NRAO ONLINE 34: URSI at 100 book Australian radio astronomy

Radio astronomy in Australia: impact and the growth of a community

Helen Sim URSI 100 - 2020

Introduction

In 1946 researchers in Australia were the first to use an interferometer to study the Sun. Today the country has world-class radio telescopes and is preparing to host the low-frequency antennas of the international Square Kilometre Array. The years between have seen the Australian radio-astronomy community grow and Australians have significant impact. Developments fall roughly into four phases, defined by changes in instrumentation.

Foundational years, 1946–1961

During the Second World War, radar operators in both the UK and New Zealand saw sporadic bursts of radio emission from the Sun. Immediately after the war, researchers in Australia and the UK began investigating this solar emission – and then, for good measure, the cosmic radio waves detected by Karl Jansky in 1932. In the first decade of these investigations Australians used, and in some instances created, several types of radio telescope, and notched up important firsts in interferometry and studies of the Sun. By the late 1950s the Australians had produced far more papers in radio astronomy than any other group in the world [1]. Many authors have explored this early period in detail. Sullivan [1, 2] gives a relatively brief treatment; Goss *et al*. [3] cover it at length.

A single government institution drove the Australian research. This was the Radiophysics Laboratory of the Council for Scientific and Industrial Research (CSIR; from 1949, CSIRO, the Commonwealth Scientific and Industrial Research Organisation). Radiophysics had been established in 1939 to work on radar defences for Australia. Its staff was drawn largely from the radio ionospheric community built up in the 1930s at the Universities of Sydney and Melbourne and in the research lab of Amalgamated Wireless (Australasia) Ltd [4]. By the war's end Radiophysics, then housed at the University of Sydney, had more than 300 staff, a well-equipped workshop, and a large stock of radio equipment, both its own and some salvaged from US and British forces. The laboratory's leader, Edward ('Taffy') Bowen, was in good standing with the CSIR Executive. In 1945 Bowen drew up a list of nine research areas Radiophysics could pursue in peacetime, 'non-thunderstorm' (i.e. cosmic) radio noise among them. By 1949 the radio-noise investigators numbered about 20 (later growing to 30). They were the laboratory's biggest research group and published the largest share of its papers [1].

Australian universities of the day could not match this effort. Government funds for university scientific research were a thirtieth those for CSIR [1]. Universities offered almost no postgraduate studies. The first Australian PhD was awarded in 1948, by the University of Melbourne [5]. Australians went abroad for their advanced training.

Radiophysics's scientific leader, Joseph L. Pawsey, had followed that path. After taking a degree in physics at the University of Melbourne he had completed a thesis on ionospheric physics under J. A. Ratcliffe at Cambridge – an important connection for the development of Australian radio astronomy. Pawsey worked in the UK on early television systems then joined Radiophysics in 1940. Already expert with antennas and transmission lines, by the war's end he had gained skills with receivers, radar systems and atmospheric propagation and experience in managing a research group.

Pawsey made the first documented use of the term 'radio astronomy' to describe the new field, in a letter dated 14 January 1948 [6]. Martin Ryle at Cambridge also used the term in April that year: he and Pawsey had probably discussed it when they met earlier that month. Both URSI and the International Astronomical Union (IAU) needed a name for the new subdiscipline, URSI for its commission J, and the previous 'cosmic noise' or 'radio noise' was considered unsuitable. Pawsey was very active in both URSI and the IAU – he was president of IAU Commission 40 (Radio Astronomy) from 1952 to 1958 – and he promoted the use of the term 'radio astronomy' to build a connection with the rest of astronomy.

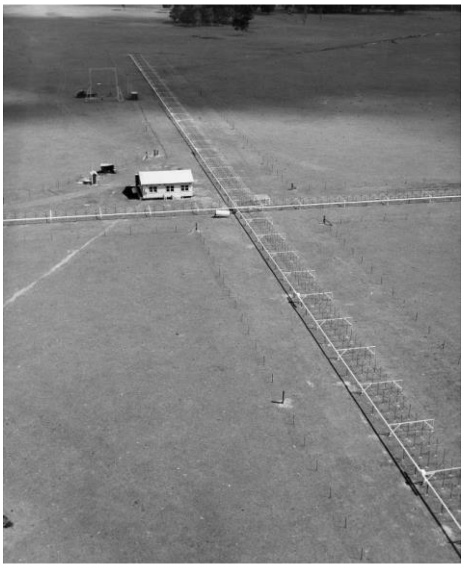
Pawsey's management style played a big role in the success of the Radiophysics astronomy group. He followed the philosophy of CSIR's Chief Executive Officer, David Rivett: get the best people possible, give them resources and let them run free. Members of the radio astronomy group worked alone or in small numbers at field stations in and around Sydney, linked only by Pawsey, who advised and encouraged each small unit. But there were also practical reasons for this way of working. Christiansen [7] notes that the number of field stations

… was partly the result of the taking over of a number of former radar sites, but it continued because maintenance work and observations at the same site by different groups produced mutual electrical interference.

Left: Radiophysics researchers John Bolton, Gordon Stanley and Joseph Pawsey. Right: the Dover Heights radar station, looking north towards Sydney Heads. Credit: CSIRO (Radiophysics Image Archive B11833-6 and B81-1)

With this freedom to experiment the researchers developed significant new instruments. In 1961 Pawsey [8] highlighted four:

- the Mills Cross at Radiophysics's Fleurs field station west of Sydney. This comprised two intersecting lines of dipoles, each about 450 m long, running north-south and east-west. It produced a pencil beam 49 arcminutes wide – excellent for the time – without the need for digital computers to do the Fourier synthesis [9, 10]
- the Christiansen Cross (Chris Cross), also at Fleurs. This combined design features of Christiansen's earlier grating array [11] and the Mills Cross to generate a grid of pencil beams for imaging the Sun [12]
- a swept-frequency receiver and interferometer at Dapto south of Sydney, used to study the spectra and location of radio bursts from the Sun [13]
- a 48-channel receiver at the Murraybank field station north of Sydney, used for a detailed survey of neutral (un-ionised) hydrogen gas over the whole southern sky [14].



Top left: the Mills Cross at Fleurs field station; top right: the Christiansen Cross (Chris Cross) at Fleurs; bottom left: Richard McGee working on the antenna at the Murraybank field station used for hydrogen-line observations; bottom right: aerials of the solar interferometer at Dapto. Credit: CSIRO (Radiophysics Image Archive R3476-1, R5804-6, R5695-8p and 2888-1)

With these instruments and others, Radiophysics researchers achieved notable results including:

- first use of an interferometer in radio astronomy (by Pawsey and Payne-Scott, January 1946)
- first published description of how Fourier synthesis could be used to make radio images [15]
- first Earth-rotation 2D aperture-synthesis image – an image of the quiet Sun [16]
- first direct evidence of a link between compact solar radio bursts and sunspots [15]
- identification of different types of solar radio bursts ([17] and subsequent work)
- early identification of three discrete radio sources (‘radio stars’), one with a supernova remnant in our Galaxy and two with extragalactic nebulae [18]
- detection and cataloguing of large numbers of discrete cosmic radio sources, in projects led (separately) by John Bolton and Bernard Mills. From 1954 to 1957, Mills and his colleagues Bruce Slee and Eric Hill used the Mills Cross to record more than 2,000 sources of discrete radio emission, creating the MSH catalogue [19-21]. MSH conflicted with Cambridge University’s 2C catalogue, leading to a controversy that took years to resolve [22]
- maps of the neutral hydrogen gas in our Galaxy. These, combined with a northern sky survey, showed conclusively that our Galaxy has spiral arms [23].

By the 1950s Australia was a world leader in radio astronomy. This was a major reason why URSI held its tenth General Assembly in Australia in 1952 (the first time this meeting took place outside Europe or the USA). But the country's expertise was essentially confined to one group, Radiophysics. A few other local investigators had tried their hand at radio astronomy. Researchers at the University of Western Australia in Perth observed the Sun in 1946–48. Clay Allen at the Commonwealth Observatory at Mt Stromlo near Canberra (in 1946) and Gordon Newstead at the University of Tasmania (in 1952) observed the Sun and cosmic sources respectively, using equipment lent by Radiophysics. From 1954, Graeme 'Bill' Ellis of the Ionospheric Prediction Service made low-frequency observations in Tasmania, initially with US radio astronomy pioneer Grote Reber. Ellis moved interstate for a few years but returned in 1960, having been appointed Professor of Physics at the University of Tasmania. There he set up a research group focused on low-frequency radio astronomy [24, 25].

But in the 1950s Australia could hardly be said to have a radio astronomy community. In fact, Radiophysics leader Bowen was not looking to have rivals. When in 1951 the Mt Stromlo observatory's director announced plans to build up a radio astronomy group, CSIRO management had this initiative squashed [26]. But without radio astronomers in universities there was no way to systematically transfer knowledge to students. This situation changed with the coming of CSIRO's 64-m Parkes radio telescope.

In the late 1940s, Radiophysics learned of the University of Manchester's plans to build a large, fully steerable reflector. This would take shape as the 76-m Lovell Telescope, opened at Jodrell Bank Observatory in 1957. Bowen began to champion the building of another large dish. Such an instrument, he argued, would provide greater sensitivity, greater resolution, and the ability to operate over a wide range of frequencies. The funding was found, thanks to Bowen's contacts in the USA, and the site chosen – a shallow valley near the town of Parkes, five hours' drive west of Sydney. Construction began in 1959. Robertson [26] gives a detailed history of the Parkes telescope from its conception through to operation.

Edward 'Taffy' Bowen with the newly completed Parkes radio telescope. Source: CSIRO (Radiophysics Image Archive B15850-2)

The Parkes telescope created new scientific opportunities but ended Radiophysics's work in high-resolution, low-frequency astronomy, and led key staff to leave. By 1959 it was clear that Parkes would absorb most of Radiophysics's radio-astronomy resources. Two proposed instruments – a larger Mills Cross and a radioheliograph for studying the sun – were competing for the rest. Asked to vote, the astronomy group backed the radioheliograph. Mills, who had lobbied for the larger Cross, moved to the University of Sydney in 1960 and took up a professorship in the School of Physics. Wilbur ('Chris') Christiansen followed soon after, becoming the university's Professor of Electrical Engineering. Pawsey was offered the Directorship of the National Radio Astronomy Observatory in the USA but died in 1962 before he could take it up. There were other departures too, but Mills's and Christiansen's were the most significant for the growth of radio astronomy in Australia.

Mills and Christiansen at the University of Sydney

Ensconced at the University of Sydney, Mills built his dream instrument: the Molonglo Cross, located 35 km from Canberra. The Cross had two 1600-m arms, running north-south and east-west. It operated at 408 MHz and had a beamwidth of 2.8 arcminutes. The Cross was used to survey the southern sky, generating a catalogue of more than 12,000 radio sources; determine an absolute scale for flux density at 408 MHz, adopted worldwide; and discover more than 150 pulsars (including the Vela pulsar), over half the total then known. McAdam [27] describes the building of the Cross and its research program.

Lifting the feed on the east-west arm into position during the building of the Molonglo Cross in 1965.

Credit: The University of Sydney

During 1978–81 Mills mothballed the Cross's north-south arm and converted the east-west one to a radio synthesis array, the Molonglo Observatory Synthesis Telescope (MOST). Operating at 843 MHz, MOST made deep imaging surveys of the southern sky, notably the Sydney University Molonglo Sky Survey (SUMSS) and complementary surveys of the Galactic Plane [28, 29]. SUMSS's sensitivity and resolution equaled that of the NRAO VLA Sky Survey (NVSS) for the northern sky, and it became a standard reference. MOST also observed Supernova 1987A, the brightest supernova seen since telescopes were invented: it detected both the prompt radio emission from the explosion in 1987 and the radio source that emerged from the explosion site in 1990 [30, 31].

In 2014–15 the radio-astronomy group at Swinburne University of Technology, led by Matthew Bailes, upgraded MOST and brought it into the 'big data' era [32]. Swinburne staff and students now use the telescope to find and study pulsars and the mysterious, fleeting signals called fast radio bursts.

Christiansen regained control of the Chris Cross in 1963 when CSIRO transferred the Fleurs field station and most of its telescopes to the University of Sydney. Over the next two decades university staff and students converted this telescope into a synthesis instrument, the Fleurs Synthesis Telescope (FST). During the 1970s and '80s it was used to study individual radio sources, particularly large radio galaxies, supernova remnants and emission nebulae [33]. In its final form the FST comprised the Chris Cross and six 13.7-m antennas. It had a resolving power of 20 arcseconds, making it the highest-resolution radio telescope in the southern hemisphere until the Australia Telescope began operating in the late 1980s [34].

These university telescopes were training grounds for students and so helped grow the radio astronomy community. Their alumni include Anthony Beasley, present director of the US National Radio Astronomy Observatory; John O'Sullivan, Terence Percival and Graham Daniels, members of the CSIRO team that developed technology forming part of the 802.11 Wi-Fi standard; David Skellern, who co-founded Radiata to commercialise wireless LAN research; and Robert (Bob) Frater, who drove the Australia Telescope project in the 1980s.

The Parkes radio telescope

With the opening of the Parkes telescope in 1961 Australia gained a world-class instrument. The telescope's design innovations included its structure (which keeps the dish a fairly constant shape even as it tilts) and its pointing system (a 'master equatorial' – small optical telescope – to which the radio dish is slaved by servo system). Parkes preceded the 64-m (later 70-m) antennas of NASA's Deep Space Network (DSN) and a NASA-funded design study of Parkes led to some of the telescope's features, such as the drive and control systems, being incorporated into the DSN antennas [3].

CSIRO had set out Parkes's likely science program in 1955 [35]. Studies of the 21-cm hydrogen line – first detected in 1951 – were thought the most important. The telescope was also forecast to study discrete sources of small angular size ('radio stars') and the Sun, and precisely measure distances to the Sun, Moon and planets using radar. By 1960, polarisation measurements were also thought likely to be important because polarised emission had been detected in the Crab nebula (a supernova remnant) in 1957.

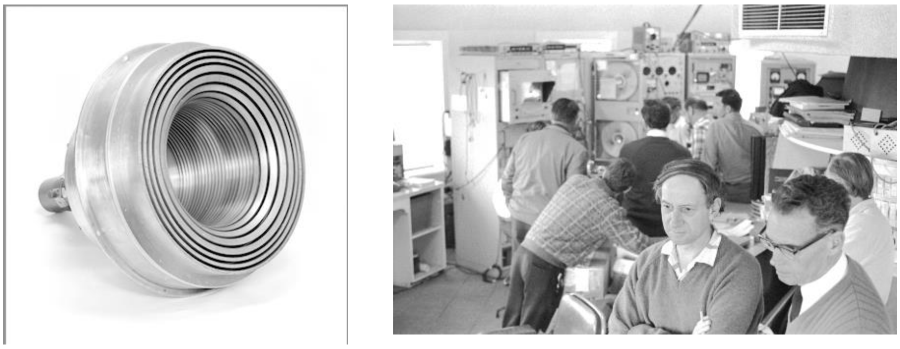
Once at work, Parkes did not stick entirely to the script. It did no significant solar work and did not measure distances to the planets. But a lot of the telescope's time early on was given to cataloguing discrete radio sources so they could be matched with optical counterparts. Hydrogen-line observations were immensely important, from the telescope's first days to the present. And in 1962 Parkes's observations of Centaurus A polarisation at two wavelengths led to the (serendipitous) discovery of the phenomenon of Faraday rotation. As Pawsey recognised, this gave "the first real chance of measuring magnetic fields in interstellar space" [3].

As astronomy advanced Parkes was also used for studies its designers had never dreamed of. The number of radio spectral lines expanded, allowing Parkes to identify molecules in space, study new kinds of objects such as cosmic masers, and map the Galaxy through radio recombination lines from regions of ionised hydrogen. In 1963 researchers used Parkes to determine the position of a radio source, 3C 273, by lunar occultation. The position was accurate to within an arcsecond – the best determination of a radio source position made to that time [36]. This allowed 3C 273 to be identified with an optical source with strange spectral lines. When US astronomer Maarten Schmidt realised these lines were those of hydrogen, but hugely redshifted, it was clear that 3C 273 must be both extremely distant and 100 times more luminous than any known galaxy. 3C 273 was the first object to be recognised as a quasar – a type of source whose power could only be generated by a black hole.

The Parkes telescope has distinguished itself above all in studying pulsars, which were unknown when it was built. It has found more than half of the ~2600 pulsars currently known, including the first (and so far, only) double-pulsar system, PSR J0737−3039. It also times a set of super-fast millisecond pulsars, the Parkes Pulsar Timing Array, with a view to detecting low-frequency gravitational waves.

In 2007 Parkes's pursuit of pulsars led to the discovery of another phenomenon. Astronomer Duncan Lorimer was searching recorded Parkes data for overlooked pulsars when he found a powerful spike of radio waves lasting just a few milliseconds. This was the first recognised 'fast radio burst' (FRB). Many more have been recorded since; Parkes found a large fraction of the early ones, thanks to its multibeam receiver. Astronomers have established that FRBs come from distant galaxies, but their cause is still unknown.

Parkes has also been used to track spacecraft on 13 occasions to date, mostly for NASA but also for ESA's Giotto mission to Halley's comet. In this regard, its best-known role is receiving the television pictures of the first moonwalk in 1969. (The telescope captured these signals with a CSIRO-designed, high-efficiency dual-hybrid-mode feed, a refinement of the corrugated, hybrid-mode feed that CSIRO had developed – specifically for Parkes – in 1968 [37]. Corrugated horns were developed independently, and around the same time, by Minnett and Thomas in Australia, and Kay and Simmons in the USA [38]. Developed largely for radio telescopes, the technology was rapidly applied to earth-station antennas.)



Left: the corrugated, hybrid-mode feedhorn used on the Parkes telescope in 1969 to receive signals of the Apollo 11 moonwalk; right: the Parkes control room during the moonwalk, with John Shimmins, Edward Bowen (front) and other CSIRO and NASA personnel watching the vision as it was received. Credit: CSIRO (Radiophysics Image Archive B9245-2 and 9190)

By becoming a hub for research, Parkes helped expand the radio astronomy community. Although the telescope was run for CSIRO staff, collaboration with outside users was encouraged. And students could use it for their thesis work. (This included Australian students, as Australian postgraduate training had expanded after the war.) The telescope's first director, John Bolton, took up his role in 1960, after spending five years at Caltech overseeing the design and construction of the Owens Valley Interferometer. He was a scientist of international repute and three of his graduate students – Ken Kellermann, Ron Ekers and Jasper Wall – became directors of observatories.

Parkes's performance has been continually increased by a series of upgrades to its surface, receivers, backend signal processing, and pointing and control systems. Of the instruments that have extended the telescope's capabilities, probably the most significant has been a 13-beam receiver installed in 1997. This receiver increased the telescope's instantaneous field of view 13-fold and made possible a ground-breaking survey of the southern sky for neutral hydrogen (essentially a blind survey for galaxies in the local universe [39]), the discovery of fast radio bursts, and a major survey for pulsars. CSIRO subsequently built similar multibeam instruments for the Arecibo and Jodrell Bank observatories and for China's FAST (Five-hundred-meter Aperture Spherical Telescope). The most recent enhancement to Parkes is an ultra-wideband receiver covering 0.7 GHz to 4.2 GHz, installed on the telescope in 2018 [40].

CSIRO radioheliograph

Radiophysics's second major instrument of the 1960s was its radioheliograph. This was located near Narrabri in northwest New South Wales, where a large area of flat land was available. Opened in 1968, it comprised 96 parabolic reflectors, each 13.7-m in diameter, arranged in a circle 3 km across; the 96 signals were combined to form a comb of 48 pencil beams in a north-south line [41]. Observations were made initially at 80 MHz (1 m wavelength) then later at 160 MHz.

The radioheliograph produced frames once a second, generating unique ‘radio movies’ that allowed the various types of solar bursts to be studied in detail. In the late 1960s and early ‘70s it was a world-leading instrument: in 1969 URSI bestowed its highest award, the Balthasar van der Pol Gold Medal, on the radioheliograph’s creator, Paul Wild [42]. By the 1980s the radioheliograph had fulfilled its mission. It was closed in 1984, ending Australia’s role in solar radio astronomy.

The Australia Telescope and the ATNF

Despite Parkes’s productivity, by the 1970s Australia was no longer at the forefront of cosmic radio astronomy, as it lacked a major radio synthesis instrument such as Westerbork in the Netherlands (operational 1968) or the Very Large Array in the US (constructed 1975–80). Over 1975–79 a working group drawn from Radiophysics, the Australian National University and the University of Sydney developed a proposal for an Australian Synthesis Telescope (AST), a set of dishes to be located at the Parkes observatory. But by 1980 this project looked unlikely to get off the ground.

In 1981 Radiophysics gained a new leader, Robert H. Frater. Frater had worked on the electronic design of the Molonglo Cross for his PhD and became Associate Professor of Electrical Engineering at the University of Sydney. He thought the AST proposal lacked ambition and pushed for a bolder plan. Six moveable antennas on railtrack would be located at the radioheliograph site near Narrabri while a seventh would be built near the town of Coonabarabran, 120 km south. Frater committed to the Australian Government that 80 per cent of the project’s funding would be spent in Australia and that the telescope would be opened in 1988, Australia’s bicentennial year. Government approved the project in 1983 and work began.

The telescope, now called the Australia Telescope, was the largest project CSIRO had ever undertaken. It came in on time and on budget. The antenna designs were developed in partnership with industry, which later adapted them for commercial Australian-built satellite earth stations. A study by the Australian Bureau of Industry Economics [43] found that the overall benefit-to-cost ratio of CSIRO’s antenna research was 2:1.

Australia’s Prime Minister, Robert (Bob) Hawke, opening the Australia Telescope on 2 September 1988. Credit: CSIRO (Radiophysics Image Archive N15191-11)

The six 22-m Culgoora antennas (the Australia Telescope Compact Array, ATCA) were designed to be as versatile as possible, with high resolving power, a spectral-line capability, wide bandwidth and the ability to measure polarisation accurately [44]. They were originally equipped to operate at centimetre wavelengths (the 1.5, 2.3, 5.0 and 8.6-GHz bands) but were designed to handle higher frequencies too, and later acquired receivers for the 16–25 GHz, 30–50 GHz and 85–105 GHz bands. Later upgrades combined the 1.5- and 2.3-GHz bands combined into a single band covering 1.1–3.1 GHz, and the 5.0- and 8.6-GHz bands combined into a 4–12 GHz band. In 1998 a short north-south rail track was added to the existing east-west track. This allowed millimetre-wave observations to be completed at high elevations, where these short wavelengths are least absorbed by the atmosphere.

In ATCA’s first year its international users came from just 10 institutions. Within six years they were coming from more than 110. An independent analysis in 2008 ranked the telescope’s impact just behind that of the larger US Very Large Array [45]. Its most influential papers are those from the 1990s describing mosaicked images of neutral hydrogen in the Large and Small Magellanic Clouds, at that time the most detailed images of atomic gas in any external galaxy. Other notable science from ATCA includes:

- observations that provided the first link between a supernova (SN1998bw) and a gamma-ray burst
- an unprecedented time sequence of observations of SN1987A from 1991 to the present day, and the first measurements of polarisation within the radio remnant
- the AT20G survey, which to date is the only large area 20-GHz survey of the sky
- follow-up of the gravitational wave event created by merging neutron stars in 2017 – the most highly cited paper using ATCA data.

The seventh, standalone antenna of the Australia Telescope is located at the Mopra Observatory 120 km south of ATCA. A 2006 upgrade gave the Mopra telescope four overlapping frequency sub-bands, each with a bandwidth of 2.2 GHz, providing a total of 8.3 GHz of continuous bandwidth. Mopra was originally used for very long baseline interferometry and single-dish observations at centimetre wavelengths; in recent years its focus has been surveys of various molecular species along the Galactic plane. Since 2012 CSIRO has managed the Mopra telescope under contract for university consortia.

In 1989 a new institution, the Australia Telescope National Facility (ATNF), came into being to operate all of CSIRO’s radio telescopes. Observing time was made freely available to all researchers who submitted competitive observing proposals. This gave Australian researchers access to world-class facilities that were beyond the means of any local university. The ATNF now also handles proposals for service observations on antennas at the Canberra Deep Space

Communication Complex, part of NASA's Deep Space Network: although dedicated to spacecraft tracking, they can be used for some astronomy.

Radio astronomy at the University of Tasmania

As already mentioned, the University of Tasmania initially focused on low-frequency radio astronomy. The discovery of pulsars in the late '60s prompted a move to higher frequencies. Today the University's main observatory houses two dishes, 14 m and 26 m in diameter. The smaller dish monitors the well-known Vela pulsar for glitches – sudden changes in the pulsar's rotation period that give clues to its internal structure – while larger one is used mostly for very long baseline interferometry, plus some studies of pulsars and cosmic masers. The university also owns a 30-m dish at Ceduna, South Australia, that adds a useful east-west baseline to the Australian array for very long baseline interferometry.

Left: poles of the Llanherne Low Frequency Array near Hobart, Tasmania. Operating at frequencies between 2 MHz and 35 MHz, this was one of the University of Tasmania's major low-frequency instruments. It was used from 1972 to the early 1980s to record bursts of decametric bursts from Jupiter and map the radio sky at low frequencies [46]. Credit: the estate of Grote Reber. Right: the University of Tasmania's 26-m antenna at Mount Pleasant Observatory. Credit: Jim Lovell

Very long baseline interferometry (VLBI)

US and Canadian institutions pioneered very long baseline interferometry – interferometry with widely separated antennas – in the 1960s. Australia made its first successful international VLBI experiment in April 1969, when the Parkes telescope was linked to an antenna in California's Owens Valley [47]. Just a few months later, VLBI observations using DSN antennas in Australia and California gave the first evidence of a radio source apparently expanding at a speed faster than light [48] – a phenomenon, later seen in many extragalactic sources, caused by the source's orientation. Routine Australian VLBI started in the 1980s with the development of a network called SHEVE, the Southern Hemisphere VLBI Experiment [49].

By the mid 1990s SHEVE had evolved into today's Australian Long Baseline Array (LBA). This network routinely uses the ATCA, Mopra, Parkes, Hobart and Ceduna antennas; on occasion it may also incorporate antennas from the

Canberra Deep Space Communication Complex, the Australian SKA Pathfinder in Western Australia, the 26-m antenna at Hartebeesthoek in South Africa, the 12-m antenna at Warkworth in New Zealand, and other antennas of the University of Tasmania mainly used for geodesy. LBA data was originally recorded on tape (the Canadian S2 system) and then on disk. Some of the LBA antennas have been used for e-VLBI – streaming data over high-speed fibre networks and correlating it in real time. Edwards and Phillips [50] describe the LBA and its operations.

Australia has made successful international VLBI observations over baselines to Antarctica, China, Europe, India, Japan, Korea, South Africa and the USA – Alaska, California and Hawai'i [51].

Australia also took part in the first space VLBI experiment, made in 1986 between NASA's TDRSS-E satellite and antennas in Australia and Japan. Australia has since contributed co-observing radio telescopes for two space VLBI missions, Japan's VSOP (VLBI Space Observatory Programme) and Russia's RadioAstron, and also designed and built a 1.6-GHz receiver that flew on RadioAstron.

The Square Kilometre Array (SKA) and Australian precursors

Australia and the SKA

In the 1980s astronomers from several countries began to discuss building an extremely large, international radio telescope to study the early universe. Their original aim was to detect the faint, redshifted hydrogen-line signals from distant galaxies.

In 1997 Australia was one of six countries that agreed to cooperate to develop technology for the telescope, now with a broader set of science goals and called the Square Kilometre Array (SKA). In the same year CSIRO began searching for areas in Australia where the telescope could be sited. By 2007 it had chosen a superbly radio-quiet location in Western Australia and began to transform it into the Murchison Radio-astronomy Observatory (MRO), building there an SKA 'precursor' telescope, the Australian SKA Pathfinder (ASKAP). ASKAP was soon joined by a second precursor, the Murchison Widefield Array (MWA).

In past decade, Australia has been active in eight of the 11 international consortia designing SKA systems. In 2019 Australia was one of seven countries that signed the treaty establishing the SKA Observatory as an intergovernmental organisation.

The MRO will host the SKA's array of low-frequency antennas, SKA-Low. Construction is expected to start in 2021. This prospect, plus the building of the SKA precursor telescopes at the MRO, has expanded the radio astronomy community in Western Australia. The Perth-based International Centre for Radio Astronomy Research (ICRAR) was created in 2009, drawing together researchers from the University of Western Australia and Curtin University: it is now the largest radio astronomy group in the country. The ATNF too has a growing presence in Western Australia.

The Australian SKA Pathfinder

The Australian SKA Pathfinder (ASKAP) is a radio interferometer, a set of thirty-six 12-m dishes [52]. It is designed as a fast, mid-frequency survey instrument and its first years of full operation will be spent on large survey projects aimed at understanding the formation and evolution of galaxies, cosmic magnetic fields, the interstellar medium and transient radio phenomena. These projects, being carried out by large international teams, will exploit ASKAP's key characteristics: sensitivity, wide bandwidth, and wide field of view. Pilot observations have begun.

ASKAP's key technology is its phased-array feeds (PAFs), designed and built by CSIRO. These replace the feedhorns traditionally used in radio telescopes. A PAF is a close-packed array of simple receptors, located in the antenna's focal plane. The voltages from the receptors are combined to form multiple beams on the sky pointing in different directions. This is computationally intensive, but allows the direction of the beams to be controlled by varying the weighting of different PAF elements, so beams can be shaped to meet a project's specific needs. PAFs also give a large instantaneous field of view (for ASKAP, 30 square degrees) and a wide bandwidth (for ASKAP, currently 288 MHz).

Left: antennas of the Australian SKA Pathfinder (ASKAP) at CSIRO's Murchison Radio-astronomy Observatory in Western Australia. Right: a phased-array feed on an ASKAP antenna. Credit: CSIRO

In addition to the usual two axes of rotation, altitude and azimuth, ASKAP has a third one that allows the PAF to be kept in the same orientation with respect to the sky while the telescope tracks. This 'roll' axis suppresses imaging artefacts and makes image processing less complex than it would be if the PAF's orientation changed. It also allows polarisation measurements to be extremely well calibrated.

ASKAP's 36 antennas generate up to 9 TB of data an hour. The data are processed and the data products stored at the Pawsey Supercomputing Centre (named after Joseph Pawsey, founder of Australian radio astronomy) in Perth, Western Australia.

ASKAP's power is illustrated by its work on fast radio bursts (FRBs) – cosmic radio bursts of unknown origin that last for just milliseconds, first found with the Parkes telescope. From January 2017 ASKAP was used to search for FRBs in a unique ‘fly’s eye’ observing mode. Within a year it detected 20, almost doubling the number known at the time. In 2018 ASKAP became the first telescope to measure accurate positions for non-repeating FRBs and so determine their host galaxies.

ASKAP has recently made a rapid radio-continuum survey of the sky from the south celestial pole to a declination of +40°, over frequencies from 744 MHz to 1032 MHz. Although intended mainly for calibrating future deep surveys, the survey images are already significantly deeper and of higher angular resolution than those of the existing radio surveys at this frequency, and include full polarisation information.

The Murchison Widefield Array

The Murchison Widefield Array (MWA) at the MRO comprises 4096 dual-polarisation dipole antennas optimised for frequencies from 70 MHz to 300 MHz [53]. The dipoles are arranged in 4 x 4 arrays called tiles. Most tiles lie in a core region about 1.5 km across while some sit up to 6 km away to give higher angular resolution. The MWA was completed in its initial form of 128 tiles in 2013 then expanded to 256 tiles in 2016. The telescope was developed by an international collaboration and is managed (as a national facility) by the Curtin Institute of Radio Astronomy at Curtin University in Perth, Western Australia.

Left: the Murchison Widefield Array (MWA); right: installing antennas of the Aperture Array Verification System, a testbed for SKA-Low, at the MWA site. Credits: ICRAR/Curtin University

Like ASKAP, the MWA is an official SKA precursor – a demonstrator for SKA science and technology, located at one of the SKA’s two sites. The MRO will host SKA-Low, the SKA’s low-frequency antennas. The MWA has already contributed to SKA-Low’s operations by measuring the local radio-frequency interference and ionospheric conditions, and helping to characterise the Aperture Array Verification System (AAVS), the testbed for SKA-Low antennas.

To date much of the MWA’s observing time has been used for projects – on systematics, foreground sources and calibration procedures – to support the detection of the redshifted 21-cm hydrogen signal from the epoch of reionisation, when the first stars formed and ionised most of the universe’s hydrogen gas. To characterise foregrounds, the MWA has carried out the GaLactic and Extragalactic All-sky Murchison Widefield Array (GLEAM) survey, covering declinations south of +30° and Galactic latitudes outside 10° of the

Galactic plane. The GLEAM catalogue [54] contains more than 307,000 radio sources, each with flux density measurements at 20 frequencies within 72–231 MHz.

The MWA had an immediate impact even during commissioning observations in 2013. While using the telescope for her Honours thesis, a University of Sydney student, Shyeh Tjing (Cleo) Loi, identified large, tubular ducts of plasma in the ionosphere that were aligned with the Earth's magnetic field. Loi used the MWA to make the first detailed images of these ducts, deduced their heights and sizes, and imaged their motion in real time [55]. This work gained worldwide attention and showed the MWA to be a superb instrument for studying the ionosphere.

Conclusion

Seven decades ago a relatively small and isolated group of Australian researchers became pioneers of radio astronomy. Today, institutions such as the ATNF, the Universities of Sydney, Tasmania and Western Australia, Curtin University and Swinburne University of Technology have sizeable groups of radio astronomers and the community is actively involved in international projects. With the advent of global facilities such as SKA, and the inevitable decrease in funding for smaller facilities, the Australian radio-astronomy community will need to deepen this international engagement. Its continuing success will rest on being involved in Australian-hosted international facilities, doing multiwavelength science, and maintaining a world-class ability to design and build instruments.

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