Observations of interplanetary scintillation with a single-station mode at Urumqi

Li-Jia Liu¹, Xi-Zhen Zhang¹, Jian-Bin Li¹, P. K. Manoharan², Zhi-Yong Liu³ and Bo Peng¹

¹ National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; liulijiaredstar@yahoo.com.cn
² Radio Astronomy Center, TIFR-NCRA, P. O. Box 8, Ooty 643 001, India; mano@ncra.tifr.res.in
³ National Astronomical Observatories/Urumqi Observatory, Chinese Academy of Sciences, Urumqi 830011, China

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Abstract  The Sun affects physical phenomena on Earth in multiple ways. In particular, the material in interplanetary space comes from coronal expansion in the form of inhomogeneous plasma flow (solar wind), which is the primary source of the interplanetary medium. Ground-based Interplanetary Scintillation (IPS) observations are an important and effective method for measuring solar wind speed and the structures of small diameter radio sources. We discuss one mode of ground-based single-station observations: Single-Station Single-Frequency (SSSF) mode. To study the SSSF mode, a new system has been established at Urumqi Astronomical Observatory (UAO), China, and a series of experimental observations were successfully carried out from May to December, 2008.

Key words: methods: data analysis — solar wind — methods: numerical

1 INTRODUCTION

Radiation from a distant compact radio source is scattered by the density irregularities in the solar wind plasma and produces a random diffraction pattern on the ground. The motion of these irregularities converts this pattern into temporal intensity fluctuations which are observed as interplanetary scintillation (IPS). IPS observations with ground-based telescopes can estimate the solar wind velocity and also the structures of distant compact radio sources (Hewish & Symonds 1969; Armstrong & Coles 1972). This kind of measurement, though indirect, can give information on the solar wind out of the ecliptic plane and close to the Sun, where direct spacecraft measurements are not possible (e.g. Ma 1993). Here we concentrate on extracting information on solar wind speed from IPS observations with a single ground-based telescope.

There are two modes for observing the IPS phenomenon with a single-station: Single-Station Single-Frequency (SSSF) and Single-Station Dual-Frequency (SSDF). Since the discovery of the IPS phenomenon (Hewish et al. 1964), many countries began making IPS observations with the single-station method, such as the Cambridge telescope in Britain (Pruvis et al. 1987), Ooty radio telescope in India (Swarup et al. 1971), and the Puschino observatory in Russia (Vitkevich et al. 1976). One
can use the power spectral fitting method to obtain the solar wind speed. The multi-station method, as used in Japan, is a three-station system (Kojima et al. 1995) where one can measure the projected solar wind speed directly. China began IPS studies in the 1990s with the phased array mode of the Miyun Synthesis Radio Telescope (MSRT) at 232 MHz. Located at the Miyun observatory (Wang 1990) in Beijing, it used the SSSF mode (Wu et al. 2001). Recently, a new IPS observation system using the 50 m parabolic radio telescope, which is based on the SSDF mode at S/X and UHF bands, started construction to serve the National Meridian Project of China.

In this paper, the theory of IPS, the technique, and the numerical simulation method of SSSF mode are introduced in Section 2. The observations made at the UAO are reported in Section 3. Finally, conclusions are drawn in Section 4.

2 THEORY

2.1 The Theory of IPS

Interplanetary scintillation is the name given to the intensity fluctuations of small diameter radio sources which are caused by density inhomogeneities in the solar wind. Figure 1 shows the geometry of IPS. The distance between the Sun and $Q$ is $r$, and $r = \sin(\varepsilon)$ AU.

The degree of scintillation is characterized by the scintillation index $m$ (Cohen et al. 1967), which increases with decreasing distance $r$ until it reaches a maximum $m_{\text{max}}$ at $r_{\text{min}}$. In this case, $r_{\text{min}}$ changes with frequency, and $r_{\text{min}} \approx 0.2$ AU for meter wavelengths (Manoharan 1993). We have

$$m = \frac{\sqrt{\sigma_{\text{on}}^2 - \sigma_{\text{off}}^2}}{C_{\text{on}} - C_{\text{off}}},$$

where $C_{\text{on}}$ ($C_{\text{off}}$) is the average intensity of the on-source (off-source) signal, and $\sigma_{\text{on}}^2$ ($\sigma_{\text{off}}^2$) is the square of the rms of intensity scintillation. Here, the on-source case refers to the telescope pointing at the radio source, and off-source to the telescope pointing at the background sky away from the source, being in the opposite pitching direction to where the radio source moves. IPS is strongest in the region nearest the Sun, where we have the “strong scintillation region.” In most of interplanetary space, IPS is weak, which is called the “weak scintillation region” (Zhang 2007). In the weak
scintillation region, \( m^2 \ll 1 \). The weak scintillation region is observed at \( r > r_{\text{min}} \) and strong scintillation is observed at \( r < r_{\text{min}} \). Previous studies show that the statistics of the scintillation are simply related to those of the turbulent interplanetary medium by a linear relationship, if the scintillation is weak (Coles & Harmon 1978). In the “strong scintillation region,” however, the relationship is not straightforward, and the present study always deals with the weak scintillation case. The distance regime for the weak and strong regions relates to observing frequencies. Table 1 shows the relationship between the frequency and distance regimes (Zhang 2007).

In the weak scintillation region, where the radio wave can be treated as a plane-wave, and the Born approximation is applicable (e.g. Walker et al. 2004), the interplanetary medium can be considered to be made up of many thin layers perpendicular to the line-of-sight. When the radio wave passes through these layers, only the phase of the radio wave changes, while the amplitude of the radio wave stays the same. This is called the “thin screen approximation,” which is commonly used in the study of the ionosphere, interplanetary medium, and interstellar medium.

### 2.2 SSSF Mode

SSSF refers to observing the IPS with a single station at a single frequency. There are two methods to obtain the solar wind speed from SSSF mode observed spectra: the spectral multi-parameter model-fitting, and the characteristic frequencies method. The former can measure the speed by adjusting the main parameters of the solar wind to fit the observed scintillation power spectra. The parameters are: \( \alpha \)-power law index of the spatial spectrum of electron density, AR-axial ratio of solar wind irregularities, and \( V \)-solar wind speed. The latter can be determined by calculating two characteristic frequencies of the spectra: the Fresnel knee frequency \( f_F \), and the first minimum of the spectra \( f_{\text{min}} \). Then the solar wind speed can be calculated by either of the formulae shown below (Scott et al. 1983)

\[
V = f_F \sqrt{Z \pi \lambda},
\]

\[
V = f_{\text{min}} \sqrt{Z \lambda},
\]

where \( \lambda \) is the observing wavelength, and \( Z \) is the distance between \( Q \) and the Earth as shown in Figure 1. According to weak scintillation theory and thin screen approximation theory, in the weak scintillation region, the observed scintillation can be regarded as the sum of contributions from all the thin layers. For a layer of thickness \( dz \), the distance from the layer to the Earth is \( Z \), \( V_x(z) \) is the solar wind velocity projected onto the plane perpendicular to the direction \( z \), and the spectra observed at the Earth should be (e.g. Scott et al. 1983; Ye & Qiu 1996):

\[
M_s(f, Z) dz = \frac{2 \pi f (\lambda r_e)^2}{V_x(z)} \int_{-\infty}^{\infty} \Phi_{ne}(k_x, k_y, k_z = 0, Z) \times F_d F_s dk_y dz,
\]

where,

\[
F_d = 4 \sin^2 \left[ \frac{(k_x^2 + k_y^2) \lambda Z}{4 \pi} \right],
\]
\[ F_s = \exp \left[ -(k_x^2 + k_y^2)Z^2 \theta_0^2 \right], \quad (6) \]

and \( F_d \) and \( F_s \) are the Fresnel propagation filter parameter and the squared modulus of the radio source visibility, respectively. We assume that the brightness of the radio source has a symmetrical-Gaussian distribution, i.e. \( B(\theta) = \exp \left[ -\left( \frac{\theta}{\theta_0} \right)^2 \right] \). \( \theta \) is the full width at half maximum of the source, so we have the angular diameter of the scintillating source \( \theta_0 = \frac{\Theta}{2.35} \) (Manoharan & Ananthakrishnan 1990). \( \Phi_{ne} \) is the electron density power spectrum at distance \( z \),

\[ \Phi_{ne}(k_x, k_y, k_z = 0, Z) = Tr^{-4} \left[ k_x^2 + (k_y/AR)^2 \right]^{-\alpha/2}, \quad (7) \]

where the amplitude of fluctuations in the electron density \( T \) is a constant. The spectrum obtained from the Earth should be the sum of Equation (4).

\[ M_s(f) = \int_0^\infty M_e(f, Z) dZ. \quad (8) \]

One can see that \( M_s(f) \) depends on the solar wind parameters: axis ratio \( AR \), power law index \( \alpha \), and the solar wind speed \( V \). Previous studies show that, when other parameters are fixed, \( AR \) mostly affects the low frequency part of the power spectrum; when \( AR \) increases, the low frequency part becomes steeper, but the high frequency part changes slightly. Furthermore, \( \alpha \) mostly affects the high frequency part of the spectra; when \( \alpha \) increases, the high frequency part attenuates quickly, but the low frequency part does not evidently change. The solar wind speed \( V \) mostly affects the Fresnel knee \( f_F \) and the first minimum of the spectra \( f_{min} \); the two frequencies both become larger when \( V \) increases. Taking appropriate values to fit the observed spectra, one can obtain the parameters of the observational data. Firstly, one fits the Fresnel knee according to \( f_F \) and \( f_{min} \), then fits the attenuated high part and the flat low frequency part (Ye & Qiu 1996).

Figure 2 is an example of the SSSF mode, where the parameters used are \( \lambda = 92 \text{ cm}, \alpha = 3.5, AR = 2.0, V = 600 \text{ km s}^{-1} \), and \( \theta_0 = 0.02'' \). One can get \( f_F = 1.05 \text{ Hz} \), then from Equation (2) we can obtain the solar wind speed of 598.7 km s\(^{-1}\), which fits the simulated value well.

![Fig. 2 Simulation results of SSSF mode, where \( \lambda = 92 \text{ cm}, \alpha = 3.5, AR = 2.0, V = 600 \text{ km s}^{-1}, \) and \( f_F = 1.05 \text{ Hz} \).](image_url)
Table 2 Information on the Current Receivers at UAO

| Wavelength (cm) | Frequency range (MHz) | System temperature (K) | Noise injection (K) |
|-----------------|-----------------------|-------------------------|---------------------|
| 92              | 317–337               | 145                     | 44                  |
| 30              | 800–1200              | 130                     | 40                  |
| 18              | 1400–1720             | 22                      | 3.7                 |
| 13              | 2150–2320             | 75                      | 40                  |
| 6               | 4720–5110             | 21.5                    | 1.7                 |
| 3.6             | 8200–8600             | 40                      | 21                  |
| 1.3             | 22100–24000           | 190                     | 14                  |

Table 3 Key Parameters of IPS Observations with the 25 m Radio Telescope Performed in 2008 at UAO

| Observing wavelength (cm) | Dates (mm/dd in 2008) | Integration interval (ms) |
|---------------------------|-----------------------|--------------------------|
| 49                        | 5/20–5/23             | 1/10/20                  |
| 18                        | 9/25–9/27             | 0.25                     |
| 13                        | 11/27–12/2            | 0.25                     |
| 6                         | 5/20–5/23             | 1/10/20                  |
| 3.6                       | 5/20–5/23             | 1/10/20                  |

Table 4 Details of the Observed Sources

| Source | Angular diameter (*) | Flux density (1.4 GHz) [Jy] | Distance from the Sun (2008 Dec.) [AU] |
|--------|----------------------|----------------------------|----------------------------------------|
| 3C345  | 0.30                 | 7.1                        | 0.3                                    |
| 3C286  | 0.30                 | 14.9                       | 0.3                                    |
| 3C147  | 0.15                 | 22.9                       | 0.7                                    |

3 OBSERVATIONS

3.1 Instrument Setup

The IPS experimental observations were performed from May to December 2008 with the 25 m radio telescope at UAO, China, in SSSF mode. The UAO radio telescope is located to the south of Urumqi city, at 87 deg East longitude and 43 deg North latitude. Table 2 shows the general information for the 25 m radio telescope receivers currently available at UAO.

The 6 cm and 18 cm bands have dual-polarization cooled receivers, while the 3.6 cm and 13 cm bands have single polarization cooled receivers. Table 3 summarizes some information on the IPS observations we carried out. Compact, strong radio sources selected for observation are listed in Table 4.

Test observations were carried out at 49 cm, 18 cm, 13/3.6 cm and 6 cm. Each time, the observation was performed on-source for 10 min, and off-source for 5 min. The integration intervals were 1 ms, 5 ms and 10 ms.

According to the characteristics of the IPS phenomenon and synchrotron radiation of radio sources, it would be easier to detect IPS at lower observing frequencies. Because the radio environment at UAO is not good at 92 cm and 49 cm, it is seldom used. Consequently, we concluded that the 18 cm band is the only window suitable for catching IPS at UAO.
After a series of experiments, the 18 cm dual-polarization receiver at UAO was chosen for the observations, and a data acquisition/receiving system was also established. The data sampling rate is adjustable with an 8-bit quantification rate. Being a real-time display system, data quality can be monitored during the observation, so parameters like gain or target source can be adjusted immediately. In order to minimize the RFI (radio frequency interference) influence in the observing window, a band-pass filter was added to the output of IF (intermediate-frequency) of the 18 cm receiver. Figures 3 and 4 show a characteristic spectrum of the 18 cm receiver before and after the filter was added.

The entire bandwidth at UAO is 500 MHz, with some interference in the band as shown in Figure 3. The central frequency of the filter was set to 420 MHz, and the 3 dB bandwidth was 100 MHz, with an insertion loss of 3 dB. It can be seen from Figure 4 that the filter works well, and the interference in this band has been effectively filtered out. The band selected was the part with the lowest interference in the whole band. The filter introduces some loss, so we added an amplifier before the radiometer but after the filter.

Figure 5 is a flowchart of the data acquisition instrument. There is a 0–40 dB step attenuator after the frontend of the 18 cm receiver, with the attenuation step of 1 dB. A PCI8335 high-speed AD image acquisition card was added to our industrial computer, with an input voltage range 0–5 V.
The AD precision of this card is 16 Bit, with a maximum sampling rate of 250 kHz, and the buffer (FIFO: first in first out) is 8 Kbytes. The radio meter has two channel outputs. The band of channel A is 5–500 MHz, and the band of channel B is 400–950 MHz. The input power for the two channels is the same: –20 dBm to –60 dBm, and the output voltage range of the radiometer is 0–5 V. Channel A was used during our observation. Raw data, together with information on the target source like observing time, source coordinates, etc., are recorded by the data acquisition software.

During the observations, each time, the on-source observations were 10 to 15 min, and the off-source observations were 5 min. In view of the different distances and orientations with respect to the Sun, we observed different sources at different times. The total observing time each day was about 2–3 h.

3.2 Data Analysis

In order to eliminate the interference, besides the hardware method (adding a filter), a software solution has also been developed. Figure 6 is a flowchart of the data analysis. First, the raw data observed are played back on the screen to identify the parts with lower noise and one subtracts the noise using software, i.e. the slowly changing component is subtracted from the raw data, and assigned to DATA1. The DATA1 set is then compared with 3 times the rms error of a long span of data to eliminate outliers. Points with absolute values higher than 3 rms are omitted and replaced by the average value of the preceding and following data points, then these data are assigned to DATA2. Because the original integration interval of an observation is 0.25 ms, we take the average of four contiguous points to form a 1 ms integrated dataset, which means that 10 ms of data are obtained by averaging 40 contiguous points. These data are assigned to DATA3.

In the filtering and re-sampling step, DATA3 values are convolved with a rectangular window of suitable width corresponding to the re-sampling rate. The time series is then broken into blocks of length 8192 samples (for 1 ms data approximately 10 s long), the mean value of each block is subtracted and the block is then multiplied by a triangular weighting function, which is unity at the center and falls to zero at both ends. The result is then altered by Fourier Transformation (FT) to obtain a power spectrum.
3.3 Observational Results

A series of experimental IPS observations were made at UAO. Figure 7 shows raw data obtained on 2008 Nov. 27. The targeted source was 2MASX J18141308–1755351. Its flux density at 1.4 GHz is 5.39 Jy, and its projected distance from the Sun is 0.23 AU.

One can see that the on-source part and off-source part are obviously identified. The fluctuations of the two parts are almost the same, which indicates that the IPS phenomenon at the time was weak, which is identical to the power spectrum in Figure 8. It is clear that the Fresnel knee $f_F$ and the first minimum frequency $f_{\text{min}}$ are difficult to identify, indicating that there was little scintillation.

Figure 9 shows a model-fit result of the data taken on 2008 Dec. 1, at a wavelength of 18 cm, with an integration interval of 1 ms. The scintillation index is in the range 0.6 to 0.7 (there is some interference in the off-source part). The model-fit method is the same as that of the SSSF simulation. According to Equations (4) to (8), the best parameters can be obtained by fitting with the observed spectra. The target source was 3C345, with a flux density at 1.4 GHz of 7.1 Jy. The solid line shows the observed power spectrum, and the dashed line is the result of parametric model-fitting, with the fitting parameters: $A\dot{R} = 1.2$, $\alpha = 3.1$, and $V = 400 \text{ km s}^{-1}$. According to the OMNI database, the
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Fig. 8 Power spectrum result of the target source 2MASX J18141308–1755351 at 18 cm, observed on 2008 Nov. 27. The x-axis is frequency, and the y-axis is power.

Fig. 9 Model-fitting result on 3C345, observed on 2008 Dec. 1 at 18 cm. The solid line shows the observed spectrum of the data, and the dashed line is the result of parametric model-fitting.

solar wind speed for the whole day ranged between 300 to 400 km s\(^{-1}\), which is in agreement with the model-fitted value.

4 CONCLUSIONS

SSSF mode IPS observations have been studied by quite a number of pioneers (Manoharan et al. 1994). Its instrument, data acquisition, and data reduction are simple. For this mode, high signal-to-noise ratio (at least 25dB) data are needed (Tokumaru et al. 1994). When AR increases, \( f_F \) becomes ambiguous, and \( f_{\text{min}} \) is easily affected by noise, AR and \( \varepsilon \). The fitting accuracy is affected by variations in the solar wind parameters, which makes it hard to calculate the solar wind speed accurately.

Compared with the SSSF mode, the SSDF technique gives the solar wind speed via the first zero point of the cross correlation spectrum, and \( f_{\text{zero}} \) is most apparently affected by the velocity of the
solar wind rather than other parameters (i.e. Zhang 2007). It has the advantages of higher accuracy in the measurement of solar wind speed and higher stability against the wide variations in solar wind parameters. However, it introduces more complexity in the observing instrument and data taking system, so it is not used as widely as the SSSF mode.

A new system that is under construction at the Miyun station near Beijing, China, with a 50 m radio telescope, adopted the SSDF mode to do the IPS observations. There are some lessons to be learned from the observations with the UAO 25 m radio telescope, such as that the integration time of the receiver system which should be sufficiently short because the IPS phenomenon varies rapidly. This implies that the effective receiving area of an IPS antenna should be large enough to ensure that the system has a high instantaneous sensitivity and its band width should be well-matched to the system time resolution. A bandpass filter and low noise amplifiers (LNA) would be needed to reduce the system noise level.

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