Comparison of Solar Wind Speed Estimates from Nearly Simultaneous IPS Observations at 327 and 111 MHz

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Abstract  Results are presented of a comparison between solar-wind speed estimates made using the time delays between three pairs of 327 MHz antennas at the Institute for Space-Earth Environmental Research (ISEE) of Nagoya University and by modeling the temporal power spectra observed with the 111 MHz Big Scanning Array (BSA) antenna at the Lebedev Physical Institute (LPI). The observations were made for 6 years in the descending phase of Solar Cycle 24. More than 100 individual records were obtained for the compact source 3C48 and the extended and anisotropic source 3C298. The correlation between the daily speed estimates from 3C48 is 50%. Their annual averages agree within the error estimates and show the expected solar cycle variation. However, the correlation between speeds from 3C298 is only 25% and their annual averages do not agree well. We investigate possible causes of this bias in the 3C298 estimated speeds.

Keywords  Solar wind · Interplanetary scintillation · Power spectra

1. Introduction

Interplanetary scintillation (IPS) is widely used for investigation of the solar wind. The main advantage of this method is that it allows for obtaining information about moving solar-wind plasma in a wide range of heliocentric distances and helio-latitudes including ranges that are inaccessible now for in situ measurements. Solar-wind speed can be measured if IPS is observed simultaneously at several spaced radio telescopes (Hewish and Dennison, 1967; Vitkevich and Vlasov, 1966; Armstrong and Coles, 1972). At present, only ISEE (Institute for Space-Earth Environmental Research) has three-site facilities for regular measuring of the solar-wind speed; the spatial distribution of the solar-wind speed and its evolution in the solar-activity cycles were investigated along the three recent decades (Kojima and Kakinuma, 1990; Tokumaru, Kojima, and Fujiki, 2012). Another possibility of
solar-wind speed estimates is based on the single-site measurements of the IPS temporal power spectra (Manoharan and Ananthakrishnan, 1990). Comparison between single- and three-site solar-wind speed estimates (Manoharan and Ananthakrishnan, 1990; Glubokova et al., 2011; Mejia-Ambriz et al., 2015) showed sufficiently good agreement. In this article we compare single-site and three-site speed estimates from a series of IPS observations during 6 years in the descending phase of Solar Cycle 24. In contrast with the earlier study (Manoharan and Ananthakrishnan, 1990), in which single- and three-site speed estimates at the same frequency 327 MHz were compared, speed estimates at two strongly different frequencies, 111 MHz and 327 MHz, are compared in this new study.

The motivations of our study are the following. The mean velocity estimates from single-station IPS can be sensitive to the radio source size, the solar-wind density spectrum, and, especially for low frequencies, to the distribution of turbulence along the line of sight. At the same time, high-frequency multi-station measurements are based on the time delay between IPS at different locations, so they are less sensitive to effects such as the size of the radio source or the power spectrum of the solar-wind density fluctuations. IPS velocity observations estimate the mean velocity over the line of sight. These can be tomographically inverted (Jackson et al., 1998) to provide a spatial map of the velocity for comparison with other solar observations. Future development of our analyses is directed to producing Carrington and daily velocity maps from the BSA LPI (Big Scanning Antenna of Lebedev Physical Institute) data using, in particular, tomographic inversion of mean velocity observations. In this context, the combination of BSA LPI and ISEE data would be very useful for two reasons: i) BSA LPI is more sensitive than ISEE allowing observation of a more rich population of scintillating sources and more detailed maps in adjacent solar-wind regions, ii) velocity and scintillation level of BSA LPI maps can be supplemented with ISEE data in the declination ranges higher than +42° and lower than -8° where BSA LPI data are not available.

2. Observations and Data Analyses

Below we compare single- and three-site data of the solar-wind speed for two strong scintillating radio sources 3C48 with closest approach to the Sun in summer time and 3C298 with closest approach in winter time.

One-site observations were conducted at the radiotelescope BSA LPI which is a beam array with 16384 half-wave dipoles. The geometrical size of the array is 200×400 m, the effective area is about 45000 m² towards zenith. After the general reconstruction of the antenna finished in 2012 (Shishov et al., 2016), BSA had independent beam systems. One system has 128 fixed beams. 96 of those beams are connected to digital recorders and cover declinations from -8° to +42°. Since 2014, IPS observations with BAS have been conducted around the clock under the program ‘Space Weather’. The antenna has a meridian passage, so every radio source at the sky is observed during approximately 3.5 minutes at half-power at the pole once a day. The central frequency of BSA is 110.3 MHz with a total bandwidth of 2.5 MHz. The signal is recorded by a digital recorder at a frequency of 10 Hz. The typical sensitivity during observations of radio sources scintillating on the interplanetary plasma is 0.2 Jy.

Multi-site observations of IPS at 327 MHz have been conducted regularly since the 1980s at ISEE, Nagoya University in Japan (Kojima and Kakinuma, 1990; Tokumaru, 2013). Cylindrical parabolic reflector antennas at Toyokawa, Fuji, and Kiso were employed for ISEE IPS observations in the analysis (Tokumaru et al., 2011). The dimensions of the
Toyokawa, Fuji, and Kiso are 108 m by 38 m, 20 m by 100 m, 27 m by 75 m, respectively. Phased array receivers are installed on these IPS antennas. The receiver bandwidth is set to be 10 MHz. The beam direction of the Toyokawa antenna is confined in the median and steerable between 60 degree south and 30 degree north with respect to the zenith, while those of Fuji and Kiso are steerable in both north-south and east-south directions. Thirty to forty compact sources within solar elongation < 90 degree are observed in a day using the three antennas simultaneously. IPS data are collected during about 3 minutes around the meridian transit at Toyokawa for a given source, and the sampling period is 20 ms.

The solar-wind speed $V_3$ is estimated using time delays of temporal cross-correlation functions calculated for simultaneous IPS records at three spaced radio telescopes of ISEE (Tokumaru, Kojima, and Fujiki, 2012). The solar-wind speed $V_1$ is estimated from temporal IPS power spectra measured at the radio telescope BSA LPI with a lower operating frequency of 111 MHz. The fitting procedure of $V_1$ is described in detail in earlier papers (e.g. Manoharan and Ananthakrishnan, 1990; Glubokova et al., 2011). We assume a spherically symmetric spatial solar-wind density distribution with a constant speed directed radially and with the power exponent $n = 3.6$ for the 3D spatial density turbulence spectrum. Furthermore, we assume the angular sizes $\theta_0 = 0.33$ arcsec for the source 3C48 and $\theta_0 = 0.52$ arcsec for the source 3C298 (Tyul’bashev et al., 2020). Following Manoharan and Ananthakrishnan, 1990; Glubokova et al., 2011) we assume that the angular brightness distributions are isotropic and Gaussian for both radio sources and the turbulence power spectrum is also isotropic. The speeds $V_1$ are found from the best fit of theoretical IPS power spectra to the speed as the only variable in the measured spectra. The temporal spectrum of scintillation is defined by the formula

$$P(f) = 4A\lambda^2 \int \frac{dz}{v(z)} \int dq \Phi_e(q) \sin^2 \left( \frac{q^2z^2}{2k} \right) F^2 \left( \frac{qz}{k} \right) |q| = \frac{2\pi f}{v(z)} ,$$

where $f$ is the time frequency, $\lambda$ is the radio wave length, $k = \frac{2\pi}{\lambda}$ is the wave number, the axis OZ is the direction along the line of sight towards the observed source (Figure 1), $z=0$ corresponds to the P-point, $A = 5 \times 10^{-25}$ cm$^2$, $r_0 = \sin \varepsilon \times 1$ AU, $v(z) = v \cos \varphi = \frac{v - v_0}{\sqrt{z^2 + r_0^2}}$ projection of the solar-wind speed on the image plane at the point ($r, z$), $v$ is the

**Figure 1** Sketch for the observation of source scintillations in presence of interplanetary plasma inhomogeneities (a case of spherical distribution of the plasma).
solar-wind speed (≈ 400 km/s near the Earth), $q$ is the spatial frequency, $q_\parallel$ is the component of the spatial frequency along the line of sight, $q_\perp$ is the component in the image plane perpendicular to the line of sight, $q = \sqrt{q_\parallel^2 + q_\perp^2}$, $\Phi_e (q) = C q^{-n}$ is the spatial spectrum of fluctuations of the electron density of the interplanetary plasma, $n$ is the turbulence index, $F (q) = \left( \frac{1}{2\pi} \right)^2 \int d^2 \theta \exp (-i k q \theta) I(\theta)$ is the spatial spectrum of the observed radio source, $I(\theta)$ is the brightness distribution across the source, $z' = z + \cos \varepsilon \times 1$ AU.

The data from BSA LPI were processed as follows:

1. For every source and for every day of observation, the time when the source passed the radiation pattern peak was predicted theoretically.

2. The source record duration of BSA is $\frac{425+16 \cos \delta}{10 \cos \delta}$, where $\delta$ is the declination of the radio source. The interval with the length which is twice longer than the source record duration and the center at the calculated time of the source passage through the pattern peak was chosen for analysis. This interval is chosen to guarantee that it contains the full record of the radio source (the predicted and actual time of the source passage through the pattern peak do not usually coincide due to the ionosphere influence or other reasons).

3. The source center was calculated (the actual time of the source passage through the pattern peak). To do this, the considered interval was split into 32 smaller intervals of the same length about 30 sec ($\frac{425+16 \cos \delta}{10 \cos \delta}$ to be more exact). The signal was averaged at those 32 intervals to compensate noise and scintillation, and to save the information of the time of the source passage through the pattern peak. Then the convolution of the obtained array and the radiation pattern $\left( \sin \frac{x}{x_j} \right)^2$ at the interval $(-\pi, \pi)$ was calculated: $s_i = \sum_{j=0}^{16} u_{i+j} \left( \sin \frac{x_j}{x_j} \right)^2$, where $u_k$ is the average signal at the $k$th interval ($k=1, \ldots, 32$), and $x_j = -\pi + \frac{\pi}{8} j$. Note that $\left( \sin \frac{x_j}{x_j} \right)^2 \to 1$ if $x_j \to 0$. To find the center more exactly, the parabola passing points $(i-1, s_{i-1})$, $(i, s_i)$, $(i+1, s_{i+1})$, where $s_i$ is the convolution maximum, was defined. The parabola vertex was considered as the source center.

4. The temporal scintillation spectrum was calculated using the fast Fourier transform of 2048 consecutive signal values around the source center. The obtained spectrum was split into 256 intervals each of which had 4 points. Each interval was averaged, and thus the final spectrum had 256 points.

5. Then the obtained spectrum was compared to theoretical spectra calculated using Equation (1) for the fixed values of the turbulence index ($n = 3.6$), angular size of the source, and its elongation $\varepsilon$ (angular distance between the directions to the Sun and to the source) closest to those at the observation times. The comparison was made for the frequency range between the 4th point of the spectrum from the lowest one and the point where the difference between the current spectrum value and the background noise value dropped by 30% compared to the difference between the top and bottom levels. The top level was defined as the average value of the points between the fourth and the eighth of the obtained spectrum. The bottom level was defined as the average value of the last 20 points. The first point from the end for which the condition ‘the values of this point and the two closest left points exceed the level $[bottom\_level + 0.7 \times (top\_level – bottom\_level)]$’ is true was chosen as the end point to compare the spectrum obtained from observations and the theoretical spectra. We chose the end point in this way because we cannot define exactly the angular size of a radio source, and we cut the part which is influenced by the angular size a lot. We do not consider the first three points, because the values for those are influenced by ionospheric scintillations. The best theoretical spectrum was chosen using the least squares method (Figure 2). The speed for
Comparison of Solar Wind Speed Estimates

Comparison of Solar Wind Speed Estimates

The chosen theoretical spectrum was considered to be the estimation of the solar-wind speed at the time of the observation for the source.

Theoretical spectra were calculated with assumptions similar to those in Glubokova et al. (2011, 2013):

i) The spatial spectrum of turbulence follows a power law of the form: $\Phi_e(q) = Cq^{-n}$, where $C$ is so-called structure constant.

ii) The structure constant depends on the distance from the Sun according to the power law: $C \sim r^{-4}$.

iii) The solar-wind speed is constant, and its flow direction is radial.

iv) The brightness distribution across the source is Gaussian, spherically symmetric: $I(\theta) = \exp\left(-\frac{\theta^2}{\theta_0^2}\right)$, where $\theta_0$ is the source radius at the level of $\frac{1}{e}$. Glubokova et al. (2013) defined $\theta_0$ as the radius at the level of $\frac{1}{e}$, and therefore $I(\theta) = \exp\left(-\frac{\theta^2}{2\theta_0^2}\right)$; however, in this study we used the former definition. So, the spatial spectrum of the source will be $F(q) \sim \exp(-\frac{1}{2}\theta_0^2k^2q^2)$.

Theoretical spectra were calculated in advance for the value of the turbulence index $n = 3.6$, for the values of angular sizes from $0''$ to $1''$ with a step of $0.01''$, for the values of elongations from $25^\circ$ to $60^\circ$ with a step of $1^\circ$, and for the values of the solar-wind speeds from 200 to 1200 km/s with a step of 10 km/s. The integration over $z$ was made between the limits $z_{\text{min}} = -\cos \varepsilon \times 1$ AU and $z_{\text{max}} = 2$ AU with the step of $\Delta z = 0.1$ AU. Other $z_{\text{max}}$ values are discussed below. The integration over $q_{\perp}$ was made between the limits of 0 and $10^{-4} \text{ m}^{-1}$ with a step of $10^{-6} \text{ m}^{-1}$.

We have also compared the speed estimations obtained at BSA and the corresponding estimations obtained at ISEE. The method for estimating the solar-wind speed at ISEE is described in Tokumaru, Kojima, and Fujiki (2012). In this study, not all the speed estimations but those selected by the criteria described below were taken into consideration:

i) Speed estimations were obtained for the days when the elongation of a given source ranged from $25^\circ$ to $60^\circ$. This is because at small elongations scintillation becomes the saturated mode and is suppressed by the effect of the source angular size. The accuracy of high-frequency ISEE data drops outside the elongation of $60^\circ$. For this reason we have a lack of ISEE speed estimates for comparison. Besides, at large elongations a model asymmetry may arise due to the influence of the near-Earth region.

ii) To analyze the scintillations, calculations of the dispersions at the peak of the radiation pattern and at its zero levels using the three-point median filter with a step of 2 were done (among the 1st, 3rd, and 5th points of the initial array, the median point was considered in calculating the variance, then among the 2nd, 4th, and 6th points the median was chosen, then among the 3rd, 5th, and 7th points the median was chosen, and so on). If the ratio of the variance in the peak to the smallest variance in one of the zero levels was less than 2, this observation was not considered.

iii) If the number of the end point for comparison between observed and theoretical spectra was 12 or less, this observation was not considered either. The narrowest temporal spectra were removed to exclude possible contribution from ionospheric scintillation.

iv) The rest of the spectra were classified as ‘good’ and ‘bad’. To do this, the variance for each spectrum was calculated (the root-mean-square deviation from the selected theoretical spectrum between the 4th point and the end point). Then, for every source, the average variance in each year was calculated. The spectra for which the variance was...
Figure 2. An example of data processing. The top panel is the initial record of 3C48, $t_{\text{theor}}$ and $t_{\text{real}}$ are the theoretical right ascension (r.a.) calculated from the coordinates of the source and the r.a. determined from the convolution maximum. The inset in the top panel shows the data for the 2048 points at the central portion used in the calculation of the power spectrum. The bottom panel is the observed temporal power spectrum of the source 3C48 (blue) with the fitted theoretical spectrum (orange).

1.5 times higher than the average variance were classified as ‘bad’, the rest were classified as ‘good’. During the comparison of estimations from BSA to those from ISEE only ‘good’ spectra were considered. This criterion is used to remove automatically the records which coincide with the calibration sequences taking place at the radio telescope several times per day.

v) For the remaining points, those which were too far from another point were also removed. To do this, the approximation by a function $y = x + b$ was made, where $x$ is the speed obtained at BSA, $y$ is the speed obtained at ISEE. The value of $b$ was defined using the least squares method. Then the root-mean-square deviation of the points from the straight line was calculated. If the deviation of a certain point exceeded the root-mean-square deviation by more than a factor of 3, this point was removed.

The signal to noise (S/N) ratio, which is the ratio between low frequency IPS level ($S$) and high-frequency noise level ($N$), is related to the criterion for the end point of the spectrum. The condition at the end point ‘$[\text{bottom}_\text{level} + 0.7(\text{top}_\text{level} - \text{bottom}_\text{level})]$’ corresponds to the relation $N+0.7(S-N) > BN$, where $B$ is the boundary constant. One can find from this relation the boundary value $S/N > (B-0.3)/0.7$. In our simulations, we assume the value $B \approx 30$, which gives $S/N > 40$. Typical values of $S/N$ are $S/N > 500$ for the source 3C48 and $S/N > 200$ for the source 3C298 at the elongations of about $25^\circ$, which means that the S/N boundary condition is fulfilled for almost all measured IPS power spectra.

The fraction of records removed by the above criteria are the following: 185-196 records during a year were not in the elongation limits (criterion 1), about 3% (criterion 2), about
10% (criterion 3), about 6% (criterion 4) were removed. Furthermore, 100 – 140 records for 3C48 and 70-120 records for 3C298 during a year were not considered due to the lack of ISEE data. Initial data for ‘good’ spectra are available at site of Pushchino Observatory (see the online data in http://prao.ru/English/index.php).

We analyzed the IPS observations obtained at BSA LPI for a 6-year period from 2014 to 2019, which corresponds to the descending phase of Solar Cycle 24. All the IPS records with source elongation angles between 25° and 60° are analyzed for each year; corresponding heliocentric distances of line of sight proximate point (P-point) are within the range 0.4 and 0.8 AU. The P-point helio-latitudes decrease from 50° to 10° with an increase of the solar elongation for each source.

Simultaneous IPS observations are carried out at three spaced ISEE radio telescopes Toyokawa, Fuji, and Kiso. The solar-wind speed vector $V_3$ is estimated from the temporal shifts of three IPS cross-correlation function maxima knowing the geometry of the radio telescope locations. One can expect that the speed $V_3$ is less sensitive to the source size and to the model of the solar-wind plasma turbulence.

### 3. Estimates of the Solar-Wind Speed from the IPS Power Spectra

The data for solar-wind speed IPS estimates are presented in Figures 3 and 4 for the sources 3C48 and 3C298, respectively. ISEE speed $V_3$ and BSA LPI speed $V_1$ are shown on the vertical and horizontal axes, the symbols for years from 2014 to 2019 appear by the the panels. One can see from the figures that all speed estimates increase with the decrease of
Figure 4  The same as Figure 3 but for the source 3C298.

Table 1  Additional information not included in Figures 1-5. The table shows yearly averaged speeds and mean-square deviations for sources 3C48 and 3C298 in km/s and includes the number of points for each source in each year.

|       | 2014     | 2015     | 2016     | 2017     | 2018     | 2019     |
|-------|----------|----------|----------|----------|----------|----------|
| BSA 3C48 | 368±24   | 385±29   | 479±32   | 565±15   | 629±9    | 623±13   |
| RMS   | 127      | 96       | 137      | 98       | 58       | 76       |
| ISEE 3C48 | 369±16   | 485±34   | 511±27   | 571±22   | 623±15   | 627±19   |
| RMS   | 84       | 113      | 114      | 139      | 98       | 112      |
| Number of points | 28      | 11       | 18       | 40       | 43       | 34       |
| BSA 3C298 | 510±29   | 615±44   | 500±31   | 667±35   | 806±37   | 754±33   |
| RMS   | 184      | 199      | 140      | 152      | 134      | 136      |
| ISEE 3C298 | 417±12   | 530±30   | 512±35   | 496±44   | 543±38   | 517±38   |
| RMS   | 73       | 132      | 155      | 192      | 138      | 158      |
| Number of points | 39      | 20       | 20       | 19       | 13       | 17       |

the solar-activity level. We calculated the cross-correlation coefficient \( \rho_c \) for the data on Figures 3 and 4, they are equal to \( \rho_{c48} = 0.48 \) and \( \rho_{c298} = 0.25 \). Not very high cross-correlation values mean that we have a rather big velocity spread on the background annual trend. The cross-correlation coefficients calculated over the one-year interval are even lower than the values found for the whole interval. The spread is evidently connected with noise in daily velocity estimates. One can see from Table 1 that the velocity variances in BSA LPI and ISEE data are in average close to each other. Figure 5, in which speeds averaged over the
years are shown, also illustrates the tendency of the speed evolution with the activity cycle for both radio sources: the averaged speed increases from minimal values of about 400 km/s for activity maximum in 2014 to more than 600 km/s for activity minimum in 2019. The diagonals in Figure 3 and 4 pass through the mid of the data cloud, and that means that the speeds $V_1$ and $V_3$ on average are close to each other. Figure 5 also shows the approximate coincidence between average values $V_1$ and $V_3$. One can see from Figure 5 that the BSA LPI speed estimates for the source 3C48 are slightly lower than the ISEE speed estimates, but this relation is opposite for the source 3C298. We can assume that the difference between $V_1$ estimates for the compact radio source 3C48 and the more extended radio source 3C298 can be explained because of a not completely known model of the modulating plasma distribution along the lines of sight. To demonstrate this, we calculated the difference $\Delta V = (V_1 - V_3)$ by modeling the IPS power spectra with different upper integration limit in Equation 1. The dependence of $\Delta V$ on the upper integration limit $z_{\text{max}}$ is presented on Figure 6 for both radio sources in the range $1 \text{ AU} \times \cos 45^\circ < z_{\text{max}} < 2 \text{ AU}$. Figure 6 shows that speed estimates are not sensitive to $z_{\text{max}}$, if $z_{\text{max}} \geq 2 \text{ AU}$. The difference $\Delta V$ is very small, about several percent, in the case of the compact source 3C48 by $z_{\text{max}} = 2 \text{ AU}$. In the case of the more extended source 3C298, the difference is minimal, about 10-20% when integrating between symmetrical limits $-\cos \varepsilon < z < \cos \varepsilon$. Such an interpretation is confirmed by the calculation of the model IPS power spectra considering the enhanced density plasma slab located near the Earth orbit. The IPS power spectra for the model with the slab are presented in Figure 7a and b at the elongation $60^\circ$ for the sources 3C48 and 3C298, respectively. The slab thickness is 0.2 AU, the constant $C$ (absolute density variance) in the slab is four times higher than in the spherically symmetric model. We see from Figure 7 that introduction of the slab results in broadening of temporal spectra in comparison with the spherically sym-

Figure 5  Yearly averaged speeds for ISEE observations in the vertical axis vs. the corresponding BSA LPI speeds in the horizontal axis. The symbols are labeled on the panel.
metric model. The broadening, which is equivalent to increase in the estimated speed $V_1$ is comparatively small for the compact source, Figure 7a, and much more pronounced for the extended source, Figure 7b.

It should be noted that the speed data on the year 2015 deviates slightly from the general trend, at least for the source 3C48. This peculiarity is somehow connected to the highest IPS level (scintillation index averaged over the year) in Solar Cycle 24 observed in 2015 (Tyul’bashev et al., 2020).

Data in Table 1 show that the yearly average BSA LPI and ISEE speeds are in close agreement for the source 3C48, but the BSA LPI speed is systematically biased to higher velocities for the source 3C298 excluding the year 2016. 3C298 bias averaged over all data in Table 1 is about 140 km/s that is about 20% from the mean speed, this value increases when approaching the solar minimum.

4. Discussion

The synchronous increase of the speeds $V_1$ and $V_3$ in Figures 3-5 is in a good agreement with the evolution of the solar-wind global structure in the solar-activity cycle. Indeed, in situ Ulysses measurements (McComas et al., 2003) and many years of IPS observations (Tokumaru, Kojima, and Fujiki, 2012; Manoharan, 2012) have shown that the spatial solar-wind structure is close to spherical symmetry in the period of solar maximum, and has a bimodal character with low speed, 300-400 km/s, at low helio-latitudes, and high speed, 700-800 km/s, at high helio-latitudes in the period of solar minimum. The region of transition from the slow to fast winds is located at helio-latitudes of about 20°. A larger and larger number of days from the observation period for a given year has lines of sight passing through the solar-wind regions of the fast streams emanating from polar coronal holes when the solar-activity level decreases, and this explains the speed increase between 2014 and 2019 in Figures 3-5.

As mentioned above, Manoharan and Ananthakrishnan (1990), Glubokova et al. (2011), Mejia-Ambriz et al. (2015) have found reasonably good agreement between $V_1$ and $V_3$ estimates. Our study is based on a richer statistics that allows for the comparison of single-
Figure 7  (a) Model IPS power spectra with the dense slab near the Earth (yellow) in comparison with the spherically symmetric model (blue) for the source 3C48. (b) The same as (a), but for the source 3C298.

and three-site speed estimates at maximum and descending phases of a solar-activity cycle, which can be considered as the base for using single-site IPS measurements for studying the dynamics of the solar-wind speed spatial distribution.

Using different behaviors of the $\Delta V$ values presented in Figure 6, one can define the boundary between compact and extended sources. The angular size of the Fresnel scale from Equation 1 is equal to

$$\theta_{Fr} = (2k \ 1 \ \text{AU} \ \cos \epsilon)^{-1/2}. \quad (2)$$

The value of $\theta_{Fr}$ is $\theta_{Fr} \approx 0.3$ arcsec for a radio frequency 111 MHz at the mean elongation $\epsilon = 45^\circ$. Thus, the source with $\theta_0 \leq \theta_{Fr}$ (3C48, $\theta_0 \approx 0.33$ arcsec) can be classified as compact, while the source with $\theta_0 > \theta_{Fr}$ (3C298, $\theta_0 \approx 0.52$ arcsec) can be considered as extended. The main contribution in radio wave modulation is produced by the region located
in the vicinity of the P-point for the compact source and by the region located between the observer and the P-point for the extended source. It follows from Figure 6 that the best accuracy for the solar-wind speed estimates from the IPS temporal power spectra will be achieved with the upper integration limit \( z_{\text{max}} = 2 \, \text{AU} \) in the case of compact sources and with the symmetric integration limits \( \pm \cos \varepsilon \) in the case of extended sources. Using symmetric integration limits would be a way to reduce the \( V_1 \) speed bias for the extended source. The difference in the \( V_1 \) vs. \( V_3 \) relation between the extended source and compact source seems to be an interesting finding of the above result. We think that the enhanced \( V_1 \) spread and some systematic bias between \( V_1 \) and \( V_3 \) for the extended source are caused by a deviation of the modulating plasma distribution on the line of sight from a spherically symmetric one. The layers located symmetrically relative to the P-point produce a comparable contribution in the IPS temporal power spectrum in the case of a compact source, while the IPS level is more sensitive to the region located between the P-point and the observer for the extended source, in particular to the solar-wind plasma near the Earth orbit. An increase in the absolute turbulence level in a region close to the Earth leads to an enrichment of the IPS power spectrum by higher frequencies, and that results in an increase in the visible speed \( V_1 \).

In the above simulation of IPS power spectra, we assumed that the turbulence is isotropic. Chang et al. (2019), Chashei, Kojima, and Tokumaru (2000), Chashei et al. (2000) consider more complicated turbulence models with anisotropic density irregularities when modeling theoretical temporal IPS power spectra. In particular, Chashei et al. (2000) have shown that turbulence anisotropy can result in a difference in \( V_1 \) and \( V_3 \), such that \( V_1 < V_3 \). To check the influence of anisotropy on the results of \( V_1 \) estimates, we include in our theoretical model the turbulence anisotropy assuming that density irregularities are elongated in the radial direction with an axial ratio 1.5. They concluded that an anisotropy of this kind does not influence practically the \( V_1 \) estimates. Indeed, the mean increase in \( V_1 \) for the overall records is about 7 km/s for the source 3C48 and about 10 km/s for the source 3C298. A rather good correspondence between BSA LPI and ISEE data with an isotropic model together with a weak \( V_1 \) increase for a 1.5 ratio show that the irregularities do not differ strongly from 1 at heliocentric distances about 0.5 AU, in contrast with considerable radial elongation in the range of the solar-wind formation (Armstrong et al., 1990; Chashei, Kojima, and Tokumaru, 2000).

In order to investigate the influence of the model source diameter on \( V_1 \), we calculated the theoretical IPS power spectra for source sizes 0.25 arcsec and 0.45 arcsec, and compared the values \( V_1 \) with \( V_1 = 370 \, \text{km/s} \) found earlier for the source size 0.33 arcsec. The results of the simulation \( V_1 = 350 \, \text{km/s} \) for the size of 0.25 arcsec and \( V_1 = 420 \, \text{km/s} \) for the size of 0.45 arcsec indicated that possible changes in \( V_1 \) are less than 10%. The changes in the angular size for the anisotropic source 3C48 in the range of elongations 25° - 60° according to our estimates are within the above angular size limits.

Another reason for the speed bias is the influence of the source anisotropy. For modeling the IPS power spectra, we assume a simple one-component symmetric model of the source 3C298 angular structure. However, the interferometric study by Fanti et al. (2002) shows that the shape of this source is more complicated. It consists of two nearly symmetric components of angular size 0.5 arcsec, the same as we used, separated by 1.6 arcsec in E-W direction. The observed bias between \( V_1 \) and \( V_3 \) can depend on the angle between the solar-wind velocity vector and the major axis of the radio source. This angle changes during the passage of the source past the Sun. If the solar-wind speed is directed perpendicular to the source major axis, the IPS level is defined by two approximately equal sources. The IPS of two sources will be uncorrelated because the angular separation between them is greater than the Fresnel angle. As a result, two IPS temporal spectra will be similar and the total IPS...
level decreases twice in comparison with the IPS level of the single source. If the solar-wind speed is parallel to the source major axis, the temporal power spectrum will contain a low frequency component corresponding to the separation between the source components that will lead to an increase in $V_1$ and, consequently, to an increase in the bias. We calculated the visible speed $V_1$ for the source with an intermediate angular size of 1 arcsec and found an increase in mean bias from about 140 km/s, see Table 1 for the size of 0.5 arcsec, to about 300 km/s. It should be noted that the angular size of 0.5 arcsec (Tyul’bashew et al., 2020) used for 3C298 in our study is based on the analysis of the scintillation index, and this IPS characteristic, in contrast to the temporal spectrum, is not sensitive to the source anisotropy due to a 2D integration of the spatial spectrum. One can obtain the following spatial spectrum for the double source:

$$F^2(q) = \exp(-q^2 \theta_0^2) \cos^2(z q \theta_1) \tag{3}$$

where $\theta_0 \approx 0.5$ arcsec is the angular size of two components and the angle $\theta_1$ corresponds to half of E-W angular separation between the centers of two components, $\theta_1 \approx 0.8$ arcsec. The first factor in Equation (3) corresponds to the symmetric angular distribution of the sources brightness, while the second factor describes the separation between two components. Using Equation 3 in Equation 1 for the temporal power spectrum, we can find the correct $V_1$ estimate, if the angle $\psi$ between the direction of the solar-wind speed and the source elongation is known from the observation geometry. In particular, the velocity will be parallel to the source axis ($\psi=0^\circ$) for equatorial observations and perpendicular ($\psi=90^\circ$) for polar observations. This angle changes within the limits $23^\circ < \psi < 90^\circ$ in our observations. The low frequency knee in the temporal power spectrum is located in the frequency range $0.1$ Hz – $0.2$ Hz at small $\psi$ values. However, we address in the analysis only higher frequencies, $f > 0.3$ Hz, in order to avoid a possible contribution from ionospheric scintillation that, according to our observational experience with BSA LPI, can be significant just near the maximal elongations $\varepsilon \approx 60^\circ$ and smallest angles $\psi \approx 23^\circ$. For this reason, exact estimates of the speed $V_1$ anisotropic source model in Equation 3 for the specific source 3C298 is not possible at our operating frequency 111 MHz. Further work is needed to study the interesting problem of temporal IPS spectra for strongly anisotropic sources or with sources having smaller angular separation between components or with observations at higher radio frequencies.

According to our estimations the density of scintillating sources on the sky is about 1 source per square degree, so BSA LPI can observe about several thousand sources daily. The recent survey at the close frequency 162 MHz (Chhetri et al., 2018) confirms this estimate and shows that about 1/3 of these sources have angular sizes of 0.3 arcsec or even less. Thus, the number of sources like 3C48 observed daily is about 1000. As a prospect, we are going to consider the population of compact sources in obtaining mass unbiased speed estimates. The IPS study for more extended sources is also of interest because: i) such sources are sensitive to the plasma close to the Earth orbit and ii) it will give the possibility for velocity bias corrections based on source statistics.

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