The Contribution of the Division of Radiophysics Potts Hill and Murraybank Field Stations to International Radio Astronomy

Thesis
submitted by

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5. ABSTRACT

During the 1950s Australia was one of the world's foremost astronomical nations owing primarily to the work of the dynamic Radio Astronomy Group within the Commonwealth Scientific and Industrial Research Organisation's Division of Radiophysics. Most of the observations were made at the network of field stations maintained by the Division in or near Sydney, and one of the most notable of these was located at Potts Hill, the site of Sydney's major water-distribution reservoirs. Another smaller field station called Murraybank was later established specifically to exploit the discovery of the hydrogen emission-line and together with Potts Hill these were the two research stations conducting hydrogen-line studies in Australia until 1962.

This paper examines the amazing range of radio telescopes developed at these field stations; the types of solar, galactic and extragalactic research programs to which they were committed; and the pioneering young men and women who played a key role in the early development of radio astronomy

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8. INTRODUCTION TO THESIS

This thesis examines the contribution to radio astronomy of work carried out at the Potts Hill and Murraybank field stations operated by the Division of Radiophysics, Commonwealth Scientific and Industrial Research Organization, Australia. While a number of histories of the early years of radio astronomy in Australia have been published (e.g. Orchiston and Slee, 2005, Robertson, 1992, Sullivan, 2005), there has not been a comprehensive review of the specific contribution made by the Potts Hill and Murraybank field stations. Twenty field stations and remote sites (Figure 1) operated during the first 16 years (1945-1961) of Australian radio astronomy, or the 'pre-Parkes' era (Orchiston and Slee, 2005a). Potts Hill and the better historically-documented Dover Heights field station (e.g. see Bolton, 1982; Kellermann et al., 2005; Orchiston and Slee, 2002; Slee, 1994; Stanley, 1994; Westfold, 1994) were the two major field stations operating during this period, although by 1952 Potts Hill had become the largest field station of the Division (Pawsey, 1952f).

The Potts Hill field station was located on vacant land adjacent to a water supply reservoir on the outskirts of suburban Sydney, some 16 km to the southwest of the central business district. A wide variety of instruments was used at Potts Hill and a number of the scientists who worked there emerged as leading researchers in Australian radio astronomy. For a period it was the focal site for Australian solar radio observations, and it was where the Australian confirmation of the 21-cm Hydrogen emission spectral-line took place. The Hydrogen line emission observations would become central to our early understanding galactic structure and this was the catalyst for establishing the Murraybank field station so as to further the receiver development and survey work that had commenced at Potts Hill.

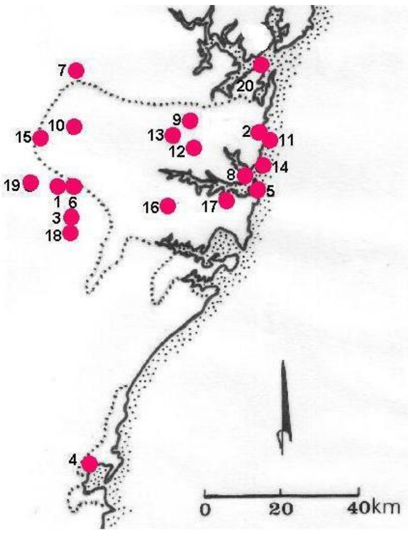

Figure 1: The twenty different sites in the Greater Sydney-Wollongong regions associated with radio astronomy. These were Badgerys Creek (1), Collaroy (2), Cumberland Park (3), Dapto (4), Dover Heights (5), Fleurs (6), Freeman's Reach (7), Georges Heights (8), Hornsby Valley (9), Llandilo (10), Long Reef (11), Marsfield (12), Murraybank (13), North Head (14), Penrith (15), Potts Hill (16), the Radiophysics Laboratory in the grounds of the University of Sydney (17), Rossmore (18), Wallacia (19), West Head (20).

The dotted outline shows the current approximate boundaries of Greater Sydney and Greater Wollongong (after Orchiston and Slee, 2005a: 121).

Potts Hill was also the site of the discovery of the discrete source known as Sagittarius A at the centre of our Galaxy, although many histories incorrectly credit this to work carried out at Dover Heights (e.g. Kerr, 1983: 297; cf. Orchiston and Slee, 2002: 30). The first use of Earth-rotational synthesis occurred at Potts Hill, but because it was not further developed, credit is now largely given to Cambridge for initiation of this technique (Christiansen, 1989b).

To understand the contribution made at Potts Hill and Murraybank it is necessary to understand the context within which this work was carried out. There have been a number of publications examining why Australia was able to make such major contributions to early radio astronomy (e.g. Bowen, 1984, 1988; Christiansen, 1984; Mills, 1988; Pawsey, 1956, 1961a; Roberts, 1954; Sullivan, 2005; Wild, 1972). Many of the histories that have been published are based on the direct recollections of the people involved and in many cases by the researchers themselves. In this context there has been much focus on achievement, and perhaps rightly so given the period of rapid development in a pioneering field by a nation still finding its feet on the global scientific and economic stage after World War II. While it is understandable that there is a sense of pride in the achievements, this thesis attempts to stand back and examine these in a broader context. Without doubt, Australia made a very significant contribution to international radio astronomy, achieved a number of world-first discoveries and developed new techniques (Sullivan, 2005: 11). However, some of the truly fundamental discoveries eluded Australian researchers (Christiansen, 1989a: 96). In some cases, where the Australian researchers did achieve world-first developments they were slow to capitalise on them (e.g. earth rotational synthesis imaging in Christiansen and Warburton, 1955a), yet in other cases they were quick to take advantage of the discoveries of others (e.g. H-line confirmation in Pawsey, 1951b). Australia's isolation is often quoted as a factor that researchers faced in the 1940-1950s (e.g. Sullivan, 2005: 23), yet some of the first collaborations with optical astronomers, and early cooperative international research projects originated in Australia (e.g. Allen, 1947; Christiansen et al., 1951). The work carried out at Potts Hill and Murraybank contains many of these examples and as such provides a rich illustration of these contrasts in the early development of Australian radio astronomy.

People shape history and Potts Hill and Murraybank involved, either directly or indirectly, nearly all of the leading scientists in first 10 years of Australian radio astronomy. Some 64 research papers were published during 1949-1962 based on work carried at Potts Hill (refer to Appendix A for a full listing of these) and a further 12 papers were produced from Murraybank in the period 1958-1964 (refer to Appendix B for a full listing of these). Many of these appeared in the *Australian Journal of Scientific Research* which was later to become the *Australian Journal of Physics.* Although these two journals were not widely read outside Australia, many of the findings also appeared in *Nature*, the *Astrophysical Journal*, *Monthly Notices of the Royal Astronomical Society* and *The Observatory*.

During the International Astronomy Union (I.A.U.) General Assembly held in Sydney in 2003, Commission 41 (History of Astronomy) and Commission 40 (Radio Astronomy) formed a joint working group on Historic Radio Astronomy under Divisions X and XII. One of the objectives of this Working Group is to document the technical specifications and scientific achievements of historically-significant radio telescopes and associated instruments worldwide (Orchiston, 2006). This Thesis covers the contribution to international radio astronomy of work carried out at the Potts Hill and Murraybank field stations and as such provides a detailed record consistent with the objectives of the Working Group.

9. RADIO ASTRONOMY IN AUSTRALIA

Jansky's original identification of radio emission of galactic origin was published in 1933 (Jansky, 1933). Initially there was little follow up in exploring the potential of this new discovery in the wider scientific and astronomical organizations of the time. This was not for a lack of publicity, as the discovery made the front page of the *New York Times* on 5 May (1933) and was widely followed up in other press and in radio news broadcasts. In the 1930s only one scientific paper appeared in response to Jansky's discovery. This was a theoretical paper published by Whipple and Greenstein (1937) that examined the mechanism that might have produced the detected radiation. Some tentative observations were made: for example, Caltech's Potapenko and Folland were able to confirm Jansky's detection working with a simple dipole aerial in the Mojave Desert (Reber, 1983). However, they were unable to obtain funding to build a more substantial instrument and no results were published. Apart from the solo efforts of Grote Reber who followed up Jansky's discovery as a self-funded hobby and produced a number of seminal papers (Reber, 1940a,b, 1944), the wider scientific community largely overlooked the potential of radio astronomy for the next ten years. Today it is difficult to comprehend why there was so little initial interest. However, the simplest explanation is that at this time astronomers were not familiar with any portion of the electromagnetic spectrum outside of the optical range and certainly did not have a background or training in radio physics or radio engineering. As Reber observed:

> "The astronomers were afraid of it because they didn't know anything about radio. The radio people weren't interested because it was so faint it didn't even constitute an interference. Nobody was going to do anything. So, alright, if nobody was going to do anything, maybe I should do something. So I consulted with myself and decided to build a dish." (Kellermann, 2005: 49).

As more than one historian of radio astronomy has already remarked, Australian radio astronomy, like its counterpart in the U.K., truly was a case of "...swords into ploughshares." (e.g. Hanbury-Brown, 1991; Haynes et al., 1996).

Australia's involvement in World War II and the Australian Government's commitment to develop radar technology for the war effort were the events that would ultimately lead to the development of radio astronomy in Australia. In 1939 the Australian High Commissioner to England, Stanley Melbourne Bruce, cabled the Australian Government with a request to send a 'physicist of discretion' to collect top-secret information regarding a new Allied development (Haynes et al., 1996). The person selected for this mission was David Forbes Martyn, who was a Research Officer with the Radio Research Board of the Australian Council for Scientific and Industrial Research - CSIR (the precursor to the Commonwealth Scientific and Industrial Research Organization – CSIRO). Martyn visited the UK to collect this information and returned it to Australia along with a special report to the Prime Minister. This report led directly to the formation of the Radiophysics Division of the CSIR with Martyn appointed as the first Chief of the Division on 2 September 1939, one day prior to the commencement of World War II. The purpose of this new Division was to specifically focus on the development of radar for the war effort, and the Division ended up making very significant contributions to the introduction of radar in the Southwest Pacific.

Meanwhile, in the U.K. James Hey, who had been drafted into the Army Operational Research Group (AORG) to examine the performance of British Army radar, was investigating jamming by the German Forces. On 27 and 28 of February 1942 severe jamming noise was reported across many radar sites, but no enemy attack was evident. Hey recognised that the maximum levels of interference appeared to follow the direction of the Sun as it rose in the east and tracked westward, coincidentally in the same direction from which a German jamming attack would commence. As Hey recalled:

> "I immediately telephoned the Royal Observatory at Greenwich to inquire whether there was any unusual solar activity, and was informed that although we were within two years of the minimum of the sunspot cycle, an exceptionally active sunspot was in transit across the solar disk and situated on the central meridian on 28 February. It was clear to me that the Sun must be radiating electromagnetic waves directly – for how else could the coincidence in direction be explained – and that the active sunspot region was the likely source. I knew that magnetron valves generated centimetric radio waves from the motion of electrons in kilogauss magnetic fields, and I thought why should it not be possible for a sunspot region, with its vast reservoir of energy and known emission of corpuscular streams of ions and electrons in magnetic fields of the order of 100 gauss, to generate metre wave radiation." (Hey, 1973).

Hey (1942) wrote a paper on his findings, but this research was classified under the wartime Secrecy Act and so its publication in scientific journals would have to wait until the end of hostilities in 1945.

Independently, also in 1942, George Southworth was conducting work on developing more sensitive centimetric receivers at Bell Telephone Laboratories in the U.S. He also detected radiation from the Sun and concluded that this was the natural blackbody radiation spectrum extending down into radio frequency for a blackbody of 6,000 K, which was the photospheric temperature of the Sun (unfortunately Southworth made an error in the calculation of the temperature conversion and so he failed to recognise that the temperature was actually 18,000 K (Pawsey and Bracewell, 1955:150)). Like Hey's report, Southworth's initial report was also classified (Southworth, 1942), so it was actually Grote Reber who became the first person to publish in a scientific journal on the radio frequency detection of the Sun (Reber, 1944).

Although both Hey and Southworth's papers of these discoveries were restricted, their findings were discussed with colleagues working in radio, ionosphere and radio communications research. Their findings were however often met with a degree of disbelief, or more often just ignored. As Bolton noted:

> "Those of us who were associated with low frequency radar during the war regarded it [extraterrestrial radio noise] as a nuisance which could limit the detection range of enemy aircraft" (Bolton, 1990: 381).

Pawsey (1961a) has noted that in 1944, F.J. Kerr made, "a preliminary attempt to observe cosmic radio waves but was frustrated by claims of military work".

In early 1945, New Zealand Air Force radar stations operating at 200 MHz observed similar radiation from the Sun as had been detected by Hey. This work was carried out by Elizabeth Alexander and was shared with Australian researchers, but apart from a brief report (Alexander, 1945), remained unpublished (see Orchiston, 2005; Orchiston et al., 2006).

At the end of World War II, the role of the Radiophysics Division was altered to focus solely on peace-time activities. This was a pivotal moment in the birth of radio astronomy in Australia. The decision was made by the then Chairman of the CSIR, Sir David Rivett. It meant that a highly-developed laboratory with a trained and experienced staff became available for a wide range of research and practical developments. Edward George 'Taffy' Bowen (1911-1991: Hanbury-Brown et al., 1992) replaced Fredrick White as the Chief of Radiophysics and oversaw this transformation. White had replaced Martyn in late 1940, initially on an interim basis, however in 1942 this became permanent when Martyn was transferred to the post of Director of the Army Operational Research Group. Martyn harboured an ongoing institutional and personal resentment against what he saw as a demotion (Robertson, 1992: 26).

Bowen had been heavily involved in the development of airborne radar in the U.K. as part of the war effort. At the time the Division had approximately 200 staff who were highly skilled in electronic research and development. Bowen prepared a draft report on the "Future Programme for the Division of

Radiophysics" which was presented for consideration to the 35th Session of the Council of the CSIR. The report was 26 pages in length and contained a short paragraph, titled "Study of Extra-thunderstorm sources of Noise (Thermal and Cosmic)":

> "Little is known of this noise and a comparatively simple series of observations on radar and short wavelengths might lead to the discovery of new phenomena or to the introduction of new techniques. For example it is practicable to measure the sensitivity of a radar receiver by the change in output observed when the aerial is pointed in turn at the sky and at a body at ambient temperature. The aerial receives correspondingly different amounts of radiant energy (very far infra red) in the two cases. Similarly, the absorption of transmitted energy in a cloud can be estimated in terms of the energy radiated to the receiver by the cloud. None of these techniques is at present in use." (Bowen, 1945: Section 1.2).

On the basis of this report, a number of independent research groups were formed focusing on air navigation, cloud physics, electronic computers, transistors, and as described above, investigation of radio noise sources. The radio noise investigation group was headed by Joseph Lade Pawsey (1908-1962: Kerr, 1963), and would later become known as the Radio Astronomy Group. Almost from the beginning of the solar and cosmic research by Pawsey's Group there was a close collaboration with the Commonwealth Solar Observatory at Mount Stromlo, as noted in the first official Programme of the Division of Radiophysics (Bowen, 1946: Section 1.2 Solar and Cosmic Noise at Radio Frequencies).

Pawsey had joined the Radiophysics Division in 1940 and had been a team leader of a research team producing radar systems. He had worked at the Cavendish Laboratory at Cambridge under J.A. Ratcliffe and had very early exposure to radio astronomy from his visit during the war to the Bell Telephone Laboratory, where he became aware of George Southworth's work on solar radio emission. Pawsey also had access to the then still secret work of James Hey, and to the New Zealand solar detections on equipment that was similar to the radars being used in Australia. With this background Pawsey, together with fellow researchers Lindsay McCready and Ruby Payne-Scott, set out to conduct the first serious project in radio astronomy in Australia in the later part of 1945. In October 1945, at Collaroy, about 20 kilometres north of Sydney, they used a Royal Australian Air Force (RAAF) 200 MHz coastal defence radar antenna operating in its passive receive mode to conduct solar observations. They noted that the radio emission that was detected indicated a temperature of up to one million Kelvin for some regions of the Sun. At this time conventional optical measurement suggested a surface temperature of 6,000 K. Their results -- the first Australian paper on Radio Astronomy -- were published in *Nature* in 1946, and the paper was titled, "Radio-frequency energy from the Sun" (Pawsey et al., 1946). A separate paper by Pawsey (1946) was later published in *Nature* alongside a theoretical paper by David Martyn (1946b) that predicted a temperature of 1 million K for the corona. David Martyn was at this time working as an ionospheric physicist at the Commonwealth Solar Observatory at Mount Stromlo near Canberra in

Australia. There has been some minor controversy as to whether Pawsey's determination of the 1 million K temperature preceded Martyn's theoretical prediction or was conducted in confirmation of the predication. Hey (1973: 42) has argued that it was clearly Pawsey's experimental results that triggered Martyn's paper. It is interesting to note that Pawsey's paper acknowledged Martyn's work, but not vice versa, even though there had been a number of discussions between the parties prior to publication. As mentioned earlier, Martyn had previously been Chief of the Radiophysics Division, but because of a combination of issues associated with his management approach and security concerns he had been seconded to the Commonwealth Solar Observatory and replaced by Bowen as the head of the Division. For this reason he retained bitterness, particularly towards Bowen, and a keen sense of rivalry towards his former colleagues. In a detailed analysis of events, Sullivan (2005: 19) has concluded that it was indeed Martyn who brought attention to the earlier astronomical evidence indicating the possibility of the million degree temperature in the corona, and that it was also likely that Martyn pointed out that the 'apparent' temperature measured by the Radiophysics team could actually be equated to thermal emission from the corona.

In March, 1946 a young Leading Aircraftsman stationed with the Royal Australian Air Force in Darwin wrote to Radiophysics about his own experiments in detection of solar radio noise using a C.O.L. Mk. 5 Radar operating at 200 MHz (Slee, 1946). This was Bruce Slee, who would go on to become a very distinguished Australian Radio Astronomer. He received a very encouraging reply from J.N. Briton (1946) who was then Head of the Division with details of Radiophysics' own research as well as an offer to visit the Radiophysics Laboratory if he were ever in Sydney.

Although the Collaroy work had been successful, one of the problems confronting the group was the low resolution of the 200 MHz radar antenna with a beamwidth of ~10°. This limited their ability to determine where on the Sun's disk the emission they detected had occurred, as the Sun's disk is only thirty arc minutes in diameter when observed from Earth. In a breakthrough, Pawsey's team established that interferometry could be used to improve resolution. The first interference fringes were observed on Australia Day (26 January) 1946. A landmark paper was eventually published in 1947 (McCready et al., 1947) after a lengthy and controversial delay by the British journal, *Proceedings of the Royal Society* (Orchiston et al., 2006: Note (2)). This paper laid the foundations for interferometry and the use of Fourier techniques in radio astronomy. A dedicated Radiophysics field station was established at Dover Heights to further the sea-interferometry research in place of relying on shared access to the RAAF site at Collaroy (see Bolton, 1982; Slee, 1994).

The Dover Heights site consisted of a concrete blockhouse on the edge of a 278-ft sea cliff, with the receiving aerials located nearby (McCready et al., 1947: 359). The configuration thus acted as an interferometer. Radio signals from the Sun as it rose over the eastern horizon were detected via the direct path, but also from the reflected path from the ocean's surface. Because the path lengths were different the arriving wavefronts constructively and destructively interfered in a Lloyd's mirror effect. Shortly after the receiving equipment was first set up at Dover Heights, a very compact sunspot group appeared. The combination of these observations together with the earlier observations at Collaroy, and a description of the interferometry approach, was published in the initial paper in *Nature*. The early-morning interference patterns recorded at Dover Heights established beyond doubt that the strong increase in radio emission observed as a vertical strip from the interferometer measurement correlated directly with sunspot regions on the solar disk. This paper also suggested the application of Fourier synthesis as an analytical technique although it was not until the advent of the digital computer that this technique could be fully exploited.

At approximately the same time a group of astronomers led by Martin Ryle at Cambridge University had independently developed interferometry and had also correlated radio emission with sunspots. In this case they used a two-element interferometer rather than the sea-interferometer technique. Although, strictly speaking, their observations occurred later, they succeeded in getting their work published ahead of Pawsey's group (Ryle and Vonberg, 1946).

During 1946 Pawsey had also attempted to confirm Hey's newly-reported discovery of a fluctuating cosmic source in the constellation of Cygnus. There is some disagreement in the historical record as to the success of these initial attempts to detect the Cygnus source. Robertson notes:

> "Within days he [Pawsey] had confirmed the existence of signals from Cygnus and also noted how fluctuations were not unlike the type of 'bursts' observed in solar noise." (Robertson, 1992: 44).

Bolton (1982) recalled that Pawsey was unable to repeat Hey's result, and this may be supported by the fact that no paper was published on the subject at that stage.

At this same time Pawsey was actively seeking to expand the emergent group and recruited two young physicists who were to become prominent figures in radio astronomy – John Paul Wild and John Gatenby Bolton (Wild and Radhakrishnan, 1995). Wild was not actively involved in the observational work at Dover Heights and was initially assigned to work in the Laboratory's Test Room. Bolton however went on to provide the foundations for research at Dover Heights.

It was David Martyn who suggested to Bolton that he investigate the polarization properties of sunspot radiation (Bolton, 1982). Martyn (1946a), working at Mount Stromlo using a 4-element Yagi array that had been installed by Radiophysics, had observed that the radiation was circularly polarized and reversed sense with passage of the central meridian. Bolton set out to test this observation, but unfortunately the Sun at this stage had returned to an almost dormant state. Despite this set back he and his assistant, Bruce Slee, set out to see if they could detect any other astronomical bodies using the two Yagi arrays in a parallel configuration looking out over the sea. Bolton's knowledge of astronomy at the time was at best very rudimentary. Their reference library consisted of only two astronomy books, *Astronomy* by Russell, Dugan and Stewart and *Norton's Star Atlas* (Bolton, 1982). With these they attempted their initial survey work. According to Bolton (1982: 349), this lasted for only about two weeks when Pawsey arrived to inspect their progress on the solar radiation work and found that the Yagi arrays were not pointing at the Sun! Their observations were cut short and both men were re-assigned to work back at the Laboratory, curtailing any further research at Dover Heights in 1946. Wild (1987: 99) has suggested that Bolton's recollection of the circumstance leading to his re-assignment to the Laboratory seemed out of character for Pawsey.

1946 had proved a defining year for radio astronomy in Australia. Pawsey's group had pioneered the technique of radio interferometry to improve resolution. This technique would become of central importance to the development of radio astronomy throughout the world, although Australia's contribution would be clouded by the rivalry from the Cambridge group (Mills, 1984). The group had also done much of the work to clarify the nature of radio emission from the Sun and had also identified sunspots as a source of radio outbursts through the use of interferometry.

In late February 1947 fortunes turned for Bolton. After his banishment from Dover Heights, he had been working in the Laboratory building equipment for a solar eclipse expedition that was to have been conducted in Brazil (see Wendt et al., 2008). The expedition was, however, cancelled and Pawsey told Bolton, "If you can think of anything to do with all this equipment – you can have it" (Bolton, 1982). He also allowed Bolton to have Gordon Stanley assist him. Bolton quickly gathered the equipment and relocated to Dover Heights. Their first task was to construct receiving equipment that would allow them to listen to the Cricket Test Match between England and Australia, which they completed by 11am on their first day.

Soon after they had set up their equipment a large bipolar sunspot appeared on the limb of the Sun. After about a week of monitoring this spot, a very large solar outburst was detected on 200 MHz, 100 MHz and 60 MHz receivers which lasted for approximately 15 minutes in total. This was the first outburst of its kind to be observed and would later be classified by Paul Wild as a Type II outburst. Based on their observations of detection time at the different frequencies they estimated an outward velocity for the outburst in the solar corona of approximately 1,000km/s, which gave a time of travel to the Earth of approximately 26 hours. On the following evening a prominent aurora was observed in Sydney, an extremely rare event given the city's latitude of 34° S. These observations were published in *Nature* in a paper titled "Relative times of arrival of bursts of solar noise on different radio frequencies" (Payne-Scott et al., 1947). The paper appeared together with data by Ruby Payne-Scott and Don Yabsley recording delays of the order of 1 second between short solar bursts observed at two frequencies. These observations showed that solar flares were associated with streams of charged particles, electrons and ions, which travelled at very high velocities through the solar atmosphere. As the charged particles reached the more rarefied corona, radio emission occurred at progressively longer wavelengths, accounting for the delays observed between the different wavelengths. The following day as the solar storm continued Payne-Scott et al. finally managed to detect the circular polarization that they had set out to find in late 1946 and which Martyn had predicted.

In August 1947 a smaller field station was operating at Georges Heights overlooking the entrance to Sydney Harbour (Orchiston, 2004b). Like Dover Heights and Collaroy, this site had been a radar station during the war. An ex-experimental 16-ft × 18-ft alt-azimuth mounted radar antenna had been converted to observe solar radiation at 200, 600 and 1,200 MHz. These observations were conducted by Fred Lehany and Don Yabsley (1949) and contributed to a better understanding of emission from solar flares and correlations to sunspots at higher frequencies (600 & 1,200 MHz) and were complementary to the solar observations being conducted at Dover Heights at the same time.

In June 1947, Bolton and Stanley switched their attention to non-solar sources of radio emission and set out to conduct an empirical search using sea interferometers at 100 MHz and 200 MHz. They quickly detected the Cygnus A source that had been previously been reported by Hey and which Pawsey had earlier unsuccessfully tried to detect. Of key importance was the nature of the interference patterns they detected, which indicated that the angular size of the source could be no more than eight arc minutes in diameter, which was a significant improvement on the early angular size estimate of being less than or equal to two degrees (Hey et al., 1946). They monitored this source for some months while attempting to improve their techniques and eventually wrote up their findings in November 1947 (Bolton and Stanley, 1948b). While Hey had inferred that Cygnus A was point-like, Bolton and Stanley's work now provided proof.

On 6 November 1947, Bolton and Stanley – who had been joined by Slee – detected a second source, Taurus A, which would later be identified with the Crab Nebula which is the remnant of a supernova reported by Chinese astronomers in A.D. 1054 (Mitton, 1978: 15). Shortly after this they detected two other sources, Virgo A and Centaurus A, and at least two other possible sources.

Thus, 1947 heralded the genesis of non-solar radio astronomy in Australia. This work was of fundamental significance in radio astronomy because it raised a number of key questions: What was the origin of these discrete sources? How many other sources were there, and how were they distributed? What was the cause of the variability in the Cygnus source? Was it possible that most of the 'cosmic static' originated from discrete sources rather than large clouds of ionized interstellar gas as Jansky and Reber had proposed?

While the majority of observational work was being conducted at the field stations, in 1948 some important high frequency solar observations were conducted by Norman Labrum, Harry Minnett and Jack Piddington using a converted WWII search light antenna (mirror) located in the 'Eagle's Nest' on top of the Radiophysics Laboratory in the grounds of Sydney University. They found the day-to-day variation in radiation at the higher frequency of 24,000 MHz was only a few percent and that the emission was consistent with 84% of the radiation coming from a uniform disk and 16% from a narrow ring around the circumference which they concluded was consistent with Martyn's prediction of limb-brightening (Piddington and Minnett, 1949b). This instrument was also used to observe the Moon at 24,000 MHz (Piddington and Minnett, 1949a). From these observations they concluded that the radio thermal emission was consistent with the Moon having a solid surface covered by a thin layer of dust about 40 cm in depth.

It was also at this time that the need for a new field station arose. At a site at Bankstown aerodrome, R.F. Treharne and A. Little were engaged in an program to develop a 100 MHz solar interferometry instrument that would become the swept-lobe interferometer described in Section 10.4.5. In the September 1947 monthly report to the Solar Noise Research Group, Treharne and Little noted:

> "Our building at Bankstown has been "sold". Eagles and Burgman are attending to the acquisition of another building." (Pawsey, 1947f).

In November 1947, they reported that:

> "The gear is now installed at Bankstown and that drift interference patterns have been obtained. The motor phase shifter is still under construction." (Pawsey, 1947c).

By April 1948, Payne-Scott was assigned to supervise the swept-lobe interferometry project, replacing Treharne. Payne-Scott was also still working with M. Clark at the Hornsby Valley field station, recording solar observations with a circularly-polarised 85 MHz aerial. In their monthly report Payne-Scott and Little noted:

> "A search for a site to replace Bankstown has resulted in the choice of Potts Hill reservoir (which should also provide a suitable stretch of water for K-band interferometry); negotiations with the Waterboard have begun. Meanwhile equipment is being made to replace that stolen, and some obvious faults in the system are being remediated" (Pawsey, 1948c).

The report also noted that Christiansen had assumed responsibility for the 200, 600 & 1,200 MHz solar observations at Georges Heights. In his report he noted that it was not possible to perform measurements due to problems with the alt-azimuth mount of the 16-ft × 18-ft Paraboloid.

In a letter to Pawsey, McCready reported:

> "We've found a good site on a large area of fenced in and reasonably guarded land at the Potts Hill reservoir between Lidcombe and Bankstown. Takes only 5 minutes longer to reach there by car than Georges Heights and large areas of water offer some possibilities for Harry Minnett and K-Band interference patterns. By a fortunate coincidence the Water Board Engineer with whom arrangements have to date been conducted visited a RP party sometime ago and quoting him "knew all about Solar Noise". He is most anxious to help us." (McCready, 1948a).

The Water Board employee referred to by McCready, was H. A. Stowe who was the Chief of Electrical Engineering. Stowe had been one of the early Australian Amateur Radio Operators and he maintained a keen interest in the activities of the Radiophysics Division that continued even following his retirement from the Water Board in 1957 (Stowe, 1962).

By August 1948, Payne-Scott and Little had installed the Swept-Lobe Interferometer at Potts Hill and obtained their first lobe patterns (McCready, 1948c).

The new site at Potts Hill provided an opportunity to consolidate the solar program, and the 1 November 1948 partial solar eclipse that would be visible throughout south-eastern Australia provided the catalyst for action. The eclipse observations presented the rare chance to more accurately determine the locations of localised radio emission on the solar disk by observing the timing of their occultation by the Moon's disk during the eclipse. In the later part of 1948 therefore, the Radiophysics Division established Potts Hill as its main solar radio astronomy field station and over the first half of the next decade it would become the Division's major field station, before ultimately succumbing to the urban growth of Sydney's western suburbs.

9.1. The Division of Radiophysics

Immediately after World War II the focus of the Radiophysics Division had shifted to peacetime research. Pawsey (Figure 2) headed the overall research group of the Division, under Bowen. Sullivan (2005) has extensively discussed the beginnings of radio astronomy in Australia, including the key role that both Bowen and Pawsey played in leading and fostering the development of a group that by the late 1950s had produced more research papers in radio astronomy than any other group in the world.

Immediately following the war, the research group comprised four main subgroups: Propagation, Radar Meteorology, Mathematical Physics, Standards and Vacuum Physics. The Propagation group was soon renamed the Solar Noise Group and following that became known as the Radio Astronomy Group in April 1949 (Christiansen, 1949a).

Figure 2: Dr. J.L. Pawsey (Courtesy of ATNF Historical Photographic Archive: B7454-1).

The June 1947 structural chart of the Radiophysics Division shows that the Propagation Group was organised into four subgroups (1947):

a)	Piddington:	Minnett
		Hindman
b)	McCready:	Payne-Scott
		Yabsley
		Smerd
		Bolton
		Stanley
		Slee
		Medhurst
c)	Kerr:	Shain
		Higgins
d)	Munro:	Treharne

Piddington was the senior member of the Group as a Principal Research Officer. The next most senior member was McCready as a Senior Research Officer. Of this group, Piddington, Minnett, Hindman, Payne-

Scott, Yabsley and Smerd would all go on to conduct research at the newly-established Potts Hill field station.

It is interesting to note when the term 'radio astronomy' was first adopted at the Radiophysics Division. During a visit to the U.S. in 1947-1948, Pawsey was invited to attend a meeting that was being organised by C.R. Burrows of Cornell University. It was intended that this meeting be held immediately preceding the March 1948 I.R.E. Convention. The title of the meeting was *Microwave Astronomy*. In reply to a letter from Pawsey on the topic Bowen stated:

> "I don't think much of Burrows' invention of the title "Microwave Astronomy". A lot of it is certainly not microwave and I am not at all sure whether it is astronomy." (Bowen, 1948c).

Pawsey did not attend this meeting, but while in the U.K. received another invitation to submit material for a session during the May 1948 U.S.R.I. Conference, titled *Radio Astronomy*. This session of the conference was chaired by J.P. Hagen. This time in response to Pawsey's advice, Bowen wrote:

> "Incidentally, I like the term "Radio Astronomy" much better than Burrows' effort and we might very well consider adopting it generally." (Bowen, 1948d).

Just over a year later the term 'radio astronomy' was formally adopted by Radiophysics with the change of name of the *Propagation Committee* to the *Radio Astronomy Committee*, as noted in the minutes of the meeting of the 11 April 1949 (Christiansen, 1949a).

The headquarters for the Radiophysics Division was located on the grounds of Sydney University. This acted as the hub of activity for the Division. From its beginnings in radar research the Division had operated a number of remote field stations. Originally these were generally at military sites. However, with the shift to peace-time activities new sites were being sought out. For a discussion of operations at the various field stations see Orchiston and Slee (2005a).

Pawsey coordinated the activities of the field stations and the overall research programme through a series of regular meetings at headquarters, but also by regularly visiting the field stations. Although he had increasingly less time for his own research, he had a major influence and his contribution was acknowledged in nearly all of the published works emanating from the Radio Astronomy Group.

J.D. Murray's recollection (2007) of the early meetings (1948-1951) of the Solar Noise Group was that it always seemed simple to get support to justify solar research within the group, but much harder to justify looking at cosmic sources. He felt this was left over from experiences during World War II. The passage of two German warships through the English Channel undetected by radar (presumably due to solar noise) meant that any research that could shed light on solar noise was always well supported. This would change substantially in later years with the success in identifying discrete cosmic sources (Bolton et al., 1949).

Pawsey promoted a strong relationship between theoretical and observational work. On 18 May 1948 he wrote a three page memo to the group outlining his views on the relationship between pursuing research on ‘theoretical lines’ and ‘exploratory lines’. He concluded his memo as follows:

> “And finally may I remark that a research group is not healthy unless the theoreticians indulge in forceful criticisms of the practical people and vice versa. Out of the clash of personalities come ideas, but it is equally essential that the criticism should be open and friendly and accompanied by a generous measure of admiration for the other man’s speciality even though it happens to be a lowly or useless branch of human achievement in comparison with one’s own.” (Pawsey, 1948b).

In 1948 Christiansen had joined the Division as a Senior Research Officer, which was of the same level as McCready and second only in seniority to Piddington. After initially working at the Georges Heights field station, Christiansen joined Payne-Scott and Little at the newly-established Potts Hill field station to observe the partial solar eclipse of 1 November 1948. He was joined by two other teams, Piddington and Hindman, and Minnett and Labrum, who conducted their own observations of the eclipse at different frequencies. Potts Hill became the centre of the Division’s solar program, with the exception of the solar spectroscopy work which had been initiated at Penrith by Paul Wild and then relocated to Dapto.

In 1951, Kerr returned from a fellowship in the U.S. and took over from Christiansen the work program on the newly-discovered H-line. Christiansen returned to his solar research, which he maintained for the remainder of his time at Potts Hill.

As the activities of the field stations expanded, coordination became more difficult and at times their activities could also be in competition. The minutes of the meeting of senior officers of the Radio Astronomy Group held on 21 August 1951 detailed the demarcation of research and some of the protocols to be applied within the group (Mills, 1951a). In attendance at this meeting were Pawsey, Mills, Bolton, Piddington, Bracewell, Shain, Gardner, Smerd, McCready and Wild. The allocations, listed in Table 1, were agreed:

Table 1 - Research Topic Allocations

Area	Research Focus	Principle Researcher
Observational Research:		
Ionosphere	D-region temperature and echoes	Gardner
Ionosphere	Long waves	Bracewell
Sun	Metre waves – Interferometry and Spectrometry	Wild

Sun	Decimetre waves – Examining and continuing records	Piddington
Sun	Decimetre waves – Interferometry	Christiansen
Cosmic	18 mc/s & 19 mc/s	Shain
Cosmic	Metre waves – Cliff Interferometry	Bolton
Cosmic	Metre waves – Michelson Interferometry	Mills
Cosmic	1420 mc/s – Preliminary experiments	Christiansen (Kerr)
Cosmic	1420 mc/s – Development of gear	McCready
Cosmic	1420 mc/s – Subsequent work	Kerr (tentative)
Non-Observational Research:		
Hydrogen	Theory of spectrum emission	Wild
Sun & Cosmic	Review of emission mechanism	Piddington
Sun & Cosmic	Review of quiet Sun	Piddington
Sun	Burst theory	Smerd
Sun	Editing of QBSA in place of Allen	Smerd
Sun	Terrestrial (meteorological) relations and exploratory investigations	Piddington

At this time, Piddington, Christiansen and Kerr were the research leaders at Potts Hill. It was agreed at this meeting, that although there was a formal demarcation of research areas, the general goal was still to promote informal collaboration and cooperation. It was also agreed that no new fields of research would be undertaken without first discussing the research with Pawsey, and that all new research papers would be first presented in draft to the Radio Astronomy Group for review.

At times there were also disputes as to priorities on research within a field station. A good example of this was a dispute between Payne-Scott and Bolton at the Dover Heights field station. As Pawsey noted in a letter to Bowen dated 8 December 1947:

> "I had a letter from Lindsay [McCready] in which he mentioned that there had been some sort of showdown between Ruby [Payne-Scott] and John Bolton. This is not unexpected to me as Ruby seemed to me to be getting in the way at Dover [Heights]. As I understand it, Lindsay has the situation well under control, at any rate when he wrote the letter, having arranged a transfer of Ruby's work to Hornsby. I don't think Lindsay had mentioned this to you, and I am only doing so because there might be some future complications in which Lindsay might require your backing. My feeling on the matter is that Lindsay's actions are likely to be above reproach. I also think that Bolton has, through his hard work and effective results, earned the right to take control of Dover, so that anyone working there, shall be doing so at his invitation." (Pawsey, 1947e).

This example shows that Pawsey supported a hierarchy of operations at the field stations with clear lead researchers.

Under Pawsey's leadership the Group took a very open and active approach to research within the Group, but also with external groups, often sharing research results prior to publication. From the very beginning the Group had a very strong relationship with the Commonwealth Observatory at Mount Stromlo. Pawsey also maintained strong relationships with overseas groups, particularly in the U.S., U.K, Canada, France and the Netherlands. Regular visits were conducted and Visiting Fellowships were supported.

As a product of World War II the Group had access to a vast store of surplus military equipment on which to draw for the construction of their original instruments (Sullivan, 2005:12). As time progressed the Group grew and the size and complexity of instruments and projects outstripped the resources of the ex-military stores. Funding of projects was always an issue, requiring a great deal of resourcefulness and creativity in constructing new instruments. However, ultimately the early success of the Group led to increased tension and competition over which projects would receive funding.

By the mid-1950s research at the Potts Hill field station had reached its peak. Insufficient space at the field station and radio interference from the growing suburbs of Sydney had begun to take their toll. Mills was the first to relocate his discrete source research, initially to Badgerys Creek and then to the Fleurs field station. He was later followed by Christiansen who needed a large area to construct his cross array. The solar monitoring work continued at Potts Hill for a period in support of both Dapto and Fleurs. Finally, the H-line survey work at Potts Hill was transferred to Murraybank and then to Parkes. The Potts Hill 36-ft aerial continued to be used as a test bed for receiver trials until the 64-m Parkes telescope was commissioned in late 1961.

10. RADIO ASTRONOMY AT POTTS HILL

This Section begins with a short history and description of the Potts Hill site. It then introduces the principal researchers who carried out observations at Potts Hill, and the instruments they used. Finally, the overall research contributions are examined in detail.

10.1. The Potts Hill Site History

Potts Hill owes its name to Joseph Hyde Potts, who bought the original allotment of land in 1834 from H.G. Douglas (Perrin, 2006). J.H. Potts was the first employee of the first bank in Australia, the Bank of NSW, which later became Westpac Banking Corporation. He was reputed to be a keen mathematician and rose to the position of accountant. He was also an excellent draughtsman and designed the bank's first notes (Macarthur, 1998).

The rapid growth of Sydney and its suburbs in the late 19th century outpaced the ability of the infrastructure, particularly sanitation and the water supply, to cope. As a result of growing public concern, in 1867 the NSW Government appointed a Commission of Enquiry to establish a system of supply of fresh drinking water for the city of Sydney and its suburbs (Lewis, 1979). The Commission heard evidence for nearly two years before recommending the construction of a scheme known as the Upper Nepean Scheme. This scheme involved tapping the head waters of the Nepean River and its tributaries, the Cataract, Cordeaux and Avon Rivers (Beasley, 1988). A series of weirs was to be used to divert water and feed tunnels, canals and aqueducts into a system known as the Upper Canal. From here the Upper Canal transported water to the Prospect storage reservoir and then via the Lower Canal to a basin at Guildford (now called the Pipe Head). It was then to be piped to a service reservoir constructed at Potts Hill and then on to Crown Street in the city of Sydney.

Much controversy ensued following the selection of this scheme, primarily fuelled by unsuccessful rivals. At the same time Sydney's infrastructure continued to deteriorate. In 1877, the NSW Government employed the English civil engineer W. Clark to conduct an independent review. This review endorsed the original selection, but also recommended that a number of additional reservoirs be constructed to cope with the increasing demand. In 1879 an Appropriation Act was passed authorizing a public works loan for the Upper Nepean Scheme. Work commenced in 1880 and continued until 1888 when the system was handed from Public Works to the Board of Water Supply and Sewerage. The Board had been constituted at the same time as construction was commenced, but was only called into being on completion of works (2006).

As Sydney continued to grow, the need to again upgrade its water supply became apparent and in 1913 construction of a second reservoir was commenced and included the construction of a railway link from Lidcombe to Potts Hill. This reservoir was significantly larger than the first and took ten years to complete. All twenty-two hectares of the reservoir was lined by concrete that was laid by hand (Beasley, 1988).

Since 1923 the layout of the reservoirs has remained the same and they continue to provide an integral part of Sydney's water supply. They have more recently been Heritage listed by the NSW Government in recognition of their historical importance to the development of Sydney (2006).

For the period 1948 to 1955 Potts Hill also served as a migrant camp for future Water Board employees. Many of these migrants worked on the City Water Tunnel which was constructed from 1946 to 1957.

In 1948, Radiophysics Division obtained permission from the Board of Water Supply and Sewerage to operate a field station on vacant land adjacent to the Potts Hill service reservoir. In a letter dated June 1948 reporting on progress during Pawsey's absence in the U.S. and U.K., McCready (1948b) noted:

> "We are still in the paper stage of negotiations with the Water Board, but all will be quite OK – not the slightest evidence to suggest that they will offer less than 100% cooperation."

This was the Division's second major field station after Dover Heights and by 1952 had become the Division's largest field station. The operating arrangement with the Water Board was largely informal in nature. In March 1952 Pawsey met with the President of the Water Board, Dr. T.H. Upton, to seek permission to expand the operations at the field station (Pawsey, 1952c). This was readily agreed to and they also agreed to continue the operation on an informal basis. Dr. Upton requested an article of general interest that could be included in the Water Board Journal and this was subsequently prepared by F.J. Kerr (1953b).

In June 1954 the Water Board began construction of a welding workshop at Potts Hill (Kerr, 1954a). Electrical interference was becoming an increasing problem and the interference from the welding shop when it became operational exacerbated the problem.

Radiophysics continued operations until 1962 when the field station's operations were fully transferred to other field stations.

10.2. The Potts Hill Site Map

Potts Hill is located 23 km south-west of the city centre of Sydney (Figure 3).

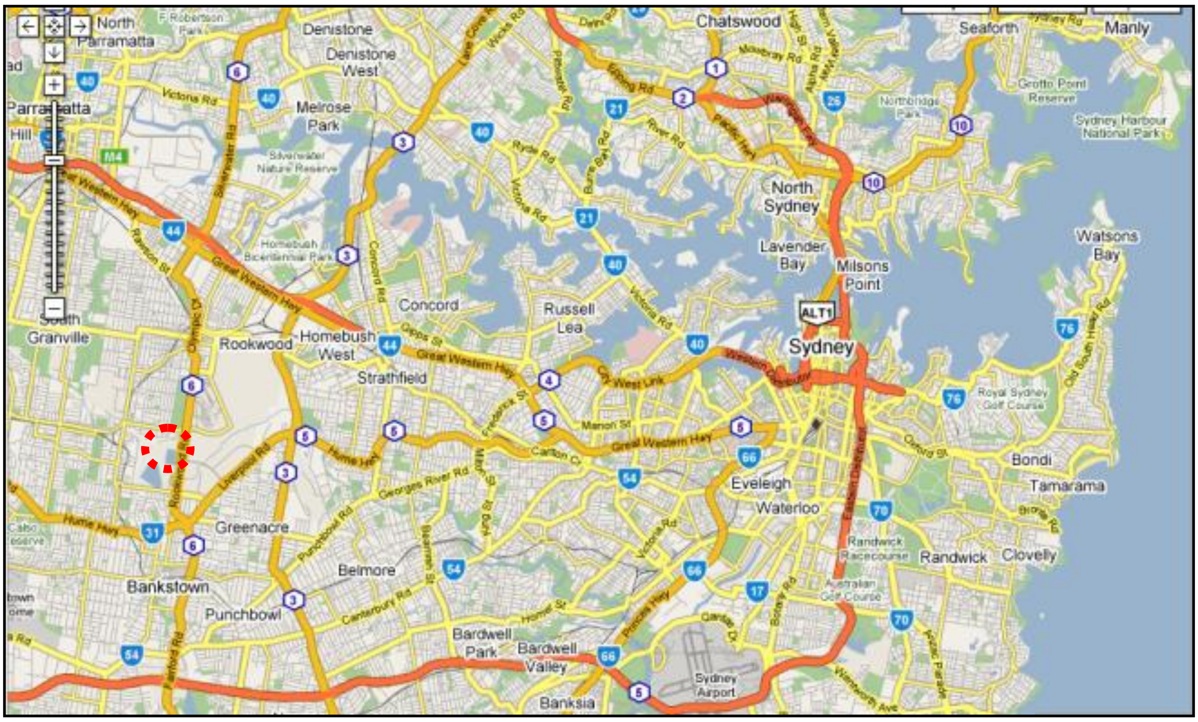

Figure 3: Potts Hill (circled) is located 23km to the south west of the central business district of Sydney (©2007 MapData Science Pty. Ltd, PSMA).

Potts Hill is part of the Bankstown local council region and is now totally surrounded by the western suburbs of Sydney. In 1948 Potts Hill was still on the outskirts of surburban Sydney. Today, the resevoirs are bordered by Rookwood Road to the east and the Regents Park rail line to the west.

Radiophysics occupied the vacant land to the immediate north of the No.1 reservoir (Figure 4). The southern and eastern sides of the No.1 reservoir were used for the east-west and north-south arms of the solar grating arrays.

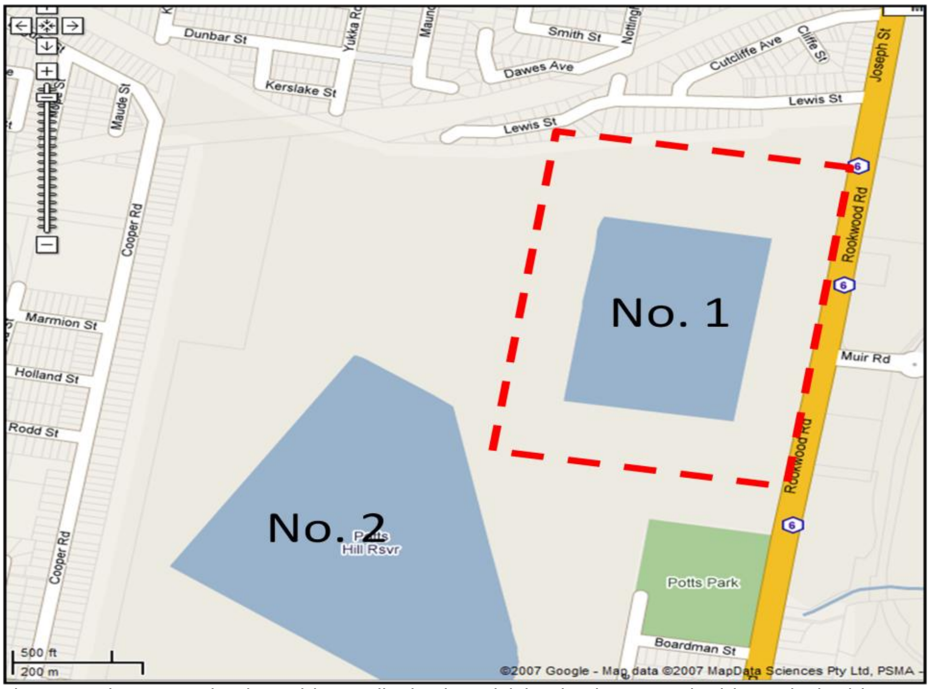

Figure 4: The vacant land used by Radiophysics Division is shown marked by a dashed box. In this diagram North is up. (© 2007 MapData Science Pty. Ltd, PSMA).

Figure 5 shows an aerial view of Potts Hill taken from the north looking south. The main part of the field station is shown in the foreground of No.1 reservoir.

Figure 5: An aerial view of Potts Hill taken from the north looking south. The main part of the field station is in the immediate foreground (Courtesy of ATNF Historical Photographic Archive: B3253-1 Image Date: 19 March 1954).

In a letter to Pawsey in 1948 soon after the field station was established, McCready notes:

"Potts Hill field station [is] a beautiful site, with all the wattle trees in full bloom." (McCready, 1948c).

Figure 6 shows an equivalent view to Figure 5 today. The layout of site remains much the same as the 1950's. The trees have grown somewhat and the reservoirs have been covered. Nearly all traces of the occupation by Radiophysics have gone. Only the remains of some foundations and two small huts remain.

Figure 6: Potts Hill in 2007. The image shows a similar aspect to Figure 4 (©2007 MapData Science Pty. Ltd, PSMA Image ©2007 DigitalGlobe).

Figure 9 shows a closer view of the field station, again taken from the north looking south. The 36' Transit Parabola is visible in the foreground and the 16-ft×18-ft Paraboloid is just visible on the left of the image. The Solar Grating Arrays can be seen in the background on the southern and eastern sides of the reservoir. Figure 10 shows the position of the Mills Cross prototype near the 16-ft × 18-ft Paraboloid.

Figure 7 shows a sketch of the original plans for Potts Hill field dating from mid 1948. The plan shows the proposed site at the northern end of the No. 1 reservoir. In this plan south is up.

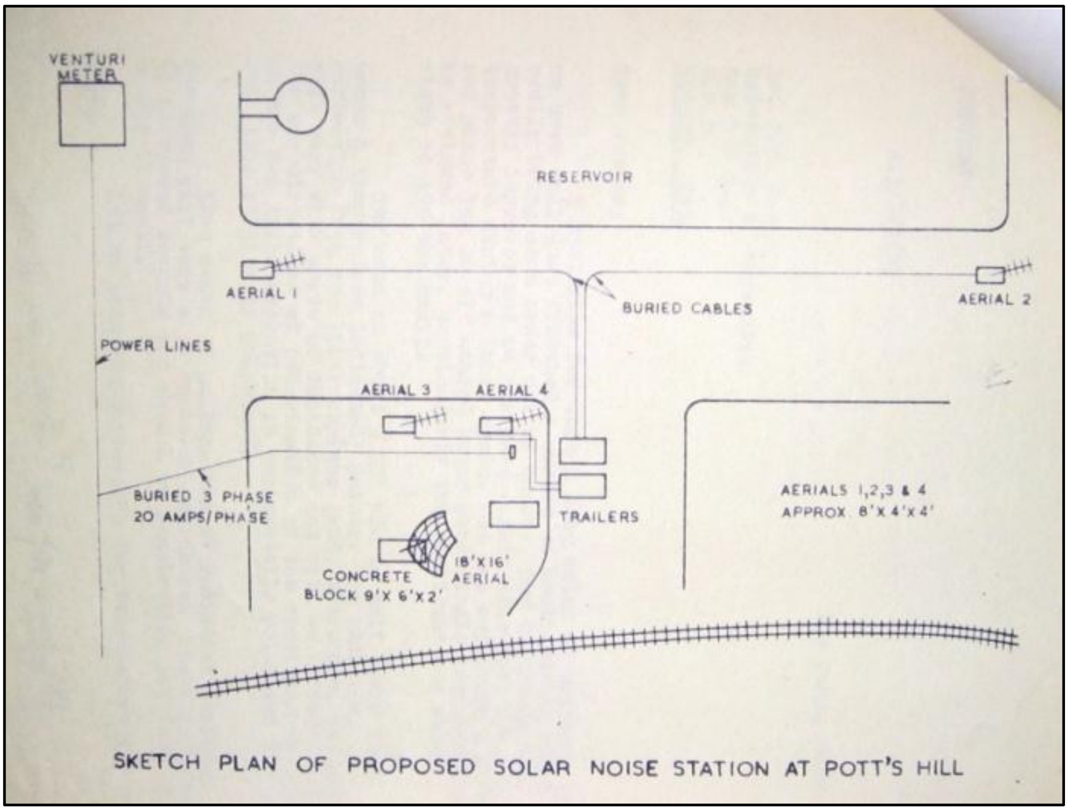

Figure 7: A sketch plan for the Potts Hill field station from mid June 1948. At this stage only the Swept-Lobe Interferometer, the 16-ft x 18-ft and two Yagi arrays appear on the plan (Courtesy of the National Archives of Australian – 972098 - C3830 - A1/1/1 Part 3 Box 1).

In this sketch plan the positions of the Swept-Lobe Interferometer aerials (Aerials 1 to 3) had not yet been aligned on an east-west baseline. Aerial 4 was the reference aerial used in conjunction with the interferometer. The 16-ft × 18-ft Paraboloid is shown on the plan in its correct position. This should be compared to Figure 8 which shows the full complement of instruments that were eventually installed at Potts Hill.

Figure 8 shows the locations of the major instruments that were operated at Potts Hill. These are described in detail in Section 10.4.

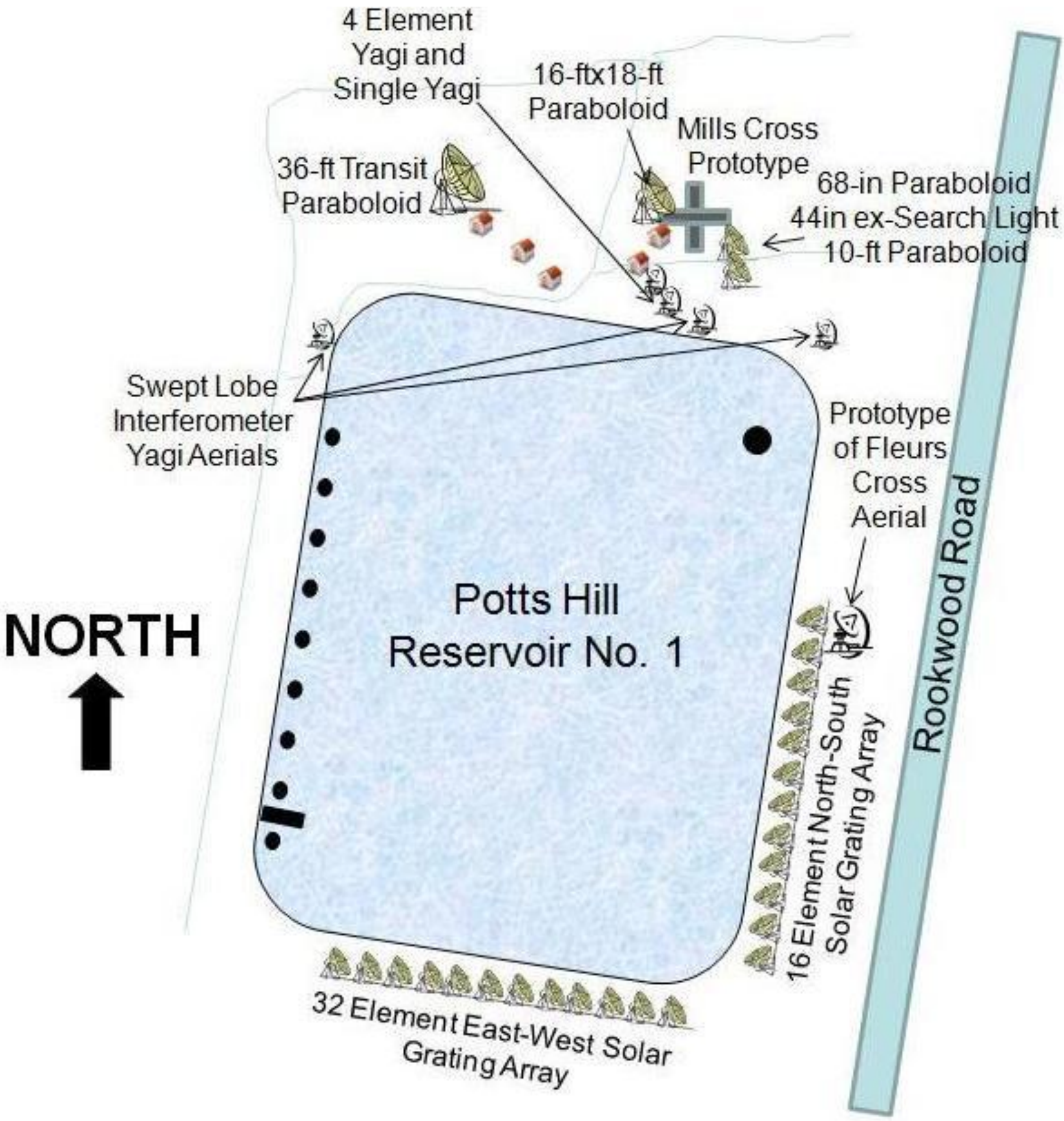

Figure 8: Site Map showing location of major radio telescopes used at Potts Hill.

Figure 9: A closer aerial view of the Potts Hill field station looking toward the south. The E-W and N-S Solar Grating Arrays are visible on the far and left banks of the reservoir respectively. The main field station with instruments marked by circles is visible in the foreground. From left to right these are the 16-ft×18-ft Paraboloid, the Four Element Yagi, the central Yagi of the Swept-Lobe Interferometer, the Single Yagi used in conjunction with the Swept-Lobe Interferometer, the 36-ft Transit Parabola and its reference aerial. The 68-in and 44-in Parabolas are just outside the image located to the left (due east) of the 16-ft×18-ft Paraboloid (Courtesy of ATNF Historical Photographic Archive: B3475-2 Image Date: 19 March 1954).

Figure 10: Potts Hill field station looking west with visible instruments marked by circles and the crossed lines. The Mills Cross prototype is in the foreground. Next to it is the 10-ft Portable Parabola and the 16-ft × 18-ft Paraboloid. In the background are the 36-ft Transit Parabola and its reference aerial. The Yagi arrays are just out of the picture to the left, however one of the equipment trailers is visible. The 68-in and 44-in Parabolas are behind the photographer and to the left (Courtesy of ATNF Historical Photographic Archive: B3171-4 Image Date: 7 October 1953).

10.3. The Potts Hill Researchers

This section provides a brief overview of the people who conducted research at Potts Hill. The instruments they used and their research programs are described in detail in Sections 10.4 and 10.5.

At the outset, three main groups began research at Potts Hill. The first of these groups was headed by Ruby Payne-Scott who had taken over development of the Swept Lobe Interferometer and was working with Alec Little. This work continued until Payne-Scott resigned in 1951. Figure 11 shows Payne-Scott and others at Potts Hill in 1948.

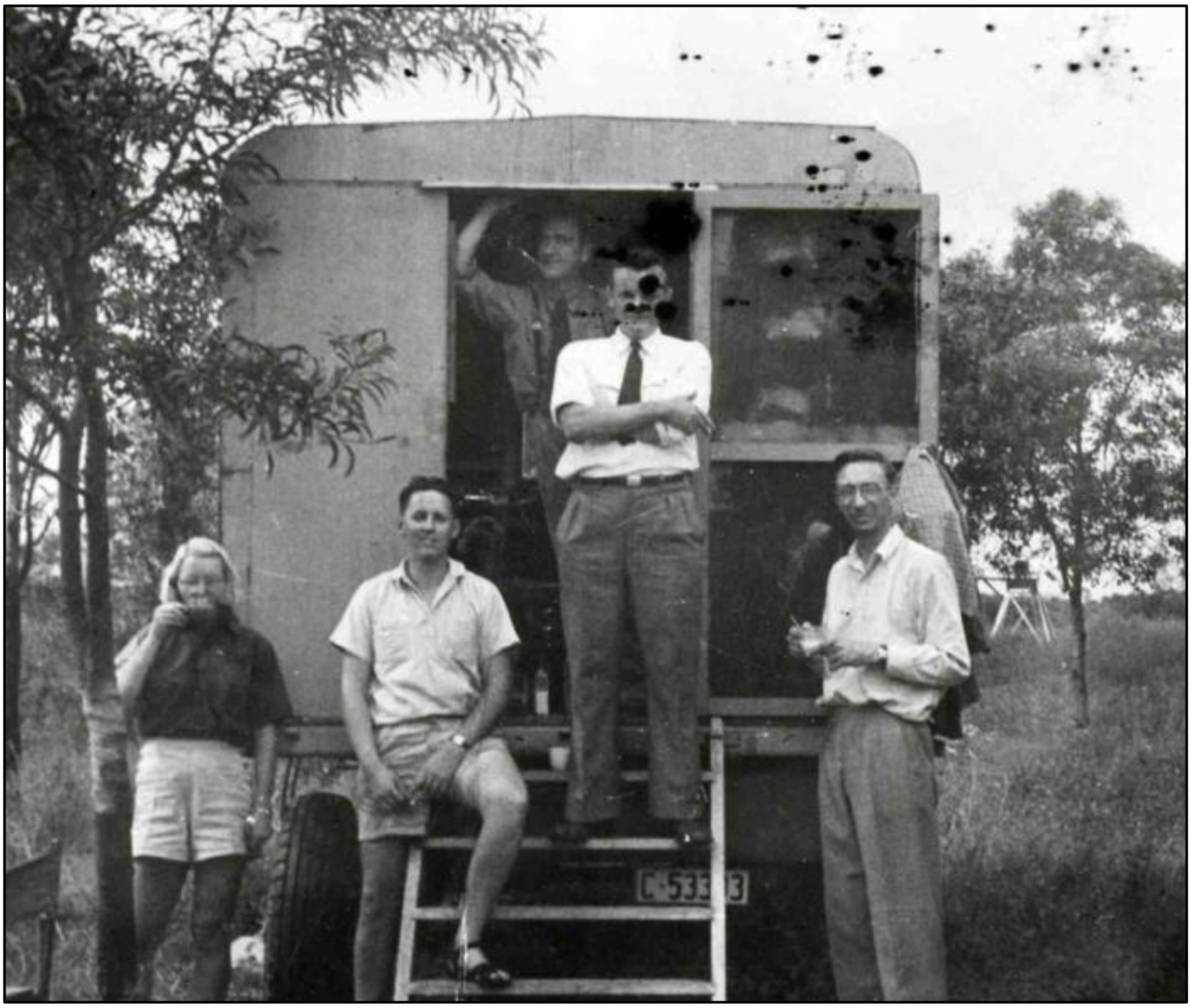

Figure 11: Potts Hill in 1948-9. From left to right are Ruby Payne-Scott, Alec Little, George Fairweather, Alan Carter and Joe Pawsey (Courtesy of ATNF Historical Photographic Archive: B12759-1).

Christiansen was placed in charge of the main solar instrument at Potts Hill, the 16-ft×18-ft Paraboloid and initially worked with Yabsley and Mills and later with Warburton on the Solar Grating Array. After a short stint in solar research followed by some initial discrete source investigations, Mills left the group to conduct his own research on discrete cosmic sources and to set up the Badgerys Creek and then Fleurs field stations. He returned briefly to Potts Hill to work with Alec Little on the construction of the prototype for the Mills Cross. The third group was lead by Piddington working with Minnett, Labrum and Hindman. From the outset Piddington was interested in conducting cosmic as well as solar research. His interests shifted away from observational research to concentrate on theoretical research. He later collaborated with Wade and Trent, with Hindman taking a lead role in observational research.

The team structures during the life of the field station were not rigid. At different times, different alliances were formed. For example for the initial H-line confirmation, Hindman joined Christiansen on the receiver development and initial survey. The H-line work was subsequently taken over by Kerr on his return from a fellowship at Harvard Observatory in the U.S., and Hindman continued to work with Kerr for the remainder of the survey.

Several junior researchers began their careers at Potts Hill, notably Davies and Robinson. Davies worked with Piddington on solar research and Robinson on the H-line survey with Kerr. In addition, two Indian radio astronomers, Swarup and Parthasarathy, took part in a Colombo Plan programme research fellowship at Potts Hill. Unfortunately, Radiophysics had no budget to support research students undertaking their PhD research. This meant that the up and coming researchers were forced to seek positions overseas to further their careers. Pawsey had noted this serious limitation on talent development as early as 1951 (Sullivan, 2005: 28).

Both Christiansen and Mills left Radiophysics near the end of the life of the Potts Hill field station. They had championed the construction of alternate instruments to that of the Parkes Radio Telescope. Ultimately the Division's budget could not support these alternate instruments and Mills and Christiansen left the Division to pursue their research at the University of Sydney.

Of the Potts Hill Group, Minnett would go on to become Chief of the Radiophysics Division while Robinson would become a leader of the Astrophysics Group at Epping in the 1970s. Christensen, Mills, Minnett, Piddington and Robinson were all elected as Fellows of the Australian Academy of Science.

10.3.1. Christiansen

Wilbur (Chris) Norman Christiansen (1913-2007: Figure 12) joined Radiophysics in 1948 from Australian Wireless (Australasia) A.W.A. where he had worked on aerial design. He was unique amongst the early recruits to Radiophysics in that despite working on radio aerial design, he had harboured a long-term ambition to work as an astronomer (Sullivan, 2005: 14).

Christiansen was recruited into a senior role within the Division, filling a vacancy that had been created by Lehany's transfer to the Division of Electro-technology. He was soon established as the lead researcher of the solar research program at Potts Hills. One of his major achievements while at Potts Hill was the development of the Solar Grating Arrays.

Christiansen, working with Hindman, was also responsible for the Australian confirmation of the H-line detection. They went on to conduct a preliminary survey of the Milky Way and obtained the first indications of a spiral arm structure in our Galaxy based on neutral hydrogen observations. After completing the preliminary survey, Christiansen handed the leadership of the H-line research program to Kerr and returned to his solar research and the construction of the N-S Solar Grating Array.

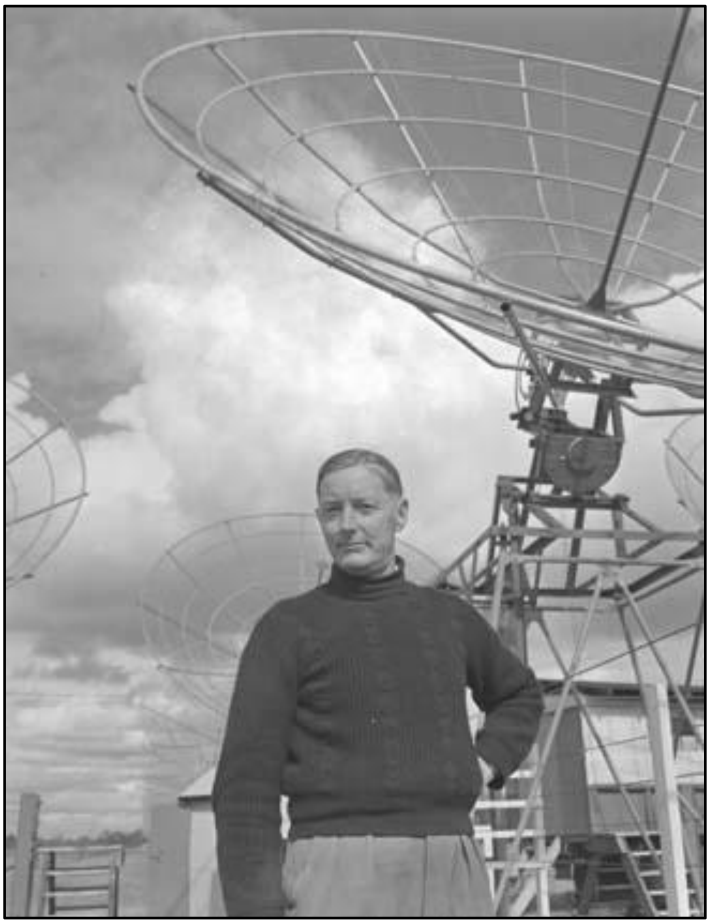

Figure 12: W.N. Christiansen in 1957 (Courtesy of National Archives of Australia: Image No. A1200, L23589)

In 1954, Christiansen spent a year as a Visiting Fellow at Meudon Observatory near Paris, France. On his return, he decided that rather than relying on earth rotational synthesis to produce two-dimensional scans of the Sun, it would be possible to construct a new type of array based on Mills' cross design that could produce daily two-dimensional images of the Sun. As Potts Hill had insufficient space to construct a cross array, Christiansen decided to move operations, joining Mills at the new Fleurs field station.

At Fleurs he built the 'Chris' Cross. This was a highly successful instrument that continued operation for many of years. Ultimately Christiansen sided with the group within Radiophysics that preferred the program of continuing with constructing special-purpose instruments rather than investing in the multi-purpose, but very expensive, Parkes Radio Telescope. He left Radiophysics in 1960 to join the University of Sydney where he continued with the development of what would become the Fleurs Synthesis Telescope.

'Chris' Christiansen died in Canberra on 26 April 2007. For a more detailed biography see Chrompton (1997).

10.3.2. Davies

Rod D. Davies (Figure 13) joined Radiophysics in January 1951 as a graduate recruit together with Warburton after having completed a Physics degree at the University of Adelaide. As part of his induction to the group he was assigned to work at Potts Hill under the direction of Christiansen. During 1951 he helped with the construction of the E-W Solar Grating Array as well as spending time at the Radiophysics Laboratory. His laboratory work led to collaboration with Piddington on an analysis of the long-term solar records and his first scientific publications.

Figure 13: R.D. Davies in 2001 (Courtesy of the European Space Agency)

After the announcement of the detection of the H-line in the U.S., Davies was assigned to help Christiansen and Hindman with the Australian detection attempt and the subsequent survey work.

In September 1953, Davies left Radiophysics to take up a position as an assistant lecturer in the Physics Department of Manchester University in the U.K. Here he began research at Jodrell Bank under Lovell and was involved in the start-up of the H-line group at Jodrell Bank. He went on to have a distinguished career in radio astronomy including the directorship of Jodrell Bank from 1988 to 1997. In 1992 he was elected as a Fellow of the Royal Society and is currently Emeritus Professor of Radio Astronomy at the University of Manchester.

For a more detailed overview of Davies' time at Potts Hill see Davies (2005).

10.3.3. Hindman

James (Jim) V. Hindman (Figure 14) was a long term member of the research team at Potts Hill. He started at Potts Hill working with Piddington on observations of the partial solar eclipse of 1 November 1948 and also worked with Christiansen on the multi-frequency solar observations program.

In 1951, he joined forces with Christiansen to work on the confirmation detection of the Hydrogen emission line and went on to make the first H-line survey of the Galaxy. On Kerr's return from the U.S., Hindman worked with Kerr on the construction of the 36-ft Parabola and then went on to survey both the Magellanic Clouds and the Milky Way at 21-cm.

Figure 14: J.V. Hindman in 1952 (Adapted from ATNF Historic Photographic Archive: B2842 Image Date: 8 August 1952).

Following completion of the H-line survey in 1959, Hindman worked with Wade on some source investigations at 1,400 MHz again using the 36-ft Parabola. This was to be the last program of observations at Potts Hill, and the last using the 36-ft Parabola.

Hindman continued a long association with Kerr, collaborating with him on H-line research using the Parkes Radio Telescope and publishing their last joint paper, part five of a series on a survey of the Milky Way, in 1970.

10.3.4. Kerr

Frank John Kerr (1918-2000: Figure 15) joined Radiophysics in 1940 having completed a BSc in Physics and an MSc on the refractive index of gases at radio frequencies with the University of Melbourne. The onset of WWII had prevented him from undertaking a PhD at Cambridge University; however he was subsequently awarded a DSc by Melbourne University in 1962. During the war years he worked on airborne radar and the effect of super-refraction on radar (Kerr, 1948).

Kerr's first foray into radio astronomy came in 1948 when he worked on a project to obtain radar echoes from the Moon (Kerr et al., 1949). He also went on to consider the feasibility of obtaining echoes from the other planets and the Sun (Kerr, 1952).

In 1951, Kerr was awarded a Fulbright Travel Grant and a research scholarship to Harvard to study astronomy. He was the first member of Radiophysics to formally undertake studies in astronomy. It was during his time at Harvard that the 21-cm hydrogen emission line was first detected. A full description of this discovery and Kerr's involvement is discussed in section 10.5.2.2.

Figure 15: F.J. Kerr in 1952 (Adapted from ATNF Historic Photographic Archive: B2842 Image Date: 8 August 1952).

Kerr returned to Australia in 1952 to take over leadership of the H-line research program from Christiansen. A new dedicated 36-ft Transit Parabola was constructed at Potts Hill and working with Hindman, Robinson and later M.S. Carpenter, Kerr conducted a survey first of the Magellanic Clouds and then the southern Milky Way. This survey was a major undertaking and would span from 1952 until the final paper in the series was published in 1959.

During 1952-1953, Kerr collaborated closely with Gerald de Vaucouleurs from Mount Stromlo Observatory to determine estimates of the rotation rates and hence masses of the Magellanic Clouds. This was the first time a galaxy's mass had been estimated based on radio data, as well as being the first detection of neutral hydrogen emission from an external galaxy. It was also one of the first examples of a joint optical and radio research project.

Kerr worked closely with the Leiden group which conducted the northern sky H-line survey from 1954 to 1957. Together, these two groups produced the first maps of the spiral-arm structure of our Galaxy. One unique discovery in this period was the detection of a 'warp' in the galactic disk, which Kerr suggested may be the result of a tidal action from the Magellanic Clouds. Part of this work led to the redefinition of the coordinates of the Galactic Plane. The I.A.U. adopted these new coordinates in 1958. By this time Kerr had become one of the leading experts in the field of galactic structure.

With the first H-line survey completed, Kerr's involvement at Potts Hill also came to end as did the useful life of the field station itself. Kerr went on to be heavily involved in the conceptual studies for the

Parkes Radio Telescope and planning for future H-line surveys. In 1966, he left Radiophysics to take up a position as a Visiting Professor at the University of Maryland, where he remained until his retirement in 1987.

Besides research publications, Kerr also published popular articles on radio astronomy at Potts Hill (e.g. see Kerr, 1953c; Kerr, 1958a) including a report specifically for the Sydney Water Board (Kerr, 1953b).

For a more detailed biography see Westerhout (2000).

10.3.5. Labrum

Norm R. Labrum (Figure 16) had a unique association with Potts Hill, being a member of a team working with Harry Minnett on observation of the partial solar eclipse of 1 November 1948, which was one of the first solar observations at Potts Hill. He then had an 11 year break in his involvement before conducting observation of the 8 April 1959 partial solar eclipse.

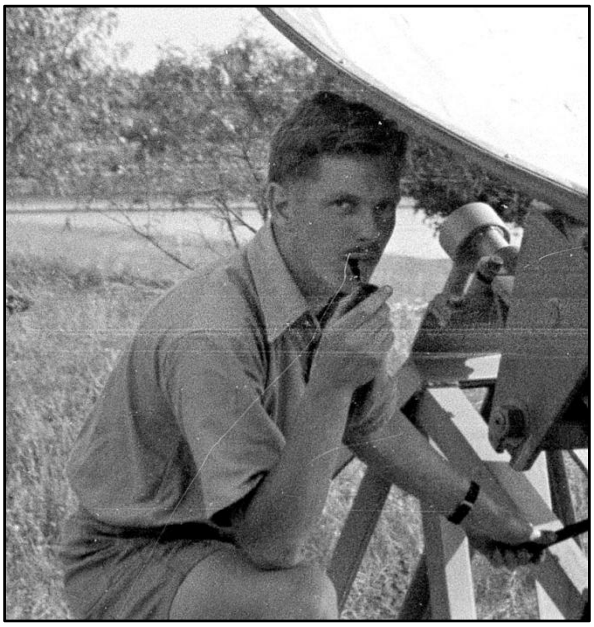

Figure 16: N.R. Labrum in 1948 at Potts hill attending to the 68-in Parabola (Adapted from ANTF Historical Photographic Archive: B1581-3 Image Date: 26 October 1948)

Labrum went on to a long career within the Division, specialising in solar radiophysics and culminating in the publication of the classic book titled *Solar radiophysics: Studies of emission from the Sun at metre wavelengths* (McLean and Labrum, 1985).

10.3.6. Little

Alec G. Little (1925-1985: Figure 17) had joined Radiophysics in 1940 as a messenger after leaving school at the age of 15. He soon acquired a position as a junior laboratory assistant and his abilities as a gifted technician were quickly recognised (Freeman, 1991: 94).

In 1947 Little was assigned to work with Treharne at Bankstown aerodrome on the development of the Swept-Lobe Interferometer. In 1948 Payne-Scott took over from Treharne and she and Little relocated the development work to Potts Hill. The Swept-Lobe Interferometer presented many technical challenges. However, these were overcome and Payne-Scott and Little went on to conduct a highly successful program of observations.

Figure 17: A.G. Little in about 1948-49 (Adapted from ANTF Historical Photographic Archive: B12759-1).

In 1951, Payne-Scott resigned from the Division. Little was much in demand as a skilled technician and in 1952 he joined Mills to work on the design and construction of the Mills Cross Prototype at Potts Hill. The prototype proved highly successful and led to the construction of the full scale Mills Cross at the Fleurs field station.

Little went on to work with R.Q. Twiss and then took two years leave as a research associate at Stanford University that had been organised by Ron Bracewell. During this period Little obtained his MSc with research on parametric amplifiers. On his return to Sydney he decided to leave Radiophysics and joined Mills at Sydney University. He went on to a distinguished career including the Directorship of the Molonglo Radio Observatory, until his untimely death of a sudden heart attack on March 20, 1985.

For a more detailed biography see Mills (1985).

10.3.7. Mills

Bernard Y. Mills (Figure 18) had only a brief association with Potts Hill, although he went on to have a very distinguished career in radio astronomy.

Mills' first foray into radio astronomy was as part of a team lead by Christiansen conducting observations of the partial solar eclipse of 1 November 1948. Prior to this Mills had worked on wartime research with Radiophysics. Mills was keen to establish an independent research topic and decided to investigate the discrete radio sources. He used the Swept-Lobe Interferometer in its static lobe mode to examine Cygnus A. Working with Thomas he established a refined position estimate for the source and determined that the observed source fluctuations were due to the F-region of the ionosphere. Although he initially proposed an optical identification of the source with a faint galaxy, he was discouraged by Minkowski from making the association due to the large positional errors still present in the measurement. In fact, it would transpire that this galaxy was the source of the radio emission when a later more accurate position was determined at Cambridge.

Figure 18: B.Y. Mills in the mid 1950s (Adapted from W.T. Sullivan).

These initial observations led Mills to further explore the discrete sources using interferometry techniques. At this point he out-grew Potts Hill and moved his observations to a new field station at Badgerys Creek.

He returned briefly to Potts Hill in 1952 to construct a prototype of a new cross-type radio telescope which would become known as the Mills Cross. The prototype was highly successful and made the first radio-frequency detection of the Magellanic Clouds. The full scale version of this array was later constructed at the Fleurs field station and was the main instrument used for survey and discrete source investigations. The subsequent history of observations and the discrete source survey controversy with Cambridge has been described in detail by Mills (1984) (also see Sullivan, 1990).

10.3.8. Minnett

Harry Clive Minnett (1917-2003: Figure 19) joined Radiophysics in April 1940 soon after graduating from Sydney University. He was attached to Pawsey's radar research group and involved in the wartime radar development work.

In 1947 Minnett teamed up with Piddington to conduct observations at microwave frequencies on the Sun and Moon, initially from the roof top at Radiophysics headquarters. Later, Minnett, working with Labrum, was one of the first to conduct observations at the Potts Hill field station. They observed the partial solar eclipse of 1 November 1948 from Potts Hill.

Following the eclipse observations, Minnett worked with Piddington on a galactic source survey that resulting in the discovery of the discrete source Sagittarius-A at the centre of our Galaxy (Piddington and Minnett, 1951a). Piddington and Minnett were keen to continue their galactic survey work and proposed the construction of a larger 20-m Parabola. However, their proposal was not supported due to the increasing funding competition for building instruments such as the Mills Cross.

Figure 19: H.C. Minnett (after Thomas and Robinson, 2005).

In 1952 Minnett left radio astronomy with his appointment as leader of the Radiophysics Microwave Navigation Group where he worked with Yabsley. In 1955 he returned to radio astronomy when he was appointed by Bowen as the liaison officer to the design company Freeman Fox and Partners in the U.K. who had been awarded the contract for the design study of the 64-m Parkes Radio Telescope.

Minnett continued a career in both radio astronomy and navigation aids. In September 1978 he was appointed as Chief of the Division of Radiophysics and retired in 1981.

For a more detailed biography see Thomas and Robinson (2005).

10.3.9. Parthasarathy

R. Parthasarathy joined Radiophysics in March 1953 together with Govind Swarup (see section 10.5.1.3) as part of a two-year Colombo Plan Fellowship. Together they conducted research at Potts Hill in the second year of their Fellowship. They used the E-W Solar Grating Array, modified to operate at 500 MHz, to investigate limb brightening of the Sun. Their findings of the evidence supporting limb brightening at 500 MHz was published in a summary paper in *The Observatory* and two detailed papers in the *Australian Journal of Physics*.

Parthasarathy had the misfortune to fall into the Potts Hill reservoir, but was rescued by his friend Swarup (2006).

On completion of the Fellowship, Parthasarathy returned briefly to India before accepting an appointment at the Geophysical Institute, University of Alaska. He remained with the University of Alaska until his retirement as Emeritus Professor of Physics.

10.3.10. Payne-Scott

Ruby Violet Payne-Scott (1912-1981: Figure 20) was one of the founding members of Radiophysics' radio astronomy group. She had graduated with first class honours in mathematics and physics from Sydney University in 1933 and in 1936 obtained her Masters in Physics becoming only the fifth woman in Australia to obtain an advanced degree in physics.

Figure 20: R.V. Payne-Scott (Courtesy of Miller Goss).

After completing her Masters, she worked in medical research in cancer radiology before joining Amalgamated Wireless Australia (AWA) as a librarian. In 1941 she joined Radiophysics as an Assistant Research Officer. Here she quickly gained a reputation for her forthright personality, intellect and technical skill. She worked with Pawsey in the first unsuccessful attempt to detect cosmic radio emission in March 1944, and their subsequent classic solar investigation that introduced Fourier analysis to radio astronomy (McCready et al., 1947).

Payne-Scott continued her solar investigations, but soon came into conflict with Bolton at the Dover Heights field station over overlapping research interests. In a move to restore the peace, McCready relocated Payne-Scott to Hornsby field station (Pawsey, 1947e).

In 1948, she took over leadership of development of the Swept-Lobe Interferometer and its subsequent installation at the new field station at Potts Hill. Little and Payne-Scott used to Swept-Lobe Interferometer to conduct a highly successful series of observations, locating the source of radio outbursts on the solar disk.

Even in the post-war period, the policy of the Commonwealth Civil Service remained that a married woman could not hold a permanent appointment in any Commonwealth organisation. Payne-Scott held the strong view that the marital status of an employee should not be the business of the Government. In 1944, she had married William H. Hall, but chose not to officially declare her marital status. Such a declaration would have meant that she could not be employed by Radiophysics in a permanent position, placing her at a significant seniority and financial disadvantage.

In 1951, with the pending approach of her first child, Payne-Scott made the decision to resign from Radiophysics. Her resignation was a major loss not only to Radiophysics, but radio astronomy as a whole. Pawsey highly valued Payne-Scott as a researcher. In 1952 he invited her to submit a paper to the URSI meeting that was being held in Sydney that year (Pawsey, 1952a). This meeting was one of the most important events in the history of Australian science and recognition of the achievements of the Radiophysics group. Although Payne-Scott did not submit a paper, she did attend the conference.

Payne-Scott never again returned to scientific research. Instead she concentrated on raising her two children and worked for many years as a high school teacher. She died of Alzheimer's disease on 25th May 1981.

For a more detailed biography see Williams (2004). Also, a book on the life of Payne-Scott is currently in preparation by Goss and McGee.

10.3.11. Piddington

Jack Hobart Piddington (1910-1997: Figure 21) was a long term member of Radiophysics having joined the group during the wartime development work on radar. In 1947, Piddington began research on solar and cosmic radio noise, shifting his focus away from the application of radar for peace-time purposes.

Piddington was one of the first to conduct observations at Potts Hill and together with Hindman observed the partial solar eclipse of 1 November 1948 at Potts Hill. Earlier in 1948, he began collaboration with Minnett to investigate both solar and cosmic sources focusing on a switched-radiometer technique. These investigations included the detection of microwave radiation from the Moon based on observations from the Radiophysics headquarters at Sydney University. One of their surveys at Potts Hill led to the discovery of a new discrete source at the Galactic Centre that would later become known as Sagittarius A.

Over time, Piddington's interests shifted progressively away from observational work and by late 1951 he had decided to focus solely on theoretical research. In this role Pawsey made Piddington the senior leader in theoretical work, although he had little interaction with the other members of this group, Smerd and Westfold.

Figure 21: J.H. Piddington (Courtesy of ATNF Photographic Archive: SP014).

Piddington had maintained a strong relationship with Martyn following their wartime collaboration, and often consulted him on his theoretical work. This may have been a factor in the strained relationship he had with Bowen who did not value Piddington's theoretical contribution and made no secret of his desire for Piddington to leave the group. An example of Bowen's attitude toward Piddington can be seen in a letter he wrote Pawsey in 1948 on progress in the group:

> "The microwave work is still in the doldrums due to Piddington's failure to provide any inspiration. Most of the work and ideas come from Harry Minnett and, while there is nothing exciting to report about the Sun, he is getting quite interesting results on the Moon" (Bowen, 1948b).

While he focused on theoretical work, he was still able to collaborate with some of the newer members of the Radiophysics team who conducted research at Potts Hill. He worked with Davies, drawing on the long-term solar records and with Trent and Wade on later cosmic source investigations.

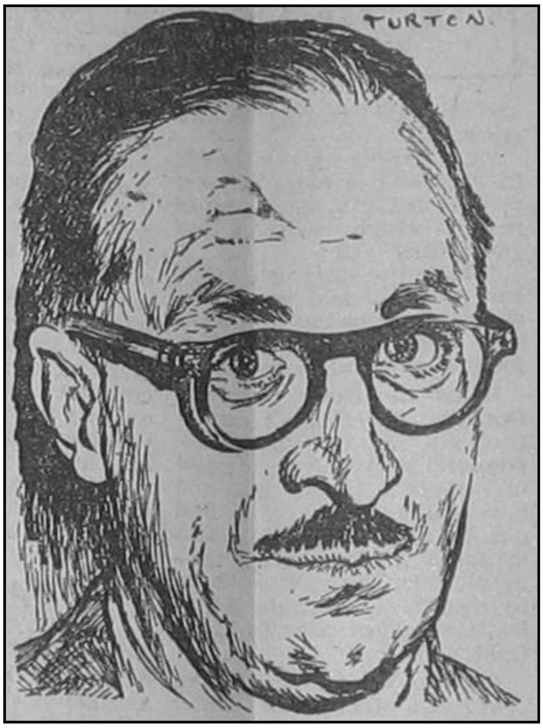

Figure 22: A drawing of Piddington in 1952 (Courtesy of the Daily Telegraph Newspaper).

From the late 1950's Piddington became increasing isolated from the rest of the Radiophysics group as he pursued his theoretical interest on a solo basis. When Radiophysics moved its headquarters to Epping, Piddington transferred to the Division of Physics and remained at the University site. He retired from the C.S.I.R.O. in 1975.

Figure 22 shows a drawing of Piddington in 1952. For a more detailed biography see Melrose and Minnett (1998).

10.3.12. Robinson

Brian John Robinson (1930-2004: Figure 23) joined Radiophysics in May 1952 as a fixed term research officer after completing an MSc at the University of Sydney. He was initially assigned to work with Kerr and Hindman at Potts Hill on the construction of the 36-ft Parabola for use in a H-line survey of the southern sky. Working with Kerr and Hindman he was involved in the first detection of neutral hydrogen from an external galaxy, the Magellanic Clouds.

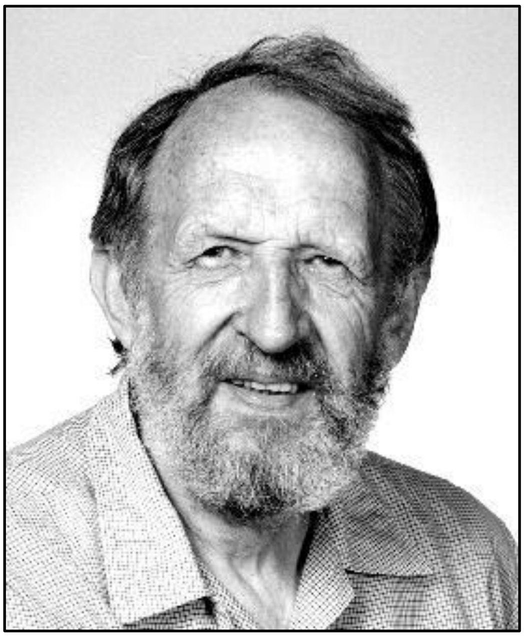

Figure 23: B.J. Robinson (Courtesy of ATNF Historical Photographic Archive: SR017-2).

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During his short time at Potts Hill Robinson also worked on the construction of the N-S Solar Grating Array, along with other more junior members of staff.

In 1953, Robinson was awarded a Rutherford Memorial Scholarship at Cambridge University that allowed him to begin a PhD at Trinity College in 1954 under the supervision of J.A. Ratcliffe and K. Weekes. After completing his PhD, Robinson was reappointed to Radiophysics, but was immediately seconded to the Netherlands Foundation for Radio Astronomy (N.F.R.A.) as a Visiting Fellow. During his time at N.F.R.A., Robinson completed important work on developing receiver equipment that would later be used in the Parkes Radio Telescope.

Robinson went on to a distinguished career in radio astronomy at the C.S.I.R.O. He retired in 1992, but continued his involvement in radio astronomy as an Honorary Fellow with the Australia Telescope National Facility.

For a more detailed biography see Whiteoak and Sim (2006).

10.3.13. Smerd

Stefan (Steve) Friedrich Smerd (1916-1978: Figure 24) joined Radiophysics in 1946. During the war he had worked on radar development in the U.K and immigrated to Australia on 29 May 1946.

Figure 24: S.F. Smerd in 1952 (Adapted from the ATNF Historical Photographic Archive: 2842-43 Image Date: 8 August 1952).

Smerd was principally employed as a theoretician and together with Kevin Westfold, made up the original theoretical section of the solar noise group. His main research interest was radio emission from the Sun. Although working mainly in theory, he was also placed in charge of the long term multi-frequency solar observation program at Potts Hill. One of Smerd's major contributions was the application of the theory of free-free transitions in an ionised gas to the quiet Sun (Smerd, 1950b). His paper on the radio frequency representation of the solar atmosphere (Smerd, 1950c) and a chapter (Pawsey and Smerd, 1953) in the book by Kuiper titled, *The Sun*, that he co-authored with Pawsey, became standard references in solar radio astronomy.

Smerd did not publish any research explicitly based on the Potts Hill long-term solar observations other than contributions to the *Quarterly Bulletin on Solar Activity*. As Wild (1980:5) has noted he was most famous for his "unpublished" works. During the International Geophysical Year 1957-58 Smerd established a World Data Centre for solar radio emission.

Smerd became one of the world's leading solar physicists and in 1971 succeeded J.P. Wild as the Head the solar radio astronomy group and the Director of the Division's Solar Observatory at Culgoora. He died in 1978 while undergoing heart surgery.

For a more detailed biography see Robertson (2002) or Wild (1980).

10.3.14. Stahr-Carpenter

Martha Stahr-Carpenter (Figure 25) spent a year during 1954-55 working at Radiophysics on a research fellowship from Cornell University's Centre for Radiophysics and Space Research. During this time she worked with Kerr and Hindman at Potts Hill on the H-line survey of the southern Milky Way, co-authoring the paper that would appear in 1957 in *Nature* on the large scale structure of the Galaxy. She also presented the preliminary findings of the survey at the I.A.U. Symposium No.4 on Radio Astronomy held at Jodrell Bank in August 1955.

Figure 25: Martha Stahr-Carpenter in 1954 (Courtesy of Sydney Morning Herald Newspaper).

10.3.15. Swarup

Govind Swarup (Figure 26) joined Radiophysics in March 1953 together with R. Parthasarathy on a two year Colombo Plan Fellowship. Prior to this Swarup had been working in the National Physical Laboratory in New Delhi, India under K.S. Krishnan. Krishnan had attended the 1952 URSI General Assembly in Sydney and had returned to India where he described the developments in radio astronomy and inspired Swarup to apply for the Fellowship.

Figure 26: G. Swarup in 2007 (Courtesy of Queen Victoria Museum and Art Gallery, Launceston Australia)

Under Pawsey's direction, Swarup spent his first twelve months on a rotation with each of the major research groups in Radiophysics in 1953. These were led by Christiansen (Potts Hill), Wild (Dapto), Mills (Badgerys Creek and Potts Hill) and Bolton (Dover Heights) (Swarup, 2006). During his assignment at Potts Hill, Swarup first worked with Christiansen and Warburton on the production of the two-dimensional map of the Sun using strip scans taken with both the E-W and N-S Solar Grating Arrays. He then worked with Mills and Little on the Mills Cross Prototype that was under construction at Potts Hill.

In their final year of the fellowship, Swarup and Parthasarathy were able to work on a project of their own choice. They chose to investigate limb-brightening of the Sun at 500 MHz. With Christiansen overseas during 1954, they modified the E-W Solar Grating Array to operate at 500 MHz and were able to confirm limb-brightening. They published their findings in a summary paper in *The Observatory* and two detailed papers in the *Australian Journal of Physics*.

Upon returning to Australia in early 1955, Christiansen decided to construct a new cross array at the Fleurs field station rather than continuing research with the Solar Grating Arrays. Swarup suggested to Pawsey that the E-W Grating Array could be donated to India and this was supported by both Pawsey and Bowen. Swarup returned to India in August 1956 to set up a radio astronomy program at the National Physical Laboratory. However, after it became clear there would be delays in shipping of the E-W Solar Grating Array antennas to India, Swarup elected to travel to the U.S. where he completed his PhD at Stanford University under R.N. Bracewell. He returned to India in 1963 and went on to use the antennas of the old Potts Hill Solar Grating Array in a new configuration for research.

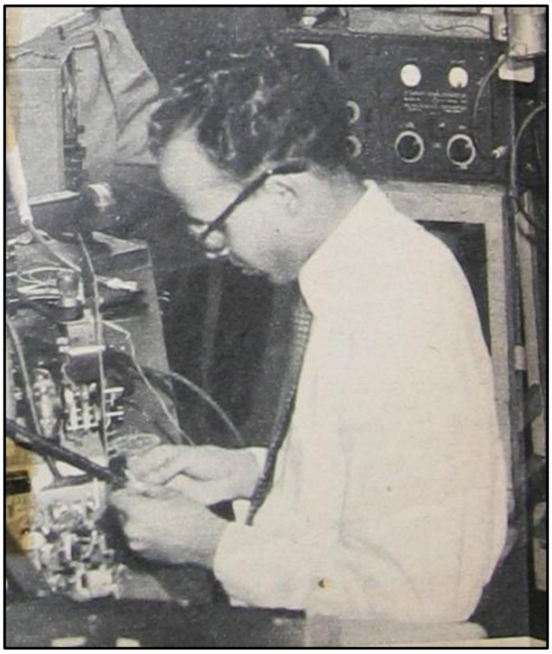


Figure 27: Swarup working in the Radiophysics Division Laboratory in 1954 (Courtesy of People Magazine).

Swarup went on to have a distinguished career in radio astronomy, becoming the Centre Director of the National Centre for Radio Astrophysics (Pune) and Professor of Eminence at the Tata Institute of Fundamental Research (Mumbai, India). He also has the distinction of being one of the two Potts Hill researchers to be elected as a Fellow of the Royal Society.

For a more detailed review of Swarup's time at Potts Hill see Swarup (2006).

10.3.16. Thomas

A.B. (Bruce) Thomas had a very brief career working at Potts Hill. Between May and December 1949, working as a research officer, he collaborated with Mills on observations of Cygnus A using the Swept-Lobe Interferometer. From their observations they obtained a more accurate position estimate for Cygnus-A, and determined that the fluctuations observed in the source were due to the F-region of the ionosphere. Prior to this he had been part of the group examining extra-terrestrial radar echoes. Thomas left the radio astronomy group in 1950.

10.3.17. Trent

During 1956 G.H. (Gil) Trent collaborated with Piddington on a 600 MHz survey of the southern sky using the 36-ft Parabola at Potts Hill. They published the results of the survey and a catalogue of 49 discrete sources in the *Australian Journal of Physics*. Following this research, Trent went on to work with Wild and K. Sheridan on solar spectroscopy.

10.3.18. Wade

Campbell M. Wade joined Radiophysics on a Junior Research Fellowship in December 1957, having completed his PhD at Harvard. Pawsey and Bart Bok were instrumental in securing Wade's appointment to Radiophysics (Goss, 2007). During his Fellowship, he conducted observations at Potts Hill with Hindman using the 36-ft Parabola and a 1,400 MHz receiver. They examined a number sources and later published the results of the observations of the Eta Carinae Nebula and Centaurus-A in the *Australian Journal of Physics*.

Following the completion of his fellowship, Wade returned to the U.S. and took up a position with the National Radio Astronomy Observatory.

10.3.19. Warburton

J.A. (Joe) Warburton joined Radiophysics in January 1951 as a graduate recruit together with R.D. Davies. He was the main collaborator with Christiansen on construction of the first Solar Grating Array and the subsequent solar research program at Potts Hill. Warburton worked briefly on the Murraybank multichannel H-line receiver project, before leaving the radio astronomy group in 1957.

10.3.20. Yabsley

Don E. Yabsley (Figure 28) was one of the pioneers of solar radio astronomy in Radiophysics. Working with F.J. Lehany, in 1947 they conducted some of the first multi-frequency solar observations at the Georges Heights field station. Yabsley had also collaborated with Pawsey on a paper about the thermal origin of the radio-frequency radiation from the Sun (Pawsey and Yabsley, 1949).

Figure 28: Don E. Yabsley in 1948 (Adapted from ATNF Historical Photographic Archive: B1031-9 Image Date: 1 May 1947)

In 1948 he joined Christiansen and Mills in a team to observe the partial solar eclipse of 1 November 1948. Yabsley conducted the observations at Potts Hill using the 16-ft × 18-ft Paraboloid.

In 1950 he left the radio astronomy group to work on the design of distance measuring equipment for use in civil aviation. In later years he returned to radio astronomy, working with the Parkes Radio Telescope and later on the design of the Australia Telescope.

10.4. The Instruments

A wide variety of instruments was operated at the Potts Hill field station, spanning both solar and cosmic research programs. This section gives a description of each of the principle instruments, their receiving equipment and some explanation of the observing techniques used. A site map showing locations of the various instruments at the field station is given in Section 10.2.

Ten different types of radio telescope were operated at Potts Hill. A summary description is given in Table 2. Each instrument is referred to by a label (A-J) which is used as a cross reference in later sections.

Before describing each instrument in detail it is useful to provide an overview of the issues facing both antenna and receiver design during this period. Two principle issues faced the designer of a radio telescope: sensitivity and resolution. Consideration also needed to be given to polarisation measurements which were of interest for solar and galactic observations.

For simplicity, the approximate beamwidth (θ) of a simple circular parabolic aerial is given by:

$$\theta = 1.2\lambda / D \qquad (1)$$

where

λ is the wavelength in metres and

D is the diameter of the aerial in metres.

Table 2: Summary of Potts Hill Instruments

Ref	Instrument	Freq (MHz)	λ (m)	θ°	Source Investigations
A	16-ft x 18-ft Paraboloid	200	1.50	21	Solar
		600	0.50	7	Solar, Cosmic
		1,200	0.25	3.5	Solar, Cosmic
		1,420	0.21	2.3	H-Line
B	10-ft Parabola	600	0.50	12	Solar
		1,200	0.25	6	Cosmic
C	44-in Ex-Search Light Parabola	9,428	0.03	2	Solar
D	68-in Parabola	3,000	0.10	3.4	Solar, Cosmic
E	Swept Lobe Interferomter	97	3.09	0.03	Solar, Cosmic
F	Solar Grating Arrays	1,400	0.21	0.05	Solar
		500	0.60	0.14	Solar
G	36-ft Transit Parabola	1,420	0.21	1.4	H-Line
		600	0.50	3	Cosmic
		1,400	0.21	1.4	Cosmic
H	Mills Cross Prototype	97	3.09	8	Cosmic
I	Yagi Arrays	62	4.84	--	Solar
		98	3.06	--	Solar
J	Suspended Dipole	20	15.31	--	Jupiter

Beamwidth (θ°) is as stated in the published material, or where resolution was not explicitly stated, beamwidth has been calculated using the formula given below and assuming D = aerial diameter. Note that Appendix A – Publications from Potts Hill
contains a cross reference to the published research from each instrument.

Therefore, the smaller the aerial or the longer the wavelength (the lower the frequency), the lower the resolution of the aerial. For wavelengths over tens of centimetres, the size of the aerial grows prohibitively large in terms of both cost and engineering difficulty where a resolution > 1° is desired.

The gain (g) of the aerial is given by:

$$g = 4\pi A / \lambda^2 \qquad (2)$$

where A is the effective aperture collecting area.

Essentially this shows that the collecting area of the aerial for a given wavelength will determine its gain. However, the aerial is only one component of the radio telescope. The other essential component is the receiver.

The receiver's purpose is to convert the signal received at the aerial into a form that can be displayed or recorded on the detecting equipment. The actual signal received from solar and particularly cosmic sources is extremely weak. The receiver noise temperatures were of the order of hundreds to thousands of degrees Kelvin. The input stages of the receiver were most vulnerable to noise. During the period Potts Hill was operating, receiver design fell into two broad groups. For frequencies above ~500 MHz, superheterodyne receivers that used crystal mixers and no signal frequency amplification were generally used, although superheterodyne receivers were also used at lower frequencies. For frequencies below 500 MHz, the signal amplification could prove impractical with the available equipment and therefore intermediate frequency conversion was generally used to convert the signal to the intermediate frequency of a crystal mixer before further amplification. The intermediate frequency amplifier generally operated at 30 MHz. Alternatively, valves with low noise output were used as first stage amplifiers followed by a mixer tube.

The sensitivity of the receivers was not only limited by internal thermal noise, but was also subject to gain variations over time. Where mains-supplied power was used, the receiver was subject to gain variations caused by fluctuations in the supplied voltage. Where battery power was used the receiver was subject to longer-term gain drift as the power of the battery supply decreased with time. This variation in gain created difficulty in calibrating the receiver to determine the absolute temperature of the received signal. This led to a variety of techniques being employed for calibration and to check the receiver gain during observations. Alternatively the need for this was negated by using highly stabilised D.C. power supplies.

The receiver gain drift could also be overcome by using a differential method developed by Dicke (1946a). This involved the rapid switching between the aerial signal and a reference signal to produce a difference signal. While this produced an inherent reduction in sensitivity as the receiver spent only 50% of the time connected to the aerial signal, it did have the advantage of receiver gain stability in detecting weak signals and was essential in the later Hydrogen Line studies. It is interesting to note that one weakness quoted in a summary of receiver technology at this time (Pawsey and Bracewell, 1955: 44) was that the Dicke method did not allow aural monitoring of the signal. In the early radio work, aural monitoring was considered important in the detection of interference from terrestrial sources:

> "All known extraterrestrial sources give the well-known swishing sound characteristic of receiver noise; crackles, crashes, clicks etc, appear to be solely of terrestrial origin." (Pawsey and Bracewell, 1955: 51).

Terrestrial interference would become an increasing problem at Potts Hill, particularly as the suburbs of Sydney were expanding rapidly in the 1950s.

10.4.1. 16-ft×18-ft Paraboloid (A)

The 16-ft × 18-ft Paraboloid was originally constructed at the Georges Heights field station as an experimental research radar as part of Radiophysics' wartime research efforts. In 1946 the aerial was converted for solar research work by Lehany and Yabsley (1949). The aerial was a section of a paraboloid measuring 16-ft × 18-ft. Figure 29 shows the aerial and receiving equipment at the Georges Heights field station.

Figure 29: 16-ft×18-ft Paraboloid at George's Heights Field Station (Courtesy of ATNF Historic Photographic Archive: B1164 Image Date: 13 Sep 1947).

In its original configuration it was fitted to an alt-azimuth mounting which made tracking of celestial objects difficult. Because of this Lehany and Yabsley used a drift/scan technique for their original solar observations. This involved positioning the aerial ahead of the Sun via a hand-crank mechanism and then allowing the Earth's rotation to sweep the aerial beam over the Sun. Once the Sun had moved through the aerial beam the aerial was repositioned and the procedure repeated. This resulted in a 'picket fence' response that is apparent in their recorded observations. An example is shown in Figure 30.

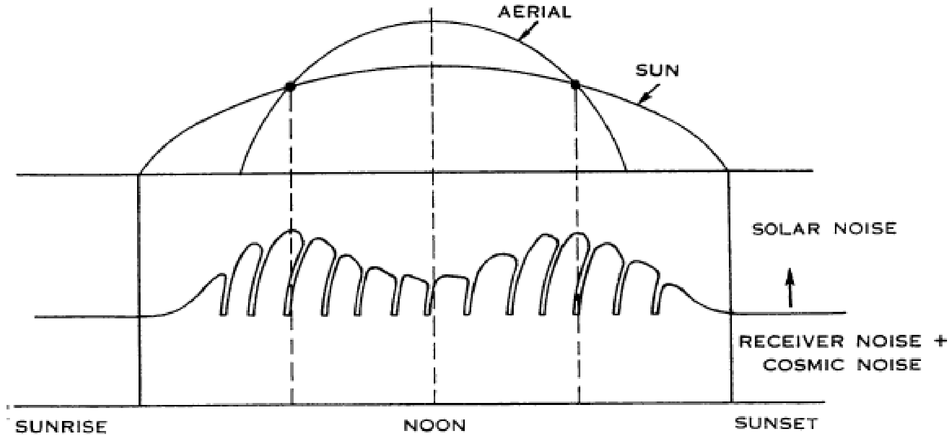


Figure 30: Example of 'picket fence' recording as a result of the drift/scan observation technique (after Lehany and Yabsley, 1949: 50).

The aerial was relocated to Potts Hill in the latter half of 1948 in preparation for observations of the partial solar eclipse of 1 November 1948. A new polar mount was constructed together with a motor drive for right ascension to improve its tracking capabilities. This mount, shown in Figure 31, allowed tracking in declination from $+40^{o}$ to -40^{o}. The right ascension and declination position of the aerial were indicated by scales on the mount.

Figure 31:16-ft×18-ft Paraboloid on the new polar mount at Potts Hill field station (Courtesy of ATNF Historic Photographic Archive: B2649-3 Image Date: 2 January 1952).

For the original solar research the aerial was fitted for simultaneous reception in three frequency bands (1,200 MHz, 600 MHz and 200 MHz) using three separate dipoles located at the primary focus of the aerial. In this configuration the aerial was linearly polarised. Figure 32 shows a close-up of the prime focus plate.

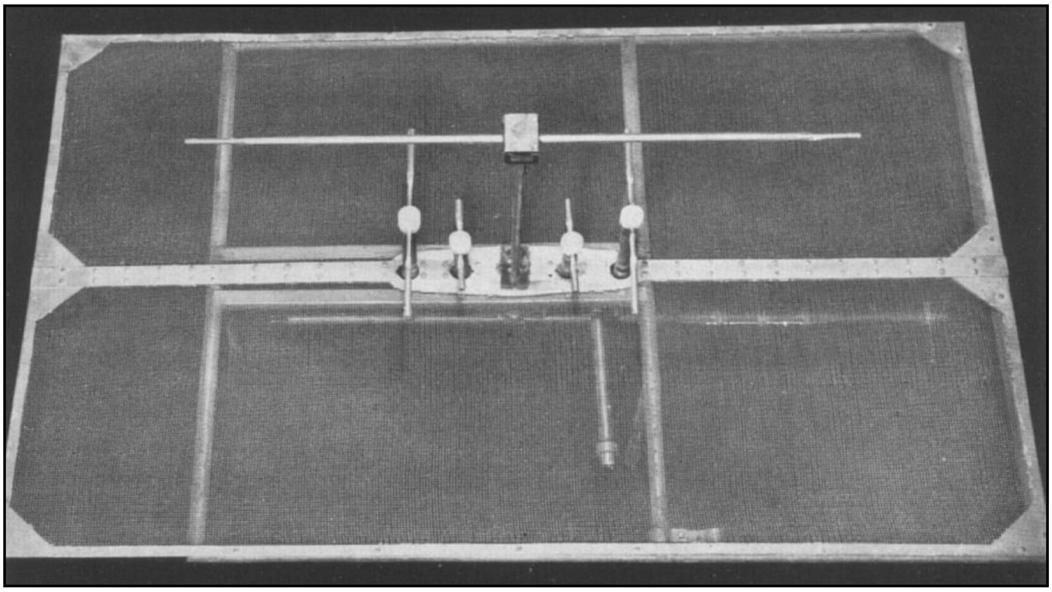


Figure 32: Close-up of the prime focus plate showing the three different feed dipoles. Note that a pair of dipoles was used at the two higher frequencies (after Lehany and Yabsley, 1949: Plate 2).

Unusually, the theoretical beamwidth of the aerial, based on the 18-ft dimension was quoted at the one quarter power points rather than the standard half-power point, being 21º at 200 MHz, 7º at 600 MHz and 3.5º at 1,200 MHz. The receivers used in this work were primarily designed for radar reception; however components were specifically selected with the aim of reducing instrument noise. To reduce signal loss at the highest of the three frequencies, the first stages of the receivers were mounted directly on the aerial frame. The 200 MHz receiver was located separately from the aerial as the feeder losses at this frequency were much less. This same configuration was used by Christiansen for observation of the 1 November 1948 solar eclipse at 600 MHz (Christiansen et al., 1949b).

The 16-ft×18-ft Paraboloid was used for solar research between 1949 to 1953 as part of a multi-frequency observing program. On 17, 21 and 22 of February 1950 a series of major solar outbursts was observed at a range of different frequencies with the 16-ft×18-ft Paraboloid contributing observations at 1,200 MHz and 600 MHz (Christiansen et al., 1951).

While solar research continued to be the primary use for this aerial, growing interest in the investigation of discrete sources meant that time was also assigned for cosmic source investigations. Thus, Piddington and Minnett were allocated some restricted periods for observations during 1950. They used the 16-ft × 18-ft as the main aerial in a Dicke radiometer configuration (1946a). When it was not available they reverted to the use of a 10-ft Parabola as the main aerial. However, this had a much lower sensitivity and resolution than the 16-ft × 18-ft antenna. The receiver noise at the observing frequency of 1,210 MHz was much higher than the noise power of the cosmic sources that were being observed. While this was not an issue for the strong solar sources, clearly a different receiver configuration was necessary for detection of the weaker sources and hence the use of the technique developed by Dicke. The Dicke method involved continuous switching between the observed signal and a dummy load to produce a modulation of the signal. The observed signal was then subtracted from the dummy load signal. This produced a more sensitive signal that was not as susceptible to receiver gain drift. In this instance instead of a dummy load a second reference aerial was used. This was a 5.5-ft parabolic reflector with a simple dipole feed at the prime focus.

The reference aerial was pointed at a 'cold' area of the sky so that the main aerial could be subtracted from this signal. A rotating-disk wave guide switch, driven by a 1,500 rpm synchronous motor, was used to achieve the signal modulation. A block diagram of the receiving system is shown in Figure 33.

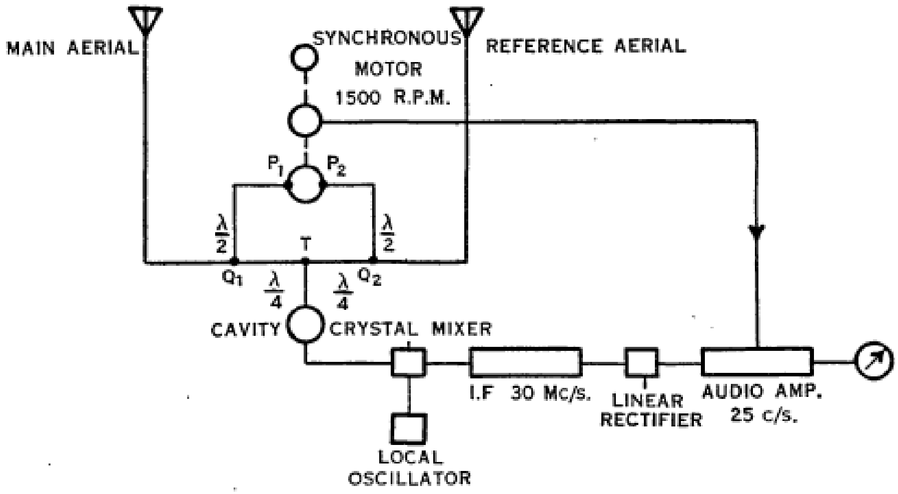


Figure 33: Block diagram of the 1,210 MHz receiver system (after Piddington and Minnett, 1951a: 460).

Rather than tracking the source as had been done for solar observations, a drift scan technique was employed. The aerial was pointed ahead of the source and the source was allowed to drift through the aerial beam courtesy of the Earth's rotation. The aerial temperature difference for an observed source was generally only in the order of a few Kelvin and hence the longest possible time constant was used in the observations. By way of example, the ratio of source power to receiver noise can be compared as follows:

$$\text{power} = kT\Delta v \tag{3}$$

where $k = 1.38 \times 10^{-23}$ JK^{-1}

Receiver Noise:

assuming $T = 1{,}000\ K$ will result in a thermal noise power = $1.38 \times 10^{-20}\ WHz^{-1}$

Source Power:

a typical strong radio source, say Cygnus A, is 1,000 Jy = $1 \times 10^{-23}\ Wm^{-2}Hz^{-1}$

Power delivered to Receiver:

the effective area of 16-ft ×18-ft antenna = 4.9 m × 5.5 m = 14.8 m^2

allowing for an efficiency of 70%, the power delivered = $1.48 \times 10^{-22}\ Wm^{-2}Hz^{-1}$

thus,

$$\frac{\text{source power}}{\text{receiver noise}} \sim \frac{1.48\times10^{-22}}{1.38\times10^{-20}} \sim 0.01$$

These observations using the 16-ft × 18-ft Paraboloid produced the first recorded detection of the discrete source at the Galactic Centre (Piddington and Minnett, 1951a).

Arguably the most notable contribution of the 16-ft×18-ft Paraboloid was its role in the confirmation of detection of the Hydrogen-line emission at 1,420 MHz in 1951 by Christiansen and Hindman (Pawsey, 1951b). For this work, and the subsequent Hydrogen-line survey, the declination range of the polar mount was increased to +50º to -50º by displacing the receiver feeds in the focal plane of the Paraboloid. This was achieved by changing the length of the guide wires that braced the receiver plate at the prime focus as shown in Figure 34.

Figure 34: 16-ft×18-ft Paraboloid showing guide wires supporting the prime focus receiver plate (Adapted from ATNF Historic Photographic Archive: B2649-3 Image Date: 2 January 1952).

While minor displacement of the feed had little impact on the directivity of the aerial, displacement beyond ±10º led to degradation of directivity. A maximum displacement of -66º was used during the survey work.

It is interesting to note that with the publication of the preliminary survey in 1952 (Christiansen and Hindman, 1952b) the aerial was hence referred to in metric terms as a "...25 square metre section of a paraboloid on an equatorial mount". Gone are the references to feet and inches and the mount is no longer referred to as a polar mount in the published research.

The most important component for detection of the Hydrogen-line emission was the receiver. This was constructed by Christiansen and Hindman who had initially been working independently, but later collaborated to produce the final working version (Orchiston and Slee, 2005a: 139). It was principally similar to that used by Ewen and Purcell in the U.S. and by the Leiden group led by Muller and Oort.

Figure 35 shows a block diagram of the major components of the receiver.

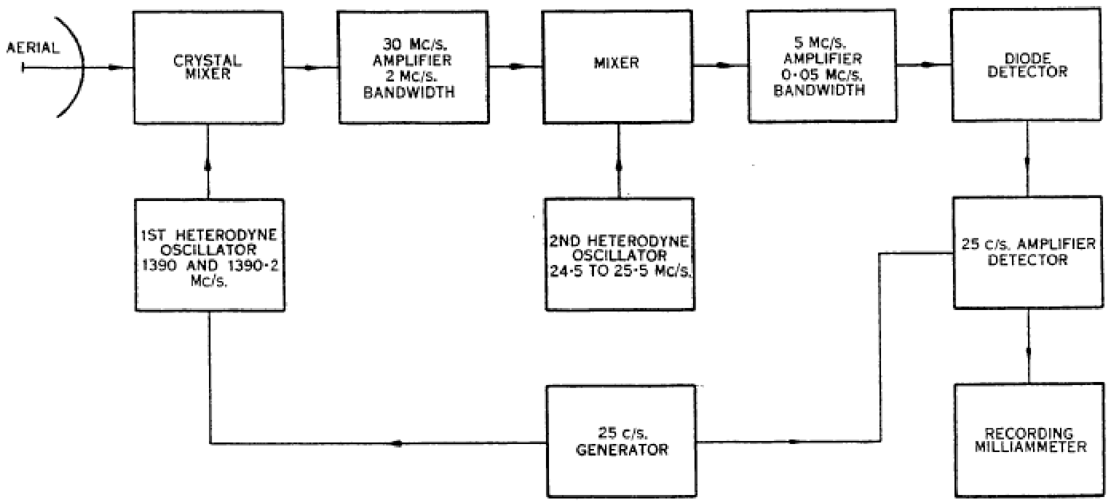


Figure 35: Block diagram of the H-line Receiver (after Christiansen and Hindman, 1952b: 439).

The receiver consisted of a superheterodyne receiver with double-frequency change. It had two intermediate-frequency channels. The first operated at 30 MHz with a bandwidth of 2 MHz and the second at 5 MHz with a bandwidth of 0.05 MHz. A second heterodyne oscillator was used to continuously sweep the tuning of the receiver back and forth over a 1 MHz range. The signal from the hydrogen-line emission was detected as a small increase in signal when the pass-band of the receiver swept over the H-line frequency. As the signal increase was very small an additional balancing method was used to improve sensitivity. This was done by switching the first heterodyne oscillator at 25 Hz between two frequencies

0.16 MHz apart at around 1,390 MHz. This caused the centre frequency of the band-pass to alternate between the two frequencies and therefore allowed comparison between the signals. Any difference between the signals appeared as a 25 Hz component of the rectified receiver output. This component could then be recognised by using a selective amplifier and a phase-sensitive detector which was synchronised with the 25 Hz generator. As the receiver was tuned over the 1 MHz frequency band where detection of the Hydrogen emission line was predicted to appear, the energy produced by the H-line was first detected in one band-pass of the two switch components 0.16 MHz apart. This caused an in-phase 25 Hz signal. It was then detected in the other component as an out of phase signal. This caused a characteristic sine-wave signal on the recorder output as illustrated in Figure 36.

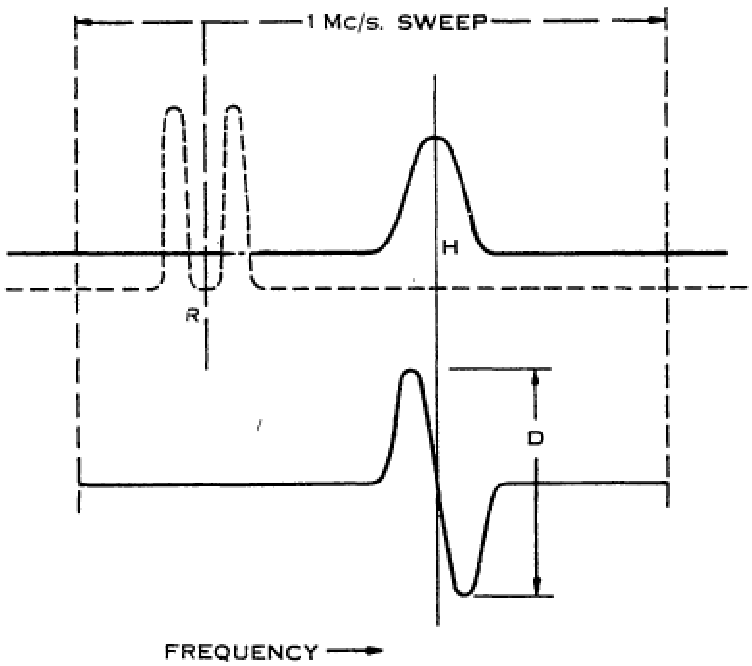


Figure 36: Illustration of H-line receiver operation and theoretical output signal - R = receiver pass-bands, H = H-line signal, D = Recorder signal output (after Christiansen and Hindman, 1952b: 440).

The 50 KHz bandwidth gave a relative velocity resolution of 10.5 kms^{-1} and with a total bandwidth of 1 MHz, the system had a relative velocity resolution of 210 kms^{-1}, which was just sufficient to provide coverage for the Galactic H-line profiles which typically have half-widths of 4-10 kms^{-1} and cover a range of 150 kms^{-1}.

The receiver for the H-line detection was assembled in approximately six weeks. As Christiansen has commented:

"Our research was done crudely but it was good fun and the results were exciting. When Purcell's research student Ewen came over and saw the gear I had, with cables lying all over the floor and ancient oscillators, he said, ‘My God. I can understand why you could do it in six weeks and it took me two years.” (Chrompton, 1997).

And,

“The fellow [Ewen] who discovered it [the H-line] in the USA came out and when he saw the equipment that Hindman and I had used for it he said, ‘I can’t believe it.’ It looks like old rubbish lying on the floor - absolute ‘string and sealing wax’.” (Bhathal, 1996b: 37).

During 1951 the aerial continued to be used for source work as well the regular solar monitoring. Piddington and Minnett used the aerial for observations of Cygnus A at 1,210 MHz (1952). From the acknowledgements in this paper it is clear that the aerial was still well and truly considered the property of Christiansen,

“The authors are grateful to …Mr. W.N. Christiansen for the loan of *his* 16 by 18 foot aerial” (Piddington and Minnett, 1952: my italics).

Christiansen maintained a program of daily solar observations at 600 MHz and 1,200 MHz. Although overall few papers were published based on these ongoing long-term observations, two papers did appear in *Nature* in 1951 (Christiansen and Hindman, 1951) and 1953 (Piddington and Davies, 1953a). These sought to draw some conclusions based on the long-term observations. A further paper appeared in the *Monthly Notices to the Royal Astronomical Society* (Davies, 1954).

In 1954 the need for a large aerial that could track objects for fine H-line structure was identified (Kerr, 1954a). Consideration was given to installing a 25-ft diameter parabola on the mounting used for the 16-ft×18-ft Paraboloid. However, by this time interference was becoming an increasing problem at Potts Hill and it was decided to set up new field station at Murraybank for this purpose. Ultimately the 16-ft×18-ft aerial was superseded by the new instruments.

10.4.2. Portable 10-ft Parabola (B)

The 10-ft Parabolas were recycled ex-U.S. Army surplus TPS-3 radar aerials (Figure 37) that had been developed during the war by the U.S. Army Signal Corps as a light-weight portable 600 MHz early warning radar (Orr, 1964). These aerials were also known as the ‘British Type 63 Radar’. The aerial was made up of 8 × 45º aluminium frame sections covered by wire mesh that could be packed in a very compact bundle and quickly reassembled through a series of speed-clips, so that two men could assemble the aerial in about 5 minutes (Murray, 2007).

Figure 37: AN/TPS-3 Radar Set in operation on 16 June 1944 at the Camp Evans Signal Laboratory, U.S. Army Signal Corps. (Courtesy of CE LCMS Historical Office Department of the Army, USA.)

At least three aerials were modified specifically in preparation for the eclipse observations on 1 November 1948. They were originally tested in their role as radio telescopes at the Georges Heights field station (Orchiston, 2004b). Figure 38 shows one of the parabolas undergoing trials at the Georges Heights field station in August 1948.

Figure 38: A 10-ft Parabola undergoing trials at the Georges Heights field station in August 1948 (Courtesy of ATNF Historical Photographic Archive: B1511 Image Date: 13 August 1948)

The 10-ft Parabola was one of the first instruments at Potts Hill and during 1948 it was used for some preliminary observations of radiation from near the Galactic Centre (Piddington and Minnett, 1951a: 465). These light weight portable aerials were used in a variety of other applications. They provided observations at the remote sites of Rockbank in Tasmania and Strahan in Victoria during the partial eclipse of 1948 (Christiansen et al., 1949b). The aerials were originally mounted on alt-azimuth mounts that were hand steered. This required a table of azimuth and elevation positions for the Sun to be calculated for each location in case of cloudy conditions during observations. For the 1949 partial solar eclipse observations the aerials were modified to include motor driven polar mounts to make tracking the Sun simpler. The receiver feed for the aerial consisted of crossed dipoles and reflectors as illustrated in Figure 39.

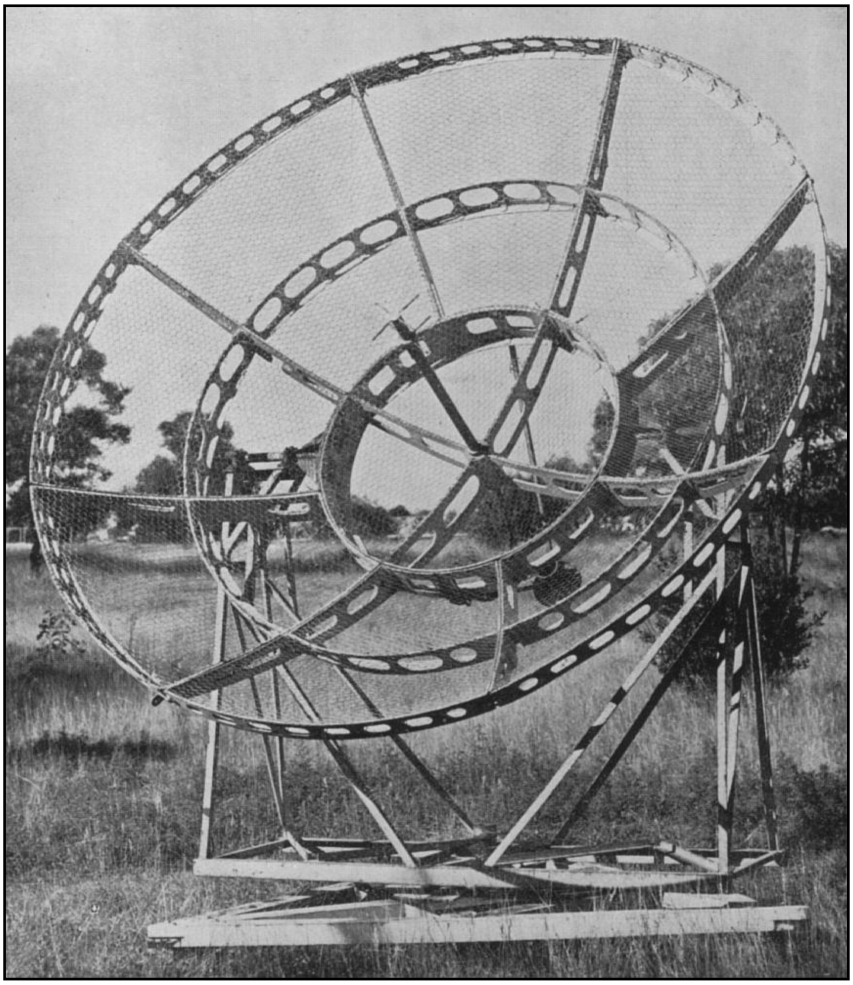


Figure 39: Portable 10-ft Parabola at Potts Hill showing crossed dipoles and reflectors at the prime focus feed (Courtesy of ATNF Historic Photographic Archive: B1803-2 Image Date: 29 May 1949).

Crossed dipoles were used to measure polarisation. Separate parallel coaxial transmission feeds to the receiver were used for each of the dipoles. By using telescopic pieces of coaxial line the lengths of the feed lines could be varied. By making one line ¼ λ longer than the other, circular polarisation in one sense could be measured. By the altering the length difference by ½ λ in the other transmission line the sense of polarisation could be reversed.

The receivers used for these observations at 600 MHz consisted of a quarter-wave transmission-type cavity-resonator, followed by a crystal converter, 30 MHz intermediate frequency amplifier and a diode second detector. After rectification the signal was passed through a D.C amplifier which was connected to a recording milli-ammeter. Receiver gain drift was a major issue for this type of receiver. To ensure a constant receiver temperature the receivers were run for several hours prior to observations and measures were taken to ensure input voltage stability. Additionally, during observation the aerial beam was moved away from the Sun every few minutes so that the receiver gain could be checked against the background sky.

This same type of aerial was used by Piddington and Minnett as the main aerial for their initial exploration of cosmic sources at 1,210 MHz in 1948. When the more sensitive ex-Georges Heights 16-ft×18-ft aerial became available during 1949, the 10-ft was only used as a back-up main aerial for when the 16-ft×18-ft aerial was unavailable (Piddington and Minnett, 1951a). The 10-ft can be seen in the right foreground in Figure 31.

Christiansen and Yabsley also used two of the ex-TPS-3 aerials as a spaced interferometer setup to explore limb brightening, something that Yabsley had been considering doing at Georges Heights. In the minutes of the Radio Astronomy Committee of November 17, 1949 (Christiansen, 1949b) they report that they are "...ready to commence" observations at Potts Hill. Shortly after this Yabsley, who had been the instigator of this experiment, left the group and no results of these experiments were ever published. By March 1950, Christiansen had tabled the concept for his solar grating array at the Radio Astronomy Committee meeting (Christiansen, 1950b) and further work using the ex-TPS-3 aerials in an interferometer configuration was abandoned.

10.4.3. Ex-Searchlight 44-in Parabola (C)

The 44-in Parabola was constructed using a surplus ex-military searchlight mirror. It was originally located at the headquarters of Radiophysics in the grounds of Sydney University and mounted on a small flat-roofed tower on top of the Radiophysics Laboratory known as the 'Eagle's Nest'. Figure 40 shows the aerial at Sydney University.

Figure 40: The ex-Searchlight 44" Paraboloid shown mounted on the 'Eagle's Nest' on top of the Radiophysics building in the grounds of Sydney University (Courtesy of ATNF Historic Photographic Archive: B1641 Image Date: 4 January 1949).

The aerial was originally used by Labrum, Minnett and Piddington for solar observations at 9,428 MHz and 24,000 MHz and for lunar observations at 24,000 MHz (1949a). For these observations the aerial was equatorially mounted and had a small telescope on its frame for visual alignment.

In late 1948 the aerial was relocated to Potts Hill to take part in the solar program. In this role it was used for the observation of the 1 November 1948 partial solar eclipse at 9,428 MHz and went on to be used for daily solar observations at this frequency. At Potts Hill the aerial had an equatorial mounting which would either be operated by hand or using a synchronous electric motor. At 9,428 MHz the half power beamwidth of the aerial was 2º. The speed of the aerial tracking in right ascension could be compared with an accurate clock to ensure tracking was within tolerance on cloudy days. When the Sun was visible the small telescope attached to the mounting could be used to check alignment.

The receiver used during these observations was based on the Dicke radiometer principle (1946a). It used the same components as those employed earlier for the lunar observations, however at the lower frequency of 9,428 MHz. A block diagram of the receiver is shown in Figure 41.

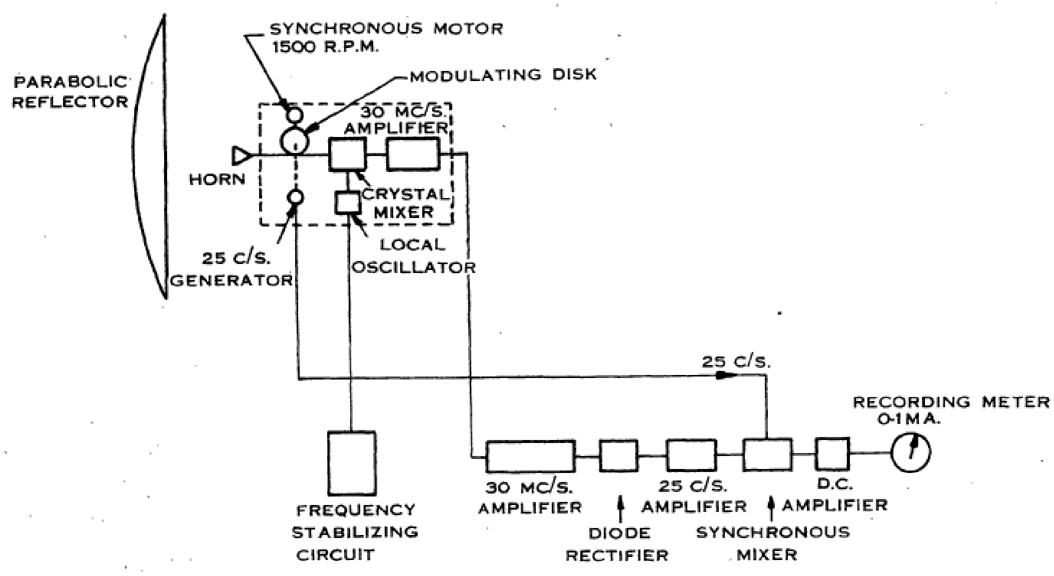


Figure 41: Block diagram of the receiver used in both Lunar and Solar observations (after Piddington and Minnett, 1949a: 66).

A rotating disk of absorbent material was rotated through the waveguide to allow comparison to the aerial signal at a rate of 25 Hz. This produced a modulated signal which was then converted to an intermediate frequency of 30 MHz using a beat oscillator and passed through a preamplifier. These stages of the receiver (shown within the dotted line box in Figure 41) were located in a box mounted near the prime focus of the aerial. The signal was then fed via a coaxial cable to the amplifier and recording stages of the receiver. These were located separately to the aerial. The receiver produced a response of two channels 30 MHz wide centred on the local oscillator frequency of 9,428 MHz.

10.4.4. 68-n Parabola (D)

The 68-in parabola was constructed to perform daily solar observations at 3,000 MHz. It was also involved in the observations of the 1 November 1948 partial solar eclipse (Piddington and Hindman, 1949). The aerial had an equatorial mounting that could either be driven manually or via an electric motor (see Figure 42: Arrow B). The declination of the aerial could be adjusted using a lead screw (Figure 42: Arrow C). The receiver was essentially similar to that used for the ex-Search Light 44-in and descried in section 10.4.3. It consisted of a horn feed (Figure 42: Arrow D) which fed the signal to a rotating disk of absorbent material that passed through the wave guide. This was driven by a motor (Figure 42: Arrow E). The first receiver stage (Figure 42: Arrow F) fed the remotely located amplifier and recorder via coaxial cable.

A screen (Figure 42: Arrow G) could be mounted in front of the parabola reflector to allow either left or right- hand circularly polarised components of the radiation to be received depending on its orientation. A frontal view of the aerial in Figure 43 shows a clear view of the polarisation screen. The ex-Search Light 44-in aerial also can be seen in the background. The screen was operated by taking a measurement with the screen set at a given orientation and then the screen was rotated by 90° and a second measurement taken, thus giving an indication of the relative intensities of the components of circular polarisation.

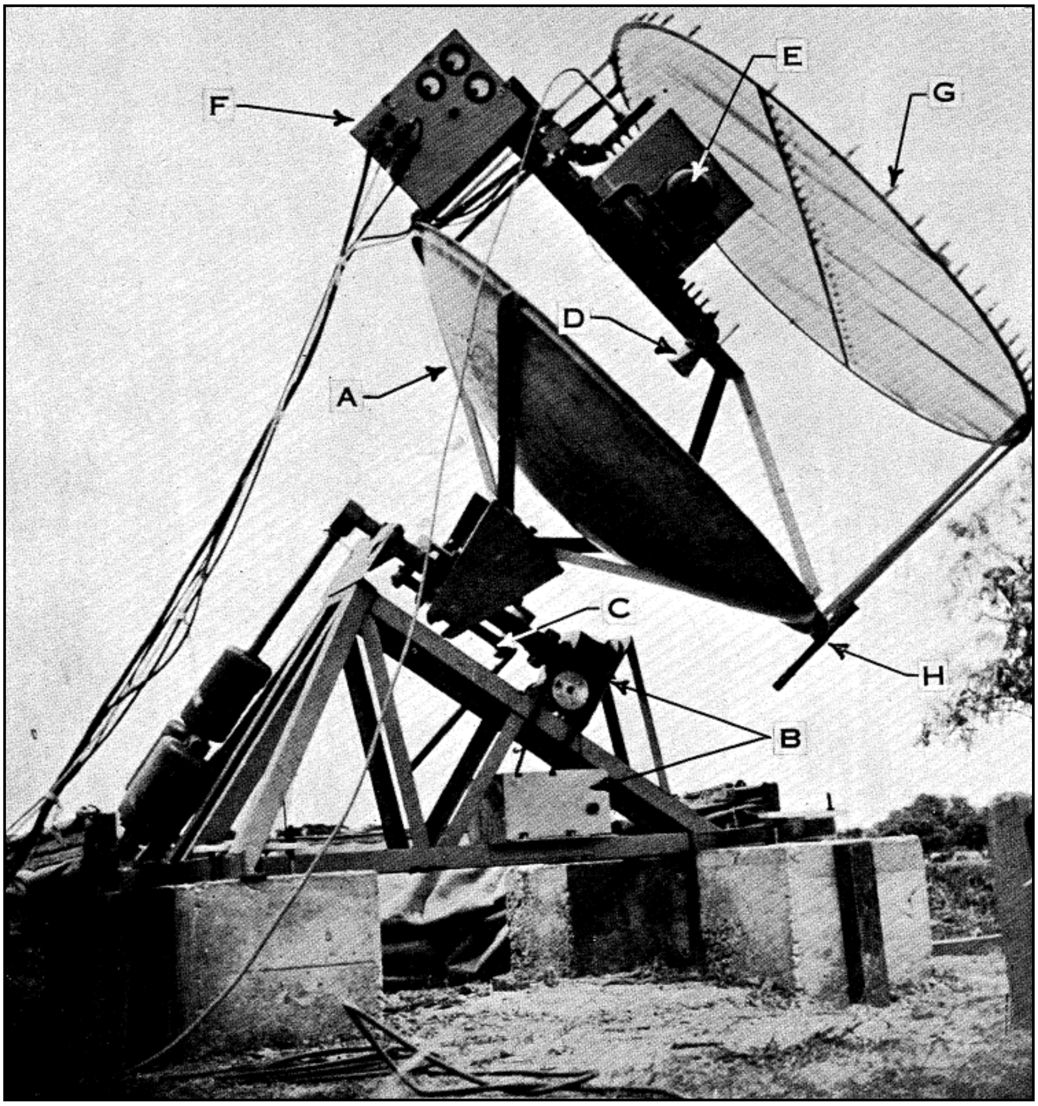


Figure 42: The 68-in Parabola at Potts Hill (Piddington and Hindman, 1949: Plate 1).

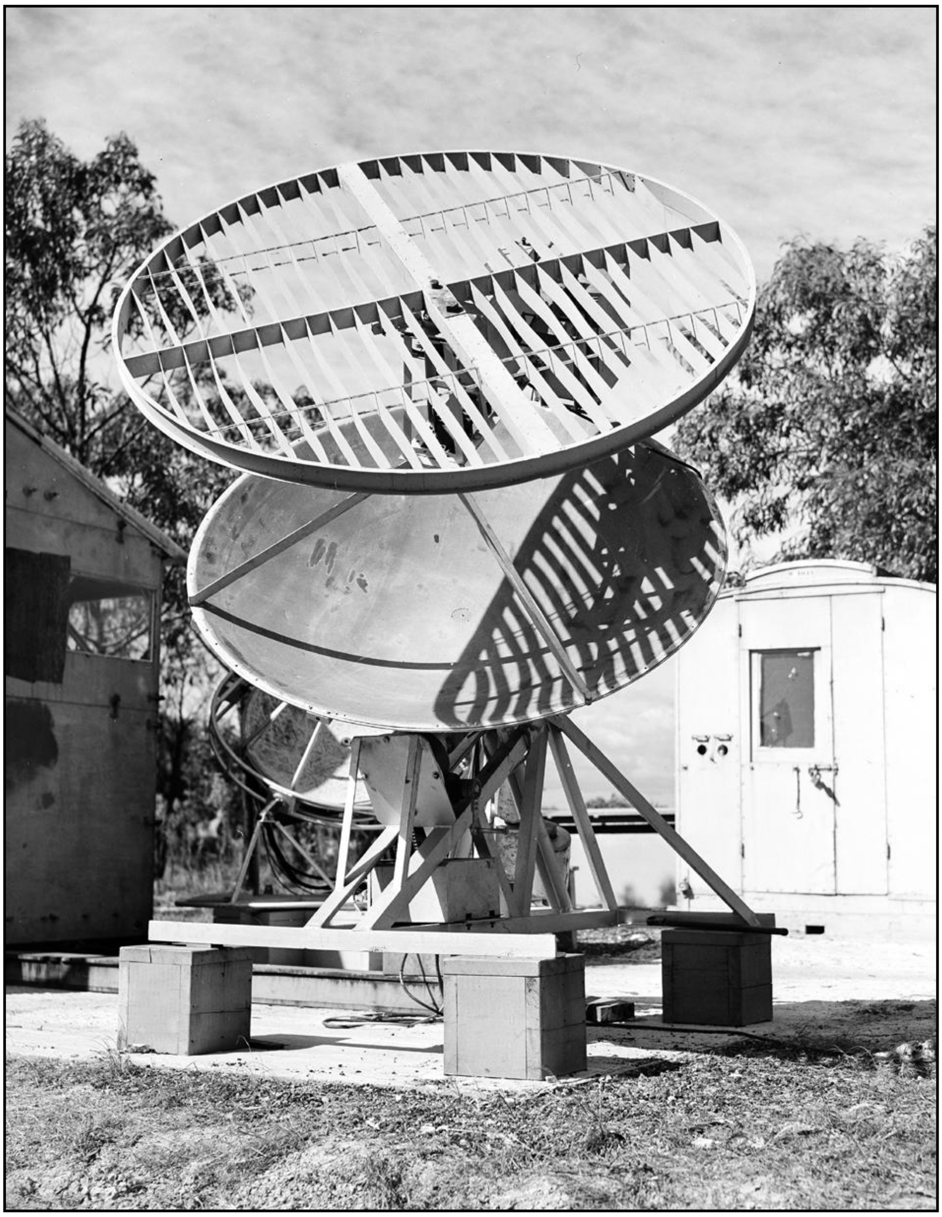


Figure 43: Frontal view of the 68-in Paraboloid (Courtesy of ATNF Historic Photographic Archive: B2475-1 Image Date: 24 April 1951).

Piddington and Minnett (1951a) also used this aerial for their cosmic source investigations, however for these observations the aerial aperture was increased to 7.5 feet by fitting wing extensions to the main parabola dish. This increased the sensitivity of the aerial and decreased its beamwidth at 3,000 MHz to 1.7º at the half-power points.

Figure 44: 68-in and 44-in aerials at Potts Hill with associated equipment (Courtesy of ATNF Historic Photographic Archive: B3171-1 Image Date: 7 October 1953).

Figure 44 shows the wing extensions, not fitted to the 68-in aerial, but lying in the grass to the left of the hut in the centre of the image. The 68-in is to the right of the 44-in and the polarisation screen can be seen leaning against the left hand side of the hut.

For the 3,000 MHz cosmic source observations, Piddington and Minnett developed an observation technique that they called 'beam-swinging'. Using a receiver time constant of about 10 seconds the aerial was pointed at a given direction relative to the Earth (position A). It remained at this position for one or two minutes and then the aerial was shifted several degrees to the west to a new position (position B). It remained pointing at position B for the same time interval it had pointed at position A. The difference in aerial temperature between the two positions was measured and plotted against time. The procedure was then repeated for the time interval that the source had taken to move from A to B via the Earth's rotation. Assuming the source caused an increase in aerial temperature of T_A, and assuming a uniform background radiation, then the curve of the aerial temperature difference would vary through a total range of $2T_A$ as the source moved between A and B. Piddington and Minnett estimated a minimum detectable flux density at 3,000 MHz using this technique was 10^{-23} $Wm^{-2}Hz^{-1}$.

For the later observations of Cygnus A by Piddington and Minnett (1952) the aerial extensions had to be removed as the aerial could not be pointed far enough north in declination with the extensions fitted. The beam-swinging technique could not be used at this declination and therefore, with the extensions also removed, the sensitivity of observations was greatly reduced. The steep radio spectrum of Cygnus A also compounded the difficulties of detection at this frequency. A drift-scan technique was used in an attempt to detect the Cygnus source, but with the limitations in sensitivity the source could not be detected, however, an upper limit for the flux density at 3,000 MHz was established.

10.4.5. Swept-Lobe Interferometer (E)

In order to investigate solar burst radiation in more detail, a new instrument was constructed at Potts Hill by Payne-Scott and Little in the latter part of 1948. This instrument had its genesis at the short lived Bankstown field station but was relocated to Potts Hill after the Bankstown building was sold. A single aerial with sufficient resolving power to accurately locate the source of the burst on the solar disk would have been prohibitively large and expensive to construct. Instead, the construction of the new instrument drew on the experience of the group’s earlier work using interferometry (McCready et al., 1947).

Previous research using interferometry techniques in both Australia and the U.K. to determine source positions had relied on the interference pattern being produced by holding the aerial beam at a fixed position relative to the Earth and allowing the source to drift through the beam lobes courtesy of the Earth’s rotation. This obviously worked well where the radiation was relatively constant in nature and emanated from a discrete source at a fixed position. However, for solar bursts this was not the case. These bursts often had durations of only a few seconds and appeared to move rapidly in position. To accommodate these observations a new type of spaced-element interferometer was required that could accurately measure both the position and the polarisation of these short-duration bursts.

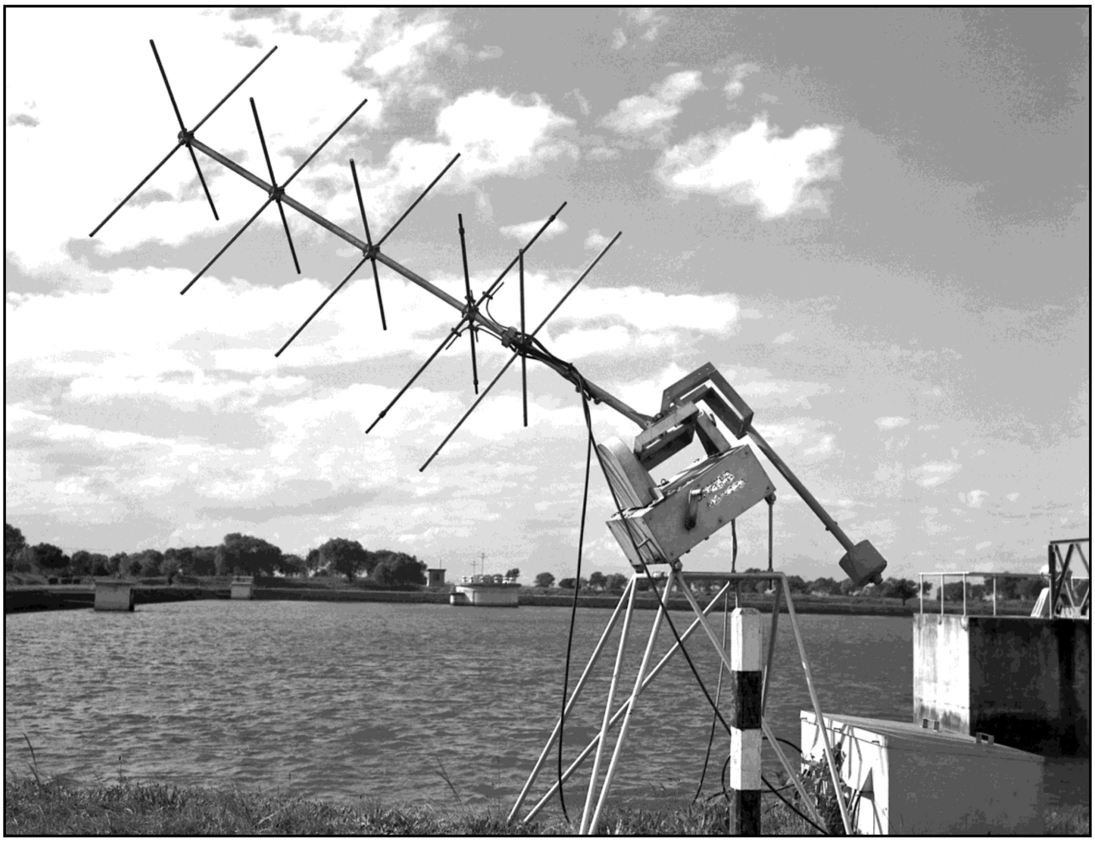


Figure 45: The western aerial of the swept-lobe interferometer at Potts Hill (Courtesy of ATNF Historic Photographic Archive: 2217 Image Date: 28 July 1950)

In an inspired piece of design such an instrument was constructed at Potts Hill (Little and Payne-Scott, 1951). It consisted of three equatorially-mounted and physically-identical crossed dipole, five-element Yagi aerials (Figure 45). The crossed dipoles allowed for switching between the horizontal and vertical elements for polarization measurement.

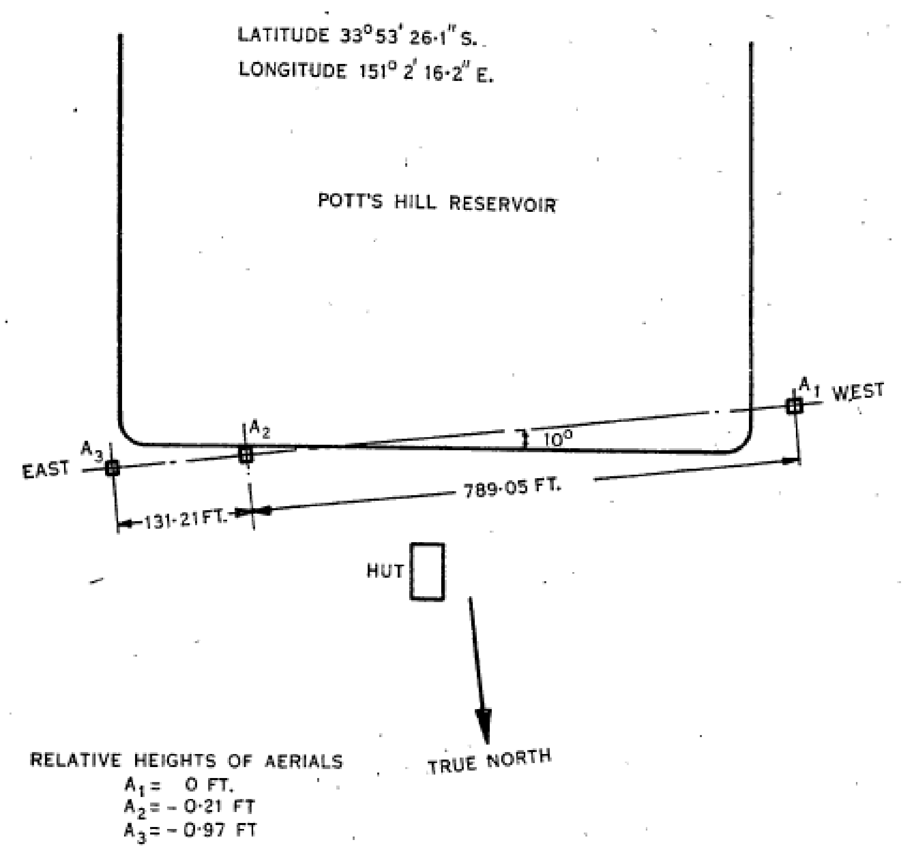


Figure 46: Site map showing aerial locations of the swept-lobe interferometer (after Little and Payne-Scott, 1951: 494).

Three aerials were used for the interferometer and were positioned to give two different spacings for interference pattern measurements. These spacings were A1 to A2 and A1 to A3 as illustrated in Figure 46. The fringe spacing at the largest spacing can be calculated as follows:

$\lambda = 3.077$ m

D = the spacing A_1 to A_3 = 280.495 m

Therefore the fringe spacing is given by:

$$\frac{\lambda}{D} = \frac{3.077}{280.495} \times 57.3° = 0.63° \tag{4}$$

In a two-aerial array position can be determined accurately, but due to the large number of lobes produced, and their angular widths being smaller than the Sun, there was the possibility of ambiguity in the position with two lobes being positioned on the Sun at any given time. By using a different aerial spacing for comparison, this ambiguity could be eliminated. Some of the lobes produced at the different spacings are coincident, and thus the position could be determined as being located in the coincident lobes that are on or near the solar disk. Using this method an accuracy of 2 minutes of arc could be achieved at the observing frequency of 97 MHz. This frequency was chosen to avoid interference from a nearby radio transmitter. The aerials were located on the northern side of the No.1 reservoir at Potts Hill with the receiving equipment located in a hut as shown in Figure 46.

A separate Yagi system operating at 98 MHz was used in conjunction with the interferometer to provide continuous recording of solar signal and to provide an independent check on polarisation measurements performed using the interferometer. This consisted of two crossed Yagi aerials connected to a standard receiver and an Esterline-Angus recorder. These were switched at intervals of 30 seconds to receive right and left-handed circularly polarised components.

As a fixed-beam interferometer, this system would have been unable to identify the position of short duration sources and was largely similar to the two-aerial interferometer used by Ryle and Vonberg at Cambridge. The innovation used at Potts Hill to overcome this issue, was to electronically sweep the lobes of the aerials across the source rather than waiting for the source to move through the lobes. This was achieved by varying the electrical length of the receiver feeds from the array elements to introduce a phase change in the signal over a time constant. The main innovation was to put the phase shift in the local oscillator signal at 171 MHz. A phase change of one wavelength resulted in a 'sweep' of one lobe width. By repeating the sweeps rapidly, with phase changes of 1¾ λ, it was possible to produce two interference patterns in the signal and, from this, the source position could be derived.

Figure 47 shows a block diagram of the interferometer receiver configuration. Pre-amplifies were used for each of the three aerials. The signals were then fed to a phase-changing unit via coaxial cable. This unit was driven by a 1,500 rpm synchronous motor that produced a total relative phase change of twice the electrical line length, 25 times per second. The output produced a 25 Hz interference pattern which was displayed as a sine wave on a cathode-ray tube. The position of the minimum of the sine wave varied with the position of the source.

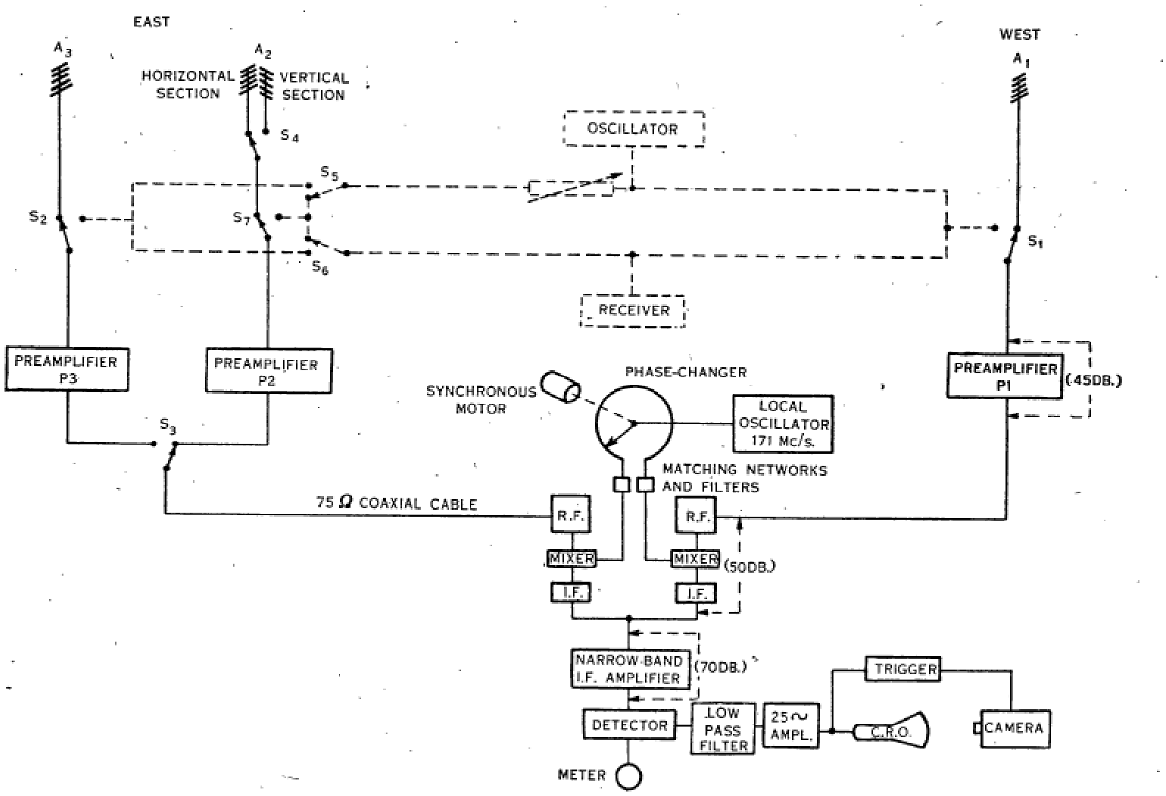


Figure 47: Block diagram of swept-lobe interferometer (after Little and Payne-Scott, 1951: 494).

A 16 mm cine-camera was used to photograph the output signal on the cathode-ray tube screen together with a clock, a film frame counter and a meter which registered the receiver output current. The camera was triggered to take three consecutive photographs automatically when the received signal reached a threshold level. The first frame was of the signal produced by the aerial spacing A1 to A2 (refer to Figure 46) as received by the horizontal elements of the Yagi array at A2. The receiver was then automatically switched to display the signal from the vertical elements of aerial A2 and the second frame photographed. The receiver was then switched to display the signal produced by the longer spacing of A1 to A3 and the final frame of the sequence taken. The entire sequence of the three frame photographs was about 1 second. Figure 48 shows an example of the recorded output of the three frame photograph for a circularly-polarised source. Comparing frame 1 (bottom) with frame 2 shows a shift in the interference pattern phase of one quarter of a wavelength indicating circular polarisation. The direction of the phase shift indicated whether the signal was left or right-handed circularly-polarised. For a randomly-polarised signal the interference pattern would disappear in either frame 1 or 2, and for linearly- polarised signals the amplitude of the interference in one of the planes was significantly less depending on the alignment.

The idea for improving interferometry techniques dates back almost to the beginnings of the Radiophysics solar noise investigations. The minutes of the second formal meeting of the solar noise group held on 6th June 1947 records the following project which was assigned to R. Treharne:

"*Improved Interferometry*. *Object:* To make equipment capable of yielding interference patterns in a fraction of a second with a view to extending this technique to "bursts". Initial ideas are to use manual phase variation to aerials connected by a transmission line. Frequency 100 Mc/s." (Pawsey, 1947a).

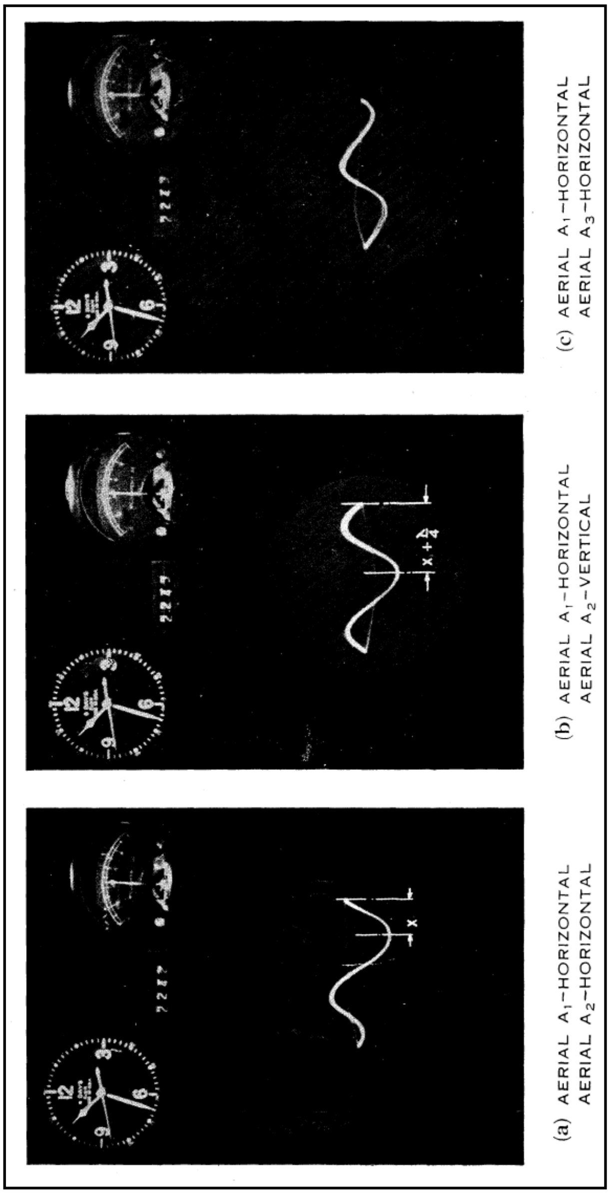


Figure 48: Example recording showing three photographed frames of a circularly-polarised source (Little and Payne-Scott, 1951: Plate 4).

By September 1947, A. Little had joined Treharne at a site at Bankstown aerodrome to work on the construction of equipment. The 23 September minutes of the Solar Noise Group record the following:

"*Solar Interferometry Research Programme – Bankstown (R.F. Treharne & A. Little). General Aim*: To establish interference methods of determining the distribution of sources of cosmic radio frequency radiations with particular reference to the Sun. Physical Applications: In particular the following physical applications appear to arise from such methods:

1. Determination of the size of sources of "burst" or short duration radiation at a frequency of 100 Mc/s and correlation with optical frequency sources. In particular, confirmation or otherwise of the hypothesis that "burst" radiation sources on the surface of the Sun are smaller size than the source which gives rise to the "general enhanced level" of the disturbed Sun.
2. Location of sources of "burst" radiation at a frequency of 100 Mc/s and correlation with position of optical frequency sources. In particular, confirmation or otherwise of the hypothesis that burst radiation emanates from positions on the Sun corresponding to the positions of optical sunspots. Furthermore, correlation of high intensity short duration "outbursts" with the appearance of "flares" may be possible.
3. Determination of distribution of solar sources of "enhanced general level" radiation of frequency 100 Mc/s and correlation with optical sunspots.
4. Determination of thermal radiation from the "quiet" Sun at a frequency of 100 Mc/s and correlation with Dr. Martyn's theoretical distribution.
5. Determination of polarisation of thermal level of "quiet" Sun by suppressing radiation received from one solar hemisphere and correlation with solar magnetic theory.
6. Determination of the size of the source of cosmic radiation "Cygnus" at 100 Mc/s.
7. Determination of the sizes of circumpolar cosmic sources of 100 Mc/s radiation.
8. Extension of experiments to other radio frequencies such as 65, 200, 1200 and 3000 Mc/s.

Technique: The technique of interferometry to be employed rests largely on the use of two or more aerials at various points on the earth's surface separated by distances chosen to give the desired interference pattern in space. Then by varying the phase difference between the signals received from the aerials taken two at a time and recording the resultant amplitude as a function of phase displacement the necessary information can be deduced.

The first experiment to be carried out consists of setting up a two aerial interferometer operating on a frequency of 100 Mc/s as shown diagrammatically in Figure SK(E)3363.

In the first instance the aerials will be so placed as to give an angular null separation of about one degree. Continuous 360 degree per cycle 25 cycles per second automatic phase changing will be obtained by using remote frequency converter units at each aerial fed by a common local oscillator. The phase of the local oscillator will be varied continually by means of a rotating transmission line phase shifter of approximately 180º electrical length synchronisation to 50 c/s mains.

The resultant noise amplitude of 2 Megacycles bandwidth will be detected and integrated over a time interval of 4×10^{-3} seconds and displayed on a 25 c/s time sweep oscillography.

Visual display methods will be used at first, and photographic recording, at a rate determined after visual inspection of the desired phenomena, will be used.

The conflicting bandwidth requirements imposed by signal path differences and by phase scanning rate have been taken into account in planning this experiment.

Drift Interferometry – It is proposed to adapt the system of SK(E)3363 for very slowly varying phenomena by using the natural drift of the Sun to produce the interference patterns and to record them by Esterline Angus mechanical recorders. In this case the phase and oscillograph are not used.

Extension of Technique – Extensions of the technique will be guided largely by experience but will probably fall into the following groups:

(i) Calibration of system in phase and amplitude to permit both size and absolute position to be established.
(ii) Extension to more than two aerials to give higher accuracy, two dimensional position for point sources or plane distribution for multiple sources.

Immediate Plans – The equipment indicated in SK(E)3363 is under construction and will be tested at the laboratory. The system will be set up at the Bankstown field station. It is hoped that:

(i) Interference patterns from bursts will be observed and the size determined.
(ii) Drift interference patterns from enhanced general level will be observed.
(iii) An experimental technique of phase calibration established to enable absolute positions to be determined.

Note by Dr. Pawsey on Treharnes's programme: This plan looks further ahead than the others [plans described in the minutes]. Many aspects will not be touched for some time, perhaps never. Details of specific planning require discussion at intervals in the future." (Pawsey, 1947b).

In the November 1947 monthly progress report, Treharne and Little report that:

"The gear has now been installed at Bankstown and drift interference patterns obtained. A recorder will be installed almost immediately and attempts to measure source distribution etc. while the motor-driven phase shifter is being constructed. Another assistant is urgently required. The matter is in Mr. Higgs [Technical Secretary of the Division] hands." (Pawsey, 1947c).

As it turned out the drift interference patterns obtained at Bankstown where not real, but rather caused by gain fluctuations in the receiver due to problems with a power supply (McCready, 1947).

By February 1947, Treharne and Little had been joined by another assistant, Johnston, and they report:

"Practically all the instrumentation has been completed. Installation at Bankstown now proceeding and interference patterns can be taken as soon as a mains stabiliser (ex. Dr. Builder) is delivered (expected within a few weeks)." (Pawsey, 1947d).

By April 1948, Payne-Scott had been assigned to head the programme in place of Treharne and she and Little were forced to search for a new location for the experiments after the building they were using at Bankstown was sold. They report in the monthly progress report:

> "A search for a site to replace Bankstown has resulted in the choice of Potts Hill reservoir (which should also provide a suitable stretch of water for K-band interferometry); negotiations with the Waterboard have begun. Meanwhile equipment is being made to replace that stolen, and some obvious faults in the system are being remediated." (Pawsey, 1948a).

As described earlier, the equipment was installed at Potts Hill in July of 1948.

The use of phase variation to produce a sweeping aerial beam would later be used by a group at Jodrell Bank to develop what they called a 'Rotating-Lobe Interferometer' (Hanbury-Brown et al., 1955). This technique would go on to underpin the long baseline interferometry at Jodrell Bank used to determine source sizes and that would ultimately contribute to the measurement of the angular diameters of quasars.

At Potts Hill, the swept-lobe technique was suitable only for strong sources as the phase switching device introduced considerable noise into the system. However, for weaker sources of longer duration the system could also be used as a fixed lobe interferometer. For this purpose the coaxial feeds were connected directly to a 97 MHz receiver with a band-pass of 150 KHz and the output fed to a recorder that was connected to a mechanical time-signal clock. This configuration was used by Mills and Thomas for investigation of the Cygnus A discrete source from May to December 1949 (Mills and Thomas, 1951). They used the fixed lobe interferometer to determine a position for the Cygnus source and to investigate intensity variations of the source signal. The right ascension of the source was determined from the time of transit through the aerial beam. The declination was determined by measuring the frequency of the interference pattern as described below (Mills and Thomas, 1951):

$$\cos\delta = \frac{n\lambda}{d\sin H_n} \quad (5)$$

where

- λ is the wavelength;
- d is the distance between aerials;
- n is the number of a minimum in the interference pattern counting from an assumed central minimum; and
- H_n is the corrected hour angle at which the nth minimum occurs.

This was Mills' first experience in using interferometry techniques and this sparked his interest in further examining discrete sources. In order to achieve higher resolution a longer baseline for the interferometer was required. In 1950 limited space was available at Potts Hill. Therefore, Mills chose to construct a new interferometer at the new field station at Badgerys Creek which was located further to the west of the Potts Hill site. This ended Potts Hill's involvement in the investigation of discrete sources using interferometry. However, the technique would continue to be developed here, but focused solely on solar observations.

With Payne-Scott's resignation from Radiophysics in 1951 (see section 10.3.10 for further detail), further work using the swept-lobe interferometer was discontinued.

10.4.6. The Solar Grating Arrays (F)

Following observation of the partial solar eclipse on 1 November 1948, Christiansen was looking for a way to perform high-resolution solar observations that did not rely on solar eclipses and would not involve great expense. He was primarily interested in high-resolution observations at wavelengths of around 20 cm. To achieve a resolution of 3 seconds of arc at this wavelength would have required a single aerial at least 1,000 wavelengths wide (~700-ft) if the same design as the 16-ft×18-ft parabola was used. Clearly this would have been impracticable.

Christiansen devised an approach that was analogous to a diffraction grating. He realised that by using a number of aerials arranged in a straight line at a uniform spacing, the combined response of the array would produce multiple beams which would be separated from each other proportionally as the inverse of the spacing between aerials. As such, the array could be configured so that only one of the response beams could be positioned on the Sun at any given time. Christiansen's inspiration for this configuration came indirectly and was influenced by his antenna design background:

> "The idea occurred while reading a description of Bernard Lyot's optical filter in which narrow frequency pass-bands are produced at widely different frequencies. This may seem particularly indirect when the analogy which is more obvious is the optical diffraction grating, but to me as an antenna designer the cos n.cos 2n.cos 4n series of the Loyt filter immediately suggested an antenna array and an array of arrays." (Christiansen, 1984: 118).

Keeping the cost of the design to a minimum level was of prime concern to Christiansen. He was given permission by Bowen and Pawsey to construct the array provided that the material cost for construction could be kept under £500 (Christiansen, 1984: 118), although on a different occasion Christiansen recalled that the cost needed to be kept below £180 (Bhathal, 1996b). The mechanical design for the array was performed by K. McAlister (Figure 49), who also proved extremely resourceful in meeting the cost target.

Figure 49: Keith McAlister, the resident Mechanical Engineer at Radiophysics who was responsible for the mechanical design of many of the aerials (Courtesy of ATNF Historic Photographic Archive).

The construction of the array commenced in July 1950. The array consisted of 32 aerials evenly spaced at 23-ft along an east-west baseline of 700-ft located on the southern end of the northern reservoir at Potts Hill (Figure 50).

The aerials were constructed in the Radiophysics workshops in the grounds of Sydney University. The array was assembled by the Radiophysics staff. A series of 32 wooden posts was aligned using a theodolite by Warburton and Davies, and as Davies has noted:

"At that time we didn't know that Ph.D. meant Post-hole Digger!" (Davies, 2005: 94).

Each aerial consisted of a 66-in solid parabolic reflector plate (Christiansen and Warburton, 1953a). A dipole receiver and reflector were mounted at the prime focus. In this form all of the aerials were horizontally polarised. To observe circularly polarised radiation the aerials could be configured so that alternate aerial dipoles were set horizontally and vertically so that there was a 90º phase shift between pairs. Each of the aerials was equatorially mounted and could manually be stepped in right ascension via a series of holes in the mounting post and a locking peg to allow tracking of the Sun. During observations the aerial positions were changed approximately every 15 minutes. This involved someone running down the length of the array and adjusting each of the 32 elements by hand.

Figure 50: The 32-element array at Potts Hill (Courtesy of ATNF Historic Photographic Archive: 2976-1 Image Date: 14 January 1953)

The aerials were combined by a branching system of transmission lines. To keep costs down, the transmission lines were a braced open-wire system separated by a ¼ λ and supported by polystyrene insulators and spacers (see Figure 51).

Figure 51: The array showing the bracing weights for the open-wire transmission lines (Courtesy of ATNF Historic Photographic Archive: B2976-1 Image Date: 28 November 1951).

To achieve the branching configuration the transmission-lines were stacked vertically in five levels and connected via short vertical connectors. Figure 52 shows a schematic of the transmission-line system.

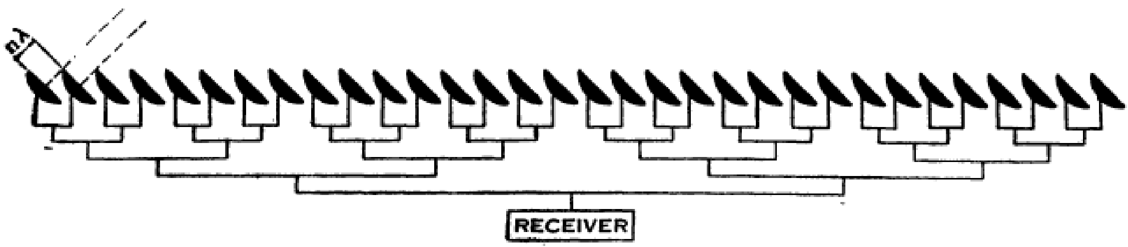


Figure 52: Schematic of the branching transmission lines on the 32-element solar grating array (after Christiansen and Warburton, 1953a: 192).

The directivity of the array can be calculated via the formula given below (Christiansen and Warburton, 1953a):

$$\Phi(\theta) = \frac{\sin^2 Np}{N \sin^2 p'} \qquad (6)$$

where

p $= \pi d \sin\theta/\lambda;$

$\Phi(\theta)$ is the power received from the source, relative to the power received from one aerial;

N is the number of elements in the array;

d is the spacing between elements;

λ is the wave length; and

θ is the angle between the perpendicular to the baseline and the direction of the source.

The array produced a series of fan-shaped beams which had a calculated beam width of 2.9 minutes of arc at 1,410 MHz. The spacing between beams was 1.7º and since the diameter of the radio Sun at this frequency was ~0.5°, this meant that the Sun could only be in one of the fan-beams at any one time. Figure 53 shows the beam response produced by the array.

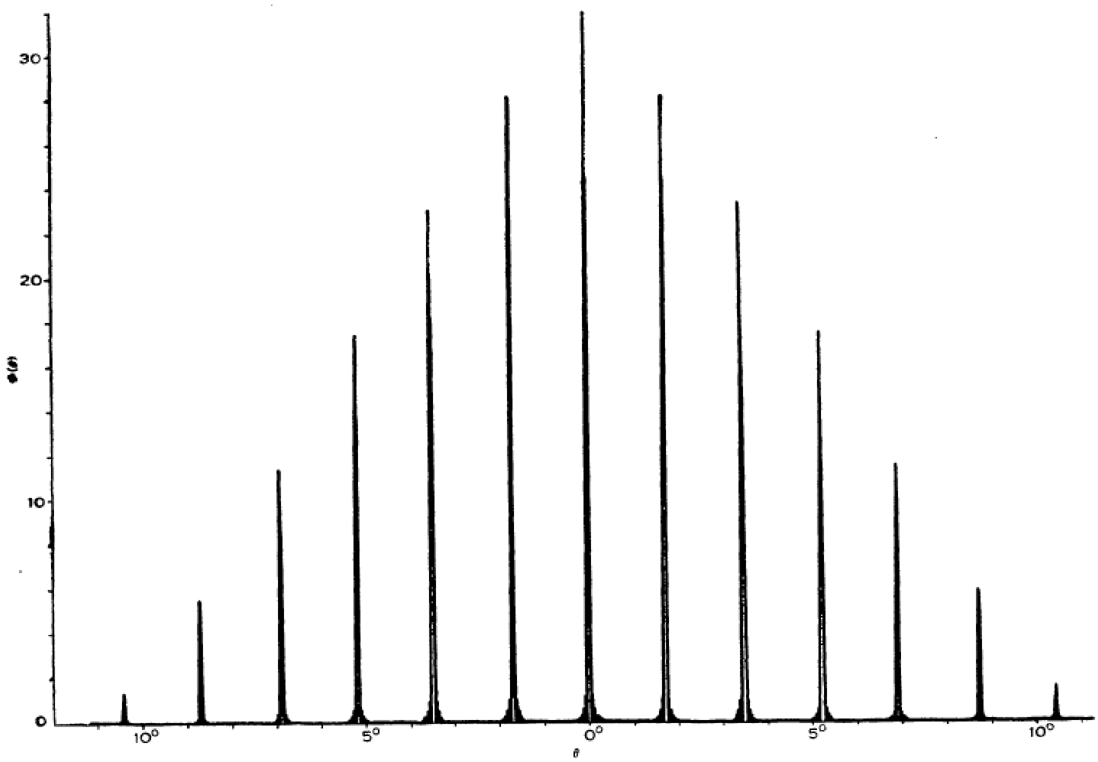


Figure 53: Beam response diagram for the 32-element array. The power received from the source is shown on the Y-axis and the direction of the source relative to the array beam on the X-axis (after Christiansen and Warburton, 1953a: 192).

A superheterodyne receiver was connected to the array transmission-line via a radio-frequency switch that contained a rotating condenser which switched the signal at a rate of 25 Hz between the transmission-line and a dummy load. The modulated signal was then passed to a crystal detector which was coupled to a line-tuned heterodyne-oscillator and a 30 MHz amplifier with a 4 MHz bandwidth. After the 30 MHz amplification was a further detector, a 25 Hz amplifier and a phase sensitive detector. This then fed a recording milli-ammeter. A typical output of the recording is show in Figure 54.

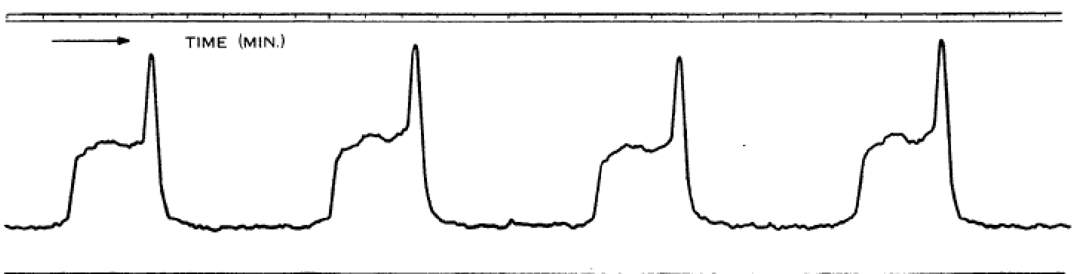
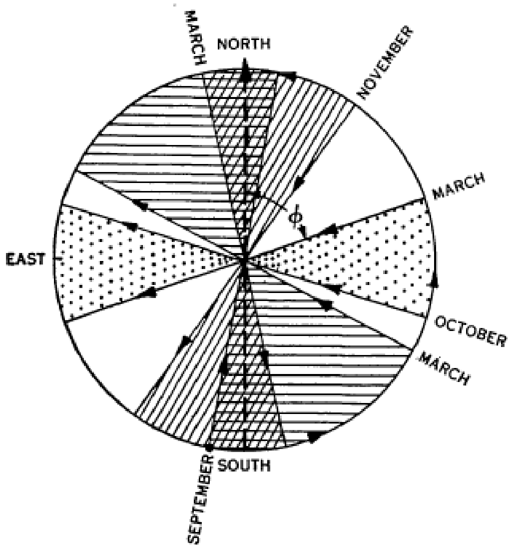


Figure 54: An example of the output recording showing the passage of the Sun through several beams of the array (after Christiansen and Warburton, 1953a: 193). In this example a strong source of emission is present near the right-hand limb of the Sun.

When the array was configured to measure polarisation the output recording characteristic would change. For linear or randomly polarised radiation, successive records would be substantially similar in strength as shown in Figure 54. For circularly polarised radiation successive records would show a diminished response depending on the strength of polarisation.

The solar grating array became operational in February 1952 and was used to make daily observations of the Sun. This was generally done by observing over a two hour period centred on midday.

One of the limitations of observations using the east-west array was that fan beams could only scan the Sun in one dimension. To calculate the distribution of radiation from the Sun it was therefore necessary to assume a symmetrical distribution. From visual observation it is clear that the Sun is an oblate spheroid and solar eclipse observation indicated that the solar corona was far from symmetrical (Blum et al., 1952). To overcome these limitations Christiansen realised that by using a second array arranged in a north-south direction the Sun could be scanned at a variety of angles. The Earth's rotation and orbit presented a very wide variety of angles for observations. By performing a Fourier Analysis on the one-dimensional scans taken over a wide variety of angles it was possible to construct a two-dimensional brightness distribution of solar radiation. Although not widely acknowledged, this was the world's first application of Earth-rotational synthesis in astronomy (Christiansen, 1989b).



SHADING	INTERFEROMETER USED	OBSERVATION PERIOD (LOCAL TIME)
(diagonal hatching)	N.— S.	0800 → 1200 HR
(dots)	E.— W.	1000 → 1200 HR
(horizontal lines)	N.— S.	1200 → 1500 HR

Figure 55: Range of scanning angles covered by the arrays (after Christiansen and Warburton, 1955a: 479)

To achieve these objectives, in 1953 a north-south array was constructed on the eastern side of the reservoir on which the east-west array was located. The aerial design for this array was quite different. Instead of 32 elements, the North-South Array had 16 elements consisting of open-mesh parabola aerials mounted on much more robust equatorial mounts, as shown in Figure 56.

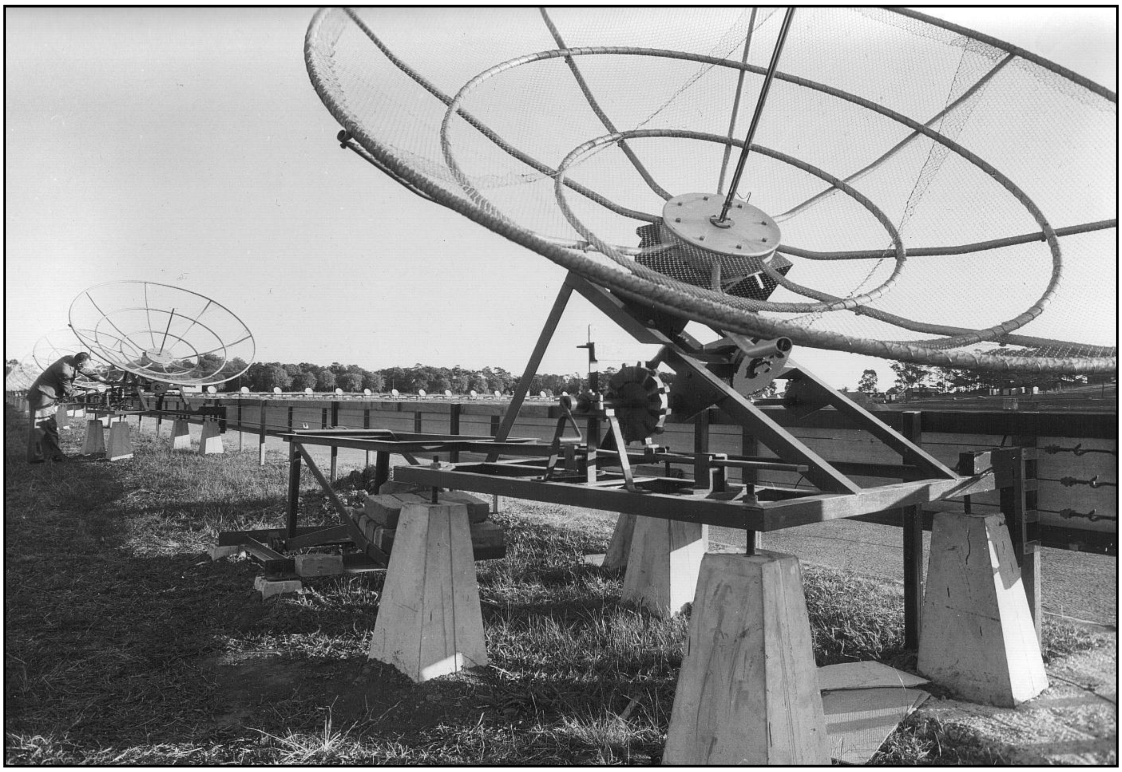


Figure 56: North-South Array (Courtesy of ATNF Historic Photographic Archive: 3116-1 Image Date: 20 July 1953)

The array was also somewhat shorter than the East-West array being 760 wavelengths in length as opposed to the 1028 wavelength of the East-West array. This meant that the aerial produced a slightly wider beam of 4 minutes of arc. The open transmission-line feeds were retained and can also be seen in Figure 56 with the East-West array in the distant background. Figure 57 shows an aerial view of the two arrays. This view is taken from the northeast looking southwest.

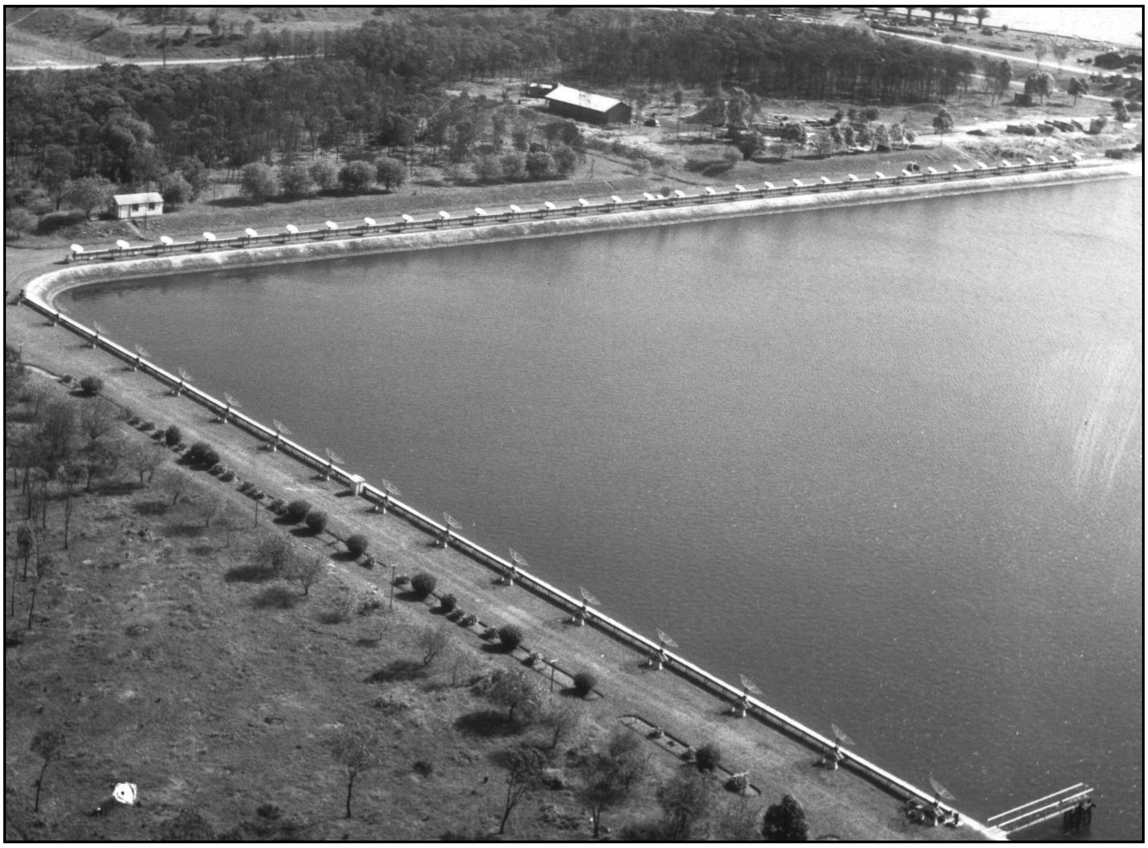


Figure 57: Aerial view of the 32-element east-west and the 16-element north-south arrays (Courtesy of ATNF Historic Photographic Archive: 3474-1 Image Date: 25 September 1954).

Daily observations were made using both arrays from September 1953 to April 1954 (Christiansen and Warburton, 1955a). By observing over a long period Christiansen and Warburton were able to make use of the seasonable variations of the Sun's orientation with respect to the two arrays. Thus, they were able to achieve coverage of 140º out of the 180º range of scanning angles, as indicated in Figure 55.

During the URSI General Assembly in Sydney in 1952 the French representatives invited Christiansen to work with them for a period. So, in 1954 he moved to the Meudon Observatory near Paris on secondment from Radiophysics for one year. In Christiansen's absence, Swarup and Parthasarathy modified the receiving equipment on the East-West Array to carry out solar observations at 500 MHz (λ = 60cm) (Swarup and Parthasarathy, 1955b). At this frequency the width of the fan beam was increased to a theoretical value of 8.2 minutes of arc at the half power points with a beam spacing of 4.9º. Swarup and Parthasarathy checked the beam response using Cygnus A as a reference and found the actual beam width to be closer to 8.7 minutes of arc. From July 1954 to March 1955 they used the East-West Array to measure the one-dimensional distribution of radio brightness of the quiet Sun and to look for limb brightening effects. By tracking the Sun over a period of months they were able to scan the Sun at angle from 90º to 60º with respect to the central meridian.

Christiansen returned from France in 1955. During his absence he had determined to build a new array. The seed for this array had been sown in 1953 following a discussion with Mills. As Christiansen later recalled:

> "While visiting Potts Hill one morning in 1953, Mills asked me why we did not couple the two arrays to produce high resolving power in two dimensions. During the ensuing discussion it was agreed that for this to be effective the centres of the two arrays must not be separated (as they were in the Potts Hill antenna), and also that some means had to be devised to multiply the outputs of the array. By the next morning Mills had devised the Cross Antenna consisting of a pair of thin orthogonal antennas with their outputs multiplied to give a single narrow response." (Christiansen, 1984: 122).

Mills went on to build the Mills Cross prototype discussed in Section 10.4.8. Christiansen decided to abandon the Earth rotational synthesis technique he had developed, largely because it was too time-consuming to be useful for observing short term changes in solar radiation. Instead he returned to the idea of the crossed arrays. Potts Hill did not have sufficient vacant land on which to build an array with a common centre, so Christiansen moved his activities to the field station at Fleurs where a new array was constructed.

However, a prototype of the aerial design that would be used at Fleurs was tested at Potts Hill. Figure 58 shows the larger prototype aerial located next to the original north-south array.

Figure 58: The prototype of the larger aerial in the background that was to be used in the new crossed array being tested at Potts Hill (Courtesy of ATNF Historical Photographic Archive: B3881-2 Image Date: 13 December 1955).

Figure 59 shows another view of the prototype aerial.

The new crossed array began operation in 1957 producing daily images of the Sun (Orchiston, 2004c). Again, this array was designed and constructed in-house in the Radiophysics workshops. This move effectively made the original Solar Grating arrays redundant and hence they were earmarked to be scrapped. Fortuitously, as noted by Swarup;

> "Pawsey liked to visit all the RP field stations unannounced to see what his staff were doing (Sullivan, 2005), and during one of his surprise visits to Potts Hill I asked whether these dishes could be gifted to India. He readily agreed to this suggestion, as did E.G. (Taffy) Bowen, Chief of the Division of Radiophysics. On 23 January 1955, I wrote to K.S. Krishnan about the possibility of transferring the thirty-two dishes from Sydney to the NPL (National Physical Laboratory) in New Delhi." (Swarup, 2006: 25).

Figure 59: Another view of the cross grating prototype aerial being tested at Potts Hill (Courtesy of ATNF Historical Photographic Archive: B3881-14 Image Date: 13 December 1955).

Although Australia agreed to donate the equipment under the Colombo Plan, there was a substantial delay before the equipment was actually shipped to India as there was no agreement as to who should bear the cost of shipping, which at the time was about 700 Australian Pounds (Swarup, 2006). Eventually the CSIRO agreed to meet the shipping costs and the 32 elements of the Potts Hill East-West Solar Grating Array was shipped to New Delhi. In mid 1963 the array was transferred from the National Physical Laboratory in New Delhi to Tata Institute of Fundamental Research and was set up at Kalyan near Bombay for solar observations at 610 MHz. The original 32 aerials were configured as two arrays, one of which consisted of 24 aerials oriented in a east-west baseline 630 metres long and the second consisting of the remaining 8 aerials in a north-south baseline 256 metres long. In this configuration it became known as the Kalyan Radio Telescope and began operations in April 1965 (ibid.) The first paper produced from observations from this instrument appeared in *Nature* (Swarup et al., 1966).

The fate of the North-South Array is not clear although some aerials may have been donated to local universities (see Section 10.4.10).

10.4.7. 36-ft transit Parabola (G)

Following the detection of the Hydrogen emission line using the 16-ft × 18-ft Paraboloid and the realisation of the importance of investigation of the line emission, it was determined to build a dedicated instrument for survey work at Potts Hill. This instrument was one of the largest radio telescopes in the world and certainly the largest in the southern hemisphere at this time. The construction work was supervised by Hindman and Kerr (upon the return of the latter from studies at Harvard College Observatory during 1950-1951). As luck would have it Kerr was visiting Harvard when the H-line discovery was first announced and hence he was able to assist in engaging Radiophysics in the confirmation of the discovery.

Initially Radiophysics considered purchasing a large aerial rather than constructing one in their own workshops. In August 1951, Pawsey contacted the Dutch company, Werkspoor, enquiring as to the feasibility of purchasing an 80-ft instrument. However, after some tentative exploration it was decided to proceed with in-house design and construction (Pawsey, 1951d).

Construction of the instrument commenced in late 1951. For the purposes of survey work it was decided to build a transit instrument that consisted of a 36-ft parabola mounted on a fixed east-west axis, which could be stepped only in declination.

Figure 60 shows the construction of the foundations for the aerial mount and the receiver hut. The aerial was located just to the west of the 16-ft×18-ft Paraboloid on the northern side of the reservoir.

Figure 60: Construction of the foundations for the 36' Transit Parabola (Courtesy of ATNF Historical Photographic Archive: B2768-1 Image Date: 6 June 1952).

The aerial was supported by two major post structures at the east and west sides of the aerial together with a further central supporting track. Figure 61 shows the post mountings during construction.

Figure 61: The two major support posts of the 36-ft aerial during construction (Courtesy of ATNF Historical Photographic Archive: B2778-5 Image Date: 19 June 1952).

The aerial itself was fabricated on site and consisted of a frame construction with a mesh reflector surface. Figure 62 shows the aerial on its construction jig during assembly.

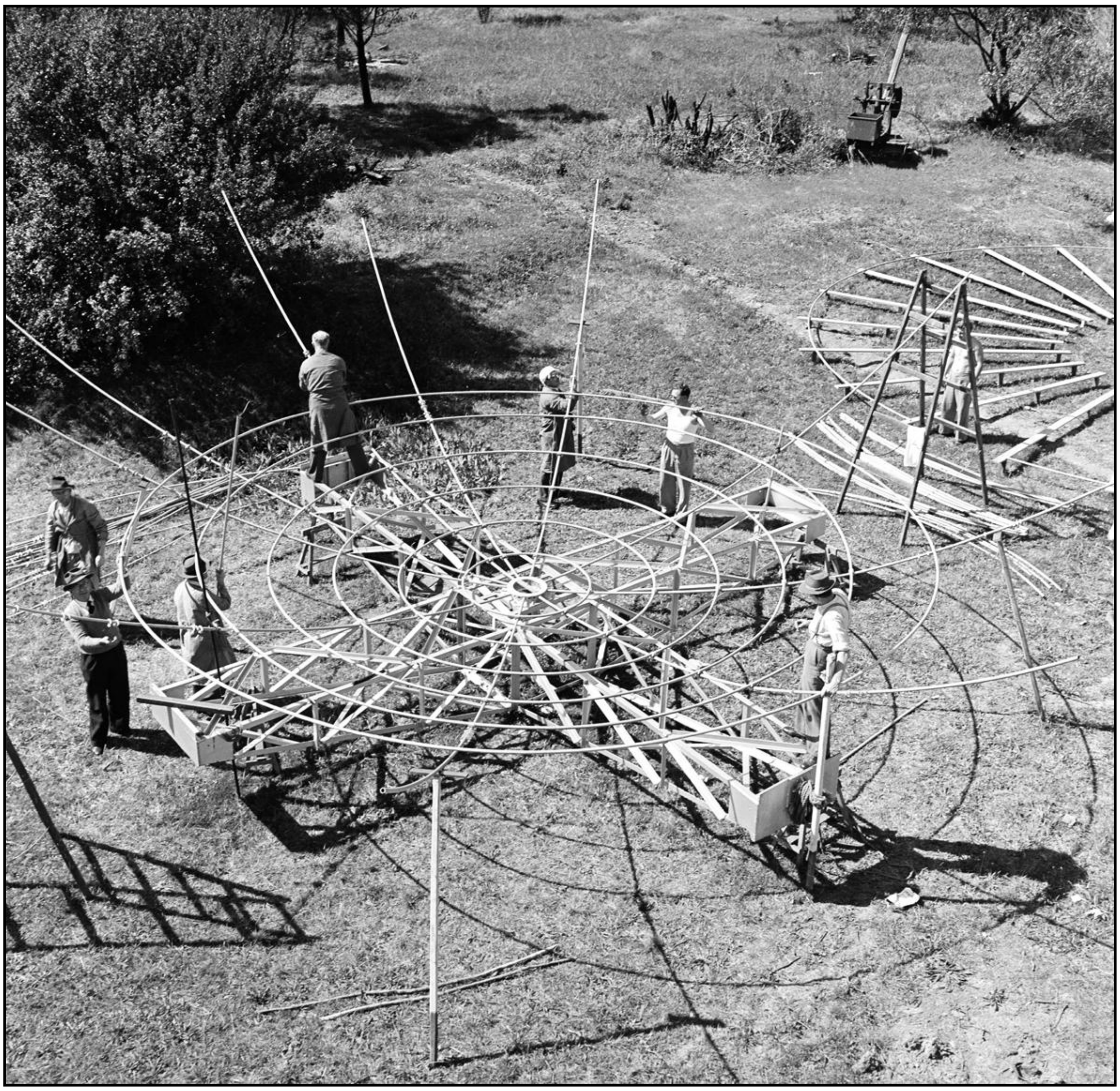


Figure 62: The onsite assembly of the 36-ft Parabola in its construction jig (Courtesy of ATNF Historical Photographic Archive: 2774-2 Image Date: 3 September 1952) .

A crane was then used to lift the parabola into its mounting as shown in Figure 63.

Figure 63: The 36-ft Parabola being lifted by crane into the transit mounting (Courtesy of ATNF Historical Photographic Archive: B2975-19 Image Date: 14 January 1953).

Figure 64 shows the aerial undergoing final assembly in its mount. The central track support is also visible in this photograph.

Figure 64: The 36-ft Transit Parabola in final assembly in its mounting (Courtesy of ATNF Historical Photographic Archive: 2975-21 Image Date: 14 January 1953).

In this configuration, and with the operating frequency of 1,420 MHz, the beamwidth of the aerial was theoretically 2º at the full width half-power points, but this was later measured using the Sun as a reference source to be 2.8º (Kerr et al., 1959). Figure 65 shows the measured radiation pattern of the main lobe compared to a Gaussian curve with the same width between half power points. The Gaussian curve is indicated by the solid line and the open circles show the actual measurements.

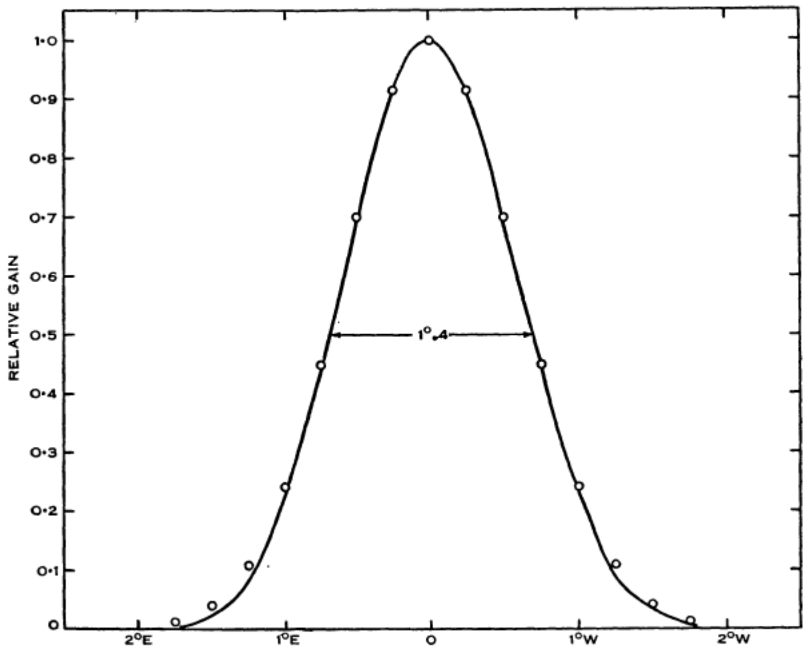


Figure 65: The measured shape (open circles) of the main lobe radiation pattern of the 36-ft parabola at 1,400 MHz compared to a Gaussian curve (solid line) (after Hindman and Wade, 1959: 260).

Despite the very robust mounting structure, structural distortions in the aerial framework and in the prime focus mounting could result in pointing errors of up to 1º and hence it was necessary to carefully measure the distortions at various aerial delineations so that corrections could be applied to position measurements. To do this, a small optical telescope was fixed to the aerial framework and the transit of stars at various declinations was observed. Direct measurements were also made using a sighting telescope. The original single pole prime focus mount proved too flexible and it was soon replaced by a tripod mount. The finished instrument ready for H-line observation is shown in Figure 66.

Figure 66: The 36-ft Transit Parabola ready for H-line observations (Courtesy of ATNF Historical Photographic Archive: 3170-2 Image Date: 14 January 1953).

The receiving equipment that had been used for the initial H-line detection and the first surveys was based on a receiver that was swept across a narrowband while rapidly switching between two adjacent frequencies (refer to Section 10.4.7 for a more detailed description of this equipment). This produced a modulated signal that was independent of the background signal; however, the modulated signal itself was very weak. This meant that long integration times were necessary to reach the required sensitivity and hence the frequency band in which the H-line was present could only be swept very slowly. To overcome this limitation, Pawsey proposed the construction of a new type of receiver (Kerr et al., 1954), the world's first multi-channel receiver (Kerr, 1984). Instead of sweeping the frequency band in which the H-line could be detected, Pawsey proposed the use of a fixed-frequency system. In this system a broad-band output covering the frequency band to be analysed was filtered into a number of parallel narrow-band channels which could all be displayed simultaneously. By comparing the mean noise levels in each narrow-band channel with the overall broadband it was possible to remove background noise from the signal. This allowed the whole frequency band covered by the broad-band input to be analysed and the line profiles determined in a single integration period and meant that observations of the same sensitivity could be made much more rapidly that with the previous receiver.

The initial tests of the multi-channel receiver were made using only a limited number of channels. The first paper published based on observations using the new receiver design used only a single channel of 40KHz bandwidth (Kerr et al., 1954). A Superheterodyne design with double frequency change was used for the receiver. A local oscillator at 1,390 MHz was coupled to a high frequency mixer which then fed the first stage intermediate-frequency channel of 30 MHz. Both of these components were mounted at the aerial feed point at the aerial's prime focus where a flanged horn acted as the primary feed. In this configuration the aerial was horizontally polarised parallel to its east-west axis. A low frequency mixer, coupled to a 23 MHz oscillator, was then fed to the next intermediate-frequency channel of 7 MHz. At this point the overall bandwidth was 1.7 MHz. From this a 40 KHz section was selected for examination by a narrowband filter. By adjusting the two oscillators and the narrowband filter, which operated at 7 MHz, the receiver could be tuned to the zero beat frequency point, which corresponded to a receiver frequency of 1,420.405 MHz. In this way the receiver output provided a direct measure of the Doppler frequency components, either positive or negative, around the 'at rest' frequency of the H-line. These Doppler components were due to the radial velocity of the hydrogen producing the emission. This velocity was then manually corrected to take account of the Earth's rotation and orbit around the Sun, as well as the motion due to the Sun's orbit in the Galaxy, to arrive at a local standard of rest. Figure 67 shows a block diagram of the 'single channel' multi-channel receiver that was used in the initial observations and trials of the receiver.

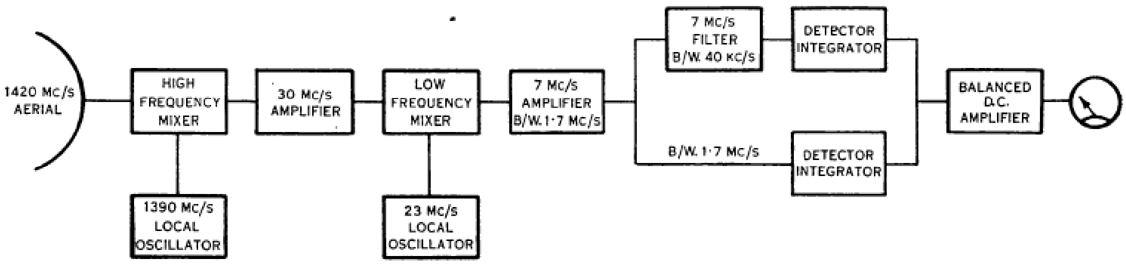


Figure 67: A block diagram of the "single-channel" multi-channel receiver prototype (after Kerr et al., 1954: 301).

In the original construction the single pole prime focus mounting had been replaced by three arms that were used to support the prime focus equipment, but this was modified in December 1953 to an even more rigid four arm system as shown in Figure 68.

Figure 68: The 36-ft aerial showing the four-arm prime focus supports (Courtesy of ATNF Historical Photographic Archive: 3679-1 Image Date: 1 June 1955).

As part of the modifications, the prime focus feed was shifted outward by about 1-ft to its correct focus point. This improved the gain of the aerial by nearly 20% and virtually eliminated the side-lobes (Kerr, 1954b).

The new receiver also required a different type of observing technique to that used in the earlier H-line studies. The aerial was positioned at a fixed declination and then the sources were allowed to drift through the aerial beam courtesy of the Earth's rotation. A continuous recording was made in the multiple frequency channels and the H-line profiles derived by fitting together a series of these recordings. For the early observations using the 'single' channel prototype receiver these observations needed to be repeated for each different frequency channel so that the line profile could be derived. By using multiple channels that gave sufficient frequency coverage to encompass the observed radial velocities, a 1º strip of the sky could be scanned and the line profile to be directly derived as a function of right ascension and declination.

Figure 69 shows an example of the H-line profile produced by the receiver. The receiver was tuned to the rest frequency of the Hydrogen emission, so the frequency shift from the central frequency was a direct function of radial velocity. Figure 69 shows the measurement at the multiple frequency channels (dots). These are fitted by two Gaussian curves to produce the profile.

Figure 69: Example of the H-line profiles produced by the prototype multi-channel receiver (after Kerr et al., 1954: Adapted from Figure 3: 303).

The prototype receiver was used to perform a survey of neutral hydrogen in both the Large and Small Magellanic Clouds. These were the first observations of neutral hydrogen from extragalactic sources. Getting the original receiver to work effectively across multiple channels had proved to be extremely difficult. In mid 1953, J.D. Murray was asked by Pawsey to see what could be done with the receiver design. Murray recalled that this was not a happy task and after 6-7 weeks work determined that the original receiver design would never work and would need to be changed to a switched design (Murray, 2007). At this point Murray returned to the laboratory and began work on an entirely new receiver design that would become the 48-channel receiver used at the Murraybank field station.

Hindman and Kerr persisted with their receiver and ultimately modified its design significantly. Instead of switching between two frequencies a continuous comparison approach was used whereby two channels were connected to opposite sides of a differential D.C. amplifier. Figure 70 shows a block diagram of the modified later stages of the multi-channel receiver. The channels could be stepped across the desired frequency band allowing a one channel overlap to produce a continuous line profile. To produce full coverage of a broad profile in the Galaxy required eight to ten observing days (Kerr, 1984).

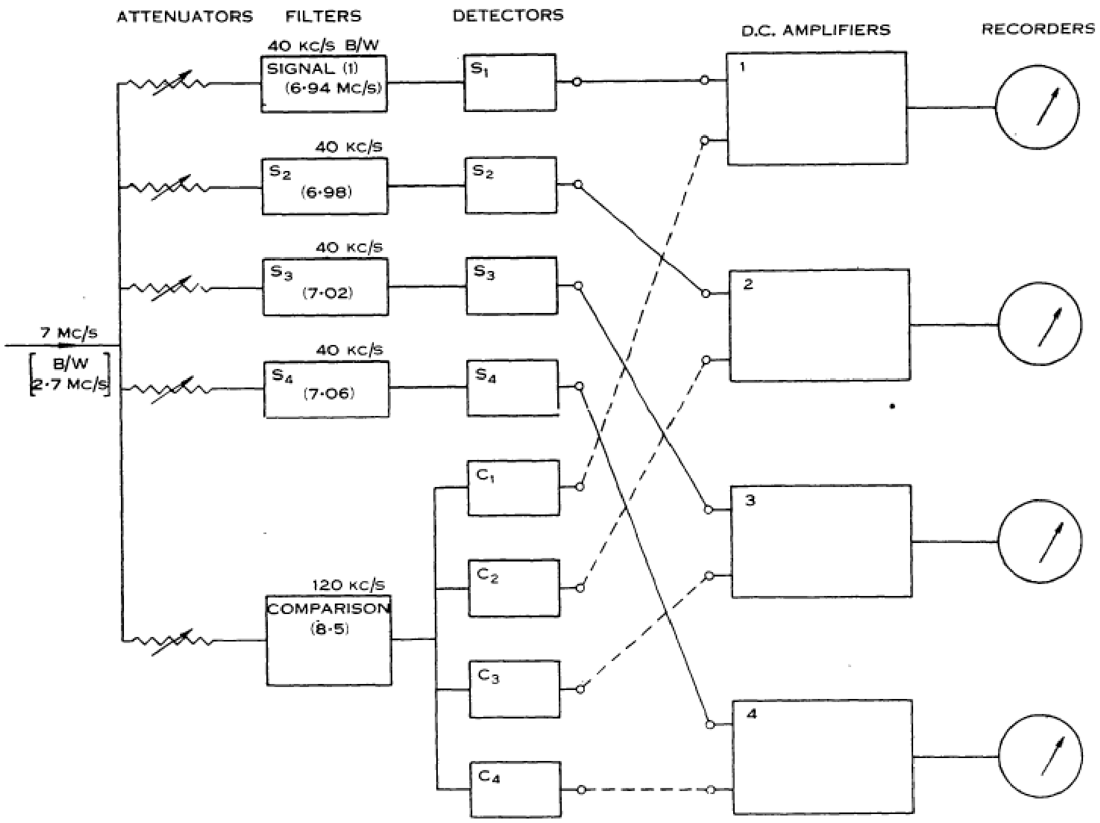


Figure 70: The modified late stages of the four-channel receiver (after Kerr et al., 1959: 274).

These receiver modifications overcame the issues inherent in the swept and switched type of receivers, namely the difficultly of maintaining a flat baseline while tuning over a wide frequency band and the precise equalisation of the local oscillator and the front end performance in the two switch positions. However, the new design introduced a new issue. Because the signal comparisons used different parts of the band-pass for comparison, they could be subject to differential gain drift. This required very careful stabilisation of the components. To check for drift and to establish a zero level, the aerial was pointed at a 'cold' part of the sky, in this case the South Celestial Pole, after each scan across the Milky Way. The output signal produced was of the 'picket fence' type reminiscent of the early solar measurement made using the 16-ft × 18-ft Paraboloid at Georges Heights (see Figure 30 for an example of the output signal). Figure 71 shows an example of the four-channel output along three constant-declination tracks across the Milky Way. The 'P' symbol indicates where the aerial was pointed at the South Celestial Pole.

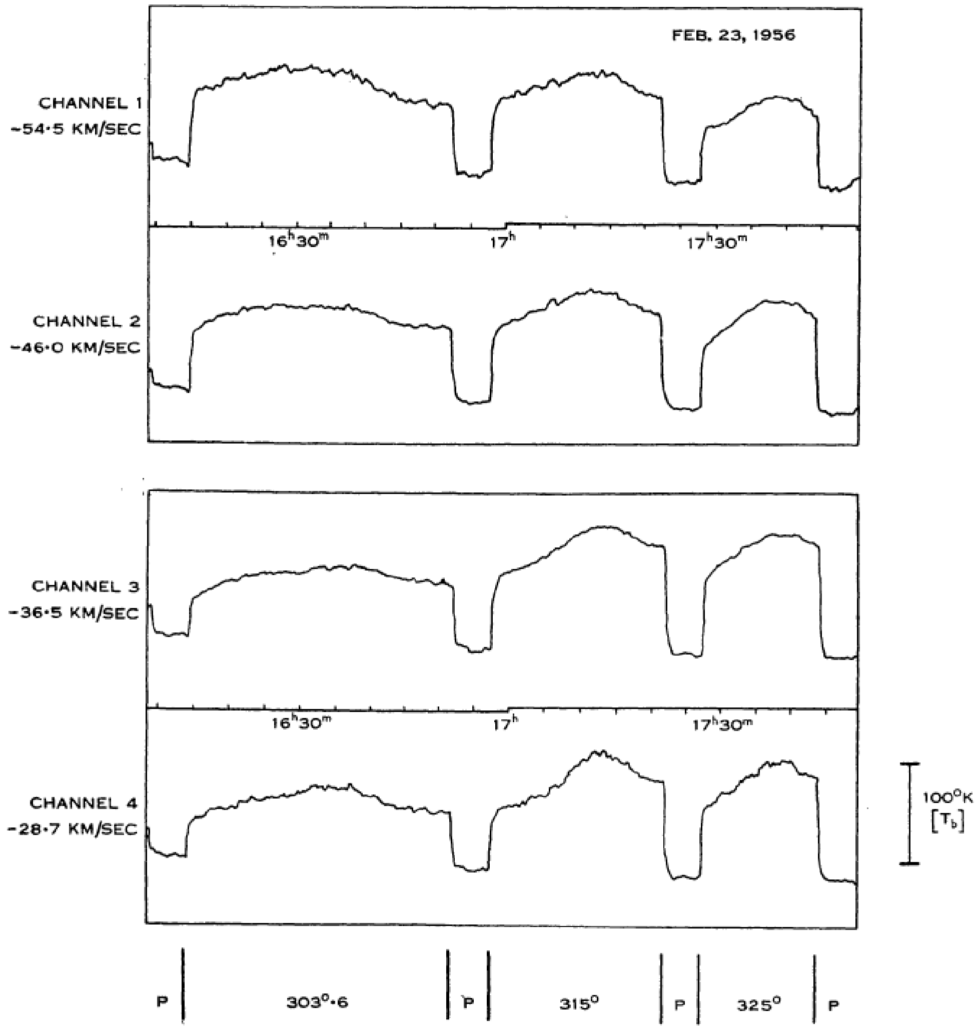


Figure 71: Example of the "Picket Fence" effect where the 36-ft aerial was pointed at the south celestial pole between declination track scans (after Kerr et al., 1959: 280).

In 1955 Piddington and Trent, in a departure from H-line work, used the 36-ft Parabola to conduct a survey at 600 MHz between declination 90º South and 51º North (Piddington and Trent, 1956b). They replaced the multi-channel receiver with a 600 MHz receiver which was fed by a single dipole and reflector plate mounted at the prime focus. The receiver was essentially identical to that used by Piddington and Minnett for their earlier survey work at 1,210 MHz using the 16-ft×18-ft Paraboloid (see section 10.4.1 and Figure 33 for detailed description). A 6-ft parabolic aerial directed at the south celestial pole was used to provide the reference source for the main aerial and is shown in the right foreground of Figure 72. This was a major undertaking as the beam width of the aerial at the half power points at this frequency was just over 3º. Observations were made by setting the aerial at a fixed declination and then allowing the beam to drift in right ascension as the Earth rotated. The declination was then stepped by 1¼ degrees and the next scan taken. The whole process was then repeated at least twice to remove instrument effects and external interference and this achieved almost full sky coverage from -90º to +51º. The results of this survey were published in 1956 (Piddington and Trent, 1956b).

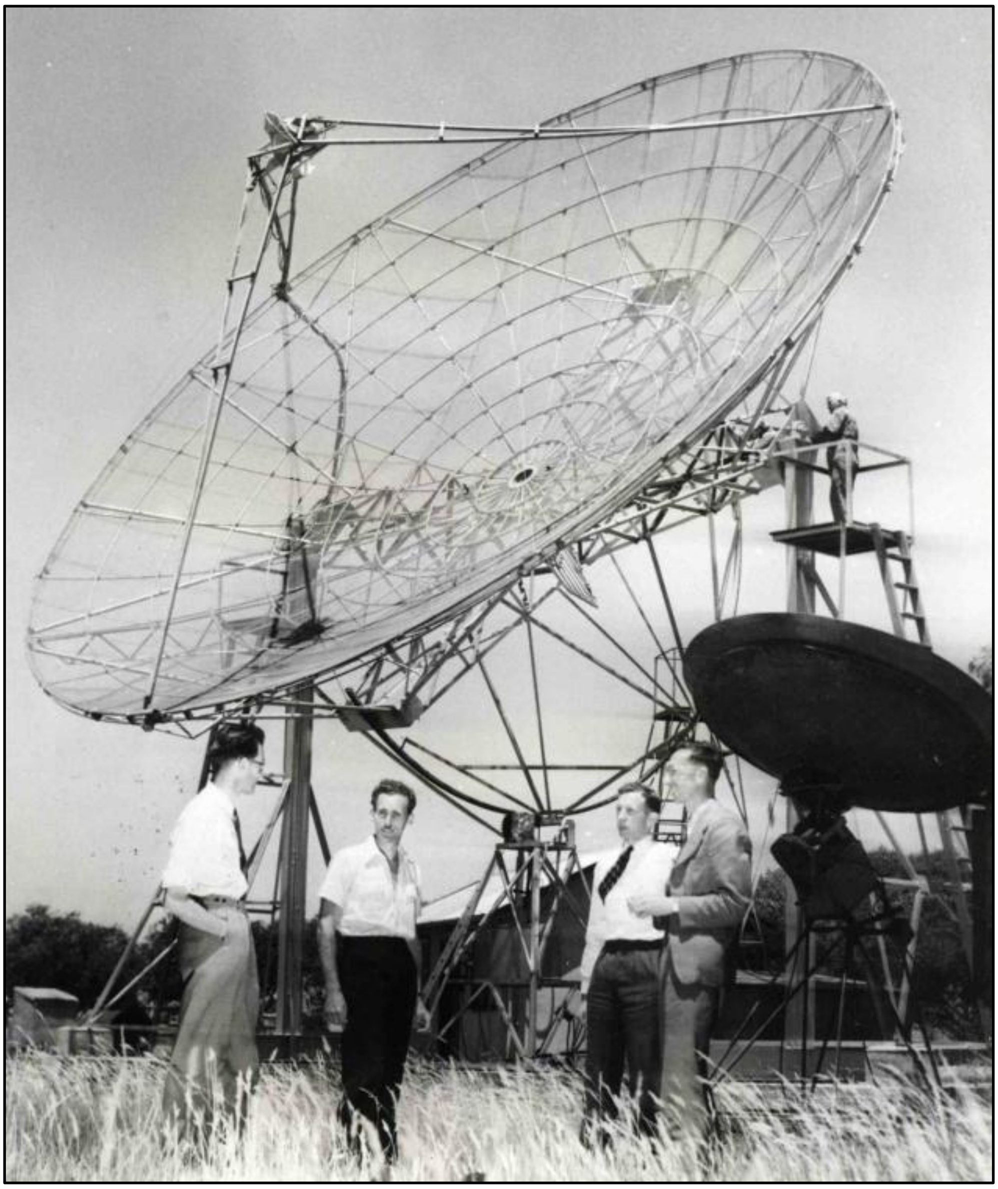


Figure 72: The 36-ft transit parabola with the 6-ft reference aerial in the right foreground. The people in the image are from left to right Kerr, Hindman, Robinson and Pawsey (Courtesy of ATNF Historical Photographic Archive)

Having got the multi-channel receiver working, Hindman and Kerr began work on the survey of the southern Milky Way. This survey work led to collaboration with the Dutch Leiden Observatory to produce a composite diagram of the spiral arm structure of our galaxy (Kerr et al., 1957). The work also was a major component of the data used to determine a new system of galactic co-ordinates based on a newly agreed centre and plane for the galaxy that was adopted by the IAU General Assembly in 1958.

With the completion of observations for the southern H-line survey, Hindman and Wade adapted the modified receiver to allow broadband detection of radiation around 1,400 MHz. They did this by modifying the receiver so that it accepted two bands, each 30 MHz away from the first stage oscillator frequency of 1,393 MHz. This way they could exclude the H-line emission signal from investigation of the broadband continuum. Figure 73 shows a block diagram of the modified receiver.

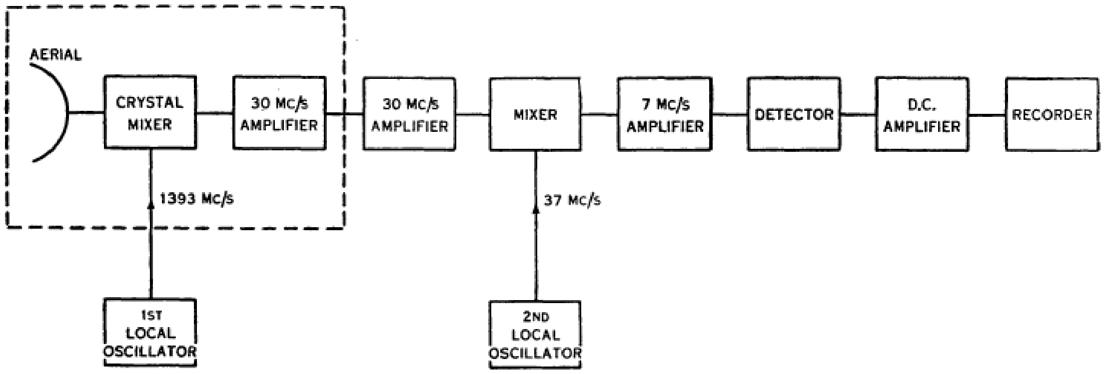


Figure 73: Block diagram of the modified receiver to allow broadband detection around 1,400 MHz (after Hindman and Wade, 1959: 261).

The modified receiver was used to investigate the Eta Carine Nebula and Centaurus A.

In 1956 a new field station was opened at Murraybank and the ongoing Radiophysics H-line research was transferred to this field station (Orchiston and Slee, 2005a). At Murraybank a fully-steerable 21-ft Parabola (Figure 74) was installed overcoming the issues with operating a transit instrument for the survey work. The Murraybank aerial was a modified design of the "Chris-Cross" aerial with increased rigidity and an increase in diameter (Pawsey, 1955b).

In a report on the projected future programme for the Radio Astronomy Group on 29 June 1959 it was noted that as the southern Milky Way H-line survey was now completed, the 36-ft Parabola and associated hut would be held in reserve as a test bed for receiver testing until such time as the new equipment facility being developed at the new Radiophysics Headquarter at Epping was completed (Pawsey, 1959a).

In the Annual Report for the Division for the year ended 30 June 1958 it was noted that the development of masers (Microwave Amplification by Stimulated Emission of Radiation) was underway in the U.S. (Bowen, 1958). It also noted that this type of receiver would be most useful for 21-cm research and therefore a small group had been organised to investigate. This group consisted of F.F. Gardner, D.K. Milne and G. Bogle. Masers were considered an offshoot of work in the field of low-temperature paramagnetic resonance in which the Division of Physics had a large body of experience and the maser development had revived an interest in 'parametric' amplification which offered low noise amplification without the engineering complexities of the maser. The report also noted that an Officer [B. Robinson] had been stationed at Leiden where work on masers for radio astronomy was underway. In 1958, an operational maser receiver was constructed and tested at Potts Hill using the 36-ft Transit Parabola (Milne and Whiteoak, 2005: 33). This was one of the first operational masers in the world. The maser used liquid helium for cooling and this proved to be impracticable for operations at Parkes and so further development was abandoned in favour of using a 20-cm nitrogen-cooled parametric amplifier (ibid.). The maser trials were the last experiments performed using the 36-ft Parabola at Potts Hill.

Figure 74: The 21-ft Parabola at the Murraybank field station (Courtesy of ATNF Historical Photographic Archive).

10.4.8. Mills Cross Prototype (H)

After his experiences in using two-element and three-element interferometers, initially at Potts Hill and then more extensively at Badgerys Creek field station during 1950 to 1952, Mills was looking for a way in which he could overcome some of the limitations inherent in this type of interferometer. Clearly a traditional parabola pencil beam instrument of sufficient size to produce high resolution would be suitable, but this would have been prohibitively expensive to construct.

One of the main issues Mills had been dealing with at Badgerys Creek was the problem that the small spacing of the interferometer aerials required long periods of integration and therefore the measurements suffered from gain fluctuation in the receiver. It was while exploring a solution to overcome this problem that Mills recalled:

> "I had begun to look for a better alternative when I received some unintended assistance from Cambridge. News came through the grapevine that a revolutionary system had been introduced there but it was all very hush-hush and no details were known; It was believed that it involved a modulation of the interference pattern. This seemed to be just what was needed. A little thought suggested modulation by interchanging maxima and minima on the interference pattern by switching phase and using a synchronous detector, as in the Dicke system. The necessary equipment was built and it worked very well. Later I found that this was precisely the system used at Cambridge, the only difference being their use of a hardware switch in the antenna feed lines whereas I had used an electronic switch following the preamplifier." (Mills, 1984: 149).

Using the new phase switched interferometer at Badgerys Creek Mills soon discovered another major issue with using spaced interferometers for survey work. Many of the sources resolved at the short spacing bore no resemblance to those detected at the longer spacing. Mills determined that this was most likely caused by the sources being extended in nature rather than being point sources. He determined that this was causing the confusion of the interference patterns.

Mills believed that sensitivity was not the issue for the source survey work; rather, high resolution was the key requirement. As he has stated:

> "By then, I knew that collecting area was relatively unimportant, the important thing was a large overall size to give high resolution. As a filled array seemed wasteful, I first looked at various passive configurations such as crosses and rings, but these all suffered from high side-lobe levels. Suddenly it occurred to me that by combining the phase-switch, which I had used on the interferometer, with a crossed array the side-lobe problem would be substantially reduced." (Mills, 1984: 151).

Mills (1984) has commented that there was a degree of scepticism within Radiophysics that the idea of the phase switched cross array would actually work. This was an example of some of the rivalry that was beginning to emerge between researchers at the major field stations. When asked if there was actually some opposition to building the cross array, Mills later commented:

> "Oh, well, that I think this was part of the Pawsey-Bowen camp division. When I put it [the cross array] up Bolton was very antagonistic and thought it wouldn't work at all. In fact, he convinced Bowen of this, who I remember told me quite clearly and unequivocally that it couldn't possibly work. However, Pawsey was

behind me and so we had to build a small experimental model first, just to show that it would work, which it did." (Bhathal, 1996a).

Ultimately it was determined that a prototype of the new array should first be constructed at Potts Hill to test the concept before moving to a full scale deployment. In hindsight this proved to be a useful undertaking as considerable experience was gained that was later applied to construction of the full-scale cross at the Fleurs field station.

The prototype array was built by Little in consultation with Mills. Govind Swarup also spent three months working with Little and Mills on the development of a phase shifter for the array (Swarup, 2006: 24). The array was designed to operate at a frequency of 97 MHz and as such used an array of 24 folded dipoles. These were arranged in two arms which were oriented north-south and east west as shown in Figure 75.

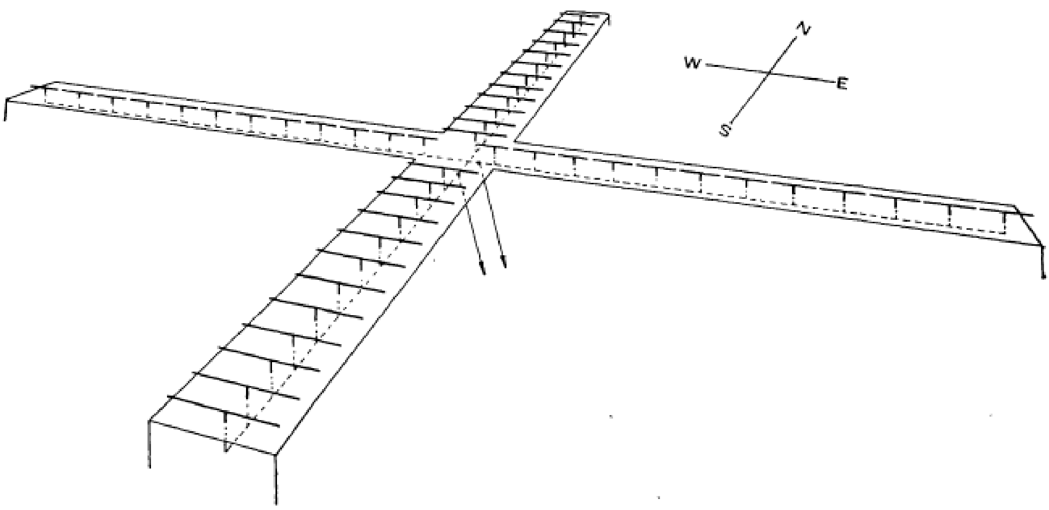


Figure 75: Diagram of the dipole arrangement of the prototype Mills Cross array (after Mills and Little, 1953: 275).

Each arm of the cross was 120-ft in length. The response of the combined arms produced a pencil beam with a beamwidth of 8º. The dipoles were backed by wire mesh suspended below the dipoles to act as a reflective surface as shown in Figure 76.

Figure 76: A close up view of the prototype Mill Cross at Potts Hill (ATNF Historical Photographic Archive: B3064-3 Image Date: 21 April 1953).

The line feeds for the dipole consisted of a two-wire transmission line that ran the length of each array, terminated at one end by matching resistors and the other leading to the common centre of the array. Figure 77 shows the arrangement of the dipole feeds.

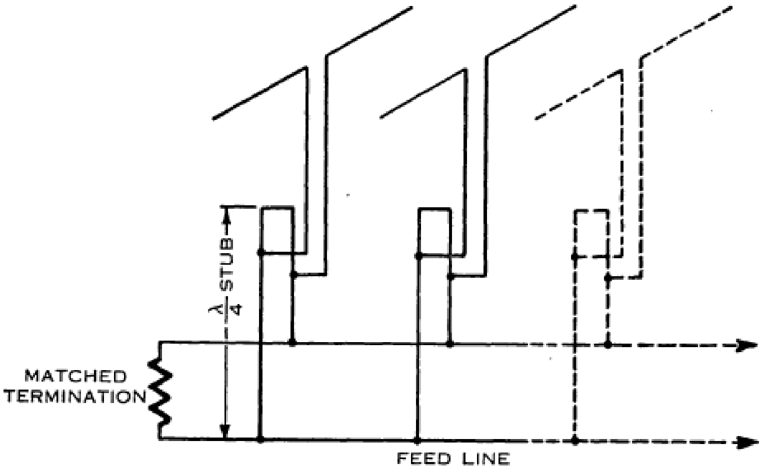


Figure 77: The line feed arrangement used on the prototype Mills Cross array (after Mills and Little, 1953: 276).

The pencil beam could be steered in declination by changing the relative phases of the currents in the dipole arms by changing the points of connection of the stubs to the line feeds. The output of each arm was first fed to a preamplifier and then combined through a phase switching arrangement; from there the signal was amplified, passed to a phase sensitive detector and then recorded. Two outputs were recorded, the phase-detected output and also the receiver output level. Calibration marks were inserted in the output record every twenty minutes by switching the preamplifiers to cold resistors for 1 minute. Figure 78 shows an example output recording of the Sun passing through the pencil beam of the array. The open dots in the figure show the computed polar diagram of the array.

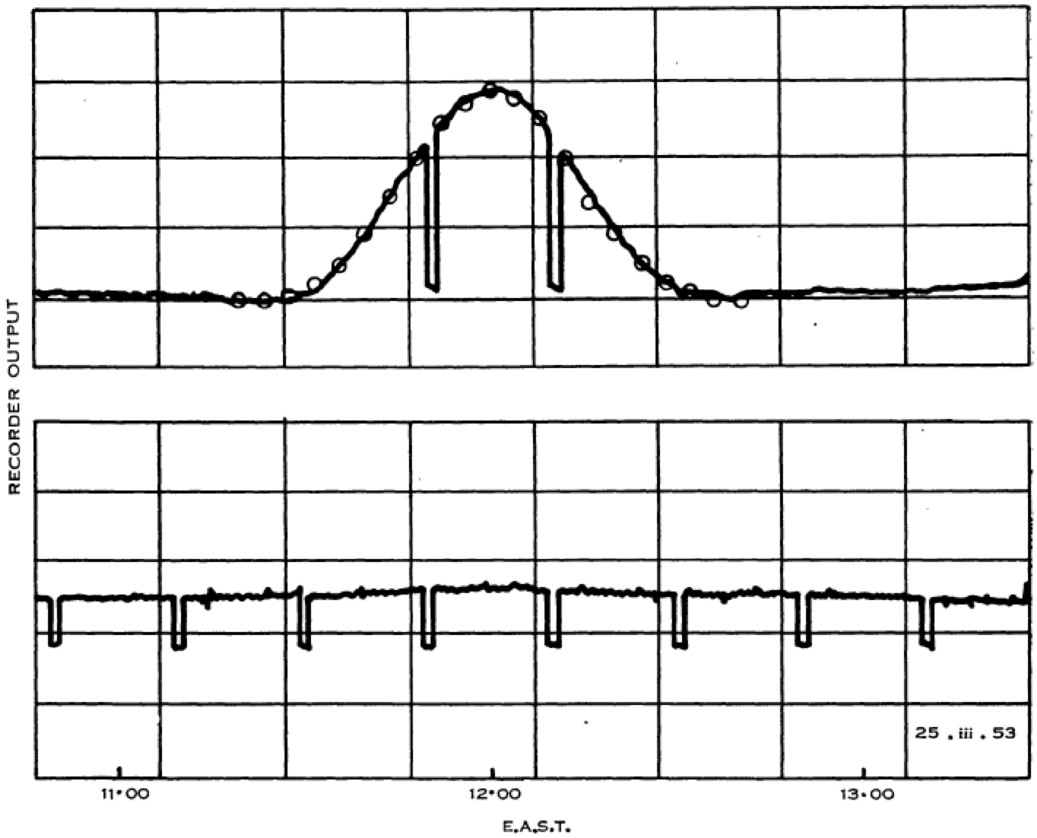


Figure 78: Example output recording of the Sun passing through the pencil beam of the prototype Mills Cross. The upper graph shows the phase-detected output while the lower graph show the receiver output level (after Mills and Little, 1953: 277).

Although the crossed array was constructed as a proof of the concept, it did produce the first radio detection of the Large Magellanic Cloud. Figure 79 shows the prototype array at Potts Hill looking west. In the background are the 16-ft × 18-ft Paraboloid and the 36-ft Transit Parabola.

Figure 79: The Mills Cross Prototype at Potts Hill. In the background is the 16-ft×18-ft Paraboloid and the 36-ft Transit Parabola (Courtesy of ATNF Historical Photographic Archive: B3171-4 Image Date: 7 October 1953).

It is interesting to note that in reply to a letter which Pawsey had written to Lovell at Jodrell Bank describing the concept of the Mills Cross, Lovell wrote:

> "Hanbury Brown must have heard something about your new aerial because he was talking to me about it the other day. As a matter of fact, Jennison put up a similar scheme for investigating the fine structure of the Cygnus and Cassiopeia sources but we were unable to proceed with it owing to financial difficulties." (Lovell, 1953).

Hanbury-Brown also noted:

> "We considered exactly the same scheme before deciding to go ahead with the big parabola, but came to the conclusion that we wanted the large gain as well as the narrow beam width especially for work at high

frequencies. I have recently re-examined the technical problems of phasing an array of this type for a wavelength of 2 metres, however in view of our programme on the 250 ft dish we shall not attempt to build it." (Hanbury-Brown, 1953).

10.4.9. Miscellaneous Instruments

This section describes some of the other instruments that were used at Potts Hill.

10.4.9.1. Yagi Arrays (I)

One of the first instruments to be used when the field station was established at Potts Hill in 1948 was a simple Yagi antenna. This was used by Little for daily solar measurements at 62 MHz and was located at the northern side of the reservoir (Orchiston and Slee, 2005a). Several different Yagi configurations were used at Potts Hill as part of the solar monitoring program. Figure 80 shows an example of a four-element Yagi used for solar observations at Potts Hill. While no individual results were published from observations from this instrument, data collected from these observations were incorporated in the multi-frequency observation and statistical research papers.

Figure 80: A four-element Yagi array at Potts Hill (Courtesy of ATNF Historical Photographic Archive: P12205-1)

10.4.9.2. Suspended Dipole (J)

The last instrument to be constructed at Potts Hill was a simple dipole antenna suspended between two poles using the ground as a reflector. It operated at 19.6 MHz and was erected in early 1956 (Orchiston and Slee, 2005a). It was used as part of a spaced aerial experiment by Gardner and Shain to examine scintillations in radio emissions from Jupiter to determine if these were inherent in the source or caused by the ionosphere (Gardner and Shain, 1958). The main instruments in the experiment were located at Fleurs field station some 25 km to the west. Simultaneous recordings were taken at both sites so that burst arrival time could be compared.

Gardner and Shain noted in their 1958 paper that there was considerable local interference at the Potts Hill site. Mills also noted that part of his reason for moving to Fleurs was the increasing levels of radio interference at Potts Hill (Mills, 1984).

10.4.9.3. Spectrohelioscope

The installation of a spectrohelioscope or spectroheliograph at Potts Hill to support the optical correlation to the solar radio observations was first proposed by Payne-Scott (1947). In her original proposal Payne-Scott (ibid.) noted that she had discussed the construction with R. Giovanelli and W. Steel from the Physics Division of the CSIR and they had offered their assistance should the proposal proceed.

Over a number of years Radiophysics considered purchasing a spectrohelioscope, however, despite a great deal of investigation no purchase was made. In October 1951, Woolley wrote to Pawsey stating that with the departure of C. Allen from Mount Stromlo, they were having a great deal of difficulty maintaining their solar program. In fact he noted that if it were not for Radiophysics' interest they would suspend the program in January 1952 (Woolley, 1951). Pawsey replied to Woolley suggesting that in view of the difficulties perhaps Stromlo's spectrohelioscope could be loaned to Radiophysics and be supervised and maintained by Giovanelli (Pawsey, 1951e).

In July 1952 Woolley wrote to Pawsey agreeing to the loan of the spectrohelioscope for a period of one year, with the possibility of extension dependent on the needs of the Ionospheric Prediction Service (Woolley, 1952).

The spectrohelioscope was ultimately installed at Potts Hill by Giovanelli in late 1952 and was employed to make regular images of the Sun using a Hα filter so comparisons could be made with the radio frequency observations. The instrument was operated by Radiophysics staff as noted by Davies:

> "…on clear days I made maps of the features of the H-alpha Sun and used Stonyhurst discs to present the data. The features included sunspots, bright plagues, and prominences (which were visible in emission on the limb or in absorption as dark filaments on the disk)."(Davies, 2005: 95).

Figure 81 is taken from a newspaper article on the overall solar program of the Radiophysics group in 1956 and shows Giovanelli and the spectrohelioscope.

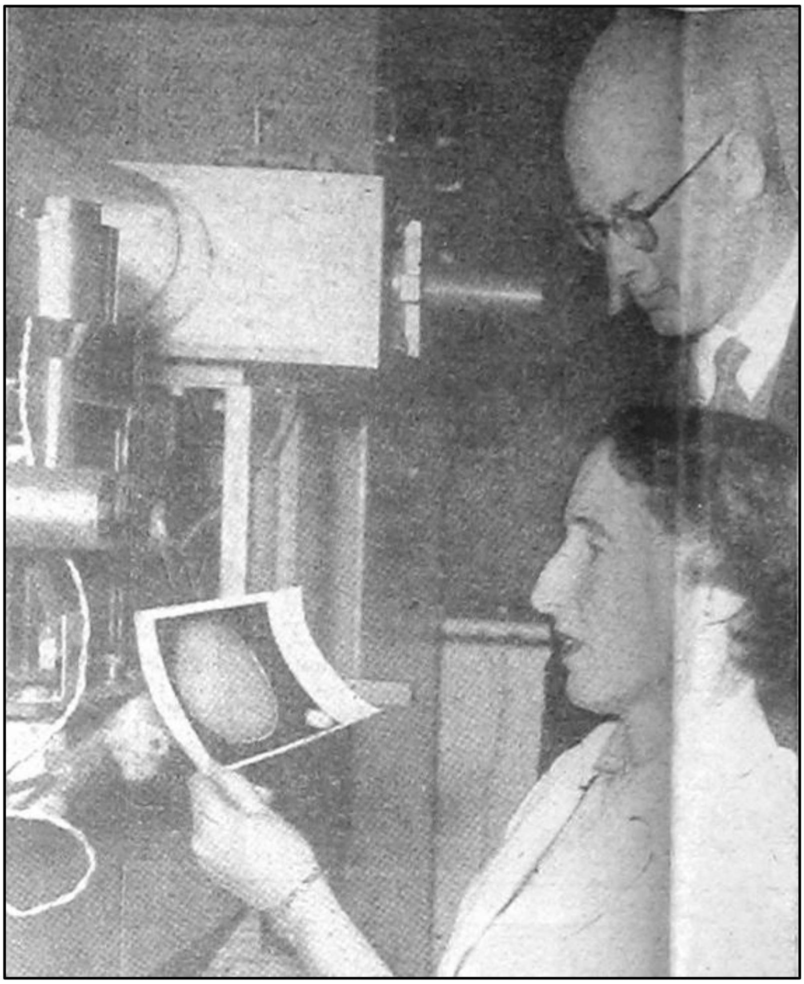


Figure 81: Dr. Giovanelli and Miss Marie McCabe examining a spectroheliograph photograph (Courtesy of Sun-Herald, Sydney 16 September 1956).

10.4.10. Fate of Instruments

While the fate of many of the instruments from Potts Hill remains unclear, it appears that at least some of the aerials were either transferred or donated to universities within Australia. In March of 1961, Professor G.R.A. Ellis of the Department of Physics, University of Tasmania enquired if it was possible to obtain any old aerials from Radiophysics. Pawsey replied indicating that "some time ago we gave one or several (old dishes) to Reg Smith [Dr. R.A. Smith, Department of Physics, University of New England, Armidale]." (Pawsey, 1961b). Dr. Smith was conducting ionospheric research at this time, although the results of his research with the ex-Radiophysics instruments were never published.

As we have already seen, the E-W Solar Grating Array was permanently loaned to India and went on to become the Kalyan Radio Telescope operational from April 1956.

At one stage consideration was given to recycling the equatorial mount of the 16-ft × 18-ft Paraboloid for use with a new larger aerial; however this was abandoned with the construction of the Murraybank aerial. The fates of both the 36-ft Parabola and the 16-ft × 18-ft Paraboloid are unknown.

Unfortunately it is likely that many of the instruments were sold for scrap metal as the research efforts of the Division were consolidated on the Parkes Radio Telescope. Figure 82 shows a 10-ft Parabola in a state of disrepair at Potts Hill in the late 1950s. Given the condition of this aerial it is likely that it would have been scrapped.

Figure 82: A 10-ft Parabola showing damage to one of its eight sections at Potts Hill in the 1950s (Adapted of the ATNF Historical Photographic Archive: B2639 Image Date: 28 November 1951).

10.5. Major Research Contributions

The research contributions at Potts Hill from 1948 to 1962 were wide ranging. At the outset the work was heavily weighted towards solar research. However, the investigation of cosmic noise sources grew steadily during the life of the field station and would dominate its later years with Potts Hill being the home of the original 21-cm H-line confirmation and then surveys of the Magellanic Clouds and southern Milky Way.

This Section examines in detail the research contributions of solar, cosmic and the Jupiter radio emission research in which the Potts Hill field station was involved. The section concludes with a brief discussion of the 1952 U.S.R.I General Assembly which was held in Sydney.

10.5.1. Solar Research

Prior to the establishment of the Potts Hill field station in 1948, solar research had been occurring at a number of the Radiophysics field stations scattered across the Sydney district (Orchiston et al., 2006). One of the key challenges of this early work had been the limitations inherent in determining positions of source radiation due to the low angular resolution of the types of instruments being used. Some early progress had been made using interferometry techniques (McCready et al., 1947). However, the opportunity to accurately determine source positions and the disk distribution of solar emission through the use of solar eclipses soon became apparent. In 1946 Covington, working in Canada, had used the opportunity presented by an earlier partial solar eclipse to accurately measure the time, and hence position, on the solar disk when radio emission was masked by the passage of the Moon's disk in front of a source (Covington, 1947). Sander (1947) also used this same eclipse to examine the Sun at the higher frequency of 9,428 MHz. The first use of a solar eclipse in radio astronomy was by Dicke (1946b), but it was Covington who was the first to show that strong emission was associated with a sunspot group that was occulted by the Moon's disk. A similar partial solar eclipse was scheduled to be observable from Australia on 1 November 1948. This opportunity turned out to be the catalyst for consolidating the majority of the Radiophysics solar research program at the new field station at Potts Hill.

10.5.1.1. 1948 Eclipse Observations

In anticipation of the 1 November 1948 eclipse, a range of instruments was relocated to the Potts Hill field station so that multi-frequency observations could be obtained. The 16-ft × 18-ft Paraboloid was relocated from the Georges Heights field station and was used as the lead instrument for observations at 600 MHz (Christiansen et al., 1949b). These observations were made in conjunction with two portable 10-ft parabolas that were located at the remote sites of Rockbank in Victoria and Strahan in Tasmania. This was the first time that radio astronomical observations were conducted in these two Australian states (e.g. see Orchiston, 2004a). A 68-in Parabola was used for observations at 3,000 MHz (Piddington and Hindman,

1949) and the 44-in ex-Searchlight Parabola was relocated from the Radiophysics headquarters at Sydney University to be used for observations at 9,428 MHz (Minnett and Labrum, 1950). Christiansen had originally considered making the observations of the eclipse from Adelaide as it was considered that the Sun in Sydney may have been too close to the horizon at the time of the eclipse for useful observations (McCready, 1948c).

The primary goals of the observations at 600 MHz were:

(1) to determine the accurate distribution of radio brightness over the solar disk;
(2) to pin point the location of localised radio emitting regions, and
(3) to look for possible polarisation effects that were predicted to be associated with the Sun's magnetic fields.

By conducting observations at three dispersed sites it was possible to triangulate position estimates of discrete sources on the solar disk. The three sites gave six possible intersecting arc solutions for any observation, three on entry and three on exit from the eclipse. Both Strahan and Rockbank had full visibility of the eclipse. At Potts Hill, sunset occurred before the last contact of the Moon's disk (i.e. the 4th contact point). Figure 83 shows the situation for the eclipse as observed from Potts Hill.

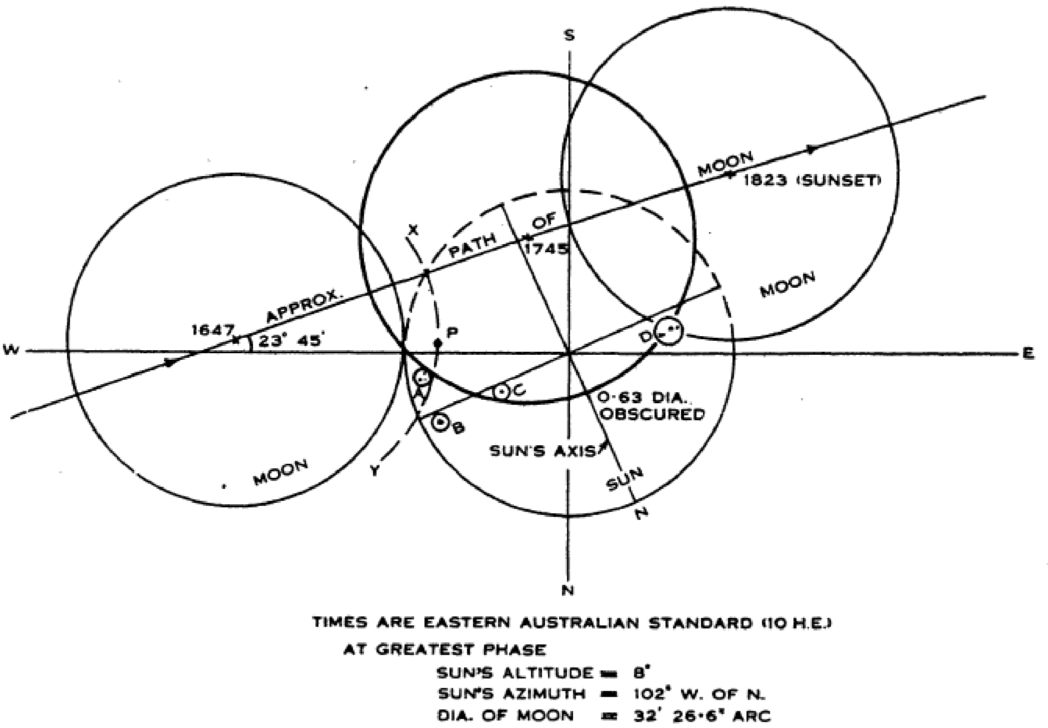


Figure 83: Circumstances of the partial solar eclipse of November 1, 1948 as observed from Potts Hill (after Piddington and Hindman, 1949: 529).

Prior research had suggested that the radio emission at these frequencies could be divided into two main components. The first was believed to be the thermal component associated with the 'quiet' Sun. The second was a slowly-varying component that had been correlated with total area of sunspots on the solar disk. Figure 84 shows a scatter plot correlating sunspot area with apparent temperature. This data was taken from earlier observations at 600 MHz (λ = 50cm) and indicates the 'quiet' background level when no sunspots are present on the solar disk.

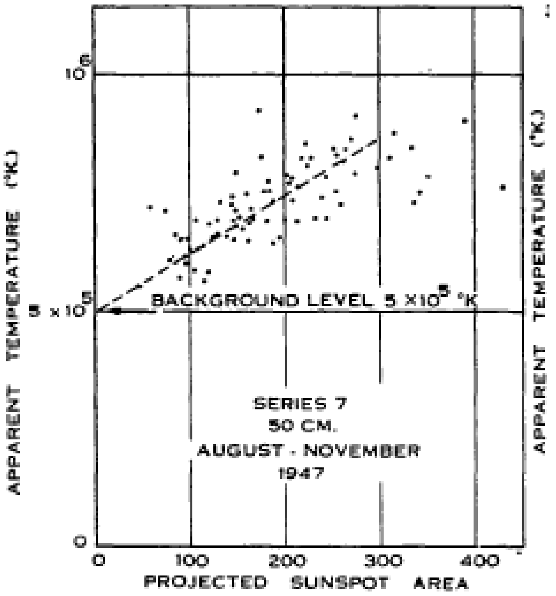


Figure 84: Correlation diagram between apparent temperature and sunspot area given as units of 10^{-5} of solar disk (after Pawsey and Yabsley, 1949: 208)

Martyn's theoretical model (Martyn, 1946b) and observations (Pawsey, 1946) had suggested a temperature for the solar corona in the order of 10^6 K at 200 MHz. This indicated that with the increase in temperature as a function of distance from the solar disk, limb-brightening should be observed as the edges of the disk would expose a greater depth of the higher temperature coronal atmosphere than face-on observations.

The orientation of the eclipse also provided an opportunity to test the prediction that the general magnetic field of the Sun should lead to inequality in the circularly polarised components from the northern and southern hemispheres of the Sun. The passage of the Moon effectively covered the southern hemisphere during the eclipse thus allowing the emission from the northern hemisphere to be compared with overall emission. To try and measure this effect, the two remote field stations aerials were configured to measure left and right-polarisation components of the solar radiation. The main aerial located at Potts Hill was linearly polarised.

On the day of the eclipse there were six small sunspot groups visible with a total area of 85×10^{-5} (0.085%) of the solar disk (Figure 85).

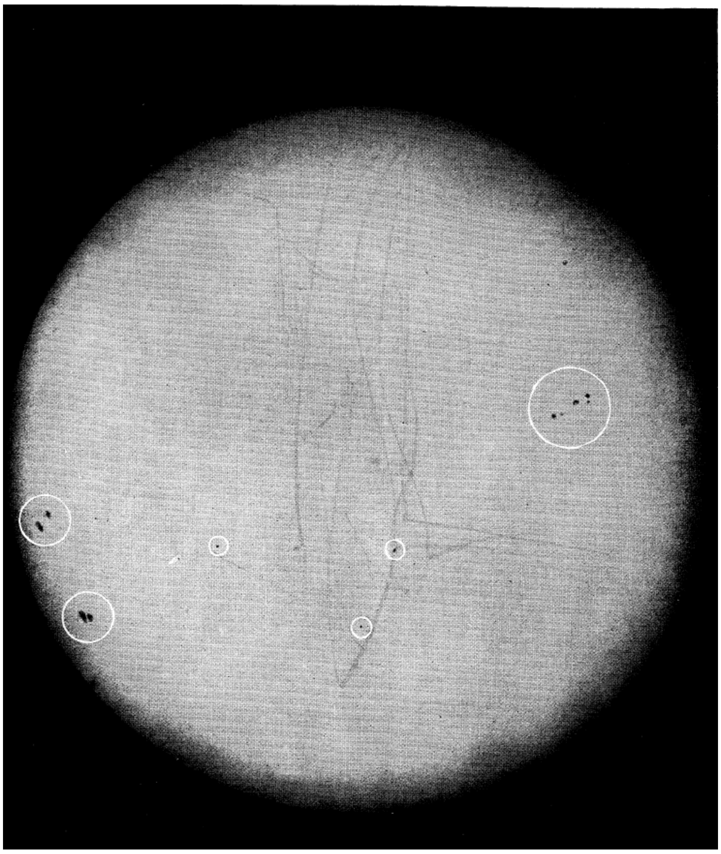


Figure 85: Sunspot groups visible on the solar disk immediately prior to the partial solar eclipse of 1 November 1948 (Christiansen et al., 1949b: Plate 2).

The Commonwealth Solar Observatory at Mount Stromlo provided eclipse predictions and optical observations during the eclipse. These contributions are acknowledged in the published observations. Optical observations were also made using a telescope located at Sydney Technical College and shown in Figure 86 (Orchiston et al., 2006: 45). However, this contribution was not acknowledged other than recording:

> "…the circumstances of the eclipse at Sydney were checked by means of a series of accurately timed photographs" (Christiansen et al., 1949b: 512).

To support the Rockbank observations a single photograph was taken at Melbourne Observatory (Clapham, 1948).

Figure 86: The Sydney Technical College telescope used for solar imaging during the eclipse observations. Photographs were taken using the 15 cm (6-in) guide-scope attached to the 46 cm (18-in) reflector (Courtesy of the ATNF Historic Photographic Archive: B1899-7).

All three of the radio observation sites made successful observations of the partial solar eclipse at 600 MHz. The eclipse record from Potts Hill is shown in Figure 87. The record for Rockbank is shown in Figure 88 and Figure 89 shows the record for Strahan.

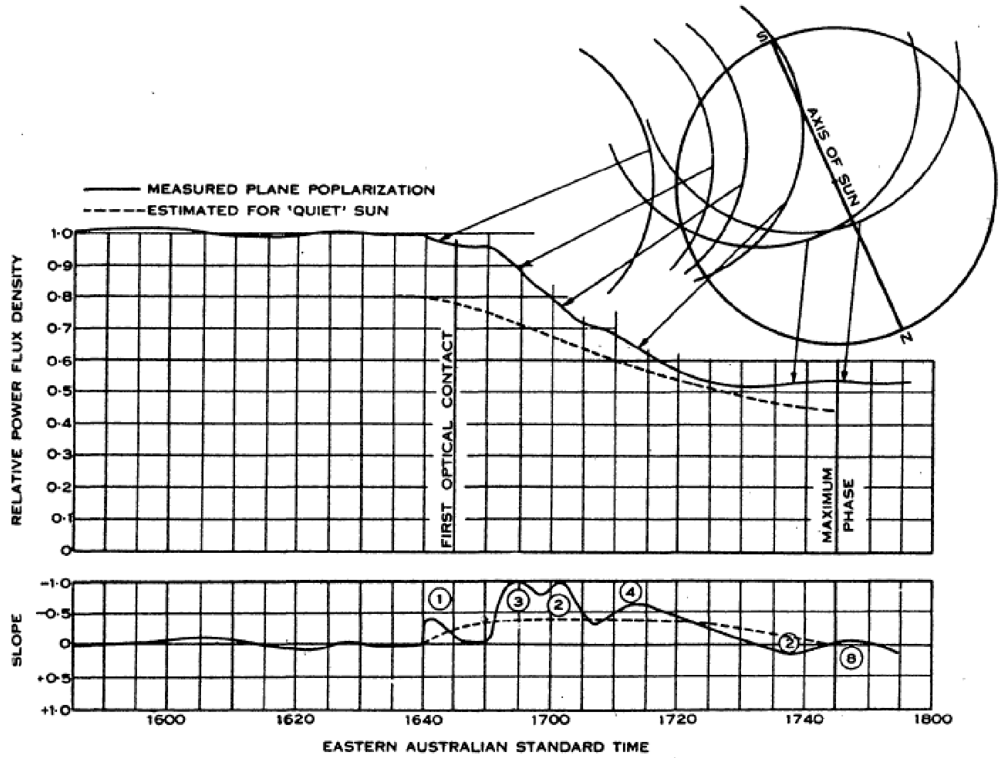


Figure 87: Eclipse record taken at Potts Hill at 600 MHz (after Christiansen et al., 1949b: 510).

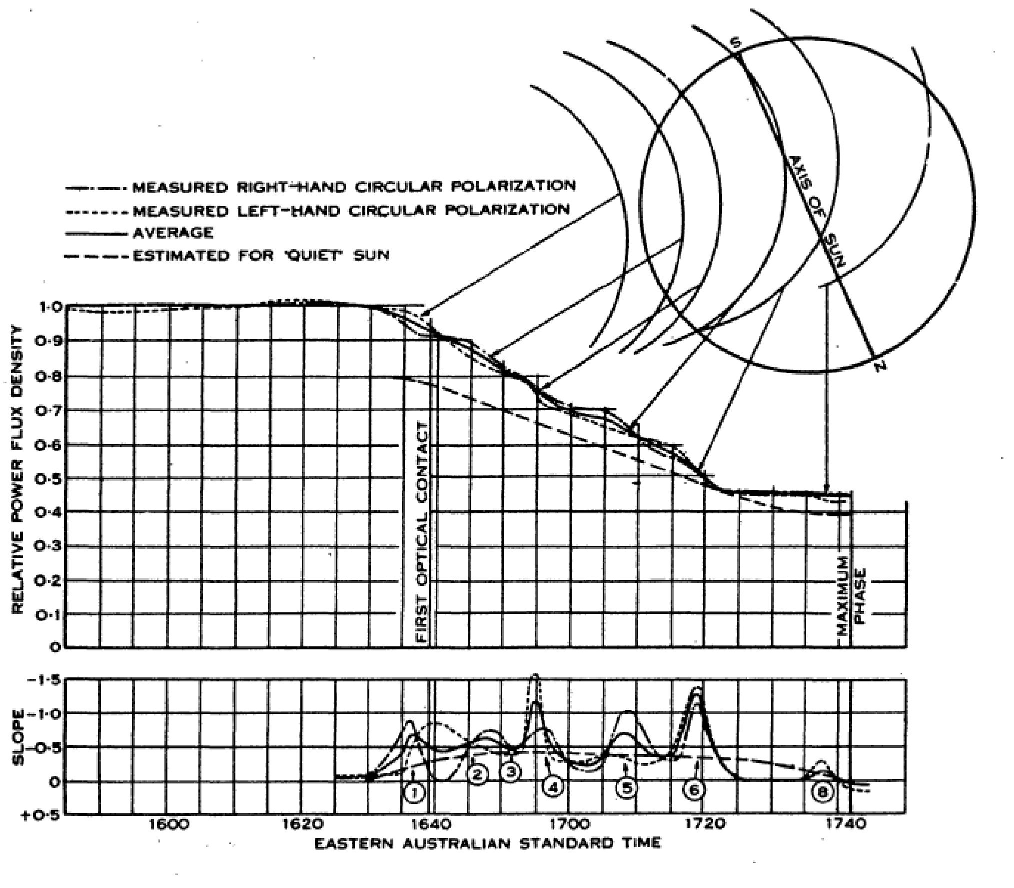


Figure 88: Eclipse record taken at Rockbank in Victoria at 600 MHz (after Christiansen et al., 1949b: 511).

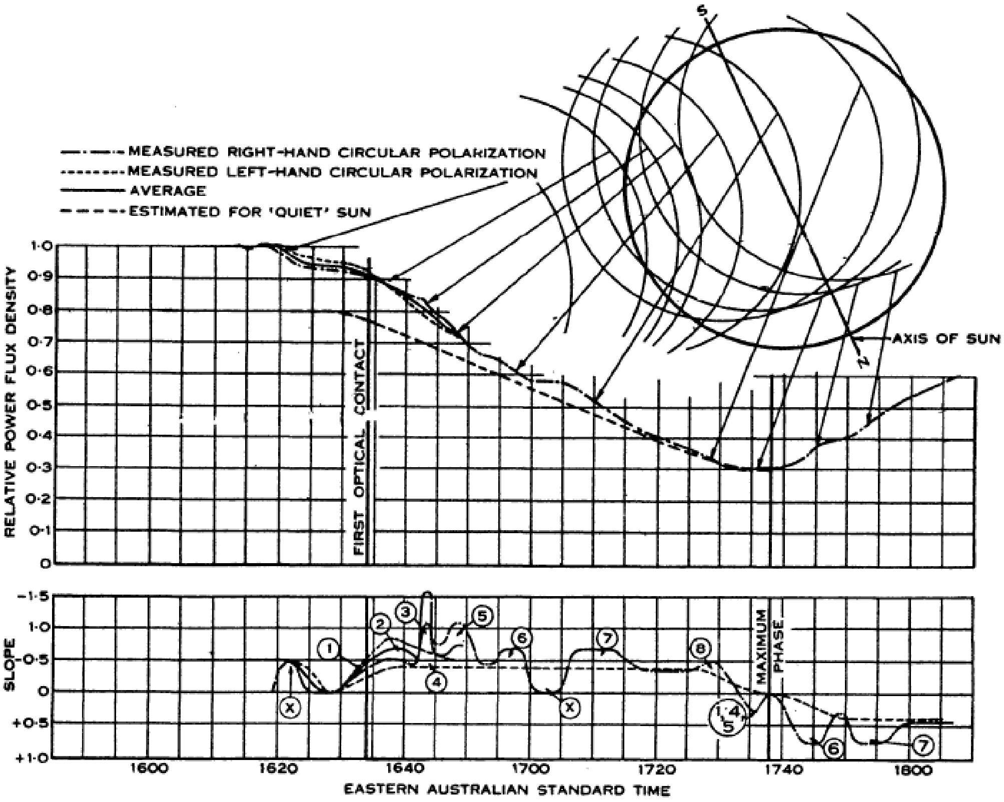


Figure 89: Eclipse record taken at Strahan in Tasmania at 600 MHz (after Christiansen et al., 1949b: 512).

As the eclipse occurred near sunset, the Sun was low on the horizon and therefore the full records of the eclipse were affected and the major focus of the analysis was on the first 2/3rd of the eclipse record. Eight prominent discrete radio sources were observed at all three sites and these are marked in the recordings as the circled numbers 1-8. A simplified illustration is also shown in Figure 94. It can clearly be seen that the radio emission began to decline well before the first optical contact of the Moon's disk and it was estimated that 40% of the radiation at 600 MHz originated outside the visible disk of the Sun, with an average effective temperature of 5×10^6 K. The effective temperature of some of the eight bright areas was estimated to exceed 10^7 K. The equivalent blackbody temperature of the Sun (T_s) was calculated from the following relationship with aerial temperature (T_a):

$$T_s = \frac{4\pi}{G\Omega_s}.T_a \tag{7}$$

where,

G is the maximum gain power of the aerial compared to an isotropic radiator; and

Ω_s is the solid angle subtended by the visible Sun's disk.

The triangulation of the positions of the bright sources from the three observation sites indicated that seven of the eight sources appeared to be associated with optical features that were visible on the solar disk. Three of these were close to visible sunspot groups, three were close to the positions of sunspot groups from the previous rotation of the Sun (27 days earlier), and one was located close to a solar prominence that appeared on the south-western limb of the Sun. It should also be noted that sources were not associated with all of the visible sunspot groups or prominences. Figure 90 shows the location of the radio sources on the solar disk.

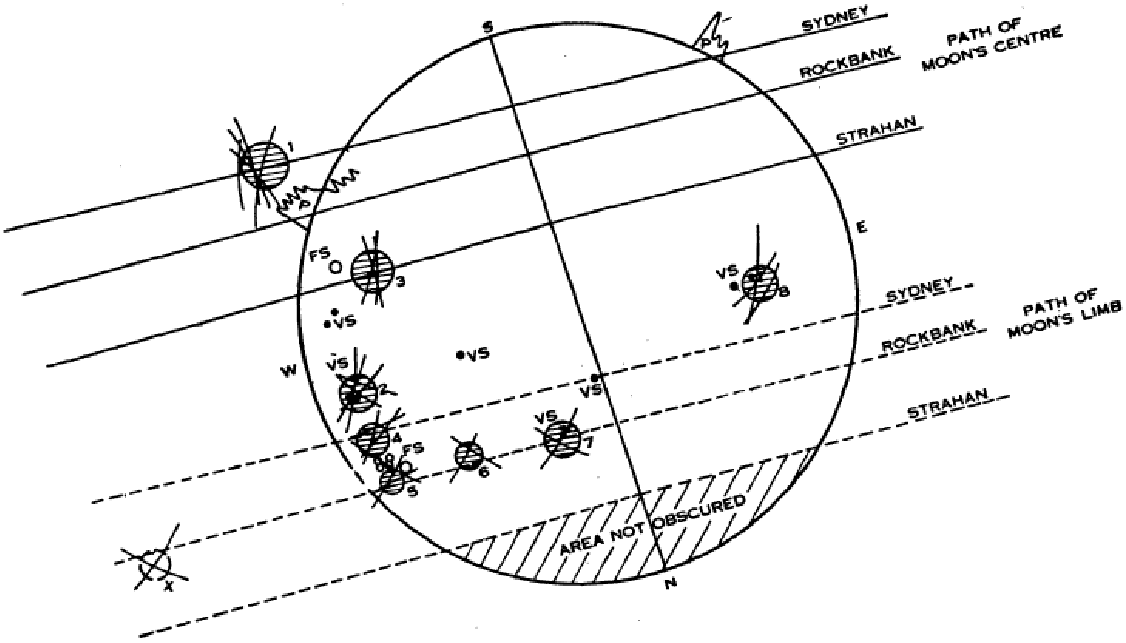


Figure 90: The location of the discrete radio sources on the solar disk. VS = Visible sunspot, FS = Position of a visible 27 days earlier sunspot, P = Solar prominence (after Christiansen et al., 1949b: 513).

It was estimated that the eight discrete sources made up ~20% of the radiation generated at 600 MHz and the remainder was generated by an approximately symmetrical source 1.4 times larger than the visible disk of the Sun (i.e. the solar corona). This result was consistent with the earlier results of Pawsey and Yabsley (1949) and shown in Figure 84. Although the measurements were consistent with the theoretical models for limb-brightening, they did not provide definitive proof of its existence at 600 MHz. However, these observations provided the most detailed evidence at the time that the bright discrete emissions were associated with sunspots and made up the slowly-varying component of the solar radiation at 600 MHz.

The polarisation measurements made during the eclipse provided less than definitive results. The measurements were made at both of the remote sites using the portable 10-ft Parabolas. A mechanical problem with the telescopic coaxial transmission feed-line was encountered at Strahan early in the observations. This prevented the aerial from being switched between polarisation senses. Consequently only right-hand polarisation could be measured at this site. The existence of a general magnetic field for the Sun had been proposed since at least 1918 (Hale et al., 1918) after optical detection of the Zeeman effect, which results in splitting of spectral emission lines. The theoretical prediction at the time was for the Sun to have a general magnetic field intensity of ~50 Gauss (Smerd, 1950a). Circular polarisation was detected associated with the bright regions. The expected differences between the north and south hemispheres were not detected and apart from when a bright area was eclipsed, the measurements quickly returned to equilibrium. The maximum change that was observed was a peak of ~2%, while the experimental accuracy would have allowed changes of 3% to be detected. This suggested that the general field must be significantly weaker than 8 Gauss assuming a 3% difference. While this did not match the theoretical model, it is actually consistent with modern measurements. Current measurements of solar magnetic fields give values ranging from 0 to 1800 Gauss while the general field for the Sun is in the order of ~1-2 Gauss (Cerdena et al., 2006). Smerd later conducted a detailed analysis of the observational results and concluded that the Sun’s general magnetic field could not be greater than 11 gauss based on the observational results (Smerd, 1950a).

The detailed results of the 600 MHz observations were published in 1949 in the *Australian Journal of Scientific Research* (Christiansen et al., 1949b) and also in a summary paper sent to *Nature* (Christiansen et al., 1949a).

The observations at 3,000 MHz (λ = 10 cm) were made using the 68-in Paraboloid at Potts Hill. By measuring the eclipse at different wavelengths it was hoped to provide data on the temperature gradient of the solar atmosphere. The earlier work had indicated a very steep rise in temperature from the photosphere through the chromosphere to the corona. Piddington and Hindman made observations over an extended period before and after the eclipse to provide a baseline for comparison to the eclipse observations. Figure 91 shows the close correlation between sunspot area and the equivalent disk temperature derived from measurement of radiation at 3,000 MHz from October 1948 to March 1949.

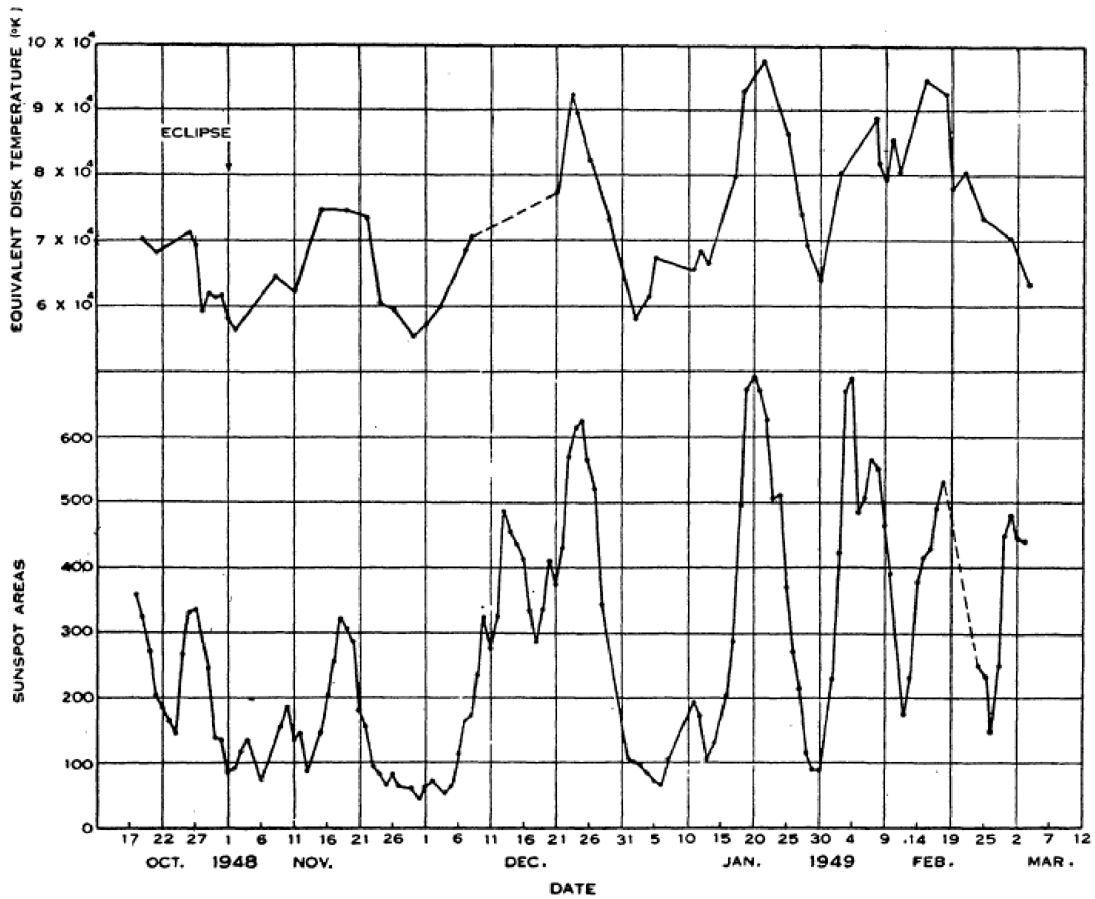


Figure 91: Correlation of sunspot area to 3,000 MHz radiation (after Piddington and Hindman, 1949: 527).

Using the method developed earlier by Pawsey and Yabsley and illustrated in Figure 84, Piddington and Minnett derived a baseline temperature for the quiet Sun of 5.4×10^4 K at 3,000 MHz. This compared to a temperature of 6.5×10^4 K derived from the analysis of Covington's earlier measurement at the slightly longer wavelength of 10.7 cm (2,800 MHz). The highest observed equivalent temperature over the period was 9.8×10^4 K. A reconstruction of the scatter plot based on the data in Figure 91 shows that the extrapolation to the zero sunspot area would yield a temperature of 5.9×10^4 K, which is slightly higher than the published value.

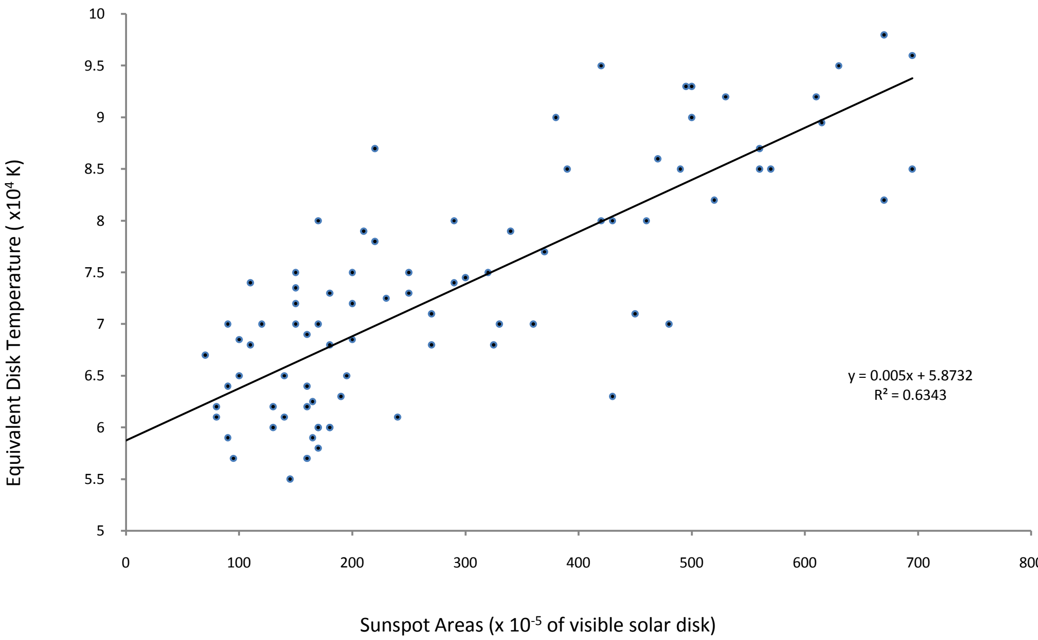


Figure 92: A reconstruction of the scatter plot used to determine the 'quiet' Sun temperature at 3,000 MHz. The graph is based on data used to produce Figure 91.

The main goal of the eclipse observation was to establish a distribution of the non-variable component of the solar radiation across the solar disk. Figure 93 shows the record of the eclipse observation.

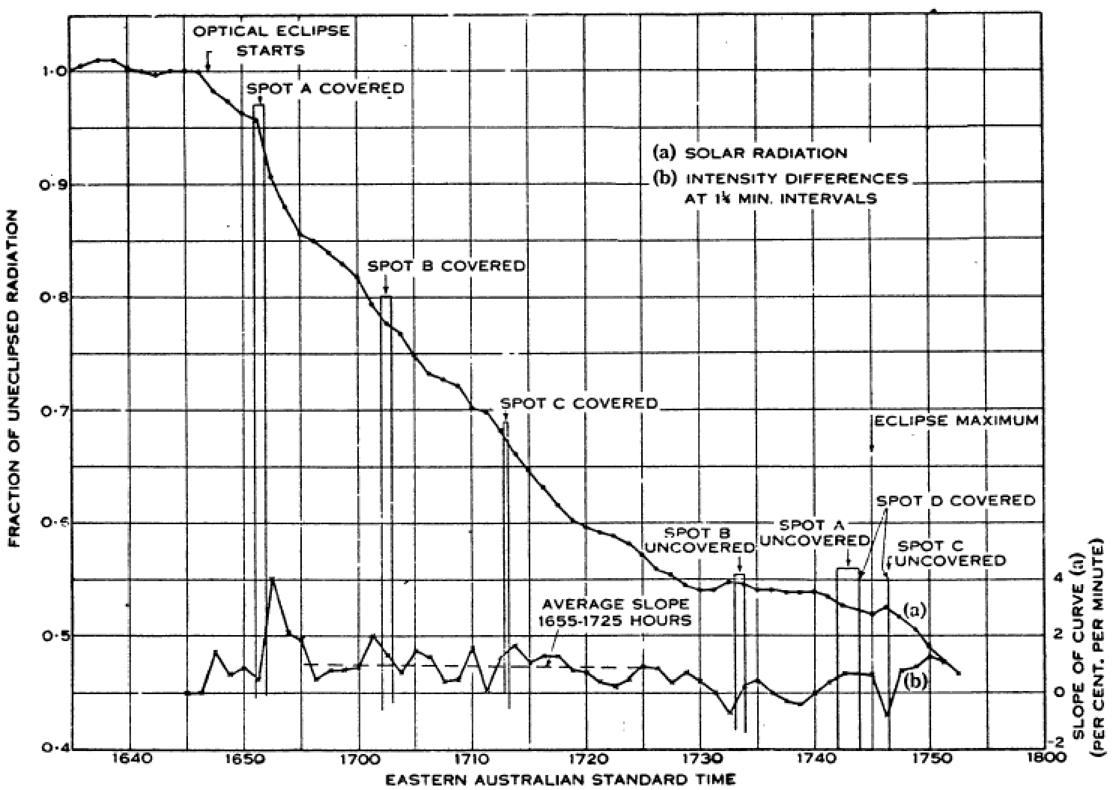


Figure 93: Eclipse record taken at Potts Hill at 3,000 MHz (after Piddington and Hindman, 1949).

Unlike the 600 MHz observations, the decline in radiation levels at 3,000 MHz almost coincided with the optical first contact. At best, the eclipse began some 30 seconds earlier. This was in contrast to Covington's earlier observations which showed the radio eclipse starting some 3 minutes prior to the optical eclipse. It was speculated that this may have been due to the fact that the Sun was in a much quieter period than the previous eclipse observation. In 1946 Covington had observed a marked drop in radiation when a large sunspot group was eclipsed, but the occultation of the sunspots at 3,000 MHz during the 1948 eclipse produced little response; again this was unlike the 600 MHz measurements. At best two weak hot-spots may have been detected with a temperature of the order of 10^6 K. One of these radio hot-spots may have been associated with one of the bright areas (No. 3 in Figure 94) seen during the 600 MHz measurements. There appeared to be no association of the hot-spots with optical features. The overall profile attained appeared to be most consistent with a model of the Sun having 68% of the radiation distributed uniformly over the disk and 32% being concentrated in a ring near the limb, thus indicating limb brightening.

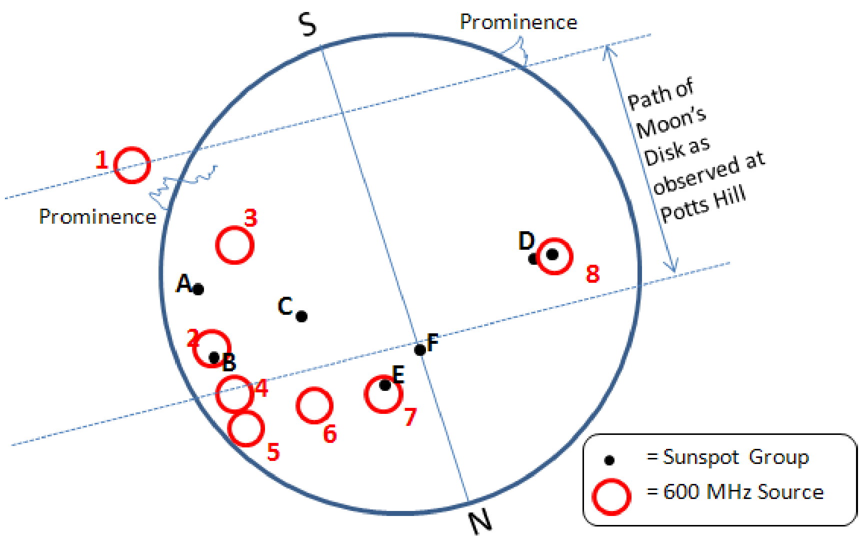


Figure 94: A simplified diagram of the eclipse showing the eight 600 MHz sources (1 to 8) and the six visible sunspot groups (A to D). Source 3 was also detected at 3,000 MHz.

Polarisation measurements at 3,000 MHz were made by fitting a screen to the 68-in Parabola just prior to the eclipse, and three times during the eclipse. Circular polarisation was detected and was believed to be associated with a discrete source. However, like the 600 MHz observations, there was no evidence of a differential between hemispheres (i.e. a change between of polarisation between left to right or vice versa) that might have indicated a strong general magnetic field.

The third team at Potts Hill, led by Minnett and Labrum, observed the eclipse at 9,428 MZ (λ = 3.18 cm). Like Piddington and Hindman, Minnett and Labrum observed the Sun for an extended period of three months to establish a 'quiet' Sun baseline. Both Piddington and Hindman had been instrumental in assisting Minnett and Labrum in setting up their experiment and their contribution is acknowledged in the published results. Figure 95 shows the correlation of apparent disk temperature to sunspot area as measured over the three month period.

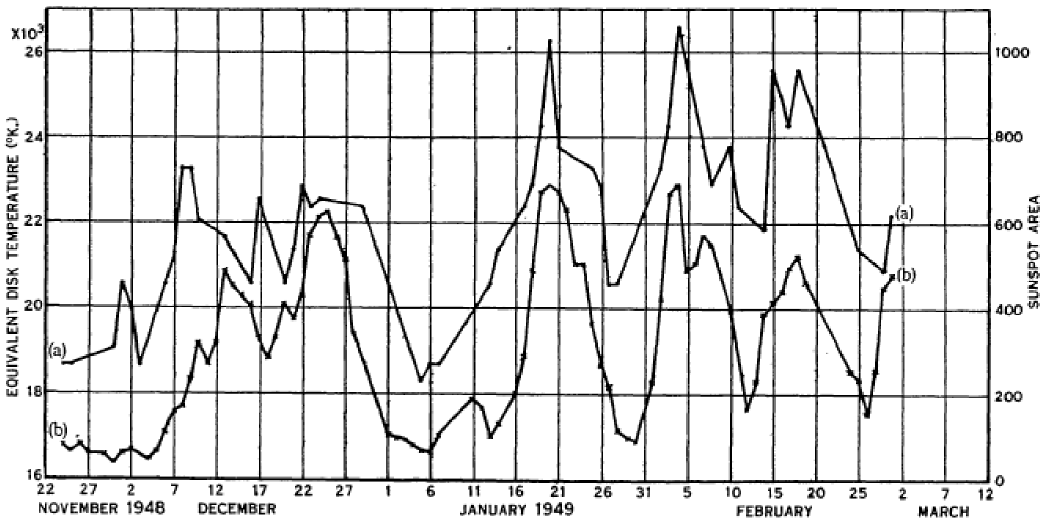


Figure 95: Correlation of sunspot area and radiation at 9,428 MHz (after Minnett and Labrum, 1950: 65).

The correlation at 9,428 MHz was much stronger than that seen in the 3,000 MHz measurements and is readily apparent from comparison with Figure 91. Based on the scatter plot analysis, the correlation at 9,428 MHz was r = 0.79 (r^2 = 0.89) compared to r^2 = 0.63 for the 3,000 MHz observations. The zero sunspot area baseline temperature for the Sun at 9,428 MHz was estimated to be 19,300 K as shown in Figure 96.

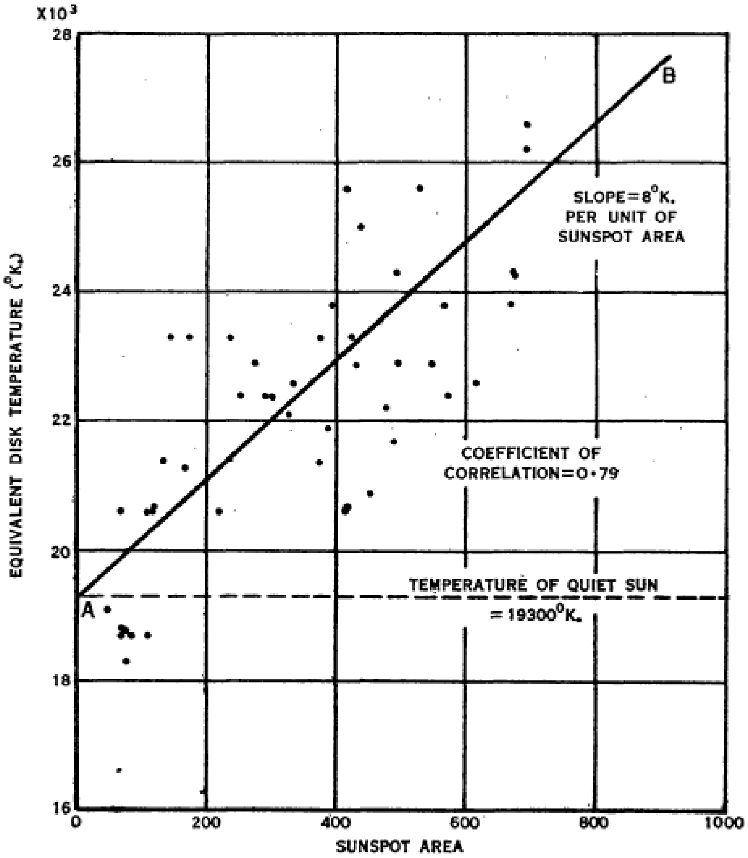


Figure 96: Scatter plot showing the correlation between sunspot area and equivalent solar disk temperature and used to establish the temperature of the 'quiet' Sun at 9,428 MHz (after Minnett and Labrum, 1950: 66).

This estimate of equivalent disk temperature was in general accord with earlier measurements for similar wavelengths. The slope of the best fit line indicated an 8 K increase per unit of sunspot area. This compares with a slope of 50 K at 3,000 MHz given by Figure 92. This showed that the variation of temperature as a function of sunspot area was very much lower at the higher frequency.

Figure 97 shows the record of the partial eclipse at 9,428 MHz.

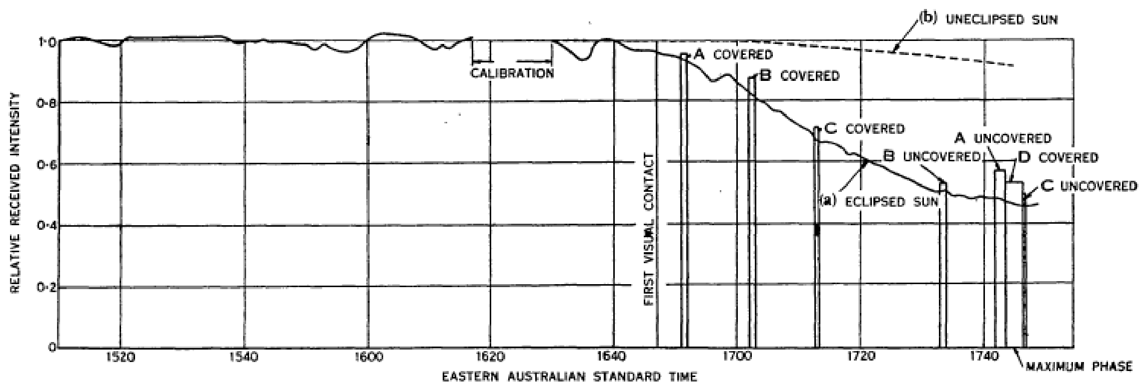


Figure 97: Eclipse record taken at Potts Hill at 9,428 MHz (after Minnett and Labrum, 1950: 69).

The sunspot groups that were in the eclipse path are labelled A to D and correspond to the labelling in Figure 94. No effect, outside of possible instrumental variation, was observed during the passage of the Moon's disk over the solar disk. Given that only an 8 K increase per unit of sunspot area would be expected based on the slope of the scatter plot analysis, any change would have been outside the sensitivity of the instrument to detect. There was some indication that the decline in radiation levels began before the optical eclipse although instrumental variations cannot be excluded. Examining the rate of temperature change during the eclipse, Minnett and Labrum concluded that two possible alternate models would fit the experimental results; either a uniform distribution with a radius 1.1 times that of the visible disk or a distribution with 74% of radiation uniformly distributed and 26% concentrated in a ring around the limb.

In summary, the 1948 eclipse observations provided key data relating to the quiet Sun and the slowly-varying component. While optical emission is strongest in the lowest layer of the solar atmosphere, the photosphere, it was becoming clear that the radio quiet component of the radiation had a very different origin. Much higher temperatures than the 5,800 K photospheric temperature were being observed and these ranged from ~10^4 K levels of the chromosphere to 10^6 K in the corona. At the time of the observations the radiation was thought to be thermal in nature, although a non-thermal origin had not been ruled out. It was also clear that at 600 MHz the source extended well beyond the visible disk of the Sun, correlating with an origin in the corona. The extended source was not clear at the higher frequencies, nor was the limb-brightening effect definitively observed. Correlation of the variable component with sunspot area appeared clear at all frequencies and the position measurements at 600 MHz clearly associated emission with existing and old sunspot groups. Circular polarisation was also detected related to the different sources and ultimately to some of the sunspot groups. The observations found no evidence of the existence of a general solar magnetic field.

A second partial solar eclipse visible in Australia occurred on 21 October 1949. This eclipse was also observed at Potts Hill and at two remote sites; one at Eaglehawk Neck in Tasmania and the other at a new site near Bairnsdale aerodrome in Victoria. The results of these observations were never published, but are discussed in Wendt et al. (2008).

10.5.1.2. Multi-Year Solar Observations

Following the success of the observations of the 1948 partial solar eclipse, Christiansen and Hindman (1951) collaborated to write up findings of the longer-term solar monitoring that had been occurring at the other field stations, and from 1948 onwards, at Potts Hill. Since 1947, daily observations had been made at 600 MHz (λ = 50 cm) and 1,200 MHz (λ = 25cm). From 1948, these were supplemented by daily observations at 3,000 MHz (λ = 10cm) and 9,400 MHz (λ = 3cm). Drawing on optical data from Mount Stromlo, daily sunspot area records could be used for comparison with the effective temperatures observed at each frequency. This allowed Christiansen and Hindman to look for longer-term trends.

In an earlier analysis, Pawsey and Yabsley (1949) had indicated that the thermal emission associated with the quiet Sun may be subject to longer-term variation in the course of the sunspot cycle. This type of change had been predicted by van de Hulst (1949) based on observations of a decrease in electron density of the corona toward the minimum in the sunspot cycle. The sunspot cycle had peaked in 1947, as indicated in Figure 98. This change in the cycle provided an ideal opportunity to examine if there were associated changes during the decline in the solar cycle.

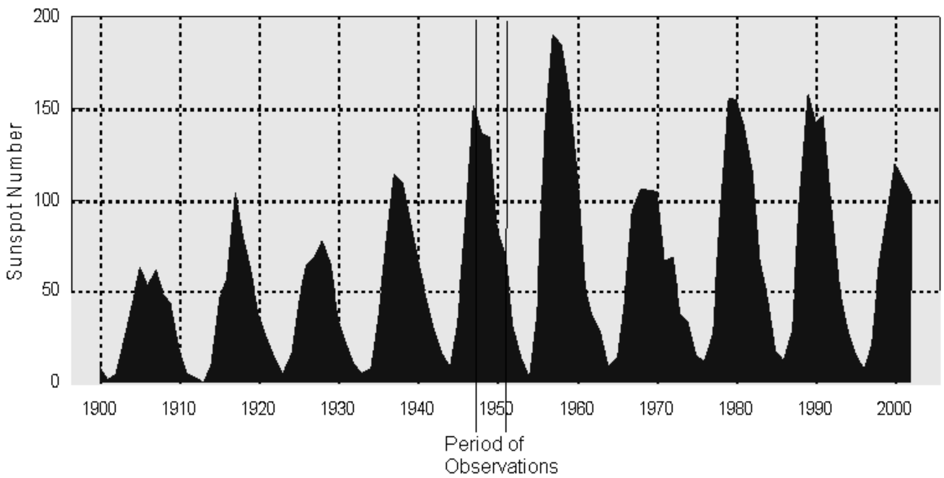


Figure 98: Sunspot numbers showing the period 1947 to 1951 (Based on data from the National Geophysical Data Centre).

During the period 1947 to 1950 there was an almost 50% decline in sunspot numbers as the cycle moved past its peak. Leading up to 1950, while the average sunspot areas declined, there appeared to be no significant decline in the base level temperature as measured in the scatter plots. There was, however, a significant decline in the slope of the line of best-fit indicating that the rate of temperature changes with sunspot area had significantly declined. This is shown in Figure 99.

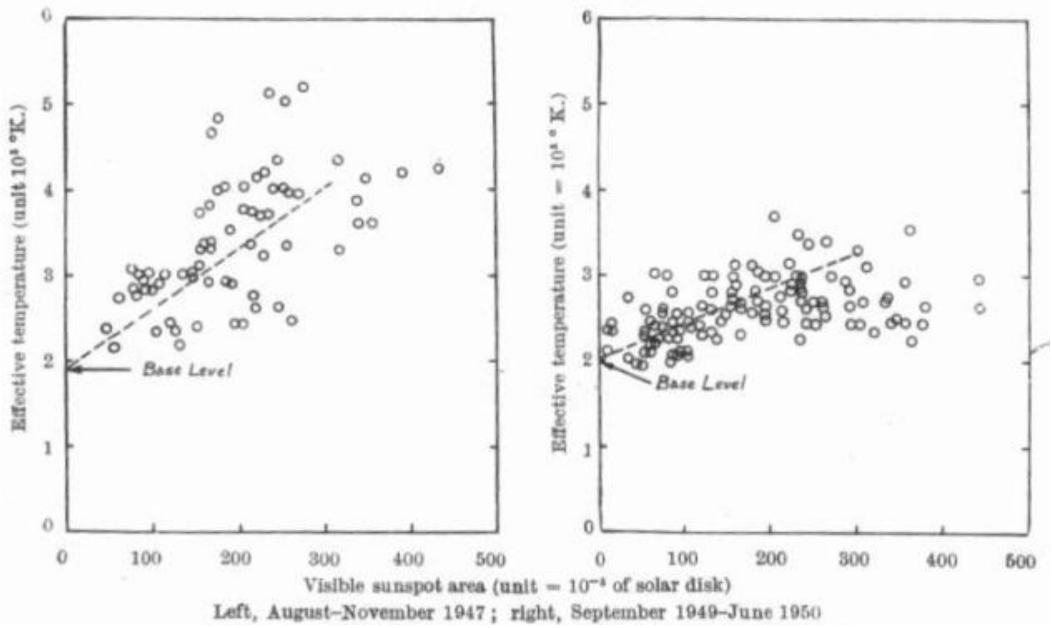


Figure 99: Correlation of sunspot area with effective solar temperature during 1947 and during 1949-50 at 1,200 MHz (after Christiansen and Hindman, 1951: 636).

This decline in the rate of change of temperature with sunspot area was observed across all frequencies (i.e. 600, 1,200, 3,000 and 9,428 MHz).

At the 1950 URSI Conference, Covington had reported that he had observed a 20% drop in the base level temperature at 600 MHz between 1947 and 1950. This same decline had not been observed in Australia. However, during 1950 a marked drop became apparent at 600, 1,200 and 3,000 MHz. No change was apparent at either 9,428 MHz or at 200 MHz (that was being observed on a daily basis at Mount Stromlo). The decline was most pronounced at 1,200 MHz. Figure 100 is a reconstruction of the observations at 1,200 MHz for three periods in 1950.

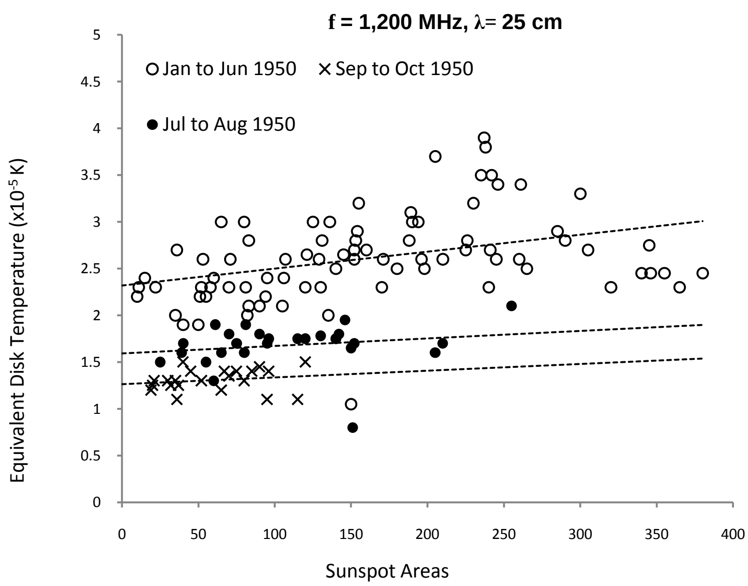


Figure 100: Plot of 1,200 MHz sunspot area versus apparent temperature correlation showing line of best fit and base temperature change for three different periods in 1950.

This shows the decline in the base level from an average of 2.3×10^5 K to 1.4×10^5 K, a decrease of nearly 40%. Christiansen and Hindman (1951) noted that these observations were consistent with van de Hulst's predictions.

Arguably, the definitive theoretical paper on the quiet Sun produced immediately after the 1948 eclipse was by Smerd (1950b). Smerd addressed some of the short-comings of earlier models proposed by Martyn, Ginsberg, and Waldmeier and Müller. In particular, he removed the need to rely on an arbitrary assumption on the size of the radiating radio disk in relation to the optical disk. In 1950 very little was known about the temperature distribution in the solar atmosphere. Temperatures in the order of 10^4 K had been inferred in the chromosphere below a height of ~6×10^3 km and temperatures of 10^6 K had been inferred in the corona above ~2×10^4 km. Somewhere in between these heights was a region of transition between these temperatures. Smerd proposed a model that was in good agreement with the observations. For frequencies above 10,000 MHz the corona was assumed to be practically transparent and therefore he referred to these as chromospheric frequencies. For frequencies below ~200 MHz it was calculated that the radiation would not penetrate the chromosphere and hence these were referred to as coronal frequencies. Frequencies between these were referred to as intermediate frequencies. The model made clear predictions on limb-brightening characteristics across the frequency range. Figure 101 shows the predicted distributions of radiation across the solar disk at a variety of frequencies assuming a coronal temperature of 10^6 K and a chromospheric temperature of 3×10^4 K. All of these predictions were subsequently confirmed by observation (Wild, 1980:9).

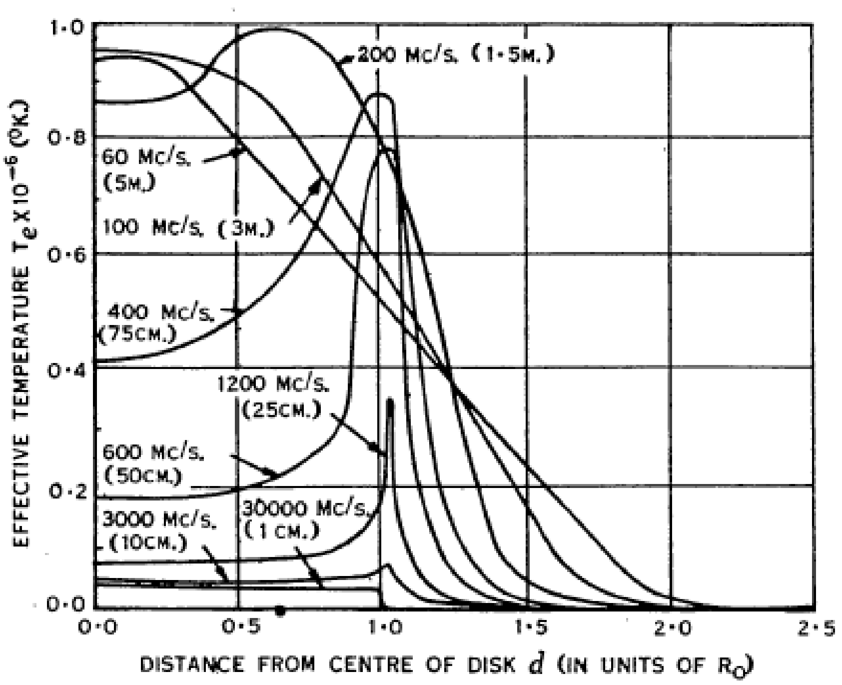


Figure 101: The theoretical distribution of temperature as a function of distance from the centre of the solar disk. Temperatures of 3 × 10^4 K and 10^6 K are assumed for the chromosphere and corona respectively (after Smerd, 1950b: 46).

Piddington and Minnett (1951b) also published a theoretical paper drawing on the eclipse observations and the longer-term studies. They proposed a model whereby the slowly-varying component of the solar radiation was due to thermal radiation from localised areas of temperature in the solar atmosphere of ~10^7 °K. These areas were believed to be often in the vicinity of sunspots, but not necessarily always associated with them. Piddington and Minnett's analysis showed that previous conclusions about the origin of radiation being at a lower level in the atmosphere were likely invalid. They identified three conditions where the refractive index of an emitted ray would be zero (i.e. reflected) for transverse, oblique and longitudinal propagation. These conditions were defined by the relations x = 1 and x = 1 ± y and are illustrated in Figure 102.

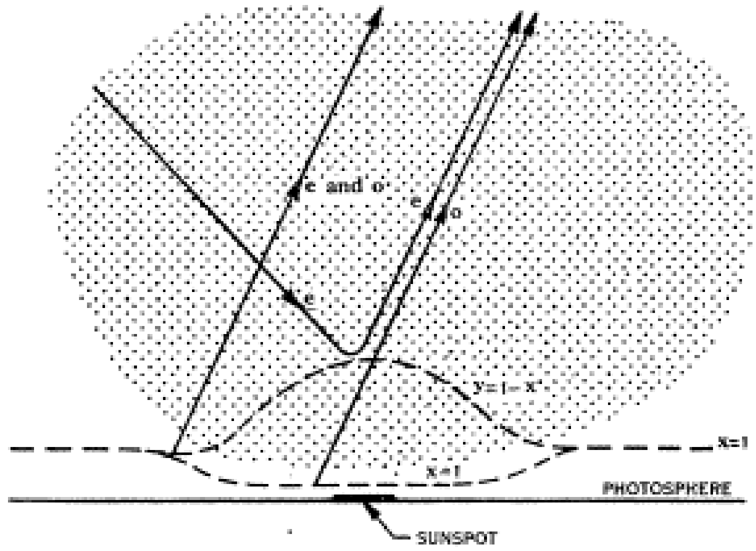


Figure 102: Illustration of the reflective levels and ray paths in a hot dense region above a uni-polar sunspot. *o* and *e* refer to the ordinary and extraordinary waves respectively (after Piddington and Minnett, 1951b: 146).

Their model also gave a reasonable account of the observed levels of circular polarisation.

In 1953, Piddington and Davies published a re-examination of the earlier statistical analysis of sunspot areas and apparent temperatures and drew on the continued daily observation of records from Potts Hill. This analysis attempted to describe the origin of the solar corona (Piddington and Davies, 1953a). The paper built on the notion of hot high-density regions being the source of the slowly-varying component above 600 MHz. Piddington and Davies observed that the sunspot component diminished less rapidly than the visible sunspots and remained in an elevated state for more than a month after visible sunspot activity had ceased. Therefore, it appeared that the earlier scatter plot analysis would overstate the base temperature level for the quiet Sun. Correcting the plots by using a composite of spot areas based on solar rotations showed a much lower base temperature for the quiet Sun, as indicated in Figure 103.

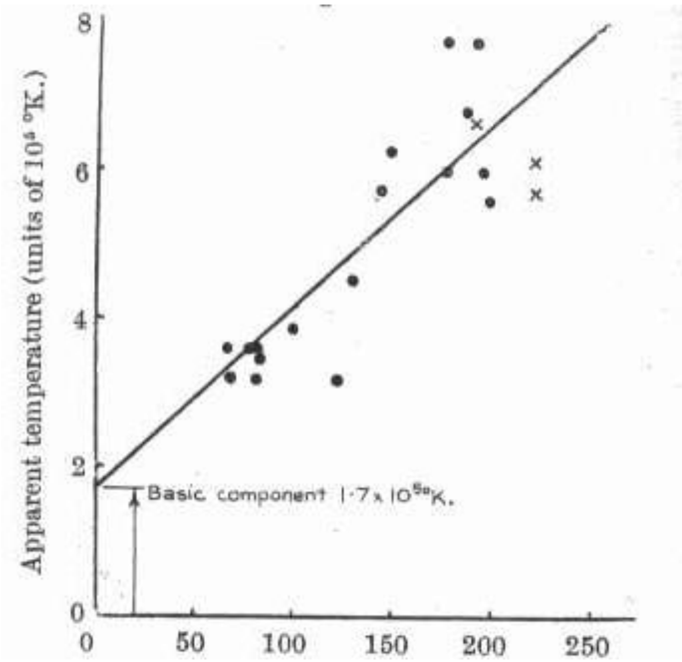


Figure 103: Corrected correlation of apparent temperature at 600 MHz to composite rotational average sunspot area based on observations from December 1949 to April 1951 (after Piddington and Davies, 1953b: 629).

This suggested that the earlier falls that had been seen in the base level of the quiet Sun, particularly in 1950, were simply the result of the longer term decline in the sunspot activity to the true base level. As the very hot gas formed in association with a sunspot it then remained after the spot disappeared and gradually spread and merged with the cooler surrounding atmosphere over the following months. Piddington and Davies calculated that this energy source was capable of maintaining the 10^6 K temperatures observed in the solar corona over the period 1949 to 1951. This analysis provided an important early step in understanding the mechanisms related to coronal heating. A summary paper was published in *Nature* and a more detailed analysis appeared in the *Monthly Notices of the Royal Astronomical Society* (Piddington and Davies, 1953b).

10.5.1.3. Solar Brightness Distributions

As discussed in the previous Section, the distribution of radio emission across the solar radio source was of prime interest as it provided information on the structure, density and temperatures of the solar atmosphere. Obtaining high angular resolution in early observations had relied on the use of solar eclipses which were clearly not practical for collecting a large pool of observational data. It was for this reason that Christiansen had decided to build a high-resolution radio telescope that could perform daily monitoring of the Sun. This was the first Solar Grating Array, which was described in section 10.4.6.

Christiansen had been temporarily diverted from solar research while he was involved in the confirmation of the H-line detection and some preliminary survey work. The first Solar Grating Array was completed in early 1952 and Christiansen then began a program of daily observations. The high-resolution beams of the grating array produced a one-dimensional response scan across the solar disk at 1,410 MHz. Figure 54 shows an example of the output of the Sun passing through the individual aerial beams. Using a succession of daily scans it was possible to determine how the one-dimensional profile changed over a number of days as the Sun rotated. Figure 104 shows the one-dimension brightness distribution on different days in October 1952.

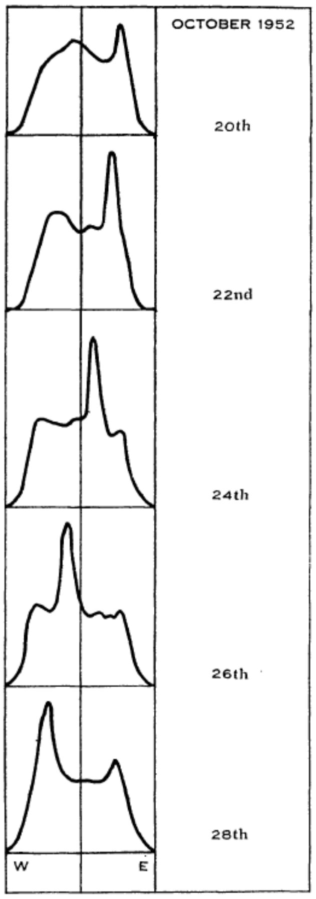


Figure 104: Daily records of one-dimensional brightness distributions across the solar disk from 20 to 28 October 1952 (after Christiansen and Warburton, 1953b: 198).

One early finding that greatly simplified the observational analysis task was that the centre of the radio record corresponded with the centre of visual solar disk, and that bright areas near the limb did not materially change the size of the radio disk. By superimposing the individual scans over an extended period a base level for the radiation became clearly evident. This independent method probably provided the final tipping point toward conclusive evidence that the base level in fact existed. Figure 105 shows an example of such a superimposition.

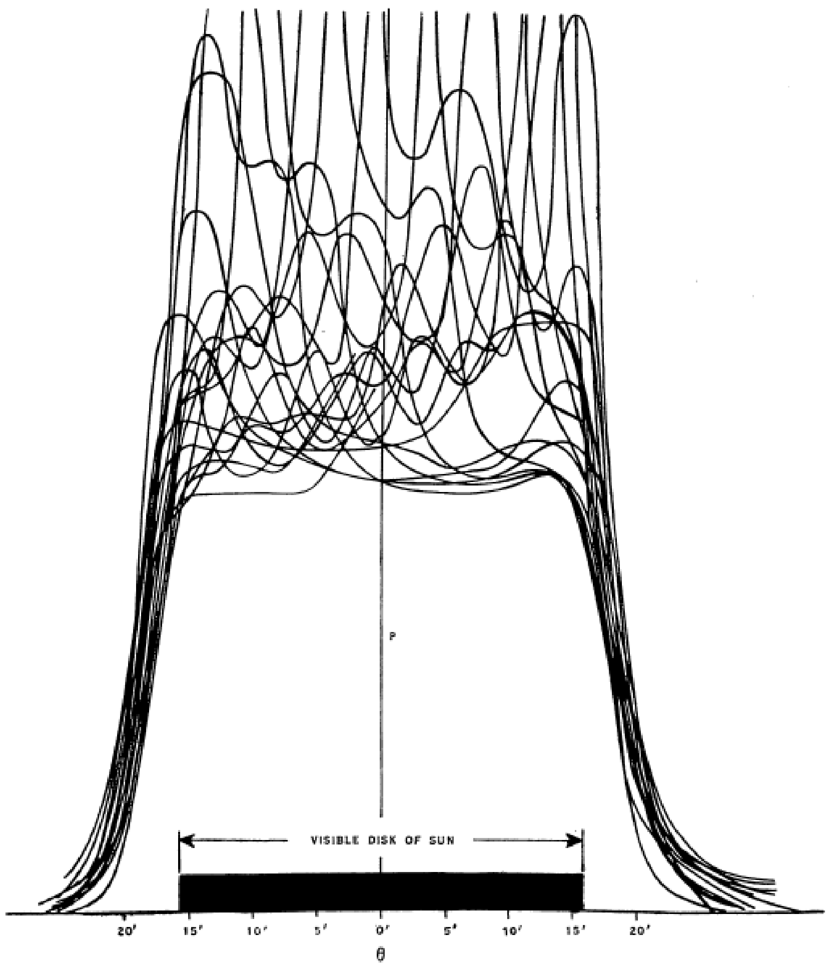


Figure 105: Twenty individual daily one-dimensional brightness distribution scans superimposed. The visual solar disk is indicated by the black bar on the x-axis (after Christiansen and Warburton, 1953b: 200).

Christiansen and Warburton (1953b) used the superimposition technique to determine that the base level temperature of the Sun at 1,420 MHz was 7×10^4 K during the period of observations. Another factor that was clearly evident from the distributions was that the source emission was larger than the optical solar disk. For simplicity a circular symmetry was assumed for the purposes of the analysis, although there were already indications that the distribution appeared more elliptical (as had already been determined from optical observations). Initially it was thought that the effect of this assumption would be small. However, it was fairly quickly recognised that taking into account the non-circular symmetry would be essential and this was to lead to the construction of the second (north-south) Solar Grating Array so as to allow two-dimensional scan (ibid.).

Even allowing for possible errors in the circular symmetry assumption, it was very clear from the observations that limb-brightening had been detected. Figure 106 shows the initial radial distributions based on the one-dimensional scans.

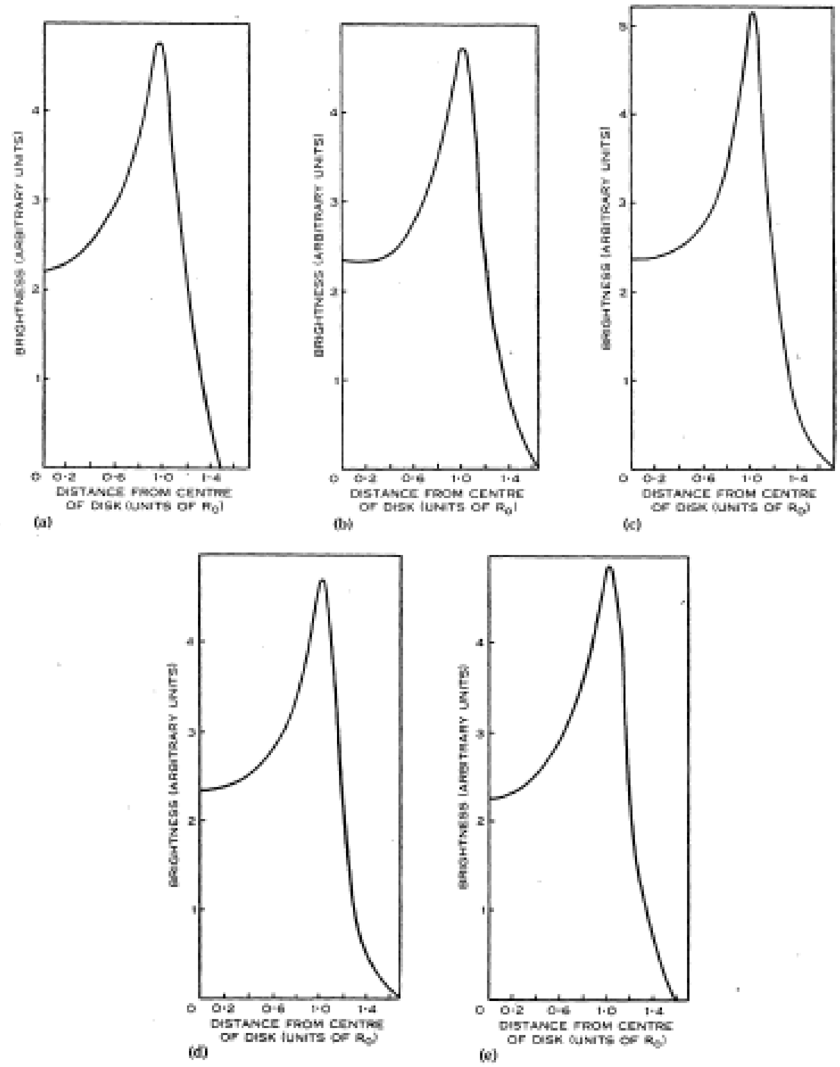


Figure 106: Radial distributions of brightness across the solar disk based on one-dimensional scan observations (after Christiansen and Warburton, 1953b: 268).

These distributions clearly show a limb-brightening effect as predicted in a number of different theoretical models, including one proposed by Smerd (1950b). Unfortunately, since the distributions were measured at only the one frequency it was not possible to determine exactly which parameters in the models best matched the observations, although they were consistent with Smerd's model for a 10^4 K chromosphere and a 0.3-3.0 × 10^6 K corona.

The North-South Solar Grating Array became operational in September 1953. This allowed the simultaneous scanning of the Sun by the east-west and north-south beam orientations as shown in Figure 107.

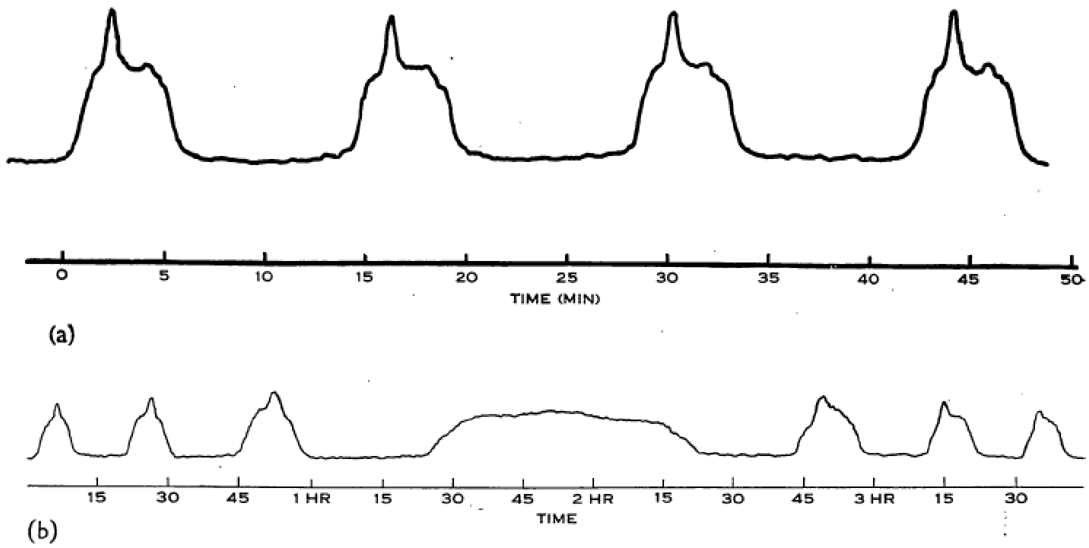


Figure 107: An example of the Sun passing through several of the beams of the east-west (a) and north-south (b) beams of the Grating Arrays (after Christiansen and Warburton, 1955a: 477).

Over the course of a day a wide variety of scan angles could be observed and these could be extended further by observation over a period of months. Figure 108 shows the result of a one-dimension scan taken at different times on a single day and thus achieving scans at different orientations relative to the Sun's axis of rotation.

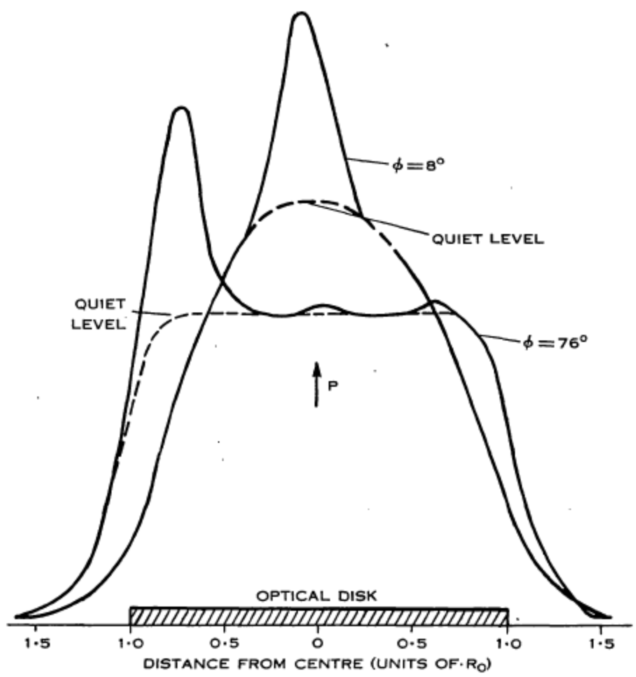


Figure 108: An example of a one-dimensional scan taken for two different scanning angles by observing at different times on the same day (after Christiansen and Warburton, 1955a: 478)

In order to produce a two dimensional image, a cosine Fourier analysis of the individual one-dimensional distributions for the different scanning angles was performed. It is important to note that by using the cosine Fourier analysis Christiansen assumed the Sun was symmetrical and phase was ignored. The numerical value for each scan was plotted radially corresponding to the direction of the scan and then strip integrated with the strip summations being perpendicular to the scan angle. The cosine Fourier transform of the strip integrals was then taken to give radial cross-sections of the brightness distribution. The final two-dimensional distribution was then constructed by plotting each of the radial cross sections and plotting contour lines joining points of equal intensity. This tedious process took months of calculation and plotting by hand to produce a single two-dimensional image as shown in Figure 109. For comparison, Figure 110 shows a photograph of the Sun taken during the total solar eclipse of 30 June 1954.

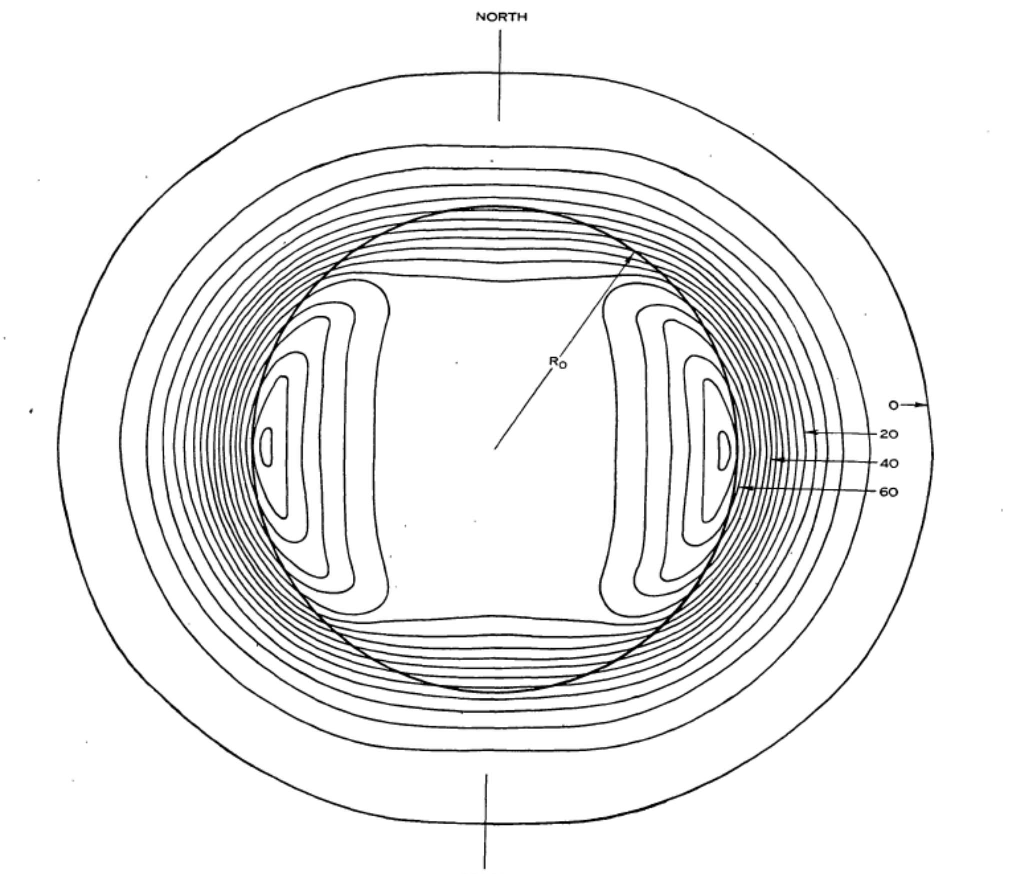
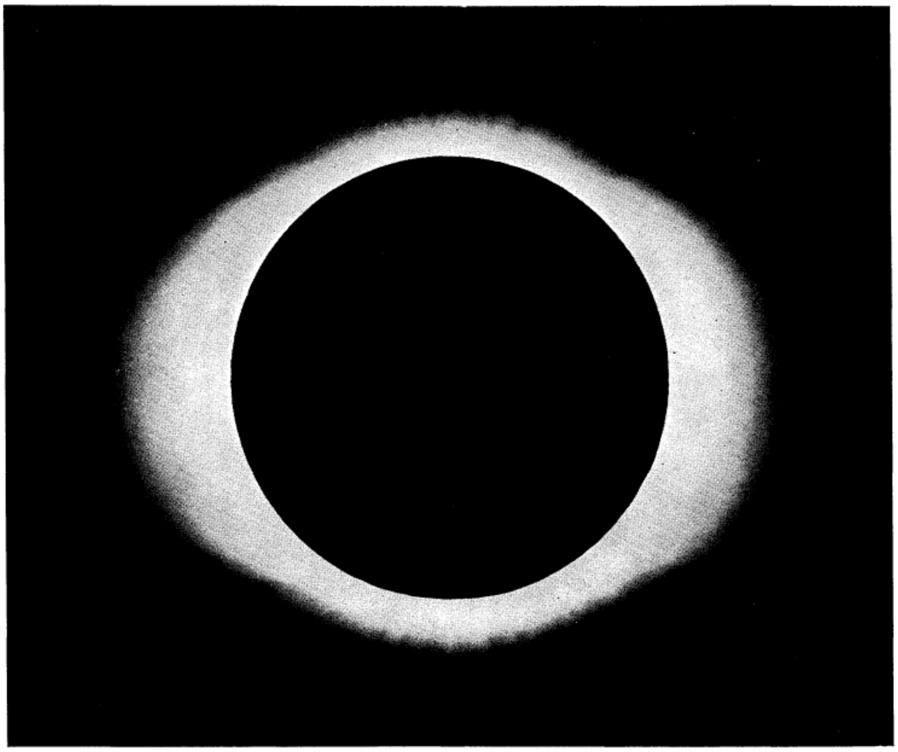


Figure 109: An example of the derived two-dimensional image of the radio brightness distribution across the Sun at 1,420 MHz. The central brightness temperature is 4.7×10^4 K and the maximum peak temperature is 6.8×10^4 K. Contours are spaced at equal intervals of 4×10^3 K (after Christiansen and Warburton, 1955a: 482).



Photograph of the Sun at the total eclipse June 30, 1954 (M. Waldmeier).

Figure 110: Photograph of the Sun during the total solar eclipse of June 30, 1954 (after Christiansen and Warburton, 1955a: Plate 2).

The hand calculations were performed by Christiansen and Warburton with the assistance of Swarup using electronic calculators (but not computers!). Bracewell has stated (1984) that the graphical method that was used for this reconstruction was adopted from his method of cord construction, although his contribution was not acknowledged in the published paper.

Bracewell had been assigned by Pawsey to work on the issue of fan-beam reconstructions and he shared an office with Christiansen and Minnett during this period. In 1956 Bracewell published a paper on strip integration based on this work. The paper included a description of the use of projection-slice theorem which would be used to underpin modern imaging techniques including computerised tomography and medical imaging (see Bracewell, 1956, 2005).

Staff at Radiophysics developed Australia's first electronic computer, which was called CSIRAC (CSIR Automatic Computer). This was the fifth (or fourth depending on the definition of 'operational') electronic stored (digital) program computer developed in the world and ran its first program in November 1949 (McCann and Thorne, 2000). Figure 111 shows an image of CSIRAC.

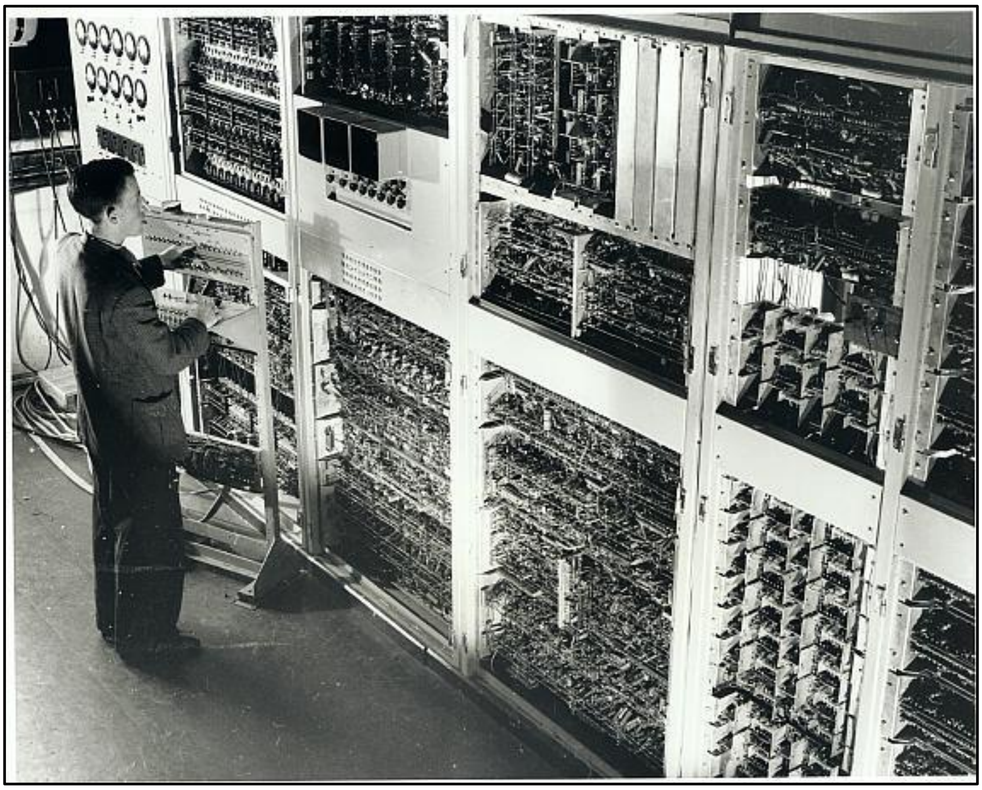


Figure 111: CSIRAC at the Radiophysics Laboratory in June 1952 (Courtesy of Geoff Hill).

CSIRAC was originally called CSIR Mk1 and was used for a variety of applications in the Division including astronomical table generation. However, the leap of imagination needed to apply this capability to the calculation of Fourier Transforms to produce imaging in radio astronomy was not made while the computer was operated by Radiophysics. Given the close proximity of the work on the computer and the repetitive nature of the manual calculations, it is surprising that this connection was not made. In 1955 it was decided not to pursue the further development of computers in the Division, and CSIRAC was transferred to Melbourne University in 1956. Some years later Cambridge made the inevitable connection by applying electronic computers to Fourier Transformations, and this went on to become the mainstay of imaging in radio astronomy. In fact, CSIRAC was eventually used for Fourier analysis after its transfer to the University of Melbourne. This application of Fourier techniques was however by Jim Morrison from the Chemical Physics section of the CSIRO who was measuring ionisation efficiency curves, and was based on his previous experiences in X-ray crystallography. Working with the programming team he implemented the equivalent of a Fast Fourier Transform routine to perform this analysis (see McCann and Thorne, 2000: 136).

Figure 109 reveals that the two-dimensional distribution of radiation at 1,420 MHz was not circularly symmetrical and showed a strong correlation with the optical form of the corona as seen at times of total solar eclipse. The elliptical source extended 1.6 times further at the equator than at the poles. The limb-brightening effect was also not evenly distributed, with the strongest brightening at the equator and practically no effect at latitudes above 55º. Christiansen and Warburton (1955a) noted that this latitude corresponded to the latitude at which structural changes in the corona could be seen optically at times of sunspot minimum, and that comparing the outline of the 8,000 K contour to the photographic image showed a strong correlation. Christiansen and Warburton (ibid.) concluded that the majority of the radiation at the centre of the image emanated from the chromosphere, while the limb-brightening effect was due to the greater depth of view of the corona with its higher temperature gradient.

Observations during 1952, 1953 and 1954 showed no change in the shape or level of temperature of the quiet component of the solar radiation (Christiansen and Warburton, 1955a). This supported the assertion made by Piddington and Davies (1953b) that previous observation of changes in the base level were due to the lag effects of changes in sunspot activity.

During Christiansen's visit to Meudon Observatory in France during 1954, the East-West Solar Grating Array was modified by Swarup and Parthasarathy to operate at 500 MHz. From July 1954 to March 1955 they performed daily observations to obtain one-dimensional distributions across the solar disk. Figure 112 shows examples of superimposed observations over a period of several months.

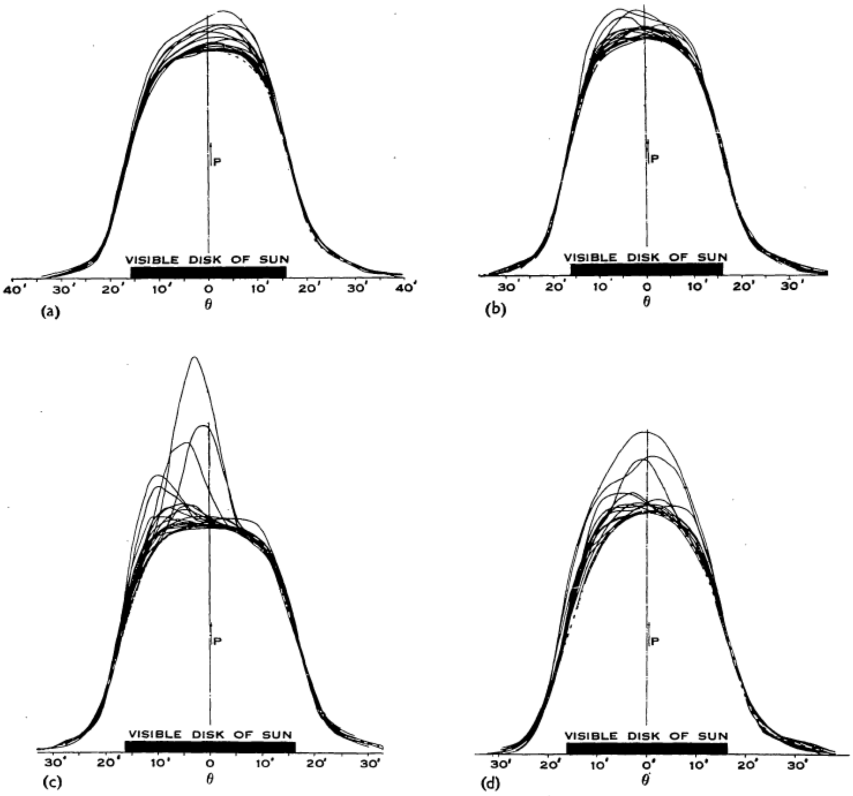


Figure 112: Superimposed one-dimensional brightness distributions at 500 MHz taken between July 1954 and March 1955. Observations were taken from (a) 18 July to 5 August ϕ = 3º; (b) 9 August to 1 September ϕ = 11.5º; (c) 15 December to 3 January ϕ = -3º; (d) 7 February to 4 March ϕ = 26º; ϕ represents the angle in arc minutes between the Sun's central meridian and the aerial beam (after Swarup and Parthasarathy, 1955b: 490).

Of major interest at the time was the comparison of these results with earlier observations by Stanier at 500 MHz using a two-element interferometer (Stanier, 1950). Stanier's observations, which occurred closer to the maximum of the solar cycle, had not disclosed limb-brightening. Figure 113 shows the comparison of the two different radial distributions detected.

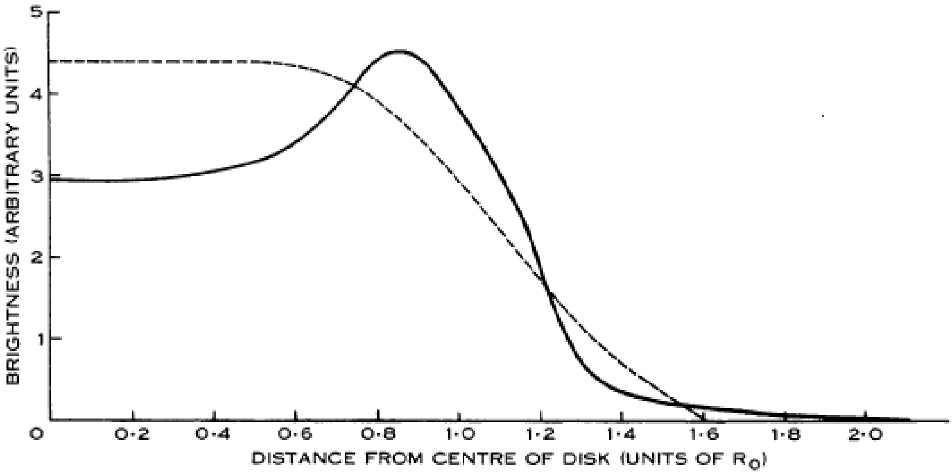


Figure 113: Radial brightness distributions at 500 MHz comparing Stanier's result (dotted) and Swarup and Parthasarathy's observations (after Swarup and Parthasarathy, 1955b: 493).

The difference in the results was suggested by Swarup and Parthasarathy (1955b) to be related to problems with the two element interferometry technique used by Stanier.

Later observations at 500 MHz (O'Brien and Tandberg-Hassen, 1955) using a two-element interferometer also detected limb-brightening, and Swarup and Parthasarathy's results were in good agreement with these. Swarup and Parthasarathy (1955b) also noted that like the higher frequency observations by Christiansen and Warburton, the source emission did not appear to be circularly symmetrical. Although they were observing only with the modified East-West Array, Swarup and Parthasarathy were able to achieve a variety of scan angles by viewing at different times during the day and over a period of eight months. Figure 114 shows the different brightness distributions for the aerial beam positioned at 90° and 64° to the Sun's central meridian. This indicates that the maximum width of the source occurred in the equatorial regions.

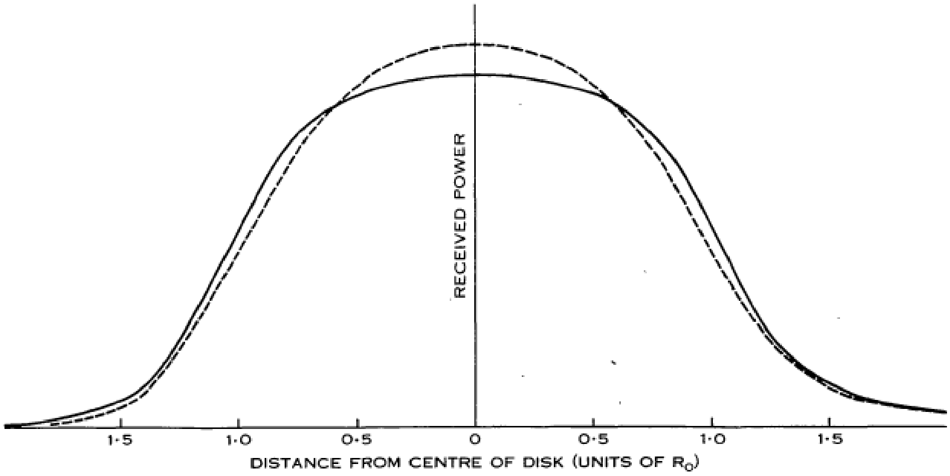


Figure 114: Brightness distributions at 500 MHz for the aerial beam at 90º (solid line) and 64º (dotted line) to the Sun's prime meridian (after Swarup and Parthasarathy, 1955b: 491).

Swarup and Parthasarathy (1955b) calculated that the base apparent temperature of the quiet Sun at 500 MHz was 3.8×10^5 K. This compared to a temperature of 5.4×10^5 K derived by Stanier. By comparison to the previous eclipse observations, they concluded that there was evidence to suggest a change in the base level temperature of the quiet Sun as a result in the decrease in the solar cycle. This is interesting because the conclusion appears to make no reference to the earlier suggestions made by Piddington and Davies (1953b), and later reinforced by the longer-term observations of Christiansen and Warburton (1955a), that this change was not in the base level, but due to the lag in sunspot activity.

In 1957, Christiansen, Warburton and Davies (1957) published the fourth and final paper in their solar series based on observations from the Solar Grating Array. This paper examined the slowly-varying component based on the observations during 1952 and 1953. Part of their analysis concluded that the lag effect first suggested by Piddington and Davies (1953b) was not sufficient to provide the sole explanation of the decline in base temperatures. They concluded that it was likely that both the quiet component and the slowly-varying component varied depending on the solar cycle. They also concluded that the original correlation method proposed by Pawsey and Yabsley (1949) gave results that were quantitatively correct. This analysis, although not published at the time, probably influenced Swarup and Parthasarathy to re-introduce the suggestion of a variation in the level of radiation from the quiet Sun.

Christiansen, Warburton and Davies's paper provided a clear illustration as to why the sunspot area correlation, although strong, was in fact only a partial correlation. This is shown in Figure 115 where three groups are indicated; old sunspot regions, new regions and regions that had reached maximum intensity.

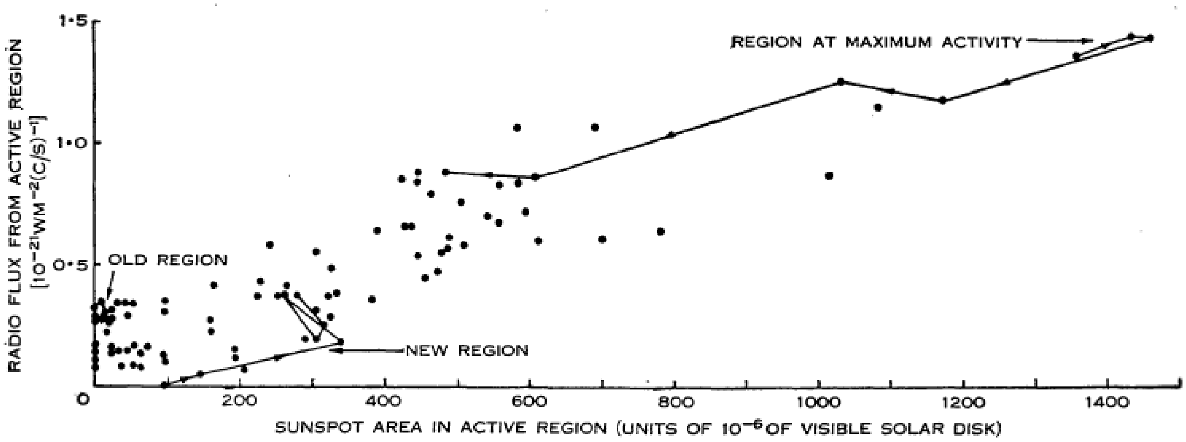


Figure 115: Scatter diagram of sunspot area to radio flux. The day-by-day development of one new and one mature sunspot are shown by line connected points with arrows showing the direction of development (after Christiansen et al., 1957: 511).

The correlation is clearly strongest for areas at maximum intensity. The new region shows a short delay before the radio emission becomes stronger, hence the moderate correlation, and the old fading sunspots show continued radio emission and the weakest correlation.

Christiansen, Warburton and Davies reached the conclusion that the radio emission appeared to be associated with plage faculiare rather than with sunspots themselves. The plage faculiare are the areas in the photosphere and chromosphere where sunspot groups grow and decay due to strong localised magnetic fields. Christiansen, Warburton and Davies based this on comparison of spectroheliograph observations from Mount Stromlo and the Solar Grating Array observations. Figure 116 shows an example of the comparisons where the vertical lines indicate the maximum point of a one-dimensional scan.

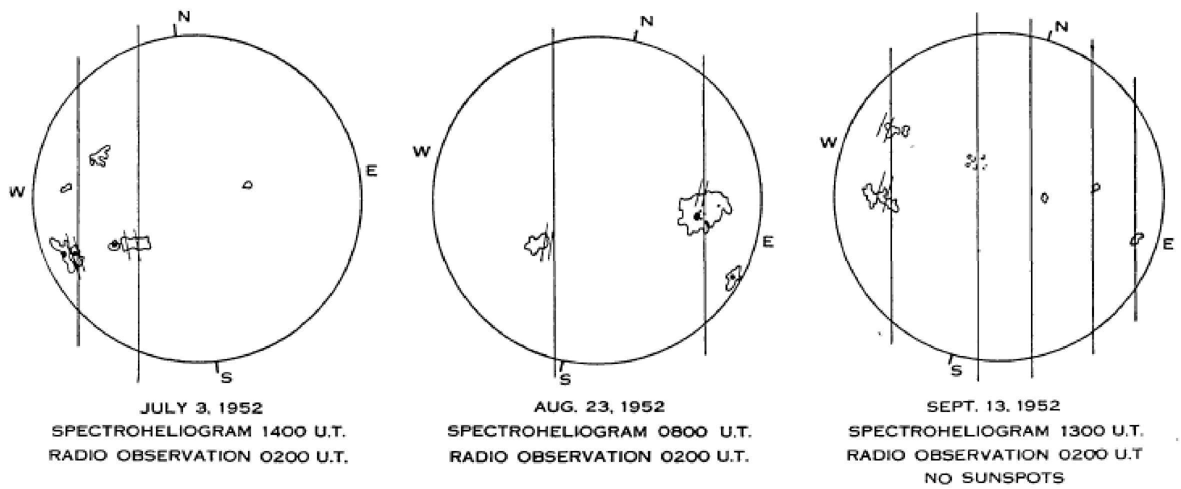


Figure 116: Spectroheliograms showing plague faculiare (Ca *K*) regions with maximum 1,420 MHz emission position lines from one-dimensional scans show as vertical lines (after Christiansen et al., 1957: 506).

A similar conclusion had earlier been reached by Dodson (1954) based on a comparison of her optical observations with Covington's radio observations, and this was discussed with Pawsey following an introductory lecture during the August 1955 IAU symposium on Radio Astronomy at Jodrell Bank (Allen, 1955: 262).

Using an analysis of the relative rates of rotation of the optical and radio sources, Christiansen, Warburton and Davies concluded that the 1,420 MHz radio emission emanated in a region about 24,000 km above the photosphere. They also found a correlation of r = 0.85 between the size of the plages and the sizes of the radio sources and noted that it appeared that the sources behaved like thin disks lying parallel to the photosphere.

In 1958 Swarup and Parthasarathy published their second and final paper on the 500 MHz observations using the modified East-West Grating Array. This paper dealt with their observations of the localised bright regions of radiation during the period July 1954 to March 1955 (Swarup and Parthasarathy, 1958). The paper found similar characteristics to those discussed by Christiansen, Warburton and Davies (1957). The sources were closely correlated with the positions of the chromospheric faculae, they were of the order of 3 to 6 arc minutes in size, and they appeared to be localised to regions approximately 35,000 km above the photosphere. Perhaps the most interesting finding was the observation of some variability in the localised sources. Figure 117 shows an example of the variation in the signal as the Sun passes between two adjacent beams.

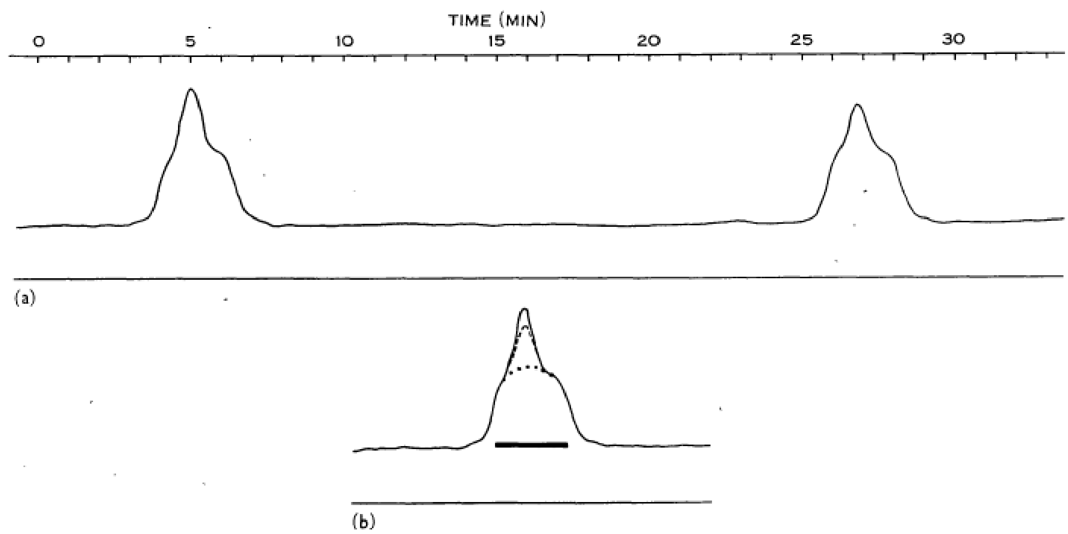


Figure 117: The Sun passing through two adjacent beams (top) and the two responses superimposed (bottom). The dotted line in the bottom graph shows the quiet Sun and the difference in strength of the discrete source in the two beams (after Swarup and Parthasarathy, 1958: 345).

These variations were observed on six occasions and lasted for periods of up to half an hour. This provided strong evidence for the non-thermal origin of some of the energy produced, as it was believed that such a rapid thermal change could not occur to an area the physical size of the source.

Swarup and Parthasarathy's paper was one of the last papers based on observations of solar sources at Potts Hill. By this stage Christiansen had already moved his research to the Fleurs field station using the newly constructed Chris Cross array (Orchiston, 2004c) and the remainder of the original Potts Hill Grating Array was transferred to India.

The final solar research paper from Potts Hill was based on observations of the 8 April 1959 partial solar eclipse (Krishnan and Labrum, 1961). The eclipse was observed both at Potts Hill using the 16-ft × 18-ft Parabola as a high sensitivity total power radiometer and at Fleurs using the Chris-Cross array to help identify areas of enhanced radiation. Figure 118 shows the local circumstances of the eclipse.

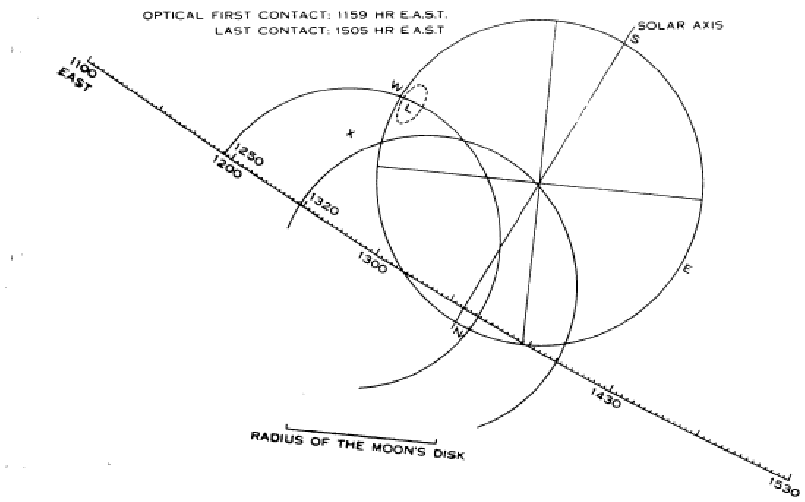


Figure 118: The circumstance of the 8 April 1948 partial solar eclipse as viewed from Potts Hill (after Krishnan and Labrum, 1961: 406).

The receiver used for the eclipse observations was a conventional superheterodyne type preceded by a Dickie switching system. It operated at 1,423 MHz with a bandwidth of 500 KHz. At this frequency its effective beamwidth at the half power points was 2.3º. The theoretical resolution that can be achieved by observing an eclipse is limited only to the diffraction of the Moon's limb and at 1,423 MHz this is ~0.1 arc minutes. During the eclipse the Moon's disk moved across the Sun's disk at ~1 arc second in 4 minutes of time. Therefore, any region on the solar disk with a size greater than 0.25 arc seconds and with more that 1% of the total flux could be resolved. The Chris-Cross was used to determine the location of areas of enhanced radiation on the solar disk during the eclipse so that their effect could be taken into account in obtaining a brightness distribution across the quiet Sun. The resolution of the Chris-Cross at this frequency was ~4 arc minutes. Figure 119 shows the brightness distribution across the solar disk obtained during the eclipse with the Chris-Cross.

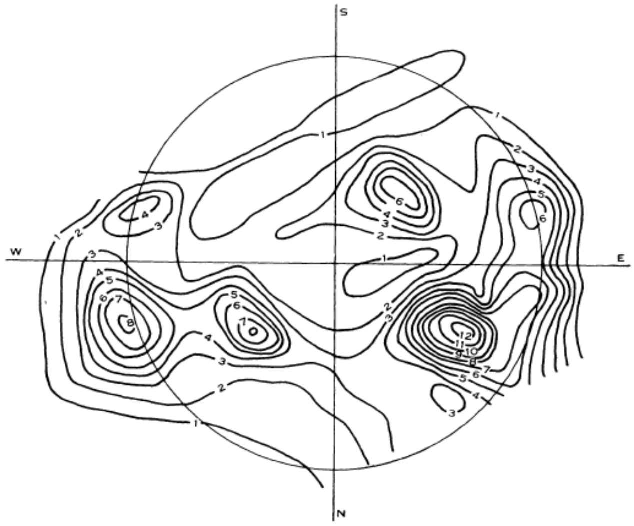


Figure 119: The brightness distribution during the partial solar eclipse of 8 April 1959 as observed by the Chris Cross. The contour spacing unit is 10,000 K, aerial beamwidth ~4 arc minutes (after Krishnan and Labrum, 1961: 407).

The eclipse was successfully observed at Potts Hill (see Figure 120). No calcium spectroheliogram observations were available in Australia at the time, however one was provided by Dobson (now Dobson-Prince) working at the McMath Hulbert Solar Observatory in the U.S. This allowed Krishnan and Labrum to compare the distribution of plage faculaires seen in the K-line of calcium with their radio observations. They found a very close relationship between optical and radio plages, both in their intensity and their overall shape. The eclipse observations provided perhaps the most detailed demonstration of the relationship up until this time and certainly a more convincing set of results than the original work at Potts Hill that had suggested this association (Christiansen et al., 1957).

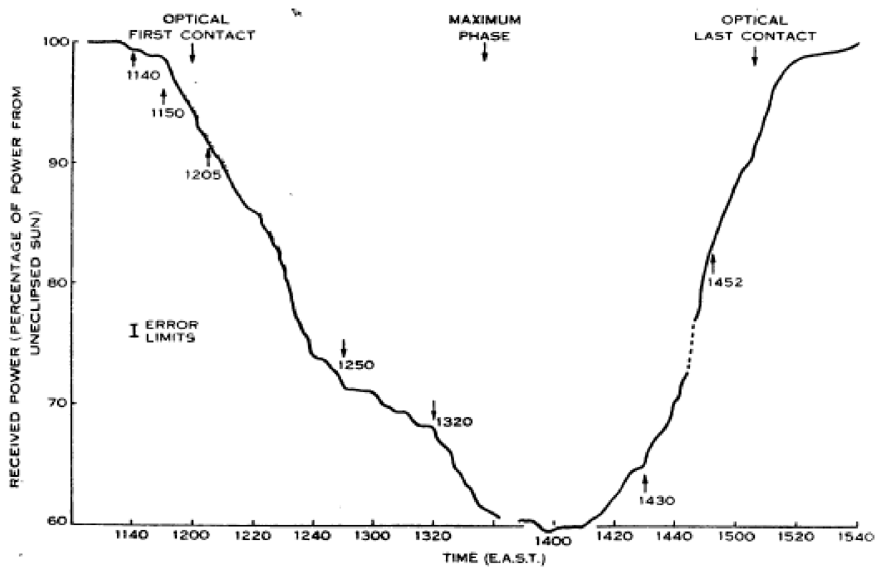


Figure 120: The eclipse curve obtained at Potts Hill for the 8 April 1959 partial solar eclipse (after Krishnan and Labrum, 1961: 408).

Krishnan and Labrum were also able to test a number of quiet Sun models against the eclipse observations. They found that the best fit was achieved by a model based on Christiansen and Warburton's (1955) work for sunspot minimum which showed limb-brightening at the equator, but absent at the poles. After allowing for an overall increase in brightness temperature by a factor of 2 to allow for the sunspot maximum, Krishnan and Labrum found that a stepped-up gradient of limb-brightening (the ear component) provided the best fit. It is likely that the lower resolution of the grating arrays used by Christiansen and Warburton for measurements of limb-brightening would have washed out the steeper gradient and therefore the ear would not appear as pronounced. The higher resolution of the eclipse observation allowed the steeper gradient to be more accurately measured. Figure 121 shows a comparison of the eclipse observations to the distribution model with the enhanced limb-brightening ears.

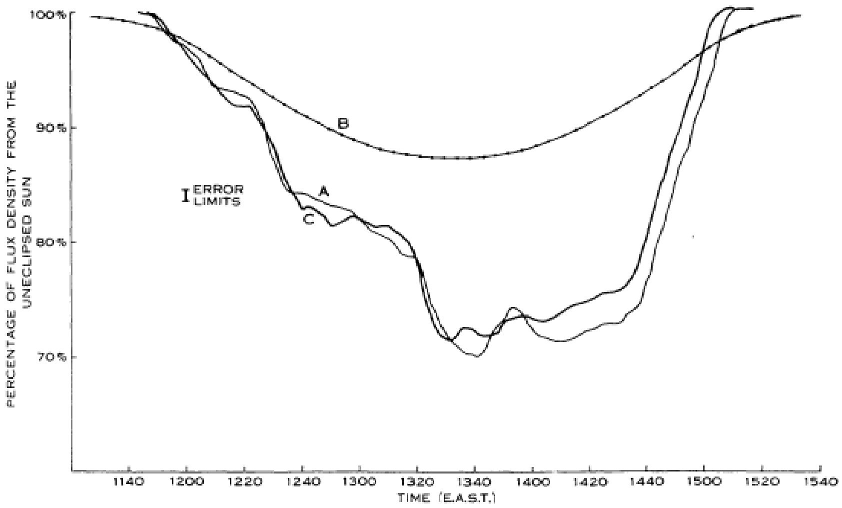


Figure 121: Line-A represents the eclipse observation adjusted for the emissions to lie radially at a height of 70,000 km above the photosphere. A theoretical model based on enhanced ears in the limb-brightening is then used to obtain the quiet Sun component during the eclipse (Line–B). Line-B is then subtracted from the eclipse curve to produce Line-C. The close fit of Line-A and Line-C was taken to indicate that the model with the enhanced ear component of limb-brightening was the best representation of the quiet Sun distribution (after Krishnan and Labrum, 1961: 415).

Figure 122 shows the different quiet Sun models tested against the eclipse observations. The model marked (4) in the diagram gave the best fit to the eclipse observations.

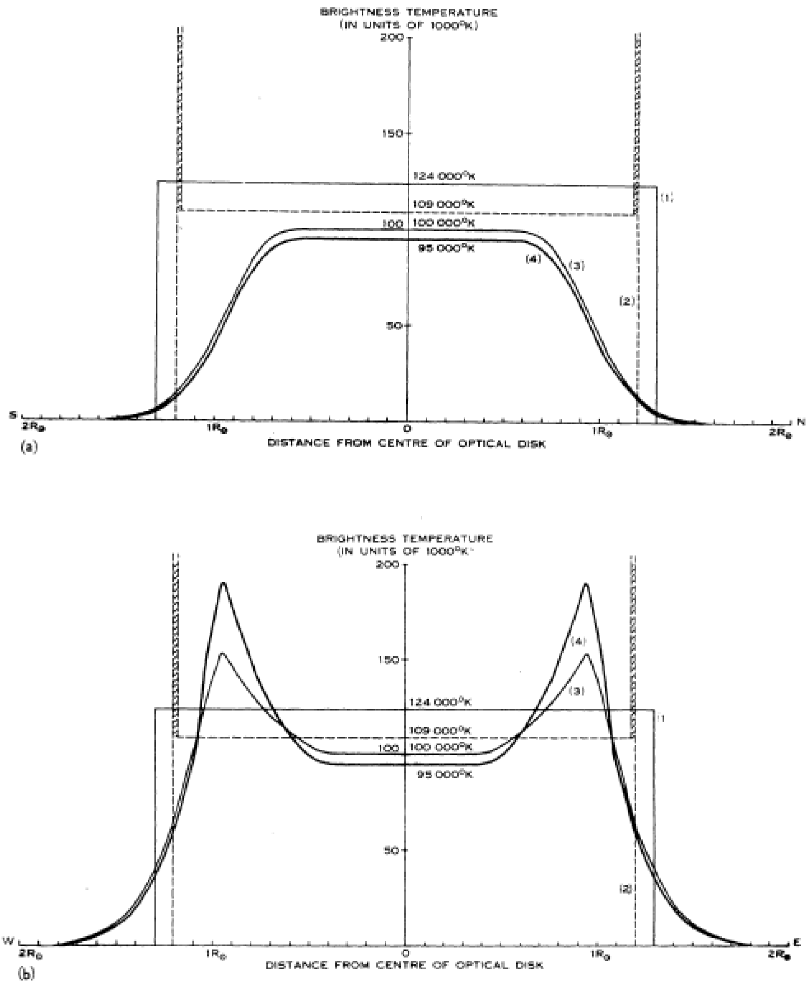


Figure 122: Four different quiet Sun models were tested against the eclipse observations. Model (1) assumes a uniform disk of radius 1.3 times the photospheric radius. Model (2) assumes a uniform disk of radius 1.2 times the photospheric radius containing 75% of the quiet Sun flux with a narrow ring around the limb containing the remaining 25%. Model (3) was based on the Christiansen and Warburton (1955) distribution with temperatures scaled up by a factor of two to account for the sunspot maximum. Model (4) is the same type of distribution as Model (3) but with the temperature gradient in the ear component of limb-brightening scaled up by a factor of 2. The upper graph shows the model distribution along the solar axis and the lower graph across the solar axis (after Krishnan and Labrum, 1961: 417).

Krishnan and Labrum were also able to measure the peak brightness temperatures of the radio plage and found temperatures of the order of 1.5×10^6 K for the larger regions. This indicated that these regions were in the range of normal coronal temperatures reinforcing the hypothesis that the slowly varying component originates in dense regions of the corona that lay above plage faculaires.

These observations were the last published solar observations at Potts Hill. The 1948 partial solar eclipse had been one of the first major research successes and it is fitting that the final observations were also of a solar eclipse some 11 years later.

10.5.1.4. Solar Burst Observations

Before beginning the discussion on the burst observations at Potts Hill, it is worthwhile reviewing the developing classification scheme that was in use in the early 1950s in Australia. For this purpose the classification of solar radio waves from Pawsey and Bracewell (1955) has been used. The basic component, or quiet Sun, and the slowly-varying component have been discussed in the previous Sections. Three other broad classifications were proposed. These are outlined in Table 3.

Table 3: Classification of solar radio sources (after Pawsey and Bracewell, 1955: 150).

		Unpolarised Burst	
	Noise Storm	**Outburst**	**Isolated Burst**
Wavelength	1-15 m	1 cm – 15 m	50 cm – 15 m
Polarisation	Strongly Circular	Random	Random
Place of Origin	Small area above sunspot	Small area – rapid movement	Small area
Associated optical features	Large Sunspot	Flare	Unknown
Remarks	With or without numerous bursts	No certain distinction	

Figure 123 provides a useful illustration of the different source classifications by wavelength.

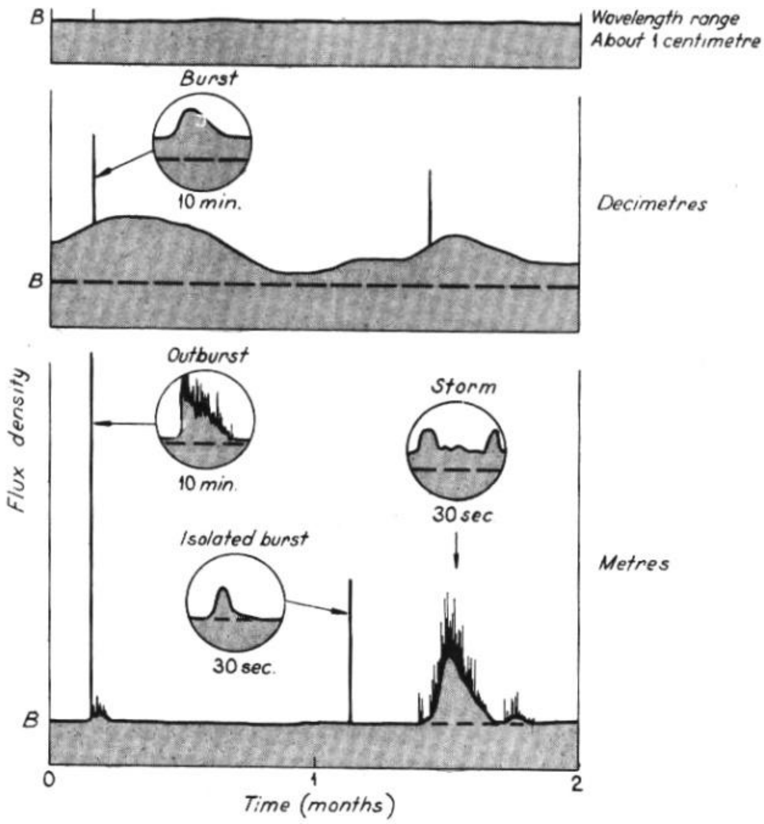


Figure 123: Idealised examples of solar radio sources in three broad frequency bands. The base level (B) increases approximately linearly with wavelength from an apparent temperature of 10^4 ºK at 1 cm to 10^6 at 1 m (after Pawsey and Bracewell, 1955: 147).

The first of the three classifications was Noise Storms. These tended to last for periods of hours to days and were named by Allen (1947) because of their similarity to magnetic storms. Individual bursts during the storm were generally for periods of seconds with irregular wave forms and amplitudes up to several hundred times the background level of radiation. The storms were always associated with large sunspot groups and showed strong circular polarisation.

The second type, Outbursts, were also named by Allen (1947). They were sporadic and infrequent events with durations of minutes and were randomly polarised. They could be of extremely high intensity, with the largest recorded outburst at the time going off the scale at 10^{13} K. This was recorded on 8 March 1947 at 60 MHz (Payne-Scott et al., 1947). In this instance the apparent temperature rose from 10^7 K to 10^{13}+ K in a matter of seconds. At decimetre wavelengths, many bursts occurred at the same time as metre wavelength outbursts and were thought to be part of the same phenomenon. In other cases there was no association. It was also believed that outbursts had an association with solar flares.

Examples of burst and outbursts at 200 MHz are given in Figure 124 based on Allen's original observations.

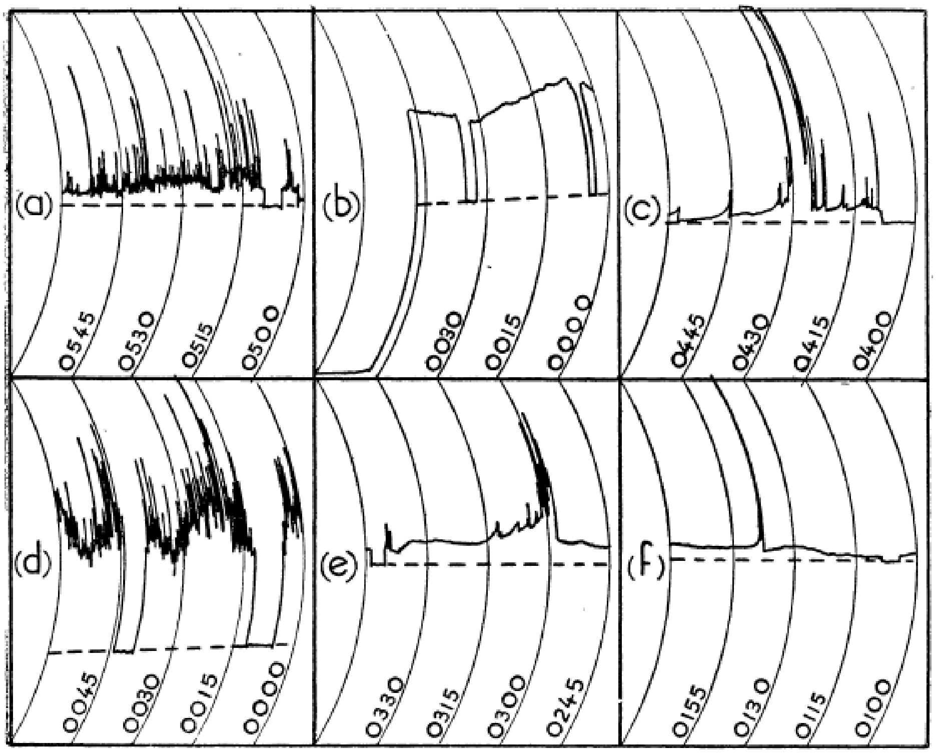


FIG. 1.—*Examples of solar radio-noise recordings. Set noise level is indicated by broken line. Note that timing is from right to left.*

(a) 1946 *September* 14. *Frequent bursts and low noise level.*
(b) 1946 *September* 20. *No bursts and high noise level.*
(c) 1947 *March* 8. *Large outburst.*
(d) 1947 *March* 10. *Frequent bursts and high noise level.*
(e) 1947 *March* 14. *Small outburst.*
(f) 1947 *March* 18. *One burst and fairly quiet.*

Figure 124: Examples of 200 MHz measurement of burst and outbursts (after Allen, 1947: 388).

The third type, Isolated bursts, were named by Pawsey (1950) because they were not associated with any other solar activity. They were generally of short duration (less than 10 seconds), randomly polarised with a moderately-simple waveform and often occurred in groups. They were also believed to have a relatively wide bandwidth of tens of megahertz. Payne-Scott (1949) referred to both outbursts and isolated bursts as ‘unpolarised bursts’ rather than distinguishing between classes.

While the solar work was underway at Potts Hill, Wild and McCready (1950) examined the spectral characteristics of solar bursts at the Penrith field station between February and June 1949. Based on these observations they proposed a new classification scheme that distinguished between the spectral characteristics of the bursts over time. This scheme would ultimately become the accepted nomenclature for solar bursts e.g. Type I, Type II, Type III (and later expanded to include IV and V). Type I bursts were characterised by having a narrowband width, with short-lived duration, and could occur in large numbers during noise storms. They were generally circularly polarised and were believed to be associated with sunspots. Type II bursts were characterised by a slow drift in frequency from high to low and appeared to be associated with the sporadic outbursts and solar flare events. They were thought to be associated with Allen's outbursts. Type III events were characterised by a very rapid change in frequency from high to low lasting in the order of seconds and were believed to be equivalent to the 'isolated outbursts'. They were reasonably common and sometimes occurred in groups. Other sporadic burst events had a diverse range of spectral characteristics that fell outside of these broad classifications and it would be some years before further classifications were proposed. The original classifications and descriptions were published in a series of four papers (Wild, 1950a,b, 1951; Wild and McCready, 1950). Examination of the spectral characteristics and classification of the solar bursts became the major focus for Wild's group. A new field station was established at Dapto specifically for this pursuit and became operational in August 1952 (Orchiston and Slee, 2005a).

The solar burst research at Potts Hill was less concerned with spectral characteristics and more with the accurate location of the events and their association with other characteristics. For this reason Pawsey's classification is used in the following descriptions rather than the 'Type' nomenclature.

The first published records of solar burst observations from Potts Hill were included with Minnett and Labrum's 9,428 MHz observations of the partial solar eclipse of 1 November 1948 (1950). They noted that bursts were very rare at this short wavelength, occurring on only five occasions in 230 hours of observations. Intensities varied from 6 to 30 percent increases in base temperatures. Two of the bursts occurred at the same time as stronger decimetre bursts that were monitored independently. One of the bursts was associated with an observed radio fadeout. The radio fadeouts were believed to be caused by the arrival of intense ultraviolet radiation in the ionosphere as a result of a solar flare.

On 17 and 21-22 February 1950 two extremely large radio-frequency solar outbursts were observed across all of the frequencies being monitored at Potts Hill. This ranged from 62 MHz using a Yagi array, 98 MHz using the swept lobe interferometer, 600 MHz and 1,200 MHz using the 16-ft×18-ft ex-Georges Heights Paraboloid, 3,000 MHz using the 68-in Parabola and finally, 9,400 MHz using the ex-Search Light 44-in Parabola. In additional, 200 MHz observations were made using the 4-element Yagi at Mount Stromlo. Figure 125 shows the power flux levels recorded at the different frequencies for observations on both dates.

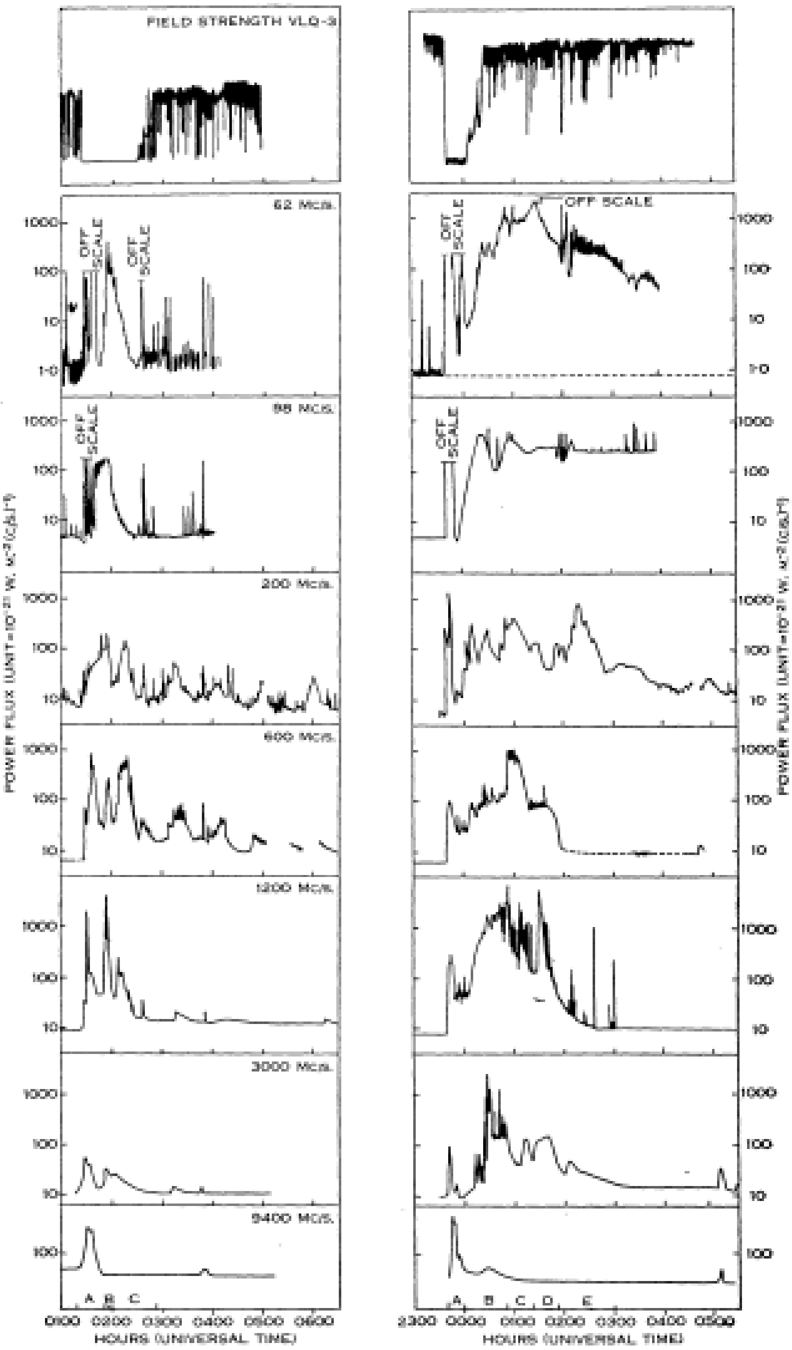


Figure 125: Power flux records for the seven frequencies observed on 17 (left) and 21-22 (right) February 1950. The top record is of the field strength for the radio station VLQ-3 from Brisbane, measured at Sydney. The 200 MHz record is from Mt Stromlo (after Christiansen et al., 1951: 53).

These observations were supplemented by a range of other data and included measurement of the short-wave radio fade out in Sydney of the Brisbane radio station VLQ-3 broadcasting at 9.6 MHz, sunspot and solar flare observations from Mount Stromlo, flare observations from Cater Observatory in Wellington, New Zealand, and from Kadaikanal Observatory in India, and magnetogram records from the Watheroo Magnetic Observatory in Western Australia. The combined observations were published in 1951

(Christiansen et al.). This demonstrates the increasingly cooperative approach being undertaken with other solar astronomy groups both domestic and international. Figure 126 shows a schematic of the start times of the outbursts as well as the radio fadeout and magnetic crochet measurement.

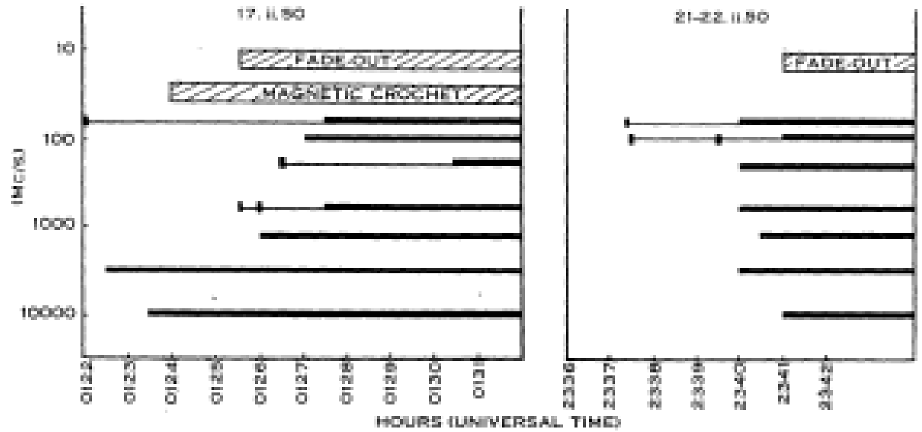


Figure 126: Schematic of the start time of the outbursts at the different frequencies, together with the radio fade out and magnetic crochet. February 17th (left) and 21-22nd (right) (after Christiansen et al., 1951: 57).

While generally similar, the two outbursts showed some distinct differences. On 17 February, the outburst was first received at higher frequencies, while the second outburst appeared almost simultaneously at all frequencies. No magnetic crochet was observed for the second outburst, although a magnetic storm was observed 35 hours after the second burst and was clearly linked to the outburst. Circular polarisation was observed in both cases with the low frequencies having a change in sense while the higher frequencies retained a fixed sense. In both cases flare activity was associated with the outburst and the radio fadeout.

Payne-Scott and Little were able to use the swept-lobe interferometer to determine the position and movement of the outbursts at 98 MHz. The first outburst occurred very close to the position of an observed flare and then slowly tracked eastward over a period of 30 minutes to a position 10 arc minutes to the east of the Sun’s limb (Figure 127).

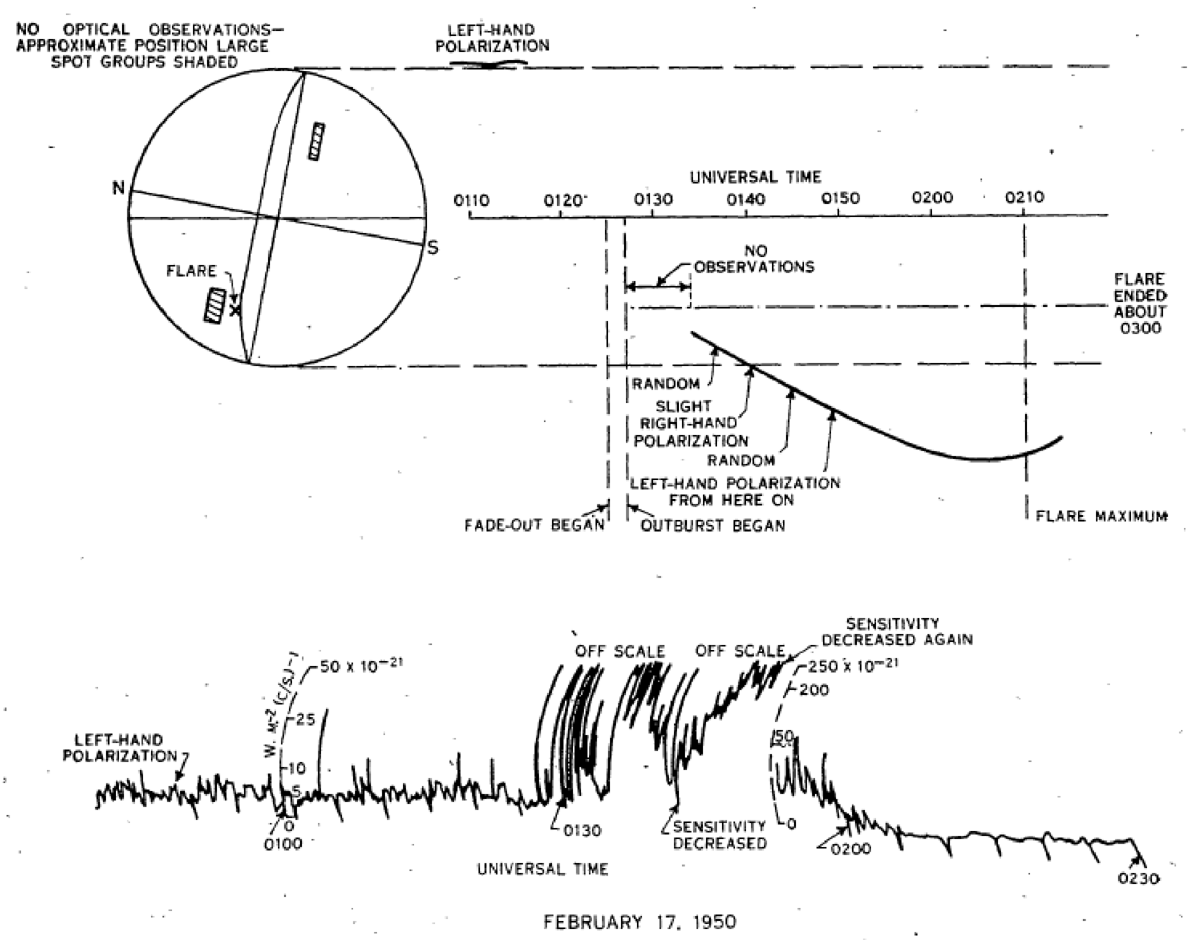


Figure 127: The outburst of 17 February 1950, showing the flare position on the solar disk, the outburst position movement and polarisation measurements. The lower chart shows the overall emission measurement at 98 MHz with timing marks indicated by the downward ticks (after Payne-Scott and Little, 1952).

An initial report on the 17 February 1950 outburst was published in a short article in *The Observatory* together with description of the swept-lobe interferometer (Bracewell, 1950).

The outburst recording shown in this paper (Figure 128) makes an interesting comparison with Figure 127. This version, although lacking the total flux charts, makes much clearer the initial one-dimensional positional strip measurement obtained from the swept-lobe interferometer against which the flare position is compared. The position movement also appears to have been considerably smoothed in the final analysis.

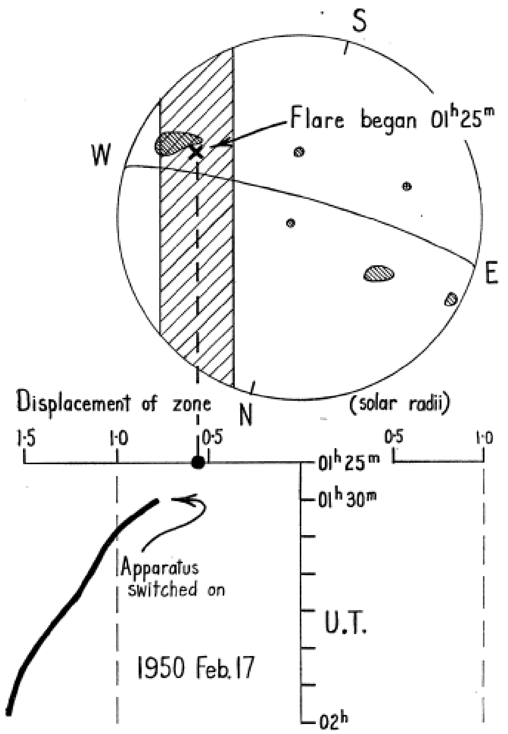


Figure 128: The earlier published version of the outburst of February 17, 1950 (after Bracewell, 1950: 186).

For the second outburst, position measurements only began after the outburst had been underway for approximately 27 minutes. At this time the source position was still close to an observed flare. Over the next 40 minutes it tracked out to the western limb of the Sun and then returned to the position of the flare after a period of some rapid oscillations between the limb and the flare (Figure 129).

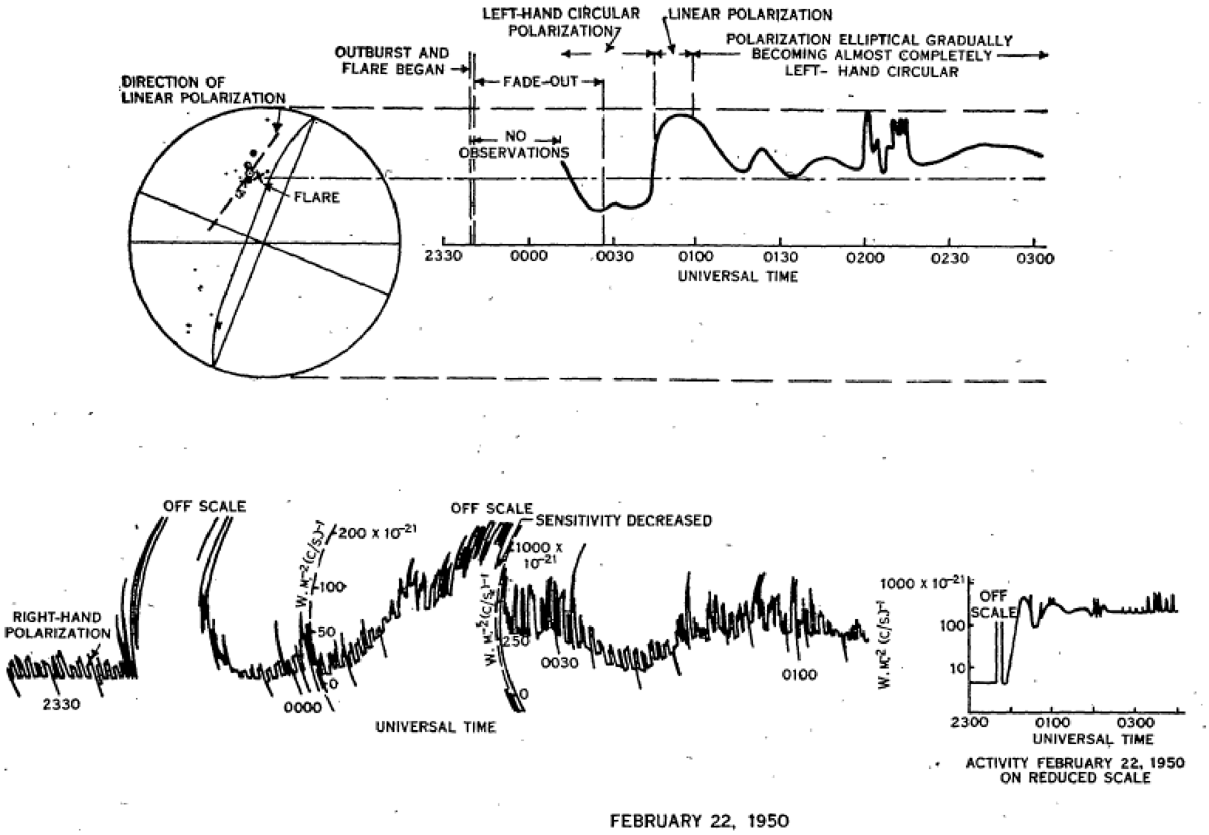


Figure 129: The outburst of 22 February 1950, showing flare position on the solar disk, the outburst position movement and polarisation measurements. The lower chart shows overall emission measurements at 98 MHz with timing marks indicated by the downward ticks (after Payne-Scott and Little, 1952: 35).

These measurements provided a clear indication that the outbursts were associated with solar flares and appeared to show movement of the source outward through the solar atmosphere. In today's terms these outburst would be classified as Type II bursts.

A further four outbursts were observed by Payne-Scott and Little and together with those of the 17 and 21-22 February 1950 made a total of six outbursts for which one-dimensional accurate positions and polarisation measurements were determined. Five of the events clearly showed an outward movement interpreted as the passage of an exciting agent through the solar corona. The most likely exciting agent was the corpuscular stream assumed to be responsible for terrestrial magnetic storms. The position measurements suggested that the origin of the outbursts was approximately 2×10^5 km above the photosphere and that they travelled outward at velocities ranging from 500 to 3000 km/sec. These velocity estimates were higher than those deduced by Wild from measurements of the frequency spectra of outbursts assuming a given electron density for the corona (Wild, 1950a: 406). However, if a higher electron density for the corona was assumed, then the results were in general agreement. One of the outbursts appeared to exhibit a downward motion (Figure 130). This was interpreted as the stream of corpuscles falling back into the Sun after first being ejected without the production of an initial outburst.

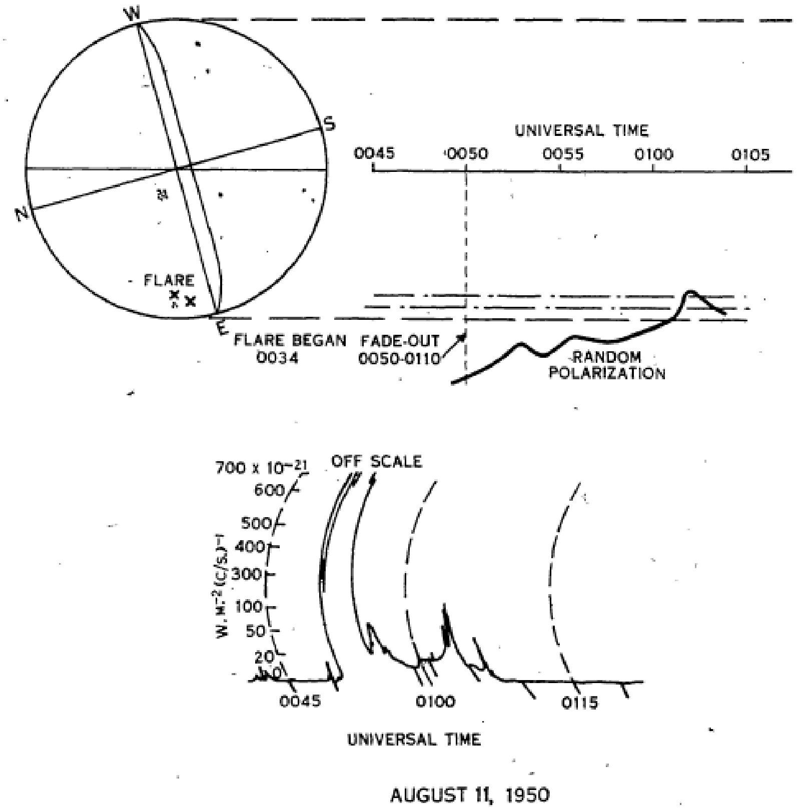


Figure 130: The 11 August 1950 outburst showing the inward movement of the outburst source (after Payne-Scott and Little, 1952: 34).

Polarisation measurements generally showed random polarisation in the early stages of the outburst, often followed by a second increase showing elliptical (mainly circular) polarisation. On two occasions linear polarisation was observed in the late stages. Payne-Scott and Little (1952) noted that the sense of polarisation followed the broad pattern that had been observed for noise storms whereby there appeared to be a relationship between the direction of polarisation based on the hemisphere of origination and the polarity of the largest sunspot in the group.

The reader should bear in mind that in interpreting these source position drift diagrams the paths shown are projections of a 3-dimensional movement onto the solar disc and corona.

While outbursts were known to be associated with chromospheric flares, up to this point no clear association had been made with other catastrophic optical events such as solar prominences. In the period 24 - 26 February 1953 three bursts were observed on the full range of frequencies being covered by daily observations at Potts Hill. The first burst occurred prior to a prominence erupting. The second burst occurred coincident with a prominence eruption that Davies also observed with the spectroheliograph that was in use at Potts Hill in support of the Solar Grating Array observations (Davies, 2005: 95). The prominence occurred on the northeast limb of the Sun and erupted to a height of 3-4 arc minutes above the limb. The third, and most intense burst, occurred as the prominence material was streaming back toward the Sun. No flare activity was evident during the period. The results of these observations were published in *Nature* (Davies, 1953) alongside observations of the same event at 100 MHz from the Kadaikanal Observatory in India (Das and Sethumadhavan, 1953).

From May 1949 to July 1950 Payne-Scott and Little carried out a systematic investigation of solar bursts using the swept-lobe interferometer. During this period they observed thirty noise storms, six of which were examined in detail. Figure 131 shows position lines from one of the storm sources shown on sunspot sketches from Mount Stromlo.

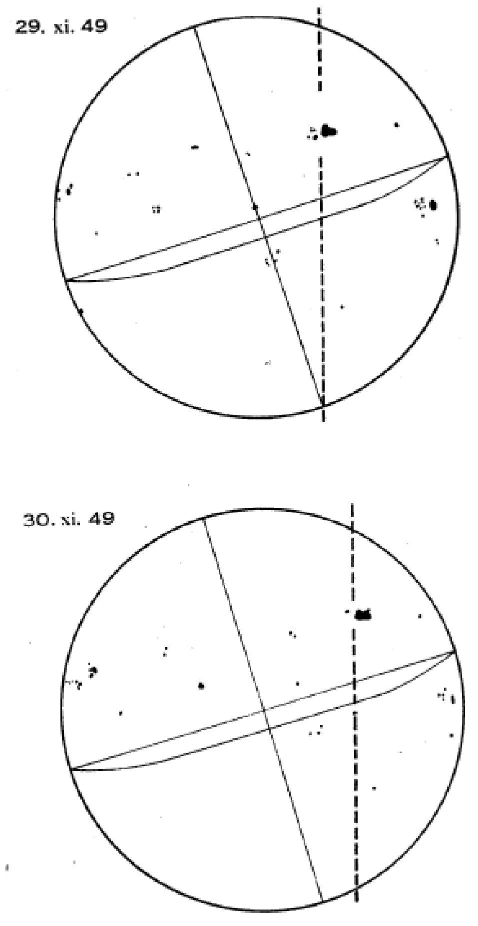


Figure 131: Storm source position lines from the swept-lobe interferometer shown on sunspot sketches from Mount Stromlo (after Payne-Scott and Little, 1951: 514).

The six noise storms showed a very strong correlation with the largest sunspots within sunspot groups. Drawing on the records of the Mount Wilson Observatory in the U.S., Payne-Scott and Little were able to show that there appeared to be a threshold of sunspot size (around 300 millionths of the solar area) of the largest sunspot in a group after which storms could occur. Figure 132 shows the scatter diagram of sunspot group area compared to the area of the largest sunspot. This is overlaid with the observations of radio noise storms.

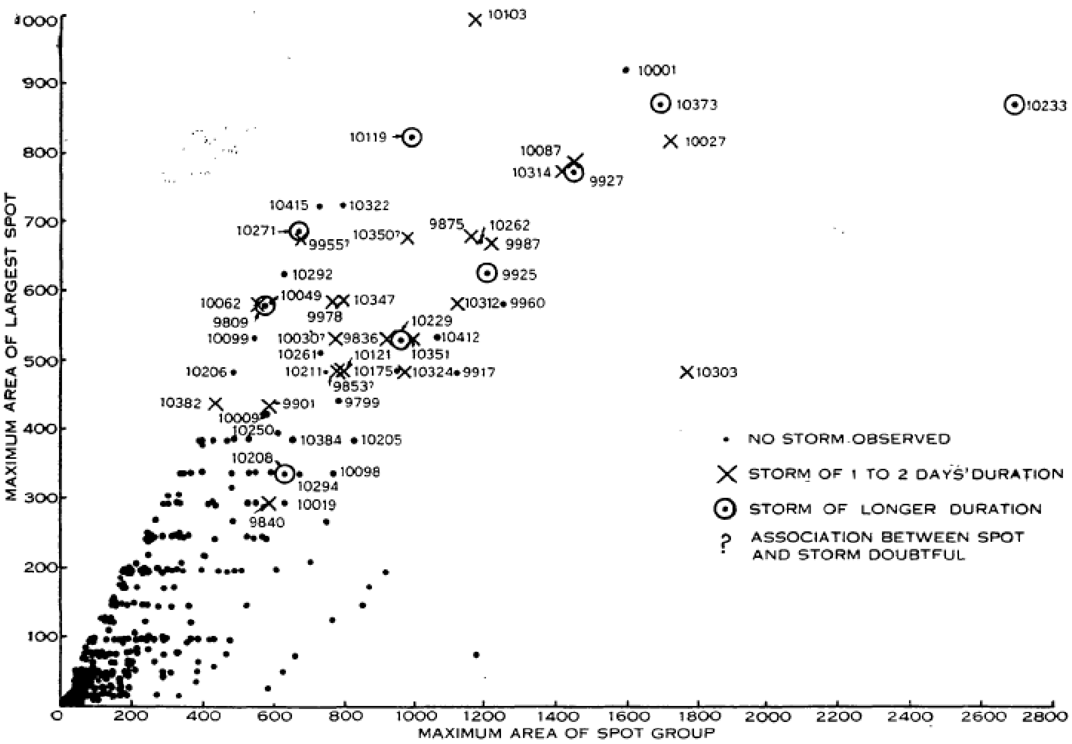


Figure 132: Scatter diagram of sunspot groups from Mount Wilson Observatory May 1949 to July 1950 overlayed with Noise Storm observations (after Payne-Scott and Little, 1951: 512).

Circular polarisation was evident in all of the noise storms and was a clear indication that magnetic fields associated with the largest sunspots were an important factor in the production of the noise storms. The observed sense of polarisation indicated a fairly simple sunspot dipole model could have been in operation, with a south seeking magnetic pole associated with right-hand polarisation and a north seeking pole with left-hand polarisation. This was, however, complicated by a predominance of right-hand polarisation in the observations.

One of the most interesting aspects of the high positional resolution observations was that it allowed for the testing of the height of the origin of the storm source in the corona. Using Smerd's model (1950b), Payne-Scott and Little constructed a model comparison of a 100 MHz source radiating above the locus of return directly above a sunspot. This model is shown in Figure 133.

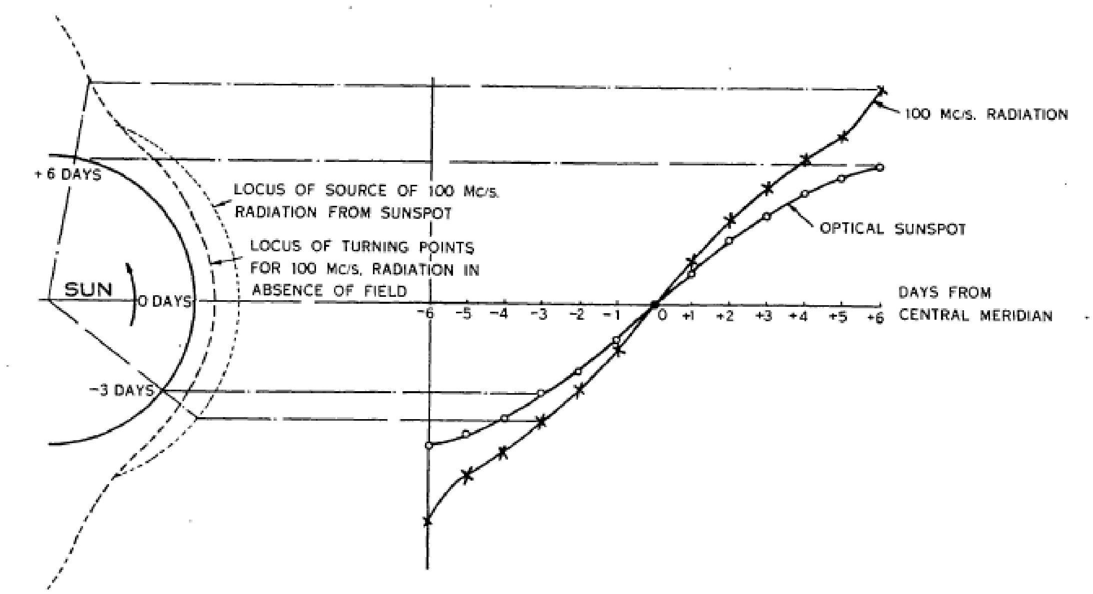


Figure 133: Model showing the relation between the apparent positions of a 100 MHz source and the associated sunspot group, assuming the source is in the corona (after Payne-Scott and Little, 1951: 522).

The model was compared to the actual observations of source positions relative to the sunspot groups and is show as part of the observational summaries in Figure 134 (lower sections of the graphs). Strong agreement was evident and this was further enhanced if a higher density of the corona was assumed. This observation and their analysis of outbursts indicated that a higher coronal density may have been present than was the assumed standard value at the time.

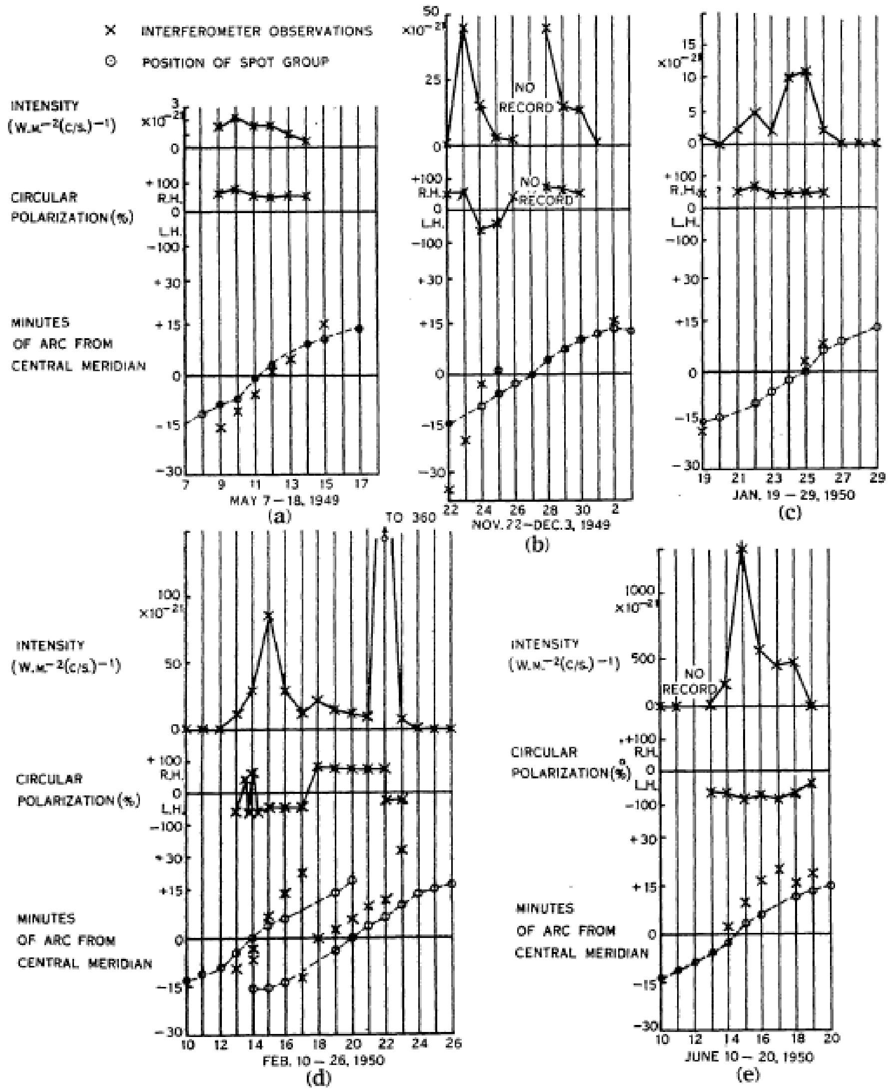


Figure 134: Observation summaries of the six noise storms observed in detail using the swept-lobe interferometer. Note graph (d) contains two storm records (after Payne-Scott and Little, 1951: 516).

These observations also ruled out theoretical models that proposed an origin of the source of radiation low in the solar atmosphere. They also provided further strong evidence for a non-thermal mechanism for the radiation.

Unfortunately further work by Payne-Scott was curtailed in a very untimely manner by her departure from the Radiophysics Division as discussed in section 10.3.10.

The final published research based on the ongoing daily solar observation program at Potts Hill was an analysis of solar radio bursts over a period of 18 months from January 1950 to June 1951 (Davies, 1954). Piddington and Davies had earlier tabulated data based on the daily records at 200, 600, 1,200, 3,000 and 9,400 MHz in an internal report. These were later extended to include the 62 and 98 MHz records. With the exception of the 200 MHz records which came from Mount Stromlo, all of the records were based on observations made at Potts Hill. Piddington was interested in tabulating the data to support his theoretical work on the origin of the solar corona (Davies, 2005: 94).

Davies used the tabulated data to perform an analysis of some 400 bursts that were observed during the period and looked at their association with other solar events and with terrestrial magnetic crochets and radio fadeouts. The data for the magnetic crochet comparisons were drawn from the Toolangi Magnetic Observatory located near Melbourne, from the quarterly reports of the *Journal of Geophysical Research* and from the 1950 *Bulletin of International Association of Terrestrial Magnetism and Electricity*. The radio fadeout data were derived from 18 MHz measurements of galactic radiation made at the Hornsby Valley field station. It is interesting to note that these were the same records that contained the detection of Jovian radio bursts that remained unnoticed until the records were re-examined (Shain, 1956) in light of the Jupiter emission discovery in the US (Burke and Franklin, 1955). The solar flare and sunspot information were based on the *Quarterly Bulletin* of the International Astronomy Union and the *Monthly Bulletin* of the Tokyo Observatory. An example of a radio burst observation from the available records is given in Figure 135.

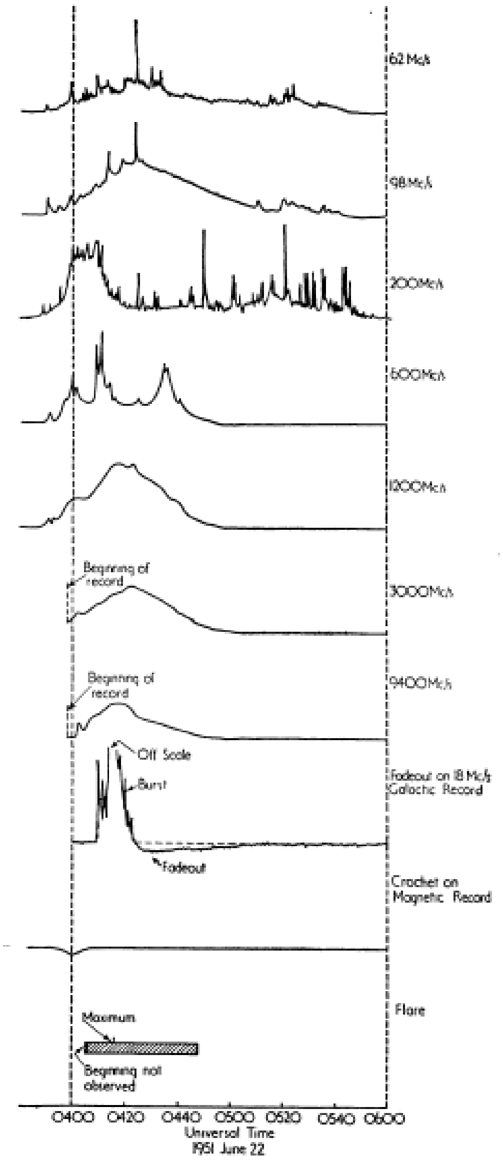


Figure 135: Example of the seven radio frequency records together with fadeout, magnetic crochet and optical solar flare records taken on 22 June 1951 (after Davies, 1954: 77).

The main aim of this analysis was to study the correlation of the radio bursts with other phenomena, therefore no attempt was made to classify burst types or examine the physical origins of the bursts. Given that the broadest definition of a burst, being any clear-cut solar radio emission rising above the daily level, was used, the analysis included all types of bursts without distinction. The broad characteristics of the bursts were described together with relationships between bursts at different frequencies. One of these features was the linear decrease in the occurrence of bursts per hour as frequency increased, as shown in Figure 136.

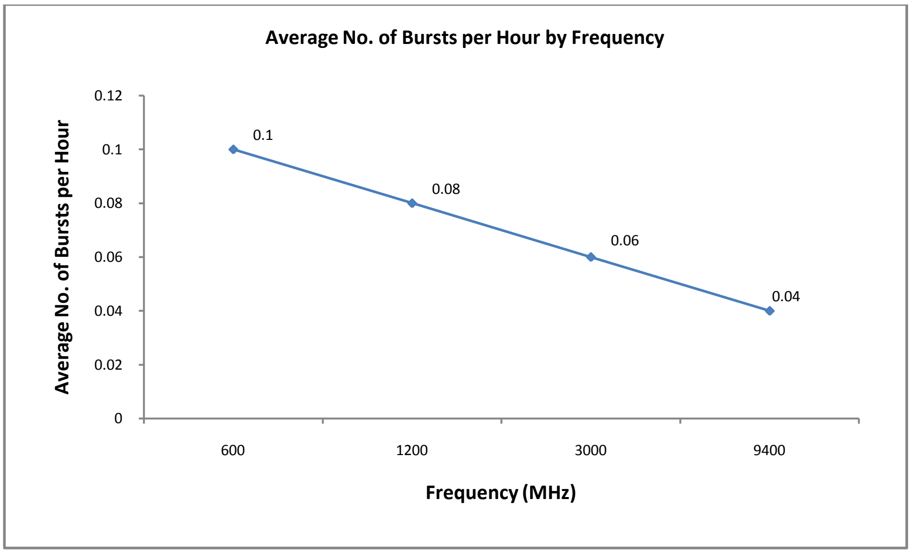


Figure 136: Analysis of the average number of solar bursts per hour by frequency for the period January 1950 – June 1951 (based on data from Davies, 1954: 78).

The analysis showed the same time delays of onset of bursts at different frequencies as had earlier been observed (e.g. Payne-Scott et al., 1947), as well as supporting the observation of both outward and inward movement of sources through successive plasma levels in the solar atmosphere, as had been observed by Payne-Scott and Little (1952). All frequencies showed a tendency to lag 3,000 MHz, suggesting a simultaneous movement up and down from the level of zero refractive index at the frequency which occurred first.

In terms of correlations with other phenomena, the analysis showed that nearly all flares and their terrestrial effects (i.e. magnetic crochets and radio fadeouts) were associated with radio bursts. Only 1% of flares and fadeouts and 2% of crochets were not associated with bursts. There was also a rough correlation between the intensity of bursts, flares, fadeouts and crochets. The onset of the bursts appeared to coincide with the onset of flares and crochets, but preceded fadeouts by about two minutes. As all types of bursts were included in the analysis there were many more bursts observed than flare, fadeouts and crochets.

This was effectively the end of the solar burst research at Potts Hill. Much progress had been made in a relatively short period of time, providing a solid foundation of observational results, through accurate position measurements, polarisation studies and long-term statistical analyse.

10.5.2. Cosmic Research

The original reason for establishing the Potts Hill field station was to consolidate the solar observations leading up to the 1 November 1948 solar eclipse. Solar research was therefore the major focus of the field station in its initial years. This focus began to change during 1949 as interest in discrete cosmic sources grew. Initially these investigations were made by using the solar instruments when solar observation was not possible, such as between sunset and sunrise (e.g. Mills and Thomas, 1951; Piddington and Minnett, 1951a). In 1951 Ewen and Purcell (1951) working at Harvard detected the 1,420 MHz (λ = 21cm) Hydrogen emission-line that had been predicted many years earlier by van de Hulst (1945). This discovery was quickly confirmed in Australia (Pawsey, 1951b) and lead to a new branch of investigations at Potts Hill and to the construction of the first instrument there dedicated to cosmic research.

In the second half of the life of the Potts Hill field station cosmic source investigations dominated the research program. Figure 137 illustrates the rise of cosmic investigations and hence publications produced as a result of research at Potts Hill.

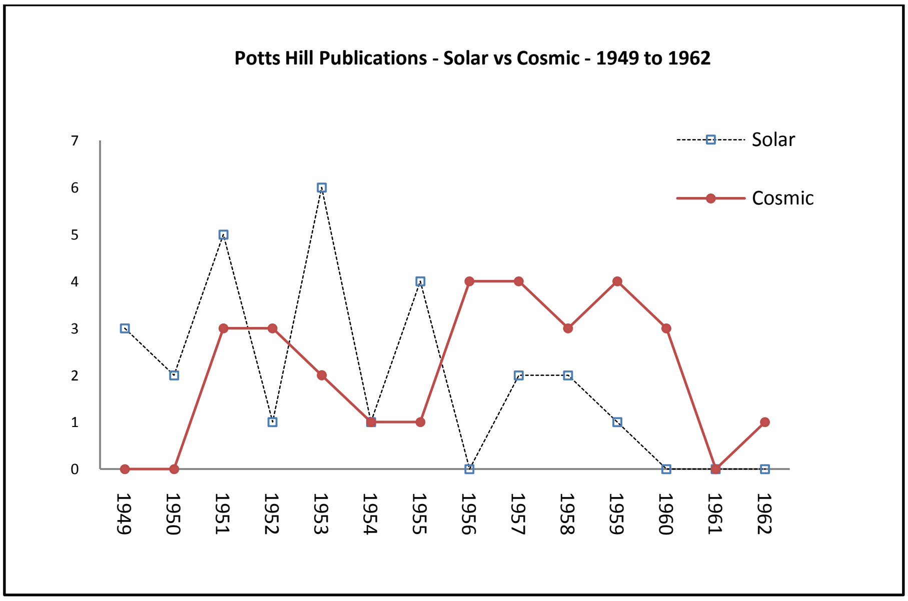


Figure 137: Count of solar and cosmic research papers based on research performed at Potts Hill during the life of the field station.

This section describes these cosmic investigations in three main parts. The first examines the discrete source investigations and survey work, and is then is followed by a review of the H-line programs. Finally a brief discussion of the contribution made to Jupiter burst observations is provided.

10.5.2.1. Discrete Sources and Surveys

After a very short foray into solar research with Christiansen and Yabsley (1949b), Mills turned his attention to the investigation of discrete cosmic sources. Together with Thomas, he used the swept-lobe interferometer in its conventional interferometer configuration to investigate the discrete radio source in Cygnus that had been discovered by Hey, Parsons and Phillips (1946). At Dover Heights significant progress had been made in identifying optical counterparts to three of eight discrete sources (Bolton et al., 1949). However, identification of Cygnus A remained problematic (Bolton and Stanley, 1948a,b; Ryle and Smith, 1948). After a number of further investigations (Little and Lovell, 1950; Smith, 1950; Stanley and Slee, 1950) the fluctuations that had been observed from the source were determined to originate in the ionosphere and although accuracy of the positional estimates was improved, no optical identification of the source was made. In another example of an event that contributed to an increasing antagonistic relationship between the Australian group and their Cambridge counterparts, Stanley and Slee examined their 1948 measurements of source fluctuations and were confident that they were caused by diffraction in the intervening medium and were not intrinsic to the source itself. They sought the help of their Cambridge colleagues to confirm this result. Subsequently the Cambridge Radio Astronomy group collaborated with radio astronomers at Jodrell Bank to confirm this, but no acknowledgement was made of the contribution of Stanley or Slee and they were left to belatedly publish their result after the Cambridge and Jodrell Bank papers appeared in *Nature* (Slee, 1994: 523).

It was with this background that Mills and Thomas undertook investigations of Cygnus A from May to December 1949. From Potts Hill, the source was relatively low in the northern sky rising to a maximum of only 16° above the horizon. This made position measurement at the relatively low frequency of 97 MHz difficult and also subject to significant refraction and ground reflection errors. As such, these factors needed to be included in the interferometry declination formula.

$$\cos\delta = \frac{n\lambda}{d \sin H_n}(1 + R_n \tan E_n) \tag{8}$$

where

- λ is the wavelength;
- d is the distance between aerials;
- n is the number of a minimum in the interference pattern counting from an assumed central minimum;
- H_n is the corrected hour angle at which the nth minimum occurs;
- R_n is the vertical refraction; and
- E_n is the angular elevation of the source above the horizon.

The right ascension of the source was determined from the time of transit. In practise it was necessary to conduct the measurements with two different aerial spacings to remove the ambiguity between which minimum of the interference pattern was related to the transit of the source. The averages of twelve minima either side of the central minimum were used to calculate the declination from a single observing run. The minima were used because the positions of the maxima are difficult to define because of atmospheric scintillations. This is clearly illustrated in Figure 138 where the second and third maxima from the left show scintillations. Mills and Thomas paid careful attention to correcting and documenting all of the different types of errors that would impact the position estimate. For example they allowed for a more accurate estimate of the speed of light in the atmosphere for the given conditions (2.9969×10^{10} cm/second), as using the standard value of 3.00×10^{10} cm/second would yield a 3 arc minute error in the declination. Figure 138 shows a typical record of the source transiting the interferometer beams and producing the interference pattern.

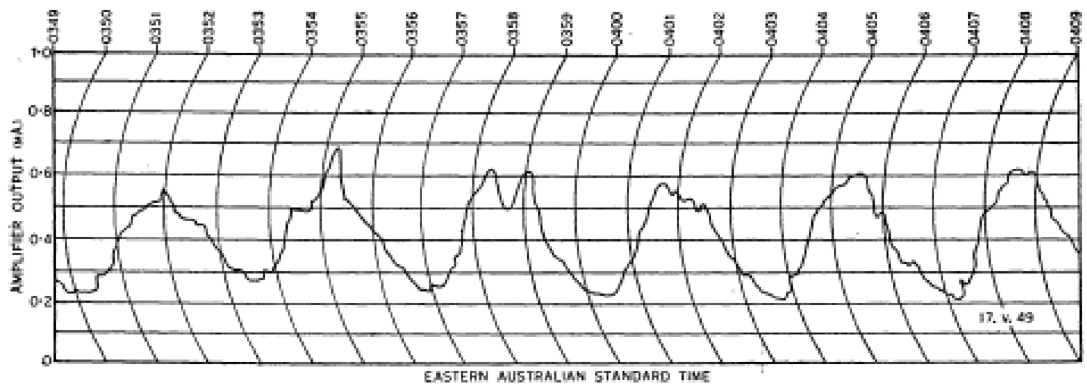


Figure 138: A typical record of Cygnus A source transiting the interferometer beams (after Mills and Thomas, 1951: 160).

After some months of observations the following position estimate was given:

R.A. 19 hr. 57 min. 37 sec.

Dec. 40° 34'

with a probable error of 6 seconds in Right Ascension and 3 minutes in Declination. In private communication with Rudolf Minkowski of Mount Wilson Observatory, Mills identified a 15th magnitude nebula at a distance of 10^7 parsec as being within the positional error box, although its position quoted in the paper was sightly inaccurate and was later corrected by Baade in a *personal communication* (see Mills and Thomas, 1951: 461n). It was one of the brightest galaxies in a cluster of galaxies, however nothing else appeared to distinguish this particular galaxy as the source of such strong radio emission. Minkowski wrote to Mills advising that he did not think it was permissible to identify the source with one of the faint extragalactic nebulae and therefore a more accurate position estimate was needed to unambiguously distinguish between the other faint nebulae (see Baade and Minkowski, 1954). As it transpired the faint galaxy that was the subject of the discussion turned out to be the source of the extraordinary strong radio emission when a more accurate position was ultimately determined by the Cambridge group (Smith, 1951).

This position was used by Baade and Minkowski (1954) to unambiguously identify the source galaxy. The final photographically-determined position was:

R.A. 19 hr. 57 min. 44.49 sec.

Dec. 40^{o} 35' 46.3"

Figure 139 shows a modern optical image of Cygnus A with a 0.05 degree field of view.

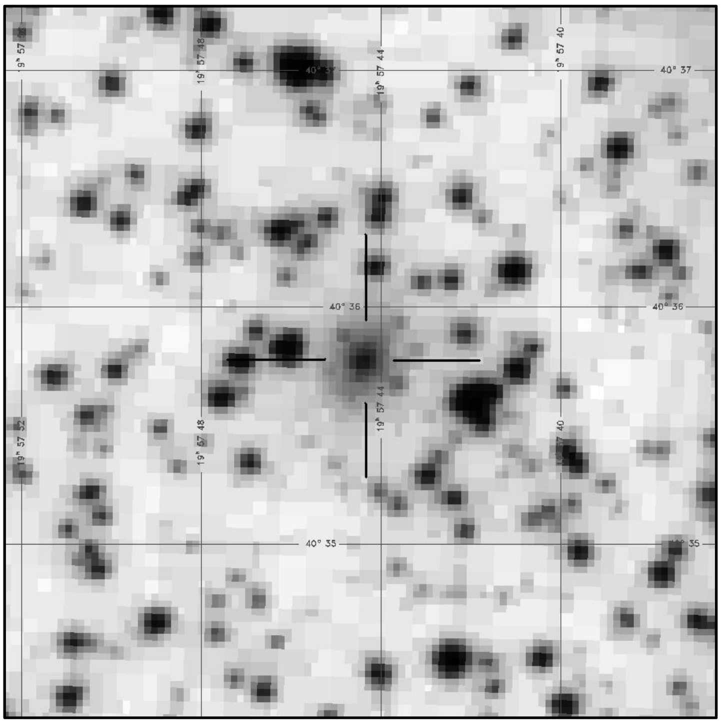


Figure 139: Optical Image of Cygnus A - 3 arcmin FoV (courtesy Digitized Sky Survey Lasker et al., 1990)

For comparison, Figure 140 shows the image plate used by Mills and Thomas in the original attempted identification. The actual position of Cygnus A has been added to the image, marked by the cross-hair, and is 7.49 arc seconds in right ascension and 1' 46.3" in declination from the position estimated by Mills and Thomas.

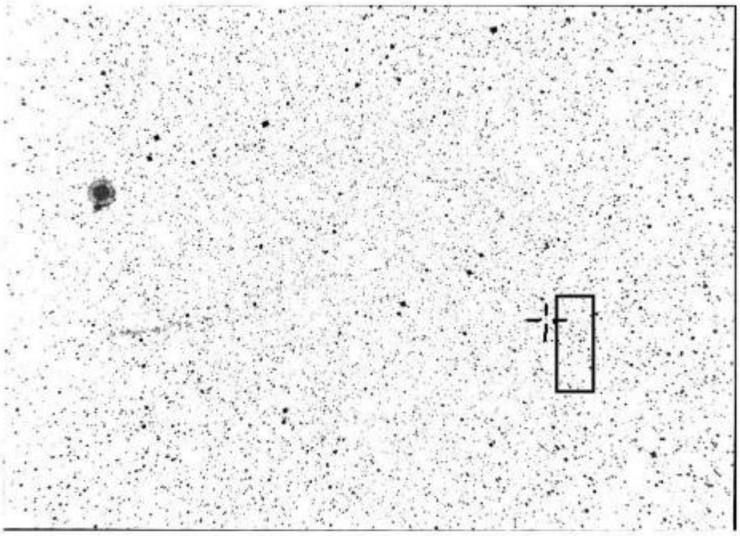


Figure 140: The original image plate (colour inverted) with the position estimate rectangle shown together with the actual position of Cygnus A marked by the cross hair (after Mills and Thomas, 1951: Plate 1A).

In their published paper Mills and Thomas (1951) concluded that it was unlikely that the source of the emission was the suspect galaxy; instead they concluded that the source was most likely located in some nearby faint star of abnormal properties. As no proper motion of the source was detected, they concluded that the source must be at a distance at least forty times the radius of Pluto's orbit, and they therefore also ruled out suggestions that the discrete sources of radio emission were associated with nearby comets (Menzel, 1950).

Polarisation measurement of Cygnus A was also attempted, but no change in the interference pattern could be detected while switching between the horizontal and vertical elements of the Yagi antennas. This indicated that if there was any polarisation of the source radiation it was less than 3%.

Mills and Thomas also undertook a detailed analysis of the source fluctuations observed. Figure 141 shows examples of the 'fast' and 'slow' fluctuations as well as an example of the correlation between signals received on aerials spaced 300 metres apart.

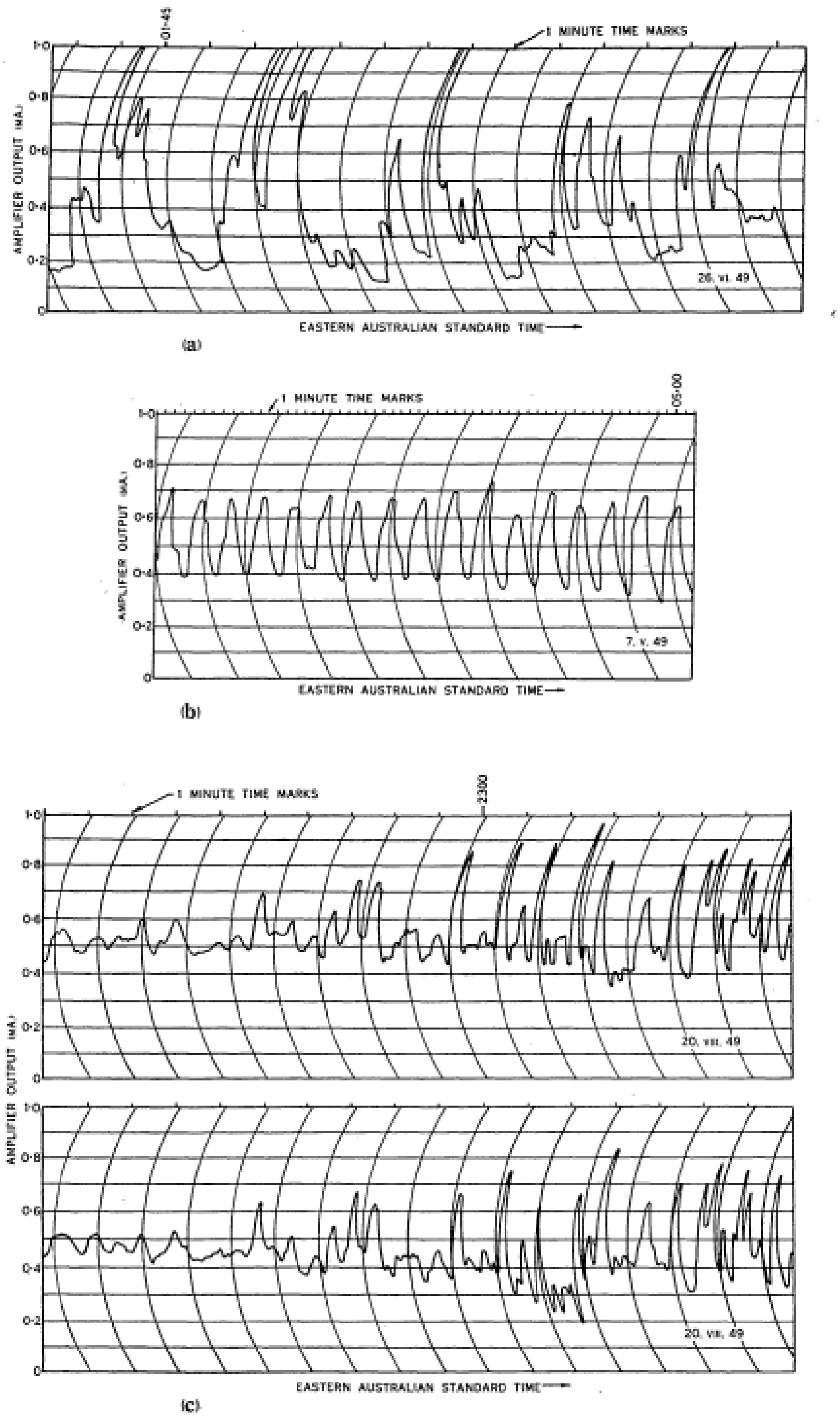


Figure 141: Examples of fluctuations observed in the emissions from Cygnus A. The top chart shows an example of the 'fast' fluctuations. The middle chart shows an example of the 'slow' fluctuations, and the bottom two charts show the correlation of signals between to aerials spaced 300 metres apart (after Mills and Thomas, 1951: 166).

Indices were calculated for the different fluctuation types and compared with the available geophysical data to look for possible correlations. The 'fast' fluctuation index was calculated by measuring the maximum and minimum intensities within each aerial lobe and hence calculating the ratio of the difference to their mean value. This was similar to the method used by Stanley and Slee in their investigations of the fluctuations (Stanley and Slee, 1950: 245). The 'slow' fluctuation index was a measure of the scatter of the average intensity of individual lobes from the mean level of all lobes in an observing period. A further 'deviation' index was calculated as the scatter of the lobe-minima transit times over a period of one hour. Using these indices a direct correlation was found between the fast fluctuations and ionospheric F-region activity. The correlations between the three indices were also examined and there was sufficient correlation to indicate a common origin of the fluctuations. Upon comparing the signals received at the two aerials spaced 300 metres apart it was found that the two records were similar, but not perfectly correlated. This indicated that the cause of the fluctuations had to be much larger than 300 metres. Records were compared with measurements at Dover Heights (~30km distant) and these showed almost no correlation. This suggested the source must be greater than 0.3 km, but less than 30 km in size. Based on this evidence Mills and Thomas concluded that the source of the fluctuations was irregularities from ~5 to 100 km across in the F-region of the ionosphere.

The observations of the Cygnus A source were the last that Mills made at Potts Hill until he returned in 1953 to test the prototype for the Mills Cross prior to its full-scale construction at the Fleurs field station. The experience Mills gained in using the swept-lobe interferometer configured in its static lobe mode whet his appetite for further source investigations. The low frequency (97 MHz) of the observations presented issues for accurate position estimation and Mills determined that investigations at higher frequencies should be carried out and also with longer baselines. He decided to build a dedicated instrument for these investigations rather than relying on borrowing observing time on the solar instruments. He was also concerned by the increasing radio interference at the Potts Hill site (Mills, 1984: 149) and so he determined to build his new interferometer at a new site at Badgerys Creek, a CSIRO cattle research station some 30 km to the west of Potts Hill. In 1952 he published an updated and refined position for Cygnus A as part of an investigation of the positions of six discrete sources (Mills, 1952b). In the intervening time since his first investigation he had returned to the idea that the original faint nebula he had observed was in fact the source. Unfortunately the position uncertainty was still roughly twice as large as Smith's (1951) claimed ±1 second error and therefore the credit would go to Smith. Figure 142 shows Mills' updated position estimate for Cygnus A, that now included the position of the faint extra-galactic nebula. This should be compared to the original estimate given in Figure 140.

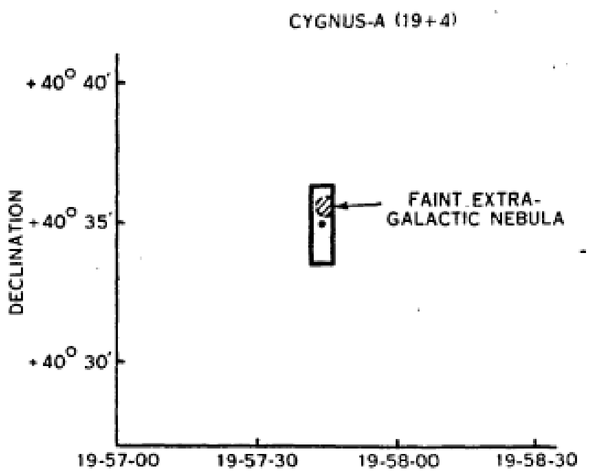


Figure 142: Position estimate for Cygnus-A with position of faint extra-galactic nebula shown (Mills, 1952b: 460).

Figure 143 shows a plot of the Mills and Thomas's original position estimate, Mills' later position and that of Smith (1951), together with the identified galaxy position. There was some confusion in the original galaxy position used by Mills and Thomas (marked B in Figure 143) as it was in error and hence fell within their original error estimates, but the actual nebulae was in fact just outside of this tolerance (marked C in Figure 143). Note the close proximity of Smith's position (marked D in Figure 143) and Mills' updated position (Marked E in Figure 143).

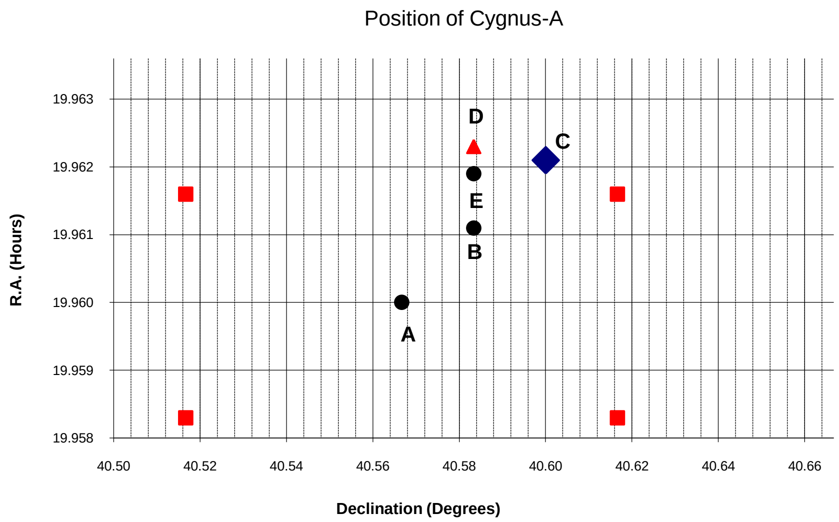


Figure 143: Plot of Position (1950) estimates for Cygnus A. (A) = Mills and Thomas (1951) radio position. (B) = The optical position of the nebulae (in error) suggested by Mills in letter to Minkowski. (C) = actual position of nebulae. (D) = Smith (1951) radio position. (E) = Mills (1951) revised position. The square markers indicate the error estimate on Mills' and Thomas' (1951) radio position.

The next investigation at Potts Hill of the Cygnus source was by Piddington and Minnett as part of a broader investigation they were making at 1,210 and 3,000 MHz using the ex-Georges Height 16-ft × 18-ft

Paraboloid (Piddington and Minnett, 1952). This instrument's primary role had been solar investigations, but like Mills and Thomas, Piddington and Minnett were able to borrow the instrument and to use it for cosmic source investigations. Originally Piddington and Minnett commenced observations at Dover Heights (Christiansen, 1950a), but soon shifted their operations to Potts Hill when the opportunity arose to use the 16-ft × 18-ft Paraboloid.

The resolution of the 16-ft × 18-ft Paraboloid was not sufficient to be useful for precise positional observations. Rather, the purpose of the observations had been to understand the broader disposition of sources at higher frequencies at 1,210 and 3,000 MHz. Piddington and Minnett noted the detection of a new discrete, but diffuse source near Cygnus A which they designated Cygnus X. They claimed in their published paper that it may be the first 'radio nebula' to be recognised. Due to the limited sensitivity of the equipment used at 3,000 MHz (the smaller 68-in parabola), Piddington and Minnett were unable to detect either of the Cygnus sources. Therefore they could only establish an upper limit for the flux density at 3,000MHz. Figure 3 shows an example of the records of both the Cygnus A and Cygnus X sources during observing runs at 1,210 MHz for three different declinations.

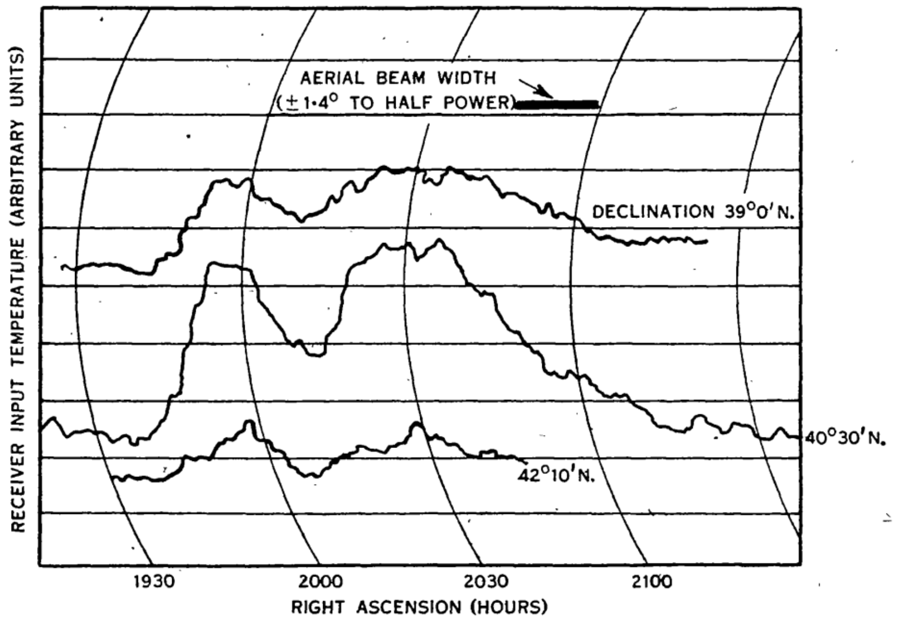


Figure 144: Example of 1,210 MHz records of Cygnus A and Cygnus X for three different declinations (after Piddington and Minnett, 1952: 18).

By making a number of observations from declinations 36° to 47° north, they were able to construct a set of intensity contours, and given the characteristic of the aerial beam, derive the flux density of the sources as shown in lower half of Figure 145. The flux density (S) is given by:

$$S = \frac{8\pi}{G}\frac{kT_a}{\lambda^2} \quad (9)$$

where

G is the power gain of the aerial compared with an isotropic radiator;

T_a is the aerial temperature;

k is Boltzmann's constant; and

λ is the wavelength.

The estimated minimum flux density that could be detected using the 16-ft×18-ft Paraboloid operating at 1,210 MHz was approximately 10^{-24}W/m^{-2} Hz^{-1} (100 Jy). For the 68-in Parabola operating at 3,000 MHz this was 10^{-23}W/m^{-2} Hz^{-1} (1,000 Jy).

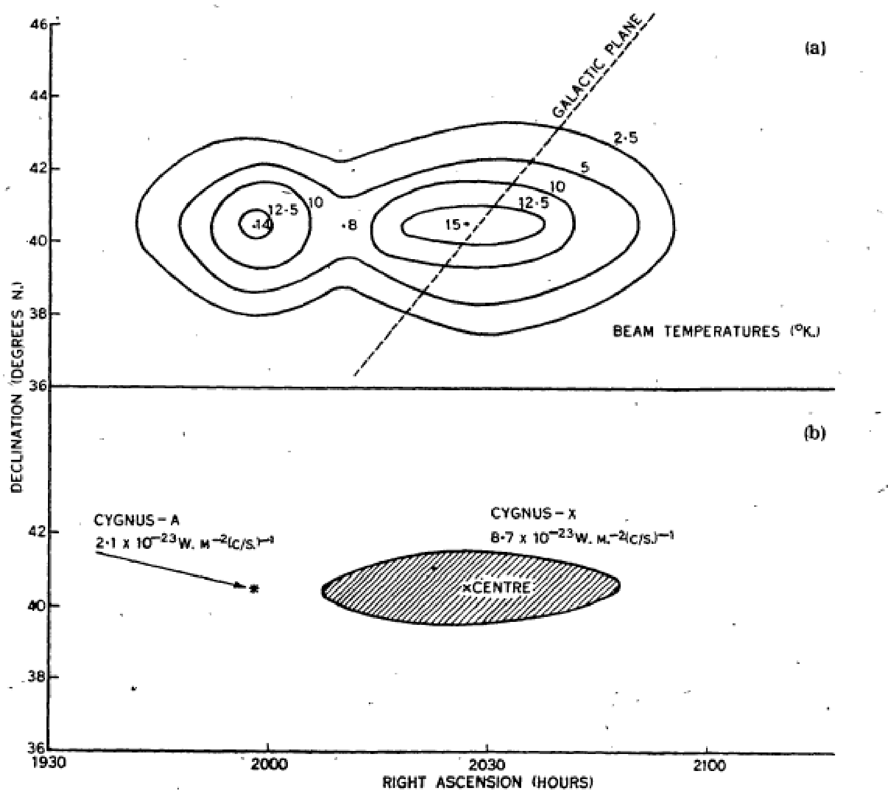


Figure 145: Upper graph shows contours of equal aerial beam temperature at 1,210 MHz. Lower chart shows the derived flux density of the sources Cygnus A and X (after Piddington and Minnett, 1952: 19).

The position estimates for the two sources were given as:

Cygnus-A:	R.A.	19 hr. 58 min. ±2 min.	Dec.	40° 30' ±1°
Cygnus-X:	R.A.	20 hr. 27 min. ±3 min.	Dec.	40° 30' ±1°

Given the large error tolerance, the position of Cygnus A was in general agreement with earlier estimates. Piddington and Minnett noted that the proximity of the large diffuse source to the discrete source may be the reason for the position errors in earlier interferometry measurements due to source confusion. The size of the Cygnus X source was too large to cause an interference pattern at the spacing used and hence it would have remained undetected. However, it may have contributed unseen confusion to the discrete source, particularly in right ascension.

Going back through the published observations of Cygnus A shows that the Cygnus X source did not appear in the 64 MHz observations of Hey, Parsons and Phillips (1946). However, a second source was present in Reber's (1948) observations at 460 MHz. Reber noted that the Cygnus source had two components with very different intensity distributions as shown in Figure 146. It is interesting to note that he also concluded that interferometry would be insensitive to the measurement of this diffuse source.

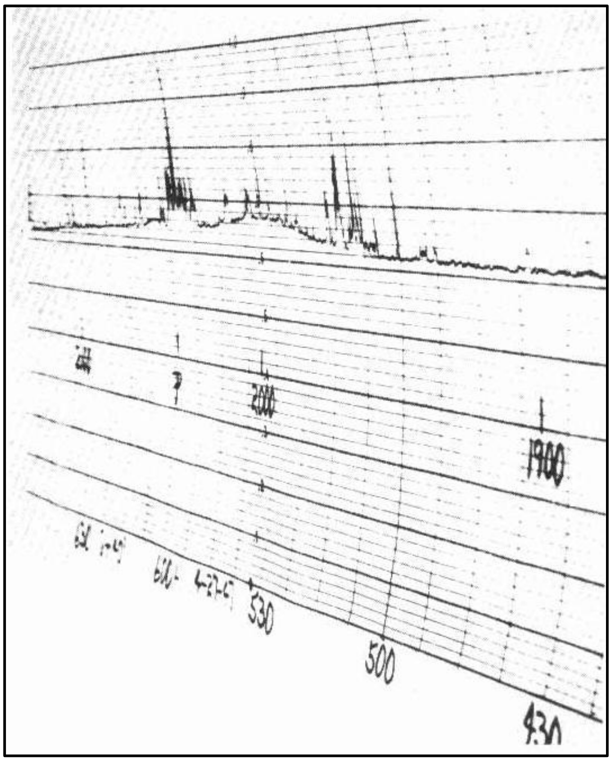


Figure 146: Reber's 480 MHz observation at a declination of +40º showing both Cygnus A (left) and the extended Cygnus X source (after Reber, 1948: Figure 5).

Bolton and Westfold (1950b) interpreted the double source detected by Reber as being due to the general galactic background radiation as deduced from their Dover Heights sea-interferometer measurements shown in Figure 147. They concluded that rather than there being a second source, Reber had detected the extended background galactic radiation.

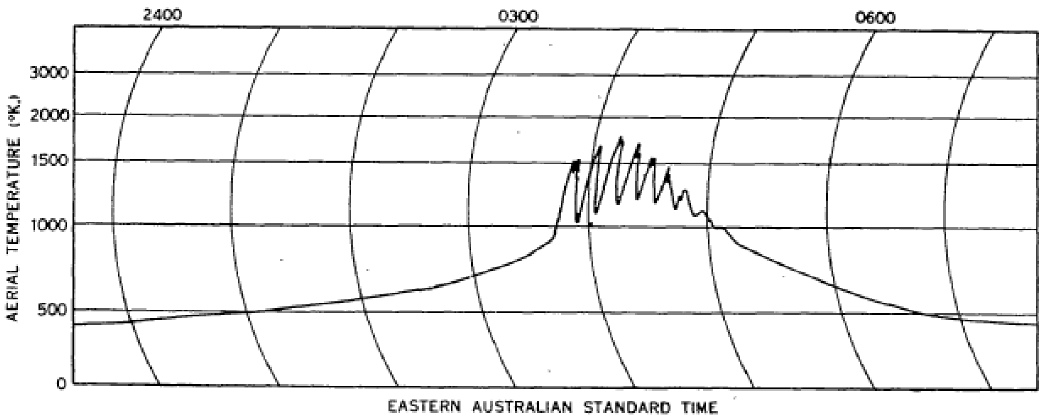


Figure 147: The Cygnus source interference pattern from the Dover Heights 100 MHz sea-interferometer. The record was interpreted as showing an interference pattern from the discrete source in Cygnus superimposed on the local diffuse maximum in galactic noise (after Bolton and Westfold, 1950a: 24).

Piddington and Minnett's observations were consistent with those of Reber with the only exception being that the orientation of the extended source that Reber observed (Figure 148) appeared to be perpendicular to that observed by Piddington and Minnett. No explanation for this discrepancy was proposed other than noting the source was near the limit of Reber's survey.

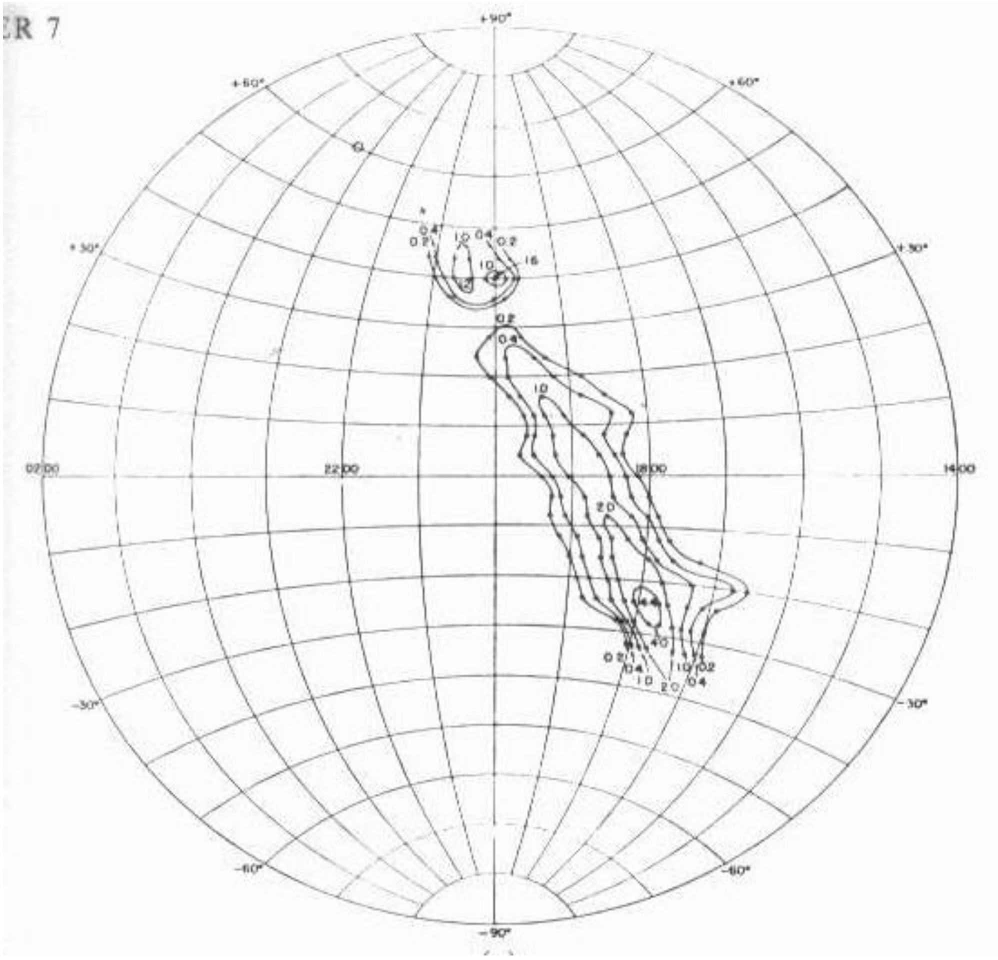


Figure 148: Reber's equatorial chart showing Cygnus A and X (top of chart). The orientation of the extended source of Cygnus X is perpendicular to that observed by Piddington and Minnett (after Reber, 1948: Figure 3).

By drawing on the past observations over a range of frequencies, Piddington and Minnett were able to examine the spectra of the two sources. These spectra were then compared with the spectrum of the general galactic background radiation. Using this comparison it was possible to show that it was unlikely that Cygnus X was part of the extended background. Rather, it appeared that Cygnus X was a separate extended source with a spectrum consistent with thermal radiation from a cloud of ionised gas. The comparison of spectra is shown in Figure 149.

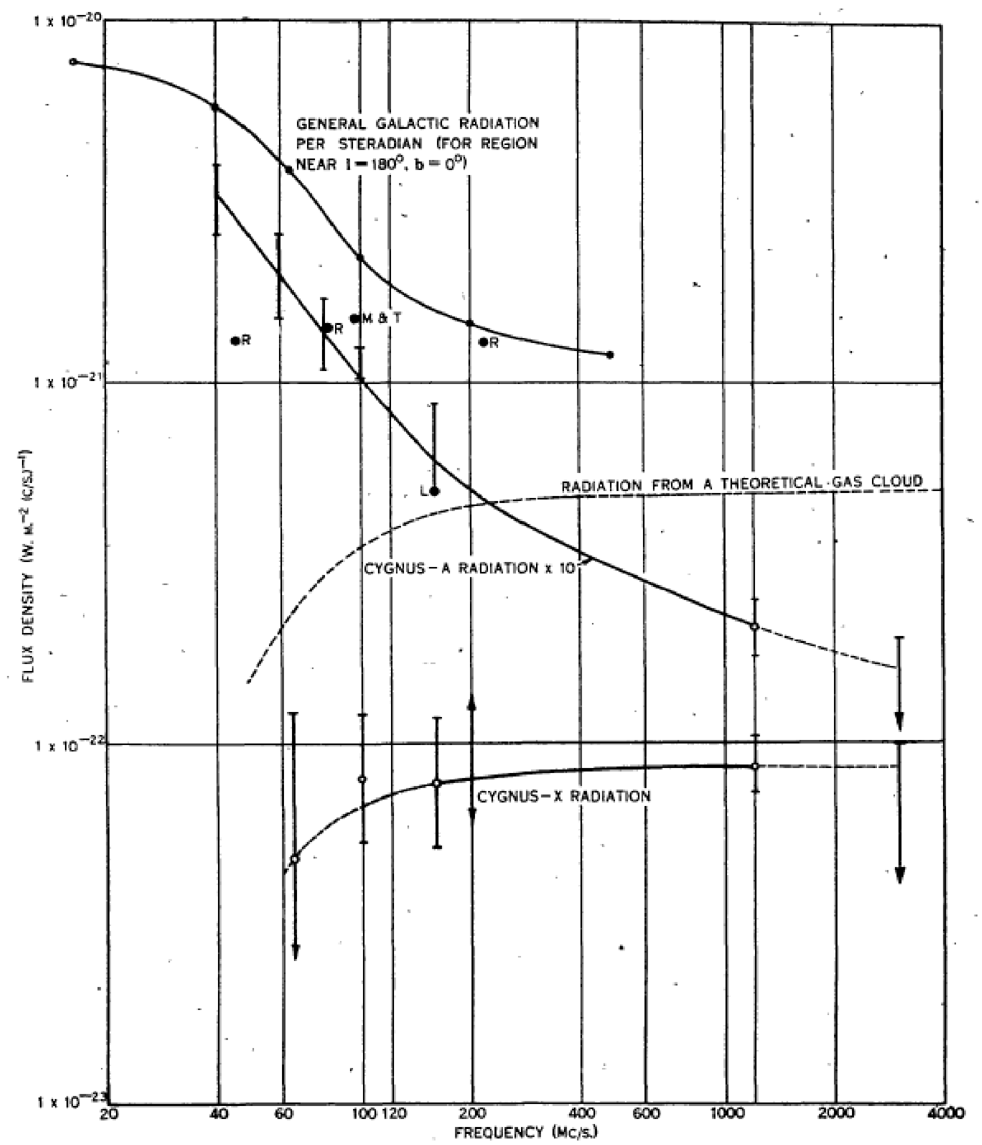


Figure 149: The radio spectra of Cygnus A and Cygnus X with comparison spectrums of the general galactic radiation and radiation from a theoretical gas cloud. Note that the value of flux densities for Cygnus A have been multiplied by 10 to avoid overlapping the curves (after Piddington and Minnett, 1952: 22).

The theoretical model of the gas cloud was based on a number of assumptions. The average brightness temperature (T_b) of a diffuse source is given by:

$$T_b = \frac{S\lambda^2}{2k\Omega} \qquad (10)$$

where

S is the observed flux density;

λ is the wavelength;

k is Boltzmann's constant; and

Ω is the solid angle subtended.

Based on Figure 145, the solid angle subtended is approximately 5×10^{-3} steradians and would give a brightness temperature of 40 K at 1,210 MHz using the above formula. The spectrum curve for Cygnus-X is consistent with thermal radiation from ionised gas with an average optical depth (τ) of 3.4×10^{-3} at 1,210 MHz. The electron temperature (T_e) of the gas is related to the brightness temperature (T_b) by the following equation:

$$T_b = T_e(1 - e^{-\tau}) \tag{11}$$

Using the assumed optical depth and the estimated brightness temperature, an electron temperature of 1.2×10^4 K is the result. This temperature was in general agreement with values determined by optical observation for HII regions at the time (e.g. Stromgren, 1948).

Piddington and Minnett proposed a tentative identification of the Cygnus X source with the bright galactic nebulae surrounding the star γ Cygni. Figure 150 shows a star chart of the region with HII regions surrounding γ Cygni. It also shows the relationship to Cygnus A.

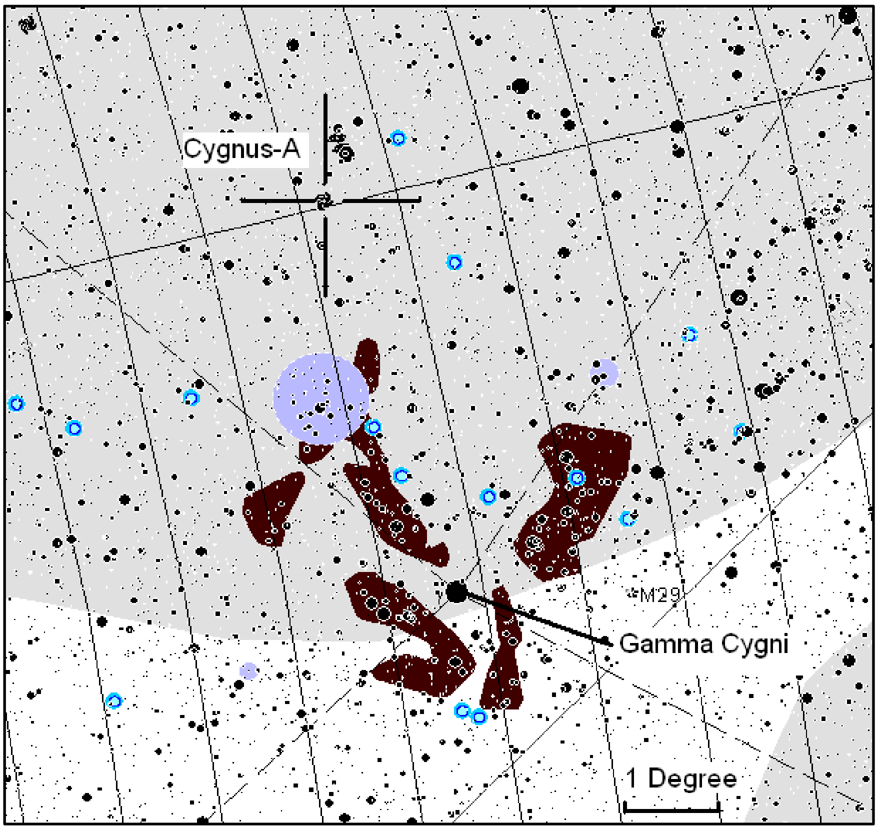


Figure 150: Star chart showing HII regions around γ Cygni. The near vertical grid lines are 1 degree declination lines. The diagonal line in the bottom right indicates the Galactic Plane. Cygnus A is marked by the cross hair (Courtesy of TheSky © Astronomy Software 1984-1998).

Piddington and Minnett noted that γ Cygni, being a spectral type F8p, was unlikely to be the sole source of excitation of the HII region and that other obscured O and B spectral class stars may be responsible. We know today that the Cygnus X region is one of the largest star-forming regions in our Galaxy with many OB stars in a coherent molecular cloud that is at a distance of ~1.7 kpc (Schneider et al., 2006).

Piddington and Minnett's program of cosmic observation had begun in 1948 with some preliminary observations of the region of the Galactic Centre using a 10-ft Parabola at 1,210 MHz. Later the opportunity arose to use the larger 16-ft × 18 ft Paraboloid and the 68-in Parabola. They used these for the Cygnus observations (discussed above) and for observations of the Galactic Centre, Taurus A (the Crab Nebula), Centaurus A, the Moon, M31 (the Andromeda Nebula and NGC 7293 (a large planetary nebula). The results of these observations were published in the *Australian Journal of Scientific Research* (Piddington and Minnett, 1951a). This was an important historical paper because it included the discovery of the discrete radio source at the Galactic centre now known as Sagittarius A. As discussed by Goss and McGee (1996) and Orchiston and Slee (2002) there are many misconceptions related to the discovery of Sagittarius A. Credit is often incorrectly given (e.g. Kerr, 1983: 297) to McGee and Bolton, who in a paper published in the more widely-read journal *Nature* (1954), drew attention to the relationship of Sagittarius A to the Galactic Nucleus.

Since Jansky's original discovery (1933), the coincidence of the maximum level of radio emission with the centre of our Galaxy had been noted. Examples of early surveys by Reber (1944, 1948), Hey, Parsons and Phillips (1946), and Bolton and Westfold (1950a,b) all showed the maximum originating near the position R.A. 17 hr. 50 min., 27°S. Figure 151 shows a summary of these early surveys converted to common projections. Apart from the survey by Hey, Parson and Phillips, which shows an unexplained complex structure, there is similarly between the surveys at the different frequencies.

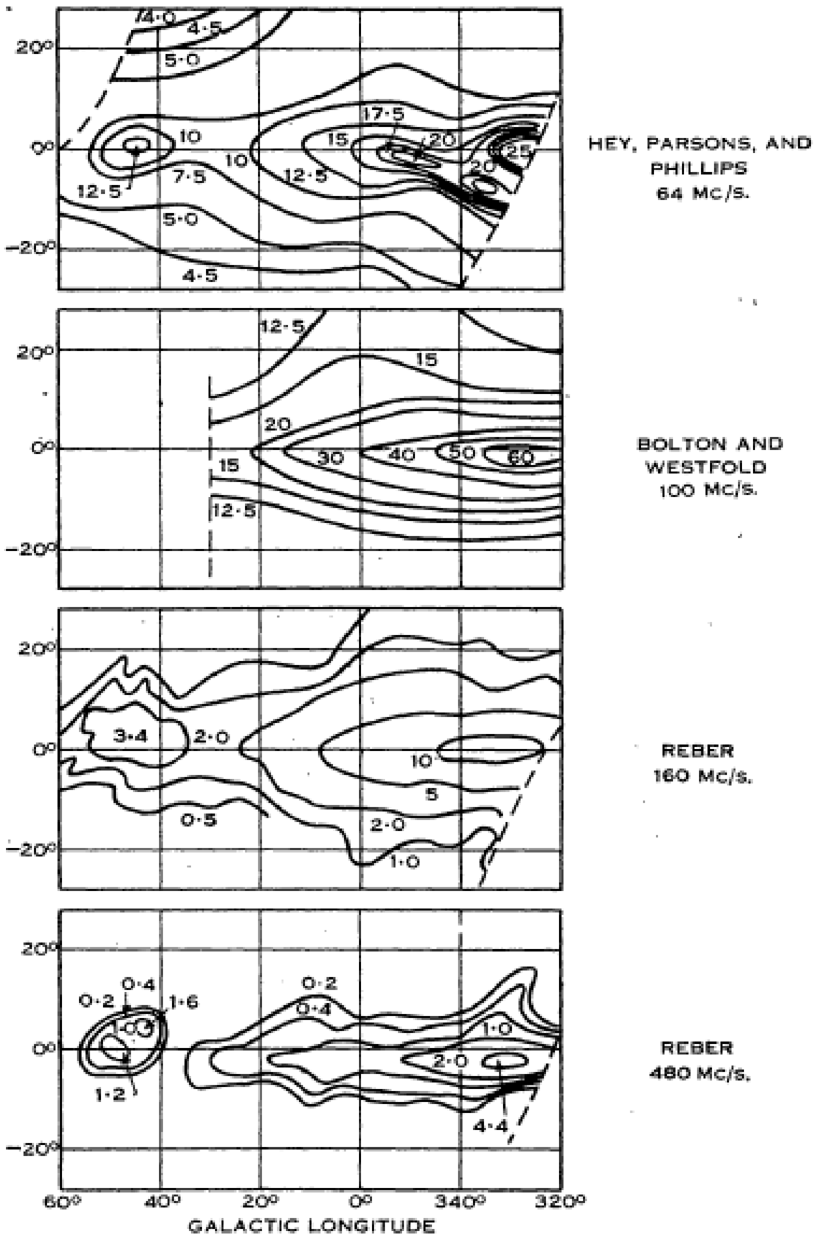


Figure 151: Examples of earlier surveys around the Galactic Centre (Bolton and Westfold, 1950b: 255).

Piddington and Minnett's survey at 1,210 MHz was made by taking a number of drift scans at different declinations spaced approximately 1 degree apart. Figure 152 shows an example of a single scan where Sagittarius A is very apparent.

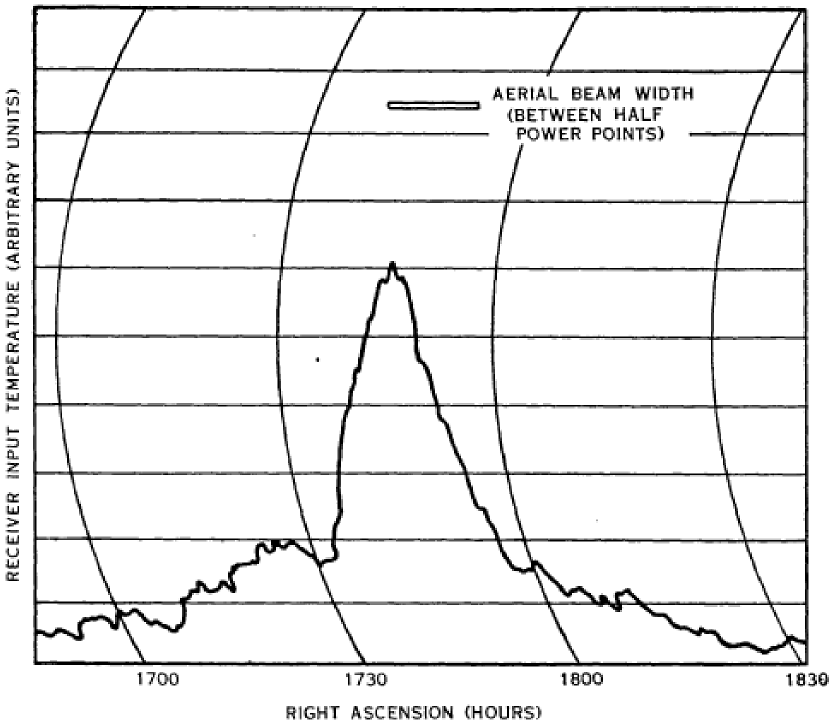


Figure 152: Example of a drift scan at 1,210 MHz across the Galactic Plane and showing the discrete source Sagittarius A. The beam width was ±1.4°. Note that the original caption published with this figure incorrectly referred to the beam width of the 68-in Parabola that was used for the 3,000 MHz observations (Piddington and Minnett, 1951a: 463).

Based on the continuous recording of aerial temperature during the drift scan, the records were reduced to a set of equal intensity contours as shown in Figure 153.

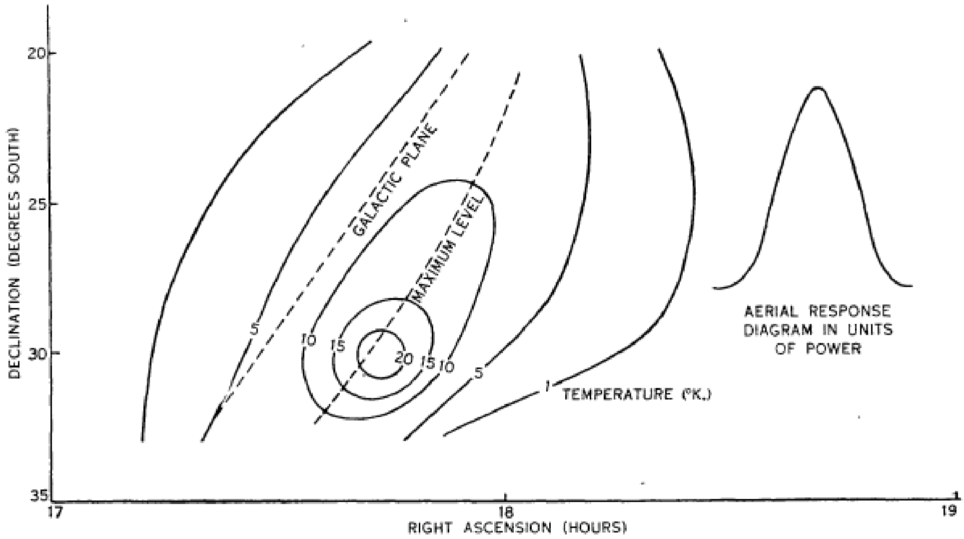


Figure 153: Aerial temperature contours at 1,210 MHz showing the discrete source Sagittarius A (Piddington and Minnett, 1951a: 465).

Based on the contour map, Piddington and Minnett announced:

"An examination of these contours reveals several points of interest. Firstly, the sharp maximum at R.A. 17 hr 44 min., Dec 30°S. appears to be a new, and remarkably powerful, discrete source. Secondly, the contours provide another determination of the position of the galactic centre. Finally the results allow a determination to be made of the excess radiation from near the galactic centre (above an unknown, but probably low, level away from the galactic plane)." (Piddington and Minnett, 1951a: 465).

Although certainly not as clearly stated as the later papers by McGee and Bolton (1954) and McGee, Slee and Stanley (1955), Piddington and Minnett do make the association of the new source with the Galactic Centre. The minutes of the Radio Astronomy Committee of February 6, 1949 also reported the discovery of "a new discrete source" found in the region of the galactic centre (Christiansen, 1951b). It is interesting that it would take nearly three years after formal publication before this association was more closely examined and the exciting linkage to the Galactic Nucleus was more clearly established. The Dover Height 80-ft hole-in-the-ground parabola was able to achieve an angular resolution in the order of 1° at 400 MHz, and with a much more sensitive receiver, the position and angular size of Sagittarius A was defined with greater accuracy.

The 3,000 MHz equipment was operating at its limits and the combination of instrument noise and receiver drift made it difficult to obtain useful results. A beam swinging technique was adapted to improve sensitivity and Piddington and Minnett were able to estimate the excess brightness temperature near the Galactic Centre. They estimated this to be 2.6 K with a 20% uncertainty. At 1,210 MHz they estimated the brightness temperature to be 17 K with a 20% uncertainty.

With a beamwidth of 1.4° the accuracy of the position of the new discrete source was estimated to have an uncertainty of 2 minutes in R.A. and approximately 1° in Declination. From the transit time of the source through the aerial beam it was estimated that the source must be smaller than 1.5° in diameter. The calculated flux density for the source at 1,210 MHz was 2.6×10^{-23} $W.m^{-2}.Hz^{-1}$. Given the coincidence of the source with the Galactic Centre, Piddington and Minnett concluded that the source must be extremely powerful. Assuming a distance of 10^4 parsec the source radiation in the radio spectrum alone would be at least 100 times greater than the *total* power radiated by the Sun.

Piddington and Minnett also make reference to *personal communication* with Mills prior to publishing their results. Mills was conducting a source survey at 100 MHz at the Badgerys Creek field station using an interferometer with spacings of 270m and 60m (Mills, 1952b). They noted that Mills had also detected a source at about R.A. 17 hr. 50 min., Dec 28.5 °S. with a very approximate flux density of 3×10^{-23} $W.m^{-2}.Hz^{-1}$ (source 17-2B in Mills, 1952a: 286) and concluded that despite the position difference, this was very likely to be the same discrete source. No reference was made to the source size. The interferometer measurement indicated a source size of 35 arc minutes. In the final published catalogue Mills listed the flux density as being one order of magnitude lower than had first been suggested. Observations were also obtained from Shain who was observing at 18.3 MHz at the Hornsby Valley field station and these gave a flux density measure of 3×10^{-24} $W.m^{-2}.Hz^{-1}$ with an uncertainty of not worse than 50 percent. Using these data Piddington and Minnett were able to obtain a preliminary spectrum of the source. Figure 154 shows this spectrum, together with an example of two other known discrete sources, Taurus A and Centaurus A.

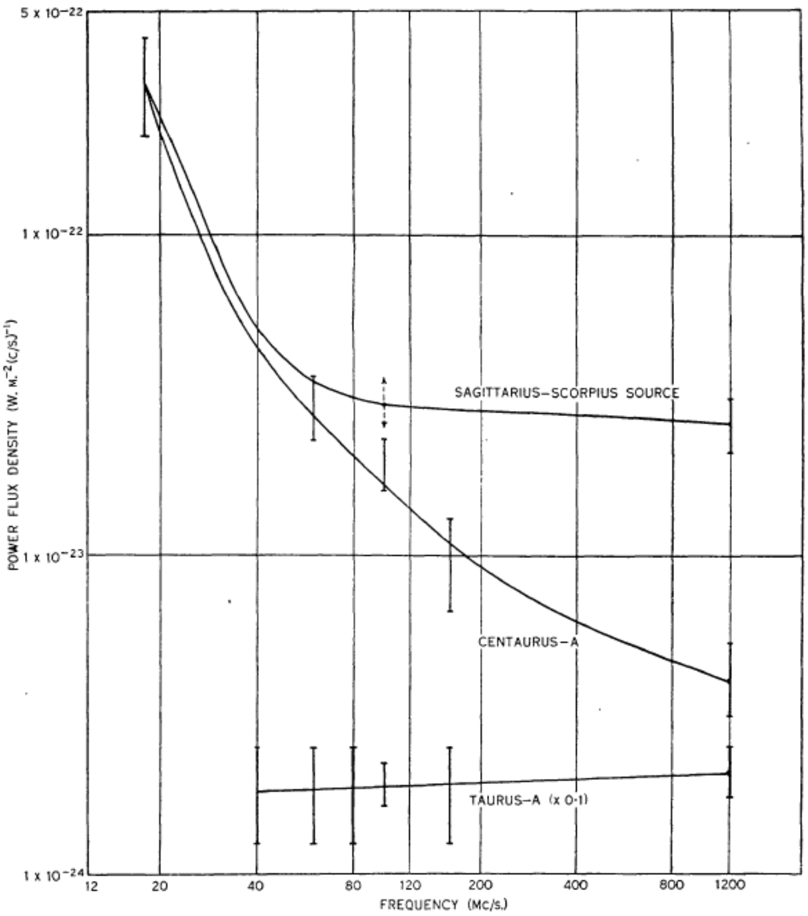


Figure 154: The radio spectra for the discrete sources Sagittarius A, Centaurus A and Taurus A. The flux density scale for Taurus A has been changed by a factor of 10 to separate the curves (after Piddington and Minnett, 1951a: 468).

Although noting that a spectrum based on three data points was tentative, Piddington and Minnett suggested the spectrum resembled that of an optically thin, thermally radiating gas, but also had some characteristics similar to that of the Taurus-A spectrum. Although Alfvén and Herlofson's paper (1950) suggesting synchrotron radiation as the possible mechanism for extragalactic radio emission had been published at this time, it was not until further work on Taurus-A and the verification of polarised light by Dombrovsky (1954) that this emission mechanism gained more general acceptance. Piddington and Minnett noted from their observations of Taurus A that when the electron temperature and density were calculated based on the radio observations there was a very large discrepancy compared to the optical data if thermal radiation was assumed. This suggested a possible non-thermal origin, but the spectrum could not be reconciled with the other non-thermal mechanisms known at the time.

Piddington and Minnett (1951a) investigated three other known discrete sources. However, only Centaurus A could be detected at 1,210 MHz with a flux density of 4.1×10^{-24} $W.m^{-2}.Hz^{-1}$ and an uncertainty of 20 percent. The two other sources investigated, Virgo A and Hercules A, could not be detected and therefore it was assumed their flux densities were less than 1×10^{-24} W.m^{-2}.Hz^{-1}. No attempt was made to observe these sources at 3,000 MHz.

Attempts were also made to detect M31 and the large planetary nebula NGC 7293 (ibid.). Neither of these sources could be detected at 1,210 or 3,000 MHz. Subsequent to the observations, but prior to publication, Hanbury-Brown and Hazard (1950) detected radiation from M31 at 158 MHz with an observed flux density of 4×10^{-24} W.m^{-2}.Hz^{-1}. Piddington and Minnett noted that if the spectrum of M31 was similar to our own Galaxy then the flux density at 1,210 MHz would be 2×10^{-24} W.m^{-2}.Hz^{-1}, which was below the detection threshold of the equipment they were using.

As a form of calibration test, Piddington and Minnett also observed the Moon and compared these observations to their earlier observations at 24,000 MHz (1949a). The apparent disk temperatures were broadly in-line, although slightly higher, than those obtained at the higher frequency.

In January 1955, as part of a joint project between the URSI and Commission 40 of the I.A.U., a catalogue of reliably-known discrete radio sources was published (Pawsey, 1955a). The catalogue was prepared in early 1954 based on surveys that had been published up to that time. This catalogue provides a good guide to the state of investigation of discrete sources in this period. A total of 38 sources was listed in the catalogue. Of these, only 8 sources were definitively established, with accurate positions determined by a number of independent observers and optical identifications obtained. The remaining 30 sources were included in the catalogue on the basis that there was reasonable agreement of the source positions from at least two independent observations. Of these, 9 had reasonable identification candidates proposed. Included in this list were both Sagittarius A and Cygnus X. These sources had first been proposed by Piddington and Minnett based on their Potts Hill observations. Thus, using Pawsey's (1955a) review as an objective measure, as at 1954 five percent of all known discrete radio sources had been determined based on research at Potts Hill.

The 1,210 MHz cosmic survey work by Piddington and Minnett was to be the last major program of observations using the 16-ft × 18-ft Paraboloid. Having originally been designed as an experimental radar, it was far from ideal as a survey radio telescope. It suffered from sagging and distortion of the reflector surface and the multiple dipoles at the prime focus caused further losses in sensitivity (see Piddington and Trent, 1956b: 490n).

The construction of the 36-ft Transit Parabola for H-line survey work presented a new opportunity. Piddington and Trent modified the receiver design that had been used at 1,210 MHz on the 16-ft × 18-ft Paraboloid to operate at 600 MHz, and, together with a 6-ft Parabola operating as the reference aerial, they used the 36-ft Transit Parabola for a survey at 600 MHz covering the declination range 90ºS to 51ºN

(Piddington and Trent, 1956b). The reason for selecting 600 MHz was because surveys of the southern sky had already been conducted at 100 MHz (Bolton and Westfold, 1950a) and 200 MHz (Allen and Gum, 1950). Instruments used for both of these surveys had low resolution, namely beamwidths of 17° and 25° respectively. Bracewell and Roberts (1954) had shown that all detail within an aerial beam could not be subsequently recovered by either graphical or other processing techniques and therefore is lost. This meant that the plots of brightness distribution, particularly in the area of the Galactic Plane, could not be even approximately accurate in terms of source structures. Piddington and Trent determined therefore to conduct a much higher-resolution survey using a pencil-beam instrument. The 36-ft Transit Parabola operating at 600 MHz had a beamwidth of 3.3°.

The observations from the survey were reduced to a measure of aerial beam temperatures from which a contour plot of isophotes was produced. The aerial beam temperature was calculated by considering that two-thirds of the total energy received would be in the main beam of the aerial with the remainder in the side-lobes. Assuming that the main beam was placed on a source of a given temperature (T) and the side lobes were directed at zero temperature regions, the aerial temperature (T_a) was given by:

$$T_a = 2T / 3 \qquad (12)$$

Therefore, in the ideal case, the aerial beam temperature was 3/2 times the measured aerial temperature. In practice many other factors such as ground reflection and the background radiation within the side lobes complicated this calculation. However, for the beamwidth and frequencies involved these errors were likely to be less than 10 percent. For the 600 MHz survey Piddington and Trent multiplied the measured aerial temperature by a factor of 100/65 to obtain the aerial beam temperature.

The aerial temperature is not an absolute measure; rather it is a measure above a minimum background level. To obtain an estimate of the actual temperature it is necessary to determine the minimum background temperature at a given frequency. Piddington and Trent used the best available measurements from earlier surveys to construct the radio spectrum curve shown in Figure 155.

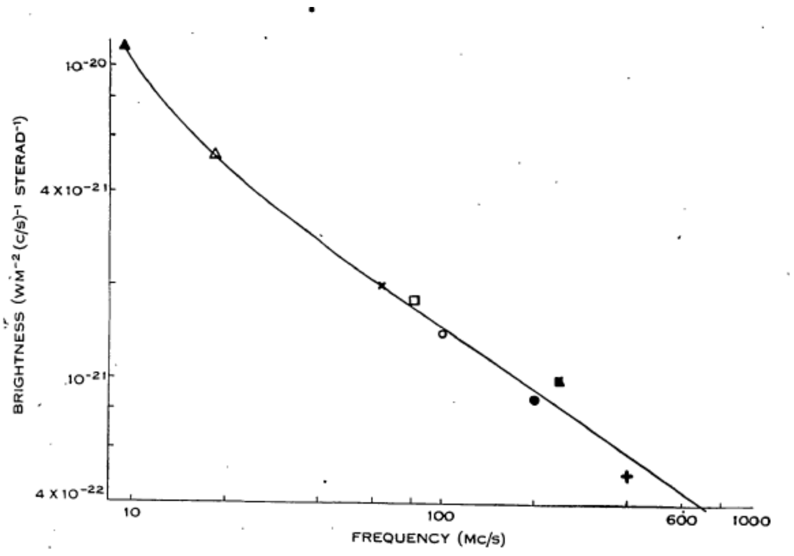


Fig. 2.—The observed cosmic radio spectrum from the coldest parts of the sky (near R.A. 09h 50m, Dec. +22° and R.A. 04h 30m, Dec. —37°) in units of brightness.

▲ Higgins and Shain (1954). △ Shain (1951). × Hey, Parsons, and Phillips (1948). □ Baldwin (1955). ○ Bolton and Westfold (1950). ● Piddington (1951), a theoretical estimate based on the survey of Allen and Gum (1950). ■ Kraus and Ko (1955). + McGee, Slee, and Stanley (1955).

Figure 155: Radio spectrum of coldest parts of the background sky based on prior surveys (after Piddington and Trent, 1956b).

By extrapolating this curve to 600 MHz an estimate of the background temperature could be obtained. From Figure 155 the brightness at 600 MHz was 4.5×10^{-22} W.m^{-2}.Hz^{-1} which corresponds to a brightness temperature of 4 ^{o}K. From their survey measurement they calculated the base level of the minimum background ranged from 4 to 8 ^{o}K, with an average value of 5.7 ^{o}K.

The results of the full survey are shown in Figure 156. The main features of the survey were the strong source Sagittarius-A which had been associated with the Galactic Centre, the two sources in Cygnus, Cygnus-A and Cygnus-X, Centaurus-A, and Taurus-A the Crab Nebula. There was also a string of sources on or near the galactic plane which Piddington and Trent proposed were likely to be related to thermally emitting HII regions. For comparison, Figure 157 shows a much later survey at 408 MHz (Haslam et al., 1982) for the equivalent region in Figure 157. The degree of detail in the 600 MHz survey is remarkable for its time, particularly given the receiver limitations in this era.

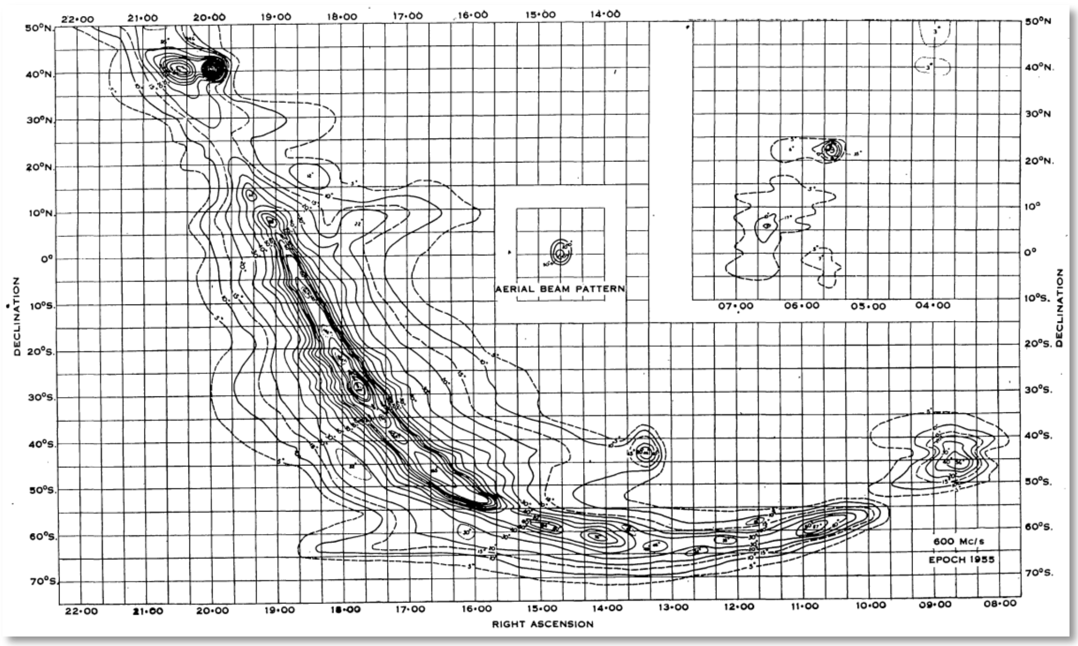


Figure 156**:** The 600 MHz survey showing contours based on aerial beam temperature (Piddington and Trent, 1956b).

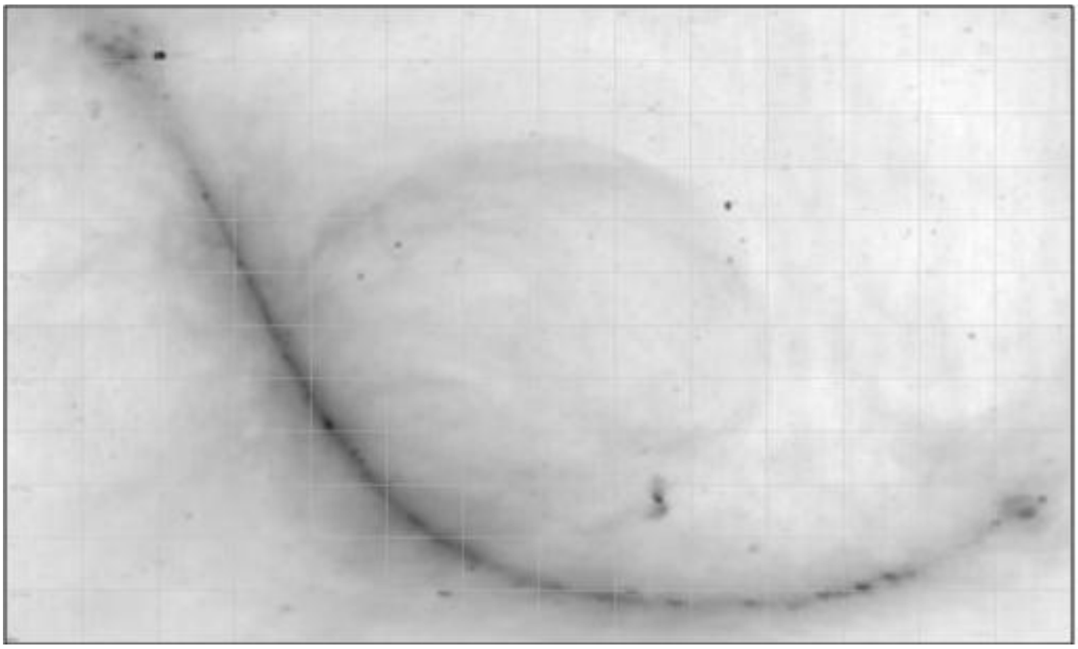


Figure 157: A more recent 408 MHz survey showing the equivalent region to the 600 MHz survey (after Haslam et al., 1982).

By the mid 1950's the synchrotron process as a source of galactic radio emission had become fairly well accepted (Piddington and Trent, 1956b: 489). Piddington and Trent observed that thermal emission from ionized hydrogen still remained a major component of the observed radiation, just as Piddington (1951) had earlier suggested. They proposed that the observations were consistent with a model of synchrotron emission constituting a single spheroidical system with a variable emission per unit volume that increased towards the Galactic Plane where thermal radiation was also concentrated. They concluded that the galactic concentration of thermal emission was consistent with the broad HII distribution of the Galaxy.

As part of the survey Piddington and Trent also noted that because of the higher frequency and narrow beam width, it was possible to make a useful re-determination of the Galactic Equator and also the position of the Sun above the Equator. Figure 158 shows the position of the ridge of maximum intensity of the radio emission plotted in galactic coordinates.

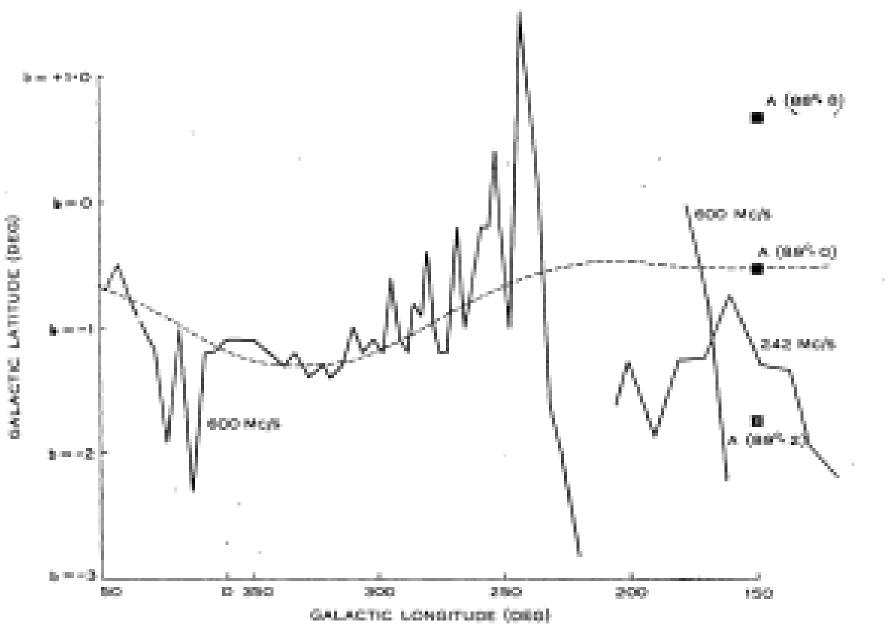


Figure 158: The position of the ridge of maximum radio emission at 600 MHz plotted in galactic coordinates. The dotted line represents a hypothetical galaxy model. 242 MHz observations near the Galactic Pole are also shown (after Piddington and Trent, 1956b: 491).

By assuming the Galaxy is circularly symmetrical with a diameter of 19,000 parsec and that the Sun is 1,600 parsecs from the outer edge, a theoretical curve of the Galactic Equator was determined. This is shown as the dotted line in Figure 158. The best fit was given by assuming a radio pole lying at b = 89.0° and l = 330°. Included in the plot are measurements at 242 MHz taken by Ko and Krauss of Ohio State University. These data favour a value of b = 89.1°. The corresponding position of the Sun above the Equator is 42 parsec, while the 242 MHz data give 56 parsec. Earlier calculations based on optical observations (van Tulder, 1942) had shown a smaller solar displacement of 13.5 parsecs, but that was in the same direction.

Piddington and Tent separately published a catalogue of 49 sources based on the 600 MHz survey (1956a). Of these sources, 31 appear to have been identified in previous radio surveys, with the remaining 18 being newly identified sources. Of these 18 sources, 12 were located within ±2° of the Galactic Plane. For 4 of the sources optical identifications were proposed, all of these being with HII regions. No optical associations were proposed for the remaining 14 radio sources. Figure 159 shows the variation of emission intensity by galactic longitude with the individual sources within a few degrees of the Galactic Plane individually marked. The numbers refer to the source numbers in the published catalogue.

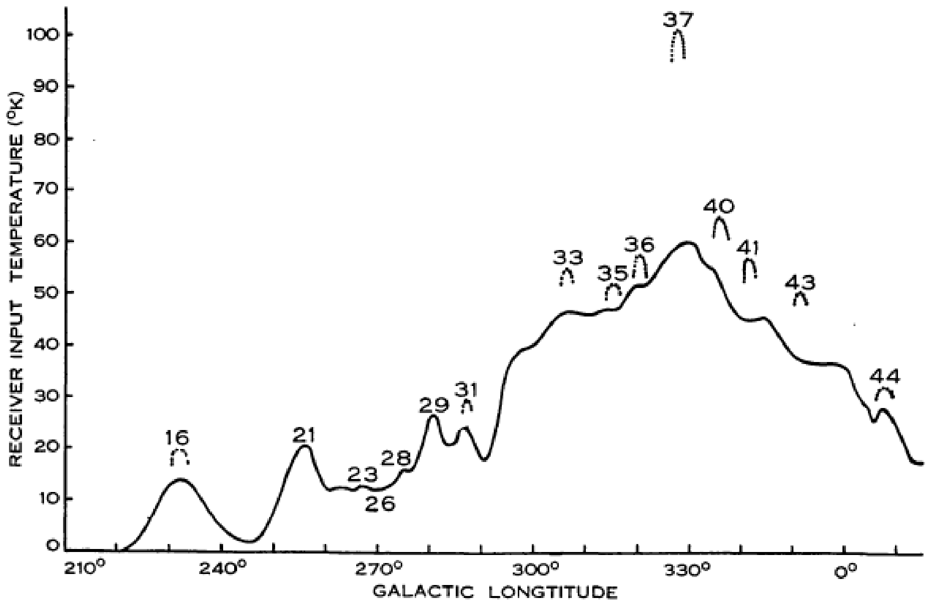


Figure 159: Variation of intensity at 600 MHz along the Galactic Plane. Individual sources, marked with their catalogue number are shown. Source 37 is Sagittarius A (after Piddington and Trent, 1956a: 81).

A key conclusion of the examination of the sources was that many of those lying close to the Galactic Plane rather than being discrete sources appeared to have more complex structures and were often more akin to local maxima. Earlier interferometer surveys assumed many of these sources were discrete. The interferometers were unable to detect extended sources and their position estimates were confusion affected, as appeared to be the case for the later Cambridge 2C survey (Mills and Slee, 1957).

With the 36-ft Transit Parabola no longer being used for the H-line survey, Hindman and Wade modified the H-line receiver to measure the general radio continuum at 1,400 MHz rather than H-line emission. They used the modified equipment to observe a number of sources, but only published their observations of the Eta Carinae Nebula (NGC 3372) and Centaurus A (NGC 5128) (Hindman and Wade, 1959).

Eta Carinae was targeted because little was known of its physical properties. It was also the only important galactic HII emission nebula that had not been covered by Westerhout's (1958) 1,390 MHz survey because it was located too far south to be visible from the Netherlands. A series of drift scans of the nebula were taken as illustrated in Figure 160. From these a set of contour diagrams of aerial temperature as a function of position was produced, as shown in Figure 161.

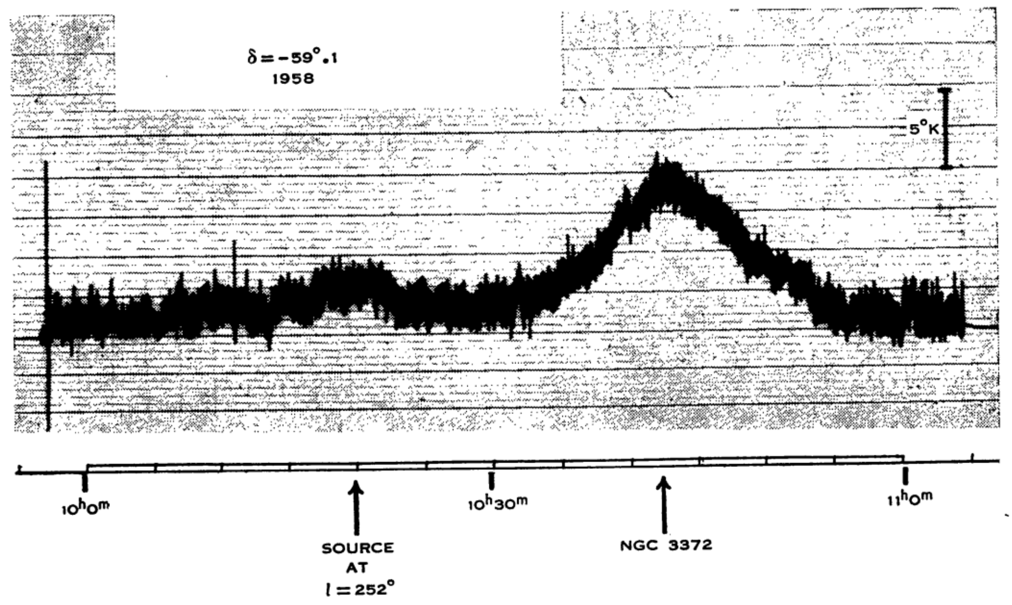


Figure 160: Example of a drift scan through the Eta Carinae Nebula (NGC 3372) (after Hindman and Wade, 1959: 262).

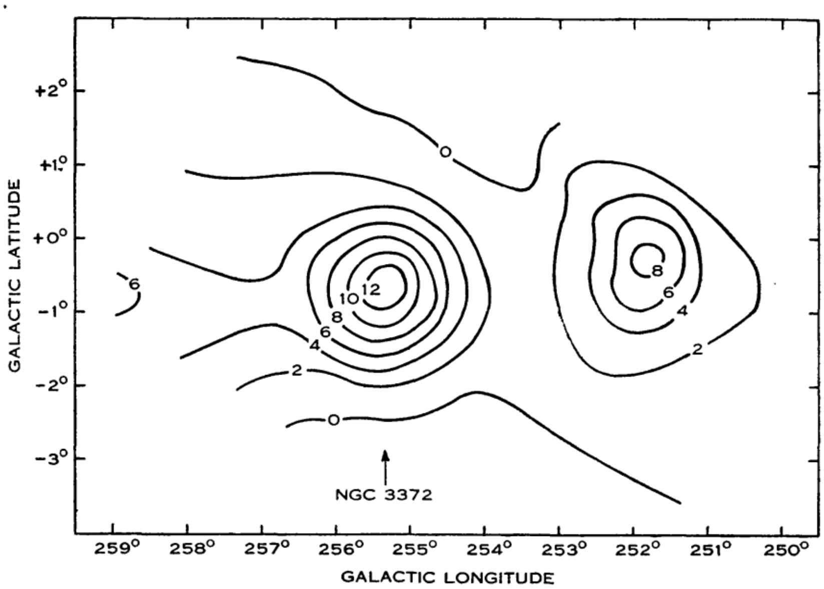


Figure 161: A map of aerial temperature at 1,400 MHz versus position showing the Eta Carinae Nebula (NGC 3372) (after Hindman and Wade, 1959: 263).

By correcting for the background galactic radiation and integrating over the contours, Hindman and Wade were able to determine a value of 5.82×10^{-24} Wm^{-2} Hz^{-1} for the flux density of the Eta Carinae Nebula, with a probable error of < 20%. They also noted that there appeared to be no large-scale asymmetry to the surface brightness distribution of the source and that the source appeared to be strongly concentrated towards its centre.

In a separate paper, Wade (1959a) examined a physical model of the Nebula based on the Potts Hill observations and also drawing on the flux density measurement at 85.5 MHz (Mills et al., 1956) and some unpublished optical measurements that had been made by Gum. Figure 162 shows the line along which Gum had measured the Hα surface brightness of the Nebula.

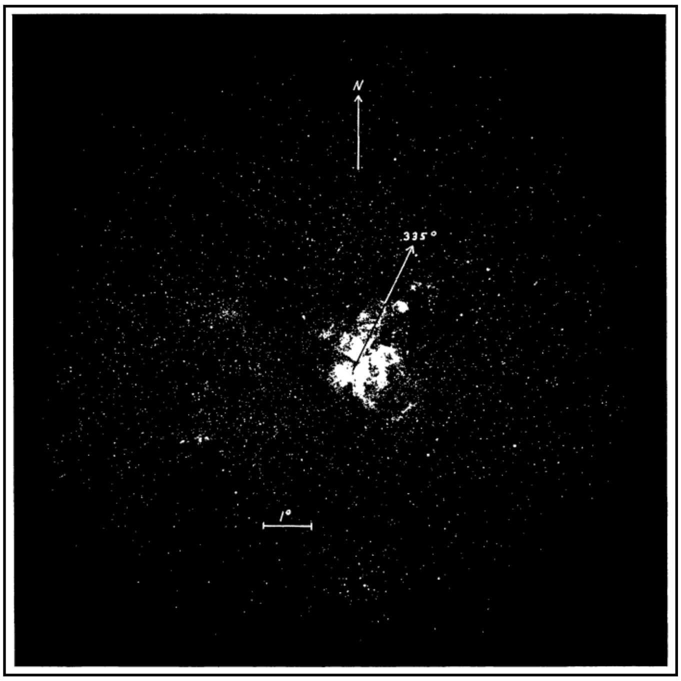


Figure 162: Hα image of the Eta Carine Nebula taken with the 8-inch *f*/1 Meinel-Pearson Schmidt camera at Mount Stromlo Observatory. The line at position angle 335º indicates the line along which Gum measured the surface brightness of the Nebula. East is to the left of the image (after Wade, 1959a: Plate 1).

Wade's findings were largely consistent with previous studies on emission nebulae, confirming that the radio emission could be explained solely by the thermal mechanism of free-free transitions. Wade found that a relatively simple model of the emission nebula having a spherical distribution with an electron temperature of 10,000 ±1,000 K, a dense core and a broad tenuous envelope, could provide a good account of both the radio and optical observations. Figure 163 illustrates the derived model.

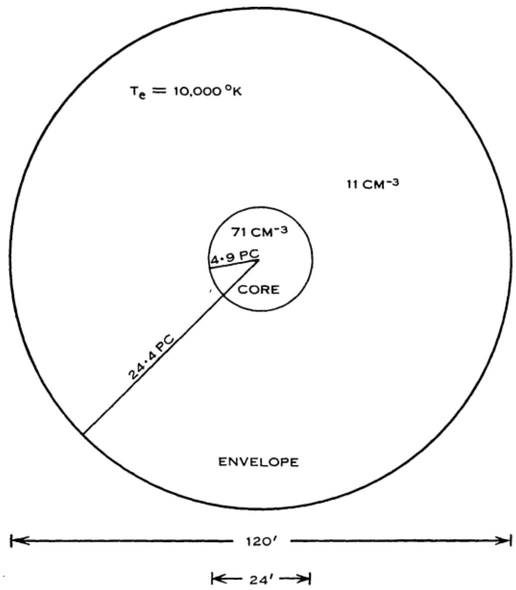


Figure 163: Wade's model of the Eta Carine Nebula (after Wade, 1959a: 426).

Assuming a distance to the Nebula of 1,400 parsecs yielded an r.m.s. density of 71 ions cm^{-3} for the core and 11 ions cm^{-3} in the outer regions of the Nebula. This meant that the total mass on the nebula was not more than 25,000 solar masses. Wade also showed that it was likely that several O class stars would be needed to maintain the observed ionization of the Nebula.

The other source observed at 1,400 MHz by Hindman and Wade (1959) was Centaurus A. Their findings were largely similar to the conclusions reached from earlier interferometric measurements (Bolton et al., 1954; Mills, 1953) and confirmed by later pencil beam measurements at 19.7 MHz (Shain, 1958) and 85.5 MHz (Sheridan, 1958). They found that the source was composed of two components. One of these was a localised discrete source associated with the optical galaxy NGC 5128. The second component was a large extended source with no optical counterpart. Figure 164 shows the contour map of aerial temperature for Centaurus A.

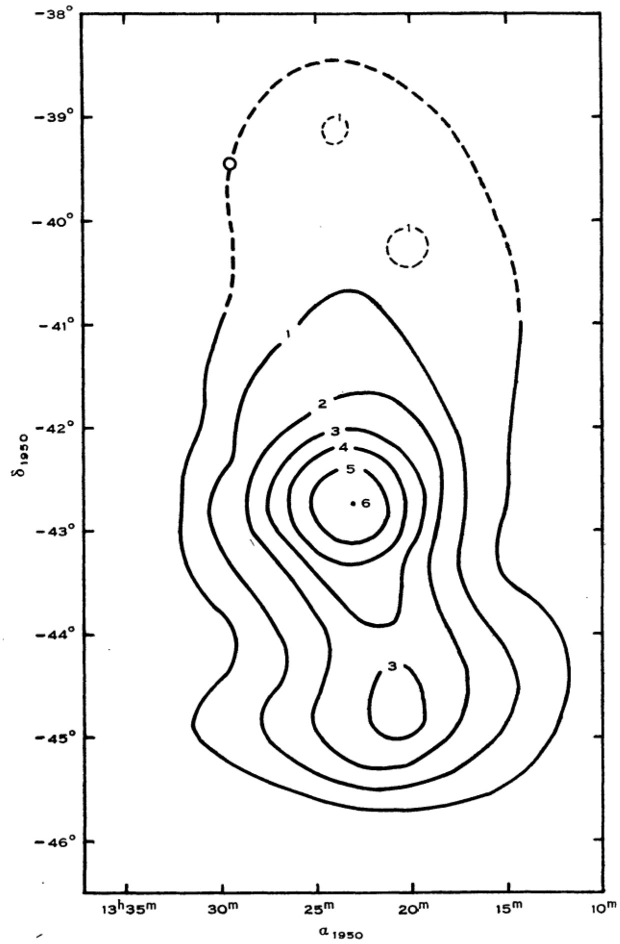


Figure 164: A contour map of aerial temperature for Centaurus-A at 1,400 MHz. The dotted lines are estimates of the contour lines which were below the detection threshold of the equipment (after Hindman and Wade, 1959: 268).

The derived flux density of Centaurus A was calculated as 1.3×10^{-24} Wm^{-2} Hz^{-1} ±20 percent, with 23 percent of the radiation coming from the point source and the remainder from the extended source. Although no new findings were made in these observations they provided additional data at previously-unobserved frequencies. Wade (1959b) subsequently published a summary of the radio observations of Centaurus A, including the 1,400 MHz Potts Hill observations, noting the similarity of the contour diagrams across the different frequencies.

Apart from the Eta Carina Nebula and Centaurus A, Hindman and Wade also used the Potts Hill 36-ft Transit Parabola to observe continuum emission from Sagittarius A at 1,400 MHz, but for some reason they never published their observation (see Gum and Pawsey, 1960: 158).

The 1,400 MHz continuum investigations by Hindman and Wade were the last investigations made at Potts Hill using the 36-ft Transit Parabola.

10.5.2.2. H-line Investigations

Nearly all of the early major discoveries in radio astronomy, including Jansky's original detection of cosmic radio emissions, were serendipitous. Serendipitous discoveries in radio astronomy have been well discussed in the literature (e.g. Kellermann, 1983). Perhaps the best example of an exception to this phenomenon was the discovery of the 21 cm Hydrogen emission line. As Sullivan has noted (1982: 299), the predication was remarkable on two counts; both for its scientific prescience and for the conditions under which it was produced. Van de Hulst was a graduate student at the time of the Nazi occupation of Holland and his supervisor from Utrecht University had been interned. Van de Hulst spent three months visiting Leiden (van Woerden and Strom, 2006: 17, Note 2), where under Oort's guidance he examined the possibility of discrete emission from neutral hydrogen. In a paper published immediately after the war ended, van de Hulst cautiously noted the possibility of detecting an emission line:

> "The ground state of hydrogen is split by hyperfine structure into two levels with a separation of 0.047 cm^{-1}. The spins of the electron and proton are pointed in the same direction in one state and are opposite in the other state. A quantum of wavelength 21.2 cm is emitted due to a spontaneous flip of the spin." (van de Hulst, 1945).

Van de Hulst noted that the transition to ground state was a forbidden transition and therefore it was necessary to assume a probability for the spontaneous transition to the preferred ground state. Provided that the life time of the hydrogen atom in the upper hyperfine-structure level was less than 4×10^{8} years, there was a possibility of detection. He also noted that the sensitivity of radio receivers would need to be improved by a factor of 100 over the 1940s levels of equipment for the emission to be detected.

The actual value of the emission frequency from the spin flip transition to the ground state is 1,420.4 MHz (λ = 21.1 cm) and is due to the hyperfine structure transition being 5.9×10^{-6} eV (Wild, 1952). This is an extremely small energy level when compared for example with the Lyman-alpha transition of 10.19 eV which produces an emission at the much shorter wavelength of 122 nm. The probability of transition to the ground state is 2.9×10^{-15} sec^{-1} ($\sim 10^7$ years), and is within van de Hulst's original limit. In 1947 the hyperfine structure of both atomic hydrogen and deuterium was experimentally measured using atomic-beam magnetic resonance at the Columbia University Radiation Laboratory under the supervision of I.I. Rabi (Nafe and Nelson, 1948; Nafe et al., 1947).

It is interesting to note that Pawsey was well aware of the potential that detecting radio spectral lines would provide to radio astronomy. He was also familiar with the predicted 1,420.47 MHz Hydrogen emission and also the prediction of Deuterium emission at 237.38 MHz. It was Reber who first alerted Pawsey to the theoretical predictions and to the possibilities of detection during a visit by the latter to the U.S. in early 1948. Reber had met van de Hulst in 1945 (Reber, 1984: 64) and subsequently promoted the possibility of detection the H-line in emission (see Reber and Greenstein, 1947: 19). Given the important implications that the detection of a radio-frequency spectral line would bring to radio astronomy, Pawsey alerted Bowen to this potential in a letter dated 23 January 1948. Pawsey also included a section titled, "The Search for Atomic Spectral Lines in Noise", in the trip report he wrote following his visit to the United States. After a discussion of the potential he concluded:

> "The position is therefore quite uncertain. Lamb of Columbia, for example, did not expect we should be able to find lines owing to low probabilities of emission or absorption and "smearing", due to changes due to magnetic fields and so on." (Pawsey, 1948d).

During his U.S. visit Pawsey also visited Harvard and met Oort who was visiting Yerkes Observatory at the time. However, there is no mention of any discussion on the H-line potential with these parties.

Bowen responded to Pawsey's U.S. visit report in a letter dated 18 May 1948, where he noted:

> "This [atomic spectral lines] possibility is certainly an interesting one but, in view of the present state of knowledge, I doubt very much whether we should yet devote a special effort to it. A search for the atomic hydrogen and deuterium lines could be made with the Georges Heights equipment but this would involve dislocation of other work which is scarcely justified at present. At the moment Harry Minnett is chasing up the references you supplied and we are hoping that Williamson will live up to the promise he made you to let us have a survey of the whole subject." (Bowen, 1948a).

The report from Pawsey triggered some activity at Radiophysics. In early 1949, Wild produced an internal report titled, "The Radio-Frequency Line-Spectrum of Atomic Hydrogen. I. The Calculation of Frequencies of Possible Transmissions". This report was a comprehensive survey of the earlier theoretical work on the subject and Bowen noted in a letter to F.W.G. White (Chief Executive Officer of the C.S.I.R.O.) on 21 March 1949:

"There is nothing very original about it but it serves to indicate the direction in which his work might go." (Bowen, 1949).

White replied to Bowen's on 28 March 1949 and noted:

"I have looked through it [the report] and find that, even to one who is not a spectroscopist, it is relatively easy to follow. The end results are certainly very interesting, and I hope that experimental data can now be found to which these can be related." (White, 1949).

As Sullivan (2005: 14) has reported, in 1949 Mills had considered taking on the H-line search as an independent line of research, but dismissed it as too speculative. Mills himself recalled that Pawsey had presented him with the choice of attempting to detect the H-line or investigating discrete sources using the Swept-Lobe Interferometer:

"If I had been a trained astronomer and therefore aware of the possible great importance of the H line no doubt this would have been my choice..." (Mills, 2006: 2)

Bolton and Westfold had also considered searching for the H-line (Robertson, 1992: 82). They had a copy of a Russian paper (Shklovsky, 1949) translated in an effort to obtain more details, however no search was undertaken. Murray (2007) has also recalled that Payne-Scott proposed a search for the H-line on a number of occasions at meetings of the solar noise group, although no record appears in the minutes.

Despite this early insight, there was no detection attempt by the Radiophysics Group. As late as February 1951, in a meeting of the Radio Astronomy Sub-Committee on Galactic Work, Shain raised the possibility of looking for line spectra as part of the Group's research efforts. In attendance at this meeting were Pawsey, Bolton, Mills, Minnett, Piddington and Shain. The outcome was recorded in the minutes:

"It was decided, however, not to plan for this as it could be easily fitted into other projects." (Mills, 1951b).

On 25 March 1951, H.I. Ewen, who was working on his Doctoral thesis at the Lyman Laboratory at Harvard University detected the 21-cm emission line (Ewen and Purcell, 1951). In a remarkable coincidence, van de Hulst was visiting Harvard at the time and discussed the detection with Ewen and his supervisor E.M. Purcell. Van de Hulst indicated that the Dutch group under Oort and Muller had been attempting to detect the H-line for some time. By Ewen's own account (2003) he was unaware of the Dutch group's work and had dismissed the possibility of the Dutch actively pursuing a detection attempt because he had interpreted van de Hulst's comments in his original paper as indicating that a detection was highly unlikely. In fact, Ewen thought it likely that his thesis would indicate a negative result. Ewen believed that if any group would undertake a detection attempt it would be from the Soviet Union on the basis of Shklovsky's independent prediction (1949), with which Ewen was familiar.

Also visiting Harvard University at this time was Kerr from the Radiophysics Laboratory in Sydney (Kerr, 1984: 137). Kerr was on a fellowship to Harvard to undertake studies in astronomy at the Harvard College Observatory under Dr. H. Menzel. Kerr had written to Pawsey on 17 March 1951 drawing to his attention the fact that two groups had already made unsuccessful attempts to detect the H-line (Kerr, 1951). At this time Ewen had still been unsuccessful and Owren at Cornell University, who was using an 8-ft Parabola and a receiver similar to Ewen's but with less sensitivity, had also been unsuccessful. On making the initial discovery Purcell and Ewen shared details of the discovery with the Dutch group and were keen to obtain an independent confirmation of the detection. Kerr sent Pawsey an airmail letter on 30 March 1951 alerting him to the discovery and asking if the Sydney group could assist in the confirmation, even though no prior work had been conducted by Sydney. The letter included a hand-drawn sketch of the H-line response on Ewen's receiver (Figure 165). In a letter dated 20 April 1951, Pawsey wrote to Purcell saying that because of the "...great potentialities..." he had assigned two separate groups to attempt the independent detection and they were optimistically hoping to get results "...in a few weeks". He also enquired as to the processes that would be used for publication of the discovery and suggested that they would privately communicate any detection and then publish a confirmation note at the time Ewen and Purcell decided to publish their result.

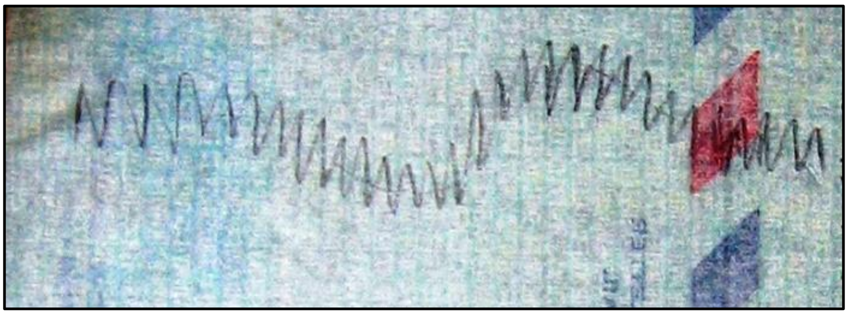


Figure 165: Hand-drawn sketch by Kerr of the H-line response detected by Ewen, included in a letter to Pawsey dated 30 March 1951 (National Archives of Australia – 972420 – C3830 – A1/3/17 Part 1).

In his letter to Purcell, Pawsey referred to two independent groups working on attempting a confirmation. A meeting was held on 12 April to coordinate the activities of the Radiophysics Group in attempting a confirmation observation. In attendance at this meeting were Pawsey, Higgs, Piddington, Christiansen, Wild and Bolton. The minutes recorded:

> "It was agreed that parallel investigations to check delectability of lines were desirable in order to obtain independent checks but that, in order to avoid cut-throat competition, the groups who were experimenting in the same field, e.g. Piddington, Christiansen and Wild, should consider themselves, at least on the 1420 Mc/s line, as a single group and possible publication should be joint.
>
> Wild outlined the theoretical results he had obtained (mainly in RPL. 33 and 34). The chief point of interest is the existence of fine-structure lines at 10,905, 3,231 & 1,363 Mc/s with "inherent" line widths of the order of 100 and 20 Mc/s respectively.
>
> It was agreed to recommend Wild to write up this material for publication.
>
> Christiansen and Bolton outlined schemes for attempting to detect the 1420 Mc/s line with which they were proceeding (also corresponding deuterium line). They hope to have equipment for tests to start in a week or so.
>
> Piddington outlined a different scheme with which he was proceeding." (Pawsey, 1951a).

Orchiston and Slee (2005a: 139) have stated that Christiansen and Hindman worked independently at the Potts Hill field station before they discovered they had both been tasked by Pawsey to work on the same problem. This is likely a reference to the early parallel work by Piddington and Christiansen. At the time Hindman was working for Piddington. It is unlikely that they did not know about each other's work, but rather this was a deliberate strategy as the minutes of the 12 April meeting reflect. After a short period, Christiansen took the leadership of the group with support from Hindman. It is unclear when Bolton's detection attempts were abandoned. However, in 1953-54, an unsuccessful attempt was made by G. Stanley and R. Price at Dover Heights to detect the postulated Deuterium line.

Purcell replied to Pawsey in a letter dated 9 May 1951. He welcomed the efforts of the Sydney group and provided further details of the detection and their receiving equipment. He also indicated that they intended announcing the discovery in *Nature* "...fairly soon...", but would allow time for a reply before proceeding. Pawsey replied in a letter dated 18 May 1951, saying that Christiansen would be, "...attempting the first observations tonight..." and that he would be away for the next fortnight and hence Christiansen would communicate directly if the attempt was successful, although he noted it would likely take several weeks. He also suggested that Ewen may wish to publish a detailed report in the *Australian Journal of Scientific Research*.

Christiansen and Hindman were able to construct a 'makeshift' receiver (1952b: 438) in a very short period through a great deal of improvision. The receiver was in principle similar to that used by Ewen, and by Muller and Oort in Holland. Coupling the receiver to the 16-ft × 18-ft Paraboloid Christiansen and Hindman were able to confirm the H-line detection. The minutes of the Radio Astronomy Committee of September 1951 record that the confirmation detection was made on 6 July 1951 (Christiansen, 1951a), only 15 weeks after the original discovery on 25 March 1951.

It is interesting to note Christiansen's own recollection:

> "We knew when we started that our gear was so rotten it mightn't work at all. Without exaggeration it was held together with string and sealing wax; Pawsey said it kept going through sheer will power. To make matters worse sparrows kept nesting in the aerial. We were stuck out at Potts Hill reservoir and it rained like all hell all the time. After observing for 10 days, without any luck we got fed up and went home, leaving the machine switched on. The next morning we found what we were after sitting up on the chart." (Christiansen, 1954).

Figure 166 shows an example of the H-line observation obtained by Christiansen and Hindman. This can be compared to Ewen's original observations, an example of which is shown in Figure 167.

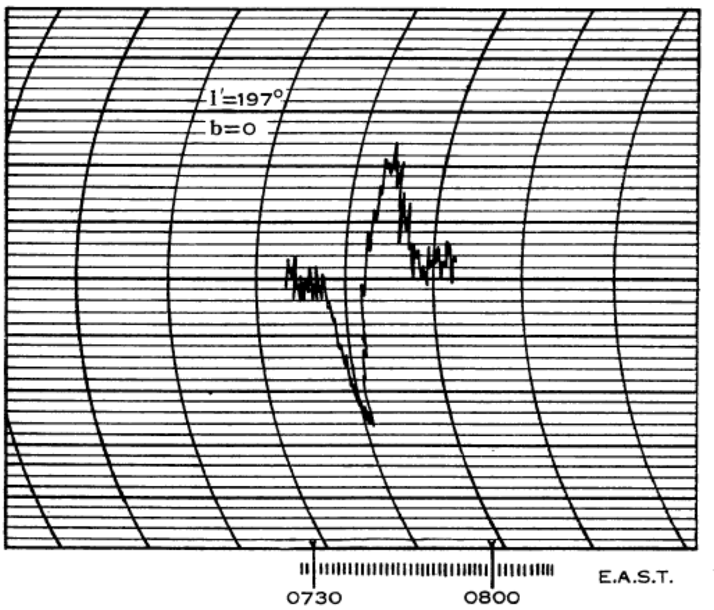


Figure 166: Example of H-line observation in the Taurus region (after Christiansen and Hindman, 1952b: 444).

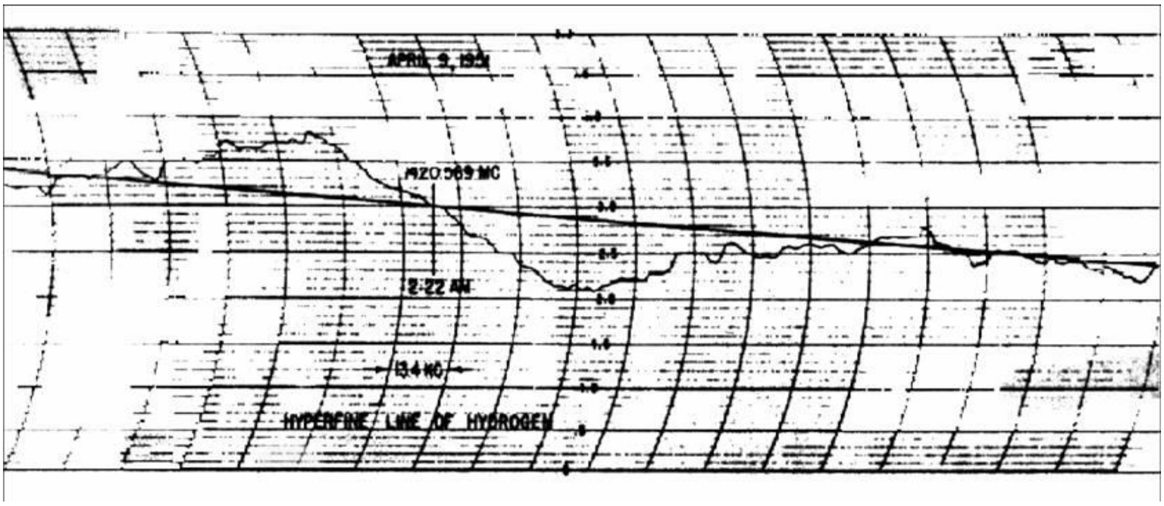


Figure 167: Example of a H-line detection made on 9 April 1951, approximately two weeks after the initial discovery (courtesy Ewen, 2003).

Ewen and Purcell's discovery was announced in the 1 September 1951 issue of *Nature* in a letter dated 14 June 1951. It appeared together with a confirmation paper by the Dutch group (Muller and Oort, 1951) dated 26 June and a short cabled communication dated 12 July from Australia also confirming the detection of the H-line (Pawsey, 1951b).

Pawsey noted in a letter he sent to Bowen on 13 July 1951 advising of the confirmation:

"Christiansen has worked like a [deleted] for the last two months trying to get this gear working and it is a very creditable performance on his part. The line is really exceedingly weak and it is necessary to make the right compromises all along the way in order to make the spectrum line evident." (Pawsey, 1951c).

Following the initial confirmation, between June and September 1951 Christiansen and Hindman proceeded to make a preliminary survey of hydrogen emission in the southern sky. The detailed findings of their survey were published in the *Australian Journal of Scientific Research* (Christiansen and Hindman, 1952b), and a summary paper also appeared in *The Observatory* (Christiansen and Hindman, 1952a).

By taking a series of measurements in progressive steps of right ascension they were able to obtain a series of profiles by declination. Figure 168 shows an example of a series of records taken along the Galactic Equator.

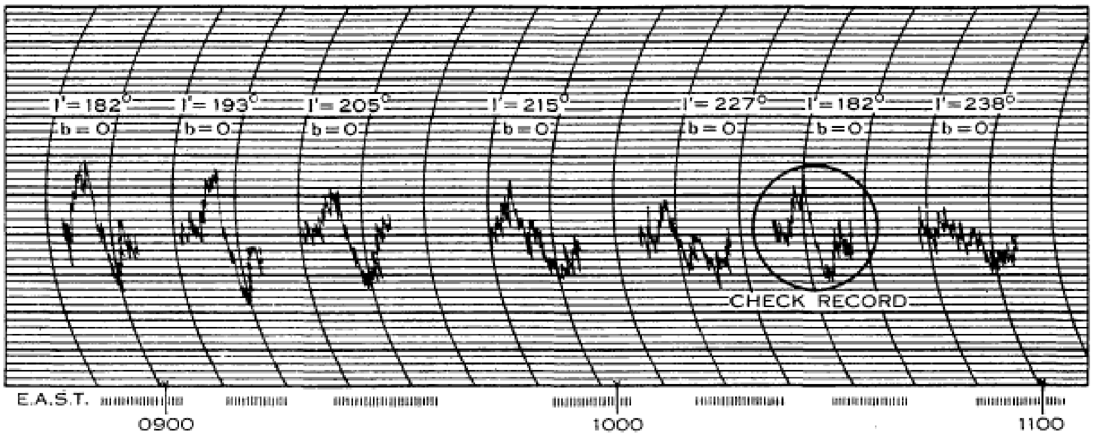


Figure 168: A series of six records taken along the Galactic Equator. A check record was performed near the end of each observing run to test receiver stability (after Christiansen and Hindman, 1952b: 445).

From these individual records, the maximum deflection could be measured and hence a series of brightness intensities could be calculated. Figure 169 shows an example of the profile of peak brightness for declination +10°.

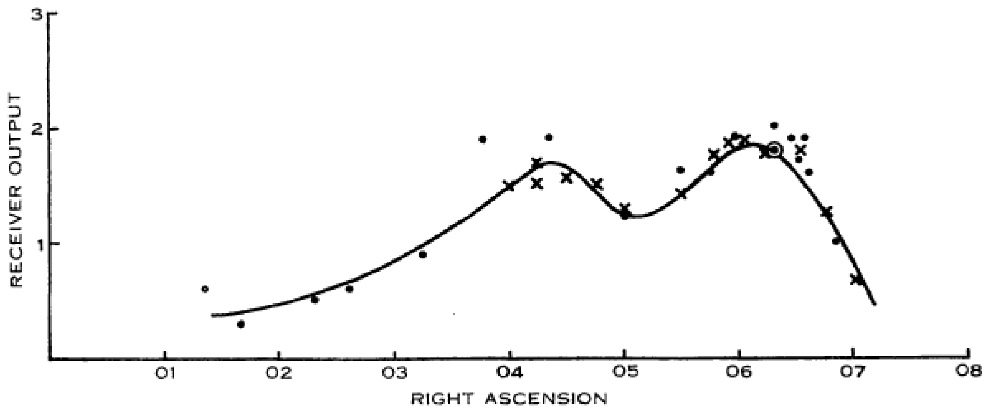


Figure 169: An example of the peak brightness profile in a strip along declination +10° (after Christiansen and Hindman, 1952b: 445).

By combining these profiles a contour chart of peak brightness was constructed. A peak brightness corresponding to a brightness temperature of approximately 100 K was observed. Figure 170 shows the final contour map of hydrogen-line emission. From this map it was evident there were marked variations in the peak brightness along the Galactic Equator. Christiansen and Hindman noted that there were two likely causes of these variations. The first was that the variations were due to line broadening caused by rotation of the Galaxy and the second, and more interesting possibility, was they were the result of structural features such as the spiral arms.

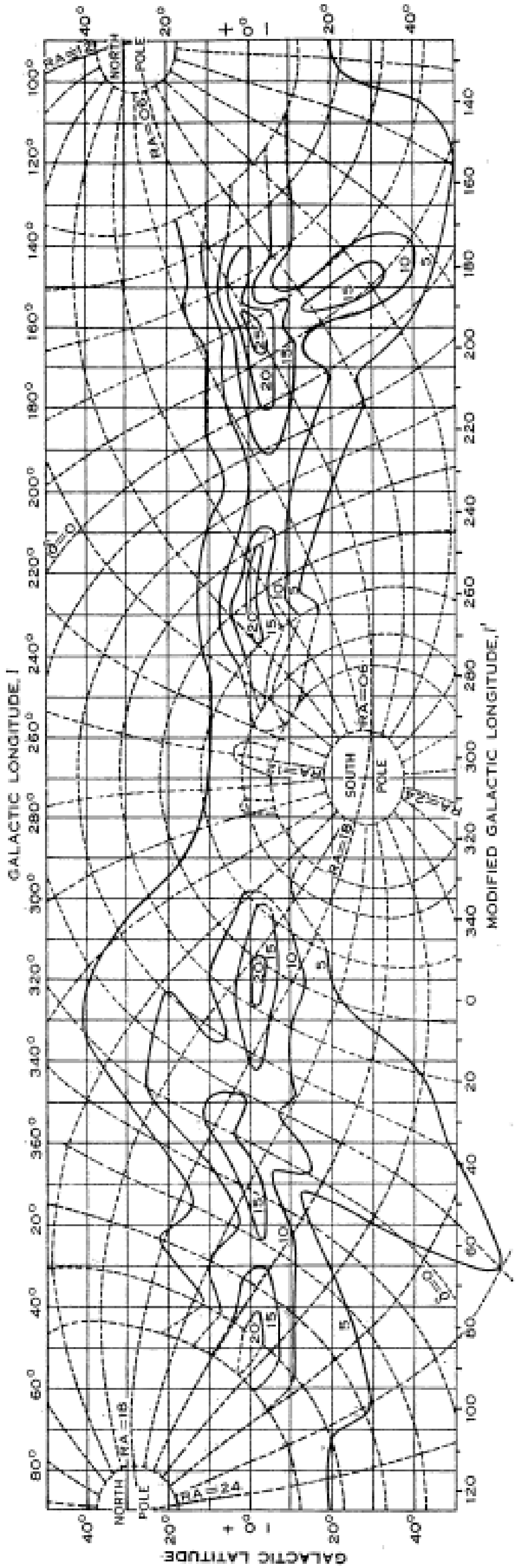


Figure 170: Full sky contour map of hydrogen-line emission. The peak brightness of 25 units corresponds to a brightness temperature of approximately 100 K (after Christiansen and Hindman, 1952b: 446).

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The line profiles were calculated based on the receiver response in the two swept-band filters of the receiver. Figure 171 shows examples of arbitrary line profiles and their corresponding receiver outputs.

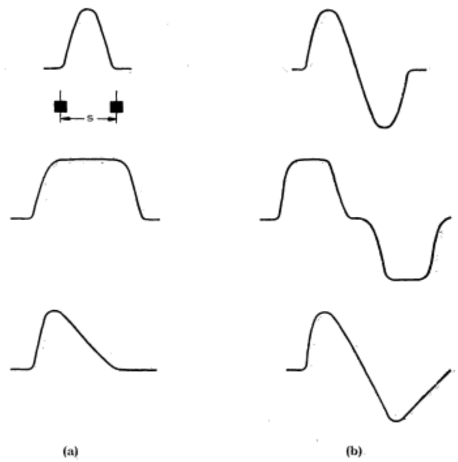

Figure 171: Example line profiles (a) and the corresponding receiver outputs (b). The sweep (s) of the two pass-bands (black boxes) is shown in the top left (after Christiansen and Hindman, 1952b: 442).

The process of reconstruction of the line profiles from the receiver records was essentially the reverse of that shown in Figure 171. Figure 172 shows examples of the smoothed records and reconstructed line profiles for the Galactic Centre, Anti-centre and Cygnus regions.

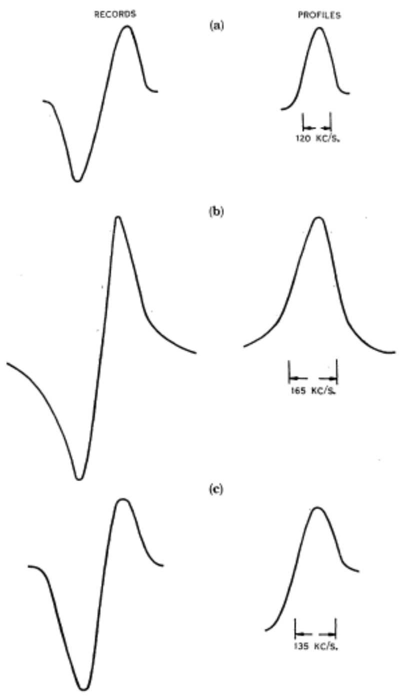

Figure 172: Examples of smoothed records and the calculated line profile in the region of the Galactic Centre (a), the Anti-centre (b) and the Cygnus region (c) (after Christiansen and Hindman, 1952b: 447).

Based on the broadening of line profiles, random velocities of the order of 12 to 18 km/s were estimated to be present in the neutral hydrogen clouds. In a number of cases double line profiles were also detected, as shown in Figure 173.

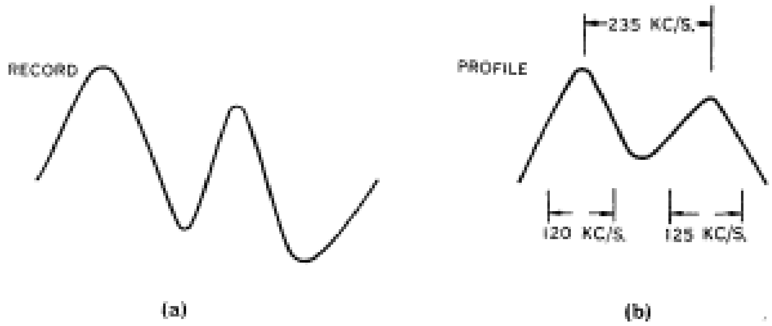

Figure 173: An example of the smoothed record and the resulting double line profile (after Christiansen and Hindman, 1952b: 448).

The existence of these double line profiles indicated regions with different radial velocities. Assuming a circularly symmetrical rotating galaxy, the radial velocity (v) of different regions is given by:

$$\mathrm{v} = r.A.\sin 2l' \qquad (13)$$

where

r is the distance of the source from the Sun;

A is 6×10^{-16} $\sec^{-1}$; and

l' is the modified galactic longitude with respect to the galactic centre.

From this equation, given a radial velocity estimate derived from the Doppler frequency shift compared to the rest frequency, a distance to the source could be estimated. The estimate for the two major regions showing double lines was 1,000 and 4,000 parsecs. Given the large size and the separation of the double lines (marked (a)) as shown in Figure 175, the structure was suggestive of spiral arms in the Galaxy.

Further evidence supporting the detection of galactic structure was found by comparing the theoretical effect of galactic rotation with the actual observations. Assuming a uniform medium producing radiation, it is possible to calculate the brightness profiles for different hydrogen densities. Figure 176 shows the theoretical plots where (n) is the number of ground state hydrogen atoms per cm^3.

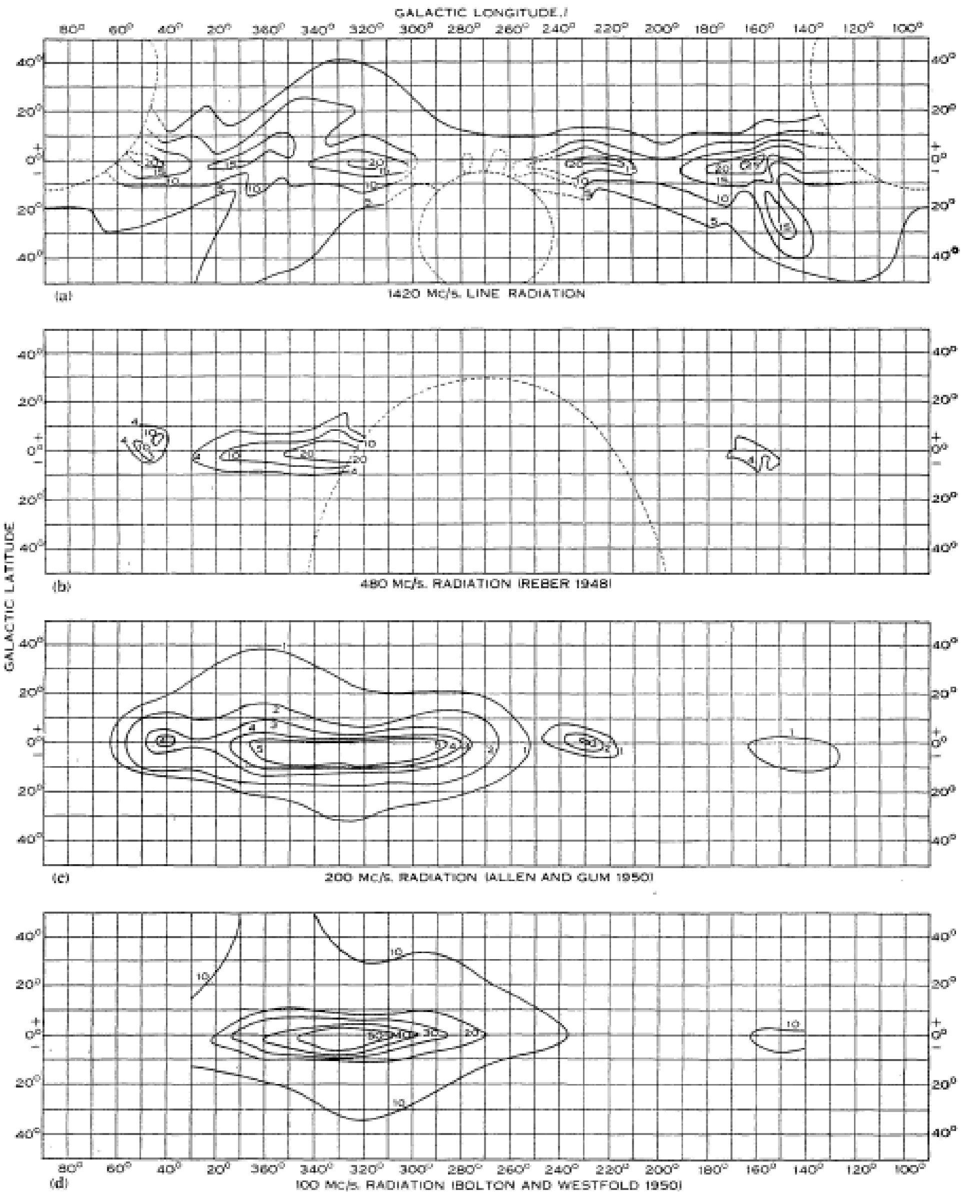

Figure 174: Comparison of hydrogen-line emission (top) to 480 MHz, 200 MHz and 100 MHz (bottom). Structural similarities are evident (after Christiansen and Hindman, 1952b: 451).

The plot showed reasonable agreement with a density of somewhere between 1 and 0.5 atoms per cm^3. However, there were clearly regions where factors other than rotation were causing brightness variations. Also, by comparing the overall hydrogen emission to the general radio emission, which would not be effected by rotation, it was clear that there was general agreement between structural areas as shown in Figure 175. These factors suggested the existence of spiral arms in the Galaxy and Christiansen and Hindman concluded that a much more detailed investigation was warranted.

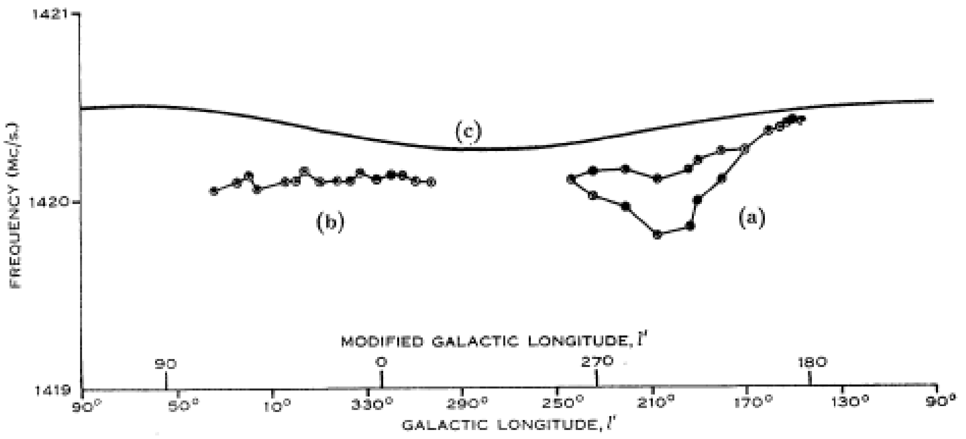

Figure 175: Plot of centre frequencies for line profiles showing double line profiles (a) and single line profile (b) regions. Line (c) is the expected frequency variation due to the Earth's relative motion (after Christiansen and Hindman, 1952b: 448).

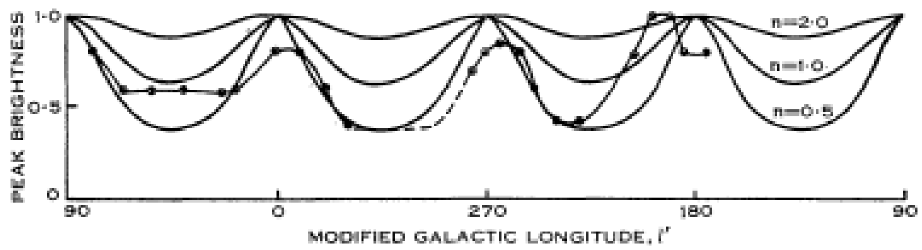

Figure 176: Calculated brightness peaks due to galactic rotation for given hydrogen densities (n). Dots indicate actual observations (after Christiansen and Hindman, 1952b: 450).

Overall there were clear indications that the hydrogen-line emission occupied roughly the same distribution in the sky as the visible Milky Way. This association and the ability to penetrate the obscuring medium to discover galactic structure heralded the beginning of a very important branch of investigations in radio astronomy. It also marked the beginning of a major international collaboration, particularly with the Dutch group working at Leiden, and was characterised by close cooperation that started with the prepublication communications by Ewen and Purcell with both the Dutch and Australian groups.

It is ironic that in the same year that the breakthrough discovery of a radio frequency emission line occurred, the first optical evidence for spiral arm structures in our Galaxy was also published (Morgan et al., 1952; Sheehan, 2008).

Immediately following the Australian confirmation of the H-line, Wild decided to update and publish the internal report he had written prior to the detection of the H-line (Wild, 1952). This was a comprehensive review of the radio-frequency line spectrum of atomic hydrogen and is largely in accordance with modern theory. The report provided a very solid theoretical base for planning of further observations by the Australians. The one exception in this analysis was the conclusion that the 1,420 MHz emission would be the only detectable line emission, and that it would be unlikely that the higher order recombination lines would be detectable. It would be nearly two decades before the recombination lines were detected in the Soviet Union (Sullivan, 1982: 300).

From 8-22 August 1952 the Tenth General Assembly of the International Union of Radio Science (URSI) was held in Sydney. Attending the meeting were Ewen from Harvard and Muller from Leiden. This meant that for the first time, those that had been involved in the initial detection of the Hydrogen emission were able to meet face to face (Figure 177).

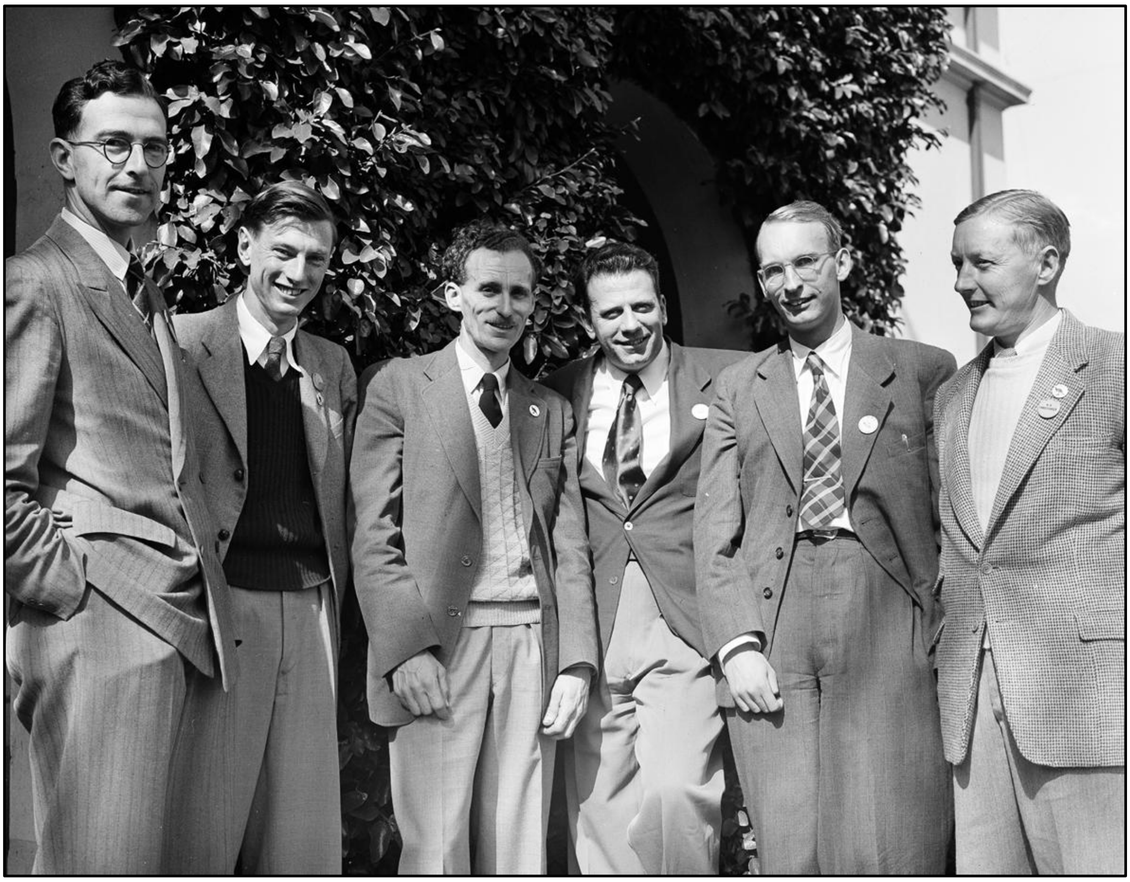

Figure 177: Gathering at the 1952 URSI meeting in Sydney of those involved in the initial detection and confirmation of the H-line. From left to right: Kerr, Wild, Hindman, Ewen, Muller and Christiansen. Note also the special URSI 'Kangaroo' lapel buttons being worn (Courtesy of ATNF Historic Photographic Archive: B2842-45R Image Date: 8 August 1952).

At the URSI meeting this group decided to arrange a regular exchange of information by way of a regular newsletter that tracked the progress of the various groups undertaking research. The first issue of this newsletter appeared in December 1952 and was circulated to those listed in Table 4.

Table 4: H-line Newsletter Recipients

Dr. H.I. Ewen	Ewen Knight Corporation, Massachusetts U.S.A
Dr. B.J. Bok	Harvard Observatory, U.S.A

Dr. C.R. Burrows	Cornell University U.S.A.
Dr. H. Tatel	Carnege Institution, U.S.A.
Dr. J. Hagen	Naval Research Laboratory, Washington U.S.A.
Dr. F.J. Kerr	Radiophysics Laboratory Australia
Dr. J.L. Pawsey	Radiophysics Laboratory Australia
Dr. O. Storey	T.R.E. Malvern U.K.
Dr. A.C.B. Lovell	Jodrell Bank U.K.
Dr. M. Ryle	Cambridge University U.K.

Following the initial H-line survey, Christiansen returned to his solar observation program. By this stage Kerr had returned from Harvard and, together with Hindman, focused on the construction a new and more reliable receiver and on the new 36-ft Transit Parabola for use in a dedicated H-line survey of the southern sky. They were also joined by the new graduate student Brian Robinson, who would go on to lead the CSIRO's radio astronomy group during the 1970s (Whiteoak and Sim, 2006: 265). The new receiver design had been devised by Pawsey and allowed for multi-channels, the first of its kind. Instead of using a narrow band that was swept over a line profile, a series of fixed frequency channels was used (see section 10.4.1).

Preliminary observations began almost immediately upon completion of the aerial and while the new multi-channel receiver was still under development. The first observations made were of the Magellanic Clouds using only a single channel of the new receiver. These were the first ever observations of H-line emission from another galaxy. Kerr and Hindman presented their preliminary findings at a meeting of the American Astronomical Society, held at Boulder (Colorado) in August 1953. They also published a summary in the *Astronomical Journal* (Kerr and Hindman, 1953), before presenting a more detailed account in the *Australian Journal of Physics* (Kerr et al., 1954). In late 1953, Robinson also unsuccessfully searched for H-line radiation from M31 (Pawsey, 1954b).

For observations of the Magellanic Clouds, a series of drift scans was taken by pointing the aerial at a fixed declination and allowing the rotation of the Earth to sweep the aerial beam in right ascension. By stepping the aerial in declination a grid of measurements covering some 250 points spaced in a lattice 1° in declination (the aerial beam width) and 10 minutes in right ascension was obtained. Figure 178 shows an example of the line profiles obtained for the Small Magellanic Cloud.

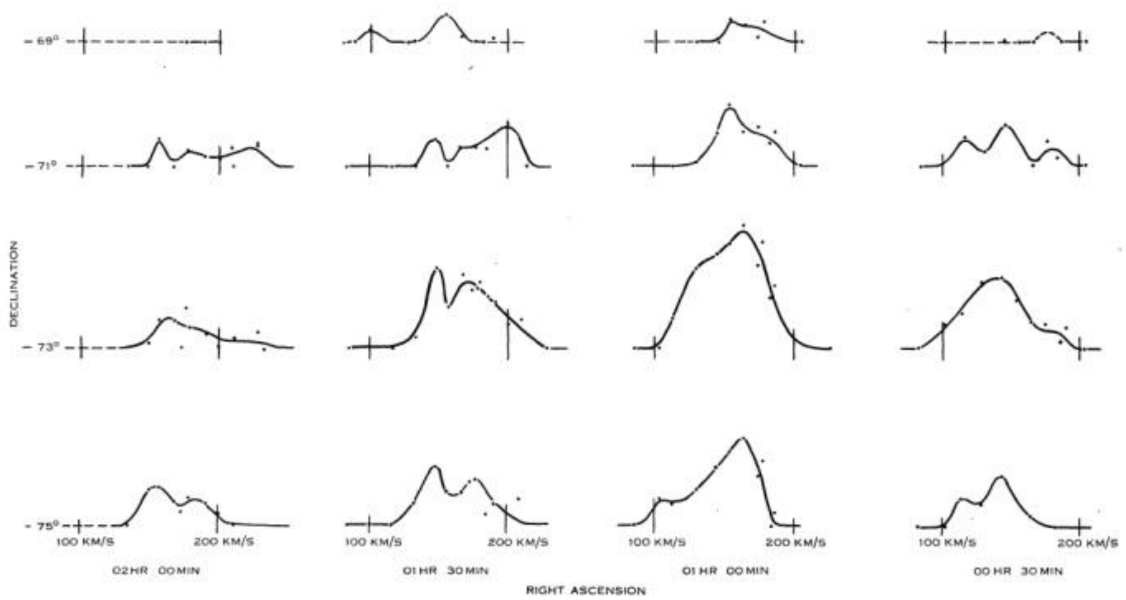

Figure 178: Examples of H-line profiles obtained from the Small Magellanic Cloud (after Kerr et al., 1954: 303).

The output of the receiver was calibrated in terms of the aerial temperature. The temperatures change (ΔT), correspond to the r.m.s. noise fluctuations and is related to the noise factor by the following equation:

$$\Delta T = \frac{2^{1/4}(N-1)T_o}{(\tau B_c)^{1/2}} \tag{14}$$

where

N is the noise for the continuous spectrum;

T_o is the ambient temperature;

τ is the output time constant; and

B_c is the Bandwidth of the single channel.

For the observations of the Magellanic Clouds the receiver parameters were N = 6, τ = 15 sec, B_c = 40 KHz, which gave a temperature fluctuation of 2.7 K. Correcting for the wideband output, the brightness temperature could be calculated. The highest brightness temperatures observed were about 30 K, which is about a quarter of the brightness temperature observed for our own Galaxy. Figure 179 shows the distribution of Small Magellanic Cloud brightness temperature for four different radial velocities.

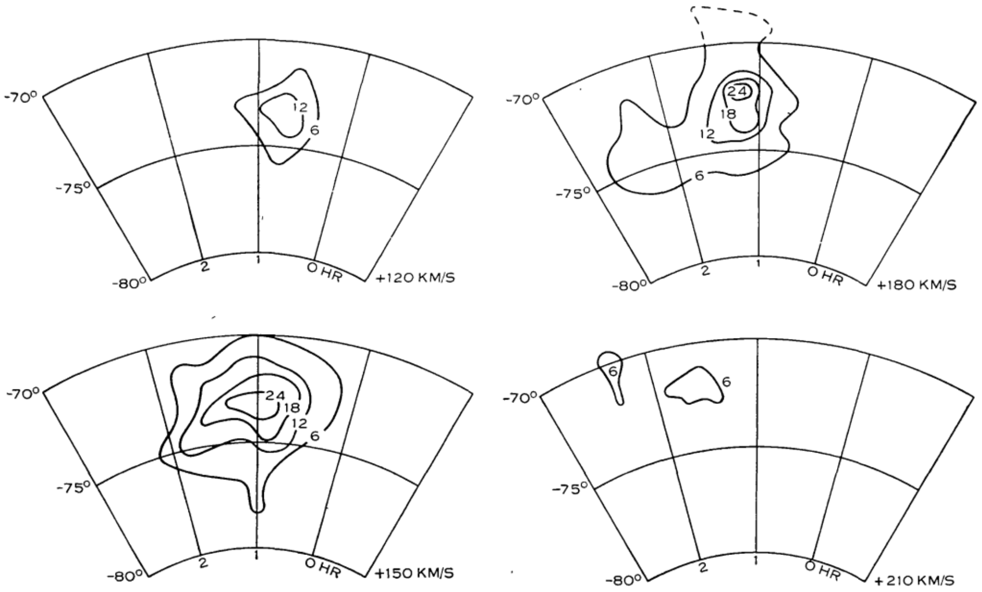

Figure 179: An example of the brightness distribution of line emission from the Small Magellanic Cloud at four different radial velocities (after Kerr et al., 1954: 302).

From the brightness temperature, the total energy received from a particular direction can be calculated in terms of the area under the line profiles. Kerr and Hindman referred to this as the integrated brightness, which is equivalent to the integrated intensity in optical spectroscopy. The integrated brightness (B_{int}) in units of Wm^{-2} $sterad^{-1}$, is given by the following equation:

$$B_{\text{int}} = \frac{2k}{\lambda^2} \int T_v dv \qquad (15)$$

where

the factor 2 covers both polarisations;

k is Boltzmann’s constant;

T_v is the brightness temperature; and

v is the frequency.

Figure 180 shows the contour diagram of the integrated brightness of the two Magellanic Clouds with a contour interval of 7×10^{-16} Wm^{-2} $sterad^{-1}$.

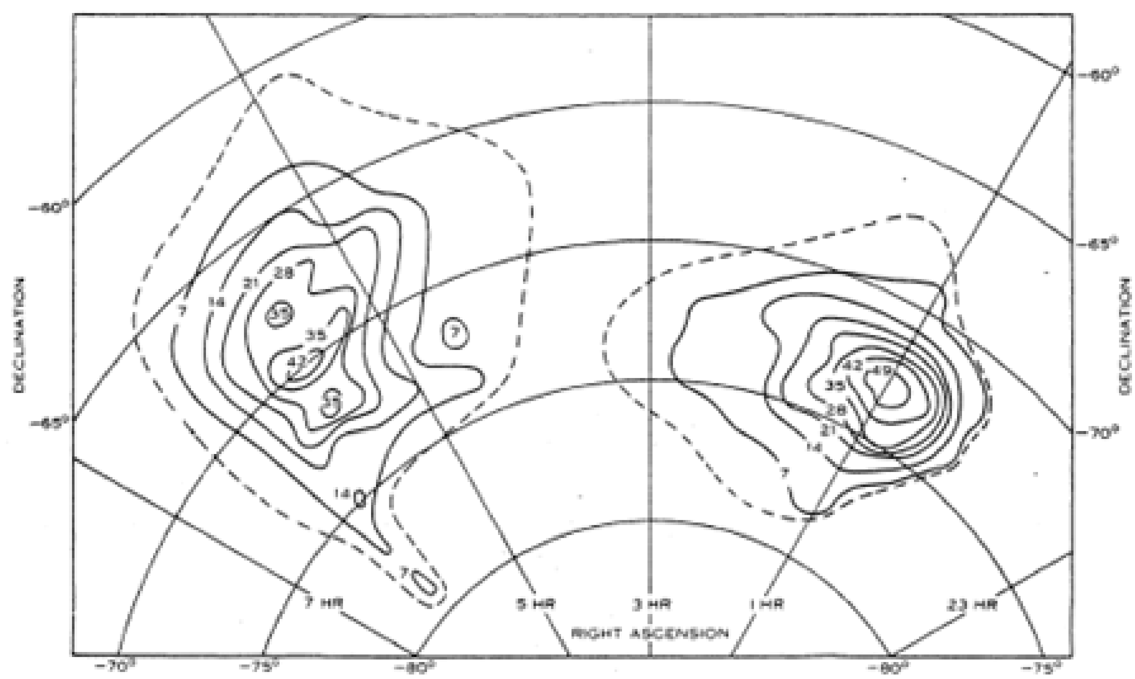

Figure 180: Integrated brightness contours of H-line emission from the Magellanic Clouds (after Kerr et al., 1954: Plate 2).

Similarly, the median radial velocity for each line profile can be calculated and a contour diagram of the velocities produced, as shown in Figure 181.

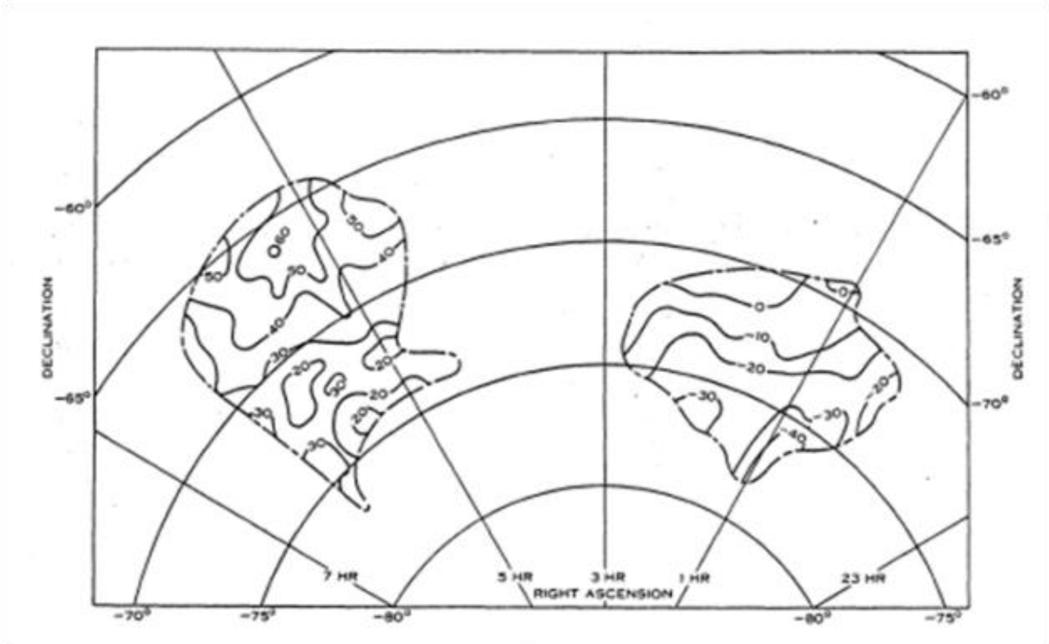

Figure 181: Median radial velocity contours, corrected for galactic rotation and motion of the Sun (after Kerr et al., 1954: Plate 2).

These preliminary observations quickly confirmed the value that radio astronomy could bring to the study of galactic structure through observation of neutral hydrogen (HI). Although the Magellanic Clouds had been extensively studied at optical wavelengths, the new radio frequency observations provided a range of new insights. The first of these was that the area of HI emission was much larger than the optical size determinations. Also, the Small Magellanic Cloud was nearly the same size as the Large Magellanic Cloud, which was a very different result from the optical view shown in Figure 182.

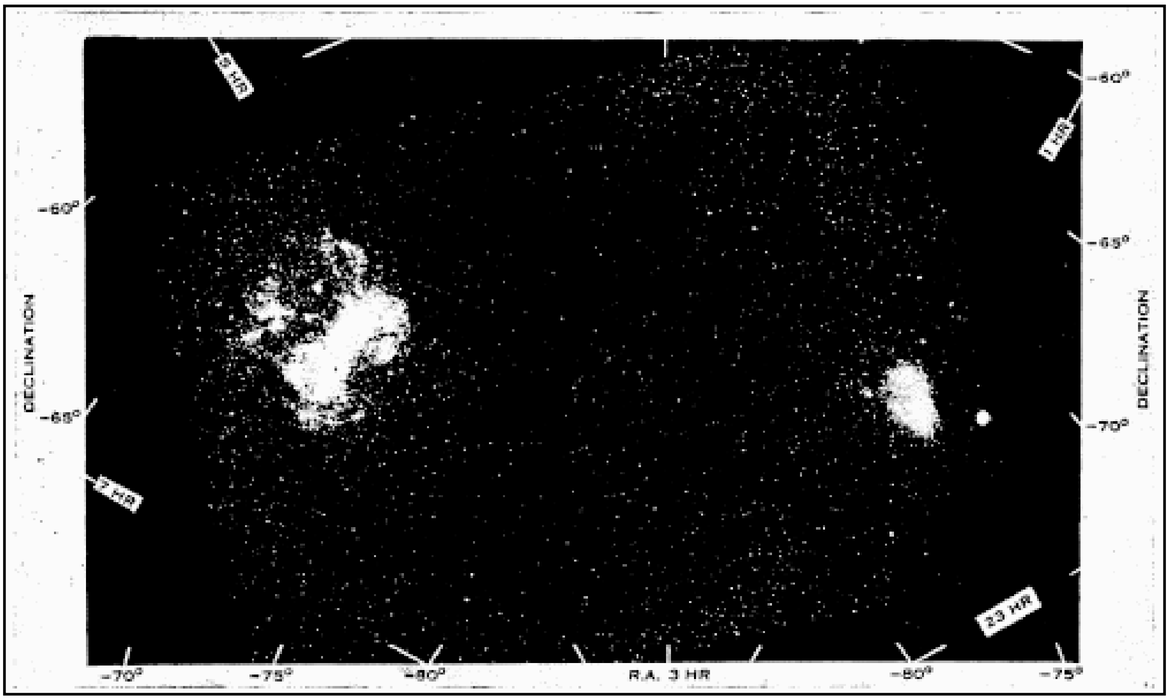

Figure 182: Optical view of the Large and Small Magellanic Clouds. This image should be compared with Figure 180 (after Kerr et al., 1954: Plate 2).

The large HI content of the Small Magellanic Cloud was not expected as it had been assumed that because of the low dust content of the Cloud there would also be a low concentration of HI. The HI emission showed that there was almost an equal mass present in both Magellanic Clouds. Assuming an optically-thin distribution, an estimate of 6×10^8 solar masses for the Large Magellanic Cloud and 4×10^8 solar masses the Small Magellanic Cloud was determined. The Small Magellanic Cloud also showed a very prominent wing extension toward the large cloud that was also faintly present in optical studies.

Optical determinations of velocities in the Magellanic Clouds had been limited to observations of 17 emission nebulae in the Large Cloud and only one in the Small Cloud (Wilson, 1944). There was also some dispute as to whether motions in the clouds were due to rotation or translative motion of the Magellanic Clouds through space. The H-line radial velocities showed that both of the Magellanic Clouds appeared to be rotating about a common centre of gravity consistent with earlier suggestions from optical observations. After publishing their preliminary findings Kerr collaborated with G. de Vaucouleurs, who was a Visiting Fellow at Mount Stromlo Observatory as part of the Yale-Columbia Southern Station program. De Vaucouleurs had been studying the Magellanic Clouds, and like Oort, quickly realised the potential that collaboration with a radio astronomer could bring to an understanding of large scale structures of these galaxies. His optical observations had shown that both Clouds exhibited spiral structure in their outer regions and that the Clouds were flattened systems inclined to the line of sight at a distance of approximately 46 kpc as shown in Figure 183 (De Vaucouleurs, 1954a,b, 1955a,b,c,d).

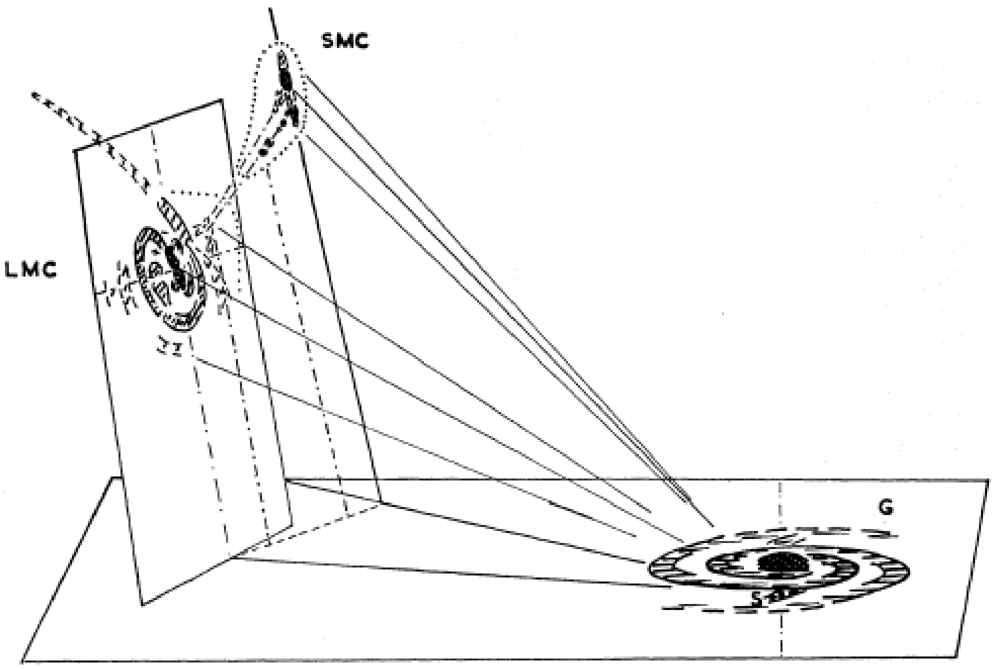

Figure 183: The relationship of the Large and Small Magellanic Clouds to our Galaxy and the Sun. The dotted line shows the approximate extent of HI (after De Vaucouleurs, 1955b: 229).

The H-line observations generally supported the conclusions de Vaucouleurs had reached from optical observation. However, they also indicated some important differences. By examining the rotational curves of both of the Clouds it was clear that the radio centre of rotation was somewhat displaced from that derived from optical observations. The optical observations had suggested an asymmetrical rotation as shown in Figure 184. This seemed physically unlikely and the radio observations supported a much more symmetrical rotation based on the displaced centre of radio emission. Figure 185 shows the equivalent radio rotation curve to that shown for the optical observations in Figure 184.

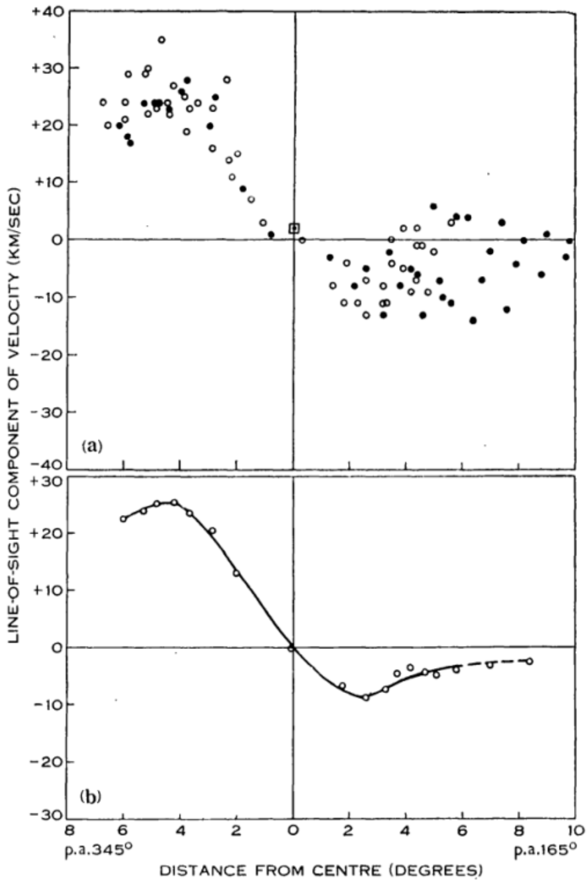

Figure 184: Optical rotation curve for the Large Magellanic Cloud with respect to the optical centre. The top chart is the full scatter diagram with solid dots representing points within ±20° of the central axis. The bottom chart is the best fit curve (after Kerr and De Vaucouleurs, 1955: 512).

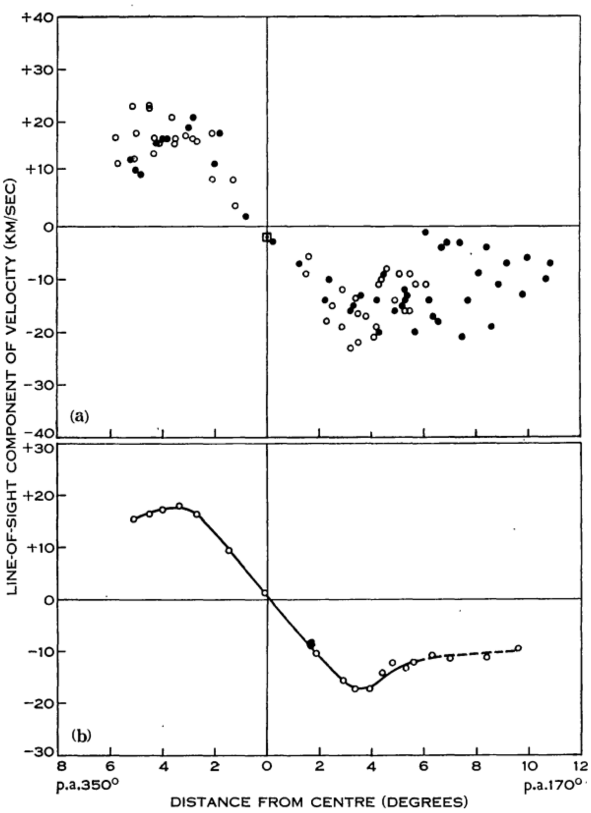

Figure 185: The H-line rotation curve for the Large Magellanic Cloud based on the radio centre (after Kerr and De Vaucouleurs, 1955: 512).

The Small Magellanic Cloud also showed a displaced HI centre of rotation compared to the optical observations and was tilted at a somewhat smaller angle (30°) than the Large Cloud. The H-line rotational curve is shown Figure 186.

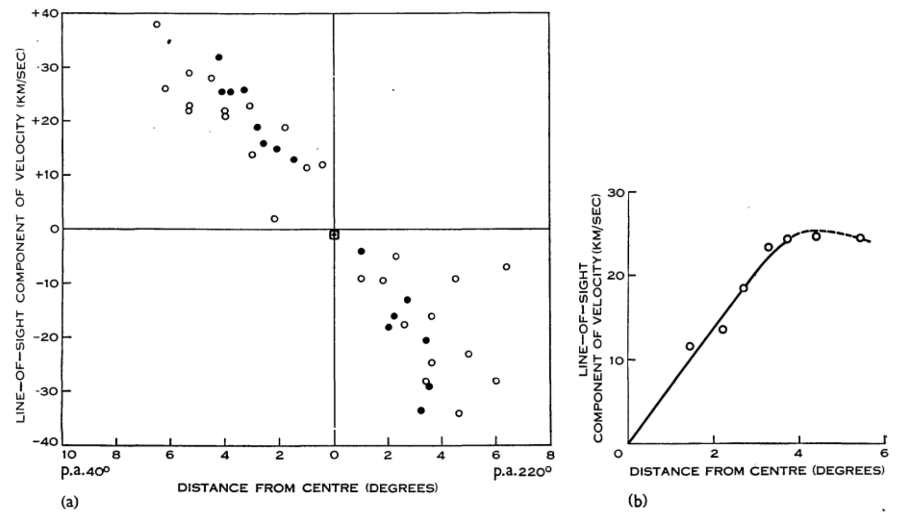

Figure 186: H-line rotational curve for the Small Magellanic Cloud based on the radio centre of rotation (after Kerr and De Vaucouleurs, 1955: 515).

In theory the radio observations could be used to estimate the tilt of the plane of the Magellanic Clouds with respect to the line of sight. The rotational velocity (v_r) can be calculated based on the relation:

$$v_o - v_s = v_r \cos\theta \cos i \qquad (16)$$

Where

- v_o is the velocity observed;
- v_s is the radial velocity of the system as a whole;
- θ is the observed azimuth angle; and
- i is the angle of inclination to the line of sight.

Unfortunately, the face-on tilt of the Large Magellanic Cloud was at a point where the method was insensitive to variations in tilt. The radio observations suggested that the tilt may be larger than the 65° tilt indicated from optical observations. However, the data were not of sufficient accuracy to provide a definitive estimate.

The systematic radial velocity of the two Magellanic Clouds was estimated by taking all of the medium radial velocities and weighting each according to its associated brightness. This gave values of +280 and +161 km/sec for the Large and the Small Magellanic Clouds respectively prior to removal of components due to solar motion and galactic rotation. This compared well to earlier optical observations.

Given an estimate of radial velocity, it was also possible to estimate the mass of both Magellanic Clouds. Kerr and de Vaucouleurs examined this problem in a separate paper (Kerr and De Vaucouleurs, 1956). Mass estimates prior to this had been tentative at best. In examining the radial velocity, a difference between the peak and medium velocities had been noted. It appeared that the medium velocities represented regions away from the equatorial plane whereas the peak profiles appeared to be associated with the plane. For the purposes of the Magellanic mass calculations the peak curve was used. Although the Clouds appeared to have more complex structures than regular spiral galaxies, no extensions to theoretical models were available at this time and as such those applying to regular spiral galaxies were used. The mass estimates obtained from a rotation curve alone yield only a lower limit of mass. This is due to the curves being insensitive to mass in the outer parts of the galaxy and it also ignores random motions which were present in the hydrogen distribution.

The observed rotation curves were somewhat smoothed by the 1.4° aerial beam and these were corrected as shown in Figure 187.

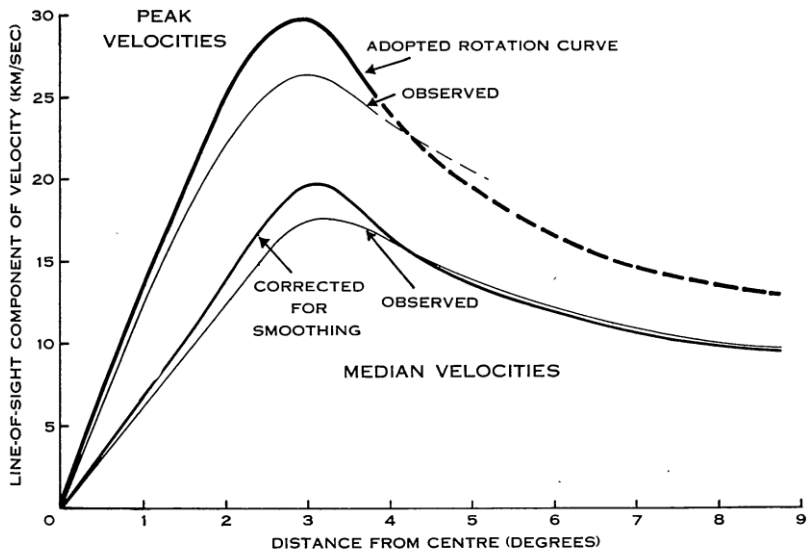

Figure 187: Corrected peak and median rotational curves for the Large Magellanic Cloud (after Kerr and De Vaucouleurs, 1956: 93).

Three different methods were used to calculate the mass. The first was to examine the Keplerian branch. This gave close agreement to a curve produced by a central point of mass of 1.5×10^9 solar masses. The second method used was the thin disk approximation (Wyse and Mayall, 1942). This yielded a mass estimate of 1.73×10^9 solar masses. The third method was based on the oblate spheroid approximation (Perek, 1950), giving a mass estimate of 1.93×10^9 solar masses. Bearing in mind that any radial velocity determination was sensitive to the tilt angle, Kerr and de Vaucouleurs adopted a mass value of 1.85×10^9 solar masses for the Large Magellanic Cloud assuming a tilt angle of $i = 65°$. This provided a minimum estimate of the mass. Allowance was then made for the observed random motions in the two Clouds and extrapolation of the spherical hydrogen shell which gave a best estimate of 3.0×10^9 solar masses. Increasing the tilt angle to 70° or 75° would yield higher mass estimates of 4.3×10^9 and 7.1×10^9 solar masses respectively. Using the Large Magellanic Cloud as an analogy, an estimate for the Small Cloud was made of 1.3×10^9 solar masses. This was the first time that the masses of the Magellanic Clouds had been estimated on any basis other than a small sample of optical observations.

The differential radial velocity of the two Magellanic Clouds based on the H-line measurements was approximately 50-60 km/sec. Kerr and de Vaucouleurs showed that by assuming the Clouds were moving as an isolated system, their combined mass (M) could be related to the relative orbital velocity (v) by the following expression:

$$M = \frac{\mathrm{v}^2}{G(2/r - 1/a)} \tag{17}$$

where

G is the gravitational constant;
r is the distance between the two clouds; and
a is the semi-major axis of the relative orbit,

The observed differential radial velocity implied that the Magellanic Clouds could only be in a closed orbit if their combined masses exceeded 5×10^9 solar masses. For a circular orbit the combined mass would need to be greater than 10×10^9 solar masses. Therefore, they concluded that the two Clouds were in a hyperbolic or near parabolic orbit relative to one another. They also noted that the two Clouds cannot be considered independent of our own Galaxy and must be treated as a three-body system.

Determination of the mass of the systems was critically dependent on the orientation of the axis of rotation. Measurement of the tilt of the Clouds has remained problematic. In 1972 de Vaucouleurs revised the tilt estimate for the Large Magellanic Cloud to i = 27° ±2° based on both optical and HI evidence (De Vaucouleurs and Freeman, 1972). Over time it was further revised to a generally accepted value of i = 45° (e.g. Sparke and Gallagher, 2000: 137). More recent evidence suggesting a warp in the disk of the Large Cloud has suggested a tilt of i = 35° (Olsen and Salyk, 2002).

While Potts Hill's location in the Southern Hemisphere provided an ideal opportunity to examine the Magellanic Clouds, the primary purpose of the H-line survey was to examine the southern Milky Way. This survey work commenced in earnest in 1954 with completion of the four-channel H-line receiver. Joining Kerr and Hindman was Martha Stahr Carpenter who was visiting Radiophysics from Cornell University. Although Christiansen and Hindman had published the first substantial survey of H-line radiation (Christiansen and Hindman, 1952a,b), the Dutch group working at Leiden quickly made significant progress mapping the northern Milky Way and set the standard for galactic examinations based on H-line observations (Kwee et al., 1954; Oort, 1953; van de Hulst et al., 1954). The leader of this group, Oort, had earlier established much of the theoretical underpinning for the study of galactic structure (Oort, 1952). During the 1900s a phenomenon for stars close to the Sun had been noted whereby their proper motions (μ) varied with galactic longitude (l) as the function:

$$\mu \propto \cos 2l \tag{18}$$

Oort (1927) was the first to propose that this phenomenon could be explained by galactic rotation. Building on their survey work of the northern sky the Dutch group soon developed a picture of the spiral structure of the Galaxy (Schmidt, 1957; Westerhout, 1957).

Although the Australian H-line survey began in 1954, it was not until 1959 that the full observational results of the survey were published in detail (Kerr et al., 1959). However, during this period there were many presentations and discussions on findings of the southern H-line survey at conferences (e.g. Carpenter, 1957). In addition there were several publications of initial findings (Kerr, 1957, 1958b; Kerr et al., 1956) and a summary paper which appeared in *Nature* (Kerr et al., 1957).

The Australian H-line survey itself consisted of examination of an 8° wide strip along the Galactic Equator with the aim of determining the three-dimensional distribution of neutral hydrogen within the strip. Observations were taken along 41 selected paths across the Galactic Equator at a variety of longitudes ranging from l = 175° to l = 5° (under the pre-1959 galactic co-ordinate system). Drift scans were used in most cases by holding the aerial stationary while the Earth rotated. Scans were taken using the 4-channel receiver which covered 4 adjacent 40 KHz bands. As this was not sufficient coverage to encompass the full Doppler shift of the line profiles, scans needed to be repeated with the receiver channels shifted to a new set of frequency bands. This was done by overlapping coverage to ensure consistency of results. It also gives some insight as to how labour intensive the survey was being limited to only four channels. Ultimately a new 48-channel receiver was built and tested at a new field station at Murraybank, giving a significant improvement in the time taken to obtain line profiles (Orchiston and Slee, 2005a: 161). Figure 188 shows a diagram of the 41 scan paths taken across the Galactic equator.

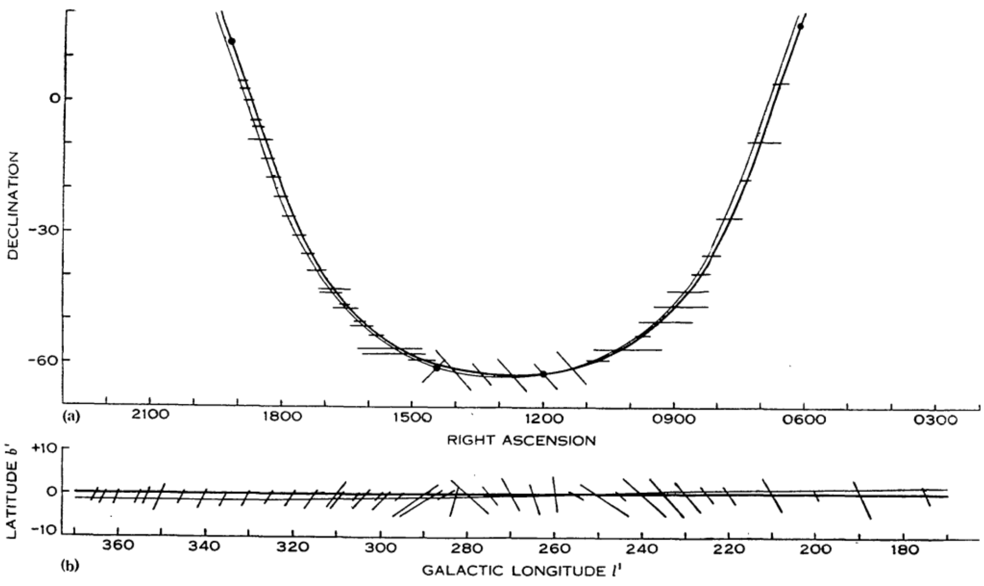

Figure 188: H-line survey paths through the Galactic Equator. Both pre- and post-1959 Galactic Equators are shown. Celestial coordinates (top scale) are epoch 1955. Galactic co-ordinates (bottom scale) are pre-1959 coordinates (after Kerr et al., 1959: 277).

The first published material to appear on the preliminary results of the Potts Hill southern galactic H-line survey was a short summary paper that appeared in the *Astronomical Journal* (Kerr et al., 1956). This paper reported on a tentative picture of the spiral structure of the southern portion of the Galactic Plane. The initial examination of the H-line profiles at longitudes between *l* = 260° and *l* = 275° showed that the outer spiral arms appeared to be trailing and showed an increasing southward shift in galactic latitude with distance in this region. These results were consistent with the Leiden observations and also showed that the hypothesis proposed by Edmondson (1955) - that the mean galactic motions would depart from a circular motion - was unlikely. These findings had first been reported by Carpenter in a paper summarising the work of the Potts Hill survey during an IAU meeting held at Jodrell Bank in August 1955. The paper was only published in 1957 (as part of the conference proceedings)(Carpenter, 1957). It contained slightly more information on the provisional picture of the southern galactic spiral arm structure, as shown in Figure 189, as well as the provisional contour profiles for *l* = 260°, 270° and 275°, as shown in Figure 190.

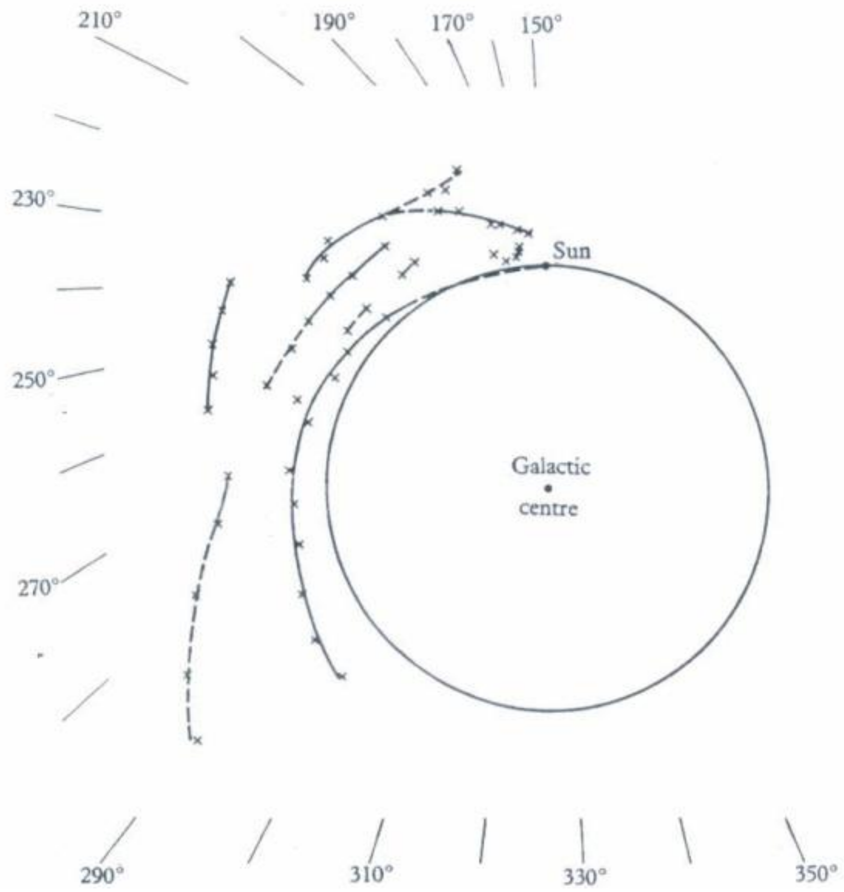

Figure 189: The provisional diagram of the galactic spiral structure based on the Potts Hill observations (after Carpenter, 1957: 15)

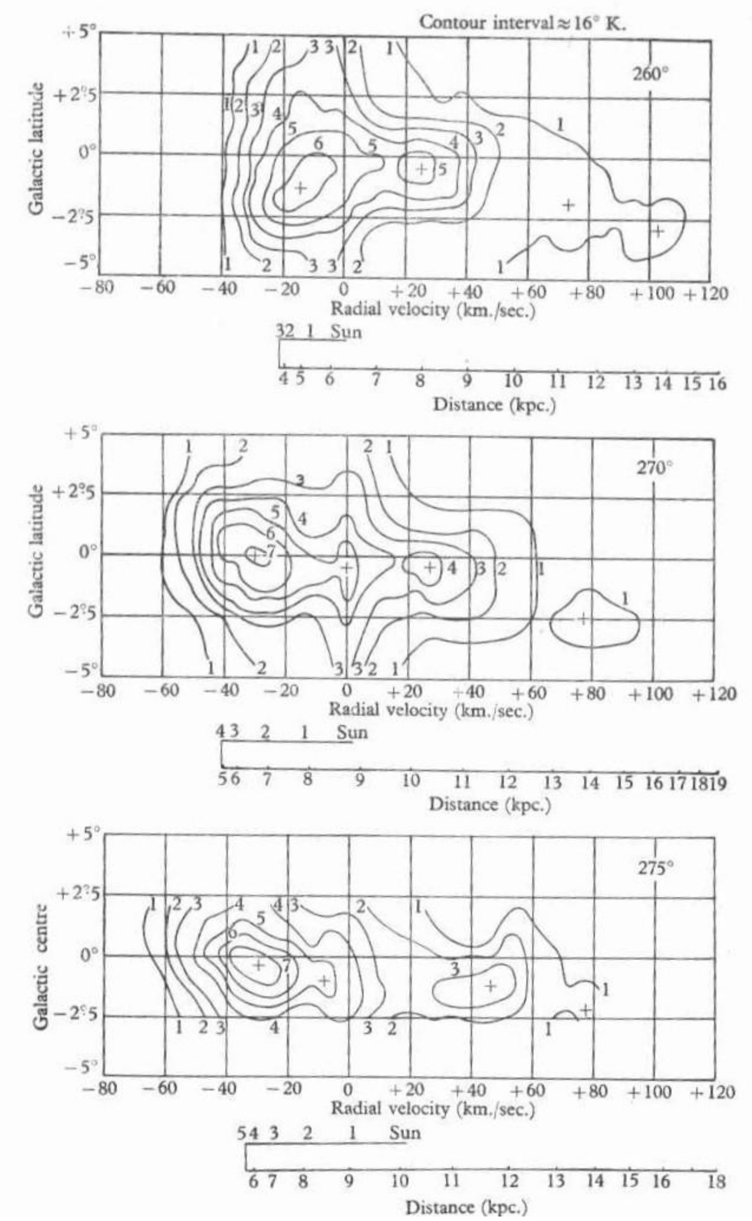

Figure 190: H-line radial velocity contour profiles for the three galactic longitude sections l = 260° (top), 270° (middle) and 275° (bottom) showing three spiral arms in this direction (after Carpenter, 1957: 15).

Figure 190 shows three distinct spiral arms. One of the arms lies within the radius of the Sun's orbit around the Galactic Centre and the other two arms lie outside of this radius. Carpenter noted that the ridge that extends from the zero radial velocity point at *l* = 270° coincided with the position of the Coal Sack.

In May 1957 Kerr published a short note in the *Astrophysical Journal* noting that the southward shift of the spiral arms, which had been discussed in earlier results, appeared to indicate a warp in the galactic disk that coincided with the direction of the Magellanic Clouds (Kerr, 1957). On face value the observation suggested a tidal influence from the Magellanic Clouds. However, the size of the warp was too large to be caused purely by a simple gravitational effect and Kerr suggested a more complex interaction effect was likely. This same effect was also independently noted by Burke (1957).

Finally, in October 1957, a full summary of the southern galactic survey was published in *Nature* (Kerr et al., 1957). Although the results of the northern sky survey had been known since 1954, this was the first time that the full southern and northern sky survey results appeared together. Even then, the analysis of the observations had not been fully reduced. No allowance in these results had been made for the smoothing effect of the aerial beam or for random motions within the interstellar neural hydrogen clouds. However, it was anticipated that these effects would not materially alter the preliminary results.

Drawing on the Leiden observations of the northern sky, for the first time a full-sky map of the structure of the galactic spiral arms could be made. Figure 191 shows the first composite map that combined the Potts Hill and Dutch results.

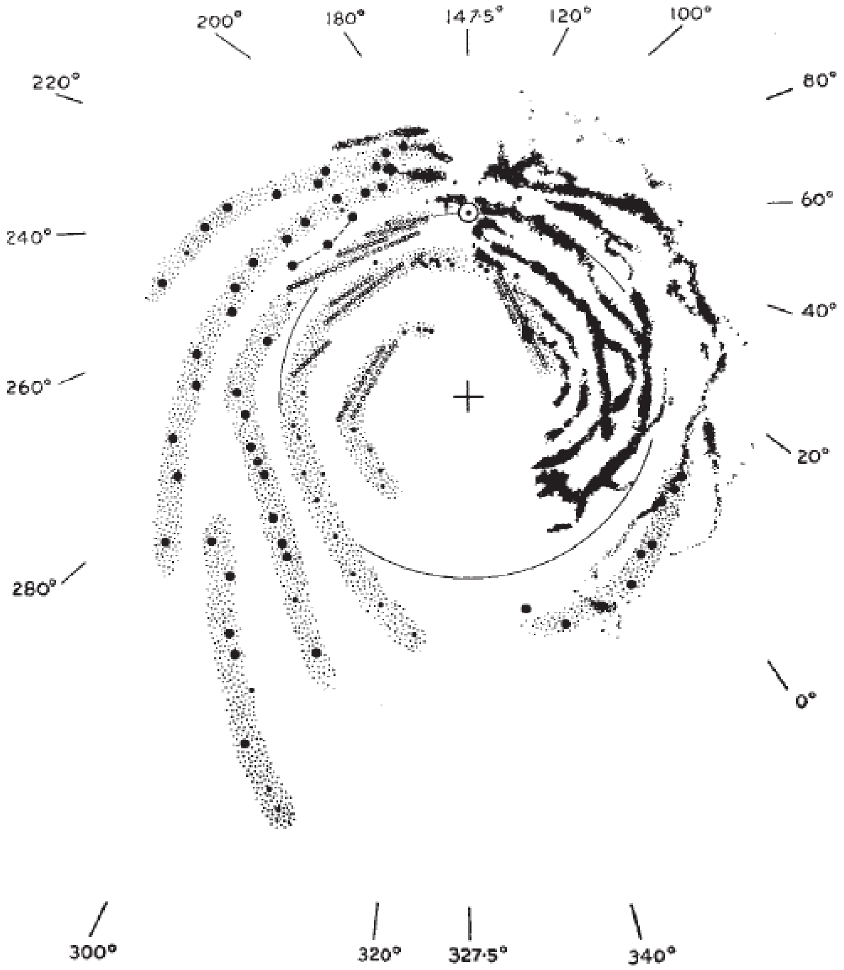

Figure 191: Composite diagram of the spiral structure of the Galaxy based on observations from Potts Hill (left half) and Leiden (right half). The Galactic Centre is marked by a cross and the Sun's position and assumed circular orbit is also shown. A distance of 8.2 kpc from the Sun to the Galactic Centre is assumed (after Kerr et al., 1957: 677).

Figure 191 shows a series of dots that mark the peak line profiles of individual measurements from the Potts Hill data only. Shading joining these dots shows the proposed spiral arm structures. The small open dots shown in the inner left of the diagram correspond to a broad peak on a given profile which was presumed to indicate a spiral arm seen nearly end-on. The distances indicated on the diagram were derived from the radial velocity measurements of the peaks using the same techniques that had been developed in Leiden. The inner 2 kpc of the diagram for the Potts Hill observations had been left deliberately blank due to difficulty in determining the component related to a spiral arm and that due to random motions.

The southern side of the chart showed four distinct spiral arms, which were identified (moving outwards from the Galactic Centre) as the Scutum-Norma arm, the Sagittarius arm, the Orion arm and the Perseus arm. The Sun was believed to be located in the inner edge of the Orion arm. The outer boundary of the Galactic disk appeared to occur at approximately 15 kpc from the Galactic Centre. This identification of the spiral arms has fared well in modern times, the only difference being that the Scutum-Norma arm is now believed to be two separate arms (the Norma arm and the Scutum-Crux arm). The Orion arm is generally referred to as the Local arm. Although today the use of neutral hydrogen to map spiral arms is generally discounted in favour of other techniques, the general picture obtained in Figure 191 was a remarkable achievement. It was not until 1976 (Georgelin and Georgelin, 1976) that a more accurate representation of the spiral arms was produced (Figure 192).

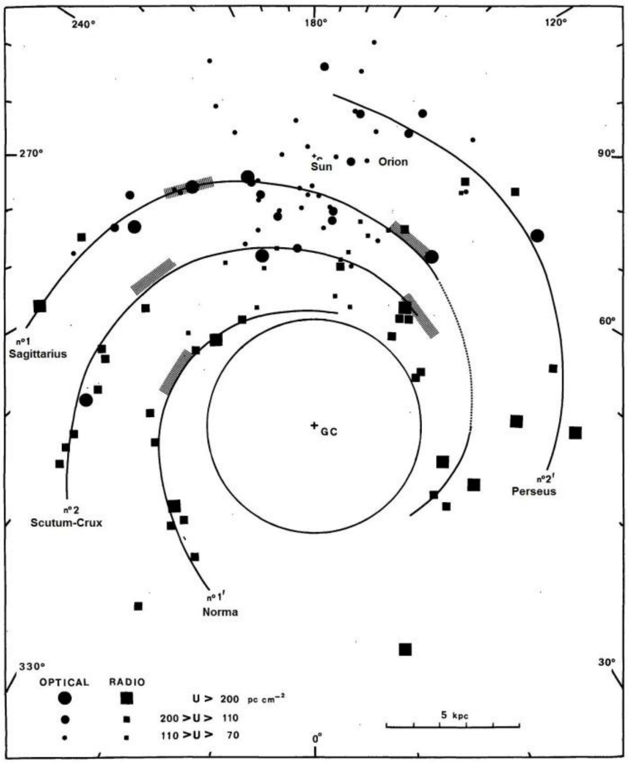

Figure 192: A revised spiral arm map based on optical and radio data with the major arms annotated. Note that the Orion arm was not considered a major feature in this map (after Georgelin and Georgelin, 1976: 74).

It should be noted that the different appearance of the two sides of Figure 191 was due to the different techniques used. The shading in the Leiden results was an ‘artist’s impression’ based on following the density contours. The Potts Hill result is a schematic representation based only on the well-defined features of the line-profiles. While these different techniques produced a different appearance there was still good general agreement between results. Overall the results clearly showed that the Galaxy has a multi-arm structure and that the arms have a general trailing tendency based on the clockwise direction of rotation used in the diagram.

Figure 193 shows a relief map of the Galaxy with contours that show the departure, both upward and downward, from the Galactic Plane. It also indicates the position of the Large and Small Magellanic Clouds.

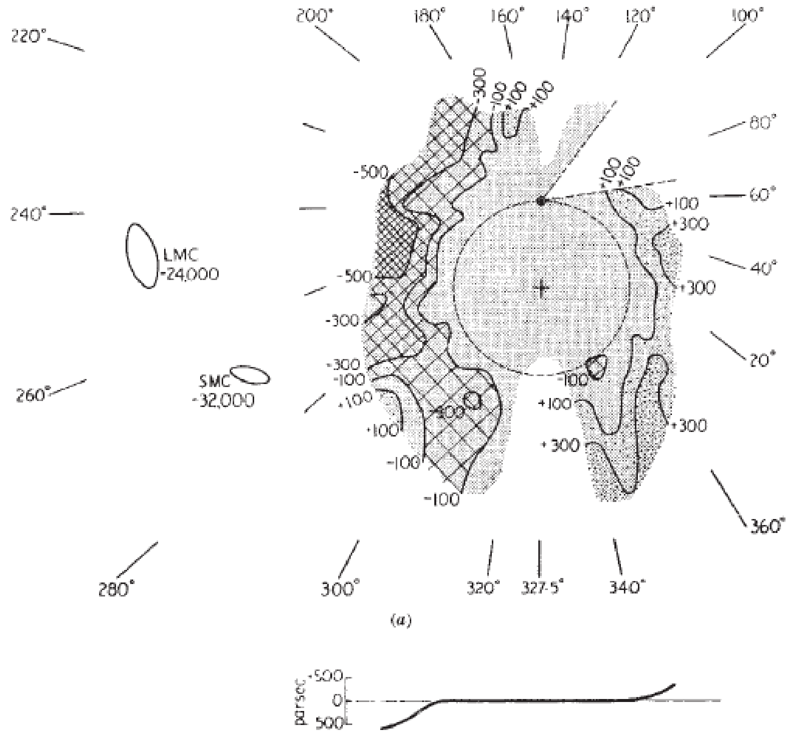

Figure 193: Relief map of the Galaxy with contours indicating the departure in parsecs from the Galactic Plane. The lower portion (b) shows a cross section in the direction of the Large Magellanic Cloud (after Kerr et al., 1957: 678).

Figure 193 clearly illustrates the observed southward and northward warp of the galactic disk. The neutral hydrogen in the galactic disk was observed to be confined to a thin layer approximately 250 parsecs between half density points. In the inner part of the Galaxy this disk was found to be remarkably flat and was used to determine the ‘principle plane’ of the Galaxy. The largest deviation from the principle plane is clearly seen corresponding to the direction of the Large Magellanic Cloud.

These same results were also reported by de Vaucouleurs on Kerr's behalf at the IAU symposium on cosmical gas dynamics held at the Smithsonian Astrophysical Observatory, Cambridge, Massachusetts on June 24-29, 1957 (Kerr, 1958b).

Shortly after the *Nature* summary paper appeared, Kerr and Hindman published a short paper on the mass distribution of neutral hydrogen in the Galaxy (Kerr and Hindman, 1957). Particularly, they noted that neutral hydrogen does not share the same distribution as other mass in the Galaxy. Whereas the visible mass is generally concentrated toward the Galactic Centre, neutral hydrogen is relatively constant beyond 4-5 kpc and falls off rapidly toward the Centre. At the distance of the Sun the relative space density was measured at approximately 15%, while integrating measurements over the whole Galaxy showed the ratio of neutral Hydrogen to total mass was only 2%. Figure 194 shows the ratio of hydrogen to total mass.

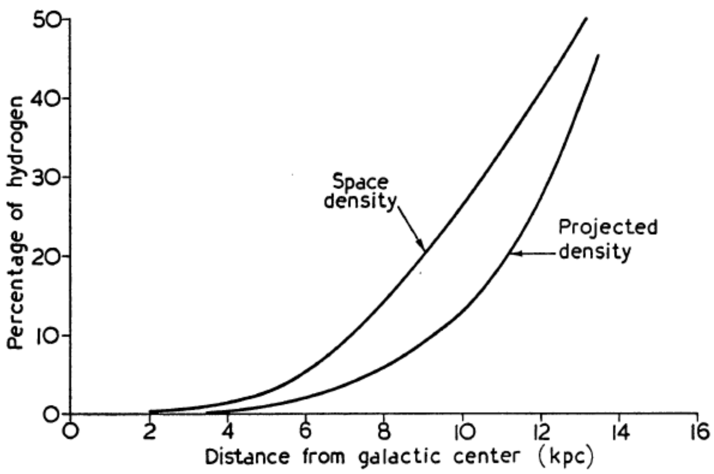

Figure 194: The measured ratio of neutral hydrogen to total mass in the Galaxy with the space density in the equatorial plane compared to the projected density that corresponds to the distribution that would be seen from outside of the Galaxy (after Kerr and Hindman, 1957: 559).

The distinction in the mass densities was important because if the density in the region of the Sun was assumed as a generalisation of overall density in spiral galaxies, large errors would result. Measurements of M31 had shown a ratio of approximately 1%, which compared well with these results. The earlier measurements of the Magellanic Clouds had suggested ratio of 20%, which Kerr and Hindman took to indicate that the two Magellanic Clouds were much younger than our Galaxy.

The final detailed paper on the southern survey was published in the *Australian Journal of Physics* (Kerr et al., 1959). This paper contained a full set of line profiles together with a set of intensity contours plotted as a function of galactic latitude and radial velocity. An example for the contour diagrams is shown in Figure 195.

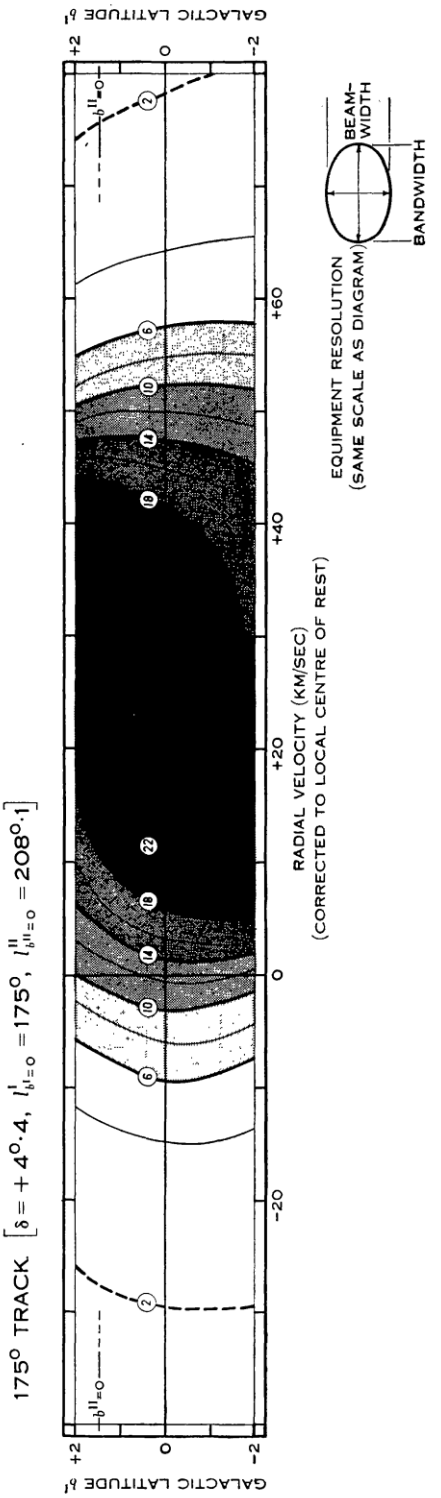

Figure 195: An example of the H-line intensity contour diagram. The galactic latitude b^{I} is the 1932 Galactic coordinate system.

During 1957, Kerr spent several months visiting the Dutch group at Leiden with the specific purpose of combining data on observations from the Southern Hemisphere. This work resulted in a joint paper between the Australian and Dutch groups summarising the understanding of the Galaxy as a spiral system

(Oort et al., 1958). This included an update of the rotation curve derived from both the Leiden and Potts Hill observations and is shown in Figure 196. It is interesting to note that the two sets of data would actually produce two slightly different rotation curves if treated individually. This is something that Kerr would examine in a later review (Kerr, 1962).

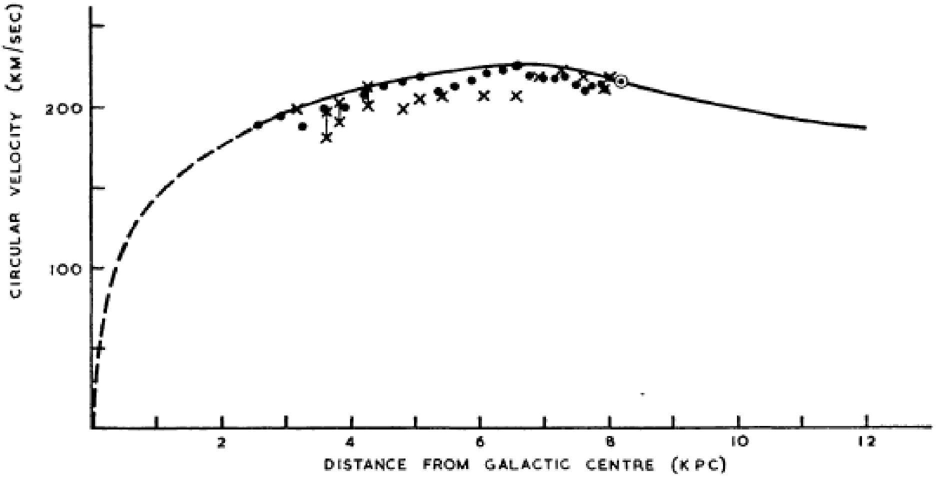

Figure 196: Derived rotation curve of the Galaxy based on the Leiden (dots) and Potts Hill (crosses) H-line observations. The assumed distance of the Sun from the Galactic Centre is 8.2 kpc (after Oort et al., 1958: 381).

For the first time Oort et al. (1958) also published a combined density map of neutral hydrogen, as shown in Figure 197.

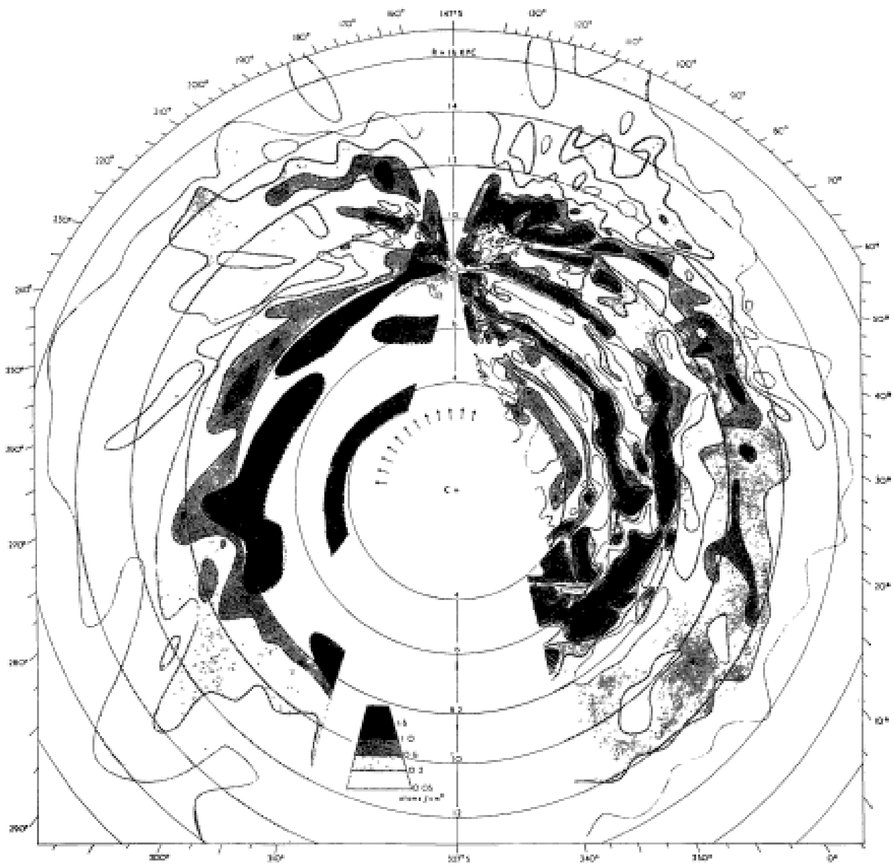

Figure 197: The density distribution of neutral hydrogen in the Galactic Plane. The maximum densities in the z direction are plotted on the Galactic Plane and the points of common density are joined by contours (after Oort et al., 1958: Plate 6).

In the inner 3 kpc of this map a tentative identification of a new ‘expanding’ arm was shown marked by a row of arrows. Within this inner region the team found evidence of an expanding motion of the neutral hydrogen with deviations from the expected circular rotation of up to 200 km/sec. They named this arm the “3-kpc expanding arm”, a name which is still used today (although generally the “expanding” term has dropped).

The joint team also published an updated map, shown in Figure 198, of the deviation of neutral hydrogen from the principle plane of the Galaxy, as measured by the H-line observations. This plane was approximately inclined 1.5° to the then ‘standard’ plane.

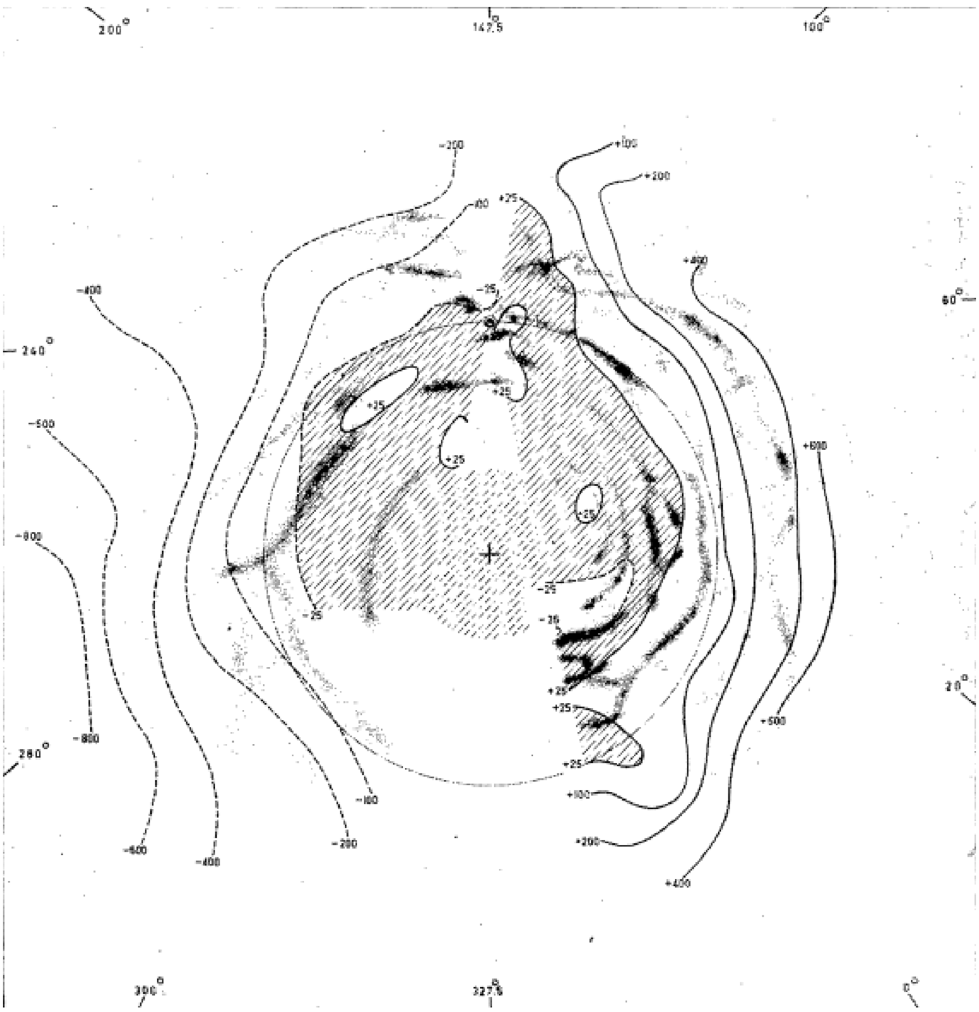

Figure 198: Deviation of neutral hydrogen from the principle plane of the Galaxy. Note the image has been colour inverted from the original (after Oort et al., 1958: Plate 5).

The deviation map showed new detail in the region inside of the Sun's orbit around the Galactic Centre.

Figure 197 appears to show some differences between the northern and southern parts of the Galaxy. However, this effect is largely due to the differences in reduction techniques used by the two groups. While the Australians had applied generally the same technique as the Dutch, including the same velocity model, they employed a less dramatic reduction for random motions, using a normal Eddington coefficient rather that the double coefficient used by the Dutch. Kerr also made no allowance for continuum radiation in the inner regions. These two differences resulted in less detail than the Dutch side of the map. Others (van Woerden and Strom, 2006: 12) have noted there appeared to have been some minor disagreements between the groups as to the validity of the corrections and this may have been why Kerr had not performed exactly the same reductions. This is confirmed by Kerr who noted:

"...our views about the best [reduction] procedure differed to some extent." (Kerr, 1962: 329)

The differences in reduction techniques used by the groups was discussed in detail in a later review by Kerr (1962), who found that the velocity model used by the Leiden group would lead to an implausible spiral structure on the southern side of the Galaxy assuming that the structure and motions are symmetrical on the large scale. Kerr proposed that the results could be reconciled if it was assumed that the Sun had an outward velocity component of 7 km/s. Figure 199 shows a revised density distribution map based on the new rotational model and allowing for the outward motion of the Sun. This map shows the spiral arm structures more clearly than the original map shown in Figure 197.

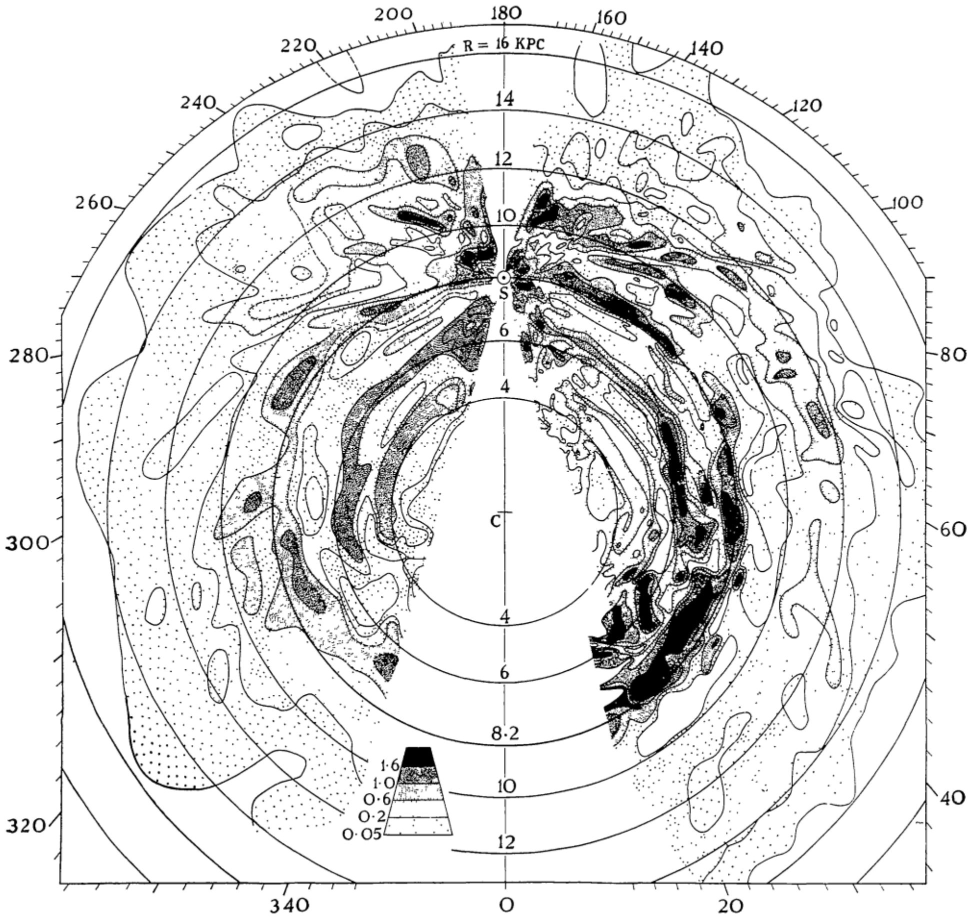

Figure 199: Revised density distribution of neutral hydrogen in the Galactic Plane based on a new rotation model and assuming an outward motion of the Sun of 7 km/s (after Kerr, 1962: 340).

The combined maps provided a solid foundation for examination of our Galaxy's HI structure. However, in later years other techniques would provide the basis for a more accurate determination of the spiral arm structure. The use of neutral hydrogen observations to determine Galactic structure has a number of short comings. Like all kinematic methods it is necessary to assume a rotation model to convert the observed radial velocities into distances. These models generally assume circular orbital motions and therefore do not cater for non-circular motions. For orbits inside of the Sun, the models give two possible distances for any observed radial velocity and this can present difficulties in determining which distance is applicable for a given observation. Possibly the largest issue with the neutral hydrogen observations was that the observations were the result of integration along the line of sight. This means that it is not clear whether a given line profile's characteristics are the result of streaming motions, a density concentration, or a variation in gas temperature (Burton, 1973). In later years, and with the discovery of the hydrogen recombination and the carbon monoxide spectral lines, the focus shifted to measuring these more discretely-concentrated sources to determine our Galaxy's structure.

Given the growing body of evidence from the radio surveys at the 1955 General Assembly held at Dublin the International Astronomy Union appointed Sub-Commission 33b "...to investigate the desirability of a revision of the position of the galactic pole and of the zero point of galactic longitude". The members of the Sub-Commission were A. Blaauw, C.S. Gum (who was unfortunately killed in a skiing accident in Switzerland on 28 April 1960 shortly after the completion of the Sub-Commission's final report), J.L. Pawsey and G. Westerhout.

Up until this time, the Galactic Pole had been located at right ascension $12^h\ 40^m$, declination +28º (1900.0) and was used as the basis for the standard conversion to galactic coordinates in the *Lund Observatory Conversion Tables* (Ohlsson, 1932). By the time of the next General Assembly meeting in Moscow in 1958, enough preliminary evidence had been gathered, particularly from the neutral hydrogen surveys, to recommend that it would be opportune to adopt a new system of galactic coordinates and as such the General Assembly passed a resolution for the Sub-Commission to define and announce a new system of coordinates. In March 1959 the Sub-Commission completed its investigations and communicated its decision to the General Secretary of the I.A.U. and various astronomical journals. A series of five papers was published which together formed the final recommendations of the Sub-Commission (Blaauw, 1960; Blaauw et al., 1960; Gum et al., 1960; Gum and Pawsey, 1960; Oort and Rougoor, 1960). The new position of the Galactic Pole was determined as:

α = 12h 49m 02s ± 30s (1950.0)
δ = 27º 22′.7 ± 7′

Figure 200 shows the position of the new Pole determined from radio observations relative to Ohlsson's 1932 pole.

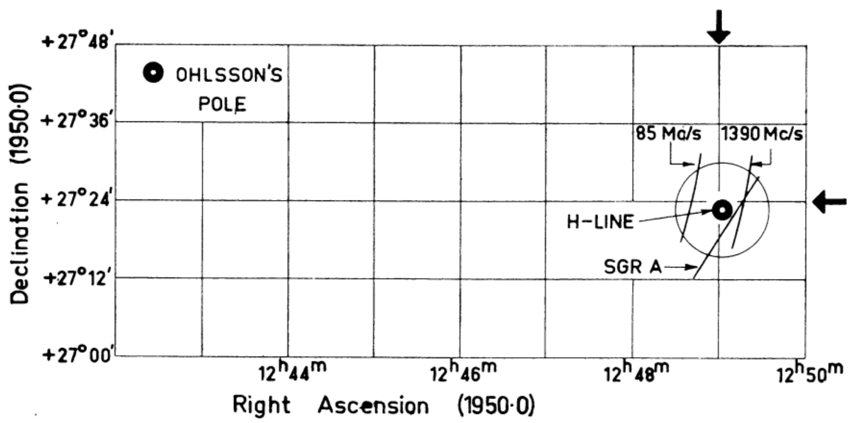

Figure 200: Position of the new (1958 revision) of the Galactic Pole relative to Ohlsson's 1932 Pole (after Blaauw et al., 1960: 129).

The key paper out of the five that made up the Sub-Committee's final report was the analysis of the combined Leiden and Potts Hill neutral hydrogen observations (Gum et al., 1960). In this analysis, Gum, Kerr and Westerhout essentially conducted a new analysis of data from the two surveys. By selecting a number of points within the inner 7 kpc of the Galaxy, a least mean square analysis of different selection groups showed close agreement and indicated that this region was virtually indistinguishable from the principle plane of the Galaxy. Figure 201 shows the distribution of points of maximum hydrogen density plotted by heights (*z*) above the new Galactic Plane against distance (*R*) from the Galactic Centre. The warping of the neutral hydrogen disk above and below the Galactic Plane is clearly evident outside of the Sun's orbit at 8.2 kpc.

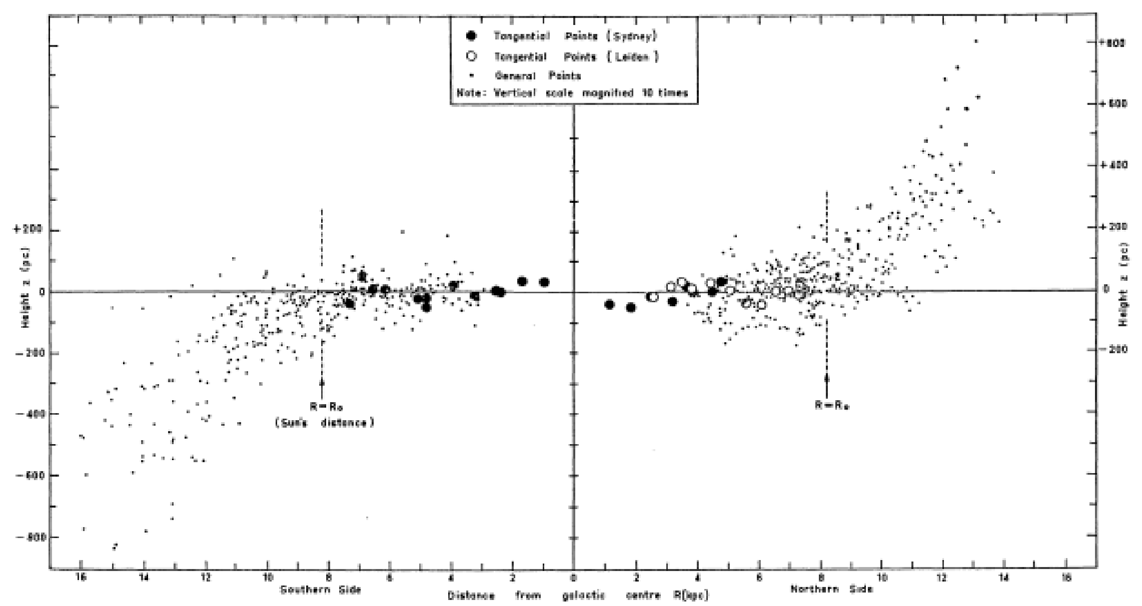

Figure 201: Distribution of points of maximum density of neutral hydrogen. Solid circles indicate tangential points measured from Potts Hill. Open circles indicate tangential points measure from Leiden. The small dots are all measure points from the two surveys (after Gum et al., 1960: 141).

The other Potts Hill contribution was in Paper III (Gum and Pawsey, 1960), which examined the overall radio continuum and the position of the radio source Sagittarius A. A key set of observations were derived from the 600 MHz survey that was conducted at Potts Hill by Piddington and Trent (1956a,b). Figure 202 shows the positions of the radio continuum ‘ridge-lines’. The central diagram contains the 600 MHz survey data and is indicated by the filled black dots. It can clearly be seen that the narrow-beam survey data provided strong support for the newly defined Galactic Equator as determined from the neutral hydrogen measurements.

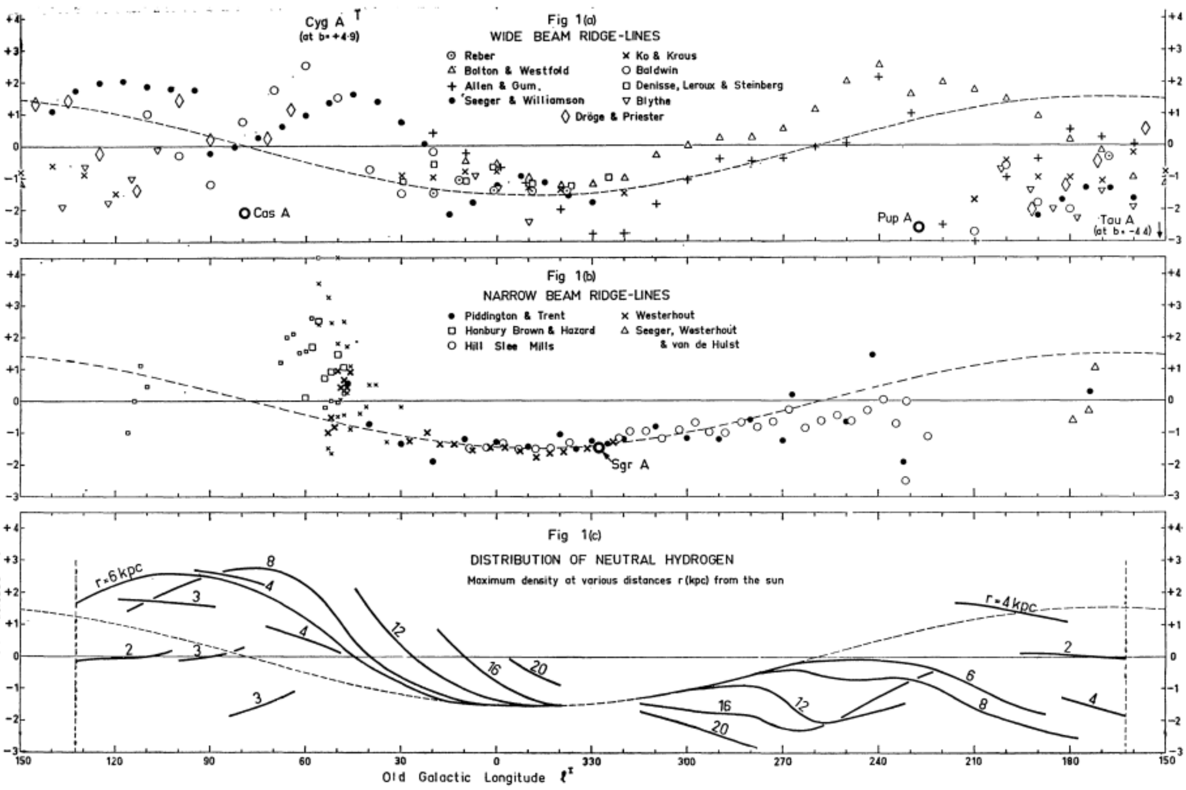

Figure 202: Wide beam (left), narrow beam (centre) and neutral hydrogen (right) radio continuum ‘ridge-lines’. Data plotted using the 1932 galactic coordinates. The dotted sine curve indicates the newly-derived Galactic Equator (after Gum and Pawsey, 1960: 153).

By mid 1959 much of the research effort at Potts Hill had been completed, as noted in an internal report (Pawsey, 1959a). The 21-cm survey of the Milky Way had been completed although the research results were still being written up. It was decided that the 36-ft Parabola and its equipment hut would be maintained at Potts Hill for receiver testing until such time as the new laboratory facilities, which were being constructed at Epping as part of the new headquarters for the Radiophysics Division, were completed. It was also noted that the continuing solar recording at Potts Hill, which was now the responsibility of Fairweather, would continue only as long as required to support observations using the Chris Cross at Fleurs and Wild's solar burst investigations at Dapto. A new 48-channel H-line receiver and fully steerable 21-ft parabola were constructed at a new field station at Murraybank in 1956 and were used to continue the H-line program of observations and to act as a test bed for equipment that would later be deployed for the Parkes Radio Telescope (Orchiston and Slee, 2005a: 160).

10.5.3. Jupiter Burst Observations

During February and March 1956, Potts Hill was used as a secondary field station as part of the investigation of radio emissions from Jupiter by Gardner and Shain (1958). The main instruments were located at the Fleurs field station some 25 km to the west of Potts Hill.

Radio emission from Jupiter had first been detected in the U.S.A. by Burke and Franklin (1955) using a 'Mills Cross' operating at 22.3 MHz. It was only after this discovery that Shain found, by examining 18.3 MHz Hornsby Valley field station records, that he had in fact detected the Jovian burst emissions in 1951 but that they had gone unnoticed at the time. In examining the 1951 records Shain (1955, 1956) found that the emission appeared to come from a localised region on the planet (Orchiston and Slee, 2005b).

In order to compare results with those from Fleurs, at Potts Hill a simple dipole antenna was suspended between two wooden poles and connected to a receiver operating at 19.6 MHz. This formed part of a spaced-aerial experiment to determine if the scintillations in the radio emission were inherent in the source itself or caused by the ionosphere. The receivers at both sites were closely tuned to avoid discrepancies caused by sharp spectral variations in the burst signals. The high levels of radio interference at Potts Hill meant that only three pairs of results from the Potts Hill and Fleurs were available for comparison. Figure 203 shows an example of the spaced-receiver records taken simultaneously at Potts Hill and Fleurs.

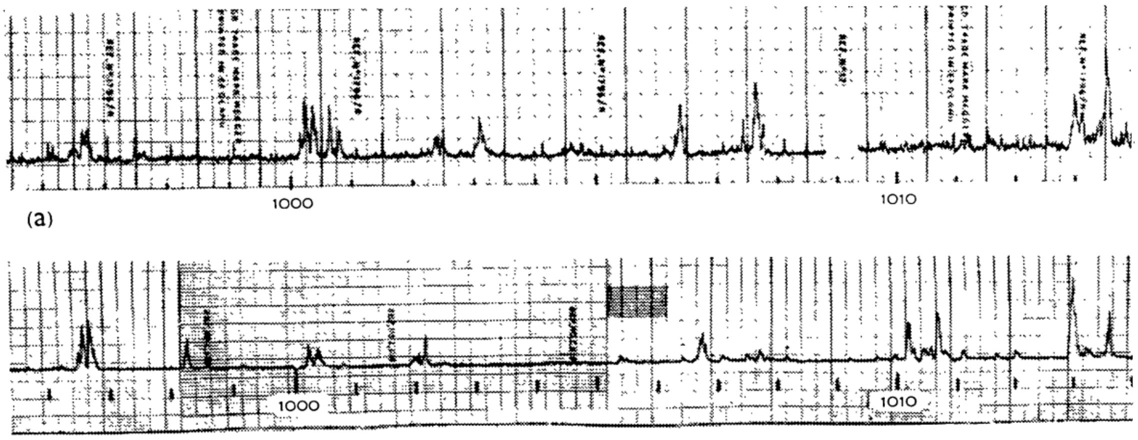

Figure 203: The spaced-receiver records for Potts Hill (top) and Fleurs (bottom) taken at 19.6 MHz on February 26, 1956 (after Gardner and Shain, 1958: 60).

An examination of the records showed significant differences between the two sites with some bursts observed at only one of the two sites. There also appeared to be timing differences between the sites and some differences in the burst characteristics. Gardner and Shain (1958) concluded that these differences between the sites indicated that the terrestrial ionosphere must have a considerable effect on the time variations of the Jupiter radiation.

Jovian observations over a 200 km baseline by Slee and Higgins (1968) later showed that the so-called bursts are due to scintillations caused by diffraction in the solar wind.

10.5.4. 1952 URSI General Assembly

In recognition of the growing contribution of Australian research to the new science of radio astronomy, the 10th General Assembly of the URSI was held in Sydney from 11 to 23 August 1952 (see Robinson, 2002). This Section provides a brief discussion of the conference and the role played by the Potts Hill researchers.

The organising committee for the Sydney event consisted of Sir J. Madsen (Chairman), Dr. E.G. Bowen, Dr. R.N. Bracewell (Secretary), Mr. J.N. Briton, Mr. F.J. Lehany (Treasurer), Dr. D.F.M. Martyn, Dr. G.H. Munro, Dr. J.L. Pawsey. All but Madsen, Martyn and Munro were Radiophysics staff.

In March 1952 Pawsey sent out a memo to all Research Officers within the Radiophysics Division calling for the submission of papers for the General Assembly (Pawsey, 1952e). Additionally, he also sent a copy of the memo to K.C. Westfold and wrote a separate letter to Mrs. Hall (Ruby Payne-Scott) asking if she and Alec Little would like to submit a paper. Pawsey stated in this letter:

"...in my 'provisional' list, unofficial, I include your work with Alec as one of our *star* efforts." (Pawsey, 1952d).

Pawsey also noted:

"...if such a paper is to be presented verbally at the Conference I think you would do it excellently." (ibid.).

Payne-Scott wrote back on 20 March noting that Alec Little was on leave and therefore she had been unable to discuss the submission with him (Payne-Scott, 1952). She included a hand-written one-page outline titled, *"The Relation between Solar Radiation at Metre Wave-Lengths and Other Solar Phenomena"*. The outline included two key sections that concluded that Noise Storms originate high in the corona with different frequencies appearing at different levels, probably excited by magnetic fields associated with sunspots, while Outbursts were probably caused by excitation from the same particles that were presumed to cause magnetic storms on Earth. On 26 March, Pawsey replied that he had discussed the outline with Paul [Wild] and that he also favoured the idea of presenting the paper (Pawsey, 1952a). He concluded that all three should meet to discuss the submission when Wild returned from a visit to the Dapto field station. For unknown reasons no further correspondence on this subject appears on file, and although Payne-Scott did attend the Conference, she did not submit a paper.

At the end of April 1952, the Radiophysics Division formally submitted four papers for consideration:

1) Galactic Hydrogen Emission on 1420 mc/s. By J.L. Pawsey (Paper 276).
2) The Nature of Discrete Sources of Cosmic Radio Radiation. By B.Y Mills (Paper 277).
3) Extended Sources of Galactic Noise. By J.G. Bolton (Paper 278).
4) A Multiple Interferometer for Solar Observation at a Wavelength of 21 cm. By W.N. Christiansen (Paper 279).

All four papers were accepted, two being based on the work at Potts Hill. In late June, Piddington wrote to Pawsey asking to include a late paper he was preparing with Davies titled, *"Thermal Radiation from the Sun and the Source of Coronal Heating"* (Piddington, 1952). Pawsey replied on 10 July that he considered that only in exceptional circumstances would a late request be granted and that he did not consider the paper to be of sufficient importance for its late inclusion (Pawsey, 1952b). He did however suggest that another of Piddington's papers on sources of galactic radiation, did warrant inclusion and he was prepared to support its late submission. This paper was accepted, and, along with another paper by J.W. Dungey from The School of Physics at the University of Sydney, made up the final two papers from Australia submitted to Commission V:

5) On Bailey's Theory of Sunspot Noise. By J.W. Dungey (Paper 280).

6) Model of Sources of Galactic Radio-Frequency Radiation. By J.H. Piddington (Paper 281).

Unfortunately the Executive Committee of the URSI decided to discontinue publication of Part II (Papers) of the Assembly Proceedings and therefore the presented papers were not published.

In the report to the URSI on the Australian National Committee of Radio Science 1950-52 under Commission V – Radio Astronomy the following was noted:

> "The greater part of the research in radio-astronomy in Australia is carried out by the Radiophysics Laboratory of the C.S.I.R.O. in Sydney, the observations being taken at a number of field stations near the fringe of the built up area. The largest of these is at Potts Hill. This laboratory is concerned with cosmic and solar radio waves."

The conference itself was a major success with many strong bonds formed between the visiting researchers and the staff from the Division of Radiophysics. It was at this conference that Christiansen established the relationship with the French group that would lead to him spending a year in France. Also, it provided the opportunity for nearly all of the people involved in the initial H-line detection to meet face-to-face. Figure 204 shows the Radiophysics members who attended the conference together with their counterparts from France, England, the Netherlands and the U.S.A.

Figure 204: Some of the attendees at the 1952 URSI Meeting in Sydney. From left to right: First Row: J.G. Bolton, O.B. Slee, M. Laffineur (France), A.G. Little, R. Payne-Scott, R. Hanbury Brown (England), C.A. Shain, C.F. Smerd, J.L. Steinberg (France), B.Y. Mills, J.P. Wild, F.G. Smith (England), W.N. Christiansen. Second Row: C.A. Muller (Netherlands), F.J. Kerr, H.I. Ewen (U.S.A.), J.V. Hindman, J.P. Hagen (U.S.A.), C.S. Higgins. Third Row: L.W. Davies, E.R. Hill, J.H. Piddington (Courtesy of ATNF Historical Photographic Archive: 2842-43 Image Date: 8 August 1952).

As an adjunct to the conference, visits were also organised to three of the Radiophysics field stations, one of these being Potts Hill. Figure 205 shows Professor Balthasar van der Pol from the Netherlands and Sir Edward Appleton inspecting the E-W Solar Grating Array with Christiansen standing next to one of his antennas. This photograph was reproduced in several Australian newspapers at the time.

Figure 205: From Left to Right are Christiansen, Appleton and van der Pol inspecting the E-W Solar Grating Array during the 1952 URSI meeting (Courtesy of ATNF Historical Photographic Archive: B2842-R61 Image Date: 8 August 1952).

The conference was recounted by Frank Kerr (1953c) in an article in the January 1953 edition of *Sky & Telescope* which helped to further publicise the contribution of Radiophysics (and hence Potts Hill) research amongst the wider astronomical community.

For further recollections of the 1952 URSI meeting see Robinson (2002) who attended the meeting having graduated in Physics in 1951.

11. RADIO ASTRONOMY AT MURRAYBANK

The researchers at Murraybank field station had a close relationship with those from Potts Hill, being the only other Australian site involved in investigating the Hydrogen-Line emission from the Galaxy and the Magellanic Clouds in the late 1950s and early 1960s. This section examines the Murraybank field station, its researchers and the scientific contribution which they made.

Murraybank operated from 1956 to 1961 (Orchiston and Slee, 2005a). The field station was established to test the operation of a new 48-channel H-line receiver in preparation for its potential installation in the 64-m Parkes radio telescope when it became operational in late 1961. This receiver (also known as the Murraybank Mk1 multi-channel line receiver) became one of the first operational observing systems to be installed on the Parkes telescope (Brooks and Sinclair, 1994).

11.1. Murraybank Researchers

In examining the development of the Murraybank field station and its scientific contribution, there are two additional members of the Radiophysics team who need to be considered and who did not work at Potts Hill; John Murray and Dick McGee.

11.1.1. J.D. Murray

John D. Murray joined Radiophysics in December 1947 after moving from Hobart, Tasmania. He was involved in both the 1948 and 1949 solar eclipse expeditions and was part of the Tasmanian observation team in both cases (see Orchiston et al., 2006; Wendt et al., 2008).

Initially he worked on the development of the Radiospectrograph that was installed at the Dapto field station. This was a major undertaking and the instrument was some two years in development. In 1953 he was asked by Pawsey to work on the development of a new multi-channel H-line receiver which eventually led to the establishment of the Murraybank field station. Together with McGee, Murray undertook a complete southern-sky survey at 21-cm using the newly developed receiver.

In October 1961 he moved to the Netherlands where he worked on the development of the Benelux Cross, and thus ended his involvement with Murraybank. Murray returned to Radiophysics in June 1964 and was a member of the team that discovered the Magellanic Stream (Mathewson et al., 1974) and went on to have a distinguished career with Radiophysics.

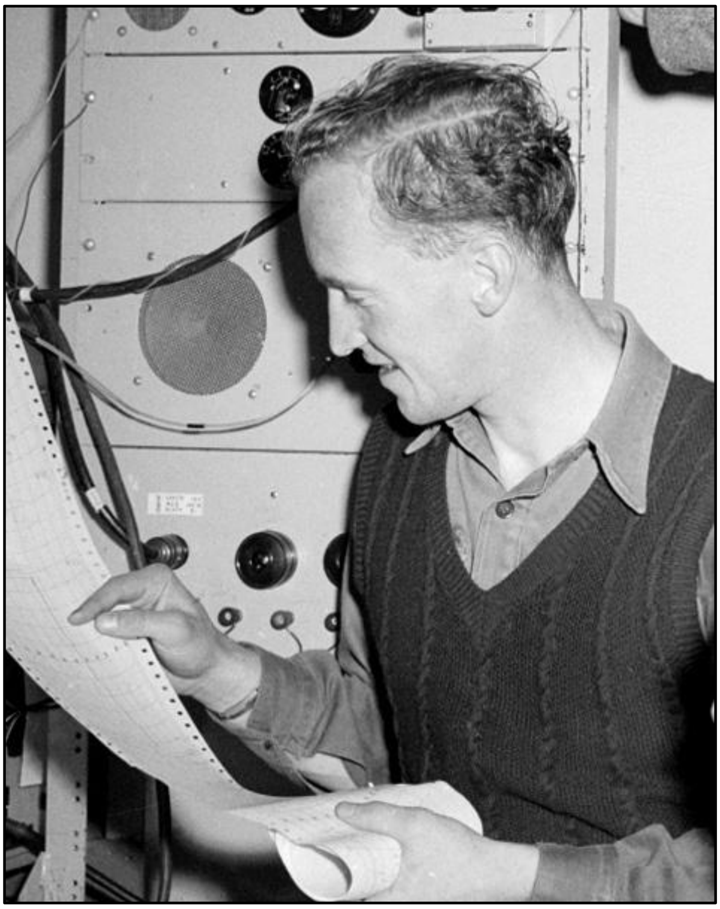

Figure 206: John Murray in 1949 (Adapted from the Mercury Newspaper, Tasmania)

11.1.2. R.X. McGee

Richard (Dick) X. McGee (Figure 207) joined Radiophysics in December 1950. He initially worked at the Dover Heights field station, and carried out much of the observing and data reduction for the 400 MHz transit survey using the 80-ft hole-in-the-ground telescope (McGee et al., 1955). An important finding from this survey was published in a joint paper by McGee and Bolton (1954) that appeared in *Nature*. It is this paper that is often incorrectly cited, crediting the authors with the discovery of the discrete source, Sagittarius-A, at the Galactic Centre (see Orchiston and Slee, 2002), although the paper certainly brought the source and its position to the attention of the wider scientific community.

From Dover Heights, McGee joined Murray to work on the development of the multi-channel H-line receiver and the 21-ft parabolic antenna that was installed at Murraybank. McGee was the lead author on all three papers in the series on the southern-sky H-line survey. He was also involved in the development of the digital recording and computer reduction system that was trialled at Murraybank prior to its installation at Parkes. The Murraybank survey of the Magellanic Clouds was the beginning of a long association with studies of these galaxies for McGee. He was also involved in some of the earliest measurement of molecules in our Galaxy using the Parkes 64-m telescope.

McGee had a 32 year career as a Radio Astronomer, retiring from Radiophysics in 1986.

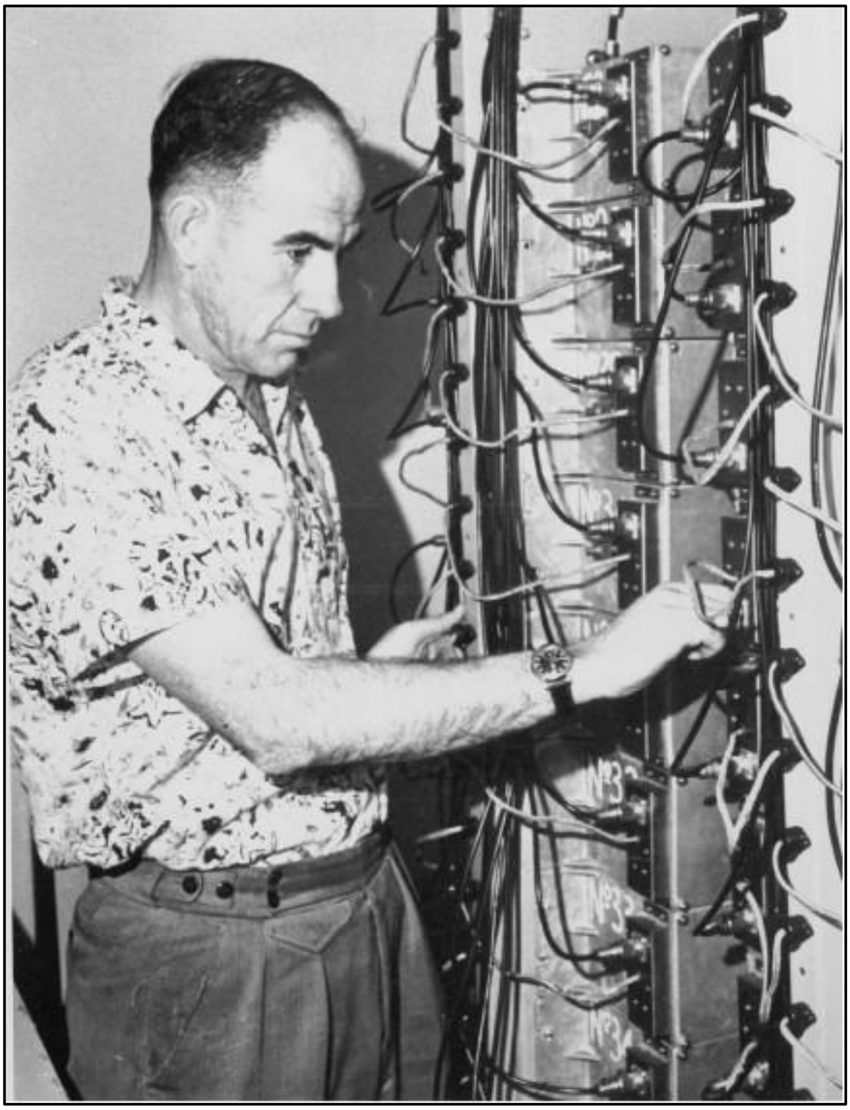

Figure 207: Dick McGee working on the 48-channel receiver at Murraybank (courtesy of Miller Goss).

11.2. The Establishment of Murraybank

In June 1953, Murray was summoned to the Radiophysics headquarters in the grounds of Sydney University to meet with Pawsey (Murray, 2007). Pawsey was unhappy with the progress being made on the development of the 4-channel H-line receiver at Potts Hill and asked if Murray would assist. Murray (2007) also recalled that while he was waiting to meet with Pawsey, John Bolton came storming out of Pawsey's office. This was the point where Bolton's proposal to construct a large interferometer had been rejected in favour of construction of the Mills Cross. Bolton therefore decided to leave the Radio

Astronomy Group and to work in Cloud Physics until January 1955 when he accepted the position as Professor of Physics and Astronomy at the California Institute of Technology.

Murray worked with Kerr, Hindman and Robinson at Potts Hill and after some time he concluded that it was very unlikely that the original receiver design could be improved and that it would be necessary to change to a switched system to overcome the issues with receiver drift that plagued the original design. Murray felt that it would be near impossible to get a stable bandwidth from vacuum tubes using the original design. While the filters were all on the same frequency the design worked well, but the further they were shifted apart in frequency, the more they drifted apart (Murray, 2008). After Murray reported back, Pawsey decided that it would be prudent to launch a new project. The aim of this project was to design a new type of multi-channel receiver that addressed the limitations of the original 4-channel design. This decision would ultimately lead to the establishment of a new field station called Murraybank, which was located at West Pennant Hills in the north-western suburbs of Sydney. To their credit, Kerr's team persisted and after many modifications to their receiver, managed to get it to a point where reliable observations were possible, first with a single channel, and later with all four channels.

By November 1953 three main streams of work were being undertaken within Radiophysics on radio frequency spectral-lines (Kerr, 1953a):

1. Work led by Kerr at Potts Hill on the 4-channel H-line receiver and the subsequent survey of the Magellanic Clouds and the Galaxy.

2. Work at Dover Heights to attempt to detect the red-shift in external galaxies and a search for the 327 MHz deuterium-line by Stanley and McGee (later joined by Price).

3. Work on development of a new type of multi-channel H-line receiver in the laboratory initially led by Murray.

The subsequent success of the Potts Hill H-line survey has already been discussed in Section 10.5.2.2.

The search for the deuterium-line at Dover Heights ultimately proved unsuccessful and no evidence of adsorption or emission from the Galactic Centre was found. Although the detection of high red-shifted HI in external galaxies had been proposed as an objective, no detection attempt was made after the negative deuterium-line result. The negative result was reported (Stanley and Price, 1956) only after other negative search attempts began to appear in the literature. At the I.A.U. Symposium No.4 on Radio Astronomy held at Jodrell Bank from 25-27 August 1955, G.G. Getmanzev and K.S. Stankevitch from Gorky State University, U.S.S.R, reported that they had detected a absorption line from deuterium at 327.4 MHz using a

4-metre paraboloid. The detection claim was met with some scepticism. In the discussion following the presentation Pawsey noted that Stanley and Price had been unsuccessful in 1954 using the 80-ft Dover Heights hole-in-the-ground aerial and Hey also noted they had made an unsuccessful attempt at Malvern in the U.K. (Getmanzev et al., 1957: see discussion notes). The interest in pursuing the detection of deuterium was, and still is, that deuterium was believed to have been formed soon after the Big Bang and hence its abundance provides important information on the formation of the early universe. Although the deuterium line at 327 MHz is well separated from other radio-frequency spectral lines, it is extremely weak. Most observers, like the Dover Heights team, were only able to establish an upper limit for detection. Although there have been many claims of a marginal detection, it has only been quite recently that a detection seems likely (Rodgers et al., 2005). The unsuccessful search for the deuterium-line also signalled the death knell for further research at Dover Heights, with the field station being decommissioned in 1954 (Orchiston and Slee, 2002).

As an interesting aside, in an outline of the potential for spectral-line investigations, Kerr raised the possibility of not only searching for the deuterium line at 327 MHz, but also the 3He line near 9,000 MHz (Christiansen, 1952). Goss (2008) has noted that this appears to be one of the earliest references to the potential for the 3He line being considered (e.g. compared to Goldwire and Goss, 1967; Townes, 1957).

The development of a new multi-channel H-line receiver was a major undertaking and, after some initial experimentation, a broad plan was drawn up by Murray in early 1954 outlining the steps necessary to complete the receiver design. In May 1954 in a letter to Oort, Pawsey noted:

> “We are working on the development of a multi-channel receiver (e.g. 30-channel) but, although I am happy about the objective, our equipment is not yet satisfactory.” (Pawsey, 1954a).

By June 1954 more progress had been made on the power supplies and the first stage local oscillator, but many components including the channel filters remained on the drawing board and the question still remained as to when an operational receiver could be produced. The work on the receiver was being conducted in the Radiophysics laboratory workshops. Murray had to compete for resources with many other projects and with the other Radiophysics groups such as Air Navigation and Cloud Physics. While attempts were made to explore the possibility of outside groups such as A.W.A. constructing some of the components, no outside interest could be generated (Murray, 2008).

At the June meeting of the Hydrogen-Line Planning Committee the need for a “...Following Aerial...” for future H-line work was discussed. The Potts Hill 36-ft aerial (being a transit instrument) imposed limitations on examining fine structure and access to some parts of the southern sky. The idea of constructing a new paraboloid of approximately 25-ft diameter and re-using a mount from Dover Heights was suggested and Hindman was tasked with looking at the feasibility of upgrading of the Dover Heights mount. It was at this stage that the question of a new site for H-line work was first raised:

> "The question of a new site more free from interference than the present Potts Hill position was deferred until more evidence on the sources of interference and the future expansion of the same become available in this regard. It was noted that the Water Board is intending building a welding shop on the old Balt camp site at Potts Hill. (Note: This has since been confirmed with the engineer on the site and steel for the construction of buildings has commenced to arrive)." (Kerr, 1954c).

With the likelihood of increased levels of electrical interference at Potts Hill, it was subsequently agreed that a new site would be necessary. The selection of the site was somewhat simplified when John Murray's father, who had an orchard called Rosebank at West Pennant Hills, offered to allow Radiophysics to setup a new field station on his property. This field station would become known as Murraybank i.e. the concatenation and abbreviation of Murray's orchard and Rosebank. Murray (2008) has also noted that there were a lot of other "bank" stations around at this time e.g. Jodrell Bank and Green Bank, so the name was entirely appropriate.

The Murraybank field station was in the corner of an approximately 2.5 hectare block of land that also contained the orchard, the Murray's home on the top of the hill and an old weatherboard cottage in which John Murray lived for some time.

Meanwhile, the design of the multi-channel receiver continued to be a very complex undertaking. In a letter to Pawsey in August 1954, McCready noted:

> "I had to give John Murray extra T.O. [Technical Officer] assistance in the 1420 Mc/s Multi-channel Receiver. This was due entirely to the large amount of detail in it. It was a bit of a struggle to get him the right type of assistance but eventually got him a Diplomat-elect from the Rain Physics Group (Keith Weir)." (McCready, 1954).

Later, McGee joined Murray on the project following the unsuccessful search for the deuterium-line at Dover Heights. In a letter to Pawsey in September 1955 McGee noted:

> "We hope to be moving into Murraybank at the beginning of next week and initial tests will be under way about the time of your return." (McGee, 1955).

Although McGee's letter indicated that tests of the equipment at Murraybank would be commencing soon, this proved extremely optimistic. On Pawsey's return from the U.K. he undertook a review of progress. The review identified nine major tasks that remained to be completed on the receiver. Pawsey assigned these tasks between Murray, McGee and also Warburton who had now been appointed to assist. McGee had earlier taken the opportunity to lobby Bowen for assignment to Murraybank of the 60-ft Kennedy Dish that was being considered for purchase and was ultimately installed at the Fleurs field station in 1959 (Orchiston, 2004c). Pawsey discounted this idea and a specification was drawn up for a new aerial. It was agreed that this would be a modified design of a Chris Cross aerial (Figure 208) with its diameter increased to 21-ft and with additional strengthening and greater depth. The design was assigned to K. McAlister and a target date for production of February 1956 was agreed.

Figure 208: The Chris Cross at Fleurs Field station. The Murraybank aerial was based on this aerial design with an increased diameter and strengthened structure (Courtesy of the ATNF Historical Photographic Archive).

Progress with the multi-channel receiver continued to be problematic. On 3 July 1957 Pawsey held another review meeting. After considering the progress that was being made, Pawsey decided to suspend any further work at Murraybank for a period of five months so that the team could properly replan their approach under the supervision of McCready. McGee prepared an internal review paper of their progress implying that they would have been better off concentrating on improving the local oscillators and finishing off individual channels before attempting to take actual line profiles at Murraybank (McCready, 1957). The first twenty filters of the Murraybank receiver had been constructed in the laboratory using high-quality three inch diameter ceramic coil formers that had been found in the Radiophysics store. The remaining filters were constructed by cannibalising surplus aerial tuning units intended for commercial aircraft radio units. These were not as good a quality as the original filters. The original twenty filters were configured around the central H-line frequency with the new filters making up the outer channels (Murray, 2008). Much of the wiring and fitting for the receiver was performed by C.J. Ohlston and M.W. Sinclair (Murray and McGee, 1963).

Another source of delays was that the Chris Cross was under construction at Fleurs and operated at the same frequency. This meant that team had to compete for access to test equipment. For some time they operated with a 'wet-finger' approach without access to a wavemeter to measure the local oscillator frequency. When they finally managed to get access to a wave-meter for a whole day, they found that they had been operating on the wrong harmonic and so had been trying to observe at 1,200 MHz instead of 1,400 MHz (Murray, 2008).

The refocus of activity on the multi-channel receiver development and access to test equipment finally proved successful and the system became operational in mid- 1958.

11.3. Murraybank Equipment

As discussed in the earlier section, the Murraybank aerial was based on a modified Chris Cross design that had been increased in diameter to 21-ft and with increased structural rigidity. The ribs of the aerial were constructed of steel and the rings were made of aluminium (Murray, 2008). The design was performed by K. McAlister and construction was carried out in the Radiophysics workshops. The aerial was mounted on a simple alt-azimuth mount and installed at Murraybank in 1956 next to a comparatively large equipment hut. The mounting was built on an ex-British Army 200 MHz gun-laying radar trailer. This was the same trailer (Figure 209) that Bolton and Stanley had taken to New Zealand and which had been used in other Radiophysics projects (Murray, 2008).

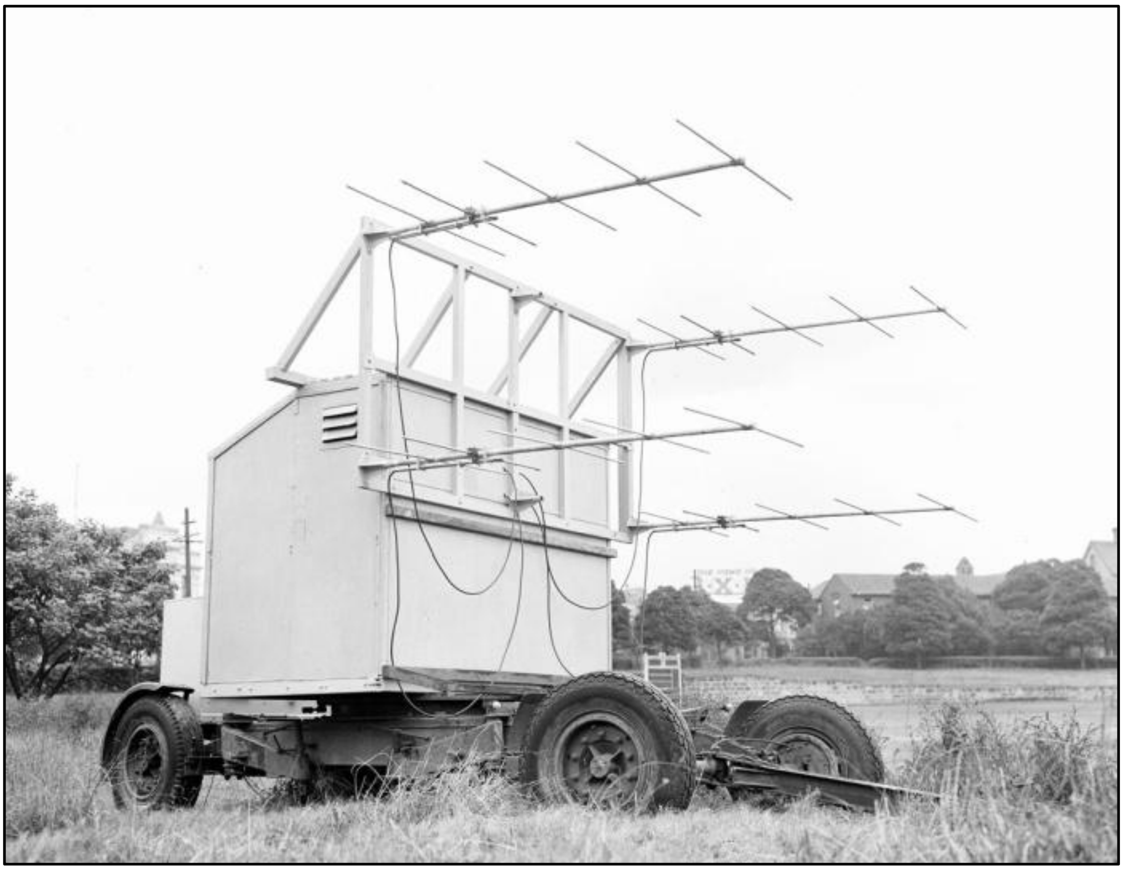

Figure 209: The ex-British Gun-laying trailer with the Yagi Array used by Bolton and Stanley (Courtesy of the ATNF Historical Photographic Archive: B1351 Image Date: 3 May 1948).

In its original configuration the trailer weighed some 6-7 tons and hence had a very solid framework including a set of elephant's feet for stability. Figure 210 shows a close-up of the trailer.

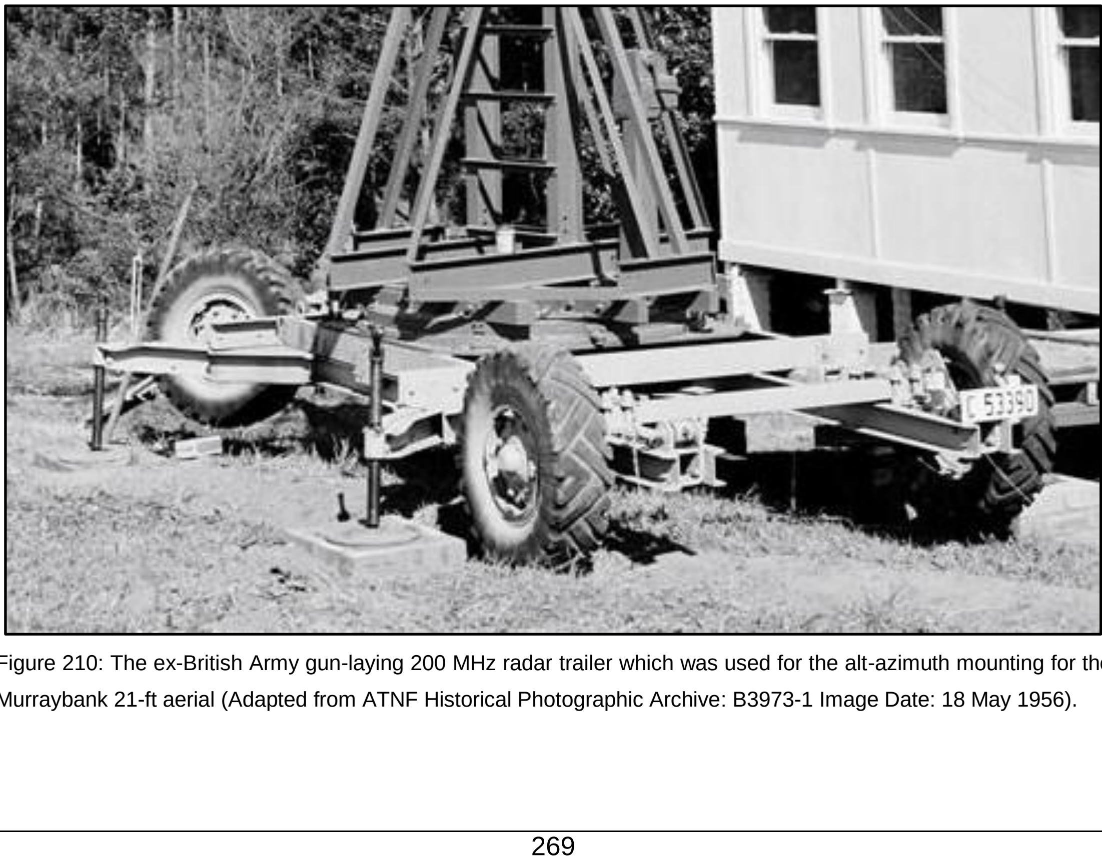

Figure 210: The ex-British Army gun-laying 200 MHz radar trailer which was used for the alt-azimuth mounting for the Murraybank 21-ft aerial (Adapted from ATNF Historical Photographic Archive: B3973-1 Image Date: 18 May 1956).

An aircraft propeller feather motor was cannibalised from an ex-WWII Liberator Bomber that was located at Tocumwal airfield. This motor was used for the elevation drive on the aerial mount (Murray, 2008), and although originally designed as a DC motor, it operated perfectly well on an AC supply. The azimuth control was provided by turning a hand crank which was part of the original gun-laying radar configuration and is visible just to the right of centre in the upper part of Figure 210.

Figure 211 shows the 21-ft aerial being lowered on to the mounting at Murraybank.

Figure 211: The 21-ft aerial being installed at Murraybank in 1956. The equipment hut is in the immediate background (Courtesy of the ATNF Historical Photographic Archive: B3973-4 Image Date: 18 May 1956).

In the original installation the primary feed was simply a long copper tube with a spilt bell and reflector, but this was soon abandoned and a new bipod feed mount was constructed which was supported by nylon guide ropes. The new feed front-end box contained the mixer, the final stage of the local oscillator and a pre-amplifier (Murray, 2008). Figure 212 shows the aerial after installation at Murraybank and with the new feed mount. The aerial was tilted toward the equipment hut and a platform ladder was placed on a small wooden ramp so that the primary feed could be accessed. Also visible in the background is the small reference aerial. This aerial had been transferred from Potts Hill with Joe Warburton when the solar program had been wound down. At one stage consideration had been given to using this aerial to provide a reference signal, but this configuration was not pursued (Murray, 2008). Warburton only stayed with the program for a short period before moving to Brisbane.

Figure 212: The 21-ft aerial at Murraybank with its new feed system. The smaller reference aerial is also visible in the background (Courtesy of the ATNF Historical Photographic Archive).

The Murraybank aerial in its initial configuration had a beamwidth of 2.8° at the half-power points. However, later changes to the primary feed of the aerial improved the beamwidth to 2.2°. Figure 213 shows McGee working on the primary feed of the aerial.

Figure 213: Dick McGee working on the primary feed of the 21-ft Murraybank aerial (Courtesy the ATNF Historical Photographic Archive: R5695-8).

Before discussing the multi-channel receiver in detail it is worth reflecting on the state of radio-frequency spectral-line receiver development when this project was first commenced. By early 1954, there were eight groups (excluding the Soviet Union) where spectral-line receivers were in development or use. Two of these were in Radiophysics, being Kerr's team at Potts Hill with the 4-channel H-line receiver project and the Dover Heights team attempting to detect the deuterium-line. Three groups were working in the U.S. at Harvard, NRL and the Carnegie Institute. In the U.K work was underway at Jodrell Bank and at Malvern. In the Netherlands a major effort was underway at the Kootwijk station. Up until this time, none of the overseas groups had initiated projects to construct large multi-channel receivers. While the Potts Hill group had considered having up to 20 channels, ultimately their design could not support more than four concurrent channels, and even this resulted in many practical difficulties in observations. Appendix C shows a summary of spectral-line receivers operating through-out the world as at February 1954 when the initial design of the Murraybank multi-channel receiver was being considered. This position would change fairly quickly. Department of Terrestrial Magnetism (D.T.M.) of the Carnegie Institute in Washington developed a 54-channel H-line receiver which they had operational before Radiophysics and were making observations by early 1957 using this receiver on an 8-m Würzburg antenna (Burke et al., 1959).

The first operating version of the Murraybank multi-channel receiver used as its first stage a crystal diode mounted in a tuned cavity. This signal was then passed to a double-conversion superheterodyne using intermediate frequencies of 31.8 and 6.74 MHz. The receiver output was switched at a rate of 385 Hz between the signal frequency of 1420 MHz and a reference frequency of 1424 MHz (Murray and McGee, 1959: 127). The reference frequency was selected as being outside of the largest Doppler shift expected in the Galaxy for the H-line. The output from the second intermediate frequency amplifier was passed into 48 double-tuned filters that were spaced at intervals of 32 KHz. The individual band pass filters had an approximately Gaussian response with a half-power bandwidth of 40 KHz which equates to a H-line radial velocity coverage of 8.4 kms^{-1}. A second detector was attached to each individual filter. The detected outputs, including contributions from the two switched frequencies, were then passed through audio amplifiers and synchronous detectors to produce the hydrogen-line signal. Signal fluctuations were smoothed by the using a two minute time constant. A telephone-type uni-selector switch allowed sampling of each of the synchronous detector outputs once every two minutes. The noise temperature of the receiver was ~800 °K. The output was recorded on a Speedomax chart-recorder as a 48-point profile with frequency on the x-axis and aerial temperature on the y-axis.

Figure 214 shows a view inside the receiver hut at Murraybank. On the left is the bank of 400 MHz amplifiers for the 48-channels. In the next rack to the right, starting from the top is an oscilloscope and receiver used to check the frequency against the WWV signal. Below this are the main local oscillator multiplier chain, the local oscillators and the local oscillator switch. The chart-recorder is in the back right of the hut.

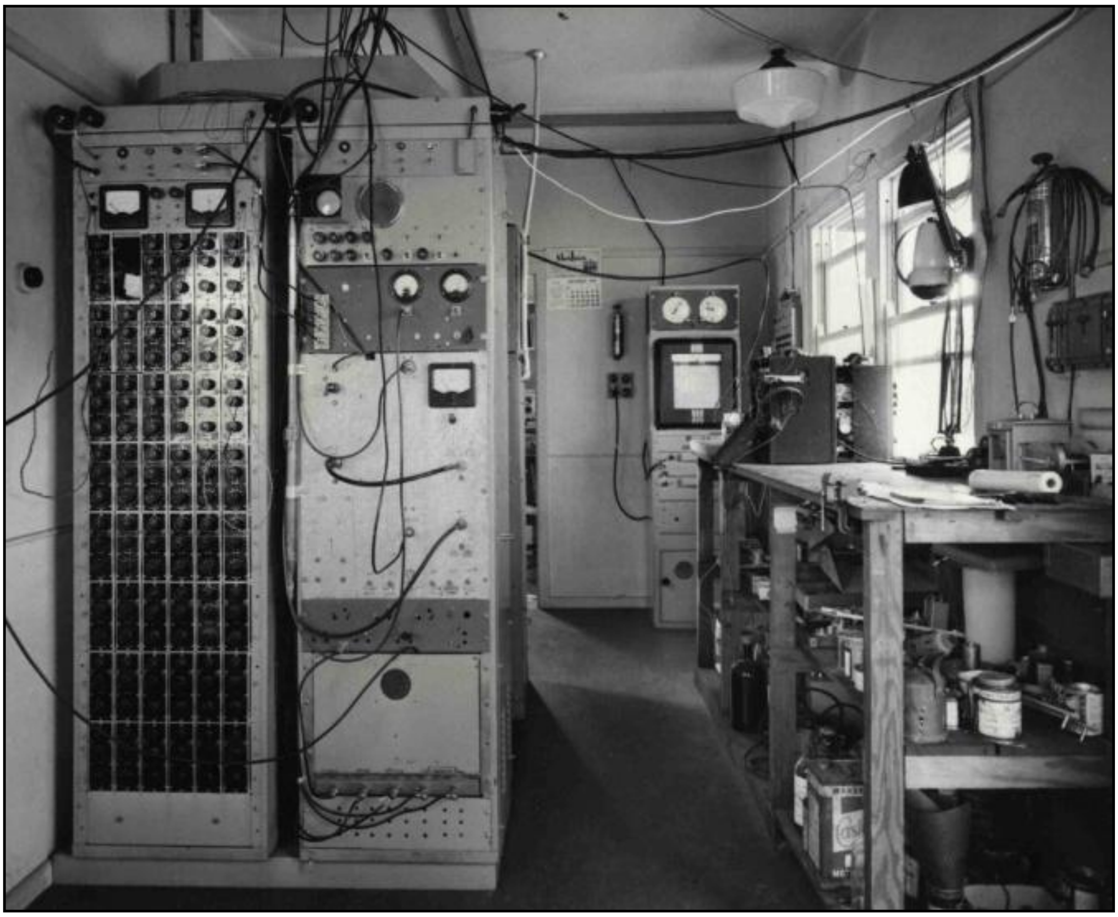

Figure 214: A view of the multi-channel receiver equipment inside the receiver hut at Murraybank (Courtesy of ATNF Historical Photographic Archive: R5695-18).

The workbench visible in the right of Figure 214 was later moved and the chart-recorder was relocated next to the other rack equipment as shown in Figure 215.

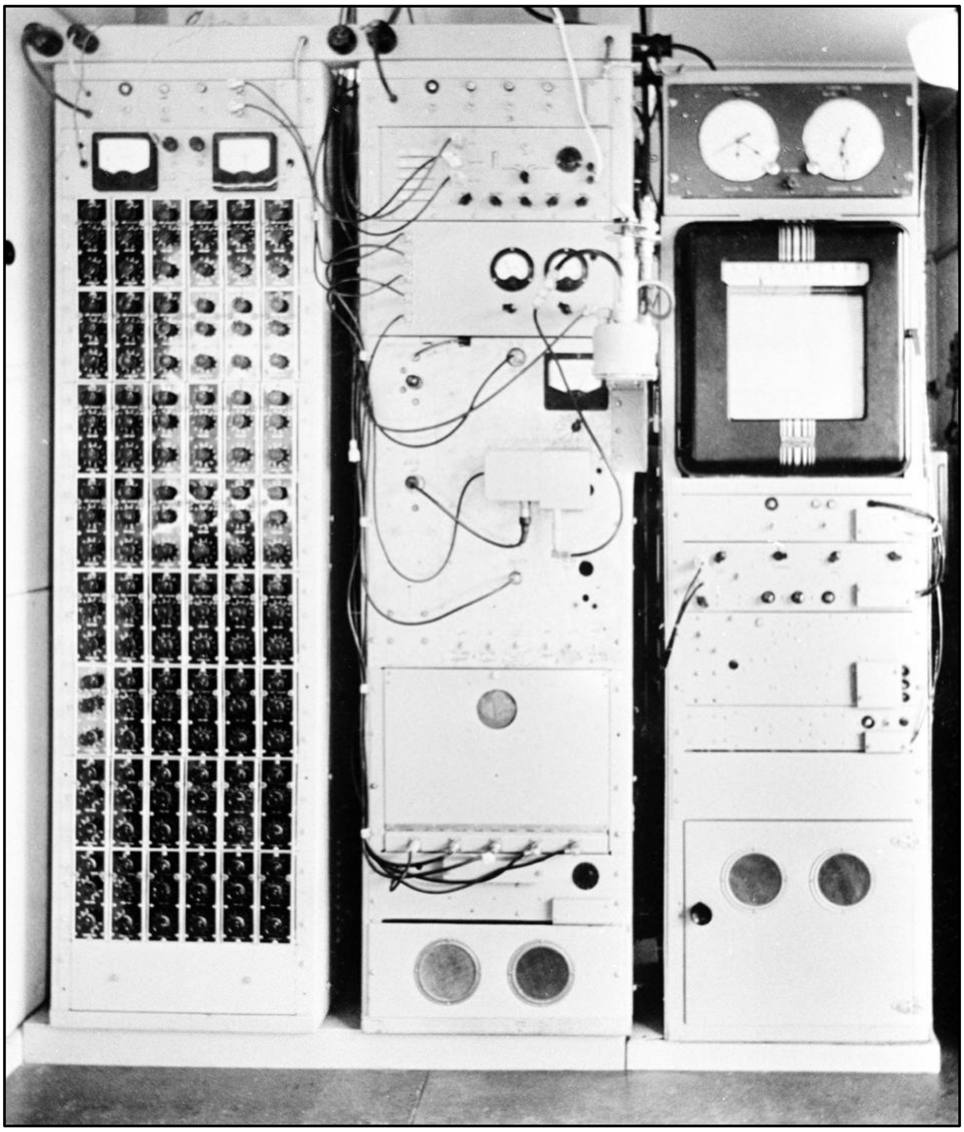

Figure 215: A later view of the receiver and recording equipment following the relocation of the recorder (Courtesy of ATNF Historical Photographic Archive: B6222-1 Image Date: 28 September 1960).

Given Murray's experiences with the problem of temperature control at Potts Hill, careful attention was paid to construction of the equipment hut. The hut was heavily insulated using 3-inch slag sheets on the walls, floor and ceiling. The roof had open eaves to allow airflow, but was shielded with netting to keep animals and birds out. The filters themselves were located inside another insulated structure inside the hut. This was accessed through a butcher's cold-room store door. Figure 216 shows a view of the filter bank.

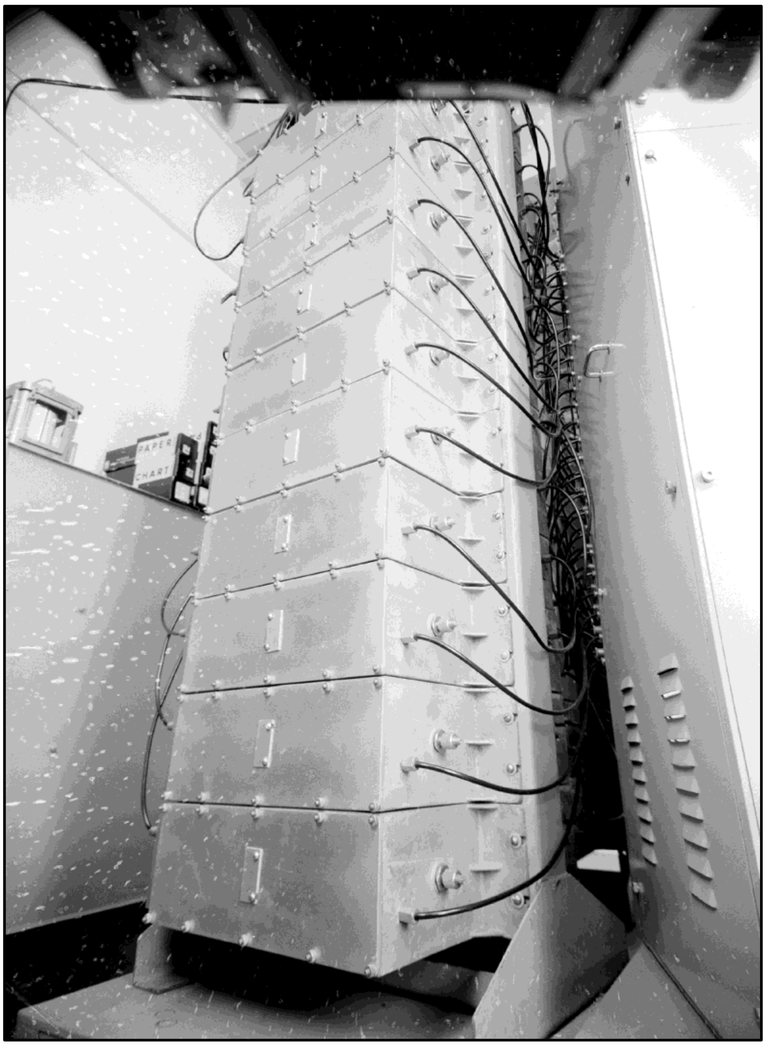

Figure 216: The filters used in the Murraybank receiver (Courtesy of ATNF Historical Photographic Archive: B5985-1 Image Date: 17 December 1959).

The filters were housed in heavy aluminium casings. To the left in Figure 216, a large water tank can been seen. This was used as a heat-sink. On top of this a recording thermometer can also be seen. With this set-up it was found that the temperature varied less than half a degree even on a hot days (Murray, 2008).

Figure 217 shows John Murray standing at the chart-recorder inside the receiver hut at Murraybank. The clocks visible above the recorder show solar and sidereal time. All of this equipment including the mounting racks and sheet metal work was constructed in the Radiophysics workshop (Murray, 2008).

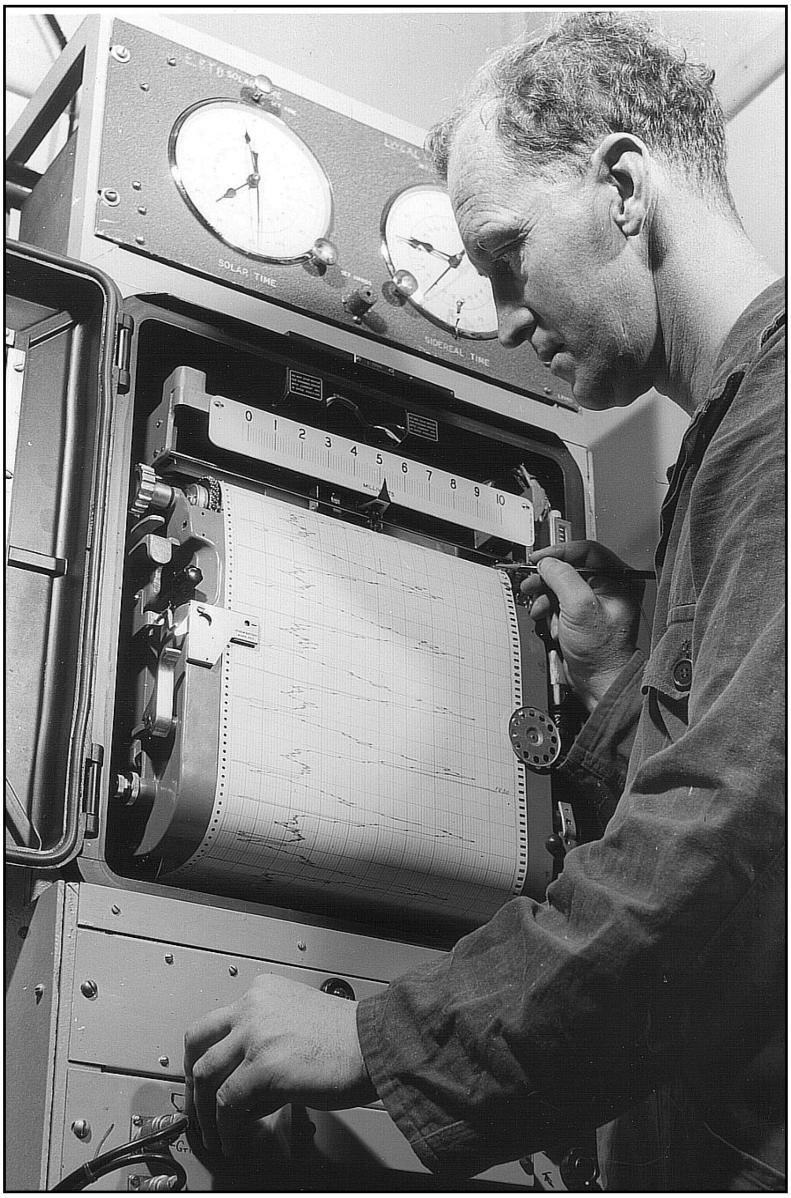

Figure 217: John Murray at the Speedomax recorder in the receiver hut at Murraybank (Courtesy of ATNF Historical Photographic Archive: R5695-9).

Figure 218 shows an example of the raw output of seven successive two-minute profiles on the Speedomax recorder.

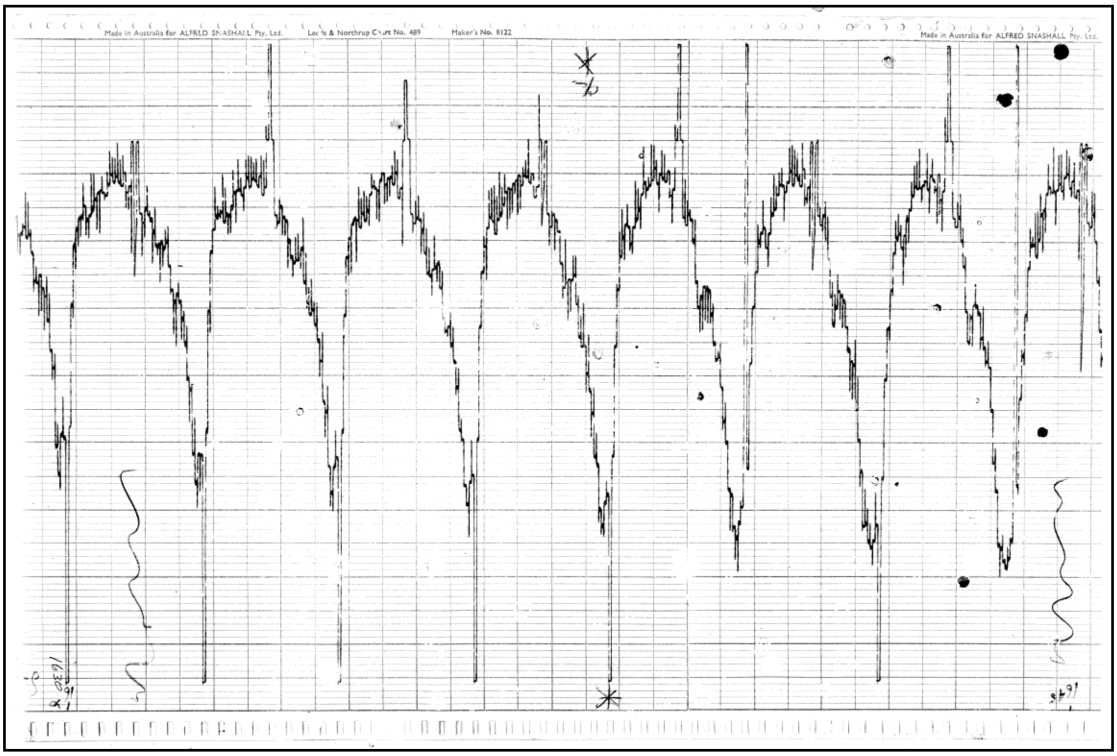

Figure 218: An example of the two minute H-line profiles produced as an output on the Speedomax chart-recorder (Courtesy of the ATNF Historical Photographic Archive: B5849-1 Image Date: 22 June 1959).

Figure 219 shows an example of a composite profile obtained from six successive two minute scans while the aerial was held in a meridian transit position set at a declination of +14° and the profiles recorded from $03^h\ 44^m$ to $03^h\ 54^m$ as the Earth rotated.

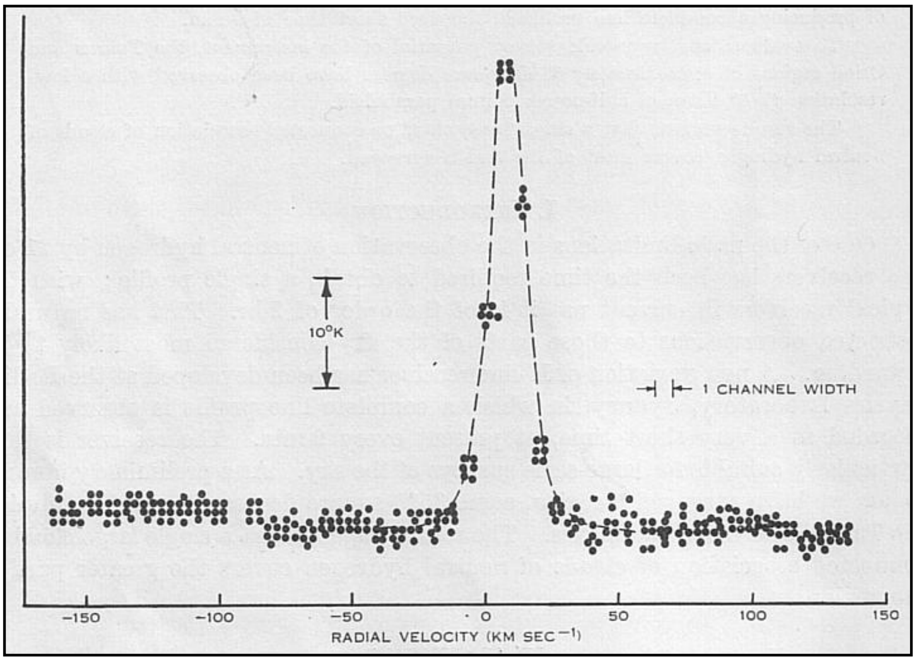

Figure 219: An example of a composite H-line profile produced by the Murraybank multi-channel receiver. The profile consists of 6, two-minute profiles taken over a period of 12 minutes while the aerial was held at a fixed declination in a meridian transit position (after Murray and McGee, 1959: 128).

As can been seen from Figure 219, the baseline showed some inherent unevenness due to individual differences between channel filters. After some initial trial surveys, the receiver was modified to add an additional two wide-band channels, taking the total to fifty. These additional channels were added to each end of the existing 48-channel bank and were used as zero-line markers. The filters in each of these channels had a bandwidth 0.5 MHz between half power points and were setup so that so that they covered the same frequency range as the first 24 and last 24 channels filters so that complete coverage of the profile frequency range was provided.

A calibration system was also added to the multi-channel receiver. A switched noise source was located at the vertex of the main aerial paraboloid. The noise signal was generated from a dipole located at the vertex of the aerial by switching alternatively on and off a high tension voltage supply to a noise diode mounted across the dipole feed point. This was used to provide a relative intensity calibration. The switching was performed in synchronisation with the frequency switching of the receiver so that the noise signal appeared only in the signal band of the receiver. In this way, the signal appeared equally in all channels and served as a means of calibrating the relative gain of each channel. The system was capable of measuring deflections of up to 200 °K aerial temperature. Frequency monitoring was made by comparison of the harmonics of the crystal-controlled local oscillator signals with signals from the radio station WWV. The team found that when a beat signal between WWV and another station JJY could be heard, it was likely that propagation effects would impact the quality of the recordings (Murray, 2008). Tests were also later performed using a laboratory frequency counter and these tests indicated the local oscillators had frequency stability better than the equivalent of 0.03 km/s.

For surveys the aerial was placed at a fixed declination in a meridian transit position. Recordings were then taken for a period of 24 hours. With a beamwidth of 2.2°, four complete profiles were produced per beamwidth and a total of 720 were produced in each 24 hour declination strip observing run. It was clear that the multi-channel receiver would produce a very large body of data in a short period of time. As the multi-channel receiver was proving successful in operation, it also became clear that much larger amounts of data would be produced when the receiver was later installed on the 210-ft (64-m) Parkes radio telescope. To deal with these very large amounts of data, a new project was launched under Hindman's leadership to develop a digital recording and data reduction system. M. Beard, who had been involved with the development of Radiophysics' original digital computer, joined the team to develop the Division's first digital recording system for radio astronomy. This was also to be the Division's first application of digital computers to the reduction of observational data. It was intended that this project should conduct a pilot survey to develop the techniques prior to the introduction of the system on the Parkes radio telescope.

The digital recording system used only 46 of the 48 channels for the original pilot. It consisted of five major components, being: an analogue to digital converter, a ten binary digit data store, a paper hole-punch control unit a paper tape hole-punch unit, and a program control unit with digital clock (Hindman et al., 1963b). Figure 220 shows a block diagram of the recorder system and an example of the paper hole-punch tape output.

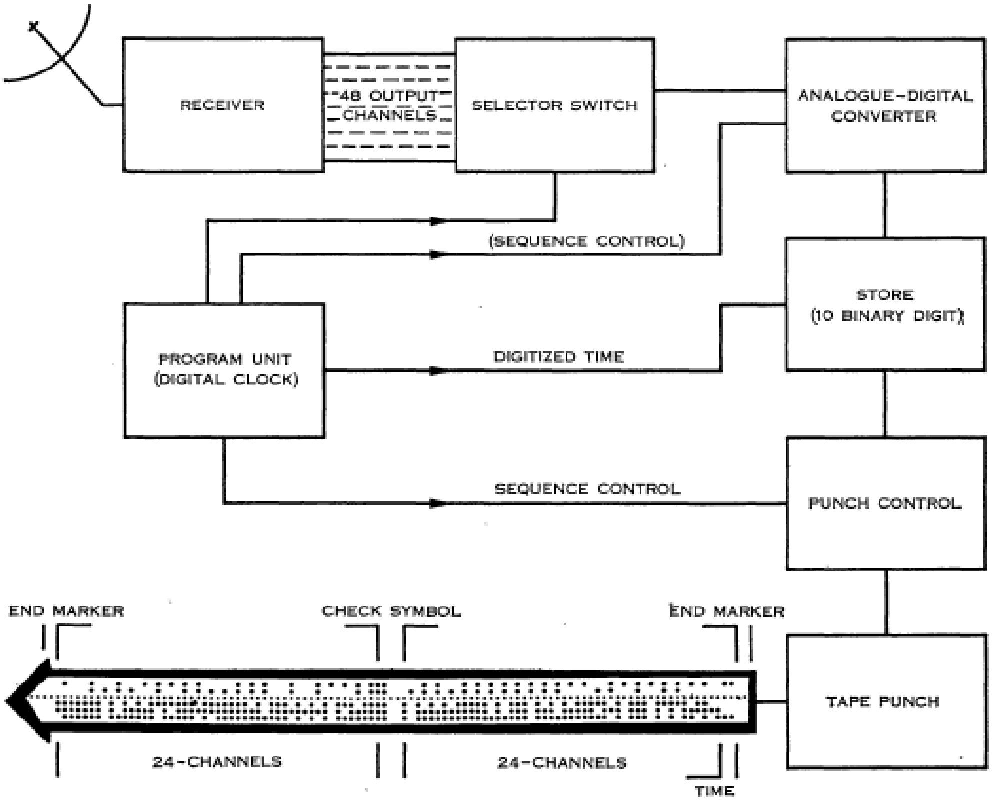

Figure 220: A block diagram of the digital recording system used at Murraybank together with the 48-channel hydrogen-line receiver (after Hindman et al., 1963b: 554).

The output produced by the digital recorder was a block of 53 pairs of characters representing the output of a single 2 minute line profile together with the sidereal time of the observation, marker characters and check characters.

In this example, the first pair of characters are blanks (or zeros) used to mark both the start and end of a single H-line profile block. This is immediately followed by 24-pairs of characters that record the relative intensity of each of the first 24 channels of the receiver, being channel numbers 0 to 23. A control symbol is then inserted represented by 2-pairs of control characters, one pair with all holes punched and the other with no holes punched. This control symbol was used to check that the paper hole-punch was functioning correctly. Following the control symbol are the next 24 pairs of characters representing channels 24 to 47. This is immediately followed by a pair of characters recording the sidereal time of the observation, and finally by the blank character pair indicating the end of the block.

The program control unit contained a clock driven at the sidereal rate with a number of shafts to achieve four revolution rates: 52 revs in 2 minutes, 1 rev in 2 minutes, 1 rev in 1 hour and 1 rev in 24 hours. Figure 221 shows a schematic diagram of the digital shaft encoder that was used to convert the shaft rotation to digital signal using a flash lamp and photoelectric readout.

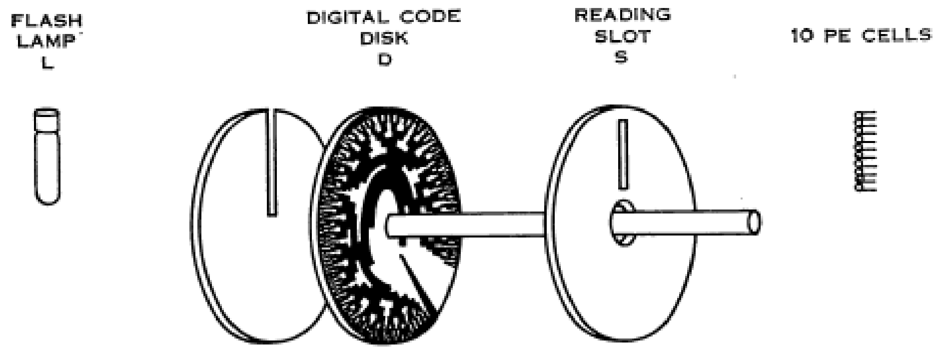

Figure 221: A schematic diagram of the digital shaft encoder in the Murraybank digital recorder program control unit (after Hindman et al., 1963b: 556).

A reading from the digital converter was obtained by flashing the lamp and a number corresponding to the shaft position was detected through the disk reading slot by the ten photo-transistors. The 1-hour and 24-hour shafts were read every two minutes to record the sidereal time of the observation and recorded as two characters in the paper tape data block. Figure 222 shows a close-up view of the digital code disk which gives 1024 numbers from 324° of rotation.

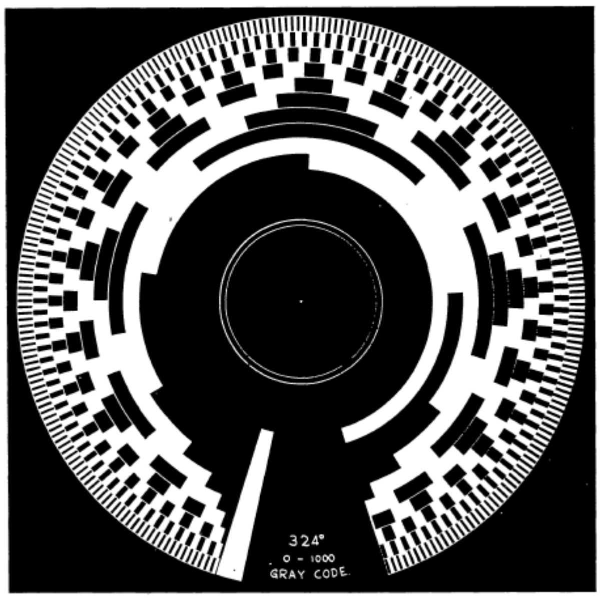

Figure 222: A close-up view of the encoding disk pattern which divided the 324° of shaft rotation into 1024 steps (after Hindman et al., 1963b: 557).

Once a number had been read by the photo-transistor cells, it was stored in the binary store which consisted of 10 bistable multivibrators. The program control unit then initiated a pulse which triggered the number to be punched on the five-hole paper tape, which used two characters to represent a number with the most significant digit being the first.

Before beginning any data reduction, each tape was checked visually to ensure that the block markers and central check characters were present. Further, each tape was passed through a reader as a check count of the number of characters per block. These checks were put in place to avoid more obvious downstream errors in the batch computer reductions. The usual chart record was recorded at the same time as digital encoding to provide a cross check.

Another feature of the digital recording method was that it made it possible to apply individual gain and zero level corrections to each individual channel. To do this a calibration tape was prepared for each data recording tape. The calibration tape had selected sections of the high and low level calibration and a base-level run that was usually the same as the low level. The calibration tape could then be fed into the computer at the beginning of the reduction process for each observation run. The calibration tape produced the base-level corrections and individual channel gain factors which were then stored in the working memory of the computer for use in reducing the observational data. Prior to the use of digital recording, manual data reductions were performed by estimating an average figure for gain corrections. In each calibration run, ten or twelve blocks of data were averaged to produce a set of calibration factors which were substantially smoothed from the receiver noise fluctuations.

The data reductions were performed using the SILLIAC (Sydney version of the Illinois Automatic Computer) computer of the Adolph Basser Computing Laboratory of the School of Physics at the University of Sydney, which had entered service in July 1956 (Figure 223).

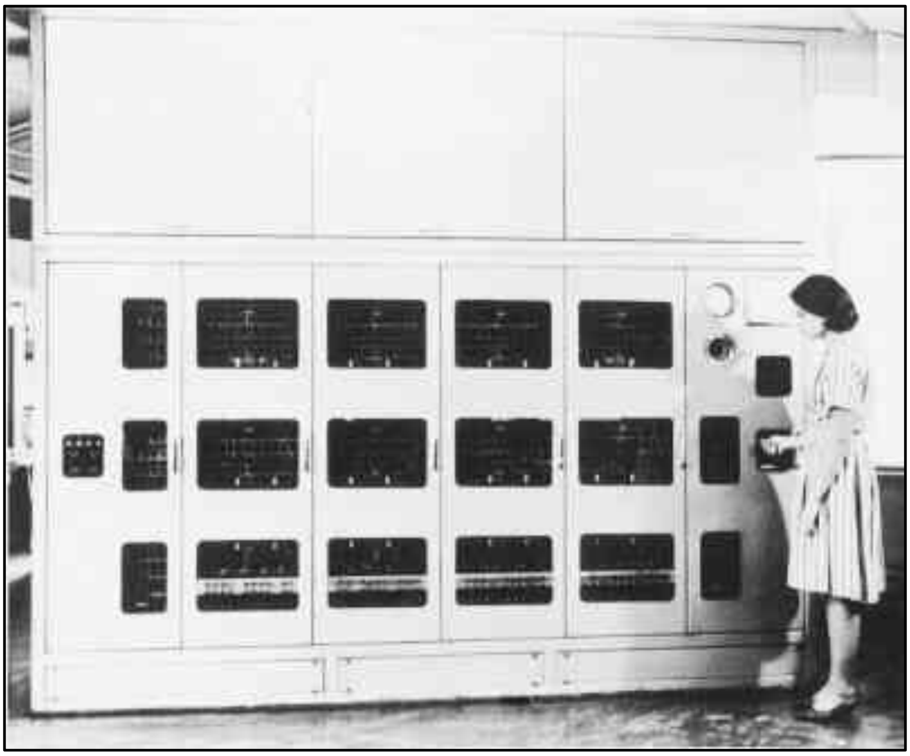

Figure 223: The SILLIAC computer of the Adolph Basser Computing Laboratory of the School of Physics at the University of Sydney (Courtesy of the Science Foundation for Physics, Univesity of Sydney).

Radiophysics had abandoned their own computer development program in 1955 and therefore it was necessary to purchase computing time from the University of Sydney. Even after negotiating a half price discount, a 'block' of 400 hours of computing time on SILLIAC cost £16,000 (Deane, 2006). As well as reducing the recorded data, the integrated brightness and median radial velocity of each profile was calculated together with the first and third quartile median velocities as channel numbers. Finally the average right ascension of the profile, corrected for the receiver time constant effect, was calculated and all the data were then recorded on an output tape. Velocity corrections to account for the Earth's rotation and then Earth's orbit about the Sun were not performed as part of the initial data reduction, but were calculated in a separate run. The computer time required to reduce 250 hours of observations was approximately 8 hours, with a further 15 minutes required to calculate the velocity corrections. Plotting of the results was still performed by hand, but this was the next obvious step for automation. Figure 224 shows a simplified flow chart of the reduction program.

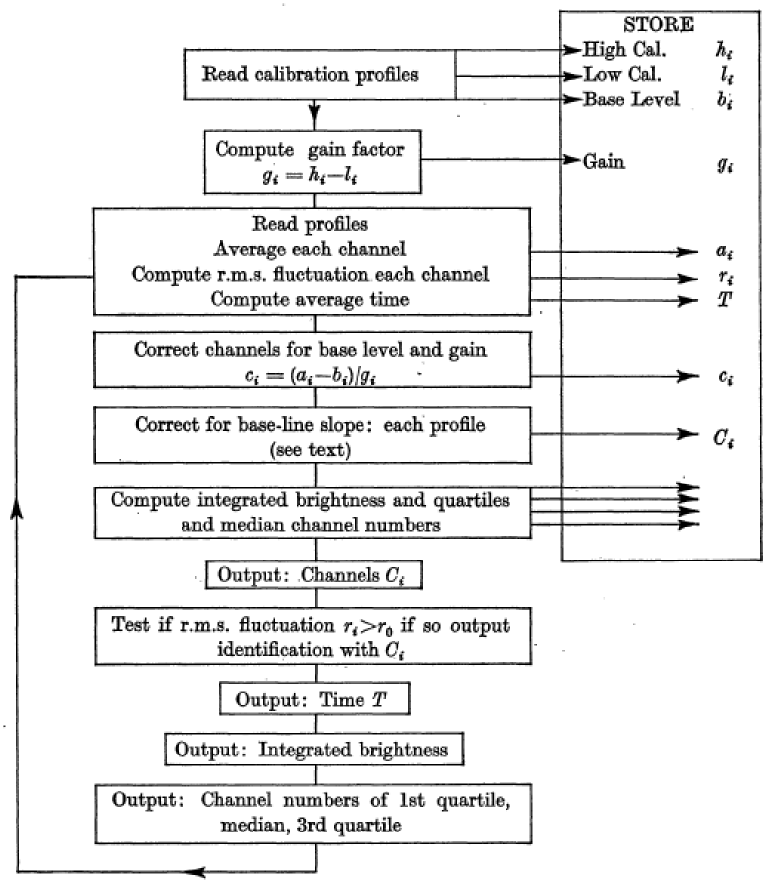

Figure 224: A simplified flow chart of the reduction program run on the SILLIAC computer (after Hindman et al., 1963b: 562).

The use of digital recording not only greatly reduced the time necessary for reduction of the initial observations, but the more rigid application of calibration data lead to the detection of a second-order receiver effect due to diurnal temperature variations which had not previously been detected. It also allowed the detection of lower level signals that had previously been averaged out in manual reductions. The pilot program was considered highly successful and allowed digital recording to be introduced when the Parkes radio telescope became operational.

11.4. Murraybank Research

Appendix B contains a listing of published material that was based on research carried out at Murraybank. The first published research appeared in *The Observatory* (Murray and McGee, 1958). This was based on a set of trial observations in the Pyxis-Hydra region in the mid galactic latitudes between longitudes 210° and 230°. The observations were made prior to the adjustment of the aerial feed so that the beamwidth at half power points was still 2.8°. At this time no absolute brightness temperature calibration had been performed, so the temperature scale was based on a comparison to Muller and Westerhout's (1957) observations in nearby regions. Observations were made by holding the aerial at a constant declination with a spacing of two degrees or less between scans. Approximately 700 profiles were recorded covering an area of ~500 square degrees.

The profiles observed in the Pyxis-Hydra region were single-peaked and therefore the distribution of neutral hydrogen was reasonably represented by the peak profile brightness temperatures and the radial velocities at this point. Figure 225 shows a contour diagram of peak H-line brightness temperatures at intervals of 5°K, together with radial velocities and an indication of HII regions from optical observations.

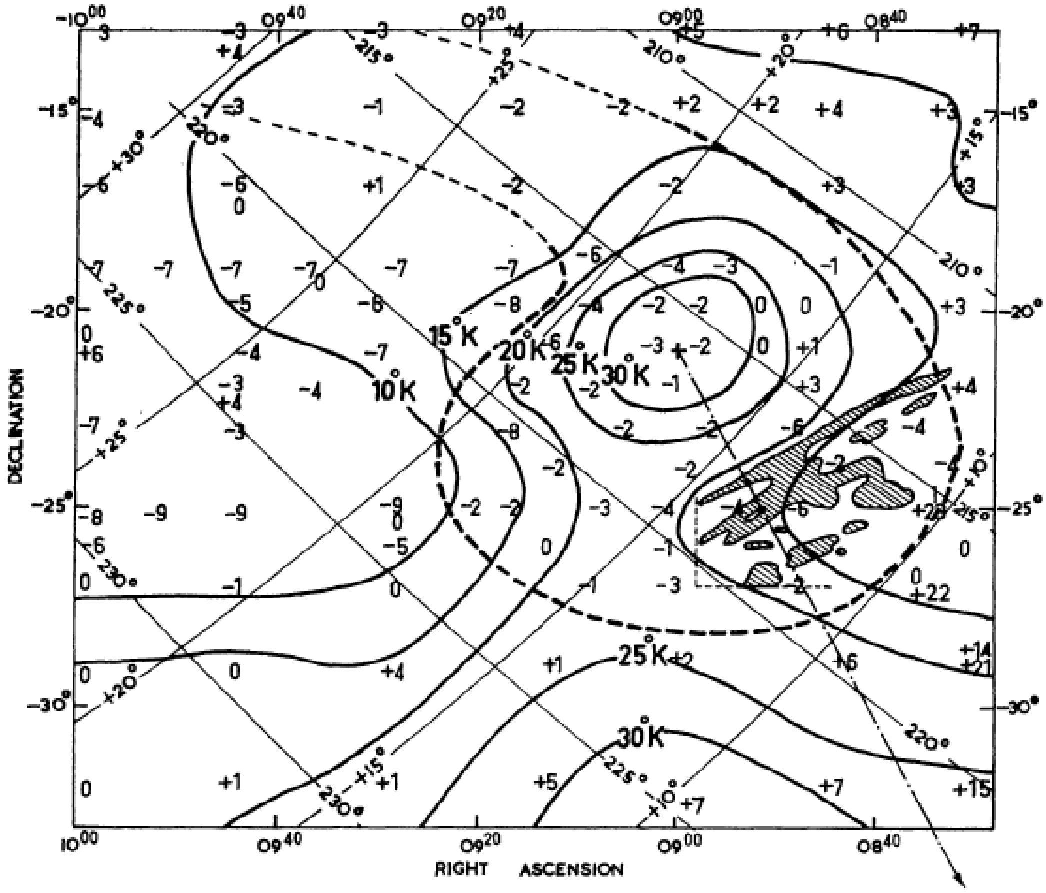

Figure 225: A contour diagram of the H-line brightness temperature in the Taurus-Orion region Contour spacing is 7.5 degrees of peak temperature. The large numbers represent the mean radial velocity in kms^{-1} over areas 10° by 10° (after Murray and McGee, 1959: 130).

Based on these observations, Murray and McGee deduced the presence of a large discrete neutral hydrogen cloud centred at right ascension $09^h\ 00^m$ and declination -21°. This was supported not only by the peak brightness contours, but also by the fact that the radial velocities immediately to the Cloud's left (East) in Figure 225 had a large step change in velocity indicating that the cloud appeared not to be associated with other HI in that region. The dotted line in the diagram encompasses the possible area of the cloud based on the radial velocity measurements. The extension in the upper left is speculative and based only on the velocity measurements. Gum (1956) had shown that the two stars γ^2 Vel and ζ Pup were the source of the ionisation radiation forming the HII region. The location of the HII region on the leading edge of the HI cloud facing these stars appeared to lend support to the idea that the two were indeed part of the same complex. Using a distance determination from Gum (1956) they reached the following conclusions:

Position of Cloud centre (max H-line brightness):	$\alpha = 09^h\ 00^m$, $\delta = -21°$ $l = 216°$, $b = +17.5°$ (1950)
Cloud Diameter:	12°
Average Peculiar Radial Velocity:	-2.5 km sec^{-1}
Maximum H-line brightness Temperature:	35° K
Average number of H atoms in line-of-sight column of 1 cm^2 section:	1.0×10^{21} H atoms

The next preliminary survey was made of the Taurus and Orion complexes which covered approximately 3,500 square degrees. Again the survey was conducted by holding the aerial at a fixed declination and then the next scan taken with two degree spacing. Some 3,500 profiles were taken in this manner. Nearly all the line profiles were single peaked with an average half-width of 19 kms^{-1} with a standard deviation of 2 kms^{-1}. As no flattening of line profiles was observed it was concluded that the gas was optically thin at all points in the region.

To investigate the radial velocity distribution in the Taurus-Orion region, over 350 uniformly distributed velocity values, corrected to the local rest standard, were calculated. Figure 226 shows a contour diagram of brightness temperature and the mean radial velocities in a grid of 10° by 10°.

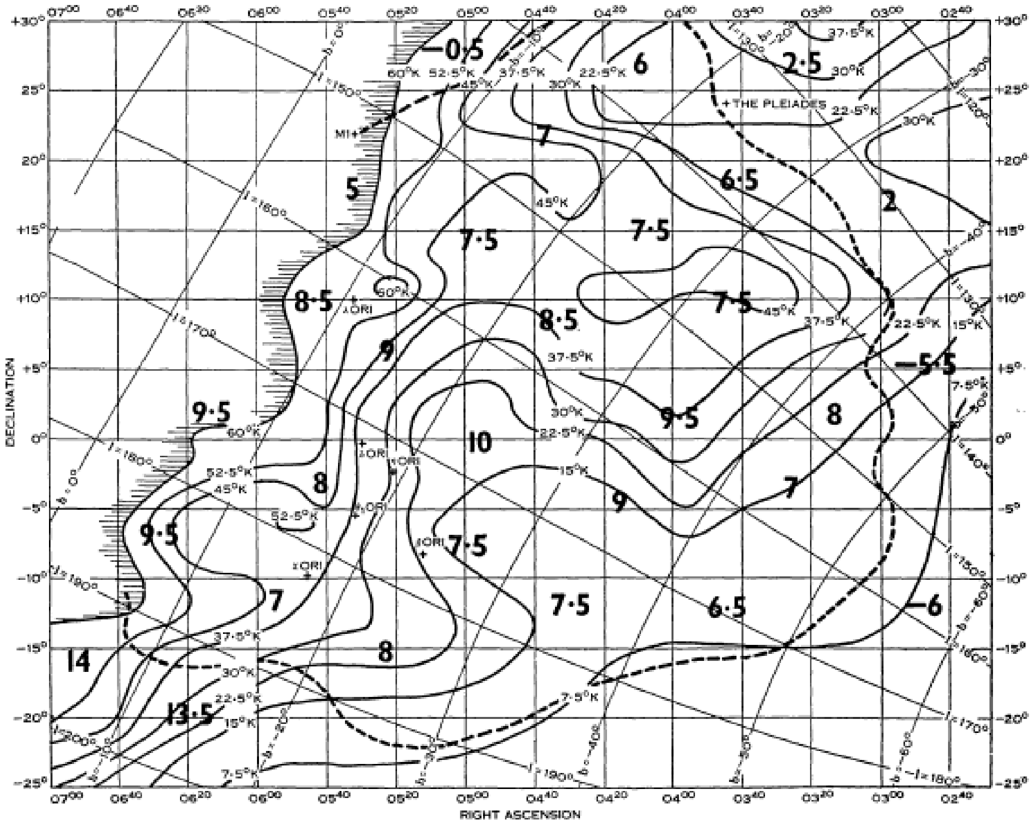

Figure 226: A contour diagram of peak H-line brightness temperature at intervals of 5° K. Radial velocity in km/sec is indicated as integers on the chart. The shaded area represents a HII region sketched from the National Geographic-Palomar Sky Survey. The arrow indicates the direction from the centre of the contours of two stars believed to be responsible for the ionisation of the HII region (after Murray and McGee, 1958: 243).

As for the Pyxis-Hydra region, both the peak temperature contours and the radial velocity profiles supported the presence of a large cloud, or connected clouds, in the Taurus-Orion region. Figure 227 shows a comparison of neutral hydrogen density in a line-of-sight column compared to dust regions defined by Hubble's zone of avoidance where there are high levels of optical extinction.

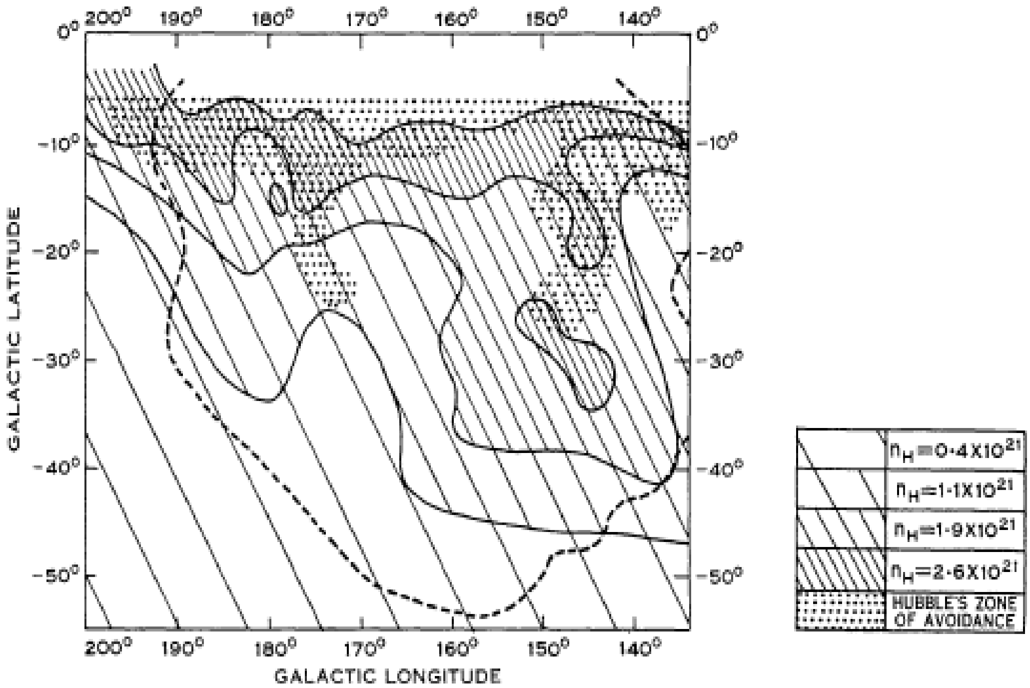

Figure 227: A comparison of neutral hydrogen density and Hubble's zone of avoidance (after Murray and McGee, 1959: 132).

The distance to the clouds estimated from a galactic rotation model (Kwee et al., 1954) was 430 parsec, however if the neutral hydrogen clouds were associated with the optically observed dust clouds in the region, as suggested by Figure 226, then there was a large distance discrepancy as these had previously been determined to be at a distance of 145 parsecs (Greenstein, 1937). A more recent VBLA measurement of the trigonometric parallax of several member stars of the Orion Nebula Cluster, showing non-thermal radio emission, has determined the distance to the cluster to be 414± 7 pc (Menten et al., 2007).

Both of the pilot surveys conducted by Murray and McGee demonstrated the viability of the multi-channel receiver coupled with the relatively low resolution 21-ft aerial. With this arrangement, large areas of the sky could be surveyed in relatively short periods. The initial surveys also demonstrated the value that could be gained in examining not only the large-scale structures of the Galaxy, but also the more detailed study of specific regions.

With the pilot surveys completed, the focus now turned to a large scale survey of the sky visible from Sydney. This survey was completed during 1960 and the first publication of results appeared in *Nature* and the *Astronomical Journal* (McGee and Murray, 1961a; McGee et al., 1961). These dealt with the large-scale streaming of neutral hydrogen in the vicinity of the Sun.

Figure 228 shows a radial velocity contour diagram of the H-line peak profiles from the Murraybank survey. The diagram shows the positive and negative peak velocities along the galactic equator associated with differential rotation of neutral hydrogen in a disk about the galactic centre. However, the interesting features evident in the diagram are the large areas of negative velocity at high galactic latitudes. Areas of negative velocity near the galactic poles had previously been reported by Erickson et al. (1959), but they had not noted the overall disposition.

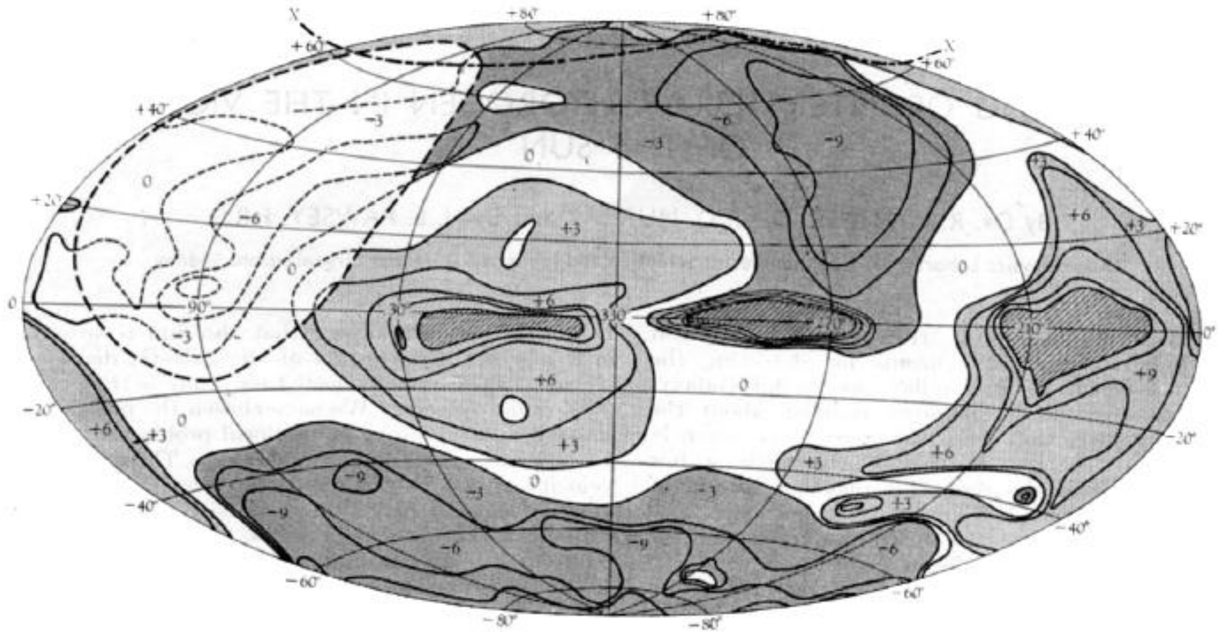

Figure 228: A contour diagram of peak H-line radial velocities from the Murraybank southern sky survey. Dark grey areas represent negative velocities. Light grey areas represent positive velocity areas. The hatching denotes areas where the radial velocity exceeds 15 kmsec^{-1}. Co-ordinates are in the old 1950 Ohlsson scheme (after McGee et al., 1961: 958).

These areas appeared to be associated with a general in-streaming of neutral hydrogen, at least within the general area of the Sun, but possibly more generally. Figure 229 compares the observed peak velocities to a derived curved based on a differential galactic rotation model. The diagram shows areas of positive velocity toward the galactic centre where negative values would be expected indicating that the gas in this region has an additional component of outwards motion.

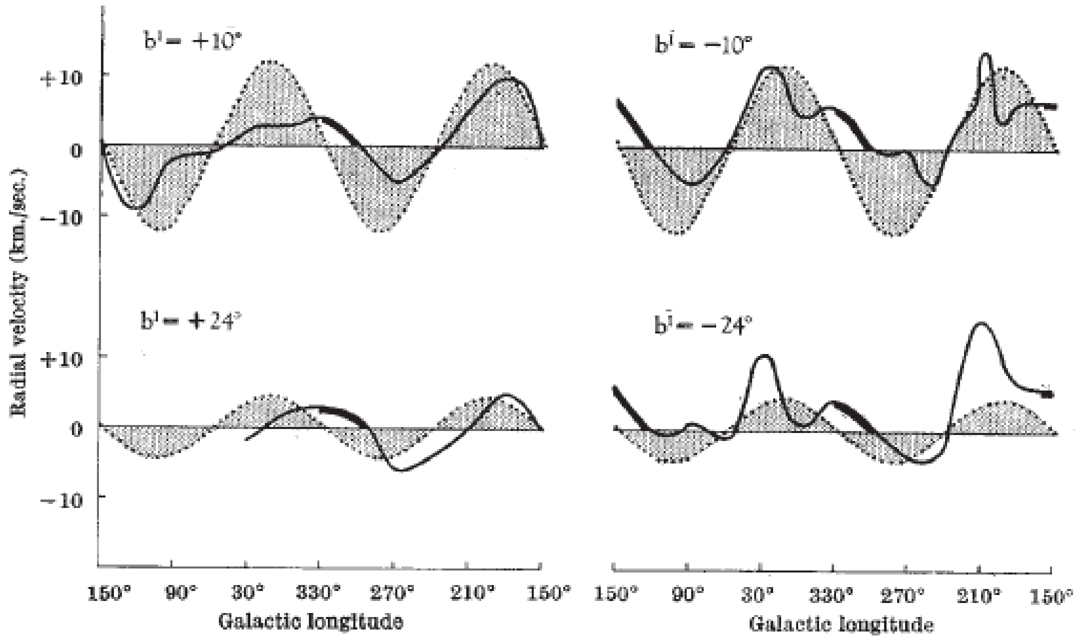

Figure 229: A comparison of observed velocity curves to the predicted velocity curve assuming differential galactic rotation. The dotted line and shading represent the predicted curve. The solid line represents the actual observations. The thickened sections of the line represent the main deviations from the prediction (after McGee et al., 1961: 958).

Without being able to determine the distance of observed peaks, other than through an assumed differential rotation model, they were unable to state whether the streaming was a more general phenomenon. However, they noted that if the observed flow was representative of the general flow over the galactic disk then the quantities of hydrogen involved would be sufficient to make this a major feature of galactic dynamics.

A further series of three detailed papers was published in the *Australian Journal of Physics* from 1961 to 1964 based on the Murraybank southern sky survey (McGee and Milton, 1964; McGee and Murray, 1961b; McGee et al., 1963). For the analysis of the southern sky survey, McGee and Murray were joined by Janice A. Milton who conducted a major part of the data reduction. She was a co-author on the later two papers and was acknowledged for her contribution in the first paper. The third paper in the series was prepared solely by McGee and Milton as by this stage Murray was working in the Netherlands.

The Murraybank southern sky survey was performed by taking observations at meridian transit with intervals of one degree in declination from -90° to +42° over a period of 24 hours for each observing run. The limit of sensitivity was believed to be set by an r.m.s. fluctuation level of the system of approximately 0.7 °K. Prior to the Murraybank survey there had been only three extensive H-line surveys that dealt with the region away from the galactic plane. The first was the pioneering survey at Potts Hill by Christiansen and Hindman (1952b) which included galactic latitudes of ±50°. The next was by Erickson et al. (1959) at

D.T.M in Washington using the 54-channel receiver and covering galactic latitudes outside of ±20°. This survey was based on profiles taken at intervals of 10° in both galactic longitude and latitude. Finally, Davies (1960) at Jodrell Bank had covered the same region and extended observations to include ±20° with observations at 5° intervals.

In the first detailed paper in their series, McGee and Murray (1961b) dealt with the general distribution and motions of the local neutral hydrogen as had been reported in summary form in *Nature*. The paper established that in the vicinity of the Sun, neutral hydrogen was flowing outwards at a mean radial velocity of +6kms^{-1} in those latitudes in the direction of the galactic centre and anti-centre, and was flowing inwards at a mean velocity of -6kms^{-1} from above and below in the high galactic latitudes.

McGee and Murray found that the recorded profiles could be divided into three broad classes. The first class was believed to be the local neutral hydrogen distributed over a wide area of the southern sky with line profile half-widths from the instrumental lower resolution limit of 12 kms^{-1} to a maximum observed value of 35 kms^{-1}. In most cases the profiles were single peaked with radial velocities not in excess of ±12 kms^{-1} and with maximum brightness temperature ~50 °K. The second class was believed to emanate from the galactic spiral structure and fell within ±12° of the galactic equator. These profiles were wide and usually multi-peaked and of much greater intensity than those of any other regions. The third class mainly occurred in low intensity regions at high galactic latitudes. These had half-widths that ranged from 36 to 140 kms^{-1} and in some cases exhibited two or three distinct peaks. McGee and Murray considered the possibility that the wide profiles may be due to hydrogen from the galactic corona but discounted this idea, as a much greater dispersion would be expected from randomly moving and highly dispersed gas clouds.

The optical depth of the neutral hydrogen was calculated based on the method from Wild (1952):

$$N_H = 1.84 \times 10^{18} \int_{-\infty}^{\infty} T(v)dv \tag{19}$$

where

N_H is the number of hydrogen atoms in a 1 cm^2 line-of-sight column;
T is the H-line brightness temperature; and
v is the radial velocity in km/second.

Figure 230 shows the calculated local distribution of neutral hydrogen density as the number of atoms/cm^2 in a line-of-sight column.

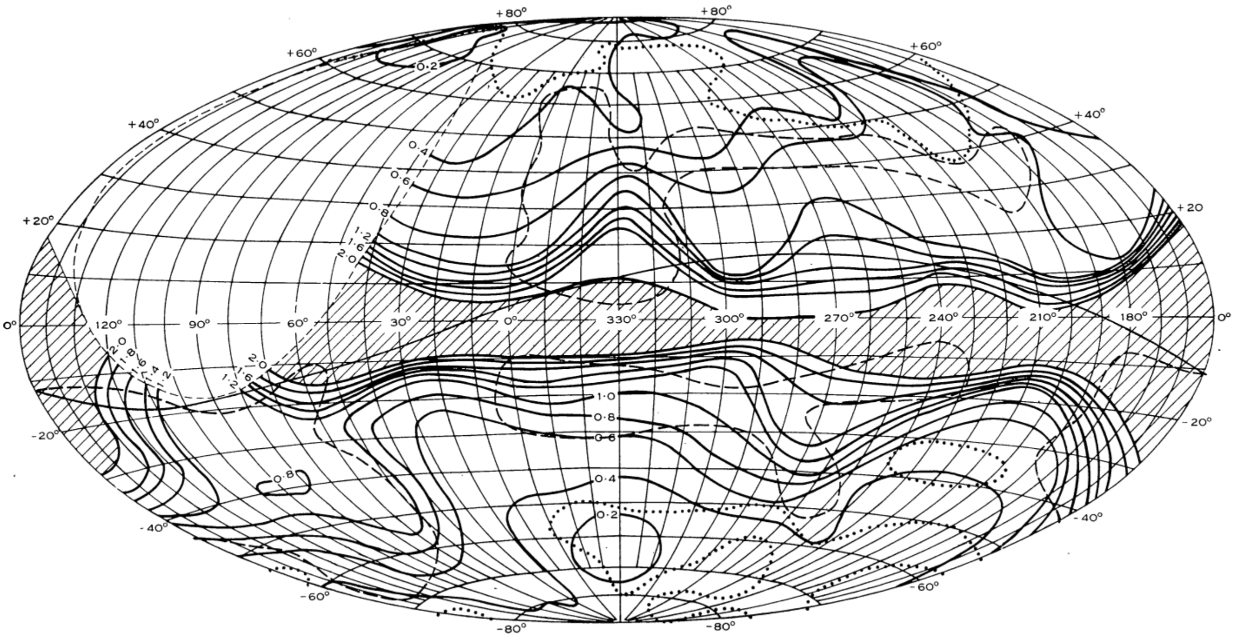

Figure 230: A contour diagram of the local distribution of neutral hydrogen shown as the number of hydrogen atoms/cm^3 in a line-of-sight column. The contour interval is 0.2×10^{21} H atoms cm^{-2}. The hatched area encloses regions where the profile half-widths were in the range 12-20 km/s. The Galactic co-ordinates are the old system after Ohlsson (after McGee and Murray, 1961b: 264).

The hatched area in Figure 230 indicates the area along the galactic plane where the neutral hydrogen density exceeds 2.0×10^{21} hydrogen atoms cm^{-2}. Also evident are a number of large scale features. The northern galactic hemisphere showed two spurs; one in the Scorpius-Ophiuchus region, and the second in Sextan’s region. A weaker ridge is also visible in the southern hemisphere. McGee and Murray noted that the mean longitudes of the major northern spur, the southern galactic minimum, the northern minimum and southern spur were approximately the same. Dr. W.C. Erickson had also alerted McGee and Murray to the fact that the position of the northern minimum agreed exactly with that of the D.T.M survey and was also the pole corresponding to the plane of the general magnetic field in the solar vicinity as derived by Shain (1957). No conclusion was drawn from the coincidence of this alignment.

McGee and Murray noted that if the neutral hydrogen is stratified parallel to the galactic plane, then the observed density should vary as the cosecant of the galactic latitude. Figure 231 and Figure 232 show the density of neutral hydrogen plotted against twelve galactic longitudes as a function of latitude.

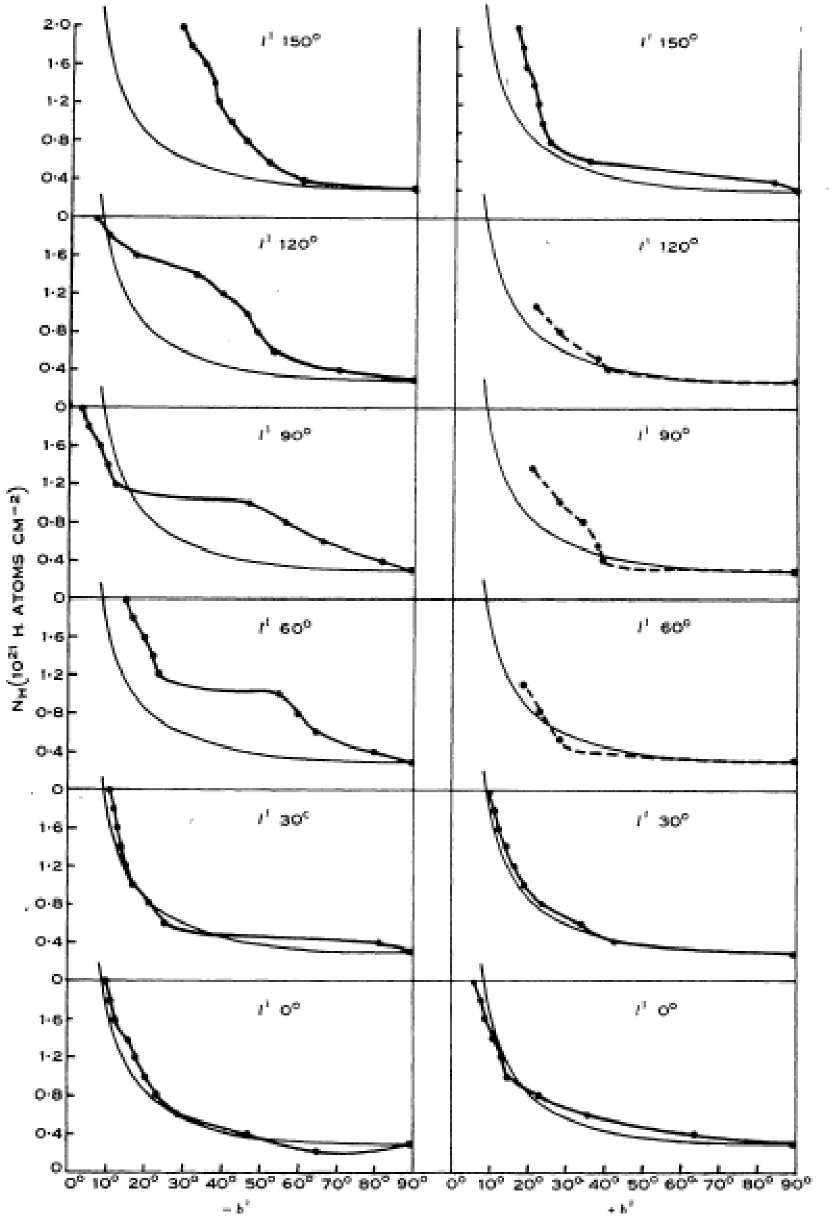

Figure 231: The variation of neutral hydrogen (N_H) density compared to the cosecant curve $N_H = \left|0.3\times10^{21} \text{ cosec } b^I\right|$. The left-hand column are +ve latitudes and the right-hand column are –ve. Longitudes 0° to 150° (after McGee and Murray, 1961b: 269).

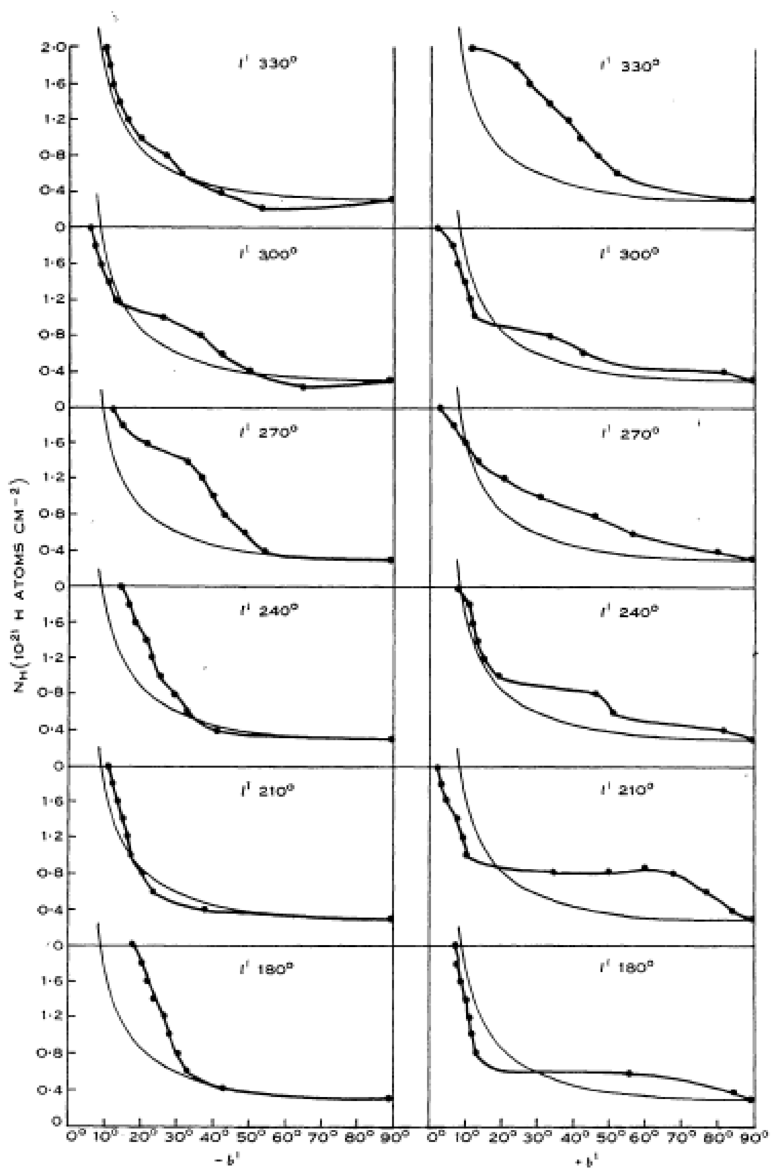

Figure 232: The variation of neutral hydrogen (N_H) density compared to the cosecant curve $N_H = |0.3\times10^{21} \operatorname{cosec} b^I|$. The left-hand column are +ve latitudes and the right-hand column are –ve. Longitudes 180° to 330° (after McGee and Murray, 1961b: 269).

The conclusion drawn from these diagrams was that the neutral hydrogen was substantially horizontally stratified in the plane of the galaxy and that there were a number of concentrations of neutral hydrogen embedded in the plane. The estimated density of neutral hydrogen in the solar vicinity was approximately 0.40×10^{21} hydrogen atoms cm^{-2}. Davies (1960) had found a variation in density in the southern galactic hemisphere, however McGee and Murray suggested that this discrepancy was most likely due to averaging effects over different areas of the sky. Their results suggested that there was little difference between hemispheres, indicating that the Sun lies at the centre of the hydrogen layer in the galactic plane.

Much of the data on the radial velocity distribution had been discussed in the *Nature* summary paper. In their paper that appeared in the *Australia Journal of Physics* a more detailed analysis was made of the departures of measured radial velocities from the predicted velocities due to differential galactic rotation. Figure 233 shows a summary of these for both northern and southern galactic hemispheres from ±20° to ±60°. The predicted curve was based on the following formula for points 11 kpc above and below the galactic plane:

$$v_g = 0.11 \times 19.5 \sin 2l' \cos b' \cot b' \qquad (20)$$

It is clear from Figure 233 that at high galactic latitudes the velocity of neutral hydrogen is not influenced by differential rotation. Based on this evidence it was concluded that neutral hydrogen was flowing toward the Sun from above and below latitudes ±90° to ±40°.

The second paper in the series (McGee et al., 1963) dealt in detail with the low velocity gas observations. Some 95,000 H-line profiles were obtained in the survey, of which about 40,000 were redundant, being for the same region of the sky. The redundant profiles were however still useful for cross-checking of the observations. By this stage they were using the term “low velocity” in place of “local” as it became clear that the low velocity areas while predominantly local were not the only regions with low velocity characteristics. In the area of the Milky Way the observations showed a close adherence to the velocities of a simple double sine curve assuming differential galactic rotation. They compared the neutral hydrogen measurements to ionised calcium optical observations (Feast et al., 1957) and found good agreement in radial velocities and distance estimates. However, as shown in Figure 233 it was apparent that a more reliable value for Oort’s constant A = 19.5 kms^{-1} kpc^{-1} may be required. Adjustment of the value of Oort’s constant to A = 13.8 kms^{-1} kpc^{-1} and assuming a distance of 2 kpc would bring the optical and radio observations into alignment. Over time the value for Oort’s constant has been refined to a current value of A = 14.8 kms^{-1} kpc^{-1} (Sparke and Gallagher, 2000: 81).

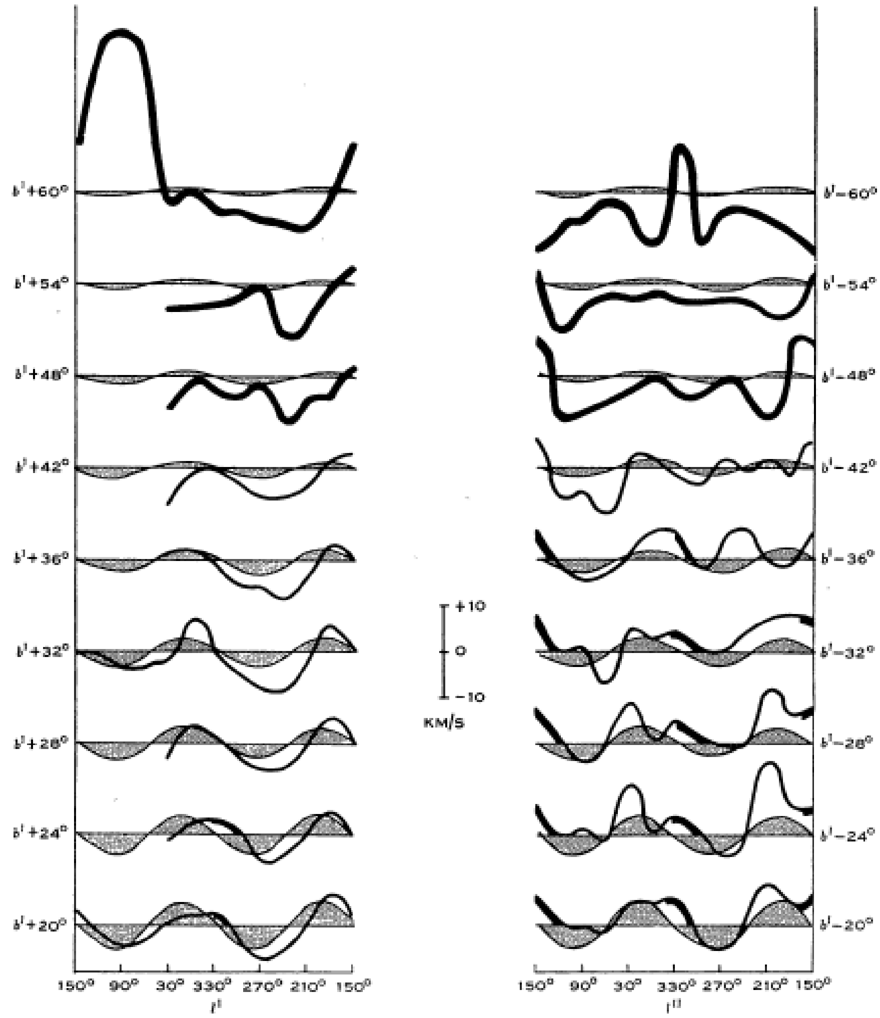

Figure 233: Radial velocity as a function of galactic longitude compared to predicted velocities at points 11 kpc above and below the galactic plane. The thick lines indicate areas of major discrepancies between the prediction and observations (after McGee and Murray, 1961b: 276).

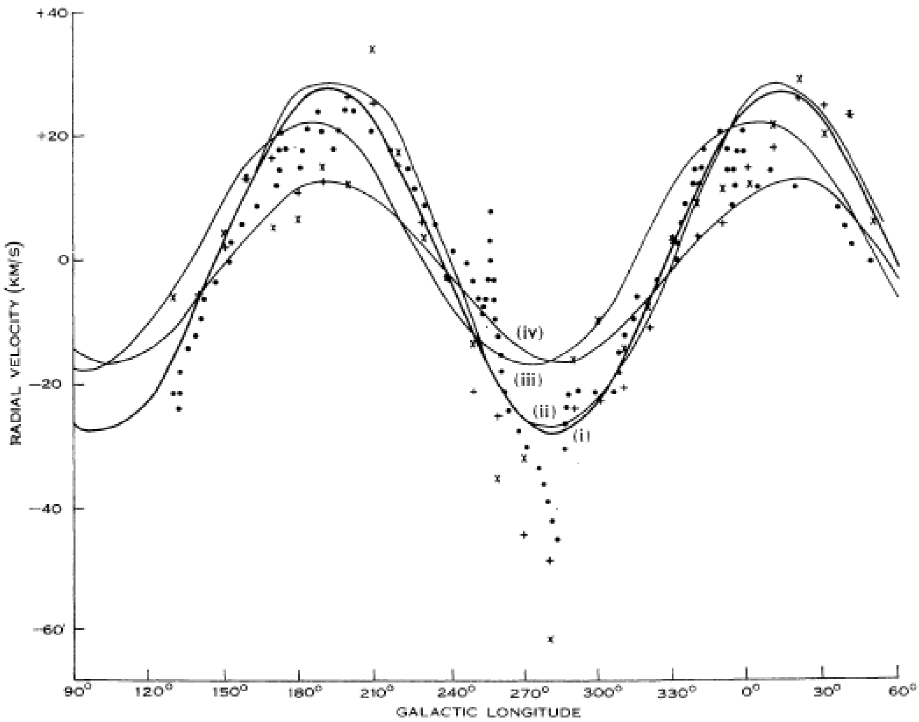

Figure 234: Radial velocity observations as a function of galactic longitude. The dots represent neutral hydrogen observations. The + points and X points are derived radial velocities using the relation $v_g = 19.5r \sin 2(l^{I} - 238°)$. The + points are positive latitudes the X negative. Curve (i) is the theoretical differential rotation curve assuming a 1.4 kpc estimated mean distance of hydrogen in the galactic plane. Curve (ii), (iii) and (iv) are those derived by Feast and Thackeray based on ionised calcium (Ca II) absorption lines in the spectra of B-type stars reduced to mean distances of 2, 1.15 and 0.75 kpc respectively (after McGee et al., 1963: 154).

A detailed comparison was made between the neutral hydrogen distribution and the other radio-frequency emission distribution. A catalogue of concentrations, depression and column density deficiencies of low velocity neutral hydrogen was produced and this was compared to surveys by Westerhout (1958) at 1,390 MHz and by Mathewson et al. (1962) at 1440 MHz. These were continuum rather than H-line surveys. The general findings from this comparison were that there was evidence of absorption by neutral hydrogen from some intense and extended sources. For some nearby thermal radio sources, strong HI and HII emissions are related. The neutral hydrogen emission along the Milky Way on the other hand, can be very intense in places where the radio continuum drops to a negligible level. The survey also confirmed that Hα emitting regions occur where there are areas of intense neutral hydrogen emission. It was noted that deficiencies in neutral hydrogen of about 8 °K occur where the position coincides with HII regions. Although the association of neutral hydrogen with dust had previously been demonstrated, the detailed survey provided very strong evidence to support this association. There were a number of outstanding examples of this correspondence in the regions of the Great Rift, the Ophiuchus Complex and the spurs in the Orion-Taurus-Perseus region, although this association was not present in all cases, for example for the Southern Coal-sack. Figure 235 and Figure 236 are examples produced from the survey of the contour diagrams of peak temperatures and the corresponding radial velocities for similar areas of the sky.

Figure 237 shows a summary diagram of the of the peak temperature from declinations +42° to -80°. In this diagram the contours have been limited to 4, 8, 16, 32 and 64 °K for simplicity. This diagram should be compared to the general radio continuum shown in Figure 156.

The third paper in the series (McGee and Milton, 1964) on the Murraybank H-line survey, addressed the high velocity neutral hydrogen believed to be associated with the Galaxy's spiral arms. Again, the detailed data was presented with a minimal amount of reduction and correction. The distribution of neutral hydrogen in the Milky Way had previously been extensively studied in Leiden (Muller and Westerhout, 1957; Ollongren and van de Hulst, 1957; Schmidt, 1957; van de Hulst et al., 1954) and at Potts Hill as discussed in section 10.5.2.2. The new IAU System of Galactic Coordinates (Blaauw et al., 1960) had been determined principally from neutral hydrogen observations in the inner part of the galaxy. The third paper therefore dealt mainly with the outer parts of the Galaxy beyond the solar orbit and within galactic latitudes of ±10°. In this region the H-line profiles exhibited multiple peaks. Figure 238 shows examples of some triple-peaked profiles.

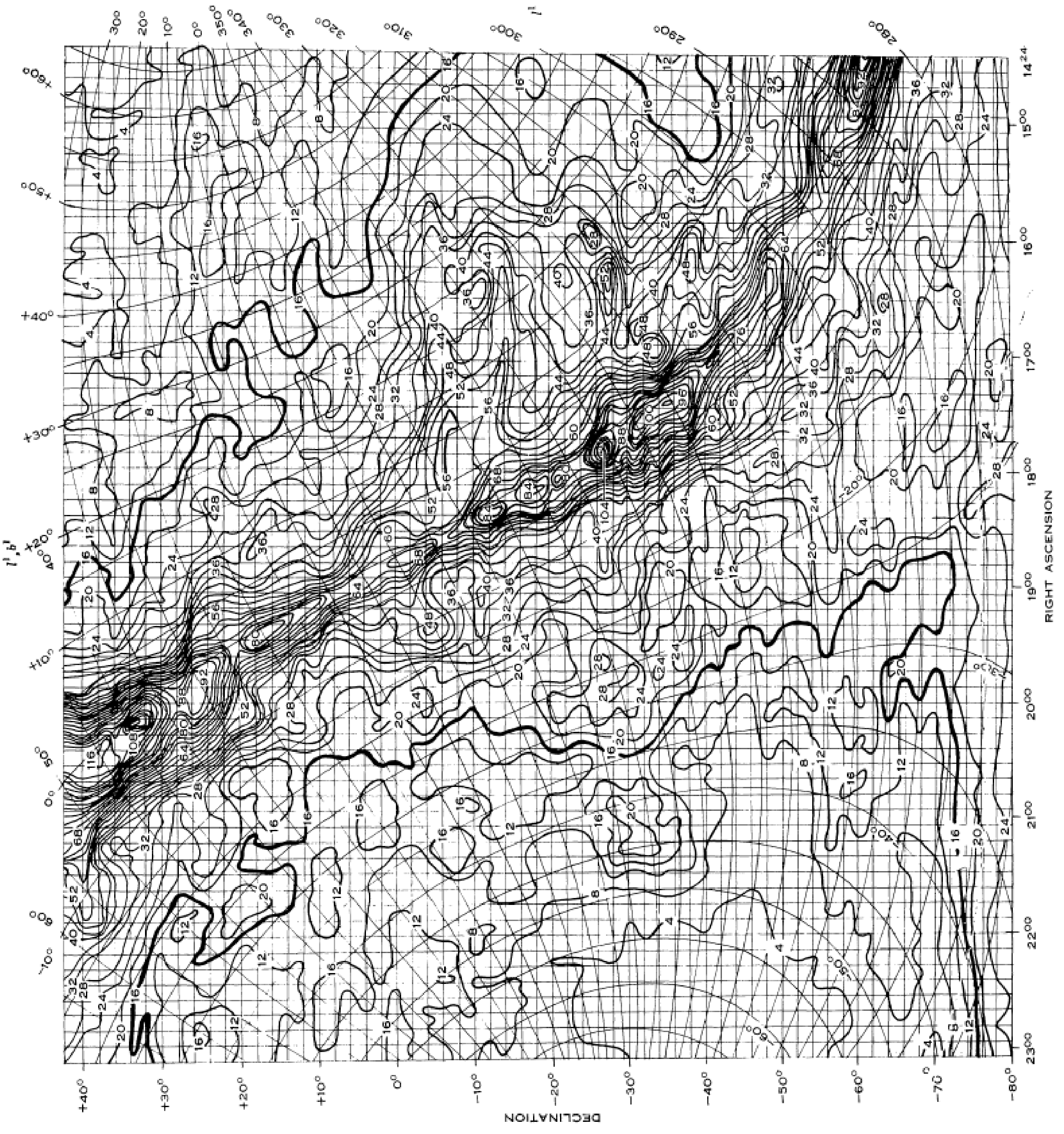

Figure 235: An example of the peak temperature of neutral hydrogen contour diagram produced in the Murraybank survey (after McGee et al., 1963: 139).

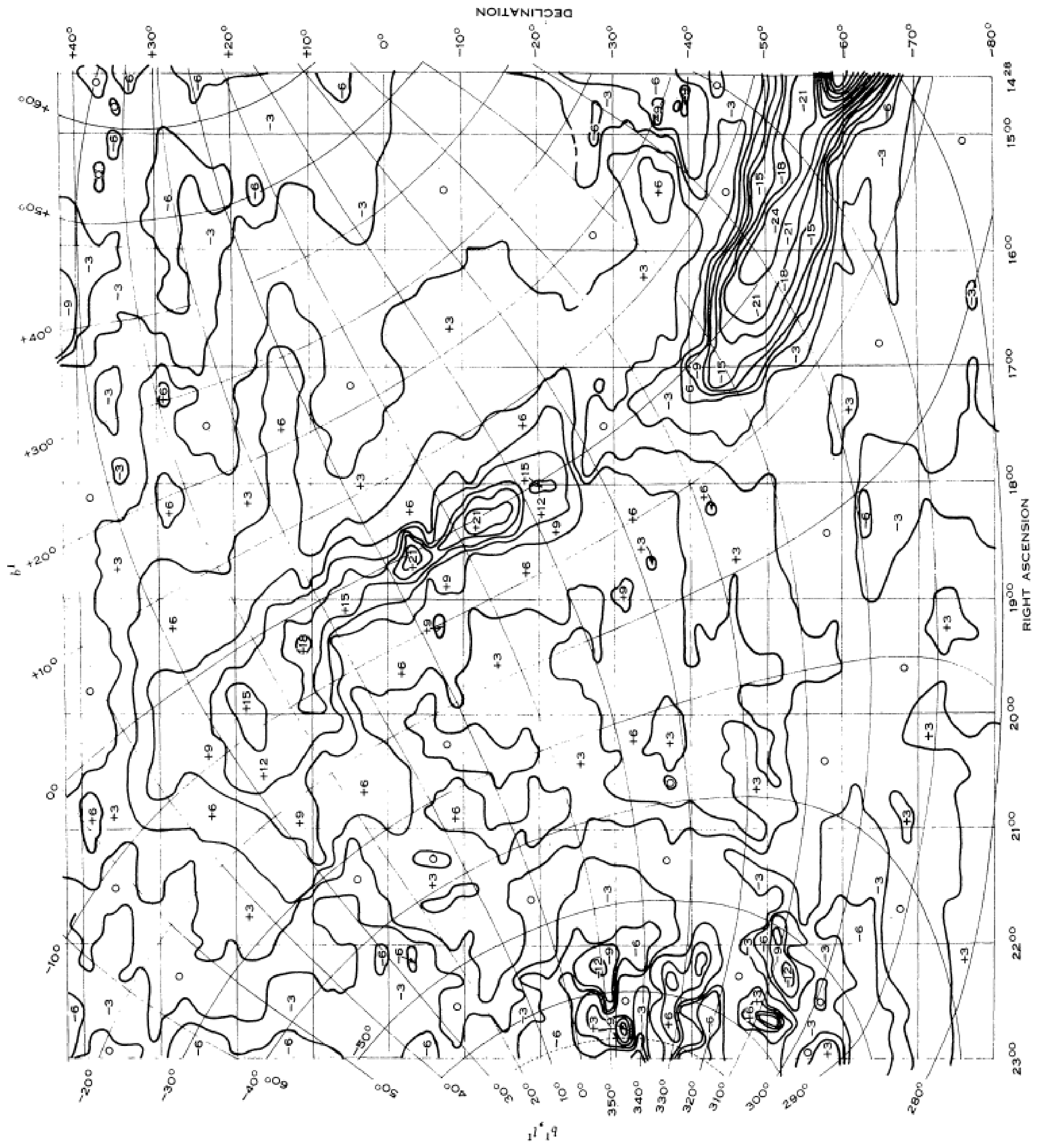

Figure 236: An example of the radial velocity contour diagram corresponding to the brightness peak of neutral hydrogen from the Murraybank survey (after McGee et al., 1963: 147).

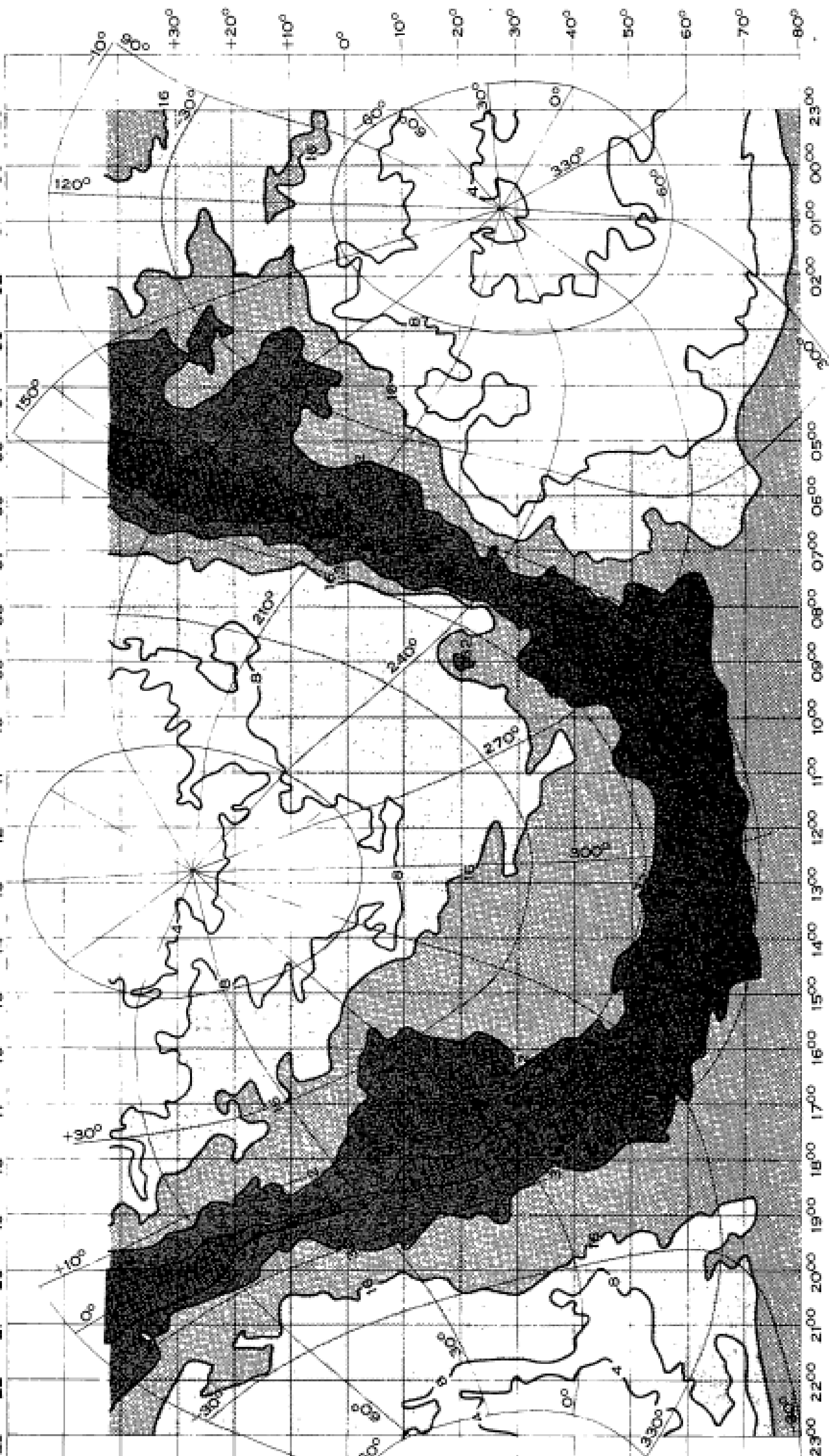

Figure 237: A composite contour diagram of peak temperature with contours limited to 4, 8, 16, 32 and 64 °K (after McGee et al., 1963: 156).

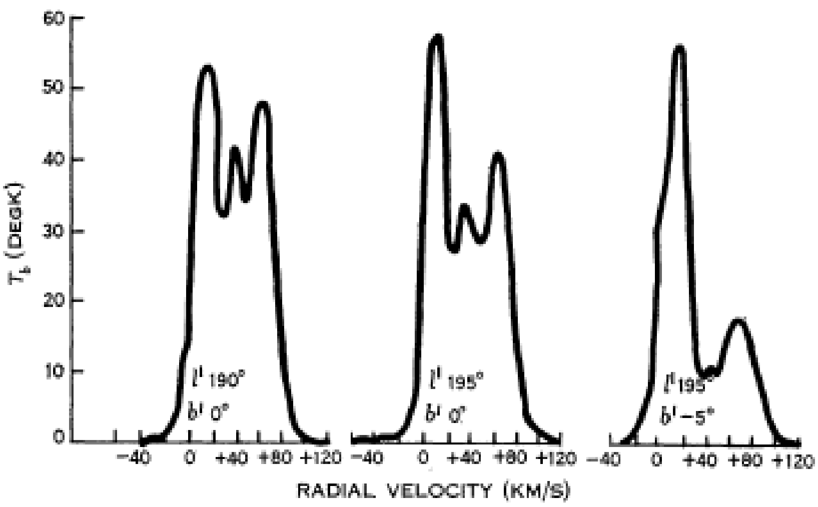

Figure 238: Examples of triple-peaked H-line profiles from the Murraybank survey (after McGee and Milton, 1964: 129).

Figure 239 shows an example of the contour diagrams produced for both peak brightness temperature and radial velocity of the peak.

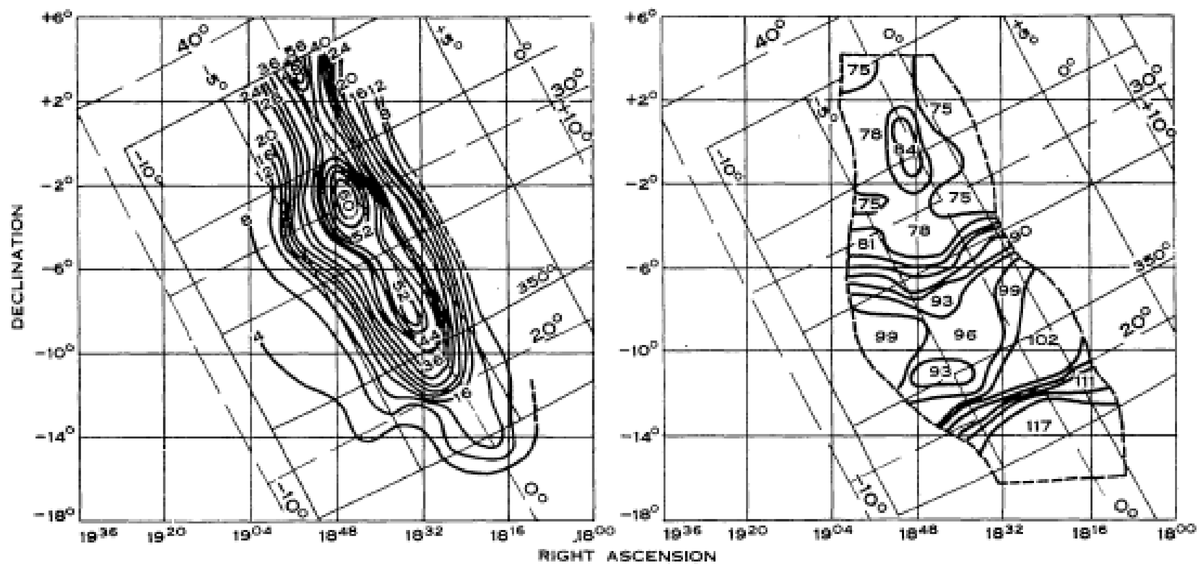

Figure 239: Examples of the peak brightness temperature (left) and radial velocity (right) contour diagrams along the galactic equator from the Murraybank survey (after McGee and Milton, 1964: 143).

To enable comparisons with previous surveys, McGee and Milton adopted the radial velocity-distance model used by Kerr (1962). This included adjustments for both the northern and southern sets of data to include the galactic rotation and an expansion component. For positions inside the solar orbit, an ambiguity of position exists and therefore no general comparisons were made for this region. Figure 240 shows the overlay of their positions of maxima (open circles) and minima (crosses) of hydrogen concentrations on Kerr's (1962) map of the distribution of neutral hydrogen. The dark line joining the positions marks the ridges of maximum intensity of four spiral arms.

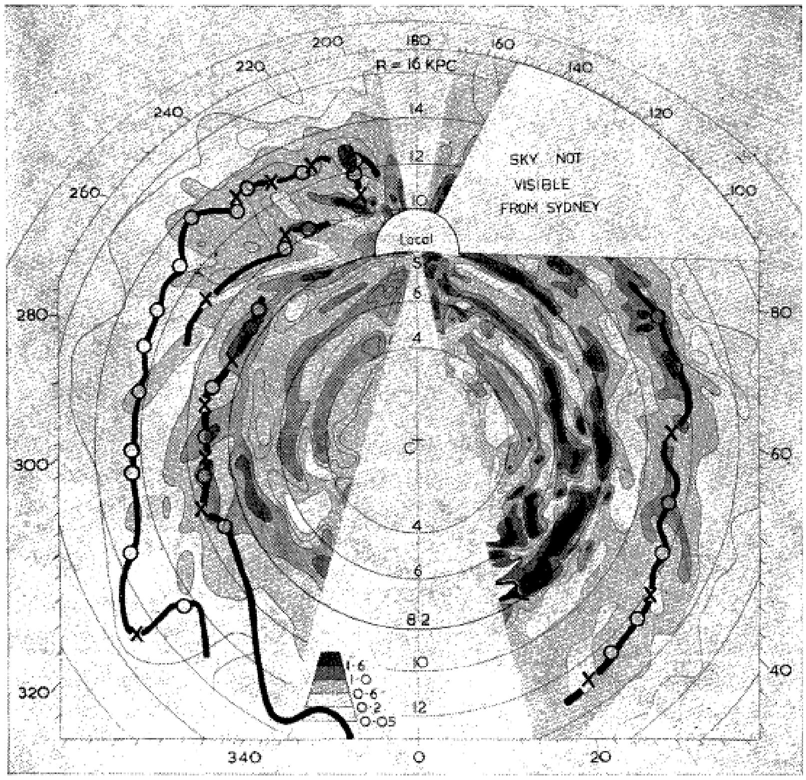

Figure 240: The ridges of maximum intensity of neutral hydrogen for four spiral arm outside of the Sun's galactic orbit over-laid on Kerr's (1962) map of hydrogen distribution (after McGee and Milton, 1964: 149).

Van de Hulst (1958) had earlier published estimates for hydrogen cloud sizes summarised as follows:

Class	Size in pc
Diameter of spiral arms in plane	500-1000
Diameter of spiral arms 90º to plane	200
Condensations in spiral arms	100
Large emission regions	60
Typical cloud, Ca+ absorption	30
Typical cloud, 21-cm emission	20-70

McGee (1964) had drawn attention to the existence of two further classes based on the Murraybank observations. The first of these was typically of 100-150 parsec and contained two or more of van de Hulst's 'typical clouds, 21-cm emission'. They were generally observed in the solar vicinity. The second class was HI clouds that were several times larger and are found in the region outside of the solar orbit. Twenty nine examples of these clouds were recorded that ranged in size from 350-1330 parsecs. The average mass of these clouds was estimated to in the order of 10^7 solar masses. McGee and Milton noted that the hydrogen in our own local neighbourhood could well be considered to form one of the large clouds with the major components being of the 100-150 parsec class, such as the Scorpius-Ophiuchus, Pupis-Vela and Orion-Taurus-Perseus clouds.

One of the major findings from this section of the Murraybank survey was that although there was good agreement with earlier surveys on the possible thickness of the hydrogen layer in the galactic plane, outside of the radius of the Sun's galactic orbit the thickness of four of the spiral arms increases with increasing distance from the galactic centre. At a radius of 13 kpc the half-power thickness of the arms was estimated to be 1,300 parsecs. This phenomenon had not previously received a great deal of attention. Van de Hulst et al. (1954) had found "...a distant arm..." had a "...true half-thickness of 750 parsecs". Westerhout (1957) in discussing a "...faint outer arm..." stated that "...its mean height between +500 and +1000 parsecs is very peculiar". In discussing their result with the Potts Hill team, Hindman had "...informed us that he had noticed the great increase in the thickness of outer arms", however this interpretation was discounted at the time. Figure 241 illustrates the observed rapid increase in cloud thickness outside of the radius of the Sun's galactic orbit.

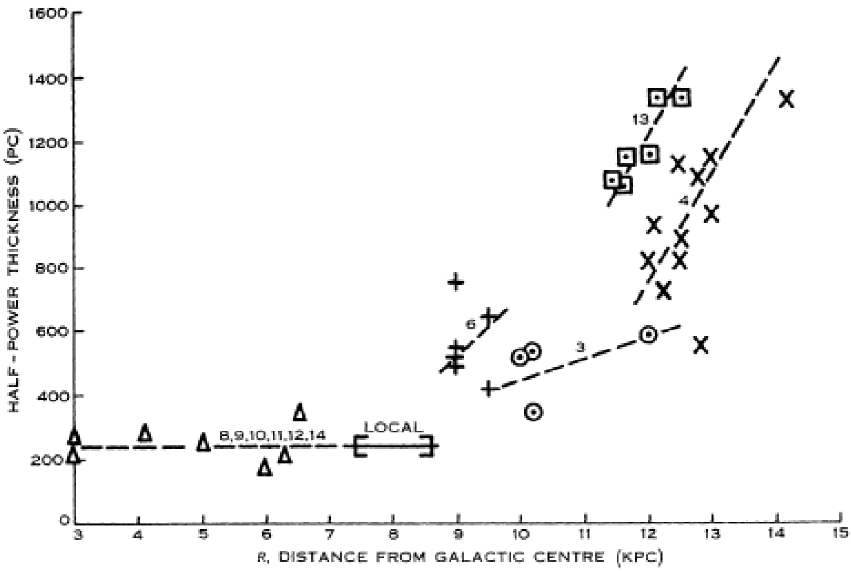

Figure 241: HI Cloud thickness at half-power points plotted as a function of distance from the galactic centre. The different symbols and associated numbers refer to the groups of observations. The triangles are from within the solar orbit. The other represents the four different spiral arms (after McGee and Milton, 1964: 152).

The third paper was the final paper in the series on the Murraybank H-line galactic survey. McGee also co-authored a paper (Howard et al., 1963) that used the Murraybank data for a study of the correlation between radial velocities of optical Ca II line and H-line observations.

The next step for the Murraybank program was a trial of a new digital recording system. For this purpose it was decided to conduct a survey of the Magellanic Clouds to test the recording system prior to its use at Parkes. This survey was conducted in late 1960. For this work McGee was joined by Jim Hindman from Potts Hill. By this time Murray had moved to the Netherlands and was working on the construction of the Benelux Cross.

The introduction of digital recording and data reduction was the first time that Radiophysics had used a digital computer in this role. The Murraybank team consisted of Hindman, McGee, Alan Carter, Eric Holmes and Maston Beard. The survey of the Magellanic Clouds was chosen as it represented a self-contained project, but with the increased sensitivity of the 48-channel receiver also provided a worthwhile extension of the earlier Potts Hill work by Kerr, Hindman and Robinson (1954).

The low resolution survey of the Magellanic Clouds proved extremely successful, not only demonstrating the value of the digital recording and computer based reduction techniques, but also resulting in two major discoveries about the Magellanic Cloud system. Two papers on the survey were published in the *Australian Journal of Physics* (Hindman et al., 1963a; Hindman et al., 1963b). The first of these covered the observations and a description of the digital recording technique, reduction procedure and equipment. The second paper provided an interpretation of the results. This paper was the first research effort that formally bought together the Potts Hill and Murraybank H-line teams prior to the move to Parkes.

The first of the major discoveries produced by the Murraybank survey is clearly evident in the contour diagram of integrated brightness of the neutral hydrogen in the Magellanic system (Figure 242).

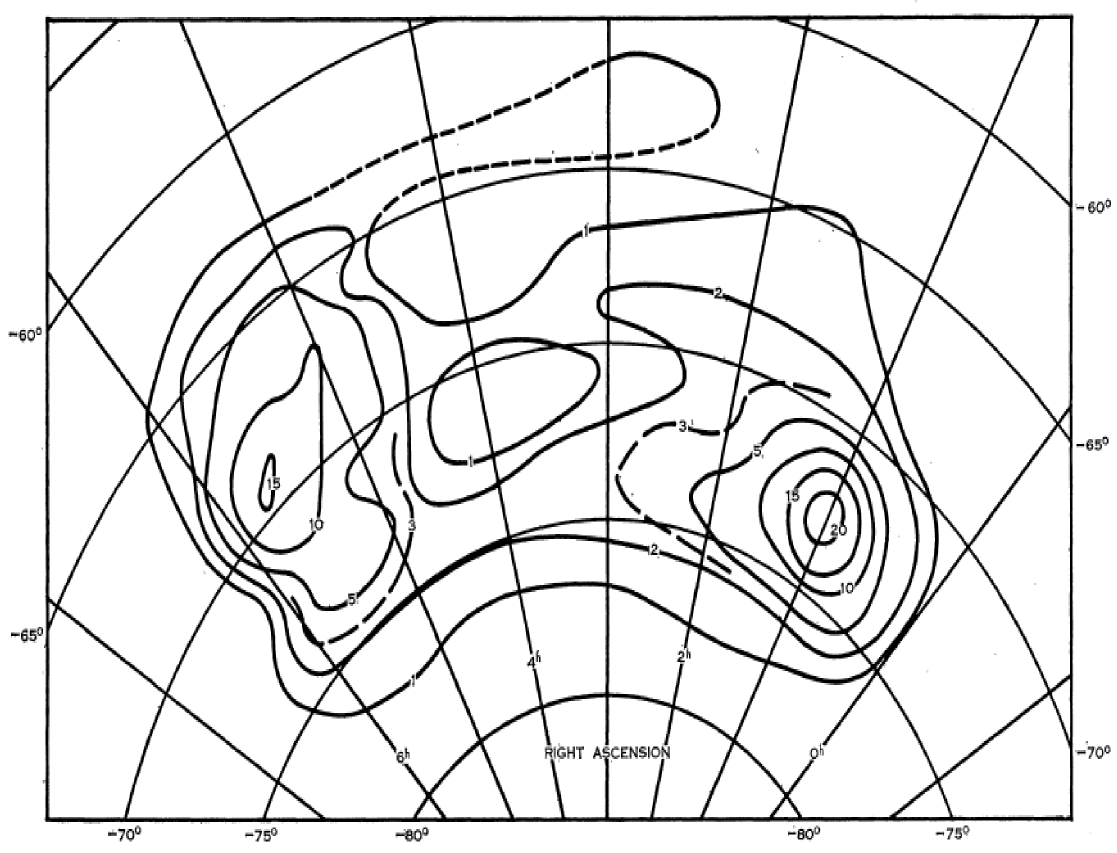

Figure 242: The contours of integrated brightness of neutral hydrogen in the Magellanic System from the Murraybank survey. The contour units = 2×10^{-16} Wm^{-2} sr^{-1} (after Hindman et al., 1963a: 572).

The brightness distribution showed that the two Clouds were joined by a bridge of neutral hydrogen gas, and that they were also within a common envelope of this gas. This detection was made possible by the increased sensitivity of the Murraybank receiver, coupled with the effect of digital integration which raised the sensitivity to a level where the low density region between the clouds could be detected. The system was estimated to be some three times more sensitive than the Potts Hill equipment. The team ruled out the possibility that the effect was caused by overlapping clouds in the line-of-sight at different distances by observing the continuity of the general radial velocity gradient across the cloud system. Although the observations had no sign of a link between the Magellanic Clouds and the Galaxy, the team noted:

> "Such a link would, however, be quite difficult to detect, because it would probably be spread widely on the sky and in velocity, and a different observing technique would be desirable in searching for it." (Hindman et al., 1963a: 577).

With the benefit of hindsight this statement proved insightful, with the Magellanic Stream (Figure 243) being discovered by a team, including Murray, using observations from Parkes (Mathewson et al., 1974). HI velocity anomalies near the South Galactic Pole had been noted as early as 1965 (Deiter, 1965) and subsequently van Kuilenburg (1972) and Wannier and Wrixon (1972) noted a large area of HI emission, but it was Mathewson et al. who recognised its full extent and associated the stream with the Magellanic Clouds. De Vaucouleurs (1954a,b) had been the first to propose a link between the Magellanic Clouds and our Galaxy some twenty years before the discovery of the stream. More recent studies (McClure-Griffiths et al., 2008) have shown that the leading arm of the stream is intersecting the Galactic disk approximately 21 kpc from Earth at a point in the sky near the Southern Cross.

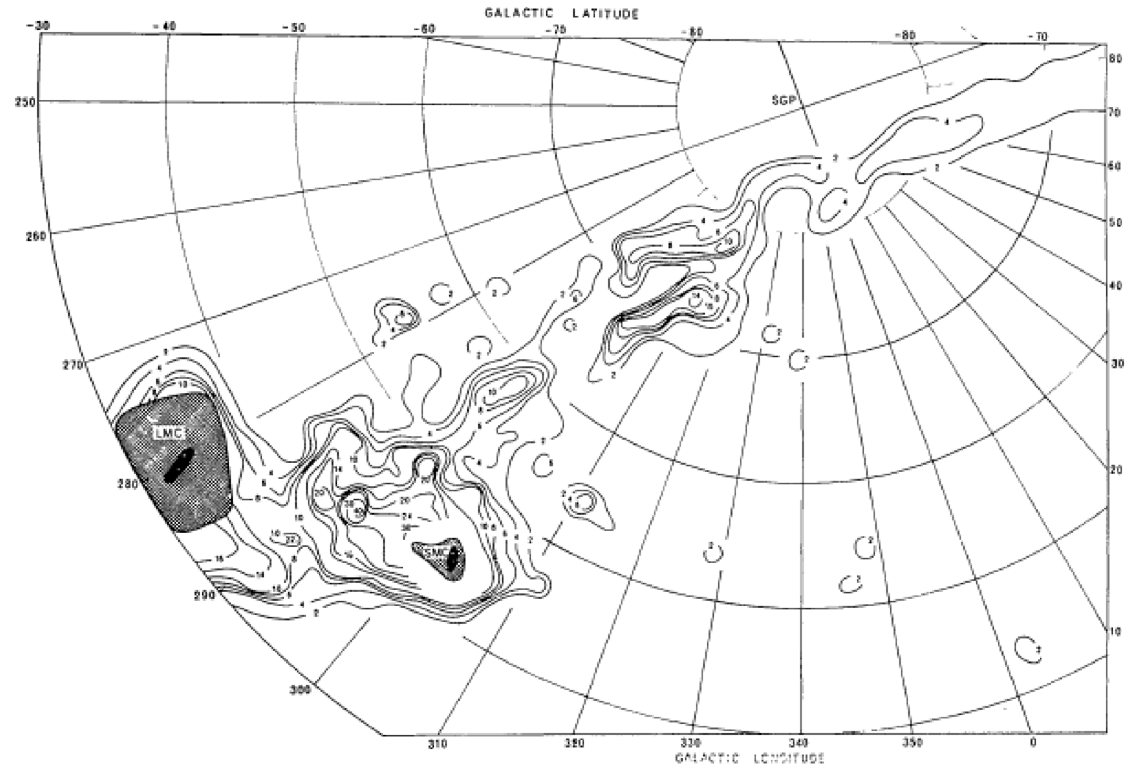

Figure 243: Contours of surface density of neutral hydrogen from Parkes 18-m (ex-Kennedy dish). The Magellanic Stream is seen extending from the Magellanic Clouds (left) across the sky (after Mathewson et al., 1974: Plate 6).

Using Wild's (1952) method for estimating the number of atoms in a line-of-sight column of optically thin gas, the team was able to estimate the following masses of neutral hydrogen:

	Solar Masses
Large Cloud (inside contour 3, Figure 242)	3.2×10^8
Small Could (inside contour 3, Figure 242)	2.8×10^8
Whole Magellanic System	1×10^9

A comparison was made between the neutral hydrogen distribution and the distribution of HII regions (Henize, 1956), globular clusters (Hodge, 1960, 1961), SMC Clusters (Lindsay, 1958) and SMC emission-line objects (Lindsay, 1961). No significant conclusion could be drawn from these comparisons other than that all the objects tended to concentrate in the main bodies of the Clouds.

Based on the observations, a rotation curve for the Large Cloud was derived (Figure 244). This curve was largely similar to the findings of the earlier survey by Kerr et.al. (1954). No clear curve could be derived for the Small Cloud.

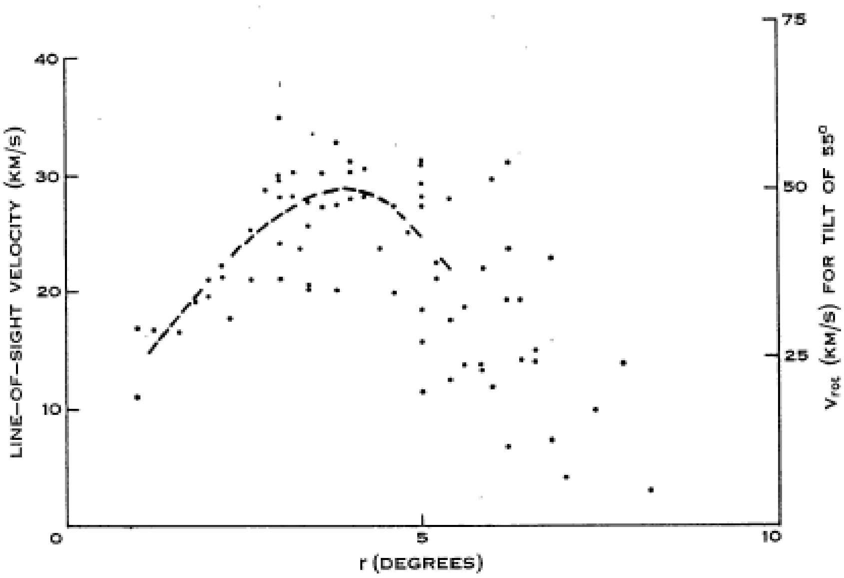

Figure 244: The rotation curve for the LMC derived from median velocities of neutral hydrogen profiles. The centre of rotation was R.A. 05:25, Dec. -68º (1960). The position angle of major axis: 5º-185º. A tilt of 55º was assumed. Note that both sides of the curve are plotted together (after Hindman et al., 1963a: 580).

Based on this rotation curve a mass estimate for the Large Cloud was found to be in the range 7-10 × 10^9 solar masses. Note this is a factor of 10 larger than the mass derived from Wild's method and could have been another of the early clues to the "missing mass problem" generally identified with galaxies and examined in detail in the late 1960s (e.g. see Freeman, 1970; Rubin and Ford, 1970).

The second major discovery came from the radial velocity measurements of the Small Magellanic Cloud. Figure 245 shows the contours of median radial velocity of the neutral hydrogen profiles from the Magellanic System that has been corrected for both the motion of the Earth's orbit and the Sun's orbit about the Galaxy.

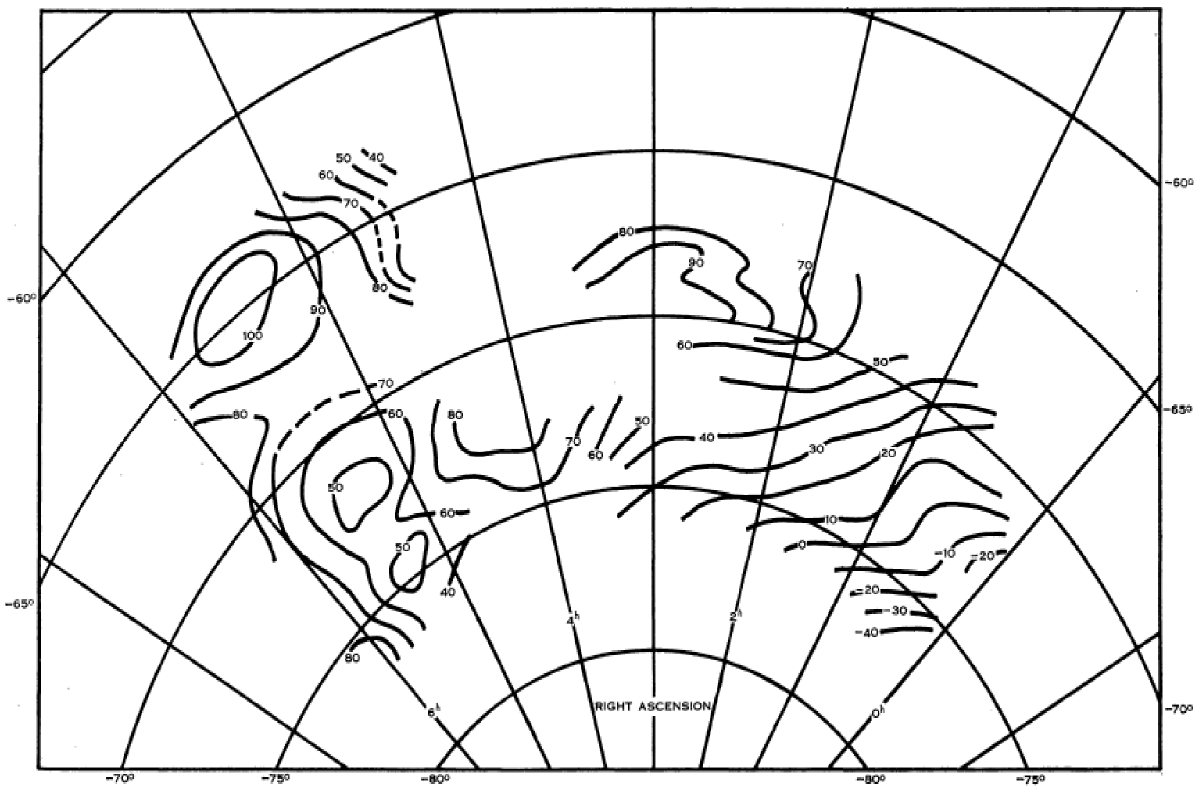

Figure 245: The contours of median radial velocity of the Magellanic System. The contour interval is 10 Km/s (after Hindman et al., 1963a: 579).

To allow for correction due to the Sun's orbital velocity, a rotational velocity of 216 km/s was assumed. This value was adopted to simplify comparison to the earlier survey which used this value. By this time evidence was building for a much higher value (i.e. 300 km/s by de Vaucouleurs, (1961)).

Figure 246 and Figure 247 show a summary of H-line profiles for the Large and Small Clouds respectively. The Small Cloud shows large areas where double-peaked line profiles are evident. The double-peak nature of some of the Small Magellanic Cloud line profiles had previously been noted by Johnson (1961) based on an examination of the original survey data from Kerr et al. (1954), although few conclusions could be drawn due to the quality of these records.

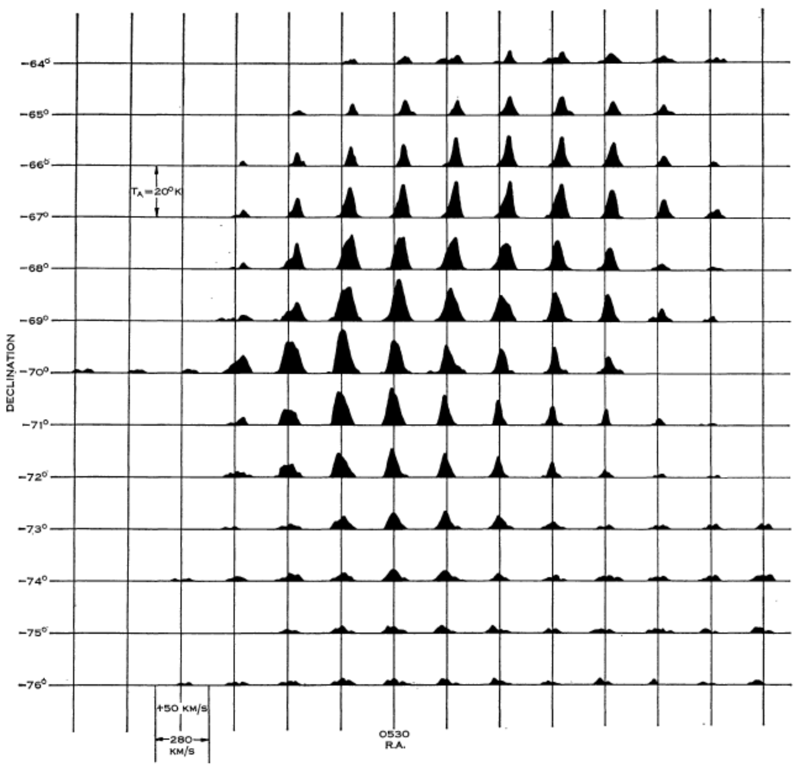

Figure 246: Line profile per square degree of sky from the LMC. The vertical line on each profile is +50 km/s (after Hindman et al., 1963b: 568).

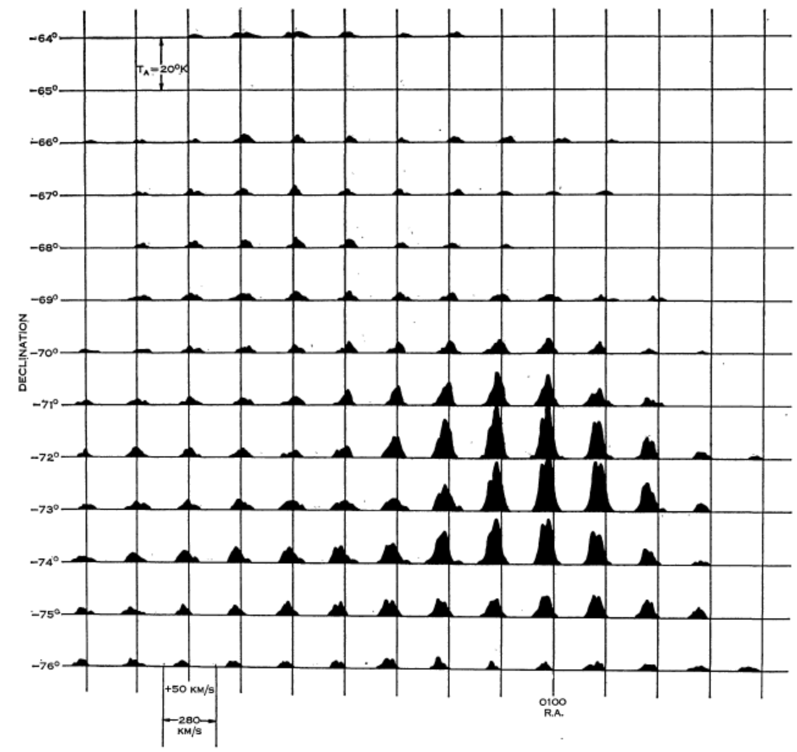

Figure 247: Line profile per square degree of sky from the SMC. The vertical line on each profile is +50 km/s. Note the large area of double-peaks. (after Hindman et al., 1963b: 568).

The splitting of the H-line profiles into two distinct groups is best illustrated in Figure 248. The difference between peaks is consistently between 25-30 km/s over a large area. This “splitting” of the Small Magellanic Cloud had not been observed in any other optical or radio observations before this time.

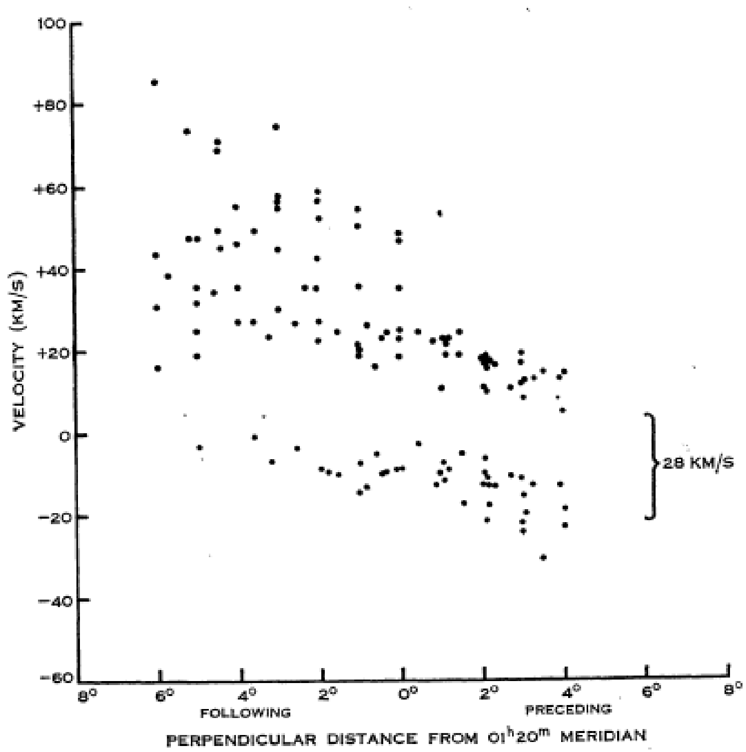

Figure 248: Velocities of the main peaks of neutral hydrogen in the SMC showing the systematic separation into two groups separated consistently by ~28 km/s (after Hindman et al., 1963a: 581).

Many years later the ‘splitting’ of the Small Cloud was seen as providing an important clue to the origin of the Magellanic Stream. Mathewson et al. (1987) found that by integrating backward in time, the Small Cloud could have collided with the Large Cloud ~4 $\times 10^8$ years ago. This could mean that the Stream originated from this collision and the split of the Small Cloud indicated it was breaking up following the interaction with the Large Cloud.

Over the period 1962 to 1964, Hindman (1967) used the 64-m Parkes telescope together with the Murraybank multi-channel receiver for a high resolution (~15 arc seconds at 1,420 MHz) survey of the Small Magellanic Cloud. At this much higher resolution, Hindman concluded that the double-peaked profiles that had earlier been observed were related to at least three broad structural features which may represent expanding shells of gas within the main body of the cloud, which itself appeared to be a flattened system, rotating in a plane observed near edge-on to the observer. This conclusion was supported some years later when data from Parkes and the Australia Telescope Compact Array were combined in a detailed study of the Small Magellanic Cloud (Stanimirovic et al., 1999).

12. CONCLUSION

The seminal period of radio astronomy prior to 1960 was arguably the most exciting and innovative era in Australian Radio Astronomy (i.e. see Robertson, 1992: 202). It marked the era before 'big science' projects emerged, a period when small scale projects dominated and radio engineers first entered the domain of the astronomers. For Australia this was a unique period in which it achieved a research leadership position in the new field of radio astronomy. As Hanbury-Brown (1993) remarked, "golden ages in science are rare and should be recorded". This thesis documents the activities at the Potts Hill field station, which operated for 12 years during this 'golden age' of radio astronomy, a period in which rich contributions to the emergent science of radio astronomy were made, both in terms of new instrumentation development and scientific research. Although the Murraybank field station operated for a much shorter period it also provided a significant contribution. The work at both of these field stations has previously not been documented in detail and as such this thesis provides a detailed record of the scientific contributions made.

Ten different types of radio telescope were operated at Potts Hill. Amongst these there were several examples of world-first instrumental developments:

- The Swept-Lobe Interferometer developed by Payne-Scott and Little used a continuously-variable path length between the two Yagi antennae to change the phase of the signal and hence sweep the aerial beam. This innovation removed the restriction of having to wait for the Earth's rotation to move the source through the aerial beam to produce an interference pattern and was hence ideal for locating the position of short duration sources. At the time of its invention interferometry was being conducted either using the sea-interferometry technique (McCready et al., 1947), or using the Michelson interferometry technique that was first used by the Cambridge group (Ryle and Vonberg, 1946). Not only could the Swept-Lobe Interferometer determine a position accurate to 2 arc minutes at 97 MHz, it could also measure the polarisation of the source. The swept or rotating lobe technique was later adapted by the Jodrell Bank group (Hanbury-Brown et al., 1955) and proved useful in their work on determining source sizes for high declination sources.

- The E-W Solar Grating Array was a unique instrument that provided the first regular one dimensional images of the Sun at radio frequency. Earlier, Stanier (1950) working at Cambridge with a two element Michelson interferometer to obtain a brightness distribution across the solar disk, had failed to detect limb-brightening. The E-W Solar Grating Array provided clear evidence of limb-brightening and was able to produce a large data set of one-dimensional brightness distributions across the solar disk at 1,410 MHz. The Cambridge group went on to develop the aperture synthesis mapping technique, producing the first two-dimensional map of the Sun

(O'Brien, 1953; O'Brien and Tandberg-Hassen, 1955). Meanwhile, with the construction of the N-S Solar Grating Array Christiansen and Warburton were also able to produce a two-dimensional distribution. However, in this instance they used the first application of earth-rotational synthesis in radio astronomy to produce their image. The use of the Earth's rotation to provide a variety of scanning angles proved a much simpler method than relocating the elements of an interferometer as had been employed by O'Brien at Cambridge to obtain the wide variety of base-lines necessary to reconstruct a two dimensional image. The grating-style array proved very useful for solar observations; it was quickly adopted by a number of research groups throughout the world, such as the Carnegie Institute in the U.S., the Research Institute of Atmospherics in Nagoya, Japan and the Meudon Observatory in France.

- The development of the Mills Cross was a major instrumental breakthrough and proved especially useful for extra-solar source surveys. The use of a phase-switched interferometer was first introduced at Cambridge (Ryle, 1952) and was one of the contributing factors for which Sir Martin Ryle was awarded the 1974 Nobel Prize in Physics. After gaining experience using a phase-switched interferometer at the Badgerys Creek field station, Mills struck on the idea of constructing a phase-switched crossed-array. This instrument produced a pencil beam response equivalent to the filled aperture of a parabola of the same diameter as the length of the cross arms. Unlike aperture synthesis techniques, it was not necessary to use a complex Fourier analysis to reconstruct the brightness distribution of the filled aperture. The prototype for the Mills Cross was constructed at Potts Hill and not only was the trial successful, but Mills and Little also achieved the first detection of the Large Magellanic Cloud at radio frequency. The 'Mills-Cross' design proved a very economical way to produce a high resolution pencil beam instrument and its design was subsequently adopted by a number of other countries. It is interesting to note that at almost the same time the Jodrell Bank group had considered a similar cross design, but in view of their existing commitment to the construction of the 250-ft dish they did not develop the idea further (Hanbury-Brown, 1953). The cross design also inspired Christiansen to build a new crossed-grating array at the Fleurs field station which became known as the 'Chris-Cross'.

- The Potts Hill 4-channel H-line receiver was the first proposed design of a multi-channel receiver for H-line observations and the idea of using the multi-channel design was quickly adopted by other radio astronomy groups engaged in H-line research. By 1954 multi-channel receivers were under development at the Carnegie Institute in Washington and at R.R.E Malvern in the U.K. The multi-channel receiver development was extended at Murraybank to produce a 48-channel receiver. Murraybank was also the site of the first deployment of digital recording and computer based reduction of observational data in Australia. The Murraybank 48-channel receiver and the digital recording system became one of the first operational instruments on the newly constructed Parkes 64-m telescope when it was commissioned in late 1961.

Although research at Potts Hill initially focused on the Sun, in later years important contributions were also made to cosmic research and in particular the investigation of the distribution of neutral hydrogen in our Galaxy.

The solar research program provided an important contribution to knowledge of the quiet Sun and the slowly varying component. Although certainly not the first eclipse observations in radio astronomy, the 1948 partial solar eclipse observations provided an important confirmation of the association of enhanced sources of radiation with sunspot groups and the slowly varying component. The development of the grating arrays allowed regular daily determinations of brightness distributions across the solar disk, something which was not practical with any other instrument at the time. The grating array observations provided the most comprehensive dataset during the 1950s on the structure of the solar atmosphere at 1,410 MHz and later also at 500 MHz. The data provided confirmation that the quiet Sun component remained constant over prolonged periods and were used to show that the slowly varying component appeared to correspond with chromospheric plage, something that had first been suggested by Dodson (1954) working in the U.S. In a fitting end to the solar research program the final published work from Potts Hill was the observation of the 8 April 1959 partial solar eclipse. Thus 11 years of solar radio astronomy at Potts Hill began and ended with eclipse observations.

Payne-Scott and Little's observations using the swept-lobe interferometer provided the first accurate positional information on solar bursts and evidence of the outward motion through the solar atmosphere of a number of sources. Unfortunately these investigations were cut short by Payne-Scott's resignation. Had this work continued in conjunction with the work being conducted by Wild's group at Dapto to include a spectral analysis, it seems likely that they would have discovered the type IV sources later discovered by Boischot (1958) using the Nançay interferometer in France (Stewart, 2007).

The initial neutral hydrogen survey conducted at Potts Hill by Christiansen and Hindman provided the first radio frequency indications of the spiral arm structure of our Galaxy. This was a remarkable achievement given that both the U.S. group at Harvard and the Dutch group at Leiden had been working in the field for a much longer period. The H-line program marked the beginning of a major international cooperative program. The Dutch group led by Oort soon overtook the Australians with their galactic mapping of the northern sky and they would have to wait some time for the Australians to complete the southern sky survey so their results could be combined to produce the famous 'Leiden-Sydney' H-line map (Oort et al., 1958). This combined work, together with the 600 MHz continuum survey conducted at Potts Hill, were key components in the redefinition of co-ordinates of the Galactic Plane. Australia's southern location provided access to the Magellanic Clouds something that was not possible for the northern hemisphere groups. It is natural therefore that the Australians dominated the early studies with the first neutral hydrogen maps of the clouds produced at Potts Hill. A later Murraybank survey detected the bridge of neutral hydrogen connecting the two clouds as well as finding the first evidence for 'splitting' of the Small Magellanic Cloud, suggesting an earlier interaction between the galaxies. Besides missing the opportunity to be the first to detect the 21-cm hydrogen line emission, the other aspect that escaped the Australian's early work was the discovery by Williams and Davies (1954) at Jodrell Bank that the hydrogen emission could also be studied in absorption. Hagen, Lilley and McClain (1955) working in the U.S. were also able to exploit this discovery to examine the properties of the interstellar medium and to determine the distance to galactic radio sources. This illustrates that while the Australians had made remarkable progress, there were also missed opportunities.

The most notable of the discrete sources discoveries at Potts Hill were made by Piddington and Minnett. Up to this time, work on discrete sources in Australia had been dominated by Bolton's group working at Dover Heights and later by Mills working first at Badgerys Creek and then at the Fleurs field station. There was intense competition and some disagreement during this period with the Cambridge group, although relationships with the Jodrell Bank group were more cordial. The two major discrete source discoveries at Potts Hill were Sagittarius A, which was associated with the Galactic Centre, and Cygnus X associated with a large Galactic HII region. While Piddington and Minnett attempted to detect M31 at radio frequencies they were unsuccessful and were soon scooped by the Jodrell Bank group who used a much more sensitive 218-ft transit telescope. Also of note during the early period of Potts Hill investigations was Mills' determination of the position of Cygnus A. Although discounted at the time, Mills had suggested an optical association of the Cygnus A source with an extra-galactic nebula. However, Smith (1951) working Cambridge obtained a more accurate position that ultimately led to the optical identification of Cygnus-A with the faint extra-galactic nebula, first suggested by Mills (Baade and Minkowski, 1954).

As discussed above, British, Dutch and U.S. scientists were prominent in both solar and galactic research during the Potts Hill-Murraybank period. However, many other international groups also made contributions during this period. For example, Covington (1947), working in Canada, showed that strong solar emission was associated with a sunspot group that was occulted during the 23 November 1946 solar eclipse and went on to develop a slotted waveguide array capable of producing strip scans of the Sun at 10.7-cm wavelength. Khalikin and Chikhachev (1947) from the former Soviet Union observed the 20 May 1947 total solar eclipse from a ship near the Brazilian shore and demonstrated that the radio emission at 200 MHz came from the solar corona. The theoretical contribution of the Soviet astronomers, particularly Ginzberg and Shklovsky, was of great importance and included the independent explanation of the million degree temperature of the solar corona, synchrotron emission and predictions of a number of radio frequency spectral lines. The French were also particularly active in solar research conducting a number of eclipse observations and constructing the 169 MHz Le Grande Interferometer de Nançay, which consisted of 32 × 5-m antennas on a 1,600-m east-west baseline and to which a north-south arm was added in 1959. This instrument was used by Boischot (1958) to discover the Type IV solar bursts. The Japanese had recognised solar radio emission as early as 1938 (Tanaka, 1984). In 1949 they began regular solar monitoring and later constructed their own Solar Grating Array. Yet, despite all of these developments, and others, Australia and Britain were widely regarded as the forefront radio astronomical nations at this time (Sullivan, 2004), and Potts Hill and Murraybank played no small part in establishing and maintaining this reputation.

Many of the Australian pioneers of radio astronomy spent time at Potts Hill and by 1952 it was the major field station of the Division of Radiophysics. Ultimately the lack of space and the encroachment of the suburbs of Sydney (with a consequential increase in radio interference) meant that research was shifted to other field stations. In late 1961 the last of the solar monitoring was transferred to Fleurs field station and Potts Hill was decommissioned in 1962. By this time work at Murraybank had also been completed and the field station was no longer used for radio astronomy after 1961. These events signalled the end of an era in Australian Radio Astronomy. With the construction of the Parkes 64-m telescope and later the Culgoora Radio Heliograph, Australian Radio Astronomy had begun a new ear of 'big science' projects.

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14. APPENDICIES

14.1. Appendix A – Publications from Potts Hill

The following table provides a chronological listing of scientific publications that were based on research carried out at Potts Hill. A selection of theoretical papers has been included in this listing only where there was a particularly close association between the theoretical work and actual observations made at Potts Hill. Also included are some summary papers reporting on the progress of Australian radio astronomy that contained major reference to the research being conducted at Potts Hill. See Table 2: Summary of Potts Hill Instruments in section 10.4 for details of the instruments used in the observations.

Year of Pub.	Reference	Instrument used for Obs.	Source Investigated	Comments
1949	(Christiansen et al., 1949a)	A, B	Partial Solar Eclipse, Nov 1, 1948.	Summary Paper of eclipse observations.
	(Christiansen et al., 1949b)	A, B	Partial Solar Eclipse, Nov 1, 1948.	Detailed Paper of eclipse observations.
	(Piddington and Hindman, 1949)	D	Partial Solar Eclipse, Nov 1, 1948 + Solar observations.	Detailed Paper of eclipse observations.
1950	(Bracewell, 1950)	E	Solar	Short description of Payne-Scott and Little's Swept Lobe interferometer.
	(Minnett and Labrum, 1950)	C	Partial Solar Eclipse, Nov 1, 1948 + Solar Observations.	Detailed Paper of eclipse observations, included burst observations.
	(Smerd, 1950b)	--	Theory - Solar	Theory of quiet Sun emission.
	(Smerd, 1950a)	--	Theory - Solar	Theory of polarisation and magnetic fields.
1951	(Christiansen and Hindman, 1951)	A,C,D	Solar	Multi-year analysis of solar emission.
	(Christiansen et al., 1951)	A,C,D,E,I	Solar	Multi-frequency analysis of solar outburst of 17, 21-22 February 1950
	(Little and Payne-Scott, 1951)	E	Solar	Description of Swept Lobe Interferometer.
	(Mills and Thomas, 1951)	E	Cygnus-A	Position estimate and fluctuations determined to be ionosphere F-region.
	(Pawsey, 1951b)	A	H-line	Announcement of H-line confirmation.
	(Payne-Scott and Little, 1951)	E	Solar	Noise Storms analysis.
	(Piddington and Minnett, 1951a)	A,D	Sagittarius-A, Taurus-A, Centaurus-A, M31, NGC 7293, Moon	Discovery of Sagittarius-A. M31 and NGC 7293 below detection threshold.
	(Piddington and Minnett, 1951b)	--	Solar	Theory of localised regions of high temperature associated with slowly varying component.
	(Piddington, 1951)	--	Theory – Galactic emission	Theory of origin of Galactic radiation drawing on Potts Hill and other data.
1952	(Christiansen and Hindman, 1952a)	A	H-line	Summary report on H-line survey.
	(Christiansen and Hindman, 1952b)	A	H-line	Detailed report on preliminary H-line survey.
	(Payne-Scott and Little, 1952)	E	Solar	Outbursts analysis including Feb 1950 outbursts.
	(Piddington and Minnett, 1952)	A	Cygnus-A & Cygnus-X	Discovery of Cygnus-X and investigation of Cygnus-A.
	(Wild, 1952)	--	Theory – H-line emission	Comprehensive theoretical review of H-line emission.
1953	(Bolton, 1953)	--	Solar / Cosmic	Summary of the 1952 URSI meeting held in Sydney, including references to Potts Hill research.
	(Christiansen, 1953)	F	Solar	Summary description of E-W solar grating array.
	(Christiansen and Warburton, 1953a)	F	Solar	Detailed paper (Part I) describing the E-W solar grating array.
	(Christiansen and Warburton, 1953b)	F	Solar	Detailed paper (Part II) on one-dimensional images of the Sun.
	(Davies, 1953)	A,C,D,I	Solar	Analysis of a burst associated with an ascending solar prominence.
	(Kerr and Hindman, 1953)	G	H-line Magellanic Clouds	Preliminary report on H-line survey of the Magellanic Clouds
	(Mills and Little, 1953)	H	Cosmic	Description of Mills Cross Prototype including preliminary observations.
	(Pawsey, 1953)	--	Solar / Cosmic	Overview paper of progress in Australian Radio Astronomy including Potts Hill research.
	(Piddington and Davies, 1953a)	A,B,C,D	Solar	Summary Paper of multi-year analysis of emission from the Sun.
	(Piddington and Davies, 1953b)	A,B,C,D	Solar	Detailed Paper of multi-year analysis of emission from the Sun.
1954	(Davies, 1954)	A,C,D,I	Solar	Analysis of 18 months (1950-51) of burst observations at multiple frequencies.
	(Kerr et al., 1954)	G	H-line Magellanic Clouds	Detailed report on H-line observations of the Magellanic Clouds.
1955	(Christiansen and Warburton, 1955a)	F	Solar	Detailed paper (Part III) on two-dimensional images of the Sun.
	(Christiansen and Warburton, 1955b)	F	Solar	Summary paper on two-dimensional images with updates.
	(Kerr and De Vaucouleurs, 1955)	G	H-line Magellanic Clouds	Measurement of rotation of the Magellanic Clouds.
1955	(Pawsey and Bracewell, 1955)	--	Solar / Cosmic	Book on Radio Astronomy including reference to

				Potts Hill research.
	(Swarup and Parthasarathy, 1955a)	F	Solar	Summary paper of limb brightening detected at 60 cm using modified E-W grating array.
	(Swarup and Parthasarathy, 1955b)	F	Solar	Detailed paper (Part I) on one dimensional images of the Sun at 60 cm.
1956	(Kerr et al., 1956)	G	H-line Galactic	Preliminary finding of southern galactic H-line survey.
	(Kerr and De Vaucouleurs, 1956)	G	H-line Magellanic Clouds	Determination of masses of the Magellanic Clouds from H-line observations.
	(Pawsey, 1956)	--	Solar / Cosmic	Overview paper of progress in Australian Radio Astronomy including Potts Hill research.
	(Piddington, 1956)	--	Theory – Solar	Theory of heating of solar atmosphere by hydro-magnetic waves.
	(Piddington and Trent, 1956b)	G	Southern Galactic Survey	Survey at 600 MHz 90ºS to 50ºN.
	(Piddington and Trent, 1956a)	G	49 Discrete Sources	18 new sources, 4 tentative optical identifications from 600 MHz survey.
1957	(Carpenter, 1957)	G	H-line Galactic	Summary paper on progress of southern galactic H-line survey.
	(Christiansen et al., 1957)	F	Solar	Detailed paper (Part IV) on slowly varying component of solar radiation.
	(Kerr, 1957)	G	H-line Galactic	Discussion of observed warping of galactic disk in the direction of the Magellanic Clouds.
	(Kerr et al., 1957)	G	H-line Galactic	Summary of results of the southern galactic H-line survey.
	(Kerr and Hindman, 1957)	G	H-line Galactic	Summary of mass distribution of neutral hydrogen in the Galaxy.
	(Pawsey, 1957)	F	Solar	Summary of observations of the quiet Sun at different frequencies.
1958	(Christiansen and Mathewson, 1958)	F	Solar	Summary description of Potts Hill solar grating array and the new Fleurs array.
	(Gardner and Shain, 1958)	J	Jupiter	Investigation of Jupiter radio bursts using Potts Hill as part of a spaced-receiver experiment.
	(Kerr, 1958b)	G	H-line Galactic	Summary paper on the southern galactic H-line survey results.
	(Oort et al., 1958)	G	H-line Galactic	Detailed paper on combination of Potts Hill and Leiden H-line surveys and findings on Galactic structure.
	(Swarup and Parthasarathy, 1958)	F	Solar	Detailed paper (Part II) on one dimensional images of the Sun at 60 cm examining localised areas of brightness.
	(Wade, 1958)	--	Theory – Emission Nebulae	Theory paper on radio emission from Hydrogen nebulae directly relevant to Potts Hill research.
1959	(Christiansen, 1959)	F	Solar	Summary description of types of directive radio aerials including the Potts Hill solar grating array.
	(Hindman and Wade, 1959)	G	Eta Carine Nebula, Centaurus-A	Observations of Eta Carine Nebula, Centaurus-A at 1,400 MHz
	(Kerr et al., 1959)	G	H-line Galactic	Final detailed report on observations from the southern galactic H-line survey.
	(Pawsey, 1959b)	G	H-line Galactic	Summary discussion of radio evidence for large-scale structure of the Galaxy and other external galaxies.
	(Wade, 1959a)	G	Eta Carine Nebula	Discussion of a physical model of the Eta Carine Nebula consistent with radio observations at Potts Hill and other radio and optical observations.
1960	(Blaauw et al., 1960)	G	H-line Galactic	Lead paper in a series of 5 on the new I.A.U. system of galactic coordinates.
	(Gum et al., 1960)	G	H-line Galactic	Paper II in series on the new I.A.U. system of galactic coordinates describing re-analysis of Potts Hill and Leiden H-line survey data to determine the galactic plane.
	(Gum and Pawsey, 1960)	G	Galactic	Paper II in series on the new I.A.U. system of galactic coordinates discussing general radio continuum surveys including Potts Hill 600 MHz data.
1961	(Krishnan and Labrum, 1961)	A	Partial solar eclipse, 8 April 1959	Detailed paper of eclipse observations in conjunction with 'Chris-Cross' at Fleurs.
1962	(Kerr, 1962)	G	H-line Galactic	Discussion of a re-interpretation of the galactic H-line survey data using a revised velocity model.

14.2. Appendix B – Publications from Murraybank

The following table provides a chronological listing of scientific publications that were based on research carried out at Murraybank. All observations were performed using the Murraybank 21-ft aerial and the 48-channel H-line receiver.

Year of Pub.	Reference	Source Investigated	Comments
1958	(Murray and McGee, 1958)	Pyxis-Hydra Hydrogen Cloud	First trial survey observations using the multi-channel receiver. Large HI cloud identified and associated with HII regions.
1959	(Murray and McGee, 1959)	Taurus-Orion Region	Trial survey suggesting a single HI cloud covers this region.
1961	(McGee and Murray, 1961b)	Galaxy	First paper in a series of three papers on results from the southern sky survey. Deals with the general distribution of neutral hydrogen.
	(McGee and Murray, 1961a)	Galaxy	Summary paper to AJ on findings of local HI streaming.
	(McGee et al., 1961)	Galaxy	Summary paper to Nature on findings of local HI streaming.
1963	(McGee and Murray, 1963)	N/A	A description of the multi-channel receiver.
	(McGee et al., 1963)	Galaxy	Second paper in survey series dealing with low velocity gas.
	(Hindman et al., 1963b)	Magellanic Clouds	First paper in a series of two detailing the observations and digital recording techniques for a survey of the Magellanic Clouds.
	(Hindman et al., 1963a)	Magellanic Clouds	Second paper in series dealing with the interpretation of the results. Evidence for a HI bridge between the clouds and evidence that the SMC is split in two.
	(Howard et al., 1963)	Galaxy	Joint paper on the correlation between optical stellar radial velocities and radio HI lines drawing on Murraybank survey data.
1964	(McGee, 1964)	Galaxy	IAUS paper on large HI clouds in Galaxy.
	(McGee and Milton, 1964)	Galaxy	Third and final paper in survey series dealing with high velocity gas.

14.3. Appendix C – Radio-Frequency Spectral-Line Programs

The following table provides a summary of the state of radio-frequency spectral line receivers and aerials as at the beginning of 1954 and is based on material from a Radiophysics archive file on receiver development.

Survey of Spectral Line Receivers at at February 1954												
				Theoretical Sensitivity				Aerial				
Group	First Local Oscillator	Second Local Oscillator	Line-Detection and Stability System	Relative Signal Level	Relative Noise Level	Relative Sensitivity	Presentation	Mounting	Diameter	Beamwidth	Channel Bandwidth	Investigation
Sydney - Potts Hill	Fixed	Fixed	Balance output of narrow channel against output from whole I.F. amplification after detection.	1	1	1 Limited Obs Time	4 Channels: 20 proposed	Transit	36-ft	1°	200 KHz 40 KHz	Magellanic Clouds: Galaxy
Harvard - Agassiz Station	Fixed	Swept	Balance narrow channel against whole I.F. output	1	1	1	Single channel: Sweeping yields profile	Equatorial	25-ft	1.75°	200 KHz 50 KHz 15 KHz 5 KHz	Galaxy: Centre & Anti-Centre
Naval Research Laboratory - Washington	Fixed	Swept	Balance narrow channel against whole I.F. output	1	1	1	Single channel	Alt-Azimuth	50-ft	0.75°	200 KHz 50 KHz 15 KHz 5 KHz	Galaxy
Jodrell Bank	Swept	Switched Δf	Push-Pull comparison of two channels separated by Δf. Produces "modulated" signal.	1	$\sqrt{2}$	0.7	Single channel	Alt-Azimuth	30-ft 100-ft	1.25° 0.375°	-	Experimental
Leiden - Kootwijk	Switch between Two Crystals	Swept	Switch single channel to produce modulated signal (assuming tuned A.C. amplification)	$2/\pi$	$\sqrt{2}$	0.45	Single channel: 2 planned	Alt-Azimuth	25-ft Wurzburg 80-ft	2.5° 0.5°	30 KHz	Galaxy
O.T.M. - Carnegie Institute Washington	Switched	Fixed	Frequency switched so that modulated signal appears in all channels	$2/\pi$	$\sqrt{2}$	0.45	Multi-channel	Equatorial	25-ft Wurzburg	2.5°	15 KHz	Experimental
Sydney - Dover Heights	Fixed	Swept & Switched	(a) Switch single channel (b) Push-Pull switching of two channels. Untuned A.C. Amplifier	$\pi/4$	$\pi/2$	0.5 Limited Obs Time	Single channel	Fixed Moveable Feed	80-ft	0.5°	200 KHz 30 KHz	Search for D-Line 327 MHz
Ministry of Supply - R.R.E Malvern	Swept	Switched?	-	-	-	-	Several channels	-	20-ft	2°	-	Experimental: Hope to detect M31