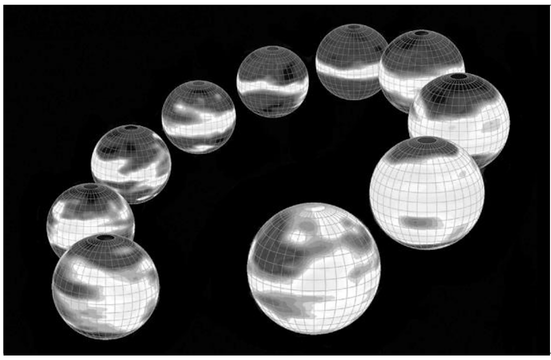
Division for Heliospheric Research



- Solar wind and heliosphere
- Interplanetary scintillation (IPS)
- Coronal mass ejection (CME)
- Long-term variation of the heliosphere
- Space weather forecast
- Radio astronomy
- Development of telescopes and instruments
- Pulsar

A supersonic (with a speed of 300–800 km/s) plasma flow, known as the solar wind, emanates from the Sun and permanently engulfs the Earth. While the magnetic field of the Earth acts as a barrier to protect the atmosphere from a direct interaction with the solar wind, a considerable fraction of its vast energy enters the near-surface layer via various processes. Thus, the solar wind acts as a carrier to transfer the Sun's energy to the Earth.

The solar wind varies dramatically with solar activity. In association with eruptive phenomena on the Sun's surface, a high-speed stream of the solar wind sometimes arrives at the Earth and generates intense disturbances in the geospace and the upper atmosphere. Space environmental conditions that significantly change with solar activity are known as "space weather," and are currently a topic of significant interest. An accurate understanding of the solar wind is required to make reliable predictions of space weather disturbances.

We have observed solar wind velocity and density irregularities for several decades using three large antennas to investigate unsolved important issues such as acceleration and propagation mechanisms of the solar wind, space weather forecasting, global structure of the heliosphere, and its variation. In addition, laboratory and fieldwork experiments were performed to improve the data quality and upgrade the instruments.

Main Activities in FY2020

Solar wind observations using the IPS system

We have been performing remote-sensing observations of the solar wind since the 1980s using a multi-station interplanetary scintillation (IPS) system. Tomographic analysis of IPS observations enables accurate determination of the global distribution of solar wind speed and density fluctuations. IPS observations provide valuable information, particularly for high-latitude solar winds, where *in-situ* observations are currently unavailable. The IPS system currently consists of three large antennas in Toyokawa, Fuji, and Kiso. The Toyokawa antenna (called the Solar Wind Imaging Facility Telescope: SWIFT) has the largest aperture and highest sensitivity among the three antennas and started daily observations in 2008. The Fuji and Kiso antennas were upgraded in 2013–2014 by installing new receivers, which significantly improved their sensitivity. These two antennas are in mountainous areas and are not used for observations during winter owing to heavy snowfall. Hence, the solar wind speed data from three-station observations were unavailable during winter. Instead, the solar wind density fluctuations were derived from the Toyokawa IPS observations, which were measured throughout the year. The IPS data were made available to the public in real time via an ftp server and used for various international collaborations, as described below. In this FY, three-station IPS observations were conducted between early April and early December using the Toyokawa, Fuji, and Kiso antennas. When restoration of the Kiso antenna was undertaken before starting IPS observations (on March 26, 2020), withered grass near the antenna caught fire from welding sparks and the surrounding area of 23100 m^2 burned. Fortunately, there was no serious damage to the observation facility owing to quick extinction by local firefighting services. Furthermore, the pillow block problem of the Kiso antenna was fixed on July 20–22. After stopping IPS observations at Kiso in December, we found that the pillow block was damaged, and we will restore it before starting IPS observations in the next FY. We noticed a breakdown of the reduction gear of the Fiji antenna on September 3, and restored it on September 7–8. For the Toyokawa antenna, we repaired the weed control sheet beneath the parabolic reflector and performed a calibration experiment on the receiver.

International collaboration for space weather forecast

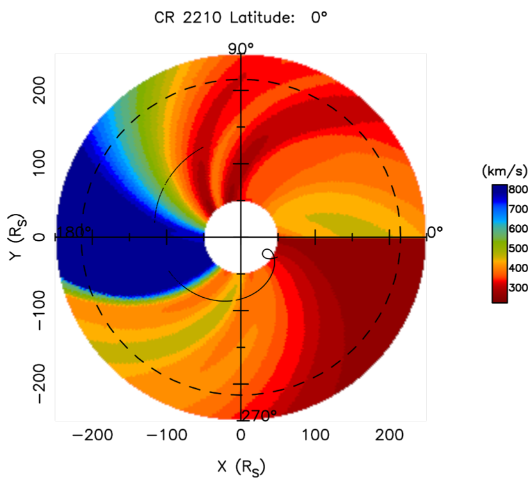
We have performed collaborative research with Dr. B. V. Jackson and his colleagues at the University of California, San Diego (UCSD) since 1996 on the 3-dimensional reconstruction of the time-varying heliosphere using tomographic analysis of IPS observations. A time-dependent tomographic program was developed through this collaborative study. Furthermore, a combined analysis system using IPS observations and the ENLIL solar wind model was developed to improve space weather forecasting through collaborative research. These programs are now available on the NASA Community Coordinated Modeling Center web server and are running in real time at the Korean Space Weather Center (KSWC) to predict the solar wind reaching the Earth. ISEE had a research exchange and cooperation agreement with KSWC to promote research on space weather forecasting using IPS data. Since this agreement will be terminated during this FY, a researcher at KSWC visited ISEE to discuss future actions. At the Met Office, which is a space weather forecast agency of the UK, a proposal for installing the IPS data analysis programs of UCSD was discussed for this FY.

With the growing awareness of the utility of IPS observations for space weather forecasting, an increasing number of IPS observations have been conducted globally. In addition to Japan, Russia, and India, where IPS observations have been conducted for a long time, new dedicated antennas for IPS observations were constructed in Mexico and Korea, and IPS observations using low-frequency large radio array systems, such as the low-frequency array (EU) and the Murchison Widefield Array (Australia), were conducted on a campaign basis. A construction project with a large-aperture antenna dedicated to IPS observations is in progress in China. The integrated analysis of IPS data from these stations enables higher-resolution 3-dimensional reconstructions of the solar wind, which varies rapidly with solar activity. Therefore, the establishment of an international IPS observation network called the World IPS Station was proposed. To promote this project, we conducted a comparison study of solar wind speeds derived from IPS observations in Russia and ISEE during this FY. As a result, we found that they were in general agreement.

Mr. Sejin Park (right) from KSWC, who visited ISEE on November 5, 2020.

Comparison with PSP observations

To elucidate the solar wind acceleration mechanism, Parker Solar Probe (PSP) was launched in August 2018. The PSP has a heliocentric orbit, whose perihelion gradually approaches the Sun and eventually reaches the radial distance of approximately 9.86 solar radii (Rs). Research on solar wind acceleration is expected to progress significantly, owing to observations with PSP. The key point is to distinguish between radial and horizontal (latitude/longitude) solar wind variations. Although it is difficult to achieve this only from PSP observations, it becomes possible by combining global observations by IPS. In this FY, we compared the IPS and PSP observations for Orbits 1 and 2, which occurred in November–December 2018 and March–April 2019, respectively. The former period corresponds to just before the three-station IPS observations ended, and the latter corresponds to when the IPS observations started. Therefore, the amount of IPS data was relatively small, and a meaningful comparison between PSP and IPS observations was limited to Orbit 1. The minimum distance of IPS observations for this period was approximately 36 Rs and the solar wind acceleration was considered to be completed by this distance. Therefore, the solar wind speeds measured by the PSP should agree with those measured by the IPS. We compared the solar wind speeds measured by PSP and IPS, considering PSP latitude and longitude time variations, and found that they were in good agreement (correlation coefficient 0.68). Further, we determined the distributions of speed, density, and temperature in the inner heliosphere from IPS observations using the 1-dimensional hydrodynamic code and compared them with the PSP observations. We found that the data derived by the IPS were generally consistent with those measured by the PSP. These results are meaningful for further extensive comparisons of PSP and IPS observations.



Distribution of the solar wind speed derived from IPS observations using the 1-dimensional hydrodynamic code in the heliographic equation for Carrington rotation (CR) 2210: Orbit 1. Solid and dashed lines indicate the orbits of PSP and the Earth, respectively.

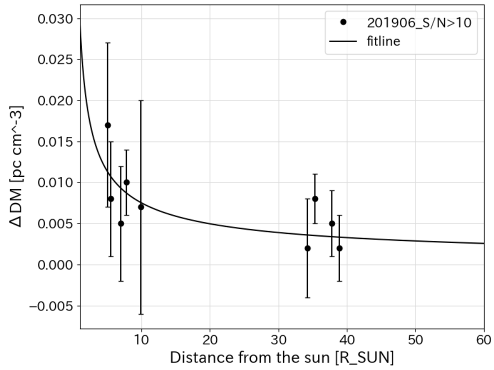
Toward a comparative study of *in-situ* and IPS observations of the inner heliosphere

A coronal hole is a low-density region where the magnetic field lines are open to the interplanetary space. This region is the main source of high-speed solar wind and the main driver of geomagnetic activity.

The PSP is currently observing the solar wind in its orbit, which is gradually approaching the closest perihelion (several solar radii), so that *in-situ* observations of the solar wind acceleration mechanism are being realized. Because our IPS observations do not cover the solar wind acceleration region, it is difficult to directly compare with PSP. Therefore, as a preparatory study, we began a numerical simulation of the solar wind acceleration along the open magnetic flux tube, which is compared to PSP measurements in collaboration with the Harvard-Smithsonian Center for Astrophysics. Simulations were performed using the reduced-MHD simulation (RMHD) code recently developed by our collaborators at the Harvard-Smithsonian Center for Astrophysics, and the coronal hole observed on November 1, 2018 and the solar wind structure within 20 Rs were calculated. In the future, we will expand the computational domain of this simulation to 30–40 Rs to perform a comparative study between PSP and IPS observations and elucidate the solar wind acceleration mechanism.

Estimating the solar wind density structure using Crab pulsar observations

Frequency dispersion can be seen when observing pulsar radio waves on Earth. The magnitude of the frequency dispersion is called the dispersion measure (DM), which represents the integral amount of electron density in the line of sight from the pulsar to the Earth. We measured the plasma density of the solar corona from the DM of the pulsar using the radio telescope SWIFT in Toyokawa. The solar wind density has significantly decreased in response to declining solar activity for some years. Therefore, a remarkable change has likely occurred in the solar corona, which is the source region of the solar wind. The target of our observations was the Crab pulsar. The Crab pulsar's line of sight approaches the Sun every June at a distance of approximately 5 Rs, so it is possible to examine the electron density near the Sun. In addition, the Crab pulsar has a giant pulse that can be used to determine the DM based on short-term observations. Since June 2018, we have been investigating the electron density of the solar corona using DM, and the same observations were made in 2019 and 2020. In June 2020, we could not obtain high-precision DM measurements; however, 2019 showed the same trend as 2018, with DM increasing as the Crab pulsar's line of sight approached the Sun. This analysis changed the criteria for selecting the pulses used to estimate and analyze the background effects of the interstellar medium, which was obtained from observations from September to March, when the Sun's elongation was large. This increased the amount of data used to determine the background effect. There was a tendency for the pulses to decrease with the approach of the Sun throughout the three years. Therefore, the decrease in the number of observations was compensated for by lowering the selection criteria for the pulses. It was expected that the accuracy of DM would decrease when the selection criteria were lowered; however, the accuracy of DM improved due to the increase in the number of analyses, and the expected decrease in accuracy was not observed. From the increased DM obtained, we fitted a spherically symmetric density model to investigate the plasma distribution of the solar corona. The 2019 fit results were consistent with the solar minimum characteristics observed in previous studies. Looking at the Large Angle and Spectrometric Coronagraph Experiment (LASCO) coronagraph data, this is expected to be due to the typical minimum period of solar activity continuing from 2018. The estimation error was reduced to approximately one-third of the 2018 result, showing an improvement in the accuracy of the fit results because the DM accuracy was improved by lowering the selection criteria for the pulses to be analyzed. Therefore, it is desirable to use the year's criteria for future analysis. We will continue to undertake pulsar observations to measure the plasma density of the solar corona, aiming to improve the accuracy of density measurement by capturing large changes when approaching.



It shows the increase in DM with the approach of the Sun. The black dots represent the increase in DM from the background effect of the interstellar medium, and the solid line shows the fitted corona density model.

Space weather forecasting system using IPS data

We developed a 3-dimensional MHD simulation based on IPS observations to predict the arrival of CMEs and validated their accuracy using 12 halo CME events. The average absolute arrival-time error of the IPS-based MHD forecast is approximately 5.0 h, which is one of the most accurate predictions that has been validated, whereas that of MHD simulations without IPS data, in which the initial CME speed is derived from white-light coronagraph images, is approximately 6.7 h. Therefore, the assimilation of IPS data into MHD simulations can improve the accuracy of CME arrival-time forecasts. This result was published by *Earth, Planets and Space*. The press release of this result has been reported in several newspapers and online media.

Next-generation IPS observation system

We investigated the scientific requirements and design of next-generation IPS observation instruments. The main scope of the next system is to elucidate the acceleration mechanisms of the solar wind. To achieve this, we considered a flat phased-array antenna system consisting of multiple dipole antennas with digital phased-array devices to obtain solar wind data 10 times that of conventional radio instruments. We also developed a prototype of a digital backend. We added an automated calibration sequence to the Field Programmable Gate Array (FPGA) of the digital backend to quickly calibrate the amplitude and phase differences of the antennas and receivers. In the laboratory experiments, we confirmed that the calibration system worked as expected. Based on these results, we submitted a proposal of the next-generation IPS observation system to the Grant-in-Aid for Specially Promoted Research.

Prototype of a digital backend for the next generation IPS observation system.