HIGHLIGHTING THE HISTORY OF JAPANESE RADIO ASTRONOMY. 3: EARLY SOLAR RADIO RESEARCH AT THE TOKYO ASTRONOMICAL OBSERVATORY

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Abstract: The radio astronomy group at the Tokyo Astronomical Observatory was founded in 1948 immediately after WWII, and decided to put its main research efforts into solar radio astronomy. The first radio telescope was completed in 1949 and started routine observations at 200 MHz. Since then, the group has placed its emphasis on observations at meter and decimeter wavelengths, and has constructed various kinds of radio telescopes and arrays operating at frequencies ranging from 60 to 800 MHz. In addition, radio telescopes operating at 3, 9.5 and 17 GMHz were constructed. In parallel with the observationally-based research, theoretical research on solar radio emission also was pursued. In this paper, we review the instrumental, observational and theoretical developments in solar radio astronomy at the Tokyo Astronomical Observatory in the important period from 1949 through to the 1960s.

Keywords: Japan, Tokyo Astronomical Observatory, solar radio astronomy, solar radio telescope, solar radio emission.

1 INTRODUCTION

The first deliberate attempts by Japanese scientists to detect radio emission from an extraterrestrial object can be traced back to the Tokyo observations at 3 GHz by Koichi Shimoda (b. 1920) of the partial solar eclipse on 9 May 1948 and observations of solar noise at 3.3 GHz by Minoru Oda (1923–2001) and Tatsuo Takakura (b. 1925) in November 1949 from Osaka (see Ishiguro et al., 2012; Ishiguro and Orchiston, 2014). However, these observations were experimental. In 1948, the radio astronomy group led by Professor Takeo Hatanaka (1914–1963; see Figure 1)[1] was founded at the Tokyo Astronomical Observatory (henceforth TAO) at Mitaka, Tokyo, with strong support from the Director of the Observatory, Professor Yūsuke Hagiwara (1897–1979). Other members of the group were Fumio Moriyama (b. 1927) and Shigemasa Suzuki (1920–2012). At that time, the TAO did not have the electronics technology which was necessary to observe radio emission from non-solar sources. In addition, the period after World War II was a very difficult one in which to get suitable equipment and stable power supplies for radio telescopes. So Hatanaka's group decided initially to put its main research efforts into solar radio astronomy, which they believed would be more easily carried out than non-solar radio astronomy.

In 1949, the first solar radio telescope at the TAO was constructed with help from the Radio Research Laboratories of the Ministry of Posts and Telecommunications at Hiraiso, which already was deeply involved in research into the ionosphere and had an excellent background in radio astronomical instrumentation and techniques. Since then, new radio telescopes for solar observations at meter and decimeter waves were constructed one after another at the TAO, as the staff there developed their own technologies and ideas. As a result, the TAO group was able to make important contributions to solar observational radio astronomy and theory. Hatanaka's group, and the vibrant solar research group at the Toyokawa Observatory led by Haruo Tanaka from the Research Institute of Atmospherics at Nagoya University, were to play a key role in researching solar radio emission during the 1950s and 1960s, and ensure Japan's international visibility in this area of astronomy. For Hiraiso, Tokyo, Toyokawa and other Japanese localities mentioned here and elsewhere in this paper see Figure 2.

Figure 1: A meeting of the Japanese National Commission V of URSI held at the Toyokawa Observatory in 1954. Professor T. Hatanaka is the 'larger than life' figure on the extreme right, in the back row. Others from the TAO in this photograph are: K. Akabane (back row, second from the left), T. Takakura (back row, third from the left), S. Suzuki (beside Hatanaka), and TAO Director, Professor Y. Hagihara (front row, right) (adapted from Tanaka, 1984: 345).

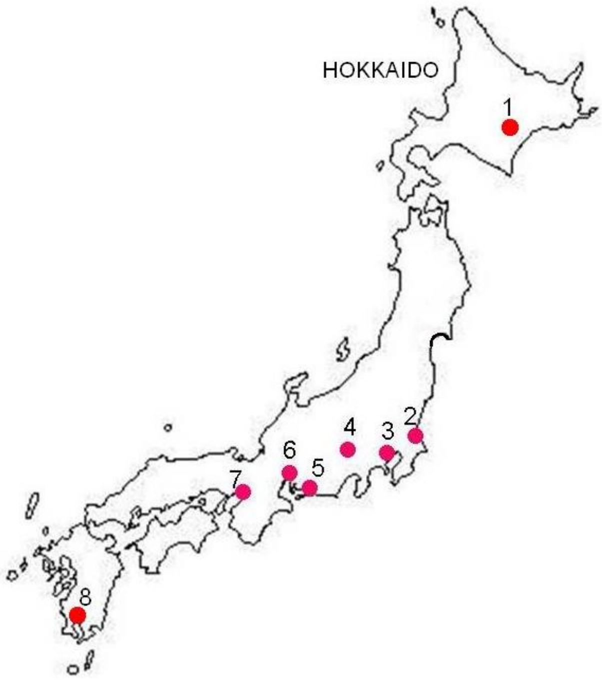


Figure 2: Japanese localities mentioned in the text. Key: 1 = Obihiro; 2 = Hiraiso; 3 = Akihabara, Tokyo; Tokyo Astronomical Observatory (Mitaka); Tokyo University; 4 = Nobeyama; 5 = Toyokawa Observatory; 6 = Nagoya; 7 = Osaka; 8 = Kagoshima.

From the summer of 1960, the future plans in radio astronomy were discussed at the TAO. One was to start non-solar radio astronomy. Another was to construct a large solar radio interferometer in order to carry out spatially-resolved observations. Later, construction of a 160 MHz compound interferometer at Nobeyama was planned. Preliminary observations for it started at Nobeyama in 1965, construction began in 1967 and this new radio telescope was completed in 1970.

In this paper, we review the early solar radio research at the TAO from 1948 to 1965 for instrumentation and from 1948 to 1967 for observational and theoretical research.

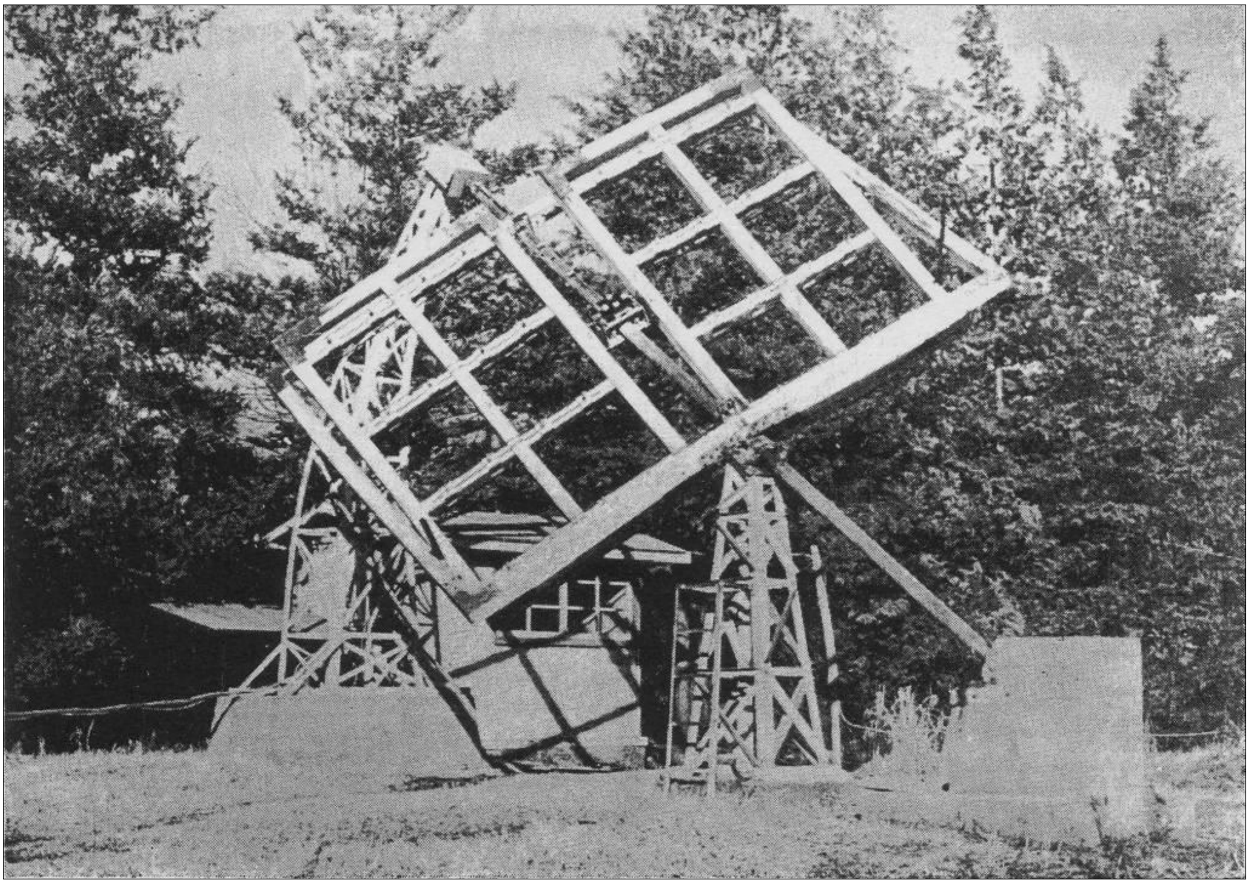


Figure 3: The 5 m × 2.5 m equatorially-mounted 200 MHz broadside array which began routine solar observations as the first radio telescope at the TAO in 1949 (after Suzuki and Shibuya, 1952).

2 INSTRUMENTATION

A 5 m × 2.5 m equatorially-mounted broadside array at 200 MHz was constructed as the first solar radio telescope at Mitaka in cooperation with the Radio Research Laboratories of the Ministry of Posts and Telecommunications (Suzuki and Shibuya, 1952), and daily observation of solar radio emission started in September 1949. The equatorial mount was a recycled mounting for a refracting telescope that was taken to Hokkaido (Japan's northern-most main island—see Figure 2) and used to observe a solar eclipse in 1936. A 4-stage 4 column beam antenna was arranged on a wooden frame which was attached to the iron polar axis (which was about 7 m long), as shown in Figure 3. The antenna was manually driven every 30 minutes in hour-angle, and the declination by about 4° every week. The antenna gain is estimated to have been 17 dB. A super heterodyne receiver was used, and the RF (radio frequency) amplifier (shown in Figure 4) used a Wallman cascode connection that gave a low noise figure and the resultant overall receiver noise figure was about 10 dB, including cable loss of 1.8 dB. The IF frequency was 10.7 MHz, and the bandwidth was about 100 KHz. The IF (intermediate frequency) signal was followed by a linear detector. There were two DC amplifiers. One was a nearly-log amplifier which used a semi-remote cutoff pentode that covered a wide dynamic range, from radio emission from the quiet Sun to intense bursts. The outputs were recorded on a chart recorder with a chart speed of 240 mm/hr. The time constant was determined by the response speed (about 0.5 s) of the chart recorder. The AC component of the detector was monitored by a speaker. Another DC amplifier was appended in order to observe the fine structure of solar radio bursts and also radio emission from the Galaxy. In this DC amplifier, the DC component was eliminated by a bridge circuit. The gain of the DC amplifier could be selected from 1, 2, 3, 10, 20. The speed of the chart recorder was 60 mm/min. The absolute flux density of solar radio emission and the receiver stability were calibrated using the difference between the open sky and a standard noise generator which used a 2-pole tube saturator (Sylvania 5722). Here, we would like to add the personal recollections of one of the authors of this paper (KA):

> A coaxial resonator attached to a miniature vacuum tube was used as each tuned circuit in the RF circuit. We could buy the miniature vacuum tube only from electrical parts discharged from the US Army in Akihabara, Tokyo. The tuned circuits had frequently poor contacts, but we could reactivate the RF receiver by knocking it by hand! In addition, the power condition at that time was very bad, i.e., the power voltage and power cycle fluctuated greatly with time beyond the standard level, such as from 60 to 90 volts and from 42 to 49 cycles, respectively. Therefore, we always had to manually adjust for these power fluctuations.

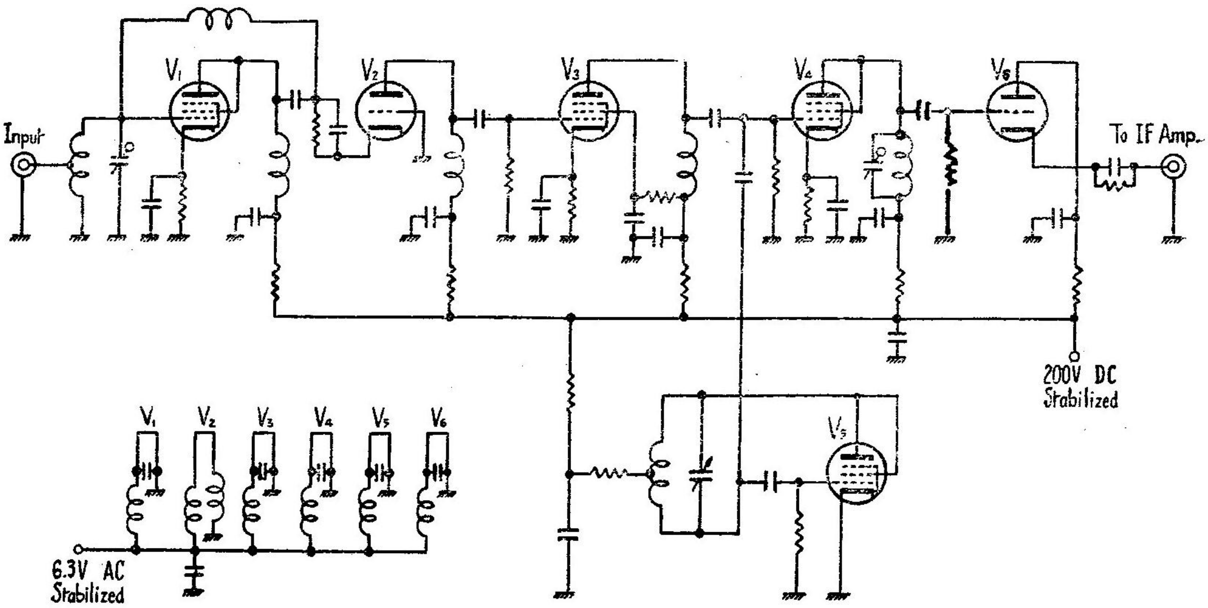


Figure 4: The RF amplifier of the first telescope at the TAO (after Suzuki and Shibuya, 1952).

Later, 100 MHz and 60 MHz total flux radiometers were installed and began routine observations of solar bursts in September 1950, and a further 60 MHz polarimeter also started trial observations in May 1951 (Suzuki and Shibuya, 1952). As a result, routine operation at three frequencies, 200, 100 and 60 MHz, became possible. It also was possible to study the circular polarization of solar bursts. The 100 MHz and 60 MHz total flux radiometer antennas, which were on alt-azimuth mounts, consisted of double Yagi antennas each with five elements, as shown in Figure 5. The polarization plane was perpendicular to the horizontal plane. The antenna gain was 13 dB. The receiver used a double super heterodyne circuit, and the first and second intermediate frequencies were respectively 10.7 MHz and 1.6 MHz. The bandwidth was 40 KHz. Since the directivity of the antenna was wide, it was difficult to point to the open sky. Therefore, the receiver was calibrated using only the reference resistance. On the other hand, the 60 MHz polarimeter antenna consisted of two dipoles with reflectors which were separated by a quarter wavelength and orthogonal to each other, as shown in Figure 6. Right- and left-handed circular polarization signals could be obtained by adding or subtracting the outputs from the two antennas. Actually, both circularly-polarized signals were observed alternately every five minutes. An example of the total flux and the polarized radiation of an outburst is shown in Figure 7.

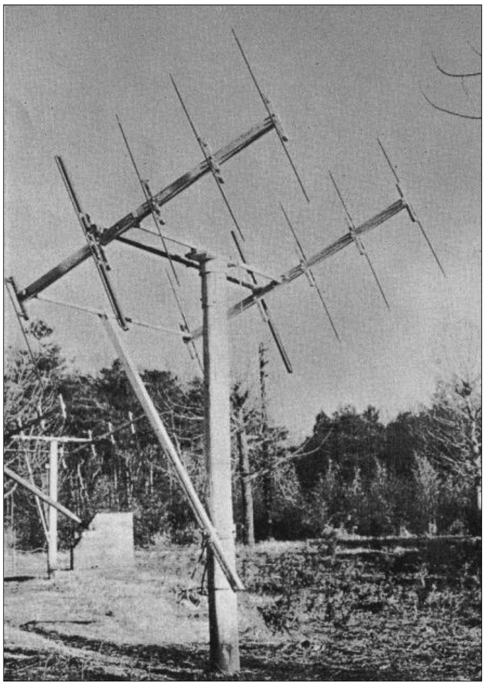
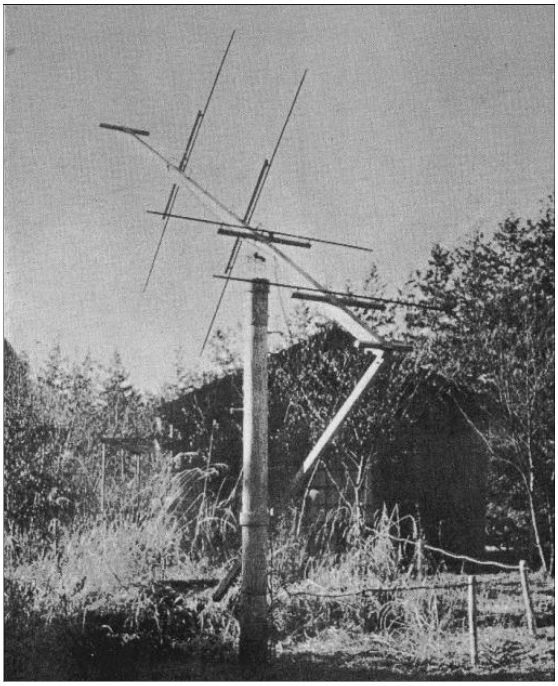



Figure 5 (left): The double Yagi antennas of the 100 MHz total flux radiometer (after Suzuki and Shibuya, 1952).
Figure 6 (right): The antenna of the 60 MHz polarimeter. The two dipoles with reflectors are separated by a quarter wavelength and orthogonal to each other (after Suzuki and Shibuya, 1952).

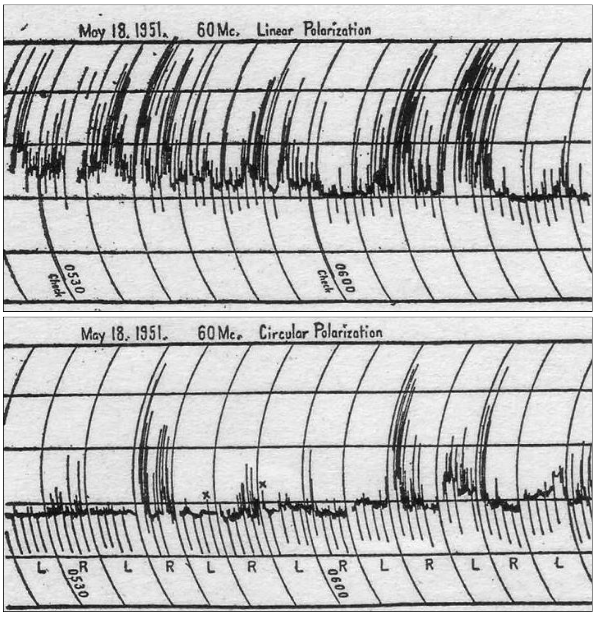


Figure 7: An example of the total flux and the circularly polarized radiation from an outburst which were respectively observed with the 60 MHz total flux radiometer and the 60 MHz polarimeter (after Suzuki and Shibuya, 1952).

At the URSI General Assembly in 1950 it was resolved to organize an international collaborative network in which continuous global solar observations at 200 MHz and 3 GHz would begin in January 1951, and the TAO participated in this program using the 200 MHz broadside array. Responding to the requirement from the URSI General Assembly, a 2-m parabolic transit type antenna operating at 3 GHz was temporally assembled by Akabane, and after some experimentation routine observations began in August 1952. The paraboloid consisted of copper plates nailed onto a parabolic wooden framework. The receiver was mostly assembled from electrical parts released by the US Army in Akihabara. Akabane's next targets were: (1) to somehow get a mounting that would allow the antenna to automatically track the Sun; and (2) to attach the existing, but improved, receiver to that new mounting. He decided to use the 2 m equatorially-mounted parabolic antenna which Koichi Shimoda from the University of Tokyo had used to observe the partial solar eclipse of 9 May 1948 (see Shimoda et al., 2013). This mounting was able to be driven by clockwork. As a result, Shimoda's antenna was transferred to the TAO and stored in its warehouse. Then in 1955, about two years later, Akabane completed the new 3 GHz radio telescope, which had much better sensitivity and stability than the previous system (Figure 8).

Figure 8: The new 3 GHZ radio telescope that used Shimoda's old parabolic dish (courtesy: K. Akabane).

In 1952, a 100–140 MHz dynamic spectrometer was constructed using a rhombic antenna, and this is shown in Figures 9 and 10.

A large parabolic antenna had been needed since 1951 in order to promote international cooperation and also pursue new research in solar radio astronomy, so construction of a 10-m parabolic antenna was planned by TAO staff. The TAO began building this antenna in 1951 and it was completed in 1953 (see Figures 9 and 10). Regular solar monitoring at 200 MHz then was taken over by the 10-m antenna, using the old broadside array receiver, until a new receiver was built for the new antenna. At that time, this was the second largest steerable radio telescope in the world. The parabolic reflector was made from square copper mesh with a spacing of 5 mm which allowed operation down to wavelengths of less than 6 cm. This radio telescope used an equatorial mounting. The polar axis was driven by a synchronous motor whose power was supplied by a 50 Hz power inverter with an accuracy of 10^{-8}. The antenna also could be driven by high-speed motors for fast slewing. The pointing of this antenna was controlled to an accuracy of 1 arcmin from the observing room.

Initially, the polarization of Type 1 bursts at meter wavelengths was thought to be circular, although no detailed investigation had been carried out. When Hatanaka was at Cornell University during 1952 and 1953, he analyzed the polarization of Type I bursts at 200 MHz based upon the data obtained at Ithaca (linear components) and Sacramento Peak (two circularly-polarized components switched every ten minutes) and reached the conclusion that the polarization of these bursts was elliptical in general, but that the shape and orientation depended on the position of the source on the solar disk. He felt it was necessary to simultaneously measure the four Stokes paramet-

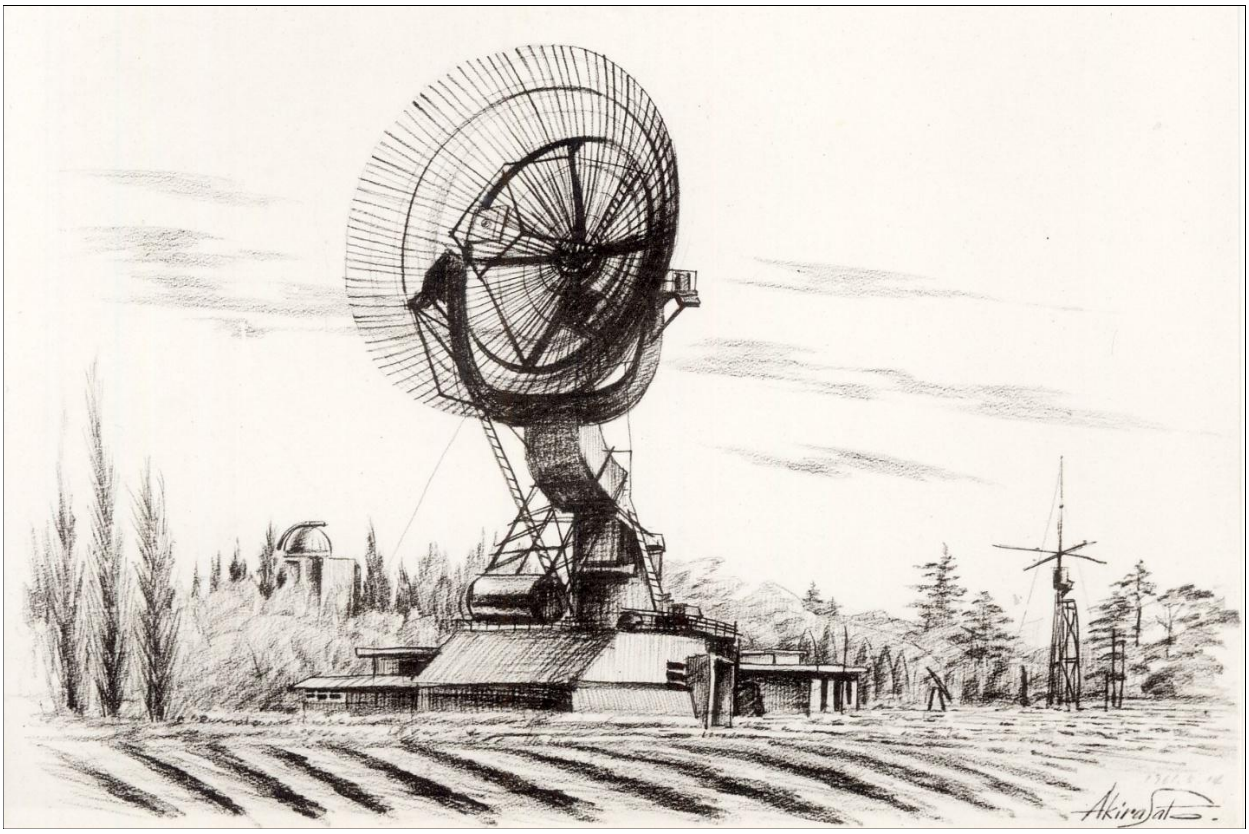


Figure 9: A sketch by Akira Sato showing the rhombic antenna of the 100–140 MHz dynamic spectrograph (on the tower above and slightly left of the artist’s signature) and the 10-m parabolic antenna. In the background, and to the left of the parabolic antenna, is the TAO’s distinctive ‘Einstein Tower’ solar telescope (courtesy: NAOJ Archives).

Figure 10: A panoramic view of the TAO radio astronomy precinct taken in about 1966 showing (from left to right) the rhombic antenna of the dynamic spectrograph, the 10-m parabolic antenna, a 612 MHz 3-element Yagi antenna, the 9.5 GHz equatorially-mounted 1.1-m parabolic antenna, the 17 GHz 8-element grating interferometer, and behind it a 17 GHz 0.8-m parabolic antenna and a 612 MHz 3-element Yagi antenna. The two Yagi antennas constitute the 612 MHz interferometer (courtesy: NAOJ Archives).

ers of the solar bursts in order to determine the precise nature of the polarization. Thus, construction of a new 200 MHz radio telescope, termed ‘a time-sharing polarimeter’, was started immediately after Hatanaka returned to Tokyo. This polarimeter was completed and began routine solar observations around the end of 1954. Details of the antenna-receiver are described by Hatanaka, Suzuki and Tsuchiya (1955a; 1955b), Hatanaka (1957b) and Suzuki and Tsuchiya (1958a; 1958b). The block diagram of this system is shown in Figure 11. In this antenna, a pair of crossed half-wavelength dipoles, which were orthogonal to each other with a degree of coupling of –35 dB, were placed at the focus of the 10-m antenna. Two outputs from the pair of dipoles were independently amplified by the RF amplifier (NF = 6 dB) and converted to two IF signals at 10.7 MHz (with bandwidths of 100 KHz). Here, the phase and gain difference between both electronic channels were corrected. These two output voltages were combined after inserting phase retardations of 0, π, π/2, and –π/2 in one of them by time sharing (repeating frequency = 1/200 s). Note that the crosstalk between the two antenna channels was kept to –50 dB. The combined signal passed through an IF amplifier and a square-law detector, and then generated four audio outputs (outputs v, h, r, and l) by demodulators. Note that the square-law detector was newly-developed by Suzuki (1955) and eliminated the disadvantages of the conventional square-law detectors, such as slow response, low output voltage, and drift. Since each output voltage also generated two other audio outputs (outputs a and b), a total of six outputs was obtained and recorded by a six-channel pen recorder at a speed of 4 mm/min (which, if necessary, could be changed to 60 mm/min). The four Stokes parameters could be calculated from these six outputs, including two redundant equations. In order to equalize the intensities of the polarization channels, the calibration signals from standard noise generators (Sylvania 5722) were inserted into the coaxial cables connected to the crossed dipoles by quarter-wave switches. Note that in addition to regular solar monitoring, the 10-m antenna was temporarily used at 3 GHz to observe the 20 June 1955 partial solar eclipse, and the Moon.

Several new radio telescopes, such as 67 and 100 MHz interferometers to detect the total radio emission, a 250–900 MHz dynamic spectrometer (using the rhombic antenna originally constructed for the 100–140 MHz dynamic spectrometer) and a 9.5 GHz polarimeter (using a 1.2-m paraboloid), were constructed during 1955 and 1957 in preparation for the International Geophysical Year (1957–1958). Some of these telescopes are now described in more detail.

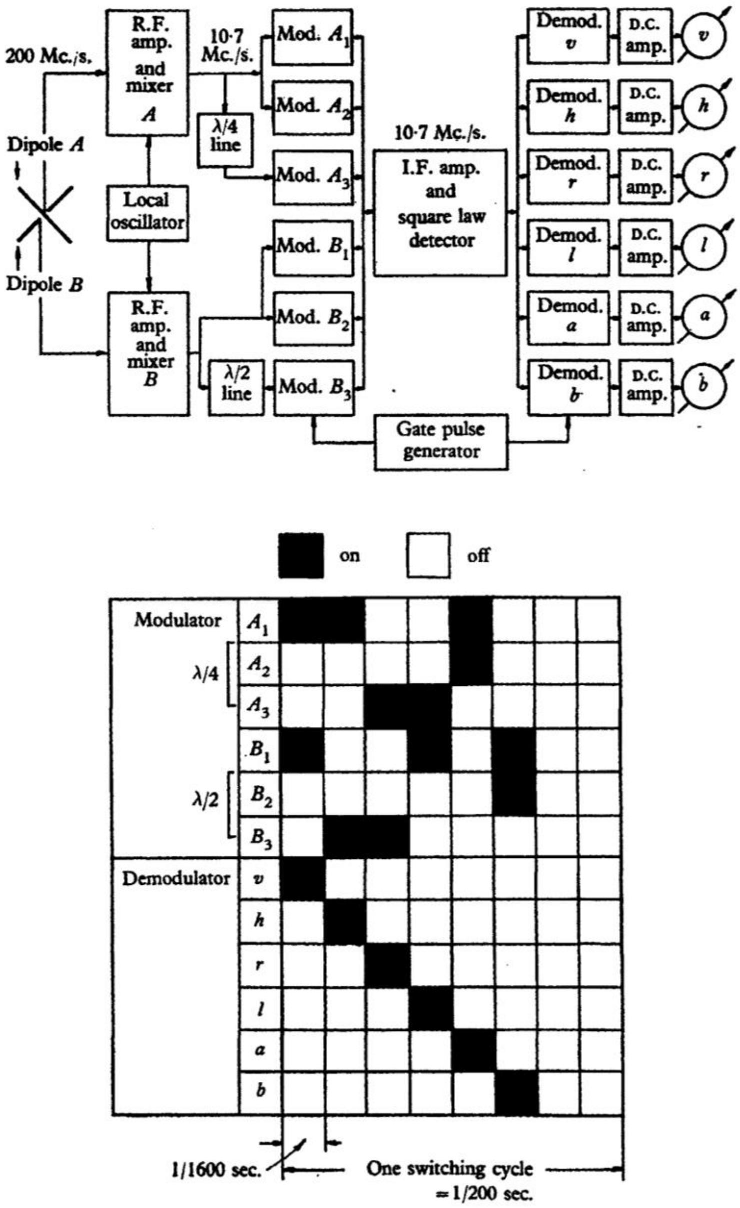


Figure 11 (top): The block diagram of the 200 MHz time-sharing polarimeter. Bottom: The combination of the modulators and the demodulators (after Hatanaka, 1957b).

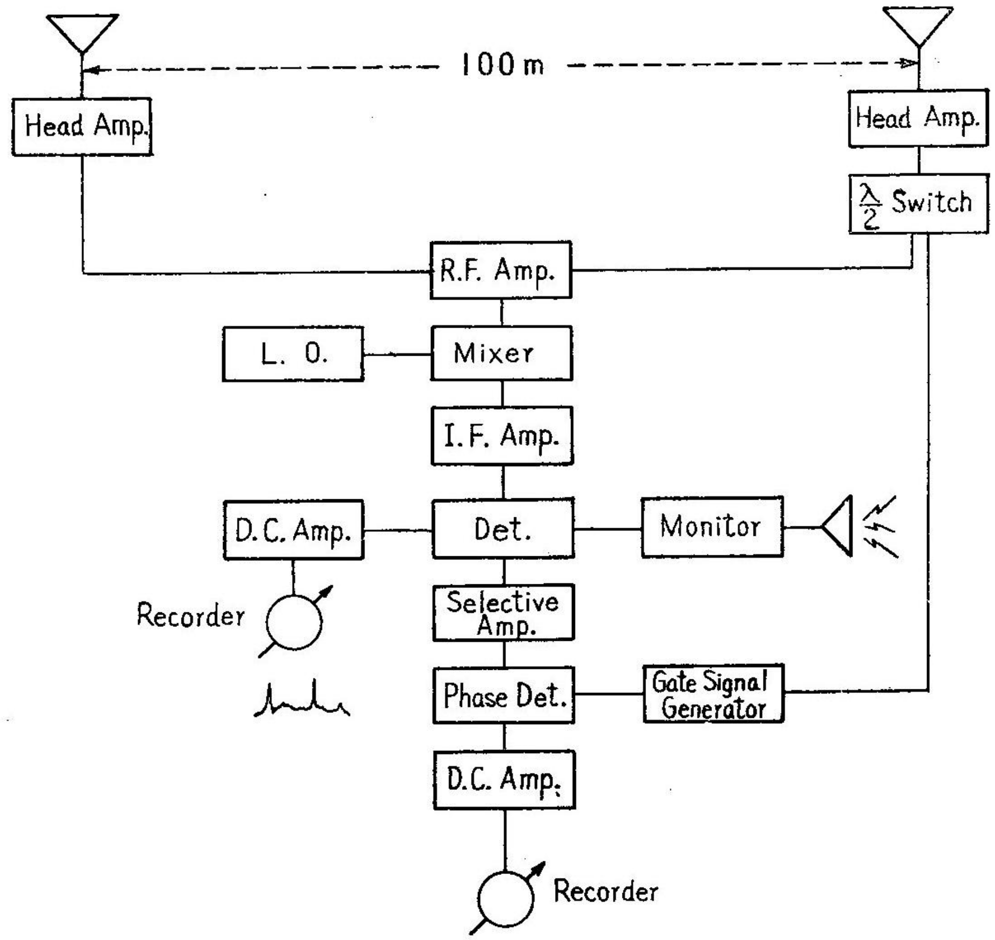
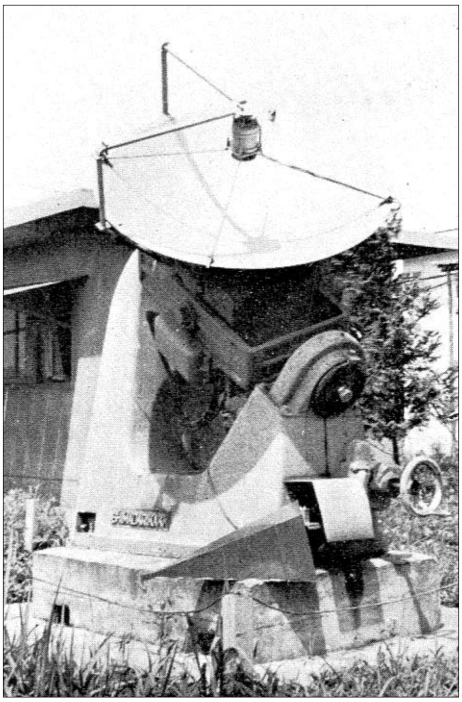


Figure 12: The block diagram of the 67 MHz interferometer. The block diagram of the 100 MHz interferometer is essentially the same as this (after Moriyama and Misawa, 1956).

A two-antenna interferometer with a longer baseline has lower sensitivity for a broad source such as the quiet Sun but higher sensitivity for compact sources such as those associated with solar bursts. Therefore, a two-antenna interferometer with a longer baseline is better than a radiometer for identifying the sources of weak bursts and distinguishing them from the background emission from the solar disk. Initially 60 MHz was selected as the observing frequency, and construction of the interferometer began in the autumn of 1954 (Moriyama and Misawa, 1956; Moriyama, 1958). However, interference from terrestrial communications was very severe, so the observing frequency was shifted to 67 MHz, resulting in successful detection of the quiet Sun and the stronger discrete radio sources in the autumn of 1955. The 67 MHz interferometer began daily solar monitoring in the spring of 1956, but unfortunately observations frequently were blocked by strong terrestrial interference. On the other hand, a 100 MHz interferometer also was constructed, and modeled on the 67 MHz interferometer (Moriyama, 1958). The 100 MHz interferometer started routine solar observations in July 1957. Details of both interferometers are provided by Moriyama (1958). Each antenna of both two-antenna interferometers consisted of a pair of five-element double Yagi antennas. The polarization plane was perpendicular to the horizontal plane. The antenna baselines of the interferometers were 60 m and 30 m in an east-west direction for the 67 MHz and 100 MHz interferometers, respectively. The receiver systems used super heterodyne circuits with phase-switching systems, as shown in Figure 12, essentially the same for both interferometers. The noise figures of the receivers were 4–5 dB. The bandwidth of the IF at 10.7 MHz was 80 KHz. The RF signal in one arm was modulated at the speed of 500 Hz using a λ/2 switch. The RF signals from both antennas were added, converted to the IF signal, and demodulated by the phase-sensitive detector to produce a multiplier output. There were two output signals. In one, just after the square-law detector the DC signal was recorded with a time constant of less than 0.1 s as the total radiation from the Sun (e.g. from solar bursts). In the other one, after the phase-sensitive detector the low frequency signal was recorded with a time constant of about 20 s as the interference pattern due to the diurnal motion of the Sun. At the end of each day's observations, the absolute value of solar radiation was determined by comparison with the flux density of the Cassiopeia A discrete radio source. Although the overall sensitivity was quite good, generally within 0.1 sfu (solar flux units) of the theoretical value, the actual sensitivity was determined by interference from city noise, which varied on a daily basis, often resulting in lower sensitivity of only 2 sfu (note: 1 sfu = 10^{-22} W/m^{2}Hz).



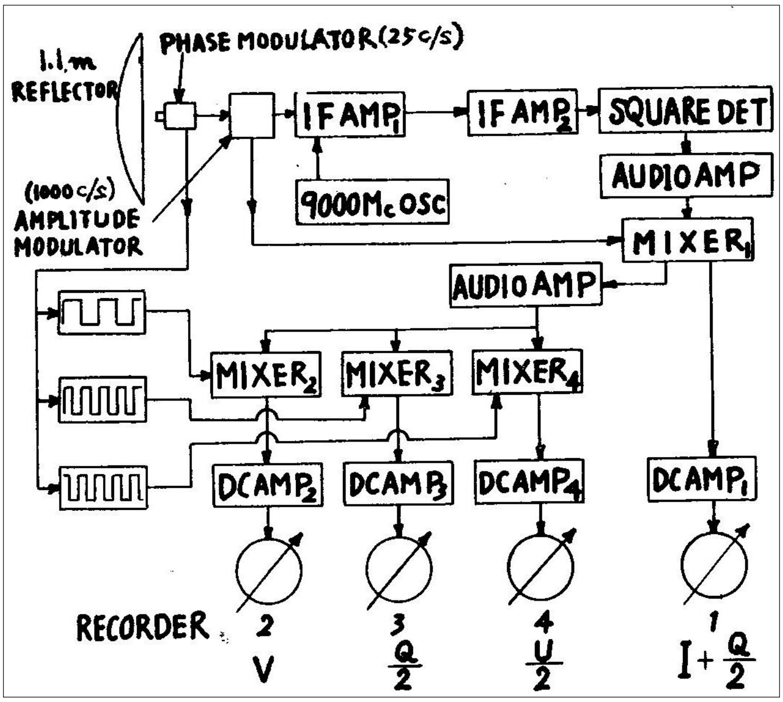


Figure 13 (left): The 1.1-m parabolic antenna of the 9.5 HGz polarimeter (after Akabane, 1958c).
Figure 14 (right): The block diagram of the 9.5 GHz polarimeter (after Akabane, 1958c).

Although the polarization of the solar radio emission had been observed in meter wavelengths, no detailed observations had been made in microwaves at the TAO, so a new type of 9.5 GHz polarimeter was constructed, and this began routine observations in May 1957 (Akabane, 1958a; 1958c). This equatorially-mounted polarimeter used a 1.1-m parabolic reflector, and is shown in Figure 13, while the block diagram of the receiver system is shown in Figure 14. The feed at the focus of the reflector was a cylindrical wave-guide used in the H_{11} mode. The phase modulator, which used a rotating λ/4 phase shifter, rotated with a velocity of about 25 Hz, and was connected to the rectangular waveguide. The amplitude modulator also operated with a ferrite-switching system at a frequency of 1,000 Hz which was independent of the frequency of the phase modulator. The intermediate frequency was 60 MHz, with a bandwidth of 8 MHz, and both the signal and the image bands were received. The noise figure of the overall receiver was about 12 db. The output of the square law detector was mixed with the reference signal from the amplitude modulators to obtain output 1. The output from mixer 1 was mixed again with the fundamental, second and fourth harmonics of the reference signal from the phase modulator to obtain outputs 2, 3 and 4. Thus, the Stokes parameters (I, Q. U, and V) could be obtained from the four outputs. The time constants of the DC amplifiers were 0.3 s for output 1 and 1 s for each of the other three outputs. The minimum detectable fluxes were 3 sfu and 6 sfu for output 1 and the other three outputs, respectively. The flux calibration of the daily measurements was carried out using the two output levels which were obtained by pointing daily at the empty sky and by inserting a carefully-matched load between the phase modulator and the amplitude modulator. The absolute flux calibration was done using a standard horn with an aperture of 205 × 255 mm.

During the International Geophysical Year (1957–1958), a narrow-band dynamic spectrometer operating at meter wavelengths also was constructed for experimental purposes and to carry out observations of Type I bursts between November 1957 and March 1958 (Tsuchiya, 1962). The observing frequency was selected to be 199–207 MHz, which was rather free from interference caused by city noise. The antenna was a 32-element transit type beam-antenna. Each element was a one-wavelength dipole. The RF signal was converted down to the IF at 50 MHz with a bandwidth of 100 KHz using a swept-frequency local oscillator. The receiver output was displayed on a cathode-ray tube, and was photographed on 35 mm film using a speed of 150 mm/min.

A new type of radio telescope referred to as a ‘multiplying multiphase interferometer’ (see Figure 15) was developed by Suzuki to locate the east-west position on the Sun of 200 MHz solar bursts (see Suzuki, 1959; Suzuki and Morimoto, 1960). The new interferometer was able to minimize the ambiguity and simplify the reduction procedure in locating the position of the radio burst sources, as compared with the amplitude ratio method which had been used up to that time. Construction of the multiplying multiphase interferometer started as an initial concept in 1957, and the final system was completed after certain improvements, such as the addition of phase-tracking electronics. The new interferometer started routine observations of both solar bursts and enhanced regions on the Sun in 1959. The block diagram of the system is shown in Figure 16. The system was composed of

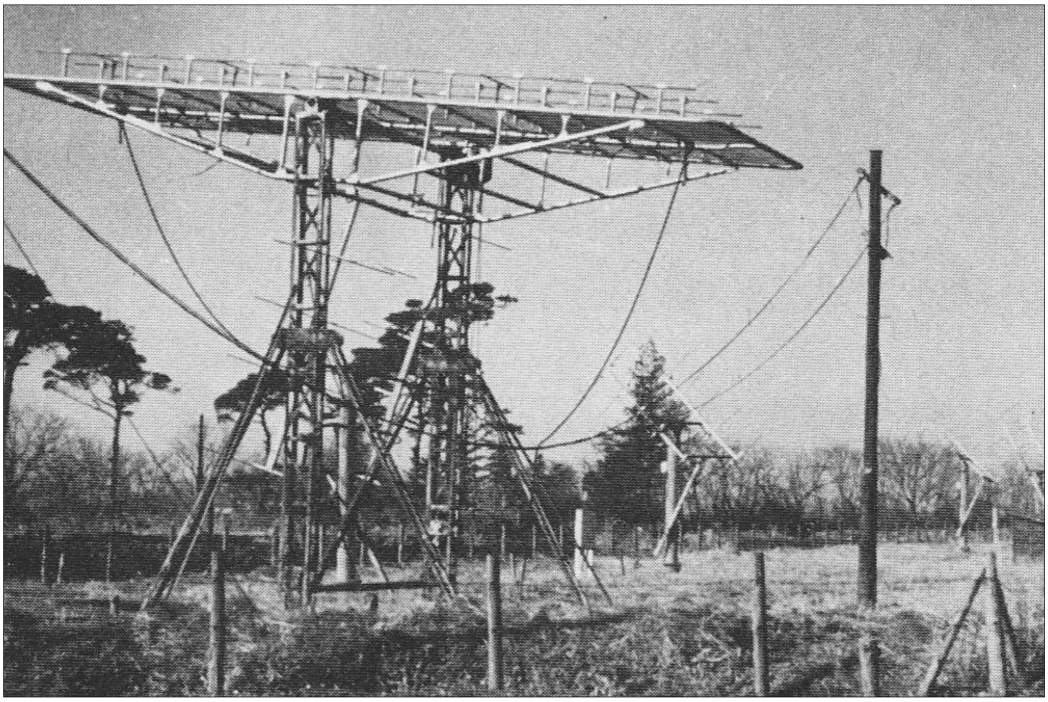


Figure 15: One of the broadside antennas used by Suzuki for his E-W position interferometer (courtesy: NAOJ Archives).

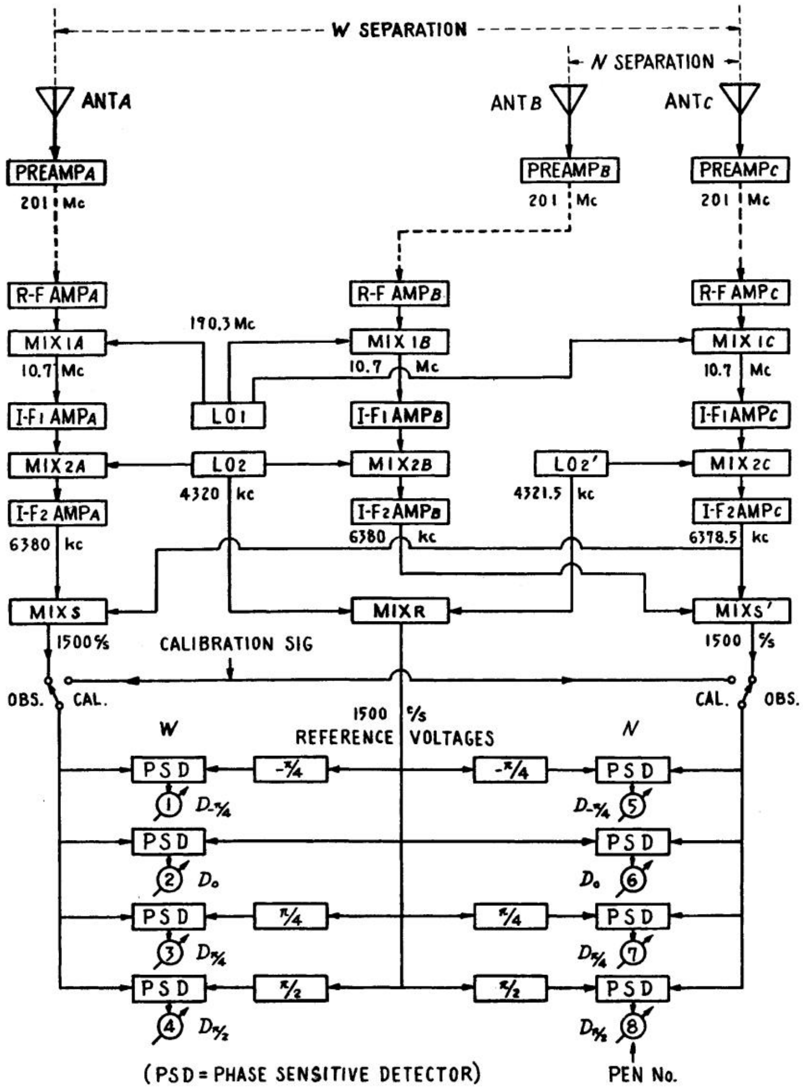


Figure 16: The block diagram of the 200 MHz multiphase interferometer (after Suzuki, 1959).

three antennas consisting of twin two-antenna interferometers arranged along an east-west baseline, one with a 338 λ baseline length and the other with a 50.5 λ baseline. The latter system was used to complement the former one only to remove the ambiguity of position-determination on the Sun of solar bursts and was similar to the former system. Each antenna was a vertically-polarized broadside array with forty dipoles (four in the horizontal direction by ten in the vertical direction). Detailed descriptions of the receiver system are given only for the former system in the following. The RF signals at 201.0 MHz from the two antennas were converted to the IF signals at 10.7 MHz by mixing with the common first local oscillator. The

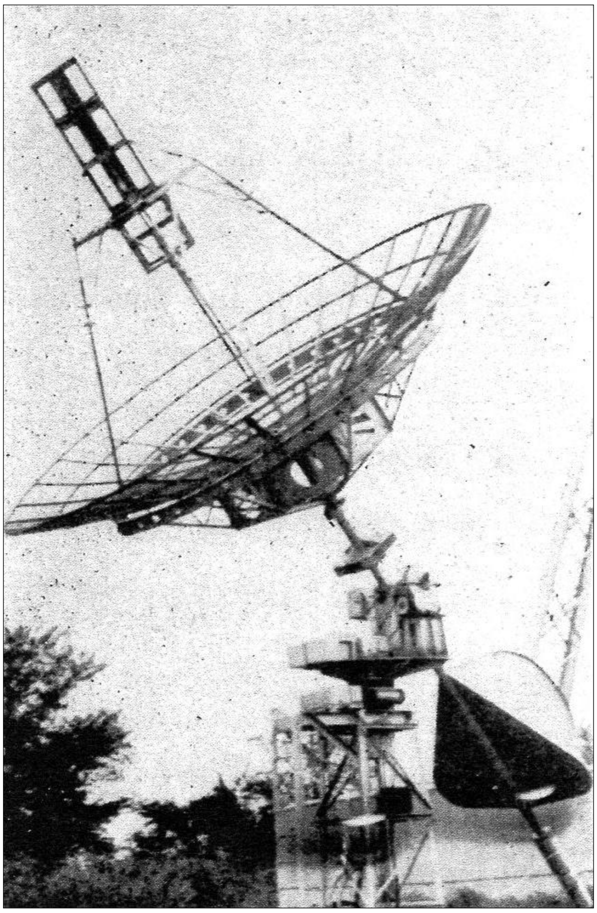


Figure 17: The 6-m parabolic antenna which was used with the 300–800 MHz dynamic spectrometer (courtesy: NAOJ Archives).

The first IF signals were again converted to the second IF frequencies at 6,380 and 6,378.5 KHz by using two second local oscillators at frequencies of 4,320 and 4,321.5 KHz, respectively. Then, the two second IF signals were mixed in a multiplier to produce the beat frequency of 1,500 Hz. On the other hand, the two second local oscillator signals were also combined in another multiplier to produce another beat frequency. The beat frequency between the two local oscillators was fed to the phase-sensitive detectors as reference signals with phase retardations of –π/4, 0, π/4, and π/2 to produce the four outputs, i.e., 1, 2, 3, and 4, respectively. The outputs were recorded simultaneously on a chart using an eight-pen recorder with a chart speed of one millimeter per second. The overall bandwidth was about 100 KHz and a time constant of 0.25 s was used. Radio sources on the Sun could be located by simple eye-estimation with an accuracy of about 6 seconds of arc under favorable conditions.

An alt-azimuth mounted 6-m parabolic antenna with a focal length of 2.5 m was constructed in 1959, and was able to automatically track the Sun. An improved receiver system for a new 300–800 MHz dynamic spectrometer was attached to the parabolic antenna (see Figure 17), and routine observations of solar bursts commenced in August 1959 (Takakura, 1960a). The parabolic antenna was illuminated by a double-tapered ridged horn. The RF amplifier consisted of a one-stage ground-grid amplifier whose plate circuit was tuned by a butterfly resonator, and a crystal mixer was attached to the resonator. The local oscillator was tuned also by a butterfly resonator and the instantaneous frequency was equal to that of the RF amplifier. By using a 1.5 MHz IF amplifier, both side bands were received. The IF bandwidth was 500 KHz. The detected output was fed to the brightness-modulation grid of a cathode-ray tube through a one-stage quasi-logarithmic DC amplifier. The tube was photographed with a CANON 35-mm continuous recorder in which the film moved about 2 cm or 1 cm per minute

A new 150–300 MHz dynamic spectrometer and 408 MHz and 800 MHz radiometers were completed and started routine observations in 1960. The primary feeds of these instruments were attached to the 6-m parabolic reflector, together with that of the 300–800 MHz dynamic spectrometer. This was because multi-frequency simultaneous observations, which were achieved by putting several different dipoles at the primary focus of a parabolic antenna, only became technically possible around 1960. Regarding observations with the 150–300 MHz dynamic spectrometer, unfortunately it was almost impossible to detect solar bursts at frequencies below 220 MHz due to terrestrial interference caused mainly by television stations and communication signals. On the other hand, 160, 200, and 300 MHz patrol radiometers, which used dipole antennas, also were constructed to monitor intense solar bursts and were put into routine operation. As a result, quantitative studies of solar bursts over a wide frequency range became possible by combining data obtained using these new radio telescopes with information obtained from previously-constructed ones.

In 1961, a north-south array was added to the 200 MHz multiphase interferometer and both arrays started solar radio observations.

In 1962, 300 MHz crossed dipoles were attached to the 10-m antenna and a new 300 MHz polarimeter started routine observations (Tsuchiya, 1963a). The primary feeds at 300 MHz shared the 10-m antenna with those of the 200 MHz time-sharing polarimeter. The block diagram of the

300 MHz polarimeter is shown in Figure 18. The RF signals from the crossed dipoles entered a polarization-switching network which consisted of coaxial cables and two variable capacitors. By switching alternately the variable capacitors placed at both ends of the two λ/4 cables at a switching speed of 50 Hz, right- and left-handed polarization components were obtained on a time-sharing basis. Cross-talk between the dipoles was about –38 dB, and insertion loss of the polarization-switching network was about 6 dB. The RF signal from the polarization-switching network passed through a quarter-wave switch and was converted down to the IF frequency of 21.4 MHz with a bandwidth of 1 MHz in the mixer. The IF signal was detected by the square law detector, and then the total flux (R+L) and difference signal (R-L) of the polarization fluxes generated by using a phase-sensitive detector were obtained. The receiver system of the 300 MHz polarimeter was different from that of the 200 MHz time-sharing polarimeter. In the 200 MHz polarimeter, the two output signals from both dipoles were converted independently to the two IF signals and then combined after passing through appropriate phase-shifters. Variations of gain and phase of any electronic circuit on the way to the combined point caused errors in measurements of Stokes parameters. Therefore, observers had to balance phases and gains among electronic passages every day. This defect became more severe in the UHF band. In the 300 MHz polarimeter, this defect was overcome by using the polarization-switching network composed of λ/4 coaxial cables which was put on the RF transmission lines placed just after the outputs of the dipoles.

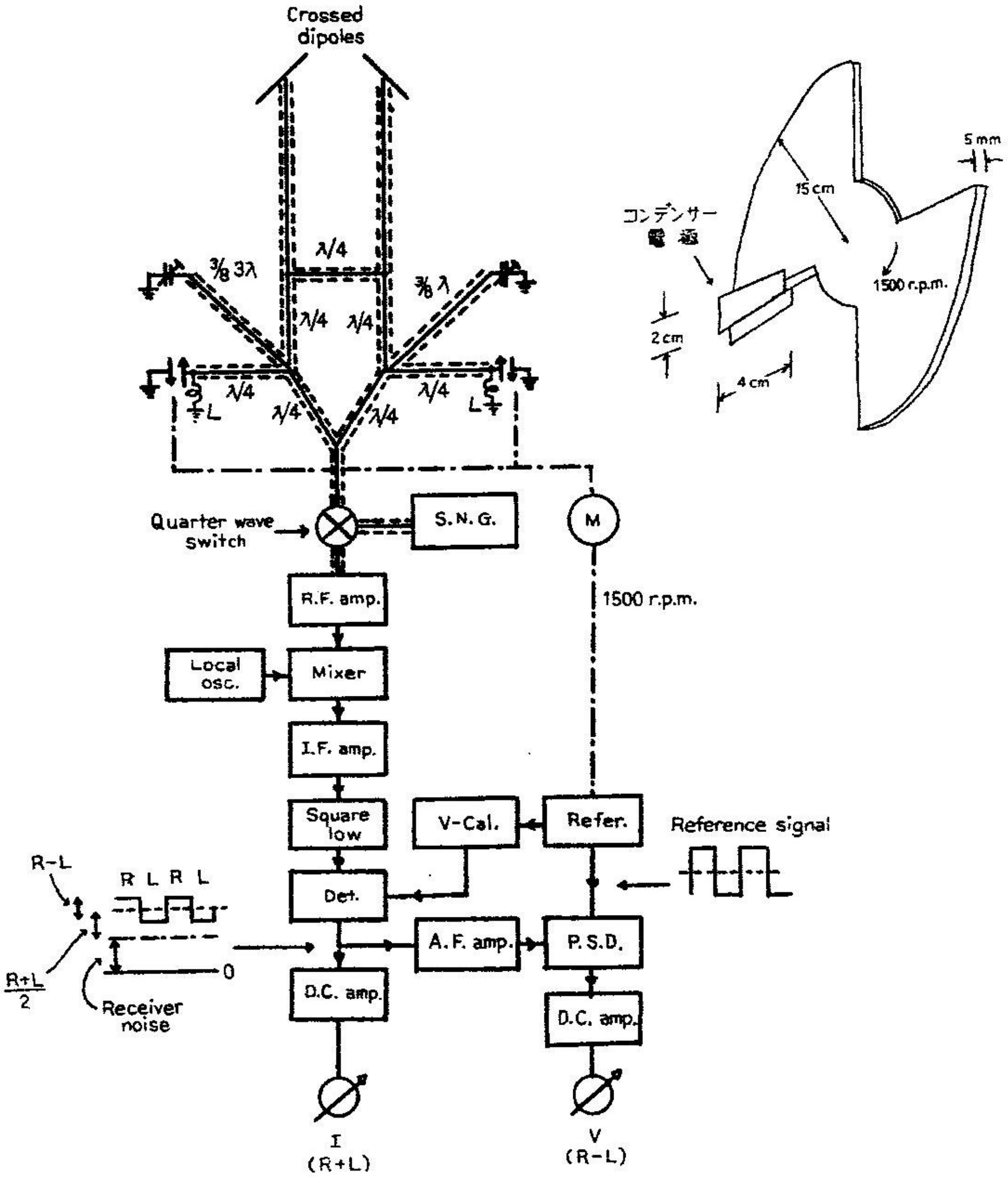


Figure 18: The block diagram of the 300 MHz polarimeter (after Tsuchiya, 1963a).

Figure 19: The 3 GHz parabolic antenna which was used to observe the partial solar eclipse in Tokyo on 14 February 1953 (courtesy: K. Akabane).

Three polarimeters at 17 GHz, 408 MHz and 614 MHz were constructed during 1964 and early 1965 in preparation of the International Quiet Sun Year (IQSY: 1964–1965). Both dipoles for the 408 MHz radiometer and the 614 MHz polarimeter were attached to the 10-m parabolic reflector. Details of the 17 GHz polarimeter are described by Tsuchiya and Nagane as follows (1965). A 0.8-m parabolic reflector with an equatorial mounting was used for the 17 GHz polarimeter. A turnstyle junction deflected the incoming waves into two rectangular waveguides to receive right- and left-handed circularly polarized waves separately. A polarization switch was constituted by a turnstyle junction and a ferrite gyrator driven by 130 Hz square waves. A similar type of switching device was also used for Dicke switching driven by 420 Hz square waves. The VSWR (voltage stand- ing wave ratio) from the input of the polarization switch to the output of the Dicke switch was less than 1.05. The overall insertion loss from the primary feed to the mixer was about 1 dB. The isolation of the polarization switch was more than 29 dB. The noise figure from the mixer to the preamplifier was 14.8 dB. The intermediate frequency was 30 MHz, with a bandwidth of 10 MHz. The overall system was calibrated by a standard circular horn with an absolute gain of 29.7 dB. The daily flux calibrations of solar radiation were done at 00:00, 02:00, 04:00, and 06:00 UT by pointing the antenna beam at the empty sky instead of the Sun to obtain the sky temperature, and next the two input waveguides of the receiver were terminated by the flap-attenuators to obtain the ambient temperature. The 17 GHz polarimeter started routine observations on 22 May 1964.

A 612 MHz multi-phase transit type interferometer was constructed and started routine observations in March 1965. This instrument consisted of two antennas arranged 50 wavelengths apart on an east-west baseline, each of which consisted of a triplicate of 12-element Yagi antennas. The Sun was observed during one hour before and after meridian transit. The total intensity was measured, as well as the output from the interferometer. The absolute flux density from the Sun was calibrated by using both a standard noise source and several discrete radio sources.

3 THE OBSERVATION AND INTERPRETATION OF SOLAR RADIO EMISSION AT THE TAO

3.1 Solar Eclipse Observations

The radio observation of a solar eclipse was an excellent chance to conduct a spatially-resolved investigation of radio sources on the Sun with a simple radio telescope.

The first such observations at the TAO were conducted during the partial solar eclipse of 12 September 1950 from Tokyo and Obihiro in Hokaido (see Figure 2) by T. Hatanaka using two 100 MHz radio telescopes. Unfortunately these observations were never published, and no records of this research project remain.

The partial solar eclipse on 14 February 1953 was observed at the TAO by Akabane using the first 3 GHz transit type parabolic antenna. Figures 19 and 20 show the parabolic antenna and time variation of radio emission observed during the eclipse, respectively. Analysis of this record showed the existence of an enhanced region near the west limb of the Sun which had been associated with a large sunspot one month before, suggesting that some regions of radio enhancement were closely related to sunspots.

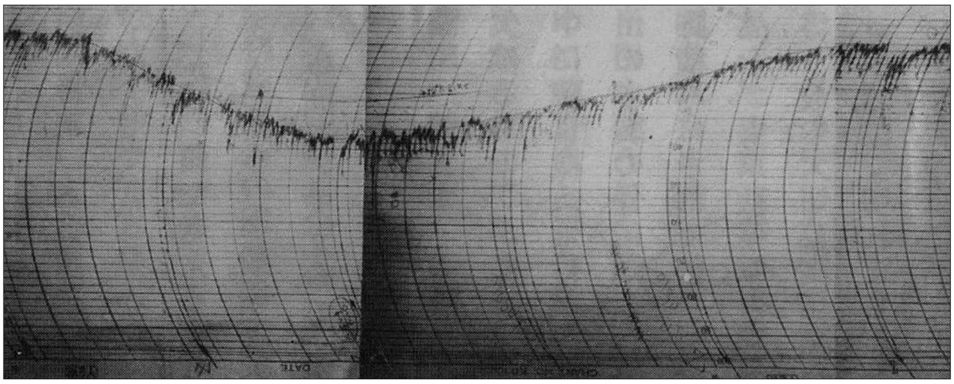


Figure 20: The chart record showing the time variation of radio emission observed during the 1953 solar eclipse (courtesy: K. Akabane).

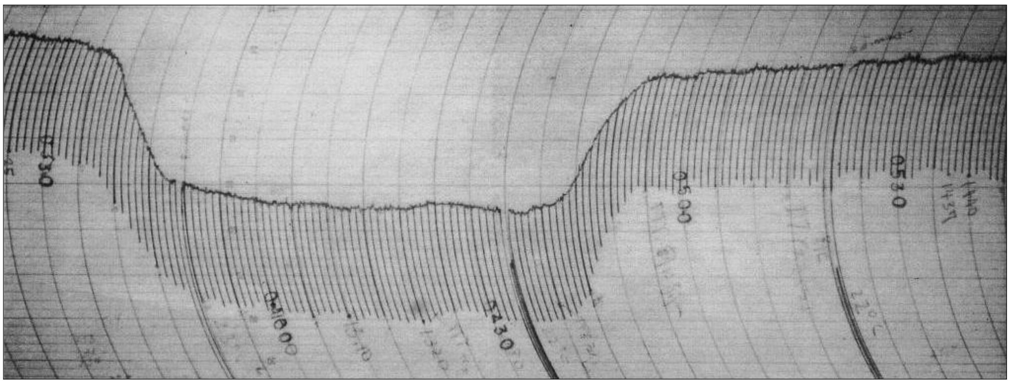


Figure 21: The chart record showing the time variation of radio emission observed during the 1955 solar eclipse (courtesy: K. Akabane).

The partial solar eclipse on 20 June 1955 was observed from three stations, Kagoshima (see Figure 2), Toyokawa and Tokyo at frequencies between 3 and 4 GHz (Hatanaka et al., 1955d; Hatanaka et al., 1955e; Hatanaka, 1957a). At Kagoshima and Toyokawa the Moon covered a large sunspot group in the southern hemisphere and a considerable decrease in flux density was observed (Figure 21), while at Tokyo the flux density decreased only by a few percent when the Moon covered the southern part of this sunspot group. The 4 GHz interferometer at Toyokawa measured the variation in the total flux density of the enhanced region, and its location, size and brightness distribution were deduced from these observations. A comparison between the radio and optical observations revealed that the radio brightness distribution was remarkably similar to the calcium plage around the sunspot group which is shown in Figure 22. Thus, the generation area of the slowly-varying component was clearly identified.

Akabane (1958d) observed the partial solar eclipse of 29 April 1957 from the TAO with the 3 and 9.5 GHz polarimeters. The area near the north pole of the Sun was covered by the Moon during the eclipse but unfortunately no sunspot groups were covered so no useful results were obtained from this eclipse observation.

Subsequently, Akabane (ibid.) observed the partial solar eclipse of 19 April 1958 from the TAO with those two polarimeters. He examined details of the intensity and polarization distributions of the enhanced region which was associated with a bipolar sunspot and proposed that the magnetic field was inclined by about 30° to the east and west from the normal of the enhanced region.

3.2 Type I Bursts

Although in this subsection emphasis is placed on Type I bursts, we will deal with observations of both Type I and III bursts simultaneously if descriptions of both types of bursts are difficult to differentiate from one another in the papers.

As of 1950, the following characteristics of noise storms were known:

(1) the radiation was correlated with the central meridian passage of large sunspots;
(2) the duration was of the order of several hours to one day;
(3) the radiation was circularly polarized, and the sense of the polarization of the storm bursts was the same as the continuum background; and
(4) The bandwidth and the lifetime of a storm burst were about 4 MHz and 1.5 seconds, respectively.

The initial results from the 200 MHz broadside array investigations were given by Hatanaka (1950). He analyzed the relation between the characteristics (or number per hour) of noise storms and the activities of sunspots, and found that burst activity persisted after large and active sunspots had disappeared or become less active.

Hatanaka and Moriyama (1952) systematically analyzed noise storms which were observed with the total flux radio telescopes at 200, 100, and 60 MHz at TAO between January and August, 1951, and they also used data obtained with 81.5 and 98 MHz radio telescopes at the Cavendish Laboratory (Cambridge) and at Potts Hill (Sydney) respectively. They also analyzed data from trial observations of circular polarization with the 60 MHz polarimeter between May and September, 1951. They were able to isolate a number of characteristics of noise storms, such as:

(1) they occurred in a sporadic manner in regions above large and magnetically-active sunspots;

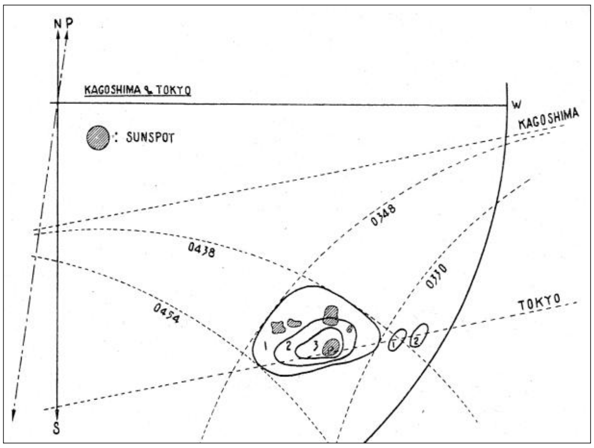


Figure 22: The brightness distribution of the 'radio spot' derived from observations of the 20 June 1955 partial solar eclipse superimposed on the optical image (after Hatanaka et al., 1955e).

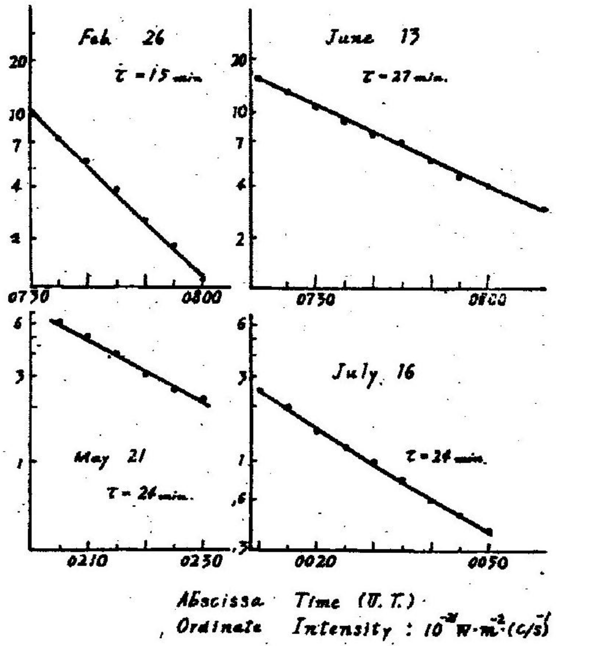


Figure 23: Decay curves of noise storms observed with the total flux radiometer at 60 MHz (after Hatanaka and Moriyama, 1952).

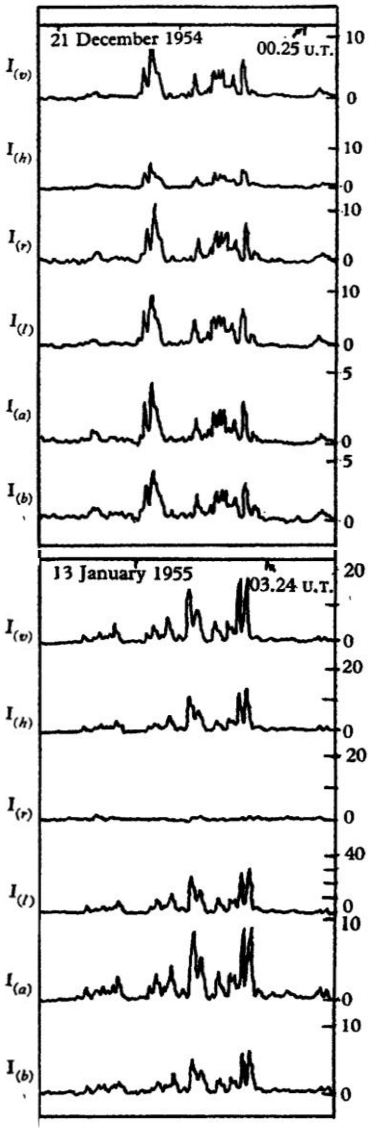


Figure 24: Examples of the records of bursts obtained by the 200 MHz time-sharing polarimeter (after Hatanaka, 1957b).

(2) their maximum occurrence was at the time of the central meridian passage of a sunspot, and it diminished by ~50% two days later;
(3) they were triggered by intense solar flares that accompanied non-polarized outbursts;
(4) they exhibited an exponential decay, with a time constant of about 15 to 30 minutes (Figure 23); and
(5) a right-handed circularly-polarized noise storm was associated with the south pole of a sunspot, and *vice versa.*

After the 200 MHz time-sharing polarimeter was constructed in 1954 the polarization of solar radio bursts was extensively studied at the TAO, with the aim of measuring the Stokes parameters. The initial results were reported as polarization characteristics of Type I bursts observed during active periods in December 1954 and January 1955 (see Hatanaka, Suzuki, and Tsuchiya, 1955b; 1955c; Hatanaka, 1957b). Some examples of these bursts are shown in Figure 24. The main results were:

(1) the radiation is a mixture of two components: one is elliptically polarized and the other is randomly polarized;
(2) the ellipticity varies from nearly 100% (circular) to 10% (nearly linear); and
(3) the degree of polarization is more than 90% on most days, but sometimes drops below 50% and even down to 10%.

Tsuchiya (1963b) carried out a statistical analysis of the degree of circular polarization of noise storms which were observed with the 200 MHz time-sharing polarimeter during 1957 and 1960, with data also contributed by the 200 MHz multiphase interferometer for noise storms observed during 1960. It was revealed that partially-polarized bursts with a degree of polarization of ~50% were most rare, while the enhanced radiation recorded during noise storms had the same polarization characteristics as that of the Type I bursts.

It was known that noise storms were composed of two components: a background continuum, and the storm bursts (Wild, 1951). Takakura (1959a) attempted to explain the background continuum as the superposition of many spikes which had an identical shape, occurred at random and were distributed in amplitude according to a probability density. To compare the theoretical results obtained from this hypothesis with observed properties of noise storms, samples of noise storms were selected from the records obtained between January and August 1955 with the 200 MHz time-sharing polarimeter. If two parameters, i.e. the occurrence frequency of bursts and the distribution of their amplitudes, changed with time, as was likely, almost all noise storms observed were in fairly good agreement with the hypothesis. The above hypothesis was further supported by measuring the post-detection low frequency spectra of noise storms (Takakura, 1959b).

Suzuki (1961) summarized studies on various properties of noise storms at 200 MHz based upon observations made with the time-sharing polarimeter and the multiphase interferometer. He found the following results:

(1) the magnetic field dependence of the sense of the radio polarization was confirmed to be in the sense of the ordinary mode;
(2) noise storms with changing or mixed polarization, including those which did not obey the general rule, were observed in a quite limited region on the Sun, and this region remained active for an exceptionally long period—at least one and a half years;
(3) partially-polarized and non-polarized bursts had much larger source sizes than strongly polarized bursts; and
(4) the bursts in high intensity storms were quite concentrated in position, i.e. towards the center of the solar disk (see Figure 25).

3.3 Type III Bursts

Wild et al. (1959) observed Type III bursts with a swept-frequency interferometer in the frequency range from 40 to 70 MHz and proposed a plasma hypothesis for Type III bursts. Morimoto (1961) compared the Japanese 200 MHz multi-phase interferometer results with Wild's results at lower frequencies. The height of the sources of Type III was found to be 0.4 $R_{\odot}$ above the photosphere. The results of Type III bursts observed at the TAO showed good agreement with the Australian observations made at lower frequencies.

Akabane and Cohen (1961) used the Cornell 200 MHz polarimeter to detect linearly-polarized Type III bursts. Two different sets of bandwidths were used: 10 and 20 KHz during March-June 1959 and 10 and 300 KHz during July-September. They found that many large Type III bursts were weakly linearly polarized (0.05–0.3) in a 10 KHz band and either unpolarized or weakly circularly polarized at 300 KHz. It was inferred from theoretical considerations that the amount of Faraday rotation corresponding to these observational results was $\sim 10^4$ radians, which was consistent with the earlier estimation by Hatanaka (1956).

Morimoto (1964) compared the positional data of Type III bursts observed with the CSIRO's 40–70 MHz swept-frequency interferometer with the corresponding flare data to obtain a more accurate height in this frequency range than had been obtained previously. The movement of the source at this frequency range was compared with the movement at 200 MHz observed simultaneously with the TAO multiphase interferometer. The apparent height of the source near 50 MHz was estimated to be 1.07 ± 0.1 $R_{\odot}$ above the photosphere, which gave an electron density for a coronal streamer about three times higher than that found optically. It was also shown that the positional movements of individual sources at the two frequencies within a group were correlated. This suggested that the trajectories of the sources of bursts were approximately parallel and the density variations across the lower and upper parts of the coronal streamer were similar.

Enome (1964) studied the circular polarization characteristics of Type III bursts at 200 MHz with respect to the positions of the sources. A relatively large number of partially-polarized Type III bursts were also found at 200 MHz. The sense of rotation of the partially-polarized Type III bursts, whose locations on the solar disk were near the sources of the noise storms occurring within a few days, was the same as the sense of the associated noise storms.

Takakura and Tlamicha (1964) compared active prominences without flares with radio emission observed with the 200 MHz multiphase interferometer and the 200 MHz time-sharing polarimeter. The number of associations of Type III bursts with optical activity was 8 out of 21. This result may support a statistical significance, considering the fact that the high frequency cutoff for Type III bursts sometimes occurred below 200 MHz and that the radio waves from the extreme limb may not have been observed.

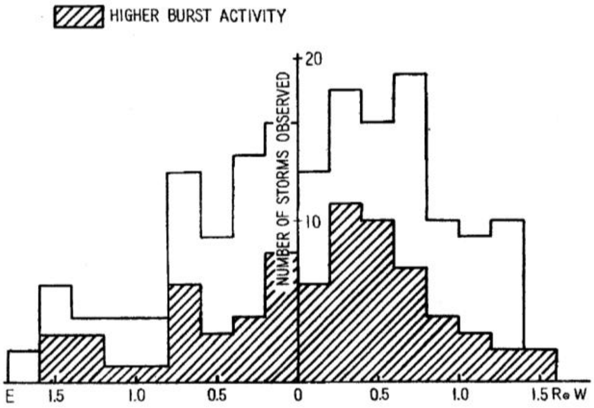


Figure 25: East-west distribution of positions of noise storms observed with the 200 MHz time-sharing polarimeter (after Suzuki, 1961).

Descriptions of Type III bursts contained in the papers by Morimoto and Kai (1961; 1962) and Morimoto (1963) are included in the previous subsection.

Morimoto and Kai (1961; 1962) carried out a statistical investigation of the heights of Type I and Type III bursts at 200 MHz by comparison of their apparent positional variation from the center to the limb of the Sun with the associated optical phenomena. The height of the sources of Type I bursts was ~0.2–0.3 solar radii above the photosphere and that of Type III bursts was slightly higher, when they are observed near the center of the solar disk. The height gradually increased with distance from the center, and for Type I bursts in particular reached 0.6 solar radii at the limb. If it was assumed that the emission originated from the plasma level, the electron density of the Type I source must have been about ten times larger than that of the normal corona. On the other hand, the occurrence distribution of Type I bursts on the solar disk showed a remarkable concentration near the center of the disk, while that of Type III bursts increased for up to 1.0 solar radius from the center and then rapidly decreased.

Morimoto (1963) then estimated the source heights and directivity of Type I and III bursts at 517, 200, 60, 55 and 45 MHz. The heights of Type III bursts at frequencies between 517 and 45 MHz give a distribution of electron densities ~30 times the value of the normal corona, while Type I bursts had a stronger limb darkening than Type III bursts. These observations showed that electron densities above active regions derived from the radio measurements were higher by a factor of 3 than those obtained by Newkirk (1959) from K-corona optical observations, as shown in Figure 26. In order to resolve this discrepancy, he sug-

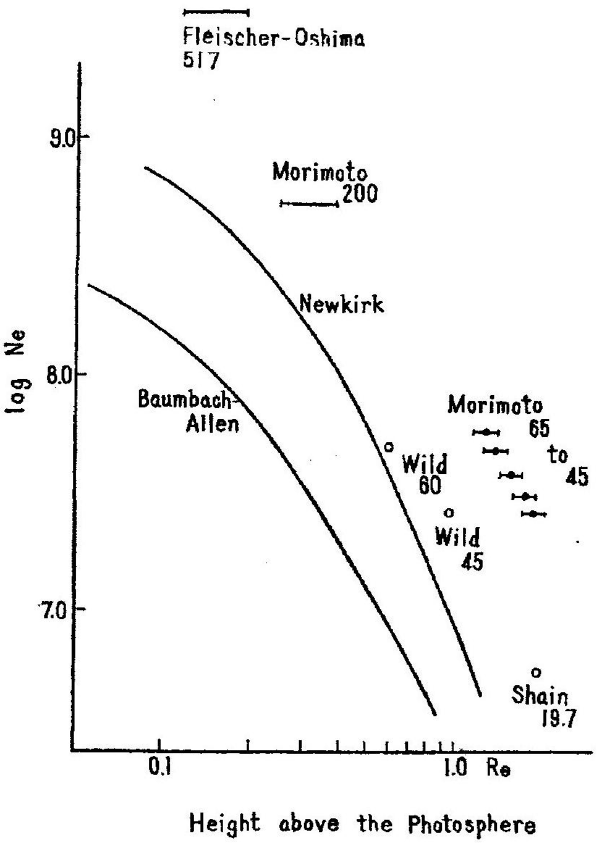


Figure 26: The height of the sources of Type III bursts at frequencies between 517 and 19.7 MHz (after Morimoto, 1963).

gested filamentary substructures within Newkirk's model as the radio sources of Type I and III bursts. In addition, he suggested that the filamentary radio sources of Type I bursts lay below a stopping level of extraordinary waves in the streamers so that escaping waves were circularly polarized (ordinary waves), while the sources of Type III bursts were just above the stopping layer so that the escaping waves were weakly polarized or unpolarized.

Kai (1962) examined the observational features of Type I bursts in detail. The extension of the region in which Type I bursts originated coincided with plages rather than the associated sunspots themselves. The extension of the Type I continuum was the same as the scattering range of individual bursts, which was consistent with the interpretation that the continuum was a superposition of Type I bursts. It was also shown that Type I bursts occurring at the limb of the Sun had a longer duration and were nearly unpolarized. From this Kai concluded that the height at the limb was far above the plasma level so the collision frequency was sufficiently low to give longer duration and both ordinary and extraordinary waves could escape, resulting in unpolarized bursts.

Tsuchiya (1962) observed Type I bursts with the 199–207 MHz narrow band dynamic spectrometer at the TAO during November 1957 and March 1958. He demonstrated that the average bandwidth of Type I bursts around 200 MHz was ~4 MHz, which was the same as at lower frequencies.

3.4 Type IV Bursts

Although emphasis is put on meter-wave Type IV bursts in this subsection, microwave Type IV bursts (long-duration bursts at microwave wavelengths) are also dealt with here. On the other hand, microwave impulsive bursts are described in the next subsection.

Boischot (1957) was the first to recognize the existence of non-storm, flare-related continuum emission at meter wavelengths, and he designated these Type IV emission. Soon afterwards, Takakura (1959c) pointed out that the characteristics and the generation mechanism of this emission were distinctly different at frequencies above and below a certain cross-over frequency between 300 and 600 MHz. He suggested that emission above this cross-over frequency fell into the same category as Type IV and was caused by synchrotron radiation from high-energy electrons. To obtain experimental evidence, the dynamic spectra covering the cross-over frequency were studied by Takakura (1960a) using data from the 300–800 MHz dynamic spectrometer and observations at fixed frequencies of 9.5 GHz and 67 MHz made at the Toyokawa Observatory and the TAO. Based upon the observational results, the distinctive short-lived bursts at frequencies above 1 GHz were called 'microwave bursts', while the long-lived microwave bursts were referred to as 'Type IV bursts'. Takakura and Kai (1961) then examined the dynamic spectra of long duration intense bursts in the frequency range 67 MHz to 9.4 GHz using single-frequency records. They found at least two distinctive groups of bursts, i.e. long-duration bursts at centimeter wavelengths (the 'centimeter-wave Type IV') and Type IV bursts at meter wavelengths (the 'meter-wave Type IV'). These groups are mixed in some frequency ranges where they accompany another group of bursts at decimeter wavelengths (the 'decimeter-wave Type IV'). The Type IV bursts at meter wavelengths were frequently followed after an intermission of 30–60 minutes by similar but longer and weaker radiation (the 'meter-wave post-Type IV'). Takakura (1963a) also analyzed the broad-band spectra of solar bursts using the records obtained during 1958 and 1960 at fixed frequencies between 9.4 GHz and 67

MHz. The histogram of the central frequencies was shown to have three maxima, at 70–100 MHz, 300–500 MHz and above 9 GHz, which corresponded to Type IV_m (Type IV at meter waves), IV_{dm} (Type IV at decimeter waves), and IV_{μ} (Type IV at microwaves). This tendency is shown in Figure 27. Type IV_{μ} bursts are almost non-directive while the intensities of Type IV_{dm} and IV_m bursts decrease at about the solar limb by a factor of 0.3 and 0.1, respectively. The center frequency of some Type IV_m bursts drifts from higher to lower at rates of 30–40 MHz per 10 minutes.

When Wild et al. (1959) studied Type IV bursts at frequencies between 40 and 70 MHz they found the position of the source moved from the position of the flare up to 5 solar radii, while the emission at all frequencies was observed at the same position. Morimoto (1961) compared the results obtained by the 200 MHz multi-phase interferometer with Wild's results at lower frequencies and found that at 200 MHz Type IV bursts usually stayed at rest near the flare site, i.e. they showed no ejected motion, which disagreed with the results obtained at lower frequencies. Morimoto (1961) and Morimoto and Kai (1962) found that the height of the sources of Type IV bursts was ~0.2–0.3 solar radii above the photosphere, similar to those of Type I and Type III bursts.

Kai (1965a; 1965c) analyzed the polarization characteristics of eighteen Type IV bursts that were observed between 1957 and 1960 using data from the TAO and the Toyokawa Observatory at frequencies between 200 MHz and 9.4 GHz. The Type IV bursts at 200 MHz were weakly polarized in the initial stage, sometimes changing sense, but after a few tens of minutes they become strongly polarized up to more than 70%. The sense of polarization was the ordinary mode. Type IV bursts observed at the limb were weakly polarized, suggesting some sort of directivity was associated with the polarization. On the other hand centimeter wave Type IV bursts were partially polarized, probably in the extraordinary mode. The degree of polarization was usually 10–30%, and was nearly constant throughout the duration of the burst. The maximum polarization seemed to occur near the frequency of the intensity maximum. In many cases a clear or complex reversal in the sense of polarization was found between 1 and 9.4 GHz. Based upon these polarization observations, Kai (1965b) suggested possible mechanisms applicable to Type IV bursts. The mechanism for microwave Type IV bursts may be synchrotron radiation from inhomogeneous sources which were distributed vertically over the lower corona corresponding to the observing frequencies. The mechanism for Type IV bursts in the decimeter and meter range may be gyro-resonance radiation due to electrons of comparatively lower energies. An alternative possible mechanism is radiation from coherent plasma waves excited by an electron beam, which requires a sufficiently strong magnetic field and comparatively lower energy electrons of density about 10^7 cm^{-3}.

Kai (1963) examined the state of linear polarization of Type IV bursts which were observed with the 200 MHz time-sharing polarimeter between 1957 and 1960. Using completely circularly-polarized bursts (usually Type I bursts) as a calibrator, he estimated that almost all of these bursts had linear components of about 10%.

Kai (1967) analyzed twenty-three microwave Type IV bursts to reveal evolutionary features of microwave Type IV bursts using data observed during 1958 and 1967 at 1, 2, 3.75, and 9.4 GHz at the Toyokawa Observatory and at 17 GHz at the TAO. He found that the turn-over frequencies (f_m) moved progressively towards the lower frequencies, and their decay times (τ) become successively longer. A plot of all available data indicated an approximate relation where $\tau \propto f_m^{-a}$ (where a = 1–2).

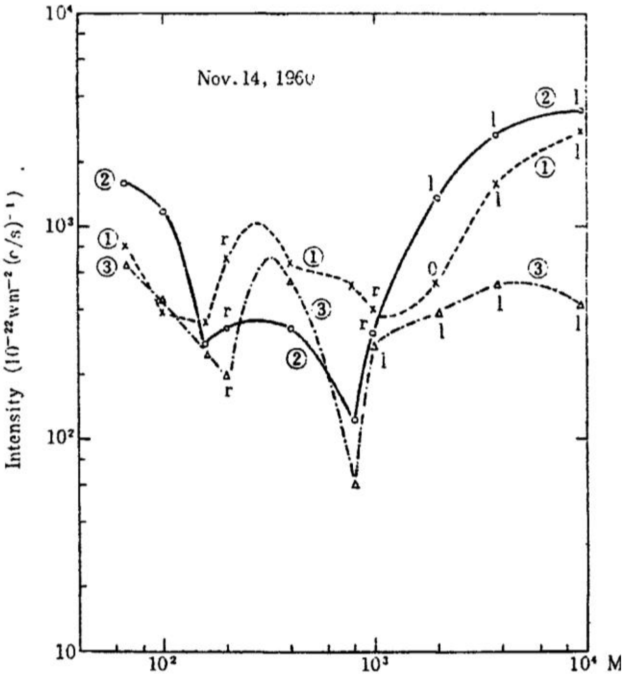


Figure 27: Intensity spectra of Type IV bursts at three times ((1): 03:40, (2) 04:00, (3) 04:20) on 14 November 1960 (after Takakura, 1963a).

3.5 Other Observations

Using the 9.5 GHz polarimeter, Akabane observed intense solar radio bursts which were associated with three large successive solar flares on 3 July 1957 (see Akabane and Hatanaka, 1957; Akabane, 1958b; 1958d). An interesting point was that the state of polarization of the burst corresponding to the third flare changed considerably. It was suggested from comparison with both the associated optical flare and the magnetic field structure that this polarization change was connected with the shift of the activity center of the optical flare. Akabane also summarized the observational results from June 1957 to May 1958 as follows:

(1) the integrated frequency distribution of occurrence for the intensity (I) and for the percentage polarization (r) were proportional to I^{-n} (with n in the range 1.8–1.9) and roughly exp $(-15r^2)$, re-

spectively; and
(2) some linear polarization was observed in many bursts (those greater than 100 sfu).

Akabane (1958d) suggested from the analysis of data observed with the 9.5 GHz polarimeter during June 1957 and May 1958 that the S-component had circular polarization ~10% and its sense seemed to change near the central meridian passage of the enhanced region when it was associated with a typical bipolar sunspot. A small amount of linear polarization also was detected in a few cases.

Concerning the emission mechanism of the S-component, two different explanations were proposed. Waldmeier and Müller (1950) suggested that the S-component may have been emitted by free-free transition within a coronal condensation associated with a region of exceptionally high electron density in the solar corona. An alternative explanation by Piddington and Minnett (1951) was that the S-component was due to the gyro-magnetic effect in the sunspot's magnetic field. Kawabata (1960a) conducted a statistical study of the S-component for the period from July 1957 through August 1959 using single frequency observations from Ottawa at 2.8 GHz, the Toyokawa Observatory at 1, 2, 3.75, and 9.4 GHz, and the TAO at 9.5 GHz. The temperature and the optical depths of coronal condensations associated with intense calcium plages were obtained. The temperatures of the coronal condensations were estimated to be $4–6 \times 10^6$ K. There seemed to be a tendency that the more intense the calcium plage, the higher the electron temperature. By examining the polarized component obtained during the eclipse of 19 April 1958 by Tanaka and Kakinuma (1958), it was found that the polarized component was due to the gyro-magnetic effect in a magnetic field of >1,000 gauss localized to a small area above the sunspot.

It had been pointed out that unusual increases in cosmic-ray emission only occurred in the ascending and descending phases of solar cycles, and avoided the maximum phases. Takakura and Ono (1961; 1962) examined variations in occurrence frequencies of H-alpha flares and microwave outbursts at 9.4 and 3.75 GHz at Toyokawa and 2.8 GHz at Ottawa and found that most intense outbursts showed the same tendency as the cosmic-ray increases, in spite of the fact that importance 3+ flares occurred most frequently at sunspot maximum. From this finding, the authors suggested that the above tendency regarding the unusual increase of cosmic-rays may simply be due to some condition which made it unfavorable for the acceleration of particles at sunspot maximum.

Sudden ionospheric disturbances (SIDs) were believed to be associated with an increase in ionization in the D-region caused by incident solar ionizing radiation. Elwert (1956) suggested that a high temperature region at 10^7 K on the Sun may produce the solar hard X-rays which cause SIDs. On the other hand, Hachenberg and Volland (1959) and Sinno and Hakura (1958) concluded from research on the relationship between SIDs and solar radio outbursts that both the microwave emission and the ionizing radiation responsible for SIDs originated from the same gaseous volume in the solar atmosphere and were generated by a similar emission mechanism. Kawabata (1960b; 1963) then conducted a statistical study of the relation- ship between SIDs and solar microwave emission by using 2.8 GHz Ottawa observations and short wave fade-outs (SWF) published by the C.R.P.L. in Boulder, for the period from January 1957 to July 1959. He also studied the spectrum of post-burst increases using data at several frequencies from 1 to 9.5 GHz obtained at the Toyokawa Observatory and at the TAO. He was able to show that SIDs were closely related to post-burst increases and that these were caused by thermal emission from very hot condensations in the solar corona, with temperatures as high as $10^7–10^8$ K. Such condensations emitted sufficient X-rays to cause SIDs.

Takakura (1966) computed the energy distribution of high-energy electrons that emitted gyro-synchrotron radiation responsible for microwave impulsive bursts as a function of time for plausible initial distribution functions. The theoretical decay curves of the radio emission from these electrons were compared with the observed decay curves of the radio bursts to deduce the initial energy distribution. Here, radio data from 1 to 9.4 GHz obtained at the Toyokawa Observatory were used. It was suggested that the most probable initial distribution was the power law $K^{-\gamma}$, with γ of 3–5. On the other hand, X-ray bursts coincident with microwave impulsive bursts were observed by X-ray detectors aboard balloons and rockets. Peterson and Winckler (1959) showed a discrepancy of the order of $10^3–10^4$ between the total number of electrons needed to radiate an X-ray burst (200–500 keV) and that required to radiate a coincident microwave burst. Takakura and Kai (1966) then proposed a comprehensive model of microwave bursts and hard X-ray bursts (>20 keV) as follows: (1) The majority of the high-energy electrons are trapped in a localized region and are the source of the hard X-ray bursts, which are invisible at microwave frequencies; while (2) a small fraction, $\sim 10^{-3}–10^{-4}$, of the high-energy electrons is trapped in an outer region and contributes to the micro- wave impulsive bursts.

Kawabata (1966b) statistically compared the soft X-ray data obtained mainly by satellite SR-1 and Ariel 1 with the corresponding microwave data obtained at the Toyokawa Observatory, and showed that soft X-ray bursts correlated with microwave long-enduring bursts (precursors, post-burst increases, and gradual rise and fall bursts). In addition, the X-ray burst of 4 September 1960 was associated with a flare which occurred at a sunspot group located about 10° behind the western limb, which suggested that the X-ray source was located in the corona. It was further estimated that the

X-ray source had a temperature of ~6×10^6 K and an electron densiuty of 1.5×10^{49} cm^{-3} at the peak of the emission.

4 THE THEORY OF SOLAR RADIO EMISSION

For frequencies less than 50 MHz Hatanaka (1953) derived a solution for the propagation path of radio waves through the solar atmosphere by elliptic integrals by assuming spherical symmetry of the atmosphere and distribution of the electron density. Then, he tried to apply it to explain the directivity found for solar radio emission such as noise storms.

Van de Hulst (1949) suggested that owing to changes in the electron density within the solar corona, the apparent temperature of the quiet Sun measured at radio frequencies might undergo a periodic change in the course of the sunspot cycle. Hatanaka and Moriyama (1953) calculated the apparent temperature of the quiet Sun with varying values of chromospheric and coronal electron densities to see how these changed with the sunspot cycle. The electron temperature in the chromosphere was assumed to increase exponentially with height until it reached a constant value (10^6 K). The electron density in the corona was presumed to vary by a factor of two during a single sunspot cycle without any change in the form, but in the chromosphere it was assumed to vary in two different ways. The calculated curve fairly well fitted the 5-yr long observations by Covington (1951a; 1951b) at 10.7 cm, but did not fit well the decrease in apparent temperature reported by Christiansen and Hindman (1951) at five frequencies (from 200 MHz to 1 GHz) for the period 1947–1950.

It was known terrestrial magnetic storms and aurorae were related to solar activity. The analysis of these relationships suggested that some agent was emitted from the Sun. Kawabata (1955) assumed that the constituents of such an agent were clouds of completely-ionized hydrogen, and he investigated their motions transverse to magnnetic fields using a simplified model that assumed that collisions between ions and electrons were negligible. The results were applied to the escape of corpuscular streams from the Sun.

Takakura (1956) proposed a possible emission mechanism for polarized bursts and noise storms. If electrons with non-relativistic energy gyrated in groups in magnetic fields above sunspots, extraordinary waves of a non-thermal nature were emitted. These waves were reflected or absorbed in the outer region of the corona where the refractive index for the waves became infinite, but on the way up to this layer a part of a wave would be transformed into an ordinary wave if there was a layer where the magnetic field and/or the electron density changed steeply along the path of the wave. Ordinary waves thus generated could propagate through the solar atmosphere and subsequently their effects would be observed at the Earth.

Hatanaka (1956) treated, in general form, the Faraday effect in the Earth's atmosphere on the ellipticity and tilt angle of the polarization ellipse of cosmic radio waves. It was shown that when the path of the radio waves was nearly perpendicular to the direction of the magnetic fields, the ellipticity varied. In the case of the solar atmosphere, the tilt angle was rotated by a very large amount even in the most favorable cases. Therefore, any linearly-polarized radiation emitted from the Sun would be obliterated because of the finite bandwidth of the receiver.

Kawabata (1958) investigated the intensity and the polarization of radio-frequency radiation emitted by an ionized gas in a magnetic field, taking into account the simultaneous interaction of electrons with the surrounding ions. The calculation was made on the assumption that the refractive index of the surrounding medium was unity. It was shown that the Stokes parameters of the radiation emitted by an ionized gas could be obtained from the Fourier transform of the correlation functions between various components of the velocity of an electron.

There seemed to be two kinds of emission, i.e. one with maximum flux between 10 and 100 MHz and the other with a maximum flux at several thousand megahertz. The former emission caused Type II and IV bursts and was probably associated with plasma oscillations, while the latter emission was probably caused by synchrotron radiation of electrons with intermediate energies. Based upon the above consideration, Takakura (1960b) calculated the emissivity, absorption coefficient, polarization and spectrum for synchrotron radiation of electrons in circular orbits with velocities of 0.25–0.90 the speed of light. The spectrum derived from radiation of electrons with electron energy spectra following a power law, as for the example shown in Figure 28, was consistent with the observed average spectra of outbursts at microwave wavelengths. On the other hand, outbursts observed at 1, 2, 3.75 and 9.4 GHz at the Toyokawa Observatory had a circularly-polarized component of 10–100%, where the sense of polarization reversed somewhere between 2 and 3.75 GHz. Takakura (1960b) also showed that this behavior could be expected from synchrotron radiation. Subsequently, Takakura (1960c) calculated the emissivity, absorption coefficient, polarization and spectrum for synchrotron radiation of electrons in helical orbits with velocities of 0.25–0.90 the speed of light. The general tendency was similar to the case in which the orbits of the electrons were circular, but a major difference was a remarkable increase in the radiation at frequencies below the gyro-frequency of ambient thermal electrons.

Uchida (1960; 1962) discussed the exciters of Type II and Type III bursts from the viewpoint of the velocities with which their sources moved in the solar atmosphere. Considering the propagation velocities of several possible types of disturbances in the physical conditions above a sunspot, he concluded that the exciters of Type II bursts were hydromagnetic shock fronts, while those of Type III bursts were the free streaming of charged particles with high velocity. It was also shown that this result was consistent with the observed characteristic features and differences of these two different types of solar radio bursts.

Takakura (1961a; 1962) discussed the acceleration of thermal electrons to relativistic energies due to hydromagnetic waves in order to account for the characteristics of Type IV bursts. The first acceleration could easily arise as a consequence of high velocities of Alfvén waves in the lower corona. In this case, the acceleration was limited

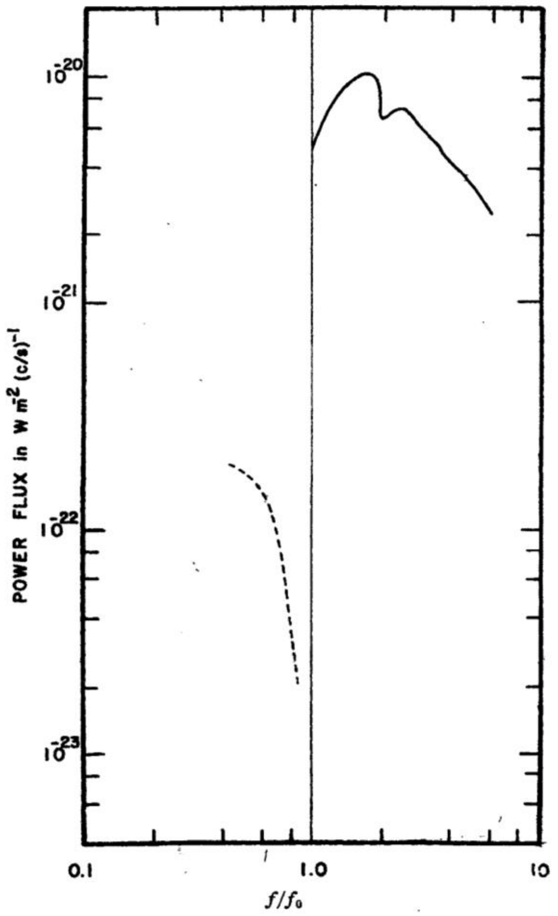


Figure 28: An example of a spectrum calculated under the assumption that the electron spectrum $\propto E^{-1}$, the total number density of high-energy electrons = 1 cm^{-3}, the gyro-frequency (f_0) = 10^3 MHz, the source diameter = 10^5 km and the source depth = 10^5 km. The dashed line shows that self-absorption is strong at frequencies from 0.6 f_0 to 1.0 f_0. (after Takakura, 1960b).

only to the direction parallel to the magnetic field. In order to accelerate the electrons further, up to relativistic energies, redistribution of the velocities of the accelerated electrons may have been caused by collisions of the accelerated electrons with ambient thermal electrons well before their energies were lost by the collisions. The accelerated electrons tended to accumulate in places where the magnetic field was better able to radiate synchrotron radiation. In the case of an intense eruption, a few magnetic bulges would be formed as separate radio sources for meter-wave, decimeter-wave and centimeter-wave Type IV bursts.

Moriyama (1961) derived absorption coefficients for free-free transitions in the radio region from emission coefficients using purely classical lines. In the computation, the Debye shielding length was adopted as the upper limit for the impact parameter. In addition, he criticized the existing chromospheric models based upon the radio data and derived a relation between the local electron temperature and the integral of the density squared over the line of sight from radio data.

Takakura (1961b) discussed limiting the sense of circular polarization of magneto-thermal radiation from two small radio sources above a preceding and a following sunspot as a function of the heliographic longitude of the sunspot, assuming a dipole magnetic field for a bipolar sunspot field and the Baumbach (1938) model for coronal electron densities. The sense of polarization at a fixed frequency was expected to reverse when the sunspot reached a certain heliographic longitude due to the rotation of the Sun. The sense-reversal occurred at western longitudes for emission from the preceding spot and at eastern longitudes for emission from the following spot. The results were compared with solar eclipse observations made on 19 April 1958 of the polarization of the radio waves from a large bipolar sunspot (Akabane, 1958d; Tanaka and Kakinuma, 1958).

Takakura (1963b) proposed a theory of Type I bursts which he suggested were radiated by Rayleigh scattering of coherent plasma waves. In this theory, the coherent plasma waves were excited by a beam of electrons with a group velocity of a few times of the mean thermal speed. The beam electrons perhaps were created by collisions of two wave packets of Alfvén waves propagating in opposite directions to each other.

The coronal magnetic field was hard to estimate from optical observations. Takakura (1964a; 1964b) estimated magnetic field intensity in the solar corona using the radio burst measurements, i.e. heights, motions, intensity spectra and polarization of Type I, II, III and IV bursts in meter waves, assuming their emission mechanisms. From these estimates he derived a magnetic field strength ~10 gauss at heights of 0.2–1.0 solar radii above active sunspot regions. However, it was suggested that the magnetic field must have been very weak, ~10^{-1} gauss or less, at the same height far from the sunspot regions. The magnetic field intensity was also estimated as 270–900 gauss and 18–90 gauss for Type IV$_{\mu}$ and Type IV$_{dm}$, events respecttively.

Kawabata (1964) investigated the gyro-resonance radiation due to electrons having an arbitrary distribution with respect to their energies and pitch angles. He formulated an equation of transfer for the gyro-resonance radiation by taking into account the re-absorption due to the gyro-resonance effect and the Faraday effect assuming that the refractive index of the medium was close to one.

The energy stored in the hot coronal condensations responsible for soft X-ray bursts amounted to 10^{31} erg. The ejection of plasma clouds which produced terrestrial magnetic storms also required energy of the order of 10^{32} erg. A possible source to generate such large energies was the energy of a sunspot magnetic field. Based upon this consideration, Kawabata (1966a) proposed a mechanism for the acceleration of the plasma clouds that produce the geomagnetic storms. If turbulences with velocity ~30 km/s were generated near an X-type magnetic neutral point in the chromosphere, a magnetically-isolated cloud would be ejected into the upper solar atmosphere. The ejected cloud then would produce a collapse of the coronal condensation which was responsible for soft X-ray bursts and microwave impulsive bursts. The cloud then escaped from the Sun and produced a geomagnetic storm. A collision-free shock ahead of the cloud was responsible for Type IV bursts. A series of scenarios is shown in Figure 29.

Takakura (1966; 1967) also wrote two review papers for *Space Science Reviews* and *Solar Physics*.

5 CONCLUDING REMARKS

After a fruitful period of solar research at Mitaka, the TAO shifted its observation site for solar radio astronomy to Nobeyama, which was located 150 km north-west of Tokyo and was free of city noise. In 1969 a new 160 MHz compound interferometer was constructed there consisting of an east-west array with a resolution of 2′ and a north-south array with spatial resolution of 4′ (Takakura et al., 1967). After a preparation period, a 17 GHz one-dimensional solar interferometer with a multi-correlator system was constructed in 1978 (Nakajima et al., 1980). In 1990, the solar radio groups at Nobeyama and Toyokawa Observatory were combined into a new group, and the 17 GHz Nobeyama Radioheliograph was constructed in 1992 based upon the technical and scientific backgrounds of both groups (Nakajima et al. 1994). In 1995, it was upgraded to a dual-frequency system operating at 17 and 34 GHz, with spatial resolutions of 14″ and 7″ respectively.

6 NOTES

1 This is the third in a series of papers reporting the results of an international collaborative project conducted under the auspices of the International Astronomical Union's Working Group on Historic Radio Astronomy to overview the early development of Japanese radio astronomy. As such, it follows an introductory paper (Ishiguro et al., 2012) and a paper detailing—for the first time—Koichi Shimoda's attempt to observe the 9 May 1948 partial solar eclipse

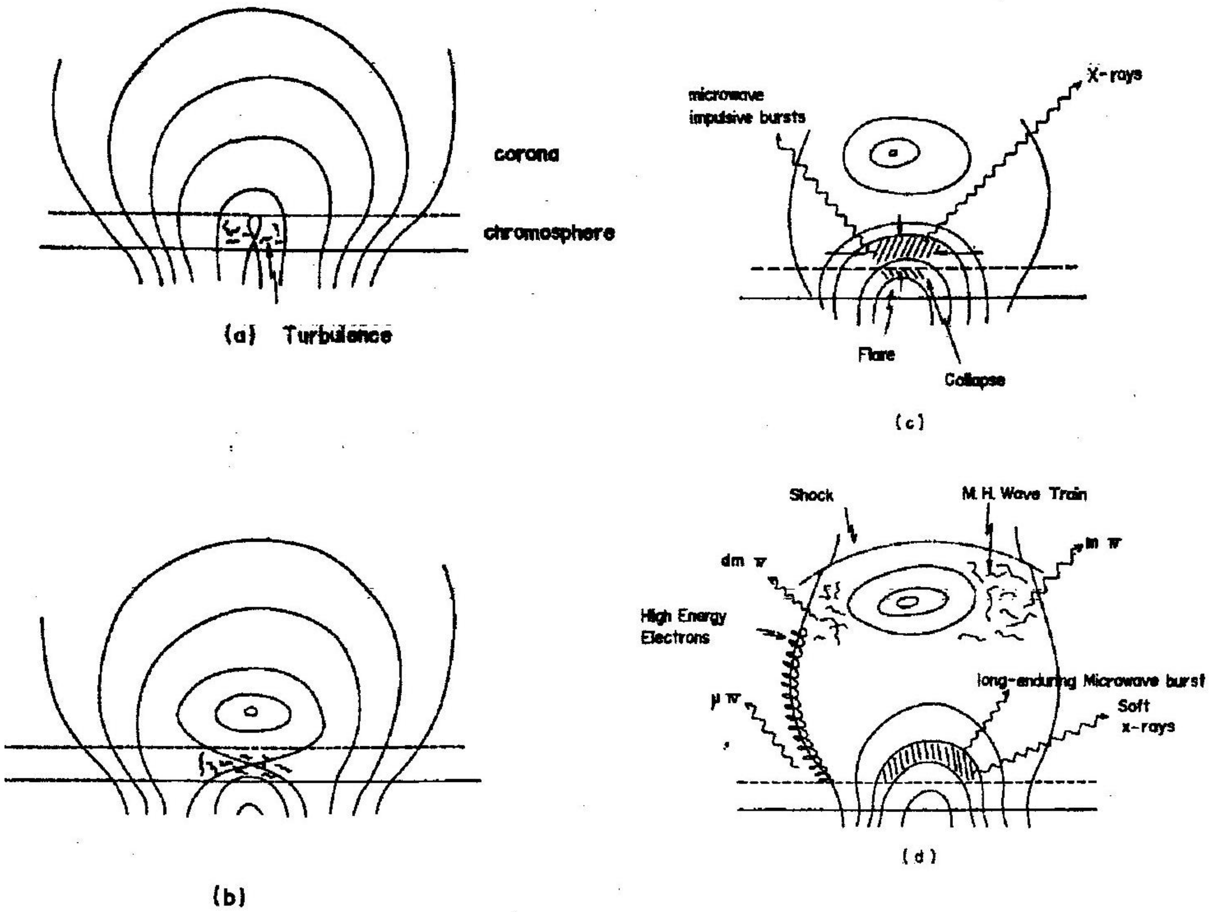


Figure 29: Various scenarios involving solar flares derived to explain the emission of associated radio emission. (a) Generation of turbulence near a neutral point. (b) Ejection of a magnetically-isolated cloud into the corona. (c) The collapse of a coronal condensation which triggers flares. (d) Escape of the cloud and generation of a geomagnetic storm (after Kawabata, 1966).

(Shimoda et al., 2013). This present paper outlines the research in early radio astronomy conducted at the Tokyo Astronomical Observatory (TAO) under the direction of Professor Takeo Hatanaka, and it is particularly appropriate that it should be published in 2014, exactly one hundred years after his birth. Accordingly we would like to dedicate this paper to the memory of Professor Hatanaka, a leading pioneer of Japanese radio astronomy.

7 ACKNOWLEDGEMENTS

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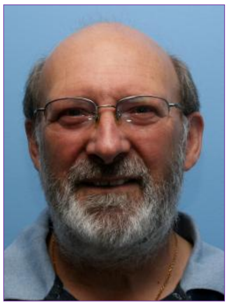
Dr Masato Ishiguro is a Professor Emeritus of the National Astronomical Observatory of Japan (NAOJ). He started his research in radio astronomy at Nagoya University in 1970 where he investigated radio interferometry techniques. In 1980, he moved to the Tokyo Astronomical Observatory of the University of Tokyo to join the project to construct large millimeter-wave telescopes at the Nobeyama Radio Observatory (NRO) where he was in charge of constructing the Nobeyama Millimeter Array. He was the Director of the NRO from 1990 to 1996 and contributed to the open use of the telescopes. While doing research at the NRO, he worked on a plan for a large array at millimeter and submillimeter wavelengths. Since 1998, he had been leading the Japanese involvement in the international project to construct the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile. He was a Professor at the NAOJ from 1988 until he retired in 2009. He is now the Japanese representative on the Committee of the IAU Working Group on Historic Radio Astronomy.



Professor Wayne Orchiston is a Senior Researcher at the National Astronomical Research Institute of Thailand in Chiang Mai. In his earlier years Wayne worked at the CSIRO's Division of Radiophysics in Sydney and later at its successor, the Australia Telescope National Facility. He has published extensively on the history of radio astronomy in Australia, France and New Zealand, and he and Masato Ishiguro lead the IAU Project on the History of Early Japanese Radio Astronomy. Wayne was the founding Chairman of the IAU's Working Group on Historic Radio Astronomy, and he currently serves as its Secretary. He has supervised five Ph.D. theses on the history of radio astronomy. In 2013 he was honoured when minor planet 48471 Orchiston was named after him.

Dr Kenji Akabane is a Professor Emeritus of the University of Tokyo. He started solar radio observations at a microwave frequency at the Tokyo Astronomical Observatory (TAO) of the University of Tokyo in 1952. He stayed in the United States from 1957 to 1960, studying at Cornell University and the University of Michigan. After coming back from the US, he showed a great interest in the field of cosmic radio astronomy and led a project to construct the 6-m millimeter wave radio telescope on the campus of the TAO, which was completed in 1970. After that he was motivated to construct the largest millimeter wave radio telescope in the world, and was appointed as the founding Director of the Nobeyama Radio Observatory in 1982. He was a Professor at the National Astronomical Observatory of Japan from 1970 until he retired in 1987. He then worked at the University of Toyama from 1987 to 1992, and then was the President of Matsusho Junior College for seven years, from 1992.

The late Professor Shinzo Enome died on 24 March 2011 at the age of 72. He began his career in solar radio astronomy in 1966 at the Research Institute of Atmospherics, Nagoya University (Toyokawa), and in 1988 moved to the National Astronomical Observatory of Japan (NAOJ) to participate in the construction of the Nobeyama Radioheliograph. He played a very important role in this project by unifying the solar radio astronomy groups from Toyokawa and Nobeyama into a single research group. As the Director of the Nobeyama Solar Radio Observatory, he led the construction of the radioheliograph and succeeded in completing the construction in two years. In 1999 Enome-san retired from the NAOJ, and was awarded an Emeritus Professorship. From the start, he was an active member of the IAU Early Japanese Radio Astronomy team and it is therefore fitting that he should be a posthumous co-author of this paper.

Dr Masa Hayashi is Director General of the National Astronomical Observatory of Japan (NAOJ). He trained in radio astronomy at the Nobeyama Radio Observatory of NAOJ and became an Assistant Professor at the University of Tokyo in 1987. He moved to the Subaru Project at NAOJ in 1994, became a Professor of NAOJ in 1998, and served as Director of the Subaru Telescope from 2006 to 2010. He then was a Professor of Astronomy at Tokyo University from 2010 to 2012, before accepting his current position.

Professor Norio Kaifu has a D.Sc. from Tokyo University, and specializes in radio astronomy, infrared astronomy and star formation. He was one of the founders of the Nobeyama Radio Observatory, led the construction of the Nobeyama 45-m mm-wave radio telescope, and found many exotic organic molecules in dark clouds. Then he was involved in the construction of the 8-m aperture Subaru Telescope on Mauna Kea as Director, before becoming Director General of the National Astronomical Observatory of Japan in 2000. As Director General he led NAOJ to be one of the three major international partners in the ALMA Project. Since his retirement as NAOJ Director, he has served the Science Council of Japan as President of the Natural Science & Engineering Division, and also was a Professor of the Open University of Japan until 2012. Currently he is President of the International Astronomical Union. In addition to 150 papers in astronomy he has published some 30 books in Japanese, both for students and for general readers. Well-known books among these are: *From Galaxy to the Universe* (Shin-Nihon-Shinsho, 1972), *Cosmic Radio Astronomy* (co-authored with K. Akahane and H. Tabara, Kyoritsu Shuppan, 1986 and 2012), *Poetries of the Universe* (Chukou Shinsho,1999), *101 Books to Understand the World* (Iwanami Shoten, 2011), etc. Besides several honors in science, Norio Kaifu was awarded the Mainichi Book-Review Award in 2011, and was honored when minor planet 6412 Kaifu was named after him.

Dr Tsuko Nakamura was until very recently a Professor

at the Teikyo-Heisei University in Tokyo, where he taught Information Sciences since 2008. Prior to that, he worked at the National Astronomical Observatory of Japan for many years. His research interests lie in observational statistics of very small asteroids and in the history of Japanese astronomy, and he has published about forty papers in this latter field. His books include *Five Thousand Years of Cosmic Visions* (2011, in Japanese, co-authored by S. Okamura), *Mapping the Oriental Sky*, *Proceedings of the ICOA-7 Conference* (2011, co-edited by W. Orchiston, M. Sôma, and R. Strom) and *Highlighting the History of Astronomy in the Asia-Pacific Region*, *Proceedings of the ICOA-6 Conference* (2011, co-edited by W. Orchiston, and R. Strom). Tsuko is now Vice-chairman of the IAU Working Group on Historical Instruments.

The late Dr Atsushi Tsuchiya died in August 2011 at the

age of 80. He began his career in solar radio astronomy in 1953 at the Tokyo Astronomical Observatory, where he specialized in low frequency observations of burst activity. In 1971 he left the radio astronomy group and transferred to the Observatory's lunar laser ranging program where he remained until his retirement in 1989. He then worked for the Japan Land-survey Association until his death. In wrote two books on land-survey applications of the GPS, and these were published in 1995 and 2008. Despite his more recent research interests, from the start Atsushi was an active member of the IAU Early Japanese Radio Astronomy team, and he contributed material for this paper prior to his death. It is therefore only fitting that he should be a posthumous co-author of this paper. The photograph of him included here was taken at the TAO when he was a graduate student.