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Ingenuity and initiative in Australian radio astronomy: the Dover Heights 'hole-in-the ground' antenna

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Abstract
During the 1950s staff from the CSIRO's Division of Radiophysics based at the Dover Heights field station employed ingenuity and initiative in response to a lack of funding and support for a new radio telescope. In order to obtain the requisite aperture for the resolution sought they spent their own time excavating a 21.9-m parabolic depression in the sand at the field station, and when the viability of this prototype transit instrument was established its diameter was increased to 24.4 m, making this the largest radio telescope in Australia at the time. Operating at 400 MHz, this instrument was employed to map the galactic centre region and in a search for new discrete sources. It also was used to investigate polarization in the plane of the Galaxy, and in an unsuccessful search for the newly-proposed deuterium line. Today the Dover Heights 'hole-in-the-ground' antenna lies buried beneath Rodney Reserve, and there is little at this public playing field to remind visitors of the important contributions made by this radio telescope, and others at this site, during the formative years of Australian radio astronomy.

Keywords*: radio astronomy, Dover Heights, galactic centre, source surveys, Rodney Reserve*

1 INTRODUCTION

Australia has a first class reputation in radio astronomy, in part because of the research that has been accomplished with radio telescopes of innovative design. The Mills and Christiansen Crosses at Fleurs and the Culgoora Radioheliograph, built in the 1950s and 1960s, respectively, serve as excellent examples of the way in which new concepts in instrumentation led to major advances in our understanding of radio sources and solar radio emission. However, this Australian tradition of designing new and novel radio telescopes began much earlier. This paper discusses the Dover Heights 'hole-in-the-ground' antenna, which was constructed half a century ago.

2 THE DEVELOPMENT OF POST-WAR RADIO ASTRONOMY

Initial post-war developments in non-solar radio astronomy were inspired by Hey, Phillips and Parson's 1946 discovery of an intense source of radio emission in Cygnus. This 'radio star' was unlike anything previously detected, and its interpretation raised innumerable questions and in the process opened up a whole new field of investigation that has been "... central to the development of radio astronomy ... [through] to the present day." (Sullivan, 1982:221).

The challenge was initially taken up in Sydney, where John Bolton, Gordon Stanley (Figure 1) and one of the authors (BS) from the CSIRO's Division of Radiophysics used a sea interferometer employing the Lloyd's Mirror principle to investigate the enigmatic Cygnus source and soon discovered others. By observing from Dover Heights as these sources rose above the eastern horizon Bolton, Stanley and Slee were able to obtain approximate celestial positions for Cygnus A, Sagittarius A, Centaurus A, Taurus A, and Virgo A, but it was only after a field trip to New Zealand in 1947, when accurate rising *and* setting times were obtained, that they were able to fine-tune the positions of these sources and begin to search for optical correlates. This was one of the earliest collaborations between optical astronomers and their radio colleagues and led to the realization that Taurus A was associated with the Crab Nebula, a well-known supernova remnant, and Centaurus A and Virgo A with extra-galactic nebulae (see Bolton, 1955; Orchiston, 1994). These pioneering efforts led to the first all-sky surveys in England and in Sydney.

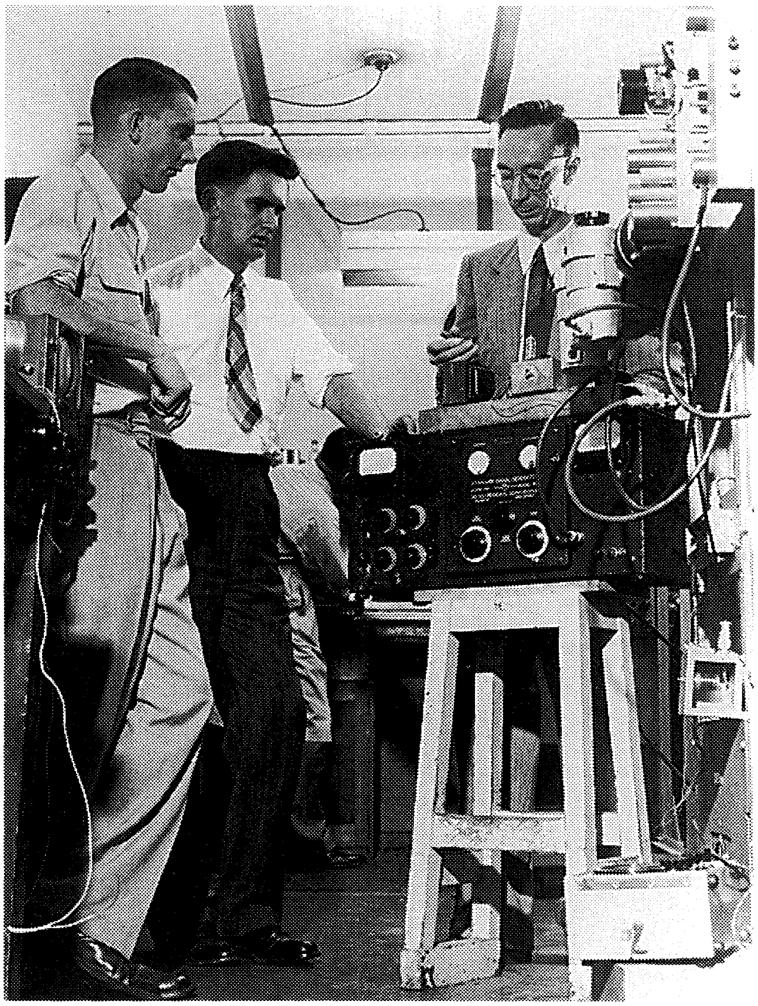

Figure 1. John Bolton (left) and Gordon Stanley (centre) with radio astronomy group leader Joe Pawsey at the Radiophysics Laboratory in Sydney. (ATNF Historic Photographic Archive: 15070)

These techniques gave interesting results, but in order to make substantial progress new ways had to be found to increase the resolution of the radio telescopes. There were two basic alternatives: to further develop interferometry, or to construct single large-aperture radio telescopes. While small parabolic radio antennas were already in use in both England and Australia, at that time engineering constraints prevented the construction of large steerable dishes. Ingenuity and a new initiative were therefore called for, and the Division of Radiophysics field team at Dover Heights responded to this challenge by constructing an imaginative new radio telescope of large aperture and innovative design, the 'hole-in-the-ground' antenna.[1]

3 THE HOLE-IN-THE-GROUND ANTENNA

The hole-in-the-ground antenna was the brainchild of John Bolton, one of the legends of radio astronomy (e.g. see Goddard and Haynes, 1994; Kellermann, 1996) and "... an extremely talented researcher, with a yen for working on his own with a minimum of assistance." (Bowen, 1984:91). It was inspired by the Jodrell Bank 66.4 m (218-ft) above-ground fixed antenna that was constructed in 1947 for cosmic ray work but was quickly re-assigned to radio astronomy and used with great success by Hanbury Brown and Hazard (see Hanbury Brown, 1984). After the simple Yagi arrays and a small parabolic dish they had previously employed, the mooted new antenna would not only offer the Dover Heights radio astronomers increased resolution but also a means of escaping the various problems associated with sea interferometers (Stanley, 1994).

The Dover Heights field station of the Division of Radiophysics was located at a 5 ha coastal wartime radar station in eastern suburban Sydney, 5 km south of the entrance to Sydney Harbour. The 73-m high coastal cliffs in this vicinity were vital for the success of the sea interferometry investigations, but now the site offered a further attraction: a large sandy expanse adjacent to the cliff top that would soon be transformed into one of Australia's most remarkable early radio telescopes (see Figures 2 and 3).

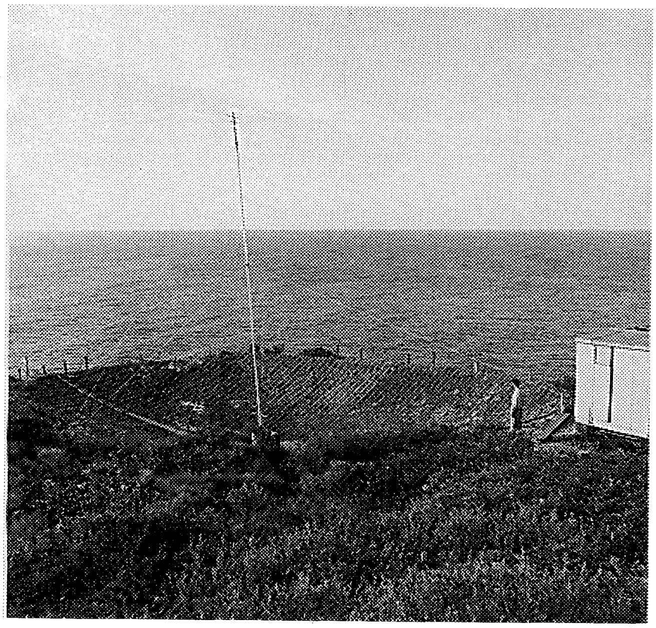

Figure 2. The 21.9m antenna in June 1952, with the small instrument hut on the extreme right. (ATNF Historic Photographic Archive:2763-3)

During a three month period in the second half of 1951 John Bolton and one of the authors (BS), with some assistance from Gordon Stanley and Kevin Westfold, spent their lunchtimes excavating a 21.9 m (72-ft) diameter parabolic depression in the sand near the cliff top (Bolton, 1982; Bolton, Westfold, Stanley, and Slee, 1954; Slee, 1994). Shovels were used to remove the sand, which was heaped into a wheelbarrow and dumped round what would become the rim of the antenna. In order to generate an appropriate parabolic shape they used a crude wooden jig. When the excavations were finished 12.7-mm metal strips from packing cases were used to obtain good reflectivity, and these were laid across the surface at 30-cm intervals and pegged in place. Finally, a mast was installed at the centre of the dish to carry a dipole that was connected to a modified ex-WWII receiver tuned to 160 MHz (Slee, 1994; Westfold, 1994). By employing this novel tactic, the Dover Heights team was able to acquire a far larger antenna than would otherwise have been available, and with a beam width of only 6° – an impressive figure in those days (Bolton, Westfold, Stanley, and Slee, 1954).

It is important at this point to place this new radio telescope in chronological perspective. As Figure 4 illustrates, the largest steerable parabolic antenna in the world at that time was the Naval Research Laboratory's 16-m (50-ft) parabolic dish in Washington, and this was only

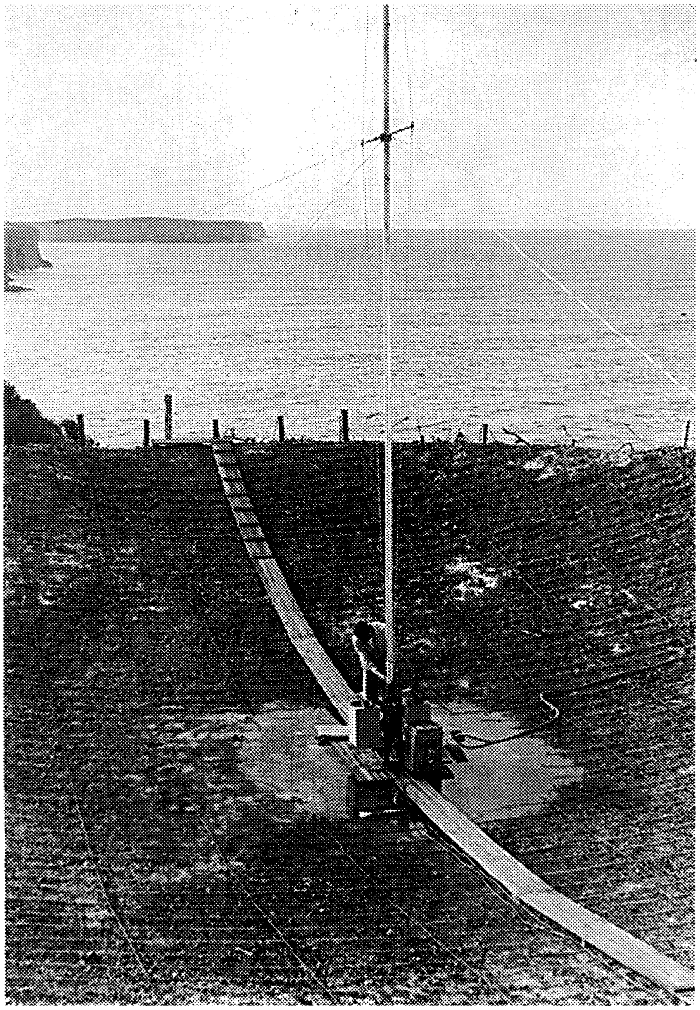

Figure 3. Close-up of part of the 21.9-m antenna after rain, showing the aerial mast and the boardwalk used to access the equipment boxes at the centre of the dish. (ATNF Historic Photographic Archive: 2763-7)

eclipsed in 1955 when the 19-m Harvard dish and the 25-m Dwingeloo Radio Telescope (in the Netherlands) were completed. The 21.9-m Dover Heights hole-in-the-ground antenna therefore was a substantial instrument by any account (although it is important to remember that it was

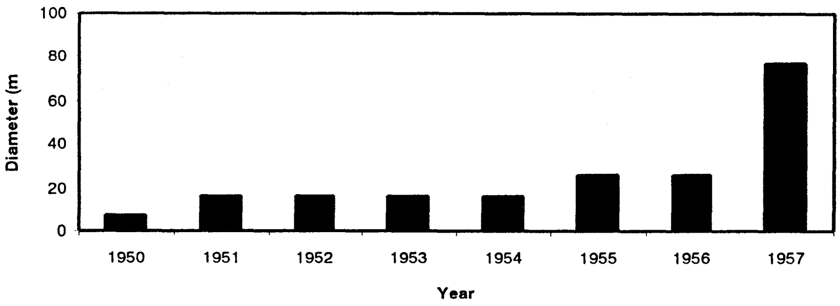

Figure 4. Histogram illustrating the increase in diameter of the world's largest steerable parabolic antenna with time (data after Kerr, 1994:7).

dwarfed in aperture by its Jodrell Bank prototype), but its very name echoed its major downside: that it was to all intents and purposes a transit instrument. Only by manipulating the supporting guy ropes and altering the position of the aerial mast was it possible to access a small region of sky adjacent to the zenith.

Observations were carried out with the new Sydney antenna in late 1951 and early 1952 between RA 14 h and 18 h and dec. –20° to –50° (1950), resulting in a map of radio emission along the galactic plane (Figure 5). This isophote plot, which clearly shows the Sagittarius A source, was published in 1954 by Bolton, Westfold, Stanley and Slee. The fact that the hole-in-the-ground antenna was capable of producing useful results finally allowed its existence to become common knowledge.

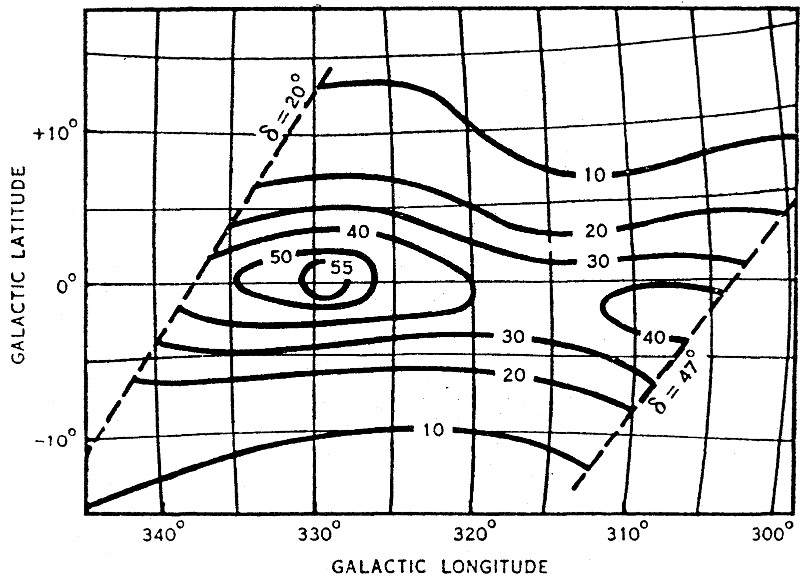

Figure 5. 160 MHz contour plots showing the Sagittarius A source (after Bolton, Westfold, Stanley, and Slee, 1954: 98).

Prior to this, the construction and use of this new antenna had been cloaked in secrecy, and when they had selected the site for the excavation the Dover Heights team had made sure that it was not easily visible from the old WWII blockhouse where the other radio telescopes were located. The reason for this tactic was simple: the team was supposed to be using sea interferometers for their celestial observations, and the leader of the Division's radio astronomy group, Joe Pawsey, was an absolute stickler for having staff keep religiously to assigned projects. John Bolton (1982:349-350) recounts that earlier in the history of Dover Heights when he and Bruce Slee were meant to be observing the Sun they decided also to use their Yagis to search for non-solar emission, a project that was "... cut short by an unheralded visit from Pawsey, who noted that the aerials were not looking at the Sun. Suffice to say that he was not amused and we were both ordered back to the Lab." and assigned to other projects. It was some time before they were permitted to return to Dover Heights!

Although E G (Taffy) Bowen, Chief of the Division, knew of the hole-in-the-ground antenna and even visited the field station when the excavation was in progress, it was only after the 160 MHz isophotes had been generated that Pawsey was informed of these developments. To everyone's surprise he was not angered by this illicit activity; to the contrary, he was excited by the research potential of this new radio telescope (Bolton, 1982). However, Haynes *et al.* (1996:226) believe that "This collusion with Bowen and simultaneous exclusion of Pawsey, prefigured an alliance that, a decade later, was to instate Bolton as autonomous director of the Radiophysics flagship [i.e. Parkes] and leave Pawsey without a function in the Division."

The move now was to improve resolution and fill a gap in other all-sky continuum surveys, and a decision was therefore made to expand the aperture of the antenna to 24.4 m (80-ft) and to use an operating frequency of 400 MHz. Extending the antenna involved further excavation, and a wooden jig was constructed in the Radiophysics Workshop and was used to refine the parabolic shape of the new dish surface that was subsequently coated in concrete.

The concrete was then covered with 12.7-mm wire mesh, and the full aperture was realized by cantilevering the periphery of the expanded dish beyond the rim in-fill using a base of aluminium tubes and annular tension wires. These are visible in Figure 6, which shows the new dish. In this context, Robertson (1992:57) reminds us that "With all this physical labour, the title Ph.D. among radio astronomers jokingly came to mean 'Post-hole Digger'."

To complete the antenna a 7.6-cm diameter aluminium mast was installed to carry a prime focus conical dipole and plane reflector, but on this occasion a preamplifier was situated at the very top of the mast in order to reduce line loss. This connected to a Dicke switch (which proved particularly troublesome (see Bolton, 1982:356-357), a mixer (fed by a local oscillator), and an I.F. preamplifier. All of these were located at the base of the mast, in a water-tight wooden instrument box that could float should water accumulate in the antenna after rain (but in fact a plug in the centre of the dish and a drainage system leading towards the cliff edge normally prevented this from occurring). The final stage of the 400 MHz superheterodyne receiver, comprising an I.F. amplifier, diode rectifier, synchronous detector, DC amplifier and finally a chart recorder, was housed in a small instrument hut adjacent to the southern rim of the dish. The Dicke switch in the wooden instrument box at the base of the mast also fed signals to the synchronous detector in the instrument hut. This hut is visible on the extreme right of Figure 2. Centaurus A was found to be "... a convenient daily reference for calibrating the overall sensitivity of the aerial and receiver." (McGee and Bolton, 1954:986).

Construction of the revitalized, enlarged hole-in-the-ground antenna took about six months, 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 guy ropes, but could be altered in the north-south plane to allow declination 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 6, taken when Gordon Stanley was busy using the theodolite.

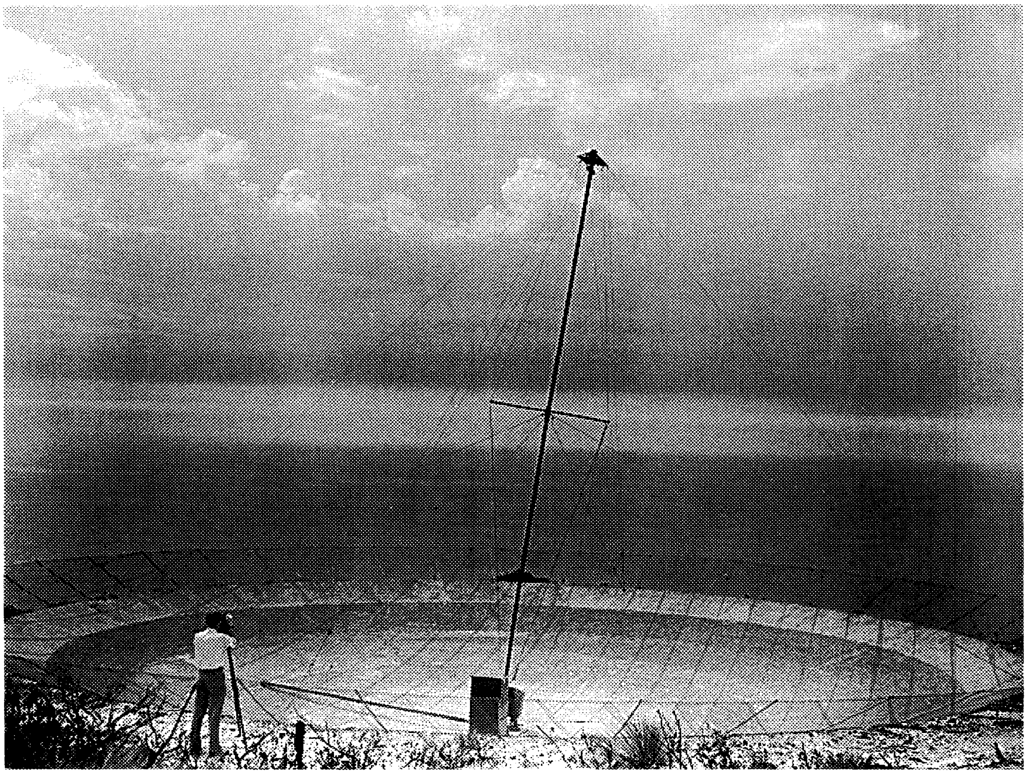

Figure 6. The enlarged concrete-coated 24.4-m antenna in September 1953, with Gordon Stanley using a theodolite to record the position of the aerial mast. (ATNF Historic Photographic Archive: 3150-2)

The first research project carried out with the new antenna was a survey at 400 MHz, modelled on the earlier one achieved with the prototype dish at 160 MHz, and this was to occupy most of 1953. Much of the observing and data-reduction was carried out by a new member of the Dover Heights group, Richard (Dick) X McGee, assisted from time to time by Bolton, Slee, and Stanley who were otherwise engaged in an all-sky search for discrete sources at 110 MHz and in a detailed investigation of selected sources using the Dover Heights 12-Yagi array that was also constructed in 1951 (Bolton, 1982; see, also Bolton, Stanley, and Slee, 1954). It should also be noted that in mid-1953 Bolton temporarily left radio astronomy when he transferred to the Division'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° to –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, Slee, and Stanley, 1955:353)

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

As Figure 7 illustrates, the most important outcome of this survey was the clear delineation of Sagittarius A, the strong source at the old galactic co-ordinate position of $l^I = 327^\circ.9$ and $b^I = -1^\circ.0$ or RA 17 h 42 min and dec. –28°.5 (1950), which McGee, Slee and Stanley correctly identified with the nucleus of our Galaxy, and it is illuminating to compare this result with the earlier isophote plot shown in Figure 5. We should note in relation to Figure 7 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 $l^I = 348^\circ, b^I = -23^\circ$ to $l^I = 341^\circ, b^I = -7^\circ$ and also from $l^I = 318^\circ, b^I = -17^\circ$ to $l^I = 310^\circ, b^I = -3^\circ$ are not real: they are artefacts generated by the coma that is associated with this type of antenna system.

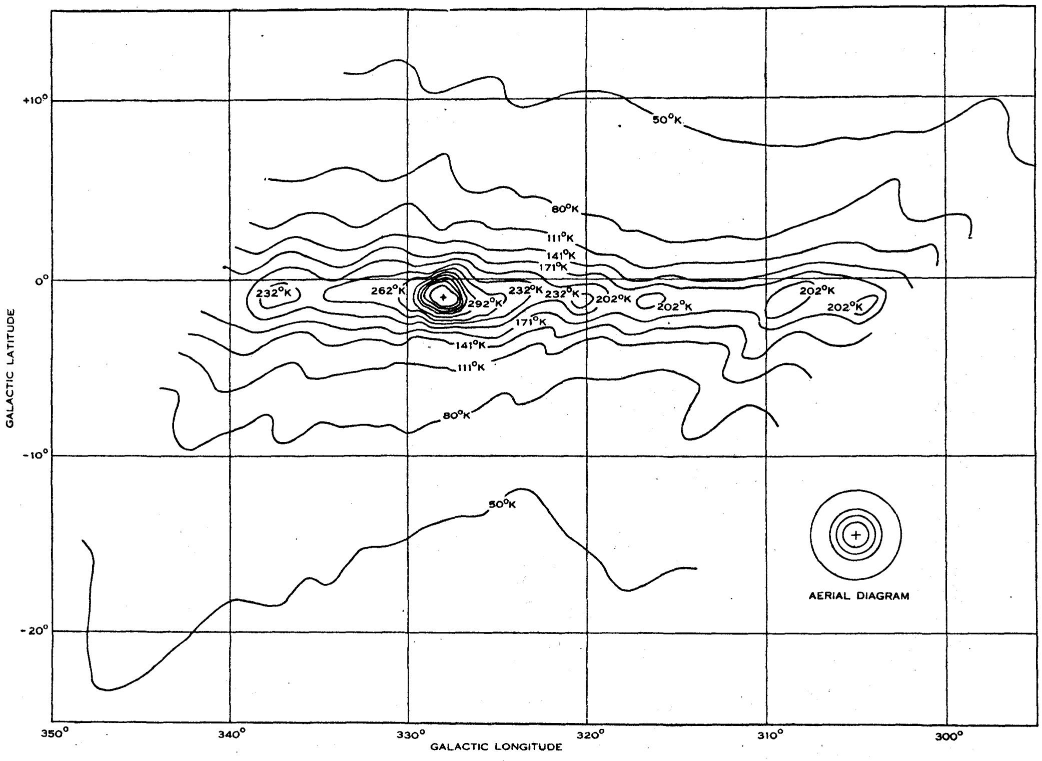

Figure 7. 400 MHz contour plots showing the strong emission source associated with the galactic centre (after McGee *et al.*, 1955:356).

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." (op cit.:347), but there was considerable confusion about the location and nature of the radio source and the authors of the hole-in-the-ground 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." (op. cit.:348). This is precisely what Walter Baade would have hoped for when he first suggested this project to the Sydney radio astronomers (McGee and Bolton, 1954).

Before the papers reporting these results were published Pawsey took the precaution of sending a copy of the isophotes shown in Figure 7 to Baade for his evaluation. His reply of 1954 February 16 must have been very pleasing to Pawsey:

> Now to the object in the center of the galaxy, the contour diagram of which you kindly included in your letter. Frankly I jumped out of my chair the moment I saw what it meant. I have not the slightest doubt that you finally got the nucleus of our galaxy!! ... The strongest argument at present is its position which coincides with the expected place of the nucleus... It is very improbable that the coincidence between inferred and observed position of the nucleus is accidental. (cited in Morton, 1985:219).

Van de Hulst happened to be visiting Pasadena at the time, and when Baade showed him the Sydney plot he immediately also penned a letter to Pawsey, mentioning that "Baade got really excited about your fine observations of the galactic nucleus and shows your plot to anyone who comes near his office. The position agrees quite well with the best we can do on the basis of the 21-cm observations ..." (ibid.). At the same time Baade also sent a copy of the plot to Oort, who likewise was impressed:

> I have been excited by Pawsey's diagram that I received from you this morning. The longitude of the concentration which the Sydney observers have found co-incides exactly with the longitude of the centre that Mr Westerhout has now deduced with considerable accuracy from the 21cm observations. (ibid.).

These comments, from some of the world's leading astronomers, reinforced Pawsey's belief that the hole-in-the-ground antenna had produced an important research result.

Publication was the next step, and although the detailed account of this project was published in the *Australian Journal of Physics*, it was the earlier preliminary account in *Nature* that reached a wider audience and had more impact. Dual publication of particularly important results was a feature of the Radiophysics publishing strategy at this time, with the recognizd status of *Nature* a primary factor, but all papers had to go through "... a system of rigid internal reviews ... often to the frustration of the authors." (Sullivan, 1988:333) before they were approved for submission. The 'galactic centre' paper was no exception, and its review generated considerable Divisional interest among senior members of staff (see Goss and McGee, 1996). Most were concerned about the claimed association between Sagittarius A and the galactic centre, and as a result the original manuscript was extensively modified and during the review process witnessed a succession of title changes. The final title, however, was decided unilaterally by Pawsey, despite concerns from some on the Radiophysics publications committee, but "Probable observation of the galactic nucleus at 400 Mc./s." was bound to generate international interest and reflect positively on the research work of the Division.

Since the original hole-in-the-ground papers were published in 1954 and 1955, the resolution of radio telescopes has improved dramatically. As a result, Sagittarius A has been resolved into a number of adjacent discrete sources (e.g. see Burke, 1965), and as long ago as 1995 one of these, Sgr B2, was itself known to contain almost sixty components. As Palmer and Goss (1996) have demonstrated, this increasing complexity has been accompanied by an evolving – and at times rather confusing – nomenclature.

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." (Mc Gee *et al.*, 1955:359, 362), this resulted in a list of 14 different sources (see Table 1, which includes Sagittarius A).

Table 1: Discrete sources observed at 400 MHz (adapted from McGee *et al.*, 1955:359-364).

Constellation	**Position (1950)**		**Flux (Jy)**	**Notes**
	RA (h min)	dec. (deg)		
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	

With the benefit of hindsight and improved resolution, about half of these 'sources' have since been shown to be a result of confusion, where several adjacent sources were unresolved with the Dover Heights beam.

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 h r55min, Dec. –23.5° plane polarization of the radiation at 400 Mc/s is less than 2 per cent." Given the 2° beam of the antenna, these locations were probably chosen at random, although it is interesting to note that the former position happens to coincide with the 400 MHz emission peak at l^{I} = 309° and b^{I} = –2° in Figure 7, a region that is populated by conspicuous HII regions.

After the 400 MHz sky survey, the hole-in-the-ground antenna 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. This search was undoubtedly inspired by the detection of the 21-cm hydrogen line in 1954, and the widely held belief that other radio spectral lines must exist. In 1952 Shklovsky had shown that a weak deuterium line may exist, and he later noted that its detection "... would have great astronomical and cosmological significance ... [and] shed light on the question of the isotopic composition of the interstellar gasses." (Shklovsky, 1960:258-259). Since the Radiophysics Laboratory was already actively involved in H-line work the search for a deuterium line was a natural progression, and on this occasion the investigators were Stanley and a visiting U.S. Fulbright Fellow named Price. Their search was carried out in 1954, and the hole-in-the-ground antenna was attached to a receiver centred on 327.369 MHz, which fed a bank of filters, each with a bandwidth of 16 KHz and spaced 48 KHz apart. The observations were made in the area of the galactic centre and in the region of the galactic plane at l^{I} = 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 integrations also failed to reveal the deuterium line, but these negative results were only published in *Nature*, in 1956, after a Russian team reported their own unsuccessful search. Later investigations revealed that these negative results were wholly to be expected, since the relatively higher abundance of deuterium in the solar system is not a valid indication of its concentration throughout the Galaxy. So instead of deuterium, it was the two main lines of OH that were next to be detected, in 1963 (Weinreb *et al.*, 1963). Since then, many other spectral lines have been found, and Radiophysics staff has played an important role in this research (e.g. see Robinson, 1994; Whiteoak, 1994). However, the deuterium line has remained elusive. It has still to be detected!

4 DISCUSSION

4.1 Sagittarius A and the Galactic Centre

Because of the wide 'visibility' of papers published in *Nature*, the Dover Heights team is generally credited with formally identifying Sagittarius A with the galactic centre (e.g. see Robertson, 1992), but as Goss and McGee (1996) have pointed out this association really belongs to two other Radiophysics staff members, Jack Piddington and Harry Minnett. In 1950 they used a 4.9-m × 5.5-m (16-ft × 18-ft) equatorially-mounted rectangular parabolic antenna at the Potts Hill field station in suburban Sydney to carry out a study of galactic radiation at 1210 MHz. This radio telescope had a beamwidth of 2°.8, and their survey revealed "... a new, and remarkably powerful, discrete source.... [at] the position of the galactic centre." (Piddington and Minnett, 1951:465). This new source was located on the Sagittarius-Scorpius border at $l^I = 328°$ and $b^I = -3°$ or RA 17 h 44 min and dec. –30° (1950), and although they noted "... an estimated uncertainty in Right Ascension of about 2 minutes and in Declination of about 1°" (Piddington and Minnett, 1951:467), their values are remarkably similar to those obtained later by McGee *et al.* with the hole-in-the-ground antenna. Piddington and Minnett published their results in 1951, but unfortunately they chose the rather obscure *Australian Journal of Scientific Research*, and although this journal was beginning to build an international reputation their paper did not reach a wide audience within the radio astronomical community. As Sullivan, (1988:328) has observed:

> ... the *Australian Journal of Scientific Research* ... started by CSIR in 1948 [was] ... a further sign of the growing independence of Australian science. RP sent thirty full articles to the journal in its first four years, but only eight to British journals (plus eight letters to *Nature*). Although this corpus in the end probably lent more stature to the journal than did any other single field, it took a while for a world readership to develop.

An interesting sequel to this Sydney-based radio astronomical work occurred at the 1958 General Assembly of the International Astronomical Union when a resolution was passed adopting 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 (see Sadler, 1960).

4.2 Personalities, Politics, and the Demise of the Dover Heights Site

As it happened, the search for deuterium marked the death knell for radio astronomy at Dover Heights. The sea interferometer concept (and consequently the Dover Heights field station) had pretty much reached the end of its viable lifetime, and new options were called for (see Stanley, 1994). However, staff at the Division of Radiophysics was vehemently divided over what form future instrumentation should take. While Bowen (1984) strongly favoured a large steerable parabolic reflector, preferably with an aperture exceeding that of Bernard Lovell's new Jodrell Bank Radio Telescope, most of the radio astronomers argued in favour of interferometry (see Robertson, 1992). John Bolton (1982:357) had three possibilities in mind, all of which were interferometers:

> One was to form a second hole-in-the-ground to form an interferometer with the first. The second, inspired by Taffy [Bowen] was to build two rolling barrels – parabolic cylinders inside circular cylinders – to form an interferometer. The third and my own choice was to build a large sea interferometer for use at 400 MHz. This would have consisted of a cylindrical paraboloid 20 ft high and 200 ft long with a focal length of about 150 ft fed by a vertical stack of dipoles. The construction of the mirror would have been similar to the fence round a tennis court and would have been rebuilt for each 40° of azimuth; the 40° interval covered by moving the dipole stack. The primary beamwidth would have been 1° in azimuth and the interference fringes 15' arc apart.

It is ironic that one of Bolton's options was inspired by Bowen, in the light of his open opposition to interferometers at this time.

For his part, Stanley (1994:511) also favoured interferometry, but had a different scheme in mind, one that involved a two-element interferometer, where

> ... two cylindrical parabolas were mounted on tracks. These were to have line feeds capable of multiple frequency operation. It was my misconception that the antennas could have been built cheaply from wood! The idea was never developed, nor did it have the enthusiastic support of the rest of the Dover Heights group... Paul Wild invited me to join him on a trip down the south coast of New South Wales in September 1950 ... [which] would be an opportunity for me to find a site suitable for the interferometer ... I chose a site at Jervis Bay and although it was never used, the idea of the interferometer was the genesis of the one built at Owens Valley in California.

In the final outcome neither of these schemes prevailed, and with support (and ultimately funding) going to the 64-m Parkes dish (see Bowen, 1981) and an interferometer in the guise of the Mills Cross at Fleurs (Mills *et al.*, 1958) there was great upheaval in Radiophysics (see Haynes *et al.*, 1996). It was some time before either of these new radio telescopes became a reality, and in the interim the Division's research focus shifted from Dover Heights to Dapto (solar astronomy) and Potts Hill (mainly solar and H-line work). It was at Potts Hill that Mills constructed a small prototype of the Mills Cross, to establish the viability of this innovative new design. By this time, those at Radiophysics realized that the end of an era was at hand, and 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). Writing in 1994, Minnett had this interesting perspective on subsequent developments:

> Over 30 years ago, Radiophysics was divided over the better path to follow in developing telescopes for future observations. The giant reflector approach pursued by Taffy Bowen created the Parkes radio telescope and its associated stream of technology. But it also swept aside the development of high-resolution interferometry for cosmic astronomy, nurtured so successfully by Joe Pawsey. Transplanted to the University of Sydney and developed by Mills at Molonglo and by Christiansen at Fleurs, interferometry returned to Radiophysics some 20 years later with Bob Frater. The two streams of development, both essential to a large modern synthesis telescope, have now merged in the Australia Telescope, a splendid national facility which has at last put the old controversy to rest. (Minnett, 1994:18).

Although radio astronomy ceased at Dover Heights at the end of 1954 (Bolton, 1982), for a while the Division'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 a playing field known as Rodney Reserve. In the process, the remarkable hole-in-the-ground antenna was filled with spoil and then grassed over. Today it lies a little north of the northern soccer goal post, and apart from a few individuals who might quite by chance notice an inconspicuous plaque hidden away in one corner of the Reserve, most of those who use this popular recreational facility would be totally unaware of the amazing scientific contribution that this site made in the early days of Australian radio astronomy. However, if they should venture across to the fence near to the cliff edge and know precisely where to look, they can still catch a glimpse of the rusting mount that supported the 12-Yagi array erected back in 1951. This, unfortunately, is all that now remains of those pioneering radio telescopes that once graced the Division of Radiophysics' Dover Heights field station.

4.3 Other Hole-in-the-Ground Antennas

Although Australian radio astronomers pioneered the hole-in-the-ground antenna concept they were not alone in thinking of this cheap and innovative way of acquiring a large parabolic antenna. In 1954-1955 F.I.A.N. scientists in Russia went one step further, constructing not one, but two, 30-m hole-in-the-ground antennas 740 m apart at their Crimean radio astronomy field station (see Figure 8). Initially these two antennas were used as an interferometer for studies of the solar super-corona and the Crab Nebula, and later the surface of one of the antennas was recast in concrete and this stand-alone instrument was used to continue these experiments at a number of different frequencies (Kalachov, 1963).

Figure 8. One of the two 'hole-in-the-ground' antennas at the F.I.A.N. radio astronomy field station in Crimea, USSR. (ATNF Historic Photographic Archive: 12766-9)

If we wish to seek modern-day analogues for the Dover Heights and Crimean antennas we need look no further than the famous Arecibo Dish, even if those who constructed it simply decided to exploit a freak of geography in order to achieve its apparent 'hole-in-the-ground' status.

5 CONCLUDING REMARKS

The Mark I and Mark II versions of the Dover Heights hole-in-the-ground antenna were interesting responses to specific research needs that arose in Australian (and international) radio astronomy during the early 1950s. This was a time when radio astronomical hardware was still affordable, and within the annual budget allocation of a single research institute, but in the case of the Dover Heights antennas expenditure in lunchtime-manpower and constructional man-hours made these even more cost-effective enterprises than would normally have been the case!

The first hole-in-the-ground antenna demonstrated the viability of the system, and the second, slightly larger radio telescope was then used for the most detailed survey of the Sagittarius A source carried out up to that point in time. The association of this discrete source with the galactic centre was a significant identification, and the subsequent re-calibration of the international galactic co-ordinate system by the IAU was a reflection of the importance of the Sydney results. Apart from Sagittarius A, this antenna was used to document a number of other discrete sources, and the integrity and importance of about half of these have withstood the passage of time. Finally, this novel hole-in-the-ground antenna was used to search for a deuterium line. Although inspired by the discovery of the famous H-line, with the benefit of hindsight we now realize that this study was premature and doomed to failure. This should not, however, blind us to the valuable contributions to science made by this radio telescope in just a few short years.

Those associated with the Division of Radiophysics' field stations remember with some nostalgia an era long gone, a time when radio astronomers were personally involved in the maintenance and sometimes even the design and construction of radio telescopes and their component parts (see Sullivan, 1988). This was the time when the 'fix it with fencing wire' ethos that permeated Australian culture reigned supreme. After all, how many radio astronomers today would be prepared to sacrifice their lunchtimes in order to construct a radio telescope with which to carry out fundamental research? The Dover Heights hole-in-the-ground antenna is a fitting reminder of a time when ingenuity, dedication, and minimal financial outlay were capable of producing significant scientific results. Today's radio astronomy, with its sophisticated multi-million dollar arrays and milli-arcsecond resolutions, is a very different world!

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7 NOTES

1 For a brief, popular, account of this radio telescope see Orchiston, 2002.

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