Annu. Rev. Astron. Astrophys. 2001. 39:457–509

THE DEVELOPMENT OF HIGH-RESOLUTION IMAGING IN RADIO ASTRONOMY*

K. I. Kellermann
National Radio Astronomy Observatory, Charlottesville, Virginia 22903;
e-mail: kkellerm@nrao.edu

J. M. Moran
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138;
e-mail: moran@cfa.harvard.edu

Key Words aperture synthesis, image processing, interferometry, radio imaging, VLBI

■ **Abstract** Since the first radio astronomy observations in the 1930s, the angular resolution of radio telescopes has improved from tens of degrees to better than one thousandth of a second of arc. This advancement has been the result of technological innovations such as stable, sensitive, short-wavelength radio receivers, digital correlators, atomic clocks, and high-speed tape recorders, as well as the development of sophisticated image processing algorithms implemented on inexpensive, fast, digital computers.

1. INTRODUCTION

When Karl Jansky (1933) made his pioneering observations of cosmic radio emission at 15 m wavelength (20.5 MHz), he used a simple Bruce-type antenna array (Oswald 1930) about 30 m, or two wavelengths, in extent. The angular resolution was only about 30°, primitive by modern standards. Like all diffraction-limited astronomical instruments, the resolution of radio telescopes depends on the size of the instrument in wavelengths. Because radio waves are some 10^3 to 10^7 times longer than light waves, for many years it was thought that the resolution of radio telescopes would always be poorer than that of optical telescopes. This has turned out not to be true, and high-resolution techniques have developed much more rapidly at radio than at optical wavelengths. This is primarily due to the atmosphere and the long wavelengths used by radio astronomers. At optical wavelengths the natural seeing is due to temperature and density fluctuations in the dry air, whereas

---

*The US Government has the right to retain a nonexclusive, royalty-free license in and to any copyright covering this paper.

at radio wavelengths it is due mostly to fluctuations in water vapor along the line of sight.

By coincidence, the natural seeing is roughly 1 arcsec at good sites for both optical and radio observations. However, at optical wavelengths ($\sim$0.5 μm) the distance along the incident wavefront over which the phase structure function (the variance of the difference of the phases at two points along the wavefront) equals 1 radian^2, is about 3 cm, whereas at radio wavelengths ($\sim$1 cm) it is about 600 m. For a typical wind speed of 10 m/s, the time scales of the resulting fluctuations are about 3 ms and 60 s at optical and radio wavelengths, respectively. Hence, at radio wavelengths the time scales are more convenient for implementing data processing algorithms. In addition, the longer wavelength used by radio astronomers greatly reduces the mechanical tolerances on antennas and other equipment. The result has been the development at radio wavelengths of larger and larger instruments that have achieved diffraction-limited imaging capability better than 0.001 arcsec.

In this review we concentrate on the historical development of high-resolution radio imaging. More-detailed technical accounts are given in earlier articles in this series by Christiansen (1963) on the construction of large steerable dishes, by Swenson (1969) and Bracewell (1979a) on the principles of aperture synthesis, by Cohen (1969) on the techniques of high-resolution imaging, and by Pearson & Readhead (1984) on techniques of image restoration based on phase closure and self-calibration. Personal accounts of some of the events described here are given by Bolton (1982, 1990), Hanbury Brown (1983, 1991), Broten (1988), Kellermann & Cohen (1988), Kellermann (1992), Heeschen (1981, 1991), Hey (1973), Moran (1998a), and Cohen (2000) and in the collections edited by Kellermann & Sheets (1983) and Sullivan (1984). An excellent historical account of the development of high-resolution radio astronomy techniques in Australia can be found in Haynes et al. (1996). We have drawn on all of these works as well as others in preparing this review.

Although Jansky's discovery of extraterrestrial radio emission created some immediate interest (e.g., Whipple & Greenstein 1939), the limited angular resolution then possible discouraged any serious follow-up observations. Grote Reber (1958) recognized that he could gain improved resolution over Jansky's pioneering observations by working at shorter wavelengths. Using a homemade 31-ft wood-frame, chicken-wire surface parabolic dish at 160 MHz (1.9 m), Reber (1944) was able to map the distribution of Galactic radio emission with a resolution of about 12° (see Sullivan 1984, p. 43), considerably better than that achieved by Jansky. Reber was able to show not only that the radio emission was concentrated along the plane of the Milky Way, but close inspection of his map shows the first evidence of the discrete radio source we now associate with the supernova remnant Cassiopeia A. Reber's later map at 62 cm (480 MHz) with improved resolution of about 3° showed, for the first time, the strong radio galaxy Cygnus A (Reber 1948).

From the earliest postwar years, radio astronomers have used interferometry to improve the angular resolution over what could be obtained with more conventional filled-aperture instruments. However, at first, although the simple two- and three-element interferometers gave greatly increased angular resolution, they were used to determine only the angular sizes of a few strong radio sources. Full imaging had to await the development of earth-rotation or aperture-synthesis techniques. Similarly, the development of Very Long Baseline Interferometry (VLBI) in the 1960s led to a large improvement in resolution, but it was the use of self-calibration techniques developed a decade later that made possible the construction of radio images with milliarcsecond resolution (Figure 1). All along the way, filled-aperture radio telescopes have played an important role owing to their versatility and sensitivity to low surface brightness emission, which are completely resolved by interferometer systems.

1.1. Filled-Aperture Radio Telescopes

After World War II, radio astronomy groups in several countries adapted war surplus German 7.5-m Würzburg radar dishes for use in radio astronomy. Operating at 21-cm wavelength, Van de Hulst et al. (1954) obtained an angular resolution of 1.9° by 2.7°. Dutch astronomers, under the leadership of Oort, built what was then the world's largest fully steerable radio telescope, a 25-m paraboloid located at Dwingeloo, The Netherlands. At its shortest operating wavelength of 21 cm, it had an angular resolution of 0.6° (Van de Hulst et al. 1957). The Dwingeloo telescope was quickly surpassed in size by the much larger Jodrell Bank 250-ft antenna (Lovell 1957), with an angular resolution of about 10 arcmin at the shortest operating wavelength of 20 cm.

Experience has shown that the cost of large steerable radio telescopes of diameter d and limiting wavelength λ increases approximately as $(d)^{2.7}$ and as $\lambda^{-1/2}$. Because of monetary constraints and the strength and thermal coefficients of construction materials, the ratio of surface accuracy to diameter for passive structures is limited to roughly 0.5×10^{-6} (von Hoerner 1967). The finest resolution is about 30 arcsec over a wide range of wavelengths, only slightly better than that of the unaided human eye. Most of the filled-aperture radio telescopes are conventional fully steerable paraboloids, but some, such as the Ohio State antenna built by John Krauss (1976), the Nancay radio telescope (Blum et al. 1963), the Arecibo 1000-ft dish (Gordon & LaLonde 1961), and the RATAN-600 (Korolkov & Parijiskii 1979) are of novel design. The new fully steerable Green Bank Telescope in West Virginia, which has an offset feed to minimize sidelobe responses and an active surface to compensate for gravitational, thermal, and wind distortions, may achieve a resolution as fine as 7 arcsec at its shortest design wavelength of 3.5 mm (Jewell 2000).

1.2. Mills Cross–Type Radio Telescopes

Another approach to obtaining high angular resolution came from Australia, where Bernard Mills built a two-dimensional cross array, later to be known as a Mills Cross (Mills & Slee 1953). Each arm of the cross was 1500 feet long and produced a fan beam in the sky. When the voltages of the two arms were multiplied a pencil beam was formed, but with rather high sidelobes. The beam could be steered in the sky by adjusting the phasing of the elements in each arm. Operating at 3.5 m (86 MHz), the resolution of the Mills Cross was about 1°. Following the success of this design, Mills proposed a much larger version of the cross antenna. A controversy developed within the CSIRO Radiophysics Laboratory over whether to build this Mills Super-Cross, a large fully steerable dish, or a new solar radio telescope (see Robertson 1992). Following the decision by the Radiophysics Laboratory to build the fully steerable 210-ft Parkes Radio Telescope, Mills moved to the University of Sydney, where he later built a large cross antenna near Canberra (Mills et al. 1963). The Molongolo Cross, as it is known, was used at 73 cm (408 MHz) for a survey of the Southern sky with a resolution of 2.8 arcmin. Later, the east-west arm was split into 88 individual elements and used as a full earth-rotation synthesis instrument (see Section 3) at 36-cm wavelength (843 MHz) with a resolution of 43 arcsec (Mills 1981). Other large cross-type radio telescopes were later built in Italy, Russia, and the Ukraine.

1.3. Lunar Occultations

The idea of using observations of the occultations of stars to measure their angular sizes and positions was first discussed by MacMahon (1909) in the context of geometric optics. In this limit the rise time of the lunar occultation light curve is directly related to the stellar angular diameter, and the light curve is proportional to the integral of the one-dimensional strip integration of the stellar intensity distribution. However, this concept was criticized by Eddington (1909), who pointed out that Fresnel diffraction would impose a finite rise time to the occultation curve even for a point source, thus limiting the resolution obtainable to about 0.005 arcsec. However, Eddington did not realize that the effect of the diffraction can be precisely removed so that the angular resolution is limited only by the telescope sensitivity.

Whitford (1939) obtained the first occultation curve of a star that clearly showed the classical Fresnel diffraction pattern of a knife edge. In 1950, Evans began a long program of measuring the separations of binary stars using this technique (Evans et al. 1985). The earliest applications in radio astronomy were to observations of the supernova IC443 by Elsmore & Whitfield (1955) and Rishbeth (1956), and of the Crab Nebula by Costain et al. (1956) at a resolution of ~1 arcmin. The technique was advanced by Cyril Hazard (1961, 1962), working with the Jodrell Bank 250-ft radio telescope, and had its greatest success with the Parkes 210-ft radio telescope when a series of occultations of 3C 273 was observed in 1962 (Hazard et al. 1963) that led to its optical identification and the subsequent recognition of quasars as a new constituent of the universe (Schmidt 1963).

An observation of a lunar occultation gives the one-dimensional strip integration of the intensity along the direction of the limb of the moon, convolved with the Fresnel diffraction pattern of a point source. The critical parameter is the Fresnel scale, $\theta_{\mathrm{f}} = [\lambda/2\mathrm{R}]^{1/2}$, where λ is the wavelength and R is the earth-moon distance, which corresponds to 7 arcsec, 1 arcsec, and 5 mas at wavelengths of 1 m, 1 cm, and 0.5 μm, respectively. For a typical angular velocity of the moon of 0.5 arcsec/sec, the characteristic time scales are 15, 2, and 0.01 sec, respectively. Getmanzev & Ginzburg (1950) suggested that higher angular resolution than the Fresnel scale could be obtained, but they did not specify a method.

Scheuer (1962) first calculated the Fourier transform of the Fresnel diffraction response to a knife edge and showed that its amplitude is the same as that of a step function (i.e., it varies with spatial frequency u, as u^{-1}), but its phase is a quadratic function of u, whereas the phase of the Fourier transform of the step function is a constant. Because a lunar occulation response is the convolution of the one-dimensional strip-integrated intensity distribution and the diffraction response, in the Fourier transform domain the diffraction phenomenon can be thought of as a filter. It passes all the Fourier components of the source distribution, albeit with increasing attenuation and phase distortion at large spatial frequencies. Because all the Fourier components are present in the response, the effect of the Fresnel filter can be removed, in principle, by invoking the usual Fourier transform techniques. This is only slightly more complicated than the case of an occultation described by geometric optics in which the image recovery is implemented by simply differentiating the light curve.

Thus, the strip-intensity distribution can be restored as accurately for the diffraction case as for the case of pure geometric optics. The angular resolution obtainable depends directly only on the sensitivity of the observations and is independent of the wavelength or diameter of the telescope. The reason for this is that by measuring the temporal occultation curve, the wavefront structure is probed over a large dimension that is limited only by the system sensitivity. This dimension corresponds to the size of an equivalent one-dimensional array that would have the same resolution. Furthermore, the high-resolution information is encoded on the diffraction pattern at the moon, so the resolution is essentially independent of the effects of atmospheric turbulence. Scheuer (1962) and von Hoerner (1964) calculated restoring functions that could be convolved with the data without the use of Fourier transforms. This approach helped to quantify the limits of resolution that could be obtained in practice. von Hoerner (1966), Cohen (1969), and Hazard (1976) gave a complete description of the radio technique, including the effects of bandwidth, integration time, and length of scan.

Multiple occultations of a source often occur in which the limb of the moon traverses the source in different directions. From the projection-slice theorem of Fourier transforms (Bracewell 2000), each occultation provides the Fourier components along a radial line in the two-dimensional visibility plane corresponding to the direction of the occultation. DeJong (1966), Taylor (1967), and Taylor & DeJong (1968) made the first two-dimensional images of radio sources with this technique by interpolating their one-dimensional Fourier transform slices onto a two-dimensional grid. Later, Bracewell & Riddle (1967) worked out a method to determine the two-dimensional intensity distribution directly from the occulation scans without the explicit computation of Fourier transforms. This technique for analyzing image projections anticipated the development of computer-aided tomography as a medical diagnostic tool (Bracewell 1979b, Medoff 1987).

The advent of large radio telescopes greatly improved the sensitivity of lunar occultation measurements and, thus, the angular resolution. Hazard and his colleagues exploited the 305 m Arecibo telescope to obtain subarcsecond intensity distributions on a number of extragalactic radio sources (e.g., Cohen & Kundu 1966, Hazard et al. 1968). In India, Govind Swarup (1971) led the construction of the novel Ooty radio telescope, which was dedicated primarily to lunar occultation measurements and made hundreds of such observations in the early 1970s (e.g., Swarup et al. 1971).

By the 1970s, the development of direct interferometric techniques for high angular resolution led to much better images than could be obtained with lunar occultations. Hence, lunar occultations no longer play a significant role in radio astronomy. However, they are still useful in infrared and optical astronomy (Richichi 1994, Ragland & Richichi 1999).

1.4. Ionospheric, Interplanetary, and Interstellar Scintillations

The rapid temporal fluctuations (i.e., scintillation or twinkling) of the radiation from Cygnus A and other sources observed at decameter wavelengths were initially attributed to intrinsic variations (Hey et al. 1946). However, the comparison of light curves at telescopes spaced by several hundred kilometers showed no correlation, which led to the correct interpretation that the fluctuations are caused by the irregular distribution of electrons in the ionosphere. Similar to the case of twinkling of star light, the ionosphere acts as a phase changing screen, which produces a diffraction pattern on the ground. The motion of the screen relative to the observer causes the scintillation. However, if the source is extended the diffraction patterns from various parts of the source overlap, and the scintillations are averaged out. Because of the dispersive character of the plasma, the critical source size for the appearance of scintillations depends inversely on the product of the distance to the scattering screen, the strength of the fluctuations, and the wavelength. At a wavelength of 4 m (74 MHz), the timescale of fluctuations is about 10 sec and the critical size is about 10 arcmin. Scintillation observations gave the first indirect limits of the angular size of Cygnus A, but it took 4 years to understand the scintillation phenomena (Smith 1950, Little & Lovell 1950).

Interplanetary scintillations were first detected by Margaret Clarke (1964) as part of her PhD dissertation work to measure the position of radio sources (Hewish et al. 1964). Interestingly, just a few years later, Jocelyn Bell (1967) discovered pulsars while investigating interplanetary scintillations as part of her PhD work (Hewish et al. 1967). The timescale for interplanetary scintillations is ~1 sec and the critical size is 1 arcsec or less. Observations made at Cambridge and Arecibo showed that many extragalactic sources contain compact components, particularly those identified with quasars (e.g., Cohen 1969). The detection of scintillation of

3C279 at 11 cm when it passed within a few degrees of the sun demonstrated that it had a component smaller than 0.005 arcsec (Cohen & Gundermann 1967).

Diffractive scintillation in the interstellar medium causes fluctuations on millisecond time scales, and the critical source size is of the order of microarcseconds. Pulsars and perhaps masers scintillate owing to this process (Scheuer 1968). The dramatic cessation of scintillation in the radio afterglow of the gamma-ray burst GRB 970508 a few weeks after its discovery strongly suggests that the radio source was rapidly expanding and reached the critical size of about 3 microarcsec at that time (Frail et al. 1997). Also, the observed intraday variability of AGN, quasars, and masers may be due to the large-scale irregularities in the interstellar medium that cause refractive scattering (e.g., Narayan 1992). Kedziora-Chudczer et al. (1997) and Dennett-Thorpe & deBruyn (2000) have used intraday variability observations to place upper limits to the angular size of several quasars of 5 and 16 μ-arcsec, respectively. Although for many purposes the fluctuations in the plasma screens along the propagation paths are a nuisance causing temporal variations and blurring of the image, they also serve a useful purpose because they deflect the incident radiation from a wide area toward the observer. Thus, the observer with a single telescope receives radiation from a large portion of the phase-changing screen. The screen has the properties of an aperture and in principle can be used to achieve extremely high resolution (Cornwell & Narayan 1993). The action of the interstellar medium has been observed in this way, wherein two prominent patches of ionization enhancement created an interference pattern on the earth of the pulsar PSR 1237 + 25 at 430 MHz. This result provided an effective resolution of 1 μ-arcsec, the equivalent to a 2-element interferometer with a 1-Astronomical Unit (AU) baseline (Wolszczan & Cordes 1987).

2. INTERFEROMETRY

2.1. The Sea Interferometer

During World War II, shipboard radar operators noticed that radar echoes from airplanes varied in amplitude because of the interference between the signal received directly from the aircraft and that reflected from the ocean. This radio analog of Lloyd's mirror led to the development of the sea interferometer by Pawsey et al. (1946) and by McCready et al. (1947), who were the first to use interferometric observations in radio astronomy. Their sea interferometers were located on cliffs a few hundred feet above the Pacific Ocean in Australia and had an angular resolution of about 30 arcmin. The sea interferometer observations showed that the variable component of solar radiation was too bright to be explained in terms of a thermal emission process and that enhanced solar radiation comes from regions associated with optically visible sunspot groups. In their classic paper, McCready et al. commented on the Fourier transform relation between source brightness distribution and the amplitude and phase of the interferometer response. They pointed out that "it is possible in principle to determine the actual form of the distribution in a complex case by Fourier synthesis," but noted that varying the height of the cliff interferometer "would be feasible but clumsy" (p. 368). Bracewell & Roberts (1954) and Bracewell (1956a,b, 1958a,b) further developed the theory and showed how the radio source brightness distribution can be reconstructed from interferometric observations made at discrete spacings that depend on the size of the source being imaged.

Later, John Bolton and Gordon Stanley (1948) used their sea interferometer to show that the size of the radio source Cygnus A was less than 8 arcmin in extent. Bolton (1948) then located several other discrete sources, and in a seminal paper, Bolton et al. (1949) went on to use sea interferometers in New Zealand and Australia to determine the position of the strong radio sources Virgo A, Centaurus A, and Taurus A with an accuracy of ~15 arcmin. This led to the identification of Virgo A and Centaurus A with the peculiar galaxies M 87 and NGC 5128, respectively, as well as the identification of Taurus A with the Crab Nebula, which was already known to be the remnant of a supernova of 1054 AD. The identification of discrete radio sources with peculiar galaxies and a supernova remnant created great interest within the astronomy community and probably marks the birth of modern radio astronomy. Interestingly, however, rather than using their optical identifications to establish the extragalactic nature of the discrete radio sources, Bolton and his colleagues were reluctant to accept the enormous radio luminosity implied by their optical identifications and considered their work as evidence that M 87 and NGC 5128 were galactic nebulosities.

Sea interferometers continued to be used in Australia for several years to study the sun and catalog discrete sources of cosmic radio emission. As discussed by Bolton & Slee (1953), in spite of the difficulties caused by the need to observe at low elevations, the sea interferometer had certain advantages. It had twice the sensitivity that would be obtained with two similar antennas connected as an interferometer, and it did not require interconnecting cables or preamplifiers. Also, the sharp horizon helped to discriminate between two close sources, in much the same way as the limb of the moon was later used for occultation measurements. As late as 1953, Bolton et al. (1954) used a sea interferometer to catalog 104 sources located between $\pm 50^\circ$ declination. Although these pioneering observations opened up the rich field of extragalactic radio astronomy, their potential was limited. Sea interferometer observations were, by necessity, made at low elevations, which introduced large uncertainties owing to refraction. In addition, the observations were confined to the few minutes each day when each source rose or set over the sea. Sea interferometers were soon superceded by interferometer arrays.

2.2. Michelson Interferometers

In 1946, Ryle & Vonberg (1946) built a two-element radio interferometer with a maximum spacing of about 0.5 km, in Cambridge, England, to measure the diameter of the sun. This was the first radio analog of the two-slit optical interferometer used by Michelson (1890, 1920) and Michelson & Pease (1921) to measure the diameter of stars and by Anderson (1920) to determine the separation of double stars. Ryle & Smith (1948) later constructed a radio interferometer to locate the strong radio source Cassiopeia A to an accuracy of about 20 arcmin and place an upper limit of 6 arcmin to its angular diameter. Ryle et al. (1950) then went on to catalog 50 sources in the Northern sky. This was the first in a long series of Cambridge interferometric sky surveys and was later referred to as the 1C survey. In Australia, Mills (1952a,b) built a three-element interferometer with a maximum baseline of about 800 m and a resolution of ∼1° at 3 m wavelength (101 MHz).

Ryle (1952) made an important advance when he invented the phase-switched interferometer. Previously, signals from the two antennas were added, squared, and averaged, much as in a classical optical interferometer. In Ryle's system a 180° phase shift was periodically introduced in one arm of the interferometer. The resulting synchronously detected signal retained only the cross-product of the signals from the antennas. This technique greatly improved the effective sensitivity of interferometers. Modern interferometers use direct multiplication of the signals but still retain phase-switching to eliminate small systematic errors.

For several decades, there was considerable interest in counting radio sources down to very low flux density levels to investigate cosmological problems (see, e.g., Mills 1984). These first systematic radio source surveys were not limited by sensitivity, but rather by their insufficient angular resolution to distinguish individual discrete sources. Surveys made with different instruments agreed well for the stronger sources, but for the weaker sources there were large discrepancies owing to multiple sources contained in the primary beam of the individual antenna elements. This phenomenon is now called *confusion*. At Cambridge, Ryle & Hewish (1955) built an array of 4 fixed elements to survey the sky, first for the 2C survey (Shakeshaft et al. 1955) at 3.7 m wavelength (81.5 MHz), and later for the 1.9 m wavelength (159 MHz) 3C survey (Edge et al. 1959). The antennas were combined in a variety of ways to form interferometer pairs with better angular resolution than given by any of the individual elements. In this way the Cambridge radio astronomers hoped to improve the accuracy of the measured source positions and thus facilitate the identification of optical counterparts.

The 2C survey contained 1936 sources stronger than 7 janskys, or flux units, as the unit of intensity was then called. The interference fringe spacing or effective resolution was about 30 arcmin in right ascension and 4° to 7° in declination. The survey contained a surprisingly large excess of weak sources compared with what was expected in a uniformly filled universe (Ryle & Scheuer 1955, Ryle 1956). In a widely publicized presentation, Ryle (1958) argued that the apparent excess of weak sources in the 2C survey required an evolutionary universe where either the density or the luminosity of radio sources increased with increasing redshift or decreasing cosmic time. The then-popular Steady State theory, promoted by Fred Hoyle and others, required a uniform source density, independent of redshift, and appeared inconsistent with the Cambridge interferometer survey.

About the same time, in Australia, as described in a series of papers, Mills et al. (1958, 1960, 1961) used their cross antenna to survey the sky south of declination $+20^\circ$ with an angular resolution of 50 arcmin and cataloged more than 2200 sources at 3.5 m wavelength. However, comparison of the Mills Cross and 2C catalogs showed little similarity (Mills & Slee 1957). Only the strongest sources were found in common to the two catalogs. Moreover, in contrast to the Cambridge surveys, the Mills Cross source count was close to that expected from a uniformly filled universe, as predicted by the Steady State theory. This started an intense and long-lasting debate about the relative merits of interferometers and pencil-beam radio telescopes, which was fueled by an equally long and bitter debate between Mills and Ryle over the correct cosmological interpretation of radio source counts.

When Edge et al. (1959) decreased the operating wavelength of the Cambridge interferometer to 1.8 m, thus doubling the angular resolution and decreasing the primary beam area by a factor of 4, the new 3C survey showed that the earlier 2C survey was heavily affected by confusion from the simultaneous presence of multiple sources in the primary antenna beam (Scheuer 1957). Most of the weaker sources listed in the 2C catalog were either not real, were blends of two or more weaker sources, or were displaced from their true position by one or more lobe shifts of the interference pattern (up to 30 arcmin in right ascension and 7° in declination). The 3C survey, with its better resolution, showed a smaller excess of weak sources than the 2C survey and better agreement with the Mills Cross surveys. Later observations using the Parkes Radio Telescope (Milne & Scheuer 1964) showed that many of the apparently extended sources in the Mills Cross catalogs were blends of weaker sources or were due to sidelobes of more distant strong sources.

2.3. Radio-Linked Interferometers

In an effort to extend the angular resolution of radio interferometers beyond distances at which direct electrical connections were practical, Australian and British radio astronomers experimented with radio links to distribute the local oscillator phase reference and to return the Intermediate Frequency signals to a central location for correlation. In Australia, Mills (1952c, 1953) and Goddard et al. (1960) used a radio-linked interferometer with a spacing up to 10 km at 3 m wavelength (101 MHz) to determine the brightness distribution across the 4 strong sources Virgo A, Cas A, Cen A, and Taurus A with a resolution of $\sim$1 arcmin.

Jodrell Bank radio astronomers had more ambitious plans. Beginning with a 1 km connected-element interferometer, Hanbury Brown et al. (1954) found that many radio sources remained unresolved. In a series of experiments Morris et al. (1957) used a radio link to join a small portable antenna working at 1.9 m (158 MHz) at series of outstations located at successively increasing distances. The most distant location of the portable antenna was near the Cat and the Fiddle Inn, 20 km (10,700λ) from a fixed 218 ft paraboloid. Although most sources appeared well resolved, 3 (3C 147, 3C 196, and 3C 295) remained unresolved with an upper limit to their diameters of 12 arcsec. Later, Elgaroy et al. (1962) and Allen et al. (1962) used the Jodrell Bank 250-ft antenna together with a portable antenna over baselines extending up to 115 km (61,100λ) and identified 5 sources that appeared to be less than ∼1 arcsec in extent. Anderson et al. (1965) then used a baseline of 134 km at a wavelength of 73 cm (180,000λ) to resolve sources bigger than 0.4 arcsec. Later, Jodrell Bank radio astronomers teamed up with the group at the Malvern Royal Radar Establishment to link telescopes separated by 127 km. Observing first at 21-cm wavelength (Adgie et al. 1965, Barber et al. 1966), and then at 11 and 6 cm, Palmer et al. (1967) showed that some radio sources were as small as 0.05 arcsec. The 127-km radio-linked interferometer was also used to place upper limits on the size of hydroxyl masers and to resolve several velocity components on a scale of 0.1–1 arcsec (Davies et al. 1967). At the same time a 13-km radio-linked interferometer between the Haystack and Agassiz radio telescopes in Massachusetts was used to make the first image of an OH maser (Moran et al. 1967a). The early very-productive long-baseline radio-linked interferometer experiments in the UK, which were led by Henry Palmer, provided much of the motivation for the later development of VLBI, as well as the foundation for the later radio and optical observations at Caltech, Parkes, and Palomar, which contributed to the identification of quasars (Schmidt 1963) and distant radio galaxies.

The success with radio-linked interferometers led Henry Palmer to develop a dedicated multi-element radio-linked interferometer, which was originally named the Multi-Telescope-Radio-Linked-Interferometer (MTRLI), but which later become known as the Multi-Element-Radio-Linked-Interferometer-Network (MERLIN) (Davies et al. 1980). With the addition of a new antenna at Cambridge, the 7-element MERLIN system produces radio images with resolution up to 0.01 arcsec and provides an important link to the even higher resolution imaging obtained from the European VLBI Network (see Section 4.5).

3. APERTURE SYNTHESIS

Motivated by the need to reduce the effects of confusion encountered when pushing the radio source count to lower flux density, the Cambridge group, under Ryle's direction, built a new interferometer consisting of a long east-west transit array plus a smaller, moveable element operating at 1.7 m (178 MHz). With an effective angular resolution of 25 arcmin × 35 arcmin, the 4C survey (Scott & Ryle 1961, Pilkington & Scott 1965, Gower et al. 1967) covered most of the Northern sky down to a flux density of 2 Jy. The 4C survey showed an even smaller excess of weak sources than the previous 2C and 3C surveys, and, indeed, the source count was close to that which the Australians had found previously. This technique of synthesizing a large aperture by successively moving a portable antenna was called aperture synthesis (Ryle & Hewish 1960, Ryle 1975, Hewish 1963). Even earlier, Cambridge PhD student, John Blythe (1957), had demonstrated the technique of aperture synthesis by using an array of fixed and movable dipoles to synthesize a 2° beam at 7.9 m (38 MHz). Each day the portable element was moved to a new location, and the rotation of the earth was used to scan the sky for 24 hours of right ascension to cover a declination swath corresponding to the primary beam of the antenna elements.

The next big step, in both technological progress and reliability, came from the innovative observations by Ryle & Neville (1962), who split the 1450-ft east-west 4C antenna into 32 elements, which they pointed toward the north pole region to observe the same region of the sky for a full 12 hours to synthesize a circular 4.5 arcmin beam. Cambridge radio astronomers referred to this technique as supersynthesis, whereas in Australia Christiansen called it earth-rotation synthesis. It should be noted that Högbom (1959), as part of his PhD dissertation work, had previously used an array of simple dipole elements to test the principle of supersythesis. Even earlier, O'Brien (1953) in Cambridge as well as Christiansen & Warburton (1953, 1955) in Australia used one- and two-dimensional arrays, respectively, for earth-rotation imaging of the sun. However, for these observations the arrays were phased in real time to form fan beams. The one-dimensional slices made at different hour angles were then Fourier transformed and used to reconstruct the brightness distribution by a two-dimensional inverse transform. Later, the 21-cm, 64-element grating cross antenna at Fleurs (Christiansen et al. 1957), which was originally built for imaging the sun, was used for full Fourier synthesis observations of the stronger extragalactic sources with a resolution of 20 arcsec (Christiansen 1973).

Most of the early interferometer work at Cambridge focused on radio source surveys made with transit instruments intended to address the cosmological source count problem rather than to image individual sources. However, some early Cambridge observations used two surplus German Würzburg antennas as elements of an interferometer to measure the position and size of several strong radio sources (Smith 1951, 1952a). In France, Lequeux (1962) used a pair of 7.5-m dishes that were moved along a 1.5-km track to study the structure of 40 strong radio sources with an angular resolution of ~20 arcsec.

3.1. The Cambridge One-Mile and 5-Km Radio Telescopes

The construction of the One-Mile Radio Telescope at Cambridge represented a significant departure from earlier Cambridge work, which concentrated on transit instruments operating at relatively long meter wavelengths. The One-Mile Radio Telescope (Ryle 1962, Elsmore et al. 1966) used 2 fixed and 1 moveable fully steerable 60-ft-diameter paraboloids as a variable spacing interferometer operating simultaneously at 21 and 75 cm (1420 and 408 MHz). By moving the portable antenna to a series of different locations spaced 23.5 m apart on each of 64 successive days, an effective aperture 1 mile in diameter was synthesized. The resulting 5C surveys had angular resolutions of 80 arcsec and 23 arcsec, respectively, at 75 and 21 cm and cataloged radio sources as faint as 2 mJy, considerably fainter than any previously cataloged radio source (e.g., Pooley & Kenderdine 1968, Pearson 1975). Observations with larger incremental spacings were used to observe individual radio sources with unprecedented sensitivity, angular resolution, and image quality (e.g., MacDonald et al. 1968, Mackay 1969, Branson et al. 1972).

Building on the achievements of the One-Mile Radio Telescope, Ryle (1972) went on to build the 5-Km Radio Telescope, which offered several improvements. The longer baseline and shorter operating wavelength (2 cm instead of 6 cm) improved the resolution from about 5 arcsec to better than 1 arcsec, and the increased number of antennas (8 instead of 3) improved the speed by nearly an order of magnitude over the 1-mile instrument (Laing 1981a,b). This was the first radio telescope at Cambridge that was specifically designed for studying the structure of individual sources.

During the 1960s and 1970s, Cambridge radio astronomers were clearly at the forefront of high-resolution radio imaging, and they jealously guarded their position in fear that the wealthier observatories in Europe and the United States might exploit their advantage if they could learn the secrets of aperture synthesis or get prepublication hints of important new results. The few students who left to work at European and American observatories were pledged to secrecy. The Cambridge staff continued to consist mostly of Cambridge graduates who were instructed to withhold data and results from visiting radio astronomers. However, ultimately, Westerbork, MERLIN, the Very Large Array (VLA), the Australia Telescope, and the Very Long Baseline Array (VLBA) greatly extended the techniques originally developed by Ryle and his colleagues at Cambridge.

3.2. The Westerbork Synthesis Radio Telescope

The Westerbork Synthesis Radio Telescope (WSRT) started out as a joint project between Belgium and the Netherlands (see Raimond 1996). As originally conceived, the Benelux Cross was to be a 5-km Mills Cross-Type antenna operating at 75 cm with a pencil beam resolution of 1 arcmin. The arms of the Benelux Cross were to consist of parabolic cylinders, but following the success of the Cambridge aperture synthesis work, the design later evolved to an array of about 100 fully steerable 30-m-diameter dishes (Christiansen et al. 1961). However, it was soon appreciated that the cost of such an ambitious instrument would be prohibitive and the operation and data analysis overwhelming. Further study, especially by Jan Högbom, led to consideration of a 28-element one-dimensional earth-rotation synthesis array. The design was again modified in 1965 when Belgium dropped out of the project, resulting finally in an east-west array of 10 fixed and 2 movable 25-m dishes with spacings up to 1 mile.

The WSRT (Baars & Hooghoudt 1974, Högbom & Brouw 1974) was dedicated in 1970 and has remained in heavy use not only by Dutch radio astronomers but by users from around the world. It originally operated at 21 cm with a resolution of 23 arcsec. Several upgrades to the instrumentation, including new receivers, a new spectrometer, two additional movable antennas, and extension of the baseline to 3 km have improved the sensitivity and angular resolution and have kept the WSRT at the forefront of radio astronomy research.

At first, the uniform spacing of the 10 fixed antennas of the WSRT with its many redundant spacings was thought to be inefficient because it did not provide the maximum possible coverage of the Fourier transform plane. However, as had been discussed earlier by Rogstad (1968), it was later appreciated that the redundant spacings greatly improve the robustness of the self-calibration procedure (Section 5.2), leading to images with considerably enhanced dynamic range (Noordam & de Bruyn 1982). The WSRT now operates with an angular resolution of 2 arcsec at its shortest wavelength of 3.6 cm and has been particularly effective in observations of neutral hydrogen in galaxies and for regions of low surface brightness, including the giant radio galaxies, so-called head-tail radio galaxies, jets, and clusters of galaxies.

It is interesting to note the influence of the international community on the Dutch designs. The early cross-type antenna was first suggested by Charles Seeger, a visitor to Leiden from the United States. Chris Christiansen from Australia and William Erickson from the United States developed the cross configuration of 100 steerable paraboloids, whereas Högbom, fresh from his Cambridge PhD work, urged the more powerful method of earth-rotation synthesis, which was finally adopted.

3.3. The Very Large Array

At Caltech Bolton and Gordon Stanley built a pair of 90-ft steerable dishes, which could be moved along 2 orthogonal 1600-ft rail tracks and operated at wavelengths as short as 10 cm. Due to the relatively small size of the primary antenna beam, the Caltech interferometer was relatively immune from confusion problems and was particularly productive. A variety of observations led to the identification of the radio source 3C 295 with the most distant known galaxy at that time (Minkowski 1960), the discovery of Jupiter's radiation belts (Radhakrishnan & Roberts 1960), polarization studies of extragalactic radio sources (e.g., Morris et al. 1963), the identification of many radio sources with bright elliptical galaxies (Matthews et al. 1965) and quasars (Schmidt 1968), the determination of radio source spectra (Kellermann 1964), the two-component nature of Galactic HI (Clark 1965), and the ubiquity of double-lobed radio sources (Maltby & Moffet 1962, Fomalont 1967).

However, there was little progress in the United States toward developing the next generation of powerful radio telescopes, and there was growing concern that the United States was losing the initiative in the rapidly developing field of radio astronomy to Britain, Europe, and Australia. Indeed, although the Caltech interferometer pioneered the use of large fully steerable paraboloids and state-of-the-art low-noise receivers to push radio interferometry to short decimeter wavelengths, Caltech radio astronomers did not make the step to full two-dimensional earth-rotation aperture synthesis taken by Ryle and his colleagues in Cambridge.

A radio telescope with a resolving power comparable to that achieved at optical wavelengths—about 1 arcsec—was needed to solve the outstanding scientific problems of the day. In 1961, the National Science Foundation (NSF) convened the Advisory Panel on Large Radio Telescopes, chaired by JR Pierce of Bell Laboratories. Bolton, then director of the Caltech Owens Valley Radio Observatory, presented plans for a 4-element array of 130-ft antennas moving on orthogonal railroad tracks to synthesize a two-dimensional beam. Interestingly, Bolton's design did not exploit the use of earth-rotation synthesis. About the same time, scientists at the National Radio Astronomy Observatory (NRAO) began to plan a much more ambitious array. The NSF panel recognized the need for good angular resolution and the power of aperture synthesis to achieve this goal. They recommended further experimental and theoretical studies that would lead to the design of a radio telescope with a resolution approaching 1 arcsec. Interestingly, the Pierce Panel report (Pierce 1960, unpublished) commented that "the primary problem of American radio astronomy appears to be the lack of radio astronomers." The panel correctly worried about achieving the needed instrumental and atmospheric phase stability for 1 arcsec resolution, but with great perception noted that "as the Manchester group has shown, three elements give the phases without the need for calibration" (see Section 5.2).

In 1964, the National Academy of Sciences convened a panel, chaired by Albert Whitford of the Lick Observatory, ". . . to study the probable need for major new astronomical facilities in the United States during the next five to ten years . . ." (Whitford 1964). Three of the eight members were radio astronomers: Ron Bracewell, Frank Drake, and Fred Haddock. The panel report (Whitford 1964) focused on the need to improve the angular resolution of radio telescopes, both to study radio galaxies and to address "the cosmological problem." The panel commented on the distinction between radio astronomy, which was limited by the power of available instruments, and optical astronomy, in which the limiting factor was inadequate observing time. Aspects of this dichotomy still survive today. The panel noted that whereas only the Caltech proposal approached the needed versatility and speed, the resolution, sensitivity, and image quality of the Caltech instrument were still inadequate for "substantial progress with the prime astronomical problems." The panel recommended "as the largest single undertaking in radio astronomy the construction of a large array that would achieve a resolution of one arc minute at 21 cm and a few arcseconds at 3 cm." An array of about 100 dishes, each 85 ft in diameter, was suggested. Due to its size and complexity, the panel argued that the proposed array should be constructed by the National Radio Astronomy Observatory (NRAO) with the advice and extensive participation of university scientists. The panel also recommended as an interim measure, the construction of the proposed Caltech Owens Valley Array, which would consist of up to 8 new 130-ft antennas to supplement the 2 existing 90-ft antennas. A second Caltech proposal, submitted in 1966, outlined the plans for an 8-element array of 130-ft dishes to give a resolution of 10 arcsec at 10 cm wavelength and 3 arcsec at 3 cm. The first 130-ft antenna at the Owens Valley Radio Observatory was constructed and put into operation in 1969. It was used together with the 2 existing 90-ft antennas to form a 3-element interferometer. No other development of the array of 130-ft dishes ever occurred, but interferometry development did continue at the Owens Valley Radio Observatory both toward longer baselines and shorter millimeter wavelengths.

Interestingly, the Whitford Committee also recommended the construction of 2 fully steerable paraboloids of about 300-ft-diameter as well as a design study for “the largest possible steerable paraboloid, with control of the reflector surface through a servo system” (Whitford 1964). However, it would be 36 more years before even one steerable antenna of this size with an active surface—the 100-m Green Bank Telescope—would be completed (Jewell 2000).

At NRAO a prototype 2-element interferometer consisting of two 26-m dishes separated by 900–2700 meters was put into operation in Green Bank in 1964. A third 26-m dish was added in 1966 along with a 45-ft portable antenna, which was located at distances up to 35 km from the larger antennas and was connected by a radio link. The first proposal for the Very Large Array (VLA), submitted to the NSF in 1967, called for an array of 36 25-m antennas operating with room temperature receivers in 2 wavelength bands, 5.5 and 11 cm, with a sensitivity sufficient to detect a 1 mJy source after 8 h integration time. The resolution was to be 1 arcsec at 11 cm. The dynamic range was determined by the goal of reducing the side-lobe level to about 1% after a 12 h track, comparable to what could be obtained from a carefully illuminated filled-aperture antenna. Funding limitations later restricted the array to 27 antennas, which, it was thought, would increase the sidelobe level to more than 2%.

The VLA concept was widely criticized (Heeschen 1991), not only by those with competing projects but even within NRAO itself. The Caltech proposal addressed essentially the same scientific goals as the VLA, but at a much lower cost and complexity. In addition to the cost and technical considerations, there was concern that the construction of the VLA by NRAO would likely reduce the role of the existing Caltech interferometer, which had been so important in developing the rationale for the VLA and in training radio astronomers, many of whom were later involved in the development and operation of the VLA.

In 1967, the NSF appointed an ad hoc committee under the chairmanship of Princeton physicist Robert Dicke to resolve the controversy. The Dicke Committee Report (unpublished) recommended as its first priority that the Caltech proposal “for an array of eight dishes be accepted in its entirety and funded as soon as possible.” As a fourth priority, the NRAO VLA proposal was recommended for further study after the upgrading of the Arecibo 1000-ft dish and design studies of large fully steerable reflectors. The design studies for the VLA continued at NRAO, but the NSF did not take any action on the Caltech array, the Arecibo upgrade, the radome enclosed 440-ft fully steerable dish proposed by the North East Radio Astronomy Corporation, or construction of the VLA.

In 1969, the NSF reconvened the Dicke Committee, which noted the progress in building radio telescopes in Great Britain, the Netherlands, Germany, and India while the United States had "stood still." In their unpublished report, the committee drew attention to the dramatic discoveries in radio astronomy in the preceding 5 years (quasars, pulsars, organic molecules, galactic magnetic fields, and a new test of general relativity) and noted that, "in no other field of science has man's understanding—even concept—of his universe been so dramatically extended and altered" (Dicke 1969, unpublished). This time the committee endorsed, without priority, the Arecibo upgrade, the Caltech array, the North East Radio Astronomy Corporation 440-ft dish, and the VLA. However, without clearly defined priorities, it was difficult to proceed with any project.

The following year the National Academy of Sciences formed a committee to update the recommendations of the 1964 Whitford Committee and to set priorities for astronomy for the next decade. Jesse Greenstein from Caltech chaired the committee and David Heeschen, director of NRAO, chaired the Radio Astronomy Panel. Following vigorous debate within both the Radio Astronomy Panel and the main committee, the Greenstein Report (1972) endorsed the construction of the VLA as the highest priority for all of astronomy. As a result, the first funds for the construction of the VLA were made available in 1972, and the VLA was dedicated in 1980 following a construction project that was completed within its budget and schedule (Heeschen 1981, 1991, Swenson 1991, Lancaster 1991).

Lubkin (GB Lubkin, unpublished) and Swenson (GW Swenson, unpublished) have discussed in more detail the events and controversy leading to the construction of the VLA. The design and performance of the VLA have been described by Thompson et al. (1980) and Napier et al. (1983). Table 1 compares the original design goals of the VLA as proposed in 1967 with the performance achieved when the VLA was completed in 1980 and with current performance. With the planned upgrade and expansion, both the sensitivity and resolution of the VLA will be increased by more than an order of magnitude and the spectroscopic capability will be improved by more than a factor of a hundred (Perley 2000). Some of the original improvements came about during the design period, mostly as a result of the

TABLE 1 VLA performance

	Goal (1967)	**1980**	**2001**
Resolution (arcsec)	1	0.1	0.02
Sensitivity in 8 hours rms (mJy)	0.1–1	0.05	0.01
Number of images/day	3	100	>1000
Sidelobe level (%)	1	0.1	0.002
Image size (pixels)	100^2	512^2	1024^2–4096^2
Spectral channels	—	256	512
Wavelength bands	2	4	8
Wavelength range (cm)	3.7, 11	1.3–20	0.7–400

rapid improvement in signal processing techniques and electronic systems, which allowed the use of cooled, very low–noise receivers. Digital circuitry was adequate at the time to handle 27 data streams at 100 mega-samples/sec for continuum and modest spectral resolution. However, the image analysis problem appeared formidable for existing computers. Optical processing was considered (see Heeschen 2000), the idea being to encode the visibility data onto film and use the Fourier transform property of a lens to produce the image. A prototype was built, but it was apparent that any analog system would lack flexibility. Fortunately, this plan was dropped in favor of what then appeared to be a more complicated digital system, but which later facilitated the dramatic improvement in image quality made possible by the powerful combination of CLEAN, self-calibration, and fast computers (see Section 5).

The decision to build the full 27-element VLA rather than the 8-element array proposed by Caltech had a profound impact. With the use of CLEAN and self-calibration, the original VLA specification of a 1% or 2% sidelobe level (dynamic range of 50–100) for observing times of the order of 12 h, was easily surpassed even with so-called snapshots of a few minutes. With full 8-h tracks the dynamic range reaches about 10,000 or better, so that spurious responses are $<0.01\%$ of the brightest feature in the image. Also, instead of imaging 8 sources per day, hundreds or even thousands of images are obtained in a single 24-h period, each with a dynamic range that exceeds the original VLA specification by an order of magnitude. As an extreme example, Condon et al. (1998) have cataloged nearly 2 million discrete sources from a full-sky VLA survey with a resolution better than 1 arcmin and rms noise of about 0.5 mJy, an accomplishment that was unthinkable at the time of the VLA's construction.

There has been considerable speculation about why the apparently attractive and cost-effective Caltech array was never built, in spite of the enthusiastic endorsement received from the Pierce, Whitford, and two Dicke Committees. In part, there appeared to be concern at the NSF about making too great an investment at a single university observatory rather than at a national observatory where the facilities would be open to users from all over the country. It may be significant, also, that the VLA project was very well documented in the first 1965 NRAO report and in great detail in three proposal volumes issued in 1967 (Vols. I and II) and 1969 (Vol. III), whereas the three Caltech proposals issued in 1962, 1966, and 1969 gave considerably less detail about the engineering design and cost estimates.

Since its completion in 1980 the VLA has been used by over 2000 scientists from hundreds of laboratories and universities around the world for more than 10,000 individual observing programs. It exceeds its design specifications by orders of magnitude in nearly all parameters and remains, today, by far the most powerful radio telescope in the world, although much of the instrumentation dates from the 1970s.

At the start of operations in 1980 observing was limited by the available computing power, especially for spectroscopic observations. It was argued by many that perhaps it would be better to build one less antenna or implement one less frequency and use the cost savings to buy more computers. Fortunately, this argument was overruled, and within a few years the cost of computers had dramatically dropped. By the 1990s, VLA users had computers on their own desks, each with far greater power than the original VLA mainframe machines. Considerable effort was expended to ensure the portability of the Astronomical Image Processing System (AIPS) (Greisen 2000), which allowed the computing load to be absorbed by the user community instead of being concentrated at NRAO. Of course, concurrent with the explosion in computing power has been the increased demand due to the development of sophisticated new algorithms for deconvolution, which have made possible radio imaging with a combination of resolution, speed, and quality undreamed of (and computationally impossible) at the time of the original VLA proposals in the mid-1960s.

4. VERY LONG BASELINE INTERFEROMETRY

4.1. The Intensity or Post-Detection Interferometer

For some years after the discovery of the first discrete radio sources, it was thought by Ryle (1949) and others that these sources were associated with stars, not galaxies. If so, they would be expected to be very small, so that interferometer baselines of thousands of kilometers would be needed to measure their angular size. Clearly, this was beyond the feasibility of any conventional interferometer because it would be necessary to stretch cables between the antenna elements to carry the common local oscillator signal as well as return the IF signals for correlation.

In the early 1950s, Hanbury Brown conceived of a new type of interferometer in which the intensity, rather than the electric field strength, of the incident radiation received at spaced antennas were cross correlated. At radio wavelengths, where the photon rate is high, the voltages at the antenna terminals, v_1 and v_2, are proportional to the incident electric fields and are Gaussian random processes. The time-averaged product is, from the fourth-order moment theorem for Gaussian noise, $\langle v_1^2 v_2^2 \rangle = \langle v_1^2 \rangle \langle v_2^2 \rangle + 2\langle v_1 v_2 \rangle^2$. The last term, which is proportional to the square of the fringe visibility, is the desired result. No interference fringes are formed, and the fringe phase cannot be determined, so the requirements for phase stability are minimal. Hanbury Brown realized that such an interferometer could be built with independent local oscillators, allowing baselines of arbitrary length by recording the power received at each antenna's element. If necessary, baselines spanning the globe could be used to resolve radio stars (Hanbury Brown 1983, 1991).

Jennison & Das Gupta (1953, 1956a,b) demonstrated the technique of intensity interferometry by measuring the angular size of the sun in 1951 and then used a radio link in 1952 over a 12-km baseline to observe the strong radio sources, Cassiopeia A and Cygnus A. Cas A was found to be a circularly symmetric source with a diameter of 4.5 arcmin (Hanbury Brown et al. 1952). The data for Cygnus A agreed with those obtained using conventional Michelson interferometers (Mills

1952c, Smith 1952a). Later intensity interferometer observations (Jennison & Das Gupta 1953) detected a null in the fringe visibility near 1200 λ, beyond which the visibility rose, suggesting for the first time that it was a double source with about 1.5 arcmin component separation (Figure 2*a*). It was later realized, however, that the limited visibility amplitude data could equally well be interpreted as a three-component source. To resolve this ambiguity, Jennison (1951, 1958) developed the concept of phase closure (see Section 5.2). Clearly, Cas A and Cygnus A were not true radio stars. Because baselines of only a few kilometers appeared adequate to resolve the discrete radio sources, the emphasis at Jodrell Bank, Cambridge, and later at Caltech moved to conventional connected-element interferometers of more modest extent.

The intensity interferometer had two drawbacks that limited its use: The sensitivity was much less than that of a conventional Michelson interferometer, and the lack of phase information made it difficult to obtain images. In spite of these problems, the technique did find some applications. In the mid-1960s a group at the University of Florida set up an intensity interferometer with independent crystal oscillators and audio tape recorders to measure the angular sizes of dekameter wavelength radio bursts from Jupiter (Carr et al. 1965). Later, Gubbay et al. (1969) used a tape-recording intensity interferometer with an intercontinental baseline to observe 3C 273 (Moffet et al. 1972). The poor phase stability of early VLBI instruments (see Section 4.2) led Clark (1968) to the analysis of interferometers of intermediate type, i.e., neither perfectly coherent (Michelson) nor incoherent (intensity).

Hanbury Brown later built an optical intensity interferometer at Narrabri, Australia, and successfully measured the diameters of a number of stars (Hanbury Brown 1968, Hanbury Brown et al. 1974). Interestingly, although the intensity interferometer was originally developed for radio astronomy, its main application has been at optical wavelengths, whereas phase coherent interferometry, which was originally developed for optical measurements, was, until recently, used by and developed almost exclusively by radio astronomers. Hanbury Brown and Twiss led the effort to understand the operation of the intensity interferometer within the framework of quantum mechanics, which was a controversial issue at the time (Hanbury Brown & Twiss 1954a,b, 1956, 1957a,b; Brannen & Ferguson 1956; Hanbury Brown 1983, 1991). Recently, the basic quantum-statistical properties that underlie intensity interferometry have also been demonstrated for Fermions in an electron gas (Henny et al. 1999, Oliver et al. 1999). Unlike the case of electromagnetic radiation, which obeys Bose statistics and leads to positive correlation, Fermions, as expected, show anticorrelation.

4.2. Very Long Baseline Interferometry

By 1965 the radio-linked interferometer measurements at Jodrell Bank had shown directly that there was a class of compact radio sources with angular diameters less than 0.05 arcsec, and interplanetary scintillation observations indicated sizes as small as a few milliarcseconds. Studies of their short wavelength radio spectra (Kellermann et al. 1962, Bolton et al. 1963) suggested that synchrotron self-absorption was important (Slysh 1963, Williams 1963) and that their diameters could be as small as 0.001 arcsec. About the same time, repeated observations of flat-spectrum sources showed remarkable flux density variations on time-scales as short as a few months or less (Sholomitsky 1965, Dent 1965, Pauliny-Toth & Kellermann 1966), implying linear scales as small as one light year or less. If located at distances corresponding to their redshift (and there was considerable controversy about that assumption) their angular sizes had to be considerably less than 0.001 arcsec, and interferometer baselines of thousands of kilometers would be needed to determine their structure.

An early discussion of using independent oscillators and tape recorders to build a phase coherent (Michelson) VLBI took place at a series of seminars led by Leonid Matveyenko (private communication) at the Russian Lebedev Physical Institute in Moscow during the autumn of 1962. Matveyenko et al. (1965) realized that it would be possible to increase the baseline length beyond what would be feasible using direct physical connections or even radio links. Recognizing the broad potential of tape recording interferometry, Matveyenko and colleagues applied for a patent, but under Soviet law they were not allowed to publish their ideas until the patent application was processed. The pending patent application, combined with cold war secrecy and Soviet bureaucracy, delayed publication for 3 years. Because Matveyenko et al. did not consider the possibility of slowing down the interferometer fringes and anticipated recording the fringes on an analog chart recorder, they assumed that integration times were limited to less than a fringe period, which is inversely proportional to baseline length. Thus, they incorrectly concluded that the sensitivity depended inversely on the length of the interferometer baseline. A later analysis by Slysh (1965) correctly derived the requirements on time and frequency stability.

In May 1963, Sir Bernard Lovell, Director of Jodrell Bank, visited the Soviet tracking station in Evpatoria, Crimea. His visit was carefully monitored by the Soviet military, but Matveyenko, Shklovsky, and others were able to discuss with him the possibility of UK-USSR tape-recording interferometry using the Jodrell Bank 250-ft radio telescope and the tracking antenna in Evpatoria, Crimea. The following year Henry Palmer traveled from Jodrell Bank to Moscow for further discussions, but neither the high-speed tape recorders nor the stable oscillators needed for VLBI were available to Russian radio astronomers, and there was little interest among senior Soviet radio astronomers in pursuing these ideas (L. Matveyenko, private communication).

By the mid-1960s, two critical technical developments led several other radio astronomy groups to think about tape-recording interferometry using independent local oscillators to allow Michelson interferometry over essentially unlimited baselines. Driven by the rapidly expanding computer industry, high-speed digital tape recorders were commercially available, and broadband analog systems were possible using tape recorders designed for the television industry.

Meanwhile, atomic frequency standards were becoming available with relative frequency stability of 1 part in 10^{11} to 1 part in 10^{14} for rubidium and hydrogen maser standards, respectively. Thus, even for frequencies as high as 1 GHz, it appeared that commercial rubidium-controlled frequency standards could give adequate stability to maintain coherence for a few tens of seconds. This combination of relatively large bandwidth and long integration time provided the basis for systems with sufficient sensitivity to detect quasars and AGN.

To align the tapes to detect "white-light fringes," the time has to be synchronized to within a fraction of the reciprocal bandwidth. The radio frequency signal is reduced to base-band using standard superheterodyne techniques. With a bandwidth of ~1 MHz, synchronization to better than a microsecond is required. In the pre-GPS (Global Positioning System) era, worldwide radio synchronization of clocks to an accuracy of a few microseconds was available from a network of LORAN transmitters operating at 100 kHz. Synchronization could also be transferred by transporting a battery-powered rubidium-controlled clock by airplane to the observing sites. Often the clocks were required to fly first class to satisfy airline regulations.

4.2.1. EARLY VLBI SYSTEMS Encouraged by the theoretical work on synchrotron self-absorption and the observation of time variations, as well as the observational evidence for subarcsecond structure from lunar occultations, interplanetary scintillations, and radio-linked interferometry, a Cornell-NRAO group recognized the opportunity made possible by these new technologies to build a tape recording interferometer with independent oscillators (see Kellermann & Cohen 1988). Initial support was made available by NRAO director David Heeschen in the late summer of 1965 on the basis of a short discussion, but the project was later supported by a brief written "proposal" (Cohen, Jauncey, Clark & Kellermann 1965, unpublished manuscript).

A digital recording scheme was chosen. The data were represented by one-bit samples (two-level quantization, i.e., signal sign only) and recorded at the Nyquist rate. It was well known from research in radar counter measures during World War II that the correlation properties of signals were preserved in this highly quantized representation (Van Vleck & Middleton 1966). This result was first exploited in radio astronomy by Sander Weinreb (1961), who built a digital autocorrelation spectrometer using one-bit data samples. Digital recording had the attractive feature of being self-clocking, since each sample bit was measured at a precise time. The data bits could be easily aligned after playback in a digital computer independent of tape recorder irregularities as long as the bit count was not lost within a data frame. By storing and shifting the data, a range of time alignments could be tried to compensate for clock errors. Interestingly, virtually all modern radio interferometers and arrays now use a one- or two-bit digital representation of the signal (e.g., Thompson et al. 2001, chapter 8).

Initially, standard computer 7-track tape drives were used to record a 360-kHz band using an overall data rate of 720 kilobits per second (kbps). Each 12-inch reel of tape lasted only for 3 min. The first VLBI playback system at NRAO used an IBM 360/50 general-purpose digital computer, which took more than an hour to correlate a pair of 3-min tapes. Later, the Haystack Observatory built a special-purpose, hard-wired correlator that worked in the equivalent of real time.

The VLBI program in Canada was initiated after a series of internal reports within the Canadian National Research Council in the summer and autumn of 1965 (see Gush 1988), about the same time the group in the United States was starting its activities. The Canadian radio astronomers were more ambitious and designed their system around analog TV studio recorders, which allowed a larger bandwidth and consequently better sensitivity. Operation was more complex than the American system because at playback time the tapes had to be manually aligned by listening to spoken time prompts and 1-sec audio ticks, and they were subject to timing errors owing to tape recorder irregularities. However, a 2-inch-wide tape could record a 4-MHz band for 3 h. The Canadian group also used more stable, but also more expensive, hydrogen masers rather than rubidium frequency standards as their time and local oscillator references.

During the design and development period in 1965 and 1966, a friendly competition developed between the US and Canadian groups to obtain the first fringes. Concerned about the poor sensitivity inherent in the narrow-band digital system, the Cornell-NRAO group planned to use the large radio telescope at Arecibo, Puerto Rico, at one end of their interferometer and the Green Bank 140-ft antenna at the other end—a baseline of 2557 km, or 5 million wavelengths at 49 cm (610 MHz), to give an angular resolution of 0.02 arcsec. The first observations made in January 1967 were unsuccessful, and the recording and timing equipment was returned from Puerto Rico to Green Bank for examination. A second trial a month later also failed to produce fringes. Meanwhile, on February 2, 1967, the Canadian group successfully operated their system using two antennas separated by only 200 m at the Alguonquin Radio Observatory (ARO) (Broten et al. 1967a). The Canadians immediately shipped their instrumentation to Penticton, BC, for a planned high-resolution test in April. However, on first examination this experiment produced no fringes.

Meanwhile, on March 5/6 the US group successfully obtained fringes over a 650-m baseline between an 85-ft antenna normally used as part of the connected-element Green Bank interferometer and the 140-ft radio telescope. One of the recording systems was then moved to the Naval Research Laboratory's 85-ft antenna at Maryland Point and was successfully operated on May 8 over the short-lived record baseline of 220 km (440,000 wavelengths at 49-cm wavelength) to Green Bank (Bare et al. 1967). This was the first coherent interferometer observation involving independently managed radio telescopes; the resolution was 0.5 arcsec. Meanwhile, the Canadian group obtained fringes on a 250-km baseline between the ARO and a 60-ft antenna at Shirley Bay, near Ottawa (Broten et al. 1967a). On May 21, 1967, after several attempts to replay the tapes, they successfully obtained fringes on the quasar 3C 273 on a 3074-km ($4.4 \times 10^6\lambda$) baseline from observations made on April 13 between the Algonquin Park 150-ft radio telescope and a 25-m antenna at Penticton, BC; the resolution was about 0.05 arcsec (Broten et al. 1967b). Both the Canadian and NRAO-Cornell teams presented their results at a meeting of the International Scientific Radio Union (URSI) held in Ottawa in May 1967.

Interestingly, a narrow-band Michelson-type independent-oscillator–tape recording interferometer experiment had been tried by the University of Florida group several months before the broadband systems described above. However, they did not attempt to correlate their data until after the publication of Broten et al. (1967a), and their paper was not submitted for publication until November 1967 (Brown et al. 1968), after the papers by Broten et al. (1967a,b) and Bare et al. (1967) appeared. The Florida interferometer was used to observe strong radio bursts from Jupiter at 18 MHz. Because the bandwidth was only a few kilohertz, the observing frequency low, and the integration time short, the requirements on recorder technology, time synchronization, and frequency stability were modest and were easily satisfied with a simple audio tape recorder and crystal oscillator.

Meanwhile, a group at MIT and the Haystack Observatory had become aware of the difficulties experienced by the NRAO-Cornell group in finding fringes from the two Green Bank–Arecibo trials. The MIT group had been studying OH masers using a radio-linked interferometer at 18 cm (Moran et al. 1967a). The masers that they observed remained unresolved over a baseline between antennas located at the Haystack and Agassiz Observatories, 13.4 km apart, although for the first time, individual velocity components were distinguishable. They realized that the relatively strong narrow-band masers might provide a powerful diagnostic tool, as time synchronization of only a few hundred microseconds was needed, compared with the microsecond accuracy needed for continuum sources. The MIT-Haystack group designed and built a compatible recording system at the Haystack Observatory by using a direct analog to digital (A/D) interface to the antenna control computer.

Following the successful operation of the Green Bank–Maryland Point interferometer in May, the NRAO-Cornell group and the MIT-Haystack group joined forces to observe on an 845-km baseline between the Haystack 120-ft and Green Bank 140-ft telescopes with a resolution about 0.04 arcsec. The MIT group studied OH masers (Moran et al. 1967b) and the NRAO-Cornell group, quasars and AGN (Clark et al. 1967b). In July the baseline was extended to 20×10^6 wavelengths, a West Virginia to California baseline with a corresponding resolution of 0.01 arcsec, a record for angular resolution at that time (Clark et al. 1967a, Moran 1968, Moran et al. 1968). By January 1968, baselines to Sweden were established, and the observations extended to 6 cm (Kellermann et al. 1968). The maximum baseline was 6319 km, or about 10^8 wavelengths. In less than a year, radio interferometer baselines had increased to a significant fraction of an earth diameter, and the minimum wavelength used had decreased by more than an order of magnitude (Cohen et al. 1968). In the following year, VLBI observations were extended to Australia over a distance of 10,592 km (Kellermann et al. 1970), and the wavelength was further decreased to 2.8 cm on a baseline to Russia (Broderick et al. 1970). The maximum baseline length reached 3×10^8 wavelengths, and the corresponding angular resolution was better than one thousandth of a second of arc. Applications of the VLBI technique to geodesy and geophysics, timekeeping and earth rotation, and tests of general relativity were quickly realized (Gold 1967, MacDonald 1967, Cohen et al. 1968, Shapiro & Knight 1970).

The VLBI observations between the United States and Russia posed a special challenge (see Kellermann 1992). Following an initial exchange of letters in 1968, American and Russian radio astronomers agreed to attempt a US-USSR VLBI experiment. At that point there had been no discussions with American authorities about sending sensitive high-speed tape recorders and accurate atomic frequency standards to the USSR, and it took lengthy negotiations to get approval from various American intelligence services and to arrange for the necessary export license. At issue was not only concern about the possibility of reverse engineering of advanced American technology, but the potential application of accurate baseline data to target nuclear missiles. Only years later was it learned that the Russian radio astronomers had faced the same hurdles with their government, and in fact KGB engineers did thoroughly study the American recorders while the visiting American astronomers slept or were taken to visit various Soviet tourist attractions. However, after the first observations in 1969 there appeared to be little or no interest from either Soviet or American authorities, and the US-USSR VLBI observations continued throughout the cold war period with repeated two-way exchanges of scientists and expanding collaborations.

The push to shorter wavelengths was motivated not only by the desire to get higher angular resolution for quasars and AGN but also by the discovery of cosmic water masers at 1.3 cm (22 GHz). Within a year after the discovery of H_2O masers in many galactic star-forming regions and late-type stars, the measurement of the angular structure of these sources began with VLBI observations linking the NRL Maryland Point Observatory, Green Bank 140-ft, and Haystack 120-ft radio telescopes (Burke et al. 1970, Moran et al. 1973). With the US to Crimea baselines, the resolution reached 0.0002 arcsec for both H_2O masers and quasars (Burke et al. 1972, Pauliny-Toth et al. 1978).

During the development of the first VLBI systems, questions were raised about whether the technique violated fundamental physics, because apparently the antennas through which each photon passed could be identified from the tape recording. However, as seen through the eyes of the electrical engineer, it was perfectly straightforward; the tape recording merely duplicates the signals that are conveyed by cable in a conventional interferometer. Burke (1969) showed that tape recording interferometry did not violate quantum mechanics, because irreducible spontaneous emission in amplifiers prevents the identification of which antenna a specific photon entered. In another misconception, one referee of an early paper questioned the effect of a curved Earth on the long intercontinental baselines, apparently not appreciating that the two ends of the interferometer formed a straight line, independent of what lay in between.

The early VLBI observations confirmed the small angular dimensions of quasars and AGN predicted from their radio spectra and time variability and revealed their complex multi-component structure (Broten et al. 1969, Clarke et al. 1969). In particular, the 3.8-cm (7.8 GHz) observations of 3C 279 by Knight et al. (1971) showed a particularly well-defined double source with a component separation of 0.00155 ± 00005 arcsec. A few months later repeated observations of the quasars 3C 279 and 3C 273 resulted in the exciting discovery of superluminal motion (Whitney et al. 1971, Cohen et al. 1971). However, concerns lingered about the uniqueness of the interpretation until the multi-baseline imaging results of Pearson et al. (1981), which clearly showed an increase in component separation of $\sim$10 parsecs in 3 years, or an apparent speed nearly 10 times the speed of light.

4.2.2. ADVANCED VLBI SYSTEMS The sensitivity of the US digital system was limited by the narrow 360 kHz bandwidth, whereas the utility of the broad-band Canadian system was restricted by its complex operation. In an attempt to address these issues, NRAO began the design of an advanced VLBI recording system, called the MK II VLBI system. The NRAO design, under the leadership of Barry Clark (1973), used digital recordings on broadband reel-to-reel video recorders with the aim of obtaining the sensitivity of the video recorder and the reliability of digital recordings. By this time the Canadian radio astronomers had replaced their studio-type TV recorders with much less expensive and more reliable portable TV recorders. These portable recorders used the same reels of 2-inch-wide tape used in their initial recording system. Each reel was 10.5 inches in diameter and weighed more than 10 pounds, but was capable of recording a 2-MHz band (4 megabits per sec) for up to 3 h, compared with the 3 min of 360-kHz MK I recordings. The Canadian VLBI group had experienced considerable difficulty using these recorders for their analog VLBI system and had recommended against their use for the NRAO MKII system. However, the NRAO team anticipated that digital recordings on the same machine would be more robust to irregularities in the playback speed and to microscopic imperfections in the magnetic coating on the tape, which could lead to the loss of time synchronization. Unfortunately, this reasoning proved to be naive. The variation in mechanical alignment among different recorders made it extremely difficult to playback the tapes without unacceptable error rates and consequent loss of synchronization. After years of frustration, hundreds of magnetic tapes were buried in Green Bank, and the recorders were replaced by a somewhat more reliable design that used 1-inch-wide tape, but only lasted for one hour.

A major breakthrough occurred in the late 1970s with the introduction of the remarkably inexpensive home Video Cassette Recorder (VCR). Allen Yen, who had engineered much of the Canadian VLBI system, was intrigued by the potential opportunities of using consumer electronics for VLBI. During a series of visits to Caltech, the Max Planck Institut für Radioastronomie (MPIfR) in Bonn, and the NRAO, Yen succeeded in recording MK II-compatible data on a standard VCR.

The VCR tapes cost only a few dollars each compared with a few hundred dollars for the professional videotapes. Moreover, they were sufficiently light-weight that they could be inexpensively shipped around the country and around the world by regular (customs-free) first-class mail, rather than the complex and costly air freight shipments previously required.

Initially, tapes were correlated one baseline at a time, so the tapes from an N station experiment had to be replayed $N(N-1)/2$ times. The first NRAO MK II two-station correlator was later expanded to allow tapes from three antennas to be simultaneously replayed. The correlator capacity, especially important for spectroscopy, was successively increased from 32 to 96 to 512 frequency channels. Caltech built a MK II correlator that was later expanded to three, then four, and then five stations to accommodate the increasing number of multi-station observations. Later, Caltech, in collaboration with the Jet Propulsion Laboratory (JPL), developed a large VLBI playback facility that allowed up to 16 tapes to be simultaneously replayed and correlated in the equivalent of real time. Other MK II correlators, patterned after the NRAO processor, were constructed and put into operation in Germany, Russia, and China.

As the sensitivity of the MK II VLBI system was restricted by the limited bandwidth of 2 MHz (4 Mbps), Yen began a program to develop a VCR-based system that would allow reliable digital recordings over a 6-MHz bandwidth (Yen 1988). Following his untimely death in 1993, Canadian radio astronomers continued this work, which led to the development of the inexpensive S2 record system based on professional-model VCRs recording at 8 MHz (16 Mbps) on a single VHS cassette. A standard S2 record terminal consists of 8 tape transports recording up to a 64-MHz band (128 Mbps) (Carlson et al. 1999). More than 20 S2 recording systems are in operation and are used especially in support of the Japanese VSOP space VLBI program (see Section 4.6), as well as VLBI observations in Australia and for Canadian geodetic VLBI observations. S2 tapes are correlated primarily in Canada, at the Dominion Astrophysical Observatory located in Penticton, BC.

Not long after the first astronomical VLBI observations in 1967, NASA initiated a vigorous VLBI program of geodetic observations based at the Goddard Space Flight Center, the MIT-Haystack Observatory, and JPL to measure earth rotation, polar motion, plate tectonics, and as a by-product, accurate radio source positions. Long-term goals included the potential for earthquake prediction. As the measurement of absolute phase was not feasible, geodetic applications relied on measuring fringe rate and/or delay. The crucial development that made precision geodesy and astrometry possible was the implementation of bandwidth synthesis (Rogers 1970), in which the recording band was sequentially switched among frequencies spanning a range of up to 100 MHz, making it possible to measure delays with 10-nanosec accuracy even with the NRAO 360-kHz bandwidth MK I system (Whitney et al. 1976).

With NASA support, a broadband VLBI recording system known as MK III was developed at the MIT-Haystack Observatory (Rogers et al. 1983). The MK III VLBI system originally recorded 28 4-Mbps tracks on a 1-inch wide tape. However, the recordings only lasted 13 min on a single tape, which cost about $1000. The MK III system was soon upgraded by the introduction of movable recording head stacks, which increased the number of tracks (and corresponding bit density) 12-fold and increased the recording time to 3 h per tape. This became known as the MK IIIa system, which was deployed by NASA in support of the NASA and, later, National Geodetic Survey geodesy programs (Clark et al. 1985). In the decade preceding the construction of the VLBA (see Section 4.4), far more money was invested in the United States by NASA for geodetic VLBI than by the NSF for astronomical VLBI observations. MK IIIa instrumentation was installed by NASA at many major radio observatories around the world for geodetic observations. However, the equipment was also used by radio astronomers to study cosmic masers and AGN.

In the United States MK III correlation was done initially at the Haystack Observatory. In Europe, a MK III processor was built at the MPIfR with support from the German organization Bundesamt für Kartographie und Geodäsie. The MPIfR processor was later expanded to support eight stations while the US Naval Observatory operated a three-station processor to support their program in astrometry and earth rotation. Although the MK IIIa VLBI system was five times more sensitive than the MK II system, the high cost of the equipment, combined with the cost of purchasing and shipping the tapes, and the lack of convenient software for imaging limited its use for radio astronomy imaging. The MK IIIa system was later superceded by the VLBA record system, which although based on MK IIIa technology, uses a longer, thinner tape that increases the recording time to slightly over 10 h per tape at the nominal recording rate of 128 Mbps or 5 h at 256 Mbps. More recently, the Haystack Observatory has developed the MK IV system, which uses multiple headstacks to achieve a sampling rate of up to 1 Gbit/sec (Whitney 1993). The last improvement, however, came at the expense of a corresponding decrease in recording time per tape, as the bit density of the MK IV system is the same as that of the VLBA system. Other VLBI systems were developed at Jodrell Bank and JPL but they have not come into widespread use.

4.3. The Network Users Group and the VLBI Consortium

In the early 1970s VLBI observations were mostly conducted on an ad hoc basis. Whereas the expansion of VLBI baselines to Europe, Australia, and Russia led to angular resolutions better than 0.001 arcsec, the technical and logistical difficulties were formidable. Multi-station observations were needed even to make simple models of radio source structures, but in spite of the successes, serious problems remained. There were too few baselines and the phase information needed to form true milliarcsecond images was missing. The multistation observations took excessively long to correlate, and long backlogs were common. Moreover, the VLBI recording systems were difficult to operate, unreliable, costly, and exhausting to ship and operate around the world. This was before the days of the Internet, and numerous telephone calls were needed to arrange for a common observing time, to arrange for shipping magnetic tapes, to prepare observing schedules, and to make last-minute changes necessitated by the inevitable technical failure or human error at one or another of the observing sites. Observing runs lasting more than a few days often fell on scheduled maintenance days at the participating observatories, a problem that had increasing impact as the size of the experiments and number of telescopes increased. Weekend and holiday observing thus became more common, but this exacerbated the technical difficulties, as support personnel were often not available on weekends to fix problems. Customs officials introduced their own level of bureaucracy, even from so-called friendly countries, with the United States being, perhaps, the most recalcitrant. It was not unknown for a US customs agent to try to collect customs duties on incoming tapes that had been exported only a few weeks earlier. Although the incoming tapes belonged to the US government, customs agents argued that because the tapes contained new data, they had acquired added value while out of the country and were thus subject to customs duties.

In order to facilitate multi-station VLBI, Marshall Cohen and his associates developed the idea of routinely scheduled VLBI observations on small networks of telescopes, the earliest of which included the Harvard College 85-ft antenna near Fort Davis, TX, the Caltech 130-ft antenna in the Owens Valley, CA, and the NRAO 140-ft antenna in Green Bank, WV (Cohen et al. 1975). In 1975 Cohen organized the Network Users Group (NUG), which began the operation of the US VLBI Network to make a VLBI network look like a single telescope that could be used by an individual or a small team. Participating observatories agreed to set aside a week six times each year for VLBI observations. The decision by NRAO to turn over scheduling authority for six weeks per year on the heavily oversubscribed 140-ft telescope to an external group was controversial and represented a major change in policy. Proposals were submitted to the NUG, reviewed by its referee committee, and scheduled. To reduce the huge effort and travel involved in implementing VLBI observations, the scientists involved provided local observing support at their own observatory for all programs including those in which they had no scientific involvement. It thus became possible for a single individual, or small group, to propose, carry out, and publish without a huge author list VLBI observations using radio telescopes around the country, all under different management. The first Network observations were scheduled in March and April 1976 and involved 6 programs at 2.8 or 18 cm on 7 telescopes. The first synthesis image of an OH maser, obtained from this session, led to a qualitative improvement in the understanding of these objects (Reid et al. 1981).

One of the early successes of the Network was the standardization of the instrumentation and observing procedures. This was not an easy step, because by 1976 each research group had adopted, and often rigidly maintained for the purposes of continuity, a specific set of observing frequencies. The Network adopted standard frequencies and polarization that reduced the incidence of failed experiments. The Network prepared a comprehensive handbook and issued a regular newsletter to help investigators cope with the volume of detailed information needed to use the different antennas.

For several years in the early 1980s, the group at the Smithsonian Astrophysical Observatory provided an almost real-time fringe check at the beginning of each Network session. Using the system developed by the MIT/NASA group (Levine & Whitney 1980, Rogers et al. 1983), 10^6 bits of data were stored in buffers simultaneously at each station and transmitted by telephone lines sequentially to the Smithsonian Astrophysical Observatory at 1200 bps. The search for fringes over an arbitrarily large delay range was conducted on a general-purpose computer. If no fringes were found, the relevant observatories were notified and setup mistakes were sought. A table of instrumental clock offsets for each station was then made available to facilitate the actual data processing.

In its first 5 years of operation, the Network scheduled 192 programs involving 119 investigators from 32 institutions. Although the absolute growth was limited by the agreement of 6 weeks per year of VLBI observing time at the 140-ft telescope, the number of programs per session increased from 3 to 10, and the average number of telescopes per program increased from 3.5 to 5.5. Other antennas, including the Arecibo radio telescope and the VLA, as well as the MPIfR telescope at Effelsberg, Germany, other European stations, and the NASA Deep Space Network (DSN) stations around the world, were added to the original seven. The large number of antennas saturated the correlator capacity, creating a major processing backlog that was not ameliorated for several years.

In order to further expedite technical improvements, a formal consortium of observatories was created at the 1981 annual NUG meeting. The Memorandum of Understanding launching the consortium was signed in January 1982 by the presidents of Caltech, MIT, Harvard/Smithsonian Astrophysical Observatory, the University of California, and the University of Illinois. The NUG became an advisory body to the Consortium, but the scheduling and operation of the Network proceeded much as before. The Network's technical advisory group became much more active and formulated an ambitious program of equipment upgrades, estimated to cost about $2 million, which included maser clocks for the VLA and Hat Creek; a MK III terminal for Iowa; better receivers at 4 and 13 cm; dual polarization receivers for 1.3, 6, and 18 cm; expansion of the MK III processor; purchase of more tape; and a dedicated DEC VAX computer for image processing. However, the only result of this plan was NSF support for buying more tape and for technical staff positions obtained through the proposals of individual observatories.

Sensitivity remained a problem, and to address this issue connected element arrays such as the VLA and the Westerbork Synthesis Radio Telescope (WSRT) were configured as phased arrays that could be used for VLBI observations with the equivalent collecting area of a 135-m or 94-m dish, respectively. It was necessary to sum the signals coherently from all the antennas of each array in order to form a beam in the direction of the source. This was achieved by removing the instrumental phases of each antenna and electronically pointing the phased array toward the VLBI target, which appeared as a point source at the resolution of the VLA or WSRT. The coherence was often less than perfect, and the VLA

35-km-diameter A-configuration at 1 cm in the summer daytime could become dephased in less than a minute. Under these conditions, it was often necessary to have an expert on site during the observations to watch the phasing and discard the signals from the outermost antennas to optimize the signal strength.

With the development of the VCR-based MK II system, VLBI became possible at a modest cost, and many radio observatories built or bought VLBI systems. By the time of its demise in the mid-1990s, more than 20 VCR VLBI systems had been built and were in operation throughout the world. In 1984, 18 telescopes were used in a series of VLBI observations called the World Array, which contained 153 baselines. Very high dynamic range images with milliarcsecond resolution were made of the AGN 3C 120 (Benson et al. 1988), M 87 (Reid et al. 1989), the giant radio galaxy 3C 236 (Schilizzi 1988a), and the quasar 3C 48 (Wilkinson et al. 1991).

4.4. The Very Long Baseline Array (VLBA)

By the mid-1970s, it was apparent that more sophisticated instrumentation and, particularly, better organization of the observing and playback facilities were needed. At a meeting held at NRAO in April 1974, a three-phase program was formulated. First, it was clear that Very Long Baseline Interferometry (VLBI) programs needed to be centrally organized, yet take into account the independence of the participating radio observatories. Second, a new antenna was needed in the midwestern U.S. to fill in the gap between the concentrations of radio telescopes in the Northeast and Southwest. Finally, to fully exploit the VLBI technique, a dedicated array was needed that would (*a*) provide good distribution of baselines by siting the antennas where needed rather than where existing radio observatories happened to be located, (*b*) work well at the short wavelengths needed to obtain the best resolution, and (*c*) be operated by a single organization as a national facility, which would make the cumbersome process of tape transport and playback transparent to the user.

The formation of the NUG as described in Section 4.3 was a result of the first recommendation. In response to the second, and with encouragement from the community and the NSF, the University of Iowa and the University of Illinois each proposed to build the Midwest telescope, initially to work together with an array of existing antennas and later as the first element of the dedicated array. Neither proposal was funded, although an existing 60-ft antenna at the University of Iowa was later put into limited use for VLBI.

In response to the third recommendation, planning for a dedicated array continued at NRAO in collaboration with university radio astronomers (Swenson & Kellermann 1975). NRAO issued a design report for an Intercontinental Very Long Baseline Array (Kellermann 1977), but by that time NRAO was preoccupied with building the VLA, and there was great pressure from the radio astronomy community for NRAO to build a 25-m millimeter-wavelength radio telescope as the next big national radio astronomy facility. Faced with these uncertainties, Caltech, in collaboration with JPL, initiated a separate design study for a VLB array, although many of the same scientists from NRAO and Caltech (and elsewhere) contributed to both design efforts (Cohen 1980). The two designs were compared at a meeting held in Green Bank, WV, in October 1980. This led to a revised NRAO plan. Based on the NRAO and Caltech design studies, a National Academy of Sciences Astronomy Survey Committee recommended the construction of the VLBA as the highest priority for a major new ground-based facility (Field 1982). In April 1982, more than one hundred scientists met at the National Academy of Science for a *Workshop on the Multidisciplinary Uses of the VLBA*, which helped to coalesce the potential astronomical and geodetic users of the VLBA (Shapiro 1983). In 1983, the NSF abandoned plans to build a millimeter-wave telescope and instead requested funds to begin construction of the VLBA.

Following a controversial debate in Congress, limited design funds for the VLBA were made available in 1984. Construction started in 1985, and the VLBA was finally put into operation in 1993, about 20 years after the first discussions (Kellermann & Thompson 1985, 1988, Napier et al. 1994). However, like many other major construction projects, it would be 5 or more years before the software was in place to fully exploit the capabilities of the VLBA. During the VLBA design phase it was unclear whether to use the MK II or MK III recording technology. The MK II system was considerably less expensive but had limited bandwidth compared with the MK III system. Initially, NRAO had proposed to use 8 VCRs in parallel, each working at 16 Mbps, but 16 Mbps VCR recording had not yet been demonstrated, and there was concern about the bookkeeping involved with the large quantity of tapes that would be produced by a dedicated 10-station array working full time. Following extensive discussion, the MK III technology was adopted for the VLBA because it appeared to offer greater potential to be upgraded to even higher data rates. The VLBA recording system (Rogers 1995) uses a narrow-track headstack that can be repositioned to allow 28 passes of the tape to give a total recording time of 10.5 hours at the nominal data rate of 128 Mbps, or 5×10^{12} bits per tape. By moving the tape at twice the normal rate of 160 inches/s, the recording rate can be increased to 256 Mbps, but at the expense of proportionally reduced recording time. The VLBA correlator can handle up to 20 simultaneous tapes, so that up to 10 non-VLBA antennas can be used to gain increased sensitivity, resolution, and image quality. In a more recent development, two recorders are operated in parallel to achieve a net record rate of 512 Mbps.

4.5. The European VLBI Network and the Joint Institute for VLBI in Europe

In 1980, 5 European radio observatories joined forces to form the European VLBI Network (EVN), which has since grown to include 14 radio telescopes located in 10 countries. The EVN includes the large radio telescopes at Jodrell Bank, UK (250 ft), Effelsberg, Germany (100 m), and the 14-element Westerbork Array in the Netherlands, along with two 32-m dishes in Italy and one each in Poland and the UK, and smaller antennas in Finland, Sweden, Spain, and China (Booth 1991, Schilizzi 1997). Up to 90 days per year are spent on VLBI at some of the EVN antennas. In 1998 the EVN completed a 16-station processing facility operated by the Joint Institute for VLBI in Europe (JIVE) to handle the growing volume of data from the EVN. With the large collecting area and relatively modest baselines of the European antennas, the EVN is an especially powerful array for imaging sources with intermediate surface brightness, particularly when combined with the MERLIN array. The EVN now operates with support from the Netherlands, Sweden, France, the UK, Italy, and Spain as a multinational-distributed facility managed by an international Board of Directors whose members are the directors of the participating observatories. Technical and operations groups oversee the operation and further technical development of the EVN.

4.5.1. GLOBAL VLBI Several times each year the EVN antennas are used together with the 10-station VLBA for global VLBI observations, typically with a total of 15–20 antennas. These large multi-station experiments are mostly correlated at the VLBA processing center in New Mexico. In Australia 6 radio telescopes, augmented by an 85-ft antenna in South Africa, form the Southern Hemisphere VLBI Experiment (SHEVE) (Preston et al. 1989), which, in turn, participates in the Asian-Pacific Network, which includes radio telescopes in China, Japan, and Hawaii. In addition to these radio astronomy VLBI networks, there are separate VLBI networks that are primarily dedicated to astrometry and geodesy, although there is considerable interchange of activity on all of the networks and arrays. The globalization of VLBI including the formation of other networks such as the Asia-Pacific Telescope is described by Schilizzi (1995).

A key factor in the development of these global VLBI networks has been the extensive cooperation of individuals as well as institutions and the migration of scientists and ideas throughout the world, especially among Caltech, NRAO, Jodrell Bank, and the MPIfR. During visits to Caltech, MPIfR, and NRAO, Allen Yen from Toronto freely shared his ideas with his American competitors, and this sharing was critical to the development and later proliferation of the global VCR-based MK II VLBI system. Canadian and American radio astronomers participated in each others' experiments and later collaborated in the experiments using a satellite link (see Section 4.7.1). The record-playback system used by the VLBA is based on the MK III data system, originally developed for geodesy at the MIT Haystack Observatory with support from NASA.

Because the MKII VLBI system was developed in the United States, the North American NTSC TV standard of 60 frames per second became the accepted global VLBI standard even in the many countries using the technically more sophisticated German PAL or French SECAM TV standards. There were no large meetings or international committees to debate standards. Recorders were purchased in the United States and, where necessary, 50–60-Hz frequency converters were used to provide power. However, with the proliferation of global VLBI programs supported by national space agencies, and the lack of effective coordination, there are now a number of incompatible VLBI systems in operation throughout the world (e.g., Canadian S2, Japanese K4).

These international collaborations involving large research facilities were accomplished without any formal government involvement, even in the case of Russia and China, once initial security concerns were satisfied. The international collaborations were established because the science required them—in the form of longer baselines and multiple antennas—and not to save money, enhance national prestige, or promote political goals. Such grassroots international collaboration is perhaps unique in modern science and is certainly in contrast to the scientific mega-projects that are currently popular among national funding agencies.

4.6. Very Long Baseline Interferometry in Space

4.6.1. THE COMMUNICATIONS TECHNOLOGY SATELLITE (HERMES) By the mid-1990s, the construction of the VLBA and the organization of the EVN led to a dramatic improvement in the high angular resolution imaging of cosmic radio sources. However, the tape recorders have limited the bandwidth and complicate the system logistics. As early as the mid-1970s, several radio astronomy groups began to think of using communication satellites both to provide a closed-loop phase-stable local oscillator link between remote radio telescopes and to transmit the IF signal to a common location for correlation, obviating the need for tape recordings.

In 1976 and 1977, a Canadian-US team lead by Allen Yen and George Swenson used the experimental Canadian Communications Technology Satellite, Hermes, to do real-time interferometry between the 140-ft radio telescope in Green Bank and the 150-ft radio telescope at the Algonquin Radio Observatory (ARO) in Ontario, Canada, and later between the Owens Valley Radio Observatory and the ARO (Yen et al. 1977). The principal challenge of this real-time system was to construct an enormous buffer storage system to accommodate the 0.25-sec signal delay in the satellite link. The satellite-linked ARO-NRAO 2.8-cm wavelength (10.7 GHz) interferometer not only operated in real time, but its 10-MHz bandwidth was much larger than the then-current MK II tape recording VLBI system and gave a significant improvement in sensitivity.

Although the Hermes link successfully demonstrated the feasibility of real-time VLBI, by this time single-baseline VLBI was of only limited scientific value. The Hermes satellite continued to be used, however, to provide a stable local oscillator link in support of a geodetic VLBI program (Knowles et al. 1982). Later, Cannon et al. (1982) used the commercial Canadian ANIK-B satellite to obtain more than an order of magnitude improvement in the relative phase stability of rubidium frequency standards located at remote observatories in Canada and the United States. However, with the continuing improvements in the precision and reliability of hydrogen maser frequency standards, in spite of their relatively high cost, there is no longer any incentive to use satellite links to stabilize remote local oscillators.

European radio astronomers also discussed the possibility of using communication satellites for real-time VLBI. Studies by the European Space Agency (ESA) resulted in a 1979 proposal to use the ESA Large Telecommunications Satellite, L-Sat, to link up to 4 radio telescopes with a 72-Mbps data rate. It became clear, however, that the use of broadband satellites for VLBI was not cost-effective if one had to pay commercial rates for the satellite time, as it requires the full capacity of a large communications satellite, which is capable of supporting tens of simultaneous (paying) TV transmissions. Although the L-Sat program was never funded, it led to increased involvement by radio astronomers with the space agencies and planning for a radio telescope in orbit to increase the length of interferometer baselines beyond that which could be achieved on the earth.

4.6.2. EARTH-SPACE INTERFEROMETRY Once the success of independent-oscillator taperecorder interferometry had been demonstrated, it was clear that, in principle, baselines could be extended without technical limits. As early as 1972, the report of the Radio Astronomy Panel of the NRC Decade Review of Astronomy (Greenstein 1972) noted the potential of earth-space interferometry. In Russia, Kardashev, Shklovsky, and others discussed an earth-moon interferometer in 1969, and in 1971, Russian and American radio astronomers exchanged thoughts on the subject during a joint US-Soviet Conference on the Search for Extraterrestrial Intelligence (SETI) in Armenia. In 1979, Russia launched the Kosmicheskii Radio Telescope (KRT-10) aboard the Salyut-6 space station. The goal of this mission remains unclear, although it was apparently related to military research. A report in *Pravda* indicated that VLBI observations were made. However, this was never confirmed, and there were unpublished reports that the 10-m-diameter antenna did not properly deploy and had to be cut from the spacecraft during a dangerous spacewalk by Soviet cosmonauts. Later, Kardashev et al. (1980) and Sagdeev (1984) described Russian plans for an earth-space VLBI mission known as RACSAS-1. Other proposals made in the United States and in Russia included using the Space Shuttle, the NASA Spacelab-2 mission, the NASA Venus Orbiting Imaging Radar probe (later called Magellan) during its voyage from the Earth to Venus, and the Soviet space station Salyut (BF Burke 1984).

Following the demise of the L-Sat communications link initiative, European and American radio astronomers initiated discussions for a joint earth-space interferometry program at a VLBI meeting held in Toulouse, France, in the summer of 1982 (Preston et al. 1982). Studies supported by ESA and NASA defined a mission known as QUASAT (Schilizzi 1988b) to place a 15-m antenna in orbit about 20,000 km above the surface of the earth to give a resolution better than 0.0001 arcsec at the shortest operating wavelength of 1.3 cm. More than 80 scientists from 12 countries participated in a meeting held in Austria in June 1984 to further define the mission (WR Burke 1984). However, following several years of study in both Europe and the United States, the estimated cost exceeded the available funds, and QUASAT was not considered for further development.

Later, a group of radio astronomers, led by Richard Schilizzi, proposed a more ambitious mission to ESA, known as the International VLBI Satellite (IVS). The IVS mission was based on a 25-m antenna capable of working at short millimeter wavelengths. It was to be launched by the Russian Energia rocket to fly in 3 different orbits ranging from 20,000 to 150,000 km (Pilbratt 1991). IVS studies were undertaken by ESA, the Soviet Academy of Sciences, various industrial contractors, and radio astronomers from Europe and the United States. However, like QUASAT and its predecessors, IVS was never funded, although many of the concepts developed for QUASAT and IVS formed the basis for the later successful Japanese VSOP mission.

In 1986, radio astronomers and engineers at JPL, together with a worldwide network of collaborators, made successful earth-to-space VLBI observations using a 4.9-m antenna on NASA's Tracking and Data Relay Satellite System (TDRSS). The TDRSS observations were made at 13 cm (Levy et al. 1986, 1989) and at 2 cm (Linfield et al. 1990). For some sources, brightness temperatures in excess of 10^{13} K were established. Because of pointing restrictions, the maximum projected baseline were only 2.1 Earth diameters. To maintain coherence between the ground-based and space-based antennas, a combination of delay-Doppler and round-trip phase comparison was used to determine the instantaneous position of the moving satellite to within a fraction of a wavelength, or $\sim$1 cm. The achievement was especially remarkable considering that the VLBI application of the TDRSS was developed only after the satellites were launched, so that no hardware modifications to the spacecraft were possible.

4.6.3. RADIOASTRON AND VSOP In 1985, at a meeting to discuss QUASAT in Budapest, Nickolai Kardashev reported that Soviet radio astronomers were planning a space VLBI mission, known as RadioAstron (Andreyanov et al. 1986). The Soviet plans for a 10-m telescope working at 1.3, 6, 18, and 90 cm were discussed more broadly at IAU Symposium No. 129 held in Cambridge, MA in May 1987 (Kardashev & Slysh 1988). Following the cancellation of QUASAT, RadioAstron appeared as the only opportunity for space VLBI, and the international radio astronomy community joined forces behind the Soviet initiative to build receivers for the RadioAstron spacecraft. A 6-cm receiver was built in the Netherlands and Germany, an 18-cm receiver in Australia, and a 90-cm receiver in India. US radio astronomers proposed to supply the 1.3-cm receiver, which would give the best resolution, but NASA did not obtain the necessary export license, and the 1.3-cm receiver was ultimately built in Finland, with the "cooperation" of American radio astronomers. When first discussed in 1985, RadioAstron was being prepared for a launch in 1988. However, owing first to competition from other Soviet space programs and later to the deteriorating economic conditions in Russia, the advertised launch date has remained about 5 years away for more than a decade.

In 1987, Japanese radio astronomers announced their plans for the VSOP (VLBI Space Observatory Project) satellite with planned operation at 1.3, 6, and 18 cm (Hirabayashi 1988). VSOP, later known as HALCA, was launched in 1997 with an apoge of 21,400 km and perigee of 560 km above the Earth's surface. The 10-m-diameter antenna aboard HALCA has been in regular use at 6 and 18 cm in combination with the VLBA, EVN, and Australian radio telescopes for a variety of continuum and OH maser observations (Hirabayashi et al. 1998). Four ground stations around the world provide the local oscillator reference, receive and record the IF signal transmitted from the satellite, and provide the spacecraft data to determine the accurate orbit parameters needed to obtain interference fringes. Unfortunately, the 1.3-cm receiver was damaged at the time of launch and has not produced any useful results. At 6 cm, the earth-to-space baselines are only comparable with the VLBA alone at 2 cm, but with considerably less sensitivity and poorer coverage of the Fourier transform plane. The scientific returns from VSOP have therefore been more limited than expected, but the mission has served to validate the technology and to pave the way for future space VLBI missions.

Although the resolution of radio interferometers can be improved less expensively by working at shorter wavelengths on the ground than by placing one of the elements in space, there are several unique advantages of space VLBI: (*a*) the observations of OH, H_2O, and other maser sources must be made at the fixed transition wavelength, so the only way to improve the resolution is to use longer physical baselines; (*b*) for ground-based interferometers, the mutual sky visibility at the two ends of the interferometer becomes limited for baselines more than a few thousand kilometers; (*c*) the motion of the satellite along its orbit and the precession of the orbit provides a denser coverage of the Fourier transform plane than can be obtained with any reasonable configuration of ground antennas alone; (*d*) the increased angular resolution at longer wavelengths provides resolution-matched imaging of the shorter wavelength ground-based VLBI images; (*e*) for a given flux density, the measured brightness temperature, T_b, is proportional only to $(\lambda/\theta)^2$. Because the resolution, θ, is proportional to λ/D, the maximum brightness temperature that can be measured interferometrically depends only on the flux density and baseline length. Coincidentally, for a typical flux density of a few Janskys, an earth-sized baseline can just barely resolve a source at the inverse Compton cooling limit of 10^{12} K (Kellermann & Pauliny-Toth 1969). Baselines significantly greater than an Earth diameter are needed to determine if there are sources that exceed the inverse Compton limit. The TDRSS (Linfield et al. 1989) and HALCA (Bower & Backer 1998) observations suggest brightness temperatures approaching or even exceeding the limiting value of 10^{12} K expected from incoherent synchrotron radiation from a stationary cloud of relativistic electrons. Such superbright sources may be expected if relativistic beaming is important, if the source is not in equilibrium (e.g., Slysh 1992), if the radio synchrotron emission is from relativistic protons rather than electrons, or if the radio emission is due to some coherent process.

5. IMAGE ENHANCEMENT IN RADIO ASTRONOMY

Due to their great efficiency, interferometric arrays have become the instrument of choice for high-resolution studies in radio astronomy. Because all of the field-of-view determined by the primary beam of the individual antennas is observed all the time, they are superior to single large-aperture telescopes that rely on raster scanning. In the radio domain, where the signals can be amplified before division, the sensitivity loss that occurs in the optical regime, owing to signal division, does not apply. Hence, the sensitivity and speed of an array increases greatly with the number of elements in the array.

The fundamental ideas that have had the most influence on the restoration of radio images are CLEAN, phase closure, self-calibration (of which phase and amplitude closure are fundamental components), and mosaicing. We discuss these developments primarily in a historical context. More comprehensive treatments are given by Pearson & Readhead (1984), by Thompson et al. (2001), and in the proceedings of NRAO summer schools edited by Perley et al. (1989), Cornwell & Perley (1991), Zensus et al. (1995), and Taylor et al. (1999). The connection with techniques of adaptive optics is described by Cornwell (1989).

5.1. CLEAN

The early interferometry data of radio sources were often interpreted by means of simple model fitting to a small number of Gaussian components. The initial selection of parameters (position, peak intensity, and angular size of each component) was done by inspection of the fringe visibility data for locations of maxima and minima (e.g., Rowson 1963). Final parameters were estimated by a nonlinear least-squares analysis.

In principle, if observations with an interferometer are made at uniform spacings corresponding to the diameter of the individual antenna elements, *d*, out to a maximum dimension, *D*, then the entire field of view of size λ/d can be synthesized at a resolution of λ/D. The response to a point source, or point spread function, is the usual form described by a $J_1(x)/x$ function, where $x = 2\theta D/\lambda$. The sidelobes of the point spread function can be reduced to an arbitrarily low level by application of appropriate weighting or apodizing functions to the visibility data. In actual practice, the coverage of the projected baseline (u,v) plane is very incomplete. Whereas the resolution is set by the longest spacing, the sidelobes can be very strong and widespread, depending on the distribution of the missing spacings.

Jan Högbom (1974) conceived an ingenious scheme to remove the deleterious effects of missing spacings, based on the idea that the image can be approximated as a collection of Gaussian components. While working on the design of the Westerbork Array in Leiden, he developed the algorithm, called CLEAN. CLEAN is implemented in the following way. The point spread function, called the dirty beam, is calculated from the (u,v) plane coverage of the interferometer for a specific set of observations. The dirty image is obtained by direct Fourier transformation of the (u,v) data. The brightest pixel is found in the dirty image, and a scaled replica of the dirty beam is subtracted from it. The process is continued until a desired residual noise level is achieved in the dirty image. The CLEAN image consists of the collection of delta functions built up from the point source subtractions. This image is usually convolved with a Gaussian restoring beam of half-power width λ/D, with the residuals from the dirty map added. The process converges for almost all source distributions as long as the process is carefully monitored and the loop gain in the iteration cycle is kept small. Restoring beams of resolution finer than λ/D are sometimes attempted but generally do not produce desirable results.

CLEAN presupposes that the sky is composed of, or can be approximated by, point sources. It has worked well in radio astronomy, although concerns persist about the uniqueness of CLEAN images. However, in the absence of digitization errors, the Fourier transform of the CLEAN image agrees with the visibility function at the points where it is measured when the effect of the convolving beam is taken into account (Schwarz 1978). CLEAN produces a specific interpolation of the visibility function at (u,v) points where no data are available. Substantial effort has been invested in producing computationally economic implementations of CLEAN (e.g., Clark 1980), and some version of the CLEAN algorithm is routinely used in the processing of schemes for all modern synthesis arrays. An example of a CLEANed image is shown in Figure 2*b*. A related problem in optical astronomy is that of photometry in crowded fields such as those of unresolved stars in globular clusters. The advent of linear photometric detectors has stimulated the development of analysis algorithms such as DAPHOT (Stetson 1987) and DoPHOT (Schechter et al. 1993). These algorithms are similar to CLEAN in that stellar images are iteratively subtracted by use of empirically derived point spread functions.

CLEAN is related to the Lucy-Richardson algorithm (Lucy 1974, Richardson 1972) widely used in optical and infrared astronomy. However, the latter is specifically based on the assumption of Poisson noise in the image. Both are examples of a more general technique of image restoration known as the method of convex projections (e.g., Stark 1987). Other deconvolution schemes, such as the maximum entropy method, have been effectively adapted for use with radio interferometry data (Gull & Daniell 1978, Narayan & Nityananda 1986). Cornwell et al. (1999) have compared the performance of CLEAN and the maximum entropy method.

5.2. Self-Calibration

The reconstruction of celestial images by calculating the Fourier transform of the fringe visibility requires the accurate measurement of the phase as well as the amplitude of the complex visibility function. The early interferometer observations at Caltech were made at relatively short decimeter wavelengths, where the instrumental phase stability was inadequate to accurately reconstruct the source brightness distribution or to determine accurate source positions. It therefore became common practice at Caltech to refer the measured phases to nearby calibration sources with accurately known positions. In this way, it was possible to maintain sufficient phase information to determine relative radio source positions to an accuracy of a few arcseconds (Read 1963, Fomalont et al. 1964, 1967) and to recover their brightness distribution (Maltby & Moffet 1962). With time, instrumental phase stability improved, but as observations moved to shorter and shorter wavelengths, atmospheric phase fluctuations became an important source of error, and it was natural to use the same procedure of phase referencing to remove these atmospheric phase errors (see e.g., Carilli & Holdaway 2000). By contrast, however, the instrumental phase fluctuations in the Cambridge One-Mile Radio Telescope were small, and it was able to track a source continually for 12 hours and produce an image shortly after completion of the observations. Thus, Cambridge workers were slow to appreciate the power of phase referencing to remove atmospheric errors, and as late as 1971 Hinder & Ryle (1971) remarked that irregularities in the troposphere with size scales of the order of 1 km would limit the resolution of radio telescopes to 0.1 to 1 arcsec.

Even with phase referencing, however, there are small errors introduced by any instrumental or atmospheric phase fluctuations that are different along the direction of the calibrator and target source. In practice, even after CLEANing, residual phase and amplitude errors in the measured visibility limit the dynamic range to about 1000:1 (see e.g., Perley et al. 1989).

In the case of the early VLBI observations, the situation was much worse. Although atomic frequency standards had sufficient stability to give interference fringes, they were not sufficiently stable to determine their phase. The analysis of multi-element VLBI observations of fringe visibility amplitude gave simple models of compact radio sources, and the absence of phase information led to the perception that VLBI observations could not make "proper images."

A method that removes the effects of instrumental and atmospheric phase and amplitude variations, generally called self-calibration, has had a revolutionary impact on high-resolution radio imaging, especially from VLBI data. The key idea is that of phase closure, which was first appreciated by Jennison (1951) in his PhD thesis and fully described later (Jennison 1958). The concept is quite simple. Consider a three-element interferometer and an observation of a point source in the absence of instrumental errors. The fringe phase on each of the three baselines is $(2\pi/\lambda)\,\mathbf{D}_{\rm ij}\cdot\mathbf{S}$, where $\mathbf{D}_{\rm ij}$ is the baseline vector linking antennas *i* and *j* and $\mathbf{S}$ is the unit vector in the direction of the source. Because the sum of the three baseline vectors is zero, the sum of the three interferometer phases must also be zero. Now consider a perturbation to the interferometer phases generated by a change in signal phase at one antenna. This might be caused by the passage of a cloud in front of the antenna or a fluctuation in its local oscillator phase. This phase will be impressed on the interferometer phases of the two baselines that link this antenna, but with opposite signs. Hence, the closure phase remains unaffected. If a resolved source is observed, then the relation between the visibility phases, $\Psi_{\rm ij}$, and the measured phases, $\varphi_{\rm ij}$, is $\psi_{12}+\psi_{23}+\psi_{31}=\varphi_{12}+\varphi_{23}+\varphi_{31}$, because any station-dependent instrumental phases are eliminated. Hence, the closure phase gives an accurate measure of the sum of the three visibility phases, unaffected by any phase errors introduced at the individual antennas. Baseline-dependent errors, which are much less important, are not removed by this process.

Later, Twiss et al. (1960) conceived a similar closure relation for amplitudes, which requires four antennas, although some relevant ideas were introduced even earlier by Smith (1952b). If the individual antennas are affected by voltage gain uncertainties, g_i, then the quantity formed from the measured visibility amplitudes, A_{ij}, ($A_{ij} = g_i g_j V_{ij}$), namely, $A_{12} A_{34}/(A_{13} A_{24})$, is independent of the gain uncertainties because the g_i factors divide out. Twiss et al. (1960) used both amplitude and phase closure to obtain error-free information about the fringe visibility. However, little attention was paid to the work of Jennison and Twiss et al, probably because of the rapid development of interferometers with stable electronic components that operated at wavelengths at which atmospheric fluctuations were not a major problem. One exception was a paper by Rogstadt (1968), which generalized the three-antenna phase closure relation to larger arrays and discussed applications to optical interferometry and adaptive optics. VLBI data were severely affected by phase noise problems induced by the atmosphere and by the frequency standards, to such an extent that phase was considered useless in most imaging situations. Rogers et al. (1974) rediscovered the "phase closure" relation and gave it the name. Both they and Fort & Yee (1976) applied it in a limited context to recover VLBI images.

Interestingly, the equivalent concept of phase closure was discovered by X-ray crystallographers in the mid-1950s and called the method of structural invariance (see Hauptman 1986, 1991). In crystallography, although only the amplitude of the diffraction pattern created by an electron distribution can be measured, the phase can be recovered from the constraints of nonnegativity and atomicity of the distribution. The process of solving a system of equations involving structural invariants, which are insensitive to the unknown coordinate origin of the crystal, in order to determine the electron distribution, exactly parallels the process of solving phase closure relations to determine the intensity distribution of an astronomical source.

The first systematic use of the phase information to obtain diffraction-limited images with VLA and VLBI data was by Readhead & Wilkinson (1978) and Cotton (1979), who combined the phase closure relations with CLEAN. This was extended to both amplitude and phase closure by Readhead et al. (1980) in a technique known as hybrid mapping. The basic problem is that while each measurement with an N element array produces $N(N-1)/2$ visibility measurements, there are only $(N-1)(N-2)/2$ independent phase closure relations and $N(N-3)/2$ independent amplitude closure relations. There are not enough closure relations to solve uniquely for the true visibilities. However, for large arrays, a large fraction of the phase and amplitude information is available, namely $(N-2)/N$ and $(N-3)/(N-1)$, respectively. Additional information in the form of approximately N phases and amplitudes (a complex instrumental calibration for each antenna) must be independently supplied. The early applications of imaging algorithms supplied the missing visibility information from an initial model or from a guess. The image constructed by solving for the remaining visibilities, taking a Fourier transform and applying the CLEAN algorithm, were constrained by conditions such as nonnegativity and finite extent, leading to an improved image model. The process was iterated and usually converged after a few cycles.

With the completion of the 27-element (351 baselines) VLA, Schwab (1980) and Cornwell & Wilkinson (1981) focused their attention on the need to associate instrumental errors with antennas rather than with baselines. This led to a generalization of hybrid mapping techniques known as self-calibration, which is equivalent to hybrid mapping but more convenient to implement for arrays with a large number of elements. With large arrays such as the VLBA (10 antennas) and the VLA (27 antennas), about 80% and 92% of the closure information is available, respectively, and the self-calibration procedure nicely converges to produce images with spurious responses less than 0.1%. The basic requirement of the self-calibration method is that the source be detectable within the coherence time of the interferometer to allow the closure relations to be solved. Point sources in the field are not required, but sufficient compact structure must be present to produce detectable fringes on baselines linking all antennas. With this condition, the interferometer operates effectively as a fully coherent instrument for an indefinite integration time and produces images that are essentially fully corrected for atmospheric and instrumental station-dependent errors. An example of images made with these techniques is shown in Figure 2. The only notable limitation is that the absolute amplitude calibration and positional registration of the image are lost through the use of the closure conditions and must be obtained by other methods. Figure 3 illustrates the flow of ideas leading to the development of self-calibration, as described by Ekers (1983).

Although self-calibration corrects for the phase errors that are due to instrumental or atmospheric effects, there has been a renewed interest in using nearby phase calibration sources for VLBI, as was done in the early years of connected-element interferometry. Only now, the emphasis is not on the measurement of the phase but on extending the coherence time to improve sensitivity of VLBI to observe very weak sources (Beasley & Conway 1995). This is particularly important for millimeter wavelength VLBI in which the sensitivity is limited by receiver noise and relatively small antennas and the coherence time is limited by fluctuations in tropospheric propagation.

6. FUTURE GOALS

6.1. Millimeter and Submillimeter Interferometry

During this decade ground-based interferometry will be pushed to the atmospheric limit of about 300 μm (1000 GHz). This effort will build on the experience with the highly successful arrays that operate primarily between 1.4 mm and 3 mm at Hat Creek, Nobeyama, Plateau deBure, and Owens Valley (Ishiguro & Welch 1994). Preliminary interferometric measurements of a few radio sources with the James Clerk Maxwell Telescope (JCMT) and the Caltech Submillimeter Observatory (CSO) (150 m baseline) instruments have already been made at wavelengths as short as 650 μm (460 GHz) (Lay et al. 1997). The submillimeter array of the

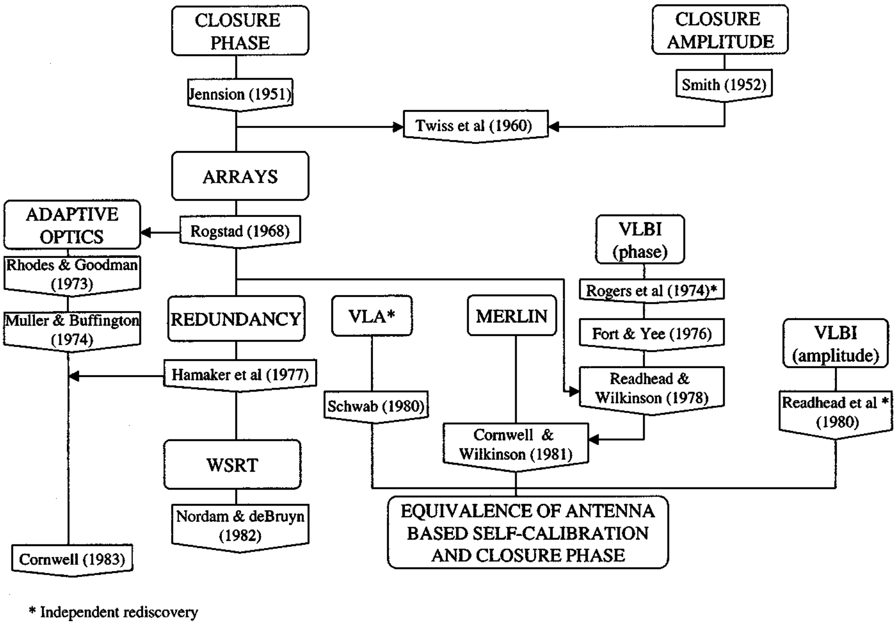

Figure 3 Web of ideas leading to self-calibration in radio and optical astronomy. Adapted from Ekers (1983).

Smithsonian Astrophysical Observatory and Academica Sinica of Taiwan (Moran 1998b) will begin operation on Mauna Kea in the next few years.

The Atacama Large Millimeter Array (Brown 2000), which will be the largest, most expensive, and perhaps the most ambitious ground-based radio astronomy instrument ever constructed, will be built by an international collaboration and will consist of 64 or more antennas with more than 7000 m^2 of collecting area spread over 10 km and covering bands from 350 μm (900 GHz) to1 cm (30 GHz). With 2016 baselines and a bandwidth of 8 GHz, divided into approximately 1 MHz channels to achieve a spectral resolution of 1 km/s, the data rate into the digital processor will exceed 10^{13} samples per second, and the output rate will exceed one terabyte per day.

6.2. Focal Plane Arrays and Digital Processing

Throughout most of their history, radio telescopes have operated with a single feed horn, thus generating one image pixel at a time. Recently, incoherent arrays of up to 144 elements (Mauskopf et al. 2000) and arrays with heterodyne receivers of up to 25 elements (Sunada et al. 2000) have been placed on single-dish instruments, greatly increasing their throughput. The next logical step will be to place arrays of feeds in the focal planes of interferometers to image many fields at once (Fisher & Bradley 2000).

At low frequencies, the goal will be to make the individual elements small. Advanced digital processing techniques, using phased array technology and interferometry, will allow large portions of the sky to be mapped at once with high resolution. Because digital technology now handles rates of 1 Gigabit per sec (Gbs), the concept of a normal heterodyne receiver will be replaced with a direct conversion of the signal from analog to digital form.

6.3. Water Vapor Radiometry

The basic techniques for dealing with atmospheric phase fluctuations involve self-calibration or the use of a nearby phase reference source. Another very promising technique involves estimating the excess phase delay due to the atmosphere above each antenna element from the sky brightness. The variable atmospheric delay, as well as signal attenuation, is almost entirely due to the fluctuations in water vapor, and these quantities are essentially proportional to each other. Hence, the sky brightness is expected to be highly correlated with the phase delay. Tests on millimeter interferometers show that the phase can be corrected, at least over short periods, to an accuracy of at least 150 μm (e.g., Welch 1999). When this technique is refined it will be possible to achieve nearly perfect coherence for indefinite periods without the use of phase closure, which requires a minimum signal-to-noise ratio, or the use of a phase calibration source, which usually is not close enough in angle to the source under study to calibrate the phase (Carilli & Holdaway 2000).

6.4. Real-Time Global Imaging and Other New Initiative

A major challenge for VLBI will be to discard the cumbersome tape recorders. They will be replaced by magnetic disk storage devices and the fiber optic transmission of data. The cost of disk storage devices is dropping dramatically and is now about $10 per gigabyte. Data storage, or buffering, on disks is expected to be less expensive than on tape within a few years (A.R. Whitney, private communication). Data can also be sent to the central correlator directly without buffering on dedicated fiber optic lines or with buffering on a shared broadband fiber optic network. The operation of such a real-time system has been demonstrated with the connection of one of the VLBA antennas (Pie Town) to the VLA via a 105-km-long dedicated fiber. There are plans to build eight new antennas for the VLA distributed around New Mexico to increase the resolution by an order of magnitude and to fill in the missing spacings between the VLA and the VLBA (Perley 2000). These new antennas and eventually the entire VLBA will be interconnected by fiber.

Space VLBI missions being discussed by Russia (RadioAstron), Japan (VSOP2), and the United States (ARISE) will extend the baselines beyond the limits of the Earth's diameter. In India, a novel construction technique has been used to build the Giant Meter Wavelength Telescope consisting of 30 45-m-diameter fully steerable dishes (Swarup et al. 1991). The Giant Meter Wavelength Telescope will offer a powerful new facility for radio astronomy at wavelengths longer than 20 cm. An even more ambitious Low Frequency Array (LOFAR) is being planned by Dutch and US radio astronomers, and there is activity around the world toward planning the next generation radio telescope, the Square Kilometer Array (SKA), with an order of magnitude-greater collecting area than the Giant Meter Wavelength Telescope.

6.5. Optical Interferometry

Many of the ideas discussed here, such as phase-closure and self-calibration, have been recently adopted in optical interferometry, which has been developing at an increasingly rapid pace (e.g., Shao & Colavita 1992, Reasenberg 1998, Lena & Quirrenbach 2000). The concepts of phase-closure and self-calibration have been used to produce images with the Cambridge Optical Aperture Synthesis Telescope in the UK (Baldwin 1996) and the Navy Prototype Optical Interferometer in Arizona (Armstrong et al. 1998). Many other instruments, such as the Very Large Telescope Interferometer and the Keck Interferometer, are in operation or under construction.

ACKNOWLEDGMENTS

We are grateful to our many colleagues with whom we have enjoyed years of stimulating collaborations that have formed part of the basis for this review, and in particular Marshall Cohen, Ron Ekers, Leonid Matveyenko, V. Radhakrishnan, Richard Schilizzi, and Dick Thompson who have provided important material and who gave helpful comments on the manuscript. The National Radio Astronomy Observatory is operated by Associated Universities, Inc. under a cooperative agreement with the National Science Foundation.

LITERATURE CITED

Adgie RL, Gent H, Slee OB, Frost AD, Palmer HP, Rowson B. 1965. *Nature* 208:275–76

Allen LR, Anderson B, Conway RG, Palmer HP, Reddish VC, Rowson B. 1962. *MNRAS* 124:477–99

Anderson B, Donaldson W, Palmer HP, Rowson B. 1965. *Nature* 205:375–76

Anderson JA. 1920. *Ap. J.* 51:263–75

Andreyanov VV, Kardashev NS, Popov MV, Rudakov RZ, Sagdeev VI, et al. 1986. *Astron. Zh.* 63:850–55 (1987. *Soviet Astron.* 30:504–8)

Armstrong JT, Mozurkewich, Rickard LJ, Hutter JA, Benson PF, et al. 1998. *Ap. J.* 496:550–71

Baars JWM, Hooghoudt BG. 1974. *Astron. Astrophys.* 33:323–31

Baldwin JE. 1996. *Astron. Astrophys* 306:L13–16

Barber D, Donaldson W, Miley GK, Smith H. 1966. *Nature* 209:753–55

Bare C, Clark BG, Kellermann KI, Cohen MH, Jauncey DL. 1967. *Science* 157:189–91

Beasley AJ, Conway JE. 1995. See Zensus et al. 1995, pp. 327–43

Bell J. 1967. *The measurement of radio source* *diameters using a diffraction method*. PhD thesis. Univ. Cambridge

Benson JM, Walker RC, Unwin SC, Muxlow TWB, Wilkinson PN. 1988. *Ap. J.* 334:560–72

Blum EJ, Boischot A, Lequeux J. 1963. *Proc. IRE Aust.* 24:208–13

Blythe JH. 1957. *MNRAS* 117:644–51

Bolton JG. 1948. *Nature* 162:141–42

Bolton JG. 1982. *Proc. Astron. Soc. Aust.* 4:349–58

Bolton JG. 1990. *Proc. Astron. Soc. Aust.* 8:381–83

Bolton JG, Gardner PF, Mackey MB. 1963. *Nature* 199:682–83

Bolton JG, Slee OB. 1953. *Aust. J. Phys.* 6:420–33

Bolton JG, Stanley GJ. 1948. *Nature* 161:312–13

Bolton JG, Stanley GJ, Slee OB. 1949. *Nature* 164:101–2

Bolton JG, Stanley GJ, Slee OB. 1954. *Aust. J. Phys.* 7:110–29

Booth RS. 1991. In *Frontiers of VLBI*, ed. H Hirabayashi, M Inoue, H Kobayashi, pp. 131–33. Tokyo: Universal Acad. Press

Bower GC, Backer DC. 1998. *Ap. J.* 507:L117–20

Bracewell RN. 1956a. *Aust. J. Phys.* 9:297–314

Bracewell RN. 1956b. *Aust. J. Phys.* 9:198–217

Bracewell RN. 1958a. *Proc. IRE* 46:97–105

Bracewell RN. 1958b. *Proc. IRE* 46:106–11

Bracewell RN. 1979a. *Annu. Rev. Astron. Astrophys.* 17:113–34

Bracewell RN. 1979b. *J. Comput. Assist. Tomogr.* 1:6–15

Bracewell RN. 2000. *The Fourier Transform and Its Applications*. New York: McGraw-Hill

Bracewell RN, Riddle AC. 1967. *Ap. J.* 150:427–34

Bracewell RN, Roberts JA. 1954. *Aust. J. Phys.* 7:615–40

Brannen E, Ferguson HIS. 1956. *Nature* 178:481–82

Branson NJBA, Elsmore B, Pooley GG, Ryle M. 1972. *MNRAS* 156:377–97

Broderick JJ, Vitkevich VV, Jauncey DL, Efanov VA, Kellermann KI, et al. 1970. *Astron. Zh.* 47:784–86 (*Soviet Astron*. 1971. 14:627–29)

Broten NW. 1988. *J. R. Astron. Soc. Can.* 82:233–41

Broten NW, Clark RW, Legg TH, Locke JL, Galt JA, et al. 1969. *MNRAS* 146:313–27

Broten NW, Legg TH, Locke JL, McLeish CW, Richards RS, et al. 1967a. *Science* 156:1592–93

Broten NW, Legg TH, Locke JL, McLeish CW, Richards RS, et al. 1967b. *Nature* 215:38

Brown GW, Carr TD, Block WF. 1968. *Astrophys. Lett.* 1:89–94

Brown RL. 2000. See Mangum & Radford 2000, pp. 243–50

Burke BF. 1969. *Nature* 223:389–90

Burke BF. 1984. *IAU Symposium No. 110, VLBI and Compact Radio Sources*, ed. R Fanti, K Kellermann, G Setti, pp. 397–403. Dordrecht, The Netherlands: Reidel

Burke BF, Johnston KJ, Efanov VA, Clark BG, Kogan LR, et al. 1972. *Sov. Astron.* 16:379–82

Burke BF, Papa DC, Papadopoulos GD, Schwartz PR, Knowles SH, et al. 1970. *Ap. J. Lett.* 160:L63–68

Burke WR. 1984. *Quasat—A VLBI Observatory in Space*. Noordwijk, The Netherlands: ESA

Cannon WH, Petrachenko WT, Davidson DA, Yen JL, Galt JA, et al. 1982. In *Very Long Baseline Interferometer Techniques*, ed. F Biraud, pp. 443–58. Toulouse, France: Cepadus

Carilli CL, Harris DE. 1996. In *Cygnus A—A Study of a Radio Galaxy*. Frontispiece. Cambridge Univ. Press: New York

Carilli CL, Holdaway M. 2000. *Radio Sci.* 34:817–40

Carlson BR, Dewdney PE, Burgess TA, Casoroso RV, Petrachenko WT, et al. 1999. *PASP* 111:1025–47

Carr TD, May J, Olsson CN, Walls GF. 1965. *IEEE NEREM Rec.* 7:222

Christiansen WN. 1963. *Annu. Rev. Astron. Astrophys.* 1:1–18

Christiansen WN. 1973. *Proc. IEEE* 61:1266–70

Christiansen WN, Erickson WC, Hogbom JA. 1961. *Proc. IRE Aust.* 24:219–25

Christiansen WN, Mathewson DS, Pawsey JL. 1957. *Nature* 180:944–46

Christiansen WN, Warburton JA. 1953. *Aust. J. Phys.* 6:190–202

Christiansen WN, Warburton JA. 1955. *Aust. J. Phys.* 8:474–86

Clark BG. 1965. *Ap. J.* 142:1398–422

Clark BG. 1968. *IEEE Trans. Antennas Propag.* 16:143–44

Clark BG. 1973. *Proc. IEEE* 61:1242–48

Clark BG. 1980. *Astron. Astrophys.* 89:377–78

Clark BG, Cohen MH, Jauncey DL. 1967a. *Ap. J. Lett.* 149:L151–L52

Clark BG, Kellermann KI, Bare CC, Cohen MH, Jauncey DL. 1967b. *Astron J.* 153:705–14

Clark TA, Corey BE, Davis JL, Elgered G, Herring TA, et al. 1985. *IEEE Trans. Geodesy Remote Sensing* 23:438–49

Clarke ME. 1964. *Two topics in radiophysics*. PhD thesis. Cambridge Univ.

Clarke RW, Broten NW, Legg TH, Locke FL. 1969. *MNRAS* 146:381–97

Cohen MH. 1969. *Annu. Rev. Astron. Astrophys.* 7:619–64

Cohen MH. 1980. *A Transcontinental Radio Telescope*. Pasadena, CA: Caltech Press

Cohen MH. 2000. In *Radio Interferometry: The Saga and the Science,* NRAO Workshop No. 27, ed. DG Finley, WM Goss, pp. 173–83. Green Bank, WVA: Natl. Radio Astron. Obs.

Cohen MH, Cannon W, Purcell GH, Shaffer DB, Broderick JJ, et al. 1971. *Ap. J.* 170: 207–17

Cohen MH, Gundermann MH, 1967. *Ap. J. Lett.* 148:L49–51

Cohen MH, Jauncey DL, Kellermann KI, Clark BG. 1968. *Science* 162:88–94

Cohen MH, Kundu MR. 1966. *Ap. J.* 143:621–25

Cohen MH, Moffet AT, Romney JD, Schilizzi RT, Shaffer DB, et al. 1975. *Ap. J.* 201:249–55

Condon JJ, Cotton WD, Greisen EW, Yin QF, Perley RA, et al. 1998. *Astron. J.* 115:1693–716

Cornwell TJ. 1983. In *Joint Topical Meeting on Information Processing in Astronomy and Optics*, pp. FA2-1–4, Washington, DC: Opt. Soc. Am.

Cornwell TJ. 1989. *Science* 245:263–69

Cornwell TJ, Braun R, Briggs DS. 1999. See Taylor et al 1999, pp. 151–70

Cornwell TJ, Narayan R. 1993. *Ap. J. Lett.* 408:L69–72

Cornwell TJ, Perley RA. 1991. eds. *Radio Interferometry: Theory, Techniques, and Applications*, Vol. 19, San Francisco: ASP

Cornwell TJ, Wilkinson PN. 1981. *MNRAS* 196:1067–86

Costain CH, Elsmore B, Whitfield GR. 1956. *MNRAS* 116:380–85

Cotton WD. 1979. *Astron. J.* 84:1122–28

Davies JG, Anderson B, Morison I. 1980. *Nature* 288:64–66

Davies RD, Rowson B, Booth RS, Cooper AJ, Gent H, et al. 1967. *Nature* 213:1109–10

DeJong ML. 1966. *Astron. J.* 71:373–76

Dennett-Thorpe J, deBruyn AG. 2000. *Ap. J. Lett.* 529:L65–68

Dent W. 1965. *Science* 148:1458–60

Eddington AE. 1909. *MNRAS* 69:178–80

Edge DO, Shakeshaft JR, McAdam WB, Baldwin JE, Archer S. 1959. *Mem. R. Astron. Soc.* 68:37–60

Ekers RD. 1983. See Kellermann & Sheets 1983, pp. 154–59

Elgaroy O, Morris D, Rowson B. 1962. *MNRAS* 124:395–403

Elsmore B, Whitfield GR. 1955. *Nature* 176: 457–58

Elsmore B, Kenderdine S, Ryle M. 1966. *MNRAS* 134:87–95

Evans DS, Edwards DA, Frueh M, McWilliam A, Sandmann WH. 1985. *Astron. J.* 90:2360–71

Field G. 1982. *Astronomy and Astrophysics for the 1980's*. Washington, DC: Natl. Acad. Press

Fisher JR, Bradley RF. 2000. See Mangum & Radford 2000, pp. 11–18

Fomalont EB. 1967. *Ap. J.* 157:1027–45

Fomalont EB, Matthews TA, Morris D, Wyndham JD. 1964. *Astron. J.* 69:772–84

Fomalont EB, Wyndham JD, Bartlett JF. 1967. *Astron. J.* 72:445–52

Fort DN, Yee HKC. 1976. *Astron. Astrophys.* 50:19–22

Frail DA, Kulkarni SR, Nicastro L, Feroci M, Taylor GB. 1997. *Nature* 389:261–63

Getmanzev GG, Ginzburg VL. 1950. *Zh. Eksper. Teor. Fiz.* 20:347–50

Goddard BR, Watkinson A, Mills BY. 1960. *Aust. J. Phys.* 13:665–75

Gold T. 1967. *Science* 157:302–4

Gordon WE, LaLonde LM. 1961. *IRE Trans. Ant. Prop.* 9:17–22

Gower JFR, Scott PF, Wills D. 1967. *MNRAS* 71:49–144

Greenstein JL. 1972. *Astronomy and Astrophysics for the 1970's*. Washington, DC: Natl. Acad. Sci.

Greisen EW. 2000. In *Radio Interferometry: The Saga and the Science*, NRAO Workshop No. 27, ed. DG Finley, WN Goss, pp. 57–74. Green Bork, WV: NRAO

Gubbay J, Legg AJ, Robertson DS, Moffet AT, Ekers RD, Seidel B. 1969. *Nature* 222:730–33

Gull SF, Daniell G. 1978. *Nature* 272:686–90

Gush HP. 1988 *J. R. Astron. Soc. Can.* 82:221–32

Hanbury Brown R. 1968. *Annu. Rev. Astron. Astrophys.* 6:13–38

Hanbury Brown R. 1983. See Kellermann & Sheets 1983, pp. 133–53

Hanbury Brown R. 1991. *Boffin.* Bristol, UK: Hilger

Hanbury Brown R, Davis R, Allen LR. 1974. *MNRAS* 167:121–36

Hanbury Brown R, Jennison RC, Das Gupta MK. 1952. *Nature* 170:1061–63

Hanbury Brown R, Palmer HP, Thompson AR. 1954. *Nature* 173:945–46

Hanbury Brown R, Twiss RQ. 1954a. *Nature* 177:27–29

Hanbury Brown R, Twiss RQ. 1954b. *Philos. Mag. Ser.* 7, 45:663–82

Hanbury Brown R, Twiss RQ. 1956. *Nature* 178:1447–48

Hanbury Brown R, Twiss RQ. 1957a. *Proc. R. Soc. A* 242:300–24

Hanbury Brown R, Twiss RQ. 1957b. *Proc. R. Soc. A* 243:291–319

Hargrave PJ, Ryle M. 1974. *MNRAS* 166:305–27

Hauptman H. 1986. *Science* 233:178–83

Hauptman H. 1991. *Rep. Prog. Phys.* 54:1427–54

Haynes R, Haynes R, Malin D, McGee D. 1996. *Explorers of the Southern Sky, A History of Australian Astronomy*. Cambridge: Cambrige Univ. Press

Hazard C. 1961. *Nature* 191:58

Hazard C. 1962. *MNRAS* 124:343–57

Hazard C. 1976. In *Methods of Experimental Physics*, ed. L Meeks, pp. 92–117 New York: Academic

Hazard C, Gulkis S, Sutton J. 1968. *Ap. J.* 154:143–422

Hazard C, Mackey MB, Shimmins AJ. 1963. *Nature* 197:1037–39

Heeschen DS. 1981. In *Telescopes for the 1980's*, ed. G Burbidge, A Hewitt, pp. 1–61. Palo Alto, CA: *Annu. Rev.*

Heeschen DS. 1991. See Cornwell & Perley 1991a, pp. 150–59

Heeschen DS. 2000. In *Radio Interferometry: The Saga and the Science*, pp. 48–56, ed. DG Finley, WM Goss. Green Bank, Washington: Washington Assoc. Univ. Inc.

Henny M, Oberholzer S, Strunk C, Heinzel T, Ensslin K, et al. 1999. *Science* 284:296–98

Hewish A. 1963. *Proc. IRE Aust.* 24:225–31

Hewish A, Bell SJ, Pilkington JDH, Scott PF, Collins RA. 1967. *Nature* 217:709–13

Hewish A, Scott PF, Wills D. 1964. *Nature* 203:1214–17

Hey JS. 1973. *The Evolution of Radio Astronomy*. New York: Sci. Hist.

Hey JS, Parsons SJ, Phillips JW. 1946. *Nature* 158:234

Hinder RA, Ryle M. 1971. *MNRAS* 154:229–53

Hirabayashi H. 1988. See Reid & Moran 1988. pp. 449–56

Hirabayashi H, Hirosawa H, Kobayashi H, Murata Y, Edwards PG. 1998. *Science* 281:1825–29

Högbom J. 1959. *The structure and magnetic* *field of the solar corona*. PhD thesis. Cambridge Univ.

Högbom J. 1974. *Astron. Astrophys. Suppl.* 15:417–26

Högbom J, Brouw WN. 1974. *Astron. Astrophys.* 33:289–301

Ishiguro M, Welch WJ. eds. 1994. *Astronomy with Millimeter and Submillimeter Wavelength Interferometry*. Conf. Ser. No. 59. San Francisco: ASP. 431 pp.

Jansky KG. 1933. *Proc. IRE* 21:1387–98

Jennison RC. 1951. PhD diss. Univ. Manchester

Jennsion RC. 1958. *MNRAS* 118:276–84

Jennison RC, Das Gupta MK. 1953. *Nature* 172:996–97

Jennison RC, Das Gupta MK. 1956a. *Philos. Mag. Ser.* 18:55–64

Jennison RC, Das Gupta MK. 1956b. *Philos. Mag. Ser.* 18:65–75

Jewell PR. 2000. *Proc. SPIE* 4015:136–47

Kardashev NS, Pogrebenko SV, Tsarevsky GS. 1980. *Astron. Zh.* 57:634–48 (*Soviet Astron.* 1980. 24:366–73)

Kardashev NS, Slysh VI. 1988. See Reid & Moran 1988, p. 443–46.

Kedziora-Chudczer L, Jauncey DL, Wieringa MH, Walker MA, Nicholson GD, et al. 1997. *Ap. J. Lett.* 490:L9–12

Kellermann KI. 1964. *Ap. J.* 140:969–91

Kellermann KI. 1977. *An Intercontinental Very Long Baseline Array*. Charlottesville, NC: Natl. Radio Astron. Obs.

Kellermann KI. 1992. In *Astrophysics on the Threshold of the 21st Century*, ed. N. Kardashev, pp. 37–51. Philadelphia: Gordon & Breach

Kellermann KI, Clark BG, Bare CC, Rydbeck O, Ellder J, et al. 1968. *Ap. J. Lett.* 153:L209–14

Kellermann KI, Clark BG, Jauncey DL, Cohen MH, Shaffer DB, et al. 1970. *Astron. J.* 161:803–9

Kellermann KI, Cohen MH. 1988. *J. R. Astron. Soc. Can.* 82:248–65

Kellermann KI, Long RJ, Allen LR, Moran M. 1962. *Nature* 195:692–93

Kellermann KI, Pauliny-Toth IIK. 1969. *Ap. J. Lett.* 155:L71–78

Kellermann KI, Sheets B. 1983. *Serendipitous Discoveries in Radio Astronomy*. Green Bank, WVA: Natl. Radio Astron. Obs.

Kellermann KI, Thompson AR. 1985. *Science* 229:123–30

Kellermann KI, Thompson AR. 1988. *Sci. Am.* 258(1):54–63

Knight CA, Robertson DS, Rogers AEE, Shapiro II, Whitney AR, et al. 1971. *Science* 172:52–54

Knowles SH, Waltman WB, Yen JL, Galt D, Fort DN, et al. 1982. *Radio Sci.* 17:1661–70

Korolkov DV, Parijiskii YN. 1979. *Sky Telesc.* 57:324–29

Krauss J. 1976. *The Big Ear.* Columbus, OH: Cygnus

Krichbaum TP, Alef W, Witzel A, Zensus JA, Booth RS, et al. 1998. *Astron. Astrophys.* 329:873–94

Laing RA. 1981a. *MNRAS* 194:301–30

Laing RA. 1981b. *MNRAS* 195:261–324

Lancaster RA. 1991. See Cornwell & Perley 1991a. pp. 165–70

Lay OP, Carlstrom JE, Hills RE. 1997. *Ap. J.* 489:917–27

Lena PJ, Quirrenbach A. 2000. *Interferometry in Optical Astronomy. Proc. SPIE* 4006

Lequeux J. 1962. *Ann. Astrophys.* 25:221–60

Levine JI, Whitney AR. 1980. In *Radio Interferometry Techniques for Geodesy*, pp. 333–36, NASA Conf. Pub. 2115

Levy GS, Linfield RP, Ulvestad JS, Edwards CD, Jordon JF. 1986. *Science* 234:187–89

Levy GS, Linfield RP, Ulvestad JS, Edwards CD, Jordon JF. 1989. *Ap. J.* 336:1098–104

Linfield RP, Levy GS, Edwards CD, Ulvestad JS, Ottenhoff CH, et al. 1990. *Ap. J.* 358:350–58

Linfield RP, Levy GS, Ulvestad JS, Edwards CD, DiNardo SJ, et al. 1989. *Ap. J.* 336:1105–12

Little CG, Lovell ACB. 1950. *Nature* 165:423–24

Lovell ACB. 1957. *Nature* 180:60–62

Lucy LB. 1974. *Astron. J.* 79:745–54

MacDonald GH, Kenderdine S, Neville AC. 1968. *MNRAS* 138:259–311

MacDonald GJF. 1967. *Science* 157:304–5

Mackay CD. 1969. *MNRAS* 145:31–65

MacMahon PA. 1909. *MNRAS* 69:126–27

Maltby P, Moffet AT. 1962. *Ap. J. Suppl.* 7:93–163

Mangum JG, Radford SJE, eds. 2000. *Imaging at Radio Through Submillimeter Wavelengths*. Vol 217, San Francisco: ASP

Matthews TA, Morgan WW, Schmidt M. 1965. *Ap. J.* 140:35–49

Matveyenko LI, Kardashev NS, Sholomitsky GV. 1965. *Radiophysica* 8:651 (*Sov. Radiophys*. 1966. 8:461–63)

Mauskopf PD, Gerecht E, Rownd BK, Edgington SF, Hristov VK, et al. 2000. See Mangum & Radford 2000, pp. 115–23

McCready LL, Pawsey JL, Payne-Scott R. 1947. *Proc. R. Soc.* 190:357–75

Medoff BP. 1987. In *Image Recovery Theory and Application*, ed. H Stark, pp. 321–68. Orlando, FL: Academic

Michelson AA. 1890. *Philos. Mag. Ser.* 5 30:1–21

Michelson AA. 1920. *Ap. J.* 51:257–62

Michelson AA, Pease FG. 1921. *Ap. J.* 53:249–59

Mills BY. 1952a. *Aust. J. Sci. Res. A* 5:456–63

Mills BY. 1952b. *Aust. J. Sci. Res. A* 5:266–87

Mills BY. 1952c. *Nature* 170:1063–64

Mills BY. 1953. *Aust. J. Phys.* 6:452–70

Mills BY. 1981. *Proc. Astron. Soc. Austr.* 4:156–59

Mills BY. 1984. In *The Early Days of Radio Astronomy*, pp. 147–165, ed. WT Sullivan. Cambridge: Cambridge Univ. Press

Mills BY, Aitchinson RE, Little AG, McAdam WB. 1963. *Proc. IRE Aust.* 24:156–65

Mills BY, Little AG, Sheridan KY, Slee OB. 1958. *Proc. IRE* 46:67–84

Mills BY, Slee OB. 1953. *Aust. J. Phys.* 6:272–78

Mills BY, Slee OB. 1957. *Aust. J. Phys.* 10:162–94

Mills BY, Slee OB, Hill ER. 1958. *Aust. J. Phys.* 11:360–87

Mills BY, Slee OB, Hill ER. 1960. *Aust. J. Phys.* 13:676–99

Mills BY, Slee OB, Hill ER. 1961. *Aust. J. Phys.* 14:497–507

Milne DK, Scheuer PAG. 1964. *Aust. J. Phys.* 17:106–27

Minkowski R. 1960. *Ap. J.* 132:908–10

Moffet AT, Gubbay J, Robertson DS, Legg AJ. 1972. In *External Galaxies once Quasi-Stellar Objects*, pp. 228–29. Dordrecht, The Netherlands: Reidel

Moran JM. 1968. *Interferometric observations of galactic OH emission*. PhD thesis. MIT

Moran JM. 1998a. In *Radio Emission from Galactic and Extragalactic Compact Sources*, ed. JA Zensus, GB Taylor, JM Wrobel, pp. 1–10. San Francisco: ASP

Moran JM. 1998b. In *Advanced Technology MMW, Radio and Terahertz Telescopes. Proc. SPIE*, ed. TG Phillips. 3357:208–19

Moran JM, Barrett AH, Rogers AEE, Burke BF, Zuckerman B, et al. 1967a. *Ap. J. Lett.* 148:L69–72

Moran JM, Burke BF, Barrett AH, Rogers AEE, Carter JC, et al. 1968. *Ap. J. Lett.* 152:L97–101

Moran JM, Crowther PP, Burke BF, Barrett AH, Rogers AEE, et al. 1967b. *Science* 157:676–77

Moran JM, Papadopoulos GD, Burke BF, Lo KY, Schwartz PR, et al. 1973. *Ap. J.* 185:535–67

Morris D, Palmer HP, Thompson AR. 1957. *The Observatory* 77:103–6

Morris D, Radhakrishnan V, Seielstad GA. 1963. *Ap. J.* 139:551–59

Muller RA, Buffington A. 1974. *J. Opt. Soc. Am.* 64:1200–10

Napier PJ, Bagri DS, Clark BG, Rogers AEE, Romney JD, et al. 1994. *Proc. IEEE* 82:658–72

Napier PJ, Thompson AR, Ekers RD. 1983. *Proc. IEEE* 71:1295–322

Narayan R. 1992. *Philos. Trans. R. Astron. Soc.* 238:963:94

Narayan R, Nityananda R. 1986. *Annu. Rev. Astron. Astrophys.* 24:127–70

Noordam JE, deBruyn AG. 1982. *Nature* 299:597–600

O'Brien PA. 1953. *MNRAS* 113:597–612

Oliver WD, Kim J, Liu RC, Yamamoto Y. 1999. *Science* 284:299–301

Oswald AA. 1930. *J. Am. Inst. Electr. Eng.* 49:267

Palmer HP, Rowson B, Anderson B, Donaldson W, Miley GK, et al. 1967. *Nature* 213:789–90

Pauliny-Toth IIK, Kellermann KI. 1966. *Ap. J.* 146:634–45

Pauliny-Toth IIK, Preuss E, Witzel A, Genzel R, Kellermann KI, et al. 1978. *Sov. Astron. Lett.* 4:32–35 (*Pisma Astro. Zh*. 1978. 4:64–69)

Pawsey JL, Payne-Scott R, McCready LL. 1946. *Nature* 157:158–59

Pearson TJ. 1975. *MNRAS* 171:475–505

Pearson TJ, Readhead ACS. 1984. *Annu. Rev. Astron. Astrophys.* 22:97–130

Pearson TJ, Unwin S, Cohen MH, Linfield R, Readhead ACS, et al. 1981. *Nature* 290:365–68

Perley RA. 2000. *The Very Large Array Expansion Project*. *Proc. SPIE* 4015:2–7

Perley RA, Dreher JW, Cown JJ. 1984. *Ap. J. Lett.* 285:L35–38

Perley RA, Schwab FR, Bridle AH. 1989. In *Synthesis Imaging in Radio Astronomy II*, ed. RA Perley, FR Schwab, AH Bridle, pp. 287–313. San Francisco: ASP

Perley RA, Cornwell TJ. 1991. See Cornwell & Perley 1991, pp. 184–87

Pilbratt G. 1991. See Cornwell & Perley 1991. pp. 102–6

Pilkington JH, Scott PF. 1965. *MNRAS* 69:183–224

Pooley GG, Kenderdine S. 1968. *MNRAS* 139:5299–550

Preston RA, Burke BF, Doxsey R, Jordon JF, Morgan SH, et al. 1982. In *Very Long Baseline Interferometry Techniques*, ed. F Biraud, pp. 443–58. Toulouse, France: Cepadus

Preston RA, Jauncey DL, Meier DL, Tzioumis AK, Ables J, et al. 1989. *Astron. J.* 98:1–26

Radhakrishnan V, Roberts JA. 1960. *Phys. Rev. Lett.* 4:493–94

Ragland S, Richichi A. 1999. *MNRAS* 302: L13–16

Raimond E. 1996. In *The Westerbork Observatory, Continuing Adventure in Radio Astronomy*, ed. E Raimond, R Genee, pp. 11–51. Dordrecht, The Netherlands: Kluwer

Read RB. 1963. *Ap. J.* 138:1–29

Readhead ACS, Walker RC, Pearson TJ, Cohen MH. 1980. *Nature* 285:137–40

Readhead ACS, Wilkinson PN. 1978. *Ap. J.* 223:25–36

Reasenberg RD. 1998. *Astronomical Interferometry. Proc. SPIE* 3350

Reber G. 1944. *Ap. J.* 100:279–87

Reber G. 1948. *Proc. IRE* 36:1215–18

Reber G. 1958. *Proc. IRE* 46:15–23

Reid MJ, Biretta JA, Junor W, Muxlow TWB, Spencer RE. 1989. *Ap. J.* 336:112–20

Reid MJ, Haschick AD, Burke BF, Moran JM, Johnston KJ, Swenson GW. 1981. *Ap. J.* 239:89–111

Reid MJ, Moran JM, eds. 1988. *The Impact of VLBI on Astrophysics and Geophysics, IAU Symposium 129*. Dordrecht, The Netherlands: Kluwer

Rhodes WT, Goodman JW. 1973. *J. Opt. Soc. Am.* 63:647–57

Richardson WH. 1972. *J. Opt. Soc. Am.* 62:55–59

Richichi A. 1994. In *Very High Angular Resolution Imaging*, ed. JG Robertson, WJ Tango, pp. 71–81. Dordrecht, The Netherlands: Kluwer

Rishbeth H. 1956. *Aust. J. Phys.* 9:494–504

Robertson P. 1992. In *Beyond Southern Skies*, pp. 188–90. Cambridge: Cambridge Univ. Press

Rogers AEE. 1995. See Zensus et al. 1995. pp. 93–115

Rogers AEE. 1970. *Radio Science* 5:1239–47

Rogers AEE, Cappallo RJ, Hinteregger HF, Levine JI, Newman EF, et al. 1983. *Science* 219:51–54

Rogers AEE, Hinteregger HF, Whitney AR, Counselman CC, Shapiro II, et al. 1974. *Ap. J.* 193:293–301

Rogstadt DH. 1968. *Appl. Opt.* 7:585–88

Rowson B. 1963. *MNRAS* 125:177–88

Ryle M. 1949. *Proc. Phys. Soc.* 62:491–99

Ryle M. 1952 *Proc. R. Soc. A* 211:351–75

Ryle M. 1956. *Sci. Am.* 195(3):205–20

Ryle M. 1958. *Proc. R. Soc. A* 248:289–308

Ryle M. 1962. *Nature* 194:517–18

Ryle M. 1972. *Nature* 239:435–38

Ryle J. 1975. *Science* 188:1071–79

Ryle M, Hewish A. 1955. *Mem. R. Astron. Soc.* 67:97–105

Ryle M, Hewish A. 1960. *MNRAS* 120:220–30

Ryle M, Elsmore B, Neville AC. 1965. *Nature* 205:1259–62

Ryle M, Neville AC. 1962. *MNRAS* 125:39–56

Ryle M, Scheuer P. 1955. *Proc. R. Soc. A* 230:448–62

Ryle M, Smith FG. 1948. *Nature* 162:462–63

Ryle M, Smith FG, Elsmore B. 1950. *MNRAS* 110:508–23

Ryle M, Vonberg DD. 1946. *Nature* 158:339–40

Sagdeev RZ. 1984. See Burke 1984, pp. 19–21

Schechter PL, Mateo M, Saha A. 1993. *Publ. Astron. Soc. Pac.* 105:1342–53

Scheuer PAG. 1957. *Proc. Cambridge Philos. Soc.* 57:764–73

Scheuer PAG. 1962. *Aust. J. Phys.* 15:333–43

Scheuer PAG. 1968. *Nature* 218:920–22

Schilizzi RT. 1988a. See Reid & Moran 1988, pp. 127–28

Schilizzi RT. 1988b. See Reid & Moran 1988, pp. 441–46

Schilizzi RT. 1995. See Zensus et al. 1995, pp. 397–408

Schilizzi RT. 1997. *Vistas Astron.* 41:303–5

Schmidt M. 1963. *Nature* 197:1040

Schmidt M. 1968. *Ap. J.* 151:393–409

Schwab F. 1980. *Proc. SPIE* 231:18–24

Schwarz UJ. 1978. *Astron. Astrophys.* 65:345–56

Scott PF, Ryle M. 1961. *MNRAS* 122:389–97

Shakeshaft JR, Ryle M, Baldwin JE, Elsmore B, Thomson JH. 1955. *Mem. R. Astron. Soc.* 67:106–54

Shao M, Colavita MM. 1992. *Annu. Rev. Astron. Astrophys.* 30:457–98

Shapiro D. 1983. *Multidisciplinary Uses of the Very Long Baseline Array*. Washington, DC: Natl. Acad. Press

Shapiro II, Knight CA. 1970. In *Earthquake Displacement Fields and the Rotation of the Earth*, pp. 284–301, ed. L Mansinha, DE Smylie, AE Beck. Dordrecht, The Netherlands: Reidel

Sholomitsky G. 1965. *Astron. Zh.* 42:673–74 (*Sov. Astron.* A–J 1965. 9:516)

Slysh VI. 1963. *Nature* 199:682

Slysh VI. 1965. *Usp. Fiz. Nauk.* 87:471 (*Sov. Phys. Uspekhi* 1965. 8:852)

Slysh VI. 1992. *Ap. J.* 391:453–55

Smith FG. 1950. *Nature* 165:422–23

Smith FG. 1951. *Nature* 168:555

Smith FG. 1952a. *Nature* 170:1065

Smith FG. 1952b. *Proc. Phys. Soc. B.* 65:971–80

Stark H. 1987. *Image Recovery: Theory and Application*. Orlando: Academic

Stetson B. 1987. *Publ. Astron. Soc. Pac.* 89: 191–222

Sullivan W III. 1984. *The Early Years of Radio Astronomy*. Cambridge: Cambridge Univ. Press

Sunada K, Yamaguchi C, Kuno N, Okumura S, Nakai N, Ukita N. 2000. See Mangum & Radford 2000, pp. 19–22

Swarup G. 1971. *Nat. Phys. Sci.* 230:185–88

Swarup G, Kapahi VK, Sarma NVG, Krishna G, Joshi MN, Rao AP. 1971. *Astrophys. Lett.* 9:53–59

Swarup G, Ananthakrishnan S, Kapahi VK, Rao AP, Subrahmanya CR, Kulkarni VK. 1991. *Curr. Sci.* 60:95–105

Swenson GW. 1969. *Annu. Rev. Astron. Astrophys.* 7:353–73

Swenson GW. 1991. See Cornwell & Perley 1991. pp. 160–64

Swenson GW Jr, Kellermann KI. 1975. *Science* 188:1263–68

Taylor GB, Carilli CL, Perley RA. 1999. *Synthesis Imaging in Radio Astronomy*. San Francisco: ASP

Taylor JH. 1967. *Ap. J.* 150:421–26

Taylor JH, DeJong ML. 1968. *Ap. J.* 151:33–42

Thompson AR, Clark BG, Wade CM, Napier PJ. 1980. *Ap. J. Suppl.* 44:151–67

Thompson AR, Moran JM, Swenson GW. 2001. *Interferometry and Synthesis in Radio Astronomy*. New York: Wiley-Intersci. 2nd ed.

Twiss RQ, Carter AWL, Little AG. 1960. *Observatory* 80:153–59

Van de Hulst HC, Muller CA, Oort JA. 1954. *Bull. Astron. Inst. Neth.* 12:117–49

Van de Hulst HC, Raimond E, Woerden H. 1957. *Bull. Astron. Inst. Neth.* 14:16

Van Vleck JH, Middleton D. 1966. *Proc. IEEE* 54:2–19

von Hoerner S. 1964. *Ap. J.* 140:65–79

von Hoerner S. 1966. *Ap. J.* 144:483–95

von Hoerner S. 1967. *Astron. J.* 72:35–47

Weinreb S. 1961. *Proc. IRE* 49:1099

Welch WJ. 1999. *Review of Radio Science 1996–1999*, ed. WR Stone, pp. 787–808. Oxford: Oxford Univ. Press

Whipple FL, Greenstein JL. 1939. *Proc. Natl. Acad. Sci. USA* 23:177–81

Whitford AE. 1939. *Ap. J.* 89:472–81

Whitford AE. 1964. *Ground Based Astronomy: A Ten-Year Program*. Washington, DC: Natl. Acad. Sci.

Whitney AR. 1993. In *Developments in Astrometry and their Impact on Astrophysics and Geodynamics*, ed. II Muller, B Kolaczek, pp. 151–57. Dordrecht, The Netherlands: Kluwer

Whitney AR, Rogers AEE, Hinteregger HF, Knight CA, Levine JI, et al. 1976. *Radio Sci.* 11:421–32

Whitney AR, Shapiro II, Rogers AEE, Robertson DS, Knight CA, et al. 1971. *Science* 173:225–30

Wilkinson PN, Tzioumis AK, Benson JM, Walker RC, Simon RS, Kahn FD. 1991. *Nature* 352:313–15

Williams PJS. 1963. *Nature* 200:56–57

Wolszczan A, Cordes JM. 1987. *Ap. J. Lett.* 320:L135–39

Yen JL. 1988. In *The Impact of VLBI on Astrophysics and Geophysics, IAU Symposium No. 189*, ed. MD Reid, JM Moran, pp. 489–90. Dordrecht, The Netherlands: Kluwer

Yen JL, Kellermann KI, Rayhrer B, Broten NW, Fort DN, et al. 1977. *Science* 198:289–91

Zensus JA, Diamond PJ, Napier PJ. eds. 1995. *Very Long Baseline Interferometry and the VLBA*. Vol 82, San Francisco: ASP

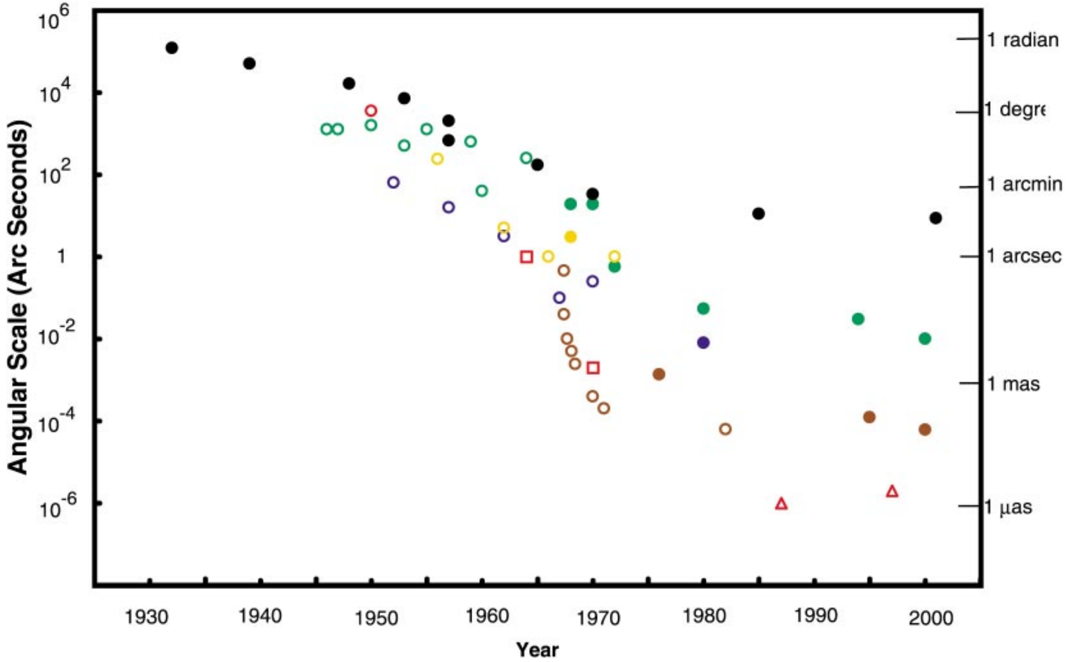

Figure 1 Angular resolution of radio telescopes versus time. Open symbols refer to instruments that were only capable of measuring the overall angular size. Closed symbols refer to imaging instruments. Filled aperture telescopes are shown in black; connected element interferometers and arrays in green; radio-linked interferometers in blue; and independent-oscillator tape-recording interferometers in brown. Lunar occultations are in orange and estimates from ionospheric (◯), interplanetary (□), or interstellar scintillations (△) are in red. In each case, the effective resolution is taken as λ/D for a two-element interferometer, 1.2 (λ/D) for a filled aperture telescope, and 0.7 (λ/D) for a multi-element array. Important performance factors ignored in this presentation include wavelength, collecting area, and sensitivity.

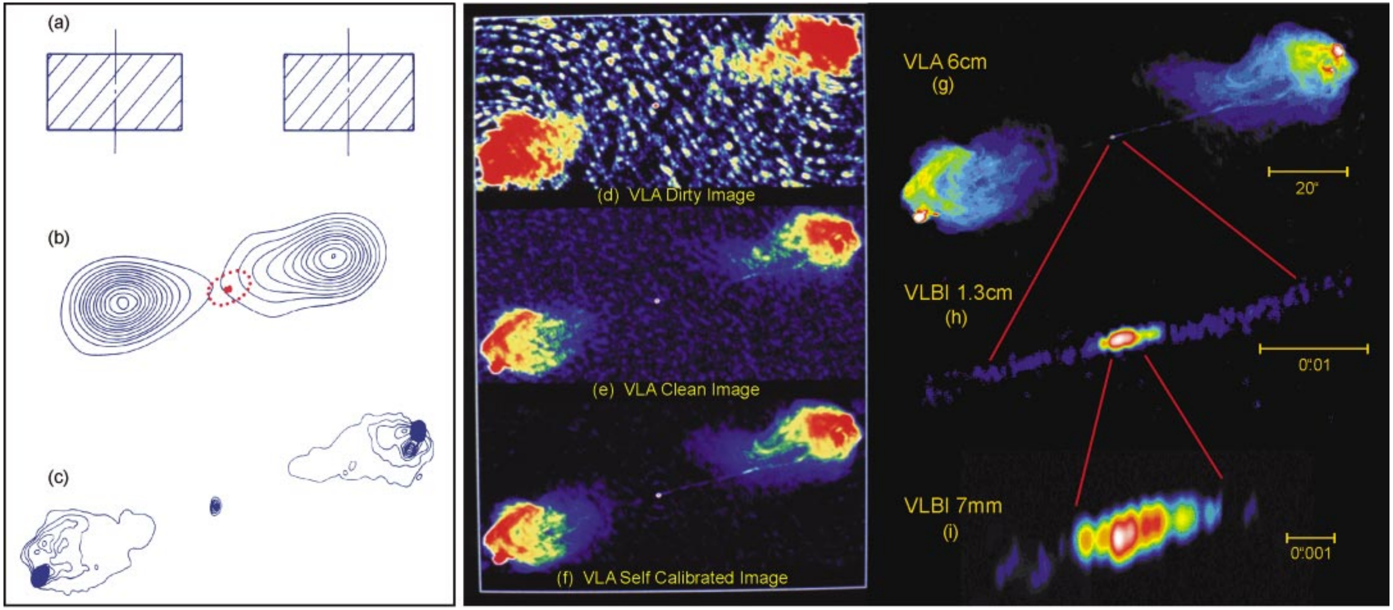

Figure 2 Illustration showing the improvement over the past half century in imaging the radio galaxy Cygnus A. (*a*) The intensity interferometer observations of Jennison & Das Gupta (1953). (*b*) Observations at 20 cm with the Cambridge 1-mile radio telescope (Ryle et al. 1965). (*c*) Observations with the 5-km radio telescope at 6 cm (Hargrave & Ryle 1974). (*d*) 6-cm VLA observations of Perley et al. (1984). (*e*) Same as in (*d*) but with CLEANing. (*f*) Same as (*d*) with CLEANing and self-calibration. (*g*) Self-calibrated CLEAN 6-cm image based on more extensive VLA observations by Carilli and Perley (see Carilli & Harris 1996). (*h*) Image of the nuclear region made with a 13-station global array working at 1.3 cm by Krichbaum et al. (1998). (*i*) The inner region of the nucleus imaged with a resolution of 0.00015 arcsec using an 8-station VLBI array at 7-mm wavelength (Krichbaum et al. 1998). The right hand panel of the figure was provided by T. Krichbaum.

Annual Review of Astronomy and Astrophysics
Volume 39, 2001

CONTENTS