Telescopes for IPS Observations

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***Abstract*- The sun especially the solar wind have influenced our Earth in many ways, and observing the solar wind is an important method to study the solar-earth environment. Interplanetary Scintillation (IPS) observations are an effective method of monitoring solar wind, forecasting the solar-terrestrial space weather and studying the structures of the long distance compact radio sources. Since the discovery of Interplanetary Scintillation, many countries began to use this method to study the solar wind and the interplanetary plasma, so some appropriative radio telescopes were built to achieve these goals. In this paper, we will review some typical IPS radio telescopes and also the current status of IPS study in China.**

I. INTRODUCTION

The solar-terrestrial environment is filled with solar wind plasma. The solar wind is the material in interplanetary space that comes from coronal expansion in the form of inhomogeneous plasma flow. The solar wind is the main source of interplanetary medium, which connects the variations in the Sun with terrestrial physical phenomena.

Radiation from a distant compact radio source is scattered by the density irregularities in the solar wind plasma, which produces a random diffraction pattern on the ground. The motion of these irregularities converts this pattern into temporal intensity fluctuations that are observed as interplanetary scintillation (IPS). There are two ways to observe the solar wind: spacecraft measurement and ground-based measurement. Using spacecraft is a direct method to observe the solar wind, but it has one limitation. It can only travel near the ecliptic plane and sample from a stable orbit, while the solar wind phenomenon is very stochastic [1]. Ground-based IPS observations can measure the solar wind at any distance and also for a long period [2], so it is an effective method to study on the Sun-Earth system [3].

Since the discovery of IPS in 1964, many countries like Britain, former Soviet Union , America, India and Japan have begun to observe this phenomenon. China began IPS studies in the 1990's with the phased array mode of the Miyun Synthesis Radio Telescope (MSRT) at 232 MHz [4]. It used the Single-Station Single-Frequency (SSSF) mode. Recently a new IPS observation system using the 50 m parabolic radio telescope, which is based on the Single-Station Dual-Frequency (SSDF) mode at S/X and UHF bands, is built to serve the National Meridian Project of China .

The theory of IPS, SSSF mode and SSDF mode are discussed in section 2, section 3 reviews the IPS radio telescopes and the conclusions are presented in section *4*.

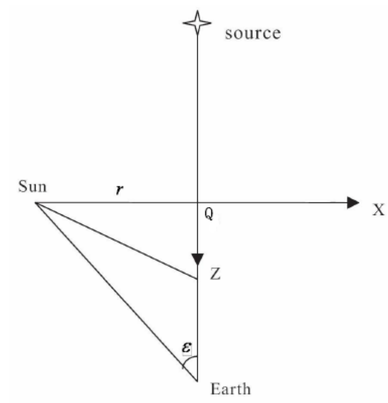

Figure 1 Geometry of IPS Concept

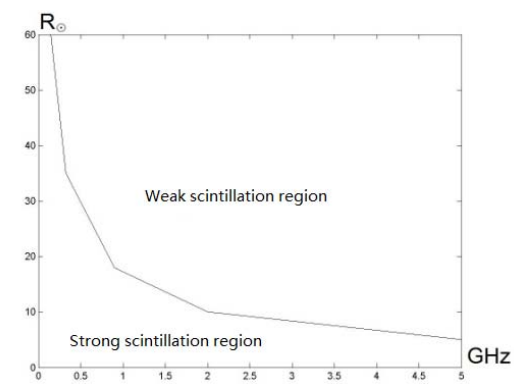

Figure 2 Frequency vs. distance for weak and strong scintillation regions

II. THEORY

A The Theory of IPS

Figure 1 shows the geometry of IPS. The *z*-axis is along the line-of-sight, and the *x*-axis is in the direction perpendicular to the *z*-axis pointing away from the Sun, with the *y*-axis being normal to the paper. Q is the point closest to the Sun along the line-of-sight, and ε is the elongation angle, Sun-Earth-source. r is the distance between the Sun and Q. z is the distance between Q and the Earth.

The degree of scintillation is characterized by the scintillation index *m*, which increases with decreasing distance r. The expression of *m* is shown below [5]:

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$$m = \frac{\sqrt{\sigma_{on}^2 - \sigma_{off}^2}}{C_{on} - C_{off}} \qquad (1)$$

Where C_{on} (C_{off}) is the average intensity of the on-source (off-source) signal, and σ_{on}^2 (σ_{off}^2) is the intensity-squared error of the on-source (off-source) signal. Here the on-source means the telescope pointing at the radio source, and off-source means the telescope pointing at the background sky away from the source. IPS is maximized in the region near the Sun, where we have the "strong scintillation region". In most of interplanetary space IPS is weak, which is called the "weak scintillation region". In the weak scintillation region $m^2 \ll 1$. 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 [6] [7]. In the "strong scintillation region", however, the relationship is not straightforward, and most of the present study deals with the weak scintillation case. The distance regime for the weak and strong regions is related to observing frequencies. Figure 2 shows the relationship between the observing frequency and the distance regimes according to reference [8]. For example, when observing at 327MHz, the regime for the strong and weak regions is: putting the Sun at the center, within 35 $R_\odot$ is the strong scintillation region, and beyond is the weak scintillation region ($R_\odot$ is the radius of the Sun).

B The Theory of SSSF Mode

One way to observe IPS is with the Single Station Single Frequency (SSSF) mode. There are two methods to obtain the solar wind speed from the SSSF mode by the observed IPS power spectra: the spectral multi-parameter model-fitting, and the characteristic frequencies methods. 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: α -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 measure the speed by calculating two characteristic frequencies of the spectra: the Fresnel knee frequency f_F corresponding to Fresnel diffraction theory, and f_{min} the first minimum of the spectra. Then the solar wind speed can be calculated by either of the formulae shown below [1]:

$$V = f_F \sqrt{Z\pi\lambda} \qquad (2)$$

$$V = f_{\min} \sqrt{Z\lambda} \qquad (3)$$

where λ is the observing wavelength, and z is the distance between Q and the Earth according to Figure 1.

C The Theory of SSDF Mode

Being different from the SSSF mode, the SSDF mode adopts simultaneous Single Station Dual-Frequency method to measure the solar wind speed, by deriving the first zero point of the normalized cross-spectrum (NCS) at two different frequencies, which wavelengths are λ_1 and λ_2, and $\lambda_1 > \lambda_2$. The expression for solar wind speed using the SSDF mode is shown below [8] [9]:

$$V = Af_{zero} \sqrt{Z\lambda_1} \qquad (4)$$

where A is a correction factor which varies slightly with the solar wind parameters and is usually set to be 1.1. In most cases, taking A=1 will cause no more than a 10 % error in the measured solar wind speed, which is acceptable [8] [9]. SSDF mode can measure the solar wind speed more precisely, for f_{zero} is only sensitive to the solar wind speed V.

III. REVIEW OF IPS TELESCOPES

A Some Typical IPS Telescopes

IPS is a fast changing phenomenon; it needs the observing instrument to have a short integration time. That is why the Interplanetary Scintillation was first discovered by the 3.6-ha array in Cambridge [10], which is shown in Figure 3.

From the 1970s, some countries like India and Japan began to observe IPS on regular basis. Figure 4 and Figure 5 show the Ooty radio telescope in India and the four stations IPS system in Japan. The two systems are both parabolic cylinder telescopes, which can have a large collecting area in order to observe more radio sources every day.

Figure 3 The Cambridge 3.6-ha array

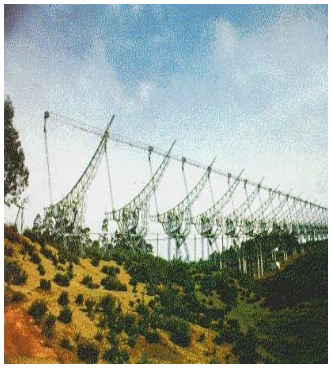

Figure 4 The Ooty radio telescope in India

Figure 5 The four stations of STELab IPS radio telescopes in Japan

Recently, some new types of IPS radio telescopes were built along with the development of new data processing method. Like the Murchison Widefield Array (MWA) (shown in Figure 6) in Western Australia [11] and the Mexican Array Radio Telescope (MEXART) in Mexico (shown in Figure 7) [12]. These two telescopes are both constructed with dipole antennas, and have simple front end and complicated data processing back end.

B IPS Telescopes in China

IPS observations have been carried out in China for decades, and some achievements have been made [4][13][14].

China began IPS studies from the 1990s first with the phased array mode of the Miyun Synthesis Radio Telescope (MSRT), which observed at 232MHz. It can investigate the region R>60 $R_\odot$. The equivalent diameter of MSRT is about 47m. Figure 8 shows the distribution of the 28 radio telescopes of MSRT.

Figure 6 The picture of MWA

Figure 7 The picture of MEXART

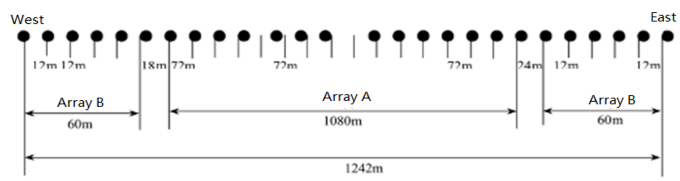

Figure 8 The distribution of the 28 radio telescopes of MSRT

Figure 9 The 25m radio telescope in Urumqi

Figure 10 The 50m radio telescope in Miyun

From 2008, a new SSSF mode IPS observation system was built in Urumqi with the 25m radio telescope in Xinjiang Province China (Figure 9). After a series of experiments, the 18 cm dual-polarization receiver was chosen for the observations, and a data acquisition/receiving system was also established. This is the first SSSF mode IPS observation system in China to carry out quasi regular IPS observations [13][14][15].

In order to explore the IPS ability of domestic radio telescopes, since 2010, some experimental observations also carried out with the 40m radio telescope in Kuming [16].

Recently a new IPS observation system using the 50m parabolic radio telescope also located in Miyun is built to serve the National Meridian Project of China (Figure 10). This system adopts the SSDF observation mode. It has two dual bands, which are S/X and UHF [17]. This observation system is constructed for purpose of observing the solar wind speed and scintillation index by using the normalized cross-spectrum of simultaneous dual-frequency IPS measurement. The system consists of a universal dual-frequency front-end and a dual-channel multi-function back-end specially designed for IPS. This radio telescope is now the only SSDF IPS telescope around the world.

IV. CONCLUSIONS

Nowadays human activity in the outer space is becoming more and more frequently. So the forecasting of space weather becomes more and more important than in the past. IPS observations provide us an effective way to monitor the Sun and solar wind, so it is necessary to build particular instrument to carry out IPS observations. The IPS observation in China is still under developing, and the observation will try to be a routine observation in the future.

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