

## Precis Solar research RPL 1945 to 1960, the influence of JL Pawsey: Metre Wave Observations

The undisputed leaders in post war radio astronomy were England and Australia...[D]ynamic and skilful leadership was provided [in Australia] by E.G. Bowen and J.L. Pawsey- two men whose styles of science and complementary personalities produced a potent mix for exploring and exploiting the radio sky... [A number of] factors... led to stunning scientific success in [the] unlikely location and time in Australia in mid-twentieth century... (Sullivan, 2009) <sup>1</sup>

### Australian Radio Astronomy Begins March 1944

The evolution of radio astronomy in Australia had a remarkable beginning a year and a half before the end of WWII in the Pacific in August 1945. Within the next half-decade, the Australians became one of the three major radio astronomy groups in the world along with the Cavendish Laboratory at Cambridge and Jodrell Bank at Manchester. The Australians dominated the field of solar radio astronomy and retained this lead for the next three decades. In Chapters 11-14, we have discussed the remarkable story of the early successes of Pawsey, Payne-Scott, McCready, Yabsley, Bolton, Wild and others in the first few years after WWII.<sup>2</sup>

In this chapter, we provide a summary of the solar work from 1945 to 1960, a period that produced startling and lasting scientific results that lead to the planning of the major RPL solar instrument, the Culgoora Radioheliograph (1967-1983). Pawsey played a key role in the first part of this period as he and Payne-Scott initiated the first solar work starting at Collaroy on 3 October 1945. In 1947 Pawsey appointed Paul Wild; a few years later Wild became the leader of the solar group in the 1950s. The planning of the Culgoora instrument was carried out by Wild and Pawsey, who assured the major financial contribution for its construction by the Ford Foundation.<sup>3</sup> Wild became the dominant solar radio astronomer of the 20<sup>th</sup> century, along with W. N. Christiansen, two of the pillars in the book by Frater, Goss and Wendt (*Four Pillars of Radio Astronomy*, Mills, Christiansen, Wild, Bracewell from 2017).

By the early 1950s, radio astronomers had realised that there were two major types of variable radio emission from the sun: (1) variable metre wave emission, characterised by three major types of bursts and (2) the slowly varying component at cm wavelengths. In addition there was

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<sup>1</sup> Sullivan, W. T., III. (2009). *Cosmic Noise: A History of Early Radio Astronomy*. Cambridge University Press, Cambridge, UK. 118.

<sup>2</sup> Later Piddington, Minnett, Smerd, Little, Leahy, Labrum and Westfold participated in solar work. In the early 1950s, Christiansen with colleagues Warburton, Swarup and Mathewson played an increasingly prominent role in cm solar work.

<sup>3</sup> See Chapters 38 and 40 for Pawsey's contacts with the Ford Foundation and his friend Carl Borgmann (head of science and engineering at the Ford Foundation) in the year before his death.

the quasi-constant emission associated with the corona, the thermal emission from the quiet sun. We treat the metre wave observations in NRAO ONLINE 20 (this text) and the cm observations in NRAO ONLINE 23. The reader will find that there is overlap with this NRAO ONLINE text and Chapters 14 and 19-26 in the published book. We have strived to present in this text (NRAO ONLINE 20) a coherent narrative of the years 1955 to 1960 in the development of RPL solar radio astronomy.

An essential by-product of the solar work was the decisive influence exerted on all radio astronomy in the rapid growth after WWII. Radio astronomy represented the second window on the universe. In contrast to the octave optical window, the radio window exists from 10 MHz to 300 GHz, a factor of  $3 \times 10^4$ . Solar radio astronomy initially provided and perfected the **tools** for this new field of “radio astronomy”<sup>4</sup>. The experiences and insights of the solar radio astronomers were to have far-reaching consequences throughout the world, especially in Australia and the UK. One of the more prominent examples is the development of radio interferometry in 1946 at RPL and the Cavendish Laboratory. A by-product was the suggestion of aperture synthesis in the RPL publication in the *Proceedings of the Royal Society* in 1947 by McCready, Pawsey and Payne-Scott. (Chapter 37).

A major factor in the success of early Australian work on “solar noise” was the coincidence of the most pronounced solar maximum of the modern era with the end of World War II. The solar cycle from 1890 to 1970 is shown in Fig 1 while the prominent sunspot of February 1946 is shown in Fig 2. This was the second largest sunspot of modern era; an even larger sunspot was to appear the next year, April 1947.

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<sup>4</sup> A new word invented by Ginzburg in 1947, independently in 1948 by both Pawsey (January) and Ryle (April). The terms “cosmic noise” and “solar noise” rapidly disappeared in the next decade. See ESM\_17.1. referred to from Chapter 17.

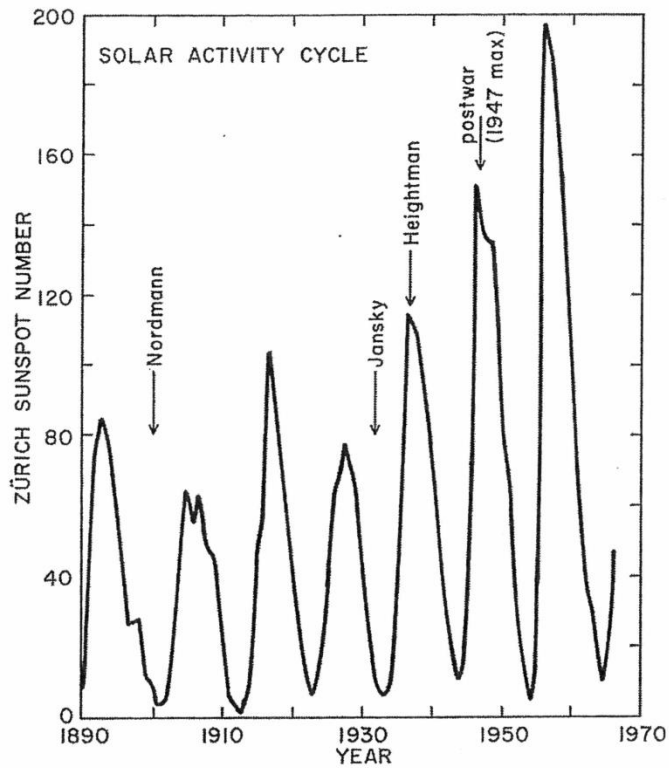


Figure 13.11 The solar activity cycle. Events in the history of radio astronomy affected by the solar cycle are indicated – solar minimum was unfortunate for Nordmann (Section 2.5), but greatly aided Jansky (Chapter 3). Maximum phase was important for Heightman in the 1930s (Section 5.4.2) and for all of the postwar solar work.

Fig. 1 above, from Sullivan, W. T., III. (2009). *Cosmic Noise: A History of Early Radio Astronomy*. Cambridge University Press, Cambridge, UK

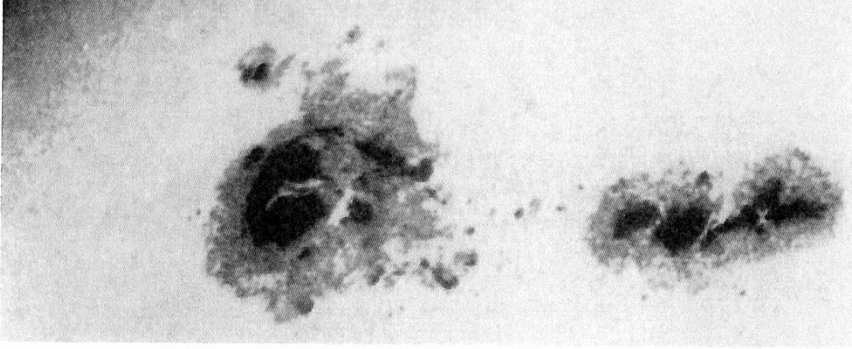
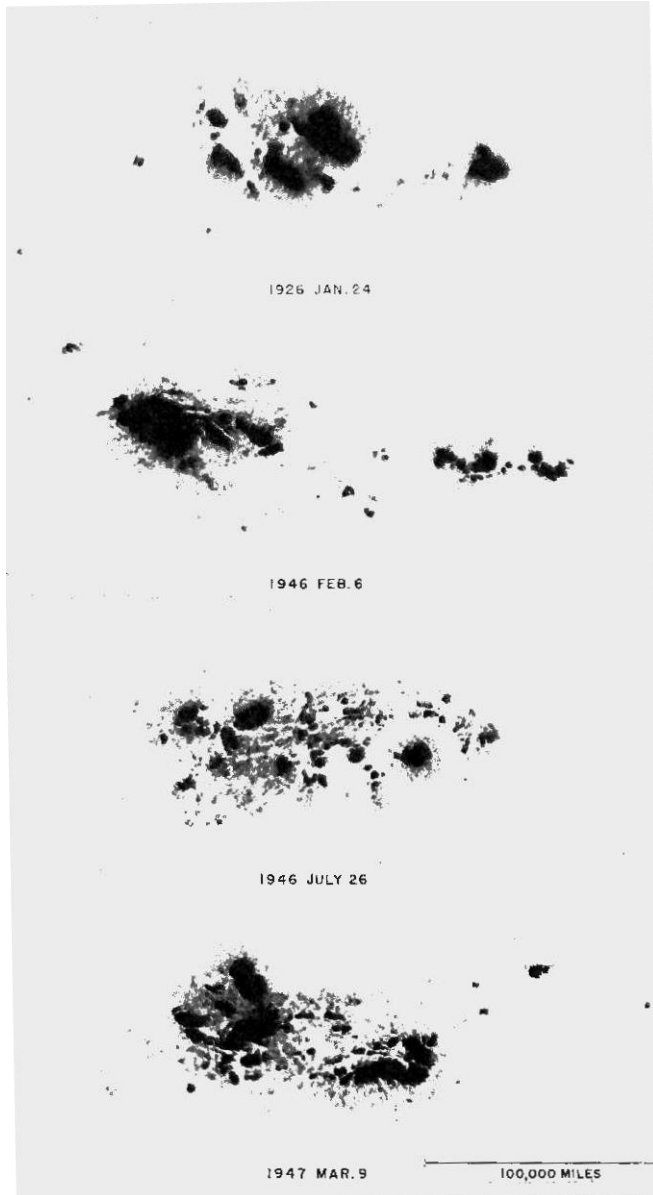


Figure 7.8 The sunspot group of February 1946, the largest ever recorded up to that time. Its associated radio bursts were seen by Pawsey's group with a sea-cliff interferometer and by Hey's group at AORG (Section 6.4).

Fig. 2 above, from Sullivan, W. T., III. (2009). *Cosmic Noise: A History of Early Radio Astronomy*. Cambridge University Press, Cambridge, UK. p 298)

An image from Edison R. Hoge of the Mt Wilson Observatory (1947 *Publ. Astron Society Pacific*, vol 59, p 109) showing some of the prominent sunspots of 1926 January 23, 1946 February 6, 1946 July 26, and 1947 March 9 is shown in Fig 3. The length of the 6 Feb 1946 sunspot was 320,000 km with a total area of 0.5 per cent of the solar surface.

Fig 3 below Three prominent sunspots from 1926 to 1947 from Mt Wilson Observatory. Credit: Hoge, Edison R. "The Great Sunspot Group of March and April, 1947." *Publications of the Astronomical Society of the Pacific* 59, no. 348 (1947): 109.



Wild ("The Beginnings of Radio Astronomy in Australia", *Records of the Australian Academy of Sciences*, vol 2, no 3, Nov 1972, page 52) wrote:

Pawsey [and his group] were extraordinarily lucky to have carried out [these early observations at Collaroy and Dover] during a period when one of the largest spot groups in recorded history was present on the sun's disk. Had the sunspot activity been weak, Australian radio astronomy might never have grown its wings.

The second major external factor was the intensity of the solar radio emission, as shown in Fig. 4 (Wild, J. P., Smerd, S. F., & Weiss, A. A. (1963). Solar bursts. *Annual Review of Astronomy and*

*Astrophysics*, 1, 291). Note that  $10^{-22}$  watts  $m^{-2}$   $Hz^{-1}$  is a **solar flux unit**,  $10^4$  Jy.<sup>5</sup> The solar bursts ranged from  $10^8$  to  $10^{11}$  Jy while the quiet sun (Chapter 12) ranged from  $10^4$  to  $2 \times 10^5$  Jy in the frequency range 60 to 400 MHz. The typical flux density of the first discovered cosmic radio sources was in excess of 1000 Jy, one or two orders of magnitude less intense.

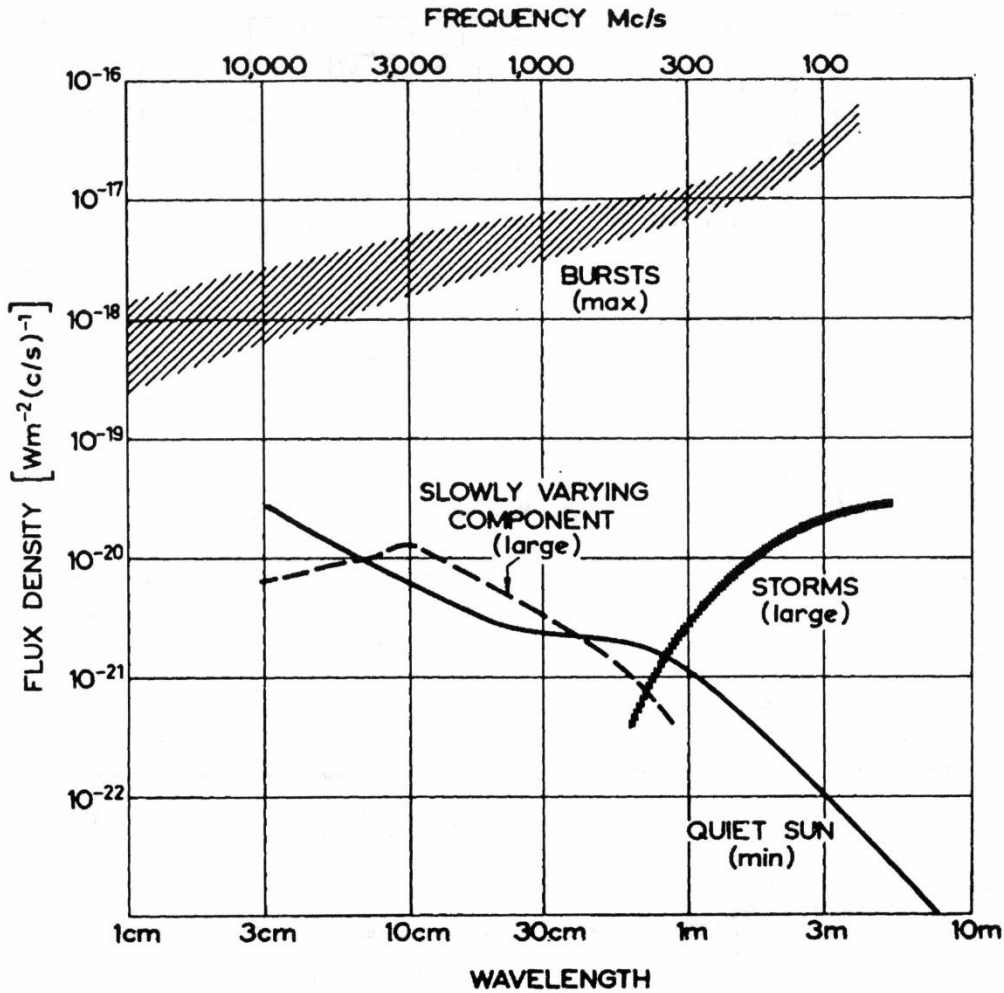


FIG. 1. Indicating the intensity of the various components of solar radio emission.

Fig 4. The intensity of the various components of solar radio emission from 1 cm to 10 m wavelength. The intensity of  $10^{-22}$   $Wm^{-2}Hz^{-1}$  is one solar flux unit,  $10^4$  Jy. Cyg-A has a flux of about  $1.5 \times 10^4$  Jy at 100 MHz. The galactic background at 10 m is about  $10^5$  Jy. Credit: Wild, J. P., Smerd, S. F., & Weiss, A. A. (1963). Solar bursts. *Annual Review of Astronomy and Astrophysics*, 1, 291

<sup>5</sup> The solar flux unit was defined to be a characteristic value of the quiet-sun flux density at metre wavelengths.

The strongest compact extragalactic sources observable from the southern hemisphere were Cygnus A at 10,000 Jy (only observable for about six hours a day from Sydney, the maximum elevation was only 14.5 deg at the northern horizon) and Centaurus A, about 5000 Jy. The strongest galactic source was Taurus A (the Crab Nebula) with a flux density of about 2000 Jy. The first detections of Taurus A by Bolton in 6 November 1947 at Dover Heights (Chapter 16, *Nature*, 1948, vol 162 page 141) had only a modest signal-to-noise ratio (noise in the range of a few 100 Jy). Later observations at the two sites in New Zealand (*Nature*, 1949, vol 164, p 101, Bolton, Stanley and Slee) had vastly improved signal-to-noise ratios due to the higher cliff heights (leading to faster fringe rates with resultant improved problems due to gain variations) and improved receivers.<sup>6</sup>

After 1947, the sensitivity of the Dover Heights radio source surveys had also improved substantially. The catalogue published in 1954 contained 104 sources, ranging from 40 to 12,000 Jy.

In Additional Note 1 at the end of the NRAO ONLINE 20 text (**Expertise of the Scientists at RPL in 1944- 1945, Lessons Acquired during WWII**), we describe a few highlights of the impact of WWII radar research on the post war radio astronomy instrumental developments. One of the prominent examples is the sea-cliff interferometer. (The sea-cliff interferometer was a Lloyd's mirror interferometer formed by interference between the radio radiation from the direct ray from the radio source interfering with the reflected ray from the sea; the baseline of the interferometer was twice the height of the cliff. (Chapters 13 and 37) In eastern Australia the interferometer was often called "dawn" observation. Observations in the evening, as the sources set over land to the west, were not possible from Sydney.)

### **RP 209, First Radio Astronomy in Australia March 1944, Pawsey and Payne-Scott**

The important contribution of Pawsey and Ruby Payne-Scott to the rapid advancement of radio astronomy occurred in March and April 1944 at the end of WWII. These events have been described in detail by Lovell (1963 in the biographical memoir for J.L. Pawsey), Sullivan (Sullivan, W. T., III. (2009). *Cosmic Noise: A History of Early Radio Astronomy*. Cambridge University Press, Cambridge, UK. p. 126) and Goss (Goss, W.M., and McGee, R. (2009). "Under the radar: the first woman in radio astronomy: Ruby Payne-Scott." Vol. 363. Springer Science & Business Media p. 88). Harry Minnett told Sullivan 1978 (Sullivan 2009, p. 126):

Receivers were getting more and more sensitive and we were concerned with the whole thermodynamic theory of their noise level and its relationship, through the antenna, to space – if the antenna were in an enclosure at three hundred degrees, what would be the noise level? This was different from the purely circuit approach that had been worked up by Nyquist and others. ...

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<sup>6</sup> Bolton, J. G., Stanley, G. J., & Slee, O. B. (1949). Positions of three discrete sources of galactic radio-frequency radiation. *Nature*, 164(4159), 101-102.

And it obviously occurred to Ruby Payne-Scott and Joe Pawsey that radiation from objects might possibly be seen. I remember that Ruby had a small paraboloid poking out a window at certain objects in the sky to see how the noise level varied.

In March and April 1944, Pawsey and Payne-Scott began testing S band (3 GHz) radar set receivers at RPL. On 11 April 1944, they published a report (RP 209), "Measurements of the Noise Level Picked up by an S-Band Aerial", 5 pages with an appendix and 5 references (Burgess, North, Jansky-4 publications, Reber and Eddington). The summary was:

Measurements are described of the noise level observed at the terminals of a 10 cm aerial. When pointed at the sky the observed level was that which would be produced by a resistor of the same impedance as the aerial but at an extremely low temperature, between zero and 140 K. The significance of this measurement is discussed.

No detectable difference in level was observed when the aerial was directed towards and away from the Milky Way, a region which other writers have reported to be, on much longer wavelengths, an important source of noise [referring to Jansky at 20 MHz and Reber at 160 MHz].

Clearly the main purpose was to test the performance of the S band radar receiver and to understand the noise performance of the entire system, receiver, horn and cables etc. A sensitive receiver was essential to the performance of the S band radar. Pawsey and Payne-Scott began with a summary of the Burgess (1941) derivation of the sensitivity of a receiver based on Johnson noise in a resistor. Pawsey and Payne-Scott continued with a complex explanation:

The presence in every electrical circuit at a temperature other than absolute zero of noise currents of all frequencies due to random electron motion is a well established fact. Any ohmic resistance  $R$  at a temperature  $T$  degrees (Kelvin) produces across its terminals as the result of the random movement of electrons a noise voltage whose mean square value in the frequency range  $\Delta f$  is given by:

$$e^2 = 4 kT_e R_a \Delta f, \text{ where } k \text{ is the Boltzmann constant.}$$

An aerial in an enclosure at constant temperature  $T_e$  and in thermal equilibrium with that enclosure develops across its terminals a noise voltage whose mean square values in the same frequency range  $\Delta f$  is given by

$$e^2 = 4 kT_e R_a \Delta f, \text{ where } R_a \text{ is the radiative resistance of the aerial.}$$

When the aerial is not in a constant temperature enclosure but is receiving energy from various sources, the same formula can be used to define an "equivalent noise temperature" that is simply a measure of the received noise. If the received noise is entirely due to thermal radiation, the equivalent noise temperature depends not on the

temperature of the aerial itself but of the objects from which it receives radiation. It follows from the reciprocal relations of radiant heat theory that these objects are those which, when the aerial radiates, absorb energy from it....

It follows that the equivalent temperature is a weighted mean of the temperature of all absorbing and emitting objects concerned. Since air is relatively transparent we expect the principal objects to include ground, clouds, possibly ionosphere, and matter in space. If the only source of noise power is thermal energy, we might expect the noise temperature of an aerial looking on the sky to be very low.

However there may be other noise sources. The noise from electrical disturbances in the earth's atmosphere appear to be of very low intensity at centimetre wavelengths, except in the vicinity of lightning. At about 20 MHz a further source of noise, called "cosmic static" and apparently originating in the Milky Way, has been investigated by Jansky (1932-1937) and Reber (1940, at 160 MHz). If Reber's suggestion as to the nature of this noise is correct, it will vary inversely with frequency and will be negligible at cm wavelengths, while if Jansky's suggestion is correct it is of the nature of thermal noise from objects at very high temperature and hence it will result in values of  $[T_e \text{ radiation temperature}]$  very much greater than ambient temperature. Thus the equivalent noise temperature of free space at cm wavelengths may have any value from almost zero to some hundreds of times ambient temperature, depending on the nature of the noise sources.

Despite the theoretical and practical interest attaching to measurements of ultimate noise levels the authors are not aware of any reported measurements of received noise powers in the cm range of wavelengths. These described here are of a preliminary nature, and the authors hope to extend them further. [see below for additional discussion by Payne-Scott in December 1945.]

Clearly, Pawsey and Payne-Scott had a thorough understanding of the thermodynamics of radio noise and the concept of the noise factor (modern term noise figure  $F$ ) invented by Harald T. Friis in 1944 (Friis, *Proc IRE* vol 32, 1944 p. 419 "Noise Figures of Radio Receivers ")  $F=1+T_R/300$ , where  $T_R$  is the noise temperature in Kelvin.

The report then summarised their experience when they pointed a 20 by 30 cm horn connected by a 1.1 metre cable to the 10 cm receiver (from one of the S band radar sets). On two days (20 March 1944 and 30 March 1944) they obtained measurements, as one person watched the output metre and the other manually moved the horn in the desired direction, either in the room or through the window to the eastern sky. They were surprised by the low temperature of the sky, less than 140 K. And they were surprised by the fact that increasing the attenuation between the horn and receiver actually **increased [their emphasis]** the measured signal. [The attenuator reduced the signal from the sky but added considerably more noise power from the ohmic resistance at room temperature.]

The concluding paragraph of the report suggested a new way to calibrate the noise factors of receivers—at least in the cm bands; the use of cumbersome signal generators could be avoided if it could be established that the temperatures of the clear sky were constant. If this were to be the case, the receiver could be calibrated by pointing alternatively at the sky and a room temperature enclosure. This technique is often used by radio engineers today as part of the calibration procedure for cm radio astronomy receivers. Goss (2013, “Making Waves: The Story of Ruby Payne-Scott: Australian Pioneer Radio Astronomer.” Springer Science & Business Media, p 89):

Pawsey and Payne-Scott attempted a single astronomical observation. They used the same receiver and attached it to a 4-foot-diameter paraboloid (the report is filled with mixed units, e.g. cm and inches). They observed a region near the galactic plane in Centaurus (new galactic longitude near 300 degrees) and reported no signals greater than 10 K (the expected value of the galactic background based on current knowledge would be a few K antenna temperature), “very much less than that observed by Jansky and Reber and so small as to have no observable effect. . . . No attempt was made to observe radiation from the sun”. Sullivan (2009) has made the surprising calculation that had they done so, the sun would have been detected easily with a large signal to noise [in the range 6 to 8]. Pawsey and Payne-Scott were apparently not aware of.... the Southworth 3.2 cm solar detection at Bell Labs by Southworth (1945).<sup>7</sup>

In summary, report RP 209 is a remarkable document, likely the first radio astronomy observations in Australia.<sup>8</sup> The upper limits are significant and the conclusions prescient. Ruby Payne-Scott is the first woman radio astronomer; the New Zealand observations of Elizabeth Alexander were made a year later as she reported on the solar data (200 MHz) data obtained by the New Zealand observers (Royal New Zealand Air Force) on the Australian territory of Norfolk Island in March 1945.<sup>9</sup>

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<sup>7</sup> Sullivan has reported that Minnett told him in 1986 that the March sun was not observable from any window in the laboratory room used by Payne-Scott and Pawsey in 1944.

<sup>8</sup> In addition, these observations may represent the third attempt to detect the Milky Way at cm frequencies. On 5 and 6 June 1943, Southworth attempted to detect the Milky Way at 3.2 cm with no success. (Sullivan, 2009, page 95.) Also Reber had attempted to detect the Milky Way at 3300 MHz and 910 MHz (see Sullivan, W.T., III. (1982). “Classics in Radio Astronomy,” Reidel Publishing Company. p 42) in 1938.

<sup>9</sup> Sullivan (2009, p 129): “On balance, it seems that the first RP solar investigations in October 1945 were mainly triggered by the New Zealand observation, but certainly also influenced by the other solar reports.” See Goss (2013) for the details of the fascinating correspondence between Elizabeth Alexander in New Zealand and Pawsey (Sydney) in 1945. Also these issues are discussed in detail, Chapter 11.

**Dec 1945 Summary Paper, entitled “Survey of Solar and Cosmic Radio Frequency Radiation: Survey of Knowledge Available and Measurements Taken at Radiophysics Laboratory to Dec 1<sup>st</sup> 1945.”**

**(A) Introduction and summary of solar research up to December 1945**

Pawsey likely asked Payne-Scott to prepare a report after the *Nature* paper (Pawsey, Payne-Scott and McCready, vol.157, p.158, 1946, publication 9 February 1946, “Radio Frequency Energy from the Sun”) was submitted at 23 October 1945, based on the Collaroy RAAF 200 MHz observations of the first three weeks of October. (see Chapter 12). This was a time for reflection as the significance of the solar results was under evaluation; the RPL group of Pawsey were making plans for the future including moving from Collaroy to Dover Heights, a site more accessible to the headquarters of the CSIR RPL on the grounds of the University of Sydney. A major issue was the possible connection of the solar data and the Milky Way observations reported earlier by Jansky and Reber. On 23 January 1946 (see Goss, 2013 page 98, NAA C3830, A1/1/1 Part 1), Bowen wrote Appleton: “Miss Payne-Scott, who with Pawsey and McCready has been largely responsible for the work here at Radiophysics, has written an internal report summarising latest ideas on the subject of solar and cosmic noise.”<sup>10</sup> The report provided a detailed background of the three influences that lead to the initiation of the first RPL radio astronomy observations: the report of Hey from the February 1942 observations in the UK, the report of the late March 1945 observations of Elizabeth Alexander at Norfolk Island by the New Zealand Air Force and the receipt of the Reber 1944 paper on cosmic noise in which he mentioned obtaining “considerable radiation when the aerial was pointed at the sun”. The purpose was to educate themselves about the solar atmosphere and the mechanism of emission of radio waves. (Sullivan, 2009, CN page 130)

Payne-Scott continued in her Summary report:

The present report is only of a preliminary nature; the above reports [Hey, Alexander and Reber] stimulated some initial observations on equipment already available, and the striking results obtained [Chapters [11-12] inspired us to continue what measurements were possible with the limited equipment and personnel immediately

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<sup>10</sup> Bowen was impressed with the summary publication by Payne-Scott from December 1945. “..[W]e propose publishing this in one of the journals. Do you think this a good thing and would you suggest the *Proceedings of the Physical Society* or the *Astrophysical Journal*?” No response has been found from Appleton in the archive. Likely Pawsey and Payne-Scott lost interest in 1946 as the exciting data from Dover Heights arrived in late January and February 1946. Later the major paper by McCready, Pawsey and Payne-Scott was being prepared during 1946, submitted 22 July 1946 and published 12 August 1947 “Solar Radiation at Radio Frequencies and Its Relation to Sunspots”. (*Proc of the Royal Society*, vol A190, p 357)

available. It is hoped in a few months time to begin a series of systematic observations [Chapter 13 for the Dover Heights campaign that began in early 1946] with equipment designed for the purpose. Meanwhile it seems desirable to record the information gathered and also to discuss the method of interpreting results, the results of other observers and any tentative conclusions, for the benefit of those who will continue the work here and of others carrying out similar investigations.

Payne-Scott then continued the discussion of the thermodynamics of the extragalactic radio emission which had begun in the internal report RP 209 of April 1944. The concept of “equivalent noise temperature” was extended with a number of examples.

This “equivalent temperature” is defined as that which the object or area would need to have in order to produce “black-body” radiation of the observed intensity at the frequency considered. We feel that the effects observed on 200 MHz are probably not due to such radiation [i.e. not black-body], but the concept of “equivalent temperature” still provides a convenient method of expressing the results in a form independent of the aerial and receiving system and at the same time indicates whether or not the phenomenon is likely to be thermal radiation. Also, in practice the radiation received from space is compared with the receiver noise, and this receiver noise is conventionally expressed in terms of the ambient temperature. In fact, Burgess has shown (Burgess 1946) that there is no real distinction between the Johnson noise developed in a resistor at a certain temperature and the thermal radiation picked up by an aerial of the same radiation resistance in an enclosure at the same temperature.

Payne-Scott then re-derived the power received from a black body, essentially the same as done in the April 1944 RP 209 using the temperature of the equivalent resistive load<sup>11</sup>. She then derived the result for the power generated at the output of the antenna in terms of the relevant object’s properties (e.g. a star of certain temperature subtending a solid angle much less than the resolution of the aerial). Next, she carried out a second equivalent calculation of the resultant power using the Rayleigh-Jeans law of black-body radiation, instead of the Johnson noise formula. The Rayleigh-Jeans result she derived is the familiar equation for the energy falling on the earth’s surface in a frequency range  $\Delta f$ :

$$2kT_{\text{STAR}}/\lambda^2 \times \Delta f \times \Omega, \quad \text{units ergs/cm}^2/\text{sec- where } \Omega \text{ is the solid angle of the “star”}.$$

Based on these concepts, Payne-Scott showed that the expectation was that the Milky Way would be easily detectable at low frequencies due to the non-thermal spectrum of the radiation. Since the radiation of an isolated star depended on the gain of the aerial

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<sup>11</sup> Where the available power is  $kT\Delta f$  for the power generated in a load matched to the aerial

(proportional to the square of the frequency) the sun was detected at cm frequencies and even 160 MHz (Reber) and 200 MHz (Collaroy).<sup>12</sup>

Hence Southworth, who failed to see the Milky Way, saw the sun at 3000-30,000 MHz, we have detected solar radiation on 1200 [North Head] and 200 MHz [Collaroy] and Reber at 160 MHz, but Jansky cannot detect it at 20 MHz.

The report of December 1945 provided numerous details of the solar work that had been successfully completed in late October 1945, to be published in the one-page *Nature* Letters to the Editor submitted on 23 October and published the following year on 9 February 1946 (see above). Numerous aspects, including additional details published in the December 1945 summary paper, have been discussed by Goss (2013)<sup>13</sup>.

Other highlights from the Collaroy solar campaign of October from the Payne-Scott December 1945 summary report:

- (1) The Collaroy antenna had a gain of 130 and a beamwidth of 10 degrees. A special receiver was constructed with noise temperature of 1800 K and a bandwidth of 2.5 MHz; the radar receiver was not used. "The first readings were taken on the morning of 3 October [1945]. The time of sunrise was 0530 hours (AEST) and the bearing 95 deg. A few sweeps were taken before sunrise and showed only a slight random variation... At 0531 an increase in noise power of about 27 per cent over the general level was observed... at 0540 the noise power on a bearing of 95 deg was 4.5 times the normal noise level. Over the next twenty minutes it declined, rose again to a smaller peak at 0610 and then declined again, the effect being just detectable at 0730." The plots of the daily averages are shown in Chapter 12.
- (2) The effect was due to the sun and not some atmospheric effect since the radiation began within a minute of sunrise and ceased at sunset. The rate of change of bearing was that of the sun while the beam size of the observed effect was that of the known field pattern.
- (3) Since the intense solar radiation could only be observed<sup>14</sup> for an hour after sunrise (over the Tasman Sea 0.5 mile to the east) and an hour before sunset (over the Blue

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<sup>12</sup> The gain of Jansky's aerial was 10 at 20 MHz, 200 for Reber's instrument at 160 MHz and 140,000 for Southworth's small cm dish.

<sup>13</sup> Chapter 7 of Goss, W. M. (2013). "Making Waves: The Story of Ruby Payne-Scott: Australian Pioneer Radio Astronomer." Springer Science & Business Media. "1945-1946: Early Radio Astronomy at Dover Heights." Pages 103 to 113 provides details of the time variations of the solar emission on day-to-day variations and short-term variations ("kicks") with 100 per cent variations with a time scale of seconds. These events were likely Type I bursts.

<sup>14</sup> The COL (Chain Home Low) 200 MHz aerial only moved in azimuth at a fixed elevation towards the horizon.

Mountains 60 miles to the west), an Army Search Light Control radar at North Head (4 Yagis at 200 MHz, gain only 24 and a less sensitive receiver) was utilised with the ability to track the sun for some hours. On 31 October 1945, the sun was detected from 1400 hours to sunset with little change in intensity. Thus the detections were not the result of low elevation atmospheric or ionospheric phenomena.

## **(B) Detections of the Milky Way, late 1945 at North Head and Collaroy**

During the North Head observations, a crude image of the entire visible sky was made at 200 MHz with a beam size of about 10 degrees. The position of the sun and the galactic centre could be determined. The centre of the Milky Way at RA 17 h and 30 m and Decl. -33 was prominent. (Unfortunately, the figure showing this image was missing from the archive copy of the December 1945 summary report; most of the figures were found in the archive. Subsequent searches in the archive for the “all-sky” 200 MHz image were not successful.

Payne-Scott continued:

It will be apparent that, in addition to the radiation from the sun, there appears to be radiation from a more diffuse area centred approximately on the centre of the galaxy.

In late November 1945, the Milky Way centre rose about the same time as the sun, about 15 degrees south of the sun. The Collaroy observations at sunrise were extended to cover these bearings. “Radiation has been obtained [from the Milky Way] over a fairly large area, covering about 20 deg in azimuth and roughly centred on the centre of the galaxy.” The level of emission was an antenna temperature of about 2000K. Payne-Scott wrote:

There are not yet sufficient results to produce a clear picture, and a number of puzzling variations have been observed; it is possible that some of these are due to absorption in the clouds of matter that cause the dark patches observable in the Milky Way.<sup>15</sup>

## **(c) Conclusions of the Dec 1945 Summary report**

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<sup>15</sup> Payne-Scott did not realise that Milky Way dark clouds (dust clouds of dense interstellar matter) were completely transparent at radio wavelengths.

The conclusions of the December 1945 report by Payne-Scott are prescient; radio astronomy in Sydney had only begun two months earlier. New vistas had opened in astronomy. Some of the conclusions were naïve or even misplaced; the novice practitioners were, however, on the path to success.

Payne-Scott concluded her summary paper:

- (1) Radiation [from the sun], at present indistinguishable from thermal radiation, has been detected over a frequency range of 44 to 30,000 MHz.
- (2) From 30,000 to 1200 MHz this radiation is such as would be emitted by a black body of the same size and position as the sun and with a temperature of the same order as that usually ascribed to the surface of the sun – possibly up to three times greater.
- (3) At 200 and 160 MHz, the amount of radiation received if produced as black body radiation by the sun would require a temperature of at least  $5 \times 10^5$  K.
- (4) This radiation is not constant but has a long period fluctuation that appears to be correlated with sunspot activity and that results in effective temperature up to  $10^7$  K
- (5) On at least one occasion such very high temperature radio has also been observed at lower frequencies – 44 to 85 MHz....
- (6) The above radiation comes from the direction of the sun and moves with it.
- (7) The long-wave radiation shows short-term fluctuations, which may originate either in the sun or in the earth's atmosphere.
- (8) Similar radiation is obtained from the collection of stars in the galaxy; it is most intense in the direction of the centre of the galaxy, and has a distribution corresponding approximately to that of the stars in the galaxy. [Within the next year or so, the radio astronomers realised that this model was impossible. The dilution factor, the fraction of the sky covered by stars such as the sun was about  $10^{-14}$ ; thus stars with radio luminosities such as the sun could not explain the non-thermal emission of the Milky Way.<sup>16</sup>]
- (9) The effective temperature of the Milky Way increases with decreasing frequency.

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<sup>16</sup> Greenstein, J. L., Henyey, L. G., & Keenan, P. C. (1946). Interstellar origin of cosmic radiation at radio-frequencies. *Nature*, 157(3998), 805-806. Greenstein et al wrote, "In other words, a hot star would have to suffer disturbances  $10^{12}$  times as intense as those observed in the sun....if such bursts are to account for the cosmic radiation at radio frequencies. It would seem probable that the solar observations present a new and different type of phenomenon from that observed by Reber, and by Hey, Phillips and Parsons." Sullivan (2009, page 131) has noted that Payne-Scott did not point out a problem that Jansky and Reber had noted earlier, "If sun and Galaxy radiation are of the same origin, why is the sun/Galaxy ratio of optical intensity so much greater than for radio?"

(10) Because of their similar nature and behaviour, it seems likely that the radiation from the sun and the Milky Way have similar origin. [Within the next years, this conclusion was shown to be incorrect.]

For the estimated origin of the radiation two ideas had emerged. Number 1 below was immediately discarded and Number 2 survived. Numbers 3 and 4 were also later confirmed. Payne-Scott **continued**:

### **Suggested Origin of the Emission**

- (1) The opacity of the outer layers of the sun may be much less for radio waves than for light waves [this is not the case in the corona], so that we can see further into the sun at these frequencies. An objection to this is that the temperature measured [the  $5 \times 10^5$  K] would correspond to very great depths [photosphere] in the sun. Also the high ion density makes it likely that the outer layers of the sun are highly absorbant [sic].
- (2) The radiation may come from the corona, [Chapter 14, NRAO ONLINE 24, "Martyn Pawsey Bowen Controversy over the Million Degree Corona 1946"], which has recently been shown to have a very much higher temperature than the photosphere, and which, although transparent to visible light, may well be opaque to long radio waves. Dr DF Martyn, of Stromlo Observatory Canberra, has suggested this origin. This theory does not seem to account for the greatly increased radiation at the time the sunspots actually cross the meridian. [her emphasis] It would also not give a continual increase in temperature with decreasing frequency, as appears to occur for the Milky Way radiation....
- (3) The radiation may be due to disturbances in the sun's atmosphere analogous to our atmospheric and linked with sunspot activity. In this case, it is not thermal in nature and may well increase with decreasing frequency.
- (4) It may be due to **plasma oscillations** [our emphasis] in the ionised atmosphere of the sun.
- (5) The theory postulated to account for the Milky Way radiation was that it is due to ionised interstellar matter. This would, of course, not account for the observed solar radiation.

Payne-Scott then continued her conclusions, suggesting the following for future investigation:

It is hoped to soon begin here a programme of more exact work, in conjunction with the Stromlo Observatory. Among questions to be investigated are the frequency

dependence of the radiation, its polarisation, further study of the long-term variations and an investigation of the short-period fluctuations. **It is also hoped to make a survey of the Southern sky; Sydney is almost at the antipodes of Reber's stations, so that we can survey areas inaccessible to him; in particular to see whether any relation can be detected from the Magellan clouds.** [our emphasis]

### **The Move from Collaroy to Dover Heights, Successful Interferometry on Australia Day 1946 by Payne-Scott**

Goss (*Making Waves*, 2013, p. 113-126) has described in detail the ground-breaking research done by Pawsey and Payne-Scott at Dover Heights from late January to the end of March 1946, published in the paper by McCready, Pawsey and Payne-Scott. The publication appeared in the *Proceedings of the Royal Society* submitted by Sir David Rivett on 22 July 1946.<sup>17</sup> The paper was published 12 August 1947: "Solar Radiation at Radio Frequencies and its Relation to Sunspots" (1947 vol 190, p. 357). This classic publication (in the Sullivan collection *Classics in Radio Astronomy* from 1982) is paper number 19 in the rubric "First Solar Interferometry".<sup>18</sup> The McCready et al paper had a far-reaching impact on solar physics as well as radio astronomy techniques. The move from the RAAF station at Collaroy to Dover Heights was due to continued use of the site by the Air Force at Collaroy; in addition the shorter distance from the RPL to the site was advantageous, 10 km compared to 24 km.<sup>19</sup> The Dover Heights site was controlled as a Shore Defence radar site by the Australian army, Fig. 5. The fringe spacing of the sea-cliff interferometer (at 200 MHz) at Dover Heights was about 30 arc min with the cliff height 85 metres.

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<sup>17</sup> The complex history of the publication of this paper is given by Goss and McGee 2009, chapter 7, p.104 and 10, footnotes number 38 and 39.

<sup>18</sup> The McCready et al paper follows paper number 18 (*Sullivan, W.T., III. (1982). "Classics in Radio Astronomy," Reidel Publishing Company*) by Ryle and Vonberg "Solar Radiation on 175 MHz", published in *Nature* vol 158, p. 339, 1946.

<sup>19</sup> In addition, a trip over the Sydney Harbour Bridge was not required for the trip to Dover Heights from the RPL at the University of Sydney (City Road).



Fig 5 RPL field station, Army Reserve, Dover Heights; the Fortress Fire Command Post was in this reserve, 2.2 km south of the Macquarie Lighthouse and 2 km north of Bondi Beach. (Also 7 km east of the centre of Sydney.) Photo, 18 February 1943. Possibly the two men near the Shore Defence Radar (ShD- 200 MHz) are John Worledge (head of the NSW Railways radar structures group) and Fred White (then Chief of RPL). This 200 MHz antenna was used for the solar radio astronomy experiments in 1946. The view is to the north, North Head is clearly visible. The antenna to the north (on top of the smaller building) is the experimental array (Credit: CSIRO Radio Astronomy Image Archive B81-1)

Sullivan (2009, p. 131) has provided a thorough summary of the monumental events of late January and early February 1946. He points out that the first interferometry in radio astronomy took place with a single radio telescope, the sea-cliff interferometer anticipated by the air warning aerials during WWII.<sup>20</sup> This was the radio analogue of a “Lloyds mirror”, after the

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<sup>20</sup> Pawsey had anticipated this event on 12 November 1945 at a meeting of the PC (Propagation Committee, later Radio Astronomy Committee). The use of interferometry was proposed as a method to determine the small-scale structure, that is, did the “noise originate in a single small area”. He emphasised that the technique was based on the direction finding techniques used by WWII radar practitioners (ADDITIONAL NOTE 1).

famous 19<sup>th</sup> century physicist Humphrey Lloyd in 1834. Payne-Scott described the method (RPL 9 from August 1947):

Briefly, at dawn (sea-cliff interferometer) both direct radiation from the sun and that reflected from the surface of the sea are received, and as the sun rises the receiver output varies sinusoidally as the phase difference between the direct and reflected rays increases; from the times of minima relative to the known time of sunrise, the elevation of the radiating source relative to, say, the centre of the sun can be calculated, while the ratio of the minimum to maximum power gives a measure of the width of the source.

Goss (2013, p 118) :

The interference arose from the portion of the incoming wavefront that arrived directly from the source to the antenna and from the reflected radiation from the sea; the latter wavefront would travel an additional distance, twice the cliff height times the sine of the angle the source is above the sea (elevation). This is equivalent to having another virtual antenna located at a cliff height below the base of the cliff, Fig. 6.

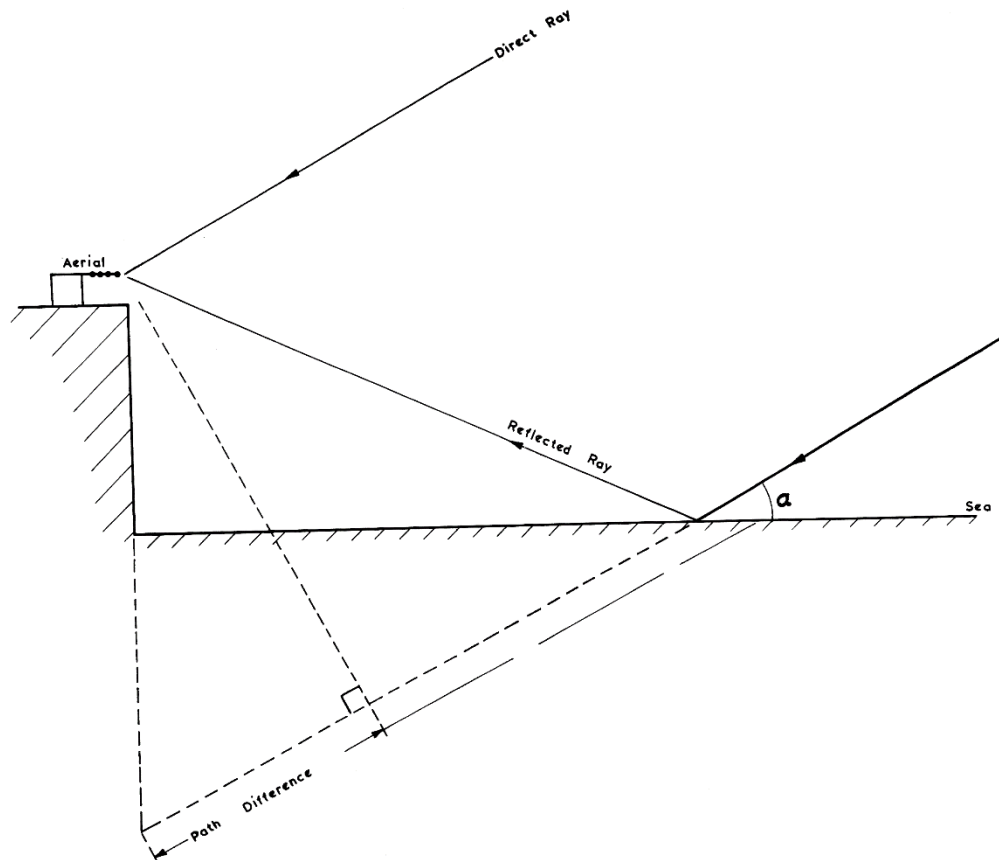


Fig 6, in CRAIA (from 1948) Schematic diagram of a sea-cliff interferometer as used by Payne-Scott on Australia Day 1946 , 26 January. Credit: CSIRO Radio Astronomy Image Archive B1639-4.

With this lobe separation of 30 arc min, the source positions could be determined with an accuracy of a few arcmin. A number of key parameters of this instrument have been identified by Goss (2013, p 119):

As Kellermann and Moran (2001) and Wild (1955) have pointed out, the sea-cliff interferometer had a number of advantages: it had twice the sensitivity as compared to an interferometer consisting of two separate but similar antennas that are connected as an interferometer; no interconnecting cables or preamplifiers were required; and the sharp horizon could be used to eliminate confusion due to sources which had not risen and there were no lobe ambiguities in identifying the maxima on the records with their corresponding lobe numbers. The obvious disadvantages were the limited observing time as the source was rising or setting and the low elevation of the observations with resulting large (and uncertain) ionospheric and tropospheric refraction corrections. In addition, the roughness of the sea due to wave action caused a loss of coherence,

especially at shorter wavelengths. [At 20 cm no fringes were detected due to the variations in the height of the sea at the level of some 10s of cm.] In addition, no delay compensation was possible as in a conventional interferometer of the Michelson type yielding a lower sensitivity due to the small bandwidths required to prevent bandwidth decorrelation. In addition, for many Michelson interferometers the elements could be tracked to follow the source during the day, avoiding the short observing periods of 30-40 min that were possible at source rise or set with sea-cliff interferometers.<sup>21</sup>

The results of the Dover Heights observations are shown in fig 7 (7a,7b and 7c—all Fig 13.3 in main book) and 8 (Fig 13.4 in main book <sup>22</sup> over a number of days in February and March in 1946 of the Type I emission associated with the giant sunspot, initially on Australia Day 26 January 1946. McCready, Pawsey and Payne-Scott (MPP<sup>23</sup>, 1947) reported:

In initial observations early in October 1945 (Collaroy) no interference pattern was observed; ...at this time there was a wide distribution of spots over the sun's surface. Towards the end of January a compact sunspot group dominated the sun<sup>24</sup> and for this reason an attempt was made to detect the lobe pattern on the morning of 26 January [at sunrise by Payne-Scott]. A regular series of maxima and minima was observed, with the expected period and with very deep minima which were less than the detection limit (3 per cent of the maxima).

An ideal opportunity to extend these observations came a few days later with the appearance of the great sunspot of February 1946. [Fig. 7 a] shows a record obtained at dawn (sea-cliff interferometer) at Dover Heights on 7 February.<sup>25</sup> The record is

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<sup>21</sup>The higher cliff tops in New Zealand used by Bolton and Stanley in 1948 –from 80 m to about 280 m– provided a major advantage. The fringe rate was then increased by about a factor of three; thus, slow fluctuations in gain with the total power interferometer were much less severe in limiting the sensitivity.

<sup>22</sup> See *Making Waves*, pages 119 and 121

<sup>23</sup> McCready, L. L., Pawsey, J. L., & Payne-Scott, R. (1947). Solar radiation at radio frequencies and its relation to sunspots. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 190(1022), 357-375

<sup>24</sup> Reported to the RPL group by Cla Allen from Stromlo (Sullivan 2009, p. 132). A short time later in February 1946, a huge spot appeared with size about 0.52 per cent of the solar surface. This was the second largest sunspot of the modern era as measured on 6 February 1946, with a lateral extent of about 40 per cent of the solar radius. An even larger sunspot (area about 0.61 per cent) appeared a year later (March 1947), associated with the giant Type II event observed by Payne-Scott, Yabsley and Bolton (1947).

<sup>25</sup> Payne-Scott would not have been surprised that the radio sun appeared 7 minutes earlier than the optical sunrise. Radio refraction is about double optical refraction at the horizon, one degree compared to 0.5 deg. Peter Hall told Goss in May 1998 (Socorro, NM USA) that his mother was surprised and thrilled as she observed the huge fringes on Australia Day, 1946. In the darkness, she realised

unmistakably an interference pattern with deep minima [indicating a small size]... The section between 0653 and 0602 shows the beginning of a remarkable series of bursts... These [Type I] bursts show interference maxima substantially in phase with the steadier component [enhanced component, Type I noise storms]. [Fig 7b] shows the pattern obtained at Collaroy on the succeeding day [a higher cliff of 120 m and a lobe spacing of 21 arc min]. The period of the oscillation is shorter corresponding to the greater height of the Collaroy aerial.... [Fig 7c, Dover Heights] shows the record obtained on a day on which the minima were shallow, corresponding to a distributed source of radiation.

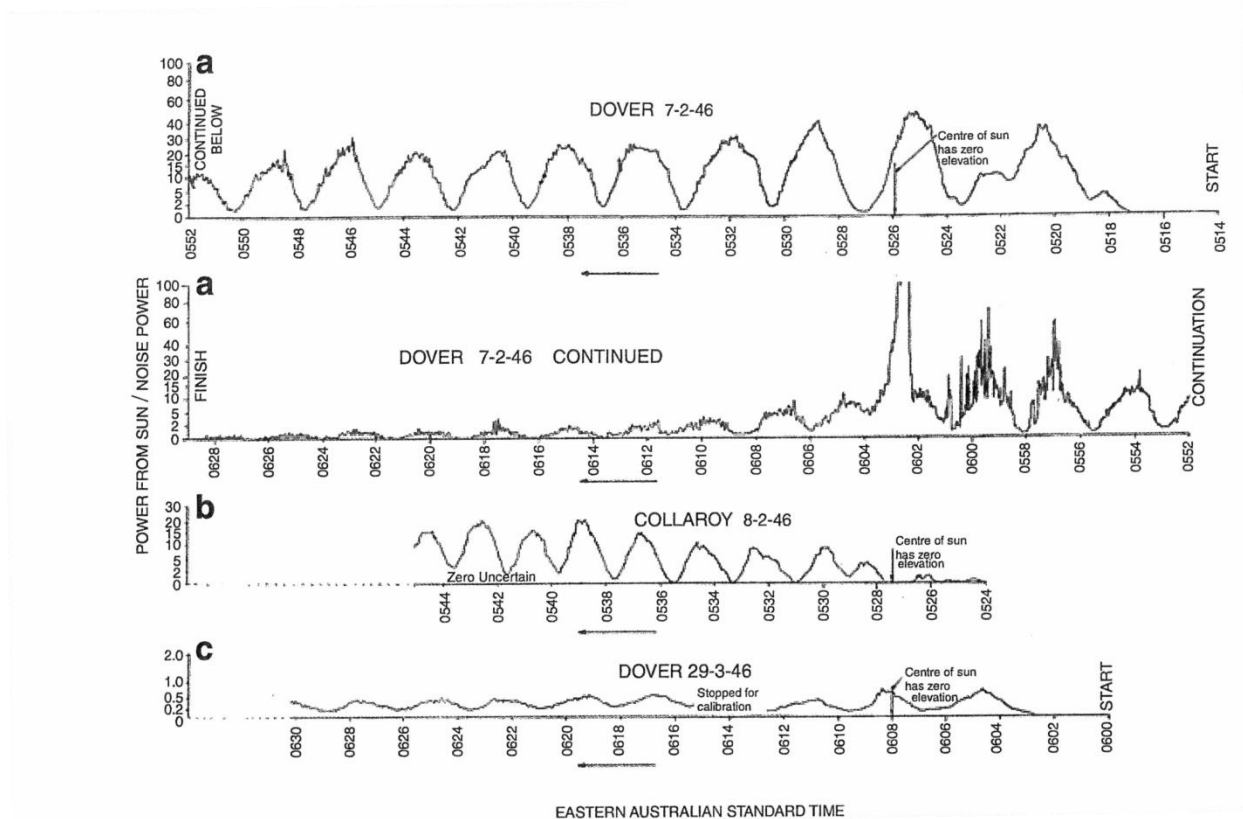


Fig. 7 Interference patterns at Dover Heights and Collaroy at 200 MHz at sunrise for the great sunspot of February 1946; note the radio emission is observed before optical sunrise (centre of sun has zero elevation) due to increased radio refraction compared to optical refraction Panel "a" from Dover shows deep minima indicating a small source size. Panel "b" is the next day at

immediately that the intensity of the fringe amplitude (about 10 million Jansky) was 100 times more intense than the quiet sun at 200 MHz. Equally importantly, she deduced from the ratio of maximum to minimum fringe intensity that the size of the radio source was less than 6-7 arc min, much less the size of the optical sun (30 arc min). For the novice radio astronomer, this was indeed a memorable occasion, the first interferometry in radio astronomy.

Collaroy; where a higher cliff height makes the period of the interference fringes shorter. Panel 'c' shows a 'normal' day when the shallow minima indicates a larger angular size. See Fig. 8 for the appearance of the radio and optical sun on these days. Time increases to the left. Optical sunrise is about 0524 eastern Australian standard time. Credit: Figure 5 from McCready, L. L., Pawsey, J. L., & Payne-Scott, R. (1947). Solar radiation at radio frequencies and its relation to sunspots. Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 190(1022), 357-375.

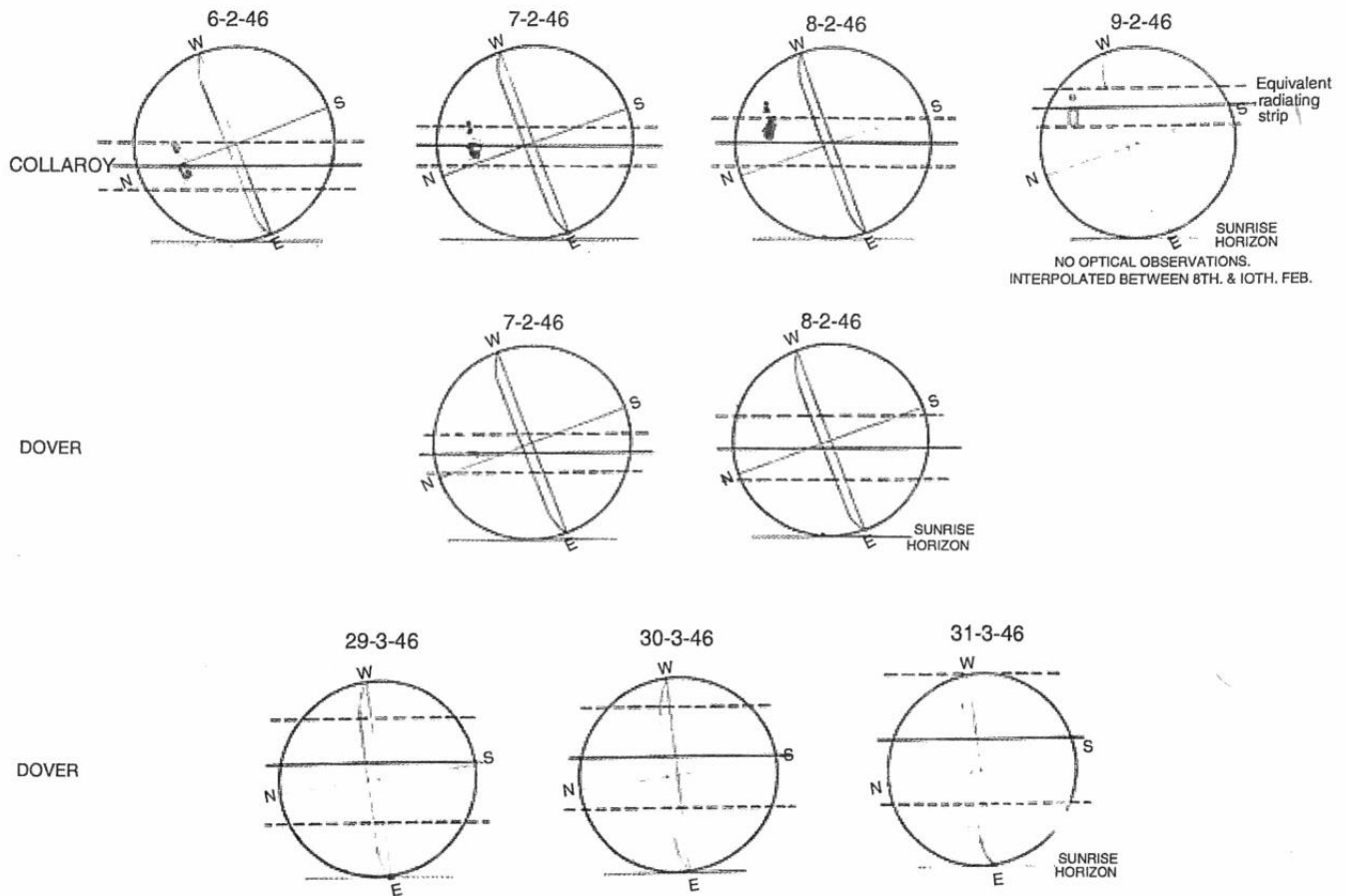


Fig. 8, also from McCready et al 1947 (their Fig. 7). Sketches of the sun with the position and the width of the radio noise source for a number of days in February and March 1946; the sea-cliff interferometer was used to derive the radio noise position and equivalent size. The positions were uncertain to a few arcmin (solar diameter is about 30 arcmin). The widths were upper limits. The top panel refers to Collaroy data while the bottom two refer to Dover observations. The sun is shown with the horizon to the east shown as a hatched area. The equator of the sun is shown (east-west) as well as the solar poles (north-south). The great sunspot of February 1946 is sketched. For the top two panels the radio emission was localised, arising from a region near the sunspot. In the bottom row, the sources of radio emission are scattered, although the emission arises mainly from one sunspot group. The intense radio emission arose from an area much smaller than the optical sun, close to the optical sunspot. Credit: CSIRO Radio Astronomy Image Archive B779-1

Sketches of the sun with the position and width of the radio noise source [in elevation] for a number of days in February and March are shown in Fig. 8. The EW equator is indicated by a double narrow strip. The inferred upper limits for the widths of the emission are shown by the dotted lines, while the solid line shows the inferred position with an accuracy of a few arc min. The positions were determined by the timing of the maxima of the fringes. The sketches show the location of the great sunspot of February 1946. For the first time, there was direct evidence that the bursts and the Type I noise storms originated from a region close to a sunspot group.

Goss (2013, p. 120) has summarised the campaign at Dover Heights from January to March 1946:

The new data extended the results of the previous campaign from October 1945: the radiation at 200 MHz consisted of possibly two types of processes: (1) a slowly varying type of emission, and (2) bursts of duration with time scales of about a second. The emission originated from different positions on the sun and could usually be associated with a compact radio source near a sunspot. For the first time a derivation of an approximate brightness temperature for the storm radiation became possible.

On 7 February 1946, the radio flux density of 10 million Jansky implied an equivalent temperature greater than  $3 \times 10^9\text{K}$ , much higher than any thermal temperature on the sun. A non-thermal emission mechanism was required.

The final major conclusion of the 1946 Dover Heights campaign was the introduction of Fourier synthesis to radio astronomy (see Chapter 37). Pawsey and Payne-Scott were led to this by their experiences observing the sun in early 1946. Based on correspondence with Christiansen, Mills, Wild and Bracewell in 1999 to 2005, we have been able to determine the origin of the concept of Fourier synthesis, a major highlight (Goss, 2013, p. 122-123). Pawsey was the originator of the concept with the mathematics contributed by Payne-Scott. In the MPP paper they wrote:

Since an indefinite number of distributions have identical Fourier components at one frequency, measurement of the phase and amplitude of the variation of intensity at one place at dawn (sea-cliff interferometer) cannot in general be used to determine the distribution over the sun without further information. It is possible in principle to determine the actual form of the distribution in a complex case by Fourier synthesis using information derived from a large number of components. In the interference method suggested here  $\Delta$  [delta, the phase difference between the direct and the reflected ray from a distant source] is a function of  $h$  [height of the cliff] and  $\lambda$  [lambda, the wavelength of the radiation], and different Fourier components may be obtained by varying  $h$  or  $\lambda$ . Variation of  $\lambda$  is inadvisable, as over the necessary wide range the

distribution of radiation may be a function of wave-length. Variation of  $h$  would be feasible but clumsy. A different interference method may be more practicable.

In Additional Note 2 (**Cavendish data from June 1946, first Michelson interferometry from Cambridge**), we describe the results of the Cambridge group as they observed the sun for the first time in June 1946, including their first interferometry (Michelson with a “spaced” interferometer with baselines of 17 m and 240 m) of the sun at 175 MHz. These results were published in September 1946, 11 months before MPP in August 1947. The RPL data of the June 1946 events are described below.

### **Payne-Scott’s success, Dover Heights, August 1946**

After the exciting solar noise results of January –February 1946 at Dover Heights, the intensity of the sun at 200 MHz reached a level of only about  $10^6$  Jy during the next solar rotation in March, an order of magnitude reduction. The RPL group began to focus on multi-frequency observations, a plan that had been discussed at length the previous November 1945, the elucidation of the metre wave spectrum of the short-term bursts. At a meeting of the Propagation Committee on 11 June 1946, Pawsey and Payne-Scott discussed plans for the future: “Future work will concentrate on an exploration of the spectrum, both of the mean level and of the bursts.”<sup>26</sup>

At this point in mid-1946, Payne-Scott was planning a major campaign at Dover Heights to continue the decisive success of January-March. From 23 July to 12 August 1946, 110 hours of observations were carried out. This time multiple frequencies were available and, more importantly, the opportunity to observe from 0900 AEST (Australian Eastern Standard Time) to 1600 AEST with smaller moveable Yagi tracking aerials (4x3 dipole broadside array) at 60 and 75 MHz, polar mounted for tracking the sun 7 hours per day. The original 6 by 6 dipoles Shore Defence broadside array (movable only in azimuth) could be used for observations for slightly less than one hour after sunrise close to 0700 AEST. A 30 MHz dipole was placed on the ShD aerial for some initial observations at this low frequency. The majority of the daytime data was obtained by Payne-Scott and Yabsley with the dawn (sea-cliff interferometer) observations carried out by McCready and D.F. Urquhart. Most of the data reduction and publication was handled by Payne-Scott.

Again, the RPL group was fortunate as a large sunspot appeared in July, the fourth largest size in the period 1874–2008, 4720 millionths or 0.00472 of the solar hemisphere. (Newton, H. W. (1955). "The lineage of the great sunspots." *Vistas in astronomy* 1: 666-674.). Many other solar groups in the world made extensive observations of this event e.g. Cambridge (Ryle), Mt

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<sup>26</sup> NAA C3830, B2/2, Part 1

Stromlo (Martyn and Allen), Jodrell-Bank (Lovell) and the AORG (Army Operational Research Group, J.S. Hey) in the UK.

The RPL group had a new problem in 1946, vandalism. From Payne-Scott's report of August 1947, "A Study of Solar Radio Frequency Radiation on Several Frequencies During the Sunspot of July-August 1946" (RPL 9):

Owing to a burglary at the beginning of the recording, we were left short of recorder pens and they were interchanged from time to time. As a result sometimes the timing and recording pens were slightly out of line, producing errors of 0.5 sec [high speed recording] to 7.5 sec [slow speed recording].<sup>27</sup>

The new sea-cliff observations were perfected with improvements in the equipment and "in accuracy of computation". The mean elevations (yielding the locations of the radio emission on the sun) determined now had an improved accuracy of 2 arc min. For simple structures, the source sizes were derived with a precision of a few arc min. With the limited angular resolution of about 15-20 arc min, the determined equivalent sizes of 5 to 8 arc min were only upper limits. In RPL 9 August 1947 ("A Study of Solar Radio Frequency Radiation on Several Frequencies During the Sunspot of July-August 1946"), Payne-Scott presented a detailed treatment of the issue of the interferometer response in the presence of multiple sources on the sun including the effect of the detection of extended source associated with the quiet sun at 200 MHz. Goss (*Making Waves* 2013, p. 130):

With this simple interferometer, the properties of weak burst sources could not be determined with any certainty. The confusion over the determination of the properties of weak "enhanced radiation" sources (noise storms) in the presence of the larger scale quiet sun—about 40 arc min—was discussed.

After the three week campaign of mid-1946, the main conclusions were (RPL 9): "...[A]lthough there is a general tendency for the levels on all frequencies to increase together, there is no correlation in detail between the variations on different frequencies."

With this simple equipment, Payne-Scott did obtain major results: the first determination of the fast drift rates of Type III [to use the term invented by Paul Wild in 1950] bursts. In 1947, these events were termed "unpolarised bursts" by Payne-Scott and "isolated bursts" by Pawsey. Her delay histogram is shown in Fig. 9. (Note that Goss, *MW*, 2013 p 133, has attributed this data to

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<sup>27</sup> Later in 1946, vandals damaged the ShD aerial. (Goss, *Making Waves*, 2013, p.139). Likely, the Payne-Scott observations of this era were the last observations executed with the ShD system.

the Hornby observations of 1948; the correct site is Dover Heights 1946.) This data is only based on the few second delay between the 75 MHz and then the 60 MHz.

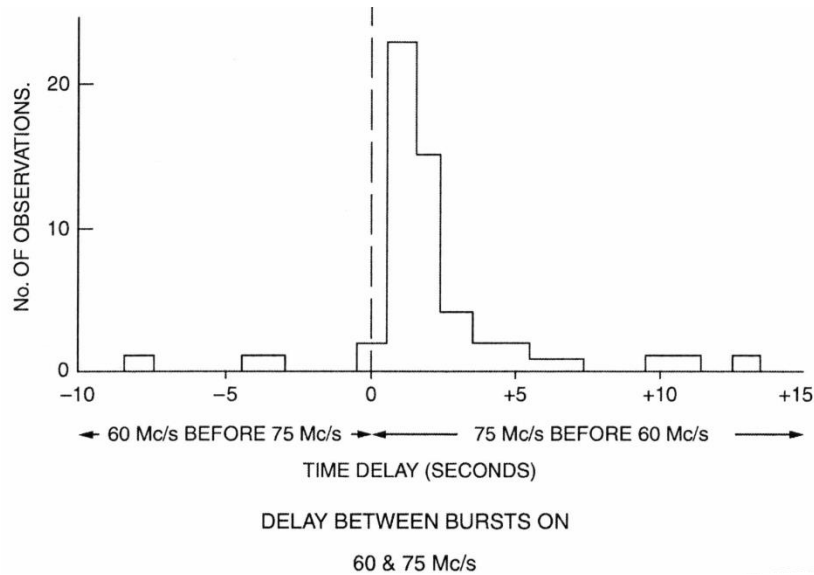


Fig. 9 Time delays (x-axis) in seconds for a number of Type III bursts observed at Dover Heights in August 1946. Data were recorded simultaneously at three frequencies. The 200 MHz bursts arrived first followed by bursts at 75–60 MHz. The distribution of these delays is shown here between 75 MHz and 60 MHz. The data suggest that the 75 MHz isolated bursts precede the 60 MHz events by about 1.5 s. This result formed the basis for the many-month campaign at Hornsby in 1948 (Figure 11 from RPL 9. CSIRO RPL archive), Fig. 14.1 in main book (Credit: "Observation of million degree thermal radiation from the Sun at a wavelength of 1.5 metres," Pawsey, J. L. (1946). *Nature* 158, no. 4018: 633-634.)

Goss (2013, *Making Waves*, p.132) has described the successful first observation of the frequency drifting Type III bursts, moving from high to low frequency:

A major result from the July–August 1946 campaign was that some bursts showed some level of correlation at 60–75 MHz, with a definite delay of about 2 s as the higher frequency preceded the lower. For some bursts, the 200 MHz radiation could be associated with the lower frequency events and this frequency also arrived earlier by a few seconds. However, this result was not published until the events of early March 1947. A few possible Type II bursts (called “outbursts” by Allen) may have also been observed; the intensities were even more impressive than the Type III events. However, the recognition of the delays (from 200 to 60 MHz) at the level of 5–6 min was not at all certain at this time in mid-1946. The major result was, of course, the recognition of the

seconds of time delays for the Type III bursts [the higher frequency preceding the lower frequency, a controversial result that was not generally accepted for a few years.]

The claimed result was to be confirmed by her own data at Hornsby in 1948 and to be solidified by Wild's ground-breaking data from Penrith in 1950 (see below). In addition, Type I events were also recognised; events with no correlation at all between the different frequencies (reported in RPL 9):

Bursts which occur more often when there is a general [enhanced] level, and seem to be a magnified version of smaller fluctuations that have been occurring previously and continued again after the burst is over. These are the bursts with the most complex and varying shapes.

The dawn (sea-cliff interferometer) data for the three-week period was only successful in the first few days near the beginning of the campaign. The data for 27 July 1946 is shown in Fig 10 below. The fading shown at 30 MHz and at 80 MHz is likely due to ionosphere effects at the low elevation of a few degrees at sunrise.

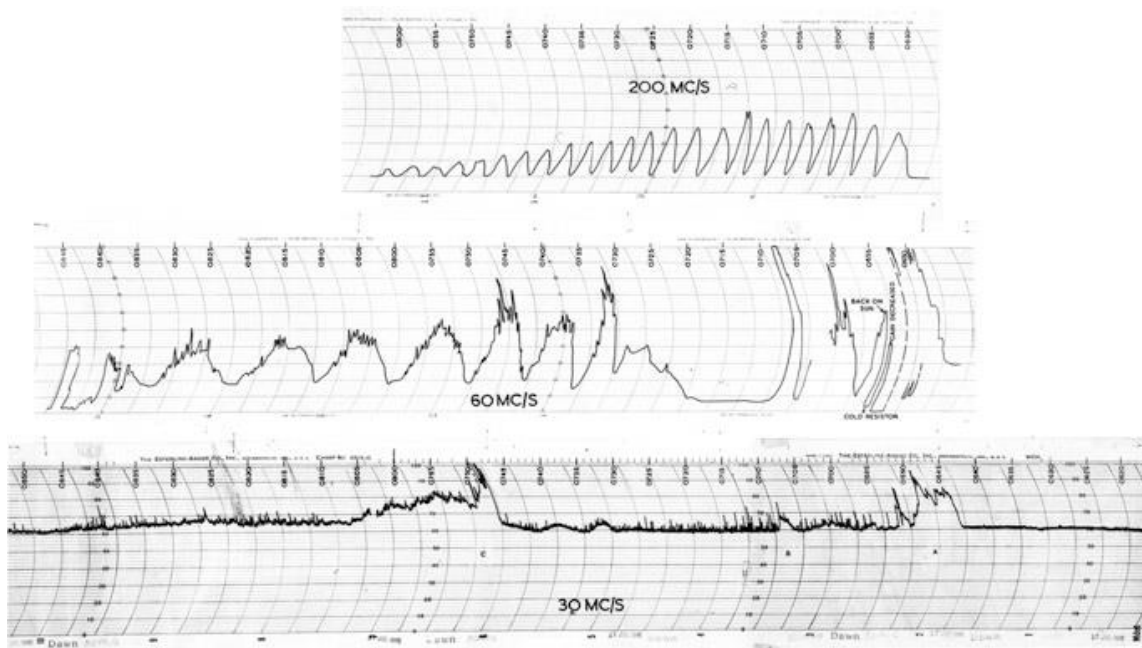


Fig. 10 Radio noise data from the major sunspot group on 27 July 1946. For the first time solar radio data were observed at a number of different frequencies simultaneously: 30, 60 and 200 MHz. The dawn (sea-cliff interferometer) records from 27 July 1946 showed severe fading

(intensity of the solar noise attenuated) at 30 and even 60 MHz, likely due to ionospheric effects at these elevations close to the horizon. Time increases to the left; optical sunrise was about 0655 EAST. The 200 MHz fringes are attenuated about 45 min after sunrise as the sun moves out of the primary beam of the ShD (Shore Defence) aerial. (Credit: CSIRO Radio Astronomy Image Archive B1285-10)

### **Payne-Scott's miscarriage, late 1946**

As Goss (2013, *Making Waves*, p 133) has discussed, the tragic events in Ruby Payne-Scott's life in late 1946 had a negative influence on her career. However, by 1947, she had recovered.

The details of these events remain unclear; the dates are not known and interviews with her contemporaries Rachel Makinson and Joan Murray have provided ambiguous information. However, a miscarriage that began at the RPL building occurred at an uncertain date (1945-1947), based on both interviews. Possibly, the event was mid-August 1946 since her observations ended abruptly before the major solar activity ended in September 1946. Apparently, Payne-Scott was absent from the RPL for one to two months. Based on the minutes of the Propagation Committee and the Solar Noise Group, she was not active at Dover Heights for a period of at least six to ten months, starting August 1946.

Clearly, she had partially recovered in early 1947; she presented a report to the Solar Noise Group on 14 January 1947, "Solar Radiation Bursts on 60, 75 and 200 MHz", a precursor of her detailed report RPL 9 describing the results from July-August 1946. By June 1947, she was fully engaged again as she began preparing the report (RPL 9). By August 1947, a month before Pawsey and his wife left on their 13-month trip to North America and Europe (Chapter 17, NRAO ONLINE 59, ESM\_17.3) the report was complete<sup>28</sup>. Although the report only appeared as an internal document, the fast drift burst (Type III) results would be presented in the *Nature* publication of the multi-frequency campaign of March 1947 (as discussed in the next section) and also influenced the major nine-month campaign in 1948 at Hornsby, see below.

### **The Behemoth Type II Burst of March 1947: Payne-Scott, Yabsley and Bolton Observe an Amazing Event**

During the one year period in which Payne-Scott had a reduced participation in the activities of the solar noise group, Pawsey had organised that John Bolton would investigate the circular polarisation of Type I bursts.<sup>29</sup> Likely, during Payne-Scott's absence, Pawsey would have been

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<sup>28</sup> Likely the delay of 13 months from observations to internal publication was impacted by the miscarriage and the aftermath.

<sup>29</sup> Bolton had arrived at RPL in September 1946 from the UK. See Goss (*Making Waves*, 2013, p. 137) for details of the March 1947 event.

concerned that the solar monitoring at low frequencies would not continue. Bolton's solar work (before his detection of Cygnus A at Dover Heights in June 1947) continued the programme.

Bolton has reported a dramatic version of these events in his presentation to the Astronomical Society of Australia in 1982 at Noosa Heads in Queensland (published in *Proc Astron Society Australia*, vol 4, 1982, p. 349 "Radio Astronomy at Dover Heights".) After the ShD aerial was no longer present, a number of Yagis at 60, 100 and 200 MHz were installed on the block-house at Dover Heights. This complex set of aerials is shown in Fig 11. In March 1947, a huge sunspot appeared which grew in size during the next solar rotation in April.<sup>30</sup>

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<sup>30</sup> The size of the sunspot on 5 March was 0.004554 (fractional coverage) and in early April (a solar rotation later) had a size of 0.006132. The latter size remains the largest sunspot since modern records have been maintained.

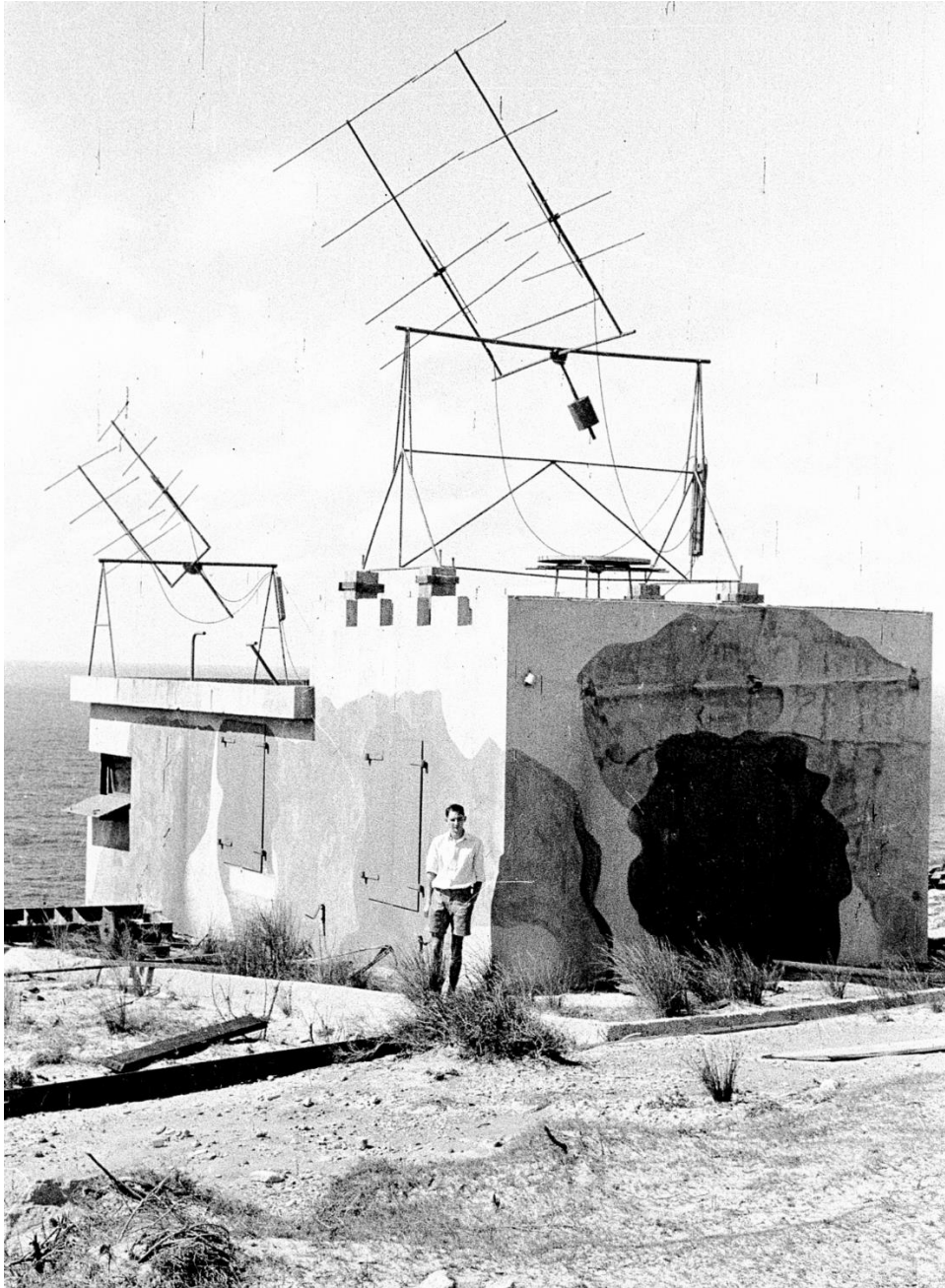


Fig. 11 John Bolton in front of the blockhouse at Dover on 1 May 1947, about 2 months after the discovery of the giant Type II burst on 8 March 1947 by Payne- Scott, Yabsley and Bolton. The 200 MHz ShD antenna was no longer present. The 100 MHz Yagis to the left while the 60 MHz Yagi to the right (note the orthogonal placement of the dipoles on the Yagi antennas, used for the determination of circular polarization of the solar radiation). The 200 MHz Yagi was on the far corner and not visible; for “radio star” observations the Yagis were used in a parallel configuration. (CSIRO Radio Astronomy Image Archive B1031-6, 1947).

Don Yabsley had provided another account of the events of March 1947 that has major discrepancies with the Bolton version. Yabsley's account was communicated to both Sullivan (10 October 1986, CN 2009, p 149) and Goss (letter 22 September 1997). Yabsley had also observed a number of bursts in which the higher frequency preceded the lower frequency. Yabsley reported that the paper was written by Pawsey and Payne-Scott. Pawsey did not include his name on the final paper since "he felt that three names on a letter to *Nature* were quite enough". Goss found in about 2007 that the original file at RPL for this publication had a different author ordering: Bolton, Payne-Scott and Yabsley.<sup>31</sup> There is no explanation of why the final published paper was Payne-Scott, Yabsley and Bolton. We can surmise that Pawsey made the change, perhaps contributing to the lingering irritations between Payne-Scott and Bolton. The last sentence of the publication reads, "Of our own colleagues we should like to thank Dr J.L. Pawsey for his interest and helpful discussions throughout all phases of the work."

Bolton was observing on Saturday afternoon 8 March 1947 when a huge outburst occurred. The 200 MHz receiver was broken. Data appeared first at 100 MHz; four min later the burst occurred at 60 MHz, Fig 12. Fortunately, Cla Allen was observing 200 MHz at Stromlo and provided the data at this frequency. In the *Nature* publication, the claim was made that the burst at 60 MHz was more intense than 100 billion Jy, possibly the largest extragalactic signal ever received. Although quite uncertain, the flux density was clearly in excess of 100 billion Jy, with a large uncertainty.<sup>32</sup>

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<sup>31</sup> Payne-Scott, R., Yabsley, D. E., & Bolton, J. G. (1947). Relative times of arrival of bursts of solar noise on different radio frequencies. *Nature*, 160(4060), 256-257

<sup>32</sup> Later Paul Wild estimated that the 60 MHz peak had an order of magnitude uncertainty.

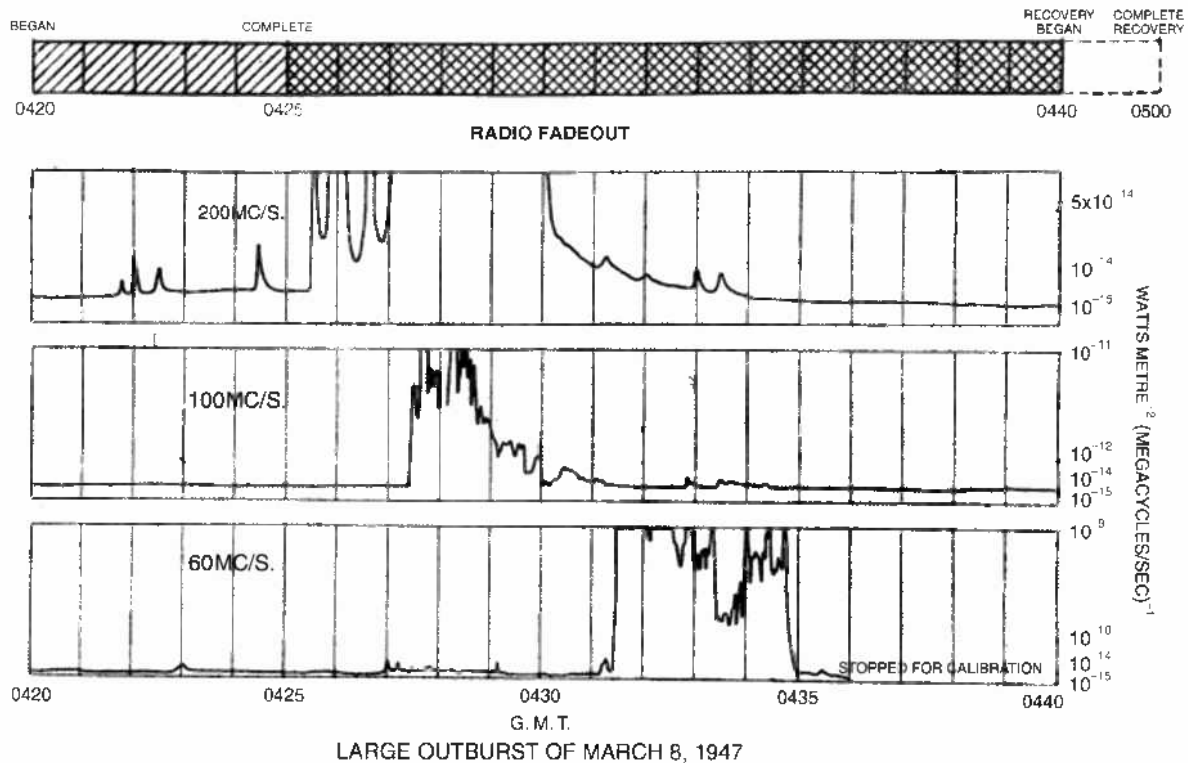


Fig 12 The giant Type II burst of 8 March 1947, the first published and the prototypical Type II burst. 200MHz observed at Mt Stromlo and other frequencies observed at Dover Heights. The 60 MHz peak intensity is quite uncertain but was in excess of 100 billion Jy. The shortwave radio fadeout at 20 MHz was used as a proxy for the time of the major flare event. A day later a major (and rare) aurora was observed in Australia. Credit: Payne-Scott, R., Yabsley, D. E., & Bolton, J. G. (1947). Relative times of arrival of bursts of solar noise on different radio frequencies. *Nature*, 160(4060), 256-257.

The paper “Relative Times of Arrival of Bursts of Solar Noise on Different Radio Frequencies” was submitted on 21 May 1947 and published in *Nature* (vol 160, page 256) on 23 August 1947. In succeeding years, most references to this paper have only emphasised the major discovery of the Type II bursts. However, two additional major results were also presented in the *Nature* paper.

Goss (*Making Waves*, 2013 page 139):

- (1) Most of the bursts were not correlated at three frequencies, suggesting that the emission at the various frequencies arose from widely separated levels in the solar corona. These bursts would be mainly described as Type I storm events in the future.
- (2) For events that would be called Type III bursts in the modern epoch, there was a good correlation in shape and ordering of the arrival times of the emission with 200 MHz

first, then 75 and finally 60 MHz. **These results were, of course, derived from the data from the July-August Dover Heights campaign of 1946, obtained by Payne-Scott as reported in RPL 9.** (our emphasis) Of 60 cases of associated bursts at 75 and 60 MHz, the most common delay was found to be 2 s. The determination of the delays between 200 and 75 MHz was comparable, but quite uncertain since the form of the bursts was found to be disparate. In a few cases, delays were obtained with the 30 MHz emission arising a few seconds after similar events at 60 MHz.

This publication is the first report of short delays implying relativistic velocities for the Type III events. Strikingly, the paper does not mention the velocities implied. As we will see below, Paul Wild determined the detailed nature of the Type III bursts in his paper of 1950, based on dynamic spectra (frequency-time) at Penrith, near Sydney.

The main thrust of the paper of August 1947 was the remarkable Type II burst and the determination of the implied velocity of the outburst. The Mt Stromlo observers had observed a major optical flare on this day and Radio Australia at 20 MHz had suffered a shortwave fadeout due to the excess ionisation of the D layer of the ionosphere at a height of about 90 km).

The authors of the *Nature* paper wrote:

The successive delays between the onset of the outburst on 200, 100 and 60 MHz suggest that outburst was related to some physical agency passing from high-frequency to lower-frequency levels. If we assume, following ideas suggested by Martyn, that radiation at any frequency originates near the level where the coronal density reduces the refractive index to zero, we can derive a rough estimate of these heights from electron-density data....

The derived velocities (from the height versus time plots) were in the range 500 to 700 km/s as compared to 1600 km/s transit speed of auroral disturbances from the sun until impinging on the earth's magnetosphere. The displacement would correspond to about 0.3 solar radii in six minutes or an angular displace of 5 arc min in this interval. A prominent Corona Borealis was in fact observed on 9 March 1947 in Australia, over a day later, a rare event in eastern Australia. The inferred velocity of the particles was consistent with this time delay. The possible existence of relativistic velocities was a major surprise since there had not been optical evidence of such events. Later in the 1950s, Paul Wild and his colleagues would provide direct evidence such motions.

### **Bolton/Payne-Scott Conflict during Pawsey's Absence 1947-1948**

The 13-month absence of Pawsey in North America and Europe from 25 September 1947 to 29 October 1948 produced a challenging period for Payne-Scott, impacting her solar noise research. She experienced adversity and set-backs; in the end, her perseverance led to success.

The plans to continue the measurements of the possible time delays for Type III bursts had been formulated in September 1947, two days before Pawsey's departure (meeting of "Pawsey's solar noise group"). The compelling rationale was to follow up on the controversial claims of the August 1947 *Nature* letter; many colleagues were not convinced that the Type III bursts showed delays of some seconds. Payne-Scott believed in the reality of this effect but had begun to doubt the "minutes" delays for the Type II bursts, which had only been observed during the 8 March 1947 event. In particular, Martin Ryle had expressed doubt about the "seconds" delays for the Type III events; Pawsey had replied to Ryle on 3 July 1947: "With regard to the "seconds delay" cases, I am not entirely happy about the evidence. I believe that the tendency exists...."<sup>33</sup>

A major problem for Payne-Scott during Pawsey's absence was the administrative arrangement that Pawsey proposed while he was overseas. The overall direction was left with E.G. Bowen (Chief of RPL) with a vague plan that Fred Lehany and Lindsay McCready were to "coordinate the research programmes"; during the course of the next year neither were prepared to mediate conflicts between Bolton and Payne-Scott.<sup>34</sup>

An immediate problem began as Pawsey and his wife departed for the US in late September 1947. By this time, Bolton had lost interest in the sun and had started his decisive "radio star" work. Payne-Scott was continuing to work on the sun during this period. Bolton and his group were also trying to test their equipment in the daytime. Conflicts were inevitable. On 18 November 1948 McCready wrote a confused letter to Pawsey in the US:

The letter would be incomplete without some gossip on personalities. To cut a long story short, Bolton and Ruby have had a "bust up" at Dover [Heights] partly due to technicalities (e.g., Ruby's local oscillator and his 100 mc/s receiver) and partly due to, I fear, her personality and, last but not least, both parties wanting to use the same gear for different experiments at the same time! Anyway, after careful examinations of the rights of all and of [the] facts we decided it be [sic] better if Ruby moved to Hornsby. No-one objects... Frank Kerr [who was already working at Hornsby suggests that Ruby move to Hornsby] ... Now [all participants] are quite happy about it. She says she can get to Hornsby [by public transport] and arrive at the site before 9:45 am and that she can't do that except on rare occasions at Dover. [due to the vagaries of complex public transport from her home to Dover Heights] We are fitting her up in a separate trailer [at

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<sup>33</sup> NAA C3830 A1/1/1 Part 2

<sup>34</sup> The exact words were: "Messrs. Lehany and McCready, as senior officers of the Group, were requested to keep Dr Bowen informed of events by meeting at suitable intervals and co-opting other Group members whenever considered necessary." (Goss, *Making Waves*, 2013, p. 148)

Hornsby]. I did not tell Taffy the full details-I mainly concentrated on technical difficulties they were naturally experiencing.<sup>35</sup>

### **HORNSBY late 1947- September 1948, Type III Bursts Seconds Delays Confirmed**

The first decisive indication that Payne-Scott would move to Hornsby was discussed in the 14 November 1947 meeting of the solar group.<sup>36</sup> Interference had rendered 100 MHz observations at Dover Heights almost impossible, not surprising given the proximity to the centre of Sydney. The deep valley at Hornsby provided some protection from interference, especially important since observations close to 19 MHz were already being carried out. The day-to-day conflicts between Bolton and Payne-Scott ceased as she moved to Hornsby in late 1947; however the clash of personalities continued. As we show in Additional Note 3 (**McCready's Reaction to the Bolton/Payne-Scott Conflict in 1948**), McCready was not effective in moderating the conflict.

The data collection at Hornsby at 85, 65, 60, and 19 MHz began at a rapid pace at the end of 1947 and early 1948. The main advantage of the lower frequency was that large time delays were expected between 60 and 19 MHz. At a meeting of the solar group on 6 January 1948, Payne-Scott had already found delays in the range 5 to 10 sec. These low frequencies (one system at 18.3 MHz and the other at 19.8 MHz) had not been available at Dover Heights. Goss (*MW*, 2013 p 154) has summarised the results:

These three frequencies and 19 MHz were used on an almost daily basis. In contrast to the earlier observations at Dover Heights, these systematic observations enabled Payne-Scott to characterise both the detailed time behaviour and polarisation properties of the metre wave bursts...The continuous nature of the observations in 1948 was a major component of the success...

Payne-Scott made rapid progress at Hornsby. Already after 1-2 months observations, she presented the results to the Propagation Committee at RPL on 9 February 1948: "Differences Between Times of Arrival of Bursts of Solar Radiation Emitting at Different Frequencies- Preliminary Measurements". The new data confirmed the uncertain Dover Heights data. "Bursts

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<sup>35</sup> NAA C4659/8

<sup>36</sup> At this meeting Payne-Scott also mentioned a possible new project. "Some thought has been given to the possibility of constructing a spectrohelioscope." This would be an instrument with continuous coverage in frequency, rather than discrete, separate frequencies. She did not follow-up on this suggestion. At the same meeting McCready, Wild and Medhurst also discussed a possible instrument using an existing WWII receiver from 280 to 610 MHz. The sensitivity was poor; a new system at 70 to 140 MHz was suggested. At a following meeting of the solar group on 30 March 1948, a detailed design of this system was described. This was to be the system used at Penrith by McCready and Wild in early 1949 with a lower frequency, 40 to 70 MHz.

on 60 MHz never arrived later than corresponding bursts on 18.3 MHz, the most common time earlier being 9 seconds with considerable scatter.”

The discussion of the results revealed that Payne-Scott was reluctant to accept that these delays implied velocities of about 25,000 km/s, about 0.08 c, an extreme velocity that had no previous counterpart in solar research. Pawsey was not present to offer his support of this surprising and controversial conclusion.<sup>37</sup>

Payne-Scott wrote:

Using Smerd's computations on radiating levels, based on Martyn's theory, the measured time differences would give a velocity of about  $0.5 \times 10^{10}$  cm/s for 60-18.3 Mc/s and  $0.7 \times 10^{10}$  cm/s for 65-60 Mc/s- in very good agreement, considering the errors and scatter in the measurements and the empirical values used in the calculations, but an **apparently unlikely velocity**. [our emphasis] However, if bursts do originate at the borders of prominence materials, it is quite possible that the much higher density gradient there, may lead to a crowding of levels by as much as 100 times, reducing the above velocities to the order of prominence velocities [that is, about 1000 km/s]

Goss (2013, *Making Waves*, page 140):

The inferred velocities were about 0.1 to 0.2 c; but these values were dismissed as being unlikely at this time and no mention of this revolutionary explanation was included in the *Nature* paper of 1947. This presentation is likely the first time the possibility of Type III bursts being caused by electron streams moving at a substantial fraction of the speed of light was discussed.

As we point out below, Wild and McCready (1950) and Wild (1950b—the Type III paper) produced results that conclusively showed that these relativistic velocities were plausible.

An additional and related problem arose in mid-1948, caused by the major uncertainties in the existence and properties of the “seconds delay” as well as major doubts expressed by many colleagues (in Australia and the UK) about their reality (Goss, 2013, *Making Waves*, page 155-157). By June even Payne-Scott and Bowen had

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<sup>37</sup> Sullivan (2009, p. 298) has also discussed this remarkable presentation given by Payne-Scott.

begun to believe that the Hornsby research was of limited value. McCready wrote Pawsey on 6 June 1948<sup>38</sup>:

... it appeared that her [Payne-Scott's] work at Hornsby was getting nowhere. Taffy [Bowen] himself suggested she fold it up and get into something more profitable ... I got her to give a talk at the Propagation Committee [the 9 February 1948 colloquium where she summarised her findings and put forth the revolutionary calculations on the inferred but unlikely extreme speeds associated with the bursts] mainly for Taffy's benefit ...

Another major factor contributing to Payne-Scott's anxiety was the planning and construction of the 100 MHz swept-lobe interferometer at Potts Hill. Clearly, because of its engineering and scientific challenges, she felt more attracted to this promising new project [a Michelson interferometer]. It is possible she had begun to feel as though she had been sidelined, exiled to Hornsby.

Again, Pawsey was able to calm the troubled waters from a distance. Payne-Scott wrote Pawsey a four-page letter on 18 May 1948 describing the results of the first four months observation at Hornsby. Goss (*Making Waves*, 2013, page 156):

[In the letter, Payne-Scott] provided a thorough description of the results of the first 6 months of observations at Hornsby. She described the circular polarization of the storm bursts (now Type I) and the lack of polarization of the (Type III) bursts. She then pointed out that the storm bursts showed little correlation at adjacent frequencies. The unpolarized bursts [called isolated bursts by Pawsey] did show correlation at adjacent frequencies; this result had been one of the major conclusions. She then discussed the delays between the three frequencies in the Hornsby data. Payne-Scott ended the letter with a request for advice. "I would like your opinion on whether to leave [the project now] or try another move... I am convinced of the reality of the delays.... You have probably heard that I am taking on 100 MHz interferometry and hence would like to get clear of [my responsibilities at Hornsby]."

Pawsey replied in an [almost] illegible hand written letter from a UK train trip. He wrote:

I think the proposed subject [Type III bursts] would make an excellent paper, subject to your being able to give sound evidence for the points you mention. You have to choose between doing work on bursts and starting interferometry. I think you should rely on what you have done. Do only what is necessary to make

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<sup>38</sup> Ibid

it a good plan. In the interferometry field you start behind Ryle [at Cambridge] and will probably take some time to catch up. Therefore go ahead with it in second place – complete the burst story first.<sup>39</sup>

Payne-Scott persevered and continued the observations at Hornsby until September 1948. She was then in a hurry to begin the Michelson interferometer observations at Potts Hill. Within three months after the end of the Hornsby campaign, the paper “Bursts of Solar Radiation at Metre Wavelengths” was completed and sent to the *Australian Journal of Scientific Research* on 5 January 1949. The paper was published in June 1949 (reference: Payne-Scott, R. [1949]. "Bursts of Solar Radiation at Metre Wavelengths." *Australian Journal of Scientific Research A Physical Sciences* 2: 214).

The abstract of the paper provided a summary of the important results:

The variable components of solar radiation observed on frequencies of 85, 65, 60, and 19 MHz over a period of nine months have been studied. It is shown that two types of variable high-intensity radiation can be distinguished. One of these, referred to as the "enhanced level", is circularly polarised. The other, a particular type of short duration increase, is not circularly polarised and such an increase is called an "unpolarised burst".

These bursts tend to occur nearly simultaneously over a range of frequencies. They decay exponentially and double-humped bursts are common. Their characteristics are shown to conform broadly with the hypothesis that the bursts originate in localized transitory disturbances in the high corona which radiate over a wide frequency range. The decay constant is correctly predicted on the assumption that it is the decay constant of the excited medium in the region of origin, and the double peaks on the assumption that the second peak is an “echo” of the disturbance after reflection at the appropriate lower level in the corona.

The occurrence of time delays between the arrival of "corresponding" unpolarised bursts on different frequencies is confirmed, the higher

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<sup>39</sup> Pawsey wrote Bowen 11 days later with a detailed account of the letter to Payne-Scott. She had been forced to face the scepticism of many colleagues, including Pawsey, about the controversial results on seconds delay in Type III bursts. On 9 June 1948 McCready wrote Pawsey telling him that Payne-Scott had been quite pleased with the Pawsey letter of encouragement. Clearly, the 13 month absence of Pawsey in 1947-1948 had a major impact on Payne-Scott's research; he was not present to provide support in the face of scepticism and opposition from some of her colleagues.

frequency commonly arriving earlier, with delays of about 0.7 second between 85 and 60 MHz and 9 seconds between 60 and 19 MHz. There is a good correlation between major radio "fade-outs" and large bursts on these frequencies. [see Fig 13 below]

The observations were carried out at 85, 65 and 60 MHz with simple Yagis that could be pointed at the sun; circular polarisation (switch between LH and RH) was available at 85 MHz. In addition there was a simple broadside array at 18.3 MHz and a fixed rhombic at 19.8 MHz. The quiet sun was not detected with the sensitivity of these simple systems. (The quiet sun is about  $3 \times 10^4$  Jy at 80 MHz.) In Fig. 13 (from the 1949 Payne-Scott publication fig. 1), we show typical data of an unpolarised burst (her nomenclature, a modern Type III) at 85 MHz and 60 MHz. The simple structure is similar at the two frequencies and the 85 MHz preceded the 60 MHz by about 0.7 seconds. The delay histogram is shown in Fig 14 (her Fig.7) with frequency comparisons: 85 to 60 MHz, 65 to 60 MHz and 60 to 19 MHz (typical delays 9 sec). These more precise results were consistent with the preliminary data obtained by Payne-Scott in August 1946 as shown in Fig. 9 with a comparison between 75 and 60 MHz.

The other type of burst phenomenon (her nomenclature enhanced radiation, modern Type I) is shown in Fig 15 (her fig 3). Payne-Scott (1949) has described the general properties of these events:

Much more rarely [than the unpolarised bursts] quite a different phenomenon occurs. The intensity reaches a high level and remains there for hours or days on end; there are continual fluctuations in intensity, both long-term and short-term. The short term increases are somewhat similar to the bursts described above, but usually have a lower ratio of maximum to background level. This type of radiation will be called "enhanced radiation", adopting the term used by Pawsey. Superimposed on it there may be bursts.

These are not a continuous procession of unpolarised bursts, since the enhanced radiation bursts are circularly polarised as shown in Fig. 15 at 85 MHz (top two panels on 30 August 1948); the lowest panel is at 60 MHz on the same date. This type of burst was seldom observed at 19 MHz.

Payne-Scott interpreted the enhanced bursts (now Type I):

The observations recorded here have shown the existence of two distinct types of radiation from the sun other than the fairly steady thermal level. One of these we refer to as "enhanced radiation" and the other as "unpolarised

bursts". Both are very variable and reach much higher intensities than the thermal level.

Enhanced radiation, rare on the frequencies considered here, lasts for hours or days and is usually associated with the passage of a large spot group. It is normally circularly polarised, suggesting that the magnetic field of the spot group plays a part in its production. This is borne out by its close association with large sunspot groups. The spot field may not normally extend far enough into the corona to give rise to this type of radiation at 19 MHz.

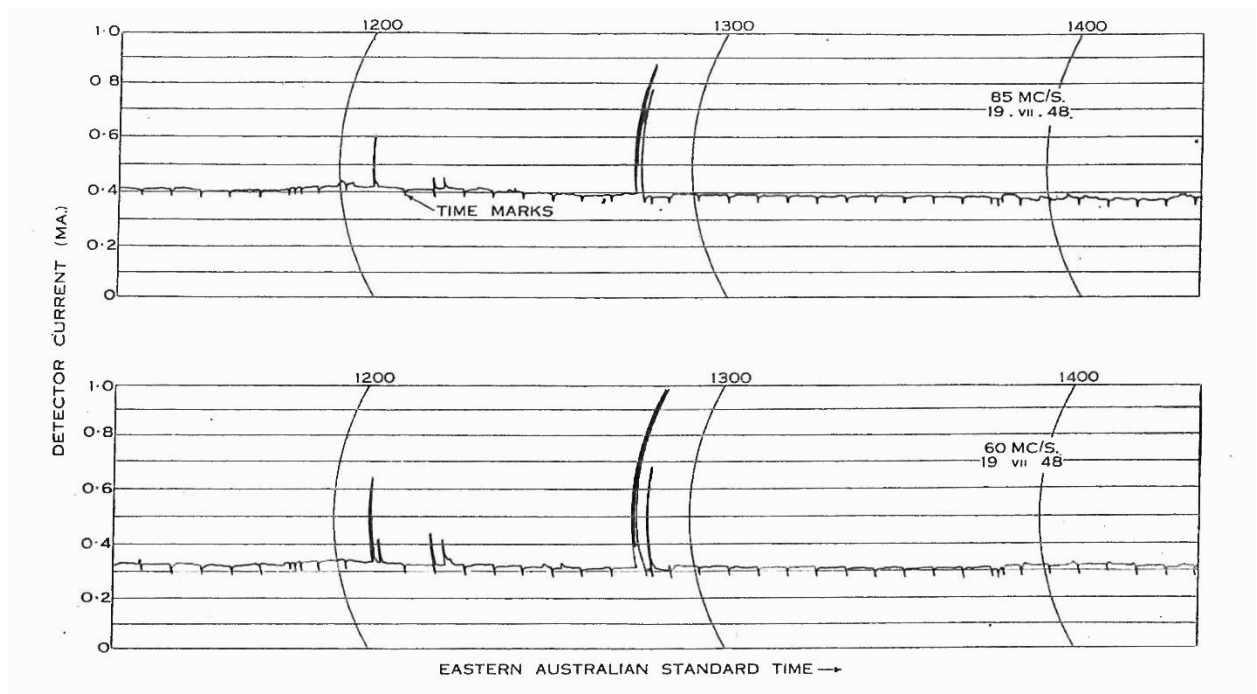


Fig 13 Caption: Hornsby - unpolarised bursts (modern terminology Type III) at 85 MHz on 19 July 1948 (top) and same day at 60 MHz (bottom), the higher frequency arrives about 0.7 sec earlier. Note the simple structure of the bursts. Type III bursts

such as these are the most common burst phenomenon in radio astronomy. During sunspot maximum there are about three bursts per hour, and much less during sunspot minimum. The duration is only a few seconds in contrast to Type II bursts where the duration is minutes. The spectral index of the bursts is non-thermal with the intensity at 60 MHz being typically twice that at 85 MHz. Type II bursts are rare, an approximate rate of only once per 50 hours in sunspot maximum. From Payne-Scott, R. (1949). "The Noise-like Character of Solar Radiation at Metre Wavelengths." *Australian Journal of Scientific Research A Physical Sciences* 2: 228, her Fig. 1, unpolarised bursts.

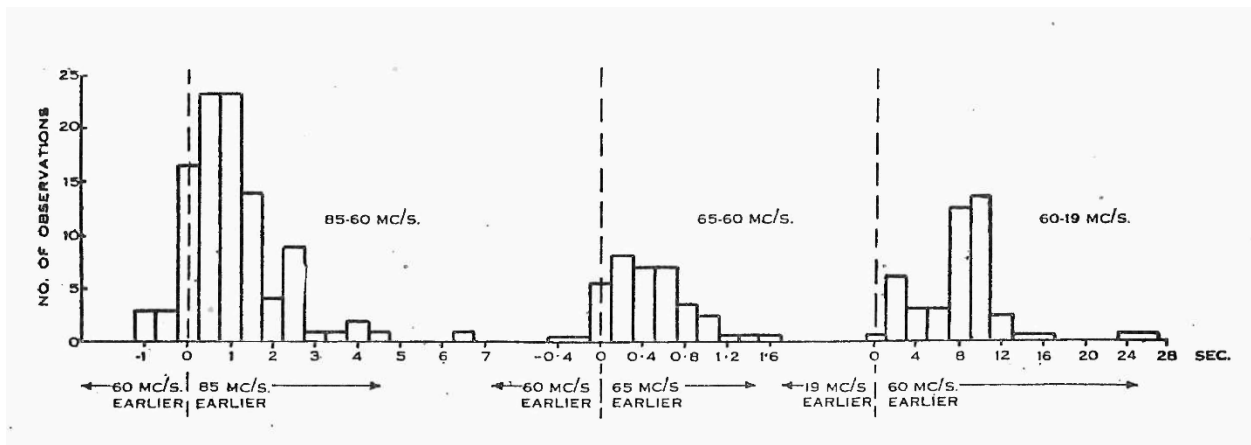


FIG 14 Caption: From Payne-Scott, R. (1949). "The Noise-like Character of Solar Radiation at Metre Wavelengths." *Australian Journal of Scientific Research A Physical Sciences* 2: 228, her Fig. 7. Type III RPS Hornsby arrival times. The comparisons are , left to right, 85 and 60 MHz (median delay 0.7 sec), 65 MHz and 60 MHz (median delay 0.3 sec) and 60 and 19 MHz (median delay 9 sec). See Fig 9 for 75 and 60 MHz delays observed at Dover Heights in 1946.

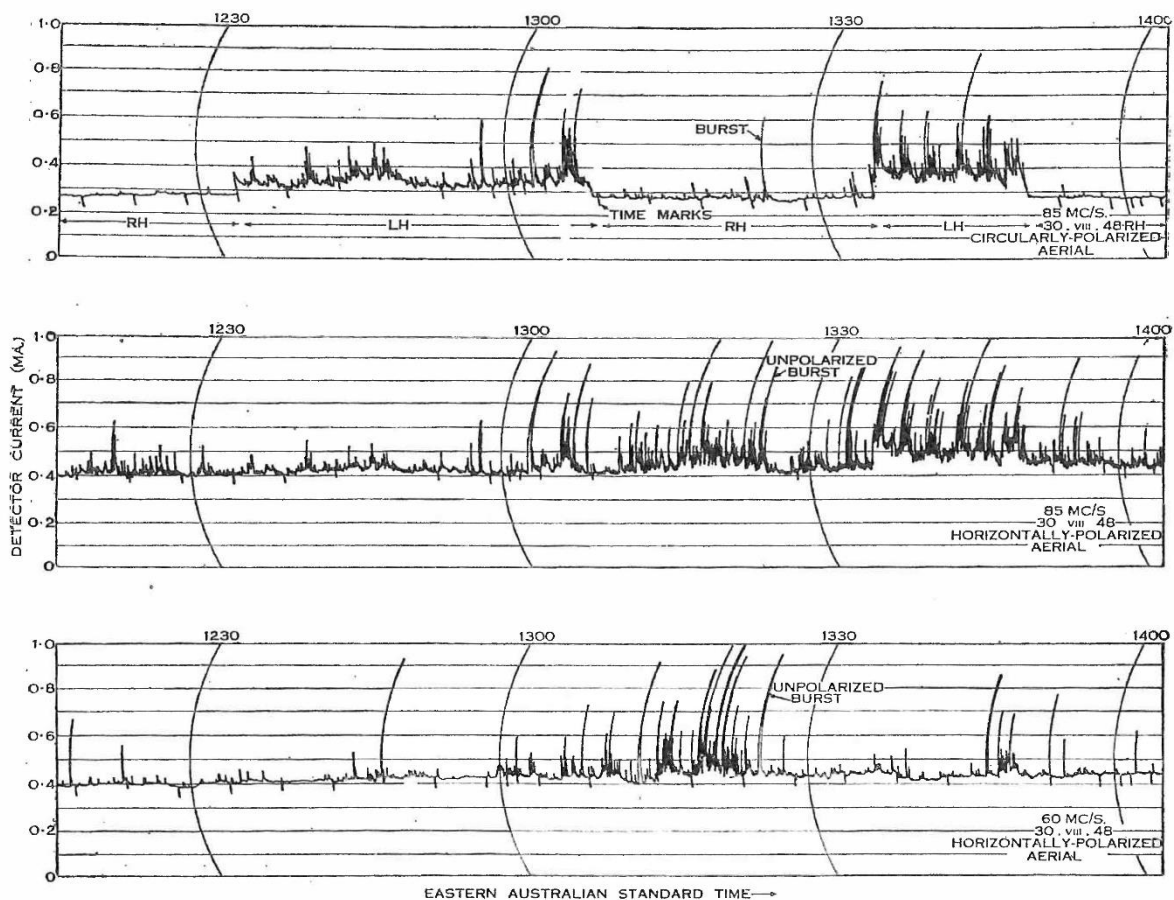


Fig 15 Hornsby Observations of Type I Bursts-enhanced radiation- 30 August 1948. From Payne-Scott, R. (1949). "The Noise-like Character of Solar Radiation at Metre Wavelengths." *Australian Journal of Scientific Research A Physical Sciences* 2: 228,, her Fig. 3.

Payne-Scott did not observe any of the rare Type II bursts, such as had been observed at Dover Heights and Stromlo on 8 March 1947. In Additional Note 4 (**Payne-Scott's failure to observe Type II bursts at Hornsby in 1948**), we summarise this failure to detect minutes of arc delay events at Hornsby. An additional complication for the acceptance of Payne-Scott's conclusions about the seconds of time delays had arisen during Pawsey's visit to the UK in mid- 1948 (see Chapter 17 ). While in the UK, Pawsey had hoped that the Hornsby observations would provide a decisive result about the reality of the time frequency behaviour of both Type II and especially Type III bursts. Two weeks after a meeting of the Royal Astronomical Society in London Pawsey wrote McCready: "People [here in the UK] do not believe the high frequency precedes low." <sup>40</sup>

<sup>40</sup> Goss (2013, *Making Waves*, page 161) for details of the interactions between Pawsey, Ryle and Graham-Smith in 1948. Graham- Smith told Goss in 2008 that he was completely unaware of the

In June 1948, he even proposed a collaboration with the Cavendish group to verify the time-frequency behaviour. But nothing came of these attempts. After Pawsey was back in Sydney, Ryle wrote Pawsey on 23 November 1948, that the Cavendish group had decided to stop work on solar bursts: "We have done nothing further on the subject [time delays], but I think there is much more important work to be done."

The confusion continued when Payne-Scott sent a preprint of her paper on the Hornsby observations to Ryle on 9 December 1948, a month before the paper was submitted to the journal:

You will see that one of the main points is the distinction between variations (bursts) in the circularly polarised "enhanced radiation" and unpolarised bursts. It is the latter that show good correspondence on different frequencies and time-delays. Much of the past confusion originated because no distinction was drawn between the two kinds of short-period variation in solar noise.<sup>41</sup>

No answer to this letter has been located. Payne-Scott had explained to Ryle that the new data provided a solution to the confusion that had been created in the previous year. The seconds delay was only relevant for the unpolarised bursts (Type III) and not the enhanced bursts (Type I – storm bursts).

However, the controversy continued during 1949 and 1950. When Ron Bracewell returned from a three-year visit to complete his PhD at the Cavendish with J.A. Ratcliffe in 1949, he brought back tracings of some of the 175 MHz data from Cambridge, clearly a Type III burst. Ryle wrote Pawsey on 21 March 1950 that "in all probability all the 'bursts'... were caused by light aircraft".<sup>42</sup> Bracewell told Goss in November 1997 that Ryle had claimed in 1949: "These types of bursts do not occur in Cambridge, but any that did were due to aeroplanes, as was known from having a loudspeaker on line."

After facing these stumbling blocks in 1948-1949, Payne-Scott's results stood the test of time. The delays for the Type III bursts were verified by the results of Paul Wild and Lindsay McCready as their new data was obtained at Penrith within the next year, February to June 1949. The impressive series of four papers were published in 1950-1951. With a continuous coverage in frequency from 70 to 130 MHz, the frequency drifts were characterised in detail. The Type III (unpolarised) drifts were consistent with the earlier data of Payne-Scott. Goss (MW, page 164):

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suggestion that he might work on the time frequency versus problem (dynamic spectra) as had been suggested by Pawsey in a letter of 24 June 1948 from the UK to Bowen in Sydney

<sup>41</sup> NAA, C3830, A1/1/1, Part 3

<sup>42</sup> NAA, C3830, A1/1/1, Part 5

The results of this period provided a solid basis for the future of solar noise research at RPL. She was then poised to begin the final stage of her scientific career at Potts Hill with the 100 MHz interferometer, [the first Michelson interferometer in Australia]. For the first time RPL astronomers could observe the solar bursts and outbursts at any time of the day, not just at sunrise. Payne-Scott had clearly shown that Type III bursts [her non-polarised bursts, the “isolated bursts” using the Pawsey nomenclature] showed rapid changes in frequency drift, from high to low frequencies [at a rate of about 20 MHz per second]. Thus, a fast exciter speed for Type III bursts was clearly required; within a few years this was the accepted explanation.

For Payne-Scott, the year had been challenging with adversity, personality conflicts and scientific setbacks; in the end, with the support of Pawsey (from a distance), she had achieved success with a confirmation of the seconds of delays of Type III bursts.

### **The Rotating Lobe interferometer at Potts Hill, Payne-Scott’s Swan Song**

In 1947, as he was preparing to leave for Europe on 25 September, Pawsey had a meeting of the solar noise group at RPL. The idea was to locate the positions of solar bursts. Payne-Scott was to be in charge of the project. The new instrument was to be “capable of yielding interference patterns in a fraction of a second with a view to extending this technique to bursts”.<sup>43</sup> As we have seen, Payne-Scott was quite frustrated that she could not spend more time on this challenging project in 1948 while she struggled to complete the Hornsby observations. This new instrument was to be the first Michelson interferometer at RPL with tracking elements that enabled up to 4 hours of continuous observation, centred at noon. The limited one-hour period at sunrise (with severe problems of refraction) with the sea-cliff interferometer would no longer remain a handicap.

Twenty years later, Paul Wild (Wild, J.P. (1968). “The Exploration of the Sun by Radio”. *The Australian Physicist*, vol 5, p 117) praised the design concept: “Another Pawsey-inspired experiment was put into operation and brilliantly performed by Payne-Scott and [Alec] Little. The idea was to locate... the instantaneous position of the dominant source on the sun at any one time.”

The instrument would be able to sweep across the sun 25 times a second with a resolution of about 40 arc min and a positional accuracy of about 2 arc min. With this

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<sup>43</sup> NAA C3830 B2/2, Part 1. Minutes of the Propagation Committee (in 1948 to be Radio Astronomy Committee) from 23 September 1947.

resolution the quiet sun, with a size of 35 to 40 arc min would be resolved out. This instrument was the first rotating lobe interferometer. In 1955 a sophisticated lobe interferometer was proposed by Brown, Palmer and Thompson.<sup>44</sup> Also, the polarisation state of the emission could be determined at a rate of once per second, again a first in radio astronomy. The data recording of these fast observations was carried out by using a movie camera, only used in the rare occasions, during intense solar activity.

A major constraint was the limited sensitivity of the instrument that was planned. The noise for observations of the sun at the sub-second time scale was about  $10^5$  Jy, only sufficient for the detection of strong solar bursts. For several hour observations (the rotating lobe system turned off) the noise was about  $3 \times 10^3$  Jy. For non-solar observations, Cygnus A (15,000 Jy at 100 MHz) was essentially the only radio source that could be observed.<sup>45</sup>

In the course of 1948, the progress of the construction of the 97 MHz interferometer was rapid (the frequency was moved from 100 MHz to avoid external radio interference), even though the group floundered during 1948 due to the 13-month absence of Pawsey. McCready was not up to the task of moderating conflicts. In a letter from 6 June 1948, he blamed himself for these unresolvable disagreements, mainly between Payne-Scott and Bolton.

By 23 April 1948, the site at Potts Hill Reservoir (Sydney Water Board, see Goss-*Making Waves* page 171) had been chosen for this instrument. The problems of security (mainly vandalism) at the other sites could be avoided since this site was closed to the public. In addition, the travel time from the laboratory at Sydney University was reasonable. Also, by mid-April, Payne-Scott's participation was assured as her responsibilities at Hornsby wound down. McCready wrote Pawsey on 23 April 1948 that she "was tapering off at Hornsby and orienting to [the new interferometer at Potts Hill]".<sup>46</sup>

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<sup>44</sup>Brown, R. Hanbury, H. P. Palmer, and A. R. Thompson. "XCVII. A rotating-lobe interferometer and its application to radio astronomy." *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 46, no. 379 (1955): 857-866.

<sup>45</sup> However, from Australia, Cygnus A was observable in the far north with a maximum elevation of 15 deg. Mills and Thomas carried out successful observations with the Potts Hill interferometer: Mills, B. Y., and Thomas, A. B. (1951). "Observations of the Sources of Radio-Frequency Radiation in the Constellation of Cygnus." *Australian Journal of Scientific Research A Physical Sciences* 4: 158. On 7 July 1949, Mills announced at the Propagation Committee meeting that he was giving up on the Potts Hill 100MHz observations (3m) due to the limited sensitivity.

<sup>46</sup> NAA C3830, C4659/8

By the time of the 22 July 1948 PC meeting, Payne-Scott was in charge of the new instrument. She provided progress reports on the status for the next two-plus years. By 16 August 1948, reports reached Pawsey (MW, page 173) that first “lobes” (fringes) had been obtained by Payne-Scott and Alec Little; serious planning had begun to establish methods to calibrate the new instrument to determine the intensity and positional scales.

As Pawsey returned to Sydney on 29 October 1948, a burst of activity occurred; an increased energy can be sensed in reading the minutes of the newly named Radio Astronomy Group. Three meetings occurred in November as Pawsey was catching up on the activities of the various radio astronomy groups at RPL. He also gave several talks about his impression of North American and European radio astronomy activities.

By 7 March 1949, Payne-Scott reported to the Radio Astronomy Committee that continuous recording with the first two yagis (Fig 16 and 17, former from the publication and the latter from the CRAIA) had begun with successful observations. Systematic observing began in May 1949, continuing until August 1950. The calibration system for amplitude and phase was operational from late June 1949. The third antenna was operational by late August, as reported at a meeting of the newly named Radio Astronomy committee (replacing the old Propagation Committee which had begun at the end of the war). By 17 November 1949, the complete system was operating with three antennas and crossed dipole polarised feeds to determine the state of polarisation every 30 sec. Payne-Scott reported that both noise storms (Type I) and unpolarised bursts (Type III) were being detected.

The final lay-out of the interferometer is shown in Fig 18.

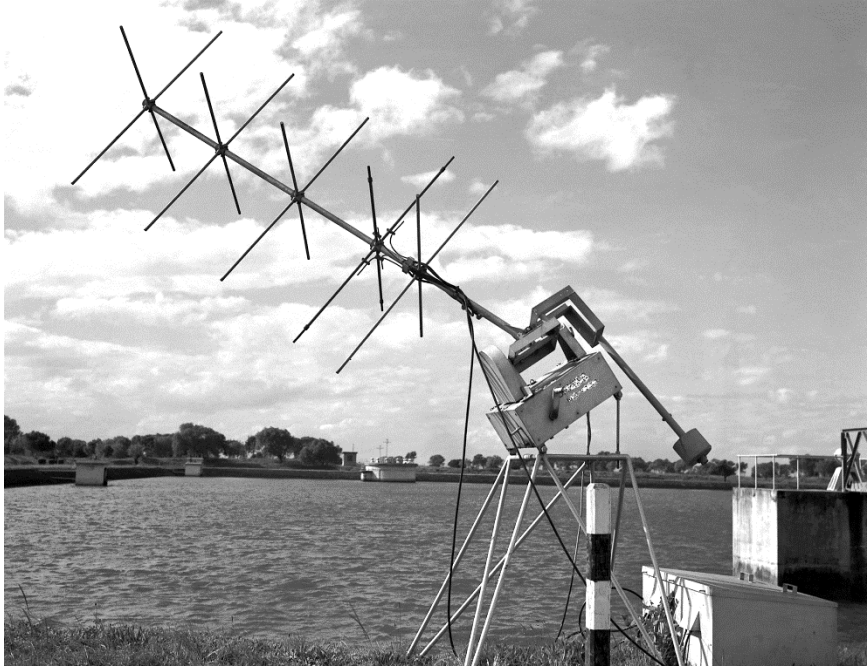


Fig 16. One of the three 97 MHz yagi aerials at the Potts Hill Reservoir, Sydney, a rotating lobe Michelson interferometer used for solar burst observations by Ruby Payne-Scott and Alec Little. See below Paper I (Little and Payne-Scott, 1951). Credit: CSIRO Radio Astronomy Image Archive 2217.



POTT'S HILL INTERFEROMETER SITE LOOKING NORTH-EAST  
PLATE I

Fig 17 Potts Hill showing the location of the 3 aerials, rotating lobe 97 MHz interferometer This figure was not published in the Payne-Scott series of papers from 1950 and 1951 (see below). Credit: CSIRO Radio Astronomy Image Archive 2312.

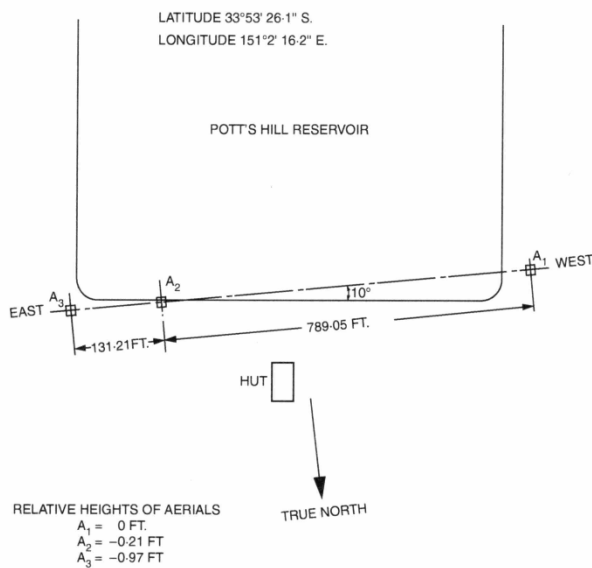


Fig 18 Layout of the interferometer used for the swept-lobe 97 MHz solar instrument at Potts Hill. The lobe spacing for the longest baseline of 280.5m was 38 arcmin. The lobes were swept across the sun 25 times a sec. The circular polarisation state was determined once every second. Little, A. G., and Ruby Payne-Scott. "The position and movement on the solar disk of sources of radiation at a frequency of 97 Mc/s. I. Equipment." *Australian Journal of Chemistry* 4, no. 4 (1951): 489-507, their Figure 3.

The results of the campaign from May 1949 to August 1950 were all published in the *Australian Journal of Scientific Research*:

- (1) Little, A. G., and Payne-Scott, R. (1951). "The Position and Movement on the Solar Disk of Sources of Radiation at a Frequency of 97 Mc/s. I. Equipment." *Australian Journal of Scientific Research A Physical Sciences* 4: 489.
- (2) Payne-Scott, R., and Little, A. G. (1951). "The Position and Movement on the Solar Disk of Sources of Radiation at a Frequency of 97 Mc/s. II. Noise Storms." *Australian Journal of Scientific Research A Physical Sciences* 4: 508.
- (3) Payne-Scott, R., and Little, A. G. (1952). "The Position and Movement on the Solar Disk of Sources of Radiation at a Frequency of 97 Mc/s. III. Outbursts." *Australian Journal of Scientific Research A Physical Sciences* 5: 32.

A number of important results were presented in Papers II and III.

The main result in paper II (Type I noise storms) is shown in Fig 19, displaying the difference between the position of the radio bursts and the associated sunspot. Goss (MW page182):

Payne-Scott and Little determined in an elegant fashion (the reduction of these records from the movie must have taken Payne-Scott many hours of tedious work) that the Type I continuum originated high in the corona over large sunspots. By locating the position of the source of radio emission for these six storms of long duration over periods of 10-16 days, Payne-Scott and Little could show that the angular rate of change of position for the radio bursts was faster than that of the optical sunspots (Fig. 19). If the assumption was made that the source of the noise-storm lay at some height above the visible surface of the sun (near the position where the plasma frequency was 97 MHz) and that the noise storm was radially displaced above the relevant spot group, it was then possible to calculate the radial displacement of the two. For most of the observations, this displacement was found to be 0.3-0.4 radii above the sun's visible surface. For the storms starting 10 Feb 1950 and 10 June 1950, the displacement was found to be 0.8-1 solar radii. The disagreements with theory for the location of the plasma frequency (the "turning points") were attributed to the suggestion that the expected values

for the coronal electron density might well be roughly a factor of two larger in these periods, at least near solar maximum.

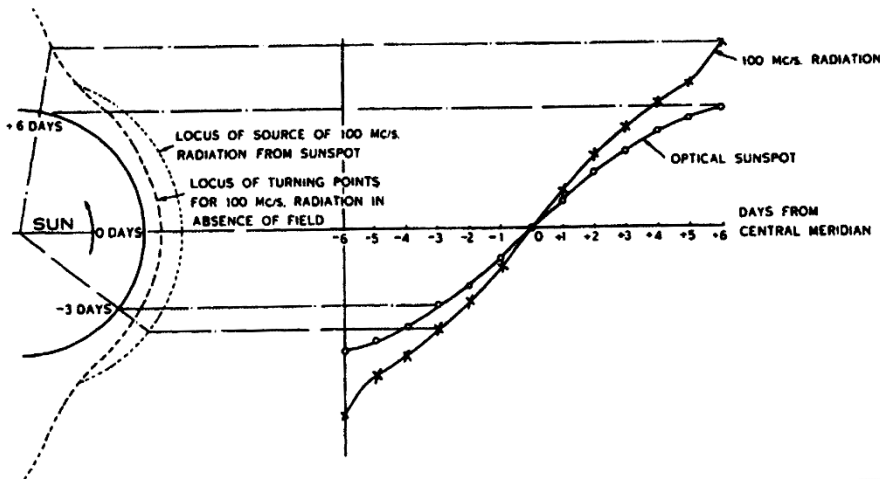


Fig 19 The relation between the motions of the 97 MHz Type I solar storms and the associated sunspot group over a solar rotation proved that the radio emission arose high in the corona; the observed range was 0.3–1 times the photospheric radius above the sun's visible surface. This deduction is one of the more important conclusions of the collaboration of Payne-Scott and Little, Paper II. Payne-Scott, R., and Little, A. G. (1951). "The Position and Movement on the Solar Disk of Sources of Radiation at a Frequency of 97 Mc/s. II. Noise Storms." *Australian Journal of Scientific Research A Physical Sciences* 4: 508, their Fig. 8.

Three additional conclusions were discussed by Payne-Scott and Little in Paper II.

1. The correlation between sunspots and the radio intensity of these noise storms was between the **size** of the largest sunspot in the group, not the size of the entire group of sunspots. Since the close connection between the size of a sunspot and its magnetic field was recognised at this time, the direct association of Type I bursts and the presence of a strong solar magnetic field was suggested.

2. The direction of the sense of the circular polarisation (which tended to be essentially either LH or RH polarised) was found to depend on the magnetic polarity of the associated spot as determined by optical Zeeman observations. The radio burst was LH when the largest spot was a north-seeing pole (positive polarity) and vice versa (positive towards the observer). The authors wrote: "The observations quoted here point to magnetic fields as the important factor in the production of solar noise storms at a frequency of 97 MHz."
3. The observed brightness temperatures were only lower limits since the angular sizes were unknown; the upper limits on the angular sizes were typically 6 to 8 arc min. The brightness temperatures were thus in excess of  $10^8$  to  $10^{11}$ K. Based on the burst duration of only seconds, Payne-Scott and Little concluded that a simple thermal origin was not likely and that "enhanced radiation [noise storms] probably originates as coherent radiation from groups of charged particles". Kai, K., Melrose, D. B. and Suzuki, S. in "Solar Radio Physics", ed. DJ McLean, NR Labrum, Cambridge University Press, 1985, page 417) wrote:

Although Type I storms have been extensively studied for more than 30 years, it is only in recent times that any convincing theories have been advanced to explain their occurrence. It is now generally accepted that Type I bursts must be some form of fundamental frequency plasma emission; this hypothesis explains important observed characteristics of Type I storms..., notably the high brightness temperature and strong ordinary mode polarisation.

The final paper described the motion of outbursts. Payne-Scott and Little assumed that these were the conventional Type II bursts (minutes delay); in fact, as we will point out below, they were Type IVM (moving Type IV events). Paul Wild (Wild, J.P. (1968). "The Exploration of the Sun by Radio". *The Australian Physicist*, vol 5, p 117) has provided a solution to this misinterpretation:

A number of outbursts [six cases in 1949- 1950] were recorded [by Payne-Scott and Little] with this technique and in several cases, it was found that when the disturbance took place near the limb of the sun the centre of the source moved out, sometimes to a position far beyond the normal limb. At first sight this seemed merely to support the evidence on Type II bursts, but two things were wrong: firstly, the movement took place rather late in the life of the disturbance

– corresponding to the second, less violent in [the outburst], and secondly, when one thought about it, no movement should really take place at all, for according to the plasma hypothesis only one level of the corona should be seen to radiate at any one frequency.<sup>47</sup> [Fig 20 shows a sketch of the plasma hypothesis<sup>48</sup>] Further, examples were subsequently observed in France by Boischoat and Denisse [1957, vol 245, p. 2149), who recognised them as belonging to a distinct class of event which they called a Type IV<sup>49</sup> burst and which characteristically followed on the heels of the Type II [thus usually appearing more distant from the site of the flare]. They suggested, furthermore, that the radiation mechanism of the type IV burst could not be one of plasma oscillation, since the sources move out far beyond the plasma level; instead they proposed that the emission was due to synchrotron radiation from high-energy electrons [0.1 to 1 Mev] moving in the solar magnetic field.

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<sup>47</sup> Stewart (2009) has defined the “plasma hypothesis”: “[Based on the observed frequencies of the leading edges of Type II and III bursts these could be] converted to radial heights by using a standard coronal density model and by assuming that the radio emission occurred at the fundamental plasma frequency.”

<sup>48</sup> Sheridan, K. V. (1963). "Techniques for the investigation of solar radio bursts at metre wavelengths." *Proceedings of the Institution of Radio Engineers Australia* 24: 174-184

<sup>49</sup> Wild et al (Wild, J. P., Smerd, S. F., & Weiss, A. A. (1963). Solar bursts. *Annual Review of Astronomy and Astrophysics*, 1, 306). “Type IV events are relatively rare in the metre-wave spectrum. They last for hours or days, start late in the lifetime of large flares, and are almost always preceded by a Type II burst. About 20 per cent of all Type II bursts are followed by Type IV continuum.” Stewart, R. T. (1985) ("Solar radiophysics." CSIRO publications) noted that from 1966 to 1980 only 56 Type IVM bursts were recorded with the Culgoora radioheliograph. During this period the Culgoora radiospectrograph observed 560 Type II-Type V bursts.] The delay of the start of the continuum after the start of the Type II burst ranges from zero (or perhaps even slight negative values) to about 30 min, with an average delay of about 10 min.”

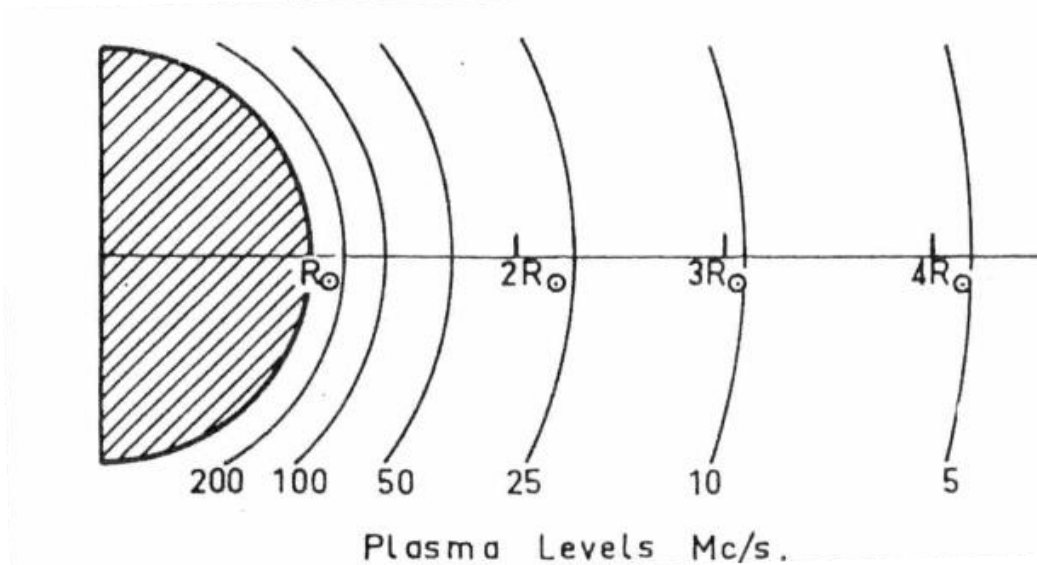


Fig 20 caption. The fundamental frequency of the radio emission associated with plasma oscillations in the solar corona varies with distance from the photosphere. Credit: Sheridan, K. V. (1963). "Techniques for the investigation of solar radio bursts at metre wavelengths." *Proceedings of the Institution of Radio Engineers Australia* 24: 174, his fig. 2.

These events in 1950 were incorrectly identified as Type II bursts on the basis that the measured source velocity was similar to that derive for Type II sources from the spectral observations of Wild in 1950 (Wild, J. P. (1950). "Observations of the Spectrum of High-Intensity Solar Radiation at Metre Wavelengths. II. Outbursts." *Australian Journal of Scientific Research A Physical Sciences* 3: 399).

Epilogue: In 2011, Ron Stewart and colleagues<sup>50</sup> discussed the circumstances of the Payne-Scott and Little observations of 1949-1950 of the Type IVM outbursts at Potts Hill. Ron Stewart had joined RPL in 1965; in 1973, he and colleagues carried out extensive observations of Type IVM bursts at Culgoora (e.g. Stewart et al. *Solar Physics*, vol 36, p. 203 and 219- two publications).

Stewart et al wrote:

[For the event of 17 February 1950] Payne-Scott and Little (1952) used the Potts Hill Swept-lobe Interferometer to observe what was probably the first [actually the second case; earlier observations of a Type IVM were made on 5 September 1949] recorded moving Type IV burst. This was another

<sup>50</sup> Stewart, Wendt, Orchiston and Slee, 2011, "A Retrospective View of Australian Solar Radio Astronomy 1945-1960" in *Highlighting the History of Astronomy in the Asia- Pacific Region* p 613

example of **reverse serendipity**<sup>51</sup>. [our emphasis] The radiospectrograph operations at Penrith had ceased at the end of 1949 and only recommenced in 1951 at Dapto with improved equipment. Consequently, Payne-Scott and Little had no spectral observations to help them distinguish between the different types of outbursts such as the Type II and the [newly determined] Type IV. From their polarisation and positional measurement (Fig 21) we can now say with the advantage of hindsight that what they observed was a polarised moving Type IV burst. Had they realised this they would have been credited with the discovery of spectral Type IV bursts some 7 years before Boischoat [had observed that this type of burst moved with comparable velocities as Type II bursts that preceded them, but to even greater heights above the solar surface of 3 or 4 solar radii].

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<sup>51</sup> These authors invented a new phrase “reverse serendipity”. A more common antonym for serendipity might be either “vicissitude” or “ill-fated”.

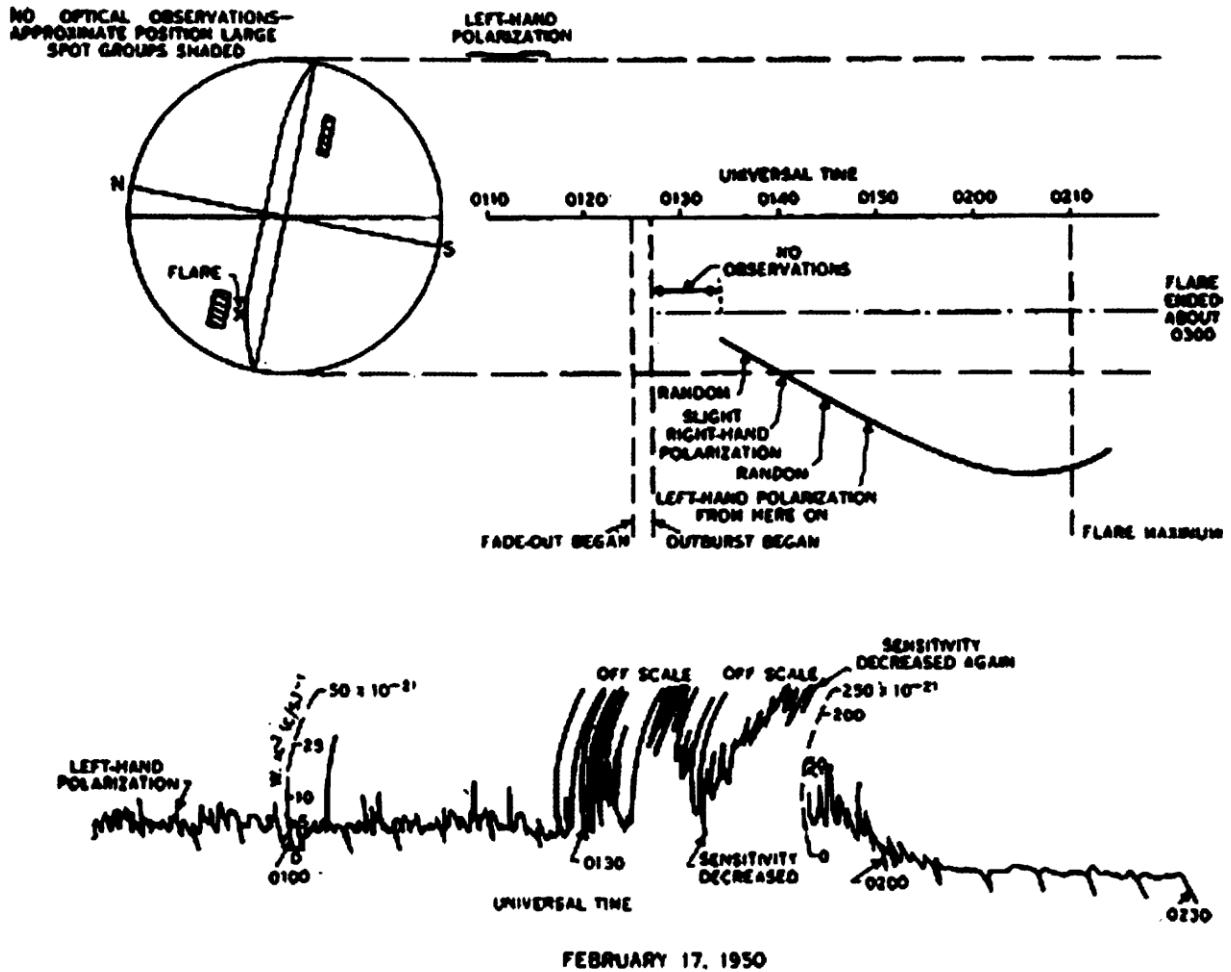


Fig 21 from Payne-Scott, R., and Little, A. G. (1951). "The Position and Movement on the Solar Disk of Sources of Radiation at a Frequency of 97 Mc/s. II. Noise Storms." *Australian Journal of Scientific Research A Physical Sciences* 4: 508.. The dramatic outburst showed that the solar emission position moved a projected distance of a solar radius in a time span of only 30 min. A prominent flare began a few minutes before the radio observations began. Fig 1b in the original publication.

The total power shown in the bottom panel of Fig 21 was obtained with a single Yagi 98 MHz aerial at Potts Hill. Pawsey is shown with this aerial in Fig 22 in a staged Fritz Goro photo at Potts Hill from March 1951 (also shown as Fig 16.1 in the main book; see Additional Note No 1 in NRAO ONLINE 23).



Fig 22 Fritz Goro image from March 1951 of Pawsey with the total power 98 MHz aerial at Potts Hill. The EW arm of the grating array is seen in the distance on the south end of the reservoir at Potts Hill. See Additional Note No 1 in NRAO ONLINE 23 ("Fritz Goro, Life Magazine Photographer at Potts Hill, Dover Heights, Mt. Stromlo and Harvard University, 1951. Photographs of RPL, ANU and Harvard Scientists.") Credit: Getty Images, Fritz Goro, The Life Picture Collection, licensed by Getty November 2021 / Licence organised by Shutterstock, Inc., New York, NY (5 Nov 2021) Original , Premium Editorial All Media

## **Paul Wild, Success at Penrith 1949-1950, Classification Type I, Type II and Type III Bursts<sup>52</sup>**

In 1987 Paul Wild described the dramatic results of 1949, his first experience as a radio astronomer<sup>53</sup> as he observed the sun with a dynamic spectrograph (frequency versus time, a spectrum from 70 to 130 MHz every 0.3 sec):

By February 1949, Bill Rowe<sup>54</sup> and I had established a makeshift field station on a cattle stud farm near Penrith railroad station to which we travelled each day by train. We observed the sun by pointing the rhombic aerial [beam size 25 deg] towards it with the aid of a pole, ropes and a winch, adjusting it every 20 minutes. Inside of the darkened "laboratory" (ex-army trailer) we took 20 minute turns to watch the display for solar bursts to turn on (originally to wind by hand!) the movie camera. Sometimes weeks would go by with nothing happening; at other times the bursts came copiously. We recorded for just four months, March-June 1949 [a year after Payne-Scott had observed for nine months at Hornsby], then closed down the field station and I buried myself in a darkened room [where the films could be viewed] to analyse the results.

From this study three characteristic types of bursts emerged, and classification, Types I, II and III remain to this day the international standard. Of special interest were the Type II bursts [five in total] which showed a gradual downward drift in frequency. These corresponded to disturbances moving out through the solar corona at speeds of order 1000 km/s, just the right kind of speed to account for the time delay between solar flares and terrestrial aurorae. And the Type III bursts which showed a rapid downward drift in frequency. After eliminating other hypotheses, we were left only with the interpretation that these also were outward moving disturbances, but at a much greater speed than the Type II's, 100,000 km/s or one-third the velocity of light. Few people believed in such an unheard-of-phenomena, until 20 years later they were detected directly by spacecraft. Thus, began a new line of investigation which proved a great stimulus for the evolving science of plasma physics and solar-terrestrial physics, as well as solar physics.

Wild's classification became the standard, still used today. He pointed out that if the radio emission occurred at the plasma frequency, then the frequency/time plots could be interpreted

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<sup>52</sup> The classification scheme that has become the standard today was the Type I, II and III system proposed by Wild and McCready in 1950. Christiansen (1984) has pointed out that before 1950, the classification had been the system suggested by C.W. Allen: "outburst"- associated with solar flares -and the "noise-storm", a longer-lived phenomenon associated with large sunspot groups. To this, Pawsey had added a third type, the "isolated burst". These became later Type II, Type I and Type III respectively following the Wild and McCready classification scheme of 1950 (below).

<sup>53</sup> Wild, J. P. (1987). "The beginnings of radio astronomy in Australia." *Publications of the Astronomical Society of Australia* 7, no. 1: 95-102.

<sup>54</sup> Surprisingly, Wild does not mention John Murray who designed and constructed the display system.

as height in the corona versus time. Thus, it would provide an estimate of the velocity as the source moved from regions of high density (highest frequency) in the corona outwards to regions of lower density in the far outer corona (the lowest frequency). In each region of the corona a broad band of frequencies would be emitted; only those frequencies that were higher than the critical frequency would escape. Stewart et al (2011) have pointed out that Wild referred to this mechanism as “the plasma hypothesis”. Thus his observations referred to a snapshot of activity every 1/3 second from the lower corona to the outer regions at heights of about three solar radii. For the speeds to be calculated a model of the density versus height in the corona was required.

Wild and McCready<sup>55</sup> submitted the paper on 10 March 1950 (paper I. “The Apparatus and Spectral Types of Solar Bursts Observed” in the series of “Observations of the Spectrum of High-Intensity Solar Radiation”), published in the September 1950 issue of the *Australian J of Scientific Research*, vol 3, p 387.

Paper I: “The Apparatus and Spectral Types of Solar Burst Observed” provided the details of the instrument (70 to 130 MHz) with descriptions of the calibration and display systems. The method was described by Wild and McCready: “To analyse the spectrum of a swiftly changing phenomena an instrument is required which registers the spectrum sufficiently often to allow the structure of the most rapid of the variations to be recorded.”

The sensitivity of the simple instrument was modest  $5 \times 10^5$  Jy. This limit was 50 times the coronal thermal emission at a wavelength of 3 meters (about  $10^4$ Jy).

In addition, the galactic background ( $10^4$  to  $10^5$ Jy) was not detectable. However, this sensitivity was quite sufficient to detect Type I, II and III bursts. The authors provided example spectra of the three types of bursts that had been observed. In Fig 23 (a,b,c and d, the sample spectra (I, II

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<sup>55</sup> Wild and McCready were joint authors. The references are: (1) Wild, J. P., and McCready, L. L. (1950). "Observations of the Spectrum of High-Intensity Solar Radiation at Metre Wavelengths. I. The Apparatus and Spectral Types of Solar Burst Observed." *Australian Journal of Scientific Research A Physical Sciences* 3: 387, (2) Wild, J. P. (1950). "Observations of the Spectrum of High-Intensity Solar Radiation at Metre Wavelengths. II. Outbursts." *Australian Journal of Scientific Research A Physical Sciences* 3: 399, (3) Wild, J. P. (1950b). "Observations of the Spectrum of High-Intensity Solar Radiation at Metre Wavelengths. III. Isolated Bursts." *Australian Journal of Scientific Research A Physical Sciences* 3: 541 and (4) Wild, J. P. (1951). "Observations of the spectrum of high-intensity solar radiation at metre wavelengths. IV. Enhanced radiation." *Australian Journal of Scientific Research A Physical Sciences* 4:36.

and III) are shown. Over a period from February to June, 1950 they accumulated 264 hours of data. The cine camera was turned on only during periods of high solar activity.

The common Type I bursts (enhanced radiation) showed no frequency drifts for these events with bandwidths of a few MHz as illustrated in Fig 21 a, top left-hand panel.

“Paper II: Outbursts”, later Type II: The most spectacular events were the rare Type II bursts; five of these were observed, with three associated with large solar flares or sudden short-wave communication fade-out. In Fig 23 b, the right-hand panel shows the radio event associated with the optical flare of 27 June 1949. No association of this type of coincidence was found for the other types of events (Type I or III). “This result indicates that outbursts conform... to a distinct spectral type and can therefore be recognised at once from a record of the spectrum.” This was an example of the massive solar event of 8 March 1947 observed by Payne-Scott et al at Dover Heights and Mt Stromlo at discrete frequencies. The figure of 23b shows a continuous slow-moving feature which begins at 70 MHz and ends 200 sec later at 120 MHz, moving 0.25 MHz per sec to lower frequencies

In the conclusion to paper II, Wild was cautious, but prescient:

In conclusion, it should be remarked that only one interpretation of the observed outburst spectra has been examined.... If this interpretation is right, or if, in general, we can associate the wave frequency of certain spectral features with the locality of disturbances in the solar atmosphere, then the study of outburst spectra seems likely to offer data of considerable value to solar research.

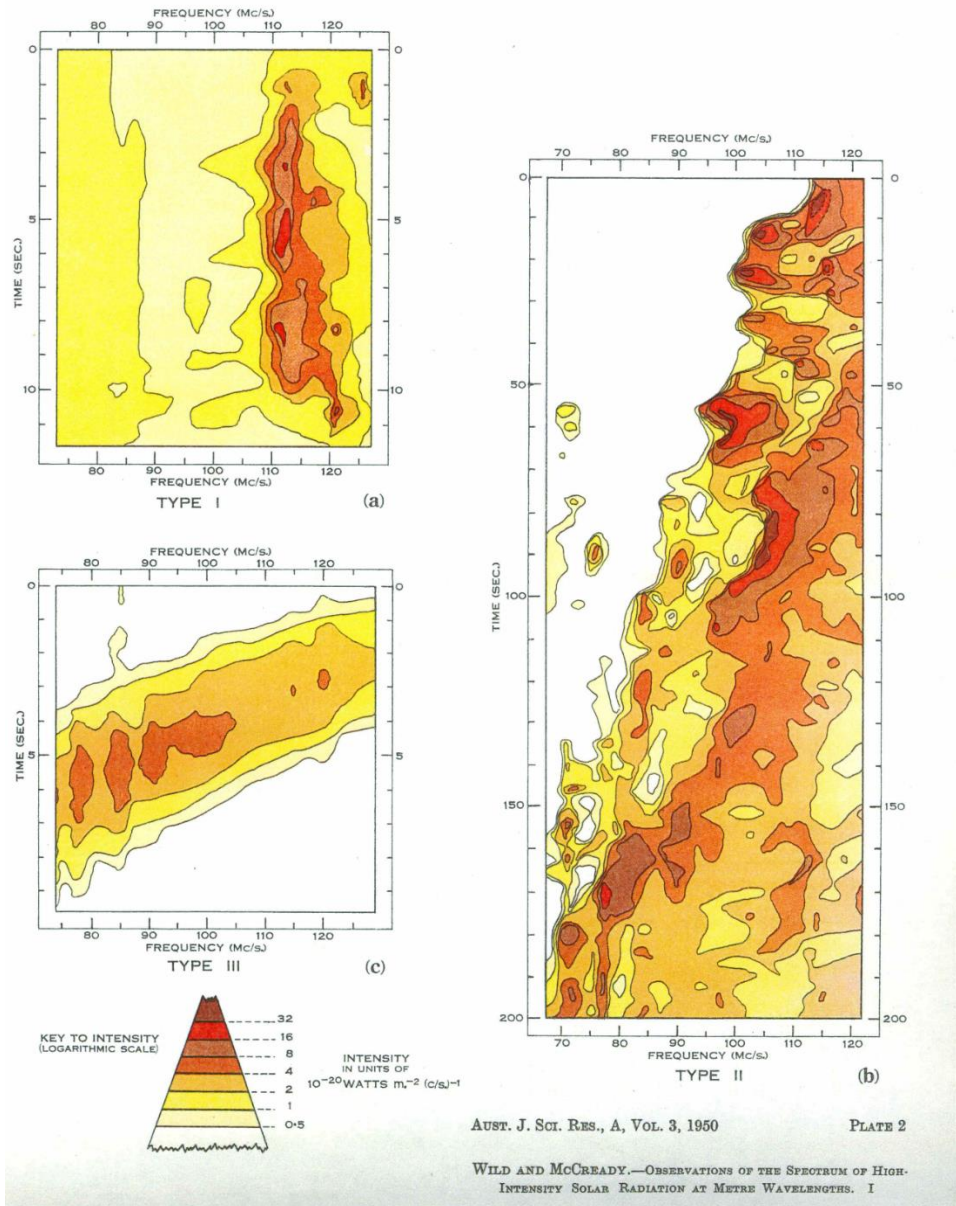
“Paper III: Isolated Bursts”, later Type III or in Payne-Scott’s nomenclature “Unpolarised Bursts”: These bursts lasted only a few seconds with bandwidths of 10 MHz (Fig.23 c). They occurred much more frequently than the Type II bursts. Wild wrote: “They occur sporadically, often in small groups; many hours sometimes elapse between successive bursts.” The surprising aspect was the rapid frequency drift to lower frequencies, almost 100 times faster than the Type II, about 20 MHz/sec. In the 264 hours of observing in 1949, 32 of these isolated bursts were observed. The 31 May 1949 event is shown in Fig 23 c, bottom left panel.

Sullivan (2009) provides a succinct description of the resolution of the dilemma facing Wild concerning the Type III bursts. The implied velocities were relativistic (about  $10^5$ km/s), velocities with no known optical counterpart. Sullivan (2009, p 305):

But although these Type IIIs were no less a distinct class than Types I and II, their origin was more puzzling since there were no known optical solar phenomena with which they correlated - the radio data were on their own. Payne-Scott (1949) had found that Jaeger and Westfold's (1949) theory of different frequencies propagating at different speeds.... seemed to work well, so Wild set out to test it against his more detailed observations. He found the theory wanting because of one test, namely the slight curvature of the

"ridge lines" along the bursts.... Wild argued that the theory was unacceptable because in all cases it predicted a degree of curvature much larger than the slight amount observed. Instead, he liked the same scheme as for the Type II bursts, namely an outward-moving disturbance somehow setting off radio waves at the local critical frequency of each level. Now, however, the much greater rate of frequency drift in the Type III bursts implied that the disturbance was moving at speeds ranging from 20,000 to 100,000 km s<sup>-1</sup>, the latter being one-third of the speed of light. Nothing had ever been observed to move on the sun at faster than ~1000 km s<sup>-1</sup> and this interpretation inevitably met with considerable scepticism. Wild himself was uncertain, but pointed out that ionized material moving at such speeds might well give no optical emission at all, and that even here on earth lightning flashes created such fast particles. Finally, he noted that these speeds all depended on a "normal" fall-off of electron density with height in the corona; if there existed regions with substantially higher densities and density gradients, deduced speeds would be reduced.

Wild's supposition has survived the test of time. The relativistic velocities would be directly confirmed. in a few years.



AUST. J. SCI. RES., A, VOL. 3, 1950

PLATE 2

WILD AND MCCREADY.—OBSERVATIONS OF THE SPECTRUM OF HIGH-INTENSITY SOLAR RADIATION AT METRE WAVELENGTHS. I

Fig 23 From The three types of solar bursts with their characteristic dynamic spectra, frequency (x axis) versus time (y axis). Type I, II and III bursts are shown in Fig 23 a, b and c. The x axis is frequency from 70 to 130 MHz, the y axis runs from 0 to 9 sec for Type I, 0 to 200 sec for Type II and 0 to 9 sec for Type III. Credit: Wild, J. P., and McCready, L. L. (1950). "Observations of the Spectrum of High-Intensity Solar Radiation at Metre Wavelengths. I. The Apparatus and Spectral Types of Solar Burst Observed." *Australian Journal of Scientific Research A Physical Sciences* 3: 387.

## TYPE I – Wild

The majority of the bursts were the Type I bursts. The characteristics of this prominent burst type are complex. The sources were associated with sunspots (McCready et al 1947) and were typically one-hundred percent circular polarised. Wild (Wild, J. P. (1951). "Observations of the Spectrum of High-Intensity Solar Radiation at Metre Wavelengths. IV. Enhanced Radiation." *Australian Journal of Scientific Research A Physical Sciences* 4: 36) described the phenomenon as follows:

Between February and June 1949 the solar spectrum in the frequency range 70 to 130 MHz was observed for many hours during noise storms. ...When severe noise storms were in progress, the spectrum showed a high steady level which usually extended over the whole frequency range, rarely showing any steep variations of intensity with frequency. Above this "background continuum" short-lived bursts occurred, sometimes many per minute... The spectrum of the bursts nearly always showed two features. Firstly, the spectrum at any instant was narrow, typically about 4 MHz between points of quarter-maximum intensity. (This narrow bandwidth is consistent with reports by Ryle and Vonberg (1948) and Payne-Scott, Yabsley, and Bolton (1947) of a lack of coincidences between bursts observed at different frequencies.) Secondly, the mid-frequency of a burst remained approximately constant throughout its lifetime.... Sometimes the rise and fall of bursts were extremely rapid--much more rapid than those observed in "outbursts" [Type II] and "isolated bursts" [Type III] ; occasionally the intensity changed by a factor of the order of a hundred in a period of one-third of a second.

The entire phenomenon was called "enhanced radiation" (by Pawsey), consisting of two discrete components, the relatively steady background continuum and the narrow band noise bursts. A typical intensity of the background continuum was  $5 \times 10^5$  to  $10^6$  Jy compared to the quiet sun (the corona,  $10^4$  Jy at 100 MHz). The noise bursts on top of the background continuum were in excess of  $5 \times 10^6$  Jy and in one case (associated with a solar flare, on 10 May 1949) the intensity at 125 MHz was in excess of  $3 \times 10^7$  Jy. A typical Type I noise burst is shown in Fig 24 (Kai, K., Melrose, D. B. and Suzuki, S. in "Solar Radio Physics", ed. DJ McLean, NR Labrum, Cambridge University Press, 1985.). The narrow frequency range imply that noise storms are not detected with discrete frequency radiometers. To study these events properly a radiospectrograph is required. A strong relation between Type I storms and Type III strongly suggested a common disturbance.

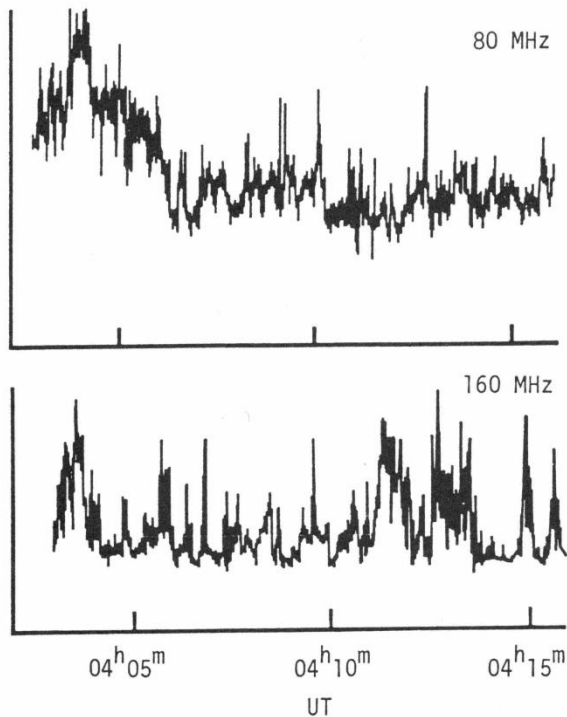


Fig 24 Typical type I bursts as observed at Cugloora at 80 MHz and 160 MHz. Note the dissimilar nature of the burst series over a 12 min time interval. Credit: Kai, K., Melrose, D. B. and Suzuki, S. in "Solar Radio Physics", ed. DJ McLean, NR Labrum, Cambridge University Press, 1985, page 415.

A controversial issue has existed for many years as to whether the background continuum could be just the superposition of a large number of small Type I bursts or a physically distinct component. Wild, Smerd and Weiss (1963. Solar bursts. *Annual Review of Astronomy and Astrophysics*, vol 1, p. 310):

At 200 MHz the scatter in position of bursts belonging to a single storm centre is the same as the extension of the source of continuum. Whether the continuum is a superposition of many bursts or is a distinct though related phenomenon is unresolved, but statistical studies of burst occurrence, and occasional differences in polarization between bursts and continuum, favour the latter [the distinct] possibility.

However, Stephen M. White, a solar radio astronomer (Air Force Research Laboratory, Space Vehicles Directorate, Albuquerque, New Mexico, USA) has shown us data from the LWA (Long Wavelength Array in central New Mexico, a project of the University of New Mexico and collaborators) on 13 January 2013 that shows remarkable series of Type I and III bursts at high time resolution in the frequency range 30 to 85 MHz. The clear narrow band Type I bursts

appear to consist entirely of discrete short (time resolution, 20 msec) bursts, suggesting that the so-called Type I continuum is made up of discrete short-lived events. This possible solution to the dilemma has and will require observations of noise storms at high time resolution. The question remains open.

### **Dapto (1952-1964)**

After the success of Paul Wild and colleagues in February to June 1949, the Radiophysics Laboratory began looking for a new site: "The Penrith site closed after only a half year's observations due to the prominent manmade interference, including a prominent FM station in north Sydney" (Stewart, 2009, PhD thesis, James Cook University, page 59).

A new site was found in January 1951. It was part of McLeod's dairy farm at Dapto, about 50 miles south of Sydney, close to Wollongong, NSW. The intervening Mt Kembla range provided some help from radio interference from Sydney. Later, Wollongong TV stations became troublesome in the 140 to 240 MHz band.

The three aerial system is shown in Fig 25. The order of the aerials was (from the left) 40 to 75 MHz, 75 to 140, and 140 to 240 MHz.<sup>56</sup> Each aerial was equatorially mounted and thus could be driven remotely to track the sun. The frequency range was tracked at a high speed and a complete spectrum was obtained in 0.38 sec with two complete spectra per second. The bandwidth was 0.5 MHz with a time constant of 0.001 sec.

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<sup>56</sup> In later years, the frequencies were extended to lower frequencies: in 1958, 24 to 40 MHz; 1960, 12 to 25 MHz; and finally in 1961, 5 to 15 MHz. In 1963, a 30 foot paraboloid was added with 200 to 2000 MHz. The station closed in 1964.



Fig. 25 The epoch of the photo is likely from the era 1958 to 1960- the initial three elements of the dynamic spectra instrument – from left 40 to 75 MHz, 75 to 140 MHz and 140 to 240 MHz. Credit: CSIRO Radio Astronomy Image Archive R12429-1 (1980).

Paul Wild realised at this time that a wider frequency range was required with greater sensitivity and a better display system. Steve Smerd told Woody Sullivan in 1978, (CN, page 306) that:

Wild had a tremendous emphasis on the need for a real-time display, so that one could actually see the solar event and have the excitement of watching it [in real time]... Later more refined analysis was of course important, but Paul realised that the immediate results were important so that one didn't accumulate miles and miles of film and never get anything out of it. ... The "cream skimming" basic discoveries came right during the observations.

In these pre-online computer days, a dual recorder system was used, one with a 36 times higher density, thus avoiding the "miles of film" problem, Fig 26 (Wild, Murray and Rowe, 1954). The system of the left in the figure was the "A type" display used at Penrith, frequency on the x axis and intensity on the y axis. The improved system on the right hand side in the figure was developed by John Murray, with a higher density or slower rate of film movement (in inch per minute) using a high dynamic range film with a logarithmic display and a dynamic range of 1000 to 1. Since the response of the film was approximately logarithmic, it was possible to record intensities of appreciably different magnitudes (the flux density scale was  $5 \times 10^5$  to  $3.2 \times 10^7$  Jy). The small size of the trace enabled successive traces (0.375 sec) to be stacked with 120 traces per inch. The display was also visible in real time as shown in Fig.27 with Paul Wild to the left and John Murray to the right, foreground – from the CRAIA 2844-4. This display form was more efficient and could be examined easily in real-time.

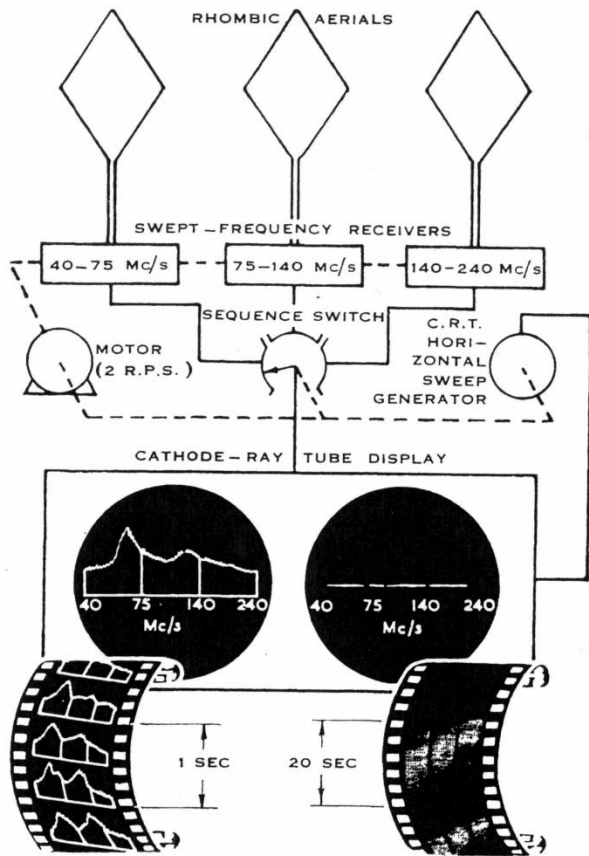


Fig. 1.—Simplified block diagram of the 40–240 Mc/s spectroscope.

Fig 26 Simplified block diagram of the 40 to 240 MHz spectroscope. Credit: Wild, Murray and Rowe in 1954 *Australian J Physics* vol 7, 439 "Harmonics in the Spectra of Solar Radio Disturbances"



Fig 27Dapto spectrograph receiver, Paul Wild to the left and John Murray to the right. Credit: CSIRO Radio Astronomy Image Archive 2833-4 (1952).

Preliminary observations began in August 1952, coinciding with the URSI General Assembly in Sydney. After the conference, there were tours of the Dapto site. Included among the visitors was Sir Edward Appleton.

### **TYPE II Bursts at DAPTO- Harmonics**

The aerial was completed in November 1952 with a frequency range 40 to 240 MHz. The beginning of routine operation was just on time: on 21 November 1952 an impressive Type II burst was detected on this “momentous occasion” (Stewart 2009, p 111) by John Murray. This observation was the first clear-cut detection of one of the major discoveries of solar radio astronomy in the 1950s, harmonic structure. A preliminary description of the rare Type II harmonic structure was published in *Nature* on 19 September 1953 (“Evidence of Harmonics in the Spectrum of a Solar Radio Outburst”, vol 172, page 533 by Wild, Murray and Rowe. The paper was published with a delay of seven months, sent to *Nature* on 10 February 1953, published on 19 September.<sup>57</sup>

This remarkable spectrum of the Type II was only one of four events detected in the period August 1952 to August 1953. The spectrum is shown in Fig. 28 (in Wild, Murray and Rowe, “Harmonics in the Spectra of Solar Radio Disturbances”, a paper describing Type II and Type III events – see *Australian J Physics*, vol 7, page 439, 21 November 1952). With the increased frequency coverage, the second harmonic (almost exactly 2.0 times the fundamental) was obvious. The two main bands showed a “marked similarity in their general features and the two patterns appear to be essentially parallel... In view of their close correspondence, there seems little doubt that the two bands are due to the same source of emission.”<sup>58</sup>

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<sup>57</sup> The delay between submission and publication of about 7 months is surprising. In September 1953, the typical delay for publication was only 3 months. Out of 45 companion papers published in early and mid-September, only one other publication has a similar delay (submitted on 29 January 1953, published on 5 September 1953, a publication about the efficiency of poisoning mice!).

<sup>58</sup> Wild, J. P., Murray, J. D., & Rowe, W. C. (1953). Evidence of harmonics in the spectrum of a solar radio outburst. *Nature*, 172(4377), 533-534. (Bill Rowe died soon after of leukemia)

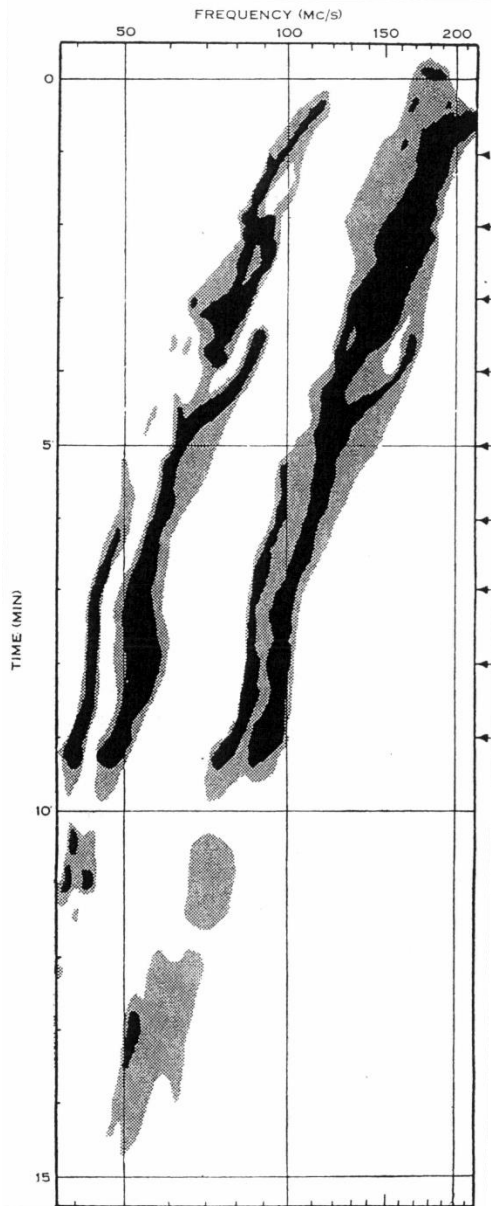


Fig. 28

An early Type II burst with clear 2 to 1 harmonic structure. Date was 21 November 1952. Frequency range was 40 to 240 MHz and the time span is 0 sec (top) to 15 min at the bottom. The interpretation of the change in frequency is related to the "plasma hypothesis". As Wild, Roberts and Murray pointed out in 1954 (*Nature*, vol 173, p. 532 a publication on Type III harmonic events). Fig 2 in the original publication:

[The interpretation of the frequency change with time as due to motions in the corona] depends on the simple hypothesis that when the spectrum shows an **abrupt** low-frequency cut-off, the frequency of this cut-off can be identified with the critical escape

frequency at the source, and hence used for determining the height of the source in the solar atmosphere.

Based on considerations of the escape of radiation from resonance levels in the corona, the consensus was that the plasma frequency was the relevant frequency for this cut-off.

Four Type II bursts were detected in the 1952-1953 observations. Two of these showed harmonic structure: (1) The 21 November 1952 event, Fig 29, was also associated with a large solar optical flare, located over a prominent sunspot group. This event was followed by a radio fade out and an attenuation of the galactic background at frequencies up to 70 MHz. Thus, the arrival time of the UV radiation from the flare could be determined. (2) Later, 5 May 1953, a large Type II burst was again observed with harmonic structure, although not as impressively complex as the November event. No flare observations were available but a radio fade out was detected.

The harmonic detection had far reaching consequences. Wild, Sheridan and Neylan (1959. An investigation of the speed of the solar disturbances responsible for type III radio bursts. *Australian Journal of Physics*, 12(4), 369-398) were quite frank in their revelation:

[The interpretation of the earlier Penrith observations in 1950 concerning the relativistic velocities of Type III bursts] was not taken particularly seriously until subsequent observations revealed that in some Type III bursts the sources radiated in two bands corresponding to a fundamental frequency and its second harmonic: this strongly suggested that plasma oscillations were responsible. However, since the deduced velocities are far in excess of those of any known optical phenomenon, it is obviously important to test their validity by direct means.

As had been done for the Penrith data, Wild and colleagues used the Type II drift rate (about 0.25 MHz sec) and a model of the electron density in the corona to show the evolution of height of the event with time. Fig 29 – 21 November 1952 Type II shows the derived drift rate. Again, the inferred velocity was comparable (but lower) than the Payne-Scott and Little (1952) observations had indicated. The left hand of the figures shows the distance above the photosphere in units of  $10^5$  km. (The solar radius is  $6.95 \times 10^5$  km- thus  $4 \times 10^5$  km corresponds to 0.58 solar radius, at which point the electron density is  $10^8$  electrons  $\text{cm}^{-3}$  in the Weiss – 1963- model of an excited corona.<sup>59</sup>)

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<sup>59</sup> Close to the photosphere, the electron density is about  $5 \times 10^9$  electrons  $\text{cm}^{-3}$ . At one solar radius above the photosphere the electron density is about  $4 \times 10^7$  electrons  $\text{cm}^{-3}$ . Weiss, A. A. (1963). "The

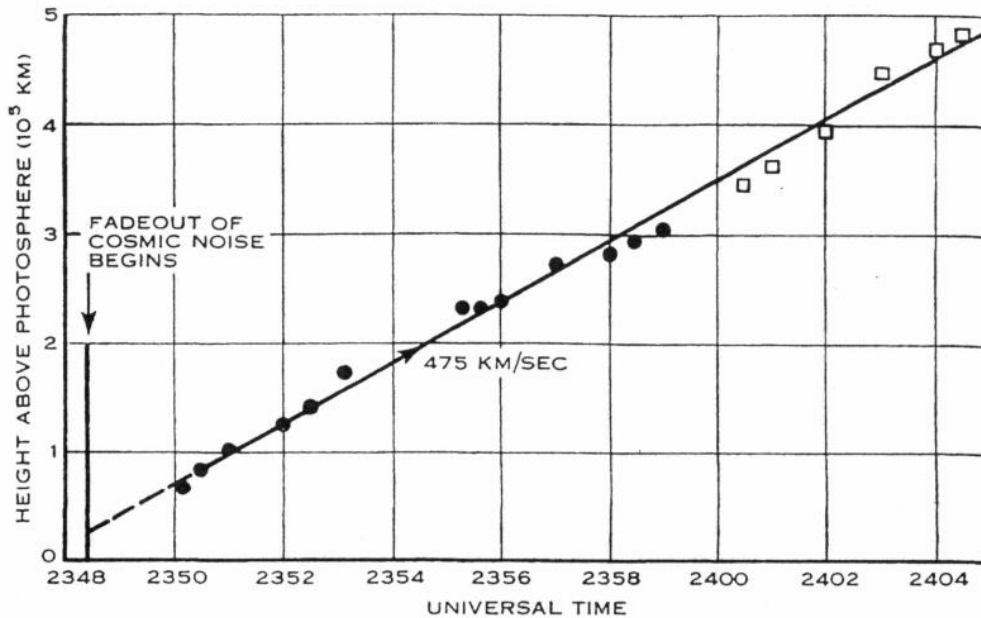


Fig. 9.—Derived height plot for the outburst in Figure 2. Where possible heights are derived from the fundamental frequency band (dots). The range is extended to greater heights by using half the frequency of the second harmonic (squares).

Fig 29 (see caption above from Wild, J. P., J. D. Murray, and W. C. Rowe. "Harmonics in the spectra of solar radio disturbances." *Australian Journal of Physics* 7, no. 3 (1954): 439-459. In Figure 28, the dynamic spectrum of this event of 21 November 1952 is shown.

The major new discovery was the presence of the harmonics, both Type II and III. Wild and colleagues realised the important implications of this striking phenomenon. At least half the Type II events showed the harmonic structure. At 200 MHz, it was likely that the greater part of the emission was in fact caused by the second harmonic, which was often of comparable intensity as the fundamental. No evidence for higher harmonics was observed greater than 10 per cent of the second. Wild et al (1954, p 449):

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positions and movements of the sources of solar radio bursts of spectral Type II." *Australian Journal of Physics* 16, no. 2: 240-271, for the case of a corona with twice the density of a coronal streamer given by Newkirk (1961, "The Solar Corona in Active Regions and the Thermal Origin of the Slowly Varying Component of Solar Radio Radiation." *The Astrophysical Journal* 133: 983.). The standard Baumbach-Allen corona model showed electron densities lower by an order of magnitude..

...[T]he emitting process is one involving oscillations of charge, as distinct from non-periodic accelerations such as those of thermal motions in the absence of a magnetic field. To produce a harmonic the oscillators must be non-linear.

Wild, Murray and Rowe (1954) produced a number of straight forward arguments pointing out that the plasma frequency and not the gyro frequency was the relevant quantity, proportional to the square root of the electron density.

[Wild, Murray and Rowe]: Several authors....have suggested oscillations at the plasma frequency as the source of high intensity solar radio noise although no complete theory has yet been given....

[In summary], the general agreement between the...suggested interpretation and the observations supports the basic proposition that the sources of sporadic bursts radiate their energy mainly at harmonics of frequencies near the plasma frequency of the surrounding medium. Indeed it appears that, of the processes which have been suggested to explain the high intensity of solar noise, those involving plasma oscillations are the only ones capable of accounting for the harmonic phenomenon. Nevertheless, it should be stressed that our knowledge of plasma oscillations is far from complete and the conditions under which electromagnetic radiation can be obtained from them are not properly understood...

⇒From considerations of the escape of radiation from resonance levels in the solar atmosphere, it is concluded that the plasma frequency is the only known proper frequency capable of accounting for the observation....

The sources are found to be in rapid motion through the corona and it is suggested that the generation of high intensities is associated with longitudinal plasma oscillations excited by fast streams of ionized matter. Assuming a standard, spherically symmetrical corona, application of the plasma hypothesis to observed spectra yields information on the position (both height and angular displacement from the centre of the disk), velocity, and size of the source. [Velocities of order 500 km/s were deduced for the major Type II burst of 21 November 1952.]

### **TYPE III DAPTO**

During the one-year period August 1952 to August 1953, several hundred Type III bursts were detected at Dapto with 20 showing harmonic structure. These bursts were by far more frequent than the Type IIs. A preliminary publication was prepared for *Nature* and submitted on 14

December 1953, published on 20 March 1954 (on this occasion a delay of only 3 months).<sup>60</sup> The remarkable harmonics appeared also for these bursts which had a drift rate a factor of 100 times that of the Type IIs, lasting only for some seconds instead of minutes.

A sample of six Type IIIs from Dapto are shown in Fig 30 from Wild, Murray, Rowe, 1954. As was the case for the Type IIs, the second harmonic often appeared before the first. From the *Nature* paper of 1954: "... [As was the case for the Type II bursts], comparison of the profiles of fundamental and second harmonic normally indicates that the low-frequency skirt of the fundamental has been cut off during escape." The derived velocities for these objects (using the Allen-Baumbach model of coronal electron densities) was in the range 0.1 to 0.3 c (velocity of light). An additional remarkable feature is also obvious in many of the dynamic spectra (the fig from Wild, Murray and Rowe), the vertical areas at the end of the bursts. Wild, Roberts and Murray (1954) continued: "[T]he disturbance is apparently brought to rest at some height within the observed range."

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<sup>60</sup> *Nature* vol 173, p.532. "Radio Evidence of the Ejection of Very Fast Particles from the Sun" by Wild, Roberts and Murray. The full report was in the *Australian J Physics* (see above) in a paper submitted on 2 April 1954, published in September 1954.

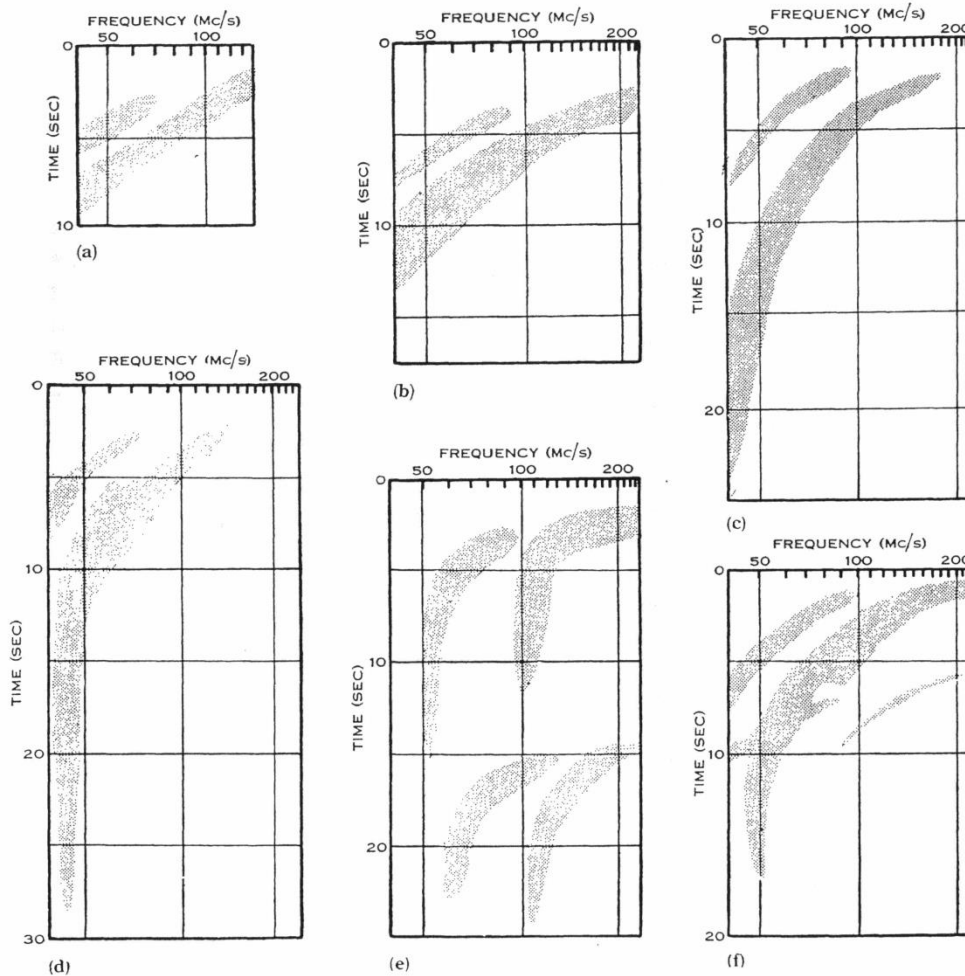


Fig. 4.—Dynamic spectra of harmonic type III bursts. Times (U.T.): (a) October 3, 1952, 23 hr 21 min ; (b) June 7, 1953, 01 hr 08 min ; (c) June 5, 1953, 01 hr 35 min ; (d) June 5, 1953, 01 hr 37 min ; (e) January 14, 1953, 06 hr 07 min ; (f) June 5, 1953, 01 hr 32 min.

Fig 30 Dynamic spectra of Type III bursts on (a) 3 October 1952, (b) 7 June 1953, (c) 5 June 1953, (d) 5 June 1953, (e) 14 January 1953 and (f) 5 June 1953. As for the Type II bursts, the time axis runs from top to bottom, with a total extent of only 10, 20 or 30 sec. Wild et al (1954)

Wild, J. P., J. D. Murray, and W. C. Rowe, ("Harmonics in the spectra of solar radio disturbances." *Australian Journal of Physics* 7, no. 3 (1954): 439-459) explained the rationale for the choice of relativistic velocities as the source of the rapid drift rates for Type III events. The burst generating sources likely radiated at harmonics of the plasma frequency of the surrounding corona, leading to both Type II and Type III events.

This provides us an experimental foundation to the speculation [made by Wild after the Penrith observations] that the fast frequency drift of Type III is to be interpreted in a similar manner to the slow drift of Type II bursts. On this basis

the Type III bursts move outwards through the solar corona with initial radio velocity components of between  $3 \times 10^4$  and  $10^5$  km/s, showing steady deceleration along the path. These [events] with “tails” are apparently brought to rest at heights of a few hundred thousand km [in the corona].<sup>61</sup>

### Compound Bursts

In the *Nature* paper of 1953, Wild, Roberts and Murray also described an additional rare occurrence, combination bursts. Either type bursts (II or III) was usually observed to occur without the presence of the other type. However, on three occasions in the year's (about 1000 hours in 1952-1953) campaign, a combination of the two occurred. The Type III occurred first followed by the Type II. See Fig. 31 for a compound burst on 1 September 1952. The calculated velocities were 230 km/s for the Type II and  $1 \times 10^5$  km/s for the Type III. In each case a backwards extrapolation of both bursts provides a point of intersection within  $10^5$  km of the photosphere, suggesting both events are associated with possible streams of matter which originated from a common source low in the solar atmosphere. “Such an ‘explosion’ may well be the primary cause of the [solar] flare.”

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<sup>61</sup> In the period just beyond the scope of the present treatment, rapid advances were made in understanding Type III bursts and their impact on the earth. In 1965, Ron Stewart used Dapto radio spectrograph data with an extended frequency range of 200 to 12 MHz. Using observations at this low frequency he showed that he could determine velocities out to an impressive height of 3 solar radii. The velocities were constant out to this height; he suggested that electrons of 20 keV traversing open magnetic field lines were responsible. Also subsequent observations with satellites showed that Type III bursts could be associated with streams of electrons which travelled from the sun to the earth in about 30 min. Later, Fainberg and Stone (1970) used the first Radio Astronomy Explorer 1 to observe Type III bursts in the frequency range 0.2 to 5 MHz, tracing the radio emission along spiral paths [far out to distances of 11 to 30 solar radii] in the solar wind. The average exciter speed was 0.38c. Fainberg, J., and Stone, R. G. (1970). "Type III solar radio burst storms observed at low frequencies." *Solar Physics* 15, no. 2: 433-445. Fainberg and Stone wrote: “The present results suggest that the exciters are electron packets which propagate with little deceleration over distances of at least 1 AU.”

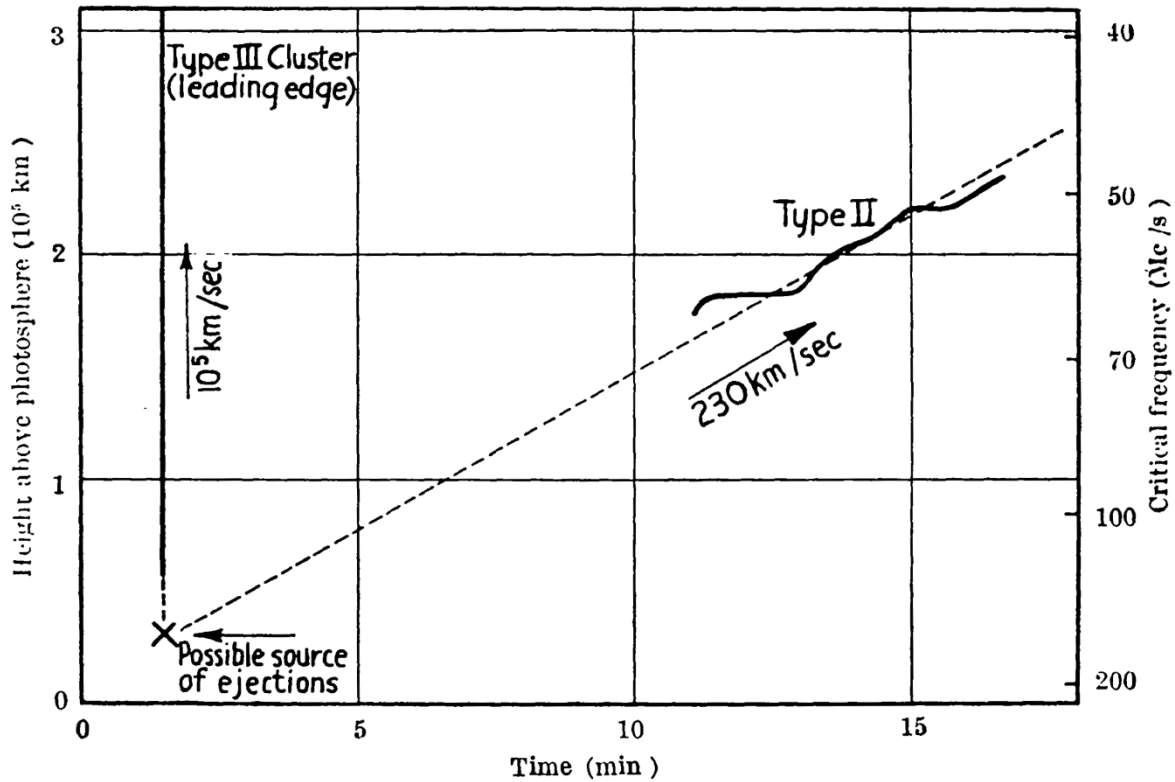


Fig 31 Plot of the derived motions in the solar atmosphere for a compound burst (Type III followed by a Type II) on 1 September 1952, during a period when the Dapto instrument was in an initial testing phases. Credit: Wild, J. P., Roberts, J. A., & Murray, J. D. (1954). Radio evidence of the ejection of very fast particles from the Sun. *Nature*, 173(4403), 532-534.

In his 1985 introduction to *Solar Radiophysics*, Wild brought the story of compound bursts forward 30 years:

The observations of Type II and Type III bursts contributed significantly to the developing subject of solar flare 'anatomy'. It was found repeatedly that groups of Type III bursts occurred at the very start of flares, coincident with the arrival of X-rays as signified by the onset of sudden ionospheric disturbances. The Type II burst, if one occurred, began some minutes later. The picture therefore developed of the flare as a phenomenon triggered by some initiating explosion which produced immediate fast electrons and X-rays, and which was also responsible for an expanding gas cloud advancing behind a magnetohydrodynamic shockfront which caused the Type II burst

and ultimately the terrestrial effects. By the 1970s this picture was taken for granted; in the 1950s, it was quite new.

Wild did not discuss the major discoveries in the early 1970s of CME (coronal mass ejections) by OSO-7 in 1971 and the spectacular images from SKYLAB in 1973-1974. The Type II bursts were found to be frequently associated with interplanetary shock waves and ejected plasma clouds (CME), now believed to be the initial cause of the geomagnetic disturbance. "The close association of Type II-IV bursts with CME's is why ground-based radiospectrographs are used to monitor space weather." (Stewart, R. T. (1985). "Solar radiophysics." CSIRO publications. p.8)<sup>62</sup>

### **Dapto Interferometer- 1955 to 1964**

In 1955, a prototype interferometer (East West) was developed by Paul Wild and Jim Roberts for scintillation studies of Cygnus A (see Chapter 25). In 1957, an improved version was installed for solar observations covering the range 40 to 70 MHz (Wild and Sheridan 1958, *Proc of IRE* page 156, "A Swept-Frequency Interferometer for the Study of High-Intensity Solar Radiation at Meter Wavelengths"). The modifications to this system were described five years later by Kevin Sheridan (the Pawsey edited *Proc of the IRE Australia*, 1963, vol 24, page 174 "Techniques for the Investigation of Solar Radio Bursts at Metre Wavelengths"). In the former publication, the authors described preliminary data from 20 June 1957 and 3 July 1957. Based on the June event, the position and size of a Type I storm were determined with a size of about 9 arc min at 55 MHz . The July event showed a Type III burst associated with a flare with an angular size of about 8 arc min, showing a slight decrease in size at the higher frequency of 70 MHz. In Fig 32, Paul Wild is shown (with car) standing near one of the three dipoles of the 40-70 MHz swept-frequency aerials at the Dapto site.

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<sup>62</sup> In addition, more than 30 instances of sudden mass ejections from the sun were observed with the white light coronagraph experiment aboard Skylab during the first 118 days of the mission in 1973-1974.



Fig. 32 Paul Wild and one of the three elements of the Dapto Swept Frequency interferometer (40 to 70 MHz). Note the open wire transmission lines used to combine the radio signals.  
Credit: CSIRO Radio Astronomy Image Archive R3750-2 (from 1955)

In 1958, the system was modified substantially. High quality data were obtained starting 4 June for a period of five weeks using the frequency range 40 to 70 MHz. These results became available just in time for the Paris Symposium (30 July to 6 August 1958, Chapter 36) where Jim Roberts presented the paper on behalf of Wild, Sheridan and Trent ("The Transverse Motions of the Sources of Solar Radio Bursts" in the Paris Symposium volume edited by Bracewell in 1959, p 176). Observations occurred for four hours a day centred at local noon.

The major modifications carried out in 1958 (both for the adding and multiplying interferometers) were three-fold: (1) the addition of a shorter baseline of 250 m to the original baseline of 1000 m, in order to resolve fringe ambiguities, (2) a real time display system<sup>63</sup> (See Fig 33) and (3) an automatic system of lobe-switching and phase-calibration (leading to an order of magnitude decrease in the efforts for data reduction). The fringe spacing of about 20 arc min (at mid frequency) at the longest baseline and 80 arc min at the shortest baseline lead to a positional accuracy of  $1-2^{64}$  arc min in the frequency range 40 to 70 MHz (5 MHz intervals) at successive times, separated by 0.5 sec.

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<sup>63</sup> A facsimile recorder was used, based on the principle of the machines used for newspaper photographs transmitted by radio. See Fig 33 with Kevin Sheridan, R 5705-9p. This system provided a real-time display of the complex interferometer output as a function of time and frequency. This was a rotating lobe interferometer operating at multiple frequencies. The recorder displayed time on the x axis and frequency on the y axis.

<sup>64</sup> For the swept-frequency interferometer, Wild et al (1959) suggested positional errors of 1 arc min; Weiss, A. A. ((1963). "The positions and movements of the sources of solar radio bursts of spectral Type II." *Australian Journal of Physics* 16, no. 2: 240-271.) estimated errors of 2 arc min.

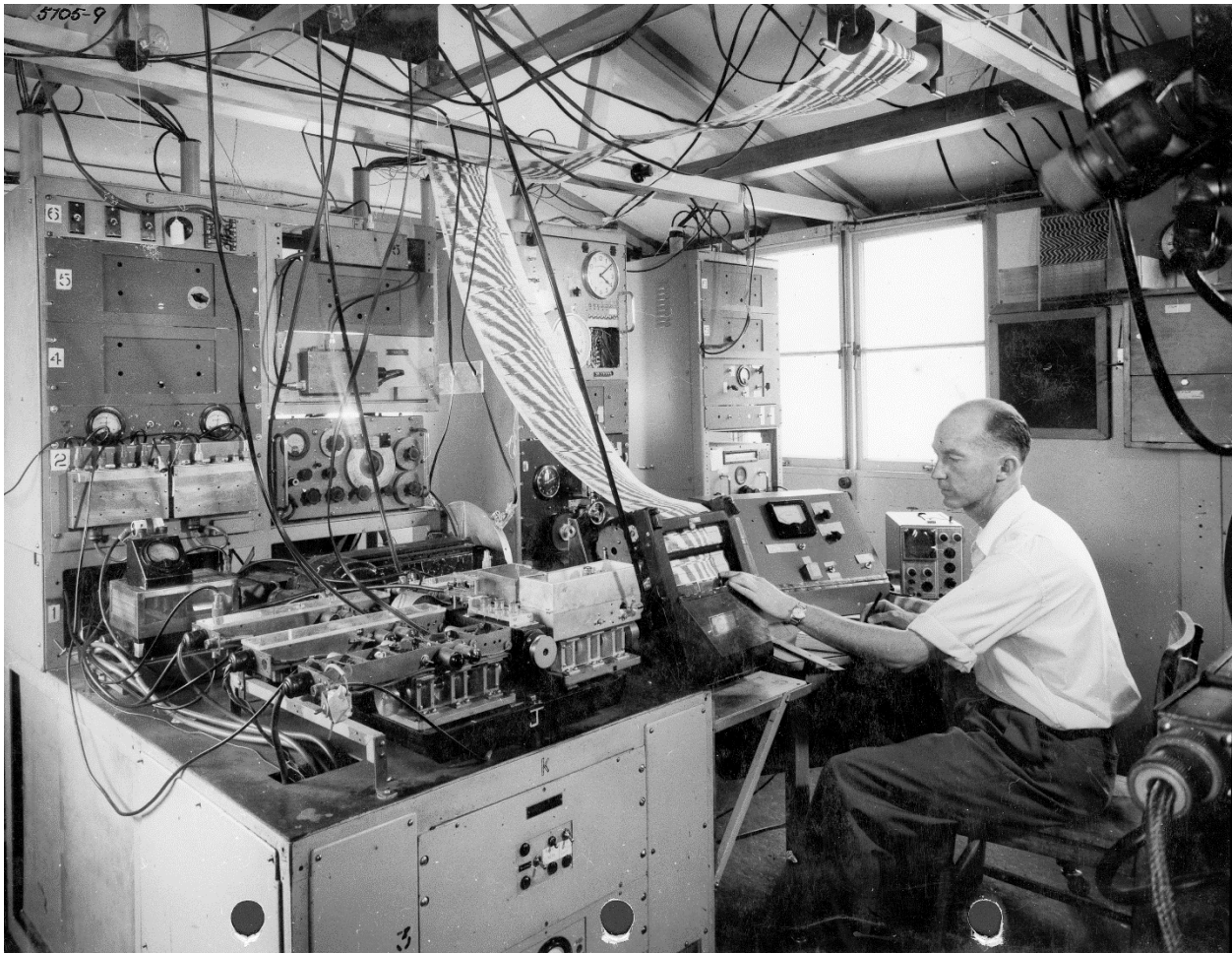


Fig 33 Kevin Sheridan in the control room at Dapto, The paper output is from a facsimile machine used by e.g. newspapers to transfer images over telephone lines in the pre-internet era. Credit: CSIRO Radio Astronomy Image Archive R5705-9. (1958).

Roberts described the one-dimensional transverse positions as a function of frequency for Type III bursts, as well as a few Type II and IV events.

The presentation given by Roberts elicited a number of comments and questions from eight prominent participants, including Hey, Minnaert, Denisse and Haddock.<sup>65</sup> The presentation contained a number of ground-breaking conclusions:

[T]he position of a burst *at a single frequency* [Type III] [their emphasis] was found to change with time ... less than 0.5 arc min. However, different frequencies were found to arrive from different directions, often being dispersed across an appreciable fraction of the sun's disk. The variation is most marked for sources beyond the limb, where the lower frequencies appear to arrive from much greater heights in the corona than at

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<sup>65</sup> Paul Wild provided additional comments on the text after the conference as he prepared his conference publication back in Sydney.

higher frequencies, as much as 10 arc min separating the 45 and 65 MHz positions.... [The data] indicate that the lower frequencies originate not only at later times but also at greater heights than the higher frequencies. They therefore strongly support the hypothesis of an outward-traveling exciting agency. ....[T]he transverse velocities are found to exceed  $10^5$  km/s in some cases...while this is of comparable magnitude to the radially-outward velocities deduced from spectra [using an assumed electron density distribution model] there are individual cases where the transverse velocity is greater by a factor of 2 and 5. This may mean we are dealing with speeds much closer to the velocity of light than was previously suspected. The reason for the discrepancy is that sources beyond the limb often originate from **heights considerably greater than those given by the standard spherically symmetrical models of the corona.** [our emphasis] This is consistent with other optical and radio evidence, which indicates that the electron density above active centres is much larger than that given by the standard models.

For the less frequent but more intense outburst events, the Type IIs, the results were similar to the Type III with the time scale increased by a factor of 100 or 200, and observed transverse velocities in the range much slower than the Type IIIs. Two Type II events were observed on 26 June 1958 and 7 July at Dapto. Again the position at a fixed frequency did not vary in time but showed angular displacement with frequency. In the July event, the flare was close to the central meridian, a transverse velocity of about 250 km/s was observed with the interferometer. In the June event, the flare was observed near the E limb; the transverse velocity was observed close to 2000 km/s. As before, the transverse velocities were observed to be in excess of those calculated from the spectra, "more closely to the corpuscular streams, which have been postulated to account for the terrestrial magnetic storms and aurorae which follow 1 to 3 days after certain flares."

The final aspect of the Wild et al presentation given by Roberts concerned the remarkable data for Type IV bursts. For example, the June event on the E limb was followed by a Type II burst 7 min later, lasting for 8 min. Then the Type IV burst began 10 min later, lasting for 15 min with motions from near the flare position to a position nearly 4 solar radii beyond the limb (transverse velocity 2600 km/s). Unlike the Type II events, the instantaneous position of the centroid was independent of frequency, all frequencies arriving from the same position. "This strongly supports the conclusion that the Type IV bursts are not caused by plasma oscillations." The 26 June 1958 (about a month before the Paris conference) event is shown below in detail. The complex plot shows the frequency, positional data and polarisation data during a 50 min interval (x axis).

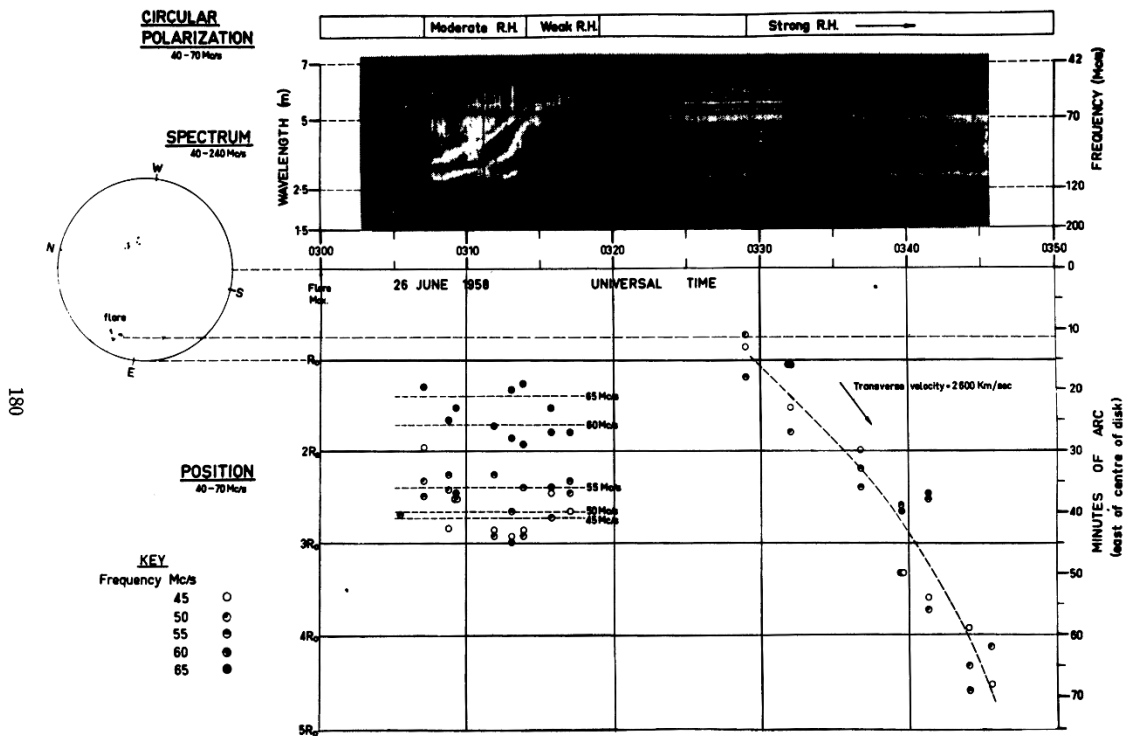


Fig 34 . The polarisation, spectrum and position data recorded during an outburst at the time of a flare of importance 2. The earlier section of the outburst is a Type II burst, the later a Type IV. From the Bracewell Paris symposium, p. 180. The remarkably complex plot shows the behaviour of the solar bursts over a 50 min period (x axis) on 28 June 1958. The top section shows the polarisation state. The B/W plot shows the frequency-time dynamic spectrum (frequency from 42 to 200 MHz, from the top). The Type II and Type IV bursts are prominent. The main portion of the plot is the position- time behaviour with position with respect to the centre of the solar disk in right ascension to the east. The sketch to the left shows the sun and the position of the optical flare. The Type IV burst was detected up to 70 arc min (more than 2 solar diameters) from the centre of the sun over a period of 55 min for an implied velocity of 2600 km/s. The position errors were about 4 arc min (only the short baseline of 250 metres was used). Credit: Paris Symposium (from early August 1958) book edited by Bracewell in 1959, Paris Symposium on Radio Astronomy, "The Transverse Motions of the Source of Solar Radio Bursts". (The paper given by Jim Roberts on behalf of Wild, Sheridan and Trent, p. 176.)

The details of these initial observations with the Dapto swept-frequency interferometer were reported in December 1959 in a paper by Wild, Sheridan and Neylan submitted on 3 August 1959. (1959, "An Investigation of the Speed of the Solar Disturbances Responsible for Type III Radio Bursts", *Australian Journal Physics*, vol 12, p 363) . New data had been added to the June and July data in late 1958. This analysis included about 100 groups of Type III bursts; eleven

events had been analysed in the presentation at the Paris Symposium in August the previous year (1958). Direct determinations of the the velocities of the Type III events were possible.

The major result is shown in Fig 35 below, which shows the sequence of observations for 8 Type III bursts in the period June to December 1958. These observations had a maximum intensity of  $10^8$  Jy, the duration of each burst was 3 to 10 sec with a drift rate of 20 MHz per sec over a band width of each event ranging from 10 to 100 MHz; in some cases the harmonic merged with the fundamental. The duration of a group of individual bursts was 0.5 to 2 min. The typical angular size was about 6 arc min, a brightness temperature of about  $10^{12}$  K at 40 MHz. The frequency of occurrence was several groups per hour with a prominent correlation with solar flares and micro-flares.

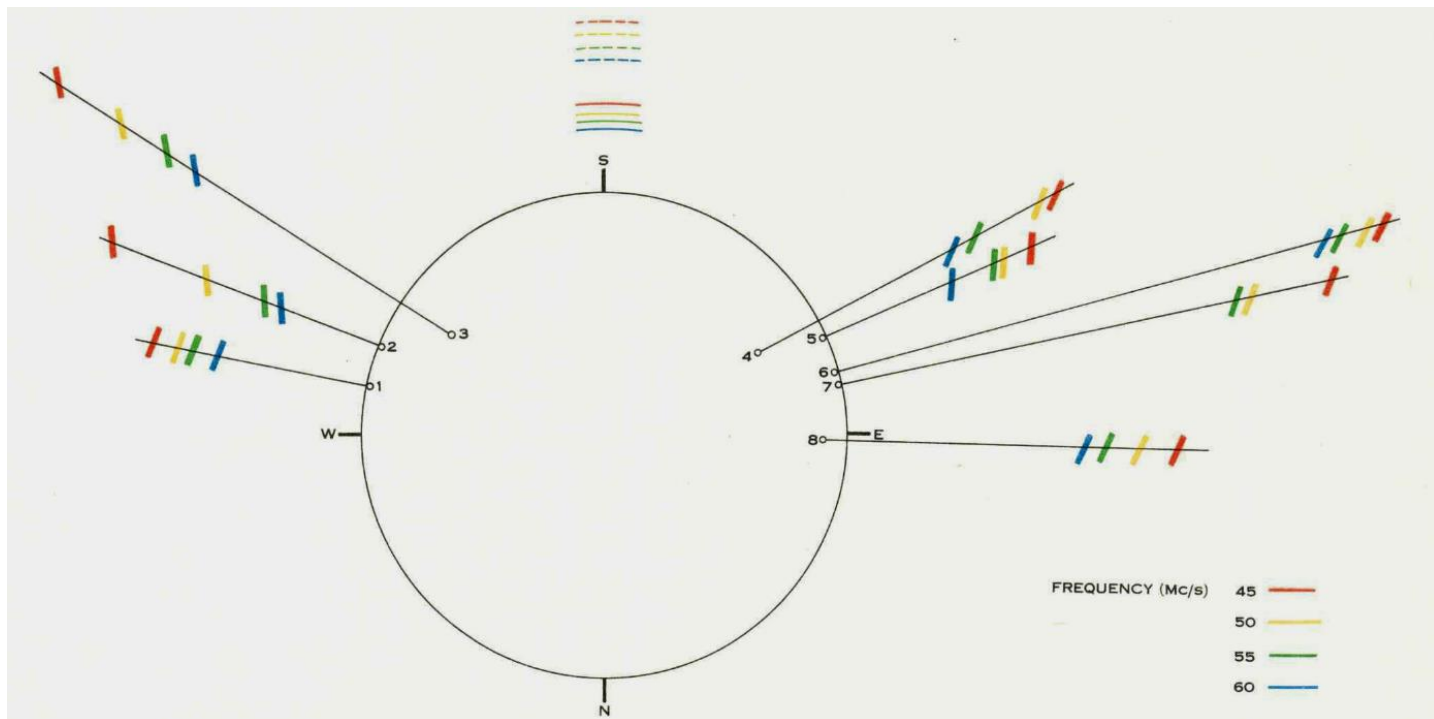


Fig 35. Wild, Sheridan and Neylan ((1959). An investigation of the speed of the solar disturbances responsible for type III radio bursts. *Australian Journal of Physics*, 12(4), 369-398, their fig.7) Type III bursts velocities: In each burst lower frequencies originate at greater heights in the corona than higher frequencies. The source positions of 8 Type III bursts associated with limb flares (optical positions indicated by circles). The positions at 4 frequencies are shown. The circular arcs at the north show the levels of the fundamentals (full lines) and harmonic (dashed) of the plasma level, based on the Baumbach-Allen model of the electron density in the corona. Note that the level is appreciably lower than the observed data from Dapto . The typical duration of a Type III burst was 3 to 10 sec with a drift rate (high frequency to low) of 20 MHz per sec. Burst came in groups of total duration 0.5 to 2 min with individual bursts with this time span. The typical flux density was  $10^8$ Jy.Type III bursts were indeed a new phenomena.

Wild et al were concerned that ionospheric refraction would be a major problem at the low frequencies of 40-70 MHz. The low frequencies had been chosen due to the spectral index of Type III bursts (stronger at lower frequencies); in addition the fundamental frequency of these bursts was usually at frequencies less than 90 MHz. As a test a Type I burst was observed over a two-hour period; the source position remained constant at 4 frequencies in the band 45 to 60 MHz to  $\pm 2$  arc min. In addition, the observations of the Type III bursts at a fixed frequency remained constant at the level of  $\pm 1$  arc min.

The data strongly supported the hypothesis that the different frequencies originated at different levels in the path of the disturbance traveling outwards in the corona. The velocity of the Type III disturbance was carried out using the interferometer determined transfer velocities (Fig 35) and then compared to the corresponding drift rates determined with the spectrograph (the dynamic spectra). Wild et al:

If it is assumed that the path of the disturbance is in fact radial and that the relative positions are not distorted by refraction, we can combine the [derived] positions ... with the corresponding drift rates given by the dynamic spectra to calculate the velocity of the disturbance. Velocities thus calculated are found to lie in the range 0.2 c to 0.8 c. These values are considerably greater than those previously inferred from spectral data. The distribution of velocities has as a mean velocity of 0.45 c.

A new aspect of the Dapto data was the determination of the transverse velocities of Type IV bursts; around 30 percent of the Type II bursts in the series were accompanied by a following Type IV moving burst (lasting for at least one min or more). These Type IV bursts were more prominent at frequencies below 150 MHz with intensities up to  $10^8$  Jy. No harmonic structure was observed, as expected for synchrotron emission. Wild et al calculated that the relativistic electrons had an energy of at least 2 Mev.

The next major step was carried out by Alan Weiss who transferred from meteor research at Adelaide to the Sydney solar group in 1959. (He died in late December 1964.) His careful methodology was effective in deriving realistic evaluation of the uncertainties in the properties of Type II bursts.

An important project was published June 1963 by Weiss: "The Positions and Movements of the Sources of Solar Radio Bursts of Spectral Type II", *Australian J Physics* vol.16, p.240". This publication represented a major step forward compared to the Wild, Sheridan and Trent account at the Paris Symposium (Wild et al 1959), Type II bursts. Twenty-two Type II bursts

observed over a time range from June 1958 to December 1961 were analysed. (The two events from June and July 1958 analysed by Wild et al were included in the Weiss sample.)

Weiss used the Dapto 40-70 MHz swept-frequency interferometer in conjunction with the dynamic spectra in the range 15 to 210 MHz. As expected, the plasma hypothesis was confirmed again for Type II and Type III bursts, originating at the appropriate plasma level in the corona. A number of Type II bursts were observed to have transverse motions in the corona of 1000 to 2000 km s<sup>-1</sup>. At each fixed frequency, there was little drift in position of the emission. Small tangential motions were observed in the Type II events in about a third of the events.<sup>66</sup> The implied tangential speeds were in the range 1000-2000 km s<sup>-1</sup> for the component of motion parallel to the surface of constant plasma frequency.

A major result of the Weiss research of 1963 was a determination of plausible coronal electron density models based on the combined interferometer and dynamic spectra from the two Dapto instruments. Fig 36 below shows the data from the Type II bursts 9 (solid squares), the data from Wild, Sheridan and Nylan (1959 ) and others for Type III bursts (circles). Three models are shown, the classical Baumbach-Allen model, Newkirk's coronal streamer model and a model with twice the Newkirk's coronal streamer model. Weiss proposed that the data was closely fit by a two times the Newkirk model (upper curve). Weiss concluded:

..[W]e may say that at heights below 1 solar radius above the photosphere, the average coronal densities in the regions of generation of Type II and Type III bursts appear to exceed by a factor of about 2 the average electron densities determined optically for coronal streamers. The course of the electron density distribution at greater heights cannot be defined with any certainty from the available radio data.

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<sup>66</sup> The typical motions were 2 arc min per min of time. The statistical significance of single observations was low, for most only at the level 1.5 to 2 sigma. For one source (28 April 1960) the signal to noise was 2.5.

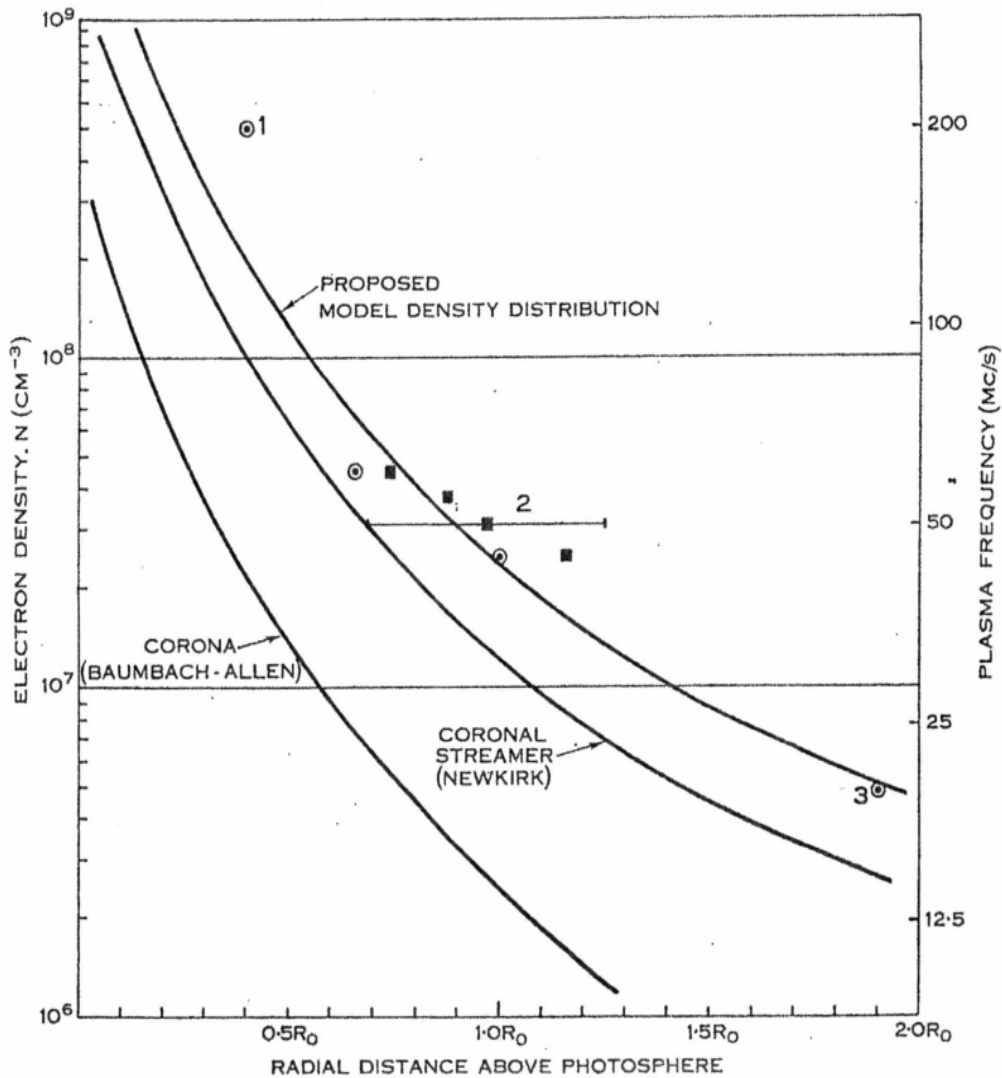


Fig 36 Weiss (1963) his fig. 5. Type II and Type III bursts derived average electron densities in the corona as a function of height. The full curves represent respectively the standard Baumbach-Allen corona, the density of the average coronal streamer as given by Newkirk (1961), and a streamer with twice the density given by Newkirk. The plotted points give the measured heights of origin of Type II and Type III bursts. Circle enclosed point, Type III bursts (Morimoto 1961; Shain and Higgins 1959; Wild, Sheridan and Neylan 1959). ■, Type II bursts of the present analysis; the bar represents the probable error of the 50 Mc/s point and is typical of the errors in all four points for Type II bursts. Credit: Weiss, A. A. (1963). "The positions and movements of the sources of solar radio bursts of spectral Type II." *Australian Journal of Physics* 16, no. 2: 240-271.

Weiss also was able to compare the behaviours of Type III bursts as compared to the later Type II events. “Almost identical results are obtained for the two types of burst in respect of the relations between flare position and burst position, and between variation of position with frequency and burst position.” Thus, the sources of the emission of both types were likely located in “equivalent regions” of the corona. The major difference between the burst types was the source of the exciters and the speed of motion in the corona. “.. [Magnetohydrodynamic shock fronts with speeds of about  $c/300$  for Type II bursts and streams of electrons with speeds of about  $c/3$  for Type II bursts were suggested. The common features of the two types of bursts are thus attributed to the properties of the plasma oscillations generated by the two types of exciting distributions, rather than to the exciters themselves.” A final point was also emphasised by Weiss: many Type II bursts occurred in multiple events with two or more bursts. Possibly multiple shock fronts were involved, with different speeds.<sup>67</sup>

Above we have shown Fig 36 from Weiss (1963). The three models are shown as solid curves (see text). The adopted model is as the upper curve. The solid curves shows Weiss’s Type II data and Type III points are shown as circles. The error bar is shown for a typical point at 50 MHz.

### **Paul Wild’s Summary of the Dapto Interferometer Results --25 Years Later**

Paul Wild provided a succinct summary of the achievements of the Dapto swept frequency – interferometer in 1985 (*Solar Radiophysics*, p. 12, his “Introductory Concepts”):

To put the matter beyond all doubt the Dapto spectrograph was modified to operate as an interferometer (*swept-frequency interferometer*). The results showed that the lower the frequency of the Type III bursts the greater the source height. Similar results were obtained for Type II bursts. This final demonstration was sufficient to permit general acceptance of the notion that Type III and Type II bursts were due to agencies travelling outwards through the solar atmosphere at velocities of the order of  $10^5$  and  $10^3$  km s<sup>-1</sup> respectively. From a variety of arguments, the conclusion was reached that Type III bursts were radiation from plasma oscillations excited by discrete bunches of fast particles (electrons); that the Type II bursts were excited by magnetohydrodynamic shock waves; and that the latter was also the causal agency of magnetic storms and aurorae at the earth one and a half to three days later. Final confirmation of the

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<sup>67</sup> Weiss also published a later paper in 1963 (submitted on 26 June 1963) “The Type IV Solar Radio Burst at Metre Lengths” *Aust J Physics*, vol 16, p 526). The Dapto spectrograph and the swept-frequency interferometer were used to investigate the properties of 24 sources of “moving” and “stationary” Type IV events.

existence of the Type III electrons came when spacecraft detected them directly in interplanetary space at the correct extrapolated times.

The legacy of the achievements of the Dapto solar observatory can be seen in the photo made by Goss in September 1967 at the opening of the Radioheliograph at Culgoora, Fig 37 below.



Fig 37 Photo by Goss in September 1967 at the opening of the Culgoora Radioheliograph, the 3 km diameter array consisting of 96 aerials. The figure shows one of the 13 m paraboloids of this instrument, initially operating at 80 MHz with an angular resolution of 3.8 arcmin. (Later upgrades added 43.25, 160 and 327 MHz.) The other two aerials in the foreground are radiospectrographs used to determine dynamic spectra of solar bursts. Credit: W.M. Goss

**The review paper by Wild, Smerd and Weiss in *Annual Reviews of Astronomy and Astrophysics*, volume one, 1963. “Solar Bursts”**

Paul Wild and colleagues wrote two review papers in *Annual Reviews of Astronomy and Astrophysics*, in 1963 and in 1972.<sup>68</sup> The first was a pre-Culgoora Radioheliograph publication, appearing 4 years before the opening of the new instrument on 22 September 1967. The second review (by Wild and Smerd) appeared in volume 10 in 1972 “Radio Bursts from the Solar Corona”, including many of the startling observations made with the imaging Radioheliograph at 80 MHz (resolution 3.75 arc min) since 1967.<sup>69</sup>

The 1963 review contained extensive material concerning observations at all radio frequencies with an emphasis on the extensive contributions made by RPL since 1945. The paper continued with discussions of the flare phenomenon and the final 26 pages summarised the theory of the origin of burst radiation including discussions on theories of emission mechanisms.

Both the introduction and the conclusion of the *Annual Reviews* publication set the stage for the accomplishments that solar radio astronomers had made since 1942. In addition Wild and colleagues posed a series of questions as they planned for the future Culgoora Radioheliograph. Culgoora made a major impact on solar physics in the 17-year period of operation (1967-1984). As Wild wrote in 1985: “During its 17 years of operation the instrument provided a wealth of new information and new insights into phenomena of the solar corona.... [A major goal] was creating theories aimed at bringing the results within the framework of physics.”

The stirring conclusion to the 1963 review presaged the events of the following decades as he anticipated future “spectacular advances”:

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<sup>68</sup> An earlier review publication was written in 1953 by RPL staff, Pawsey and Smerd. This appeared in a compilation edited by Gerard Kuiper, *The Sun*, chapter 7 “Solar Radio Emission”, p 466 to 531. The authors discuss the work of Wild and McCready in 1950 and 1951 concerning the classification of metre wave bursts. Surprisingly, they use the old terminology (bursts and outbursts), with no mention of the pioneering classification of Wild and McCready (1950) and Wild (1950, 1951), Type I, II and III.

<sup>69</sup> In their introduction to the 1972 review, Wild and Smerd stress that due to the expansion of the literature on solar physics since 1963, “[W]e have been forced to be selective on the topics covered. The paper concentrates on the radio emission from traveling disturbances in the corona, Type III, Type II and moving Type IV bursts- and the role they play in the flare phenomenon. Considerable progress has been made in the understanding of these bursts during the last decade, owing to the introduction of interplanetary and new forms of ground-based observations and to developments in plasma theory.” No mention was made of microwave bursts or X-ray emission. The 1972 review was 38 pages compared to 76 for the earlier publication.

The subject is now younger than two eleven-year solar cycles. Progress has obviously been rapid and in this short time the solar radio studies have helped to transform our knowledge of solar flares, solar-terrestrial relations and plasma physics on the astronomical scale. They have also helped to advance radio techniques in certain directions, from the simple radar receiving systems used in the Second World War to the extremely high-resolution techniques now required for radio astronomical investigations. During the next solar cycle, which begins in 1965, we may expect further **spectacular advances in the physical penetrating power of observation** [our emphasis], in the search for the origin of the energy released in the flare event, and in the basic understanding of the transformation of the energy in particle streams into electromagnetic radiation. The desirable extensions in observational techniques are clear: since observable properties are restricted to intensity and polarization as functions of time, direction, and frequency, the most obvious current need is for complete two-dimensional observations of the sun at closely spaced intervals of time; indeed such observations will become essential at a few carefully chosen frequencies spaced across the radio spectrum. There is also need for comprehensive spectral observations covering the entire radio band simultaneously, and for adequate coverage of polarization measurements, which allow complete specification of the polarization parameters. We believe that the gathering and investigation of comprehensive data on individual events is of much greater value than the use of partial data on many events. In practice, no single observatory can hope to cover all observable properties, and cooperative ventures will continue to be vital.

Stephen White<sup>70</sup> discussed this text with the authors in late 2018 and again in mid-2020. White pointed out that the questions posed in 1963 were pertinent at that time and remain so in 2019. "They still remain the relevant questions 55 years later. An essential element of any solar radio telescope remains the ability to cover the entire band of frequencies simultaneously."

The introduction to the review by Wild, Smerd and Weiss (1963) provided a snapshot of the physical questions which Wild and colleagues hoped to answer with their future observations:

Solar activity takes many and varied forms; all are in some way linked with the emergence into the Sun's atmosphere of strong magnetic fields. The places where the field breaks through the surface are marked by sunspots. It appears that magnetic energy is stored in such active regions and can be triggered under suitable

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<sup>70</sup> Australian-US solar physicist, an authority on radio investigations of the sun.

circumstances. The explosive release of the pent-up energy can lead to the emission and ejection of the gamut of electromagnetic and particle radiations. These eruptions range from the many small to the rare great ones that cause solar-terrestrial disturbances. The complex manifestations of an eruption may be classed together as the solar flare event even though the term solar flare has been used specifically to describe the sudden brightening in chromospheric plages.

The properties of radio bursts were well known in 1963, with distinctive characterisations for Type I, II, III and IV. The radio events were spectacular with changes in the total flux density of the sun exceeding a factor of 1000 or greater in a few seconds, then remaining at high levels for hours. Wild et al continued:

The combination of large brightness temperatures at the expense of a small fraction of the flare energy suggests that radio bursts may be sensitive indicators of eruptions on the sun, as indeed they are. Another implication is that there may be an embarrassing variety of possible energy sources for solar radio bursts. This, however, is not so. One limiting factor is that we are not merely looking for a heating mechanism. The mechanisms of non-thermal emission are few in number and prescribe very stringent source properties. Basically, the emissions depend on the conversion of kinetic energy of fast-moving, free charges into electromagnetic energy. Indeed the linking of radio bursts with fast particle streams has been one of the most fascinating problems posed by the radio observations.

The high speed with which some burst sources [the Type IIIs] seem to move through the sun's corona is quite unsuspected from optical observations. Other burst sources move more slowly while some show no movement at all. However, even in the static cases one cannot escape the conclusion that the source must harbour large numbers of very fast particles; these may be magnetically or electrostatically constrained from leaving the source region. In this way radio bursts provide evidence for the ejection, acceleration, trapping, and storing of fast charges in the sun's atmosphere during and following an eruption.

Were the expectations for the Culgoora Radioheliograph fulfilled in the 17 years of operation (1967 to 1984)? The authors asked Stephen White this question in mid-2020. He responded as follows (some of the comments are paraphrased):

The group of Paul Wild and colleagues had hoped for spectacular discoveries. Perhaps the lack of wide-continuous frequency coverage remained a major obstacle. But “what they achieved did lead to a much better understanding of [the details of the solar corona]. The importance of Culgoora compared to the earlier work was that [Wild et al] had a better imaging [instrument] at the same time that .... [new] information from space observations started to be available [e.g. Skylab and coronagraphs] that provided [information] that couldn't be [observed from earth]. “

“An example was the association of moving Type IV bursts with CME (coronal mass ejections] could not have been done earlier, although you could speculate. You needed the better imaging that Cugoora provided [in order to succeed]. The Culgoora instrument showed that there is no simple description of where a Type II burst might occur in relation to other phenomenon in a solar flare. Also, the RPL group at Culgoora observed coronal holes at radio frequencies for the first time. These observations lead to connections experienced by the RPL solar radio group to the rest of the solar physics community, rather than just the plasma physics community.”

“Finally, the range of different phenomena that could be observed became clearer because of the imaging capability of the instrument [at the impressive rate of about once per second]. Culgoora showed the importance of ducting and scattering in low frequency imaging of the sun.”

In the modern era of 2020, low frequency imaging of the sun has experienced a renaissance- LWA (Low Frequency Array 10 to 85 MHz), MWA (Murchison Widefield Array 70 to 300 MHz) and LOFAR (Low Frequency Array 30 to 240 MHz) are operating in the US (New Mexico), Australia (Western Australia) and Europe (centred in the Netherlands).

“I think that the [group of Paul Wild and colleagues] were quite pleased with that they achieved with Culgoora, even if it was not as dramatic as they had anticipated in 1967 at the 22 September 1967 opening.”

## ADDITIONAL NOTES

### ADDITIONAL NOTE 1

#### Expertise of the Scientists at RPL in 1944- 1945, Lessons Acquired during WWII

The RPL staff experiences obtained in the construction and outfitting of the LW/AW (Chapter 9) system became the building blocks of the first radio astronomy observations at Collaroy and Dover Heights in 1945-1946. There were two essential aspects of this process: (1) calibration of radio astronomy systems and (2) interferometry using the sea-cliff interferometer ( see also Chapter 37).

Ruby Payne-Scott was given the job of providing absolute calibration of the S band (10 cm) receivers for the 10 cm radar system constructed at RPL in 1944. She wrote three reports (Goss, *Making Waves*, p76). The summary report was TI 121/1 "The Present Position of Low-Power S-band Measurements in the Radiophysics Laboratory"<sup>71</sup>, from 6 June 1944. The abstract:

The various measuring techniques are reviewed and the results correlated. It is concluded that any power in the range  $10^{-4}$  to  $10^{-13}$  watts can be measured at S band frequencies to accuracies of  $\frac{1}{2}$  db [12 per cent] by using our S band signal generator, calibrated by an appropriate standard.

The standard was a lab set up using a 2100 K tungsten lamp. Various receivers could be checked out in the lab and then the more portable signal generator was used at the remote radar stations, based on the calibration against the standard lamp.

Payne-Scott wrote an internal report on 7 December 1945 for Pawsey: "Derivation of Incident Radiation from Resistance Noise Concept". She had read George Southworth's paper (see *Cosmic Noise* pages 91 to 99) published in 1945: "Microwave Radiation from the Sun" in the *Journal of the Franklin Institute* vol 239, p 285, describing his detection of the sun in 1942 and 1943 at Bell Labs in New Jersey at 3.06 GHz, 9.4 GHz and 24 GHz. Payne-Scott had found an error of about a factor three in his derived flux density.<sup>72</sup>

Pawsey wrote Southworth (whom he had met in Princeton in 1941) on 7 December 1945 and included a copy of Payne-Scott's memo<sup>73</sup>:

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<sup>71</sup> Details of the hardware designed by Payne-Scott were published in RP 211 in 1944 "A Thermal Noise Generator for Absolute Measurements of Receiver Noise Factor at 10 cms" from 29 May 1944. A photo of the noise tube designed by Payne-Scott is shown in *Making Waves*, p. 78

<sup>72</sup> Sullivan (, p 97) has provided an illuminating explanation of this error: "Southworth's Miscalculation of Solar Brightness Temperature"

<sup>73</sup> NAA C3830 B 51/14

We have in this Laboratory recently been interested in radiation received from the sun and stars [sic]. Some observations at 1.5 m (200 MHz) showed a very high level of radiation from the sun during periods of solar activity, corresponding to a black body temperature of  $10^7$ K. This high level was absent at the time of the peak at wavelengths of 50 and 25 cm...

The results at 25 and 50 cm are in conformity with the results on 1-10 cm you have reported .. in the April issue of the *Journal of the Franklin Institute*... A colleague of mine, Miss Ruby Payne-Scott has pointed out what appears to be an error in your calculations.... I agree with [her] working and would like to ask your opinion on the subject....

... [W]e conclude that you have over estimated the black body radiation by a factor of order 3 and conversely that the equivalent temperatures at the low [3.06 GHz] and intermediate frequencies [9.4 GHz] should be not 6000 K but about 20000 K.

.. I myself retain very pleasant and vivid memories of my visit [to Bell Labs] in 1941 and I hope that if I should visit the States in the not far distant future I may have the privilege of renewing our acquaintance.

Payne-Scott's three-page memo provided a simple straight forward derivation of the relation of the measured temperature and the total flux density using the Rayleigh-Jeans law and the Johnson noise formula. Payne-Scott referred to her derivation: "[My] formula, [which] was derived in a less direct fashion, is given by RE Burgess of the National Physical Laboratory of the UK."

Southworth replied to Pawsey on 4 September 1945<sup>74</sup>. He seemed to have been embarrassed by Pawsey's letter:

The error in my paper entitled: "Microwave Radiation from the Sun" which has been noted by Miss Payne-Scott is, of course, quite real. I had, however learned of it (ad nauseam) through one of my colleagues [name not mentioned but known to be Charles Townes] and accordingly had sent a correction note to the editor of the *Journal of the Franklin Institute*. [Townes's name was listed in the published erratum.]

To have made such a mistake is, of course, quite inexcusable particularly that it was in the nature of a blunder rather than one of the many elusive errors that may on occasion creep into an experiment. Although I had previously been suspicious of sizable errors of experiment, possibly greater than the three-fold error you have mentioned, it now seems possible that the higher temperatures which seem to follow, are real.....

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<sup>74</sup> NAA C3830 A1/1/1 Part 1

Paul Wild gave the first S.F. Smerd Memorial Lecture, "The Sun of Stefan Smerd" published in 1980 (in Kundu and Gergely, "Radio Physics of the Sun", IAU Colloquium, page 5) in which he included a short text describing the success of October 1945, and the work done by Payne-Scott on the calibration of the radio intensities:

By the end of the war Hey, at metre wavelengths, and Southworth, at centimetre wavelengths, had discovered the Sun's radio emission. Meanwhile in Sydney the CSIRO Division of Radiophysics, which had been preoccupied for 6 years with military radar, sought new fields of research appropriate to peacetime. Joe Pawsey, later to become the father figure of Australian radio astronomy, learned of the metre wavelength solar emission through a New Zealand report, and immediately sought to detect the emissions using military radar receivers north and south of Sydney Harbour. The Sun was first detected on 3 October 1945.

The radiation was highly variable and found to correlate with sunspot number. A few months later, using the sea as the mirror in a Lloyd's mirror interferometer and with the fortuitous aid of a giant sunspot group, Pawsey and his colleagues demonstrated that the emissions came from the vicinity of sunspots. **Meanwhile much attention was being given to the question of accurate calibration of the receiving equipment and the quantification of the radiation [Payne-Scott's research]. This led to Pawsey's concept of the "apparent temperature",  $T_a$ , of the solar disk.**[our emphasis] Pawsey noticed that whilst on many days there were readings of  $T_a$  hundreds or thousands of millions of degrees Kelvin, the value at metre wavelengths never went below about  $10^6$  K. He discussed this result with the eminent ionospherist, Dr D. F. Martyn....

### **Radio Interferometry proposal by Pawsey 1940**

Pawsey's proposed Michelson radar interferometer has not been discussed in previously published descriptions of his career. At the end of 1940, he had been at RP in Sydney for about 11 months. On 20 December 1940<sup>75</sup>, he published an internal technical memo RP 58/1: "Phase Dependent Elevation Aerial", classified as "most secret".

The problem was to directly determine the elevation of oncoming aircraft with a GL (Gun Laying) anti-aircraft radar. The sea-cliff AW/LW (aircraft warning-light-weight) system could

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<sup>75</sup> His report had been submitted a month earlier on 29 November 1940 for approval.

only determine the elevation in an indirect fashion with large uncertainties. The memo described an interferometer (see Chapter 37):

It is possible to determine elevation from measurements of the phase difference [his emphasis] between the equal fields at two points separated in a horizontal line. This method has the virtue that the readings are independent of the reflection coefficient of the ground, [due to the large angular extent of the foreground, which would be resolved out by the interferometer.]

Pawsey's scheme consisted of a proposed set-up where it was "possible to move aerials which have fixed feed arrangements". Fig. 38 shows his simple sketch. Although Pawsey ended his report with the suggestion that the system was "worthy of an experimental investigation", there is no evidence that this was attempted. In 1942, the Australian military (Chapters 9, ESM\_9.4 and ESM\_9.5) realised that the necessity for aircraft warning required a simple, robust system. The LW/AW system was invented to provide defence against Japanese air attacks, with a system that delivered ranges and azimuths of the incoming aircraft. The determination of elevation was indirect, with low accuracy. The interferometer scheme would have been a complex system. During an interception operation of the radar, it would have been necessary to change the separation of the aerials. Pawsey concluded: "The moving aerial system appears to be a precision system... but it is bulky and complicated mechanically." But a seed had been planted; the first Michelson interferometer at RPL was built by Alec Little and Ruby Payne-Scott in 1948 and 1949 with observations carried out between May 1949 and August 1950. Mills and Thomas also used this system to observe Cygnus A in the period May 1949 to December 1949. (Mills, B. Y., and Thomas, A. B. (1951). "Observations of the Sources of Radio-Frequency Radiation in the Constellation of Cygnus." *Australian Journal of Scientific Research A Physical Sciences* 4: 158.)

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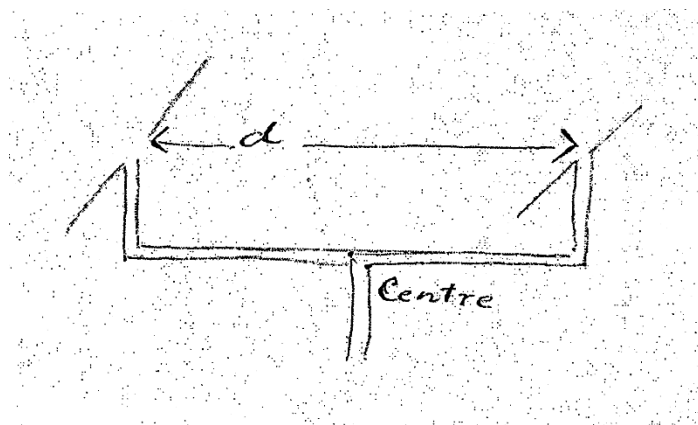


Fig 38. Pawsey's simple two-element interferometer. From the CSIRO RPL archive RP58/1.

### **The Sea-Cliff Interferometer**

The principle of the sea-cliff interferometer was described in detail by John Jaeger in 1943: "Theory of the Vertical Field Pattern for RDF [Radio Direction Finding] Stations", RP 174.

Sullivan has described this report in *Cosmic Noise*, pages 132-133:

..[D]uring the war radar beams [at frequencies below 500 MHz] often pointed at the horizon, as with search radars on a ship or a coastline. The reflected signal from a distant aircraft was well known to oscillate as it passed through the fringes of such a radar.

This set-up was a "Lloyds mirror" interferometer as the direct wave from the aircraft interfered with the reflected wave from the sea. (Chapter 37) The effective baseline of the interferometer was twice the cliff height (e.g. a cliff height of 85 m at Dover Heights near Sydney). The Jaeger paper contained a mathematical description of the interference principles with detailed descriptions of many effects: the serious problem of refraction (see Appendix A13 of Goss and McGee, 2009), the earth's curvature, tides (leading to changes in the baseline of the interferometer), the orientation of the aerial and imperfect reflections from a choppy sea and a rough earth surface. He also provided numerous examples of the effects of complex foreground geographical features between the aerial and the sea. An example of the lobe pattern of a radar at 200 MHz at a height of 250 ft (76 m) is shown in Fig 39. The first three maxima responses of the radar interference pattern are shown.

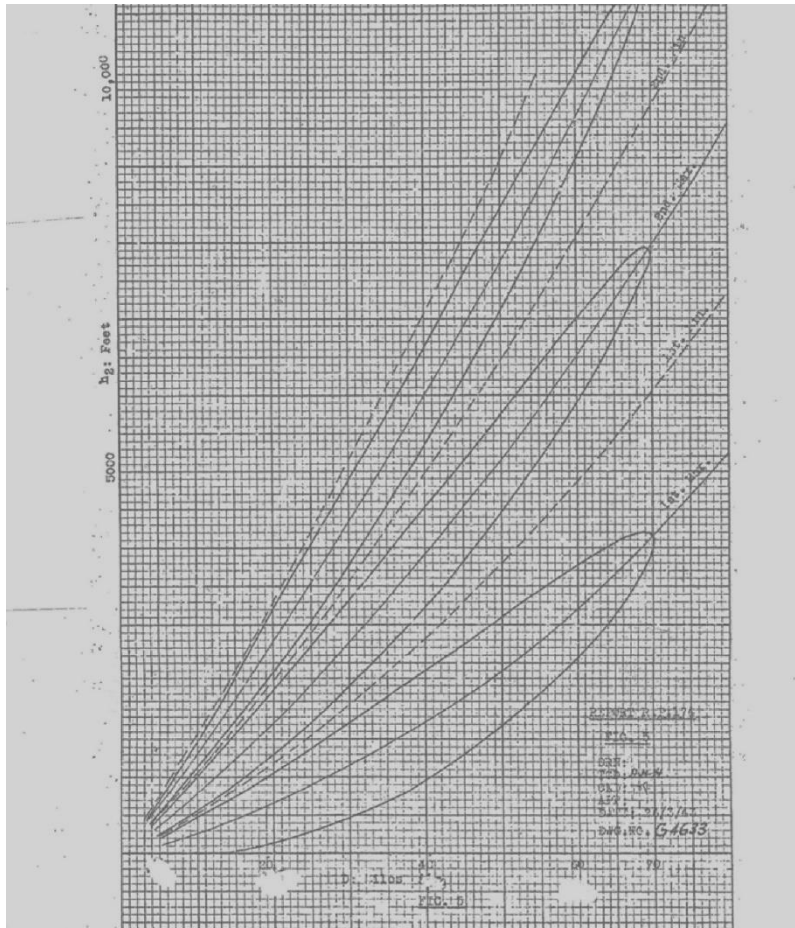


Fig 5. Jaeger: The x axis is 0 to 60 miles (0 to 96 km) and the y axis is the height of the aircraft from 0 to 10,000 feet (0 to 3000 m). Note the first three maxima responses of the radar pattern are indicated.

Fig 39. From John Jaeger: 200 MHz radar RP 174 from the CSIRO RPL Archive. The x axis is 0 to 60 miles (0 to 96 km) and the y axis is the height of the aircraft from 0 to 10,000 feet (0 to 3000 m). Note the first three maxima responses of the radar pattern are indicated.

Later during WWII, Jaeger and Pawsey with Joan Freeman published additional reports on the response of the sea-cliff radar. On 3 December 1943, Jaeger (TI 86/1) described additional calculations of “pick-up ranges” for low flying aircraft at heights ranging from 50, 100 and 200 feet. A typical transmitter (200 MHz) at 500 feet could detect a low flying aircraft at 200 feet elevation at a distance of 35 miles.

On 7 February 1944, Pawsey and Freeman wrote a “secret” memo, “Effect of the Earth-Reflected Wave on the Broad-Narrow Beam Method of Height Finding”, RP 196. The authors evaluated a British proposal in which a target was observed “alternatively on aerials having broad and narrow beams each symmetrical about the horizontal.” In this case, a test set-up at

200 MHz was constructed at Dover Heights. A number of serious problems were discovered “due to the presence of the ground at elevated points a few hundred yards in front of the aerial.” The system was subject to serious errors due to the presence of the earth reflected wave. The experimental results were somewhat ambiguous; the authors decided that uncertainties in the reliability of the proposed method precluded further investigations. The method was abandoned.

The experience with the sea-cliff interferometer during the war insured that Payne-Scott and Pawsey now recognised the power of the interferometer to achieve a higher angular resolution. In addition, they could interpret the intensity of the radiation received from the astronomical sources. They could evaluate the calibration of their instruments, that is interpret the signals received in physical units, including the derived brightness temperatures. When Ruby Payne-Scott observed fringes at sunrise on Australia Day 26 January 1946 at Dover Heights (chapter 12), she knew immediately the brightness temperature of the solar signals. Her recognition that the sizes of the solar emission regions were much less than the 30 arc min size of the solar disk and the large brightness temperatures of at least  $3 \times 10^9\text{K}$  implied a non-thermal emission mechanism for the solar emission associated with the sunspot.

#### **ADDITIONAL NOTE 2. Cambridge data from June 1946, first Michelson interferometry from Cambridge**

The Cambridge 175 MHz observations carried out from 20 July -1 August 1946 by Ryle and Vonberg provided a limit on the size of the strong radio emission associated with the prominent sunspot of late July. The upper limit of 10 arc min lead to the conclusion (*Nature* vol 158, p.339, 1946, “Solar Radiation at 175 MHz”, published 7 September 1946, paper submitted 22 August 1946): “Since the value obtained [10 arc min] does not greatly exceed the diameter of the visual spot, it is reasonable to relate the source of this radiation with the visual spot itself, or a region closely associated with it.”

Another important result in the Ryle and Vonberg paper was the detection of circular polarisation of the Type I bursts. In an adjacent publication (also 7 September 1946), Appleton and Hey reported circular polarisation of the solar bursts. In the preceding week’s edition of *Nature* (31 August 1946) David Martyn had also reported circular polarisation based on his observations at 200 MHz at Mt Stromlo, using the receiving system provided by RPL.

In contrast to the Sydney data obtained earlier in 1946, no positional information was available from the Cambridge data since absolute phase information was not available. The Sydney observations (MPP) were carried out in January to March 1946, the paper was submitted 22

July 1946 and finally published 13 months later on 22 August 1947, 11 months after Ryle and Vonberg.

### **ADDITIONAL NOTE 3. McCready's reaction to the Bolton/Payne-Scott conflict in 1948**

Goss (2013, p. 165) has described the chronic conflict in 1948 between Bolton and Payne-Scott. McCready wrote to Pawsey on 9 June 1948<sup>76</sup>: "... the 'feud' between Bolton and Ruby is still on, and leading to stupid and undesirable secrecy". This open infighting probably continued until Pawsey returned in October 1948. McCready exhibited weak leadership in handling this major disruption:

If you are wondering why we can't solve our own problems I would point out that everyone rightly regards you as leader and my impression is that Taffy has too many other worries at the moment to be bothered with things I should attend to ... far better to handle it the way we are attempting than getting Taffy to give orders ... Please don't imagine that people have gone completely haywire in your absence. As I said before I think I could patch it up and would have, but for many reasons decided to take no direct action as the matter is by no means urgent now that John [Bolton] is occupied in N.Z. [Cosmic Noise Expedition to New Zealand from June to mid-August 1948] ... and it has one advantage viz. Ruby is greatly spurred on!

In this letter McCready was also critical of Bolton for the first time: "There is evidence that he is attempting to go beyond his 'sphere of influence' and terms of reference as laid down before your departure ... it must be done with the leader's approval and the knowledge of other members." Clearly McCready was out of his depth in dealing with these two strong personalities!

### **ADDITIONAL NOTE 4. Payne-Scott's failure to observe Type II bursts at Hornsby in 1948**

In the publication of 1949 (Payne-Scott, R. (1949). "Bursts of Solar Radiation at Metre Wavelengths." *Australian Journal of Scientific Research A Physical Sciences* 2: 214), Payne-Scott described the confirmation of the second delays (Type III). However, there was a striking non-detection of any Type II events with delays of minutes, as had been observed on 8 March 1947, the *Nature* paper of August 1947:

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<sup>76</sup> NAA C4659/8

The present section takes up again the question of time delays of the order of seconds, confirming and elaborating the original suggestion [in the *Nature* paper of 1947]. However, on the question of longer delays, the present author has never since, in the recording of hundreds of bursts, obtained any evidence for delays of the order of minutes. Either the case reported earlier was very unusual, or the record was misinterpreted; as the relative amplitude of different portions of a complex burst may be very different on different frequencies, such a misinterpretation of a single case is quite possible.

During the course of 1948, Payne-Scott wrote Pawsey twice with serious misgivings about the minutes delay bursts. She was especially fearful that he would emphasise these events in his major solar review paper that was being prepared at this time.<sup>77</sup> She wrote in two letters from 18 May and then 11 June 1948 to Pawsey in London<sup>78</sup>:

[I have] never seen anything like this [the 4 min delays for various frequencies during the outbursts] since. There is the possibility that it was a bad interpretation.

I am still rather worried by the use of this figure [the 8 March 1947 giant outburst] in so far as it shows delays. The Dover records were very messy and Martyn at the time criticised our interpretation of them. Of dozens of outbursts during the last six months, I have only once seen an analogous case, in which outbursts appeared to have a markedly different appearance on different frequencies. This occurred on May 14 last, when a fade-out was accompanied by outbursts on 200, 85 and 60 MHz.... when an outburst occurred on 200 and 60 there was nothing on 85 [her emphasis] for over a minute...

But in the end, Pawsey did publish a copy of the famous figure of the giant outburst of 8 March 1947 in his review paper (page 293 his Figure 4).

What is the reason that Payne-Scott failed to detect the Type II bursts with their minutes delays?

Both Paul Wild and Woody Sullivan have discussed this dilemma. Wild has provided a similar response in both 1955 and 1985 with more details in the latter. In his 1955

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<sup>77</sup> "Solar Radio-Frequency Radiation" published in 1950: *Proc. Institute Electrical Engineering Part III*, vol 97, page 290. See Goss and McGee (2009, UTR, page 286, appendix E) for a description of the tortured history of this review paper. Goss (*Making Waves*, page 158) has also described Payne-Scott's attempt to persuade Pawsey not to include a description of the 8 March 1947 Type II burst.

<sup>78</sup> NAA C4659,8 and C3830 F1/4/PAW/1 Part 2

review paper in *Vistas in Astronomy*, vol 1, p. 573 “Outbursts of Radio Noise from the Sun” he wrote:

Evidence of interest in the interpretation of outbursts has been obtained from the study of the relative times of onset at different frequencies. The first evidence on time delays was given by Payne-Scott, Yabsley and Bolton (1947). Recording simultaneously on 200, 75 [sic, actually 100], and 60 MHz they found that outbursts of exceptionally high intensity occasionally showed systematic time delays of the order of minutes, the high frequencies preceding the low. However, in a subsequent extended series of observations Payne-Scott (1949) found no further evidence of similar delays and pointed out the difficulty of relating different portions of a complex burst at different frequencies. To resolve the difficulty a technique is required by which the spectrum of the outburst is examined over a continuous range of frequencies. Such a technique is the basis of the first of the [new] investigations.

In 1985, Paul Wild elaborated in his thorough introduction to the volume *Solar Radiophysics*, edited by Don McLean and Norm Labrum<sup>79</sup>:

However, in a subsequent extended series of observations Payne-Scott (1949) found no further evidence of similar delays and was inclined to believe that the long delays of that one event were fortuitous. She stressed the difficulty of identifying corresponding features of a complex burst at different frequencies. Clearly, a technique was required by which the phenomena could be examined over a continuous range of frequencies. An obvious next step, therefore, was to develop a radiospectrograph to record the intensity of the solar emission as a continuous function of frequency and time, [a dynamic spectrum].

Sullivan (*Cosmic Noise*, 2009, page 305] followed with additional details, including some aspects of the interpretation, attributed to Wild:

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<sup>79</sup> In his Pawsey lecture of 30 April 1968 (*The Australian Physicist*, vol 5, 1968, p 117) “The Exploration of the Sun by Radio”, Wild discussed the problems faced by Payne-Scott in her observations of 1948 at Hornsby. “In 1949, the first spectroscopic observations were made [at Penrith]. In four months of solar observations, five outbursts [Type II] were recorded, each showing a slow frequency drift consistent with [the Payne-Scott] results [of March 1947]. ... In most cases [the later observations at Hornsby], it would have been difficult [for her] to recognize the drift without continuous frequency observations and then only with a lucky choice of frequencies.”

The complex frequency-time structure now seen in the Type IIs made it clear why Payne-Scott had not been able to find them despite long observations during 1948 with separate receivers at spaced frequencies. Wild assumed that their drift in frequency indicated a disturbance moving outwards through the solar corona, somehow exciting the emission of radio waves in regions of lower and lower density. In each region, a broad band of frequencies might be generated, but only those with frequency greater than the critical frequency at that location could escape.

The major issue with the low-angular resolution Payne-Scott observations of 1948 was that for the rare and **slowly evolving** Type II outburst, a large simultaneous observation over a wide frequency range was required in order to discern the continuity of the drifting burst at a rate of about 0.25 MHz per sec. leading to delays in time of some minutes.