HIGHLIGHTING THE HISTORY OF JAPANESE RADIO ASTRONOMY. 1: AN INTRODUCTION

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Abstract: Japan was one of a number of nations that made important contributions in the fledgling field of radio astronomy in the years immediately following WWII. In this paper we discuss the invention of the Yagi-Uda antenna and the detection of solar radio emission in 1938, before reviewing radio astronomical developments that occurred between 1948 and 1961 in Osaka, Nagoya, Tokyo and Hiraiso. In order to place these early Japanese experiments in a national and international context we briefly review the world-wide development of radio astronomy in the immediate post-War years before discussing the growth of optical astronomy in Japan at this time.

Keywords: Japan, radio astronomy, Yagi-Uda antenna, Dellinger Effect, 1948 solar eclipse, Osaka University, Osaka City University, Nagoya University, University of Tokyo, Tokyo Astronomical Observatory, Radio Research Laboratories of the Ministry of Posts and Telecommunications; optical astronomy in Japan.

1 INTRODUCTION

Radio astronomy started in Japan in 1948, about the same time it was launched in France (see Orchiston et al., 2007; 2009), and just two years after the first post-war solar radio observations were made in Australia, England and Canada (see Covington, 1973; Orchiston, et al., 2006; Sullivan 2009). But as Tanaka (1984: 335) points out, "… considering the difficult social circumstances arising from the nation's defeat in World War II, its development was not so slow." Part of the reason for this was the ready availability of suitable equipment:

> Radar was also intensively developed in Japan during World War II, although it was not as technically advanced as that of the Allies. Once the defeated nation began to recover in the 1940s, however, radio physicists could draw not only on domestic stores, but also on American radar parts, readily available from War surplus dealers. (Sullivan, 2009: 225).

By the early 1950s researchers in Hiraiso, Osaka, Toyokawa and Tokyo were actively involved in solar research, and the last two groups went on to make important contributions to international radio astronomy. For Japanese localities see Figure 1.

Figure 1: Japanese localities mentioned in the text. Key: 1 = Sendai; 2 = Hiraiso; 3 = Tokyo Astronomical Observatory (Mitaka); 4 = Nobeyama; 5 = Toyokawa Radio Observatory; 6 = Nagoya; 7 = Osaka; 8 = Okayama Astrophysical Observatory; 9 = .Norikura Solar Observatory.

Figure 2: Hidetsugu Yagi with one of the early antennas that he and Uda developed (after: microwaves101.com).

This is the first paper in a series aimed at providing a detailed account of these developments in Japanese radio astronomy from 1948 through to the mid-1960s,[1] and it builds on the foundations laid by Tanaka and by Ishiguro and Orchiston[2] in their review papers of 1984 and 2013 respectively. In his paper, Tanaka (1984: 347) was quick to point out that "… my selection is far from complete, and not a few hidden topics have been left out." These "hidden topics" (or gaps in documentation) are identified in the Ishiguro and Orchiston review paper, and will be discussed in more detail in this paper and others that will follow it in this series on 'Early Japanese Radio Astronomy'.

But before commencing the post-War review of Japanese radio astronomical achievements we will examine the development of the Yagi-Uda antenna, which was to play a critical role in the early development of radio astronomy worldwide, and we will also discuss an experiment conducted in 1938 that led to the detection of solar radio emission. After reviewing the activities of the active post-War radio astronomy groups in Osaka, Toyokawa, Tokyo and Hiraiso we will place these Japanese efforts in international context by examining overseas trends in radio astronomy during these critical post-War years. We will also review developments that occurred in optical astronomy in Japan between 1930 and 1960 so that these pioneering local efforts in radio astronomy can be seen within the overall framework of Japanese astronomy during this era.

Figure 3: Shintaro Uda, the initial inventor of the Yagi-Uda antenna (after: ieeecincinnati.org).

2 THE INVENTION OF THE YAGI-UDA ANTENNA

One of the most widely-used aerials in early radio astronomy world-wide was the Yagi-Uda antenna (Figure 2), more commonly but incorrectly termed the 'Yagi antenna', which was invented by the Japanese radio engineer Shintaro Uda (1896–1976; see Figure 3) in 1925 (see Uda, 1925) with some assistance from his Professor, Hidetsugu Yagi (1886–1976). Both worked at the Tohoku Imperial University in Sendai (see Figure 1) and they published an account of the new antenna design in a Japanese journal in February 1926, but it was Yagi who brought it to an international audience when he published a description in the *Proceedings of the Institute of Radio Engineers* two years later (Yagi, 1928). The design became widely known as the 'Yagi Antenna', but Yagi was always quick to acknowledge Uda's pivotal role in its invention and development. Consequently, we will refer to it here as the Yagi-Uda antenna.

In its simplest form the Yagi-Uda antenna is a directional aerial that comprises a driven element (which is typically a half-wave dipole or a folded dipole) plus a parasitic reflector, but generally the reflector also is accompanied by one or more directors. The reflector is usually about 5% longer than the driven element whereas the directors are a little bit shorter than it, and these are placed at specified locations along the antenna axis. The dipole is the only element that is directly excited, and is connected electrically to the feed-line. These antennas only operate effectively over a narrow band-width and were ideal for radio astronomical investigations.

Yagi-Uda antennas were used extensively by the Allies and Germans during WWII (Brown, 1999), but

> … many Japanese radar engineers were unaware of the design until very late in the war, partly due to rivalry between the Army and Navy. The Japanese military authorities first became aware of this technology after the Battle of Singapore when they captured the notes of a British radar technician that mentioned "yagi antenna". Japanese intelligence officers did not even recognise that Yagi was a Japanese name in this context. When questioned, the technician said it was an antenna named after a Japanese professor. (Yagi-Uda Antenna).

Soon after the War, Yagi-Uda antennas were used by radio astronomers in Australia, Britain, Japan, New Zealand and the USA for solar and/or non-solar investigations (Sullivan, 2009; Orchiston, 2005a).

3 A MISSED OPPORTUNITY: THE DELLINGER EFFECT AND SOLAR RADIO EMISSION

The 'Dellinger Effect' was defined by its discoverer as:

> … the occurrence of a very sudden change in ionization of a portion of the ionosphere. It manifests itself by the complete fading out of high frequency radio transmission for a period of a few minutes to an hour or more, and by perturbations of terrestrial magnetism and earth currents. The effect was discovered in 1935. (Dellinger, 1937: 1253).

In 1936 and 1937 respectively, Daitaro Arawaka and J. Howard Dellinger (1886–1962) reported that "… a kind of 'grinder' like noise sometimes appeared almost simultaneously with [the] Dellinger phenomena in short-wave telecommunication receivers." (Tanaka, 1948: 335).

In 1938 Drs Minoru Nakagami and Kenichi Miya (1915–2004) from the International Telecommunication Co. Ltd. in Tokyo (see Figure 1) were interested in the origin of this 'grinder' noise, so they erected two horizontal half-wave dipoles, one at h = λ/2 and the other at h = 5λ/4 above the ground, and compared their outputs. With this arrangement they could measure the incident angles of the incoming radiation if it was >70° (Nakagami and Miya, 1939). From April through to September 1938 they monitored telecommunication signals, watching the output meters and writing down the observed values in a notebook every minute. Their patience was rewarded on 1 August when they noted a short-term increase in noise that coincided with a Dellinger phenomenon. This is shown in Figure 4, where the noise

> … suddenly increased to 40-50 dBμV as soon as the communication signal from station PLJ at 14.6 MHz faded out. The noise decreased rapidly in five minutes. They were surprised that the noise received by the h = 5λ/4 antenna was more than 10dB stronger than the one received by the h = λ/2 antenna, which clearly showed that the incident angle was more than 70 degrees, as plotted in the upper part of the Figure. As the Sun was then placed at about 70 degrees in elevation angle, Miya believed naturally that the noise came directly from the sun. However, his senior Nakagami was too cautious to accept the young Miya's simple idea, and imagined that the noise originated around the E-layer, connected with a Dellinger disturbance of the atmosphere. In the end, the possibility of direct noise from the Sun was not mentioned in their paper. (Tanaka, 1984: 336-337).

Dr Kenichi Miya, who provided Tanaka with this account, subsequently became the President of the International Telecommunications Installation Co. Ltd., and made many research contributions in the fields of radio waves and satellite communications. At one time he was the President of the International Satellite Communications Society (ISCS), and he was involved in ionospheric research during the International Geophysical Year. In honor of his many achievements, he received the IEEE Award in International Communications in 1987. He died in 2004 at the age of 89 (see Smith, 2004).

Finally, it is of interest to note that although these pre-War Japanese observations were carried out in isolation, 'ham radio operators' in England and a number of other countries also recorded anomalous noise during the 1930s (e.g. see Ham, 1975). While some of them also assumed that the noise was of solar origin, they were unable to take the vital step and attribute it directly to radio emission from the Sun (for an excellent overview see Sullivan, 2009:

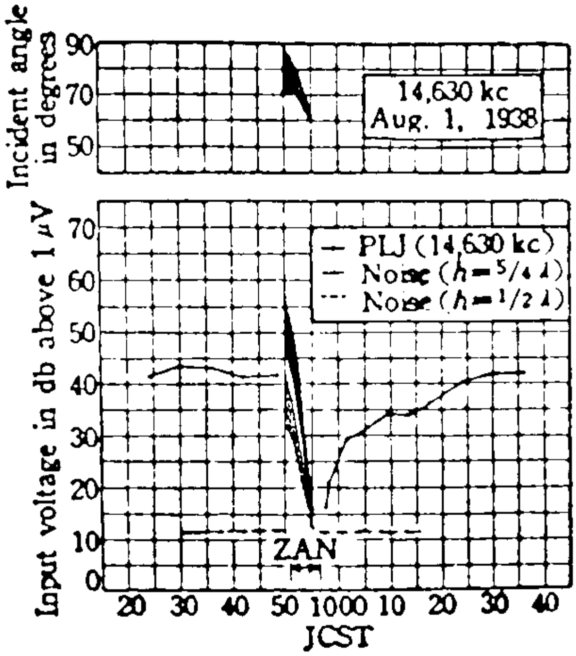

Figure 4: Observations conducted on 1 August 1938 showing (lower) the fade-out of the telecommunications signal (ZAN), and (upper) a simultaneous increase in noise received by the two antennas, which we can now associate with solar radio emission (after Nakagami and Miya, 1939: 176).

85-89). Sullivan (2005: 89) appropriately refers to the Nakagami and Miya episode as "Another near-miss …"

4 EARLY DEVELOPMENTS IN JAPANESE SOLAR RADIO ASTRONOMY: AN OVERVIEW

4.1 Koichi Shimoda and the Solar Eclipse of 1948

Tanaka (1984) claims that Japanese solar radio astronomy began in 1949, but he was not aware of an earlier investigation which was conducted by Koichi Shimoda (1919–; Figure 5) in 1948. Nor does this investigation feature in Sullivan's (2009) encyclopaedic history of early radio astronomy.

Figure 5: Dr Koichi Shimoda, Japan's first radio astronomer (osahistory.org).

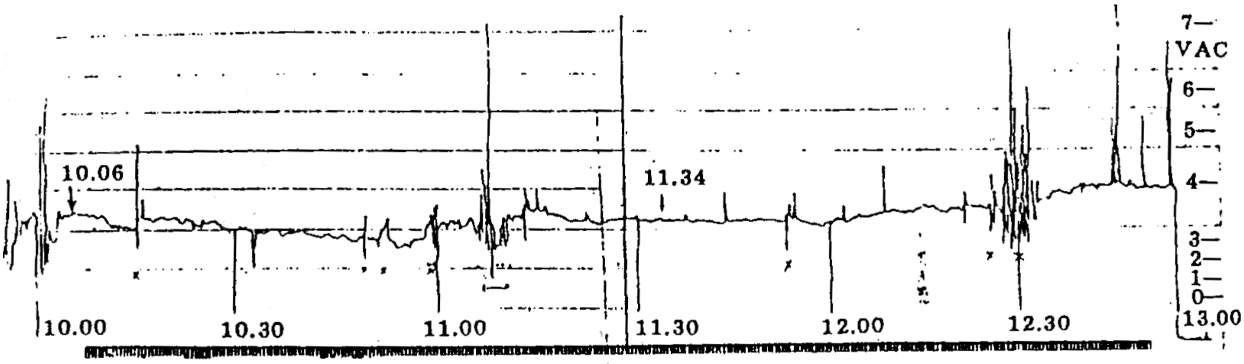

Figure 6: A copy of the oscilloscope display during the 3000 MHz observations of the 9 May 1948 partial solar eclipse, as observed from Tokyo. This little-known pioneering observation marked the start of Japan's early radio astronomy program (after Shimoda, 1982: 33).

The foundations for Shimoda's 1948 experiment can be traced back to 1930 when two 2-m parabolic reflectors were manufactured for the Aeronautical Research Institute (ARI) at the University of Tokyo (Shimoda, 1982). Following WWII the Institute of Science and Technology was established in 1947 to replace the ARI, and after completing his graduate studies in physics at the University of Tokyo (Figure 1) Koichi Shimoda began research at the Institute. He then discovered one of the two 2-m antennas among the relics of the ARI, and promptly installed a micro-wave feed at the focus and attached the dish to a 3 GHz radar receiver and observed the partial solar eclipse of 9 May 1948 (see Figure 6). This was the first radio astronomical experiment made in Japan, and it and subsequent Japanese and overseas observations of solar eclipses will be the focus of the next paper in this series on early Japanese radio astronomy.

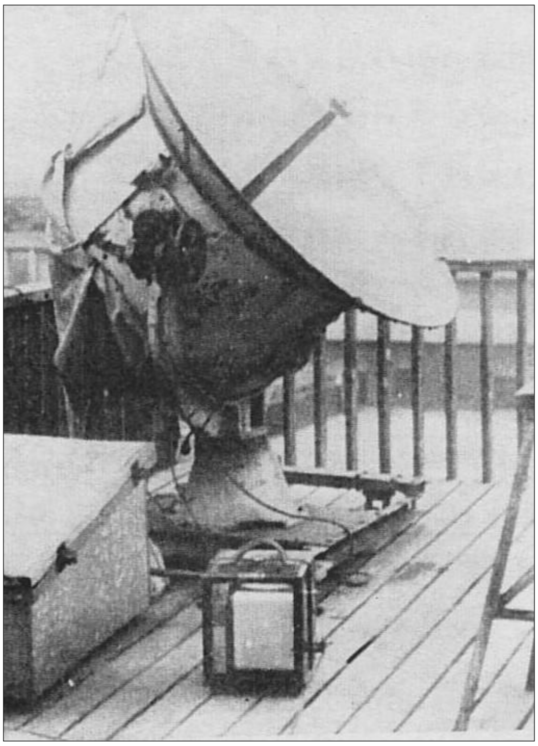

Figure 7: A photograph taken after the move to Osaka City University, showing the refurbished radio telescope which now features a solid-surface parabolic reflector in place of the horn. This instrument was used to monitor solar radio emission from April 1950 to July 1951 (after Takakura, 1985: 163).

As it turned out, Shimoda's antenna was just beginning its career in radio astronomy, for in 1951 it was transferred to the Tokyo Astronomical Observatory by Kenji Akabane and went on to do good service in the name of Japanese solar radio astronomy Shimoda, 1982).

4.2 Observations by Oda and Takakura in Osaka

After Shimoda's exploits, the next experiment in Japanese radio astronomy occurred in November 1949 when Minoru Oda (1923–2001) and Tatsuo Takakura (1925–) from the Physics Department at Osaka University (see Figure 1) observed solar noise at 3300 MHz using a hand-made metallic horn on a searchlight mounting (Tanaka, 1984). They then moved to Osaka City University, where the horn was replaced by a small parabolic dish (see Figure 7). From April 1950 Oda and Takakura (1951) used this radio telescope to monitor solar radio emission during the next 15 months.

4.3 The Solar Radio Astronomy Group at the Tokyo Astronomical Observatory

Radio astronomy began at Tokyo Astronomical Observatory (henceforth TAO) at Mitaka, Tokyo (Figure 1), in September 1949 under Professor Takeo Hatanaka (1914–1963), who was assisted by Fumio Moriyama (b. 1927) and Shigemasa Suzuki (1920–2012). They received strong support from the Director of the Observatory, Professor Yūsuke Hagihara (1897–1979), who realised the potential of this new line of research. Most of these individuals are shown in the 1954 photograph reproduced here as Figure 8.

The first radio telescope at the TAO was a 5 m × 2.5 m broadside array that operated at 200 MHz and was installed in 1949 (see Figure 9). Soon 60 and 100 MHz Yagi antennas were erected, and multi-wavelength observations of solar bursts began. This program was expanded in 1952 when a 100-140 MHz spectrometer became operational, and at the same time the radio telescope that Shimoda had used during the 1948 eclipse was set up at Mitaka for observations at 3000 MHz.

The collection of instruments was expanded further in 1953 with the completion of two more rhombic antennas (thereby allowing solar spectral observations from 200 to around 700 MHz), and with the erection of a 10-m equatorially-mounted parabolic dish that could operate at both 200 and 3000 MHz.

Figure 8: Meeting of the Japanese National Commission V of URSI held at Toyokawa Observatory in 1954. Front row (left to right): Professor A. Kimpara (Director, Institute of Atmospheric Physics, Nagoya University) and Professor Y. Hagihara (Director, Tokyo Astronomical Observatory). Back row (left to right): H. Jindo (Toyokawa), K. Akabane (TAO), T. Takakura (TAO), T. Kakinuma (Toyokawa), H. Tanaka (Toyokawa), S. Suzuki (TAO) and T. Hatanaka (TAO) (after Tanaka, 1984: 345). The only other Japanese radio astronomers active at this time, but missing from the photograph, were F. Moriyama (TAO) and T. Takahashi (Hiraiso) (after Tanaka, 1984: 345).

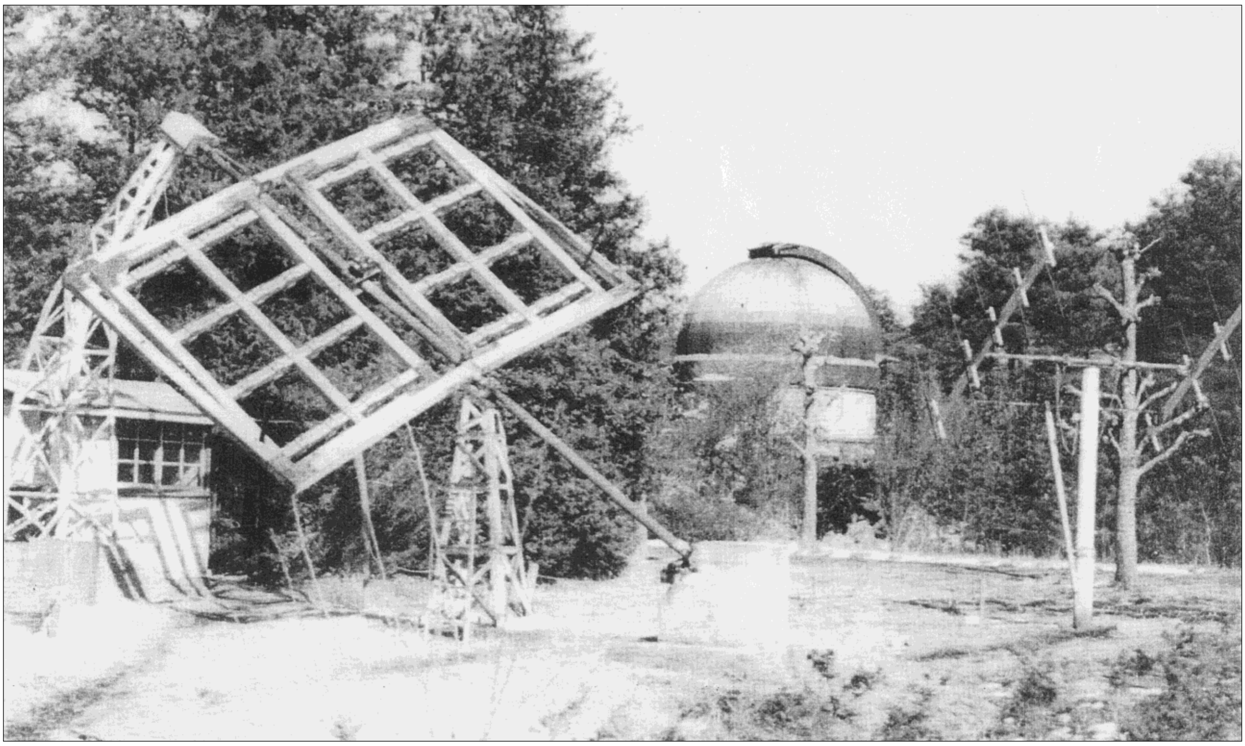

Figure 9: On the left is the broadside array that was the first radio telescope erected at the Tokyo Astronomical Observatory. From September 1949 it was used to monitor solar radio emission at 200 MHz. On the far right is a 2-element 60 MHz Yagi antenna that was installed in 1950 (courtesy: National Astronomical Observatory of Japan Archives).

At the time, this was the second-largest radio telescope of this type in the world. This dish is shown in Figure 10.

In 1954 Suzuki (1959) installed a four-element interferometer which was designed to investigate the positions of the sources of 200 MHz solar bursts. Fin-

Figure 10: The 10-m equatorially-mounted dish erected at the TAO in 1953, which was used to monitor solar radio emission at 200 and 3000 MHz (courtesy: National Astronomical Observatory of Japan Archives).

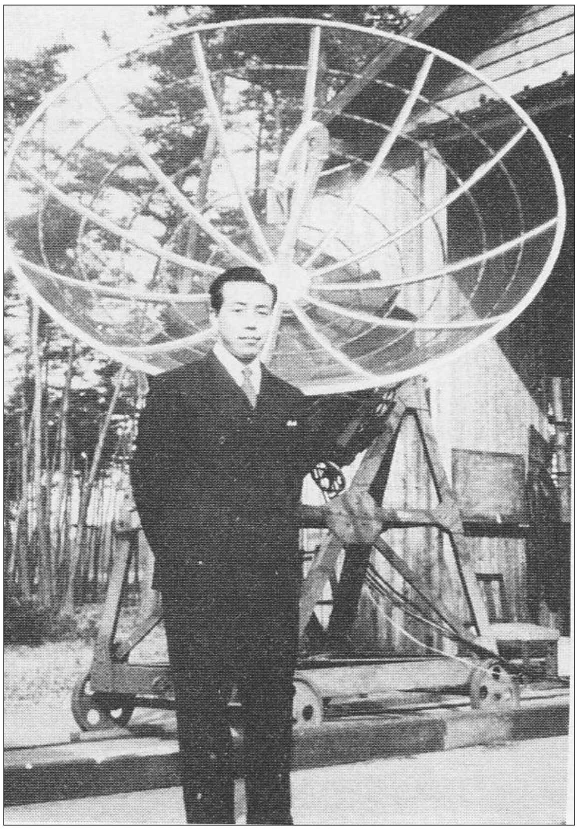

Figure 11: Haruo Tanaka and the first radio telescope installed at Toyokawa in April 1951. The parabola was 2.5 m in diameter and recorded solar emission at 3750 MHz (after Tanaka, 1984: 344).

ally, in 1957 a 1.2 m dish was erected to detect solar emission at 9500 MHz.

Most of these instruments were installed in a dedicated 'radio astronomy precinct' near the south-western boundary of the Observatory grounds, far from the main buildings and their associated electrical interference. After a short hiatus, further instruments were added from 1963 onwards.

The initial research at 200 MHz by the Tokyo Astronomical Observatory radio astronomers focussed on the relationship between solar bursts and sunspots and calcium plages (Hatanaka, Akabane, Moriyama, Tanaka and Kakinuma, 1955) and the polarization of these bursts (e.g. see Hatanaka, Suzuki and Tsuchiya, 1955a; 1955b). With the construction of the Suzuki 4-element interferometer research turned to the positions and heights of the sources responsible for the 200 MHz bursts. Given access to this new instrumentation and the low-frequency spectrometers, from 1961 Kai and Morimoto began an investigation of specific types of solar bursts, with emphasis on the characteristics, polarization parameters and source heights of Type 1, Type III and Type IV bursts (Kai, 1962; 1963; 1965; Morimoto, 1961; Morimoto and Kai, 1961; Takakura and Kai, 1961; see, also, Tsuchiya, 1963). Meanwhile, observations conducted at 3000 and 9000 MHz centred on long-term variations in solar emission at these higher frequencies (Hatanaka and Moriyama, 1953), and included observations of a partial eclipse in 1955 which produced a model for the region assumed to be responsible for the emission (see Hatanaka, Akabane, Moriyama, Tanaka and Kakinuma, 1956). By 1960 about ten TAO staff were actively studying solar radio emission.

4.4 The Solar Radio Astronomy Group at the Toyokawa Observatory

The Research Institute of Atmospherics at Nagoya University was established in June 1949 under the Directorship of Professor A. Kimpara, and a radio astronomy field station was established at Toyokawa, a former naval arsenal and radio-quiet site 60 km south-east of Nagoya (see Figure 1). The plan was to observe the Sun at high frequencies in connection with the ionospheric disturbances that impact on radio communications and terrestrial radio noise.

At the end of 1949 H. Tanaka was appointed to lead a radio astronomy group, and nearly one and a half years later he was joined by T. Kakinuma. In 1951 the first Toyokawa radio telescope was completed. This was a 2.5 m dish connected to a 3750 MHz receiver (Figure 11) and operated as a total power radiometer.

Tanaka (1984: 339) describes what happened next:

> After the completion of our first radiometer at 3750 MHz, we designed a one-dimensional grating interferometer and applied for funds for construction in 1951. The frequency of the interferometer was 4000 MHz … The budget was partly approved in 1952, and the first 5-element interferometer was completed in March 1953 …

The dishes were 1.5 m in diameter (see Figure 12). The following year this interferometer was expanded to eight elements (Tanaka and Kakinuma, 1953b). It

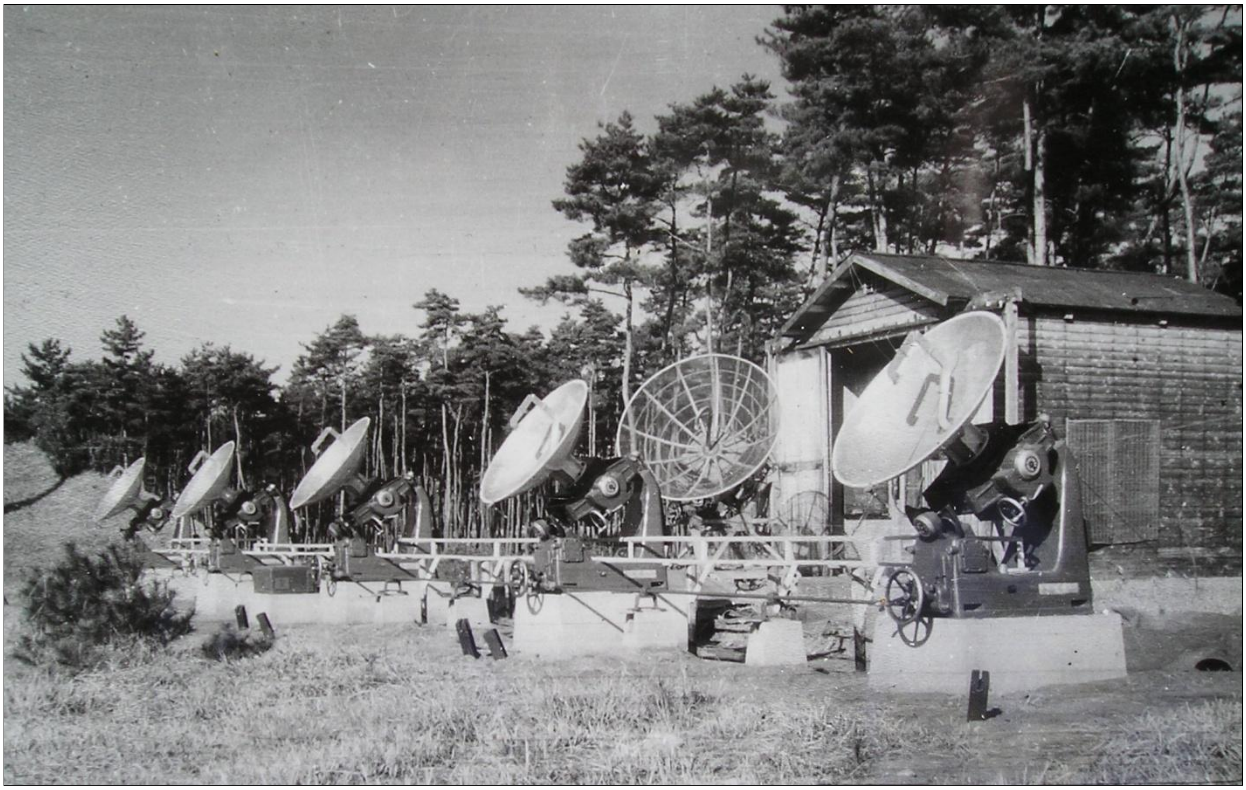

Figure 12: The 5-element E-W grating interferometer in 1953, with the original Toyokawa antenna in the background (courtesy: Tanaka Family).

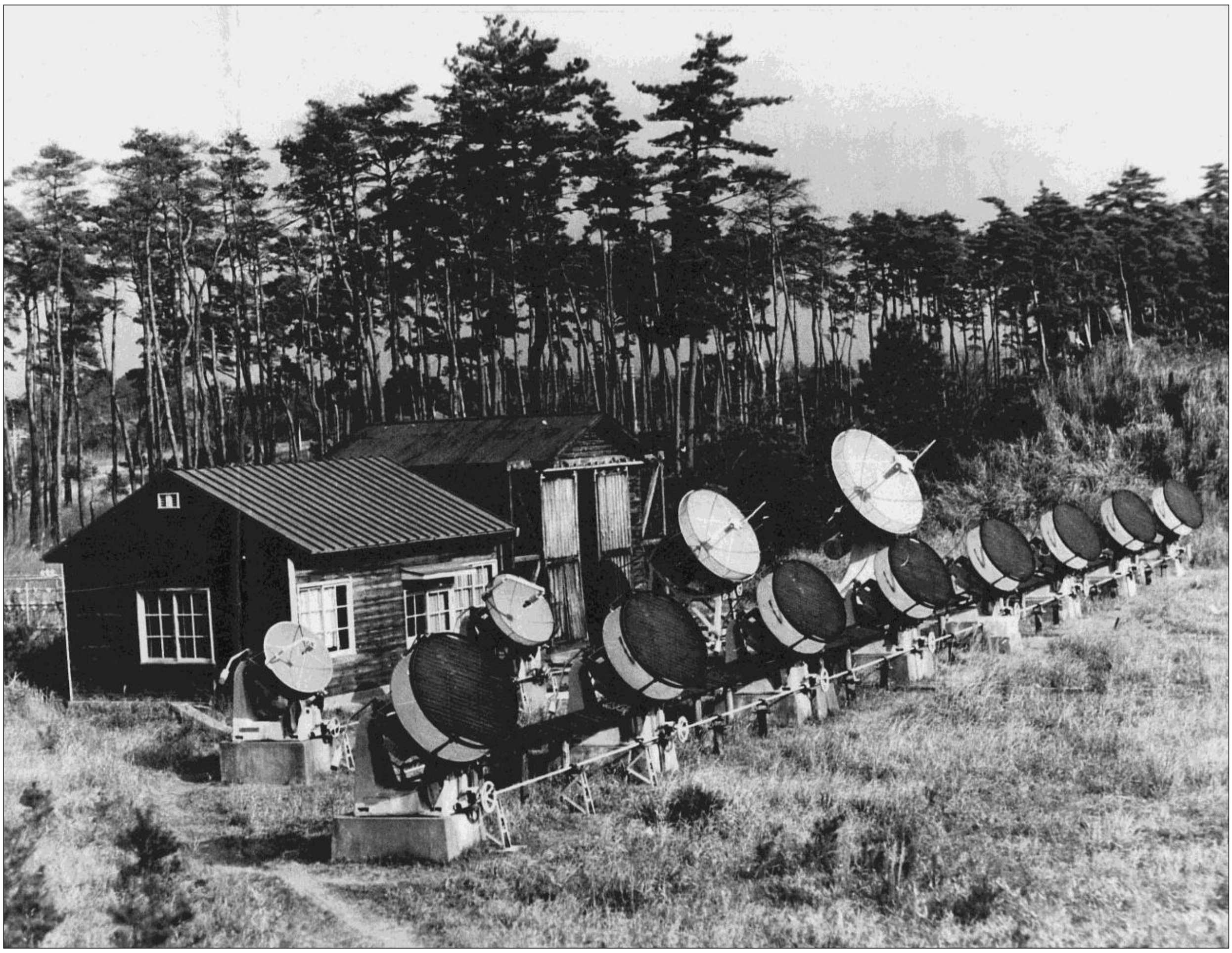

Figure 13: The expanded 8-element solar grating array, complete with polarisation screens, and behind it the four total power radiometers that monitored the Sun at 1000, 2000, 3750 and 9400 MHz (courtesy: Tanaka Family).

is important to remember (see Tanaka, 1984: 340) that this grating interferometer was planned and built quite independently of the one at Potts Hill in Sydney which was constructed by W.N. Christiansen at about the same time (see Wendt et al., 2008b). In 1954, polarization screens were added to the Toyokawa dishes (see Figure 13).

The next phase in the development of the Toyokawa Observatory involved the construction of three dishes with diameters of 3 m, 2.2 m and 1.2 m, which operated at 1000 MHz, 2000 MHz and 9400 MHz respectively (Tanaka and Kakinuma, 1956a). These were used as total power radiometers in conjunction with the original 2.5 m dish (which continued to record at 3750 MHz). These four radiometers are shown in Figure 12, behind the 8-element grating array.

The final phase in the development of the pre-1961 instrumentation at Toyokawa occurred in 1959 when another 8-element grating array was constructed, but this one utilized 1.2 m dishes and operated at 9400 MHz. During the 1960s, a two-dish antenna, another grating array, two compound interferometers and a radioheliograph were constructed.

The Toyokawa radio telescopes were used to study the characteristics of radio plages at 4000 and 9400 MHz (Kakinuma, 1956; Tanaka et al., 1956) and the intensity and polarization of bursts at these two frequencies and at 2000 and 1000 MHz (Kakinuma, 1958; Kakinuma and Tanaka, 1961; Tanaka and Kakinuma, 1956b; Tanaka and Kakinuma, 1962). Tanaka and Kakinuma (1958) also used multi-frequency observations of the partial annular solar eclipse of 19 April 1958 to examine the brightness distribution over the solar disk. International collaborative programs were also undertaken with Australian, Canadian, Indian and U.S. colleagues (e.g. see Christiansen et al., 1960; Kakinuma and Swarup, 1962; Swarup et al., 1963). By 1960 there were eleven staff members and a few students from the Faculty of Engineering at Nagoya University involved in radio astronomical research at Toyokawa.

4.5 The Solar Radio Astronomy Program of the Radio Research Laboratories, Ministry of Posts and Telecommunications

The Radio Research Laboratories of the Ministry of Posts and Telecommunications was interested in monitoring solar noise in connection with Japan's international telecommunications network (Obayashi, 1954), and maintained a field station at Hiraiso on the east coast of Japan about 150 km northeast of Tokyo (see Figure 1). In 1950 an experimental broadside array was installed, but in 1952 this was replaced by the new 200 MHz array shown in Figure 14, and regular solar monitoring began (see Takahashi et al., 1954).

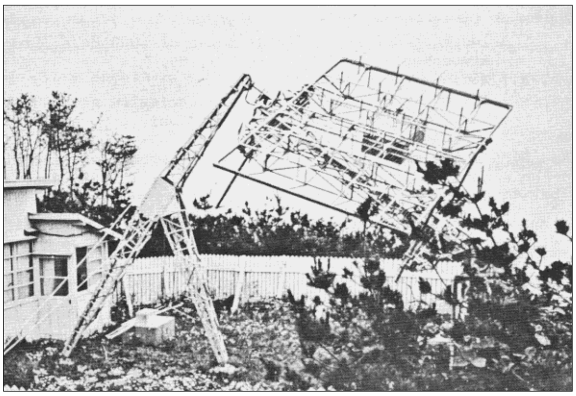

Figure 14: The broadside array at Hiraiso that was used to monitor 200 MHz solar emission from 1952 in connection with the overseas telecommunications network (after Tanaka, 1984: 347).

5 NON-SOLAR RADIO ASTRONOMY

Soon after beginning solar radio astronomy the Toyokawa group observed the background sky temperature at 3750 MHz in a bid to calibrate solar flux density at that frequency. They obtained a result of 0-5 K, which was reported in Tanaka et al. (1951), but only the abstract was written in English. Two years later a full English-language version was published (Tanaka and Kakinuma, 1953a), fourteen years before Penzias and Wilson reported the discovery of the 3 K cosmic microwave background.

Non-solar radio astronomy in Japan only began in earnest in 1963 when a 24-m spherical transit dish was erected by Kenji Akabane at the TAO and serious research began on 1420 MHz H-line emission. Then three years later (in 1966) a 10-m altazimuth-mounted parabolic antenna was erected at Toyokawa so that the Nagoya University radio astronomers could launch a serious non-solar research program.

6 DISCUSSION

6.1 Japanese WWII Radar and the Possibility of the War-time Detection of Solar Radio Emission

One of the remarkable features of WWII was the independent discovery of solar radio emission by radar operators in Norway (Schott, 1947), England (Hey, 1946), Australia (see Orchiston and Slee, 2002; Orchiston, Slee and Burman, 2006) and New Zealand (Alexander, 1946; see Orchiston, 2005). In addition, Grote Reber (1944) also detected solar radio emission at this time in the course of his study of galactic radiation (see Sullivan, 2009). All of these war-time detections were made at meter-wavelengths, but Southworth (1945) was also successful in detecting solar radio emission at cm wavelengths.

Since the radar detections in Norway, Britain, Australia and New Zealand were at first mistaken for interference or some ingenious jamming mechanism developed by the enemy, the question arises as to whether solar radio emission was ever recorded by Japanese WWII radar operators. To our knowledge, there are no published accounts of this occurring, but since reasonable numbers of metre-wave land-based radars were operated by the Imperial Japanese Army and the Imperial Japanese Navy around the coasts of Japan during the latter stages of the War (Nakagawa, 1997; Nakajima, 1988) and potentially these were capable of solar detections, a systematic examination of Japanese war-time radar records is justified. The Sun was active at this time, so we estimate that the prospects of a successful search are reasonably high. The Imperial Japanese Navy also maintained reasonable numbers of microwave radars (see Wilkinson, 1946), and in light of Southworth's detections, their records also deserve to be scrutinized.

6.2 Instrumentation: The Original Idea of the Solar Grating Interferometer

In the course of their solar observations at the Osaka City University, Oda's group developed the concept of a grating interferometer that would operate at 4000 MHz and would be used to identify the locations of the sources responsible for the solar noise. The interferometer would consist of 25 circular horns each 50-cm in diameter arranged in the configuration illustrated in Figure 15. While this interesting concept was presented at the annual assembly of the Physical Society of Japan in 1950 (see Ojio et al., 1950), it was never acted on. Had it been, then Japan rather than Australia would have hosted the world's first solar grating array. However, Tanaka was inspired by this idea, which led him to construct the grating interferometers at Toyokawa mentioned above in Section 4.4.

6.3 Early Japanese Radio Astronomy in International Context

It is notable that all of Japan's early (pre-1961) radio astronomical investigations focussed on the Sun, and even Tanaka and Kakinuma's measurement of what we would now term the 'cosmic microwave background' was motivated by solar observations. However, as Sullivan (2009: 225) has pointed out, this solar pre-occupation is easy to understand considering "Japan's long tradition of research on the ionosphere and radio communications …, [which was] natural for an island nation …" Note that the solar program at Hiriaso was linked to Japan's telecommunications efforts, and this was also the motivation for the early initiatives at Toyokawa (although this was soon to change).

Let us now focus on international solar radio astronomy. Table 1, which is adapted and developed from Stewart, 2009: 263-265 and Stewart, Wendt, Orchiston and Slee, 2011: 618-621, lists the most significant developments that occurred in instrumentation between 1948 and 1960. While it is apparent that Australia was at the forefront of solar radio astronomy during this period (e.g. see Sullivan, 2005; 2009; Orchiston and Slee, 2005; Stewart, Wendt, Orchiston and Slee, 2011), both France and Japan played very prominent roles.

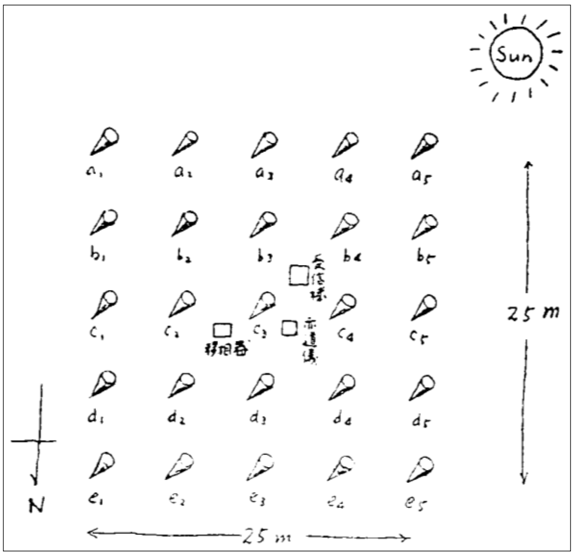

Figure 15: The solar grating array that was designed by Oda's group in 1950 but was never built (after Tanaka, 1984: 338).

The vibrant Solar Group in the CSIRO's Division of Radiophysics in Sydney was responsible for developing the world's first radio-spectrograph (1949), position interferometer (1949), solar grating array (1951) and crossed-grating interferometer (1957), but Japan was quick to follow: its first radio-spectrograph was installed at Mitaka in 1952; its first grating array was constructed at Toyokawa in 1953 (quite independently of the Australian initiative); and a position interferometer was operational at Mitaka by 1954. In each case, Japanese radio astronomers were the first, after their Australian colleagues, to construct these innovative types of radio telescopes and use them to investigate the nature of burst emission and the 'slowly-varying component'.

Table 1: Significant Developments in International Solar Radio Astronomy, 1949-1960. Japanese entries are shown in red print.

1948

- In Australia, solar observations at 18.3, 19.8, 60, 65 and 85 MHz using Yagi-Uda antennas were commenced at the Division of Radiophysics Hornsby Valley field station on the northern outskirts of Sydney (Payne-Scott, 1949; see also Goss and McGee, 2010).
- In Australia, solar observations at 24,000 MHz commenced at the Division of Radiophysics Headquarters in cental Sydney using a recycled WWII searchlight dish (Piddington and Minnett (1949).
- In Australia, solar observations at 200, 600 and 1200 MHz using a recycled experimental WWII radar antenna commenced at the Division of Radiophysics Georges Heights field station in suburban Sydney (Lehany and Yabsley, 1948; see also Orchiston, 2004).
- In France, solar observations at 555 MHz using 7.5-m Würzburg antennas began at Meudon (Laffineur and Houtgast, 1949); they were extended to 255 MHz in 1949 (Laffineur, 1954; see also Orchiston et al., 2007).
- In the Netherlands, solar monitoring at 75 MHz with a corner reflector and at 140 and 200 MHz with a 7.5-m Würzburg antenna began at three sites; extended in 1951 to a world-wide network for the study of solar effects on the ionosphere (de Voogt, 1952; see also Strom, 2005).
- In the New Zealand, solar monitoring at 100 MHz with a twin Yagi-Uda antenna at Auckland University College leads to the world's first graduate thesis on solar radio astronomy (Maxwell, 1948; see also Orchiston, 2005a).

1949

- In Australia, the world's first radio-spectrograph operating at 70-140 MHz was constructed at the Division of Radiophysics Penrith field station, in Sydney. Observations led to the classification of Type I, II and III bursts (Wild and McCready, 1950; see also Stewart et al., 2010).

• In Australia, the world's first swept-lobe interferometer was installed at the Division of Radiophysics Potts Hill field station in Sydney, Australia, to measure source positions and polarizations of solar bursts at 97 MHz (Little and Payne-Scott, 1951; see also Wendt et al., 2011).
• In Japan, solar monitoring with a 200 MHz broadside array commenced at the Tokyo Astronomical Observatory, Mitaka (Tanaka, 1984; see also Ishiguro and Orchiston, 2013).
• In Japan, solar monitoring at 3,300 MHz using a horn mounted on a recycled searchlight mounting commenced at Osaka University; the horn was replaced by a 1-m dish in 1950 at Osaka City University (Oda and Takakura, 1951; see also Ishiguro and Orchiston, 2013).
• In Russia, metre wavelength studies of the Sun were begun by FIAN in the Crimea (Chikhachev, 1950; Salomonovich, 1984).

1950
• In Japan, solar monitoring with 60 and 100 MHz Yagi-Uda antennas commenced at the Tokyo Astronomical Observatory, Mitaka (Tanaka, 1984; see also Ishiguro and Orchiston, 2013).

1951
• In Australia, the world's first solar grating array was installed at the Division of Radiophysics Potts Hill field station to investigate the one-dimensional distribution of radio brightness across the solar disk at 1420 MHz. This consisted of 32 x 1.7 m antennas on a 213 m east-west baseline; a north-south array was added in 1953 (Christiansen, 1953; Christiansen and Warburton, 1955; see also Wendt et al., 2008b).
• In Canada, 2,800 MHz strip-scans of the Sun commenced at Goth Hill using a slotted waveguide array (Covington and Broten, 1954).
• In Japan, solar monitoring at 3,750 MHz using a 2.5-m dish commenced at Nagoya University's Toyokawa Observatory (Tanaka, 1984; see also Ishiguro and Orchiston, 2013).

1952
• In Australia, a new radio-spectrograph operating at 40-240 MHz was installed at the Division of Radiophysics Dapto field station to the south of Sydney, Australia. This led to the first detection of harmonic structure in Type II and III bursts (Wild, Murray, and Rowe, 1954; Wild, Roberts and Murray, 1954; see also Stewart, Orchiston and Slee., 2011).
• In Japan, a 100-140 MHz radio-spectrograph was installed at Mitaka for research on solar bursts; in 1953 this was joined by a 200-700 MHz radio-spectrograph (Tanaka, 1984; see also Ishiguro and Orchiston, 2013).

1953
• In Japan, a 10-m diameter equatorially-mounted dish was erected at Mitaka and used for solar monitoring at 2000 and 3000 MHz (Tanaka, 1984; see also Ishiguro and Orchiston, 2013).
• In Japan, a 4,000 MHz 5-element grating interferometer was constructed at the Toyokawa Observatory for one-dimensional solar mapping (Tanaka and Kakinuma, 1953b); this array was extended to 8 elements in 1954 (Tanaka, 1984; see also Ishiguro and Orchiston, 2013).

1954
• In Australia, the east-west grating array at the Division of Radiophysics Potts Hill field station was converted to 500 MHz and used to measure the one-dimensional distribution of radio brightness across the solar disk and evidence for limb-brightening (Swarup and Parthasarathy, R., 1955; see also Wendt, Orchiston and Slee, 2008b).
• In Japan, a 201 MHz four-element multi-phase interferometer was installed at Mitaka to measure the positions of the sources of solar bursts (Suzuki, 1959; see also Ishiguro and Orchiston, 2013).

1955
• In France, a two-element variable-baseline interferometer was set up at Nançay for synthesis mapping of solar active regions at 9350 MHz (Kundu, 1959; see also Orchiston et al., 2009).

1956
• In France, at Nançay, the 169 MHz Grande Interferometer consisting of 32 x 5 m antennas on a 1600 m east-west baseline began observations (Blum et al., 1957); a north-south arm was added in 1959 (see also Pick et al., 2011).
• In Canada, regular one-dimensional solar mapping began at 3,000 MHz using a compound interferometer at Goth Hill (Covington and Broten, 1957); in 1959 this was converted to a 4-element array (Covington, 1984).
• In Japan, three single-dish polarimeters were installed at 1,000, 2,000 and 9,400 MHz at the Toyokawa Observatory (Tanaka, and Kakinuma, 1956; see also Ishiguro and Orchiston, 2013).
• In the USA, Harvard University's radio-spectrograph at Fort Davis, Texas, began recording solar bursts over the 100-580 MHz band (Maxwell et al., 1958; this was extended to 25-580 MHz in 1959 and 2100-3900 MHz in 1960 (Thompson, 1961; see also Thompson, 2010).

1957
• In Australia, the world's first crossed-grating interferometer was installed at the Division of Radiophysics Fleurs field station to generate daily two-dimensional isophote maps of solar emission at 1423 MHz (Christiansen and Mathewson, 1958; see also Orchiston and Mathewson, 2009).
• In Australia, a swept-frequency interferometer operating at 40-70 MHz was installed at the Dapto field station to investigate the positions of the sources of solar bursts (Wild and Sheridan, 1958; see also Stewart et al., 2011).
• In France, one-dimensional solar mapping began at 9,350 MHz using a 16-element east-west array at Nançay (Pick and Steinberg, 1961; see also Pick et al., 2011).
• In the USA, the University of Michigan's 100-580 MHz radio-spectrograph began observing solar bursts (Haddock, 1958).
• In the USA, an east-west grating array constructed by the Department of Terrestrial Magnetism at the Carnegie Institute of Washington began observations at 340 MHz and 87 MHz (Firor, 1959, Kundu and Firor, 1961).

1958
• In Australia, the Dapto radio-spectrograph was extended to 25-210 MHz (Sheridan et al., 1959).

• In Russia, 35,000 MHz solar observations began at Puschino (Salomonovich, 1984).

1959

• In the Netherlands, a 254 MHz interferometer and a 200 MHz polarimeter at NERA were used to study noise storms (Fokker, 1960; Cohen and Fokker, 1959).
• In Japan, an 8-element grating array operating at 9400 MHz was installed at the Toyokawa Observatory (Tanaka, 1984; see also Ishiguro and Orchiston, 2013).
• In Norway, a high-time and high-frequency resolution spectrograph operating over the 140-170 MHz and 310-340 MHz bands was installed by the University of Oslo (Elgaroy, 1961).
• In the USA, a radio-spectrograph operating at 500-900 MHz began observations at Owens Valley (Young et al., 1961)
• In the USA, a 15-38 MHz radio-spectrograph and two-element interferometers operating at 18 and 38 MHz set up at the High Altitude Observatory, University of Colorado, were used to study Type I noise storms and Type III bursts (Boischot, and Warwick, 1959).

1960

• In Australia, the Dapto radio-spectrograph was extended to 15-210 MHz (Sheridan and Trent, 1960).
• In the USA, solar mapping began at 3,260 MHz using the Stanford University compound interferometer crossed array (Bracewell and Swarup, 1961; see also Bracewell, 2005).

By the end of the 1950s, less than two decades after the full-frontal attack on solar radio astronomy mounted by Australia and Canada immediately following WWII, other nations had joined the challenge, and apart from the French and Japanese efforts notable contributions were being made by the Netherlands, Norway, Russia and the USA (see Sullivan, 2009). Japanese solar radio astronomers were in good company, and their research was highly valued. The fact that they generally published in English (unlike their French colleagues) was one of the reasons for this. As a result, their research results were widely available to the international solar radio astronomy community.

While Japan may have made an important international contribution to solar radio astronomy in the decade and a half following WWII, what is puzzling is that there was no attempt at this time to observe ‘radio stars’. These discrete localized sources of intense radio emission were reported in the international literature by British and Australian radio astronomers and “… long remained the most mysterious and hotly-debated [objects] in astronomy.” (Sullivan, 2009: 101). Cygnus-A, the first radio star, was announced in *Nature* by J. Stanley Hey, S. John Parsons and James W. Phillips in 1946, and by 1950 when three Japanese groups were actively involved in radio astronomy, the number of confirmed discrete sources had grown to seven (see Sullivan, 2009: Table 14.1 on page 316), and Sydney-based John Bolton, Gordon Stanley and Bruce Slee (1949) had correlated three of them with distinctive galactic and extragalactic optical objects, namely the Crab Nebula (Taurus-A), Messier 87 (Virgo-A) and NGC 5128 (Centaurus-A). Two of these identified sources, and Cygnus-A, were ideally located in the northern sky and the Japanese certainly had the requisite instrumentation to join in the investigation of these enigmatic objects but chose not to, and even when the steerable 10-m dish was erected at the NAO in 1953 its very obvious non-solar potential was all but ignored.

6.4 Early Japanese Radio Astronomy in the Context of the Development of Optical Astronomy in Japan Between 1930 and 1960

In other parts of the world, following an initial period of caution, even mistrust, of radio astronomers by optical astronomers (e.g. see Jarrell, 2005; Sullivan, 2009), at a national level the growth of radio astronomy and astrophysics often went hand-in-hand. In Japan, however, the emergence of radio astronomy appears to have occurred in comparative isolation, with little if any inspiration from developments that were occurring in Japanese optical astronomy at the time, as the following review indicates.

The development of twentieth century optical astronomy in Japan is discussed by Nakamura (2008; 2013) and his colleagues (Nakamura et al., 2008) and by Tajima (2011), and it is significant that although the Tokyo Astronomical Observatory (TAO) completed its move to the dark-sky Mitaka site on the outskirts of Tokyo in the mid-1920s and acquired a 65-cm Zeiss refractor with a 38-cm guide scope in 1929, there was little effort to redirect Japan from classical astronomy to astrophysics at this time. Nakamura (2013) explains why:

> In spite of astronomers’ expectations for this first large telescope, this telescope thereafter did not bring about any conspicuous scientific outcomes. The reasons for the failure are considered to be due to the large chromatic aberration of the objective lens of the telescope, and the world trend in astrophysical studies [by this time] had already shifted to using 1m-class reflectors; a refractor as small as 65cm in diameter obviously was insufficient for up-to-date astrophysical observations.

Nevertheless, in 1939 Sekiguchi et al. published a short paper on the spectra of 30 A-B stars obtained using the Zeiss telescope in order “… to make a quantitative analysis of their hydrogen absorption lines …” (ibid.), but in the overall context of Japanese optical astronomy these were to remain isolated and anachronistic astrophysical observations until the advent of the Okayama Astrophysical Observatory (OAO; see Figure 1) in 1960—at the very end of the period under review.

Yet the origin of the OAO can be traced back to the immediate post-WWII period when Japanese radio astronomy also was experiencing its first awakening. In 1948 Yusake Hagihara, the Director,

> … reorganized the TAO, creating new posts for researchers and introducing a series of new research divisions … Japanese astronomers wanted to embark on front-line astrophysical studies of stars and galaxies, but they had no telescope which was capable of

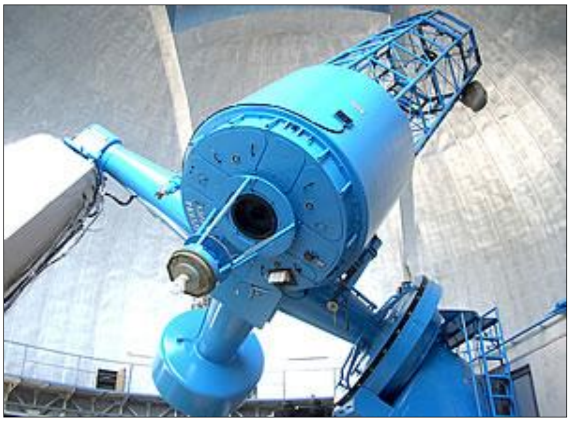

Figure 16: The 1.88-m Grubb Reflecting Telescope at the Okayama Astrophysical Observatory (after (Tajima, 2011: 220).

carrying out detailed spectroscopic investigations of such objects. (Tajima, 2011: 218-219).

With support from the Science Council of Japan the TAO started lobbying for a large telescope, which ultimately resulted in the acquisition of a 74-in (1.88-m) Grubb reflector (Figure 16). When the OAO opened in 1960 Japanese astronomers finally had access to a locally-based telescope designed for astrophysical research, and "A whole new generation of astronomers and technicians was trained through the operation of the OAO, which greatly enhanced the growth of the community of Japanese optical astronomers." (Tajima, 2011: 220).

While the rapid early development of radio astronomy in Japan did not foster galactic and extragalactic astrophysical research, the story was more promising for solar astronomy, but only after an abortive start. In 1922 Einstein visited Japan, and this possibly sparked the concept of constructing an Einstein Tower[3] at the TAO modelled on the original one at the Potsdam Astrophysical Observatory in Germany. Japan's Einstein Tower (Figure 17) was completed in 1930, but it was only in the post-WWII era that it began to contribute to solar physics (Nakamura, et al., 2008). However, optical solar astronomy in Japan really came of age with the advent of the Norikura Solar Observatory (NSO; see Figure 1):

> From its foundation in 1949, observations using its 10 cm and 25 cm aperture coronagraphs were conducted continuously until it was closed in March 2010 … this observatory played an important role in the development of solar astronomy in Japan … (Tajima, 2011: 217).

The NSO was an outstation of the TAO, and perhaps the fact that about half of Japan's early radio astronomers also were employed by the TAO might explain their overwhelming preoccupation with solar radio astronomy, even if—initially—there was little research collaboration between the two groups.

Finally, we may conclude that through the combined efforts of the early Mitaka and Toyokawa solar radio astronomers Japan was able to dramatically increase its international visibility in solar physics at a time when most Japanese optical astronomers were struggling to break free from the long-entrenched shackles of classical astronomy in order to embrace the 'new astronomy', astrophysics

6.5 Heritage Issues: The Survival and Preservation of Japan's Early Radio Telescopes

One of the projects of the IAU Working Group on Historic Radio Astronomy is to compile a worldwide inventory of all surviving pre-1961 radio telescopes, and—where relevant—lobby for their preservation. It is a sad fact that none of the early Japanese radio telescopes described in this paper has survived, although a full-scale replica of the initial 200 MHz TAO broadside array, incorporating the original polar axis from Mitaka, has been erected at the Nobeyama Radio Observatory (Figure 1) and is accessible to visitors (see Figure 18).

A field examination of the original 'radio astronomy precinct' at Mitaka (Figure 19) in December 2011 failed to reveal any vestiges—even founda-

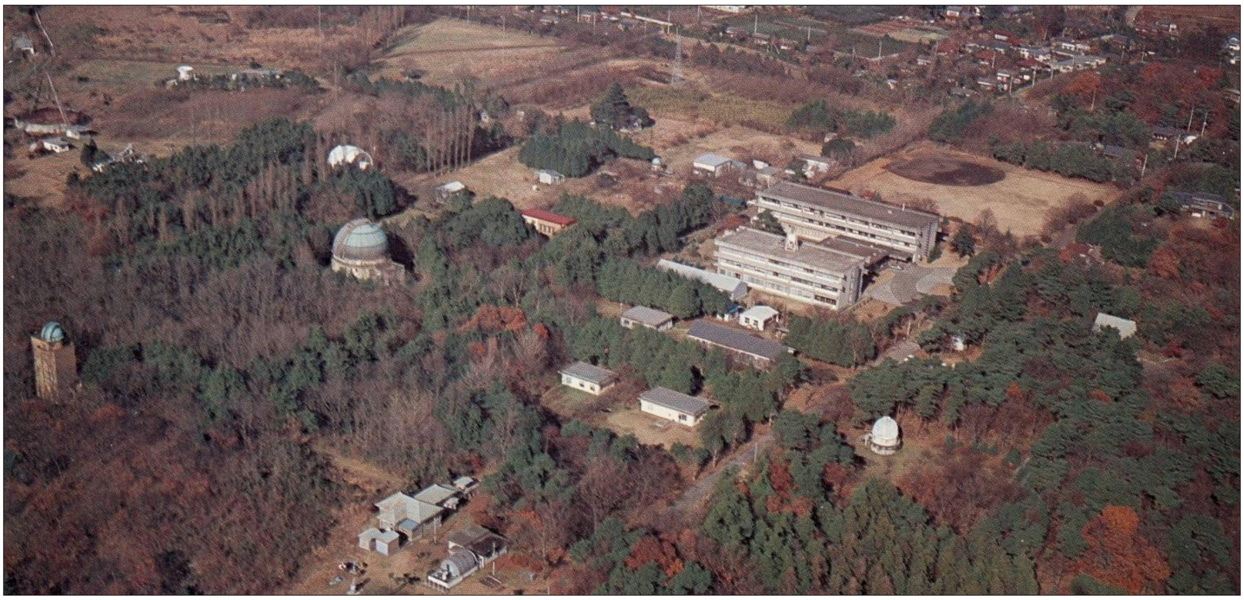

Figure 17: A later aerial view of the Mitaka precinct with the brown brick green-domed Einstein Tower on the extreme left of the image. Directly above it, just beyond the wooded area, is the radio astronomy precinct (courtesy: National Astronomical Observatory of Japan Archives).

Figure 18: A replica of the original TAO broadside array on display at the Nobeyama Radio Observatory. Only the polar axis is from the original radio telescope of 1949 (photograph: W. Orchiston).

tions—of the original instruments at this site, but early in 2012 an interpretative display panel was installed at the site of the 10m parabolic antenna (see Figure 20). As Japan's foremost radio astronomical institution it would be appropriate for the National Astronomical Observatory of Japan to develop this historic precinct further by erecting a full-scale replica of the 200 MHz broadside array, modelled on the one now on display at Nobeyama.

Likewise, a visit by the authors to the Toyokawa Observatory site in December 2010 failed to reveal remains from any of the antennas discussed in this paper, but just prior to the visit a number of rusting antennas belonging to a T-shaped solar grating array erected by the first author of this paper in the 1970s were discovered during a detailed examination of the area by Dr T. Watanabe. Two of these antennas are shown in Figure 21, surrounded by dense vegetation.

Apart from a number of buildings in varying stages of preservation (e.g. see Figure 22) and the rusting antennas of the T-array, the site of the Toyokawa Radio Observatory contains no other surviving evidence of its pivotal role in early Japanese radio astronomy. But what the site does contain is an amazing assemblage of tunnels, bunkers, earthworks and other field evidence that reflects its important military associations during the 1930s and through into WWII (see Figure 23). Now that the site is no longer required by the Nagoya University we hope that it will be developed as a heritage park where its important military and radio astronomical associations can be interpreted for the benefit of future generations. If such a program proves impossible to implement then we recommend that *all* of the surviving rusting antennas of the 1970s T-array be removed and relocated to the historic radio astronomy precinct at the National Astronomical Observatory of Japan in Mitaka.

7 CONCLUDING REMARKS

If we discount Nakagami and Miya's examination of the Dellinger Effect in 1938 we can conclude that Japanese radio astronomy began in 1948 when Shimoda observed the 9 May solar eclipse from the University of Tokyo. By the early 1950s, small groups at the Osaka City University, the Radio Research Laboratories at Hiraiso, the University of Nagoya (Toyokawa) and the Tokyo Astronomical Observatory (Mitaka) were actively involved in solar radio astronomy. Healthy competition between the two largest groups, at Toyokawa and Mitaka, was very effective in promoting the development of radio astronomical research in Japan, and inspired the construction of an impressive range of instruments designed to investigate solar radio emission between 60 MHz and 9000 MHz. Eventually this culminated in the merger of the two groups and the construction of the Nobeyama Radioheliograph. In this way, Japan was able to play an important part in the early development of international solar radio astronomy, but the value of its overall contribution was even more significant if we allow for the pivotal role that the Yagi-Uda antenna played in the early development of both solar and non-solar radio astronomy world-wide.

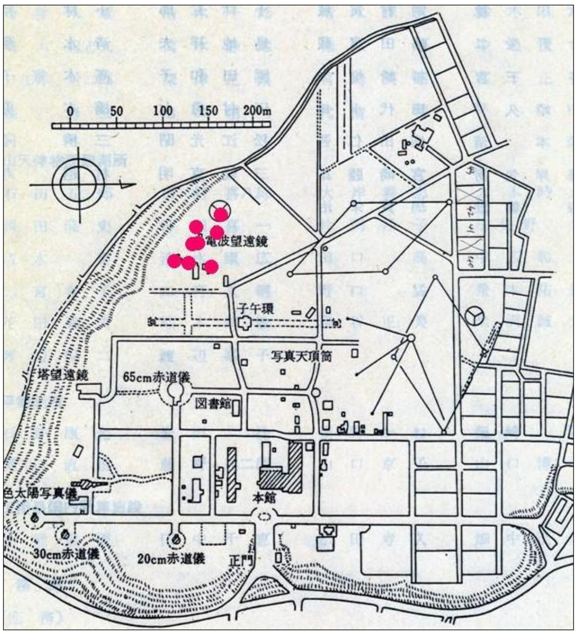

Figure 19: Map of the TAO grounds showing the Main Building and Library wing (the hatched buildings on the eastern side of the site, near the entrance gate) and to the west of them the radio astronomy precinct, where the various red dots mark the positions of different radio telescopes. The largest and most westerly of these was the 24m transit antenna (courtesy: National Astronomical Observatory of Japan Archives).

Figure 20: A recent photograph showing the interpretative panel installed at the site of the 10-m parabolic antenna at Mitaka (courtesy: NAOJ).

Figure 21: Two of the surviving antennas of a T-shaped array erected in the 1970s, discovered overgrown by dense vegetation just prior to a visit to the Toyokawa Observatory site by the first two authors of this paper in November 2010 (photograph: W. Orchiston).

Figure 22: A photograph of the main research building at the Toyokawa Observatory site taken in November 2010. This majestic building is now no longer used by the University of Nagoya and is now surplus to requirements, but is still in sound condition and could easily be utilised in any future development of the site as a heritage precinct (photograph: Wayne Orchiston).

Figure 22: One of the tunnels and bunkers which reflects the original military role of the site, photographed in November 2010. Some of these bunkers were used to house the radio telescope receiving equipment (photograph: Masato Ishiguro).

Initially solar research was the mainstay of Japan's early involvement in radio astronomy, but with the passage of time the fledgling non-solar radio astronomy community grew rapidly and its efforts finally crystallised in the construction of the Nobeyama Millimeter Array, the 45-m Radio Telescope at Nobeyama and eventually the Atacama Large Millimeter/ submillimeter Array (ALMA). Japan is now seen as a leading international contributor to solar and non-solar radio astronomical research.

8 NOTES

1. This ambitious international project is conducted under the auspices of the IAU Working Group on Historic Radio Astronomy, and follows the succession completion of a similar project that documented early French radio astronomy through a series of seven papers that were published in this journal between 2007 and 2011.
2. Parts of this first paper in the series on early Japanese radio astronomy draw heavily on the review paper by Ishiguro and Orchiston (2013) that was prepared recently for the book *The History of Astronomy and Development of Astrophysics in Asia* which will be published by Springer in 2013.
3. The original 'Einstein Tower' at the Potsdam Astrophysical Observatory was erected in 1924 to facilitate research on the solar spectrum (see Hentschel, 1997). Hermann Brück (2000: 123) describes this famous solar telescope:

> The instrument used two mirrors of a coelostat … to send the Sun's light vertically down on to a lens of 60-cm aperture and focal length 14.5 metres. The solar beam, turned into a horizontal direction by an auxiliary mirror, was then thrown into a large prism or gating spectrograph with a collimator of 12 metres focal length … The Einstein Tower was acclaimed as a truly modern and effective instrument which would lead to significant advances in the field of relativity theory and of solar physics in general.

While the Einstein Tower at the Tokyo Astronomical Observatory was inspired by the Potsdam prototype, its rather rustic building lacks the architectural charm of its German counterpart.

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