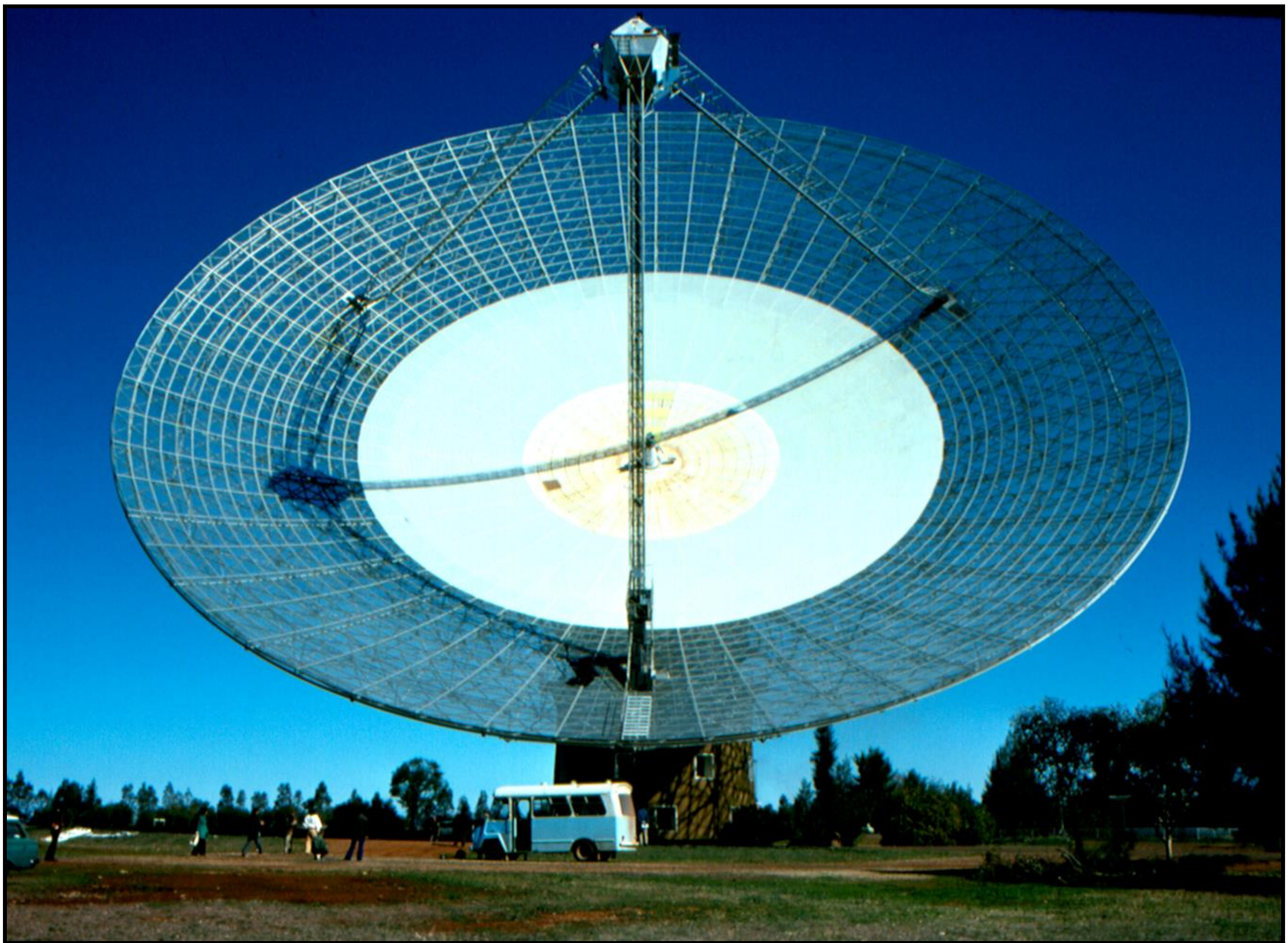


The Parkes Radio Telescope turns 60

A brief history of the first 60 years of the Parkes Radio Telescope and the people who used it. Published by Starfield Observatory, © 2021, J. R. Henley.

Joseph Lade Pawsey (1908-1962, *left*), a country boy from Ararat in Victoria's mid-west, won scholarships to Melbourne University and then to Cambridge where he studied under J. A. Ratcliffe, gaining his PhD in physics in 1935. He joined the CSIR's Radiophysics Laboratory in 1939, and when it became the Division of Radiophysics he was appointed head of the Radio Astronomy Group during those pioneering years and into the years following its metamorphosis into the CSIRO. Members of his group invented techniques that later were incorporated into general use in radio astronomy and made important discoveries about the discrete sources of radio emission in the Milky Way and external galaxies.

Using a 200 MHz coastal defence antenna at the ex-RAAF Collaroy Radar Station with Ruby Payne-Scott and Lindsay McCready as his staff in October 1945, he was the first to prove that sunspots produced increased radio noise from the Sun, and that temperatures in the solar corona could reach one million kelvins. Until then, the temperature of the Sun's atmosphere was thought to be 6000 kelvins, like the photosphere. Not only was this the first serious radio astronomy project conducted in Australia, but it was the first occasion that radio astronomy had provided important information that solved a problem posed by traditional optical astronomy. To improve the resolution of the equipment, Joe invented sea-interferometry, and moved their operations to another radar site at Dover Heights which, being on top of a 278 feet (85 metre) high vertical sea-cliff, gave better results. He then appointed John Bolton, Gordon Stanley and Bruce Slee to this site, and supervised their work.

Joe Pawsey did some other great work on his own, but his main contribution was the inspirational leadership of his research group. In 1952 he became assistant chief of the Division of Radiophysics and president of the Radio Astronomy Commission of the International Astronomical Union, serving until 1958. This latter position enabled him to travel widely, spreading the word about radio astronomy and establishing a close rapport and spirit of friendly co-operation with the overseas radio astronomy groups. He was president of the Australian Branch of the Institute of Physics in 1960 and 1961, but remained with the CSIRO. In 1961 he was offered Directorship of the five-year-old US National Radio Astronomy Observatory (NRAO) at Green Bank, West Virginia to replace unhappy Otto Struve, who had been there for two years. Struve was a fine optical astronomer but was not comfortable with administration and did not understand radio astronomy. 1944 Nobel Prize winner Isidor Rabi of MIT had been looking for the world's best, and had visited Joe in London (where he was staying with Hanbury Brown) to sound Joe out. On his return to the US, he wrote to Pawsey in Sydney with details of the offer (*right*), on the very day the Parkes Radio Telescope was being opened. This letter also shows the world-wide esteem that Joe enjoyed.

Joe knew that his future prospects at Radiophysics had been blocked by Taffy Bowen, who regarded himself as "the Bernard Lovell of the southern hemisphere", and accepted the NRAO appointment on 26 November 1961. He said he would be ready to take up duty in September 1962, in time for the commissioning of the new 300 feet radio telescope, and would stay for three years. Rabi was thrilled to be getting him, and said, "Joe Pawsey is saving my life by coming as director of the NRAO next year. We hope now that we are off to a better start."

U.S. POST FOR AUST. SCIENTIST

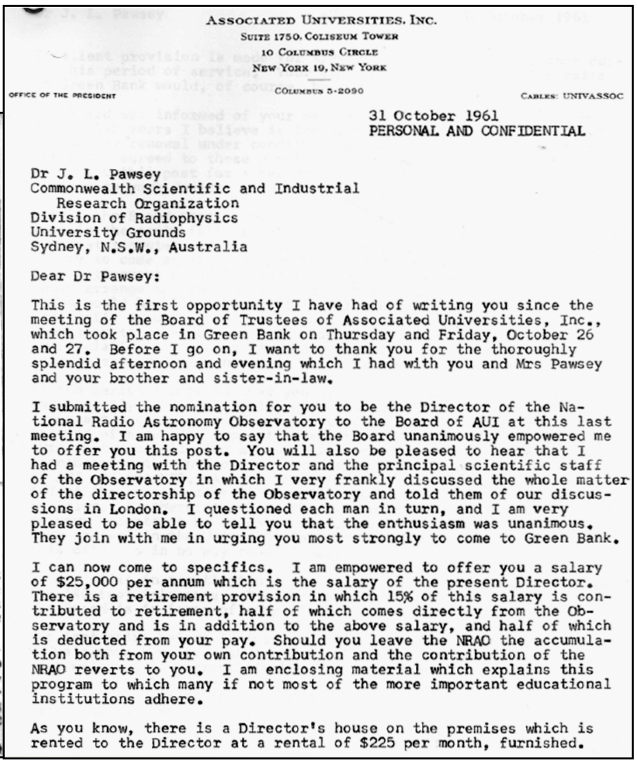
WASHINGTON, Mon. — An Australian has been appointed director of the National Radio and Astronomy Observatory at Green Bank (West Virginia).

He is Dr. Joseph Pawsey, now assistant chief of the Australian C.S.I.R.O.'s radio-physics division.

The director of the West Virginia National Science Foundation (Dr. Allan Waterman) announced the appointment.

It would improve exchanges between U.S. radio astronomers and Australians "who, in many respects, lead the world in this important scientific field."

Dr. Pawsey will take up



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31 October 1961
PERSONAL AND CONFIDENTIAL

Dr J. L. Pawsey
Commonwealth Scientific and Industrial
Research Organization
Division of Radiophysics
University Grounds
Sydney, N.S.W., Australia

Dear Dr Pawsey:

This is the first opportunity I have had of writing you since the meeting of the Board of Trustees of Associated Universities, Inc., which took place in Green Bank on Thursday and Friday, October 26 and 27. Before I go on, I want to thank you for the thoroughly splendid afternoon and evening which I had with you and Mrs Pawsey and your brother and sister-in-law.

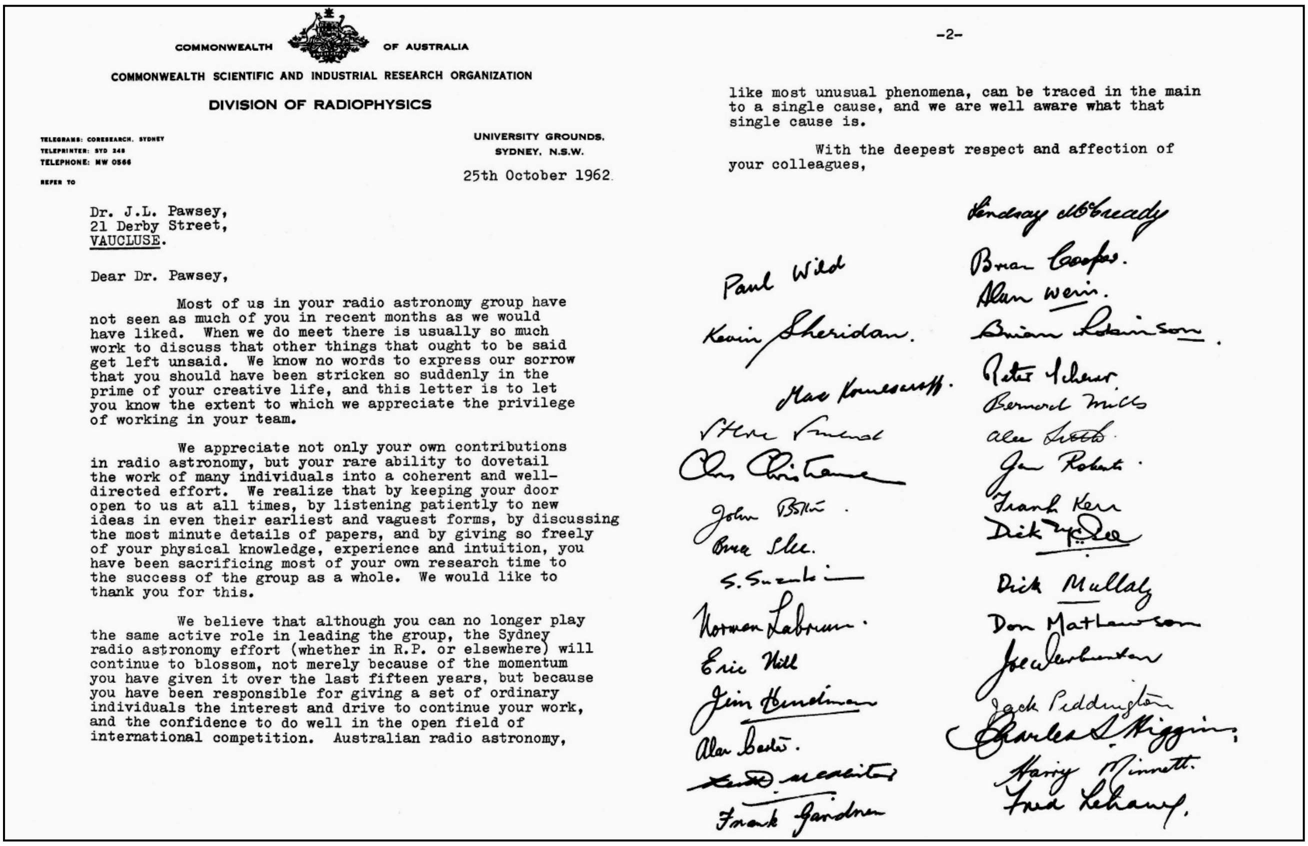
I submitted the nomination for you to be the Director of the National Radio Astronomy Observatory to the Board of AUI at this last meeting. I am happy to say that the Board unanimously empowered me to offer you this post. You will also be pleased to hear that I had a meeting with the Director and the principal scientific staff of the Observatory in which I very frankly discussed the whole matter of the directorship of the Observatory and told them of our discussions in London. I questioned each man in turn, and I am very pleased to be able to tell you that the enthusiasm was unanimous. They join with me in urging you most strongly to come to Green Bank.

I can now come to specifics. I am empowered to offer you a salary of $25,000 per annum which is the salary of the present Director. There is a retirement provision in which 15% of this salary is contributed to retirement, half of which comes directly from the Observatory and is in addition to the above salary, and half of which is deducted from your pay. Should you leave the NRAO the accumulation both from your own contribution and the contribution of the NRAO reverts to you. I am enclosing material which explains this program to which many if not most of the more important educational institutions adhere.

As you know, there is a Director's house on the premises which is rented to the Director at a rental of $225 per month, furnished.

Pawsey arrived at Green Bank for a six-week familiarisation visit on 20 March 1962, but within four days the left side of his body became paralysed. The Associated Universities Incorporated (AUI, a consortium set up in 1946 of nine powerful eastern universities which operates the NRAO: Cornell, Columbia, Harvard, Johns Hopkins, MIT, Pennsylvania, Princeton, Rochester and Yale) sent him to hospital in Washington DC, and he recovered slowly but no diagnosis was made. Joe went to stay with his brother at Princeton, but the paralysis returned and his wife flew from Australia to his bedside. He was operated on in Boston for a malignant brain tumour, the largest they had ever seen. All expenses were paid by AUI. The prognosis was grim, and AUI decided to fly him back to Sydney with his wife, VIP class. Isidor Rabi said sadly, “If character were all, Joe would now be a well man.” Paul Wild, who was also visiting the US, delayed his return to Australia so that he could accompany the Pawseys and look after arrangements for them. As they were leaving, Rabi offered Wild the Directorship of the NRAO, as it was now clear that Joe would not be able to take up his appointment. Paul declined – construction was due to start on his new ‘Radioheliograph’ in Australia. Rabi also offered the NRAO Directorship to Bernard Mills and offered to build a bigger Mills Cross for him as an inducement, but Bernie refused – he loved the southern sky and had negotiated with Harry Messel in Sydney to build a Mills SuperCross near Canberra.

On his return to Sydney, Joe tried to continue working sporadically for a few months, but his condition continued to deteriorate and he was admitted to the Victoria Convalescent Hospital on 26 October 1962. There would be no more treatment except pain-killing morphine. David Heeschen, the replacement Director of the NRAO (and later the driving force behind the Karl G. Jansky Very Large Array in Socorro, New Mexico) and Jerry Tape of the AUI travelled all the way from Virginia to pay their respects and say goodbye. Fred Hoyle, one of Joe’s last visitors, flew from London to his hospital bed on 3 November to present him with the Royal Society’s Hughes Medal (awarded in 1960 but up until then not officially handed over) “for distinguished contributions to radio astronomy both in the study of solar and of cosmic ray emission.” Joe passed away on 30 November, aged only 54. A month before he died, he received this letter from his colleagues. It speaks for itself:



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DIVISION OF RADIOPHYSICS

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REFER TO

UNIVERSITY GROUNDS,
SYDNEY, N.S.W.

25th October 1962

Dr. J.L. Pawsey,
21 Derby Street,
VAUCLUSE.

Dear Dr. Pawsey,

Most of us in your radio astronomy group have not seen as much of you in recent months as we would have liked. When we do meet there is usually so much work to discuss that other things that ought to be said get left unsaid. We know no words to express our sorrow that you should have been stricken so suddenly in the prime of your creative life, and this letter is to let you know the extent to which we appreciate the privilege of working in your team.

We appreciate not only your own contributions in radio astronomy, but your rare ability to dovetail the work of many individuals into a coherent and well-directed effort. We realize that by keeping your door open to us at all times, by listening patiently to new ideas in even their earliest and vaguest forms, by discussing the most minute details of papers, and by giving so freely of your physical knowledge, experience and intuition, you have been sacrificing most of your own research time to the success of the group as a whole. We would like to thank you for this.

We believe that although you can no longer play the same active role in leading the group, the Sydney radio astronomy effort (whether in R.P. or elsewhere) will continue to blossom, not merely because of the momentum you have given it over the last fifteen years, but because you have been responsible for giving a set of ordinary individuals the interest and drive to continue your work, and the confidence to do well in the open field of international competition. Australian radio astronomy,

-2-

like most unusual phenomena, can be traced in the main to a single cause, and we are well aware what that single cause is.

With the deepest respect and affection of your colleagues,

Lindsay McCready
Paul Wild
Brian Cooper
Alan Weiss
Kevin Sheridan
Brian Robinson
Max Komesaroff
Peter Scheuer
Bernard Mills
Alec Little
Chris Christiansen
Jim Roberts
John Bolton
Frank Kerr
Bruce Slee
S. Suzuki
Dick Mullaly
Norman Labrum
Don Mathewson
Eric Hill
Joe Warburton
Jim Hindman
Jack Piddington
Charles S. Higgins
Harry Minnett
Fred Lehany
Frank Gardner

Radio astronomy flourished in Sydney due to Joseph Lade Pawsey and his remarkable colleagues, who created a comprehensive international network in astronomy. Bart Bok wrote to Joe’s wife Lenore, quoting from his eulogy for Joe: “There are very few scientists in the world who will be able to look back upon a life in which they have helped produce so many other distinguished scientists.”

Pawsey's legacy is Australia's reputation and world status in radio astronomy, created by him between 1940 and 1959 and carried on by his followers, which is still a source of national pride. If anyone deserves the title of 'Founder of radio astronomy in Australia', it is undeniably Joe Pawsey. In 2009 the Federal Government provided $80 million to build the **Pawsey Centre** in Perth with a latest-generation Cray XC30 high-performance petascale supercomputer called ***Magnus*** to support the Square Kilometre Array (SKA). *Magnus*, now operational, is the fastest scientific computer in the southern hemisphere and one of the fastest in the world.

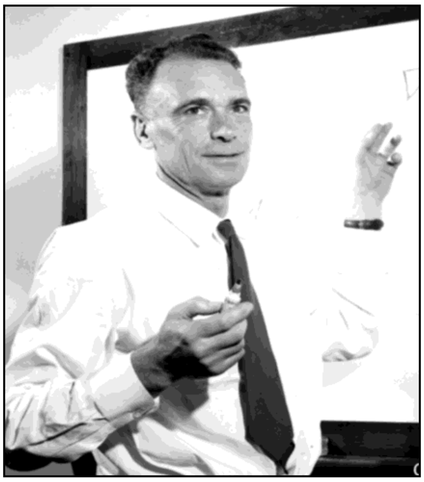
Dr Marcus 'Mark' Laurence Elwin Oliphant (1901-2000), born in South Australia, attended the University of Adelaide where he gained a Masters degree in Science with Honours, and won a scholarship to any British university of his choice. He chose and was accepted by Trinity College in Cambridge, and in 1927 began work in nuclear physics at the famous Cavendish Laboratory, in a team led by the most celebrated physicist in the world, Sir Ernest Rutherford. Oliphant became Rutherford's protégé, and was there when his co-worker and life-long friend James Chadwick discovered the neutron in 1932. Rutherford and Oliphant collaborated together for ten years, investigating radioactive isotopes, hydrogen fusion and subatomic particles (*both men pictured at right*), until Rutherford died suddenly after an operation on 19 October 1937.

That same month Oliphant took up the Poynting Chair of Physics at the University of Birmingham, for they had been looking for a well-known physicist who would be able to bring their university to the forefront in the latest research. Oliphant began by persuading the car manufacturer Lord Nuffield to provide £ 60 000 to build and house a 60-inch cyclotron for atom-smashing. (Cyclotrons were invented in 1929-30 by Ernest O. Lawrence at the University of California, Berkeley and were the most powerful particle accelerators for a generation until superseded by the synchrotron in the 1950s.) The cyclotron Oliphant designed was the biggest in Europe and generated particles with energies of 25 million volts. When the Danish physicist Niels Bohr was told of the plans, he remarked that "only Oliphant would want to build one so big!"

As war approached in 1938, Oliphant became involved in the development of **R**adio **D**irection **F**inding (**RDF**, the precursor of Radar), which was then working with limited success at wavelengths of a metre or more using early vacuum tubes. He saw that the effectiveness of RDF increased with the frequency of the radio waves, which meant making it work at shorter wavelengths. He was contacted by **John Randall**, a technician working on radio transmitters for the General Electric Company, who wished to join the team. With Oliphant's guidance, Randall and the research student **Harry Boot** developed in 1940 a new kind of transmitter called a ***resonant cavity magnetron*** which would enable radar sets to work in the microwave spectrum with a wavelength of only 10 cm. This new device provided very high power, leading to better resolution, precision and range.

From 1939 the British were desperately working to beat Hitler in the race to build an atom bomb, so Churchill set up within the Department of Scientific and Industrial Research (DSIR) a 'Directorate of Tube Alloys' (a code name for their atomic project). Oliphant was sent to the US to try to get the Americans interested. He found that all the secret British reports sent to them were locked unread in a safe at the National Bureau of Standards. He told them that such a bomb could bring the war to a speedy end, but not until Japan attacked Pearl Harbor on 7 December 1941 did they awaken. They co-opted Oliphant, J. Robert Oppenheimer, Niels Bohr and James Chadwick to the Manhattan Atom Bomb Project, for they had many problems in trying to initiate chain reactions in uranium 235 – Fermi said it couldn't be done.

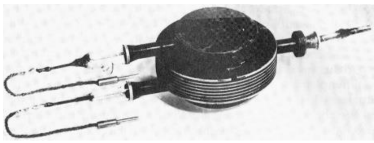
Oliphant spent the remainder of the war years commuting many times across the Atlantic and back in cold and draughty bombers. For his service, the US government wished in 1946 to award him the highest accolade it could grant a foreigner, the *Citation for the Medal of Freedom – Gold Palm*. The award was vetoed by H. V. Evatt, the Australian Minister for External Affairs whose Labor Government was rigidly opposed on ideological grounds to honours and distinctions for civilians, and so was withdrawn. Oliphant never knew that the Medal had been offered until 1980. After the war he returned to Australia and devoted his energies to the establishment of the Australian National University, becoming in 1950 the first Director of the Research School of Physical Sciences and Engineering. In 1954 he co-founded the Australian Academy of Science with David Martyn. In 1955 Oliphant built in Canberra the world's largest homopolar generator weighing 38 tonnes and producing 500 mega-joules of electricity. Funded by the Australian Atomic Energy Commission, it was used from 1963 to 1985 for research in plasma physics. "Olly" was the Governor of South Australia from 1971 to 1976.



Edward George 'Taffy' Bowen (1911-1991, *left*) was a Welsh physicist who played a major rôle in an English five-man team led by Robert Watson Watt in the years from 1935 to 1940, charged with the development of a method of using radio waves to detect enemy aeroplanes, ships and submarines. This was successfully achieved by using the powerful new ***resonant cavity magnetron*** invented in 1940 by John Randall and Harry Boot at the University of Birmingham (*see previous page*), and became known as ***Ra****dio* ***D****etection* ***a****nd* ***R****anging*, or ***Radar***. It enabled the Battle of Britain and the Battle of the Atlantic to be won. Bowen led the production of miniaturised radar sets for fighters and bombers, flying thousands of hours, often with Robert Hanbury Brown.

In the USA, Dr Vannevar Bush (head of the National Defense Research Committee, NDRC) was encouraging research on radar by wealthy Dr Alfred Loomis at his Tuxedo Park laboratory near New York. Loomis, who knew most of the distinguished scientists of his day including Einstein, Bohr, Heisenberg and Fermi, had visited Britain before the war and knew what Watson Watt's group was attempting. At his lab, his team produced a working radar transmitter using klystron vacuum tubes, but its 10 watt power at a one metre wavelength was too feeble to be useful and they had come to a dead-end.

England decided to share the new magnetron with them, with no strings attached. The Tizard Mission of seven persons (Bowen was the only radar expert) travelled from England to the US in September 1940. Taffy took to Washington 'Magnetron No. 12', and a few days later, at the General Electric labs in New Jersey, he showed the Americans how it worked and how it made microwave radar possible. Bowen has written, "They were shaken to learn that it could produce a full 10 000 watts of pulsed power at a wavelength of 10 centimetres. The atmosphere was electric – they found it hard to believe that such a small device could produce so much power, and that what lay on the table in front of us might prove to be the salvation of the Allied cause. It was taken up with tremendous enthusiasm." Magnetron No. 12 is shown above. The American historian James P. Baxter has written, "When the Tizard Mission brought a magnetron to America in 1940, they carried the most valuable cargo ever brought to our shores."



The British also offered military secrets regarding jet planes, rockets, proximity fuses, bomb sights and the Frisch-Peierls Memorandum on atomic weapons in return for American manufacturing capacity. The Americans generously repaid the favour six months later by sending Lend-Lease war matériel worth a total of US$ 697 billion (today's values) to assist the Allies. The Bell Telephone Company in New York was charged with making magnetrons at once, and had produced over a million by September 1945. It is often said that "the atom bomb ended the war, but radar won it." Bowen became good friends with Bush, Loomis and Lee DuBridge at MIT, where together they set up a "Radiation Laboratory" known as the "Rad Lab". Its real purpose was improvements to radar, and Bowen stayed for three years until it was perfected. Because of this work he was invited to join the CSIR Division of Radiophysics in Sydney. Arriving on 1 January 1944, he was Chief of the Division by 1946. He promoted the new science of radio astronomy, and construction of the Parkes Radio Telescope came about in the following way:

After the war, Bowen kept in touch with Vannevar Bush (by now President of the Carnegie Corporation), Alfred Loomis (a Trustee of the Carnegie Corporation and also of the Rockefeller

Foundation) and Lee DuBridge (now President of Caltech and also on the Carnegie Board). In 1951 they asked him to design a 250 feet radio telescope for Caltech, himself to be Director and John Bolton to be Assistant Director. He presented his detailed plans in May 1952 and also sent copies to the CSIRO, suggesting that a similar radio telescope could be built in Australia.

When the Americans heard of this, they said that if a big telescope was going to be built in Australia, then their philanthropic foundations would make substantial donations towards the project if the Australian government contributed equally. A large Caltech radio telescope could wait. In response, Bowen said he would put the nascent US radio astronomy on a firm footing by sending two of his best researchers to teach at Caltech, Bolton and Stanley – in 1957 these two built Caltech's first radio telescopes at Owens Valley. In 1959, Lee DuBridge offered to use his influence to obtain more funds for the Parkes Telescope, telling Bowen, "As you know, we are only repaying a tiny portion of our debt to you, as it was you who gave us John Bolton in the first place, without whom we would not have had the finest radio observatory which will be in existence…. until 1961." The Radio Telescope at Parkes was inaugurated on 31 October 1961 and is Taffy's legacy, his gift to the nation. Bowen later guided the Anglo-Australian Telescope project through turbulent political waters.

John Gatenby Bolton was one of the two men Bowen seconded to go to Caltech in order to introduce radio astronomy there. He arrived in California aged 32 in January 1954, and was joined by **Gordon Stanley**, also 32, six months later. Given the position of Senior Research Fellow in Physics and Astronomy, Bolton was tasked with designing and constructing a radio telescope for them. In 1956 he erected a 32 feet (9.75 metre) temporary radio telescope just a handy short walk from the dome of the Mt Palomar 200 inch Hale telescope. This was used to detect and pinpoint discrete radio sources which could then be identified optically with the 200 inch. It was so successful that Bolton and Stanley were asked to build a large radio observatory at a more radio-quiet site.

They selected Owens Valley, 420 km north of Los Angeles and east of San Francisco. Bolton and Stanley completed an interferometer using two 25.9 metre parabolic dishes in mid-1957, and two years later Owens Valley was the best radio observatory in the US. Bolton was the first Director and in 1958 he was made Caltech's first Professor of Radio Astronomy. He returned to Australia permanently in January 1961 to supervise completion of the Parkes Radio Telescope. Stanley became the second Director of the Owens Valley Radio Observatory, a post he held until 1975.

Above: John Bolton, Mike Jeffery and Taffy Bowen stand on the hub of the under-construction Parkes Radio Telescope.

Left: John Bolton, Gordon Stanley and Joe Pawsey in 1953.

In 1947 the radio signals being received from space were called 'cosmic noise' or 'cosmic hiss' and a group at Cornell University in the USA coined a name for the study of this noise: 'microwave astronomy'. Neither Bowen nor Pawsey warmed to the term, Bowen saying that most of their work was not in the microwave spectrum and he didn't know if it was really 'astronomy' anyway.

In a letter on 14 January 1948, Joe Pawsey suggested a better name for the new science, labelling it 'Radio Astronomy', an appellation that immediately found favour and has been used worldwide ever since. This led to the terms 'radio telescope' and 'radio observatory' being adopted instead of 'aerials', 'antennas' and 'field stations' soon after.

The 'Acre of Ear'

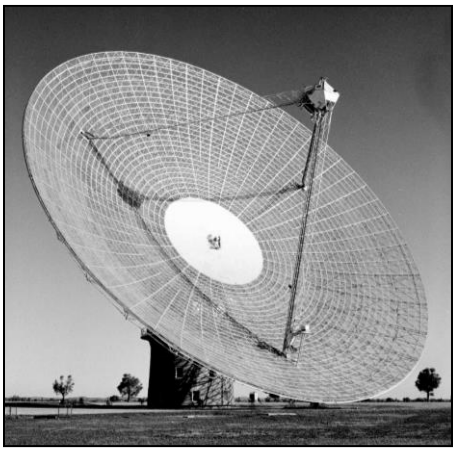
Bart Bok has said that radio changed the face of astronomy. Radio engineers and physicists were transformed into radio astronomers, laboratories into observatories, antennas into telescopes, and radio noises into visible images. By 1951 the need for a powerful radio telescope in Australia was realised when the 21 cm emission line of neutral hydrogen was detected in Sydney. The Chief of the CSIRO's Division of Radiophysics at the time was Dr Edward G. 'Taffy' Bowen, and his foresight, enterprise and enthusiasm brought the need to a reality. Fund-raising began in 1954, and donations came from overseas and the Australian public. The Carnegie Corporation and then the Rockefeller Foundation each donated US$ 250 000, the Rockefeller Foundation later adding US$ 107 000 more. The International Astronomical Union (IAU) and Bernard Lovell at Jodrell Bank sent letters to the Commonwealth government, strongly supporting the project. The Prime Minister Mr Robert Menzies was impressed by this level of foreign backing, and agreed that the government would pay the remainder of the total expenditure of an estimated £677 000. In the end, cost over-runs brought the total outlay to about £ 900 000, and the government had to contribute rather more than half.

In 1959 a London engineering firm who had built the Sydney Harbour Bridge, Freeman, Fox and Partners, won the contract to prepare detailed plans and drawings for an instrument with a steerable dish antenna 210 feet in diameter. It was a completely unique design, and totally different from Jodrell Bank, the only other large radio telescope then in existence. In fact, it provided a pattern for most of those which followed. Bowen sent Mills, Wild and Christiansen to find a possible site for the radio telescope near Cowra, but Christiansen suggested travelling further west to Parkes, where he knew of an excellent site. In the end, a committee consisting of Mills, Wild, Christiansen, Kerr and McCready came out very decidedly and unanimously in favour of Parkes.

The contract to build was signed that July, and work began under Project Manager Mike Jeffery, who later worked on the Anglo-Australian Telescope. First, the foundations were laid, and that November the Sydney firm Concrete Constructions began erection of the three-storeyed concrete tower. The top floor of this tower houses the control centre, with the main control desk and data handling equipment. The middle floor houses most of the receiving equipment, and is connected by cables to the focus cabin. The ground floor has storage areas and a workshop where repairs and maintenance are carried out.

The concrete tower was ready to receive the turret and hub structure by February 1960. The turret and hub machinery were constructed by Maschinenfabrik Augsburg-Nürnberg AG (generally known as MAN) The drive and servo-control system was subcontracted to the Manchester firm of Metropolitan-Vickers, and the master-equatorial unit was constructed by Askania-Werke of West Berlin. These parts were shipped to Parkes and installed on the tower, ready to receive the 'Dish'. Grote Reber paid a visit in December 1960 to see how construction was progressing. The surface of the parabolic reflector was supported on 30 radial ribs, cantilevered out from the central hub. The ribs were cut and assembled in jigs on the site, and welded at night, when all parts were at the same temperature. A huge crane 240 feet high was used to lift them into place. Assembly of the ribs on the hub was begun in March 1961. The dish was completed by September of that year, and installation of the complex computer and electronic equipment used for driving the telescope was completed just prior to the official commissioning of the **Parkes Radio Telescope**.

This ceremony was performed by His Excellency the Governor General, Viscount De L'Isle on 31 October 1961, and Grote Reber was an honoured guest. The first Director at Parkes was **John Bolton**, and the first object observed was the source Fornax A, now known to be the elliptical galaxy NGC 1316. Meanwhile, Joe Pawsey had set up another group to invent new types of super-sensitive receivers and amplifiers for Parkes. He sent Brian Cooper to Harvard to help them build such equipment using innovative low-temperature maser technology, and sent Brian Robinson to the Kamerlingh Onnes Laboratory, where he helped Jan Oort's group to build new parametric amplifiers for the Leiden Observatory. In return for his assistance, Robinson brought some similar amplifiers back to Parkes.



The reflecting surface of the paraboloid is 210 feet (64 metres) in diameter and has an area of more than three-quarters of an acre, or about one third of a hectare. It weighs 300 tonnes, and the whole movable structure 1000 tonnes. As originally built, the inner section, 54 feet (16.5 metres) in diameter, was formed from segments of thick steel plate welded together, and the remainder was covered with panels of $^{5}/_{16}$ inch (8 mm) mesh, woven from high-tensile steel galvanised wire. The mesh reflected 98% of the incident radio power at a wavelength of 10 centimetres. The surface is formed to the shape of a paraboloid of revolution with a focal length of 89 feet (27.4 metres, $f/0.41$), and adjustments are provided at intervals on the purlins which support the mesh panels so that the surface can be adjusted to the correct shape. This is the configuration as shown above.

Since 1970, the dish's reflecting surface has been dramatically improved as described below. An aerial cabin is supported by three legs above the focal point of the reflector and provides shelter for about 1000 pounds (nearly half a tonne) of front-end receiving equipment, and working space for its maintenance. The cabin is about 10 feet (3 metres) across, and is accessible by means of a small elevator in one of the tripod legs, and by a stairway in another. Radio waves collected by the reflector are picked up by feeds which are supported from a platform suspended below the cabin on threaded rods, so that the feeds may be brought exactly into the focal plane of the reflector dish.

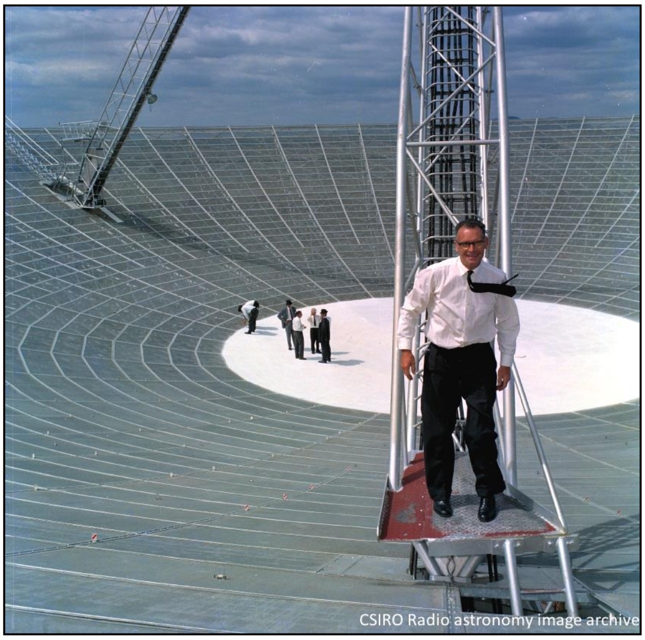
The dish is mounted in alt-azimuth fashion, i.e. it can move up and down and around the horizon. It is supported on two short shafts which project from near the base of the hub, the hub itself being extended to form two counterweights. Rotation about these shafts provides movement in altitude, from the zenith down to 30 degrees above the horizon, the drive being by means of pinions engaging gear racks fitted to the bottom of the counterweights. At maximum depression, the rim of the telescope almost touches the ground. The azimuth bearings are carried on a compact and rigid A-shaped turret which rotates as a whole on a 37 foot (11.3 metre) diameter horizontal track fastened to the top of the three-storeyed concrete tower. The turret structure is carried on four bogies, two of which are driven, and a total motion in azimuth of 450 degrees is provided.

The drive and control system is a unique feature which arose out of an original suggestion by Dr Barnes Wallis (of World War II 'Dambuster' fame). Barnes Wallis was still working for Metropolitan-Vickers at the time, and after an approach by Joe Pawsey in late 1954 was seconded to the CSIRO as a consultant. He designed a miniature precision-built optical equatorial unit (effectively a small telescope) for placement at the intersection of the altitude-azimuth axes of the radio telescope. This unit, built by Askania, can be slewed to and made to track any sky object, and the Big Dish follows it obediently and exactly by means of an ingenious master-slave system. In the hub of the radio telescope is an error detector which operates by means of a beam of light; this senses if the radio telescope is not exactly aligned with the master unit and generates signals that operate the altitude and azimuth motors to bring the Dish into perfect alignment.

These motors were the first on a large telescope to use servo control, a major engineering innovation on a large Dish that was solved by the CSIRO's **Harry Minnett** (*right*). It was also the first time that computer guidance systems had been used to convert equatorial co-ordinates to alt-azimuth co-ordinates, something that is now routinely handled by tiny computers in amateur alt-azimuth optical telescopes. It proved so successful that most of the major optical telescopes that followed it have been placed on computer-controlled alt-azimuth mounts – Parkes had led the way forward and had shown that it could be done. Minnett also devised a method for high-precision adjustment by laser of the curve of the dish to maximise its resolution – see the illustration at right. He was rewarded by being promoted to Chairman of the CSIRO's Division of Radiophysics in 1978. Barnes Wallis also advocated supporting the dish from its centre, instead of from a trunnion bearing on each side as at Jodrell Bank, and designed the geodesic framework that would hold it rigid.

The Parkes Radio Telescope is completely operated from a control desk located on the top floor of the tower. A skilled controller is in charge at all times, and sees that the programs asked for by the radio astronomers on duty are carried out. In the second half of 1970, the dish's steel centre section was replaced with more accurate panels, in order to allow it to observe at higher frequencies, around 43 GHz. They extended out to a diameter of 17 metres. At the same time, the 8 mm steel wire mesh was replaced by perforated aluminium panels in stages, out to a diameter of 37 metres (*see next page*). This work was finished around 1973, and was explicitly funded by the Apollo 12 tracking contract. It enabled observations at 23 GHz, at a 13 mm wavelength. In the early 1980s the surface was upgraded out to 45 metres diameter, and in 2003 the perforated aluminium panels were extended to 55 metres. Thanks to a new holographic measuring device that can be mounted in the centre of the dish as it slews and tilts, the accuracy of the surface is now ± 0.8 mm RMS. This has enabled the 55 metre diameter portion of the telescope to operate at microwave frequencies as high as 43 GHz, at wavelengths as short as a world-class 7 mm, and so the Parkes Radio Telescope may now be called the **Parkes Radiothermal Telescope**.

Although smaller than the first large dish built at Jodrell Bank in England (64 metres diameter compared with 76 metres), the Parkes dish owed nothing to its English predecessor. Parkes was technically a much superior instrument and it still is. The **Lovell Telescope**, although its surface was completely replaced in 2001-2002, can operate only up to a frequency of 6 GHz, at a longer, less precise wavelength of 50 mm. It rarely works as a stand-alone radio telescope now, and is used instead as part of the e-MERLIN (enhanced Multi-Element Radio-Linked Interferometer Network, an array of seven English dish antennas), and as part of the European VLBI (Very Long Baseline Interferometer which has twelve telescopes across eight countries). Both of these networks claim to achieve resolution in radio images that approach the detail found in the Hubble Space Telescope's optical images.

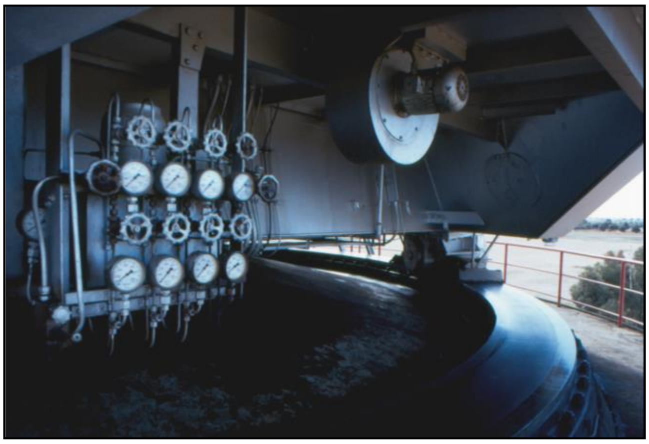


*Left: In 1969, E. G. 'Taffy' Bowen (Chief of the Division of Radiophysics) hosted a party of visiting radio astronomers at the **Parkes Radio Telescope**. Here he is seen at the base of one of the two ladders leading to the aerial cabin. The elevator track is on the aerial cabin support in the far background, but the elevator itself is at the top, out of sight.*

Right: The visiting radio astronomers step onto the Dish when it is at maximum depression. The one-person elevator can be seen at upper right.

Above: The Dish in 1974, showing the centre section enlarged through the use of perforated aluminium panels. The structure is faintly visible through these panels.

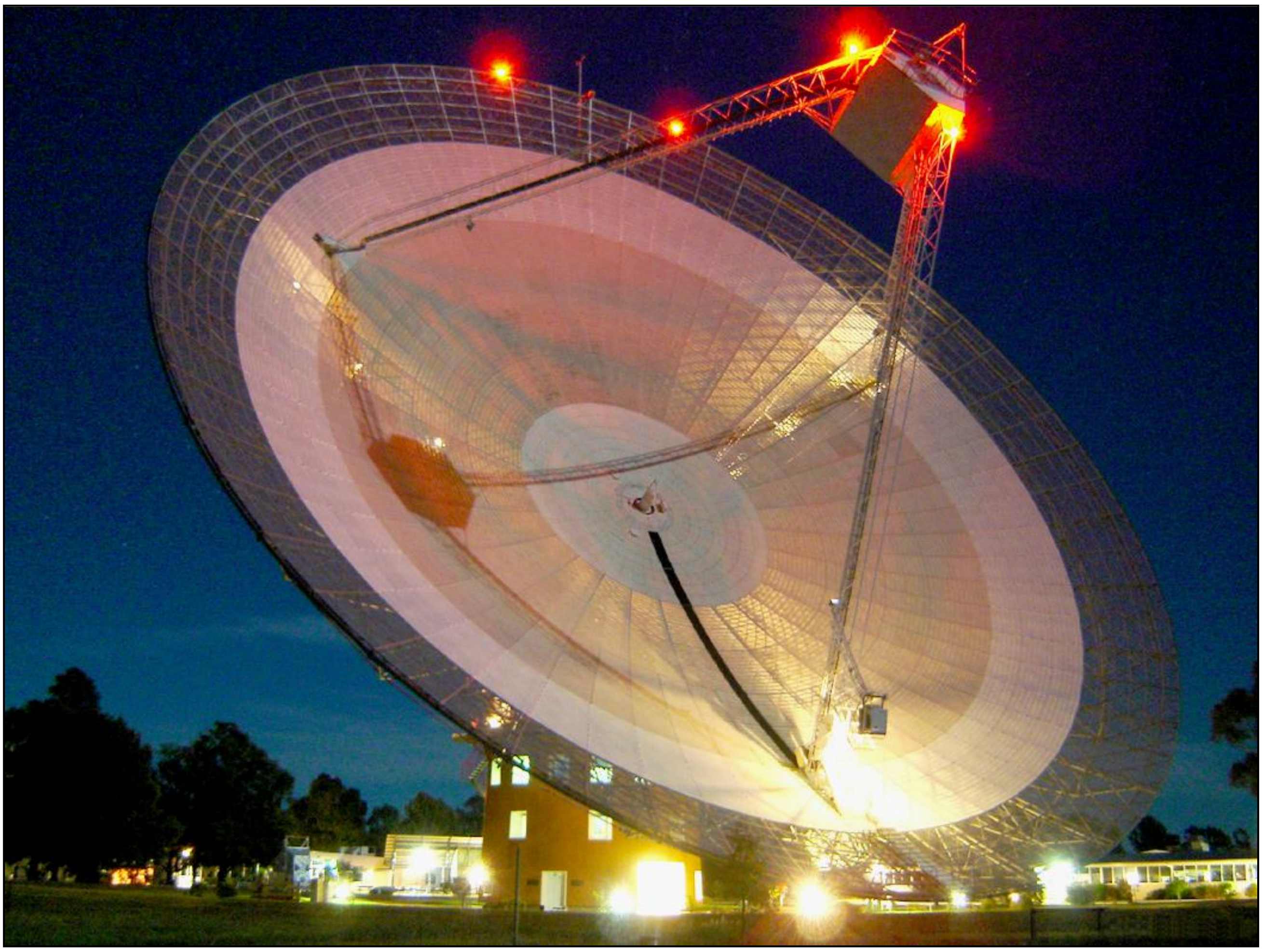
The focus cabin in 1972 was called the 'aerial cabin'.



The azimuth track.

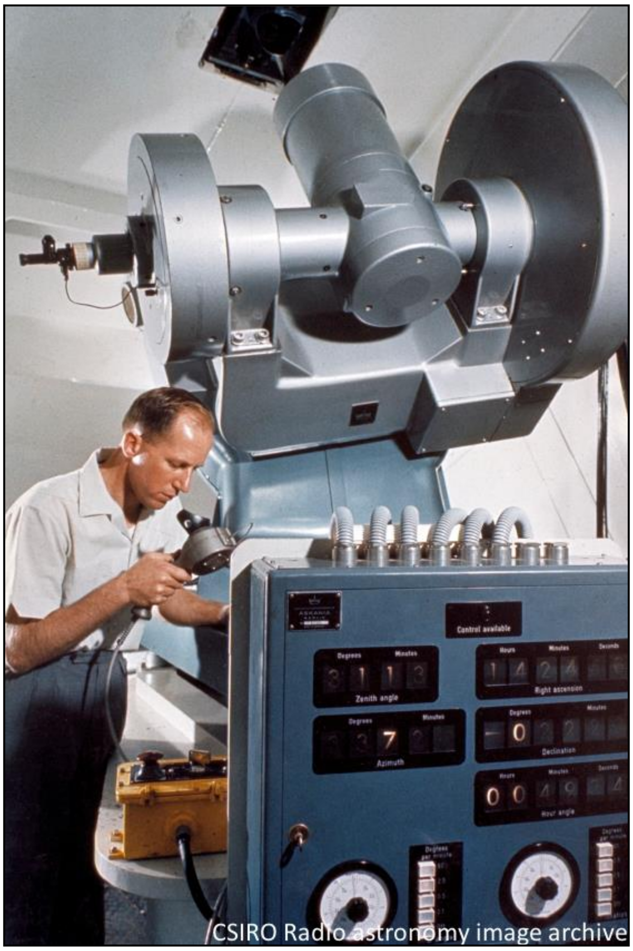
The new focus cabin and the extended aluminium panels on the dish, as they appeared in 2012. The old aerial cabin had been replaced by a much-larger one in 1995, to carry three receivers instead of one. The old cabin remains on display at ground level. The new one now contains multiple radio and microwave detectors, which can be rotated into the prime focus when required for specific observations, at the press of a button. Two technicians can be seen leaving the cabin by a stairway, eschewing the elevator at right.

The 18 metre parabolic Kennedy Dish that had been installed at the eastern end of the Fleurs Chris Cross in 1959 was moved to the Parkes Observatory permanently in late 1962, for interferometric purposes. Used in the Apollo program, it was declared surplus to requirements in the 1980s when the Australia Telescope and Mopra Telescope◊ were commissioned. Due to its historic significance, it has been allowed to remain on site.



Above: *Parkes by moonlight, showing the different improvements to the reflecting surface.*

Right: *Barnes Wallis' Master-Equatorial Unit, which converts tracking in Right Ascension and Declination into movement of the Parkes Radio Telescope in Elevation and Azimuth. It gives the Big Dish a pointing accuracy of 11 arcseconds, better than many optical telescopes.*



Centaurus A

Cornell Mayer's group at the Naval Research Laboratory in Washington DC had found some radio-frequency polarisation in our Galaxy (the Crab Nebula and the Galactic plane) and outside our Galaxy (the Cygnus A radio galaxy), and for this reason in April 1962 Brian Cooper and his technical assistant Tom Cousins installed on the Parkes Telescope an 11 cm receiver and equipment to rotate the feed antennas in the focus cabin to see if any polarisation was observable. After completing the installation they retired for the night, leaving the telescope unattended except for **Ron Bracewell**, a former Radiophysics employee who was now teaching electrical engineering at Stanford University in California and was visiting Parkes to see the new Dish. Bracewell noticed that the new polarisation equipment was in place, and, knowing the details of Mayer's as-yet unpublished findings, on a whim he pointed the telescope at Centaurus A. Rotating the feed antennas, he immediately found that the radiation from that galaxy was indeed polarised.

Describing his observations in the Visitors' Book, he quickly prepared a short communication to *Nature*, with himself, Cooper and Cousins as authors, but Bolton, furious at this unauthorised use of the telescope, intervened to delay the submission of the paper. Easter occurred soon after, and the telescope was officially shut down for the holiday. The one person remaining on the station was Marcus Price, at that time an irrepressible Fulbright scholar from Colorado State University who spent most of his time at Parkes. During the long weekend, Price conveniently 'forgot' the prohibitions concerning unscheduled use of the telescope and decided that, as no one was around, he would see if he, too, could detect the polarisation in Centaurus A at 21 cm. He was successful – far beyond his expectations. He later wrote about the discovery: "I thought, 'Gee, that's nice, we've confirmed it, but there's one problem. Poor old Ron got his feed angle wrong,' because at 21 centimetres the position angle of the linear polarisation in Centaurus is exactly 90º different than it is at 11 centimetres." But Bracewell had got the angle right and so had Marc Price.

The apparent discrepancy led to an important discovery – the phenomenon of **Faraday Rotation** in radio astronomy. Price and Brian Cooper hastily performed further observations at several other wavelengths up to 30 cm, and found that the direction of the polarisation angle varied as the square of the wavelength. They correctly inferred from this that they were observing the radio equivalent of the well-known Faraday Effect, in which the plane of polarisation of a beam of electromagnetic radiation is rotated by the electrical and magnetic properties of the medium through which it is passing. Further observations showed that the Faraday Rotation was not a feature of the sources themselves, but was caused when their radiation passed through the magnetic field within our own Milky Way. The rotation was greatest for sources near the galactic plane, and virtually zero for sources near the galactic poles. This was an exciting discovery because, if the Faraday Rotation of a source is known, then the intrinsic direction of polarisation and hence the magnetic field direction on the plane of the sky can be determined. As the amount of rotation depends on the wavelength of the radiation, it thus opens a way of measuring the magnetic fields of our Galaxy. It also provided convincing evidence that radio sources produce their prodigious amounts of radio energy by the synchrotron process.

To the great delight of Bowen and Bolton, both of these discoveries in 1962 quickly established the Parkes Observatory at the forefront of radio astronomy, a position it has maintained to the present day. The team showed that Centaurus A is a radio galaxy with huge double lobes, covering an area of sky some 10º × 7º, the largest area covered by any radio galaxy (*see image, next page*). In 1965 Price, Cooper and Douglas Cole used the Parkes Telescope to map the magnetic field distribution across Centaurus A and found magnetic fields across large parts of it. The map they produced was the first such map of an external galaxy, but this exciting field of research could not be pursued further until a much improved polarimeter was acquired.

In 1990 with the benefit of a new polarimeter, better receivers and improved image processing techniques, a group led by Raymond Haynes undertook a new series of much more sensitive polarisation surveys of Centaurus A, at four different wavelengths between 20 cm and 3 cm. These surveys have produced high quality radio images, which for the first time make it possible to trace the changing magnetic field direction throughout this enormous galaxy and to elucidate details of its dynamic structure. From either end of its central core, a jet of radiating plasma (charged particles with their entrapped magnetic fields) is flung far into the outer parts of the radio lobes. The core powering the jets appears to be rotating in an anticlockwise direction, while at the same time precessing about the axis of the jets. The net effect gives rise to the helical pattern which characterises the radio lobes. Because Centaurus A is the closest radio galaxy and the one most easily resolvable, study of the violent forces producing its complex structure gives an important clue to understanding the structural details of other more distant radio galaxies.

Back in the 1960s, Frank Gardner, a newcomer to radio astronomy, and John Whiteoak, one of Bart Bok's students who had spent some time at Caltech, had also begun polarisation studies at Parkes and were intent on finding the origin of the Faraday Rotation. Suspecting that all polarised radio sources would be affected by Faraday Rotation produced by magnetic fields originating in our own Galaxy, they investigated a large sample of polarised extragalactic sources and, by plotting the degree of rotation against Galactic latitude, they found convincing evidence that Faraday Rotation was indeed linked to the magnetic field in the plane of the Milky Way. This work gave a correction factor that could then be subtracted from all polarisation readings to give the orientation of the magnetic field in the extragalactic sources, independent of the Milky Way.

In the CSIRO radio image of the Centaurus A galaxy at right, particles emitting radio waves stream millions of light-years into space from the core of the galaxy. Data for the image was gathered with the Australia Telescope Compact Array and the Parkes telescope. The frequency of the radio waves was 1.4 GHz. The smallest structure visible in the image is 680 parsecs (2215 light-years) across: the scale bar at lower right represents 50000 parsecs (about 163000 light-years). The white dots are not stars but background radio sources, each a huge galaxy like Centaurus A in the distant universe. There are no optical data (visible light) in the image. Polarised emissions have now been discovered at Parkes from many sources, including the suspected supernova remnant Vela-X, described by Gardner and Whiteoak in 1963. Douglas Milne followed up this observation and made supernovae his lifelong interest.

Quasars

John Bolton and Gordon Stanley worked together at Pasadena in California for six years (from early 1955 to late 1960) introducing radio astronomy to Caltech. They built for them a small 32 feet (9.75 metre) radio dish on Palomar Mountain. The design was by Stanley and was based on the 16 feet (4.9 metre) antenna they had used at Dover Heights. The intention was to discover the positions of new radio sources, and then stroll over to the 200 inch telescope where the optical astronomers would photograph the sky in those positions. In this way they hoped to identify the sources with known optical objects. The success of this work led to Caltech supplying funds to build an interferometer at an electrically quiet site 400 kilometres away at Owens Valley, using two 90 feet (27.4 metre) parabolic antennas on equatorial mounts. Stanley, an electronics genius, would design and build all the ancillary receiving equipment, tuners, correlators, amplifiers and recorders.

One of the sources observed in late 1960 was 3C 48, (No. 48 in the Third Cambridge catalogue). The optical object photographed by the 200 inch at the same position appeared to be a faint star of an unusual blue colour, made up of a combination of strong emission and absorption lines, unlike the spectrum of any star known. A further puzzle was that the spectrum showed no sign of the presence of hydrogen, the main element in most stars. Jesse L Greenstein, Allan Sandage and Guido Münch were unable to identify any of the lines. Bolton made an attempt, finding lines of Neon [V], Argon [III] and Argon [IV]. He saw that the lines were greatly redshifted, and wrote to Pawsey, Bowen and Hoyle, stating that 3C 48 was red-shifted by a factor of $z = 0.37$ and was therefore the most distant object in the known universe. To shine optically at an apparent magnitude of 16 meant that its absolute magnitude was -24, two magnitudes or six times brighter than any other known object. Bolton found such power at such a distance to be beyond belief, but he told his Caltech colleagues Greenstein and Thomas A. Matthews, who said that the redshift must be wrong. Greenstein even wagered a case of whisky that 3C 48 was a close Milky Way 'radio star'. Bolton decided not to publish his discovery, but Greenstein and Matthews later did, and so were given credit for it. We now know that Bolton's work was correct, and by rights he should be acknowledged as discovering the first 'quasar'. Greenstein never made good on his wager.

On taking over as Director at the new Parkes Radio Telescope in 1961, Bolton would not be caught a second time, and when the radio source 3C 273 was due to be obscured by the Moon in a series of three occultations in 1962, he determined to use these events to make precise determinations of the source's positions in Right Ascension and Declination, and then have the positions matched with a known optical object. This project was a resounding success. Other people on two continents were involved in the identification of 3C 273 as a quasar, so there is no single person who can claim to have discovered the first of these strange objects (if 3C 48 is not counted, as its true identity was not revealed until after 3C 273's).

The **13th Solvay Conference** was held in Brussels in 1964, the topic being "*The Structure and Evolution of Galaxies*". John Bolton was invited to participate, and was asked to deliver a lecture entitled "*Extragalactic Radio Sources*". This was a great honour for him personally, and shows how the Parkes Radio Telescope had burst upon the world's astronomical scene like a thunderclap. Much of his talk described Australian pioneering discoveries and the recent ones at Parkes, including the identification of the Crab Nebula as a radio source in 1948; the identification of the most intense extragalactic source, Cygnus A, with a distant galaxy in 1951; the identification of a new class of object, quasars, which were remote, compact galaxies of unprecedented luminosity; and the recognition that synchrotron radiation revealed magnetic fields over vast regions of space. The Chairman J. Robert Oppenheimer from Princeton declared, "I think no astronomer has failed to be astonished by some of the things that have been said."

Pulsars

The first pulsar seen at Parkes was the first one discovered at Cambridge by Jocelyn Bell on 28 November 1967, called at the time CP1919. Parkes observed it thirteen days after the discovery was published in early 1968. This northern pulsar in Vulpecula was only visible at Parkes for a couple of hours each day. On the day of the first attempt there was no sign of anything on any of the numerous receivers that had been set up. With fifteen minutes to go Brian Cooper, who was the only one of the observing team left (everyone else had gone back to their quarters), was in the words of Bill Butler, "*wandering around as he usually did, muttering and kicking things, twisting knobs etc. and he saw it – the first pulsar observation at Parkes."* When this was published soon after, the exact period of the pulses was given, something that the Cambridge observers had got wrong. The Cambridge radio group was not happy at having been caught out by the Australians yet again, and Fred Hoyle had to mollify them.

New instrumentation is provided

Parkes' large collecting area makes it a very sensitive instrument, ideally suited to finding pulsars (rapidly spinning neutron stars the size of a small city). Two-thirds of the 1 800 known pulsars, including the only binary pulsar system, were found using the Parkes telescope. Another major project was the Pulsar Timing Array aimed at detecting gravitational waves from colliding super-massive black holes. The 13-beam Multibeam Receiver is a revolutionary instrument designed by the ATNF for the Parkes dish. Installed in 1997, it provides unprecedented efficiency for large-scale radio surveys of the sky. Recent surveys include **HIPASS**, the **HI P**arkes **A**ll-**S**ky **S**urvey that found over 2500 new galaxies in our local region. A new project, **GASS**, the **G**alactic **A**ll-**S**ky **S**urvey, is mapping the hydrogen in our Galaxy in high detail.

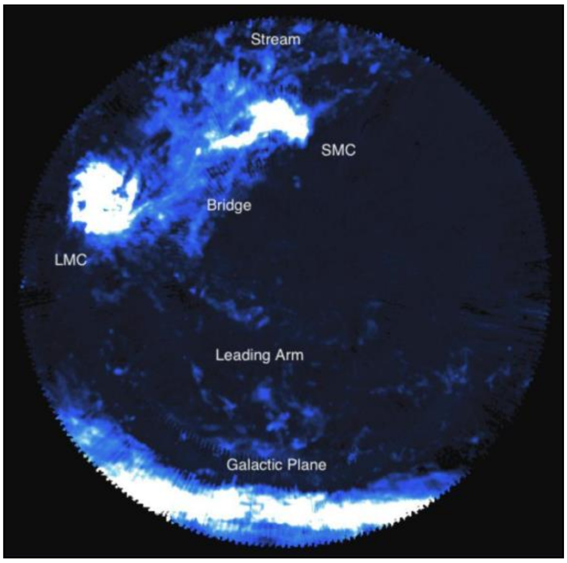
The Magellanic Clouds

Situated very conveniently for southern observers are two of our closest neighbouring galaxies – the Large and Small Magellanic Clouds. After promising results at the CSIRO's Murraybank field station north of Parramatta, where they discovered a bridge of hydrogen gas between the Large and Small Clouds, Dick McGee, James Hindman and Frank Kerr were keen to continue hydrogen line spectroscopy, surveying the plane of the Milky Way and the two Clouds with the much improved resolution of the Parkes Telescope. McGee and Janice Milton were able to show conclusively that regions of ionised hydrogen and supergiant stars, recognised by Bart Bok and other astronomers as star-forming regions, were situated, as suspected, at the centres of large clouds of neutral hydrogen. The velocity patterns indicated that far from being an irregular galaxy, as indicated by optical observations, the LMC appeared to possess a spiral pattern. This had been postulated by Gerard de Vaucouleurs in the 1950s, but his suggestion had received little support from other optical astronomers. The HI map of the LMC made by McGee and Milton is still one of the most detailed HI maps of any galaxy, including those made by large synthesis telescopes.

The Small Magellanic Cloud (SMC), on the other hand, raised more problems than could be solved merely by the vastly increased angular resolution (from 150 to 15 arcmin). Hindman's survey at Parkes confirmed the Murraybank results and revealed the SMC to be two separate clouds moving apart at a rate of some 40 kilometres per second. This effect has given rise to much conjecture over the years, and as yet no definitive explanation has emerged.

Hindman believed that it indicated three large spheres of gas, whilst Donald Mathewson at the Mount Stromlo and Siding Spring Observatories (MSSSO) proposed that the Small Cloud may be two colliding dwarf galaxies. Early versions of this work, along with a quick survey of the Magellanic Clouds in the continuum at 73 and 20 cm by Mathewson and his student, John Healey, were just in time to be presented at an IAU-URSI symposium, *'The Galaxy and the Magellanic Clouds'*, held in Canberra and Sydney in March 1963. Organised and hosted by Bart Bok of Mt Stromlo Observatory, it attracted more than forty of the world's leading optical and radio astronomers – a visit to the new Parkes Radio Telescope was included, and most attendees are in the group picture (next page).

The fact that this Symposium was held in Australia indicated the esteem in which our radio astronomers were held and the impression made on world astronomy by the new discoveries of polarisation, Faraday Rotation and the structure of the Magellanic Clouds described above, and the interest generated by other new discoveries made by the Parkes Radio Telescope.



Just as the URSI General Assembly in Sydney a decade before had represented world recognition for the first generation of Australian radio astronomers, so this meeting marked the debut of the Parkes Telescope on the international scene and did much to enhance its profile amongst the astronomical community.

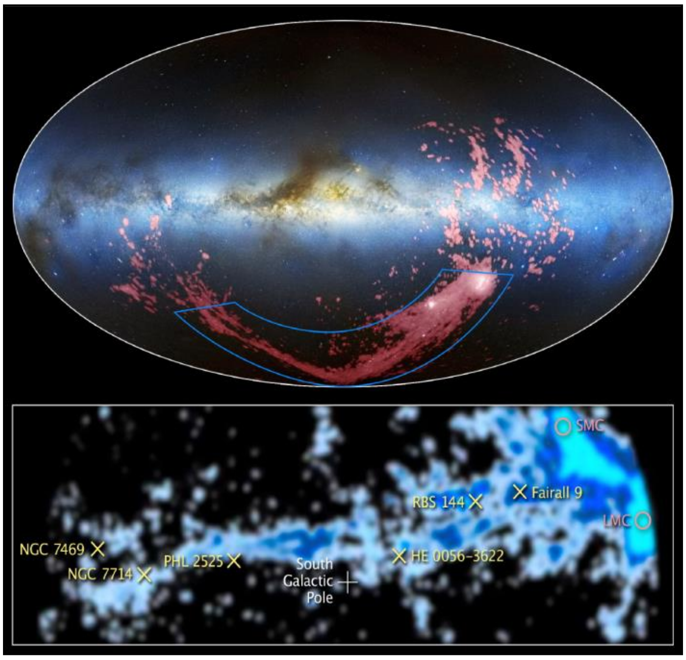
During the early 1970s, another continuum survey of the Magellanic Clouds at several wavelengths was carried out by McGee and others, incorporating an earlier survey at Parkes by Canadian visitor Norman Broten, one of the two flag-raisers at the inauguration of the Telescope.

Participants in the 'Galaxy and Magellanic Clouds Symposium' of 1963 assembled at the Parkes Airport.

1. *Lawrence H. Aller (University of California)*
2. *Bertil Lindblad (Stockholm Observatory)*
3. *R. H. Stoy (Royal Observatory at Capetown)*
4. *Michael W. Feast (Radcliffe Observatory)*
5. *Frank J. Kerr (Division of Radiophysics)*
6. *Maarten Schmidt (Hale Observatories)*
7. *Taffy Bowen (Division of Radiophysics)*
8. *Jim V. Hindman (Division of Radiophysics)*
9. *Jack Rothwell (Vickers Armstrong)*
10. *Gart Westerhout (University of Maryland)*
11. *James Lequeux (Observatoire de Paris)*
12. *J. H. Heard (David Dunlop Observatory)*
13. *G. Courtès (Observatoire de Marseilles)*
14. *J. Landi Dessy (Córdoba Observatory)*
15. *Mrs Heard*
16. *Bernard F. Burke (Carnegie Institute)*
17. *Gérard de Vaucouleurs (University of Texas)*
18. *Mrs Meike Oort*
19. *Y. N. Parijsky (Pulkovo Observatory)*
20. *Bill G. Tift (Lowell Observatory)*
21. *Jan H. Oort (Leiden Observatory)*
22. *A. D. Thackeray (Radcliffe Observatory)*
23. *A. Blaauw (Kapteyn Astronomical Laboratory, University of Groningen, The Netherlands)*
24. *Miss J. Streeter (Office of Naval Research, USA)*
25. *G. Hulburt (Office of Naval Research, USA)*
26. *Victor A. Ambartsumian (Armenian Academy of Science, Erevan, USSR, a long-time friend of Bok)*
27. *Harold F. Weaver (University of California)*
28. *W. Becker (University of Basel)*
29. *Bart J. Bok, (Mount Stromlo Observatory)*
30. *T. Walraven (Mount Stromlo Observatory)*

At the beginning of 1973 Don Mathewson of the MSSSO (Mount Stromlo and Siding Spring Observatories) went to Parkes with an exciting idea. Whilst reading papers about the then-current searches for high velocity hydrogen clouds, he had come across one that reported a very long hydrogen filament in the northern sky whose radial velocity varied along the filament. He noticed that if the line of the filament were extended south, it would possibly intercept the bridge region discovered at Potts Hill and Murraybank in the late 1950s between the Large and Small Magellanic Clouds, and he immediately set out to see if this were true.

One night with a new digital correlator on the 64 metre telescope was sufficient to detect H-line emission along the extrapolated line at the predicted velocities. The broad features of what Mathewson named the **'Magellanic Stream'** could then be surveyed with the 18.2 metre ex-Fleurs Kennedy Dish, and in the following three years fine details were filled in with the 64 metre telescope. The HIPASS team generated important observational data on neutral hydrogen (HI) in the Stream in 1998.



The Magellanic Stream (*left and above*) appears to grow from the disturbed interCloud region and stretch in a broad arc across 120° of sky, from Doradus north-west through Phoenix, Sculptor, Piscis Austrinus and Pisces to Pegasus. Inevitably, the existence of the Stream has been a source of much speculation as to its origin and movement, but Mathewson and his colleagues believe that it results from a collision between the Large and Small Clouds some 400 million years ago.

Since it opened, the Parkes Radio Telescope has conducted on-going surveys of the radio sky. These have concentrated on seven main areas: discrete-source surveys, broad-scale surveys, supernova remnants, atoms and molecules in space, pulsars, space research, and VLBI (Very Long Baseline Interferometry) operations. The first survey at 408 MHz was started by Bolton, Gardner, Mackey and associates in 1964 in which they were able to produce a list of about 2 000 southern sources including the discovery of quasars, considered one of the most exciting astronomical achievements at the time. This became the first iteration of the highly respected **Parkes Catalogue of Radio Sources**, and was published in four papers between 1964 and 1966, and later as a whole in 1969.

The second Parkes survey began in 1968 at a frequency of 2 700 MHz and lasted 12 years. It was started by Bolton and Shimmens plus two students, Jeannette Merkelijn and Jasper Wall. Others involved later were Ann Savage, Dave Jauncey and Alan Wright. For the first time a special 'continuum-only' receiver was built by Bob Batchelor, John Brooks and Brian Cooper who were known collectively as 'the BBC'. The second survey was completed in 1980. Bruce Slee conducted an **A**ustralian **R**adio **S**tar **S**urvey (**ARSS**) in co-operation with the 74 inch reflector at Mount Stromlo in the 1980s, and also conducted long-baseline interferometry using the big dishes at Parkes and Tidbinbilla as a pair. In 1990 the Parkes telescope was part of a collaborative project (the PMN survey) along with MIT and NRAO to conduct a 5 GHz survey of the Southern Hemisphere.

This increased the number of southern sources from about 10 000 to 50 000, making it possible to claim as Alan Wright put it in 1991: "*The Parkes 64 metre telescope has discovered and catalogued more radio sources than any other radio instrument – not bad for an old lady of thirty!"* In 2007 Parkes data revealed the first **fast radio burst**s (FRBs – millisecond transient radio signals from the depths of extragalactic space).

On 15 April 2015, a pulse lasting no longer than a millisecond but containing as much energy as the Sun's output over 10 000 years was detected by Parkes through its link to the Swinburne University's **Gstar** supercomputer in Melbourne. The ATCA pinpointed the source which optical telescopes found to be an old galaxy six billion light-years away. By studying the burst's afterglow, which illuminated the tenuous material lying in vast regions across intergalactic space, astronomers confirmed that the atoms in the universe that we can observe only amount to 5% of its contents. The rest must be dark matter / dark energy. By the end of June 2018, eighteen FRBs have been detected from different parts of the distant universe, with no associated gamma rays nor X-rays, and no sign that they are related to gamma ray bursts, merging neutron stars or even evaporating black holes.

The scope of the work done at Parkes in the 21st century is shown in this list of papers presented at the Radio Telescope's 50th Birthday Science Symposium, held from 31 October to 4 November 2011:

- the Parkes Continuum surveys;
- the first search for glycine and other biomolecules;
- the Parkes-Tidbinbilla Interferometer – from masers to quasars;
- **CARPARCS** (**Car**ina **P**arkes-**A**TCA **r**adio **c**ontinuum **s**urvey);
- circumstellar masers in the Magellanic Clouds;
- weighing supermassive black holes with water megamasers;
- OH maser studies of evolved stars;
- millisecond pulsar survey;
- the PMN survey and its high-resolution sequel;
- HI in Magellanic Clouds;
- pulsars at radio and gamma ray wavelengths;
- high-mass star formation;
- the eighth anniversary of the Double Pulsar;
- molecular cloud studies;
- the methanol multibeam survey;
- globular clusters;
- the Parkes Pulsar Timing Array project;
- looking for dark galaxies;
- supernova remnants and magnetars;
- Centaurus A at 20 cm;
- the high time resolution universe;
- spin-orbit coupling in the erratic binary pulsar B1259-63;
- the variable nature of the radio magnetar PSR J1622-4950;
- gamma ray pulsars – spin-down vs gamma ray luminosity and the distance problem;
- understanding atomic hydrogen in the Milky Way with Parkes;
- spectro-polarimetric observations of the giant lobes of Centaurus A;
- galactic supershells and GSH 006-15+7;
- the diffuse polarised emission from the Milky Way;
- S-PASS and polarised CMB foregrounds;
- the Parkes 300-900 MHz Rotation Measure survey;
- HIPASS – surveying the extragalactic HI universe;
- the rise of multibeam astronomy;
- gravitational lensing of HI galaxies – a new probe of dark matter;
- neutrino astronomy with Parkes;
- Parkes – the fulcrum of southern hemisphere VLBI;
- phased-array feeds for Parkes.

All of these papers are available on-line as sets of slides.

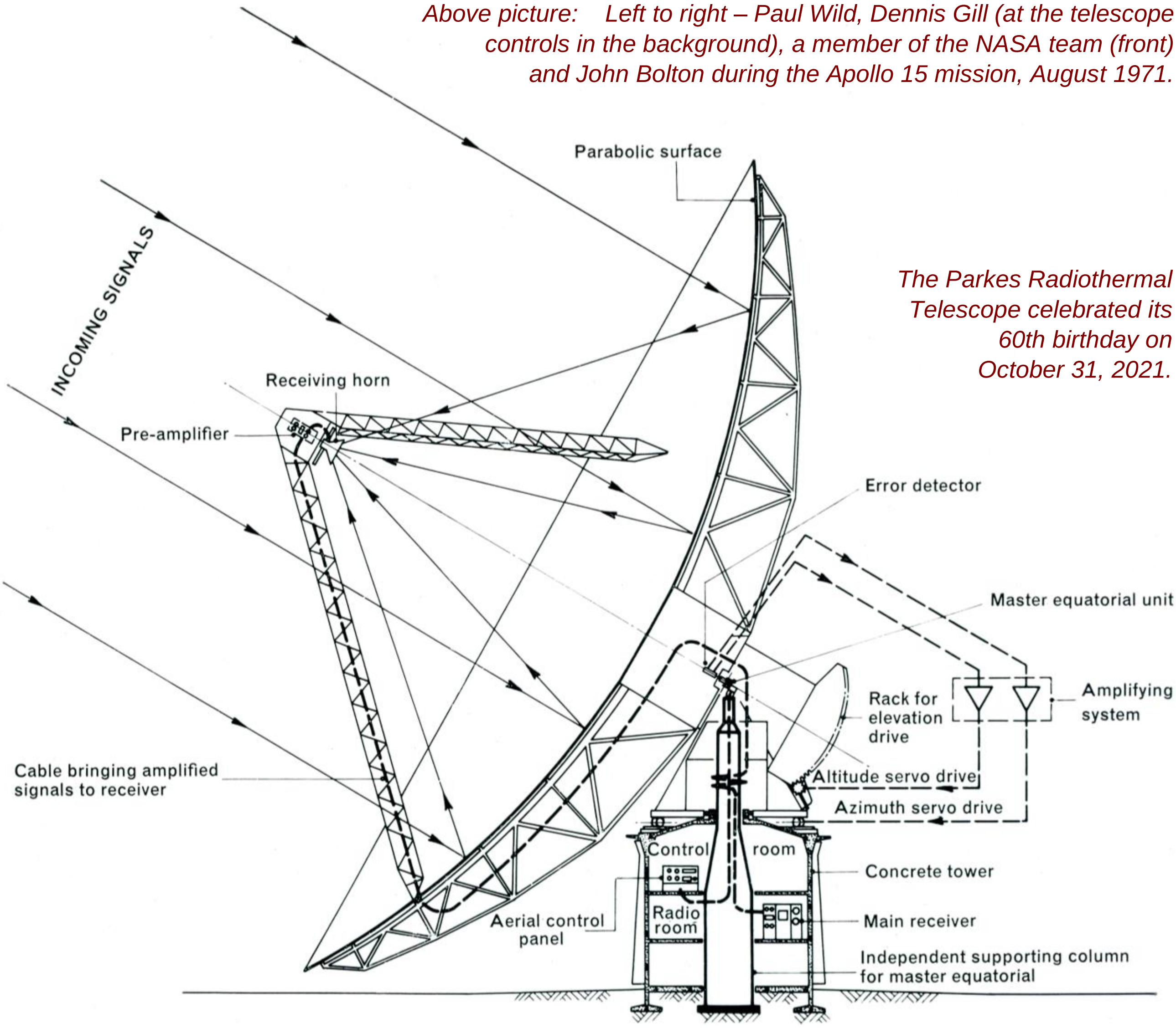
[Note: **LASER** = **L**ight **A**mplification by the **S**timulated **E**mission of **R**adiation.
MASER = **M**icrowave **A**mplification by the **S**timulated **E**mission of **R**adiation.]

Although designed and operated as a radio telescope for astronomical observations, Parkes has also been used for tracking and receiving data from many space probes. As well as playing a leading rôle in the reception of the video footage of the first Moon walk by the crew of Apollo 11 in 1969, the Parkes telescope, under John Bolton's guidance, was central in securing communications between Houston and the damaged Apollo 13 spacecraft, and the successful return of its crew to Earth.

Other spacecraft handled at Parkes include the *Galileo* probe to Jupiter, the *Voyager* exploration of Uranus and Neptune, the *Giotto* project to examine Halley's Comet and the various Mars missions in early 2004. In January 2005, Parkes was a key element in a global linkup of 17 radio telescopes observing the descent of the *Huygens* probe through the atmosphere of Saturn's moon Titan to a successful landing on its surface.

Bolton relinquished the Directorship of Parkes in 1971 after ten years, but continued research projects of his own. He assisted in the Anglo-Australian Telescope project, was awarded Fellowship in the Royal Society in 1973, and in 1977 received the Gold Medal of the Royal Astronomical Society. In 1981 he was invalided out of the CSIRO due to health problems (he had suffered two heart attacks and a stroke, whereupon he immediately gave up heavy smoking), and moved with his wife Letty to the heights of Buderim on Queensland's Sunshine Coast for a well-earned retirement.

Above picture: Left to right – Paul Wild, Dennis Gill (at the telescope controls in the background), a member of the NASA team (front) and John Bolton during the Apollo 15 mission, August 1971.



The Parkes Radiothermal Telescope celebrated its 60th birthday on October 31, 2021.

Note the tracks on which the 18.2 metre dish could move, to vary its angle and distance from the main instrument.

The Parkes Radio Telescope from space: note the proportion of the dish now covered with aluminium panels.

The Parkes Radio Telescope's support for the Apollo 11 lunar mission

It was one giant leap for mankind, and it was taken at 12.56 pm Australian Eastern Standard Time (AEST) on Monday 21 July 1969. Six hundred million people, or one fifth of mankind at the time, watched Neil Armstrong's first steps on the Moon. Three tracking stations were receiving the television signals simultaneously. They were CSIRO's Parkes Radio Telescope, the Honeysuckle Creek tracking station outside Canberra, and NASA's Goldstone station in California. The signals were relayed to Mission Control at Houston. During the first few minutes of the telecast, NASA alternated between the signals from its two stations at Goldstone and Honeysuckle Creek, searching for the best quality images. When they switched to the Parkes pictures, they were of such superior quality that NASA remained with Parkes for the remainder of the 2½ hour telecast. But it almost didn't happen.

In late 1966, NASA put forward a proposal to include the Parkes 64 metre dish permanently in its worldwide tracking network. Until then, their network of 26 metre dishes had met most of NASA's requirements. Plans to send probes to more distant planets as well as the upcoming manned Apollo missions to the Moon demanded a network of larger dishes. NASA was near to completing the construction of its 64 metre dish at Goldstone, California, but budget cutbacks meant that the second and third stages of its 64 metre network, at Tidbinbilla and Madrid respectively, had to be postponed until the early 1970s. These three dishes were all based on the Parkes Radio Telescope. Such developments made Parkes' inclusion an attractive alternative, at least until the other two 64 metre dishes were constructed. This proposal was, however, turned down owing to the fact that a growing number of observing requests from Australian astronomers meant that many would miss out on getting precious observing time on the telescope.

In October 1968 the Director of the Parkes Observatory, John Bolton and his wife Letty, while on a trip to the USA, attended a dinner party at the home of one Bob Leighton. Bob was a brilliant Caltech engineer who had been a colleague of John's when John was building the Owens Valley Radio Observatory as Professor of Radio Astronomy at Caltech in the 1950s. Also present at the party was the Head of the Goldstone Project, Eb Rechtin of NASA's Jet Propulsion Laboratory (JPL). During the course of the evening, John was asked if he could make available the observatory's 64 metre telescope for reception of signals from the Apollo 11 spacecraft, particularly during the most critical phases of the mission when the Lunar Module (LM, *Eagle*), was on the lunar surface. The historic nature of the mission, combined with the fact that human lives were at risk in space, convinced both Bolton and 'Taffy' Bowen, the Chief of CSIRO's Division of Radiophysics, to support the mission.

Following high level representations, Cabinet level meetings approved the Parkes Observatory's involvement in the upcoming Apollo 11 mission.

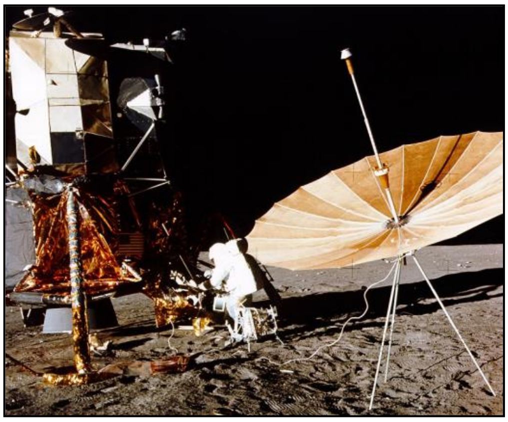
In February 1969 a meeting was convened with the Australian Department of Supply to arrange contract details. John Bolton had spent the previous evening with Robert Taylor, the American engineer who was to manage the NASA operations at Parkes. They had discussed their respective rôles extensively, and the problems to be overcome.

Right: John Bolton, Robert Taylor and Edward 'Taffy' Bowen.

John Bolton ended the meeting by saying that he would be happy to work with Taylor, but that he would only accept a one-line contract: "The Radiophysics Division agrees to support the Apollo 11 mission." NASA agreed to pay $ 3500 per day to cover costs at Parkes, plus $ 15 000 to cover necessary modifications to the telescope.

For the tracking operations at Parkes, NASA provided the S-Band front-end receiving equipment. Also provided were tape recorders and 'translating' equipment for converting the incoming signals into a TV picture so that the operators could check that everything was functioning correctly. The Observatory provided the feeds, cabling, power, weatherproofing of the aerial platform, and facilities for the OTC (Overseas Telecommunications Commission) link equipment. In addition, the PMG (Post-Master General's Department) established a network of microwave links and voice communication channels to relay both the Parkes and Honeysuckle Creek signals to Houston.

The original mission plan of Apollo 11 had Parkes acting as a backup during the moonwalk for NASA's two tracking stations, the 64 metre dish at Goldstone in California (*left*), and the original DSS-42 26 metre dish at Tidbinbilla near Canberra (*right*). This was in case of a delayed moonwalk, or some other reason. A second 26 metre dish at Honeysuckle Creek tracking station, also near Canberra, would track the command module (CM, *Columbia*), and co-ordinate the effort between the Australian stations. The Goldstone dish was to be the prime receiving station.



The flight plan had the astronauts performing the Extra-Vehicular Activity (EVA or 'moonwalk'), shortly after landing. The Moon was not due to rise at Parkes until 1:02 pm AEST, by which time the EVA would have been completed. In addition, the astronauts were to deploy a 3 metre, erectable, S-band antenna, as was later done on Apollo 12 and 14 (*right*). The purpose of this was to provide greater signal strength from the Moon.

All this was changed some two months before the launch. In May 1969 it was decided to alter the Apollo 11 mission plan and allow a rest period before commencing the lunar EVA. This would have given the astronauts an opportunity to adjust to the Moon's one-sixth gravity, and to start the EVA refreshed. The new plan had the EVA starting about ten hours after landing, at 4:21 pm AEST, which was some twenty minutes after the Moon had set for the Goldstone dish, but which had the Moon high overhead at Parkes. Parkes' rôle was consequently upgraded from backup to 'Prime Receiving Station'.

The subsequent upgrading from backup to prime station meant that all equipment had to be duplicated at Parkes. Two sets of receivers, two sets of microwave relays, two sets of voice and command links etc. were installed. Since Parkes could only receive and not transmit, it was regarded as an auxiliary station to Honeysuckle Creek and was assigned the honorary designation of Station Number 23 in the Manned Space Flight Network (MSFN).

Originally, only voice communications and spacecraft and biomedical telemetry were to be received. Mission planners had not included a broadcast of television pictures of the first moonwalk until quite late in the planning. For them, what mattered most was the vital telemetry on the status of the astronauts and the LM systems. Television was an unnecessary secondary concern. The LM was severely weight restricted, which meant that every additional kilogram it carried required many times more its weight in fuel. These weight restrictions had already delayed the development of the LM by several months. In order to include a television camera, other equipment had to be modified and lightened accordingly. Stan Lebar, the Program Manager for the Westinghouse Lunar Surface Camera, described the decision:

> *"Probably one of the most amazing meetings on this subject occurred at NASA's Manned Spacecraft Center, Houston, some time in the early part of 1969. The meeting was convened to determine if the television camera should be taken to the Moon on the Apollo 11 mission, which was only a few months away. The session was attended by just about every manager at NASA and anyone else who knew how to spell TV. It was, to say the least, a very large audience. The basic information about how the television was to be used, and the timelines for its use, was covered by a gentleman by the name of Ed Fendell. Ed was part of NASA operations and responsible for the use and scheduling of the television during the flight to the Moon and on the lunar surface. Ed played 'devil's advocate' and concluded his presentation by saying, in summary, that there was no reason to have television on the Moon and the camera should not be taken. The audience en masse rose to its feet and objected loudly to Ed's conclusions. The old timers in the audience who had brought this program to where it was, stood up and delivered impassioned speeches about how NASA owed it to the people to be able to witness this historical event live as it unfolded. When it was all done, it was unanimous that the Apollo would carry a television camera."*

Once the decision had been made to include television, the addition of Parkes was even more crucial. The large collecting area of the Parkes telescope provided for extra gain in signal strength from the Moon. This meant that the astronauts need not deploy the 3 metre S-band antenna. The tight schedule of the first moonwalk was such that NASA planners had decided the extra time and effort needed in deploying the antenna (about 20 to 45 minutes) was not warranted. Instead, the smaller 0.66 metre S-band antenna, located at the top of the LM ascent stage, would be used, and having Parkes in the link would make up for the slight reduction in signal from the LMs smaller transmitter. Also, NASA wanted television pictures of Armstrong descending to the lunar surface, which of course would have been before he could deploy the erectable antenna. Parkes thus provided the maximum reliability and quality for the telemetry which the mission planners demanded.

Honeysuckle Creek (*left, on 21 July 1969, with the 5-day-old Moon near the left margin)* was the main NASA tracking station out of seven in Australia for all the manned Apollo missions. It co-ordinated the tracking effort between the other NASA stations and Parkes. All seven stations were operated for NASA by the Department of Supply and were manned by Australians. Thomas Reid was the Station Director at Honeysuckle Creek from 1967 to 1970, and then moved to the Tidbinbilla Station where he took over as Director of the whole Canberra Deep Space Communications Complex (CDSCC) until 1988. Honeysuckle Creek was closed in December 1981 and its antenna moved to nearby Tidbinbilla.

In the pre-mission plan for Apollo 11, Tidbinbilla was scheduled to track the LM, *Eagle*, on the lunar surface, and Honeysuckle Creek was to track the command module, *Columbia*, in lunar orbit. Tidbinbilla had a maser low noise amplifier that gave it greater sensitivity than Honeysuckle Creek. A third NASA tracking station at Carnarvon in Western Australia was scheduled to track the LM with its 9 metre antenna and receive the telemetry from the surface experiments the astronauts were to deploy. The signals were then to be sent to Houston via the INTELSAT III geostationary satellite. The CSIRO Division of Radiophysics' Culgoora Radioheliograph, near the town of Narrabri in northern NSW, was used to observe the Sun and warn NASA of impending solar flares. Because the astronauts would be outside the protection of the Earth's Van

Allen radiation belts, the sudden eruption of a solar flare could expose the astronauts to lethal doses of radiation. The Radioheliograph would give them sufficient warning to abandon the EVA and return to the relative safety of the LM. The personnel at Tidbinbilla, under the directorship of Don Grey, were looking forward to receiving the historic television of the EVA. Unfortunately for Tidbinbilla, a fire in the transmitter just one day into the mission on 18 July altered the plan drastically. Despite engineers being able to repair the damage in just 12 hours, the incident dented NASA's confidence in the station, so its rôle was switched with that of Honeysuckle Creek. This was a great disappointment to the engineers at Tidbinbilla who had worked tirelessly to get the system back up and running in such a short time. For Honeysuckle Creek however, this twist of fate would prove to be significant.

At 6:17 am AEST on 21 July, astronauts Neil Armstrong and Edwin (Buzz) Aldrin landed their LM, *Eagle*, on the Sea of Tranquility. It was still some seven hours before the Moon would rise high enough to be seen from Parkes. The schedule required the astronauts to rest before attempting the moonwalk, by which time the Moon would be high overhead at Parkes. However, Armstrong departed from the original plan, opting for an immediate moonwalk instead. To the astronomers at Parkes, it looked as though the moonwalk would be all over before the Moon even rose at Parkes, and the weather was cold and miserable. However, it took the astronauts such a long time to get into their spacesuits and depressurise the LM cabin that, as they prepared to leave the module, the Moon was just rising at Parkes. It seemed as though they might get the signals after all.

Suddenly, trouble loomed as a storm approached. Whilst fully tipped over to an elevation of 30º, waiting for the Moon to rise into its beam, the telescope was struck by severe 110 kilometre per hour wind gusts. The telescope's zenith angle drive rack was forced back against its gears and the control tower shuddered. This was a dangerous situation, threatening the integrity of the telescope structure. The atmosphere in the control room was tense, with the wind alarm ringing and the telescope ominously rumbling overhead. Fortunately, cool heads prevailed, and as the winds abated, Buzz Aldrin activated the TV camera just as the Moon approached the telescope's field of view, and tracking began. Using a less sensitive 'off-axis' detector, Parkes was able to receive the TV pictures just as the LM camera was switched on, but better signals were coming from Honeysuckle Creek, whose 26 metre dish was able to be tilted right down to the horizon. Despite the claims made by the crew at Parkes as described on the next page, the signals from Honeysuckle Creek were the ones used to broadcast the first eight minutes of the moonwalk, including Armstrong's iconic "one small step for man, one giant leap for mankind." Eight minutes after the transmission began, the Moon had risen into the field of view of the Parkes telescope's main detector. Because Parkes was a much larger antenna, it captured more signal and so produced better pictures. Houston switched to Parkes and remained with those pictures for the rest of the 2½ hour broadcast.

Parkes staffer Neil 'Fox' Mason (*right*), who was seated at the control desk, drove the telescope with utmost concentration, while John Bolton sat alongside him, controlling the antenna's feed rotator. Both were riveted to the controls of the telescope at this most critical period. Tracking a radio source with an off-axis receiver was a tricky and complicated procedure. Essentially, it involved turning the feed rotator so that the off-axis receiver was directly above the main receiver. This gave the off-axis receiver its maximum field-of-view below the main beam.

Then, by slowly moving the telescope in azimuth angle, while simultaneously turning the feed rotator, one could keep the off-axis beam centred on the radio source. A signal strength indicator (a voltmeter), located on the top of the control panel, was used to determine the pointing of the off-axis beam on the source. If they tracked off the source, then the signal strength indicator would register a drop in voltage. The telescope would then be moved appropriately to centre the beam on the source and maximise the signal strength again. Once the off-axis beam was level with the main, on-focus beam, the telescope was moved quickly in azimuth to lock onto the radio source and track it in the main beam of the telescope. This, then, was the procedure employed to receive the pictures of Armstrong's first step on another world, by the Parkes Radio Telescope. Jasper Wall recalled:

"There were no cheers amongst us; just the sudden realisation that 'Bloody hell, there's a man on the Moon!' We could see all the data, like heart monitors on the astronauts, and in fact there was so much information that what was really going on was hard to discern. Nevertheless, none of us present will ever forget it."

John Bolton was an expert in identifying radio sources in the sky. His success in acquiring the Apollo 11 television signal in very trying conditions, even before the source had risen into the main beam of the telescope, was surely one of the most breathtaking examples of his expertise in action. Years later, Bolton would insist that he had acquired the signal simultaneously with the Goldstone and Honeysuckle Creek stations. Only after the signal had been acquired by the main telescope beam and locked on, did he relax and view the pictures being received at Parkes on the ten-inch television monitor. Robert Taylor, who had been monitoring the pictures from the outset, assured John that the TV was acquired just as Aldrin turned on the TV switch. He also viewed the replay of the telescope's master tape, and saw no difference between it and the ABC-TV version replayed later that evening. Indeed, a second small television set in the control room allowed the staff to view the ABC-TV broadcast's transmitted signal, and to compare it with their telescope's recorded signal.

Fox Mason had the important task of maintaining the pointing of the telescope by keeping close watch on the signal strength indicator, and moving the telescope accordingly. Owing to the critical nature of the moment, John Bolton would not allow him to take a short break and view the pictures as they were coming in live, lest the winds pick up again and threaten the signal reception. The ten-inch monitor was located on the far side of the control room, with the central support column blocking the view from the control desk. It was ironic that he had to wait until later that evening at home to watch the replay of the moonwalk on ABC-TV. Asked why he didn't take a quick peek, Fox remarked, "I was disappointed, but I had an important job to do. Besides, I had to be on my best behaviour because all the bosses were there looking over my shoulder!"

The weather remained bad at Parkes, with the telescope operating well outside its safety limits for the entire duration of the moonwalk. The EVA lasted a total of 2 hours 31 minutes and 40 seconds – hatch open to hatch closed. The telescope continued tracking the LM and receiving TV pictures from the camera until it was shut off by the astronauts about half an hour after the end of the EVA. The tracking continued at Parkes until 6:17 pm AEST. Following the EVA the master tapes were replayed in the control room, and it was during this period that David Cooke stepped outside. The weather was finally beginning to clear and the Moon was visible for the first time that day. The realisation that two men were actually on the Moon suddenly overwhelmed him. He took this photograph of the dish (*right*), with the passing storm clearly visible on the horizon. It had been a dramatic day!

The signals were sent to Sydney via specially installed microwave links. From there it was split. One signal went to the Australian Broadcasting Commission (ABC) studios at Gore Hill for distribution to Australian television networks. The other went to Houston for inclusion in the international telecast. Because the international broadcast signal had to travel halfway around the world from Sydney to Houston via the INTELSAT III geostationary communications satellite over the Pacific Ocean, a 300 millisecond delay was introduced to the signal. Australian audiences therefore witnessed the moonwalk, and Armstrong's historic first step, some 0.3 seconds before the rest of the world.

The huge success of this first broadcast from the Moon was a result of the professionalism and dedication of the CSIRO and NASA staff at Parkes and Honeysuckle Creek, and of the technicians and workers of Australia's communication network, notably from the Post-Master General's office (PMG), the Overseas Telecommunications Commission (OTC), the Australian Broadcasting Commission (ABC), and the Australian Department of Supply. Upon the crew's safe return to Earth, NASA handed over a cheque for US$ 60000 for the use of the telescope, which was used to fund an upgrade of the Big Dish's surface.

(Based on a report by J. Sarkissian, Operations Scientist, Parkes Observatory, October 2000.)

The Parkes telescope also played an important rôle in NASA's other Apollo missions. An unplanned occasion was when a sudden life-threatening explosion in the Apollo 13 Service Module on 13 April 1970 required Parkes to come on line in a matter of three hours to save the crew. A visiting Indian radio-astronomer, V. Radhakrishnan, was to have observed that night, and had to quickly clear the aerial cabin of his equipment that he had spent all day assembling and testing. In a situation of such urgency, kicking someone off 'the Dish' was no problem but, to quote the London *Times:* "Bolton, typically, left nothing to chance. With the Australian sun beating down, he stood, stopwatch in hand, rehearsing teams of his perspiring staff in hand-cranking the axis gearing of the 1000-ton Dish at rates correct to follow the spacecraft, should electrical power fail." The ability and sensitivity of Parkes to receive the severely-weakened signals from the Apollo 13 Command Module, together with tracking telemetry from the Tidbinbilla, Honeysuckle Creek and Carnarvon stations, were crucial for maintaining communication with the three astronauts, and returning them safely to the Earth.

[**Present Day Note:** In 1945 Percy Spencer, a radio engineer, worked at the Raytheon Company in Waltham, Massachusetts overseeing production of magnetrons for military radar. Whilst observing one being tested, he realised that a candy bar in his pocket was melted by the microwaves being emitted. Other technicians had noticed the phenomenon and ignored it, but Spencer was intrigued. He experimented, heating popcorn which was successful and heating an egg which was not – it exploded. He determined that the heat was caused by water molecules in the food absorbing the microwaves. The heating power could be concentrated by placing the magnetron in a metal box from which the radiation could not escape.

This was the birth of the microwave oven, the first to go on sale being Raytheon's "RadaRange" of 1947 (showing its link to Radar).

Built for cooking and reheating food in hotels, hospitals, ships, restaurants and planes, it was 1.8 metres tall, weighed ⅓ tonne (340 kg) and cost US$ 5000 (US$ 55 000 in today's money). Its 1600 watt magnetron ran so hot it had to be water-cooled. Three early units are shown at right in a hospital kitchen.

Much smaller microwave ovens are now common in homes worldwide. The oven doors are perforated with tiny holes so that the cooking process can be watched without opening them. As most modern microwave ovens use radiation with a wavelength of about 12.2 cm, the waves are far too large to fit through the perforations, while the much shorter waves of visible light, λ = 0.0005 mm, can easily pass through. The heating radiation in most microwave ovens is emitted from a resonant cavity magnetron. Raytheon Australia is a subsidiary company with 1500 staff. Based in Canberra to be close to the Department of Defence, it develops naval, submarine and aerospace systems and technologies.]

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