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Extremely long baseline interplanetary scintillation measurements of solar wind velocity

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[1] We present results of observations of interplanetary scintillation (IPS) made using the telescopes of the MERLIN and EISCAT networks in which the beam separation approached 2000 km, much larger than in any previous IPS experiments. Significant correlation between the scintillation patterns was observed at time lags of up to 8 s and fast and slow streams of solar wind were very clearly resolved. One observation showed clear evidence of two discrete modes of fast solar wind, which we interpret as originating in the crown of the northern polar coronal hole and in an equatorward extension of the polar hole. We suggest that experiments of this type will provide a new and important source of information on the temporal and spatial variation of small-scale turbulence in the solar wind. The improved velocity resolution available from extremely long baseline measurements also provides new information on the development of the large-scale velocity structure of the solar wind in interplanetary space.

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1. Introduction

[2] The rapid variation of the apparent intensity of distant, small-diameter radio sources was first observed in the early 1960s. It was soon realized that measurements of this interplanetary scintillation (IPS) could provide information on the solar wind [e.g., *Hewish et al.*, 1964; *Dennison and Hewish*, 1967]. Developments in the technique led to the use of two-station observations, in which the scintillation pattern is measured at two widely separated sites [*Armstrong and Coles*, 1972; *Kailua et al.*, 1973]. Provided that the IPS observations are made at a time when the ray paths from the radio source to the two receiving sites lie in a plane which passes through the center of the Sun (Figures 1a and 1b), a high degree of correlation may be present between the scintillation patterns seen at the two sites and in this case the time lag for maximum cross-correlation provides a first estimate of the solar wind outflow speed [e.g., *Bourgois et al.*, 1985; *Coles*, 1995]. The accuracy to which IPS can estimate solar wind speed improves as the separation of the antennas projected into the plane of the sky (the parallel baseline, B_{par}, as illustrated in Figure 1b) used to sample the scintillation pattern increases, with the time lag for maximum correlation increasing, and as this happens so the ability to resolve two different solar wind speeds across the ray path improves [e.g., *Grall*, 1995; *Rao et al.*, 1995; *Grall et al.*, 1996]. However, the irregularity pattern giving rise to the IPS will be evolving with time, so the degree of correlation between the scintillations observed at the two sites will decrease as the parallel baseline increases.

[3] Until the early 1990s two-site IPS measurements typically used parallel baselines of ~100–150 km, but in 1993 a series of observations at 933.5 MHz from the EISCAT facility in northern Scandinavia were undertaken to support the first Ulysses polar pass. The geometry required for these observations forced the use of much longer parallel baselines than had hitherto been employed, in excess of 300 km, and unexpectedly good correlation between the scintillation patterns recorded at the two sites was observed [*Breen et al.*, 1996a]. Furthermore, the improved sensitivity of the measurements to differing velocities of solar wind meant that fast and slow streams across the ray-path could be clearly distinguished, with their contributions appearing as two distinct peaks in the correlation function [*Grall*, 1995; *Coles*, 1996]. *Rao et al.* [1995] combined measurements from the GMRT and Ootacamund radio telescopes (operating at 327 MHz), giving a parallel baseline of 560 km. Again, good correlation between the scintillation patterns at the two sites was observed.

[4] *Moran et al.* [1998] considered the relationship between maximum cross-correlation of the scintillation patterns recorded at EISCAT sites and the parallel baseline length and showed that the rate at which the degree of correlation fell away with increasing parallel baseline was best represented by a Gaussian curve.

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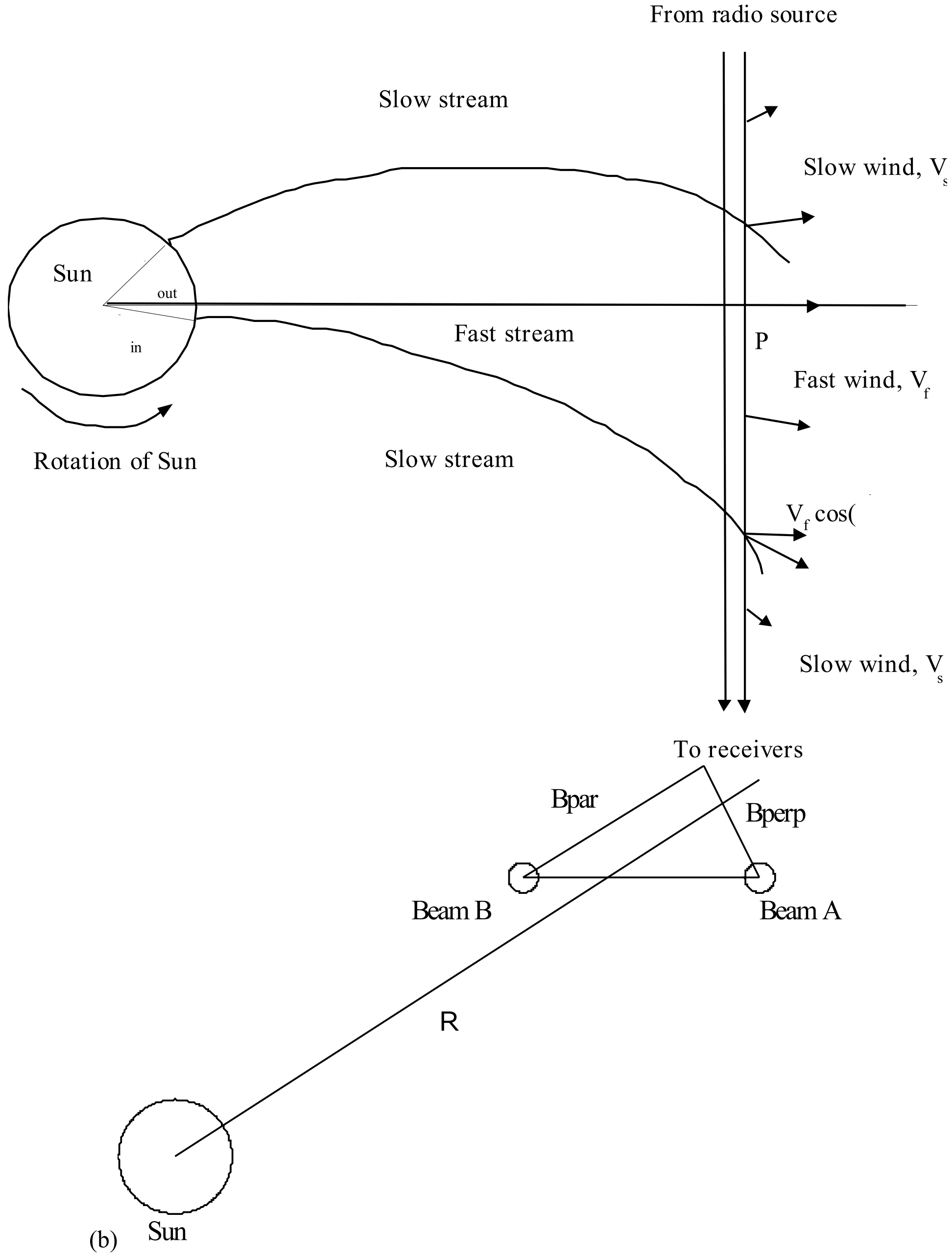

Figure 1. Schematic diagrams of an IPS observation (not to scale) (a) shown as if looking down on the north pole of the Sun. The ray paths from radio source to receiver pass through the extended solar atmosphere, with their point of closest approach to the Sun (P) lying at a distance of R solar radii from the center of the Sun. Here θ_{in} and θ_{out} define the angular extent of the ray path which is immersed in fast solar wind: in the coordinate system adopted in this study angles are measured from the Sun-P direction and are positive toward the radio source, negative toward the Earth. (b) Shown as if looking from the direction of the radio source toward the receiving antennas. Beams A and B represent the ray paths from the source to the two receiving stations. The ray paths are separated by a distance B_{par} is the direction radial to the Sun and by B_{perp} in the direction tangential to the Sun. The correlation between the scintillations seen at the two sites is greatest when B_{perp} is small. Velocity resolution increases for larger B_{par}.

[5] Analysis of IPS data using a two-dimensional weak scattering model [*Grall*, 1995; *Coles*, 1996; *Klinglesmith*, 1997; *Massey*, 1998] have shown that, provided the observation is sufficiently far from the Sun as to be in weak scattering, it is possible to detect the presence of separate fast and slow streams across the ray path [*Grall et al.*, 1996; *Coles*, 1996; *Breen et al.*, 1996b]. Interplanetary scintillation measurements in the late 1970s [*Kailua*, 1977] sug-

gested that near to solar minimum the solar wind has two distinct components: a fast stream flowing at about 750 to 800 km s^{-1} and a slow stream with a flow speed of about 350 to 400 km s^{-1} and these results were later confirmed by in situ measurements [e.g., *Schwenn*, 1990; *Phillips et al.*, 1994; *Woch et al.*, 1997; *McComas et al.*, 2000]. The fast wind originates from open magnetic field regions which are conspicuous as dark regions in maps of coronal white-light intensity [e.g., *Snyder and Neugebauer*, 1966; *Krieger and Timothy*, 1973; *Neupert and Pizzo*, 1974; *Nolte et al.*, 1976]. This bimodal distribution of solar wind speed has been confirmed in IPS data [e.g., *Breen et al.*, 1996b], and, together with the clear association between large regions of dark corona (coronal holes) and high-speed streams, makes it possible to use white-light intensity in coronal maps to determine whether a given region of an IPS ray path is immersed in fast or slow flow and thus separate the contributions to the observed scattering pattern of the fast and slow winds [*Coles*, 1996]. It should be noted that this analysis assumes that the density irregularities giving rise to IPS are drifting with the background solar wind flow; a recent study by *Harmon and Coles* [2005] suggests that the real situation is unlikely to be so simple, but at the distances from the Sun discussed in this paper the likely deviation should be small.

[6] The observations discussed in this paper combine measurements of IPS from telescopes of the MERLIN network in Britain and the EISCAT facility in northern Scandinavia. The EISCAT system was constructed as an ionospheric radar operating near 930 MHz and in this role is described by *Rishbeth and Williams* [1985], but its low-noise receivers, high timing accuracy, and long baselines between sites (up to 390 km) make it suitable for IPS observations [e.g., *Bourgois et al.*, 1985; *Coles et al.*, 1991]. MERLIN [*Thomasson*, 1986] was first used for IPS observations in 1989 by *Rickett* [1992], and since 1999 IPS observations have been run each year [*Breen et al.*, 2000, 2002].

[7] In 2002, duplicate two-channel receiver systems centered on 1.4 GHz were installed at the Kiruna and Sodankylä EISCAT sites, allowing IPS to be observed at higher frequencies and over a wider bandwidth than was possible at 930 MHz [*Wannberg et al.*, 2002]. This opened up the possibility of using EISCAT and MERLIN together to make observations of IPS at 1.4 GHz with an unprecedentedly large parallel baseline. The first EISCAT-MERLIN combined observations were carried out in May 2002, with more extensive programs in May 2004 and 2005.

[8] The purpose of this paper is to present results showing that correlation between the scintillation patterns detected at receiving sites separated by up to 2000 km exists and can be used to provide information on solar wind speed and large-scale velocity structure. IPS observations are sensitive only to the component of solar wind velocity perpendicular to the ray path, so simple estimates of solar wind speed taken from the time lag for maximum correlation include a degree of "foreshortening" [e.g., *Coles*, 1996], these "plane-of-sky" speeds are therefore lower than the true radial outflow speed. In previous papers [e.g., *Breen et al.*, 1999] we corrected for this effect and determined other solar wind parameters by fitting the data with a weak-scattering model [*Klinglesmith*, 1997]. As it was not immediately apparent that some of the assumptions made in this model, particularly the assumption that the temporal evolution of the irregularity pattern could be adequately modeled, would remain valid when time lags for maximum correlation approached or exceeded 7 s, we did not attempt to model the data used in this paper (with the exception of the EISCAT-only observations from May 2005 used for comparative purposes). Instead we estimated the path-integrated plane-of-sky speed of the solar wind directly from the time lag for maximum correlation and used this to estimate the outflow speed by determining the probable location of regions of fast and slow flow in the ray path (by projecting the ray path down onto SOHO/LASCO maps of white-light intensity in the corona), assuming a 1:3 density weighting between fast and slow wind [*Fallows et al.*, 2002] and solving the path-integration problem across the region of the ray path immersed in each stream). This approach has some limitations, the most important being that a finite spread in solar wind speeds across the stream considered will introduce a skew of the correlation function to shorter time lags, leading in turn to an overestimate of the plane-of-sky speed [e.g., *Breen et al.*, 1996a]. The plane-of-sky speeds quoted in this paper and the outflow speeds deduced from them may therefore be overestimates of the true solar wind speeds. We considered that this was acceptable as the purpose of this paper was to show, by comparing results from different pairs of sites, that extremely long baseline IPS observations could be used to estimate solar wind speeds and that the ability of the observation to resolve regions of flow with different outflow speeds was greatly improved. The application of the weak-scattering model to extremely long baseline observations and its use to estimate true solar wind speeds will be discussed in a future paper.

2. Observations

[9] The results presented in this paper were obtained from measurements made in May 2002, 2004, and 2005. The 2002 observations were intended to determine whether significant correlation existed between scintillation patterns recorded at such widely separated sites. Once this was established, more extensive programs of observation were developed in 2004 and 2005. The baselines for the various combinations of receiving sites are set out in Table 1, which also includes a summary of plane-of-sky speeds for flow (estimated directly from the time lag for maximum correlation and the parallel baseline for the observation) and the outflow speed for the solar wind inferred from this.

[10] The periods of observation were compared with the SoHO|LASCO lists of coronal mass ejections (http://cdaw.gsfc.nasa.gov/CME_list/ and http://lasco-www.nrl.navy.mil/cmelist.html). None of the CMEs listed was likely to have crossed the IPS ray-path within 3 hours of the period of observation, with the exception of the event launched at 1700 UT on 13 May 2005, which appears to correspond to the change in solar wind characteristics seen in IPS observations after 1410 UT on 14 May 2005.

2.1. May 2002 Observations

[11] The first series of extremely long baseline observations were carried out on 15 May 2002, when two compact, isolated radio sources were observed. Of these, 0319 + 415

Table 1. Summary of Results From MERLIN and EISCAT Long-Baseline Observations in May 2002 and 2004[a]

Date	Source	Sites	B_{par}, km	B_{perp}, km	Maximum Cross-Correlation for Faster Peak, %	Time-Lag for Faster Peak, s	Plane-of-Sky Speed for Faster Peak, km s^{-1}	Maximum Cross-Correlation for Slower Peak, %	Time-Lag for Slower Peak, s	Plane-of-Sky Speed for Slower Peak, km s^{-1}
15 May 2002	0319+415	JK	−1827	72	12.5	2.25	812	13.8	7.54	242
		JK	−1827	52	13.5	2.24	816	13.9	7.42	246
		JK	−1828	32	11.0	2.20	832	11.1	7.39	248
		JK	−1829	−8	6.0	2.29	799	8.6	7.37	248
		JS	−1938	127	6.0	2.50	775	11.2	7.86	247
		JS	−1941	84	11.5	2.45	792	13.8	7.82	248
		JS	−1943	59	10.2	2.48	783	12.1	7.86	247
		JS	−1945	−5	8.0	2.47	787	10.5	7.86	247
		CS	−1974	90	12.4	2.47	799	6.0	8.45	234
		CS	−1975	77	9.4	2.45	806	7.1	8.05	245
		CS	−1976	55	7.5	2.48	797	7.4	7.95	249
		CS	−1978	11	-	-	-	8.5	8.01	247
		CS	−1979	−33	-	-	-	7.9	8.01	247
	0431+206	JK	−1356	−201	19.3	2.57	528	-	-	-
		JK	−1385	−209	21.6	2.61	531	-	-	-
		JK	−1412	−218	19.1	2.67	529	-	-	-
		JK	−1440	−227	11.5	2.74	526	-	-	-
		JK	−1466	−236	10.7	2.83	518	-	-	-
		JS	−1320	−78	23.2	2.26	584	-	-	-
		JS	−1344	−84	38.2	2.36	569	-	-	-
		JS	−1361	−88	35.6	2.38	572	-	-	-
		JS	−1389	−95	35.7	2.41	576	-	-	-
		JS	−1422	−103	36.2	2.44	583	-	-	-
		JS	−1455	−112	27.1	2.50	582	-	-	-
		JS	−1487	−121	20.3	2.59	574	-	-	-
		JS	−1550	−139	13.4	2.63	589	-	-	-
12 May 2004	0319+415	JK	−1824	119	14.5	2.47	738	-	-	-
		JK	−1826	79	16.8	2.48	736	-	-	-
		JK	−1826	39	14.7	2.48	736	-	-	-
13 May 2005	0319+415	JK	−1824	113	11.2	2.54	718	-	-	-
		JK	−1826	72	21.2	2.49	733	-	-	-
		JK	−1827	32	22.0	2.48	736	-	-	-
		JK	−1827	−8	9.8	2.52	725	-	-	-
		JT	−1926	155	8.8	2.49	774	-	-	-
		JT	−1929	114	15.6	2.40	804	11.0	3.60	536
		JT	−1930	72	17.7	2.61	740	8.5	3.75	515
		JT	−1931	30	18.3	2.62	737	7.5	3.85	502
		JS	−1939	134	15.3	2.65	732	8.0	3.70	524
		JS	−1941	90	23.4	2.64	735	-	-	-
		JS	−1942	45	20.1	2.65	733	-	-	-
		KK	−1885	95	9.0	2.40	786	-	-	-
		KK	−1887	53	17.6	2.51	752	-	-	-
		KK	−1888	12	7.1	2.50	755	-	-	-

Table 1. (continued)

Date	Source	Sites	B_{par}, km	B_{perp}, km	Maximum Cross-Correlation for Faster Peak, %	Time-Lag for Faster Peak, s	Plane-of-Sky Speed for Faster Peak, km s^{-1}	Maximum Cross-Correlation for Slower Peak, %	Time-Lag for Slower Peak, s	Plane-of-Sky Speed for Slower Peak, km s^{-1}
13 May 2005	0319+415	CK	−1867	146	15.2	2.44	765	10.5	3.85	485
		CK	−1869	106	19.0	2.39	782	-	-	-
		CK	−1870	66	11.3	2.45	763	-	-	-
		CK	−1871	26	11.9	2.65	706	-	-	-
		CS	−1972	144	13.0	2.78	763	-	-	-
		CS	−1974	100	23.8	2.63	751	-	-	-
		CS	−1975	56	18.6	2.61	757	-	-	-
		CT	−1984	73	23.8	2.67	743	10.0	3.85	515
		CT	−1985	31	17.6	2.58	769	8.5	3.75	529
		KS	−161	−16	56	0.25	639	-	-	-
		KS	−162	19	64	0.27	600	-	-	-
14 May 2005 (before 1410 UT)	0319+415	KK	−1885	104	10.0	2.60	725	-	-	-
		KK	−1886	92	17.6	2.57	734	-	-	-
		KK	−1887	59	11.0	2.60	726	-	-	-
		CS	−1977	61	10.0	2.8	706	-	-	-
14 May 2005 (after 1410 UT)	0319+415	KK	−1887	59	10.5	2.85	662	-	-	-
		KK	−1888	17	6.0	2.85	663	14.5	3.28	576
		KK	−1889	−25	-	-	-	13.4	3.21	589
		KK	−1890	−66	-	-	-	15.6	3.11	608
		KK	−1889	−107	-	-	-	14.5	3.06	617
		KS	−1998	155	-	-	-	11.3	3.57	560
		KS	−2001	110	-	-	-	14.8	3.52	569
		KS	−2004	64	7.0	2.9	691	13.4	3.46	579
		KS	−2005	18	10.0	2.92	687	-	-	-
		KS	−2006	−28	15.9	2.92	687	-	-	-
		KS	−2007	−74	13.8	2.92	687	-	-	-
		JS	−1935	181	7.6	2.86	676	-	-	-
		JS	−1938	136	9.0	2.85	680	12.6	3.47	559
		JS	−1941	91	9.2	2.85	681	13.9	3.41	569
		JS	−1943	47	7.5	2.85	682	11.5	3.34	582
		JS	−1944	3	11.5	2.84	685	-	-	-
		JS	−1945	−42	15.6	2.82	690	-	-	-
		JS	−1945	−86	10.9	2.81	692	-	-	-
		CK	−1867	−247	16.3	2.74	681	-	-	-
		CK	−1864	−286	9.5	2.70	690	-	-	-
		CS	−1976	61	9.5	3.0	659	10.5	3.52	561
		CS	−1977	17	-	-	-	15.4	3.42	578
		CS	−1978	−27	-	-	-	13.1	3.37	587
		CS	−1978	−71	-	-	-	15.7	3.20	618
		CS	−1978	−115	-	-	-	9.2	3.24	610

[a] MERLIN-EISCAT observations are shown in normal type, EISCAT-only observations in italic type. The abbreviations used for telescope sites are J1 = Jodrell Bank Lovell (76 m) telescope; J2 = Jodrell Bank Mk.2 telescope; C = MERLIN 32 m Cambridge telescope; K (MERLIN-EISCAT observations, first letter in pair) = MERLIN 25m Knockin telescope; K (MERLIN-EISCAT observations, second letter in pair) = EISCAT Kiruna telescope; S = EISCAT Sodankylä telescope; T = EISCAT Tromsø telescope (Ramsfjordmoen). In EISCAT-only observations K = EISCAT Kiruna telescope. All telescopes operate on a central frequency of 1418 MHz apart from EISCAT Tromsø, which has a central frequency of 928 MHz. The plane-of-sky speeds are estimated from the parallel baseline and the time lag for maximum cross-correlation. The baselines between sites are positive westward (B_{par}) and southward (B_{perp}) in the plane of the sky.

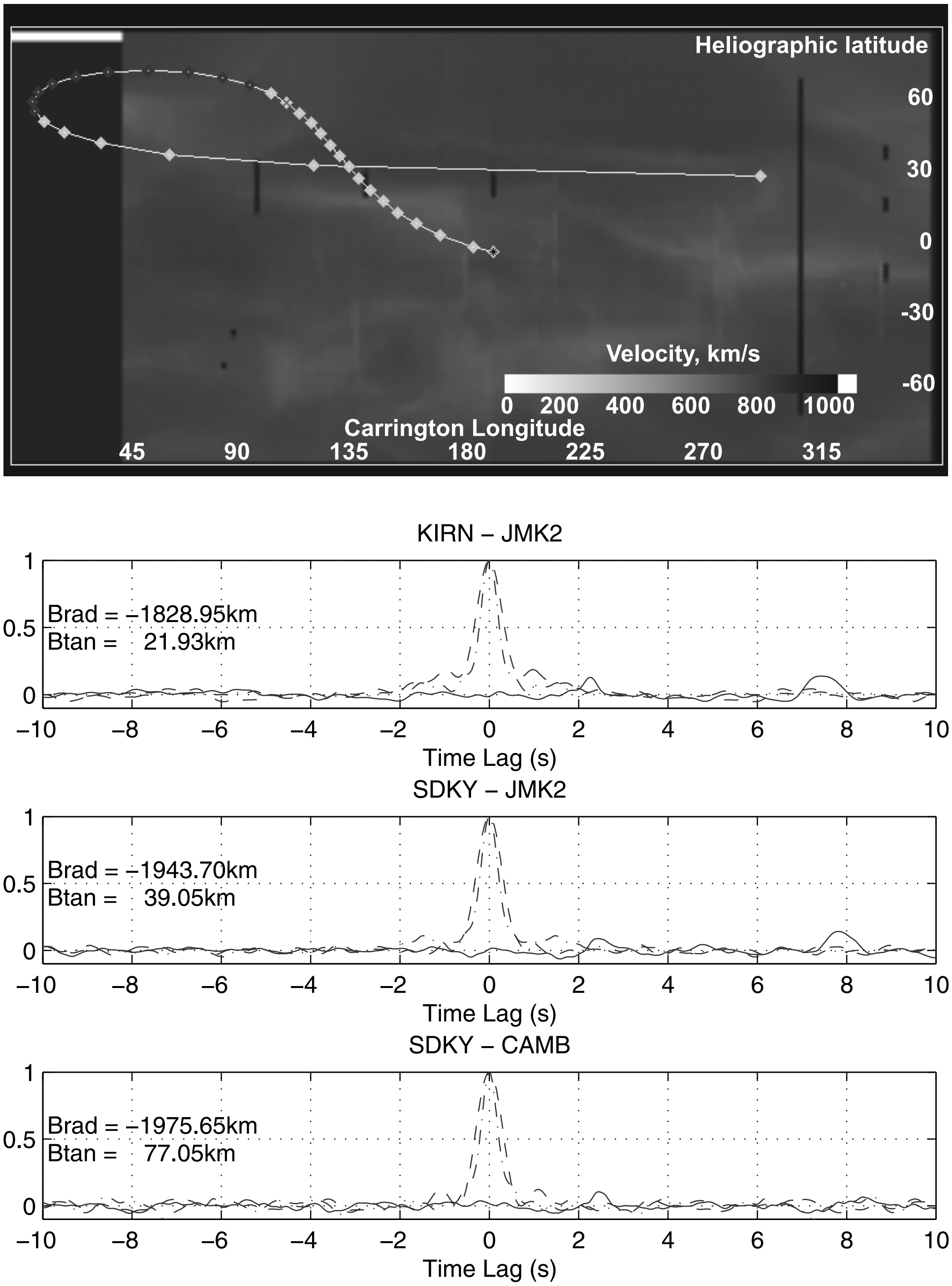

Figure 2. (a) Ray path for the observation of 0319 + 415 (3C84) on 15 May 2002, ballistically projected down to 2.5 R at a constant velocity of 800 km s^{-1} and overlaid on a map of white-light intensity in the corona at 2.5 R off the east limb of the Sun constructed from LASCO C2 data taken during Carrington rotation 1989. (b) Correlation functions for observations of 0319+415 using (top to bottom) Jodrell Bank and Kiruna, Jodrell Bank and Sodankylä, and Cambridge and Sodankylä. The two peaks in the correlation functions correspond to plane-of-sky speeds of 792–816 and 234–248 km s^{-1}.

(3C84) lay 83 solar radii (R_s) off the northeast limb of the Sun at a heliographic latitude of 60° while 0431 + 206 lay at a lower latitude of $-12°$, 56 R_s off the southeast limb and both sources were observed for 60 min. The parallel baselines ranged from a minimum of 1285 km between Jodrell Bank and Sodankylä at 0600 UT for 0431 + 206 to a maximum of 1981 km for 0319 + 415 at 1435 UT Cambridge and Sodankylä.

[12] The observation began at 1400 UT and lasted 60 min. The data were analyzed using a 20 min running window, advanced in steps of 5 min. Correlation functions and spectra were therefore obtained for overlapping 20-min intervals centered 5 min apart for the whole of the observing period. The correlation functions shown in Figure 2b are those with the highest correlation for each baseline, and it is noticeable that in all cases the perpendicular baseline B_{perp} is significantly different from zero. The observations, to-

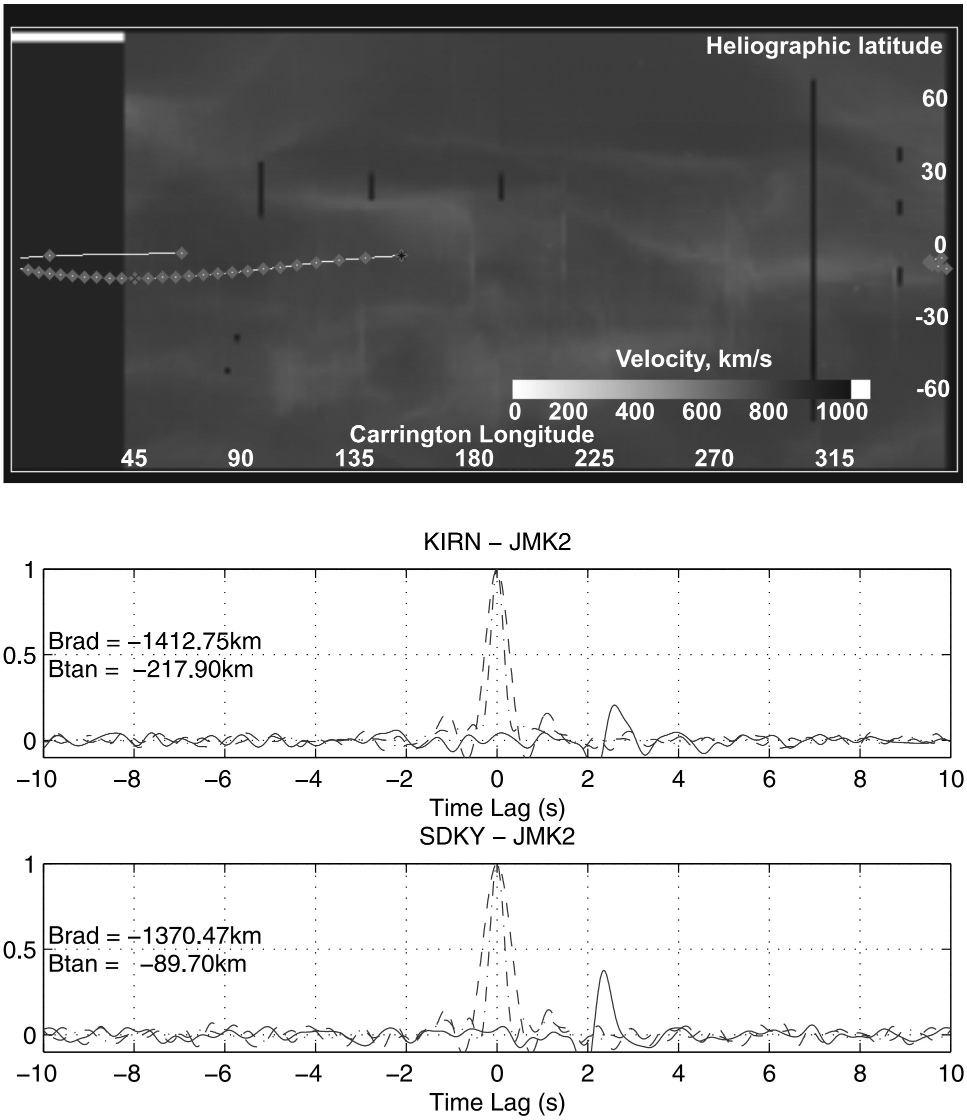

Figure 3. (a) Ray path for the observation of 0431 + 206 on 15 May 2002, ballistically projected down to 2.5 R at a constant velocity of 600 km s^{-1} and overlaid on a map of white-light intensity in the corona at 2.5 R off the east limb of the Sun constructed from LASCO C2 data taken during Carrington rotation 1989. (b) Correlation functions for observations of 0431 + 206 using (top to bottom) Jodrell Bank and Kiruna and Jodrell Bank. The peak in the correlation functions corresponds to a plane-of-sky speed of 531 (JK) or 569 (JS) km s^{-1}.

gether with the variation of correlation height, time lag, and inferred plane-of-sky speed with baseline length are summarized in Table 1.

[13] When the IPS ray path through the solar wind was projected ballistically down to 2.5 R_s and overlaid on a map of white-light intensity in the corona at 2.5 R_s constructed from LASCO C2 data (Figure 2a), it was clear that the observation contained contributions from both fast and slow streams. The correlation functions (Figure 2b) show the presence of these two streams most clearly, with a fast peak at a time lag of just over 2 s and a slow peak with a time lag of 7.5 to 8 s. The correlations between the scintillation patterns seen at the four pairs of sites are low, never reaching 20%, but the consistency with which the same pattern of fast and slow peaks corresponding to the same plane-of-sky speeds appears in completely independent observations using different combinations of antennas strongly suggests that these correlations are real and represent the motion of small-scale irregularities in the solar wind. The plane-of-sky speeds (the path-integrated component of flow speeds perpendicular to the ray path for the observation) for the fast and slow streams are given in Table 1 and correspond to outflow speeds of around 850 km s^{-1} for the fast wind and slightly less than 300 km s^{-1} for the slow wind, though these speeds may be overestimated if a significant spread in fast or slow wind speed exists [e.g., *Breen et al.*, 1996b]. These results are consistent with other solar wind data and with what might be expected from the configuration of the corona below the ray path, with fast

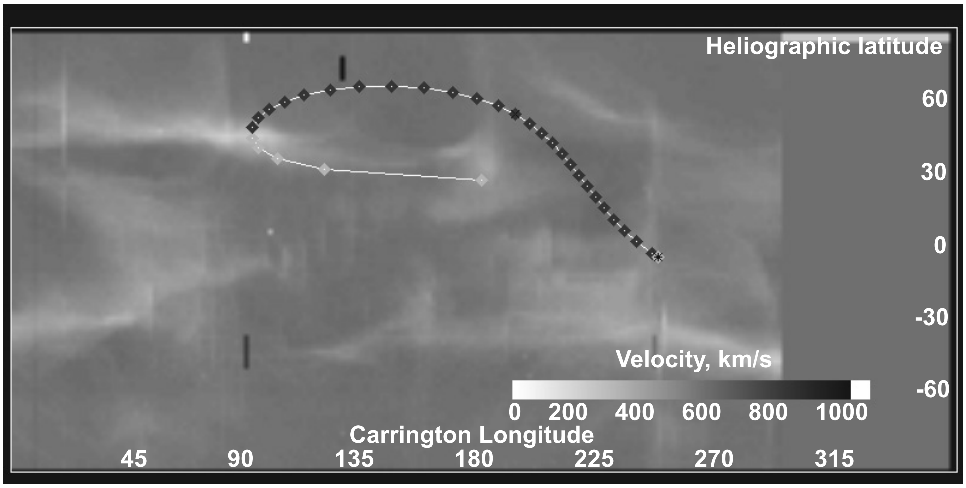

Figure 4a. Ray path for the observation of 0319 + 415 (CTA-21) on 12 May 2004, ballistically projected down to 2.5 R at a constant velocity of 800 km s^{-1} and overlaid on a map of white-light intensity in the corona at 2.5 R off the east limb of the Sun constructed from LASCO C2 data taken during Carrington rotation 2016.

wind emerging from the high-latitude coronal hole and its equatorward extension.

[14] Here 0431 + 206 was observed for an hour on the morning of 15 May 2002 when it lay 56 R_s off the east limb of the Sun at a latitude of 12° south. The ray path for the observation lay above an equatorial coronal hole (Figure 3a) and so relatively high-speed flow could be expected, though slower than the outflow above a large polar hole [e.g., *Kojima et al.*, 2004]. The observed correlation functions (Figure 3b) did indeed show a single peak at a time lag of about 2.5 s on parallel baselines of 1350 to 1490 km, corresponding to a plane-of-sky speed of about 550 km s^{-1} and an estimated outflow speed between 600 and 700 km s^{-1}. This range of speeds is quite typical of the outflow above coronal hole boundary layers [e.g., *Breen et al.*, 1999].

2.2. May 2004 Observations

[15] A more extensive series of observations were made on 12 May 2004, using the MERLIN antennas at Jodrell Bank (the Mk.2 telescope) and Cambridge and the Kiruna and Sodankylä antennas of EISCAT, all operating at 1418 MHz, as well as the Tromsø antenna of EISCAT, receiving on 930 MHz. During these observations 0319 + 415 lay 85 R_s off the northeast limb of the Sun at 56° north heliographic latitude. The parallel baselines ranged from 174 km between the EISCAT Tromsø and Kiruna sites to 1980 km between Cambridge and Sodankylä, as seen in the summary given in Table 1. As in 2002, the source was observed for an hour and the data were analyzed using a 20 min running window advanced in 5 min steps.

[16] On 12 May 2004 0319 + 415 lay 83.7 R_s off the northeast limb of the Sun at a latitude of 60°. The ray path for the observation lay mainly above a dark coronal hole, but as the solar magnetic equator was considerably tilted (and twisted) during the spring of 2004, the distance of the ray path into the coronal hole varied considerably (Figure 4a). The correlation functions (Figure 4b) showed a clear peak at a time lag of 2.47 to 2.71s, corresponding to plane-of-sky speeds of 729 to 746 km s^{-1}. In addition to this, the correlation functions for Jodrell-Sodankylä, Jodrell-Tromsø, and Cambridge-Sodankylä baselines showed a second, lower, peak in the correlation function at time lags of 3.20 to 3.48s, corresponding to plane-of-sky speeds of 554 to 612 km s^{-1}. Ulysses in situ measurements [e.g., *Riley et al.*, 1997; *Woch et al.*, 1997; *McComas et al.*, 2000] have shown that the solar wind speed over the polar crown is higher than that above the equatorward edges of polar coronal holes, while there have long been suggestions [e.g., *Nolte et al.*, 1976; *Kojima et al.*, 2004] that the outflow above narrow equatorial coronal holes may be slower than that above the polar crown. Possible interpretations of this observation are discussed in section 3.

2.3. May 2005 Observations

[17] Here 0319 + 415 was again observed on 13 and 14 May 2005, when the point of closest approach to the Sun of the ray path for the observation lay at a heliocentric distance of 83–84 R_s, 58–59° latitude off the northeast limb of the Sun. As in 2004 the coronal configuration was complex, to a degree which was surprising so late in the solar cycle, with a twisted streamer belt (Figure 5a). The ray paths for the observations lay mostly above the northern polar coronal hole, but some contribution from slow wind could be expected.

[18] The May 2005 observations were analyzed in a similar way to those from 2003 and 2004, but a 10 min sliding window was employed, advanced every 5 min, instead of the 20 min window previously used, it being found that the maximum correlations were generally greater when a shorter "snapshot" was used. The parallel baselines ranged from 1874 km to 1985 km on 13 May 2005 and from 1828 km to 2007 km on 14 May 2005, and the cross-correlation functions for observations made on 13 May and before 1410 UT on 14 May showed a consistent peak at 2.39 to 2.80 s, corresponding to plane-of-sky speeds of 708 to 803 km s^{-1}, with most observation intervals suggesting plane-of-sky speeds of ~730–770 km s^{-1} (Figure 5b).

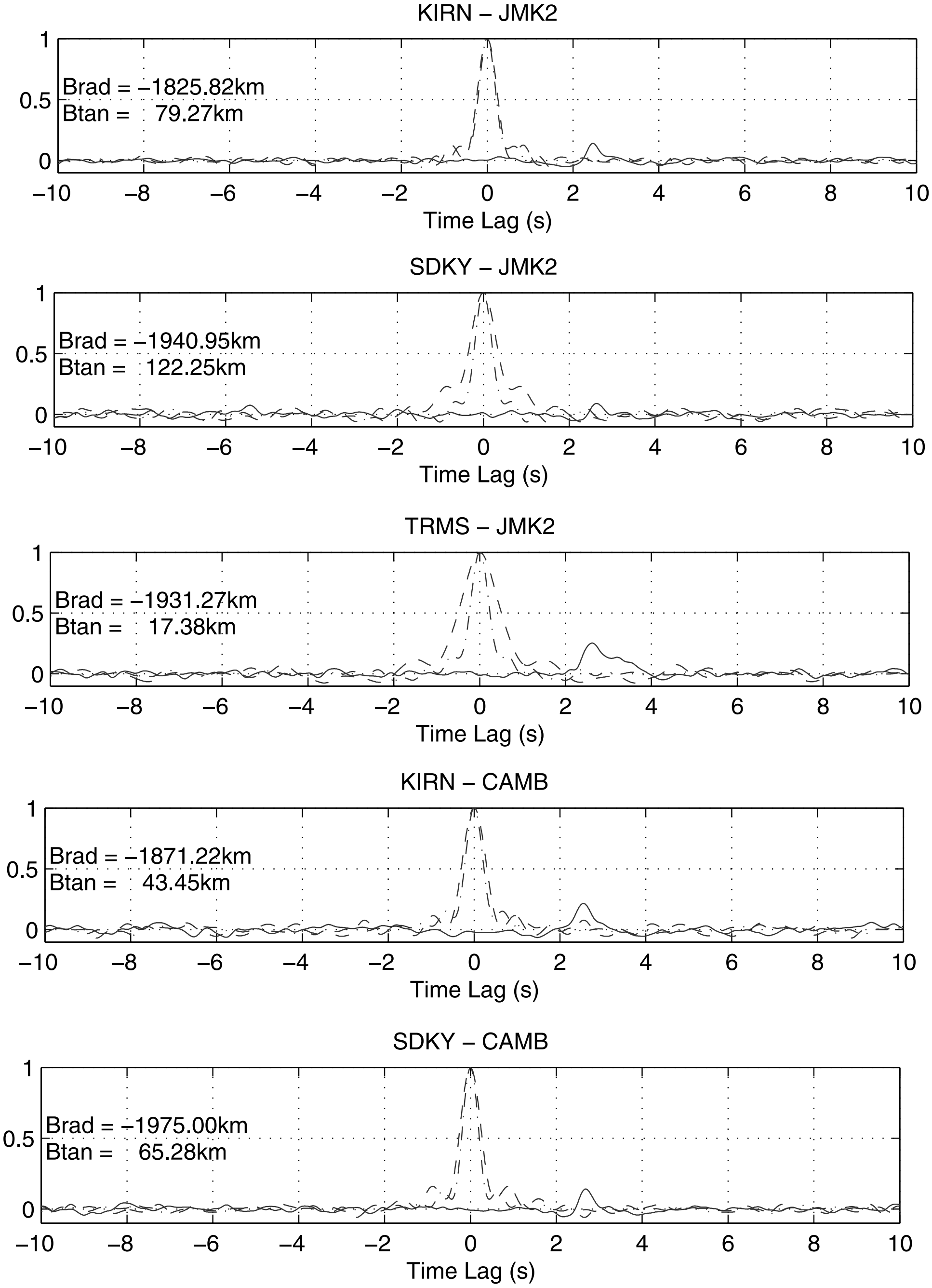

Figure 4b. Correlation functions for observations of 0319 + 415 using (top to bottom) Jodrell Bank and Kiruna, Jodrell Bank and Sodankylä, Jodrell Bank and Tromsø, Cambridge and Kiruna, and Cambridge and Sodankylä. The main peak in the correlation functions corresponds to a plane-of-sky speed of 731–746 km s^{-1}. A clear secondary peak, corresponding to a plane-of-sky speed of 581–585 km s^{-1} is apparent in the Jodrell Bank-Tromsø results.

Some of the observations also showed a secondary peak, corresponding to plane-of-sky speeds of 484–600 km s^{-1} (Table 1). If these two peaks are associated with outflow from higher- and lower-latitude regions of the polar coronal hole then they imply solar wind speeds of 743–846 km s^{-1} for the highest-latitude flow and 677–747 km s^{-1} for lower-latitude fast flow. Note, however, that the likely positions of fast stream boundaries assumed in this analysis can only be rough estimates, due to a gap in SoHO|LASCO coverage (Figure 5a).

[19] Observations of the same source with the Kiruna and Sodankylä antennas of EISCAT on parallel baselines of 161–162 km showed 56–64% correlation at time lags of 0.25–0.27s, corresponding to plane-of-sky speeds of 600–639 km s^{-1}, between the "fast" and "intermediate" velocities detected in the very long baseline observations. If the

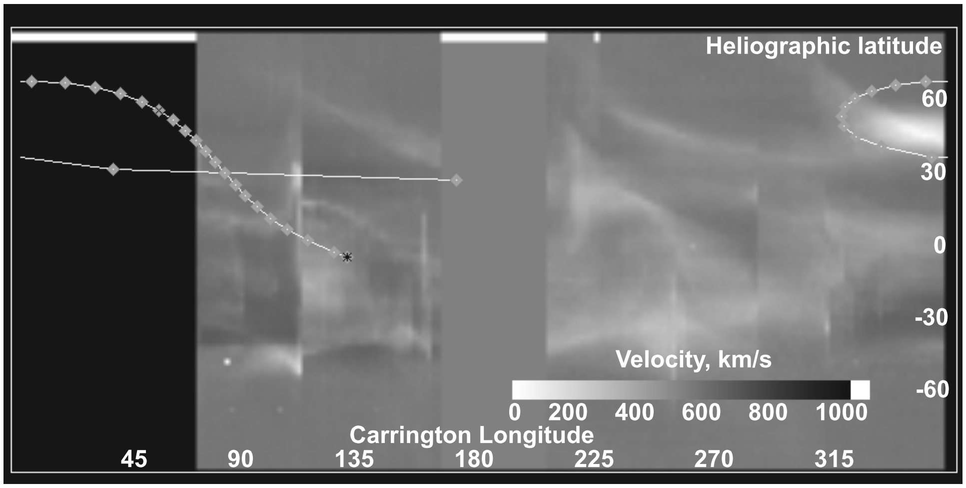

Figure 5a. Ray path for the observation of 0319 + 415 (CTA-21) on 13 May 2005, ballistically projected down to 2.5 R at a constant velocity of 800 km s^{-1} and overlaid on a map of white-light intensity in the corona at 2.5 R off the east limb of the Sun constructed from LASCO C2 data taken during Carrington rotation 2029.

stream which appears as fast wind in the shorter-baseline EISCAT (only) observations extended across the "fast" and "less fast" components seen in the extremely long baseline observations, then this would correspond to outflow speeds of 690–734 km s^{-1}. Fitting the EISCAT observations with a weak scattering model [*Coles*, 1996; *Klinglesmith*, 1997] indicated an outflow speed of 809 km s^{-1}, with a spread of speeds of 120 km s^{-1} in the fast wind and 400 km s^{-1} with a spread of 20 km s^{-1} in the slow wind, implying that the true solar wind speeds lay in the range 749–869 km s^{-1} for fast wind and 380–420 km s^{-1} for slow wind. These results are consistent with the extremely long baseline observations of the high-latitude fast wind and suggest that the EISCAT-MERLIN observations are capable of resolving the high- and low-latitude components of the fast wind separately, while EISCAT observations see the outflow as a single fast stream with a significant spread in velocities. As in the case of the 2004 observations, the extremely long baseline observations did not detect the slow outflow seen in the EISCAT data.

[20] The results from the observations on 14 May 2005 were very similar to those from the previous day up until 1410 UT, after which a sharp change in the time lag for maximum cross-correlation was seen (Table 1). We consider that this change is likely to be caused by the passage of an interplanetary magnetic cloud, probably associated with the solar eruption at 1645–1700 UT on 13 May. We will consider this issue in greater detail in a forthcoming paper.

3. Discussion

[21] Table 1 summarizes the plane-of-sky velocity results from this study. Fast and slow stream speeds are consistent between observations taken on different baselines and, in the cases where EISCAT-only observations of the same source on the same day are available, with the EISCAT IPS velocities. This gives us confidence in claiming that the correlation peaks seen in the extremely long-baseline observations are real and can be used to provide information on solar wind outflow speeds.

[22] There are two interesting differences between the extremely long baseline results from 2004 and 2005 and those seen in the corresponding EISCAT observations. The first of these is that several EISCAT-MERLIN observations show secondary fast peaks in the cross-correlation functions, indicating the presence of a second, slightly slower component of flow. The EISCAT observations, by contrast, show a "fast" peak which is generally intermediate in speed between the two components seen in the extremely long-baseline observations and which shows evidence of a significant spread in speed. These results are consistent with the improved velocity resolution which should arise from increasing the parallel baseline: they also suggest that there is genuinely a difference in character between the fast wind above polar coronal holes and above equatorward extensions of these holes. A recent study of IPS observations and Ulysses data by *Bisi et al.* [2006] suggests that the fast wind may show near-constant velocities with latitude at high latitudes, with a steeper gradient of velocity with latitude at lower latitudes. Several studies using Ulysses data have shown that fast wind from lower latitudes is slightly denser than the outflow from the polar crown [e.g., *Riley et al.*, 1997] so the roughly density-squared dependence variation of IPS production would lead to a greater bias toward lower-latitude regions of the "flanks" of the fast stream, and thus to the slowest regions, resulting in observations appearing to contain two discrete components of fast wind.

[23] The second difference between the results from the EISCAT-MERLIN and EISCAT-only observations is that the former only detected slow wind outflow in 2002 when a substantial proportion of the ray-path lay above bright corona, but the latter always showed some evidence of slow flow. It is not immediately apparent why the extremely long baseline observations do not show the slow component seen in the EISCAT results, but we hypothesize that an explanation may lie in slight differences in meridional

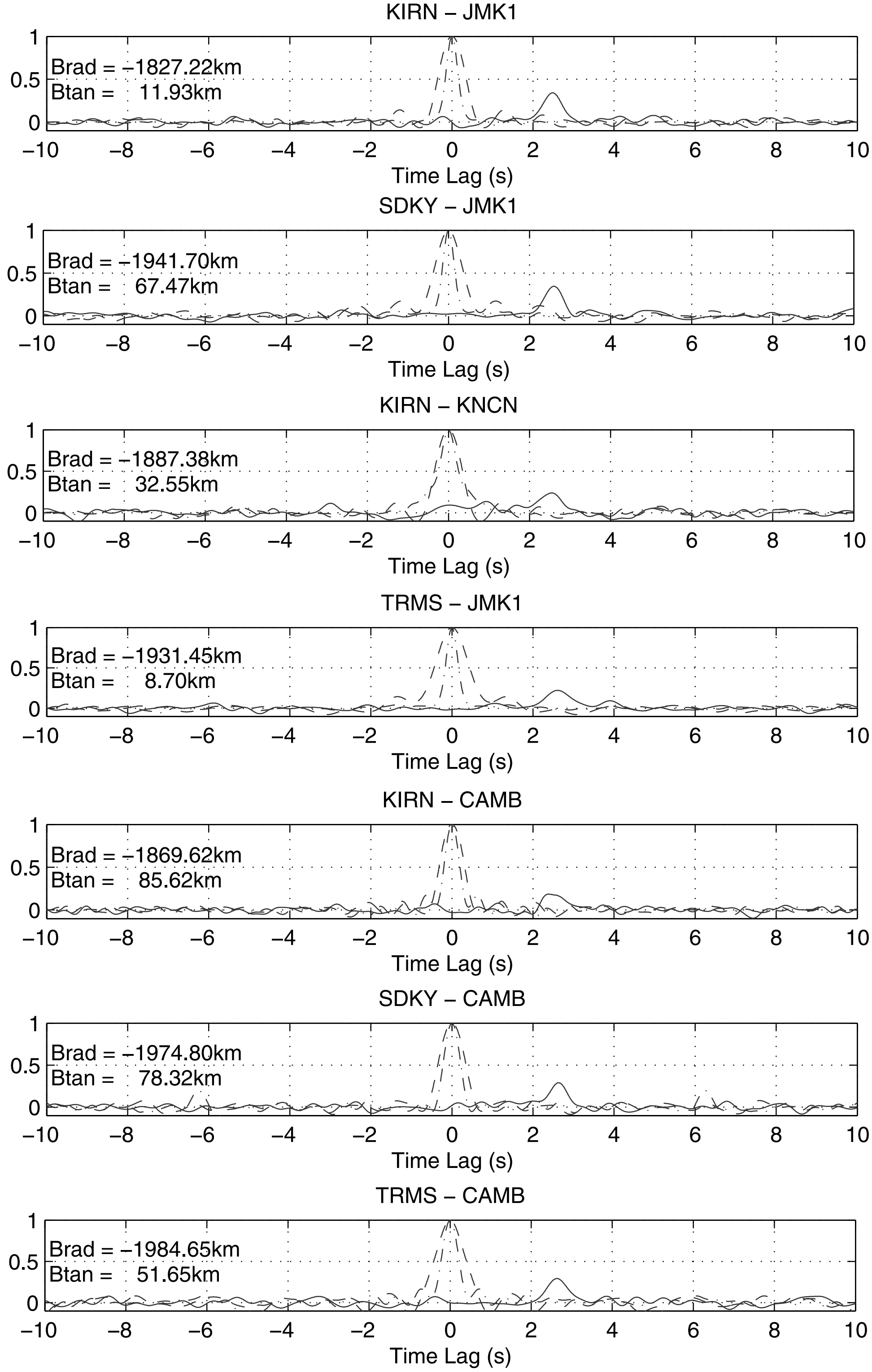

Figure 5b. Correlation functions for observations of 0319 + 415 using (top to bottom) Jodrell Bank and Kiruna, Jodrell Bank and Sodankylä, Jodrell Bank and Tromsø, Knockin and Kiruna, Cambridge and Kiruna, Cambridge and Sodankylä, and Cambridge and Tromsø. The main peak in the correlation functions corresponds to a plane-of-sky speed of 733–782 km s^{-1}.

(north-south) velocity between the fast and slow components. *Breen et al.* [1996a] suggested that the cross-correlation between the scintillation patterns observed at the two sites should be maximized if the projection on the plane of the sky of the baseline between the receiving sites was parallel to the projection onto the plane of the sky of the solar wind outflow, and *Moran et al.* [1998] used this approach to detect nonradial flow in the solar wind. As the parallel baseline increases so the sensitivity of the observation to meridional flow direction improves (as increasingly large changes in perpendicular baseline are required to produce the same angular deviation), if there is a slight difference in meridional direction between the fast and slow components, then this could provide an explanation as to why the extremely long baseline observations do not detect the slow flow seen on shorter baselines by EISCAT. An alternative explanation is that the irregularity pattern in the slow wind did not remain coherent over the time it took to drift from one ray path to the other and so did not give rise to a feature in the correlation function. This is possible but appears doubtful in the light of the clear slow wind correlation peaks seen in 2002 and, at present, the directional explanation appears more convincing. The evidence from extremely long baseline IPS observations for meridional flows in the solar wind will be discussed in a forthcoming paper.

[24] The outflow speeds inferred from these observations for fast flow are rather higher than those detected by Ulysses during its first (solar minimum) polar pass, though not significantly greater than those seen in earlier IPS results [e.g., *Breen et al.*, 1999]. There are two possible explanations for this: the use of time-lag for maximum correlation to determine the plane-of-sky speed introduces a potential bias to higher speeds (as discussed in section 1) while the irregularities themselves may be moving faster than the background flow. We intend to investigate both of these possibilities in a forthcoming paper.

4. Conclusions

[25] The results presented in this paper provide convincing evidence that the peaks in the cross-correlation functions between scintillation patterns detected up to 2000 km apart are real and are produced by scattering in the solar wind. The velocities deduced from the observations are consistent between entirely independent antenna pairs, strong evidence that the correlations seen arise from radio scattering in the solar wind.

[26] The use of extremely long baselines in IPS observations greatly improves the ability to resolve subtle variations in solar wind outflow speed. The results presented in this paper include clear observations of two different velocities of fast flow, which we interpret as respresenting outflow from the polar coronal hole (the faster flow) and from equatorward extensions of the polar hole. These measurements therefore provide strong support for the suggestion [e.g., *Kojima et al.*, 2004] that flow from equatorial coronal holes differs in character from the outflow above the polar crowns.

[27] In many ways the most surprising result of these observations the unexpectedly high degree of correlation observed between the scintillation patterns when the receiving sites are so widely separated. In the fast wind maximum correlations of 20–30% typically seen at time-lags of 2.5–2.7s on parallel baselines of 1800–1900 km, while in the slow wind significant correlation (up to 14%) was seen at time lags approaching 8 s, indicating that some proportion of the irregularity pattern giving rise to the scintillation must remain coherent for at least this time. We suggest that extremely long baseline IPS observations can provide a unique source of information on the temporal evolution of small-scale (∼100 km scale size) structure in the solar wind.

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