Journal of Astronomical History and Heritage, 11(1), 63-70 (2008).

MOLONGLO OBSERVATORY: BUILDING THE CROSS AND MOST

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Abstract: When Bernard Mills left the CSIRO in 1960 to establish a radio astronomy group in the School of Physics, University of Sydney, he had not only invented the principle of cross-type radio telescopes but proved their great efficiency at surveying the positions, intensity and structure of radio sources. He had ambitious plans for a second generation Cross—a radio telescope with arms one mile long.

This paper describes the circumstances of Mills' appointment as Professor of Astrophysics and the recruitment of an international Department that achieved his vision with the Molonglo Cross. The construction involved interaction with many colleagues—engineers in other university departments and government agencies, and with the contracting firms. Formal links were set up with the Electrical Engineering Department through The Radio Astronomy Centre in the University of Sydney and then with Arecibo Observatory through the Cornell-Sydney University Astronomy Center.

When the Molonglo Cross completed its main survey in 1978 after eleven years, it was switched off and the EW arm was then converted to the Molonglo Observatory Synthesis Telescope. Many of the staff involved with the MOST are now challenged by SKAMP, testing systems for the Square Kilometre Array with cylindrical geometry in the Molonglo Prototype. These two later developments out of the original Cross telescope are described briefly.

Keywords: radio astronomy, Molonglo Cross, MOST, SKAMP, B.Y. Mills.

1 THE CONCEPT—THE FIRST CROSS-TYPE RADIO TELESCOPE

Much of the earliest radio astronomy in Australia was carried out by staff from the CSIR's Division of Radiophysics at a number of field stations in or near Sydney using simple aerials, some of which were based on radar technology (Orchiston et al., 2006; Orchiston and Slee, 2005; Sullivan, 2005). In the case of the famous Dover Heights cliff interferometer, sources were observed at low elevation angles and a second 'antenna' was formed vertically below the cliff by an image in the ocean (see Bolton and Slee, 1953). In 1949, the Head of the Division's radio astronomy group, Dr Joe Pawsey, suggested to one of the young research scientists, B.Y. Mills (Figure 1), that he should begin a research program on discrete radio sources. However, "… Pawsey knew that the future lay with the use of horizontal baselines and Bolton was still making effective use of the interferometer that had proved so successful for him previously." (Mills, 2006: 3).

In the early 1950s, Mills developed large EW baselines with a 3-element interferometer at Badgery's Creek near Sydney (see Figure 2, inset) and observed near the zenith to obtain accurate positions in a sky survey of 77 discrete sources (Mills 1952). He realised that the next deeper survey would require more sensitivity and greater NS and EW spacings. His solution in 1953 was a new cross-type telescope in which the correlation of two intersecting fan beams yielded a high resolution pencil beam. The design could also separate the sensitivity of the telescope (dependent on its area) from the resolution (dependent on the maximum arm length and hence the extent of the intercepted wavefront). In the face of official skepticism, Mills built a 120-ft prototype cross at Potts Hill field station near Sydney (Figure 2, inset) to prove his concept, and he was joined in this venture by a Technical Officer, Alec Little, at the start of what would turn out to be a 32-year partnership (Mills and Little, 1953).

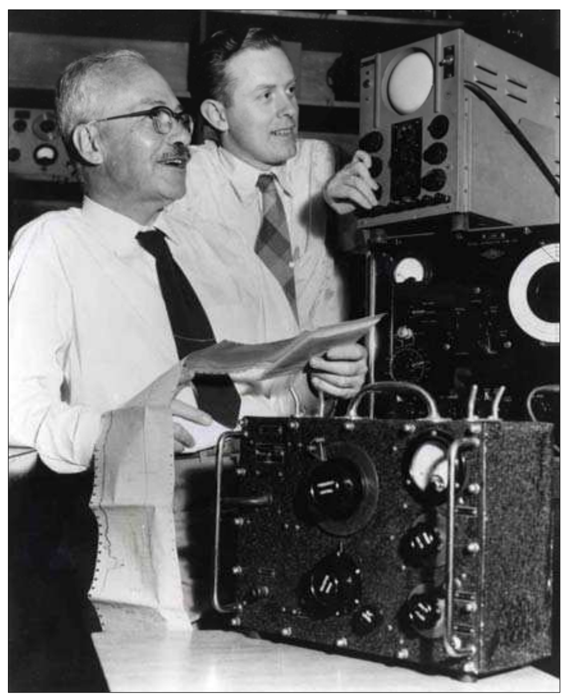

Figure 1: Rudolph Minkowski (left) and Bernard Mills at the Radiophysics Division's Fleurs field station during the 1950s (courtesy: Woody Sullivan).

CSIRO allocated the necessary resources and the 85.5 MHz 'Mills Cross' was built at Fleurs field station (Figure 2, inset) in 1953-1954, largely by Little while Mills was on a 6-month study tour in the USA. The subsequent MSH survey was an outstanding success, giving Mills data on source counts and structure for the Galactic Plane and the extragalactic sky with 49 arcminute resolution (Mills et al, 1958).[1] At about the same time, W.N. Christiansen developed a cross array of small dishes at 1,415 MHz for synthesis mapping of the solar disk (Christiansen et al., 1961) and C.A. Shain built a third cross at Fleurs for low frequency observations (Shain, 1958).

Despite the versatility and performance of these cross-type radio telescopes, CSIRO abandoned their 15-year tradition of astronomy using ingenious small aerial systems and did no further development at Fleurs. The era of large parabolic dishes had already begun in Netherlands, Germany and England, especially with the 250-ft Jodrell Bank Radio Telescope. In 1953, the CSIRO's Division of Radiophysics embarked on the planning of a 'Giant Radio Telescope' (GRT). Chief of the Division, Dr E.G. ('Taffy') Bowen, succeeded in obtaining funding from both the Carnegie Corporation and the Rockefeller Foundation in USA for a GRT in Australia and the design contract for it was placed in 1956 (Robertson, 1992). When Mills and Christiansen drove in the peg to mark its position on a farm near Parkes, both knew that there was no future within CSIRO for their types of cross and array radio telescopes. All remaining resources available to the Radiophysics Division were reserved for Paul Wild's Culgoora Radioheliograph, and there was nothing left for a large cross (Bowen, 1981).

The planning and commitment to the GRT at Parkes triggered major career changes for Mills and many other Radiophysics staff who left for research positions elsewhere.[2] Mills investigated chairs of Electrical Engineering at Adelaide, Melbourne and Sydney but these did not offer the financial support to build his large cross-type telescope. He found this in 1960, not in Engineering, but in Physics, at Sydney University.

2 THE SCHOOL OF PHYSICS AT SYDNEY UNIVERSITY

Harry Messel was appointed as Professor of Physics at Sydney University on 1 September 1952 and established The Nuclear Research Foundation (the first in the British Commonwealth) to "… promote, foster, develop and assist …" research with grants from "… fees, donations and the like." Between November 1959 and November 1961 Messel recruited new Physics Professors in Theoretical, Thermo-nuclear (plasma), High Energy Nuclear (cosmic rays) and Electronic Computing (The Nuclear Research Foundation, 1962). When Robert Hanbury Brown in Manchester sought funds and a site for his optical intensity interferometer, Messel began an astronomy group with Richard Twiss, Cyril Hazard and John Davis to build the interferometer near Narrabri in northern NSW. Messel also had funds for a complementary photometric telescope and sent Colin Gum to Europe to examine optical designs. Unfortunately, in April 1960 Gum died in a skiing accident in Switzerland and the telescope project never went ahead. Messel contacted Mills, approved the concept of a large cross-type radio telescope and offered him seed money sufficient to build a 408 MHz Cross with arms about 400m long. Mills joined the School of Physics in June 1960 with his initial plans dependent on funding. He comments:

> From the beginning there seemed to be few problems in constructing a Cross within the available budget of $200,000 which would be able to survey the sky at metre wavelengths with a sensitivity and resolution at least equal to that anticipated for the Parkes radio telescope operating at its optimum wavelength. But why stop there? (Mills, 1991: 720).

Any further funds would mean longer arms replicating a flexible modular design. The challenge was to find the additional financial support for a large cross.

Through some of his many overseas contacts (probably Thomas Gold at Cornell) Messel learned that the newly-established National Science Foundation was willing to make grants outside of the USA. Mills quickly wrote a proposal for his ambitious 1-mile cross-type radio telescope. In support of this he provided results from his 85.5 MHz Fleurs Mills Cross survey, and made precise predictions of possible observing programs, the number of fainter sources expected, their confusion levels and the sensitivity required of the telescope.

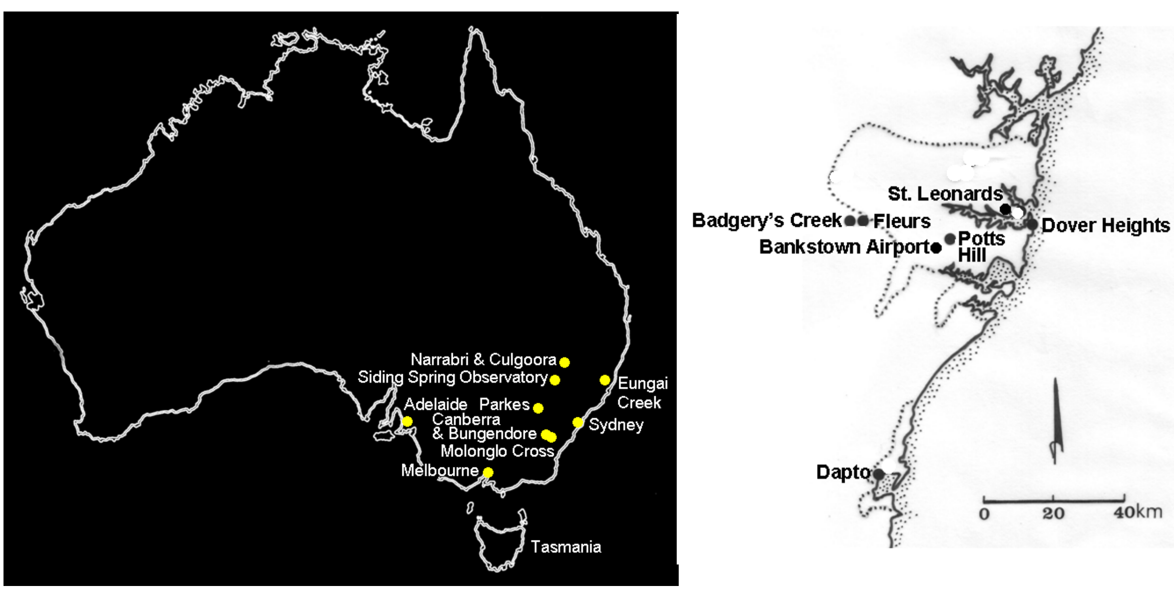

Figure 2: Australian localities mentioned in the text. The map on the right shows sites in or near Sydney (the dotted lines show the approximate present-day boundaries of suburban Sydney and Wollongong).

The application was received sympathetically, but then met opposition from Dr Bowen who advised against any grant, stating that a small university group could never manage such a large project. When the NSF sent a staff member, Geoffrey Keller, to Australia to investigate, Messel advised him to go to Canberra and talk to Bart Bok. The visit reassured the NSF, and in 1962 they approved the first (and perhaps the only) large foreign grant that the NSF ever made. The initial funding of US$746,000 was followed by US$107,500 in 1964 and allowed the Molonglo Cross project to go ahead with its planned mile-long arms. In his first published description of the project, Mills (1962) wrote: "This is a greatly enlarged version of the original 'Mills Cross' put into operation by the CSIRO in 1954 ... the beamwidth would be about 2.8 arcmin and the sensitivity adequate to detect more than a million radio sources."

Meanwhile Messel negotiated the purchase of a site for the new Cross in a wide flat valley near Canberra. This was one of the sites that had been investigated for the GRT but which had been rejected in favour of Parkes. The height of the GRT would have put it in line of sight over hills to the transmitters on Black Mountain in Canberra but the cylindrical reflectors of the Cross were lower and remained shielded. Thus in the Parish of Molonglo on a branch of the Molonglo River, construction of the Molonglo Radio Observatory was commenced in 1961.

2.1 The Astrophysics Department and Colleagues

Mills recruited staff for his new Department from industry and radio astronomy centres around the world. Arthur Watkinson joined first from CSIRO in 1960 and Terry Butcher, tool maker, recently returned from radio and TV work in Canada. Alec Little, who had been Mills' assistant at CSIRO since 1948 and was completing an M.Sc. at Stanford University with Ron Bracewell, was persuaded to return to Sydney early in 1961, but only after two meetings with Harry Messel in San Francisco. The appointment of Pat O'Brien (Cambridge) was a disappointing bungle—the letter of offer never reached him, and he took a Chair of Physics at Khartoum instead. Bruce McAdam (Cambridge) came from New Zealand in Easter 1961 to visit Dapto, Parkes and Sydney University before deciding to join Mills in June. Two more technical staff members, Jack Howes (from AWA) and Grant Calhoun, were appointed in 1962. The initial academic team was completed when Michael Large (Jodrell Bank) and Tony Turtle (Cambridge) arrived from the UK in February 1963. Table 1 gives dates of appointments and resignations of relevant staff at the University of Sydney in the order of their association with the Molonglo story, up to 1978.

This small university group built the Cross over the next six years, but did so in cooperation with many university and industrial colleagues. Many years later, Mills (2006: 10) was to reminisce: "I found myself manager of a big engineering project. It was not an enjoyable job but there was no one else to do it and I was much helped by my engineering contacts, stretching back in some cases to student days."

From the start there was a major partnership with W.N. ('Chris') Christiansen in the Department of Electrical Engineering who took responsibility for the receiving system. The cooperation was made formal with the formation of the Radio Astronomy Centre in the University of Sydney (Messel, 1960). Professor Aitchison enticed Bob Frater to leave industry (AWA, OTC and then DUCON) and join the Electrical Engineering Department in 1961 specifically to work on the electronic design of the Molonglo Cross using the (then new) transistor technology. Frater (2005) later commented: "I jumped at the opportunity. Bernie had in mind an instrument where the technical demands stretched significantly beyond the technology of the time."

Table 1: University of Sydney staff associated with Molonglo Observatory, 1960 to 1978.

Name	First University Appointment	Resigned or Retired	Comments
School of Physics			
Richard Twiss	1 July 1957	14 May 1963	Returned to UK
Colin Gum	1959	Killed 28 April 1960	skiing accident
Bernard Mills	11 July 1960	31 December 1985	Retired in Sydney
Arthur Watkinson	10 October 1960	22 December 1961	To Dwingeloo
reappointed	16 April 1964	16 August 1964	To Fleurs Observatory
reappointed	January 1967	?	Died 1997 May 12
Terry Butcher	6 February 1961	29 January 1965	Retired in Tasmania
Alec Little	13 April 1961	Died 20 March 1985	
Bruce McAdam	21 June 1961	21 September 1993	Research Associate
Alan Le Marne	5 February 1962	30 April 1972	Retired in Sydney
Jack Howes	1 February 1962	6 March 1976	Died
Grant Calhoun	2 May 1962	6 July 1979	Retired in Eungai Creek
Tony Turtle	6 February 1963	30 November 1998	Research Associate
Michael Large	12 February 1963	Died 4 March 2001	
Michael White	5 January 1964	31 August 2005	Retired in Bungendore
John Horne	22 February 1965	6 August 1993	Retired in Sydney
Hugh Murdoch	January 1951	August 1986	Retired in Sydney
David Crawford	January 1969	2004	Back from Cornell
John Durdin	1 July 1975	10 January 1986	Now in Tasmania
Electrical Engineering			
Wilbur Christiansen	21 April 1960	21 December 1978	Died 26 April 2007
Ron Aitchison	?	?	Died
Ian Lockhart	?	?	Died 2 May 1976
Bob Frater	5 June 1961	31 October 1980	Now in Sydney

Dudley Rannard, one of Mills' student colleagues, took leave from the NSW Government Public Works Department and lived at Molonglo as site engineer during the concrete and steel construction stages. Specialist surveying help came from Phil Jones, Lecturer in Civil Engineering, who did the local survey to define the cardinal directions of the Cross and later, in October 1963, checked the aperture of the EW steel frames. In December 1965, B.P. Cook of the Division of National Mapping fixed the location of the intersection of the arms and alignment on the Australian Geodetic Datum (Cook, 1965). The arms of the Cross have become a land mark for local pilots. They are true north and east within 4 arcseconds and are known to 0.3 arcseconds.

Figure 3: The beginning of the Cross. Terry Butcher and Alec Little with the prototype EW module at the old St. Leonards brick pit in Sydney. The prominent building in the background is part of the Royal North Shore Hospital.

2.2 The Cornell-Sydney University Astronomy Centre

Through the close friendship of Messel and Tommy Gold, the Radio Astronomy Centre was soon expanded to the Cornell-Sydney University Astronomy Center which shared expertise between Molonglo and the newly established Arecibo Observatory. Many Sydney students spent some years at Ithaca or Arecibo, including Ron Wand, Don Campbell, John Sutton, Tony Bray, Juris Ulrichs, Dave Jauncey, Michael Yerbury, Ian Johnston and David Crawford. Other staff made short visits on study leave: Raphael Littauer came to Sydney in 1963 and Hugh Murdoch visited Cornell in 1969.

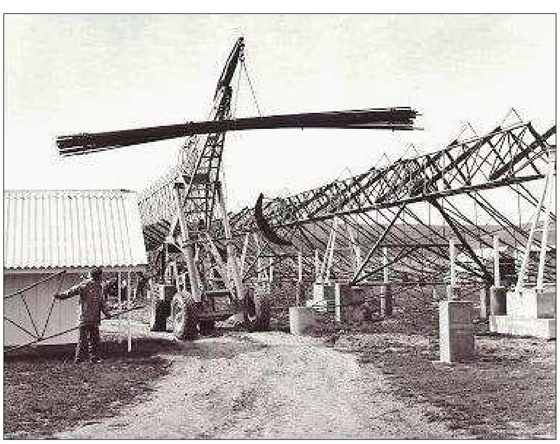

Figure 4: Erection of the East arm reaches the centre. The insulated phasing hut is on the left.

3 CONSTRUCTION OF THE MOLONGLO CROSS

The Cross was formed by two intersecting parabolic cylinders that were built with 29 foot modules. The east and west arms each had 88 modules and were separated by the continuous north-south arm with 177 modules. The foundations and steel parabolic frames were designed under the supervision of consulting engineers Macdonald Wagner and Priddle, with advice from Dudley Rannard and De Havilland engineers. Prototype modules with mesh and feeds were erected in a disused brickpit at St. Leonards for mechanical and RF testing (see Figure 3).

Contracts with Samsons (foundations and buildings) and Tubewrights (Australia) Ltd (steelwork) were signed in May 1962 and construction began at Molonglo at the end of 1962. The telescope foundations, control buildings and quarters were built while the steel frames were prefabricated in Sydney. Assembly at Molonglo was rapid (see Figure 4): the EW arms were completed first, and then the whole mile of fixed NS frames were erected in just three weeks, by mid 1963.

The design of the radio antenna feed systems for the two arms took much longer. The RF dipoles were supported along the line focus by aluminium frames. For the E and W arms, the frame for a module formed two waveguide cavities, each excited by eight dipoles. The two arms formed a meridian transit telescope with 2,816 in-phase dipoles exciting 352 waveguides. The contracts for these waveguides and dipoles were placed in March 1963 with De Havilland at Bankstown Airport where Mills knew a colleague from student days. Assembly and testing was relatively simple for the waveguide feeds along the EW arms and they began operating in May 1965 as a fan beam with a resolution of 4 degrees × 85 arcseconds. Astronomy had commenced at last.

The Molonglo Radio Observatory was formally opened by Prime Minister, Robert Menzies, on 19 November 1965 in the presence of the US Ambassador, NSF and Cornell representatives and many astronomers (Figure 5).

The RF design of the NS arm was much more complex. Technically the major problem was phasing the 4,248 dipoles along the mile arm. Each module had 24 dipole elements at the focus that required a different phase gradient for every declination observed. After some experimenting, the phase for each dipole was set by rotating a helical directional coupler within a parallel transmission line (Figure 6). The RF phase changed as the coupler was set to its appropriate angle by a chain of gears, different for each dipole in a module, and driven by a common 1 mile shaft (Mills et al, 1963). It was an ingenious but complicated scheme that worked reliably for eleven years.

A prototype NS feed arrived from De Havillands on 29 December 1964 and was hoisted to the roof of the Physics building where testing and final RF design took place over several months before factory production could begin. The first batch of feeds was delivered to Molonglo in August 1965. The dipoles, couplers and gears were then fitted and each feed was checked for mechanical and RF performance until it met Mills' stringent requirement that all dipoles had RF phases within 3 degrees (6 mm path) and gains equal within 0.6 dB. The assembly, testing and adjustment was a slow and meticulous task. After a batch of 10-15 feeds was ready all staff would join for a day to lift them into position along the NS arm. With experience, the production rate increased from one module in the first week to eighteen per week during the final month and the last of the 177 feeds was completed on 16 November 1966.

During this time the receivers, IF phasing, delay lines, display and recording systems were designed and built. All demanded innovative design using silicon transistors and the first simple integrated circuits that were only just coming available. Signals from the 177 NS modules were phased into a comb of eleven fan beams across a 15 arcmin zone of declination. When correlated with the EW transit fan beam they produced eleven overlapping pencil beams. In December 1970, two more EW early and late transit beams were added to give 33 simultaneous pencil beams.

Mills realised that the detailed analysis of the observations made by this complex system required a computer and hence a digital output system: "The principal output of the instrument will be punched paper tape for processing by an electronic computer." (Mills, 1962). The School of Physics had built and operated the SILLIAC computer since 1956. With a memory of 1,024 words, this was far too small for the Molonglo data but a larger KDF9 computer was about to be commissioned. KDF9 had adequate processing and memory, but its input was also only by punched card or paper tape. Astrophysics collaborated with Dr Sam Luxton in the Mechanical Engineering Department to design and build a system that recorded data at a field station on digital magnetic tapes. The slow data rate from the Molonglo Cross observing over 18 hours each day used the same protocols as the fast data rate from Luxton's low-turbulence wind tunnel with short experiments on heat exchange. The magnetic tapes were later transferred for replay to a KDF9 input buffer. This data transfer could take several days and Mills insisted that there must be an analogue display for monitoring the telescope during an observation. A facsimile chart recorder was designed that displayed the output of the fan beams and eleven pencil beams together with a contour plot of all sources within the declination zone while the transit observation was made (Large and McAdam, 1966).

'First light' for five pencil beams occurred in March 1967 and the full comb of eleven pencil beams was ready soon after. In August 1967 the Cross began routine observing with 2.8 arcminute resolution. The sensitivity was improved in 1969 by installing preamplifiers on the EW arms. There was a similar upgrade in 1976 in collaboration with CSIRO. For the second pulsar survey of the Galactic Plane, Andrew Lyne, on leave from Jodrell Bank, built low-noise RF amplifiers for each of the 352 waveguides along the EW arms. Table 2 shows the final performance specifications for both the Cross and its successor, the MOST.

4 OBSERVATIONS 1965 TO 1978

Up to the start of observations using the EW fan beam in May 1965, only four papers had been published by the group. The first paper using Molonglo data was a survey of nearby spiral galaxies (Mills and Glanfield, 1965). In the following three years twenty papers were written, mostly by the research students who had done much of the repetitive construction and were given priority in observing. Their targets were spiral galaxies, planetary nebulae and the Galactic Centre. Once the Cross was observing, its major task for eleven years was a 408 MHz survey of the southern sky from the South Celestial Pole to declination +18 degrees. The resulting catalogue of 12,141 sources was published by Large et al in 1981.

Figure 5: Alec Little at the control Desk on Opening Day, 19 November 1965.

Other papers gave source positions better than 2 arcsec and consequent optical identifications, describeed Galactic sources, mapped the Large and Small Magellanic Clouds, and reported many pulsar discoveries. The scientific output was an average of sixteen papers each year and the total reached 194 by 1978. Among these, Mills (1991, 2006) mentions two that had particular significance: David Wyllie used a standard dipole with the East and West arms to determine an absolute flux density scale at 408 MHz which was eventually adopted worldwide, while Peter Shaver (from Canada) and Miller Goss (from USA) did much to quell the rivalry between the Molonglo and CSIRO radio astronomers as they jointly observed radio emission from Galactic HII regions using data with comparable resolution from both Cross (408 MHz) and Parkes (5006 MHz). Brian Robinson (2002) comments on the origin and resolution of this rivalry:

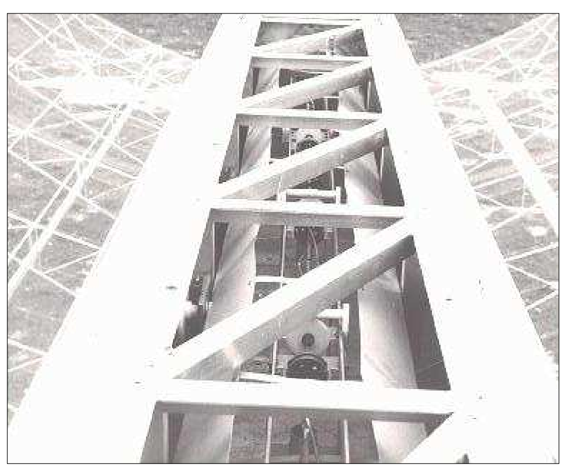

Figure 6: The top view of N88 feed showing worm gears and directional couplers.

Table 2: Specifications and Final Performance of the Cross and MOST

Feature	Cross	MOST
Centre Frequency (MHz)	408	843
Effective Bandwidth (MHz)	2.5	3
Time resolution (microsec)	0.5	0.5
Declination Coverage (°)	+18.5 to –90	+18.5 to –90
for full HA Synthesis	----	–30 to –90
Meridian Angle Swing (°)	0 (transit)	60
Field size for full synthesis	----	23' × 23' cosec dec
Time shared	----	160' × 160' cosec dec
Synthesized Beam	2.8' x 2.8'sec Z	43" × 43"cosec dec
System Temperature (K)	120	110
System noise (12 hr, mJy)	16	0.2

Table 3: Molonglo Research Students and their Topics, 1960 to 1978

Student Name	Submitted	Thesis Title
John Sutton	1962*	Aerial Performance and Information Theory in Radio Astronomy.
Ross Glanfield	1962*	Observational Properties of Relativistic World Models at Radio Wavelengths.
John Rome May	1964*	Galactic structure deduced from radio measurements.
Donald Campbell	September 1964*	Data Reduction in Radio Astronomy.
Kent Price	January 1966*	Strip Scanning of Seven Radio Sources with a 1.6'arc Interferometer.
John Sutton	November 1966	The determination of the positions of radio sources.
Michael Kesteven	January 1968	Radio Observations of Some Supernova Remnants.
David Wyllie	September 1968	An Absolute Flux Density Scale at 408 MHz.
Alan le Marne	1969 #	
Philip Harris	January 1969*	Number-Flux Density Relationship for Radio Sources.
Peter Shaver	1970	Radio Emission from Galactic HII Regions.
Malcolm Cameron	September 1970	Radio Observations of Bright Galaxies.
Trevor Clarke	August 1971	The Measurement of the Angular Sizes of Radio Sources by Model Fitting.
Robert Munro	August 1971	Identifications of Radio Sources from the Fourth Cambridge Catalogue.
Richard Hunstead	May 1972	Studies of Selected Radio Sources.
Anne Green	September 1972	Spiral Structure of the Galaxy from a Radio Continuum Survey.
Richard Schilizzi	November 1972	Structures of Extragalactic Radio Sources.
Ian Davies	1973 #	
Alan Vaughan	May 1974	Pulsar Observations at Molonglo.
James Clarke	May 1974	A High Resolution Survey of the Magellanic Clouds at 408 MHz.
Robert Milne	January 1976	Interplanetary Scintillation at 408 MHz.
Michael Batty	February 1976	Low Frequency Recombination Lines.
Gordon Robertson	December 1976	Radio Source Surveys at 408 MHz.
Graeme White	February 1977*	Optical and Radio Studies of a Molonglo Deep Survey.
David Hoskins	1977 #	
Andrew G Wilson	April 1977*	Absolute Flux Density Measurements at 111 MHz.

Key: * = M.Sc. thesis
= Did not complete

In 1958-1960 there was much strife at Radiophysics, arising from Bowen's support of the Culgoora Solar Observatory as a second project after the Parkes dish. Chris Christiansen resigned and went to the Chair of Electrical Engineering at Sydney University, then Bernie Mills went to the Chair of Astrophysics set up by Harry Messel. A right royal battle then raged between Bowen and Messel. Animosity existed until the combined Parkes-Molonglo observations of Peter Shaver and Miller Goss. Then later came the Molonglo-Parkes observations of pulsars by Michael Large and Dick Manchester. I was Leader of the Astrophysics Group at Radiophysics over that period, and worked very hard to convince Bernie Mills that he could trust us to work with Molonglo on those two projects.

From the start of the Astrophysics Department in 1960 until 1978, the range of projects observed by the fan beam and the Cross are shown in Table 3 which lists the research students and their thesis topics completed in this period. The cut-off is chosen because on 24 August 1978 at 10am the Cross was switched off and we prepared to lift feed modules down for conversion from 408 to 843 MHz (Figure 7).

5 AFTER THE CROSS

5.1 The Molonglo Observatory Synthesis Telescope (MOST)

By the early 1970s, digital computers had both the speed and reliability to take real-time control of a radio telescope. Mills realised that if a fan beam tracked a field for twelve hours, the rotation of the Earth would move the beam through 180° on the sky and allow the synthesis of a pencil beam (Mills et al, 1976). He designed a synthesis telescope for 1,420 MHz, and Alec Little had developed a prototype feed for the EW modules when they learned that CSIRO was planning the Australian (later The Australia) Telescope for this and higher frequencies. Mills then chose a new frequency of 843 MHz which is not a protected radio astronomy band but, with cooperation from the Australian Post Office, has been kept reasonably free of interference by nearby radio phone links.

The conversion of the Cross to the MOST reused the East and West arms and gave a powerful new telescope at very low cost. The NS arm was abandoned. All the concrete, steel and mesh of the EW arm had been designed with possible use at 1,420 MHz in mind and needed no change except for the addition of a slow tilt drive. A new mile of RF focus at 843 MHz reused the waveguides from the Cross, but replaced dipoles with 7,744 ring elements that were phased by computer to track a field for twelve hours. The conversion of the feeds and construction of new receivers, digital delays and correlators to produce 128 contiguous fan beams took three years to complete (Robertson, 1991).

The first synthesis map of source 1836-631 was made on 15 July 1981 with 43 arcsec resolution over a 23 arcmin field. Switching beams across three adjacent centres increased the field to 70 arcmin and detailed images of known sources up to one degree in size were observed for a decade. In 1991, development of precise digital phase units (Amy and Large, 1992) gave computer control of phase for all 176 modules, thus removing grating lobes and giving a great improvement in dynamic range over the 70 arcmin field. A further installation of phase control to the separate waveguides within each module in 1996 increased MOST's field of view to 2.7° (and the current observing parameters for MOST are given in Table 2). With the large field of view, it became feasible to undertake an 843 MHz survey of all of the southern sky (from declination –30° to –90°). The Sydney University Molonglo Sky Survey (SUMSS) was began in 1998 and is now (August 2007) effectively finished. A second project has mapped the southern sweep of the Galactic Plane through the Galactic Centre.

5.2 The Square Kilometer Array and SKAMP

Evolution of the Molonglo Telescope is continuing. Like many of the world's radio observatories, MOST staff are testing concepts and systems for the future Square Kilometer Array in a project called the SKA Molonglo Prototype (Square Kilometer Array). They have developed wide-band feeds for the cylindrical reflector as well as new correlators and agile control elements. First fringes from modules of the new system were produced on 5 May 2004 but the full SKAMP has to wait for the MOST surveys to finish. MOST has a 10 hectare collecting area, wide field of view and complete uv-coverage out to its maximum 1 mile spacing. We expect its successor, the third Molonglo telescope, covering frequencies 300 to 1,420 MHz will explore hydrogen in the high red-shifted Universe.

6 NOTES

1. This extensive source survey "… had profound cosmological implications in terms of the competing 'Big Bang' and 'Steady State' theories which were prevalent at the time and led to the notorious 'Fleurs-2C Controversy …" (Orchiston and Slee, 2005: 152). For details of the 'Controversy', which soured relations between Australian and Cambridge radio astronomers for many years, see Mills (1984) and Sullivan (1990).
2. R.N. Bracewell went to Stanford and Frank Kerr to Maryland. In 1961 J.L. Pawsey was offered the first Directorship of the National Radio Astronomy Observatory in USA, but tragically, died on 30 November 1962 before he could take up the position. J.H. Piddington moved to the CSIRO Division of Physics. K. Westfold went to the University of Sydney and later became the Dean of Science at Monash University in Melbourne. J.V. Hindman went to the ANU's Siding Spring Observatory. W.N. Christiansen went to the University of Sydney on 21 April 1960, succeeding Professor D. Myers in the Peter Nicol Russell Chair of Electrical Engineering (*Nature*, 188, 784, 1960). He was soon joined by R.F. Mullaly and A. Watkinson.

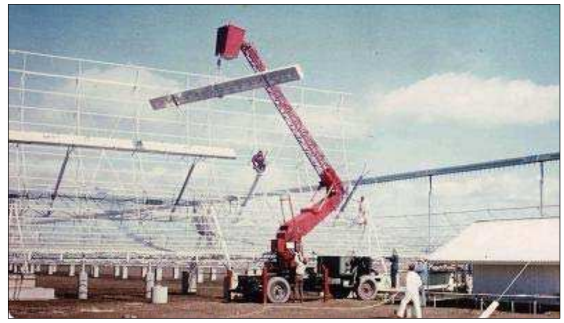

Figure 7: Closing the Cross. The East 1 feed is lifted off the telescope near midday on 24 August 1978.

7 ACKNOWLEDGEMENTS

I thank many colleagues for discussions about Molonglo history, especially Terry Butcher, Bob Frater, Richard Hunstead and Bernard Mills for details of the 1960s decade and Wayne Orchiston for references to early CSIRO research. The late Brian Robinson provided reminiscences of Cambridge and CSIRO. I thank Nyree Morrison, Reference Archivist, for details of University staff appointments, and Woody Sullivan (University of Washington) for providing Figure 1. I appreciate my access to the Physics archives, now held at Molonglo, as well as log sheets and notebooks used by Alec Little and Michael Large. Above all, I am grateful for my experience of stimulating research over 45 years with Molonglo colleagues.

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