

# New Interplanetary Scintillation Array in China for Space Weather

Yihua Yan <sup>1,2</sup>, Wei Wang <sup>1</sup>, Linjie Chen <sup>1</sup>, Fei Liu <sup>1</sup>, Lihong Geng <sup>1</sup>, Zhijun Chen <sup>1</sup>

<sup>1</sup> CAS KLSA, NAOC, Beijing 100101, China

<sup>2</sup> School of Astronomy and Space Sciences, University of CAS, Beijing 100049, China

E mail ([yyh@nao.cas.cn](mailto:yyh@nao.cas.cn))

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**Abstract.** Interplanetary Scintillation (IPS) is a useful ground-based method to investigate solar wind structure and its parameters through the scintillation of distant, compact radio sources at radio wavelengths. Current worldwide IPS facilities include both single-site systems (which are typically a large telescope or array), and multi-site systems (which are typically more varied telescope/array sizes). To combine the advantages of both of these system types, we propose a new design for the IPS telescope in China, implementing a large collecting area at one main site, with smaller collecting areas at the other sites. This new IPS telescope concept is a part of the Phase-II Meridian Space Weather Monitoring Project under the 2016-2020 National Infrastructure Program in China to be constructed in near future. Some specifications and basic considerations of this telescope are described in this paper.

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## 1. INTRODUCTION

There are two ways to investigate the basic properties of the solar wind plasma in the inner heliosphere: (i) through direct *in-situ* measurements, or (ii) via indirect remote-sensing observations (*e.g.*, Tokumaru 2013). Compared to *in situ* measurements, which typically require expensive missions, ground-based observations are usually more economically effective. The interplanetary scintillation (IPS) of compact radio sources at meter to centimeter wavelengths is an effective tool to investigate the structures and properties of the solar wind throughout the inner heliosphere. Observations of IPS, usually at a frequency of 327 MHz, have been carried out since 1970s in the world. Observations of IPS are extremely useful in determining the physical parameters and structure of the solar wind throughout the inner heliosphere (*e.g.*, Manoharan 1993, Kojima *et al.* 1995, Breen *et al.* 2002, Manoharan & Agalya 2011, Bisi *et al.* 2007, 2010, Chang *et al.* 2016, and Morgan *et al.* 2018).

It is desirable to achieve high sensitivity of the telescope for observations of IPS. Therefore, a sufficiently-large collecting area is necessary for an IPS-capable telescope. There are different technical solutions to carry out observations of IPS: a traditional steerable parabolic radio telescope, a very large cylinder antenna, or an array type system made up of many small antennas/receivers. At present, the main IPS dedicated telescopes are the Institute for Space-Earth Environmental Research (ISEE), Nagoya University stations in Japan, the Ooty radio telescope (ORT) in India, and the Mexican Array Radio Telescope (MEXART) in Mexico. Many other radio-telescope systems are used mainly on a 'campaign' basis.

The ISEE IPS telescopes consist of four cylinder antennas with reflector size 88m\*38m, 20m\*100m, 20m\*100m, and 27m\*73.5m. After the 1990s, the observations were improved with innovative methods for data analysis (*e.g.* Tokumaru 2013). Even though the number of radio sources used for ISEE observations of IPS are fewer than that for the ORT (below), it has been very successful to study the three-dimensional (3-D) structure of CMEs and their formation processes (*e.g.* Tokumaru *et al.* 2000, 2003, 2005, 2006, 2007). However, it is expected that the 3-D solar wind structure would be better modeled and reconstructed with more radio sources employed (*e.g.* Jackson *et al.* 2010, 2011, 2013).

The ORT is an offset parabolic cylinder, 530m\*30m in size, which was commissioned in 1970 (Swarup *et al.* 1971). ORT has been recently upgraded to the Ooty Wide Field Array (OWFA), which has both a larger instantaneous bandwidth as well as a

significantly-larger field of view (Subrahmanya *et al.*, 2017). Its sensitivity is upgraded to 8 mJy with 1 second integration time, and more than 10,000 radio sources can be observed by the OWFA. In the distribution of radio sources, more than 80% of them can be used as IPS sources (*i.e.*, they exhibit scintillation because they have one or more compact components). These sources are valuable to study solar-wind transients (*e.g.*, Coronal Mass Ejections-CMEs and interplanetary Co-rotating Interaction Regions-CIRs) as well as the ambient solar wind.

The MEXART consists of a 64 × 64 (4096) full-wavelength dipole antenna array, operating at 140 MHz, with a bandwidth of 2 MHz, occupying about 9,660 square meters (69 m × 140 m) (*e.g.*, Mejia-Ambriz 2010). Only some strong IPS radio sources can be detected at present because the sensitivity is currently limited.

Miyun Synthesis Radio Telescope (MSRT), located at the Miyun observatory in Beijing, China was used in the phased array mode at 232 MHz for IPS studies in the 1990s (Wu *et al.* 2001). Later, an IPS-observation system using the 50m parabolic radio telescope, used S/X and UHF bands for IPS experiments in China (Liu *et al.* 2010).

Compared with single-site observations, the flow velocities of the solar wind can be derived from simultaneous observations of IPS at multi-stations (*e.g.* Kakinuma *et al.* 1973). The projected solar wind speed and other parameters can be determined directly by cross-correlations of the multi-site data, whereas for single-station observations of IPS, these parameters have to be deduced from proper models of the solar wind. In order to derive 3-D solar wind structures, it is very important and necessary to have large collecting area so as to observe more radio sources. For observations of IPS with more than one frequency, one can achieve higher accuracy in the calculation of the characteristic frequency, reduce the effects from the variation of the solar wind parameters, and obtain higher sensitivity (Scott *et al.* 1983, Zhang 2007).

A well-used IPS space-weather technique actually applies Computer Assisted Tomography to reconstruct the 3-D solar wind structure (*e.g.*, Jackson *et al.* 2010, 2011, 2013, Bisi 2016, and references therein). It would benefit from receiving direct results from observations of a larger number of radio sources. Therefore, a new IPS telescope solution is proposed which includes one main site and two sub-sites. At the main site there are three cylinder antennas placed side by side each having a large size of 140m in N-S direction and 40m in E-W direction, plus an available 20m parabolic antenna (dish 1) used for the calibration of a present solar radio array at the main site. At the two sub-sites, there is a 16 m parabolic antenna (dish 2) with cryogenically cooled receiver at

each site. In this way, we can achieve observing more radio sources with direct measurements for strong sources so that the 3-D solar-wind structure can be better reconstructed than with the currently-available real-time facilities alone (this is predominantly ISEE only at present). The detailed description of the new IPS concept is discussed in the next section.

## 2. DESCRIPTION OF NEW IPS TELESCOPE ARRAY

### 2.1. Arrangement of IPS Telescope Array System

As mentioned in the previous section, we are aiming to utilize the advantages of the multi-site and dual-frequency observations of IPS, so we propose a new telescope design for observations of IPS while under a limited budget. The whole IPS telescope array is made up of three sites: one main site with the largest collecting area, and two sub-sites each with an intermediate-size collecting area. At each site the antennas not only observe IPS sources independently with dual frequencies (and the dish antennas observe one more frequency than the cylinder antenna), but they also work together in multi-site mode as a whole.

In order to scan the sky quickly and for other scientific targets, the cylinder antennas are designed to be rotatable in the E-W direction, but do not allow for tracking of sources on the sky because of the limited budget. Therefore, they can be set to point to a direction in short time and wait for the passing of the IPS sources. Each cylinder antenna has a line focus, along which an array of 304 dipoles is placed. Each feed has two dipoles, which can work at dual frequencies, 327MHz and 654MHz. Each dipole is connected by a Low Noise Amplifier (LNA). The output of each LNA is digitalized with an AD converter. The signals are bandpass sampled to give an effective bandwidth of ~40 MHz. Then the digital signal is transmitted through optical fiber to the control room. After some amplifiers and filters, the signals from each dipole can be easily combined to form multiple-beams in the digital beam-forming unit and without the need for a complicated phase-shifter arrangement. In total, 36 (3x12) beams from the cylinders will be simultaneously formed. The efficiency of antenna aperture is about 65~70%. The system temperature is about 120K with a well-designed LNA at these two frequencies. The sensitivity of the main station is about 4.4 mJy with a one-second integration time. The sensitivity is better than the performance of Ooty IPS telescope. For each IPS source, the observing time is determined by the width of main beam at half power of the telescope (since the source can be tracked in E-W direction with the synthesis beam) depending on beamforming technology, *i.e.*, about 2.5 minutes for 654MHz and 5 minutes for 327MHz. The actual data sampling cadence could be as fast as tens ms.

At each of the two sub-sites, there is a ~16m parabolic dish antenna with cryogenically cooled receiver. The antenna is azimuth-elevation mounted. Due to the size of each feed, a rotated feed support structure is considered. One side of this structure is for the 327 MHz and 654 MHz feeds, and the other side is for a 1,420 MHz feed. The system temperature is about 120K. Therefore, compared to room temperature, the sensitivity of the 16m dish can be greatly improved. Some relatively-strong radio sources can be observed. The RF signals at three frequencies (327 MHz, 654 MHz and 1,420 MHz) from IPS sources are transmitted to the indoor unit by optical fibers. The indoor equipment includes optic receivers, analogous receivers, AD converters, digital correlation receivers, local oscillators, monitors, computers, and so on. After the AD converter, the digitized data will be transmitted to a data computer server in the observing room. These observations can be correlated with the data observed by the cylinder and the 20m dish telescopes in main station.

### 2.2. Specifications and Telescope Configuration

The main specifications are listed in Table 1 and the configuration of the IPS Telescope Array is shown in Figure 1.

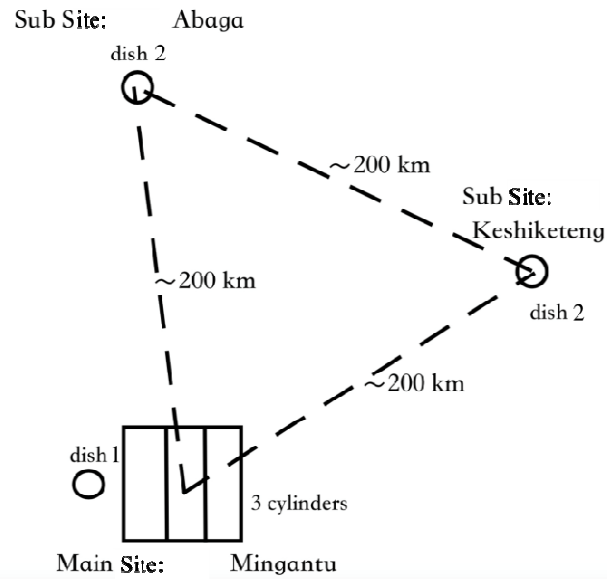


Figure 1. Configuration of the IPS Telescope Array

### 2.3. Data Transmission and Processing

The data center for storage, processing, and distribution of the data is located at the main site. The data transmission among the three stations depends on renting commercial optical cable. A computer cluster environment is proposed for the IPS data processing. The system should be realized efficiently with the load balance, high compatibility, and easy-upgrading capacity. An acquisition server will be used to receive observational data from the digital receiver and store the raw IPS data to the storage system. Meanwhile, the acquisition server would repeatedly forward the observational data to monitoring servers for real-time monitoring. The data from the main site and both smaller sites will be processed using a high-performance distributed data-processing pipeline.

## 3. DISCUSSION

The design of a new multi-site IPS telescope is described briefly. The cylinder antennas at the main site are rotatable, but will not have tracking capability, and will have a total collecting area slightly larger than the ORT. Therefore, more radio sources should be able to be observed provided there is no loss in sensitivity. It is hoped that the additional data for use in 3-D tomography and models will mean that the solar-wind structure can be better reconstructed than from the currently-available facilities alone.

## 4. SUMMARY

In summary, a new IPS telescope concept has been proposed with the following features: large collecting areas with high sensitivity, multiple sites to measure solar-wind parameters directly for strong sources, and dual-frequencies to achieve higher accuracy in the calculation of the characteristic frequency. This new IPS telescope concept is a part of the Phase-II Meridian Space Weather Monitoring Project under the 2016-2020 National Infrastructure Program in China to be constructed in near future. Therefore, it will play an important role for space weather studies when finished. As the Parker Solar Probe and Solar Orbiter will be approaching the Sun, then the combination of *in-situ* measurements and remote-sensing observations will significantly improve our understanding of solar wind properties and of space-weather processes.

Table 1. Main Specifications

Antenna	Cylinder: 3 × 140m×40m
	Dish 1 & Dish 2: 1 × Ø20m and 2 × Ø16m
Frequency	327 MHz, 654 MHz, 1420 MHz(*)
Frequency Bandwidth	40 MHz
Frequency Resolution	39 KHz
Beam (with 36 =3×12 simultaneously-formed beams for the cylinder antennas)	Main site Cylinder: 1.60× 27' @ 327 MHz 0.8°× 13.7' @ 654 MHz Dish 1: 0.74°× 0.74°@ 1420MHz
	Sub-sites Dish 2: 4° @ 327MHz 2° @ 654MHz 0.9° @ 1420MHz
System Temperature	Cylinder: ~110K
	Dish 1 & 2: ~ 120K
System Gain	~80 dB
ADC	12 bits @ 100 MSPS
Sensitivity	Main-site: Cylinder: ~4.4 mJy@1s with 65% efficiency Dish 1: ~167 mJy@1s with 70% efficiency
	Sub-sites: ~261 mJy@1s with 70% efficiency

(\* only available for the 20-m and 16-m dish antennas.)

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