2 Solar and Solar wind

2-1 Optical and Radio Solar Observation for Space Weather

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Researches on solar observation technique and data utilization are important issues of space weather forecasting program. Hiraiso Solar Observatory is a facility for R & D for solar observation and routine solar observation for CRL's space environment information service. High definition H alpha solar telescope is an optical telescope with very narrow pass-band filter for high resolution full-disk imaging and doppler mapping of upper atmosphere dynamics. Hiraiso RAdio-Spectrograph (HiRAS) provides information on coronal shock wave and particle acceleration in the soar atmosphere. These information are important for daily space weather forecasting and alert. In this article, high definition H alpha solar telescope and radio spectrograph system are briefly introduced.

Keywords
Space weather forecast, Solar observation, Solar activity

1 Introduction

1.1 The Sun as the Origin of Space Environment Disturbances

The space environment disturbance phenomena studied in space weather forecasting at CRL include a wide range of phenomena such as solar energetic particle (SEP) events, geomagnetic storms, ionospheric disturbances, and radiation belt activity. All of these space environment disturbance events are believed to have solar origins. Therefore, solar observation technologies are the key to space weather forecasting studies. Fig.1 shows the schematic relationship between solar surface phenomena and near-Earth space environment disturbances. Solar flares and Coronal Mass Ejections (CME) are thought to be generated when the magnetic-field energy accumulated on the solar surface through magnetic field activities induced by dynamo activity within the Sun is released by some mechanism. The X-ray and ultraviolet radiation resulting from solar activities and solar flares cause disturbances in the ionosphere and the upper atmosphere, which in turn cause communication disruptions and affect the density structure of the Earth's atmosphere. CME induce geomagnetic storms and ionospheric disturbances upon reaching the Earth's magnetosphere, and are believed to be responsible for particle acceler-

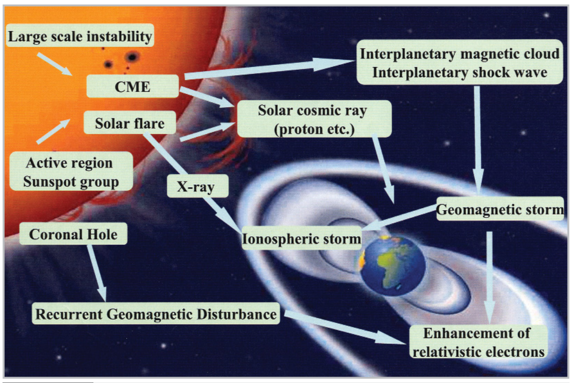

Fig.1 *The Sun and various space environment disturbances*

ation in SEP. Furthermore, high-speed solar winds may continuously flow out from regions called coronal holes without being confined to the solar atmosphere depending on the solar-surface magnetic field distribution, and these high-speed solar winds are also a major cause of geomagnetic disturbances.

1.2 Space Weather Forecasting and Solar Observation

Space weather forecasting involves the monitoring of the Sun and various space environments and prediction of future conditions. Near-Earth space environment disturbances have their origin in solar-surface phenomena, such as solar flares. In recent years, satellite observations have revealed that CME also plays an important role[1]. For example, flares displaying a wide region of brightenings in monochromatic imaging for analysis of chromospheric absorption lines such as Hα-lines (referred to as "two-ribbon" flares since, in many cases, they appear as two bright lines) often accompany filament eruptions and CME, and are mainly categorized as LDE-type flares of long duration (Fig.2). Compared to impulsive flares of short duration, the LDE-type flares have been known to be more likely to trigger geomagnetic storms and strong SEP events[2]. Furthermore, radio bursts with characteristic time-frequency variation patterns apparent in radio spectral observations (called Type-II and Type-IV bursts) are often found to accompany solar flares accompanied by eruptions. Thus, these bursts may serve as an important indicator for occurrences of geomagnetic storms and proton events.

Information regarding the scale, morphology, and change of the active region on the solar surface is required to assess the hazards of solar activity. It has been empirically determined that flares have a high probability of occurring in Emerging Flux Regions (EFR), where new magnetic flux rope rises continuously from below the photosphere, and in regions with complex magnetic field structures[3]. Furthermore, major solar flares are highly likely to occur where regions of opposite polarities meet, especially when accompanied by a delta configuration, in which the sunspot groups of opposite polarities are in close proximity and contained in a single penumbra. The solar-surface magnetic field must be observed with higher precision using such instruments as magnetographs and Stokes polarimeters that measure the Zeeman effect of absorption lines by polarization observations. Also, it is believed that the fibrils, thread patterns present in the Hα-mono-

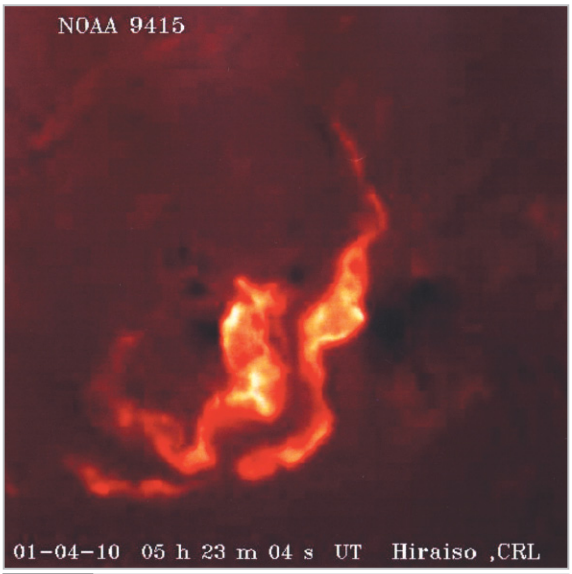

Fig.2 Solar flare on Apr. 10, 2001 observed by high-definition Hα solar telescope (at Hiraiso)

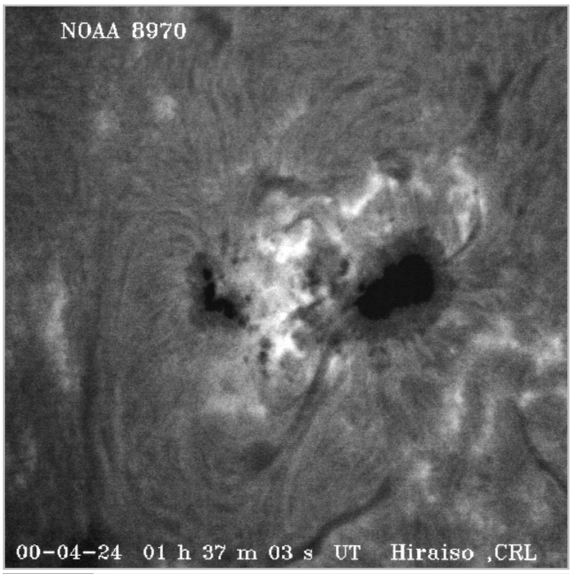

Fig.3 Fine structure of sunspot groups seen in monochromatic Hα-line imaging

chromatic image, reflect the magnetic field structure of the chromosphere, and may provide valuable insights in determining the magnetic field structure. The EFR appears as an arch filament system in an Hα-monochromatic image, due to the magnetic field lines in the emerging dipole field being observed as absorption materials with a loop-shap. Therefore, high-resolution Hα-monochromatic images may be regarded as a powerful tool for evaluating the complexity of the magnetic field structure on the solar surface in the horizontal direction.

With the development of the SOHO (Solar and Heliospheric Observatory) by NASA and the ESA, significant advances have been made in observation of the CME, which drives SEP events and geomagnetic storms. In particular, the observation data of LASCO/C3, which has an observation range of 30 times the solar radius, has not only advanced scientific research on the Sun and the heliosphere, but has greatly improved the level of space weather forecasting overall[4]. The interactions between the plasma and magnetic field on the solar surface are considered as a key factor in the origin of CME and flares generated in the outer part of the solar atmosphere; i.e., in the corona and the chromosphere. For space weather forecasting, as well as solar physics studies, it is necessary to cover the entire active region of the Sun by visible wavelength observations of the solar surface and X-ray, ultraviolet, and radio observations of the upper solar atmosphere.

This paper will introduce the optical telescope (high-definition Hα solar telescope) and the radio spectrometer (broadband solar radio observation system) that has been developed by the Hiraiso Solar Observatory of CRL and is currently employed in routine observation for space environment information service duties and space weather forecasting studies. The details of the development of this system have already been presented in our quarterly journal (Journal of the Communications Research Laboratory), and readers may refer to past reports for technical details[5][6].

2 High-Definition Hα Solar Telescope

The high-definition Hα solar telescope is a spectral imaging system that uses a birefringence interference filter with variable wavelengths (Lyot filters). The system has been under development since 1991, and in July 1994, it was incorporated into routine observation activities. By acquiring images near an absorption line of hydrogen Balmer α, it is possible to obtain images of the lower chromosphere (at an altitude of approximately 3,000 km from the solar surface). Furthermore, the Doppler shift can be measured by alternating the image acquisition between both ends of the absorption line and calculating the difference. Thus, this instrument enables us to estimate the velocity of the radial motion of the upper solar atmosphere. The system design and the present state of its operation are briefly given below.

2.1 System Outline

The main specifications of the high-definition Hα olar telescope are given in Table 1. The Carl Zeiss 15-cm refracting telescope is used as the basic platform for the system, and various improvements and modifications have been made to it, such as the addition of automatic operation functions and improvements in performance. For example, to reduce the deterioration of the acquired image due to temperature perturbations and non-uniform temperature distribution in the lens cell and the lens by the heat from the Sun, a heat-rejection filter with an effective diameter of 150 mm was inserted in front of the objective lens, and the cells of the filter and lens were all painted white. The system was also provided

Table 1 *Primary specifications of high definition Hα telescope*

	Full-disk mode	Close up mode
Pixel format	2029×2048	1340×1037
Pixel size	9×9μm	6.8×6.8μm
Spatial sampling	1.15arcsec/pixel	0.64arcsec/pixel
Field of view	38.9×39.4arcmin.	14.3×11.1arcmin.

with a function for switching the field-of-view by shifting the Sun guiding telescope.

The focal plane package, which consists of the Lyot filter, field lens, full-disk reducing lens, full-disk close-up selection stage, and CCD camera, is set on a base fixed to the polar axis. The Lyot filter is a narrow-band filter that utilizes the birefringence of crystals such as calcite, and the transmission width for this system is 0.25Å. By inserting or removing the Polaroid in the final stage, it is possible to select the transmission width (0.25Å/0.5 Å). The transmitted wavelength can be changed by rotating the retardation plate with a motor. The angle of rotation is read by the potentiometer that is coupled with the gear of the retardation plate.

The imaging system can be switched between full-disk view (1.1 arc sec./pixel) and close-up view (0.64 arc sec./pixel). The full-disk view utilizes a camera lens (55-mm MicroNikkor lens) to reduce the image by 1.4 times, and the image is captured by a 4-million pixel CCD camera (Kodak MegaPlus 4.2) set behind the lens. For the Lyot filter used in our system, a beam slower than F15 is required. Therefore, a field lens is placed directly at the focal point, and the beam speed is controlled to F15 by narrowing the iris on the MicroNikkor blade aperture. In the close-up view mode, the image is acquired directly by a CCD camera placed at the primary image (Kodak MegaPlus 1.4). This optical design is rather tricky, but it can reduce the cost of the system by using commercial catalogued components, as well as realize a compact design for the focal plane package.

To enable independent focus adjustment of the full-disk and close-up view imaging systems, the systems are each placed on a compact linear stage that can be moved in the direction of the optical axis with a stroke of 20 mm. Each imaging system on the compact stage is then fixed onto a larger linear stage with a stroke of 100 mm that can be driven perpendicular to the optical axis. By moving the larger linear stage, it is possible to switch between full-disk and close-up views.

The telescope system and the focal plane package are controlled by the telescope control system developed on personal computers and filters. Each actuator and control system are GP-IB-interfaced and connected to workstations via optical RS-232 C link. The software is written in Microsoft Quick-Basic code.

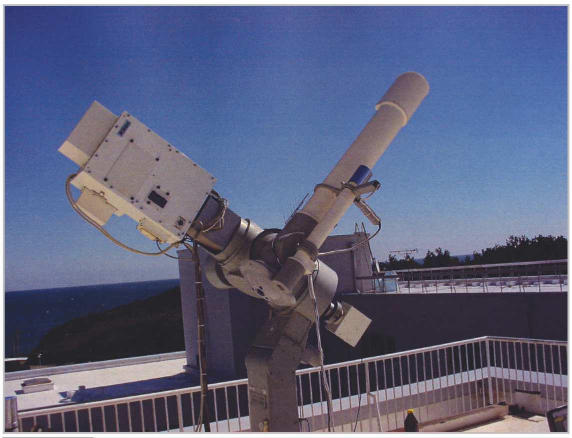

Fig.4 *High-definition Hα solar telescope*

2.2 Operation of the High-Definition Hα Solar Telescope

The high-definition Hα solar telescope is operated until sunset on every clear day. An operator starts up the telescope, sets the observation target, and adjusts the focus. After completion of the setup, the system shifts into automatic observation mode, in which image acquisition and control tasks are executed according to preset time intervals. The imaging software determines the most suitable exposure using the auto-set function for exposure time, also implementing an automatic exposure control function that halts the imaging acquisition process when there is lack of light. The quality of the image changes from moment to moment due to atmospheric fluctuation; thus a function has been developed (within the image selection function) that selects the image with the maximum contrast. With this system, a portion of the field-of-view for the highest-quality image is cut out and given a file name based on the date and time of acquisition, and the file is compressed and stored on a hard disk.

The operator screens the data collected for the presence of active regions indicating high solar activity such as solar flares and filament disappearance, and results are reported to the forecasting center. At the forecasting center, the forecasting staff also checks the close-up view and full-disk data on the terminals at the center. These data will clearly reveal the level of activity at active regions and the transition of magnetic field structures and provide critical information in forecasting solar flares. Furthermore, the high-resolution full-disk image has been proven to be a powerful tool in monitoring the birth and sudden growth of active regions and other sudden phenomena such as filament disappearance. Normally, forecasts are announced daily at 15:00 JST, summarizing the activity of the previous day and hours leading up to the announcement.

The collected data are temporarily stored on the hard disk of the workstation, and archived on CD-R as they accumulate. The archived data can be accessed by the staff and visiting researchers at CRL, as well as by researchers in Japan and abroad. The Solar Image Data Base (described in a later section) is being constructed so that the data can be searched, and even at this point, the database is widely utilized to check for existing data, to obtain an overall view of phenomena, and for educational purposes.

3 Solar Radio Observation System

The current solar radio observation system at the Hiraiso Solar Observatory is composed of a broadband solar radio observation instrument that conducts observations in the 25-2,500 MHz bandwidths (HiRAS: Hiraiso Radio Spectrograph) and a polarimeter that performs single-frequency observations at 2.8 GHz. These systems were installed in 1992, and routine observations began in 1993. The details of the initial solar radio observation system have been reported elsewhere[6]. Since then, improvements have been made to the system such as the backend section and the data collection system. This section will report on the present state of HiRAS (**3.1**), the outline of the single-frequency observation system (**3.2**), the observation data processing (**3.3**), and the management and publication of data (**3.4**). A summary and a discussion of the future of solar radio observation will be presented in the closing section.

3.1 Dynamic Spectrograph (HiRAS)

The HiRAS, which conducts observations in the 25-2,500 MHz bandwidths, consists of an orthogonal log periodic antenna (HiRAS-1 25-70 MHz), a 10-m ϕ parabolic antenna (HiRAS-2, 70-500 MHZ), and a 6-m ϕ parabolic antenna (HiRAS-3, 500-2,500 MHz).

The HiRAS-1 is an orthogonal log periodic antenna with an open-V configuration that receives linear orthogonal-polarized components in the 25-70 MHz bandwidths. It is set on an AZ-EL mount on top of a tower approximately 15-m high, and tracks the Sun at 1-minute intervals. The 3.5-80 MHz broadband hybrid is used as the hybrid for the circular polarization synthesizer unit.

The HiRAS-2 antenna is a parabolic antenna 10-m in diameter installed in 1988, before the installations of HiRAS-1 and HiRAS-3. It uses an orthogonal 20-element log periodic antenna as its primary radiator and has an equatorial mounting with a solar tracking precision of approximately 0.1˚. The main beam width of the antenna is 29˚ at 70 MHz and 4˚ at 500 MHz.

The HiRAS-3 is a parabolic antenna with a diameter of 6 m and uses an orthogonal 23-element log periodic antenna as its primary radiator. It has an AZ-EL mount with a solar tracking precision of 0.1˚, the precision of calculation included. The main beam width of the antenna is approximately 6.5˚ and 1.4˚ at 500 MHz and 2,500 MHz, respectively.

Using independent spectral analyzers, frequency analyses are performed separately on the right- and left-polarized components received by each antenna. In the conventional system, a single computer handles multiple tasks from antenna control and data collection from spectral analyzers. This causes the data collection interval to vary between 2-5 seconds, depending on the relative timing of antenna drive tasks. At present, separate computers are used to execute antenna drive and data collection tasks, and this problem has been largely resolved. The data acquired by PC is transferred to the data analysis server (HP9000/710) through the network. File sharing between the PC and server allows the data collection program in the PC to create files directly on the server.

For nearly a decade after the installation of the HiRAS system, no major troubles were encountered, and observation had been carried out successfully. However, almost 15 years have passed since the installation of the HiRAS-2 10-m antenna, and it is showing serious signs of degradation with age. Therefore, we have updated the control system in FY2001, and constructed a new control system on an industrial-use DOS-V PC. Furthermore, in FY2002, we have performed major refurbishment of the antenna hardware.

Table 2 Primary specification of HiRAS back-end

	HiRAS-1	HiRAS-2	HiRAS-3
Freq. resolution	100 kHz	300 kHz	100 kHz
Sweep time	500 ms/sweep	500 ms/sweep	500 ms/sweep
Sweep range	20-70 MHz	50-550 MHz	500-2500 MHz
Sampling point	401	701	501

Fig.5 The 10-m and 6-m HiRAS antennas

3.2 Single-Frequency Observation System

The 2.8-GHz single-frequency observation system uses a parabolic antenna with a diameter of 2 m. It has a septum polarizer as its primary radiator, and directly separates the left- and right-circular polarized components. It is set on an AZ-EL mount with a solar tracking precision of approximately 0.1˚ and main antenna beam width of 3.5˚. To reduce the effect of temperature variations in the front-end section, all units except for the polarizer were moved behind the main reflector. Data is collected using the spectral analyzer in the zero-span mode, converted into digital time-series data, and transferred to the data collection PC via GP-IB. The solar radio intensity at 2.8 MHz (wavelength of 10.7 cm) is known to have good correlation with number of sunspots, and so F10.7 is regarded as an important indicator of the level of solar activity. It is also used as an important parameter in correcting for atmospheric drag in satellite orbit prediction.

3.3 Observation Data Processing

The volume of data collected by the system on a daily basis varies with season, but is approximately 150-250 Mbytes. Since the volume of data of the single-frequency observation system is not large, it is stored in the same format as the raw data. In contrast, the volume of raw spectral data for the HiRAS is massive, and is compressed by the data analysis server upon storage. The 1,603 data points from the spectral analyzer in the direction of the frequency axis are compressed into 501 points of logarithmic function. Here, data resampling is performed by using the minimum value of the corresponding frequency range as the representative value to remove interference. Furthermore, the signal intensity information is compressed from 2 bytes to 1 byte. This compression scheme will limit the data to approximately 20-30 Mbytes/day.

The compressed data accumulated on the hard disk are saved on magnetic optical disks approximately once a month. Since 1997, data have also been archived on CD-R to create back-ups for the MO disks. With the lowering of prices of mass-memory media in recent years, archiving of uncompressed raw data is also being considered.

3.4 Management and Publication of Observation Data

As described above, antenna control, data acquisition, and compression functions are all performed by computers. Thus, much of the operation of the system, except for back-up of observation data, is automated. To utilize the data for space weather forecasting duties, the dynamic spectra for the current and previous days are displayed on the X-terminals of the forecasting center, and the spectrum for the current day is updated every 30 minutes. This enables the forecaster and researchers to comprehend ongoing solar radio phenomena immediately, and serves as an important element of the forecasting process. Also, the spectral plots and the single-frequency plots of the previous day are output to the printer in the forecasting room, ready for review by the staff.

The data analysis server creates images such as the dynamic spectra and summary-plots single-frequency data from the HiRAS spectral data and the single-frequency data. These images are available to the public on the website for external outreach (http://sunbase.crl.go.jp/solar/denpa/index.html). The data analysis server sends the HiRAS spectral data to the server every 30 minutes for quasi-real-time updates. Other information available at the website includes the spectral plots and single-frequency plots for the previous day, the HiRAS spectral data since August 1996, and a monthly summary of observation reports. Besides the WWW, observation data are also publicized in the CRL's "IONOSPHERIC DATA IN JAPAN (monthly report)." The report contains data for the radio intensities for the single frequency of 500 MHz, anomalous events observed at 200 MHz, 500 MHz, and 2.8 GHz, a summary-plot for the 2.8 GHz single-frequency observation, and F10.7 values.

When major events such as Type-Ⅱ radio bursts occur, researchers extract the data for the event from the observation data and upload this data to the external publication server. Figure 6 shows an example of the publicized data for Type-Ⅱ, Type-Ⅲ, and Type-Ⅳ radio bursts that accompanied solar flare X2.3/3B on April 10, 2001. During this event, the two-ribbon flare shown in Fig.2 was observed by the CRL Hα solar telescope. The occurrences of Type-Ⅱ and Type-Ⅳ radio bursts indicate that an ejection of a plasma cloud accompanied this solar flare event, which would increase the risk of a geomagnetic disturbance being triggered within several days. As predicted, a strong geomagnetic storm occurred late on April 11.

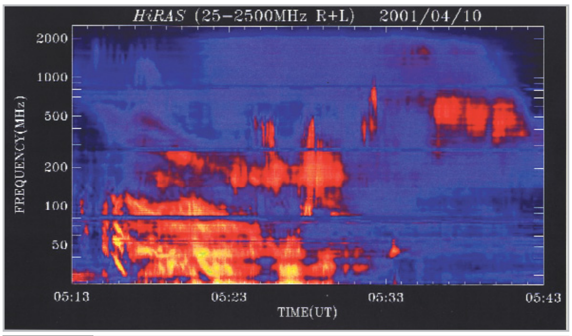

Fig.6 A radio burst accompanying the solar flare on April 10, 2001

4 Conclusions-Future of Studies in Solar Observation Technology

The core of solar studies at CRL lies in the observation technologies necessary for successful space weather forecasting and in the development and operation of the instruments. What makes space weather studies at CRL unique is that these studies are not restricted to research and development of measurement and data-utilization technologies for forecasting, but that it also involves routine forecasting duties as well. The performance of and technology behind the instruments developed at CRL are verified through routine duties and are operated continuously afterwards, and the entire system plays an important role in space weather studies and in providing space environment information services. Therefore, the themes of our future research will also be centered on areas of high priority in the study of space weather phenomena and in forecasting. Among these, one of the most important themes is the observation of CME propagation through interplanetary space, which drives geomagnetic storms and SEP events. Details of this theme will be provided in a separate paper.

In optical observation, polarization spectroscopy for detailed investigation of the solar-surface magnetic field is considered to be the most important subject of basic research and development. It is possible to determine the magnetic field of the atmosphere on the solar surface by measuring the detailed polarization properties of the outline of spectral lines using a combination of spectrometer and polarization analyzer. To observe the change in magnetic field induced by the energy released by a solar flare, polarization detection precision on the level of 0.01% is required. To achieve such precision, numerous problems must be overcome, such as the development of technologies for high-speed polarization modulation, correction for atmospheric fluctuation, and suppression of the false polarization that may result from the optical system during observation. This will be undertaken as a long-term theme for basic research.

In the field of radio observation, a new direction for development is under investigation based on our achievements using current methods of dynamic spectral observation (HiRAS). High-quality data acquisition by broadband radio observation is presently inhibited on the ground by interference from radio waves used for communication and broadcasting. It might be necessary to develop plans to conduct solar radio observations using satellites. A feasibility study will also be required on radio observation with higher temporal resolutions in future.

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