W.N. CHRISTIANSEN AND THE DEVELOPMENT OF THE SOLAR GRATING ARRAY

Harry Wendt
Centre for Astronomy, James Cook University, Townsville, Queensland 4811, Australia.
E-mail: Harry.Wendt@jcu.edu.au

Wayne Orchiston
Centre for Astronomy, James Cook University, Townsville, Queensland 4811, Australia.
E-mail: Wayne.Orchiston@jcu.edu.au

and

Bruce Slee
Australia Telescope National Facility, PO Box 76, Epping, NSW 2121, Australia and Centre for Astronomy, James Cook University, Townsville, Queensland 4811, Australia.
E-mail: Bruce.Slee@csiro.au

Abstract: By 1950 the C.S.I.R.O's Division of Radiophysics was emerging as a leader in solar radio astronomy. Early observations at radio frequencies were hampered by a lack of angular resolution. In seeking a method to produce regular high-resolution observations W.N. Christiansen devised the solar grating array. This unique instrument was constructed on the banks of the Potts Hill water supply reservoir in suburban Sydney and operated from 1951 to 1957. This paper discusses the inspiration for the design of the solar grating array, its physical characteristics and the contribution made to international solar radio astronomy through the observational programs carried out at Potts Hill.

Keywords: W.N. Christiansen, radio astronomy, solar grating array, Division of Radiophysics, C.S.I.R.O.

1 INTRODUCTION

By 1950 the C.S.I.R.O.'s Division of Radiophysics had already established itself as a leader in the new field of solar radio astronomy (Orchiston et al., 2006; Sullivan, 2005). Some highlights from the early research program were the observation of the million degree temperature of the solar corona (Pawsey, 1946); the association of enhanced radiation with sunspots, established through sea interferometry (McCready et al., 1947); and measurement of delays in the arrival times of bursts at different frequencies, suggesting the motion of the burst source through the decreasingly-dense coronal atmosphere (Payne-Scott et al., 1947).

A limitation of the early radio observations was the poor angular resolution of the instruments used. One way of gaining improved resolution was to exploit the technique of sea interferometry (see Bolton and Slee, 1953), and observations were also made during partial solar eclipses in 1948 and 1949 in an attempt to obtain even better resolution at a number of different frequencies (see Orchiston et al., 2006; Wendt et al., 2008a). It was during the partial solar eclipse of 1 November 1948 that W.N. ('Chris') Christiansen obtained his first major exposure to solar radio astronomy (see Christiansen et al., 1949a; 1949b).

2 INSPIRATION FOR THE GRATING ARRAY

Christiansen had joined Radiophysics in 1948 from Amalgamated Wireless (Australasia), where he had worked on aerial design. However, he was unique amongst the Division's early recruits in that he harboured a long-term ambition to become an astronomer (Sullivan, 2005: 14).

Christiansen was appointed to a senior role within Radiophysics, filling a vacancy created by Fred Lehany's transfer to the Division of Electro-technology. He was soon installed as the lead researcher of the solar program at the newly-established field station at Potts Hill in the western suburbs of Sydney. The main radio telescope there was a 16 × 18-ft ex-WWII experimental radar which had been relocated from the Georges Heights field station to Potts Hill in time for the 1948 solar eclipse (see Orchiston and Wendt, n.d.).

The accurate measurement of the distribution of radio emission across the solar disk was of prime interest as it provided information on the structure, density and temperature of the solar atmosphere, but particularly the chromosphere and corona. By measuring the distribution at different frequencies it was possible to compare the observations with various theoretical models (e.g. see Martyn, 1946; Smerd, 1950). These models predicted a progressive rise in the observed brightness temperature as the wavelength of emission increased from centimetre to metre wavelengths. The rise in brightness temperature was due to the area of origin varying from the comparatively cool chromosphere (10^4 K) to the hot corona (10^6 K). Also of interest was the prediction of increased brightness at the limb of the Sun, particularly at decimetre wavelengths. Meanwhile, earlier investigations had shown that at this wavelength the solar radio emission could be divided into two main components. The first, believed to be of thermal origin, was associated with the quiet Sun, and the second was a slowly-varying component that was correlated with the total area of sunspots visible on the solar disk. Both components provided information on the distribution of radio emission across the disk of the Sun.

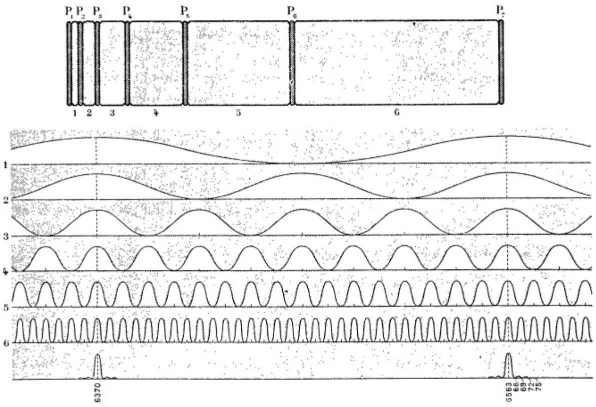


Figure 1: An illustration of Bernard Lyot's optical narrowband filter. The wavelength in Angstroms is shown on the X-axis. The two widely-separated narrowband responses at 6370 and 6563 Angstroms (bottom) are the result of summing the six different band-pass frequencies. The filter configuration is shown in the upper diagram. It was this work that gave Christiansen his inspiration for the design of the solar grating array (after Lyot, 1945: Figure 1).

Observations carried out during the partial solar eclipses of 1 November 1948 and 22 October 1949 (see Wendt et. al., 2008a), were successful in associating the enhanced emission with sunspot groups, but were inconclusive in detecting limb-brightening. Christiansen was looking for a way to perform high-resolution solar observations that did not rely on these relatively rare eclipses and would also not involve great expense. He was primarily interested in high-resolution observations at wavelengths of around 20 cm. To achieve a resolution of 3 arc minutes at these wavelengths would have required an aerial >1,000 wavelengths in diameter if a conventional parabolic design were to be used. Clearly this was not practicable.

Figure 2: View looking east showing W.N. Christiansen and the 32-element solar grating array at Potts Hill in the western suburbs of Sydney (courtesy ATNF Historic Photographic Archive).

At this time, John Bolton, Gordon Stanley and Bruce Slee (1949) were using sea interferometers to investigate discrete sources of cosmic radiation at the Radiophysics Dover Heights field station and Martin Ryle and D.D. Vonberg (1946) at Cambridge were making similar advances using a standard two-element interferometer. H.M. Stanier used a two-element interferometer to obtain the brightness distribution across the solar disk in 1950, and Alex Little and Ruby Payne-Scott (1951) were making good progress in measuring the accurate positions of solar bursts with a swept-lobe interferometer located at Potts Hill in the western suburbs of Sydney.

Stanier's use of the two-element interferometer to determine the solar brightness distribution was the first practical application of the Fourier imaging technique in radio astronomy (although this approach had been suggested by Joe Pawsey, Payne-Scott and Lindsay McCready in 1947). In doing so, Stanier made the simple assumption that the Sun was circularly symmetrical so that the distribution could be calculated from one scanning angle, but this also implied that all the components of the interference pattern were even (cosine), and therefore only the amplitudes and not the phases of the interference fringes needed to be measured. The use of the circularly-symmetrical assumption, and possibly the presence of localised active regions on the solar disk during observations, contributed to Stanier's failure to detect limb-brightening.

K.E. Machin (1951) followed up on Stanier's work, improving on the technique and conducting observations at 81.5 MHz. He was followed by P.A. O'Brien (see O'Brien, 1953a, 1953b; O'Brien and Bell, 1954; O'Brien and Tandberg-Hassen, 1955), who, during 1951-1952, used a two-element interferometer at a number of wavelengths and a variety of spacings and observing angles to calculate the two-dimensional brightness distribution across the solar disk. This was the first time that two-dimensional Fourier synthesis had been used to produce an image of the Sun.

In late 1949, Christiansen and Don Yabsley began experiments using two ex-WWII TPS-3 aerials as a two-element interferometer in an attempt to detect limb-brightening (see Christiansen, 1949). In February 1950 Ryle wrote to Ron Bracewell, stating he was very interested to hear that the Australians planned to carry out spaced-aerial work at 600 and 1,200 MHz to look for limb-brightening, and particularly if "… a Fourier analysis …" was to be used. He pointed out that Stanier (1950) had performed this experiment at 600 MHz and not detected limb-brightening.

It was around this time that the initial idea for the construction of a solar grating array occurred to Christiansen, and he then abandoned further work with Yabsley on the two-element interferometer.[1] Ultimately 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 uniform spacings, the combined response of the array would produce multiple narrow beams which would be separated from each other as the inverse to the spacing between the aerials. As the Sun's disk is 30 arc minutes in diameter, the array could be configured so that only one of the beams could be positioned on the Sun's disk at any given time. Christiansen's inspiration for this configuration came indirectly, and was influenced by his background in antenna design:

> 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 Lyot filter immediately suggested an antenna array and an array of arrays. (Christiansen, 1984: 118).

The analogy Christiansen drew from Lyot's (1945) paper is best demonstrated by Figure 1, which shows that the sum of each of the different band-pass filters produces the two widely-separated narrowband responses.

It is likely that Christiansen was also familiar with a lecture on the topic that was given by Bruce Billings at the American Astronomical Society meeting on 29 December 1946 (see Billings, 1947).[2] Christiansen (1950) first presented the idea for his 'Multi-beam Interferometer' to RP's Radio Astronomy Committee when it met on 14 March 1950.

3 CONSTRUCTION OF THE GRATING ARRAY

Keeping the cost of the design to a minimum was one of Christiansen's prime concerns. He was only given permission by Taffy Bowen and Joe Pawsey to construct the array provided that the cost could be kept under £500, or ~AU$12,500 in today's terms (Christiansen, 1984: 118).[3] The mechanical engineering for the array was performed by Keith McAlister, who proved extremely resourceful in meeting the project's cost target.

The construction of this innovative solar radio telescope commenced in 1951. However, Christiansen was temporarily diverted from this task when Pawsey asked him to confirm the detection of the 21cm hydrogen line by Ewen and Purcell (see Wendt et al., 2008b). Nonetheless, the first Potts Hill solar grating array was completed in February 1952,[4] and Christiansen immediately began a program of daily observations. These observations were generally made over a two hour period centred on midday.

The array consisted of 32 aerials (Figure 2), which were evenly spaced at 23-ft (7m) intervals along an east-west baseline of 700-ft (213m) located at the southern end of the northern reservoir at Potts Hill.

The array was constructed by Radiophysics staff. Initially a series of 32 wooden posts was aligned by Joe Warburton and Rod Davies using a theodolite, and Davies (2005: 94) was later to comment: "At that time we didn't know that Ph.D. meant Post-hole Digger!"

Each aerial comprised a 66-in (1.7m) solid metal parabolic reflector plate. 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 there was a 90° phase difference introduced between adjacent pairs of aerials. In this way the complete system could resolve circular polarisation into its right-hand and left-hand components. Each of the aerials was equatorially mounted and could be manually 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 by having someone run down the length of the array and adjust each of the 32 antennas by hand!

The aerial outputs were combined using a branching system of transmission lines. To keep costs down, the transmission lines were a braced open-wire system separated by a ¼ wavelength and supported by polystyrene insulators and spacers (see Figure 3).

Figure 3: Another view of the east-west array, showing the bracing weights for the open-wire transmission lines. The parabolas were equatorially mounted, with the declination set for the given day. The right ascension was changed in 15 minute steps using holes and a locking pin on the mount (courtesy ATNF Historic Photographic Archive).

To achieve the branching configuration the transmission lines were stacked vertically in five levels and connected via short vertical connectors. A schematic of the transmission-line system is shown in Figure 4.

The directivity of the array can be calculated from

$$\Phi(\theta) = \frac{\sin^2 Np}{N \sin^2 p} \qquad (1)$$

where $\Phi(\theta)$ is the power received from the source relative to the power received from one aerial; N is the number of elements in the array; and $p = \pi d \sin \theta/\lambda$, where d is the spacing between elements, θ is the angle between the perpendicular to the baseline and the direction of the source, and λ is the wavelength (after Christiansen and Warburton, 1953a: 192).

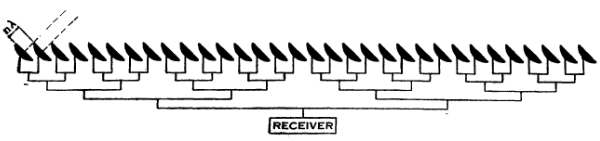


Figure 4: Schematic diagram of the branching transmission lines used for the 32-element solar grating array (after Christiansen and Warburton, 1953a: 192).

The array produced a series of fan-shaped beams each of which, at 1,420 MHz, had a calculated beamwidth of 2.9 minutes of arc at the half power points. The spacing between beams was 1.7°, which meant that at any one time only one beam would fall on the 30-arc minute solar disk. Figure 5 shows the beam response produced by the array.

A superheterodyne receiver was connected to the array transmission lines via a radio-frequency switch that contained a rotating condenser which switched the signal at a rate of 25 Hz between the transmission lines 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.

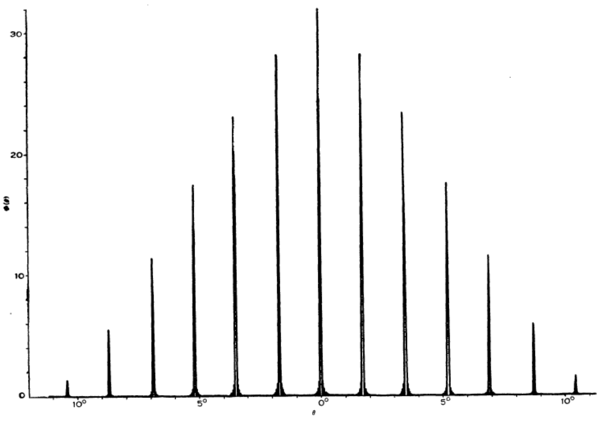


Figure 5: Beam response diagram for the 32-element array at 1,420 MHz (21cm). The power received from the source is shown on the Y-axis and the direction of the source relative to the array beam, on the X-axis. The beamwidth of each fan beam is 2.9 arc minutes, and the beams are separated by 1.7°. The overall response envelope of the individual beams is equivalent to the response of one of the individual aerials in the array (after Christiansen and Warburton, 1953a: 192).

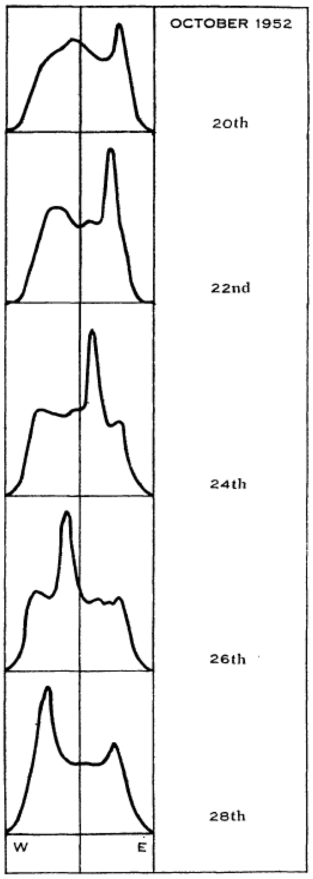


Figure 6: Daily records of one-dimensional brightness distribution across the solar disk between 20 and 28 October 1952. Each scan is just over 30 arc minutes in width, with the power received shown on the Y-axis. The successive scans show a source of enhanced emission associated with a sunspot group that was initially near the eastern limb of the Sun and progressed towards the western limb as the Sun rotated (after Christiansen and Warburton, 1953b: 198).

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

The high resolution beams of the grating array produced a one-dimensional response scan across the solar disk at 1,420 MHz. 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 6, for example, shows a succession of daily scans taken between 20 and 28 October 1952.

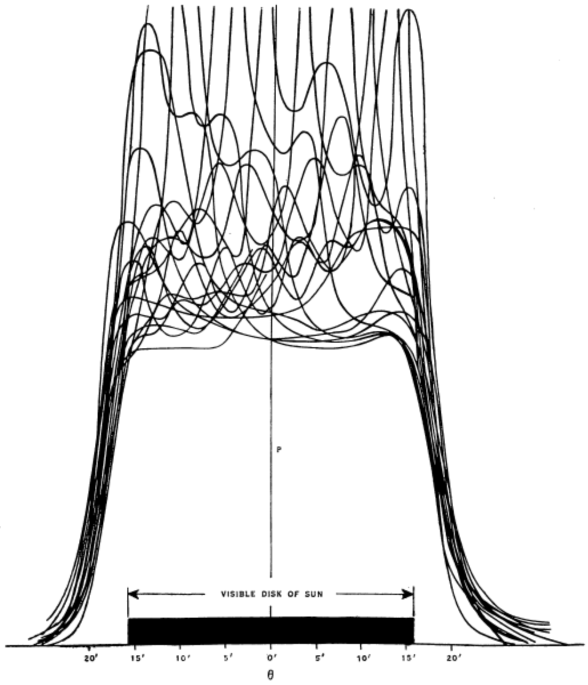


Figure 7: Twenty individual daily one-dimensional brightness distribution scans superimposed. The visual solar disk is indicated by the black bar on the X-axis. The inside envelope of the scans indicates the quiet base component of the solar emission (after Christiansen and Warburton, 1953a: 200).

One early finding that greatly simplified the analysis of the observations was that the centre of the radio record corresponded with the centre of the optical Sun, and that bright areas near the limb did not materially change the size of the radio disk. By superimposing the individual daily scans obtained over an extended period and ignoring localised areas of enhanced emission (termed 'radio plages'), a base level of radiation quickly became evident (e.g. see Figure 7). This base level indicated by the envelope of the successive scans is due to the quiet Sun, while the areas of enhanced emission above the envelope are due to the slowly varying component. Christiansen and Warburton (1953b) determined that the base level temperature of the Sun at 1,420 MHz was 7×10^4 K in 1952, during the period when the observations were made.

Another feature that is clearly evident in Figure 7 is that the source of the radio emission is larger than the width of the optical disk. For simplicity a circular symmetry was assumed for the purposes of the analysis, although there were already indications that the actual distribution was elliptical. Initially it was thought that the effect of this assumption would be small. However, it was fairly quickly recognised that taking the non-circular symmetry into account would be essential. Even allowing for an asymmetrical distribution of solar emission, it was very clear from the observations that limb-brightening was present. The brightening of the limb is due to the greater optical depth of the corona, which has a much higher temperature than the photosphere. Figure 8 shows examples of the radial distribution based on the one-dimensional scans, and these clearly contain evidence of limb-brightening—as predicted in a number of different theoretical models, including that proposed by Christiansen's Radiophysics colleague Steve Smerd (1950). Unfortunately, as the distributions were only measured at one frequency, it was not possible to determine which particular parameters of the models best matched the observations (although the latter were consistent with Smerd's model for a 10^4 K chromosphere and a 0.3-3.0 × 10^6 K corona.

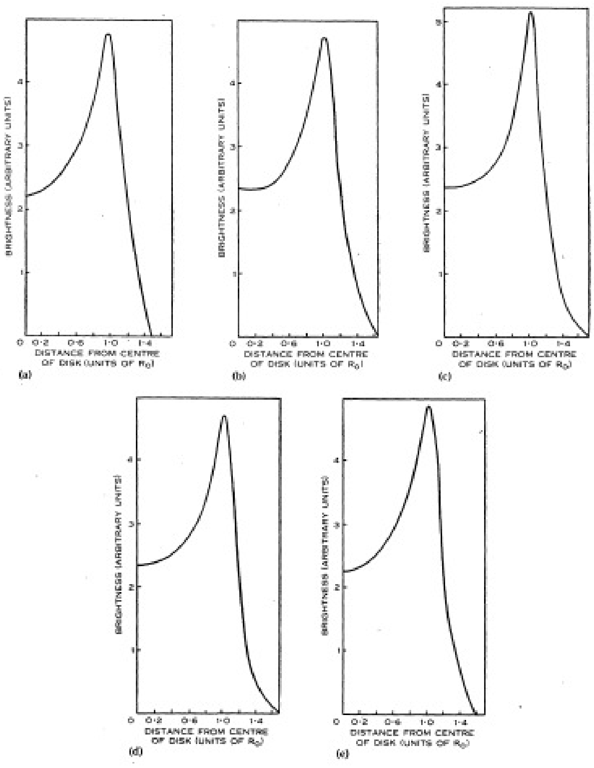


Figure 8: Examples of radial distributions of brightness across the solar disk based on one-dimensional scans. R_0 is the radius of the visible optical disk (after Christiansen and Warburton, 1953b: 268).

One of the limitations of observations using the east-west array was that fan beams could only scan the Sun in one dimension. In order to calculate the distribution of radiation across the solar disk it was therefore necessary to assume a symmetrical distribution, yet visual observation had revealed that the Sun is an oblate spheroid, and solar eclipse observations indicated that the solar corona was far from symmetrical (e.g. see 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.

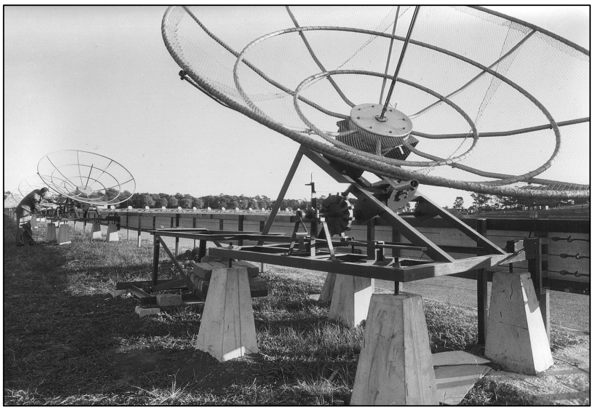


Figure 9: Close up of the north-south grating array, looking south, showing the robust equatorial mounting and the use of mesh rather than a solid reflector (courtesy ATNF Historic Photographic Archive).

4 THE NORTH-SOUTH GRATING ARRAY

A north-south grating array was then constructed on the eastern side of the same reservoir where the east-west array was located, but the aerial design for this new array was quite different. Instead of 32 elements, the north-south array had 16 elements, each consisting of open mesh parabolic dishes supported by robust equatorial mounts (see Figure 9).

The new array was also somewhat shorter than the east-west array, being 760 wavelengths (160m) in length as opposed to the 1,028 wavelengths (214m) of the east-west array. This meant that the array produced a slightly wider beam of 4 minutes of arc. The open transmission-line feeds were retained, and these can also be seen in Figure 9, with the east-west array in the distant background. Figure 10 shows an aerial view of the two arrays. This photograph was taken from the northeast, looking southwest.

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 seasonable variations in the Sun's orientation with respect to the two arrays and achieve a coverage of 140° out of a 180° range of scanning angles, as indicated in Figure 11.

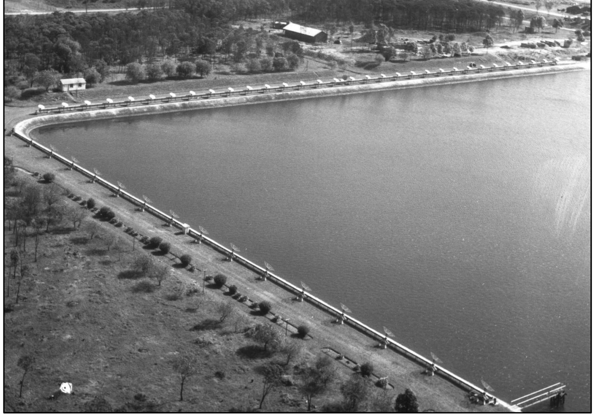


Figure 10: Aerial view of the 32-element east-west and the 16-element north-south arrays, looking southwest (courtesy ATNF Historic Photographic Archive).

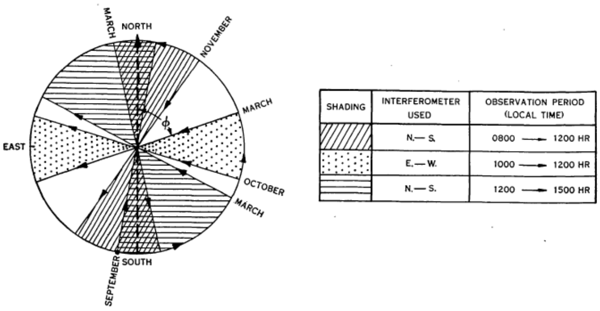


Figure 11: By observing the Sun over an extended period a large variety of different scanning angles could be achieved. This figure shows the coverage of the scanning angles by month for the two arrays (after Christiansen and Warburton, 1955a: 479).

Figure 12 shows an example of the scanning of the Sun with both the east-west and the north-south arrays. A source of enhanced emission on the solar disk is evident on all scans. The observations made with the east-west array were taken at an hour angle when the inclination of the aerial beams was fairly constant relative to the Sun's central meridian, and hence successsive scans are almost an exact replication. By contrast, the north-south array observations were made over a wide range of hour angles, and during the period of observation the scanning angle changed through a range of ~50°. As the hour angled changed during the observations the rate at which the solar disk passed through the beams also changed. This is evident in the lower plot in Figure 12 where, from left to right, the Sun passes more slowly through each scan until the central scan, then the process is reversed.

Over the course of a day a wide variety of scan angles could be observed and these could be extended further by observing over a period of months. Figure 13 shows the result of one-dimensional scans taken at different times on a single day, thus achieving different orientations relative to the Sun's axis of rotation.

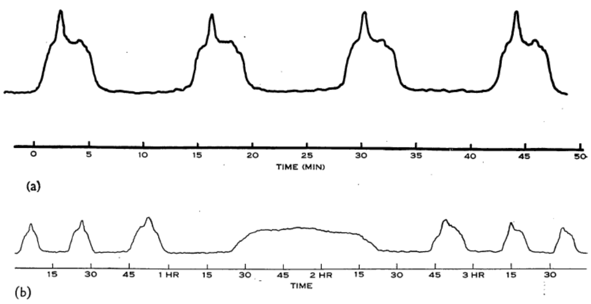


Figure 12: An example of the Sun passing through several of the beams of the east-west (a) and north-south (b) grating arrays. A source of enhanced emission on the solar disk is evident on each of the scans (after Christiansen and Warburton, 1955a: 477).

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 that the Sun was symmetrical, and phase was ignored. The numerical value for each scan was then 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 process took months of calculation and plotting by hand in order to produce the single two-dimensional image shown in Figure 14. For comparison, Figure 15 shows a photograph of the Sun taken during the total solar eclipse of 30 June 1954. The use of the symmetry assumption leads to the two-dimensional symmetry evident in Figure 14.

Although not widely acknowledged (see Christiansen, 1989), creation of the image in Figure 14 was the world's first application of Earth-rotational synthesis in radio astronomy.

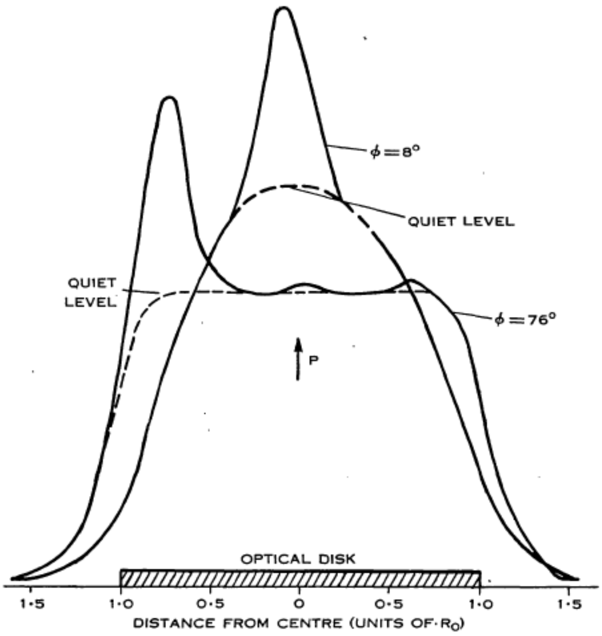


Figure 13: An example of one-dimensional scans taken for two different scanning angles by observing at different times on the same day. The angle Φ represents the scan angle of the aerial beam with respect to the Sun's central meridian, P (after Christiansen and Warburton, 1955a: 482).

The hand calculations that led to Figure 14 were performed by Christiansen and Warburton, assisted by Govind Swarup, using electronic calculators (but not computers; see Swarup, 2008). Bracewell (1984) has stated that the graphical method that was used for this reconstruction was adopted from his method of chord construction, although his contribution was not acknowledged in the published results. Bracewell had been assigned by Pawsey to work on the issue of fan beam reconstructions, and he shared an office with Christiansen and Harry Minnett at the time. Bracewell (1956) subsequently published a paper on strip integration based on this work. This paper includes a description of the use of the projection-slice theorem which would be used to underpin modern imaging techniques, including computerised tomography and medical imaging .

Figure 14 shows a strong correlation with the optical view of the corona seen at times of total solar eclipse. Furthermore, the elliptical radio source extended 1.6 times further at the equator than at the poles. In addition, the limb-brightening effect was not evenly distributed, with the strongest brightening at the equator and very little at latitudes beyond ±55°. Christiansen and Warburton noted that this latitude corresponded to the latitude at which structural changes in the corona could be observed at times of sunspot minimum. Also, there was a strong correlation between the outline of the 8,000 K contour and the photographic image. Christiansen and Warburton (1955a) concluded that the majority of the radiation at the centre of the image emanated from the chromosphere, while the limb-brightening was due to the greater optical depth of the corona, with its higher temperature gradient.

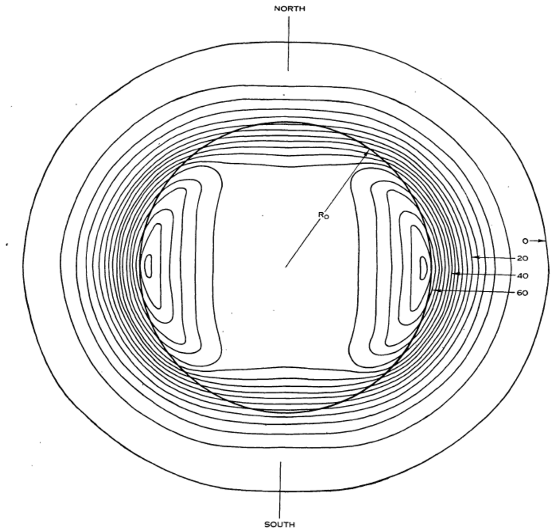
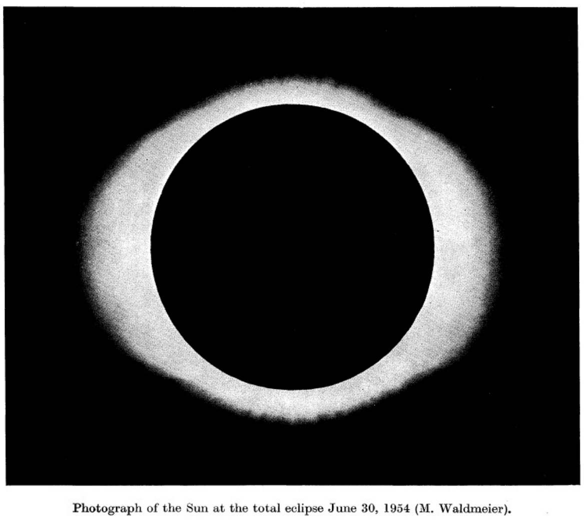


Figure 14: An example of the derived two-dimensional image of the radio brightness distribution across the Sun at 1,420 MHz. The central brightness temperature is 4.7×10^4 K and the maximum peak temperature is 6.8×10^4 K. Contours are spaced at equal intervals of 4×10^3 K. Observations were made during the period April 1952 to April 1954 (after Christiansen and Warburton, 1955a: 482).



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

Figure 15: Photograph of the Sun taken during the 30 June 1954 total solar eclipse, representing a comparable period in the solar cycle to the radio observations (after Christiansen and Warburton, 1955a: Plate 2).

Observations over 1952, 1953 and 1954 showed no change in the shape or temperature of the quiet component of solar radiation at 1,420 MHz (Christiansen and Warburton, 1955a), thus providing support for the assertion by Jack Piddington and Davies (1953) that earlier reported changes in the base level of solar radiation were due to lag effects of changes in sunspot activity. Piddington and Davies (ibid.) concluded that the enhanced radio emission persisted for some time after sunspots had disappeared from the solar disk.

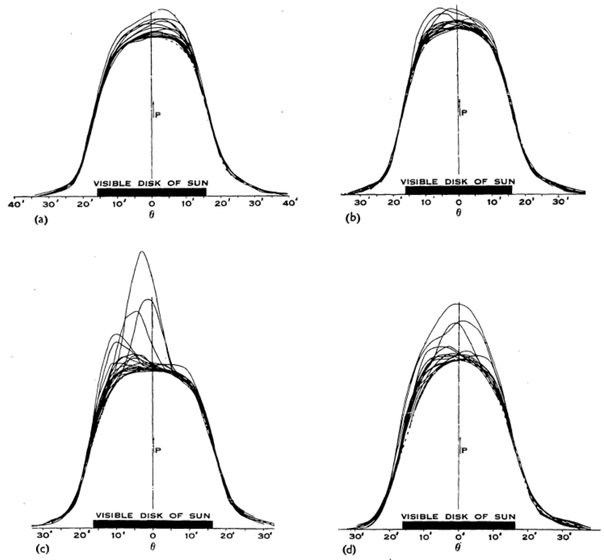


Figure 16: Superimposed one-dimensional brightness distributions at 500 MHz taken between July 1954 and March 1955. Observations were made during (a) 18 July to 5 August $\Phi = 3°$; (b) 9 August to 1 September $\Phi = 11.5°$; (c) 15 December to 3 January $\Phi = -3°$; (d) 7 February to 4 March $\Phi = 26°$; Φ represents the angle in arc minutes between the Sun's central meridian and the aerial beam (after Swarup and Parthasarathy, 1955b: 490).

5 THE 500 MHz GRATING ARRAY

During the U.R.S.I. 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 R. Parthasarathy (1955b), who were working at Radiophysics under Colombo Plan Fellowships, modified the receiving equipment on the east-west array in order to carry out observations at 500 MHz (λ = 60cm). At this frequency the width of the fan beam was reduced to a theoretical value of 8.2 minutes of arc at the half power points, with a beam spacing of 4.9°. Swarup and Parthasarathy checked the actual beam response using Cygnus-A as a reference source and found the beamwidth to actually be closer to 8.7 minutes of arc.

From July 1954 to March 1955 Swarup and Parthasarathy used the east-west array to measure the one-dimensional distribution of radio brightness across the solar disk and to look for limb-brightening. By observing over a period of months they were able to scan the Sun at angles from 60° to 90° with respect to the central meridian. Figure 16 shows examples of superimposed observations over a period of several months.

One major interest at the time was the comparison of these results with the earlier observations by Stanier (1950) at the same frequency. Stanier had carried out his research closer to sunspot maximum and he did not detect limb-brightening. Figure 17 shows the two different radial distributions detected in 1950 and 1954/1955.

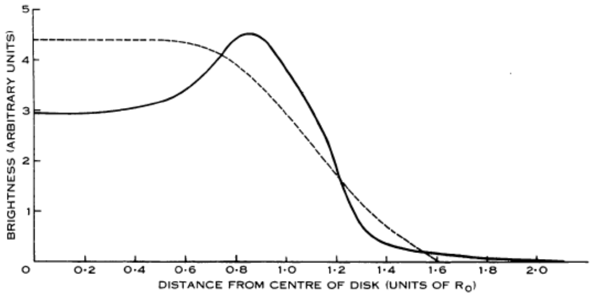


Figure 17: Radial brightness distributions at 500 MHz comparing Stanier's result (dashed line) and Swarup and Parthasarathy's observations (after Swarup and Parthasarathy, 1955b: 493; cf. Swarup and Parthasarathy, 1955a).

The interferometer observations made by O'Brien and Tandberg-Hassen (1955) had also detected limb-brightening, and Swarup and Parthasarathy's results were in good agreement with this. They also noted that like the higher-frequency observations by Christiansen and Warburton, the radio Sun did not appear to be circularly symmetrical. Although they were observing only with the modified east-west array, they were able to achieve a variety of scan angles by viewing at different times during the day and throughout the months. Figure 18 shows the different brightness distributions for aerial beams oriented at 90° and 64° to the Sun's central meridian. This indicated that the maximum width of the source occurred in the equatorial regions.

Swarup and Parthasarathy (1955b) calculated that the base apparent temperature of the quiet Sun at 500 MHz was 3.8×10^5 K, whereas Stanier obtained a figure of 5.4×10^5 K. Comparing their result with the previous eclipse observations, Swarup and Parthasarathy 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.

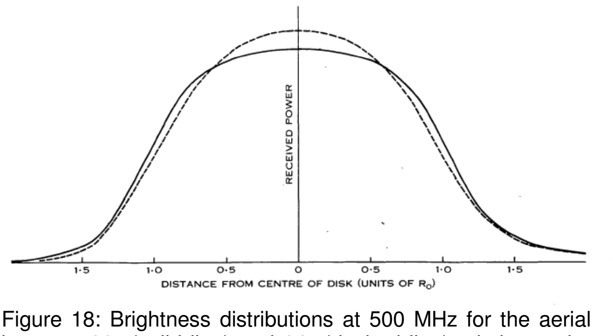


Figure 18: Brightness distributions at 500 MHz for the aerial beam at 90° (solid line) and 64° (dashed line) relative to the Sun's prime meridian. The observations show the maximum width of the emission occurs in the equatorial regions (after Swarup and Parthasarathy, 1955b: 491).

In 1957, Christiansen, Warburton and Davies published the fourth and final paper in their solar series based on observations made with the first solar grating array. This paper examined the slowly varying component based on the observations obtained during 1952 and 1953 (Christiansen et al., 1957). They concluded that the lag effect first suggested by Piddington and Davies (1953) was not sufficient to provide the sole explanation for the decline in base temperatures, and that it was likely that both the quiet component and the slowly varying component changed in the course of the solar cycle. They also concluded that the original correlation method proposed by Pawsey and Yabsley (1949) gave results that were quantitatively correct.

The paper by Christiansen, Warburton and Davies (1957) provided a clear illustration as to why the sunspot area correlation was in fact only a partial correlation. This is shown in Figure 19 where three groups are indicated: old sunspot regions, new regions and regions that have reached maximum intensity. The diagram shows that for new sunspots there was a delay before there was any correlation between sunspot area and the strength of the radio emission (see the path marked 'new region' in Figure 19). The larger active regions (see the path marked 'region at maximum activity' in the figure) showed some correlation between sunspot area and strength of emission, while the old sunspot groups ('old regions', in the figure) had almost disappeared in area, but continued to be associated with relatively strong radio sources. Although this analysis of the partial correlation with sunspots appears to require a great leap of faith, Christiansen, Warburton and Davies reached the conclusion that the radio emission was probably associated with plages rather than with sunspots. Plages occur in areas in the photosphere and chromosphere where sunspot groups grow and decay in the presence of strong localised magnetic fields. Christiansen and his two collaborators based this conclusion on a comparison of Mount Stromlo Observatory spectroheliograms and their solar grating array observations. Figure 20 shows an example of the comparisons, where the vertical lines indicate the maximum points during the one-dimensional radio scans.

A similar conclusion was reached earlier by Helen Dodson (1954) after comparing her McMath-Hulbert Observatory optical observations with Arthur Covington's Canadian radio observations, and she discussed this with Pawsey following an introductory lecture at the August 1955 IAU Symposium on Radio Astronomy at Jodrell Bank (see Allen, 1955: 262).

Using an analysis of the relative rates of rotation of the optical and radio sources, Christiansen et al. (1957) concluded that the radio emission emanated in a region about 24,000 km above the photosphere. They also found a strong correlation ($r^2 = 0.85$) between the size of the plages and the size 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 made with 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. They found similar characteristics to those discussed by Christiansen et al. (1957): the sources of radio emission were closely correlated with chromospheric plages, were of the order of 3–6 arc minutes in size and appeared to be localised in regions ~35,000 km above the photosphere. Perhaps their most interesting finding was evidence of some variability in the localised sources. Figure 21 shows an example of the variation in the signal strength as the Sun passed through two adjacent beams.

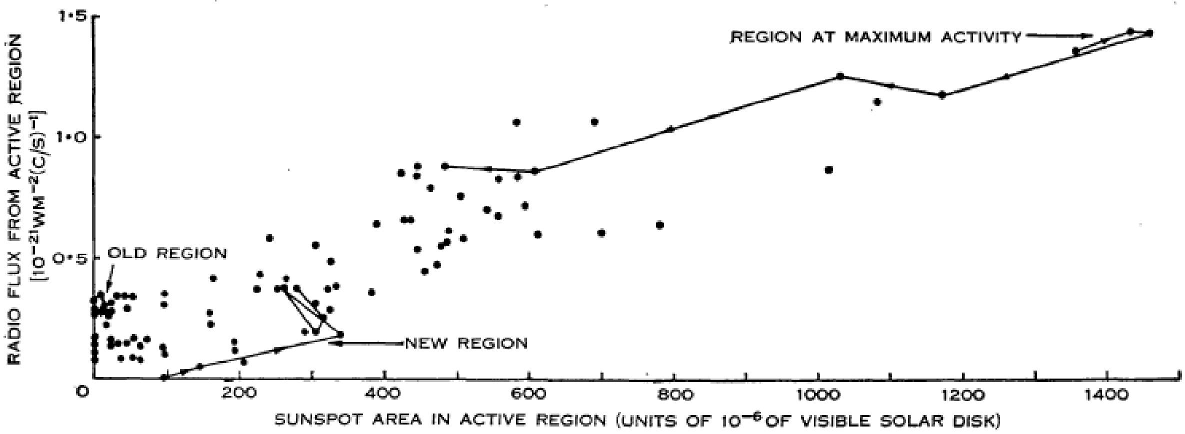


Figure 19: Scatter diagram of sunspot area versus radio flux. The day-by-day development of one new sunspot and one mature sunspot are shown by the lines connecting the points, with arrows marking the directions of development. Christiansen et al argued that the correlation of new and old sunspot areas with radio emission was not strong and only mature groups showed a strong correlation (after Christiansen et al., 1957: 511).

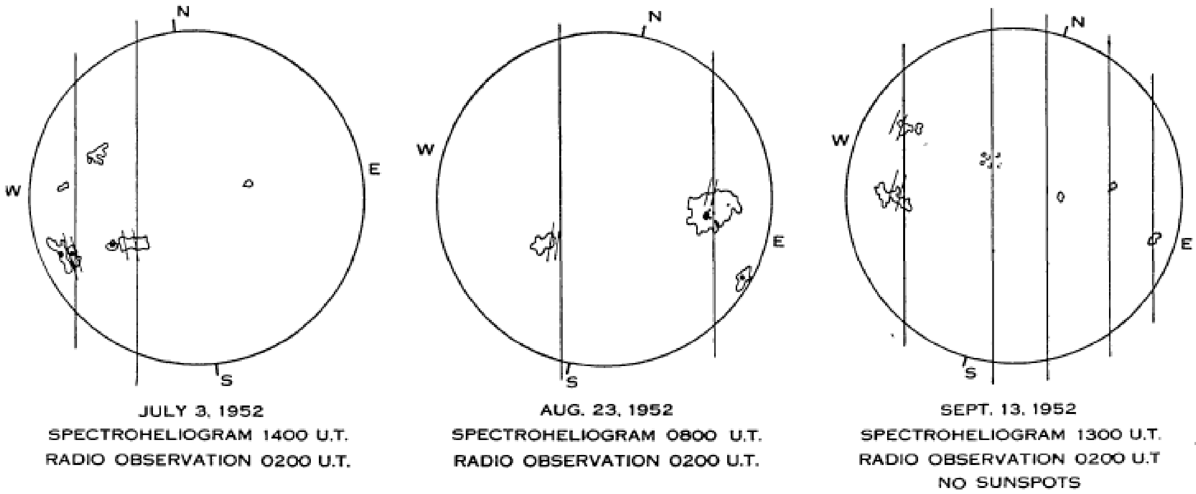


Figure 20: Mount Stromlo spectroheliograms showing calcium K-line plage regions. The vertical lines indicate the positions of maximum emission on the Potts Hill scans. Note the strong correlation with plage regions (after Christiansen et al., 1957: 506).

These variations were observed on six occasions and lasted for periods of up to half an hour. This provided strong evidence for a non-thermal origin of some of the energy produced since a thermal change to an area the physical size of a radio plage could not occur that rapidly.

Swarup and Parthasarathy's paper was to be the last one based on solar observations made at Potts Hill.

6 THE PROTOTYPE CHRIS CROSS ANTENNA

Christiansen returned from France in 1955. However, 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 Bernard 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).

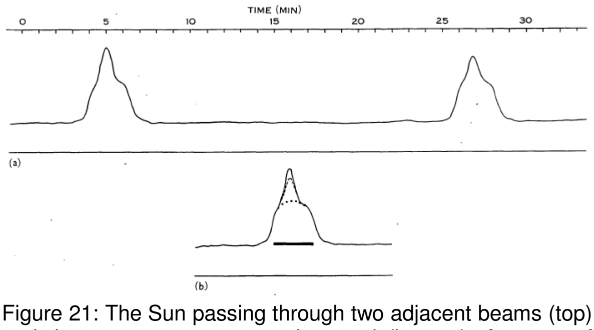


Figure 21: The Sun passing through two adjacent beams (top) and the two responses superimposed (bottom). An area of enhanced emission is present on the solar disk. The lower dotted line in the bottom graph (b) shows the level of the quiet Sun, while the upper dotted line shows the right-hand scan superimposed on the left-hand scan. This indicates the difference in solar intensity between the two scans, which were taken 22 minutes apart. The change in the level of enhanced emission during this short interval suggested that the source of the radiation must be non-thermal, as such a rapid change in the temperature of an area of this physical size could not occur (after Swarup and Parthasarathy, 1958: 345).

Figure 22: The prototype of the larger 5.8m aerial (left) that would be used in the new crossed array at Fleurs being tested at Potts Hill in 1956 adjacent to the north-south grating array (courtesy ATNF Historical Photographic Archive).

Mills went on to build the Mills Cross prototype at Potts Hill (Mills and Little, 1953) and ultimately the full-scale version at the Fleurs field station (Mills, et al., 1958). 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 array. Potts Hill did not have sufficient vacant land on which to build an array with a common centre, so Christiansen decided to also move his activities to Fleurs, where a new array was ultimately constructed.

A prototype of the aerial design that was to be used at Fleurs was tested at Potts Hill. Figure 22 shows the larger prototype aerial located next to the original north-south array, and a close-up of one of these new antennas is given in Figure 23.

Figure 23: Close-up of the 5.8m Fleurs Chris Cross prototype antenna undergoing testing at Potts Hill (courtesy ATNF Historical Photographic Archive).

7 TRANSFER OF THE EAST-WEST GRATING ARRAY TO INDIA

The new Fleurs array—known affectionately as the 'Chris Cross'—began operation in 1957, and produced daily 1,410 MHz maps of the Sun (see Orchiston, 2004). With this development the Potts Hill grating arrays became redundant, and they were earmarked to be scrapped. Fortuitously,

> Pawsey liked to visit all the RP field stations unannounced to see what his staff were doing … and during one of his surprise visits to Potts Hill I asked whether these dishes [in the east-west array] 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).

Although Australia agreed to donate the equipment under the Colombo Plan Scheme, 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 (ibid.). Eventually the C.S.I.R.O. agreed to meet the shipping costs and the 32 antennas were dispatched to New Delhi in the late 1950s.

In mid-1963 the array was transferred from the National Physical Laboratory in New Delhi to the 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 along a 630 metres east-west baseline and the remaining 8 aerials along a 256 metres north-south baseline. Known as the Kalyan Radio Telescope, this new instrument began operations in April 1965 (for further details see Swarup, 2008).

The fate of the Potts Hill north-south array is less clear although it appears that at least some of the aerials were either transferred or donated to universities within Australia. In March 1961, Professor G.R.A. Ellis from the Department of Physics at the University of Tasmania asked if it was possible to obtain any old aerials from Radiophysics. Pawsey (1961) replied stating that "… some time ago we gave one or several (old dishes) to Reg Smith." Dr. Smith, from the Department of Physics at New England University in Armidale, was conducting ionospheric research at this time, although the results of this work were never published.

8 CONCLUDING REMARKS

Dr W.N. ('Chris') Christiansen played a key role in the early development of solar radio astronomy. His first (east-west) Potts Hill solar grating array, which had the ability to produce high-resolution one-dimensional scans across the solar disk in a short interval of time, was unique. This array was used very effectively to investigate the 1,420 MHz brightness distribution across the solar disk, and it provided valuable data on the structure of the solar atmosphere.

Once a second, north-south, grating interferometer was operational at Potts Hill the two arrays were used to produce a map showing the two-dimensional distribution of radio brightness across the solar disk. In constructing this contour map, Christiansen and his collaborators made the first application of Earth-rotational synthesis in radio astronomy. Although O'Brien, working at Cambridge, had earlier used a two-element interferometer to produce a two-dimensional image, Christiansen's Earth-rotation technique proved to be a far simpler method.

After 1,420 MHz solar astronomy was abandoned at Potts Hill, Swarup made sure that Christiansen's legacy would live on in India in the form of the Kalyan Radio Telescope.

9 NOTES

1 Don Yabsley subsequently left the Radio Astronomy Group to work on the development of air navigation technology.
2. A copy of Billings' paper and lecture slides were held on file at Radiophysics and are now in the National Archives of Australia in Sydney.
3. Although this is the accepted figure, on a different occasion Christiansen recalled that the cost needed to be kept below £180 (see Bhathal, 1996).
4. The completion of the east-west array in February 1952 meant that it was operational in time for the Tenth General Assembly of the International Union of Radio Science (URSI) which was held in Sydney between 8 and 22 August 1952. A field trip to Potts Hill and an inspection of the solar grating array was included in the program.

10 ACKNOWLEDGEMENTS

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Harry Wendt, B.Sc. (Hon), M.Sc. (Astronomy), recently completed a Ph.D. at James Cook University, Townsville, Australia. His thesis topic was "The Contribution of the Division of Radiophysics Potts Hill and Murraybank Field Stations to International Radio Astronomy".

Dr Wayne Orchiston is a Senior Lecturer in Astronomy at James Cook University, Townsville, Australia. His research interests include Australian, New Zealand and French radio astronomical history. He has published extensively, and has edited the book *The New Astronomy. Opening the Electromagnetic Window and Expanding our View of Planet Earth* (2005). He also has a book on early Australian radio astronomy, co-authored by Woody Sullivan and Jessica Chapman, which (hopefully) will be published by Springer in 2009. Wayne is a member of IAU Commissions 40 (Radio Astronomy), 41 (History of Astronomy) and 46 (Astronomy Education and Development). Currently he chairs the IAU Working Group on Historic Radio Astronomy.

Dr Bruce Slee is an Honorary Associate at the Australia Telescope National Facility in Sydney, and an Adjunct Professor in the Centre for Astronomy at James Cook University. He was one of the original discoverers of the first discrete radio sources and participated in one of the first metre-wave sky surveys for radio sources, followed by measurements of their angular sizes with medium base-line interferometers. His other interests include scattering in the interplanetary medium, radio emission from active stars, absorption in the interstellar medium, pulsar research, surveys of clusters of galaxies, radio relics in clusters and, in more recent years, the history of Australian radio astronomy. Bruce is a member of the IAU Working Group on Historic Radio Astronomy, and he continues to research topics which have engaged his attention for more than 60 years.