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Ronald N. Bracewell: an appreciation

A. Richard Thompson* and Robert H. Frater**

*National Radio Astronomy Observatory, Charlottesville, VA, USA
**Resmed Ltd, Elizabeth Macarthur Drive, Bella Vista, NSW, Australia

Email: athompso@nrao.edu
Email: BobF@resmed.com.au

Abstract

Ronald Newbold Bracewell (1921–2007) made fundamental contributions to the development of radio astronomy in the areas of interferometry, signal processing, and imaging, and also to tomography, various areas of data analysis, and the understanding of Fourier transforms. He was born in Sydney, Australia, and received a B.Sc. degree in mathematics and physics, and B.E. and M.E. degrees in electrical engineering from the University of Sydney, and his Ph.D. from the University of Cambridge, U.K., for research on the ionosphere. In 1949 he joined the Radiophysics Laboratory of CSIRO, where he became interested in radio astronomy. In 1955 he moved to Stanford University, California, where he became Lewis M. Terman Professor of Electrical Engineering. He retired from teaching in 1991, but continued to be active in radio astronomy and other applications of imaging techniques, etc. During his career he published ten books and more than 250 papers. Honors that he received include the Duddell Premium of the Institute of Electrical Engineers, London, the Hertz Medal of the IEEE, and the Order of Australia. For his work on imaging in tomography he was elected to Associate Membership of the Institute of Medicine of the U.S. National Academy of Sciences.

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Education and Early Years

Bracewell attended the Sydney Boys High School 1933–1937. In addition to science and mathematics he was interested in languages and passed oral exams in French and German. In 1937, he was awarded the Alliance Française Prize and came third in the state in French. After high school, he was a student at the University of Sydney and in 1941 graduated with a degree in physics and mathematics, and in 1943 with a degree in Electrical Engineering with First Class Honours. He also received an M.E. degree in 1948 for his work at CSIRO. He spoke of the influence of Oxford-trained Victor A. Bailey in his approach to physics and of Joseph L. Pawsey, a student of Cambridge Professor John A. Ratcliffe, in the duality of his physical versus mathematical approach to transmission lines and antennas.

In 1943–1945, during WWII, he was a member of the Radiophysics Laboratory of the CSIR (from 1949, CSIRO, Commonwealth Scientific and Industrial Research Organization), in Sydney, and worked with Pawsey and Edward G. ('Taffy') Bowen on development of radar and radio communications. In 1946, after the War, Bracewell went to Sidney Sussex College at Cambridge (England) as Ratcliffe's graduate student. His research topic was the study of the ionosphere using propagation measurements at 16 kHz, for which he obtained his Ph.D. The ionospheric work resulted in the discovery that the D layer ionization consists of two components, for which he was awarded the Duddell Premium of the Institute of Electrical Engineers in 1952. The effect of solar activity on the ionosphere was one of the factors that led to Bracewell's lifelong interest in the Sun. His interest in the theory and applications of Fourier transforms, which was initiated by mathematics courses at Sydney University, was further stimulated by Ratcliffe who was a recognized authority on the subject.

Introduction to Radio Astronomy

In 1949 Bracewell returned to Australia and again took up a position at CSIRO. Initially, he continued his work on the ionosphere, but soon became involved in radio astronomy which was being actively pursued. He shared an office with radio astronomers W. N. ('Chris') Christiansen and Harry Minnett, who were working on solar radio observations (see Orchiston, Slee and Burman, 2006). Christiansen had built grating arrays of parabolic antennas, aligned in N-S and E-W directions, along the edges of a reservoir at Potts Hill near Sydney (see Wendt et al., 2008). These produced fan-beam scans of the Sun over a range of angles each day. From these it was possible to derive radio brightness contours of the Sun in two dimensions (see Christiansen and Warburton, 1955a; 1955b). Bracewell was interested in this analysis, which involved Fourier transforms. He was also intrigued by the possibility of using two grating arrays to produce a matrix of pencil beams, using the cross configuration developed by Bernie Mills for linear arrays (see Mills and Little, 1953). During this time Pawsey, the leader of the radio astronomy group, invited Bracewell to be co-author of the book *Radio Astronomy* (Pawsey and Bracewell, 1955), and Bracewell later surmised that this was partly a device to get him more involved in the subject. Pawsey also asked him to produce a pictorial dictionary of Fourier transforms, which later led to Bracewell's most important book, *The Fourier Transform and its Applications* (Bracewell, 1965).

During the academic year 1954–1955, Bracewell was invited by Otto Struve to give a series of lectures on radio astronomy at the University of California, Berkeley. He also lectured at Stanford University, which led to his joining the Electrical Engineering Department at Stanford in December 1955. An interesting autobiographical account of the period from his first interest in radio astronomy through the early years at Stanford can be found in his paper, "Early work on imaging theory in radio astronomy", published in Sullivan's *The Early Years of Radio Astronomy* (1984), while his recollections of the Stanford years can be found in Bracewell (2005).

Important Early Papers and a Book

During the period 1949–1965, from his first interest in radio astronomy through his early years at Stanford, Bracewell produced a number of publications on interferometer theory, imaging with interferometers and arrays, and data analysis that established his expertise in this area. Examples of notable publications are discussed below.

"Aerial Smoothing in Radio Astronomy" (Bracewell and Roberts, 1954)

This paper was particularly important in the early years of radio astronomy, when the relation between the true profile of a source and the profile obtained by scanning with an antenna was not well understood. Bracewell and James A. (Jim) Roberts explained the scanning as a convolution of the brightness function and the point-source response of the antenna. The convolution theorem of Fourier transforms shows that the Fourier components of the source profile are filtered by the Fourier spectrum of the antenna response. The concept of invisible distributions (i.e. Fourier components not detectable with a given aperture distribution) was introduced in this paper. This provided essential insights into the observing process. The later part of the paper is concerned with reducing the effect of aerial smoothing by analytically adjusting the antenna response so that all of the Fourier spatial components to which it responds are given equal weight. Bracewell referred to this process as *restoration* and the resulting profile as the *principal response*. The angular resolution is usually improved by the restoration process, but the sharp cutoff in angular frequency at the maximum to which the antenna system responds can result in extensive sidelobes which limit the dynamic range.

"Strip Integration in Radio Astronomy" (Bracewell, 1956)

This paper considered the construction of two-dimensional images from one-dimensional scans of a source with a range of position angles as was required, for example, to obtain a solar map from Christiansen's early grating-array observations. The Fourier transform relationships involved are succinctly illustrated in a diagram (Figure 5 in his paper) which Bracewell later refers to in his chapter in Sullivan's 1984 book as the 'projection-slice theorem'. He used the term *reconstruction* to describe this method of production of two-dimensional images, a technique which was later adapted to tomography. Further development can be found in "Inversion of fan beam scans in radio astronomy" (Bracewell and Riddle, 1967).

"Radio Interferometry of Discrete Sources" (Bracewell, 1958)

This paper provides a precise development of the interferometer response and the Fourier transform relationship between the fringe visibility and the brightness distribution. The paper also unifies material discussed in earlier publications by various authors. Bracewell introduces the use of direction cosines for the angular coordinates on the sky, thereby avoiding the small-angle approximation used in most of the earlier discussions of interferometry. This paper also uses the sampling theorem of Fourier transforms to determine the most efficient choice of the spacings of antennas in interferometry.

"Tolerance Theory of Large Antennas" (Bracewell, 1961)

This paper precedes by several years the famous paper on the same subject by J. Ruze (1966). It is difficult to be sure about precedence of ideas on this subject, which was developing during the 1950s. Bracewell's paper is one of the earliest detailed analyses.

***The Fourier Transform and its Applications* (Bracewell, 1965)**

The end of this period saw the publication of Bracewell's most important book, *The Fourier Transform and its Applications*. This book cemented the early 'physical versus mathematical' learnings from Pawsey, and the period with Ratcliffe, in a book that became the Fourier transform 'bible' for many in the radio astronomy scene.[1] Through it, Bracewell established a level of recognition for his elucidation of the convolution theorem and its importance in the interpretation of observations. He developed a reputation for his demanding exactitude from those who worked in his space.

Stanford and the Heliopolis Observatory

At Stanford, Bracewell established a Radio Astronomy Institute and also an observatory, which he named Heliopolis. This was located on the outskirts of the Stanford lands. The first instrument developed at Heliopolis was a solar cross, i.e. a crossed-grating array for solar observations, as he had considered earlier while at CSIRO. This array was made to Bracewell's design, and consisted of 32 parabolic antennas arranged in two linear arrays and operated at 9.1 cm wavelength. It is described by Bracewell and Swarup (1961). Phase adjustment of the cross led to the invention of the round-trip phase measurement technique by Bracewell's graduate student Govind Swarup,which is described by Swarup and Yang (1961). An adaptation of this round-trip technique has subsequently been used in almost all large radio astronomy arrays. The solar cross was used to make daily maps of the Sun, with an angular resolution of 3.2 arcmin from June 1962 to August 1973.[2] These were published monthly, and the observations also resulted in a number of papers on radio emission from the solar corona. Two additional antennas were added to extend the east-west arm of the cross to form a compound interferometer. This produced fan beams of width 52 arcsec, and east-west scans of several strong radio sources were obtained with this angular resolution (Swarup, Thompson, and Bracewell, 1963; Thompson and Krishnan, 1965).

The east-west arm[3] of the cross array was also used to study the radio source Centaurus A, a radio galaxy that was strong, optically identified, and of sufficient angular width that the beam of the arm could reveal interesting structural detail. The two components of the central part of the source were detected (Little, Cudaback, and Bracewell, 1964). In April 1962, during a trip to Australia, Bracewell had the opportunity to observe Centaurus A with the Parkes Radio Telescope at 10 cm. He was able to resolve the two components in the central part by driving the telescope in both azimuth and elevation simultaneously, so as to scan in the direction of the component separation. He was also able to rotate the feed and discover the linear polarization. However, there appeared to be some question of whether the observation was made during an officially-granted observing time, and Bracewell's letter

[1] Petrosian (2009) recounts that "before an observing run at Kitt Peak, I needed to refer to this book. I looked for it in the shelves of the library at the National Optical Astronomical Observatory in Tucson, Arizona, but could not find it. The librarian informed me that the book had been signed out. I told her that this [was] a very useful book, and they should have more than one copy. She agreed and said that there were indeed eleven copies; all were in use by the resident astronomers."

[2] Petrosian (2009) remarks that this "provided daily maps of the Sun for more than a decade encompassing more than one solar activity cycle of eleven years. These maps were useful in predicting magnetic storms caused by solar activity and were used by NASA during the first landing on the Moon."

[3] The maximum elevation of Centaurus A was too low for useful resolution with the north-south arm. For observations of Centaurus A, a parametric amplifier developed by A.G. Little (1961) was used to improve the sensitivity. Alec Little obtained an M.S. degree from Stanford for his amplifier work.

to *Nature* (Bracewell, Cooper, and Cousins, 1962) was not published until 29 September 1962. Meanwhile, other observations made shortly after Bracewell's, also reporting polarization of Centaurus A, appeared in print a few weeks before Bracewell's letter. More detailed accounts of these circumstances can be found in Bracewell (2002) and Haynes et al. (1996).

At Heliopolis, there were also two 30-ft diameter equatorially-mounted parabolic antennas, and during the 1960s these were used as a two-element interferometer at 9.8 cm (~3.1 GHz). They could be moved between several foundations to vary the length and direction of the baseline. The interferometer provided material for several of the Ph.D. theses listed in Section 8, but the collecting area was too small for observation of more than a few of the strongest galactic and extragalactic sources. Bracewell considered building an instrument with a much larger collecting area, using several long cylindrical reflectors. He envisaged an instrument that would grow with time, by the addition of more elements as funding allowed (Bracewell, Swarup, and Seeger, 1962). However, funds for a large instrument proved to be unavailable, and the development of Earth-rotation synthesis by Martin Ryle showed the advantage of fully steerable antennas. Thus, Bracewell concluded that the most economical way to obtain sensitivity would be by building an array of tracking antennas which could be designed and constructed under his direction. This resulted in five 18.3-m (60-ft) diameter antennas, which were made to Bracewell's design and constructed on-site at Heliopolis. The antennas were configured as an east-west, minimum-redundancy, linear array devised by Bracewell (1966), in which all spacings up to nine times the unit spacing are included. The operating frequency was 10.7 GHz, allowing synthesis of a beam of width 18.8". A well-illustrated description of the construction project is given in Bracewell et al. (1971) and full details of the array in Bracewell et al. (1973). Observations with the array provided data for a number of papers and theses by Bracewell's students, including further work on Centaurus A (Price and Stull, 1973). This array was in operation from 1972 until the closing of the Heliopolis observatory in 1979.

The discovery in 1964 of the cosmic background radiation (CMB) by Arno Penzias and Robert Wilson (see Penzias and Wilson, 1965) provided a radio astronomical feature that could be investigated without the use of large antennas. Bracewell realized that although the measurements made in the early years after the discovery indicated a uniform brightness temperature, the motion of the Earth with respect to the CMB would cause an observable variation, which he and his graduate student E.K. Conklin were able to calculate (Bracewell and Conklin, 1968). From observations at Heliopolis, only upper limits on the variation could be obtained. To reduce atmospheric absorption, the project was moved to a high-elevation site in the White Mountains of California, using two small horn antennas at a frequency of 8 GHz. Conklin (1969) was then able to publish a determination of the velocity of the Earth from measurements of variation of the observed CMB temperature at the mK level. This was the first detection of the effect, and a notable achievement considering that it was made with a simple system using two small horn antennas with an uncooled receiver.

In the late 1960s, Bracewell's work on reconstruction of images from one-dimensional scans became recognized as having an important application in medical imaging by X-ray tomography. As mentioned above, the theory of reconstruction of a two-dimensional image from one-dimensional scans had been explained by Bracewell (1956). The implementation was further advanced in the paper with graduate student A.C. Riddle on "Inversion of fan-beam scans in radio astronomy" (Bracewell and Riddle, 1967). In this later paper, the procedure is simplified by the avoidance of the need to compute Fourier transforms. Bracewell wrote two further papers specifically on tomography, one with graduate student J. Verley (Verley and Bracewell, 1979). He also devoted a chapter on tomography in his book *Two-Dimensional Imaging* (Bracewell, 1995). For his contribution to tomography, Bracewell was awarded associate membership of the Institute of Medicine of the U.S. National Academy of Sciences in 1962, the first Australian to achieve this distinction.

Work at Stanford after Heliopolis

Funding for the operation of Heliopolis was discontinued in 1979, as a result of the general policy of supporting a single national observatory for radio astronomy rather than a number of smaller ones operated by individual universities. Thus, radio astronomical observations at Stanford were discontinued, but Bracewell's interest in radio astronomy and related sciences continued unabated. In Bracewell (1978) he suggested the use of interferometry in space for detection of non-solar planets, and this idea and further details are discussed in several later papers.[4] These describe a proposed application of infrared interferometry using space vehicles, in which a null in the fringe pattern is steered onto the position of a star to allow a search for much fainter images of planets. The idea has been widely discussed as a possibility for terrestrial telescopes or a future space mission (see, e.g., Hinz et al., 1998).

Starting in 1983, Bracewell published 13 papers (e.g. Bracewell 1984b) and a book (Bracewell 1986) on mathematical development of the transform introduced by Hartley, which is similar to the Fourier transform but does not involve complex factors. He developed Hartley versions of the numerous theorems and relationships that are well known in Fourier transform theory, and also a fast Hartley transform (FHT) algorithm, which could in many cases be used as an alternative to the fast Fourier transform (FFT). The avoidance of complex quantities for transformation of real data in the FHT allowed it to perform twice as fast as the versions of the FFT in use at the time, but later improvements to the FFT overcame its disadvantage in speed.

During the period 1985–1989 Bracewell published a number of papers on sunspot statistics and the solar cycle. In a much earlier paper (Bracewell, 1953) he had pointed out that since the magnetic polarization of sunspots changes sign in alternate 11-year sunspot cycles, the sign of the sunspot number should be reversed in alternate 11-year cycles, revealing a 22-year periodicity. This applies to studies in which the

[4] On May 16, 1978, Bracewell gave the Pollock Memorial Lecture at the Royal Society of NSW, outlining his ideas for detecting life in outer space (Bracewell 1979).

sunspot number is used as a measure of the active nature of the Sun. Without this sign reversal, the oscillations of the 22-year sunspot function are effectively rectified, and artificial frequency components can be introduced. This important derectification step was included in Bracewell's later work in the 1980s. Examination of the sunspot numbers when plotted with the derectified 22-year cycle led him to the discovery of a three-halves power-law in the annual mean values, which he considered to be one of the more important results of his analysis (Bracewell, 1988a). He was interested in the basic mechanism of the sunspot cycle, and in Bracewell (1989) discussed a possible theory in which magneto-mechanical waves propagate outward from a source at the center of the Sun.

Another sunspot-number feature that Bracewell investigated involved a possible relationship with a series of geological laminae from the late Precambrian era, located in the Elatina area of South Australia, and hypothetically identified as varves (Bracewell, 1988b).[5] These had been studied by a geologist (Williams, 1985) who suggested that periodic variations in the thickness of the layers could be interpreted as indicating a time scale similar to that of the sunspot numbers. A putative mechanism linking the structure to solar radiation involved flow of melt-water and resulting variations in water levels on depositions in a lake. Thus, hypothetically, the thickness of the layers could provide an indication of the variation in the strength of solar radiation from year to year. However, a similar layered structure was later found in a different region of South Australia (Sonett et al., 1988) in which the geological situation suggested a luni-solar tidal mechanism rather than a solar radiation mechanism. The tidal mechanism was also found to be applicable to the Elatina laminae, and the solar cycle interpretation of the Elatina data has been largely abandoned.

Bracewell as a Teacher and Mentor

Bracewell always presented his lectures with an infectious enthusiasm. He was a challenging taskmaster for his graduate students. Bracewell had a good eye for, and an appreciation of, capable people and delighted in being able to stretch their capabilities. He was a great mentor and always demanded clear and detailed thinking when approaching any problem. He insisted upon precise definitions and disliked making changes in them. Thus, in his papers on interferometry he preferred to follow Michelson's original definition of fringe visibility, in which the zero-spacing value is normalized to unity, rather than expressing it in units of flux density as has become the common practice. He never fully approved of the use of image processing routines that introduced Fourier components of the brightness that had not been measured in the observations. His careful understanding of basic concepts and detailed thinking enabled him to make contributions in many fields, and influenced the lives of students and colleagues who worked with him.

When examining students, Bracewell liked to try to judge their ingenuity and power of observation as an indication of aptitude for experimental research. During

[5] The Elatina layers were measured in detail from core samples. In terms of the solar cycle interpretation they covered a range of more than 1,300 years and thus might have provided a major chronological increase in solar-cycle data. Note that the term "varves" applies specifically to layers deposited in annual cycles.

annual interviews with prospective Ph.D. students in the Department of Electrical Engineering, he often tested their reaction to unusual things that they had not seen before.[6] One year he asked each student to examine a piece of wood that he had made. This was approximately boat-shaped and had the property that when set spinning in either a clockwise or counter-clockwise direction, it ended turning in the clockwise direction.[7] He wanted to see a careful inspection of the object, and tests of how it behaved under various conditions, rather than an attempt at a mathematical exposition. In another year he asked the students to examine a sample piece of the circular waveguide used for signal transmission in the VLA, without telling them what it was. A careful visual examination of this would show that the surface impedance of the inner wall was very low in the circumferential direction, but much higher in the longitudinal direction, which could provide a clue as to its use.

Bracewell retired from teaching in 1991, but continued to work in his areas of interest. His list of publications from these later years contains 22 papers and 12 book reviews. In 1994 he was awarded the Heinrich Hertz Medal of the IEEE for pioneering work in antenna aperture synthesis and image reconstruction as applied to radio astronomy and to computer-assisted tomography. In 1998 he was named Officer of the Order of Australia for his service to science in the fields of radio astronomy and image reconstruction.

[6] For a list of his graduate students and their affiliations, see Section 8 of Thompson and Frater, 2010.

[7] The "rattleback" phenomenon (see, e.g., Walker, 1979). The examination in which the device was used was in 1977.

Breadth of Expertise and Interest

Bracewell's mathematical expertise is evident from much of his work, especially his books on the Fourier and Hartley transforms. He also had an excellent understanding of physics as is evident in publications such as "Rotation of artificial earth satellites" (Bracewell and Garriot, 1958) and "An observer moving in the 3° K radiation field" (Bracewell and Conklin, 1968). In Mihovilovic and Bracewell (1991) he and his student introduced the concept of chirplets as a representation for ionospheric whistler signals and similar data in a time-frequency domain. Practical engineering skills can be seen in Bracewell's designs of both the solar cross and the five-element array. In the latter, the detailed antenna design was his conception, and enabled the array to be implemented at relatively low cost. He enjoyed being involved at a hands-on level in engineering projects. An example of his understanding of fundamental theory in engineering is the paper on "Impulses concealed by singularities: transmission-line theory" (Bracewell, 1998).

The remarkably wide range of Bracewell's scientific interests can be clearly seen in the diversity of the subjects of his publications and lectures. Throughout his career he had a long-term interest in the possibility of the existence of extraterrestrial intelligence, and the practicality of extraterrestrial communication. This resulted in 19 papers and the book The *Galactic Club* (Bracewell, 1974). An example of his interest in the history of science and engineering can be seen in the paper "Planetary influences on electrical engineering" (Bracewell, 1992). He designed sundials, one of which was installed at the Terman Building on the Stanford campus. Bracewell had a life-long interest in trees, particularly those native to Australia, and in California he identified more than seventy species of the introduced eucalypts. He wrote two books on trees of the Stanford area (see Bracewell, 2005) and had some fine examples of banksias growing in the garden of his house at Stanford.

Further Information

Some of Bracewell's own descriptions of his work can be found in his chapter in Sullivan (1984), Bracewell (2005), and the text of a recorded interview by Ragbir Bhathal FRSN on 10 June 2000, for the Oral History Section of the National Library of Australia.[8] Bracewell's scientific papers are archived at the National Radio Astronomy Observatory, Charlottesville, VA. A complete list of his publications can be found at http://www.nrao.edu/archives/Bracewell/bracewell_top.shtml. This list includes 10 books, 218 articles in the open literature, 33 book reviews, and 34 internal reports.

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[8] See Bracewell and Bhathal (2019).

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