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THE HISTORY OF EARLY LOW FREQUENCY RADIO ASTRONOMY IN AUSTRALIA. 8: GROTE REBER AND THE 'SQUARE KILOMETRE ARRAY' NEAR BOTHWELL, TASMANIA, IN THE 1960s AND 1970s

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Abstract: In the 1960s, Grote Reber (1911–2002) established and used an antenna array near Bothwell in Tasmania. Working independently, he produced a radio map of the southern sky at a frequency of 2.085 MHz (a wavelength of 144 metres). Encouraged by this success, he modified the array in the 1970s to work at ~1.155 MHz, but this second endeavour failed to produce any usable results.

Keywords: Radio astronomy, Tasmania, Reber, Bothwell, low frequency arrays

1 INTRODUCTION

Even prior to 1960, it was clear that radio astronomy at frequencies below 20 MHz was well worthwhile. Several researchers in this field, particularly in Australia, had produced results (see, e.g., Higgins and Shain, 1954; Shain, 1951; Shain and Higgins, 1954; cf. Orchiston et al., 2015a, 2015b). Beginning in 1946, the CSIR (later CSIRO) Division of Radiophysics maintained many field stations, mostly in the Sydney area (see, e.g., Orchiston and Slee, 2017; Robertson, 1992).

However, radio astronomy at low frequencies is hampered considerably by the absorption of radio waves by the Earth's ionosphere. A frequency of 10 MHz is often taken to be the lowest at which observations can normally be made, but under ideal conditions it is possible to detect celestial radiation down to about 1–2 MHz. Winter nights around the time of solar minimum offer the best conditions, because of the lower degree of ionisation of the ionosphere. However, the ease of observation at the lowest of these frequencies depends on the location on Earth from which the observations are made. In general, the lowest values of the critical frequency foF2 occur at locations that are sufficiently distant from both the geographic equator and the magnetic poles. Studies of ionospheric conditions in various parts of the world (see, e.g., Reber, 1982) showed that two important locations are north eastern North America (in the vicinity of the Great Lakes), and the island of Tasmania immediately to the south of the Australian mainland.

Several years after Karl Jansky's discovery of radio emissions from the Galaxy, Grote Reber (1911–2002) constructed the world's first purpose-built radio telescope in Wheaton, Illinois. He made a radio map of the sky at 160 MHz, and the resulting papers (Reber, 1940; 1944) became classic papers in radio astronomy (see Sullivan, 1982), largely setting the scene for future research at around this frequency.

Reber arrived in Tasmania in late 1954 and was involved in two major endeavours in low-frequency radio astronomy in the course of that decade. The first was at Cambridge, near Hobart, in collaboration with Graeme Ellis (Reber and Ellis 1956; George et al., 2015a). The second was a four-dipole array that he set up at Johnson Valley near Kempton, 50 kilometres by road to the north of Hobart, in an attempt to detect radiation at 0.52 MHz (Reber, 1958a; George et al., 2015b).

Thoughts of returning to Tasmania from the USA in order to carry out further low frequency research clearly were on Reber's mind following the Kempton work. Indeed, he even considered returning to the same valley in which he carried out his 1956–1957 observations. Thus, in May 1958 he wrote:

> I expect to find my way back to the land of the Southern Cross in the autumn of 1960 and string up my wires again at Johnson Valley. (Reber, 1958b).

In late 1959, Reber made a brief trip to Macquarie Island, part of Tasmania but well to the south of the main island, where he considered the possibility of setting up a low-frequency array,

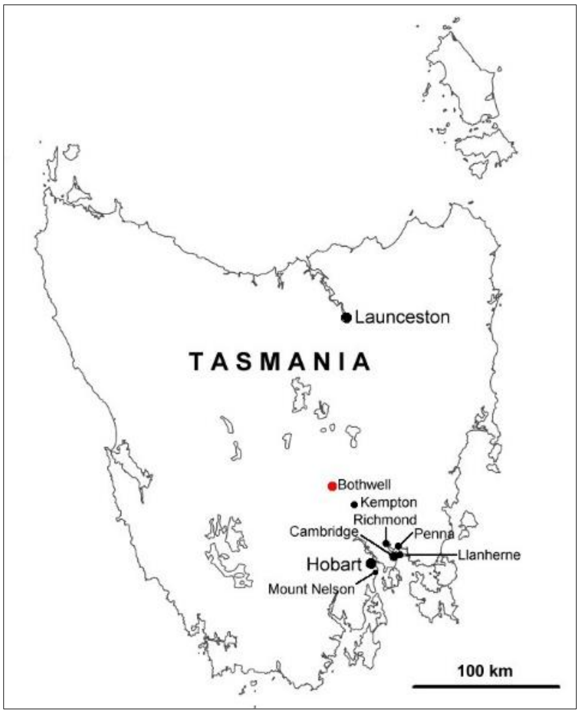

Figure 1: Key radio astronomy sites in Tasmania. This paper discusses Grote Reber's radio astronomy array near Bothwell, in southern central Tasmania, about 67 kilometres north-northwest of Hobart (map: Martin George)..

as well as making further observations from Kempton (Reber, 1960a).

However, his main location of interest was on the Tasmanian mainland, and from 1960 he embarked on a major project to map the low-frequency southern-hemisphere sky, not from Kempton, but from Dennistoun, a property seven kilometres from the town of Bothwell. The project was essentially in two parts: observations were made at a frequency of 2.085 MHz during the 1960s, and further observations were attempted at ~1.155 MHz in the mid-1970s. Although the earlier observations were successful in producing a radio map of the sky, the 1970s observations failed to produce useful results.

This paper describes Reber's research at Dennistoun, near Bothwell, undertaken in two distinct phases over a decade and a half between 1960 and 1976. Figure 1 shows the location of Bothwell and other key radio astronomy sites in Tasmania.

Figure 2: Grote Reber at Dennistoun in 1985 (photograph: Peter Robertson).

2 BIOGRAPHICAL NOTE: GROTE REBER

In 1937 Grote Reber (1911–2002; Figure 2) constructed the world's first purpose-built radio telescope at Wheaton, Illinois, in the USA. After following several other radio astronomy related pursuits, Reber developed a great interest in low frequency radio astronomy, and because of Tasmania's excellent location for such work, this led him to choose the island as a suitable site for southern-hemisphere observations, interspersed with several trips back to the USA.

Following his initial Tasmanian low frequency work in 1955 (at Cambridge), and then in 1956–1957 (Kempton), Reber continued his interest in low frequency observations.

During the 1960s, Reber (1968) set up a large array of dipoles near Bothwell, and over the period 1963–1967, mapped the sky at a frequency of 2.085 MHz. This was the biggest project of his lifetime, and made use of a large, flat piece of land on a property owned by Geoffrey Edgell.

Reber subsequently returned to Bothwell and modified the array in an unsuccessful attempt during the mid-1970s to map the sky at about 1.155 MHz.

Through this work, Reber became well known in the Bothwell community, and befriended many of the residents. He engaged several Tasmanian contractors to perform various aspects of the work, such as the erection of the poles and anchors, and kept detailed notes of his work.

After finishing his Tasmanian radio astronomy work, Reber constructed an energy-efficient house in Bothwell, which became his main home for the remainder of his life.

From the 1950s and for most of his life, Reber made many return trips from Tasmania to the USA, and in the mid-1980s he attempted low-frequency observations of the sky from a location near Ottawa, Canada.

Reber was not a mainstream astronomer; indeed, he disagreed with the concept of the Big Bang, preferring to interpret redshift as 'tired light' (see Kragh, 2017)—a view he promoted in his 1968 paper and especially later in life during many lectures and talks that he delivered in Tasmania and elsewhere. Nonetheless, he received many awards, including the Bruce Medal of the Astronomical Society of the Pacific, the Elliot Cresson Medal of the Franklin Institute, and an Honorary Doctor of Science Degree from Ohio State University.

He was keen on many other scientific and technological pursuits, including the study of cosmic rays, Tasmanian prehistory, plant growth and efficient transport.

Grote Reber never married and had no children. He passed away on 20 December 2002, two days before his 91st birthday. Further biographical and autobiographical details are provided in Kellermann (2005), and Reber (1983, 1984), respectively.

3 INSTRUMENTATION

3.1 Location and Planning of the Array

Following Reber's trip to Macquarie Island, he returned to Tasmania to visit the Kempton site of his 1956–1957 observations. For years he had been considering re-using this location, but this plan changed in January 1960:

> During the past couple of weeks I've been rather on vacation here. However, I dug up the cable at Johnson Valley [the Kempton site]. It was somewhat damaged and not safe to lay in the ground again, but may be used for other purposes such as delay lines ... (Reber, 1960b).

At this stage Graeme Ellis, with whom Reber had worked at Cambridge in 1955 (Reber and Ellis 1956; George et al., 2015a), was based at Camden, New South Wales, and Reber was expecting to be able to team up again with Ellis:

> We ... have located another good site at Bothwell which is 20 miles northwest of Kempton. Bill [Ellis] thinks he can get transferred back to Hobart and obtain at least part of the equipment money. I'd like to go along with this and secure a part in it with some Research Corp. money[1] along about 1961 or 2. (ibid).

The location mentioned was not actually at Bothwell itself, but on a property known as Dennistoun, 5.6 kilometres to the north-northeast of Bothwell, owned by Mr Geoffrey Edgell.

Collaboration with Ellis was, however, not to transpire, with Reber (1960c) entering into independent negotiations for the use of the land. This was not palatable to Ellis:

> I was surprised to find out on a recent visit to Tasmania that you had proceeded independently toward getting permission to use the site at Bothwell ... In any case I consider I have a prior right to use this site if no others become available. (Ellis, 1960a).

Reber continued to suggest collaboration, but Ellis (1960b) decided not to entertain the idea:

> I think it would be unwise and inconvenient to have two large radio telescopes on the same property operated by different organisations, and if you [Edgell] decide that Reber should have permission I shall look elsewhere.

From mid-1960, therefore, the Dennistoun property became solely Reber's location for radio astronomy. The arrangement between Reber and landowner Geoffrey Edgell was formally documented by a legal agreement on 4 May 1961 (Reber and Edgell, 1961) and was to continue for many years. The agreement had many specifications as to the use of the land and the amount of land that would be used by Reber. It allowed Reber to construct—in addition to the array itself—a hut, roads, bridges, and cattle grids. It also specified that Reber's work was not to "… interfere with impede interrupt or hinder the use of the property by the owner for grazing and as a home …", and that the annual fee payable to the landowner would be £50.[2] The agreement was to last for five years but interestingly, it included an option for Reber to continue the arrangement for a further eleven years—an option that Reber was to use.

The scene was therefore set for Reber to make use of the land, although animals would be grazing there.

Perhaps inspired by the newly-erected 19.7 MHz Shain Cross near Sydney (see Orchiston et al., 2015a), Reber was at first considering the erection of a similar cross-type antenna, with north-south and east-west arms 7,260 feet (2,213 metres) and 8,260 feet (2,518 metres) long, respectively (see Figure 3). However, in early 1961 he changed his plans, and decided to build a filled-aperture, approximately circular, dipole array. In March he performed calculations on a proposal that would see an array covering just under one square kilometre (Reber, 1961a). Later that year he wrote:

> The idea of wires strung out on long pole lines at rightangles in the form of a cross has been replaced by a more compact arrangement. Now the wires are to be in form of several parallel lines like rulings on paper. The lengths are adjusted so periphery is approximately a circle. (Reber, 1961b).

Detailed plans of the array, dated 22 November 1962, made it quite clear that the 'present structure' formed only the central part of what Reber planned to be a much larger (but still approximately circular) array with more than twice the diameter. However, there are no known records that show that this enlargement was ever attempted.

3.2 Construction and Layout of the 2.085 MHz Array

The array as eventually constructed was of the form of an ellipse (Figure 4) of eccentricity 0.54, based on the east-west and north-south extents of the poles being about 1212 and 1015 metres, respectively. Between the eastern and western halves was a north-south transmission axis (Figure 5). The array covered an area of 0.97 square kilometre, although the outermost east-west poles were used only to support the end di-

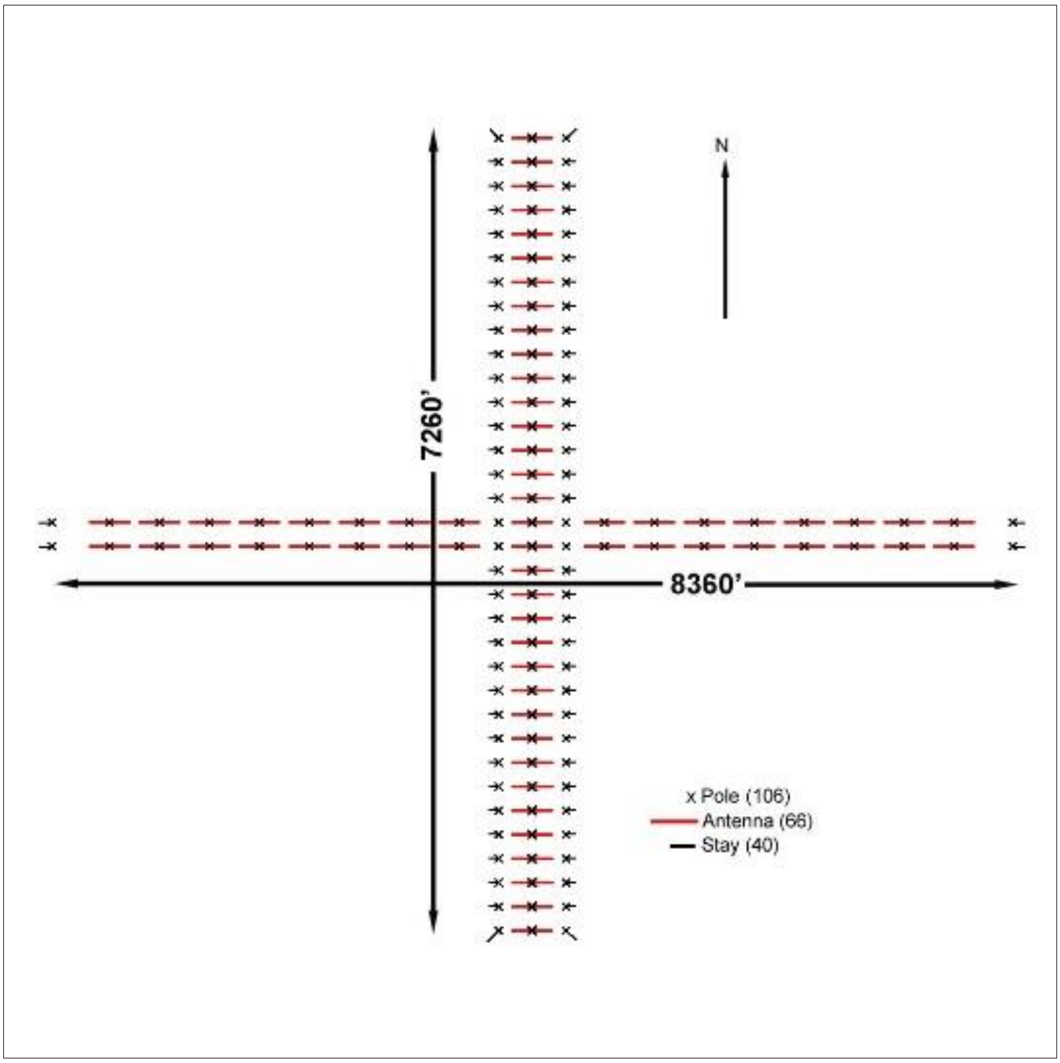

Figure 3: Reber's original cross-type concept for the Bothwell Antenna, adapted from his original diagram drawn on 18 April 1960. Courtesy Henry Edgell.

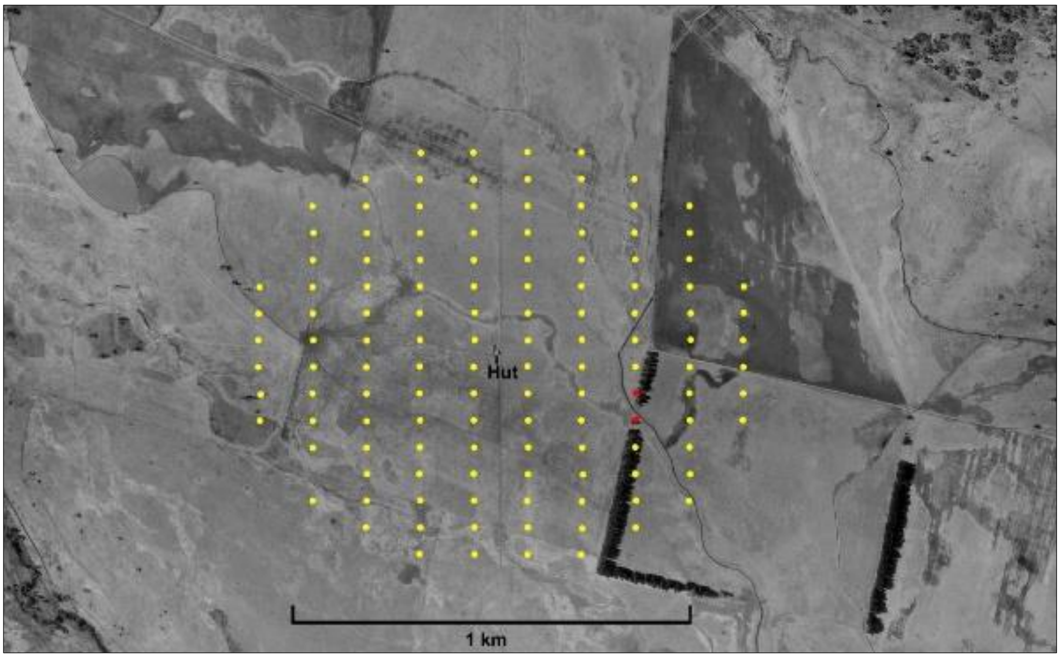

Figure 4: The locations of poles that can be identified on an aerial photograph taken on 15 February 1968. Yellow dots mark the positions of the 'pole' end of identified shadows; red dots are extrapolated from incomplete shadows. One pole, in the southwestern part, may have fallen (Base data from theLIST, www.thelist.tas.gov.au, © State of Tasmania).

poles in each row, making the filled-aperture area rather less than this. However, the construction, over this area, effectively made this the world's first 'Square Kilometre Array'. Figure 6 is an aerial view taken in 1965, showing a significant portion of the array.

The array was complete by August 1962. On 15 August, Reber (1962) issued a statement 'to whom it may concern', which included:

> Mr Leo Jeffries, as contractor has recently completed a radio astronomy installation at Dennistoun near Bothwell, Tasmania. The work consisted of securing and erecting 128 poles each 77 feet long plus numerous short posts and overhead trusses and stays. Several hundred crossarms, insulators, pulleys, counterweights, fortyseven miles of wire plus about one hundred each line transformers and antenna coupler boxes were all properly attached to the poles, posts and trusses and connected in an appropriate manner.

Figure 7 shows one frame of a 16 mm movie film depicting the erection of one of the tall poles; Leo Jeffries and his employees may be the people in this image.

The poles were separated by 440 feet (134 metres) in the east-west direction and 220 feet (67 metres) in the north-south direction. This allowed for two half-wavelengths of wire between each east-west pair of poles, separated by a spacer (see Figure 8). Except for the poles

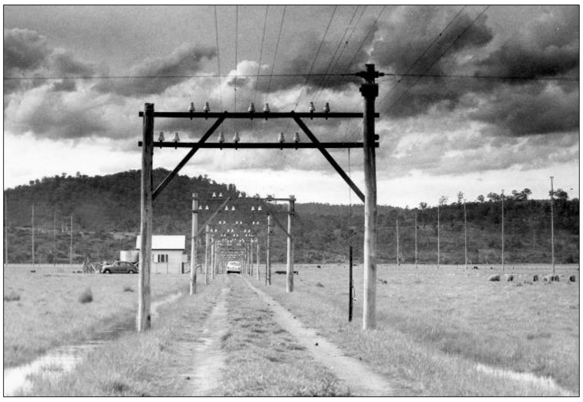

Figure 5: A view looking north along the central north-south transmission axis of the array, with the receiver hut on the left (courtesy Estate of Grote Reber).

at the extreme eastern and western ends, each pole was the centre of an east-west full-wavelength dipole, with each dipole wire running over a pulley before dropping vertically and being kept straight by a counterweight (see Figure 8, upper part, and Figure 9).

Raymond Haynes (pers. comm., 2017) commented that the counterweights were too heavy and placed too much strain on the wires. As a result, some of them broke while he was there as a student in 1965.

The tall poles were buried 10 feet (3 metres) in the ground, so the height of each above ground level was 67 feet (20.4 metres). Midway

Figure 6: An aerial photograph taken during an afternoon in 1965. The original colour slide was processed in December 1965; the shadow lengths and azimuths make the likely date of the photograph early October (more likely, given the lush appearance of the scene) or early March. The photograph is likely to have been taken by Vern Reid (courtesy: Estate of Grote Reber).

Figure 7: A tall pole being inserted into the ground at Dennistoun in the early 1960s. This is a single frame from a 16 mm movie film by Geoffrey Edgell (courtesy Henry Edgell).

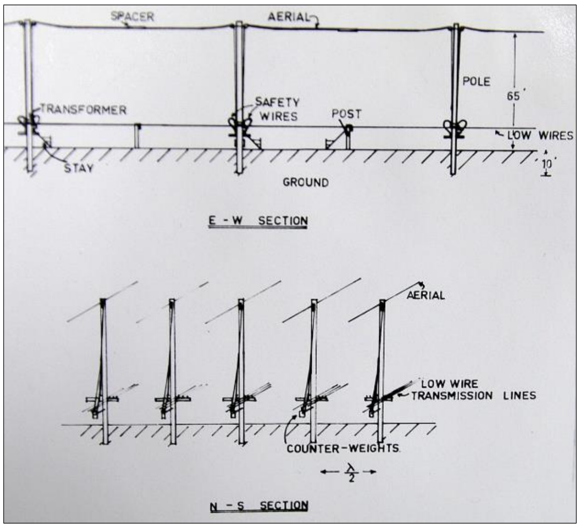

Figure 8: The east-west and north-south arrangement of the array. The east-west and north-south scales are not the same; the poles were separated by 440 feet (134 metres) (after Haynes 1966: 51).

Figure 9: A pair of pulleys that were mounted atop a tall pole. The east and west components of each dipole passed over the pulleys then dropped down to a few metres above the ground (photograph: Martin George; courtesy Estate of Grote Reber).

Figure 10: Reber climbing a pole just southeast of the receiver hut on 6 March 1979. Photographer unknown (courtesy: Estate of Grote Reber).

between the poles, a short insulating spacer was used to separate the dipoles (see Figure 8).

Reber would often climb the poles himself, using special grips that he had had made. He was still doing this as late as 1979 at the age of 68, well after both series of observations (Figure 10).

Reber was concerned about possible decay of the sections of the poles that were below ground; he added creosote to protect them. However, both Raymond Haynes and Graeme Ellis were of the opinion that the entire array was over-engineered, and that the creosote to protect the poles should not have been necessary (ibid.).

A hut was constructed very close to the centre of the array. This was to house the receiving equipment and was, essentially, Reber's 'workstation' (see Figures 5, 11 and 12). Using the 1968 aerial photograph (Figure 4) and comparing this with modern aerial images, the hut (WGS84 Datum) was positioned at longitude 147° 01′ 22.8″ East and latitude 42° 20′ 05.8″ South, plus or minus a few metres.

The array had a 'Christmas tree' feed and could be steered by inserting delay lines along the north-south transmission axis (Figure 5). The delay line lengths on the transmission lines were altered by moving terminators on those lines (Haynes, R., pers. comm., 2017). Reber (1966) commented that

> Steering is limited to plus and minus (north and south) 48° from zenith as this covers the entire south celestial hemisphere.[3] The beam direction may be shifted in two hours by two men and a tractor operating along the line of arches [the main north-south axis].

Electricity for the equipment was supplied by several batteries, to avoid interference from mains lines. Reber regularly measured the battery levels; indeed, many handwritten notes from the 1970s observations (see Section 6) mention checking the batteries.

Even after the array was completed, Reber was clearly concerned about the stability of the tall poles. Around October 1963 he advertised in *The Mercury*, Hobart's newspaper, for a contractor to provide and bury a number of poles in trenches in the ground to serve as anchors. The idea was that a hole would be bored through each pole before burying it, and a rod would be inserted that protruded from the ground and could be used to connect with the tall array pole via a cable. Reber (1964a) considered this to be correcting 'false economy'.

The successful tenderer was the young Darrell Browning of Fentonbury, who recalls:

> It [the advertisement] was in the Mercury. I was born in 1945 so I wasn't very old. If you

> didn't go out and get a job there was no Government money. I was working with my father. We had a farm; we used to do a lot of post and rail fencing. I just put in the tender. My father helped me with the work. He and another friend of ours helped. He [the friend] had a Ferguson Tractor – a 'Fergie' – a little grey one when they first came out … and a post hole digger on the back. (Darrell Browning, pers. comm., 2017).

4 THE 1960s OBSERVATIONS

4.1 Reber's Main Observations

The array had a quoted beamwidth of ~7.1° and was operated at a frequency of 2.085 MHz, slightly less than the ~134-metre length (67 metres each side, less half the spacer length) would suggest. The output was recorded on a pen recorder, with a chart speed of about 3 centimetres per hour (Reber, 1968b; Figures 13 and 14). The final choice of 2.085 MHz was based on finding a frequency most free of artificial interference (Haynes, 1966).

Reber was not present for all of the observations; indeed, the setup did not require constant attention. For much of the day-to-day work, at least during parts of 1962 and 1963, Reber engaged the services of Veio Fletcher, a young Dennistoun farm hand. Geoffrey Edgell agreed to Fletcher's partial secondment to Reber, noting in his diary that Fletcher was engaged in such activities as "harrowing middle race course", "sewing and rolling wheat", and "Reber" (Edgell, 1962; 1963).

Reber clearly regarded Fletcher as having given important assistance:

> Things are going well here with much good data being secured at Bothwell. The operation is now mostly in the hands of my capable man Veio Fletcher. (Reber, 1963).

The 2.085 MHz survey of the southern sky occupied the years 1963 to 1967. As expected, Reber noted the unfavourable summer periods, during which the higher degree of ionisation precluded obtaining good results. As with Reber's work at Kempton (Reber, 1958a), he was also often plagued by 'atmospherics' caused by poor weather. Indeed, one of the pen recorder illustrations (Figure 14) is annotated with the note "ELECTRICAL STORM OVER NORTHWEST TASMANIA".

The solar minimum of the 1960s took place in 1964. By the end of that year Reber (1964b) wrote:

> A large amount of good cosmic static data has been secured over the past two years. One more year of the present minimum still remains. When solar activity begins to rise, I will close this adventure and report my findings.

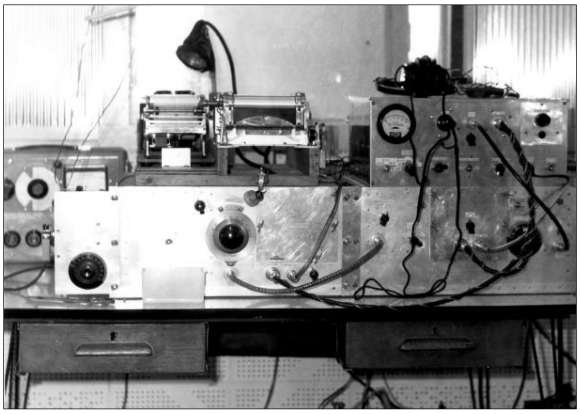

Figure 11: Reber's equipment in the hut. At far left is a Marconi Receiver Tester model TF888/3, which is on display in the Grote Reber Museum at Mount Pleasant, near Cambridge in Tasmania (courtesy: Estate of Grote Reber).

Figure 12: From left, Graeme Ellis, Bart Bok, Grote Reber and Peter McCulloch outside Reber's hut in the middle of the array, about 1965. Photographer unrecorded (courtesy: Peter McCulloch).

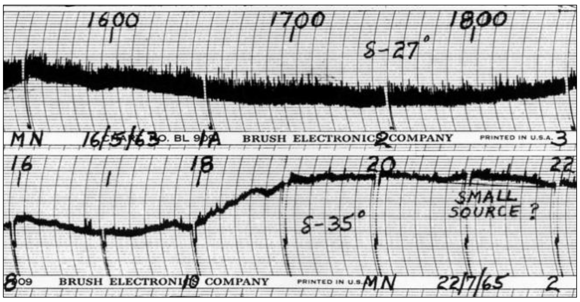

Figure 13: A typical pen recording of Reber's observations at 2.085 MHz on 16 May 1963 (top) and 22 July 1965 (bottom) (after Reber, 1968a).

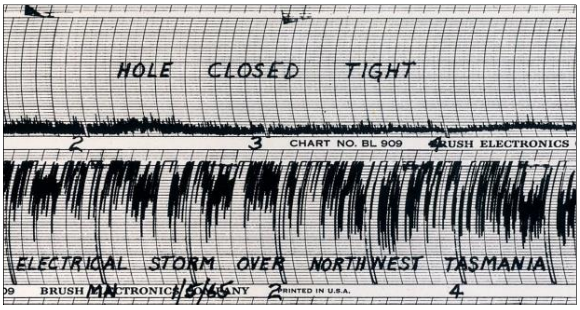

Figure 14: A pen recording of Reber's observations at 2.085 MHz on 1 May 1963 (top) and 1 May 1965. In the 1963 trace, the ionosphere precluded observations, and in the 1965 trace an electrical storm was spectacularly recorded. (after Reber, 1968a).

Reber's 2.085 MHz observations ran from 4 February 1963 to 10 May 1967 (Reber, 1968a). For many years later in life, he proudly displayed a panoramic picture of the array in his house, with annotations confirming that the observations ran from 1963 to 1967.

Even before the specified date of cessation of observations, Reber, on 8 May 1967, submitted his manuscript to The Franklin Institute for publication (Reber, 1967a), having returned to the USA in the few weeks preceding this. The paper was published in January 1968 (Reber, 1968b), and contained his 2.085 MHz map of the sky in both celestial and galactic coordinates, and a number of illustrative pen recorder traces.

The map (Figures 15 and 16) clearly shows the Milky Way in absorption, with noticeable regions of absorption by interstellar electrons in and near the Galactic Plane (the isophotes within a few degrees of the Galactic Plane all show minima). This was in agreement with other observations (see, e.g., Hoyle and Ellis, 1963; Ellis and Hamilton, 1966a; 1966b), although the displayed resolution shown in the region of the Galactic Plane appears rather high for the instrument he was using.

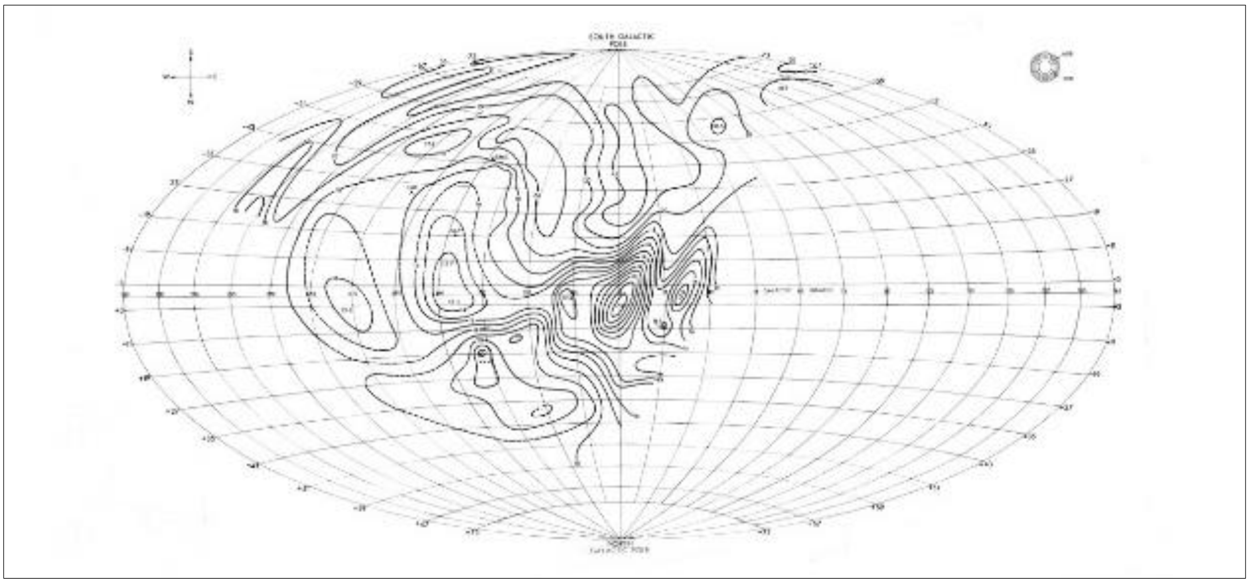

Figure 15: Grote Reber's 2.085 MHz map (Reber, 1968a). This is the version that was presented in galactic coordinates with the Galactic Equator running horizontally through the centre of the diagram, and the south and north Galactic Poles at the top and bottom, respectively.

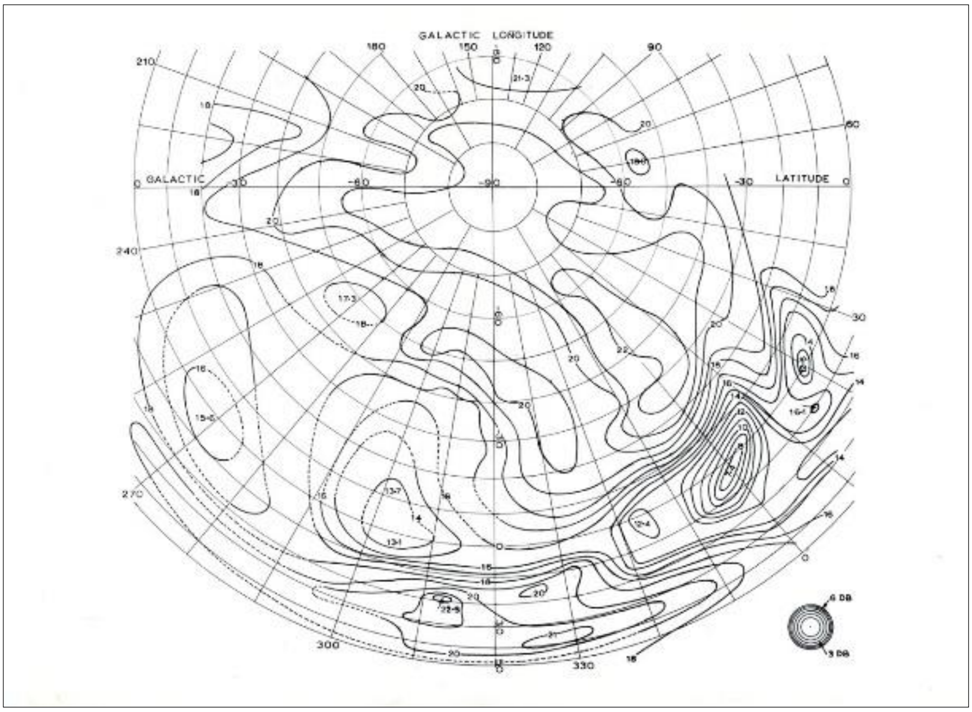

Figure 16: Reber's 2.085 MHz map in galactic polar coordinates. This version was not included in Reber's 1968 paper (courtesy Estate of Grote Reber).

There was no known attempt by Reber to publish his paper in a more mainstream astronomical publication such as *The Astrophysical Journal* or *The Astronomical Journal* (see the Discussion section near the end of this paper).

4.2 The Array as an Ionosonde

During 1965 the array was also used as an ionosonde.[4] This was a project supervised by Graeme Ellis and conducted by Raymond Haynes for a B.Sc. Honours thesis (Haynes, 1966). Ellis was keen to continue studying the Z-mode echoes from the ionosphere, [5] and

> … saw the opportunity to use Grote's array to do this. [The radio telescope at] Penna was too high a frequency … [We] needed a frequency that was in the right range; 2 MHz was a good option. (Haynes, R., pers. comm., 2017).

Haynes' ionosonde operated from about May until the beginning of November, 1965 (ibid.). It was set up to work at the same frequency (2.085 MHz) Reber was using for his astronomical observations. However, the ionosonde operated for only two minutes every hour (ibid.).

Many useful results were obtained, including frequent observations of Z echoes from the predicted region 8° north of the zenith. What, in retrospect, was an amusing incident occurred in October 1965:

> About the middle of October, a couple of burly guys turned up and they'd hunted down that some blighter was radiating Hobart with ionospheric radiation ... They suspected the Physics Department [of the University] had something to do with it so they came, and I had to admit that this happened when the beam was pointed to the south, and the beam came down straight over Hobart. (ibid.).

5 REBER'S RETURN TO TASMANIA

In 1964, while observations were proceeding at Dennistoun, it was clear that Reber intended to make his next series of observations from the USA or Canada. In a letter to G.L. Nelms of the Defence Research Board in Ottawa (Reber, 1964b), referring to the period following his Dennistoun observations, he wrote:

> Shortly thereafter, I expect to setup more elaborately in your part of the world in anticipation of the next solar minimum. The northern sky should be even more interesting than the southern at hectometer waves.

This plan is likely to still have been on Reber's mind when he wrote to Edgell in May 1967, showing little concern about the maintenance of the array:

> If a wire comes down, pull it up out of the way ... If a major disaster causes any of the poles to come down, please try to salvage the hardware. Remains of poles may be cut up for firewood. (Reber, 1967b).

In the same letter, Reber confirmed that he would continue to send cheques to Edgell, as clearly he had exercised his option to use the land beyond the expiry of the original agreement (see Section 3.1).

However, it did not take long for Reber to make a decision to return to Tasmania to make further observations. Certainly, this decision had been made by December 1968, but it may have been made earlier:

> I would like to establish myself somewhere just north of Bothwell within a few minutes drive of the scientific installation. This will cut down the amount of driving I used to do. (Reber, 1968b).

In the same letter, Reber describes the preparation of equipment for a new 'multibeam telescope'. He was also deciding on which items of equipment he would need to transport to Tasmania. He made further reference to this in 1969:

> Things are going well here [in the USA]. I've designed nearly all the electronic equipment for my new multibeam telescope. Prototypes of half the major assemblies have been built and tested. (Reber, 1969).

It is also clear, however, that Reber's problem was one of obtaining more funding from the Research Corporation. He had received this funding for his work since the 1950s, and he now needed further financial support for his new research program.

Following his application for further funds, letters were sent by the Research Corporation to prominent astronomers seeking their opinions. Several replied positively about Reber's ability to perform this work. No negative opinions on that topic appear in the records, but there was a difference expressed between Reber's ability to gather data and his ability to interpret it. Walter Orr Roberts, who was then the President of the University Corporation for Atmospheric Research in Colorado, wrote of Reber's proposal:

> ... it is highly meritorious of support. He is an unusual, imaginative, and utterly honest man, and the kind of person that I think deserves backing. He will do things the unconventional way, and sometimes his interpretations will be criticized, but his work always has a touch of experimental genius in it. (Roberts, 1971).

Reber also applied to the National Science Foundation for funding, but his application was rejected. However, as a result of the supportive letters, Reber was granted further financial support from the Research Corporation for his next venture in Tasmania.

6 THE 1.155 MHz ATTEMPT: 1971–1976

On 1 November 1971 Reber arrived back in Aus-

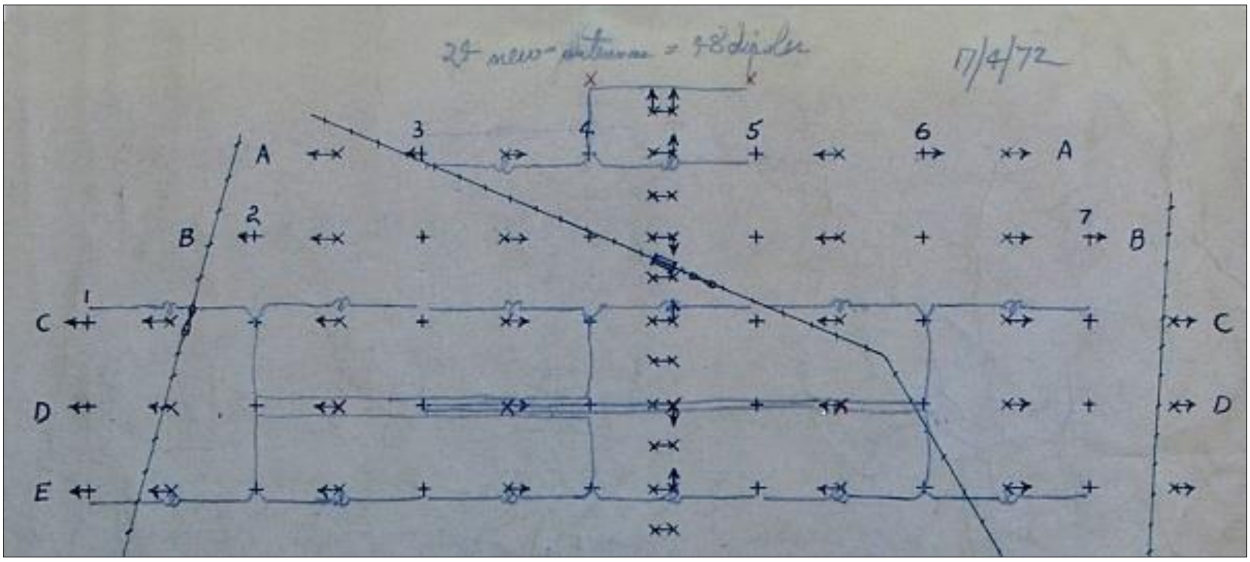

Figure 17: Part of Reber's plan, dated 17 April 1972, for re-wiring the array for use at 1.1 MHz (courtesy Estate of Grote Reber).

tralia. By then he was confident in his plans to re-establish the Dennistoun array for use at approximately 1 MHz. He wasted no time checking the status of his array. He discovered that about a quarter of the low wires (presumably meaning the transmission lines) had come down, but most of the high wires (the dipoles) were in place. Even so, he knew that all of the existing wires would need to come down anyway. He stated that his targets were to re-wire the array to get it into working order at one megacycle during that same summer, and extend it to larger dimensions the following year (Reber, 1971).

Neither of these targets was realised, but by April 1972 Reber had completed a pre-wiring plan based on the existing 128 poles, setting up 24 new antennas (Reber, 1972; see Figures 17 and 18 here). Reber counted one antenna as being two dipoles, so he considered his 24-antenna dipole system to have 48 dipoles.

However, by May 1973 Reber had re-wired the array to accommodate 48 antennas, which became the final configuration. In a handwritten list of activities that he had undertaken between November 1971 and May 1973 (Reber 1973), he noted a long list of achievements, including removal of 96 small poles and arches; testing of the 128 tall poles for internal decay; the purchase of pole-climbing hoops and the invention of new pole climbing claws; the rehabilitation of two miles of road and the construction of a quarter of a mile of new road; and the purchase of a tractor and four used Renault R4 vehicles. The array, as it appeared in 1975, is shown in Figure 19.

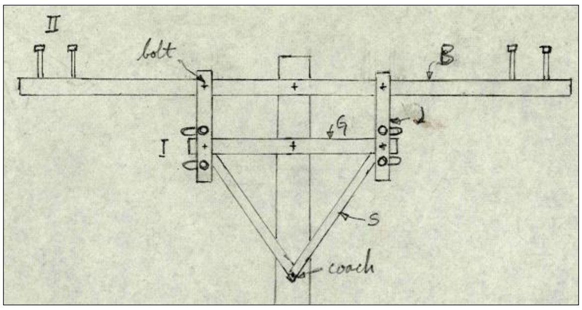

Figure 18: One of many crossarm designs, for transmission lines, that Reber produced in 1972. This example was drawn in December. These were either attached to the main poles or mounted on shorter, stand-alone poles (courtesy Estate of Grote Reber).

In early February 1974 Reber finally began actually living close to the site, as had been his desire for several years (Reber, 1968b). He rented a dwelling at 'Wetheron', a property with several cottages, just south of Bothwell and approximately 14.5 kilometres by road (about 15 minutes' drive) from the array.

Reber began attempting actual observations with the 'new' array during the winter of 1974, but through that year he was still erecting poles with crossarms, and adding crossarms to the existing tall poles (Figure 15); in mid-1974 only two dipoles were connected to the receiver system (Reber, 1974b). Reber recorded only three partial openings of the ionospheric hole at 1155 kHz, mentioning that solar activity and foF2 remained much too high (ibid.).

Reber was spending a lot of his time performing 'listening tests' in order to find a channel clear of broadcasting stations. At these new, lower frequencies, this task was much harder than at around 2 MHz, which had been his target in the 1960s. He found a multitude of stations, especially Radio Station 2WD in Wagga, New South Wales, which broadcast on 1150 kHz. This—the presence of 2WD and many other stations—was a problem that he encountered throughout. Because of this, the use of a minimum reader, to record the lowest intensity over a given (short) period of time, was most important. Reber also made use of two bandwidth

Figure 19: The Dennistoun array, looking south, photographed on 19 June 1975. Three images from a set of seven by Grote Reber, processed by us into a panorama (courtesy: Estate of Grote Reber).

filters: one 8.5 kHz and the other 2 kHz wide. With a wide, clear channel, the 8.5 kHz filter would have been preferable, but the frequencies were well populated and Reber calmly recorded his frustration, as in this example from 15 July 1974 (Reber, 1974a):

> 505a [5:05 a.m.] Another station came on at 1150 kc quite strong.
> 509a Another station came on at 1160 kc quite strong. Now entire region using band 2 [8.5 kHz] filter is covered by stations. Decided to let operate a while to see what will happen.
> 540a These stations will keep the receiver saturated. Decided to change back to band 1 (2.0 kc) filter. Splatter still present. Both stations at 1150 and 1160 kc will drive receiver to saturation when turned right on.
> 600a All stations on every channel very strong. Nothing more can be done.
> 620a Left. Moon peeks through clouds at intervals.

During early 1975 Reber continued to add the necessary components to the array, including the crossarms and tuner boxes. The attempt at making observations continued over the winter, although broadcasting stations continued to be a problem, and 1975 saw increasing physical problems with the array. On 25 January one of the poles—likely to have been a transmission pole—blew down (Reber, 1975a) and over several months many wires broke. He had problems with animals grazing on the property (although this was likely to have also been the case in the 1960s), and on 27 April he noted: "Cow number 343 is a pest." (Reber, 1975b).

Reber's increasing frustration is particularly apparent from his diary entry of 3 October 1975:

> During past few days they have plowed the entire area west of N/S road and some of area east of road. A few more wires have gotten tangled in machinery and come down. Whole place is big muddy mess. Don't feel like even trying to put wires back up. (Reber, 1975c).

After a trip back to the USA over the Tasmanian summer, Reber spent one more winter at Dennistoun attempting his observations. He tried recording when he could find a quiet channel. He had obviously performed some repairs since the problems of 1975, as he wrote on 12 June 1976 that

> Fixing the antenna has certainly reduced pick-up of BC [broadcasting] stations. Perhaps if entire array is finished the BC stations will be greatly suppressed further and allow a much wider bandwidth to be used. (Reber, 1976).

Reber was not necessarily referring to his original 1970s plans needing completion; it is more likely that he was referring to his thoughts of a much larger ~1 MHz array, which was never built.

Attempts in 1976 at recording celestial radiation in the ~1 MHz area produced no improvement over those of 1975 (see Figure 20), and this was the final Tasmanian effort made by Reber at making a low frequency survey of the sky. Reber (1977a; 1977b) attributed this singular lack of success to the relatively shallow 1976 solar minimum. Indeed, solar activity data (Meeus, 1983; Royal Observatory of Belgium, Brussels, 2017) do show that the 1976 minimum

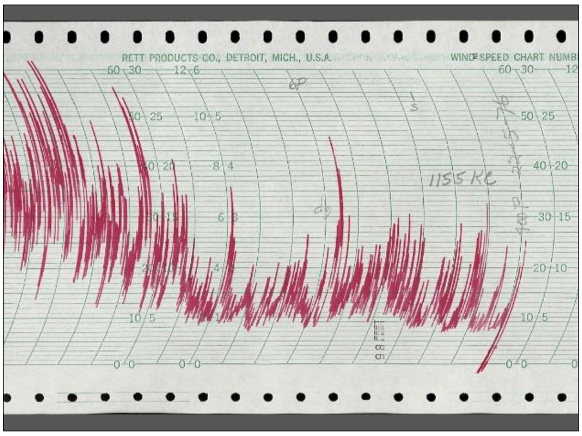

Figure 20: A pen recording at 1155 kHz, made on 22 May 1976. Time runs from right to left. The recording started at 16:00 hours, and the pictured section is five hours wide. Reber commented in his diary that the recording was useless because of a broadcasting station on this frequency (courtesy: Estate of Grote Reber).

Figure 21: The last remaining artefacts from the array at Dennistoun, 2003. Left to right: David Jauncey, Dale Blanchard, Henry Edgell, Anastasios Tzioumis, Esko Valtaoja, and David McConnell (photograph: Martin George).

was not quite as low as that of 1964, which in turn was less deep than the minimum of 1954.

7 THE END OF THE DENNISTOUN ARRAY

Even after the failed attempt of the 1970s, Reber was clearly still hoping for the possibility of more observations. Surprisingly, this was following the solar activity minimum. In a letter of 15 August 1977 to the landowner, Geoffrey Edgell, he wrote:

> As mentioned to you a few months ago, I intend to dismantle the installation in your paddock. However, it would be a shame to tear it down and then find good observing conditions had unexpectedly reappeared. I now intend to maintain it for a few more years just to see what is going to happen. It will never be expanded according to my grandiose ideas of several years ago. (Reber, 1977b).

As it happened, the array was gradually dismantled over a number of years; indeed, some tall poles and shorter transmission poles were still standing around 1991. An arrangement for their removal was proposed about 1980 with Henry Edgell, the landowner's son, using some of the last remaining funds received by Reber from the Research Corporation (Reber, 1980b);

Figure 22: An October 2004 photograph showing the Dennistoun hut arriving at its final home—the University of Tasmania's Mount Pleasant Radio Observatory (photograph: Martin George).

it was around 1980 when Reber was ending his long association with the Research Corporation (Reber, 1980a).[6] However, Henry Edgell (pers. comm., 2015; 2017) recalled that no formal arrangement was agreed, that there was a gradual removal over quite some time after 1980, and that eventually, some poles had started to rot. A photograph found amongst Reber's possessions, undated but likely to have been taken about 1991 or early 1992, shows some tall poles still standing.

In the mid-1980s the shed that had housed the receiving equipment near the centre of the array was moved to Reber's house in the town of Bothwell, and used as a storage shed.

In 2003, one of us (George) and several others visited the site and examined the remains of several parts of the array: some poles that had been cut up, and a number of counterweights (Figure 21).

In 2004, the shed was moved (Figure 22) to the University of Tasmania's Mount Pleasant Radio Observatory near Cambridge, and eventually formed part of the Grote Reber Museum, which was opened in 2009.

8 DISCUSSION

It is interesting to consider Reber's undertaking at Dennistoun in light of the fact that the University of Tasmania was concurrently making independent observations at 4.7 MHz and 10 MHz at Penna (George et al., 2017).

The 2.085 MHz map certainly filled a gap at the time, and was indeed the first such map made at this low frequency. Later, the University constructed an array near Hobart airport that was used to make observations at a range of higher frequencies up to 16.5 MHz; this will be the subject of a future paper in this series.

Reber was well known for working independently, beginning with the construction of his first radio telescope in the USA, and another example was the work that he performed at Kempton in 1956–1957 (George et al., 2015b). One may therefore wonder whether his early suggestions of collaboration with Graeme Ellis at Bothwell were purely because he wanted to be seen to be doing the 'right thing', while all the while actually preferring to work independently. However, it is interesting that it was Ellis who refused to collaborate when Reber raised the idea, especially after their earlier successful joint effort at Cambridge.

Perhaps Reber's quest for independence can also be traced back to the difficulty that he experienced when trying to get research published and accepted in the 1940s (but at that time radio astronomy was in its infancy). We believe that Reber's realisation that his research was still controversial most likely led him to decide to publish his Dennistoun results in the *Journal of the Franklin Institute* rather than in a mainstream astronomical journal such as the *Astrophysical Journal*.

Reber's decision to attempt to conduct successful observations at ~1 MHz was a gamble, despite his gaining financial support—perhaps granted somewhat reluctantly—from the Research Corporation. He realised that the project would require an exceptionally low solar minimum in the mid-1970s, and this did not eventuate. Later he made it very clear that this was the reason for his failure; however, his many diary entries make it equally clear that broadcasting stations, even with a minimum reader, were a major problem. In addition, none of his diary notes contains information about making use of phasing on the array during the 1970s attempt, even though he had constructed a number of phase shifters in the USA around 1970, presumably for use in Tasmania. He had certainly long planned to have phasing performed electronically, rather than mechanically (Reber 1966).

It is interesting to contemplate whether Reber would have attempted the lower frequency observations anyway in the 1970s if the Research Corporation had turned down his funding request. He was not without private means, so in keeping with his known determination, he may still have proceeded (and the scientific result would have been the same).

Finally, during the solar minimum in the 1980s Reber attempted to make low frequency observations of the northern sky from near Ottawa, Canada. We mention this here because of his continued drive to make more and more low frequency observations. However, the Ottawa attempt also failed, but even this did not deter Reber: in 1987 he drew up plans for a large 1 MHz array, although he did not disclose its proposed location. It was never built.

9 CONCLUDING REMARKS

Grote Reber's project at Dennistoun was carried out in two parts and was a major undertaking. But only the first part was a success, and this resulted in the 2.085 MHz map of the southern radio sky. This was the first such map, and it has an important place in the history of radio astronomy.

Although we believe that Reber's Dennistoun research paper does not stand as high, historically, as his landmark paper of 1944 (Reber, 1944), the Dennistoun array was a major engineering challenge and a remarkable achievement, and it can justifiably be called the world's first 'Square Kilometre Array' since it covered nearly that area and was indeed a filled-aperture array at the wavelengths used.

10 NOTES

1. The Research Corporation or, more correctly, the Research Corporation for Scientific Advancement, was founded in 1912. It is a private foundation that supports innovative research at colleges and universities in the USA. As a US citizen, Reber had a long association with the Research Corporation, which helped fund his radio astronomical research for nearly 30 years.
2. Until 14 February 1966, Australia's unit of currency was the pound (£), divided into twenty shillings each of 12 pence. On that date Australia changed to a decimal system with the dollar being the unit, equivalent to ten shillings (half a pound). In 1967 Reber (1967b) paid $100 to the landowner, and this arrangement likely continued.
3. The distance from the zenith (the point overhead) to the Celestial Equator is equal to the observer's latitude, which in this case was 42° 20′ South. Forty-eight degrees would allow the beam of the array to have complete coverage of the southern celestial hemisphere.
4. An ionosonde is a device that transmits pulses toward the ionosphere and receives reflections from it, in order to examine the ionosphere. In particular, an ionosonde can be used to measure the current value of foF2, the frequency that indicates to radio astronomers the lowest frequency that may be observed from the ground.
5. There are normally two ionosonde reflections from the ionosphere, corresponding to the two main modes of wave propagation in a magneto-plasma, called the ordinary (O) and extraordinary (X) modes. However, a third mode, called the Z mode, can occur, resulting in a third reflection (see, e.g., Benson et al., 2006). The Z mode is a branch of the X-mode and was studied extensively by Graeme Ellis (see, e.g., Ellis 1955; 1956).
6. Reber received a total over US$ 200,000 from the Research Corporation between 1951 and 1981 (Kellermann, 2004). This was used for array construction, air fares, and various other expenses.

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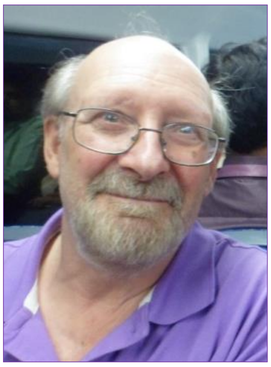
Professor Wayne Orchiston was born in New Zealand in 1943 and works as a Senior Researcher at the National Astronomical Research Institute of Thailand and is an Adjunct Professor of Astronomy at the University of Southern Queensland in Toowoomba, Australia. In the 1960s Wayne worked as a Technical Assistant in the CSIRO's Division of Radiophysics in Sydney, and forty years later joined its successor, the Australia Telescope National Facility, as its Archivist and Historian. He has a special interest in the history of radio astronomy, and in 2003 was founding Chair-man of the IAU Working Group on Historic Radio Astronomy. He has supervised six Ph.D. or Masters theses on



historic radio astronomy, and has published papers on early radio astronomy in Australia, England, France, Japan, New Zealand and the USA. He also has published extensively on the history of meteoritics, historic transits of Venus and solar eclipses, historic telescopes and observatories, and the history of cometary and asteroidal astronomy. In 2016 and 2017 Springer published his two latest books, *Exploring the History of New Zealand Astronomy: Trials, Tribulations, Telescopes and Transits* (733 pp.), and *John Tebbutt: Rebuilding and Strengthening the Foundations of Australian Astronomy* (603 pp.). Wayne's next book, co-edited by Tsuko Nakamura, is on *The Emergence of Astrophysics in Asia: Opening a New Window on the Universe*, and will be published, also by Springer, in 2017. Currently, Wayne is the Vice-President of IAU Commission C3 (History of Astronomy), and he is a co-founder and the current Editor of the *Journal of Astronomical History and Heritage*. In 2013 the IAU named minor planet 48471 Orchiston after him.

Professor Richard Wielebinski was born in Poland in 1936, and moved with his parents to Hobart, Tasmania, while still a teenager. Richard completed B.E. (Hons.) and M.Eng.Sc. degrees at the University of Tasmania. In his student days he met Grote Reber and was involved in the construction of a low frequency array at Kempton. After working for the Postmaster General's Department in Hobart he joined Ryle's radio astronomy group at the Cavendish Laboratory, Cambridge, and completed a Ph.D. in 1963 on polarised galactic radio emission. From 1963 to 1969 Richard worked with Professor W.N. (Chris) Christiansen in the Department of Electrical Engineering at the University of Sydney, studying galactic emission with the Fleurs Synthesis Telescope and the 64-m Parkes Radio Telescope. He also was involved in early Australian pulsar research using the Molonglo Cross. In 1970 Richard was appointed Director of the

Max-Planck-Institute für Radiostronomie in Bonn, where he was responsible for the instrumentation of the 100-m radio telescope at Effelsberg. In addition, he built up a research group that became involved in mapping the sky in the radio continuum, studying the magnetic fields of galaxies, and pulsar research. Further developments were the French-German-Spanish institute for mm-wave astronomy (IRAM), and co-operation with the Steward Observatory, University of Arizona, on the Heinrich-Hertz Telescope Project. Richard holds Honorary Professorships in Bonn, Beijing and at the University of Southern Queensland. He is a member of several academies, and has been awarded honorary doctorates by three universities. After retiring in 2004 he became involved in history of radio astronomy research, and is currently the Chair of the IAU Working Group on Historic Radio Astronomy.