The Nobeyama Radioheliograph

HIROSHI NAKAJIMA, MASANORI NISHIO, SHINZO ENOME, KIYOTO SHIBASAKI, TOSHIAKI TAKANO, YOICHIRO HANAOKA, CHIKAYOSHI TORII, HIDEAKI SEKIGUCHI, TAKESHI BUSHIMATA, SUSUMU KAWASHIMA, NORIYUKI SHINOHARA, YOSHIHISA IRIMAJIRI, HIDEKI KOSHIISHI, TAKEO KOSUGI, YASUHIKO SHIOMI, MASAKI SAWA, AND KEIZO KAI

A new 17-GHz radio interferometer dedicated for solar observations was constructed in 2 years at Nobeyama, Nagano. It consists of eighty-four 80-cm-diameter antennas arranged in a Tee-shaped array extending 490 m in east–west and 220 m in north–south directions. Since late June of 1992, radio full-disk images of the Sun have been observed for 8 h every day. The spatial resolution is 10″ and the temporal resolution is 1 s and also 50 ms for selected events. Every 10 s, correlator data are synthesized into images in real time and displayed on a monitor screen. The array configuration is optimized to observe the whole Sun with high spatial and temporal resolution and a high dynamic range of images. Image quality of better than 20 dB is realized by incorporation of technical advances in hardware and software, such as 1) low-loss phase-stable optical-fiber cables for local reference signal and IF signals, 2) newly developed phase-stable local oscillators, 3) custom CMOS gate-array LSI's of 1-b quadraphase correlators for 4 × 4 combinations, and 4) new image processing techniques to suppress large sidelobe effects due to the solar disk and extended sources.

I. Introduction

A new radioheliograph at short centimeter wavelengths (the Nobeyama Radioheliograph) was constructed at Nobeyama Radio Observatory, National Astronomical Observatory, Japan, and began routine observations in late June 1992. This instrument is dedicated to solar observations and achieves high spatial and temporal resolution imaging of the whole Sun with high image quality. This is a realization of more than a decade of discussions by the Japanese solar radio group about the feasibility of a dedicated solar radio telescope.

Radio imaging observations are important to reveal the physical mechanism of solar flares. They will give us new information about locations of electron acceleration sites. Usually, the flaring regions have complicated geometrical configurations. Therefore, two-dimensional imaging observations are quite essential. Clearly, the new instrument should have high spatial resolution to resolve radio sources on the Sun. The spatial resolution of the Nobeyama Radioheliograph is about 10″, which depends on the ratio of observation wavelength and maximum antenna spacing.

High-resolution imaging observations of the Sun have been carried out in microwaves using large interferometers such as the Very Large Array [1] and the Westerbork Synthesis Radio Telescope [2], which are mainly designed for rotational synthesis observations and suitable to observe quasi-stationary objects such as cosmic radio sources or solar active regions. These instruments consist of element antennas of large diameter designed for their large collecting area which gives a narrower field of view. In this type of instrument, the observation time is shared with various solar and nonsolar projects according to observation proposals. In solar flare studies, statistical or systematic observations are quite essential to reveal general properties of the flare, and an instrument is required that is dedicated to routine base observations with a wide field of view to cover the whole Sun.

In solar flare observations, the observation frequency should be in short-centimeter to millimeter wavelengths where radio sources are optically thin, and preferably multifrequency in order to determine frequency spectra and hence energy distribution of accelerated electrons. In the Nobeyama Radioheliograph, the observation frequency is chosen to be 17 GHz as an initial step, and an expansion plan is considered of simultaneous operations at 17 and 34 GHz in the near future.

Manuscript received January 6, 1993; revised August 18, 1993. The Nobeyama Radioheliograph was supported by the Ministry of Education and Culture, Japan.

H. Nakajima, M. Nishio, S. Enome, K. Shibasaki, T. Takano, Y. Hanaoka, C. Torii, H. Sekiguchi, T. Bushimata, S. Kawashima, N. Shinohara, T. Kosugi, Y. Shiomi, and M. Sawa are with the Nobeyama Radio Observatory, National Astronomical Observatory, Minamisaku, Nagano 384-13, Japan.

Y. Irimajiri is with the Communications Research Laboratory, Koganei, Tokyo 184, Japan.

H. Koshiishi is with the Department of Astronomy, School of Science, The University of Tokyo, Bunkyo-ku, Tokyo 113, Japan, and the Nobeyama Radio Observatory, National Astronomical Observatory, Minamisaku, Nagano 384-13, Japan.

K. Kai (deceased) was with the Nobeyama Radio Observatory, National Astronomical Observatory, Minamisaku, Nagano 384-13, Japan.

IEEE Log Number 9400198.

0018-9219/94$04.00

Table 1 Nobeyama Radioheliograph Characteristic and Performance

Observing frequency	17 GHz (λ = 1.7635 cm)
Bandwidth	33.6 ± 0.9 MHz asymmetry among antennas: < 0.6 dB
Field of view	40′
Spatial resolution	10 ″
Temporal resolution	1 s for entire observed period 50 ms for selected events
Dynamic range of images	≥ 20 dB for snapshot ≥ 30 dB for rotational synthesis
Observing period	±4 h around meridian time of about 0245 UT
Sensitivity in solar observations flux density (brightness temperature)	4.4×10^{-3} sfu (1300 K)* for 1-s snapshot 7.3×10^{-5} sfu (22 K) for 1-h rotational synthesis
Polarization	Both circular polarizations (time sharing every 25 ms)
Isolation of polarization SW	≥ 20 dB (several: 18 dB)
Overall phase stability	≤ 0.3 (rms)
Overall gain stability	≤ 0.2 dB (rms)

* 1 sfu = 10^{-22} W · m^{-2} · Hz $^{-1}$

Solar flares typically show impulsive time variations at their early phase and quick changes of geometrical configurations can be expected. Therefore, a high temporal resolution is required of observation instruments. The temporal resolution should be considerably higher than 1 s in order to trace streaming of energetic electrons from particle acceleration sites.

Circular polarization measurements are important in solar radio observations to reveal relations between the coronal magnetic field and energetic electrons. In the Nobeyama Radioheliograph, a polarization degree of about 1% is detectable.

The major characteristics of the Nobeyama Radioheliograph are shown in Table 1. A detailed description is given of the heliograph's instrumentation with particular emphasis on the stability and accuracy of the total system.

II. Antenna and Array Configuration

The primary objectives of the Nobeyama Radioheliograph are rapidly changing phenomena such as impulsive flares. The array configuration is designed to be suitable for the snapshot imaging. We adopted a multiple, equally spaced Tee-array, extending 488.960 m in the east–west direction and 220.060 m in the north–south direction. Eighty-four 80-cm-antennas are arranged with increasing antenna spacings from the phase center of the Tee-array of d (fundamental spacing), $2d$, $4d$, $8d$, and $16d$ with symmetry to the center for each arm of the array. The fundamental spacing is determined to yield the field of view of 40′, sufficient to cover the whole Sun. This array configuration has a great advantage in image processing so that the FFT algorithm can be applied directly without gridding. This is quite important to process large amounts of data of high time resolution. Comparatively, large portions of the antennas are arranged in the central part of the Tee-array to synthesize high-quality images of the whole Sun. The outline of the array is shown in Fig. 1 and the geometry of antenna allocation is given in Fig. 2 and Table 2. The location of each antenna was adjusted with deviation of 0.5 mm rms with respect to the required horizontal and vertical coordinates of the Tee-array. This is necessary to keep the phase errors due to the setting errors of antennas as small as 3° or less for 1-h aperture synthesis observations.

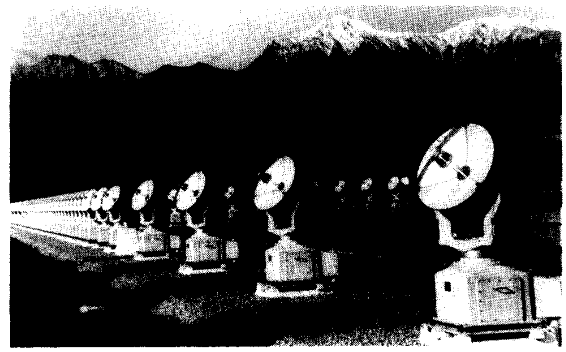


Fig. 1. A view of the Nobeyama Radioheliograph.

The element antennas are parabolic reflectors of 80-cm diameter. The half-power beamwidth of the reflector is 87.′1 ± 0.′4, which results to a degradation of the gain by 9% at the solar limb, if the antenna points to the center of the Sun. Pointing errors of element antennas result in correlator-based phase errors of observed Fourier components, which cannot be corrected after observations. The pointing errors are serious to an extended source such as the quiet Sun. Mechanical pointing accuracy of less than 30″ is obtained for all antennas and this is a sufficient value. Each antenna is supported by an alt–azimuth mount, which was chosen because it is easy to be set in the required position as compared with the equatorial mount.

Azimuth and elevation axes of each antenna are driven by stepping motors, respectively, which are controlled by a 16-b microcomputer attached to each antenna. These microcomputers are connected to a central microcomputer in the observation building by communication lines of the HDLC protocol. Control parameters of the stepping motors are refreshed by the central microcomputer every 5 s. Overall pointing accuracy of the antennas is better than ± 1.′ 5, which includes the mechanical pointing error and the error caused by the control algorithm.

III. Receiver System

A block diagram of the receiver system is shown for only one antenna channel in Fig. 3.

A. Frontend and IF Receiver

In the Nobeyama Radioheliograph, the right- and left-handed circular-polarization signals are received alternatively every 25 ms through polarization switches mounted to each antenna. Isolation of better than 20 dB is obtained between right- and left-handed circular polarizations for most channels.

The RF signal of 17 GHz is amplified by an uncooled HEMT amplifier with an average noise temperature of

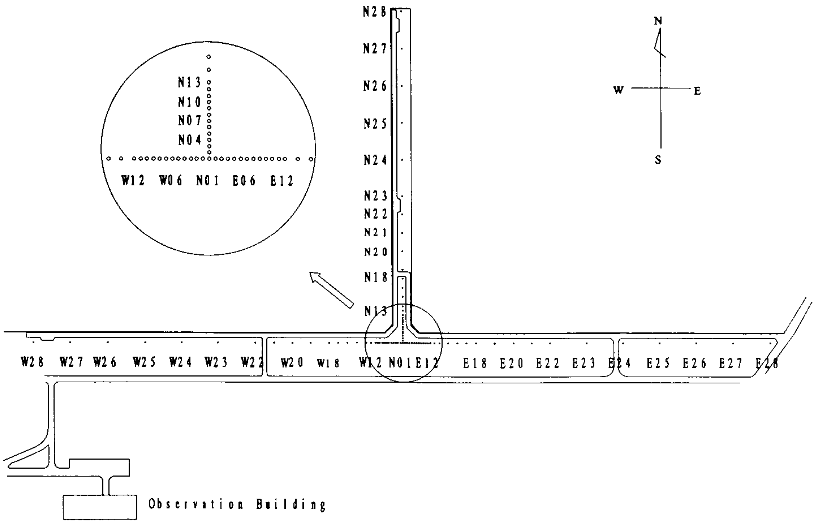


Fig. 2. Geometrical layout of the Nobeyama Radioheliograph.

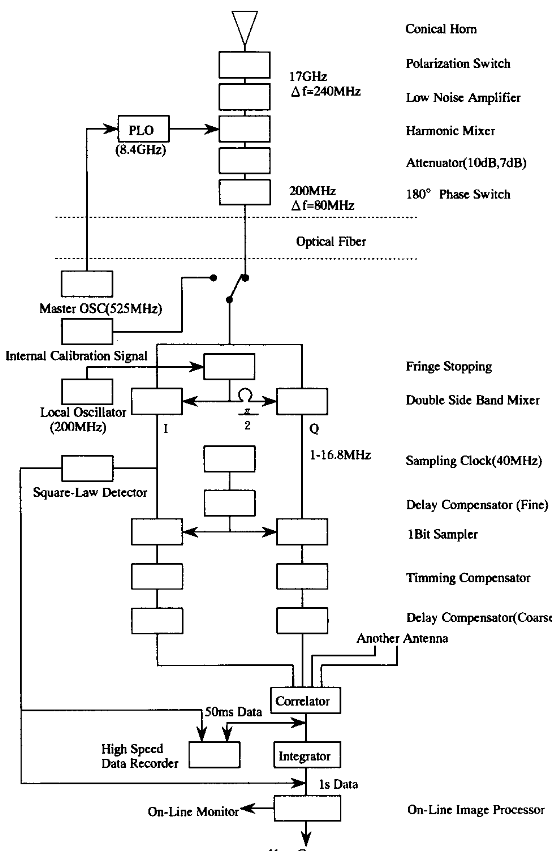


Fig. 3. Block diagram of the receiving system.

Table 2 Parameters of the Antenna Array

Total baseline length	488.960 m for E–W array 220.060 m for N–S array*
Fundamental spacing (d)	1.528 m
Antenna spacing	(1, 2, 4, 8, 16) × d
Location of array center	longitude 138°28′37.″14 latitude 35°56′20.″04
Number of antennas	84
Diameter of element antenna	80 cm
Half-power beamwidth of element antenna	87.′1±0.′4 at 17 GHz
Antenna temperature (Sun)	550 K (average) at 17 GHz
Overall pointing accuracy	< ± 1.′5

* E–W base line is on the horizontal line, while N–S base line inclines by 1.4998/100 toward the north.

180 K, which is installed close behind the polarization switch within each frontend box. The overall receiver noise temperature is 360 K rms, which includes the insertion loss of the feedhorn and the polarization switch. The amplified RF signal is mixed with an 8.4-GHz local signal and down-converted to a single-sideband IF signal at 200 MHz using a harmonic mixer. The IF signal from each antenna is transmitted to the observation building through a phase-stable optical fiber. The 8.4-GHz local signal is phase-locked to a reference signal transmitted from a master oscillator in the observation building via a phase-stable optical fiber. The IF signal is modulated, making use of the Walsh function with a 180° phase switch inserted in the IF line and demodulated after analog-to-digital conversion of the digital backend. The gain and phase of the HEMT amplifier and the local oscillator are quite sensitive to ambient temperature variations. Therefore, these devices are installed in a frontend box, together with the harmonic mixer and the IF amplifier, where the temperature is controlled at 35 ± 1°C.

The IF signal transmitted from each antenna is converted to two baseband signals orthogonal to each other by double-sideband mixers. The baseband signals have a frequency

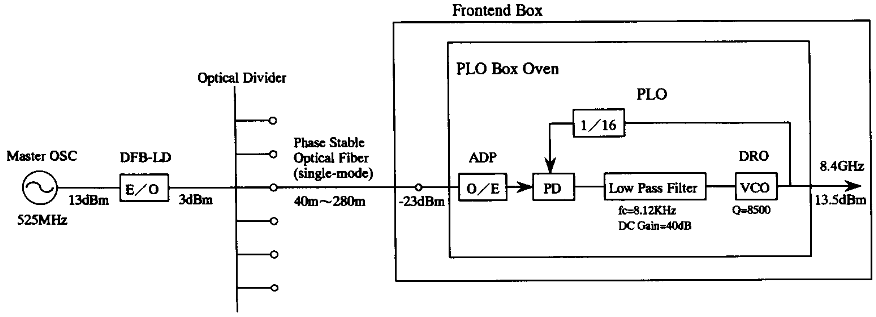


Fig. 4. Block diagram of the phase-lock network.

range from 100 kHz to 16.8 MHz. Phase angles between mutually orthogonal signals are adjusted to be 90° ± 0.°6 for all antenna channels. In order to stop the fringe variations, the phase rotator is inserted on the local signal line. The phase is changed in steps of 0.°36 with the overall accuracy better than ± 0.°6.

Fiber-optic signal transmission lines are extensively used in the Nobeyama Radioheliograph.The optical fiber is especially suitable for cabling in small antennas. Single-mode optical fibers are used to transmit the IF signal from the frontend boxes to the observation building and the local reference signal from the observation building to the frontend boxes. The optical fiber has advantages in that the transmission loss is very low and the bandwidth of the carrying RF signal is wide; therefore, the equalization of band characteristics for transmitted RF signals is not necessary, which is usually indispensable in case of coaxial cables. Optical fibers have also an advantage of producing no electrical interference. However, fiber-optic signal transmission lines have a disadvantage in that the dynamic range of the transmitted signal is limited because of poor S/N ratio as compared with coaxial cables. Further, they have limited maximum amplitude when electro-to-optical converters (E/O converters) and optical-to-electro converters (O/E converters) are used for analog signal transmission, as in the present case. This is especially severe in case of transmission of the IF signal, because the input signal of the E/O converter varies over a range of 21 dB, which corresponds to the ratio of the system temperature (910 K average) and the expected maximum antenna temperature from the Sun (10^5 K). The available dynamic range of the fiber-optic lines is only 16 dB in the present case, when the lowest signal level is kept 15 dB above the noise level of the O/E converter to avoid deterioration of the system S/N ratio. Actually, the dynamic range of the input signal to the E/O converters is limited to 11 dB by inserting 10-dB attenuation switches in the IF lines of the frontend.

In the Nobeyama Radioheliograph, multimode optical fibers are also used to transmit timing pulses for polarization switches, 180° phase switches, and control signals of the 10-dB attenuation switches from the observation building to the frontend boxes.

B. Fiber-Optic Phase-Lock Network

In order to obtain good phase stability of the receivers, distributions of a phase-stable local oscillator signal (LO signal) to the antennas is a key issue. Fig. 4 shows a block diagram of the phase-lock network to distribute a phase-stable LO signal. The LO signal at 8.4 GHz is phase-locked to the reference signal of 525 MHz, which is sent to each antenna through a 1-to-84 optical divider and phase-stable optical fiber cables from the master oscillator in the observation building.

The phase-lock network used in the Nobeyama Radioheliograph is a open-loop type. Therefore, temperature responses of the optical fiber cables govern the phase stability of the receivers. We are using a phase-stable optical fiber cable developed by Sumitomo Electric Industries Ltd [3]. This cable has a temperature coefficient of 0.2 ppm/°C for temperature ranges from −10°C to 20°C. The cables are buried 1.2 m under ground, where the temperature ranges from 4°C to 10°C and its variation is less than 0.1°C/day and 10°C/year. Accordingly, the phase stability of the 17-GHz signal due to temperature variations through the buried optical fibers is kept to less than 0.°8 /day for the maximum cable length of 280 m.

The phase lock of the local oscillator is achieved by comparing the phase between the reference signal of 525 MHz and the down-converted signals of local oscillator output obtained by using a digital frequency divider. As the phase-lock circuit has a rather high temperature coefficient (8.° 5/°C at 8.4 GHz), it is enclosed in a small box in which the temperature is maintained to within 40 ± 0.1°C using a Pertier cooling unit. As the O/E converter has also a high temperature coefficient of −5°/°C at 8.4 GHz, it is enclosed in the same box. As a result, the overall temperature coefficient of the phase-locked oscillator is −1.°3/°C, which includes the O/E converter.

The internal noise caused by the fiber-optic devices reduces the C/N ratio of the 8.4-GHz local signal and degrades the level of correlation. The C/N ratio of the 525-MHz reference signal to the 10-kHz offset point is about 110 dB/Hz, which is sufficient to produce clean local signals at 8.4 GHz, and thus the degradation of the correlation is less than 0.1%.

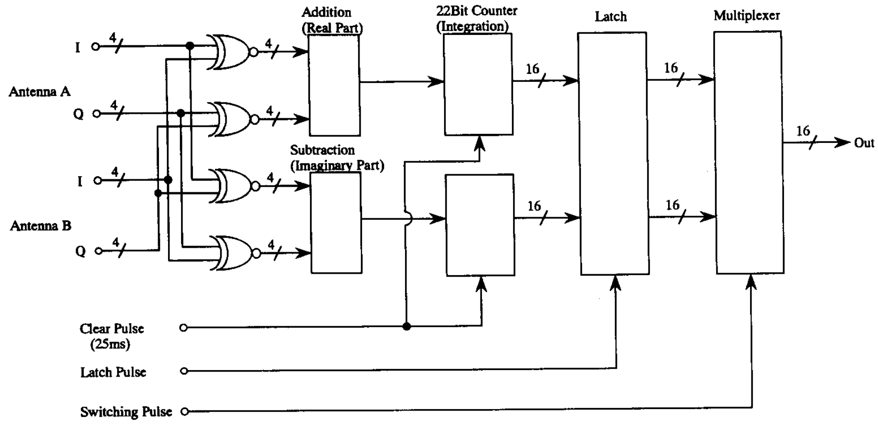


Fig. 5. An elementary circuit of the complex correlation LSI.

C. Digital Backend Receiver

In the Nobeyama Radioheliograph, complex correlations are calculated for all antenna pairs of 3486 combinations of 84 antennas. This calculation is made by 1-b correlators [4], which can be assembled with simple digital logic, and yields great stability to the backend. In case of solar observations, the received signal is so strong that the loss of sensitivities by a factor of $2/\pi$ is not severe.

Differences of signal arrival time among antennas are digitally compensated by a step of 1 ns with accuracy of less than 1 ns. This compensation is performed by combining a fine delay with the range from 0 to 24 ns in steps of 1 ns each and a coarse delay in the range from 0 to 1700 ns in steps of 25 ns each. The former is performed by shifting the sampling clock of 40 MHz and the latter is performed by using a shift register attached to the output of the 1-b sampler.

As large offsets of the 1-b samplers result in correlation errors, the offsets are compensated by counting the difference of the 0 state and the 1 state of the sampler output during about 50 ms and then returning it to the sampler input through a D/A converter. The offset voltage at the sampler input is less than 0.5 mV for the input signal raninge from 60 to 320 mV. For the correlator system, a specially designed correlator chip was developed using a CMOS gate array (30 000 gates). This chip is composed of 16 complex correlator units, which corresponds to 4 $\times$ 4 combinations of antennas, and each unit consists of four 4-b-parallel exclusive–OR circuits, an addition and subtraction circuit, two integration circuits, a latch, and a multiplexer circuit. The complex correlations for 3486 antenna pairs are measured by using 231 chips. Fig. 5 shows a unit of the correlator chip. As the conventional clock rate of the CMOS gate array is 10 MHz and is one-quarter of the sampling clock at the 1-b sampler, the calculation in the correlator chip is performed in parallel by four sets of circuit after resampling the 40-MHz bit stream to four 10-MHz bit streams shifted by 25-ns interval of each other. The interval of data integration in the correlator chip is synchronized to the timing of the polarization switching of 25 ms. The integration time is 24.615 ms and the remaining 0.385 ms is a dead time to the transient of polarization switching.

The 1-b correlations result in the loss of amplitude information of measured Fourier components. Therefore, the signal strength, including the received signal and the receiver noise, is measured to each antenna using the square law detectors every 25 ms. The correlation data, together with amplitude data, are read out every 25 ms alternately for right- and left-handed circular-polarization components, and are stored into buffer memories after the Van Vleck correction [5] is applied. As a result, a complete set of complex correlation data is produced every 50 ms.

D. Data Storage and Real-Time Monitor

All data with 50-ms time resolution (50-ms data) are averaged for 1 s, and are stored in optical disks of 5 Gbytes after being sent to the host computer (NEC SX-JL). On the other hand, all original 50-ms data are recorded once every day in a high-density MT of 20 Gbytes using a high-speed data recorder (SONY DIR1000). After the end of daily observations, flares which occurred during the observation are searched with some criterion (such as flux density is greater than a predetermined threshold), and the 50-ms data of the flares are played back and transferred to the host computer. These flare data are also saved on the optical disks of the host computer. The host computer has a computing speed of 285 MFLOPS, a main memory size of 128 Mbytes, and a disk storage volume of 45 Gbytes. A part of the 1-s data is picked up every 10 s and synthesized into real-time images using the host computer. The synthesized images are transmitted to a workstation and displayed on a monitor CRT as well as recorded on a video tape. Both real-time images and video tapes are very useful for determining what kind of activities are in progress and to examine whether the receiving systems are working properly. In addition, the images recorded on video tapes function as a measure for selecting events from the optical disks. The data users will be able to survey an outline of events from the image recorded on the video tapes and then synthesize images of high quality from the correlation data recorded on the optical disks for selected periods of time.

IV. Calibration and Image Restoration

The diameter of the individual antennas is too small to use nonsolar compact sources as calibrators. The multiple, equally spaced Tee-array has redundant antenna combinations at lower Fourier components, which provides a convenient gain and phase calibration method by using the Sun as a calibrator [6], in which antenna-dependent amplitude and phase errors are estimated from the data of redundant antenna combinations by using the least square method. This calibration method does not interrupt the observations and can compensate atmospheric phase variations in a short timescale. The calibration method was first developed for the 17-GHz solar radio interferometer at Nobeyama [7] as a limited case and then extended to the λ 8-cm Radioheliograph at Toyokawa [8]. In order to co-align the radio map with other data such as optical and X-ray images, high positional accuracy of less than 5$''$ is necessary, but is not obtained in the above calibration method. The absolute position of each observed source is determined relative to the solar disk using the sharp edge or limb of high-quality radio images of the solar disk.

The amplitude and phase errors included in measured correlation components are corrected using the data estimated by the above calibration method, and the radio images are synthesized by applying the FFT to the correlation data. The array configuration of the Nobeyama Radioheliograph produces high sidelobe levels in directly synthesized images or in dirty maps. This effect is usually reduced by applying the CLEAN algorithm [9] to the images. In solar radio images, a solar disk and extended components associated with active regions are dominant except for maximum phases of large flares. Therefore, the original CLEAN algorithm is not sufficient with respect to efficiency and accuracy. We have developed a modified CLEAN algorithm to extract the solar disk and the extended components directly from dirty maps. In this algorithm, the solar disk convolved by the synthesized beam is deducted first, and then the extendied components and compact components are extracted. In extracting the extended components from the images, various sizes of Gaussian sources are tested to choose most appropriate size according to certain criteria. The size of the 17-GHz radio disk is empirically determined and is 2.5% larger than that of the optical disk. An observed dirty image and a restored map processed by the new CLEAN algorithm are shown in Fig. 6.

In the Nobeyama Radioheliograph, the CLEAN algorithm is applied to images in total intensity (Stokes parameter I) and circular polarization (Stokes parameter V), which are obtained by adding and subtracting the right- and left-handed circular-polarization data. For the images of the V-component, the deduction of the disc component is not necessary, but the extraction of both positive and negative components is required.

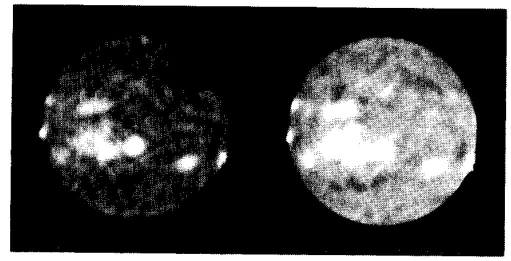


Fig. 6. The dirty image and the restored image of the Sun observed on April 23, 1992. Large sidelobe levels due to the disc component can be seen in the dirty image, while those are almost completely removed in the restored image.

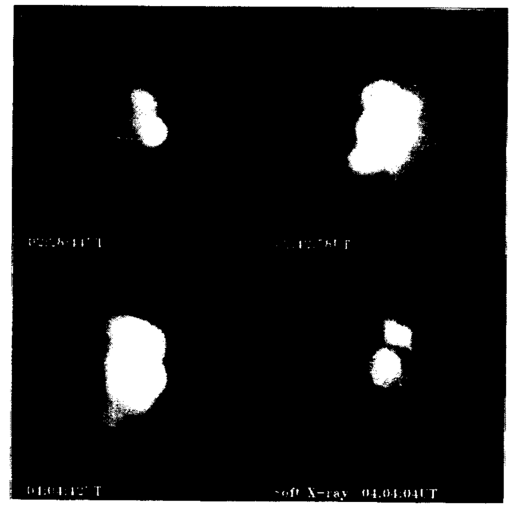


Fig. 7. Time evolution of the medium-class solar flare observed on June 28, 1992. The images are synthesized from 1-s data. The field of view of images is 315$''$ $\times$ 315$''$.

V. Total Performance

The Nobeyama Radioheliograph has been put into routine operation for 8 h every day since late June 1992. About a hundred solar flares have been recorded so far, which demonstrates our optimization of the total system.

Fig. 7 shows a time evolution of a medium-class solar flare which occurred on the east limb on June 28, 1992. A strongly polarized compact source initially appeared on the limb, followed by upward expansion, and developed into a large complex structure in the decay phase. In these images, we can see the brightest feature of 1.5×10^6 K in the flare region as well as faint features less than 5000 K in the disc. Therefore, a dynamic range of about 25 dB is attained in these images.

The closure amplitude and phase [10], [11] are good indices to estimate the quality of calibrated images. These values give a limit to the accuracy of the gain and phase calibration method using the redundant antenna combinations. In the case of the GOES X9 class flares on November 2, 1992, variations of the closure amplitude and phase were less than 1% and 0.° 5 in peak-to-peak values among all combinations of fundamental antenna spacing and their second harmonics. In addition, with respect to all combinations of the 16th and the 32nd harmonics of the fundamental antenna spacing, they are less than 8% and 1°. These values are nearly equal to amplitude and phase errors included in calibrated images. Therefore, the dynamic range of the image is estimated to be greater than 30 dB, which is much better than expected [12], [13].

ACKNOWLEDGMENT

The authors wish to thank H. Nohmi, N. Futagawa, K. Nishikawa, K. Honda, H. Shinohara, T. Itoh, T. Takabayashi, M. Miyawaki, and A. Imoto of NEC Corporation; H. Morikawa of Akasaka Diesels Ltd.; K. Mishima of Pasco Corporation, and S. Tanaka of Sumitomo Electric Industries Ltd. for their valuable contributions to ensure that the Radioheliograph met its design specifications and was completed within the time limit. They also wish to thank M. Ishiguro and K.-I. Morita of NRO for their valuable discussions in the design phase; the Faculty of Agriculture, Shinshu University, for allowing us to use the radioheliograph antenna site; and President Minoru Oda of the Institute of Physical and Chemical Research and the late S. Hayakawa, President of Nagoya University, for invaluable support to and understanding of this project.

REFERENCES

[1] P. J. Napier, A. R. Thompson, and R. D. Ekers, "The very large array: design and performance of a modern synthesis radio telescope," *Proc. IEEE*, vol. 71, pp. 1295–1320, 1983.

[2] J. W. M. Baars, J. F. Van der Brugge, J. L. Casse, J. P. Hamaker, L. H. Sondaar, J. J. Visser, and K. J. Wellington, "The Synthesis Radio Telescope at Westerbork," *Proc. IEEE* , vol. 61, pp. 1258–1266, 1973.

[3] S. Tanaka, Y. Murakami, Y. Sato, and J. Urakawa, "Precise timing signal transmission by a new optical fiber cable," *KEK Rep.*, vol. 90, no. 9, pp. 1–23, 1990.

[4] S. Weinreb, "A digital spectral analysis technique and its application to radio astronomy," Research Lab of Electronics, MIT, Cambrigde, MA, Tech. Rep. 412, 1963.

[5] J. H. Van Vleck and D. Middleton, "The spectrum of clipped noise," *Proc. IEEE*, vol. 54, pp. 2–19, 1966.

[6] K. Kimura, "Study on a phase and gain calibration method of radio interferometers," Master thesis, Nagoya Univ., 1988.

[7] H. Nakajima, H. Sekiguchi, S. Aiba, Y. Shiomi, T. Kuwabara, M. Sawa, H. Hirabayashi, T. Kosugi, and K. Kai, "A new 17-GHz solar radio interferometer at Nobeyama," *Publ. Astron. Soc. Japan*, vol. 32, pp. 639–650, 1980.

[8] M. Nishio, Y. Tsukiji, S. Kobayashi, K. Shibasaki, and S. Enome,"A real-time image processor with multi-channel correlator for solar radio observations," *Astron. Astrophys.* , vol. 198, pp. 370–374, 1988.

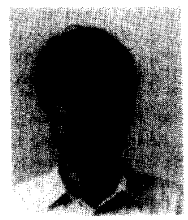
[9] J. Högbom, "Aperture synthesis with a non-regular distribution of interferometer baselines," *Astrophys. J. Suppl.*, vol. 15, pp. 417–426, 1974.

[10] R. C. Jennison, "A phase sensitive interferometer technique for the measurement of the Fourier transforms of spatial brightness distributions of small angular extent," *Mon. Not. Roy. Astron. Soc.* , vol. 118, pp. 276–284, 1958.

[11] A. R. Thompson, J. M. Moran, and G. W. Swenson, Jr., *Interferometry and synthesis in radio Astronomy*. New York: Wiley, 1986.

[12] M. Nishio, "Study on measurements of solar radio emission with radio interferometers," Ph.D. dissertation, Nagoya Univ., 1990.

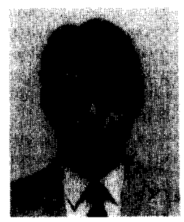
[13] H. Koshiishi, "Evaluation of the image quality of the Nobeyama Radioheliograph on the bases of closure relations," Master thesis, Tokyo Univ., 1993.



Hiroshi Nakajima was born in Nagano, Japan, on January 4, 1941. He received the B.S. and M.S. degrees in physics from Nagoya University, Japan, in 1965 and 1967, respectively, and the Ph.D. degree in astronomy from the University of Tokyo, Tokyo, Japan, in 1981.

He was a research staff member of Nobeyama Solar Radio Observatory, Tokyo Astronomical Observatory, the University of Tokyo, from 1970 to 1988, and has been a research staff member of Nobeyama Radio Observatory of the National Astronomical Observatory, Japan, since 1988. Since 1970, he has been involved in the design and construction of solar radio astronomy instrumentation and solar hard X-ray telescopes hardware systems. He has also worked on solar physics based upon data from those instruments.

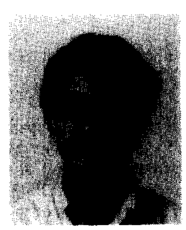
Dr. Nakajima is a member of the Astronomical Society of Japan and the International Astronomical Union.



Masanori Nishio was born in Gifu, Japan, on May 25, 1955. He received the B.E. degree from the University of Electro-Communications, Tokyo, Japan, in 1978, and the M.E. and Ph.D. degrees in electrical engineering from Nagoya University, Japan, in 1980 and 1989, respectively.

From 1980 to 1988, he was a staff member of the Research Institute of Atmospherics, Nagoya University, Aichi, Japan, where he was engaged in the development of solar radio telescopes and real-time image processing system. In 1988, he joined the Radio Astronomical Division of the National Astronomical Observatory in Nobeyama, Nagano, Japan, to work on the construction of the Nobeyama Radioheliograph in receiver system.

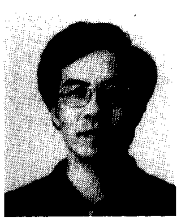
Dr. Nishio is a member of the Institute of Electronics, Information and Communication Engineers of Japan, the Astronomical Society of Japan, and the International Astronomical Union.



Shinzo Enome was born in Tokyo, Japan, on June 29, 1938. He received the B.S., M.S., and Ph.D. degrees in astronomy from the University of Tokyo, Japan, in 1962, 1964, and 1972, respectively.

In 1966, he joined a staff member of the Research Institute of Atmospherics, Nagoya University, Toyokawa, Japan, where he was engaged in studies of solar activities with special emphasis on high-energy phenomena on the basis of radio, optical, X-ray data. He also worked on development of solar radio-astronomy instrumentation. In 1988, he joined the Radio Astronomy Division of the National Astronomical Observatory in Nobeyama, Nagano, Japan to work on the construction of the Nobeyama Radioheliograph, which was completed in two years in 1992. He has been the Director of the Solar Radio Telescope Facilities of Nobeyama Radio Observatory since 1991.

Dr. Enome is a member of the Astronomical Society of Japan and the International Astronomical Union.



Kiyoto Shibasaki was born in Onomichi, Hiroshima, Japan, on January 6, 1950. He received the B.S. and Ph.D. degrees in physics from Nagoya University in 1972 and 1979, respectively.

From 1974 to 1988, he was a member of the research staff of the Research Institute of Atmospherics (Toyokawa), Nagoya University, where he was engaged in the study of solar radio emission and in the development of radio telescopes and data analysis software for solar observations. In 1988, he joined the Nobeyama Radioheliograph Project, where he worked on the data acguisition and reduction system.

Dr. Shibasaki is a member of the International Astronomical Union and the Astronomical Society of Japan.

Toshiaki Takano received the M.S. and Ph.D. degrees in physics in 1979 and 1983, respectively, from Nagoya University, Japan.

From 1983 to 1985 he was at the University of Cologne, FRG, as a research fellow of the Humboldt Foundation, and from 1985 to 1987 he worked at Nobeyama Radio Observatory, Japan, as a post-doctoral fellow of the Japan Society for Promotion of Science on investigation of star forming regions. In 1987, he joined the Solar Radio Astronomy Group, the Research Institute of Atmospherics, Nagoya University, and in 1988 moved to Nobeyama Radio Observatory, the National Astronomical Observatory, Japan. Since then he has contributed to construction of the Nobeyama Radioheliograph. His research interests include development of unique instruments for radio astronomy, investigation on solar physics, and the like

Dr. Takano is a member of the Institute of Electronics, Information and Communication Engineers of Japan, the Astronomical Society of Japan, and the International Astronomical Union.

Yoichiro Hanaoka was born in Nagano, Japan, on January 11, 1961. He received the B.S., M.S., and Ph.D. degrees in 1983, 1985, and 1988, respectively, in astronomy from Kyoto University, Japan.

From 1988 to 1990, he was a postdoctoral fellow at Kyoto University. At Kyoto he worked on solar physics with optical data. In 1990, he joined the Nobeyama Radioheliograph Project at Nobeyama Radio Observatory, the National Astronomical Observatory of Japan, as a post-doctoral fellow. He worked on the computer system and the imaging software system of the Nobeyama Radioheliograph. He has been a research associate of the National Astronomical Observatory, Japan since 1991. He continues to work on solar physics, especially on flare-related phenomena of the Sun

Dr. Hanaoka is a member of the Astronomical Society of Japan and the International Astronomical Union.

Chikayoshi Torii was born in Aichi, Japan, on November 21, 1934. He graduated from the Junior College (the Department of Law and Economics) of Aichi University, Japan, in 1973.

From 1953 to 1988, he was a member of the technical staff of the Research Institute of Atmospherics, Nagoya University, Japan, where he was engaged in the development and construction of solar radio astronomy instrumentation. In 1988, he joined Nobeyama Radio Observatory, the National Astronomical Observatory, Japan, to work on the construction of the Nobeyama Radioheliograph in the antenna, receiver, and signal cable systems.

Mr. Torii is a member of the Astronomical Society of Japan.

Hideaki Sekiguchi was born in Nagano, Japan, on March 12,1944. He received the B.S. degree in chemistry from Chiba University, Japan, in 1967.

He was a technical staff member of Nobeyama Solar Radio Observatory, Tokyo Astronomical Observatory, the University of Tokyo from 1970 to 1988, and has been a staff member of Nobeyama Radio Observatory, the National Astronomical Observatory, Japan, since 1988. Since 1970, he has been involved in the development of solar radio astronomy instrumentation. He has worked on data analysis based on data from those instruments.

Mr. Sekiguchi is a member of the Astronomical Society of Japan.

Takeshi Bushimata was born in Niigata, Japan, on March 27, 1948. He received the B.E. degree in telecommunication engineering from Tokyo Denki University, Japan, in 1973.

From 1970 to 1989, he was a technical staff member of the Mechanical Engineering Faculty, the University of Electro-Communication, Japan, where he was engaged in the measurements of machine vibrations and sounds from streams and the development of automatic machines. In 1989, he joined Nobeyama Radio Observatory, the National Astronomical Observatory, Japan, to work on the construction of the Nobeyama Radioheliograph receiver system. He also works on automatic control of radiometers for solar patrol observations.

Mr. Bushimata is a member of the Astronomical Society of Japan.

Susumu Kawashima was born in Nagano, Japan, on June 13, 1952. He graduated from Iwamurada High School, Nagano, Japan, in 1971.

He was a technical staff member of Nobeyama Solar Radio Observatory of the Tokyo Astronomical Observatory, the University of Tokyo from 1971 to 1988, and has been a staff member of Nobeyama Radio Observatory of the National Astronomical Observatory, Japan, since 1988. Since 1970, he has been involved in the development and construction of solar radio astronomy instrumentation. He worked on the receiver and antenna control system of the Nobeyama Radioheliograph.

Mr. Kawashima is a member of the Astronomical Society of Japan.

Noriyuki Shinohara was born in Nagano, Japan, on May 16, 1962. He graduated from Usuda High School, Nagano, Japan, in 1981.

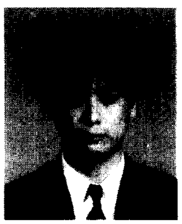
He was a technical staff member of Nobeyama Solar Radio Observatory, the Tokyo Astronomical Observatory, the University of Tokyo from 1981 to 1988, and has been a staff member of Nobeyama Radio Observatory of the National Astronomical Observatory, Japan, since 1988. Since 1981, he has been involved in the development and construction of solar radio astronomy instrumentation. He worked on the antenna-control and data-analysis computer systems in the Nobeyama Radioheliograph.

Mr. Shinohara is a member of the Astronomical Society of Japan.

Yoshihisa Irimajiri was born in Kochi, Japan, on March 20, 1964. He received the B. E. degree from Hiroshima University in 1987 and the M.E. degree from Nagoya University in 1989, both in electrical engineering. He received the Ph.D. degree in astronomy from the University of Tokyo in 1992.

He was a postdoctoral fellow at Nobeyama Radio Observatory, the National Astronomical Observatory, Japan in 1992, where he worked on the development of frequency-selective surface, as well as solar radio astronomy. He is currently a researcher in the Millimeter-wave Remote Sensing Section, Global Environment Division, Communications Research Laboratory, Ministry of Post and Telecommunications to work on millimeter-wave remote sensing of the terrestrial atmosphere.

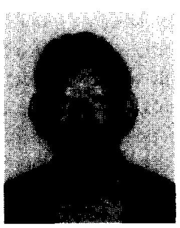
Dr. Irimajiri is a member of the Institute of Electronics, Information and Communication Engineers of Japan and the Astronomical Society of Japan.



Hideki Koshiishi was born in Tokyo, Japan, on October 30, 1966. He received the B.E. degree in electrical engineering fromYamanashi University, Japan, in 1990 and the M.S. degree in astronomy from the University of Tokyo in 1993.

He is currently a graduate student in the Department of Astronomy, the University of Tokyo and is closely associated with Nobeyama Radio Observatory, the National Astronomical Observatory, Japan, working on solar physics and astronomical instrumentation.

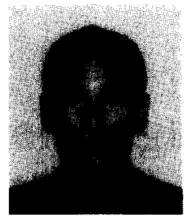
Mr. Koshiishi is a member of the Institute of Electronics, Information and Communication Engineers of Japan and the Physical Society of Japan.



Takeo Kosugi was born in Aichi, Japan, on January 6, 1949. He received the B.S., M.S., and Ph.D. degrees in astronomy from the University of Tokyo, Japan, in 1972, 1974, and 1984, respectively.

From 1976 to 1988, he worked as a research associate at the Nobeyama Solar Radio Observatory, the Tokyo Astronomical Observatory, the University of Tokyo, Japan. From 1988 to 1991, he was a staff member of the Faculty of Science, University of Tokyo, as an associate professor. Since 1992 he has been a professor of Solar Radio Astronomy, National Astronomical Observatory, which was founded in 1988 as Japanese first inter-university research institute for astronomy. Throughout these periods he has been conducting research of solar radio astronomy and solar flare physics. He had been involved in development and construction of radio telescopes as well as X-ray telescopes, among which representatives are the Nobeyama Radioheliograph and the Hard X-ray Telescope on-board the Yohkoh satellite launched in August 1991.

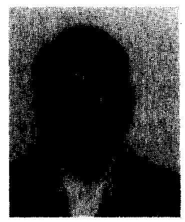
Dr. Kosugi has been a committee member of the Astronomical Society of Japan since 1989. He is a member of the International Astronomical Union.



Yasuhiko Shiomi was born in Tokyo, Japan, on September 7,1938. He graduated from Kunitachi High School, Tokyo, Japan, in 1957.

He was a technical staff member of the Tokyo Astronomical Observatory, the University of Tokyo from 1957 to 1988, and the technical staff member of Nobeyama Radio Observatory of the National Astronomical Observatory, Japan, in 1988. Since 1957, he has been involved in the development and construction of solar radio astronomy instrumentation. He worked on the antenna system of the Nobeyama Radioheliograph.

Mr. Shiomi is a member of the Astronomical Society of Japan.



Masaki Sawa was born in Tokyo, Japan, on March 12, 1943. He received the B.S. degree in physics from the Science University of Tokyo, Japan, in 1966.

From 1966 to 1988, he was a member of the technical staff of the Tokyo Astronomical Observatory, the University of Tokyo, Japan, where he was engaged in the development and construction of solar radio astronomy instrumentation. Since 1988, he has been a technical staff member of Nobeyama Radio Observatory, the National Astronomical Observatory, Japan, where he has been engaged in the construction of X-ray telescopes on-board Solar-A or Yohkoh satellite.

Mr. Sawa is a member of the Astronomical Society of Japan.

Keizo Kai (deceased) was born in Osaka, Japan, on August 11, 1934. He received the B.S., M.S., and Ph.D. degrees in astronomy from the University of Tokyo, Japan, in 1957, 1959, and 1965, respectively.

From 1959 to 1965, he was a staff member of Tokyo Gakugei University, Japan. From 1965 to 1988, he was a research staff member of the Tokyo Astronomical Observatory, the University of Tokyo, Japan, and from 1988 to 1991, a research staff member of Nobeyama Radio Observatory, the National Astronomical Observatory, Japan. Since 1981, he had been Professor of Solar Radio Astronomy, Tokyo Astronomical Observatory and the National Astronomical Observatory. Throughout this period he had conducted research of solar radio astronomy and solar flare physics. He had been involved in the development and construction of radio telescopes as well as X-ray telescopes for solar observations. He passed away in March, 1991, before he saw an observational result from either of the Nobeyama Radioheliograph or the Hard X-ray Telescope on-board the Solar-A or Yohkoh satellite.