AU). The g-level, or disturbance factor, g, is defined by Eq. (1).

$$g = m/\langle m\rangle \tag{1}$$

Here, m is the observed scintillation level, and $< m >$ is the mean level of scintillation for the source at the elongation at the time of observation. Scintillation-level measurements from STELab are available for each astronomical radio source as an intensity variation of signal strength (resulting from small-scale variations in density, ΔN_e). These data are automatically edited to remove any obvious interference. Further discussion regarding the calculation of and use of g-level as a proxy for density (and also the real-time calculation used for space-weather forecasting) can be found in Refs. [11, 12].

When two or more radio antennas are used (such as with the STELab and EISCAT systems) and the separation of the ray-paths in the plane of the sky from source to each telescope lies close to radial (the solar wind flow direction) centered at the Sun, a high degree of correlation between the patterns of scintillation recorded at the two telescopes may be observed, e.g. Ref. [21]. The time lag for which maximum cross-correlation occurs (taking into account 'plane-of-sky' assumptions) can then be used to estimate the outflow speed of the irregularities producing the scintillation, e.g. Refs. [22, 23, 10]. More sophisticated methods involving the fitting of the observed auto- and cross-correlation spectra with the results from a weak-scattering model, have also been adopted for IPS data analyses, e.g. Refs. [10, 24–27]. For a single radio antenna (such as with Ooty) the outflow speed is determined from the power spectrum of the IPS observation as described in Ref. [28].

The three-dimensional (3D) reconstructions[11] of both speed and density are obtained through the use of a purely kinematic solar wind model and a technique which uses perspective views of solar co-rotating plasma[29] and of outward-flowing solar wind[12] crossing our IPS lines of sight from Earth to the radio source. The IPS data are iteratively fitted using our model over 18 iterations to make sure the model converges to a final solution. We then compare the resulting 3D reconstructions with *in situ* measurements from both the Wind — Solar Wind Experiment (Wind|SWE)[30,31] instruments and the Advanced Composition Explorer — Solar Wind Electron, Proton and Alpha Monitor (ACE|SWEPAM).[32,33]

Section 2 discusses some low-resolution 3D reconstructions of the Whole Heliospheric Interval (WHI) using STELab IPS data. Section 3 provides a preliminary summary of Ooty IPS 3D density reconstructions of the interplanetary counterparts of Coronal Mass Ejections (CMEs) seen by the SOlar and Heliospheric Observatory — Large Angle Spectrometric COronagraph (SOHO|LASCO)[34,35] responsible for the early-November 2004 geomagnetic storms. Section 4 discusses some preliminary work on a comparison of a CME observed by both EISCAT and the Solar TErrestrial RElations Observatory Ahead (STEREO-A)[36] spacecraft's Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI)[37,38] instrumentation. We give an overall summary in Sec. 5.

2. Low-Resolution 3D Reconstructions of STELab IPS Data for the WHI Period

The Whole Heliospheric Interval (WHI) covers Carrington Rotation 2068 (CR2068) and runs through the period 20 March 2008 through 16 April 2008. Figures 1 and 2 are summaries of the portion of CR2068 for which

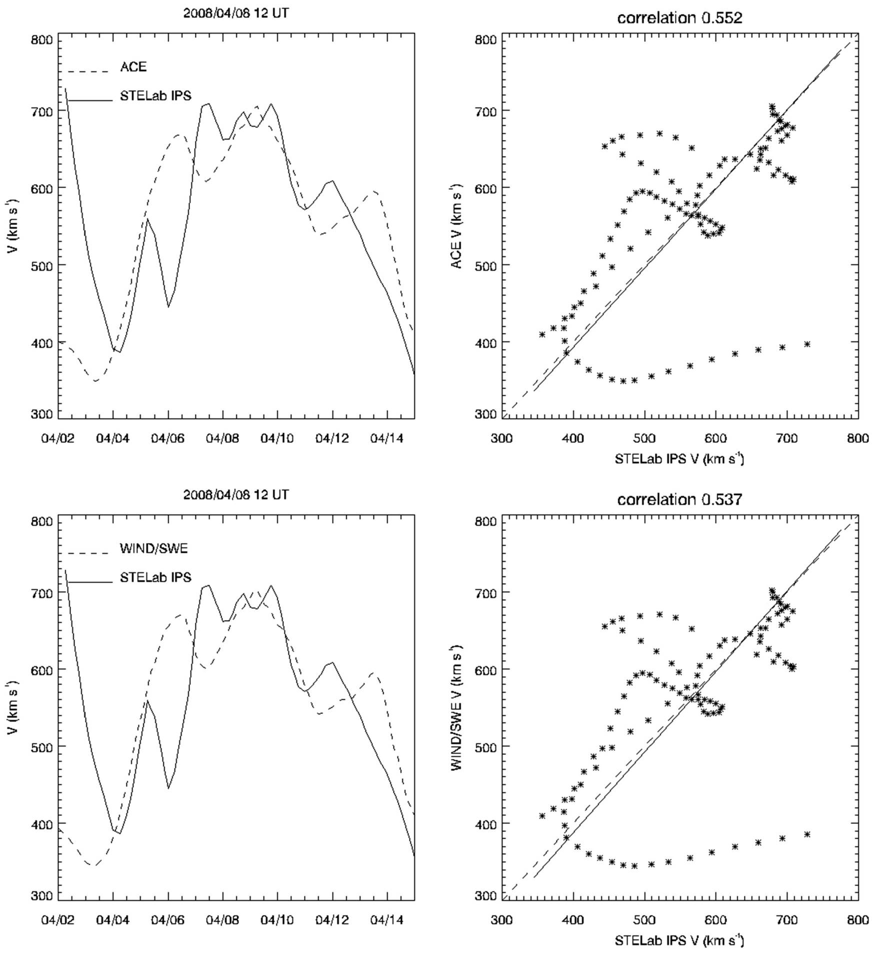

Fig. 1. 3D-velocity-reconstruction time-series extraction from STELab IPS data as compared with (top) ACE and Wind (bottom) *in situ* plasma measurements extracted from the reconstruction at the L_1 position (left-hand plots). Also shown are the correlation plots (right-hand plots) of the two data sets in each case as a measure of the accuracy of the reconstruction. In both cases, the results are very similar and give a good visual match as well as reasonable correlations.

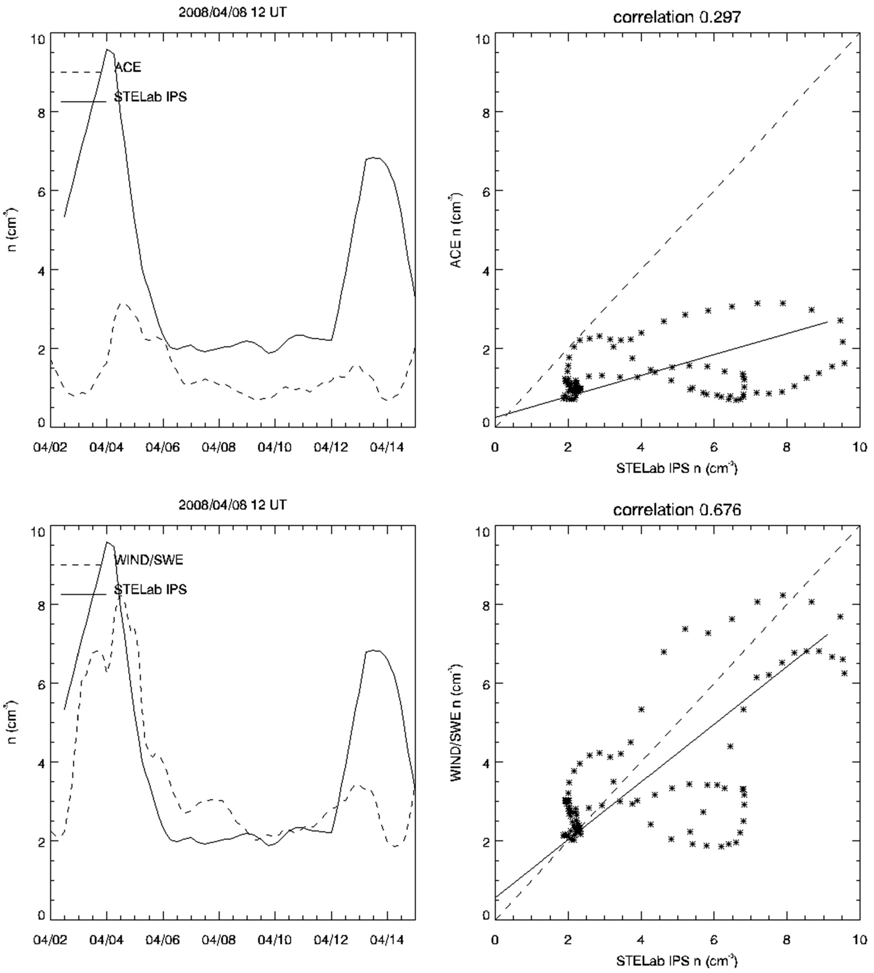

Fig. 2. 3D-density-reconstruction time-series extraction from STELab IPS data as compared with (top) ACE and Wind (bottom) *in situ* plasma measurements extracted from the reconstruction at the L_1 position (left-hand plots). Also shown are the correlation plots (right-hand plots) of the two data sets in each case as a measure of the accuracy of the reconstruction. The spacecraft data differ somewhat in their measurements of velocity, but as only Level-0 ACE data are presently available, it is likely that the Wind density measurements are more reliable; and it is these that provide both a better visual match when comparing with the extracted 3D-reconstruction time series and also the better correlation value.

there were STELab observations and these show successful reconstruction comparisons with the near-Earth *in situ* spacecraft ACE and Wind.

The velocity measurements recorded at each spacecraft are very similar when averaged on a daily cadence and result in equally-good correlations with time-series velocity extracts from the reconstructions at the position of the spacecraft. There are only relatively minor differences between the two spacecraft's daily-averaged velocity measurements. However, the density measurements differ somewhat between spacecraft. As only the ACE Level-0 data are available at present, it is likely that the Wind data are more accurate for L_1 *in situ* measurements presently and so it is this reconstruction comparison in density with the Wind spacecraft measurements that is considered as the baseline comparison in this paper. The *in situ* data have been averaged over a period of one day to match that of the 3D-reconstruction temporal cadence. The 3D reconstruction has a latitude and longitude digital resolution of 20° by 20°.

This is a preliminary analysis of the 3D reconstructions of speed and density from the STELab IPS observations during WHI. The extraction of time series at the L_1 point produce good comparison with measurements taken *in situ* by spacecraft and the goal in the future when all the spacecraft data are available is to perform full multi-point *in situ* comparisons with other spacecraft such as the STEREO spacecraft plasma measurements. However, from the analysis performed here, it seems that the heliosphere is well reconstructed at least in the direction of the Earth. The reconstructions seem to reveal a co-rotating feature around a period of three days from 04 April 2008 to 06 April 2008 (as do the *in situ* measurements). Further work on identifying this feature, by comparing these data with multi-point *in situ*, coronagraph, and other white-light data to attempt to identify transient candidates during this time, will be the subject of a forthcoming paper.

3. Summary of 3D Density Reconstructions from Early November 2004 using Ooty IPS Data

Interplanetary CMEs (ICMEs) around early-November 2004 led to a series of geomagnetic storms (as previously discussed[6,39,40] for STELab IPS and for the Solar Mass Ejection Imager (SMEI)[41,42] white-light reconstructions[6,40]). These geomagnetic storms formed part of the Coordinated Data Analysis Workshop (CDAW) master paper, Ref. [43], and its corrected table, Ref. [44]. Here we present results of improved 3D

IPS density reconstructions of this time period using Ooty data (previously STELab low-resolution 3D reconstructions were performed).

The greater number of sources observed by Ooty allows for an increase in the resolution (and therefore the detail) for the reconstructions (in the same way that 3D reconstructions of SMEI white-light observations can be performed at much higher resolutions, e.g. Ref. 45). The density reconstructions used here from Ooty data are at a 10° by 10° latitude and longitude digital resolution, with a half-day temporal cadence.

Figure 3 shows a time-series extraction and correlation of the Ooty 3D density reconstructions at the position of, and compared with, the *in situ* spacecraft density measurements around L_1 (Wind and ACE). In both cases, the spacecraft data were smoothed over half-day periods to be commensurate with the temporal cadence of the reconstructions. The data from both spacecraft differ from each other slightly, but overall agree well. In addition, as can be seen from both the shape and position of the reconstruction-extraction time series, the Ooty density reconstructions agree well on both the timing and the magnitude of the main peak in density, and agree well with the timing of the smaller peaks. Overall, the Ooty reconstructions seem to have a better agreement with the Wind spacecraft measurements than that of the ACE spacecraft measurements since these yield a higher correlation value. A similar case was seen when comparing both STELab density and SMEI density reconstructions with the same *in situ* data.[6,40]

These are the first results from 3D tomographic reconstructions using Ooty IPS data and a more-detailed discussion of these will be carried out in a future paper.

4. Preliminary CME Observation in EISCAT IPS Data of the 16 May 2007 CME and its Comparison with STEREO-A SECCHI White-light Observations

On 16 May 2007 at 00:22:30 UT, a CME was seen off the East limb of the Sun by the STEREO-A Outer Coronagraph (COR2) instrument. Later at 13:30 UT it was seen rather well developed by the STEREO-A Heliospheric Imager (HI) 1 instrument. During this time the EISCAT system in northern Scandinavia was conducting IPS observations of radio source J0431+206 located 50.1° East and 12.1° South of the Sun-Earth line. The point of closest approach (P-Point) of the line-of-sight (LOS) to the Sun lay at around 52.2 $R_\odot$ throughout the 30-minute observation on 16 May 2007 from

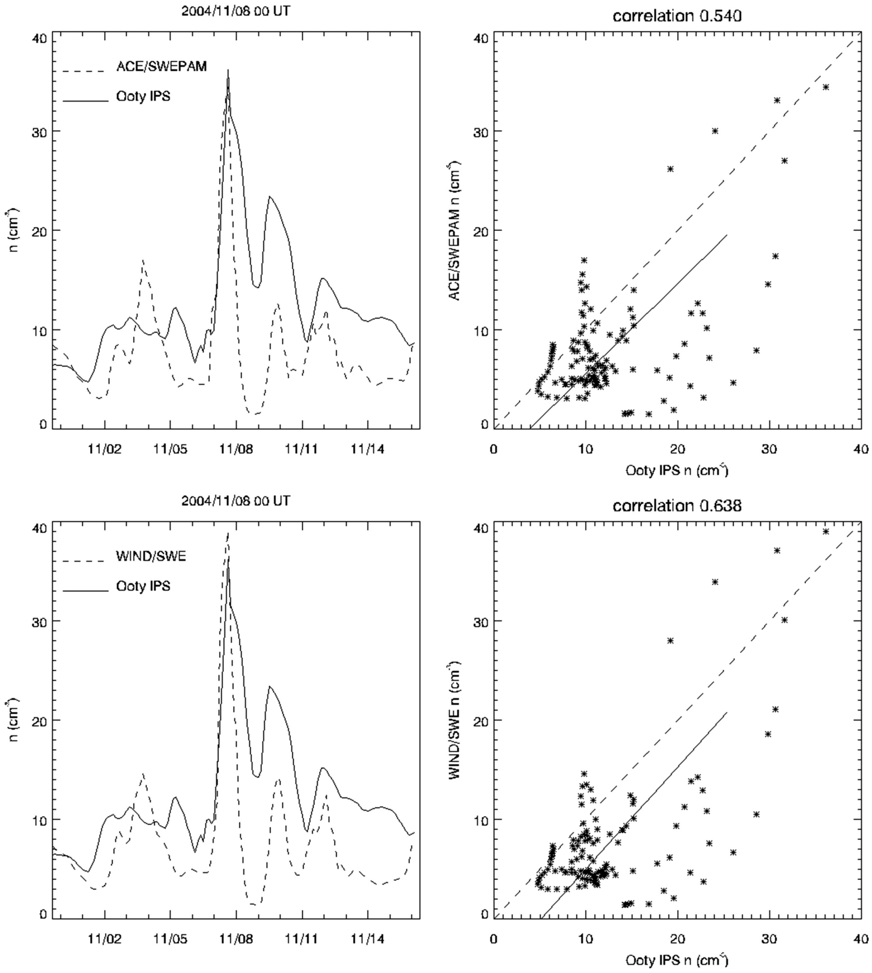

Fig. 3. Time-series comparison in density of the 3D Ooty reconstruction data extracted at the Sun-Earth L_1 point and compared with solar wind plasma measurements taken with (top) the ACE spacecraft and (bottom) the Wind spacecraft in the left-hand plots. The right-hand plots show a correlation of the two time series for each of the spacecraft. Note that the higher correlation is obtained with the Wind-spacecraft comparison.

13:30 UT to 14:00 UT. Figure 4 shows an image from the STEREO-A HI1 at 13:30 UT with the approximate apparent P-Point position of the radio source projected onto the image.

The two EISCAT antennas which gave suitable geometry to perform the two-site cross-correlation analysis were Kiruna in Sweden, and Sodankylä

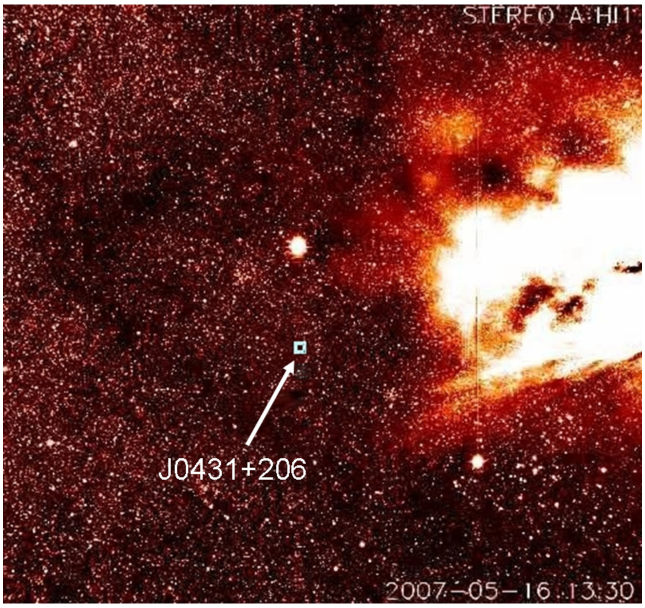

Fig. 4. A STEREO-A HI1 image frame on 16 May 2007 at 13:30 UT showing the CME expanding out from the Sun (on the right-hand-side of the image). The projection of the P-Point of the LOS for the EISCAT IPS radio source J0431+206 is approximately marked in the field of view of the imager. At this time, the angular separation between the STEREO-A spacecraft and the Earth was small (5.461°).

in Finland. The cross-correlation of the two signals along with the baseline geometry allows an approximation of the outward solar wind flow speed to be calculated from the location of the peak maximum in the cross-correlation function (CCF) of the two simultaneous IPS signals. A more detailed description of how the solar wind velocity can be directly obtained from the CCF can be found in Refs. [46, 47]. Negative lobes at, or near to, zero time lag in the CCF can occur as a result of a transient, e.g. a transient, passing through the LOS such as a CME.[48] Other determining factors include an enhanced level of scintillation.[49,50] The shape and evolution of the negative lobe associated with the passage of a transient feature along with the shape of the CCF can be used to infer the motion of various parts of a CME crossing the IPS LOS.[5] Figure 5 displays the changing CCF with time in 5-minute intervals of the Kiruna-Sodankylä observation.

The six parts of Fig. 5 are each a 5-minute segment of the 30-minute observation showing the CCF for each segment. The time intervals of the

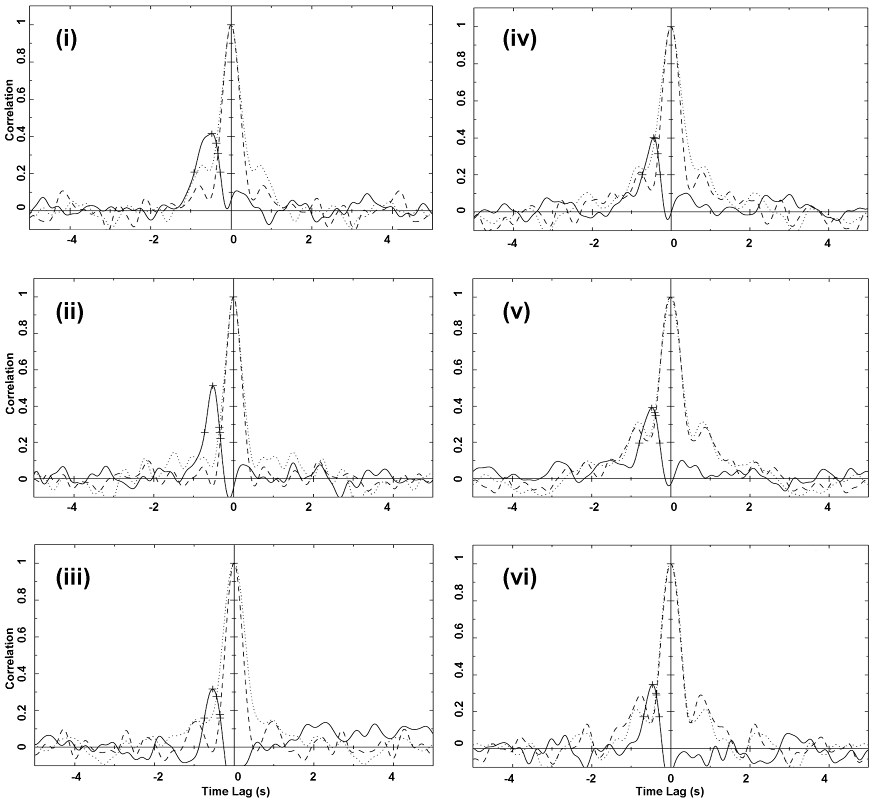

Fig. 5. The cross-correlation functions (CCFs) of the Kiruna-Sodankylä IPS observation in 5-minute intervals starting with (i) 13:30 UT to 13:35 UT up to (vi) 13:55 UT to 14:00 UT. Velocities range from 390 km s^{-1} to 530 km s^{-1} with a baseline around 240 km. The description of the observation can be found in the text.

segments are as follows: (i) 13:30 UT to 13:35 UT, (ii) 13:35 UT to 13:40 UT, (iii) 13:40 UT to 13:45 UT, (iv) 13:45 UT to 13:50 UT, (v) 13:50 UT to 13:55 UT, and (vi) 13:55 UT to 14:00 UT. Interpreting each of the CCFs with the assumption of the passage of the interplanetary counterpart of the CME as observed by the STEREO|HI white-light instrumentation, then (i) shows the onset of what may be the passage of a transient across the LOS since there are hints that a negative lobe in the CCF at zero time lag may be forming. 5-minutes later in (ii), a negative lobe around zero time lag is clearly forming which indicates the passage of a transient; likely in this case to be an ICME. It is possible that the negative lobe is caused by the geometry of the LOS with respect to the compression at the "nose" of the ICME. In (iii) we see the passage continue as a very deep negative lobe occurs. (iv) shows the negative lobe disappearing and thus signifying the passage of the ICME as coming to an end. However, (v) shows what seems to be another ICME/transient passage starting and (vi) confirms this. It should be noted though, only one CME was seen in that direction by the STEREO spacecraft. This means that (iv), (v) and (vi) are likely to be showing a different "part" of the transient than is seen in (i), (ii), and (iii) since there are hints that a negative lobe in the CCF at zero time lag may be forming. 5-minutes later in (ii), a negative lobe around zero time lag is clearly forming which indicates the passage of a transient; likely in this case to be an ICME. In (iii) we see the passage continue as a very deep negative lobe occurs. (iv) shows the negative lobe disappearing and thus signifying the passage of the CME as coming to an end. However, (v) shows what seems to be another ICME/transient passage starting and (vi) confirms this. However only one CME was seen in that direction by the STEREO spacecraft. This means that (iv), (v) and (vi) are likely to be showing a different "part" of the transient than is seen in (i), (ii), and (iii).

An argument is generally made in the IPS community that the changing and rotation of the baselines/geometry can cause a negative lobe at zero time lag to fade and return throughout an observation. However in this case, it should be duly noted that the baselines and geometry varies almost inconsequentially throughout the observation thus removing this possibility as an option for the fading and re-initiating of the negative lobe seen at zero time lag.

The only present solution for this occurrence must be that different parts of the ICME are crossing the LOS. This may be perhaps the "front" of the ICME where there are often shocks and there can be a high amount of turbulence, and perhaps the "ejecta" portion (of a CME) where the majority of the mass generally occurs (which can also have an effect on scintillation level even though the level of scintillation is usually determined by the level of turbulence in whatever material crosses your LOS). The other solution is that the first part represents the initial shock ahead of the ICME front, and the second part the front itself. Further investigation is needed to determine exactly what is being observed here, but the timings, geometry, and velocities measured by both EISCAT and STEREO for this event seem to agree. The reader is referred to Ref. [51] for a more-detailed analysis of this event and its comparison with the HI-1A white-light observations.

5. Summary

This paper provides a brief summary of the most-recent advances of using the 3D-tomographic-reconstruction technique and also of EISCAT IPS observations as compared with those of STEREO|SECCHI white-light instrumentation. These include 3D tomographic reconstructions of both STELab and Ooty IPS data, and showing the improvements to the density reconstructions of the Ooty data for the complex November 2004 period; and a good correlation between the observation of a CME by both STEREO and EISCAT.

The 3D-reconstructed heliosphere from STELab data from a latter part of the WHI period show what appears to be a co-rotating region passing across the Sun-Earth L_1 point with time. The time-series extraction from the reconstruction in both speed and density give good comparison with the ACE Level-0 and Wind data presently available. Further investigation is needed in determining the exact characteristics of this feature and also to check in greater detail for possible transient candidates from white-light corona and heliosphere observations. The 3D reconstruction can also be verified further for it's global accuracy by comparing with multi-point *in situ* observations; as is the aim of future work when the *in situ* data are more readily available in the very-near future.

The geoeffective storms during November 2004 discussed here and also in greater detail by Refs. [6, 39, 40, 43, 44] are very well reproduced in g-level-to-density 3D reconstructions using Ooty IPS data, and are a great improvement over previous[6] reconstructions using these data. The reconstructions are shown to be associated with known *in situ* signatures by comparing these data with the Wind and ACE spacecraft. Overall, the Ooty data reconstruction appears to show improved density values compared with the STELab[6,40] density values when time-series of the two are compared with *in situ* measurements. The Ooty reconstructions have the advantage of having double the spatial and temporal resolution from those of STELab since there are many more Ooty IPS observations during this time, and thus should provide a better comparison with those measured *in situ*. The Ooty IPS velocity measurements were also incorporated into these reconstructions which further improved on the density reconstructions shown previously and these improved reconstructions as well as velocity reconstructions will be discussed in a future paper.

An EISCAT IPS observation from May 2007 shows evidence of the passage of an ICME that was noted from STEREO-A HI white-light imaging on the same day. The CCFs of 5-minute blocks of the 30-minute observation showed some substantial variation, indicating that different parts of the ICME passed through the LOS during the course of the observation. Attempts will be made in a future paper to firmly link the CCF variations with the passage of different parts of the CME seen by the STEREO-A spacecraft's remote-sensing instruments.

In conclusion, for our 3D tomography we continue to follow CMEs from near the solar surface outward until they are observed *in situ* near Earth, and a study is now underway to compare in near-real-time with both STEREO spacecraft, as is already being done routinely with Wind, ACE, and Ulysses. These events, reconstructed in 3D in terms of both speed and density for WHI and density alone for November 2004, show that the heliospheric response to CMEs and co-rotating features can be large. We also see that there is good comparison with the EISCAT IPS observations with those see by STEREO|SECCHI ahead instrumentation, along with such timings of the 16 May 2007 event. We look forward to other (true-multi-point) *in situ* comparisons such in forthcoming papers for the WHI period now that the *in situ* data are becoming more widely available. As our 3D tomographic models become more sophisticated, possibly incorporating a 3D MHD solar wind model, and multi-point calibrations are realised, we expect the comparisons to improve even further from those demonstrated in Ref. [40] and in this paper, as well as a full paper on the 16 May 2007 event.

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