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THE ORIGIN AND DEVELOPMENT OF EXTRAGALACTIC RADIO ASTRONOMY: THE ROLE OF THE CSIRO'S DIVISION OF RADIOPHYSICS DOVER HEIGHTS FIELD STATION IN SYDNEY

Wayne Orchiston
National Astronomical Research Institute of Thailand, 260 Moo 4, T. Donkaew, A. Maerim, Chiang Mai 50180, Thailand.
Email: wayne.orchiston@narit.or.th

and

Peter Robertson
School of Physics, University of Melbourne, Parkville, Victoria 3010, Australia.
Email: prob@unimelb.edu.au

Abstract: Initial post-war developments in non-solar radio astronomy were inspired by Hey, Phillips and Parson's report in 1946 of an intense source of radio emission in Cygnus. This so-called 'radio star' was unique, and questions immediately were raised about its true nature. But it did not remain unique for long. Observing from Sydney, John Bolton, Gordon Stanley and Bruce Slee followed up the Cygnus discovery with more radio star detections, beginning what would evolve into a long-term multi-faceted research program and one of the mainstays of the CSIRO's Division of Radiophysics. But more than this, these early discoveries in England and in Sydney opened up a whole new field of investigation, extragalactic radio astronomy, which has remained a major area of investigation through to the present day.

This paper focusses on the early years of this program when the observations were carried out at Dover Heights Field Station in Sydney, and the ways in which new developments in instrumentation that allowed a major expansion of the program eventually led to the closure of Dover Heights and the founding of the Fleurs Field Station.

Keywords: radio astronomy, field stations, Dover Heights, 'radio stars', discrete sources, sea interferometers, John Bolton, Richard McGee, Bruce Slee, Gordon Stanley, Kevin Westfold

1 INTRODUCTION

Towards the end of 1945 and in early 1946 pioneering solar radio astronomy was carried out by staff from the Division of Radiophysics (henceforth RP) at a number of WWII radar facilities in Sydney (Orchiston et al., 2006). Some of these soon became RP field stations (Orchiston and Slee, 2017), and one of these was situated at Dover Heights in the eastern suburbs of Sydney. This 5-ha facility was located on a 79-m cliff top overlooking the Tasman Sea, 5 km south of the entrance to Sydney Harbour (see Figure 1). The site offered two concrete blockhouses, a WWII radar antenna and direct access to water and power (Figure 2). Despite its suburban location and the presence of a nearby road, it proved a radio-quiet site at the wavelengths the RP scientists were interested in.

From the start, three young RP staff members would form the nucleus of a team that for the next eight years would investigate non-solar radio emission at Dover Heights. They were John Bolton, Gordon Stanley and Bruce Slee, and all three would go on to build international reputations in radio astronomy. The leader of the group was John Gatenby Bolton (1922–1993; Figure 3; Robertson, 2017), who was born in England and after graduating from Cambridge University served in the Royal Navy. In 1946 he joined RP, and was assigned to the Dover Heights Field Station. He later served as Professor of Radio Astronomy at the California Institute of Technology (Caltech) in the USA and inaugural Director of the Owens Valley Radio Observatory before returning to RP as Director of the Parkes Radio Observatory. He remained at RP until his retirement. Gordon James Stanley (1921–2001; Figure 4; Kellermann et al., 2005) was born in New Zealand and trained as an engineer. In early 1944 he began working at RP, and in 1954 joined Bolton at Caltech, becoming the second Director of the Owens Valley Radio Observatory. He then set up a company specialising in sensor technology. Owen Bruce Slee (1924–2016; Figure 5; Orchiston, 2004; 2005) was born in Ade-

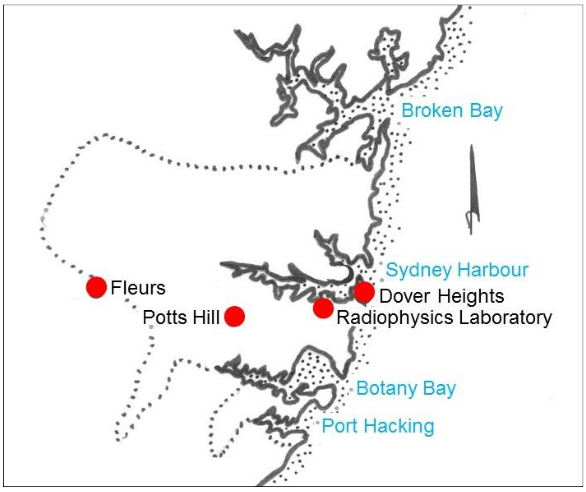
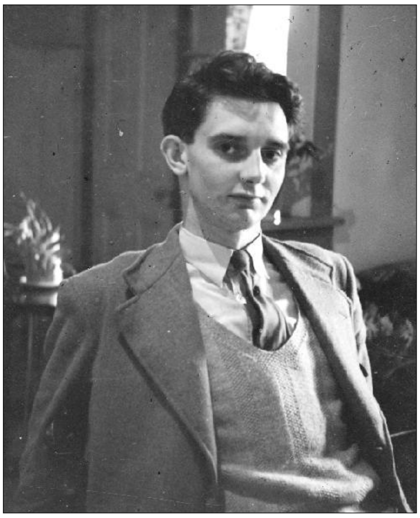


Figure 1: Radio astronomy localities in the Sydney region mentioned in text. The dotted outline shows the current approximate boundary of Greater Sydney. Scale: from Fleurs to Dover Heights is 48 km (map: Wayne Orchiston).

Figure 2: A view looking north showing the Dover Heights radar station in the foreground, and beyond it North Head (where there also was a radar station) and the entrance to Sydney Harbour. The radar antenna on the roof of the cliff-side blockhouse was used initially for solar radio astronomy, then it was removed and the Yagi antennas used by Bolton, Stanley and Slee were installed on the roof of the blockhouse (courtesy: CSIRO Radio Astronomy Image Archive (henceforth CRAIA) B81-1).



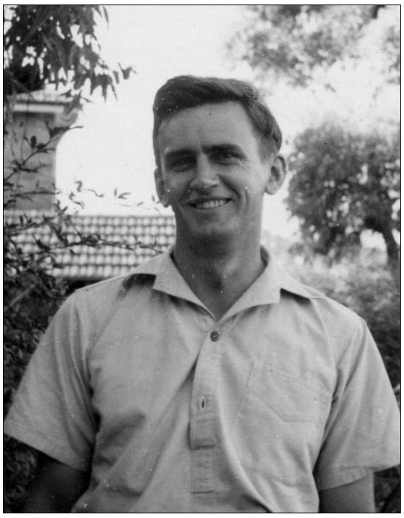


Figure 3 (left): John Bolton in 1948 (courtesy: Bolton family). Figure 4 (centre): an undated photograph of Gordon Stanley (courtesy: Stanley family). Figure 5 (right): Bruce Slee in 1947 (courtesy: Bruce Slee).

laide, and trained as a radar technician. After serving at a number of different radar stations during the War and independently discovering solar radio emission (Orchiston and Slee, 2002a), he joined RP and apart from a short period in England he remained at RP and its successor, the Australia Telescope National Facility, until his retirement.

Although these three scientists were the mainstay of the source survey work at Dover Heights, they were joined for short intervals by other scientists, who will be introduced at the appropriate spots in the following narrative.

2 THE EARLY SEA INTERFEROMETERS AND DETECTION OF THE FIRST 'RADIO STARS'

In early 1947 February, Bolton and Stanley installed two different Yagi arrays at Dover Heights in order to study solar radio emission. One consisted of a 100 MHz 2-Yagi array (Figure 6), and the other a 200 MHz 4-Yagi array (Figure 7). Bolton and Stanley succeeded in detecting solar bursts in March and April (see Payne-Scott et al., 1947), but solar activity declined during May and by June had all but ceased. It was at this stage that Bolton and Stanley decided they would "… conduct an empirical search for radio sources …" (Bolton, 1982: 350).

In order to do this the two arrays were set up facing due east, with the Yagis positioned horizontally. The plan was to use each array as a sea interferometer, the principle of which is clearly explained by Pawsey and Bracewell (1955: 62):

> The simplest method of realising a twin-wave interferometer is that employing a single aerial on a cliff overlooking the sea. The beam is directed horizontally towards the place where the source being studied [or searched for] will rise or set and interference is produced between the direct ray and one reflected from the sea in a manner similar to the interference fringes produced by Lloyd's mirror in optics.

This is illustrated in Figure 8.

After correcting for refraction, curvature of the Earth's surface, and in some circumstances tidal variations, the commencement of the interference fringes pinpointed the position of a source as it rose over the eastern horizon, while the ratio of fringe maxima to minima provided a measure of source size, *W*, via the formula

$$W = (\lambda/\pi h)\sqrt{3R}, \qquad (1)$$

where *R* is the ratio of the received power (above the extrapolated background level) at the maxima and minima of the interference pattern, *h* is the height of the antenna above sea-level and λ is the wavelength (for details see Bolton and Slee, 1953; Stanley and Slee, 1950).

Almost immediately Bolton and Stanley were successful in their quest:

> On the first night of observation a cable broke on the 200 MHz aerial … [but] The 100 MHz equipment which was directed towards the north-eastern horizon gave a sea interferometer pattern of a source in Cygnus which was clearly that previously seen by Hey. (Bolton, 1982: 350).

In his account of this initial detection, Stanley (1994: 509) was a little more circumspect: although "Cygnus appeared on the first record … it took some days until we could be perfectly sure, as the system was erratic." The fringe pattern, meanwhile, indicated a source size of less than 8 minutes of arc, although Bolton and Stanley (1948b: 31) were careful to stress that this "… is an upper estimate and the source may well be effectively a point." Over the next three months Bolton and Stanley observed the Cygnus A source (as it became known) at 60 MHz (with a 2-Yagi array), 85 MHz (with a single Yagi), 100 MHz and 200 MHz, using converted radar receivers in each instance, with no notable modifications apart from the introduction of a 2-stage preamplifier in the 200 MHz set (Bolton and Stanley, 1948a). The majority of the observations were obtained at 100 MHz (a frequency free from man-made interference), and these revealed an approximate position for the source of R.A. 19h 58m 47 ± 10s and Dec. +41° 47 ± 7′, a position devoid of any obvious optical correlates (ibid.) Meanwhile observations at the four different frequencies provided useful spectral data.

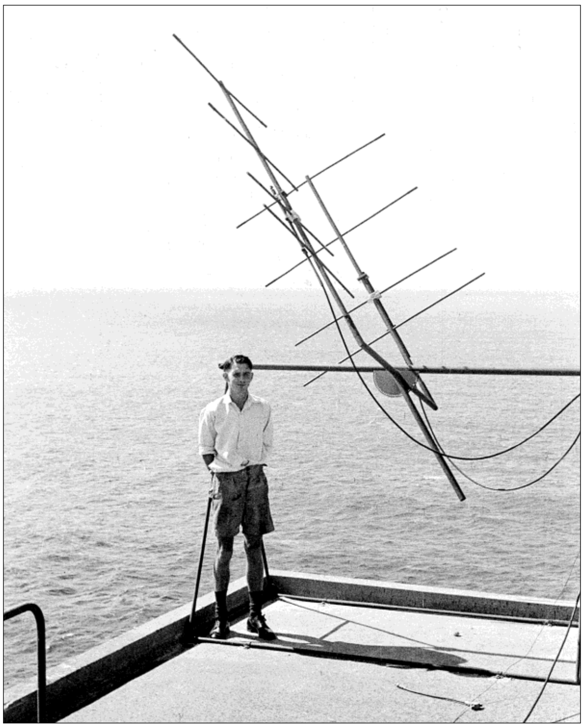


Figure 6: John Bolton and the 100-MHz twin Yagi antenna on the roof of the blockhouse at Dover Heights. The two elements could be positioned horizontally, pointing to the eastern horizon, to form a sea interferometer (courtesy: CRAIA, B1031-7).

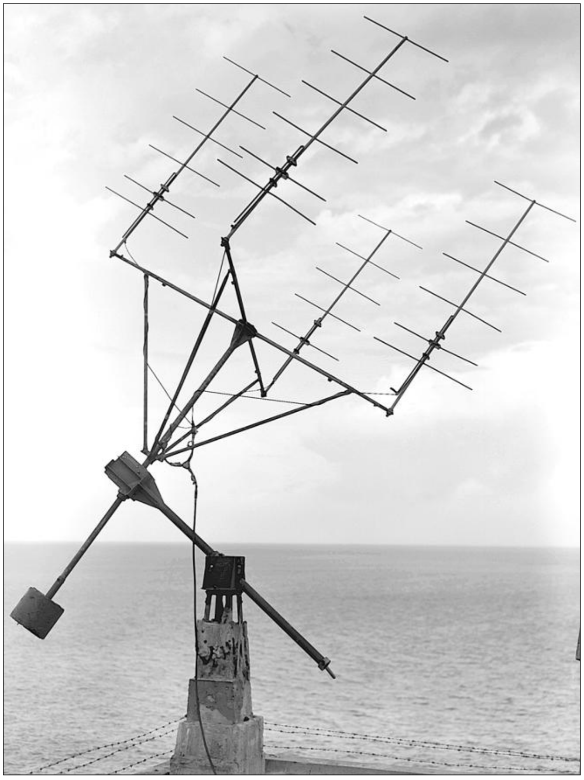


Figure 7: The 200 MHz 4-element Yagi array on the roof of the blockhouse at Dover Heights (courtesy: CRAIA B1165-2).

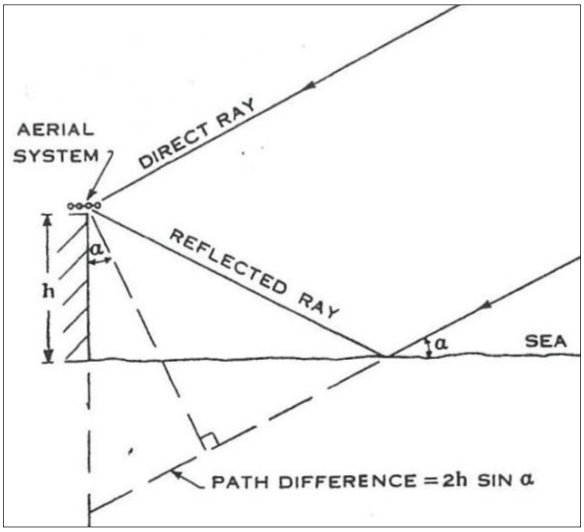


Figure 8: A schematic diagram of the sea interferometer. The cliff-top aerial combines the direct signal with the signal reflected from the sea to create an interference pattern. These two signals produce maximum intensities when their path lengths differ by an even number of half-wavelengths and minimum intensities when path lengths differ by an odd number of half-wavelengths. The reflected signal simulates an imaginary aerial, spaced from the real aerial at a distance equal to twice the height of the aerial above sea-level. The difference in path length between the direct and reflected signals is given by $2h \sin\alpha$, where h is the height of the aerial above sea-level and α is the angle of incidence of the reflected signal to the sea surface, corrected for the curvature of the Earth and atmospheric refraction of the signal (after Stanley and Slee, 1950: 236).

One of the features that Bolton and Stanley (1948b: 312–313) noted was that

> The radiation consists of two components, one constant and the other showing considerable variation over short and long periods … The periodicity of the variations decreases with decreasing frequency. No close correlation has been found between short-period variations on frequencies as close as 85 and 100 Mc./s., but the general activity of the variable component shows good correlation on different frequencies.

This variable component had already been reported by Hey et al. (1946) and was non-solar and non-terrestrial in origin, but what Bolton and Stanley (1948a) found particularly interesting was the fact that it was virtually absent at 200 MHz. A typical record obtained at 100 MHz is reproduced here as Figure 9, where the constant and varying components are both evident.

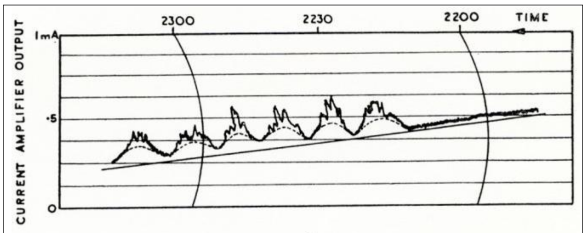


Figure 9: The interference pattern for Cygnus A recorded at 100 MHz after 10 pm on the evening of 19 June 1947 at Dover Heights. The strength of the signal decreases (towards the left) as the source rises higher above the horizon (after Bolton and Stanley, 1948b: 60).

The dashed sine wave helps clarify this.

While analysing their Cygnus A observations, Bolton and Stanley continued their search for other sources at 100 MHz, "… over about one quarter of the celestial sphere." (Bolton, 1948: 141). On 6 November 1947, immediately after having written up their Cygnus A results, they detected a second source, Taurus A, and within the next two months five additional sources. Some information on these is in Table 1.

In the *Nature* paper reporting these discoveries, Bolton (1948) comments on the difficulties associated with obtaining precise positions, and also notes that as in the case of Cygnus, the new sources do not appear to be associated with any notable stellar objects. He further suggests that the emission from these sources derives from a combination of three different components:

(a) A 'base-level' due to free-free transitions in the interstellar medium, as proposed by Henyey and Keenan (1940);
(b) Emission from individual stars in regions of high star-density;[1] and
(c) "A contribution from individual discrete sources, which may be distinct 'radio-types' and for which a place might have to be found in the sequence of stellar evolution." (Bolton, 1948: 142).

With the benefit of hindsight, these conclusions would prove to be naïve and premature. But the true nature of the 'radio stars' would only be revealed when precise source positions were available, and given the geographical circumstances at Dover Heights (and adjacent coastal New South Wales sites), this was an insurmountable challenge.

Bolton and Stanley's solution was to seek a location where the risings *and* settings of the sources could be observed without interruption, and after considering various options in New South Wales they settled on the Northland region of New Zealand (Figure 10). A simple 4-Yagi array operating at 100 MHz was mounted horizontally on an ex-Army radar trailer, and at the end of May 1948 it was shipped to Auckland. For the next three months, Bolton and Stanley carried out sea interferometer observations, first from Pakiri Hill (Figure 11) and later from Piha, near Auckland, at what could be considered RP's two most easterly field stations (for details see Orchiston, 1993; 1994; Robertson et al., 2014). Apart from the advantage of recording rising and setting times, the two New Zealand cliff-tops were considerably higher than Dover Heights (at 279 m, 265 m and 79 m, respectively), and offered horizontal beamwidths of 12° as opposed to 30° at Dover Heights (Bolton and Stanley, 1949). As a result,

> Despite the foul weather at Leigh [i.e. Pakiri

Table 1: Radio sources detected at Dover Heights up to 1 February 1948 (adapted from Bolton, 1948: 141).

Source	Position		Flux at 100 MHz (Jy)	Size	Type
	R.A.	Dec.			
Cygnus A	19h 59m	+41° 47′	6000	< 8′	Variable
Taurus A	05h 13m	+28°	1000	<30°	Variable?
Coma Berenices A	12h 04m	+20° 30′	1500	<15′	Constant
Hercules A	16h 21m	+15°	200	< 1°	
8.48			200		Constant
5.47			300	< 1°	Constant
Centaurus A			1000	<15′	Variable?

> Hill], all the NZ records were of a much higher quality than those at Dover Heights and this had a lot to do with the identifications. Also, in hindsight, custom had corrupted our thinking. Had we constructed the simplest of east-west interferometers, we could have detected Cygnus A much more easily at Dover Heights. (Stanley, 1994: 509).

To illustrate his point, Figure 12 compares Taurus A fringe patterns at Dover Heights and Pakiri Hill, where the fringe amplitude $P_{max} - P_{min}$ is given by:

$$P_{max} - P_{min} = 4P_o \quad (2)$$

and if

$$P = 2P_o[1 - \cos(4\pi h \sin\alpha/\lambda)] \quad (3)$$

then

$$P_{max} - P_{min} = 2P/[1 - \cos(4\pi h \sin\alpha/\lambda)] \quad (4)$$

where P is the power received by the antenna, P_o is the power received with the same antenna in space, h is the height of the antenna above mean sea-level, α is the altitude of the source and λ is the wavelength (Bolton and Slee, 1953: 421–422).

Because of these improved fringe patterns the New Zealand fieldtrip was a resounding success, and the observations there provided more precise positions for Cygnus A, Taurus A, Centaurus A and Virgo A. Bolton and Stanley (1949) first wrote up the Taurus A result, noting that the Crab Nebula (NGC 1952) lay within the error box of the source position. Then in a paper published in *Nature*, Bolton et al. (1949: 101) discussed all four sources, reporting that "… three [of these] sources correspond within limits of experimental error to positions of certain nebulous objects." They confirmed the association of Taurus A with the Crab Nebula, an expanding shell of the AD 1054 supernova (see Stephenson, 2004), and linked Centaurus A with NGC 5128, a well-known nebula featuring a distinctive dark 'lane' (Robertson et al., 2010), and Virgo A with M87 (NGC 4486), an unusual nebula accompanied by a conspicuous blue jet. Most astronomers identified these last two objects as extra-galactic nebulae, so it is interesting that Bolton, et al. (1949: 102) used the presence of associated radio sources to question their true nature:

> Neither of these objects has been resolved into stars, so there is little definite evidence to decide whether they are true extra-galactic nebulae or diffuse nebulosities within our own galaxy. If the identification of these objects with the discrete sources of radio-frequency energy can be accepted, it would tend to favour the latter alternative, for the possibility of an unusual object [NGC 5128] in our galaxy seems greater than a large accumulation of such objects at a great distance.

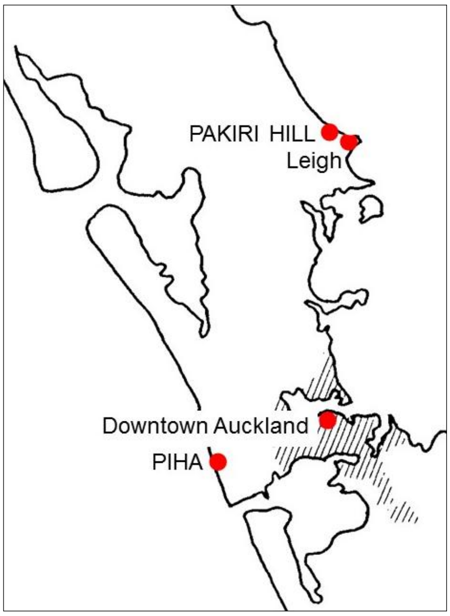


Figure 10: A map showing Auckland city and suburbs (stippled), and Pakiri Hill and Piha, where the RP observations were made (map: Wayne Orchiston).

Figure 11: The mobile radio telescope on the Greenwood farm at Pakiri Hill in June 1948. The cabin mounted on the trailer could swivel in azimuth to observe sources rising at different declinations along the horizon (courtesy: Stanley family).

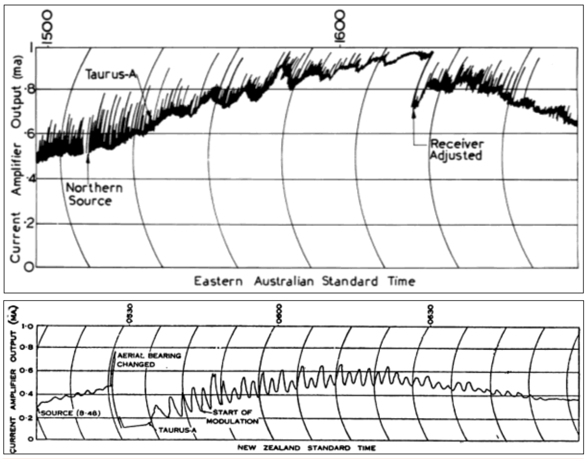


Figure 12: A comparison of Taurus A interference fringes obtained at Dover Heights (top) and Pakiri Hill (bottom) (courtesy: CRAIA, B1651-2; after Bolton and Stanley, 1949: 141).

Redshifts would soon resolve this issue leaving only the identity of the Cygnus A source in doubt, and although the derived New Zealand position of R.A. 19h 58m 14s and Dec. +40° 36′ was an improvement on the Dover Heights value (Stanley and Slee, 1950), it would take several more years and even more precise positions before an optical correlate would emerge (see Bolton, 1955; Robertson et al., 2014). Meanwhile, upon reflection and with the benefit of hindsight, Bolton (1982: 352) would later assert that

> The identification of the Crab nebula was a turning point in my own career and for non-solar radio astronomy. Both gained respectability as far as the 'conventional' astronomers were concerned. (cf. Orchiston and Slee, 2006).

One other interesting outcome of the New Zealand field trip was a resolution of the enigmatic intensity fluctuations that were so conspicuous a feature of Cygnus A (e.g. see Figure 13). While Bolton and Stanley were in New Zealand, Slee remained at Dover Heights and carried out complementary observations. A comparison of their Cygnus A records revealed that the anomalous source variations

> … were not intrinsic to the source but were probably scintillations caused by diffraction in the intervening medium, with the diffraction scale size less than 2000 km (the projected spacing between Leigh and Dover Heights).

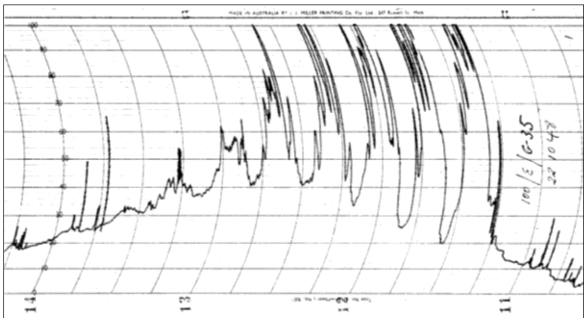


Figure 13: An example of the variable interference fringes exhibited by Cygnus A (courtesy: CRAIA, B1639-2).

> We did not get the opportunity to announce this important result [at the time] because we tried first to enlist the aid of the Cambridge Radio Astronomy group to perform some experiments with baselines up to a few hundred km in order to define the scale size with some precision. Cambridge and Jodrell Bank performed the experiment and published the results (scale sizes were 5-10 km) without acknowledgement. (Slee, 1994: 523).

Many years later, Bolton (1982: 352) mentioned how at the 1950 URSI meeting Bernard Lowell "… very graciously apologised for the form of this publication, for he had not been told of our prior work!" Soon after the publication of the Cambridge and Jodrell Bank papers in *Nature* the initial results of the Dover Heights group appeared in print, where Stanley and Slee (1950) favoured an ionospheric explanation (cf. Bolton et al., 1953).[2] They noted that intensity fluctuations also were associated with a number of other sources, particularly Centaurus A, but that "The degree and incidence of fluctuation … is considerably less than that of the Cygnus source …" (Stanley and Slee, 1950: 246).

After returning from New Zealand and while analysing their newly-acquired data, Bolton and Stanley continued their Dover Heights source survey, with assistance from Slee. Seven new discrete sources were detected during 1948.

3 LARGER YAGI ARRAYS AND THE SEARCH FOR MORE SOURCES

Early in 1949 staff from the RP workshop installed a 9-Yagi array on top of the blockhouse at Dover Heights (see Bolton and Westfold, 1950), which replaced the small 2-Yagi and 4-Yagi antennas that had been used there previously. This new radio telescope (Figure 14) operated at 100 MHz and had a beamwidth of 17°. It comprised three pairs of three Yagis on the one equatorial mounting that could, when required, be readily converted into an altazimuth mounting suitable for sea interferometry observations.

This new antenna was used to survey galactic radio emission between galactic latitudes +60° and –60° and longitudes 140°and 40°, an area of the sky that

> … includes the portion between the galactic centre (*l* = 330°) and Monoceros (*l* = 200°), which cannot be observed from northern latitudes. (Bolton and Westfold, 1950: 19).

Bolton and newcomer to the Dover Heights group, theoretician Kevin Westfold (1921–2001), also were quick to point out that their 100 MHz survey was close in frequency to the earlier surveys carried out by Hey et al. at 64 MHz and Reber at 160 MHz thus enabling

> … a complete picture of the noise distribution over the whole celestial sphere to be constructed. Such a picture will undoubtedly be of

> value in studying correlation between radio-frequency and optical data and possibly in deducing the form of the Galaxy. (ibid.).

While they were indeed able to plot the all-sky distribution of radio emission at 100 MHz (Bolton and Westfold, 1950: 30), from our viewpoint the more interesting outcome of this survey was the discovery of six new discrete sources. As a result, by the end of October 1949 Stanley and Slee (1950) were able to cite 18 different sources detected at Dover Heights between 1946 and 1949. These are listed in Table 2 in chronological order of discovery, and it is illuminating to compare some of the values given here with those in Table 1. This is particularly so of the source fluxes, and also of positions listed for Cygnus A, Taurus A, Virgo A and Centaurus A, where the benefits of the New Zealand field trip are in evidence. However, Stanley and Slee stressed that the positions entered for most other sources were approximate only, and this is borne out by referring to the positional error boxes published in their paper, and reproduced here in Figure 15.

One benefit of the sea interferometer technique is that the interference fringes could provide values or upper limits for the angular widths, *W*, of sources (see the second-last column in Table 2), via formula (1).

A particularly interesting source is 5.47, one of the 1947 sources listed in Table 1, and entered in Table 2 simply as 'Centaurus' (it is the first of the two unspecified 'Centaurus' sources). Stanley and Slee (1950: 241) discuss its status:

> One example of a possible temporary source is 5.47 … Some 10 records of this source at rising were obtained in November and December 1947. No further records were taken until June 1948, when no trace of the source could be found. Subsequent attempts to obtain records with higher sensitivity have also failed. There have been several other cases when small sources have been detected during systematic surveys—sometimes on several nights in succession—and attempts to secure additional confirmation at a later date have not succeeded … A much longer period of observation, however, will be necessary before the existence of temporary sources can be established beyond doubt.

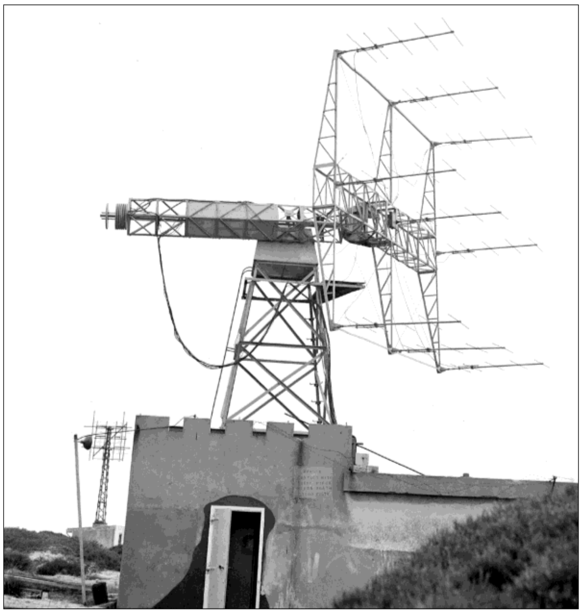


Figure 14: The 100 MHz 9-Yagi array installed on the roof of the blockhouse at Dover Heights in early 1949 and set up in sea interferometer mode (courtesy: CRAIA, B1830-2).

The other interesting discussion in Stanley and Slee's 1950 paper relates to the spectra of the sources. Using observations made at 40, 60, 85, 100 and 160 MHz, they plotted the spectra of Cygnus A, Centaurus A, Virgo A and Taurus A, and these are shown here in Figure 16.

Table 2: Discrete sources detected at Dover Heights as at 4 November 1949 (after Stanley and Slee 1950: 238).

Source	Position		Flux 100 MHz (Jy)	Size (Arc min)	Comments
	R.A.	Dec.			
Cygnus A	19h 58m 14s	+40° 36′	12500	<1.5	Amplitude variations
Taurus A	05h 31m 30s	+22° 01′	1850	< 6	Possibly the Crab Nebula
Virgo A	12h 28m 06s	+12° 41′	1250	< 5	Possibly M87
(Centaurus)			800	< 30	
Centaurus A	13h 22m 20s	–42° 37′	1850	< 7	Possibly NGC 5128
Hercules A	16h 50m	+05°	200	< 30	
Taurus C	04h 38m	+28°	300	< 15	
Taurus B	05h 32m	+24°	600	< 30	
Fornax A	03h 11m	–36°	200	< 15	
Serpens-Cauda A	18h 43m	+05°	300	< 15	
(Centaurus)			200	< 30	
(Leo)	11h 52m	+17°	100	< 30	
Scorpius A			200	< 30	
Serpens-Cauda B	18h 11m	–15°	200	< 30	
Sextans A	09h 55m	–05°	200	< 30	
(Colomba-Caelum)	05h 01m	–36	200	< 30	
Puppis A	08h 18m	–42°	300	< 30	
Pictor A	05h 18m	–44°	300	< 30	

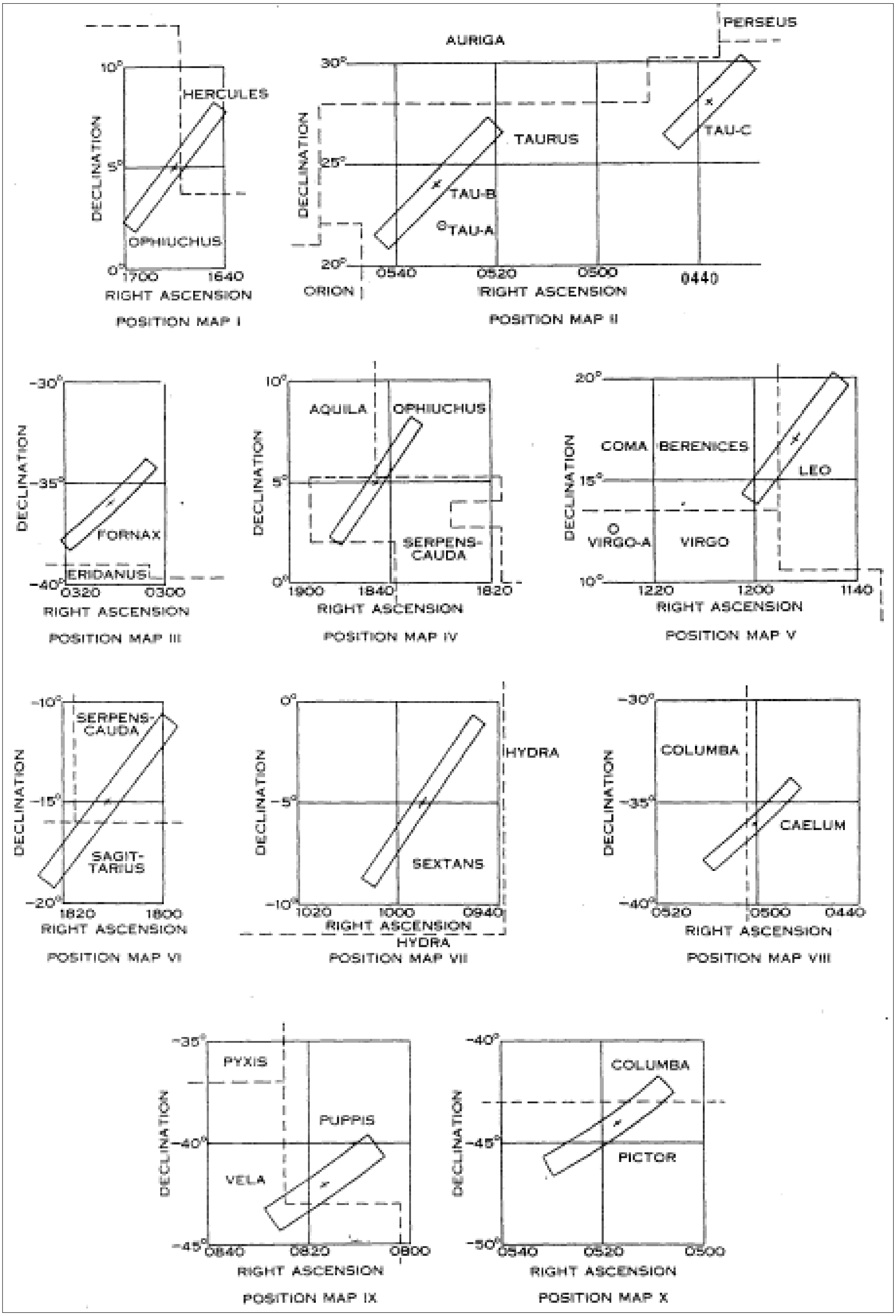


Figure 15: Positional error boxes for those sources listed in Table 2 that were discovered at Dover Heights in 1948 and 1949 (after Stanley and Slee, 1950: 240).

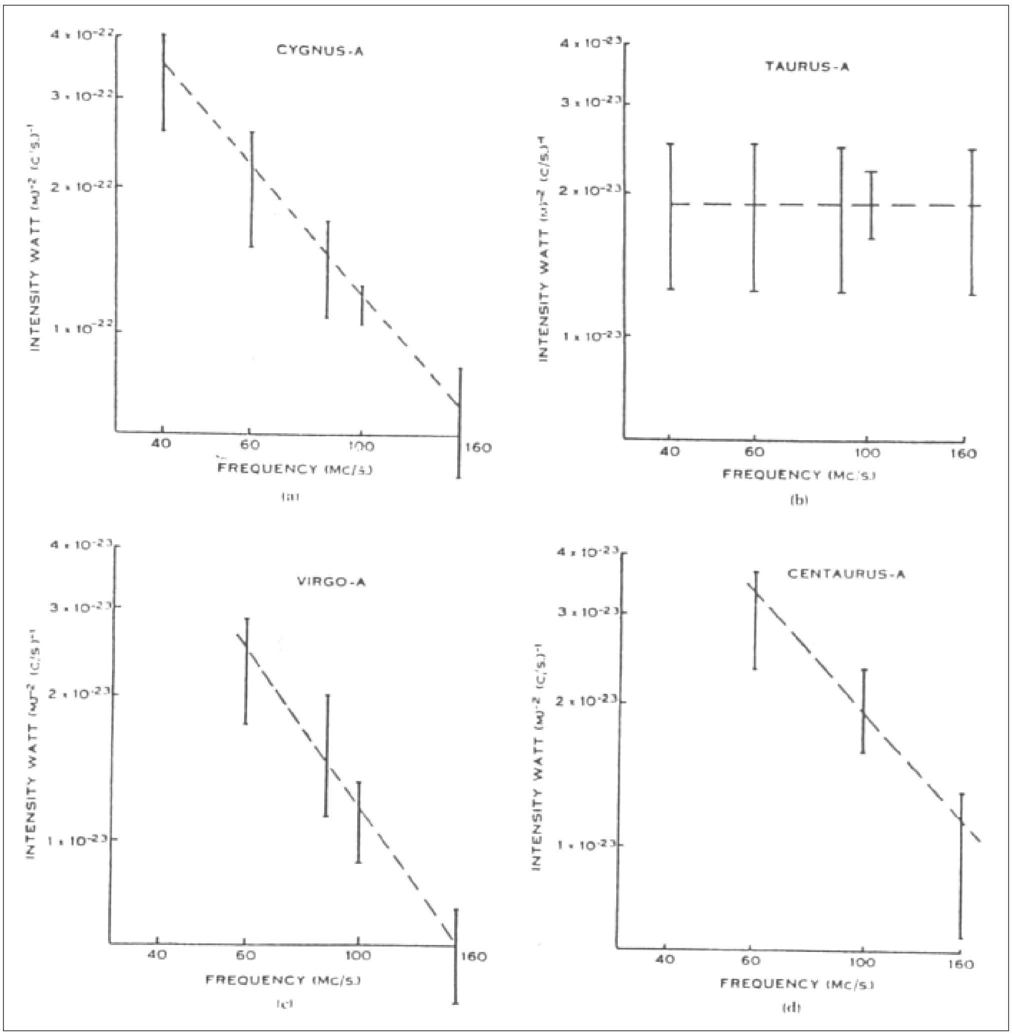


Figure 16: Spectral plots for Centaurus A, Cygnus A, Taurus A and Virgo A (after Stanley and Slee, 1950: 243).

The first three sources display typical non-thermal spectra that are associated with synchrotron radiation, but of course at the time this emission mechanism was unknown to radio astronomers (e.g. see Ginsburg and Syrovatski, 1965). Meanwhile, Taurus A reveals what at the time appeared to be a flat spectrum, "… consistent with "thermal" radiation from an optically thin shell." (Stanley and Slee, 1950: 242). In hindsight, we now know this interpretation to be wrong, and that the four data bars can just as easily accommodate a non-thermal spectrum but with a quite different gradient to that found for the other three sources. This is consistent with the non-thermal emission that is characteristic of a supernova remnant.

John Bolton spent most of 1950 overseas, and Stanley and Slee were left to carry on the radio astronomy at Dover Heights. Slee (1994: 525) continued his "… methodological study of the diurnal and seasonal behaviour of the scintillation phenomenon …" using Cygnus A, Taurus A, Virgo A and Centaurus A, and he and Stanley also constructed a 16-ft (4.9-m) parabolic dish that initially was mounted on the gun-laying trailer used on the New Zealand expedition (Figure 17), and later was relocated to the equatorial mounting on the blockhouse. This instrument was used to observe the stronger sources at frequencies between 100 and 400 MHz (Figure 18) in order to investigate their spectra (Bolton 1982; Stanley, 1994), but no searches for new sources were carried out.

A new source survey only became possible in 1951, after Bolton's return from overseas, when a new 8-Yagi array was constructed by the RP workshop staff, and installed on an ex-WWII radar altazimuth mount at Dover Heights (Figure 17). Soon after, it was extended to a 12-Yagi array, still on the same mount (Figure 19). Nine of the twelve Yagis were cannibalised from the earlier 9-Yagi array. This new radio telescope, which also operated at 100 MHz, was only possible because its "… cost was very small and [it] needed no special budgetary allocation." (Stanley, 1994: 512).

The 12-Yagi array was used during 1951 and 1952 to carry out what would prove to be the last major source survey at Dover Heights, and by far

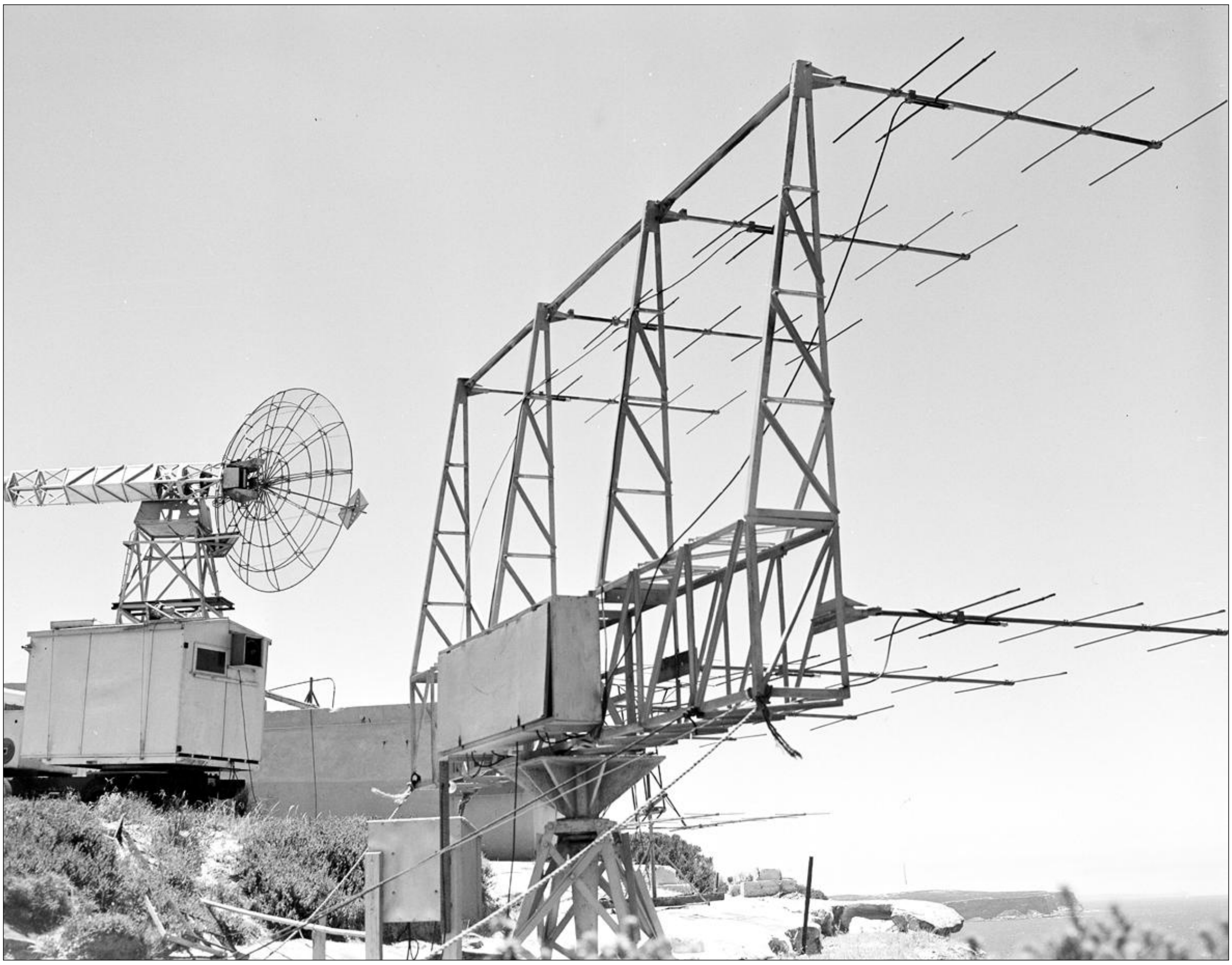


Figure 17: On the left is the 16-ft parabolic dish mounted on the gun-laying trailer and used as a sea interferometer, and in the foreground is the short-lived 8-Yagi array (courtesy: CRAIA B2650-6).

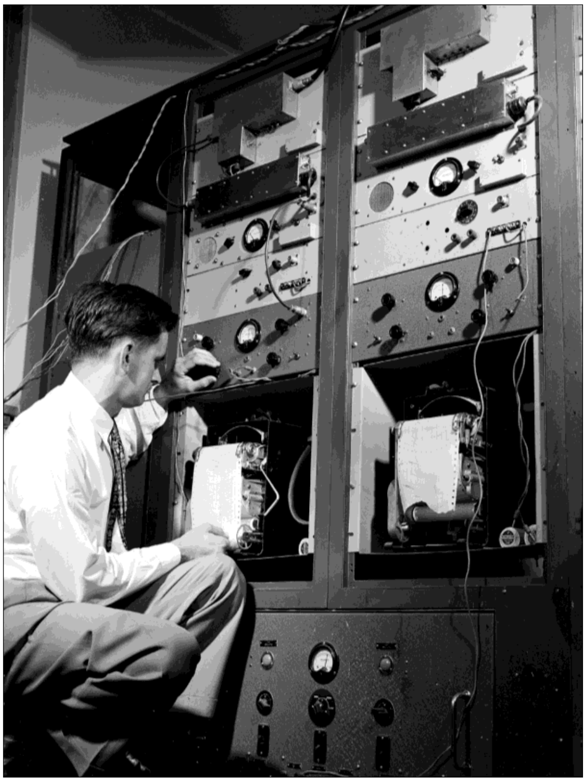


Figure 18: Gordon Stanley with two of the receivers used with the 16-ft parabola (courtesy: CRAIA, B2650-1).

most successful one. With the benefit of improved electronics and a beamwidth of just 12°, this survey produced a total of 104 sources (Figure 20; Tables 3a-3e). However, not all of the reported sources were of equal standing: while those in Tables 3a, 3b and 3c were well established, and Bolton, Stanley and Slee were reasonably confident of those in Table 3d despite some degree of confusion, the 19 sources in Table 3e were not so clear cut. They report that this table

> … contains sources for which a considerable degree of confusion exists in our observations and the particulars given are only reliable provided the observations have been correctly interpreted. (Bolton et al., 1954a: 112).

In hindsight, this level of scepticism was fully justified, for few of these 'sources' appear in the later 85.5 MHz surveys carried out by Mills, Slee and Hill at Fleurs Field Station (see Hill et al., 1958; Mills and Slee; 1957; Mills et al., 1958; 1960).

Another interesting development relating to discrete sources which occurred in 1951 was the construction of a prototype 2-element azimuth interferometer at Dover Heights. Bolton and Slee

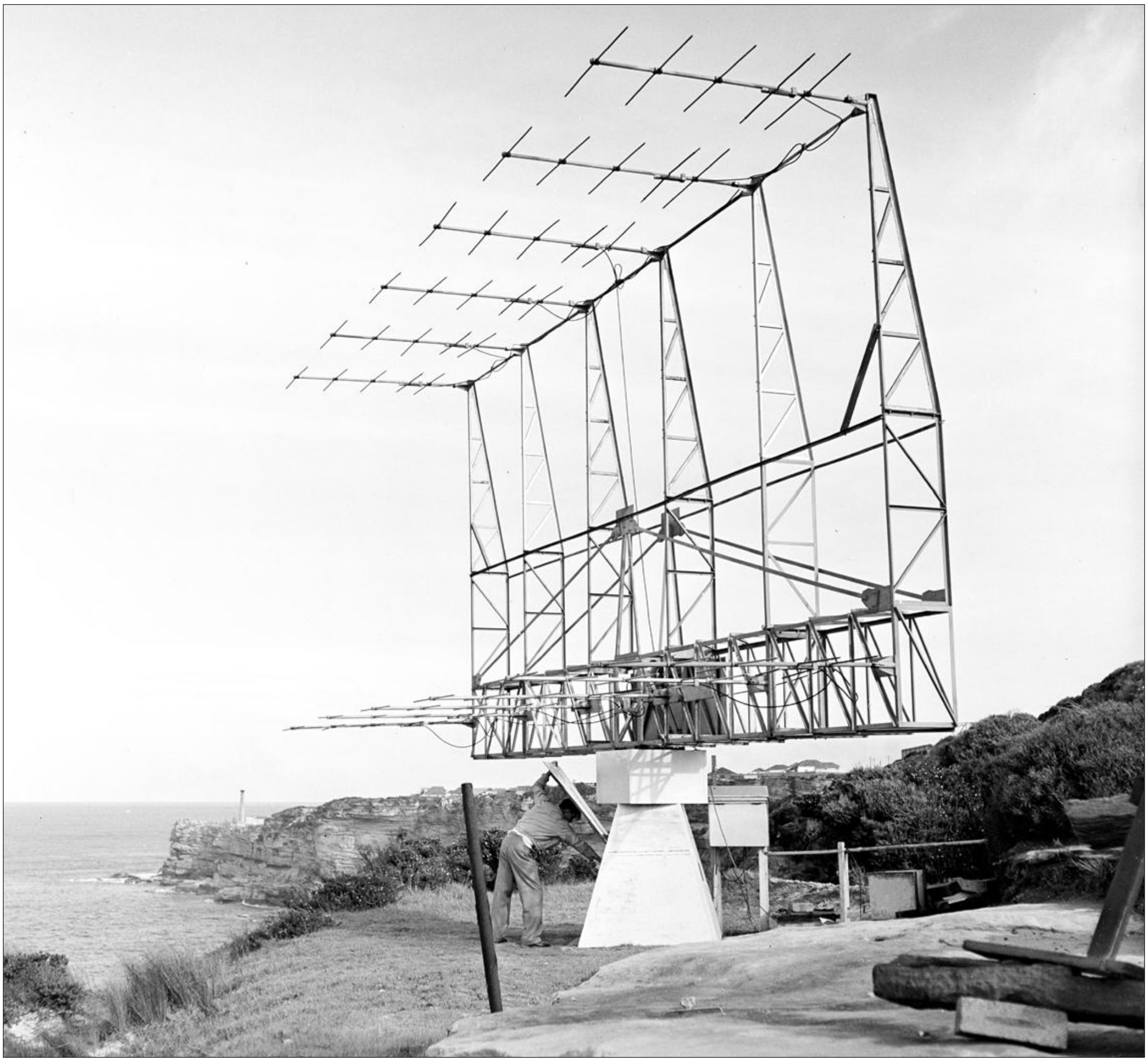


Figure 19: The Dover Heights 12-Yagi array, completed in 1952 (courtesy: CRAIA, B2763-5).

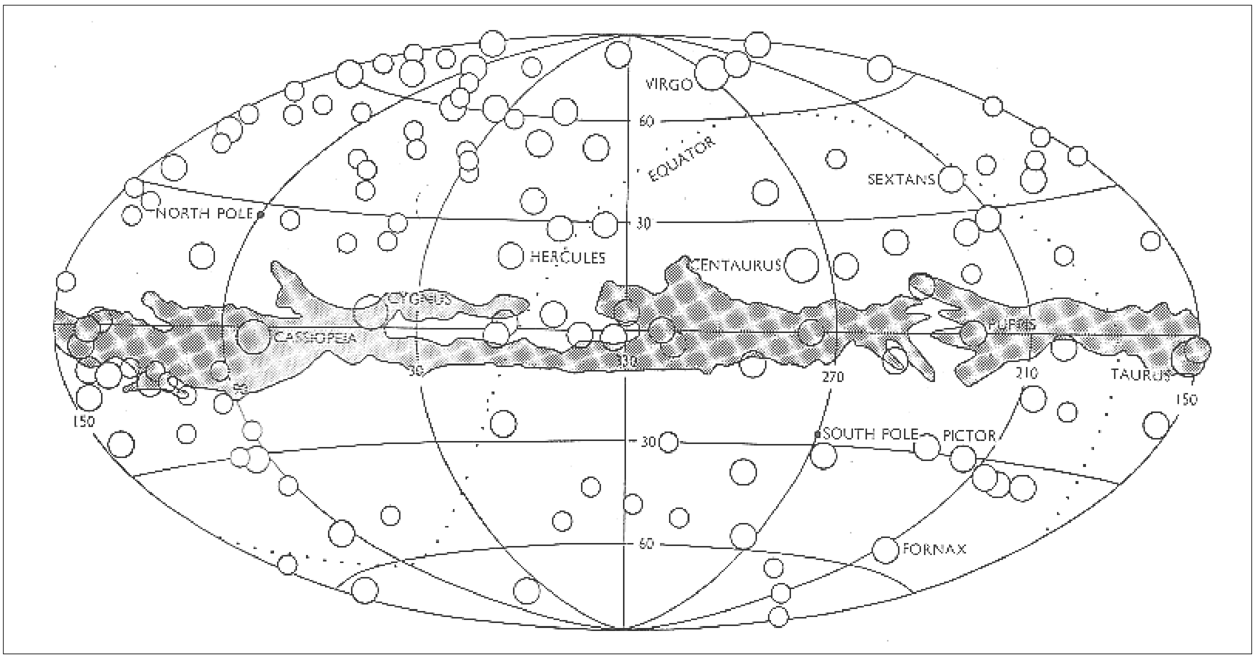


Figure 20: The distribution of discrete sources detected with the 12-Yagi array (courtesy: CRAIA).

Table 3a: Well-known bright sources recorded during the 12-Yagi array survey in 1952 (after Bolton et al., 1954a: 113).[3]

BSS Catalog Number	Position		Flux 100 MHz (Jy)	Other Catalog Numbers	Comments
	R.A.	Dec			
10	03h 17m	–37° 15′	240	M03-3	Fornax-A
2	05h 31m	+22°	1850	M05+2, R05.01	Taurus-A
21	08h 20m	–42° 30′	180	M08-4, S08-4	Puppis-A
26	09h 16m	–12°	280	M09-1A, S09-1	Hydra-A
4	12h 28m	+12° 30′	1250	M12+1, R12.01, S12+1	Virgo-A
6	13h 22m	–42° 45′	1800	M13-4, S13-4	Centaurus-A
7	16h 49m	+06°	400	M16+0, R16.01	Hercules-A
1	19h 58m	+40° 30′	12000	M19+4, R19.01, H.B.19, S20+x	Cygnus-A

Table 3b: Other well-established sources recorded during the 12-Yagi array survey in 1952 (after Bolton et al., 1954a: 114).

BSS Catalog Number	Position		Flux 100 MHz (Jy)	Other Catalog Numbers	Constellation
	R.A.	Dec			
71	01h 56m	–40°	50	M02-4	Phe
97	02h 36m	–03°	50	M02-0	Cet
62	02h 04m	–10°	70	M02-1	Cet
40	03h 09m	+41°	80	M03+4, H.B.6, R03.02	Per
8	04h 30m	+31°	300	M03+4, R04.01	Per
76	05h 08m	+46°	70	H.H.9, M05+4	Aur
22	05h 09m	–43° 30′	250	M05-4, S05-4	Pic
99	08h 08m	–06°	60	M08-0	Mon
86	09h 16m	+46°	70	H.B.12, R09.01, M09+4	Lyn
50	10h 20m	–43° 30′	80	M10-4	Vel
56	11h 38m	–15°	50	M11-1	Crt
28	13h 35m	–60°	700	M13-6, S13-5	Cen
80	15h 10m	+11°	60	M15+1	S Cp
81	16h 36m	+41°	80	M16+4, R16.03	Her
27	16h 10m	–61°	800	M16-8	TrA
120	18h 16m	–08°	150	M18-0	SCd

Table 3c: Sources recorded during the 12-Yagi array survey in 1952 for which no confusion exists, but which have not been documented by other observers (after Bolton et al., 1954a: 115–116).

BSS Catalog Number	Position		Flux 100 MHz (Jy)	Other Catalog Numbers	Constellation
	R.A.	Dec			
35	00h 58m	+15°	70	(M00+1)	Psc
38	00h 40m	–02°	70		Cet
73	00h 11m	–08°	60		Cet
83	00h 23m	–29°	50		Scl
92	01h 38m	+32°	60	(R01.01)	Tri
41	01h 30m	+28°	40	(R01.01)	Tri
95	02h 02m	+15°	50		Ari
53	03h 00m	+03°	90		Cet
39	04h 06m	+10°	60		Tau
69	05h 12m	–25°	70		Lep
52	06h 26m	–06°	70		Mon
70	08h 57m	–25°	70		Pyx
96	09h 51m	+08°	70	(M09+0)	Leo
98	10h 42m	00°	120		Sex
102	10h 07m	–29°	70		Ant
15	11h 42m	+18°	90		Leo
30	12h 19m	+05°	140		Vir
65	13h 08m	+30°	100	(M13+2)	Com
111	13h 58m	–25°	80		Hya
49	15h 30m	+20°	80		SCt
79	14h 05m	+10°	70		Boo
64	15h 58m	+03°	80		SCt
74	15h 20m	–02°	50		SCt
114	16h 44m	–43°	150		Sco
58	17h 44m	–20°	200	M17-2A	Oph

68	17h 43m	–31°	120	M17-2B	Sco
17	17h 08m	–34°	150		Sco
23	18h 45m	+08°	120	M19+0	Aql
11	18h 39m	+02°	270		Aql
48	19h 18m	+16°	200		Aql
75	19h 33m	–17°	80	S19-2	Sag
66	19h 34m	–46°	80	M19-5	Tel
33	20h 00m	+25°	70		Vol
113	20h 57m	–25°	90	S21-3	Cap
63	21h 22m	–20°	70		Cap
89	22h 26m	–05°	50		Aqr
61	23h 30m	–14°	50		Aqr

Table 3d: Sources recorded during the 12-Yagi array survey in 1952 for which some confusion exists, but which are believed to be fairly accurate (after Bolton et al., 1954a: 116).

BSS Catalog Number	Position		Flux 100 MHz (Jy)	Other Catalog Number	Constellation
	R.A.	Dec			
54	00h 56m	+03°	60		Cet
105	00h 27m	–20°	50	S00-1	Cet
57	00h 37m	–40°	70		Phe
107	02h 00m	–25°	50	(M01-2)	For
72	02h 22m	–47°	70		Phe
100	04h 20m	–16°	50	(S04-2)	Eri
91	06h 20m	+36°	60	(R06.01)	Aug
67	06h 41m	–20°	70	(M07-2)	CMa
90	07h 16m	+36°	60		Gem
94	07h 00m	+20°	60		Gem
103	07h 14m	–33°	70		Pup
84	08h 00m	+48°	70	H.B.11, R08.01	Lyn
82	10h 30m	+43° 30′	60	(M10+4)	UMa
87	11h 42m	+31°	100	(M11+3A)	LMi
59	15h 04m	+43°	60	(M14+4)	Boo
44	14h 43m	+30°	60	(M14+2)	Boo
88	17h 45m	+24°	80		Her
55	17h 23m	+20°	70		Her
116	18h 00m	–44°	90		CrA
106	21h 53m	–16°	80		Cap
118	21h 52m	–33°	50		PsA
60	22h 30m	–14°	60		Cap
77	23h 07m	+05°	40		Psc
108	23h 18m	–17°	50		Aqr

Table 3e: Sources recorded during the 12-Yagi array survey in 1952 for which considerable confusion exists (after Bolton et al., 1954a: 117).

BSS Catalog Number	Position		Flux 100 MHz (Jy)	Other Catalog Number	Constellation
	R.A.	Dec			
109	01h 35m	–12°	40		Cet
47	03h 08m	–16°	60		Eri
122	04h. 46m	–30°	60	(M04-03)	Cae
121	05h 48m	–17°	70	(M06-1), (S06-1)	Lep
32	07h 00m	+15°	60		Gem
93	09h 56m	+28°	70		Leo
19	09h 40m	00°	40		Sex
119	09h 08m	–42°	100		Vel
101	10h 46m	–20°	50		Hya
123	11h 00m	–32°	50	(M10-3)	Hya
78	13h 26m	+10°	40		Vir
110	14h 54m	–29°	100		Hya
112	15h 48m	–34°	140		Lup
51	17h 12m	+10°	150		Oph
36	18h 47m	+12°	100		Aql
31	21h 13m	+20°	100		Vul
117	21h 30m	–42°	50	(M21-4)	Gru
45	22h 24m	+04°	50		Peg
115	23h 32m	–29°	50	(S23-2)	Scl

(1953: 431–432) explain the basics of this new system:

> In this system two aerials spaced along the cliff edge are used. The spaced aerials produce a second set of interference fringes at right angles to the normal sea interference fringes. The two aerials are connected to the receiver alternatively in and out of phase, thus switching the azimuth fringe system through half a fringe width. A synchronous rectifier at the receiver output detects only signals due to sources or irregularities in the background distribution smaller than the angular separation of the azimuth fringes.

Figure 21: In the foreground is one of the two Yagi arrays of the azimuth interferometer (courtesy: CRAIA).

One of the two 4-element Yagi arrays is shown in the foreground in Figure 21, and although the two Yagi arrays were just 15-m apart, "To our surprise we recorded a large number of sources … which did not appear on the sea interferometer." (Bolton, 1982: 355). Amongst the sources detected was Puppis A, which Baade and Minkowski were able to associate with a supernova remnant. Although further research was carried out on some of the extended sources, unfortunately no attempt was made to plot the numerous discrete sources that did not show up on the sea interferometer records.

4 THE 'HOLE-IN-THE-GROUND' ANTENNA AND THE 400 MHz SOURCE SURVEY

4.1 Introduction

The sea interferometers used in the aforementioned source surveys offered both advantages and disadvantages (see Stanley, 1994), but if Dover Heights was to remain at the forefront of international research on discrete sources new ways had to be found to increase the resolution of the radio telescopes based there. The alternatives were to develop interferometry further or to construct a radio telescope with a large parabolic antenna. As we have seen the 8-Yagi was constructed at Dover Heights in 1951 and the 12-Yagi array would soon replace it, but in the interim Bolton, Stanley and Slee also decided that they would construct a new antenna of relatively large aperture and innovative design, the so-called 'Hole-in-the-Ground' Antenna, or HitGA (see Orchiston and Slee, 2002c, d).

4.2 The Original HitGA

This was Bolton's brainchild, and was inspired in part by the Jodrell Bank 66.4-m (218-ft) above-ground fixed antenna that was constructed in 1947 and later used with great success by Hanbury Brown and Hazard (see Hanbury Brown, 1984). After the simple Yagi arrays and the small parabolic dish they had previously employed at Dover Heights, the new antenna would not only offer Bolton, Stanley and Slee increased resolution but also a means of escaping the various problems associated with sea interferometers (B. Slee, pers. comm., 2001).

As a lunchtime exercise, in the second half of 1951 John Bolton and Bruce Slee, with some assistance from Gordon Stanley and Kevin Westfold, excavated a 72-ft (21.9-m) diameter parabolic depression in the sand near the cliff top at Dover Heights (Bolton, 1982; Slee, 1994 and pers. comm., 2001). They employed shovels for the excavation work, and a wheel-barrow to dump the spoil round what would become the rim of the antenna. A crude wooden jig was used to approximate the parabolic shape. The excavations took about three months, and when it was finished metal strips from packing cases were stretched across the surface and pegged in place, to improve the reflectivity. A mast supported by guy-ropes was installed at the centre of the dish to carry the dipole, which was connected to a modified ex-WWII 160 MHz receiver (Slee, 1994).

This new radio telescope was completed in late 1951 (Figure 22), and observations were carried out through into early 1952, resulting in a map of galactic radio emission along the galactic plane. The resulting isophote plot clearly showed the Sagittarius A source, now identified with the Galactic Centre (see Figure 23), but at the time this result was not published.

In a bid to improve the resolution and fill a gap in other all-sky continuum surveys a decision was then made to expand the aperture of the antenna to 80 ft (24.4 m) and to use an operating frequency of 400 MHz.

4.3 The Final HitGA

Extending the original antenna involved further excavation (Slee, pers. comm., 2001), and a wooden jig constructed in the RP Workshop was

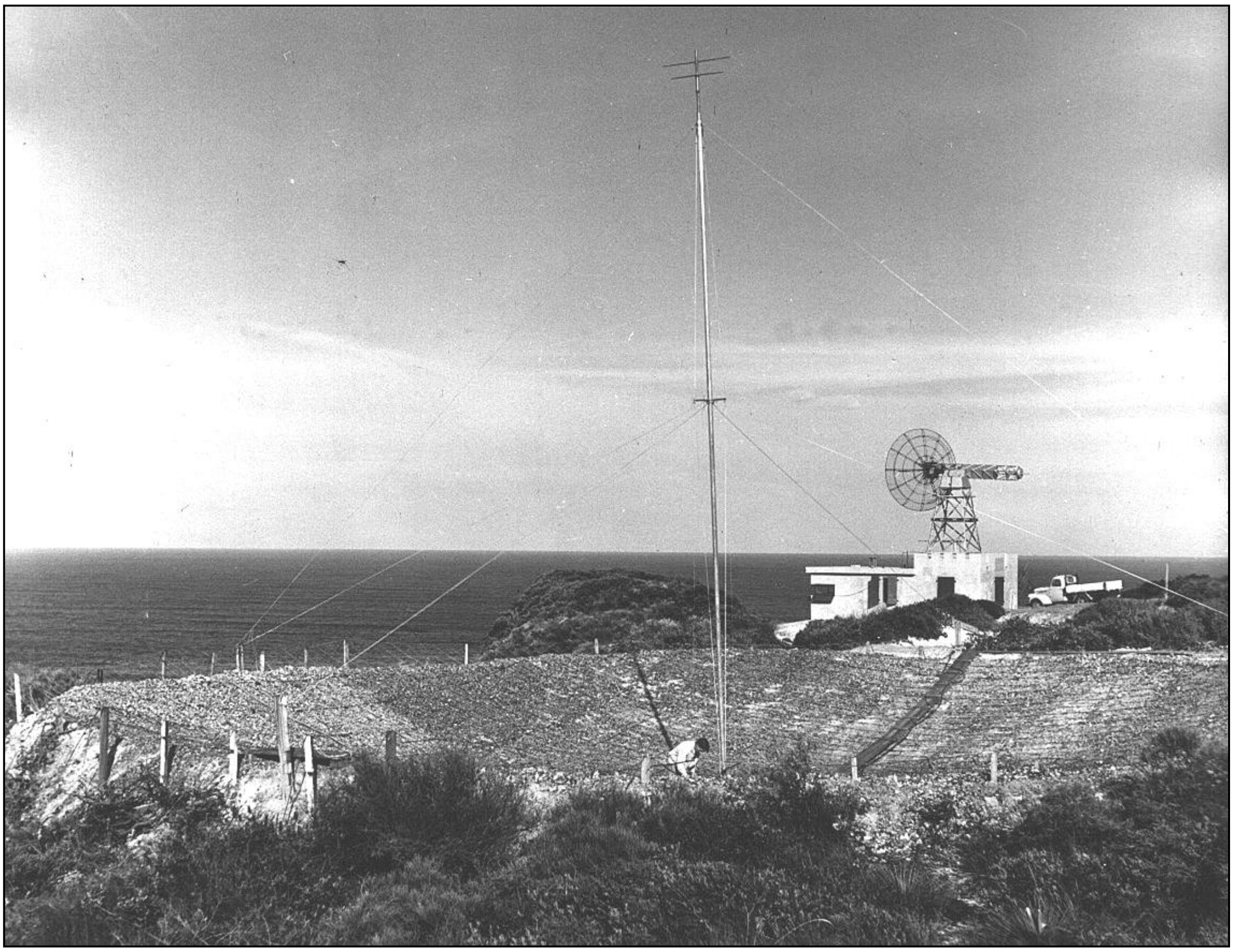


Figure 22: The 72-ft HitGA in June 1952, with the WWII blockhouse and the 4.9-m parabolic dish in the background (courtesy: CRAIA, B 2763-1).

used to finalize the parabolic form of the concrete surface (a photograph of this is included in Bolton, 1982 as Figure 10). The concrete surface was coated with 12.7-mm wire mesh, and the full aperture was only reached by cantilevering the periphery of the expanded dish beyond the rim in-fill using a base of aluminium tubes and annular tension wires (see Figure 24).

A 7.6-cm diameter aluminium central mast was installed to carry a conical dipole and plane reflector, but on this occasion a Dicke switch (which proved particularly troublesome—Bolton, 1982: 356–357) and preamplifier were situated at the very top of the mast. Meanwhile, the second stage of the 400 MHz superheterodyne receiver was located at the base of the mast in a water-tight wooden box (Figure 25) that would float should water accumulate in the antenna after rain (but a plug in the centre of the dish and a drainage system leading towards the cliff edge normally prevented this from happening—Slee, pers. comm., 2001). Connected to this were the detector, an amplifier, and the chart recorder, all of which were located in a small instrument hut adjacent to the southern rim of the dish (Figure 26). Centaurus A served as "… a convenient daily reference for calibrating the overall sensitivity of the aerial and receiver." (McGee and Bolton, 1954: 986).

Construction of the new HiTGA took about six months (B. Slee, pers. comm., 2001), resulting once again in a transit instrument, but this time with a focal length of 12.2 m (40 ft) and an angular resolution of 2°. The position of the aerial mast was maintained by nylon guy ropes, but could be altered in the north-south plane to allow

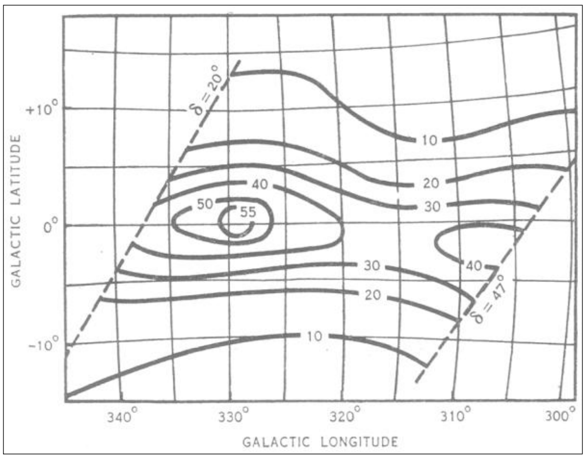


Figure 23: Isophotes of 160 MHz emission obtained with the prototype HitGA, showing the Sagittarius A source (after Bolton et al., 1954b: 98).[4]

Figure 24: The enlarged concrete-coated 80-ft HitGA in September 1953, with Gordon Stanley using a theodolite to record the position of the aerial mast (courtesy: RAIA B3150-2).

strips of the sky adjacent to the zenith to be observed. Whenever the mast was realigned it was important to measure its precise position, and this was accomplished with a theodolite. For this purpose, a platform was constructed adjacent to the western margin of the dish, and this contained position markers for the tripod legs that supported the theodolite. This arrangement is illustrated in Figure 24, taken when Gordon Stanley was busy using the theodolite (ibid.).

The first research project carried out with the new antenna was a survey of part of the southern sky at 400 MHz, modelled on the earlier one achieved with the prototype dish at 160 MHz, and

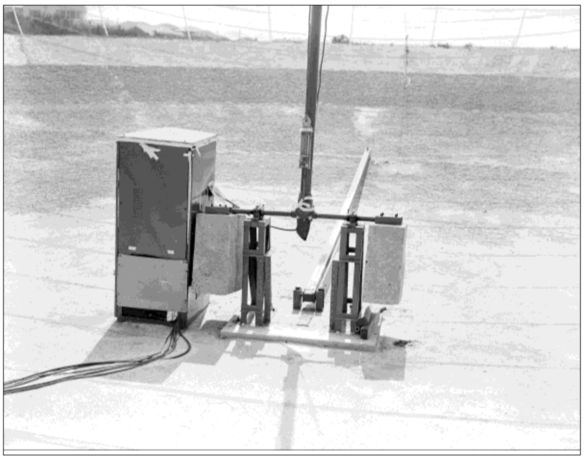


Figure 25: A close up of the water-tight box containing the second stage of the 400 MHz receiver located at the centre of the 80-ft HitGA (courtesy: CRAIA, B3150-5).

this was to occupy the remainder of 1952 and through into 1953. Most of the observing and data reduction was carried out by a new member of the Dover Heights group, Richard (Dick) X. McGee (1921–2012), assisted from time to time by Bolton, Slee and Stanley who were otherwise engaged in an-all-sky survey at 110 MHz and in a detailed investigation of selected sources using the Dover Heights 12-Yagi array (Bolton, 1982). It also should be mentioned that in mid-1953 Bolton temporarily left radio astronomy when he transferred to RP's Cloud Physics group.

The primary effort of the 400 MHz survey

> … was concentrated on the Milky Way in the zone of declinations from –17° and –49° ... The Milky Way was observed on one fixed declination per day, changes in Right Ascension occurring as the rotation of the Earth swept the aerial beam across the sky. In a preliminary survey observations were made at intervals of 1° in declination. Later, in order to cover the more interesting regions in greater detail, intervals of ½° were used. The record obtained at a particular declination was repeated until features of the variation of equivalent temperature with sidereal time were either satisfactorily reproduced or revealed as spurious and discarded. (McGee et al., 1955: 353).

The main account of the survey was published by McGee et al. (1955) in the *Australian Journal of Physics*, but only after an abbreviated version had appeared in *Nature* (McGee and Bolton, 1954).

As Figure 27 illustrates, the most important outcome of this survey was the clear delineation of Sagittarius A, the strong source at *l* = 327.9° and *b* = –1.0° or R.A. 17 hr 42 min and Dec. –28.5° (1950), which McGee, Slee and Stanley correctly identified with the nucleus of our Galaxy. We should note in relation to Figure 27 that in a footnote added when their paper was in press, McGee et al. (1955: 349) pointed out that the conspicuous contour 'bulges' that extend obliquely from *l* = 348°, *b* = –23° to *l* = 341°, *b* = –7° and also from *l* = 318°, *b* = –17° to *l* = 310°, *b* = –3° were not real: they were artefacts generated by the coma that is associated with this type of antenna system.

Earlier investigations had already shown

> … that the contours of radio brightness ascend to a rather broad peak close to the calculated position of the galactic centre. (McGee et al., 1955: 347),

but there was considerable confusion about the location and nature of the radio source and the authors of the HitGA survey were happy to report that their research "… clears up this confusion to a large extent and indicates considerable detail in the fine structure of the Milky Way." (McGee et al., 1955: 348). This is precisely what

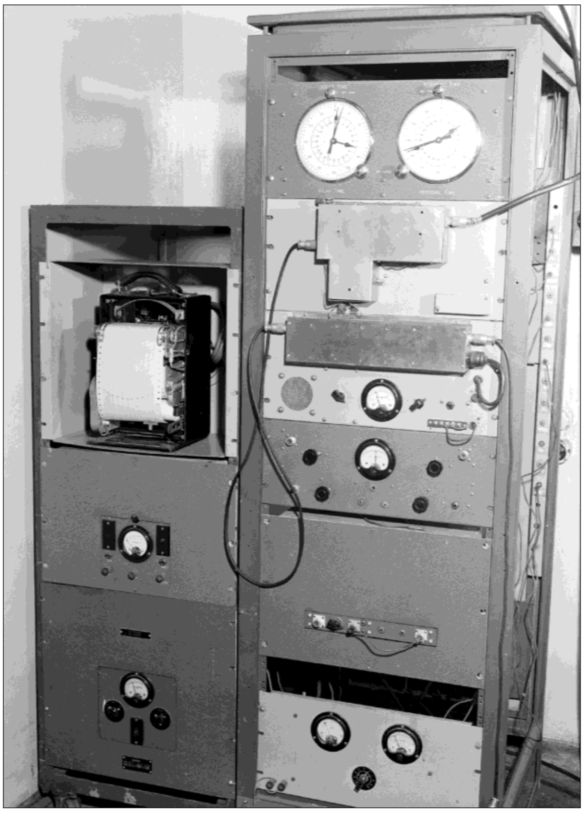


Figure 26: The receiver and chart recorder located in the hut beside the 80-ft radio telescope (courtesy: CRAIA, B3150-4).

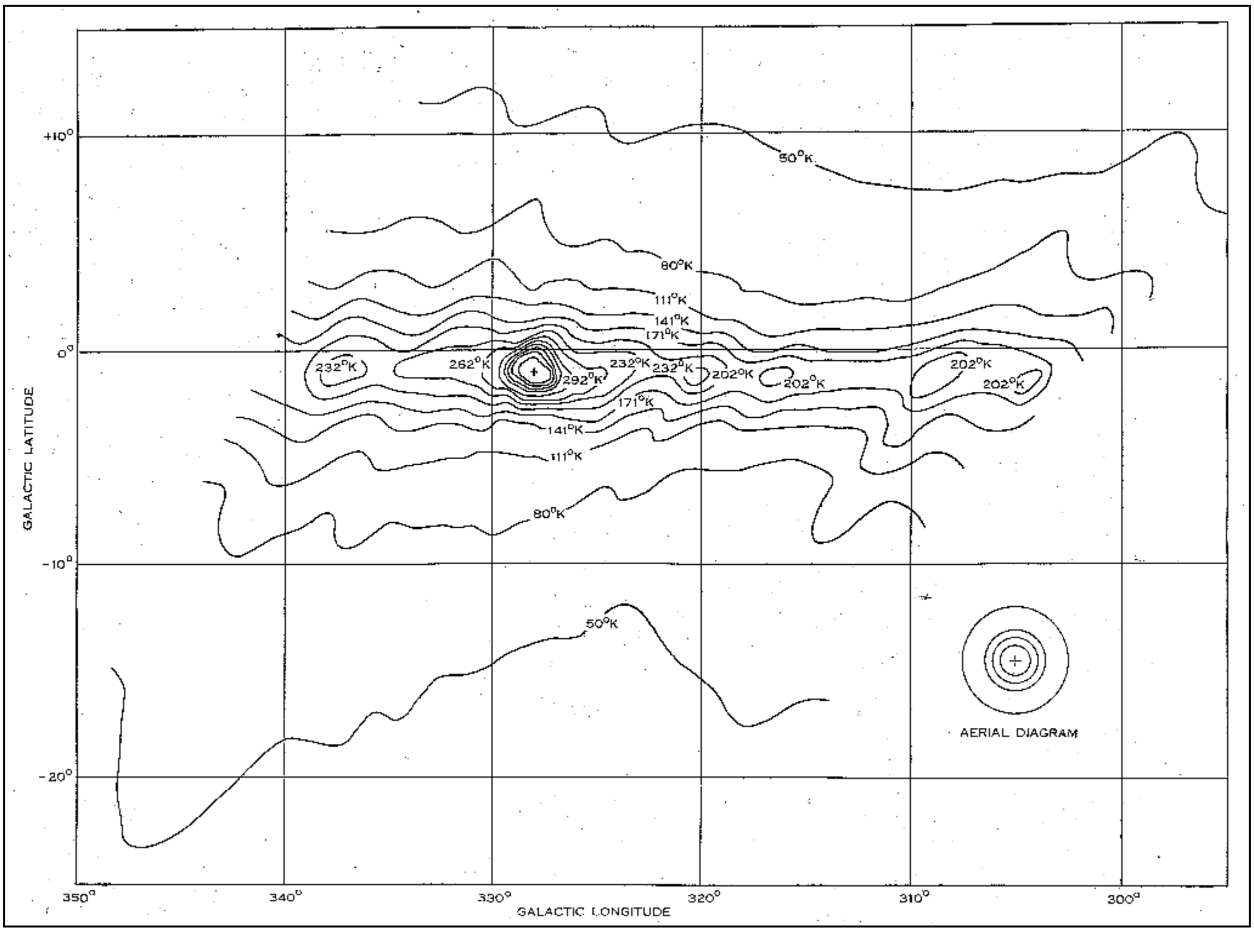


Figure 27: Contour plots at 400 MHz showing the strong emission source associated with the Galactic Centre (after McGee et al., 1955: 356).[4]

Table 4: Discrete sources observed at 400 MHz (adapted from McGee et al., 1955: 359–364).

Constellation	Position (1950)		Flux (Jy)	Notes and Comments
	R.A. (hr min)	Dec. (°)		
Fornax	03 20±1	–37.25 ± 0.5	140	
Pictor	05 09±1 05 16±1	–42.75 ± 0.5 –45.0 ± 0.5	150	Two maxima of approximately equal intensity, slightly spread.
Puppis-Vela	08 24±2 08 35±2	–43.2 ± 1 –45.1 ± 1	150	The first of these is Puppis A and it is superimposed on an extended source with peak intensity at the second position listed.
Antlia	09 59±1	–28.5 ± 0.5	90	Only one observation of this was obtained.
Vela	10 41±1	–43.7 ± 0.5	200	
Centaurus	13 22.5	–42.75 ± 0.1	600	Centaurus A.
Lupus	15 04.1	–30.9 ± 0.5	60	
Ara	16 34±1	–47.7 ± 0.5	230	Associated with an HII region?
Scorpius	17 04±1	–44.4 ± 0.5	260	
Scorpius	17 13±1	–38.1 ± 0.5	330	Associated with an HII region?
Scorpius	17 23±1	–35.0 ± 0.5	510	Associated with an HII region?
Sagittarius	17 42±1	–28.5 ± 0.2	1640	Sagittarius A, associated with the Galactic Centre.
Sagittarius	17 59±1	–21.5 ± 0.5	280	Associated with an HII region?
Sagittarius	18 07±1	–19.6 ± 0.5	360	

Walter Baade would have hoped for when he first suggested this project to the Sydney radio astronomers (McGee and Bolton, 1954). An interesting consequence of this work was that the International Astronomical Union subsequently agreed to adopt the Sydney position of Sagittarius A as the location of the Galactic Centre, thereby re-calibrating the datum point of the galactic co-ordinate system (Bolton, 1982).

Apart from the Galactic Centre result, another important outcome of the 400 MHz survey was the detection of a number of other discrete radio sources. Even though

> … there was not the same attention given to establishing their presence as was given to checking the features in the central region of the Milky Way. (McGee et al., 1955: 359, 362),

this resulted in a list of 14 different sources (see Table 4, which includes Sagittarius A).

As one brief investigation that formed part of the 400 MHz survey, trial polarization measurements were taken in two different areas of the sky, but McGee et al. (1955: 359) found that

> … at regions centred in R.A. 16 hr 54 min, Dec. −42.75° and R.A. 17 hr 55 min, Dec. −23.5° plane polarization of the radiation at 400 Mc/s is less than 2 per cent.

After the 400 MHz sky survey, the HitGA was used for just one further research project: a search for the 327 MHz deuterium line, which would be expected to show up as an absorption feature in the region of the Galactic Centre. In a paper published in *Nature*, Gordon Stanley and a U.S. Fulbright Fellow, Robert Price (1956) reported on their unsuccessful search. This project was carried out in 1954, and employed a receiver centred on 327.369 MHz, with a filter bandwidth of 16 kc/s and a spacing of 48 kc/s between the filters. The observations were made in the area of the Galactic Centre and in the region of the galactic plane at l = 220° by

> … automatically scanning with the receiver through 200 kc/s as the direction of the galaxy passed through the antenna. Such methods failed to detect any radiation. In the later records graphical integration was performed to increase the sensitivity. (Stanley and Price, 1956: 1221).

These latter observations also failed to reveal deuterium emission.

5 DISCUSSION

5.1 The Demise of Radio Astronomy at Dover Heights

The search for the deuterium line spelled the death knell for radio astronomy at Dover Heights, and although Bolton (1982) and Stanley (1994) had plans for other more ambitious antennas there, including a second HitGA that could be used with the first one as an interferometer (B. Slee, pers. comm., 2001), these did not eventuate.

Instead, the focus of RP's non-solar research turned to the Potts Hill (Wendt et al., 2011) and Fleurs (Orchiston and Slee, 2002b; Orchiston et al., 2015: 7–11) Field Stations, and it was at about this time that the RP radio astronomers realized that

> … more and more sophisticated instruments would be necessary. The days of hasty improvisation were over – more and more planning would be required and much more money would be needed for capital expenditure. Little did we realize how large these sums would become. (Bowen, 1984: 96).

Thus, the sea interferometers that had been the mainstay of the Dover Heights field station for much of its existence would soon be replaced by spaced interferometers, grating arrays and cross-type radio telescopes at other RP field stations (see Orchiston and Slee, 2017).

5.2 The Dover Heights Site Today

Radio astronomy ceased at Dover Heights at the end of 1954 (Bolton, 1982), but for a while RP's Cloud Physics group made use of the site. Finally, in 1959, the field station was closed, and most of the site was converted into Rodney Reserve (Figure 28), complete with a football field. From all accounts, the HitGA was simply filled with spoil and then grassed over. Today it lies not far north of the northern goal post, about where the 'N' of RODNEY is located in Figure 28.

Until 2003 there were no scientific relics at Rodney Reserve to serve as a reminder of this site's remarkable scientific past, apart from a rusting mounting near the cliff-top (Figure 29) that originally supported the 8-Yagi array and later the 12-Yagi array (shown here in Figure 17). In 2003, when the first author of this paper was employed as the Archivist and Historian at the Australia Telescope National Facility, one of his projects was to design an interpretive display panel about radio astronomy at Dover Heights and a scaled-down replica of the 8-Yagi antenna that graced the site in 1951 (see Orchiston et al., 2003) and install these at Rodney Reserve, along with a commemorative plaque about the site that already existed (Figure 30). The historic precinct shown as the inset in Figure 28 was officially opened on 20 July 2003 by Professor the Honorable Dame Marie Bashir, Governor of New South Wales, during the Sydney General Assembly of the International Astronomical Union.

During the ensuing 13 years the display panel suffered damage and fading, and in 2017 it was replaced by an updated version (Figure 31) prepared by Dr Jessica Chapman from CSIRO Astronomy and Space Sciences. Meanwhile, the 8-Yagi replica antenna continues to grace the site (see Figure 32), and is a fitting reminder of the amazing scientific contribution that the Dover Heights Field Station made in the early days of Australian radio astronomy.

6 CONCLUDING REMARKS

The Dover Heights Field Station is famous in world radio astronomy. More than any other site it was associated with the discovery of the true nature of 'radio stars'—that they were discrete sources of radio emission, and most of them were at extragalactic distances.

This paper merely provides an overview, and the full drama of the research by John Bolton, Gordon Stanley and Bruce Slee on discrete sources is detailed in the recent biography of Bolton by Robertson (2017) and in a paper by Robertson, Orchiston and Slee that was published in 2014. In that paper, we suggested that the identification of optical correlates for Centaurus A, Taurus A and Virgo A marked

> … an extraordinary development [in astronomy]. The discovery of the two extragalactic objects did not diminish the importance of the *Nature* letter—on the contrary it raised some profound questions. What was the mechanism responsible for this prodigious output of radio energy? If two of the strongest radio sources were distant galaxies could some of the fainter sources be even more distant? Might the fledgling field of radio astronomy be able to 'see' much further out into the Universe than traditional astronomy? (Robertson et al., 2014: 301–302).

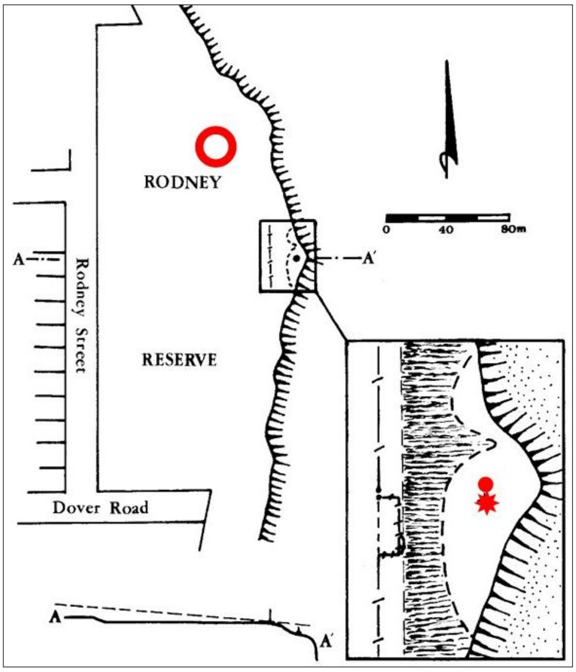


Figure 28: A plan of Rodney Reserve showing the locations of the 80-ft HitGA (red circle, to scale), the rusting antenna mounting (red dot), replica 8-Yagi array (red star) and the 'alcove' in the fence-line with the interpretive display panel and commemorative plaque. The A–A′ transect (bottom left) shows that the replica antenna is invisible from houses located along Rodney Street (map: Wayne Orchiston).

Woody Sullivan (2009: 324) also comments on the seminal place of these observations in the annals of radio astronomy:

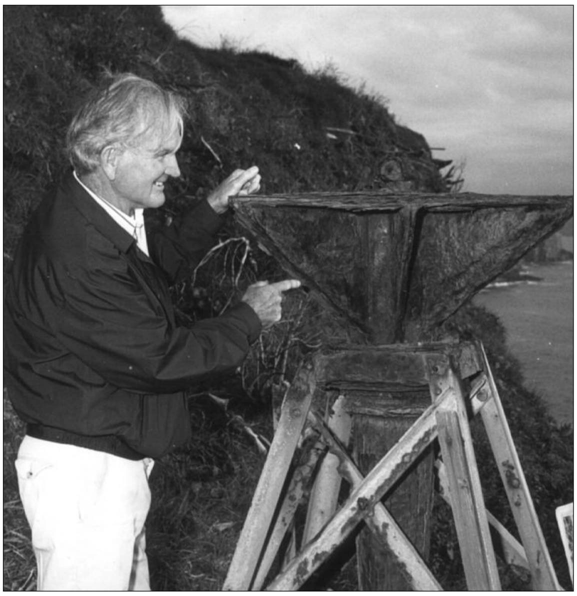


Figure 29: An undated photograph showing Bruce Slee examining the rusting mounting (courtesy: CRAIA).

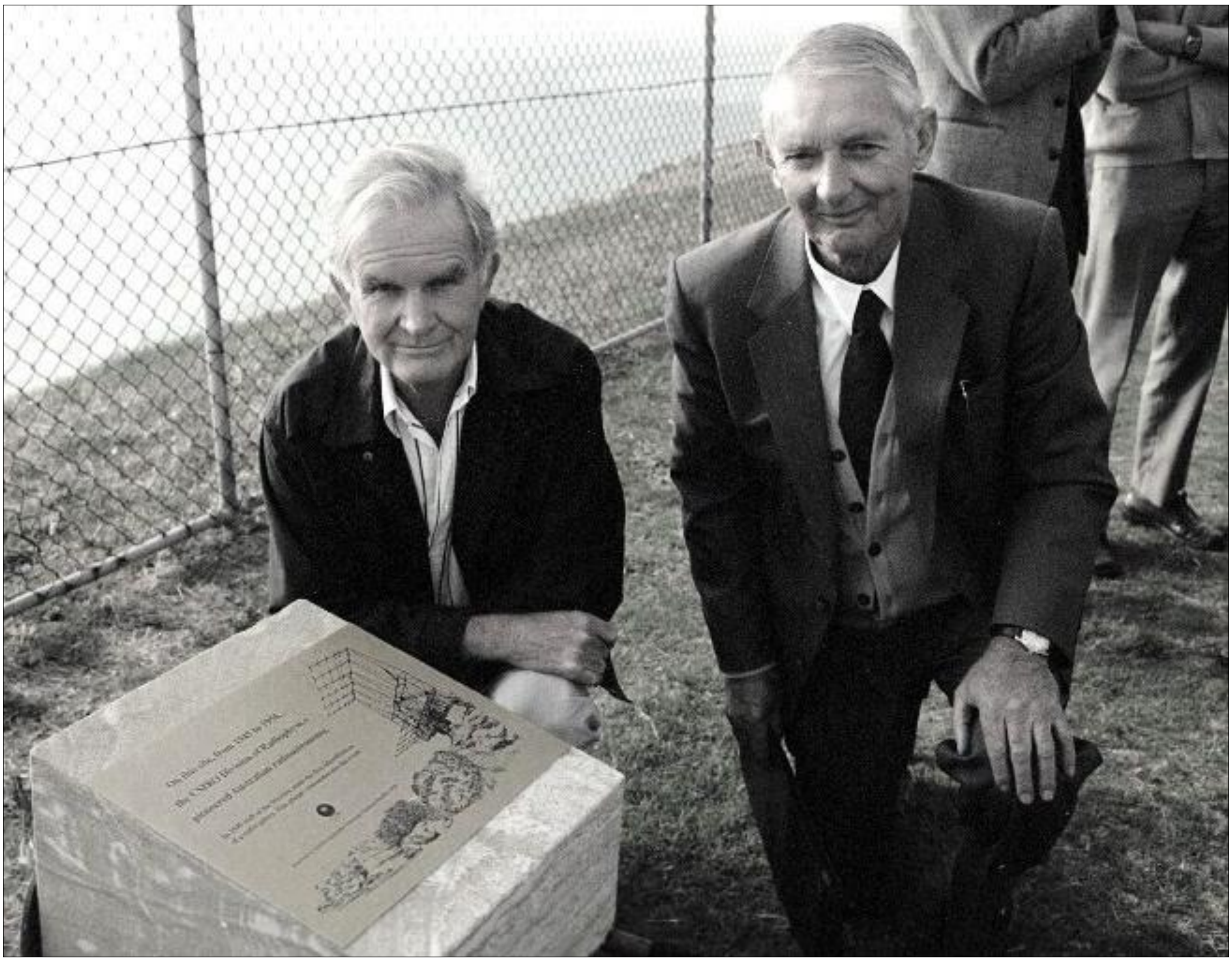


Figure 30: Bruce Slee (left) and John Bolton (right) and the commemorative plaque at Rodney Reserve in 1989 (courtesy: CRAIA, N15506-4).

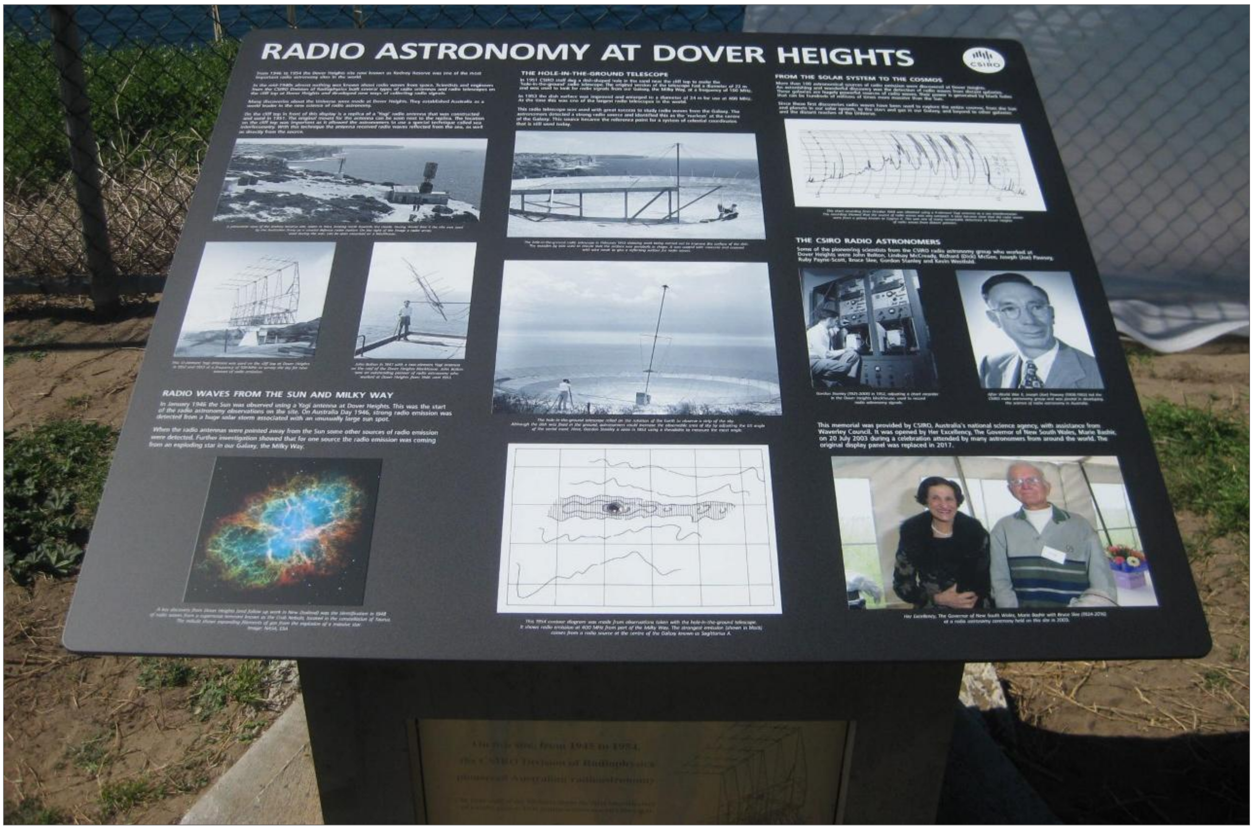


Figure 31: The new interpretive display panel installed at Rodney Reserve in 2017 (courtesy: Dr Jessica Chapman).

> The short paper [in *Nature*] by Bolton, Stanley and Slee (1949) was one of the most important in early radio astronomy, presenting a first plausible link between "galactic noise" and traditional astronomy.

Indeed, we would go further and suggest that although Bolton, Stanley and Slee would go to build international reputations in radio astronomy, none of them "… would produce another paper to rival the importance of their 1949 *Nature* letter." (Robertson et al., 2014: 302).

As we documented in that paper, this research at Dover Heights on the first 'radio stars' launched an ambitious program to detect discrete sources at frequencies from 40 to 400 MHz that would span almost eight years and involve a succession of Yagi arrays and ultimately the remarkable HitGA. Back in 2001 one of the authors of this paper (WO) asked Bruce Slee for his overall assessment of the HitGA, and after pondering a moment he was moved to reply:

> It certainly was a lot of hard work digging it out—all those blisters—but the research output certainly justified the physical input! (Slee, pers. comm., 2001).

This is a fitting reflection on an era long gone (see Orchiston and Slee, 2017; Robertson, 1992; Sullivan, 2009), when ingenuity, dedication and minimal financial outlay could produce significant astronomical results. Today's radio astronomy, with its sophisticated multi-million dollar arrays, is a very different world!

Arguably, one of the most important scientific contributions made by the HitGA to international radio astronomy was to show isophote details of the Sagittarius A discrete source that marks the site of the centre of our Galaxy. Through the paper published in *Nature* by McGee and Bolton (1954) this discovery reached a wide audience but, because of the journal it was published in, the earlier detection of this source by Piddington and Minnett (1951) at Potts Hill Field Station was not so well known. This interesting interplay of personalities, politics and publications is discussed further by Orchiston and Wendt (2017).

In ending this paper we can do no better than to repeat our earlier evaluation of Dover Heights. This field station launched a whole new branch of astronomy, extragalactic radio astronomy, which

> … would revolutionise astronomy in the second half of the twentieth century. The detection of increasingly-distant radio galaxies and then the discovery of quasars in the 1960s led to an expansion in the size of the known Universe by almost two orders of magnitude. Extragalactic radio astronomy revealed a Universe populated by objects undergoing violent, energetic processes on a scale previously unimaginable to 'traditional' optical astronomers. (Robertson et al., 2014: 302).

7 NOTES

1. Dr James Lequeux (pers. comm, December 2017) mentioned that even in 1954, when he began working in radio astronomy, scientists still believed that stars were responsible for most of the radio emission observed in our Galaxy.
2. We now know that the solar wind is responsible for these scintillations.
3. In Tables 3a to 3e (inclusive), in the second-last column, the 'H.B.' sources refer to Hanbury Brown and Hazard, 1953: 125; the 'M' sources to Mills, 1954: 282–287; the 'R' sources to Ryle, Smith and Elsmore, 1950: 514; and the 'S' sources to Shain and Higgins, 1954: 140.
4. Note that positions in this figure are shown in the old galactic co-ordinates.

Figure 32: The rusting old antenna mount (on the left) and beside it the scaled-down replica of the 8-Yagi antenna (photograph: Harry Wendt).

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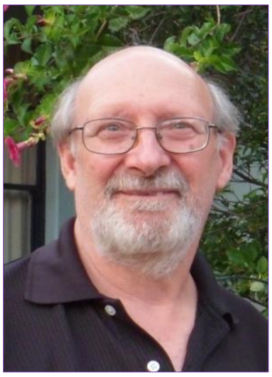
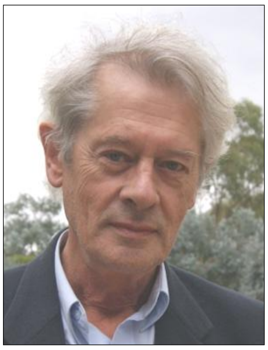
Dr Wayne Orchiston is a Senior Researcher at the National Astronomical Research Institute of Thailand (NARIT), and an Adjunct Professor of Astronomy at the University of Southern Queensland (USQ) in Australia. In November 1961 he began work as a Technical Assistant at the CSIRO Division of Radiophysics (RP) Fleurs Field Station, assisting Bruce Slee, one of the Dover Heights stalwarts who features in this paper. Forty years later he joined RPs successor, the Australia Telescope National Facility, as their Archivist and Historian. After working at James Cook University (JCU) in Townsville, Australia, he moved to NARIT (Thailand) in January 2013, and will retire in January 2018 and move back to northern Australia. Wayne has a special interest in the history of radio astronomy, and through JCU and USQ he supervised 6 Ph.D. theses and 1 Masters thesis. He has published papers about early radio astronomy in Australia, France, India, Japan, New Zealand and the USA, and among his recent books, *Exploring the History of New Zealand Astronomy: Trials, Tribulations, Telescopes and Transits* (Springer, 2016) and *The Emergence of Astrophysics in Asia: Opening a New Window on the Universe* (Springer, 2017, co-edited by Tsuko Nakamura) contain vari-ous chapters on early radio astronomy. Wayne also has published extensively on the history of asteroidal, cometary and meteor astronomy; the history of meteoritics; historic transits of Venus; solar eclipses and the development of solar physics; early devel-opments in astrophysics; historic telescopes and observatories; early astronomical societies; amateur-professional relations in astronomy; and ethnoastron-omy. Currently he is the Vice-President of IAU Commission C3 (History of Astronomy), and in 2003 founded the IAU's Working Group on Historic Radio Astronomy. In 1998 he and John Perdrix founded the *Journal of Astronomical History and Heritage*, and he is the current Editor. Wayne also is on the Editorial Board of Springer's Historical & Cultural Astronomy Series. In 2013 the IAU named minor planet 48471 Orchiston after him.



Dr Peter Robertson is an honorary research fellow in the School of Physics, University of Melbourne. He is a former managing editor of the *Australian Journal of Physics* (1980–2001), published by CSIRO Australia and the Australian Academy of Science. Peter recently completed a Ph.D. through the University of Southern Queensland on John Bolton's early research on discrete sources, supervised by Brad Carter and



Wayne Orchiston. He also recently published a full-length biography of John Bolton, titled *Radio Astronomer: John Bolton and a New Window on the Universe* (2017, NewSouth Publishing), which nicely complements his earlier book *Beyond Southern Skies – Radio Astronomy and the Parkes Telescope* (1992, Cambridge University Press).