# 2 Measurement and Prediction of Solar-Terrestrial Environment

## 2-1 Monitoring and Warning of Solar Activity and Solar Energetic Particles

### 2-1-1 Monitoring of the Solar Activity and Solar Energetic Particles

**AKIOKA Maki, KUBO Yûki, NAGATSUMA Tsutomu, and OHTAKA Kazuhiro**

Solar activity is the source of various space weather phenomena in geospace and deep space. Solar X-ray radiation in flare, energetic particles, coronal mass ejection (CME) can cause various kind of disturbance near earth space. Therefore, detailed monitoring of the solar activity and its propagation in the interplanetary space is essential task for space weather. For example, solar energetic particle which sometimes affect spacecraft operation and manned space flight, is considered to be produced by solar flares and travelling shockwave caused by flares and CME. The research and development of monitoring technique and system for various solar activity has been an important topic of space weather forecast program in NICT. In this article, we will introduce the real time data acquisitions of STEREO and optical and radio observations of the Sun at Hiraiso Solar Observatory.

***Keywords***
Solar activity, STEREO, Real-time data acquisition, Optical observation, Radio observation

## 1 Introduction

The solar-terrestrial system — the stage for space weather — consists of various regions having different characteristics such as the sun, space between the sun and earth (called the inner heliosphere), and the earth's magnetosphere and ionosphere. The sun is the major source of huge matter and energy in our solar system, and flows of matter and energy from the sun released into the inner heliosphere that reach the earth's magnetosphere and ionosphere are the basic cause of space weather phenomena, and entail chains of physical processes among those regions. One objective of space weather forecast is to "estimate and predict the occurrence of space weather phenomena." Meeting that objective entails monitoring the sun and inner heliosphere — the region upstream of such phenomena.

The National Institute of Information and Communications Technology (NICT) conducts optical and radio observation of the sun at the Hiraiso Solar Observatory, and acquires STEREO data in real time. Chapter **2** of this paper describes the real-time acquisition of STEREO data; Chapter **3** discusses optical and radio observation of the sun at the Hiraiso Solar Observatory.

## 2 Real-time acquisition of STEREO data

### 2.1 Physics of the solar-terrestrial system and the STEREO mission

STEREO (Solar TErrestrial RElations Observatory), as its name indicates, is an observatory mission designed to focus on the relations between activity phenomena on the surface of the sun and the associated space weather phenomena of the earth in response to such activity through observation, and gain a comprehensive understanding of such issues. STEREO was launched by NASA in December 2006. Development of the observation devices involved the cooperation of researchers from Europe as well. Japanese research institutes also participated in joint observations and other areas of interest.

When an explosive phenomenon known as a “solar flare” occurs on the surface of the sun, corona gas is released into outer space. In the inner heliosphere, a mass of plasma (a state in which atoms are divided into electrons and ions) is ejected through the inner heliosphere and drives away solar wind (a low-density plasma) in the background. This is called coronal mass ejection (CME). CME and solar wind due to a solar flare have electrical properties given their nature as plasma, and are also magnetized. Various electromagnetic interactions therefore occur midway through that process. In some cases, particles are also known to be accelerated up to a state with extremely high energy (velocity). Particles accelerated this way by high energy are called solar energetic particles, and are known to exercise various influences on living things as well as on electronics parts, optical devices, and other functional materials, similar to radiation released in accidents occurring at nuclear power plants and related facilities. For the specific effects, please refer to another paper in this feature issue[1].

When CME due to a solar flare happens to be directed toward the earth, the plasma ejected by CME will reach the earth one to three days later. The earth has a magnetic field and is fully enveloped in plasma by the action of solar winds, thereby forming the earth’s magnetosphere wrapped in magnetism. Therefore, when CME caused by a solar flare collides with the earth’s magnetosphere, the plasmas and magnetic fields of both cause various electromagnetic interactions, thereby creating a very interesting laboratory environment for the study of plasma.

The density of the solar corona has various irregularities but is about $10^{10}$ particles/cc. Considering that the density of the atmosphere on the surface of the earth is $2.7\times10^{19}$ particles/cc, the density of the solar corona (or atmosphere of the sun) is one-billionth the density of the atmosphere on the surface of the earth, and can be considered extremely thin. However, the solar corona is the densest plasma of the inner heliosphere (except for inside the sun). The density of solar winds near the earth is only several particles/cc to several dozen particles/cc. In other words, the solar corona and inner heliosphere in which it flows out constitute regions where extremely thin plasma plays a leading part. To observe both regions in detail is very interesting in terms of demonstrating extreme cases of the plasma theory.

For the STEREO mission, two STEREO observatory spacecraft equipped with the same set of observation equipment were launched into orbit approximating the earth’s orbit, with one spacecraft ahead and one trailing behind the earth. From a different perspective, both spacecraft orbit on both sides of the earth at a certain elongation. The mission involves remote sensing observation of the sun in a stereoscopic manner from these two points on the orbit, and multi-point measurements using various sensors of the plasma environment encountered. In other words, this mission allows the same set of data to be simultaneously acquired from two or more viewpoints and observation points, which is why the mission is nicknamed “STEREO” (Fig. 1).

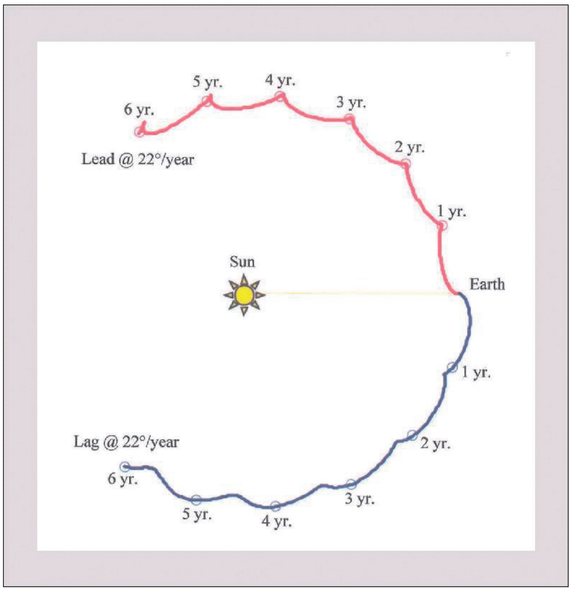


**Fig. 1** *Temporal changes in location relative to the earth on the orbit between STEREO-A and STEREO-B*

A and B are in an almost symmetric location relationship as viewed from the earth, and the elongation of orbit increases by a little more than 20 degrees per year.

The STEREO mission is equipped with comprehensive observation equipment designed to comprehensively observe plasma in the heliosphere. Figure 2 is an external view of the spacecraft; Table 1 summarizes the observation equipment in detail. The sensors are enhanced versions of observation equipment already mounted and implemented in various scientific missions. Rather than offering an advantage in adopting observation equipment based on a totally new concept, this mission aims to discover a new frontier by conducting stereoscopic or multi-point measurements from a completely new orbit.

## 2.2 STEREO real-time option

The STEREO mission aims mainly to scientifically elucidate plasma phenomena in the inner heliosphere, and its observation data was expected to be extremely effective in alerts as pertaining to studies on applications for space weather and related areas, as well as satellite operation and related areas. For that reason, the mission is designed to operate a data transmission line on a real-time basis, rather than rely on the main means of data transmission for scientific missions called a Space Weather

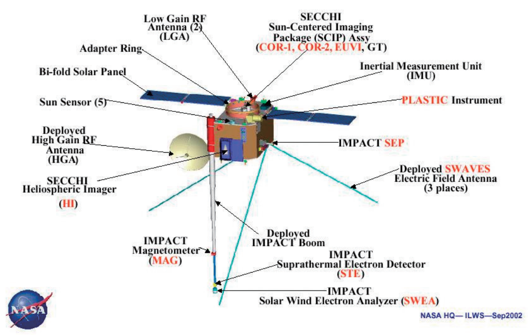


**Fig.2** *External view of the STEREO spacecraft*

**Table 1** *Payload instruments of STEREO*

| | |
|---|---|
| Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) | Extreme UV telescope for solar corona and coronagraph for CME (Coronal Mass Ejection) observations. |
| STEREO/WAVES (SWAVES) | Radiowave observation emitted from solarcorona and CME plasma. |
| In-situ Measurements of Particles and CME Transients (IMPACT)/PLAsma and SupraThermal Ion Composition (PLASTIC) | In-situ measurement of solar plasma and high energy particle property. |

Beacon (SWB)[2]. Scientific mission data is quickly reproduced and transmitted to the earth in a limited time frame of about several hours each day by using large ground station equipment in NASA's Deep Space Network (DSN). In addition, a line (albeit a slow communication line) capable of constantly transmitting data is installed for also receiving data 24 hours a day on a real-time basis, even when using a relatively small antenna. When a small antenna proves sufficient, two or more collaborating establishments can facilitate the buildup of a network that enables operation while taking turns. The SWB has a data rate of 632 bps and can enter receiver output from the sound input device of a PC.

The STEREO-A and STEREO-B spacecraft currently transmit low-speed real-time data at all times using a frequency of the X band. Data is received at the following five stations:

- **NASA's Deep Space Network**
- **NICT, Koganei, Japan**
- **National Center of Space Research (CNES), Toulouse, France**
- **Amateur station DL0SHF, Kiel-Ronne, Germany**
- **AMSAT-DL/Bochum Observatory, Germany**

After being edited in the form of one file per 16 seconds, data is transmitted to a server operated by the STEREO Science Center of NASA's Goddard Space Flight Center (GSFC). The server at GSFC processes received files sequentially and uniformly edits those files for publication on the WWW. The very short time lag constitutes a response sufficient for checking the status of aboveground station operation (such as alleviating human stress about the process of resuming operation, waiting for a plot to be resumed on the WWW, and completing the task). In collaboration among the five stations, the framework eliminates the need to adjust a follow-up schedule and allows data to be received in the range possible for the respective stations and sent to GSFC, so that any overlapping of data received is handled by the server at GSFC. Conversely, all mission data is received by NASA's Deep Space Network (DSN) and sequentially registered in the archive database although not on a real-time basis. Therefore, even if anything is missing in real-time data acquisition, the main objectives of scientific observation and analysis are not affected. Since our real-time data is used as supporting data for observation, however, generating such a great gap is not desirable.

### 2.3 Reception system at the National Institute of Information and Communications Technology

At the National Institute of Information and Communications Technology (NICT), an 11-meter antenna system for VLBI experiments was developed and arranged around 1996, and is still being used for VLBI experiments[3]. It was decided that this 11-meter antenna system would be used, with part of it being used to build up an SWB reception system for STEREO. Since VLBI observation is a leading-edge experimental study, this antenna use is only for the period necessary for experiments, but could be used for other purposes during other time period. For that reason, it was decided that, with VLBI experiments given top priority, an 11-meter antenna system would be used with all the free time used for STEREO reception. Fortunately, VLBI observation now being conducted is not intended to occupy the equipment at all times, so that a considerable amount of time can now be allocated to STEREO reception.

Figure 3 gives an overview of the reception system. It was decided to branch the IF signals (844 MHz and 846 MHz) corresponding to the X band frequency from the X-band terminal in the IF signal divider ( "IFD" in the figure) of the backend portion of the 11-meter antenna system. This frequency is entered into the down converter of the backend portion of the STEREO reception system for down-conversion to 70 MHz IF. It is then entered into the RDM-201 digital receiver, and demodulation signals output by using a PM demodulation function are processed by entering those signals from the sound input port into a PC. The PC then conducts bit and frame synchronization, and processing software outputs the results in a file standardized in terms of output

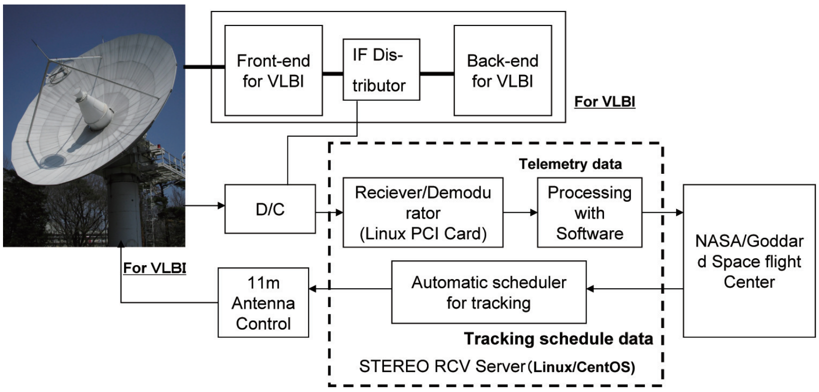


**Fig.3** *Conceptual diagram of the STEREO reception system additionally arranged with the backend of VLBI observation equipment*

interface (file), with the participating establishments directed to use a common software package. Figure 4 is an external view of the VLBI-use 11-meter antenna used for reception; Figure 5 is a photo of the backend portion.

### 2.4 Data publication and use

Observation data is processed with a data server operated by the STEREO Science Center installed at GSFC, and published on the WWW in the form of real-time images and plots. The facility not only displays real-time data but also accumulates previous real-time data, thereby enabling search and viewing. For that reason, it is a very useful tool not only for monitoring the space environment but also for preliminary analysis (such as searching for events, checking the availability of data, and tracking the development status of a given phenomenon) prior to detailed analysis for research purposes. Figures 6 and 7 show a WWW screen for real-time publication. Figure 6 is a webpage for image observation data, and the observation of solar extreme ultraviolet imaging and the solar extended atmosphere (corona) due to electron-diffused light allows images to be viewed as observed from a different angle when CME occurs. Figure 7 is a webpage that plots sensor data about plasma and high-energy particles from sensors mounted on spacecraft. Since environments closest to the spacecraft are measured, this is called "in-situ" measurement. The physical quantities (e.g., density, magnetic field, temperature) of solar wind plasma itself and the arrival of high-energy particles, along with other events, can thus be observed. The patterns of the sun and solar winds rotate synchronously along with the sun's rotation, so that the plasma environment surrounding STEREO-B is considered a good approximation of the environment closest to the earth several days later. Data analysis is now under way to consider the effectiveness of this concept. For details of that issue, refer to another reference in this feature issue [4].

**Fig.4** *External view of the VLBI-use 11-meter antenna*

## 3 Monitoring solar activity from the ground

The National Institute of Information and Communications Technology (NICT) conducts observation of the sun by using visible

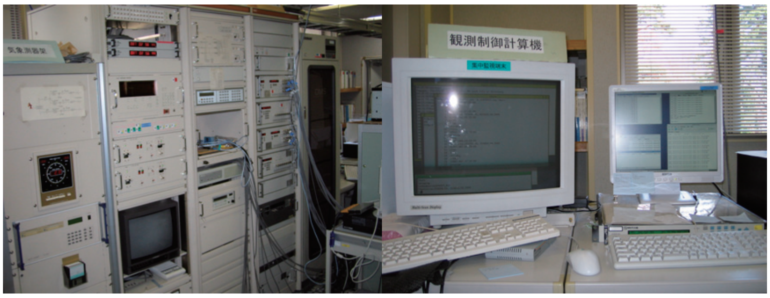


**Fig.5** Backend portion

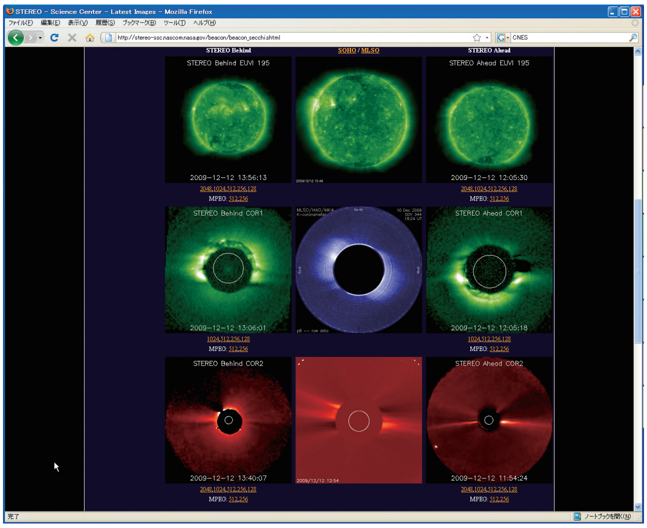


**Fig.6** WWW site of STEREO real-time data (image data)

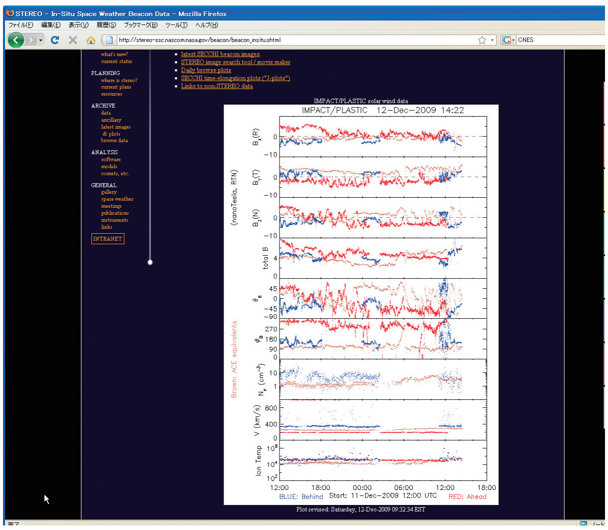


**Fig.7** WWW site of STEREO real-time data (on-the-spot measurements)

light and radio waves at the Hiraiso Solar Observatory in order to monitor solar activity. This section gives an overview of each observation system for visible light and radio waves, and describes the importance of monitoring solar activity by using visible light and radio waves.

### 3.1 High-precision H$\alpha$ solar telescope

The high-precision H$\alpha$ solar telescope at the Hiraiso Solar Observatory is designed to observe the absorption line of the Balmer-series $\alpha$ line (H$\alpha$ line) of hydrogen (Figure 8). The observation system employs as its platform a Carl Zeiss 15-cm refracting telescope — a dispersion imaging device based on a complex-refraction interference filter (Lyot filter) capable of wavelength shift. This system has been used on a steady-state basis since fiscal 1994 to monitor solar activity by using visible light over long periods exceeding one solar activity cycle, which is said to last about 11 years. Since fiscal 2009, with the Hiraiso Solar Observatory having switched to unmanned operation, remote control from Koganei enables the system to be used virtually unattended. The following describes the current status of the high-precision H$\alpha$ solar telescope. For technical details of the system, refer to references [5] and [6].

**Fig.8** High-precision H$\alpha$ solar telescope

#### 3.1.1 Observation system

A high-precision H$\alpha$ solar telescope is a system in which various enhancements are implemented to ensure automatic operation and better performance based on using the above-mentioned telescope as a platform. For example, to alleviate the temperature irregularities of lens cells and lenses due to solar heat, and degraded images due to temperature changes, we manufactured a heat ray reflection filter having an effective diameter of 150 mm for placement immediately before the field lens, and painted the filter metal frame, lens cells and flanges white. Moreover, the system also comes equipped with a function to change the field of view by shifting the sun guider.

The focal plane package consists of a Lyot filter, CCD camera, and various other items of equipment arranged on a base fixed on the polar axis. The Lyot filter in the package is a narrow-band filter based on the double refraction of calcite or other stone, and has a grid resolution of 0.25 Å. The transparent wavelength is changed by spinning the rotary wavelength plates with a motor, while the rotation angle is read by using a potentiometer installed to ensure interaction with the wavelength plate gear.

The imaging system toggles between entire-screen mode and enlarged image mode. The entire-image system is reduced in size by a factor of 1.4 by using a lens for a single-lens reflex camera, and equipped with a 13-million-pixel CCD camera behind it. Enlarged images are taken directly with a CCD camera for enlarged imagery placed at the positions of primary images. These imaging systems for the entire surface and for enlargement are placed on a small linear stage with a stroke of 20 mm for being driven in the optical axis direction, and on a linear stage with a stroke of 100 mm for being driven perpendicularly with the optical axis together with the small stage so that they can each be adjusted in focus independently. This 100-mm linear stage is driven to toggle between the entire surface and enlargement.

The imaging software comes equipped with an automatic exposure control function. Determining the optimal exposure time, aborting imaging in case of insufficient light, and other related operations are also performed automatically. Moreover, in response to changes in image quality due to atmospheric fluctuations, the software is designed so that images with the best image quality (with high image contrast) will be selected at image selection. Imaging data is output in FITS format — the most common data format used by astronomers — and archived on the hard disk of the personal computer (PC) used for imaging. Imaging data measures 4096×3248 at entire-surface imaging and achieves a high space resolution 0.68 arcseconds per pixel (Fig. 9).

#### 3.1.2 Remote use and operation of solar monitoring with visible light

The high-precision H$\alpha$ solar telescope at the Hiraiso Solar Observatory has been remotely operated by Koganei headquarters since fiscal 2009. Local personnel need only open and close the telescope at the beginning and end of observation. All other operations such as adjusting focus and imaging can be performed remotely. These operations are done using an imaging PC running the Linux OS. Remote operation is not only possible for operations from the command line by remote log-in but also the power supply of the PC can be turned on and off remotely.

The H$\alpha$ solar telescope automatically takes images of the sun with three wavelengths (i.e., central wavelength of H$\alpha$ absorption line, both wings of absorption line ± 0.8 Å from the center) at each determined time interval. Imaging on the H$\alpha$ center line observes the bottom-portion chromosphere at an altitude of about 3,000 km. Moreover, taking the differences in data obtained by imaging both wings of absorption line enables the Doppler shift of absorption line to be measured, thereby allowing motion of the solar chromosphere to be estimated in the line of sight direction. This also allows levitation of the flux tube on the chromosphere surface, filament motion, and other events to be estimated. And all this is helpful in monitoring signs of solar flares and filament eruptions.

### 3.2 Solar radio observation system

The solar radio observation system at the Hiraiso Solar Observatory consists of wide-band solar radio observation equipment (Hiraiso Radio Spectrograph or HIRAS) that is used to observe radio waves with bands of 25 to 2500 MHz, and a polarization meter to observe radio waves with a fixed frequency of

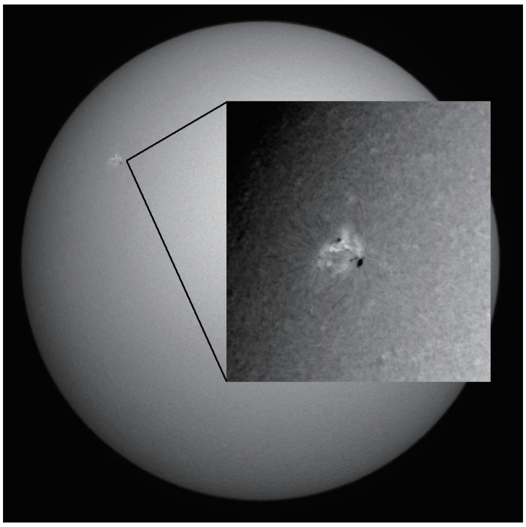

**Fig.9** *Group of small sunspots imaged with high spare resolution on June 1, 2009*

**Fig.10** *10-m antenna (background on the left), 6-m antenna (background on the right,) and 2.8 GHz fixed frequency observation antenna (foreground on the right) of a HIRAS system*

2.8 GHz (Figure 10). This system has continued steady-state observations since fiscal 1993 and monitors solar radio waves over long periods exceeding one solar activity cycle. In the meantime, various enhancements have also been made to the backend portion, data collection system, data analysis system, and other components. Since fiscal 2006, the observatory has been operated in an unattended manner by remote control from Koganei headquarters. The following describes the present condition of the solar radio observation system. For details of this system about 10 years since it commenced operation, refer to references [6] and [7].

### 3.2.1 Wide-band solar radio observation equipment (HIRAS)

The wide-band solar wave observation equipment (HIRAS) is a solar radio observation system that covers one of the widest-freguency bands in the world — from 25 to 2500 MHz. The system consists of three antennas, denoted in ascending order of the lowest reception frequency as HIRAS-1, HIRAS-2 and HIRAS-3. All antennas follow the sun under computerized control, and the sun's position is determined by calculating the real-time solar orbit. The control interface is based on GP-IB.

The HIRAS-1 antenna is a log periodic antenna with its parts crossing each other at right angles. It receives an orthogonal linear polarized component of the band from 25 to 50 MHz. The hybrid of the circular polarized synthesis portion is based on a wide-band hybrid of the band from 3.5 to 80 MHz. The rack is installed on a tower about 15 m from ground level, and the system tracks the sun in an AZ-EL drive system. The main beam width of the antenna is as large as about 60°, thereby eliminating the need for precise solar tracking, with solar tracking precision being about 10°.

The HIRAS-2 antenna is a parabola antenna 10 m in diameter arranged in fiscal 1988 prior to arrangement of the HIRAS system. There had thus been concerns over the antenna's aging, so it underwent major refurbishment work in fiscal 2002, and the antenna has been that way until the present. The primary radiator uses an orthogonal 20-device log periodic antenna. The main beam width of the antenna is 29° for 70 MHz and 4° for 500 MHz. The rack is driven in an equatorial system, with solar tracking precision of 0.1°.

The HIRAS-3 antenna is a parabola antenna 6 m in diameter, with its primary radiator consisting of an orthogonal 23-device log periodic antenna. The main beam width of the antenna is about 6.5° for 500 MHz and about 1.4° for 2500 MHz. The rack is on an AZ-EL drive system, with solar tracking precision of about 0.1°.

Signals received with these antennas are analyzed in terms of frequency by using a total of six spectrum analyzers independently for the right-handed polarization component and left-handed polarization component, respectively, and these items of data are accumulated by the data collection PC via GP-IB and saved in the form of a data file. Data taken in from the spectrum analyzer includes 1,001 items of data in the frequency direction of HIRAS-1, -2 and -3, respectively, with significant enhancements made to exceed the frequency resolutions of conventional systems (501 points at a logarithmic interval for frequencies from 25 to 2500 MHz). Moreover, the time resolution achieved is nearly double that of conventional versions (about 1.8 seconds on average) to less than 1 second in existing systems.

#### 3.2.2 2.8 GHz fixed frequency observation equipment

The 2.8 GHz fixed frequency observation antenna is a parabola antenna 2 m in diameter, with the main beam width of the antenna being about 3.5° (based on actual measurement). As its primary radiator, the system uses a septum-type polarization separator to separate waves directly into left-handed and right-handed circular polarization components. The rack is on an AZ-EL drive system, with its solar tracking conducted under computerized control similarly to the group of HIRAS antennas, with tracking precision of about 0.1° and a control interface based on GP-IB.

Signals received with the antenna are taken in and saved on the data collection PC via GP-IB in the form of time series data by using two spectrum analyzers in zero-span mode. The system intermittently handles data with a high time resolution of 0.5 to 1 millisecond (Fig. 11).

#### 3.2.3 Remote use and operation of solar radio wave monitoring

Linux is used in most cases as the operating system for PCs designed for antenna control and data collection for HIRAS and 2.8 GHz fixed frequency observation equipment, thereby allowing users to log in from a remote location and operate the system from the command line. Moreover, the system is designed so that remote operation can be performed not only for PCs but also for the backend portion of the solar radio observation system, including even the turning the power supply of PCs and the backend portion on and off. Moreover, as a tool that facilitates remote operation from such remote locations, the equipment comes equipped with a system that can perform all remote operations mentioned above by a user simply operating the mouse from a webpage (Figure 12). Furthermore, a web camera can be installed to monitor the status of antennas and other equipment at local sites, and the systems are now operated in a steady state in a virtually unattended manner.

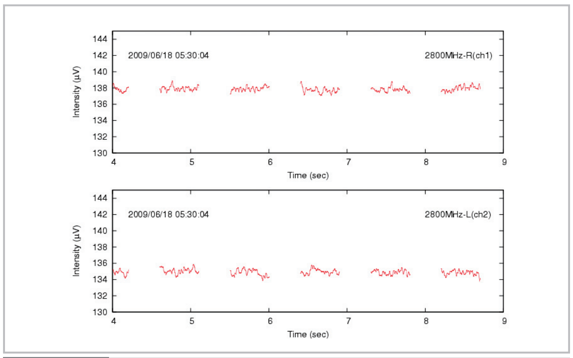


**Fig. 11** 2.8 GHz solar radio waves observed with high time resolution of 0.5 to 1 millisecond

Data acquired at Hiraiso is transferred to the data analysis server in Koganei over a LAN every five minutes, and dynamic spectral images are prepared on a real-time basis and published on a webpage (http://sunbase.nict.go.jp/solar/denpa/index-J.html). Also published are image data from previous observations, monthly summary reports on HIRAS and 2.8 Hz fixed frequency observations, and various other data. In addition, “Ionospheric Data in Japan (Monthly Report on the Ionosphere)” issued by NICT reports radio wave bursts observed at 2.8 GHz, a monthly summary plot of 2.8 GHz observations, and the F10.7 value (to be discussed later). “Solar-Geophysical Data” compiled by the National Geophysical Data Center of the National Oceanic and Atmospheric Administration (NOAA) gives monthly summary reports on HIRAS and 2.8 GHz fixed frequency observations. At the moment, “Solar-Geophysical Data” is published on the Internet (http://ngdc,noaa,gov/sgd/jsp/solarindex.jsp).

Observation data is not only saved on the data analysis server but also periodically archived on DVD-R. Moreover, given the growing amounts of data, archiving data from the grid file system (Gfarm) being prepared by this group is now being considered.

Among the solar radio wave burst phenomena important in space weather forecasts are type-Ⅱ and type-Ⅳ radio wave bursts. Figure 13 shows an example of type-Ⅱ, -Ⅲ, and -Ⅳ radio wave bursts observed with HIRAS. The type-Ⅱ and -Ⅳ radio wave bursts show that CME was released with the outset of a solar flare, and mean that there is a high

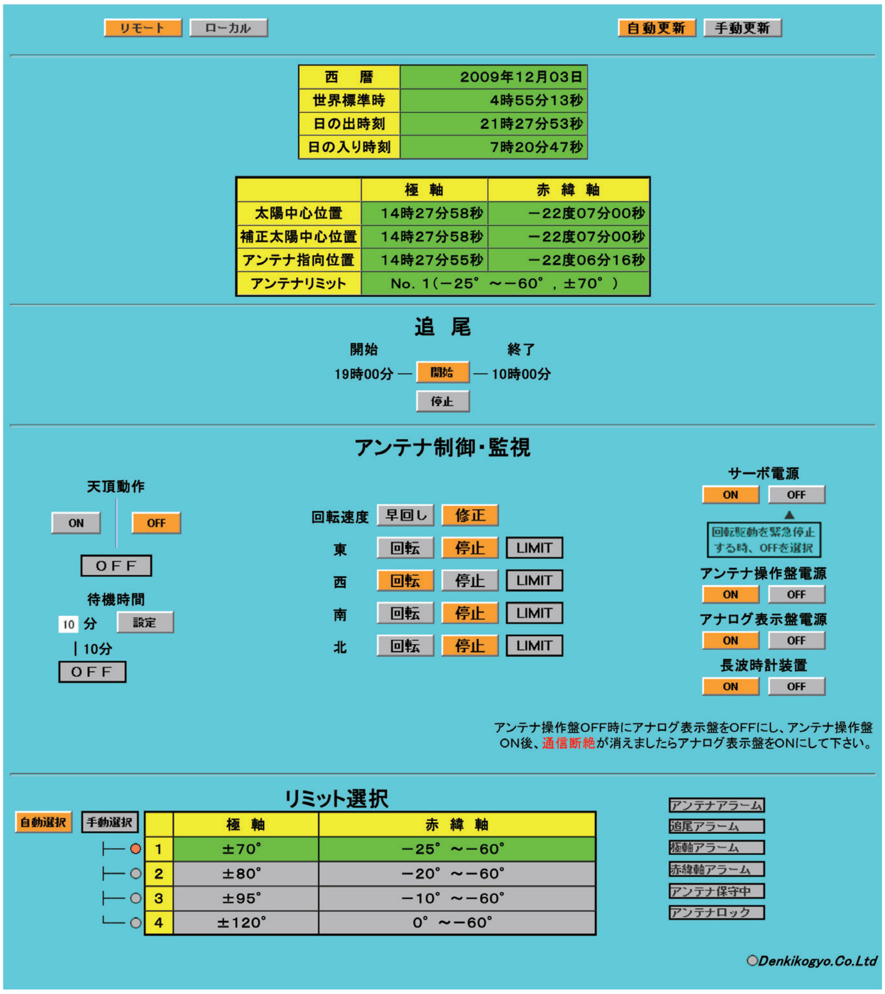


**Fig.12** *Webpage for controlling a 10-meter antenna*

possibility that solar radiation will increase (for several hours to several days) and geo-magnetic disturbances will occur (several days later). Any such type-II and -IV radio wave bursts and other important phenomena are published on a webpage in the form of images and other data about phenomena based on the observation data taken.

The intensity of 2.8 GHz solar radio waves (with a wavelength of 10.7 cm) is called F10.7, which is known to have a good correlation with the sunspot relative number. For that reason, F10.7 is used as an indicator of solar activity. Moreover, in predicting the orbit of an artificial satellite, it is also used as an important parameter for correcting atmospheric drag.

Moreover, a recent report stated that a solar radio wave burst reduced the carrier-to-noise ratio of the Global Positioning System (GPS), thereby affecting positioning precision. Yet another view submitted holds that consideration should be given to the effects of solar radio wave bursts in operating GPS positioning[8][9].

## 4 Conclusion

This paper described the monitoring of solar activity and solar radiation. Needless to say, these efforts are important for space weather forecasts. However, considering that the solar-terrestrial system is based on inter-regional linkage, another challenge for further using the information obtained by monitoring is to build up a monitoring and forecast sys-

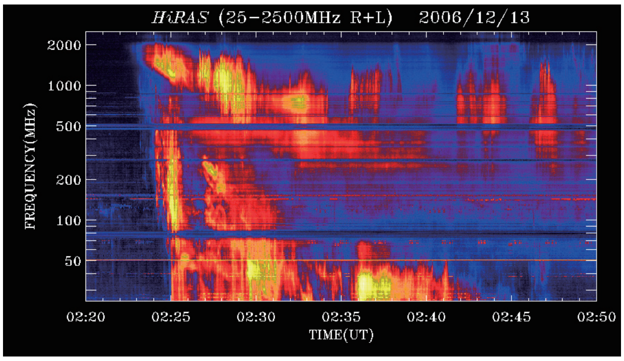


**Fig. 13** *Radio wave burst observed with HIRAS with a solar flare that occurred on December 13, 2006*

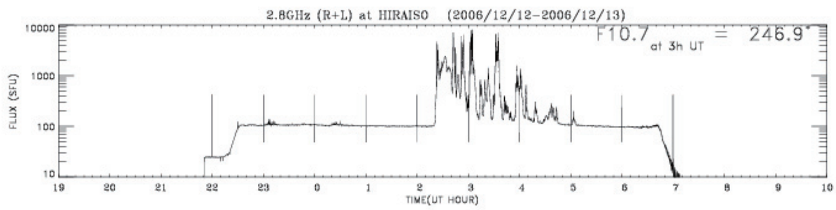


**Fig. 14** *Example of a series of radio wave bursts that occurred in December 2006 and affected GPS positioning precision*

tem that connects the regions. On a research level, efforts are under way to conduct simulations that connect regions in order to achieve future numerical forecasting, though it will still take a long time for these operations to mature to a practical level. It will be necessary from now on to build up an integrated forecast scheme and a model that take full advantage of various observation data, empirical models, and other tools to study the solar-terrestrial system.

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