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# The Very Long Baseline Array

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*Summary.* The Very Long Baseline Array is a high-resolution synthesis radio telescope consisting of ten antennas, each 25 meters in diameter, located throughout the United States from Puerto Rico to Hawaii. Each antenna will be equipped with low-noise receivers spaced throughout the frequency range from 330 megahertz to 43 gigahertz, a hydrogen-maser frequency standard for time and frequency reference, and broadband digital tape recorders. Tapes recorded at each antenna will be simultaneously replayed and correlated in a specially built digital correlator, and the correlator output will, by Fourier transformation, be used to construct images of celestial radio sources with an angular resolution better than one thousandth of an arc second.

The earliest radio telescopes had barely enough resolving power to distinguish one constellation in the sky from another, and for many years it was widely accepted that, because radio telescopes operate at such long wavelengths, their angular resolution must be fundamentally poorer than that of optical telescopes.

Actually, this is not the case, for two reasons. First, the resolution of large, ground-based optical telescopes is ordinarily limited to about 1 arc second, not by the size of the telescope but by irregularities in the earth's atmosphere. At radio frequencies, the atmospheric fluctuations in the path length of the incoming signal are small compared with the wavelength of radio waves, so that the effect of atmospheric irregularities is less important. Second, to form clear images, the phase of the signals must be preserved over the entire dimensions of the instrument. Because of their longer wavelength, radio waves are easier to manipulate than light waves, so that radio telescopes of very large size can be built and operated close to the theoretical diffraction limit given by the ratio of wavelength, $\lambda$, to overall array dimensions, $D$.

This history of radio astronomy has been one of ever-increasing angular resolution achieved by increasing the dimensions of the instruments and operating at the highest frequencies (shortest wavelengths) technically feasible. But even the largest single-radio antennas, such as the 100-m steerable reflector near Bonn, Germany, operating at their shortest wavelengths (~1 cm) provide only an angular resolution ($\lambda/D$) of approximately 1 arc minute, which is comparable to that of the unaided human eye ($D$, reflector diameter).

For this reason, radio astronomers long ago turned to interferometric techniques to increase the effective aperture size beyond that feasible from a single structure. A radio interferometer can be regarded as a radio analog of the well-known optical instrument developed by Michelson in the early part of this century to measure stellar diameters. Two antennas, spaced by a baseline of length $D$, are connected to a receiving system (Fig. 1A). After amplification and filtering, the signals are combined in a correlator. The difference $\Delta$ in the path lengths of an incoming wavefront from a distant source determines the delay difference of the two signals and thus their relative phase. Signals of the same phase, which occur when $\Delta$ is an integral number of wavelengths, produce a maximum in the correlator output, and signals in antiphase produce a minimum. With respect to the angle of incidence of the radiation, $\theta$, the response is proportional to

$$F(\theta) = \cos[(2\pi D/\lambda)\sin\theta)] \quad (1)$$

$F(\theta)$ is the fringe pattern shown in Fig. 1B. The fringe spacing varies with the wavelength. Over the finite bandwidth of the receiving system, this variation causes the fringe amplitude to decrease for large values of the relative delay. The corresponding effect in optics is the white-light fringe phenomenon (*1*).

The fine structure in the fringe pattern enables the position and structure of a source to be studied with an angular resolution comparable to the fringe width, which is $\lambda/(D \sin\theta)$ radians. In terms of Fourier analysis, the interferometer responds to the Fourier component of the source with spatial frequency on the sky equal to $(D \sin\theta)/\lambda$ at a position angle given by the projection of the baseline onto the sky. To obtain a full two-dimensional map of a radio source, it is necessary to scan it with fringe patterns covering a wide range of fringe widths and position angles. The rotation of the earth provides part of this required variation because an observer looking down at the earth from the direction of the source sees the position angle of the baseline rotate through 180° in 12 hours (Fig. 1C). Thus the required information can be obtained by using antennas that track a source across the sky, together with different baseline lengths obtained by using a number of antennas or by moving the positions of the antennas and repeating the observation on another day (or both). The range of spatial frequencies included in the measurements is conveniently presented in the Fourier transform plane, which shows the projected interferometer spacings as seen from the direction of the source. Figure 1D shows an example of the form of the coverage for an array consisting of three antennas in an east-west line (see Fig. 1C). Although a linear arrangement is

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adequate for mapping sources at high declinations, a two-dimensional array is needed for sources near the celestial equator, where the earth's rotation introduces foreshortening rather than rotation of the baselines.

The measured response to a radio source is expressed in terms of visibility, a complex quantity that represents the magnitude and phase of the fringe oscillations at the interferometer output. The source brightness distribution is reconstructed from the two-dimensional visibility function by an inverse Fourier transformation, a technique known as synthesis mapping (*2*).

The recently completed Very Large Array (VLA) radio telescope gives, for the first time at radio wavelengths, images of high sensitivity with angular resolution and image quality equal to or better than that given by optical telescopes. The VLA consists of 27 antennas, each 25 m in diameter, located at intervals along the three linear arms of a Y-shaped configuration. The arms run outward from the array center at 120° intervals in azimuth and extend to 21 km. A double railroad track allows the nine antennas on each arm to be moved between four sets of foundations to provide four configurations with arm lengths ranging from 600 m to 21 km. With the largest configuration, the resolution is better than 1 arc second, which is comparable with that of large optical telescopes at the best observing sites; the lower resolution of the more compact configurations enables extended objects (such as nebulae) to be observed without loss in sensitivity. Circular waveguide is used to carry the phase-reference signal to each antenna and to carry the received signals back to the main control building, where they are combined in a digital correlator. Each of the 351 [(27 × 26)/2] interferometer outputs, corresponding to a different antenna pair, is averaged and sampled at intervals as short as 1 second and then Fourier transformed to produce a high-resolution image.

The VLA is the most powerful radio telescope in the world and has given a tremendous improvement in angular resolution, sensitivity, and image quality over previous radio telescopes (*3, 4*). More than 500 scientists each year use the VLA for a wide variety of extragalactic, galactic, and solar system studies. Of particular interest have been the observations of the radio emission from galaxies and quasars. Up to $10^{53}$ J of energy is found in clouds of relativistic plasma ejected from these objects, and understanding the source of this energy has been one of the most challenging problems of modern astrophysics. Observations made with the VLA indicate that the origin of the energy may be traced to a remarkably compact but highly luminous core found in quasars and in the nuclei of active galaxies, from which long thin jets extend up to millions of light years toward the giant extended radio clouds (*5*). These compact nuclei radiate as much as $10^{39}$ W (the radio power of 100 million normal galaxies) from a volume of space only a few light years across, or about $10^{-9}$ of the volume of the Milky Way system (see Fig. 2).

The angle subtended by the radio nuclei is very small, typically about one-thousandth of an arc second, or a factor of 100 to 1000 beyond the resolution limit of the VLA. In order to obtain radio pictures on this angular scale array, dimensions comparable to the radius of the earth are needed. However, for dimensions much larger than those of the VLA, physical interconnections of antennas by transmission lines become costly, and there are practical problems of avoiding obstacles such as rivers and hills.

As early as the 1950's, radio astronomers in England and Australia experimented with microwave radio links to connect the distant elements of interferometer systems. Although baselines of more than 100 km were used, there were too few antenna elements to synthesize the structure of radio sources in detail. Several years ago, the Nuffield Radio Astronomy Laboratory at Jodrell Bank brought the multielement radio-linked interferometer (MERLIN) system into operation, which uses up to six simultaneous antennas with overall dimensions of 134 km (*7*). Operating primarily at wavelengths of 18 and 70 cm, MERLIN has been used to investigate the angular structure of radio sources with sizes as small as 0.1 arc second.

In principle, there is no limit to the dimensions that can be achieved with radio links, but the need to install repeaters every 50 km or so would make the cost prohibitive for an array of continental dimensions. Satellite repeaters have been used to distribute a phase-reference signal to distant antennas and to link the received signals at intermediate frequency (IF) to a central station. But the operation of a multielement, broad-bandwidth array would require the full capacity of a modern communications satellite, and so far only experimental satellites have been used for brief periods (*8*).

Fortunately, it is not necessary to have a direct, real-time connection between interferometer elements. A more cost-effective method is to record the IF signals on magnetic tape at each antenna and to transport the tapes to a central facility where they are replayed simulta-

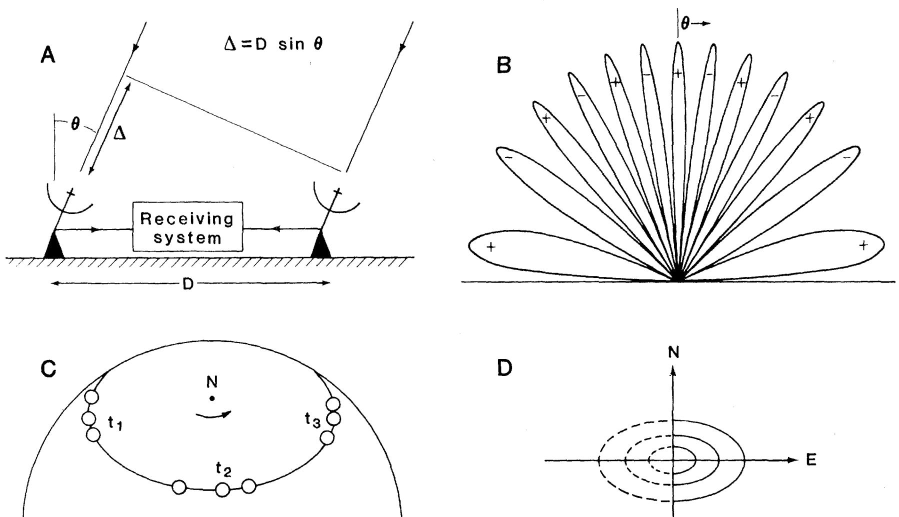


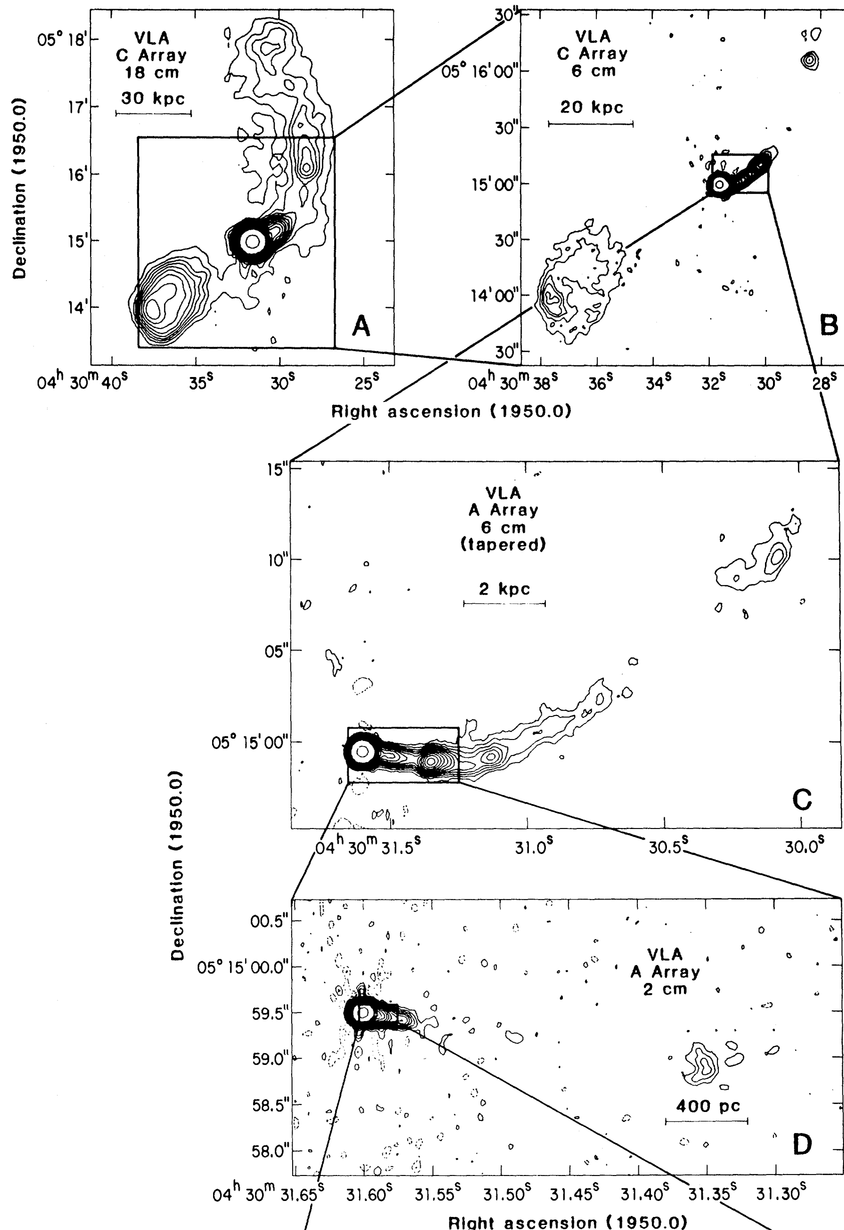

Fig. 1. (A) The two antennas of a basic interferometer showing the differential path length Δ for a wavefront incident at angle θ. The receiving system contains a correlator that forms the time average of the product of the voltages, thus giving the cross-correlation. (B) The form of the fringe pattern given in Eq. 1, which represents the interferometer response to a point source at position θ. In practice, the number of fringes in the 180° interval shown varies from hundreds to more than a million. (C) An east-west array of three antennas as viewed from the direction of a radio source at three instants of time, $t_1$, $t_2$, and $t_3$, showing how the position angle of the baseline changes with time. (D) The projected antenna spacings for the three-element array in (C), N and E being the directions on the celestial sphere. The full lines represent a 12-hour interval; during the remaining 12 hours (indicated by the broken curves), the same spacings and position angles are repeated and no new information is obtained.

neously. Time synchronization of the recordings is provided by atomic frequency standards at each antenna, which also supply a stable reference signal for the local oscillators. This technique of using independent oscillators and tape recorders is known as Very Long Baseline Interferometry (VLBI) and was developed in the late 1960's, primarily in response to the need for ultrahigh resolution to study the compact radio nuclei in quasars and active galactic nuclei (*9*).

Since that time, more than 25 independently operated radio telescopes throughout the world have been used in coordinated VLBI programs, with up to 18 antennas being employed simultaneously. Approximately every 2 months, 1 to 2 weeks are set aside at six or more radio telescopes in the United States for simultaneous VLBI observations. In Europe, similar sessions are scheduled four times per year. Frequently a number of European and North American antennas are combined to form a global network. Regular VLBI observations are also scheduled by NASA, the National Geodetic Survey, and the Jet Propulsion Laboratory for a variety of terrestrial experiments to study global tectonics, polar motion, earth rotation, and time synchronization. Many pioneering discoveries have been reported from these networks of existing antennas, but by 1975 the need for a full-time dedicated array of specially designed and strategically located antennas had become apparent (*10*).

## The VLBA

In 1982, after 7 years of study and evaluation, the National Radio Astronomy Observatory submitted a request to the National Science Foundation to construct a dedicated Very Long Baseline Array (VLBA) to provide high-quality radio images of very small galactic and extragalactic radio sources (*11*). The VLBA is being designed to give resolutions ranging from a few tenths of a milli-arc second to a few hundredths of an arc second, which correspond to the planned wavelength range from about 1 cm to 1 m. The VLBA will consist of ten precision antennas, each 25 m in diameter, located throughout the United States, including Puerto Rico and Hawaii. The configuration of the elements (Fig. 3) has been chosen to optimize the resolution from within the United States while maintaining uniform coverage of projected interferometer spacings to minimize the sidelobes. However, it is also necessary to choose locations that minimize



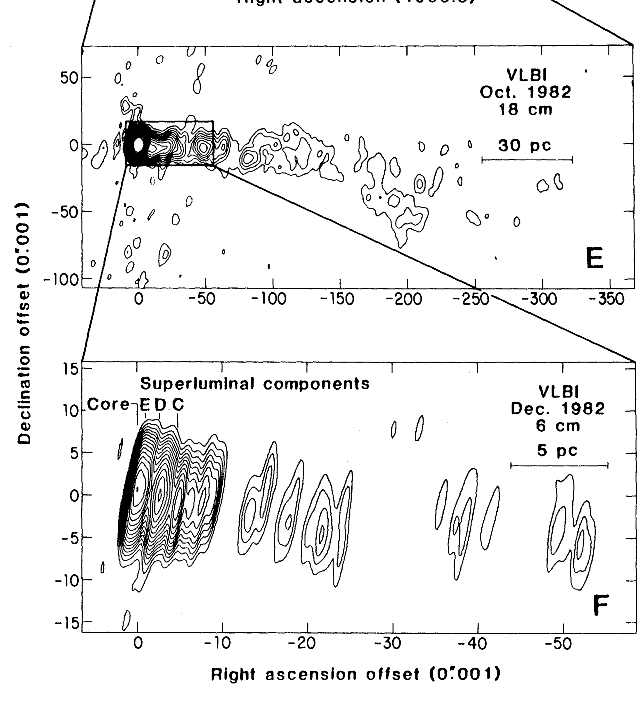




Fig. 2. Structure of the active radio galaxy 3C120 over a wide range of angular scales. The resolution is varied by changing the baseline length and observing frequency. The images shown here were made with maximum baselines of (A) $D/\lambda = 1.9 \times 10^4$ ($D$, 3.4 km; $\lambda$, 18 cm); (B) $D/\lambda = 5.7 \times 10^4$ ($D$, 3.4 km; $\lambda$, 6 cm); (C) $D/\lambda = 6 \times 10^5$ ($D$, 34 km; $\lambda$, 6 cm); (D) $D/\lambda = 1.8 \times 10^6$ ($D$, 34 km; $\lambda$, 2 cm); (E) $D/\lambda = 5.5 \times 10^7$ ($D$, 10,000 km; $\lambda$, 18 cm); and (F) $D/\lambda = 1.7 \times 10^8$ ($D$, 10,000 km; $\lambda$, 6 cm) (*6*).

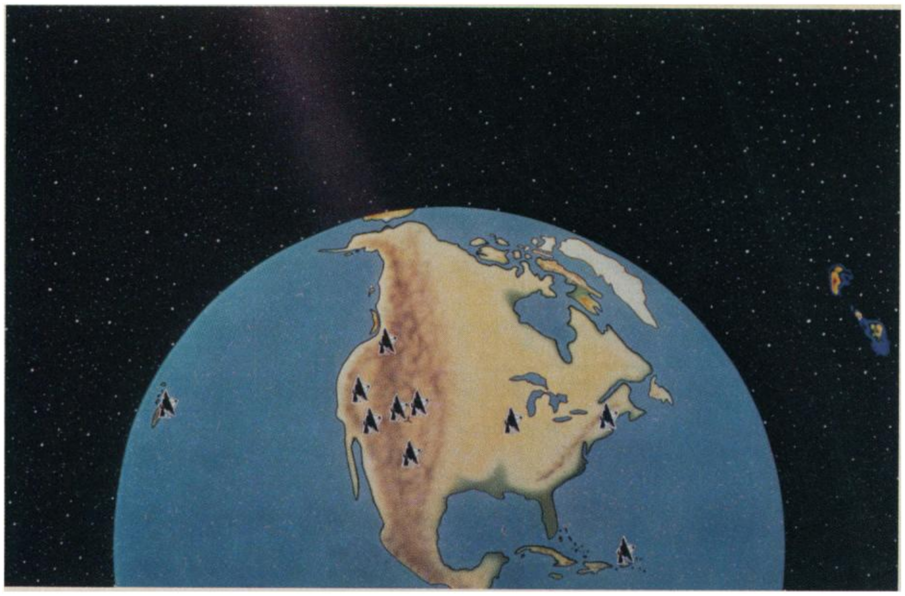


Fig. 3. The VLBA configuration showing the antennas in Hawaii, California, Oregon, Arizona, New Mexico (two), Texas, Iowa, Massachusetts, and Puerto Rico.

radio interference and atmospheric water vapor, which introduce phase fluctuations. Proximity to major transportation centers has been an important consideration and, wherever feasible, sites at existing radio observatories or other sources of technical support have been preferred. Considerable weight has therefore been given to locating as many elements as possible in the relatively dry, cloud-free southwestern United States. It is also desirable that the resolution gap between the VLBA and the largest configuration of the VLA be kept to a minimum. This in particular influences the location of the elements nearest the VLA to allow coordinated observations to be made with the combined VLA and VLBA to cover angular scales that range over a factor of more than 100,000.

Each VLBA antenna will be equipped with radio receiving systems covering assigned radio astronomy bands in the frequency range from 330 MHz to 43 GHz, giving a broad range of resolution and surface brightness sensitivity. The principal bands covered are listed in Table 1. Feeds for 330 and 610 MHz will be located at the prime focus of each antenna, and for the other frequencies feeds will be at the Cassegrain focus. The Cassegrain feeds will be arranged on a circle 1.7 m in diameter, and the subreflector will be mounted so that it can be adjusted under computer control to direct the received radiation to any desired feed element. Each feed will have outputs for opposite senses of circular polarization, and two low-noise amplifiers for each band will allow both polarizations to be received simultaneously. Most of these amplifiers will use gallium arsenide field-effect transistors (GASFET's), and for frequencies above 1 GHz they will be cooled to 15 K by closed-cycle helium refrigerator systems. By cooling the amplifiers, system noise temperatures in the range of 30 K to 70 K can be obtained, thus providing high sensitivity. At the two highest frequency bands, high-electron mobility transistors (HEMT's) and superconductor-insulator-superconductor (SIS) mixers will be used.

Table 1. Sensitivity and angular resolution in various frequency bands.

| Frequency (GHz) | Receiver input state | | System noise temperature (K) | Noise level† | Angular resolution (milli–arc seconds) |
|---|---|---|---|---|---|
| | Type* | Physical temperature (K) | | | |
| 0.312 to 0.342 | GASFET | 300 | 120 | 0.2 | 24 |
| 0.608 to 0.614 | GASFET | 300 | 75 | 0.1 | 13 |
| 1.35 to 1.75 | GASFET | 15 | 30 | 0.04 | 5.4 |
| 2.15 to 2.35 | GASFET | 15 | 35 | 0.04 | 3.5 |
| 4.6 to 5.1 | GASFET | 15 | 35 | 0.04 | 1.6 |
| 8.0 to 8.8 | GASFET | 15 | 45 | 0.06 | 0.9 |
| 14.4 to 15.4 | GASFET | 15 | 65 | 0.08 | 0.5 |
| 22.2 to 24.6 | HEMT | 15 | 70 | 0.1 | 0.4 |
| 42.3 to 43.5 | SIS mixer | 3 | 75 | 0.1 | 0.2 |

*High-electron mobility transistors (HEMT's) may replace the standard GASFET's at other high-frequency bands as development permits. †Root-mean-square noise level for an 8-hour observation, measured in millijanskys (1 millijansky is equivalent to $10^{-29}$ W $m^{-2}$ $Hz^{-1}$).

## Recording System

In recording the signals on tape, a digital rather than an analog representation is almost always used. The signal is then sampled periodically, and the accuracy with which the phase is preserved depends on the timing of the sampler. In a digital system, the accuracy of the tape speed and similar mechanical factors are less critical. For preserving the information in the signal, the sampling frequency should be no less than the Nyquist rate, which is twice the signal bandwidth. Thus, if the received bandwidth is $\Delta f$, the bit rate (number of bits per second) that must be recorded is

$$f_r = 2\Delta f\, n_s \qquad (2)$$

where $n_s$ is the number of bits per sample. The overall sensitivity (signal-to-noise ratio) increases as $\Delta f$ and $n_s$ are increased. In the common situation where the limit on the received bandwidth is imposed by the tape recorder, which limits $f_r$ in Eq. 2, optimum performance is obtained by using two-level or three-level quantization for which $n_s$ is 1 or about 1.6, respectively. In two-level quantization only the sign of the signal voltage is recorded, and information about the magnitude of the voltage is lost. However, the output of the interferometer is the cross-correlation of the signals received in two antennas, which take the form of Gaussian random processes. The effect of two-level quantization in this case is simply the reduction of the output signal-to-noise ratio by a factor of 0.64 relative to that for similar signals without quantization. Because of its simplicity, two-level quantization has been used almost universally in VLBI systems, with the signal bandwidth equal to half the recorded bit rate. However, in cases where the signal bandwidth is limited by factors such as the width of a spectral line or an interference-free frequency band, increasing the number of quantization levels offers an increase in sensitivity.

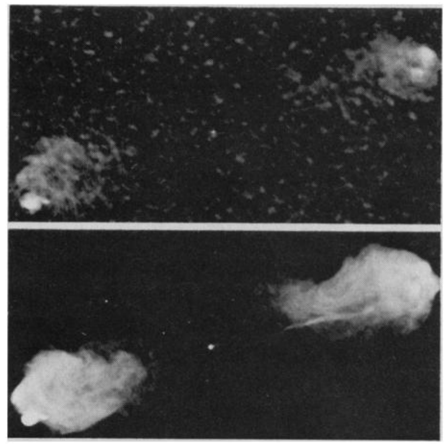
When the first VLBI system went into operation in the United States in the late 1960's, conventional computer tape drives were used, and the recorded bandwidth was restricted to a few hundred kilohertz (*12*). Since that time, in response to commercial and consumer needs, bandwidths and bit densities have increased significantly.

Two VLBI recording systems are in common use today. One, the MKII system, is based on a modified home video cassette recorder (VCR) that is used to obtain 4 hours of uninterrupted digital recording with a sampling rate of 4 megabits per second for a 2-MHz bandwidth with two-level quantization. More than 25 radio telescopes throughout the world have recording systems of this type. The recorded data can be replayed at any one of three processing facilities located at the Max-Planck Institut für Radioastronomie in Bonn, Germany; at the National Radio Astronomy Observatory in Charlottesville, Virginia; and at the California Institute of Technology in Pasadena, California.

The newer MKIII system, developed at the Massachusetts Institute of Technology Haystack Observatory largely under NASA sponsorship, uses a 28-track longitudinal instrumentation recorder to obtain data rates up to 224 megabits per second (112-MHz signal bandwidth) with a tape speed of 270 inches per second. But because the bit density of the MKIII recording system is an order of magnitude less than that of the MKII system, the high data rate is achieved only at the expense of using prodigious amounts of magnetic tape.

In recent experiments at the Haystack Observatory, good signal reproduction has been achieved with narrow recording heads machined from gap bars used to fabricate standard VHS heads for the home VCR market. The VLBA will use 32-track head stacks, with each track 20 $\mu$m wide, writing at a data rate of 4 megabits per second for a recording rate of 128 megabits per second. A piezoelectrically controlled mechanism will be used to reposition the head stack to allow 26 passes of 1-inch-wide tape. In this way a single 16-inch reel of tape (13,000 feet) will last for 8 hours and will hold approximately $3 \times 10^{12}$ bits of information. Even longer recording times may be possible with thinner tapes or larger reels (or both). Tests run with a prototype system at the Haystack Observatory have been successful in keeping the position of the recorded track to within 1 $\mu$m over tape lengths of up to 9000 feet (*13*).

The recording rate of 128 megabits per second will accommodate a total bandwidth of 64 MHz with two-level quantization. Provision will also be made for use of four-level quantization for spectral-line observations. Higher recording rates will be possible for short periods of time to increase the sensitivity for special experiments. The total recorded bandwidth may be subdivided into as many as 16 subbands, over which the received signals can be distributed in frequency and polarization. For example, the most common form of observing is likely to make use of a single frequency band with both senses of circular polarization being received and with half the recorded bandwidth assigned to each one. It will be possible to position the subbands contiguously in frequency or to spread them out over a wide range (up to 500 MHz). It will also be possible to make simultaneous observations in certain pairs of frequency bands.



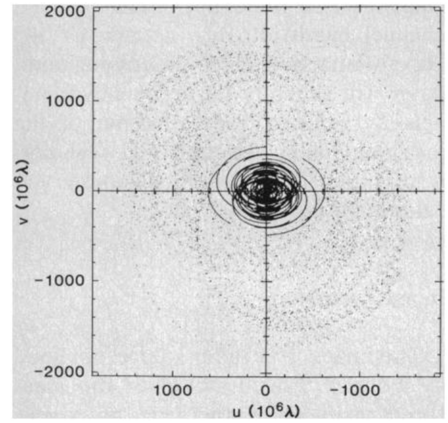



Fig. 4 (left). (Top) Unprocessed image of the radio galaxy Cygnus A obtained with the VLA by Perley, Dreyer, and Cowan. The splotchy background does not represent real structure but is the result of the inability of the VLA to measure the entire Fourier transform of the object. (Bottom) Top image corrected for incomplete coverage of the Fourier transform plane (CLEAN) and atmospheric phase fluctuations (self-calibration). The dynamic range (ratio of peak brightness to root-mean-square noise) has been improved from about 100:1 to 4000:1, and structural details obscured in the top image are now readily discernible. Fig. 5 (right). Coverage of Fourier transform plane of VLBA (solid lines) with proposed extension to space by means of the QUASAT satellite (dotted lines). *u* and *v* are the projected interferometer spacings in wavelengths at a frequency of 22 GHz.

## Time and Frequency Standards

The VLBA will use a hydrogen maser frequency standard at each antenna as an independent time and frequency standard. A hydrogen maser makes use of the well-known line of atomic hydrogen at 21-cm wavelength that is emitted when the spin vector of the electron changes sign relative to that of the proton in the ground-state atom. In the maser molecular hydrogen is dissociated, and atoms with the desired excitation are selected by a magnetic field and passed into a cavity that is resonant at the line frequency of 1420.405 MHz. The resulting stimulated emission provides a signal that is stable in frequency to the order of 1 part in $10^{15}$ for periods up to a few thousand seconds. The maximum possible integration time is set by the requirement that the relative oscillator phase must drift by no more than, say, 0.2 radians. Then at the maximum VLBA frequency $f$ of about 40 GHz, with $0.2/(2\pi f\tau)$ approximately equal to $10^{-15}$, the maximum integration time ($\tau$) is about 1000 seconds.

In maintaining coherence over the entire signal bandwidth, the incoming wavefront must be sampled at the two antennas of each interferometer with an accuracy of the order of the reciprocal bandwidth, and this accuracy must be preserved on playback. With a bandwidth of 50 MHz, time synchronization accurate to 20 nsec is required to detect interference fringes. In actual practice, the signals are combined with a range of possible delays, so that the necessary timing accuracy is easily achieved with hydrogen maser clocks.

## The Playback System

Approximately 7 miles of data tape will be accumulated each day at each antenna element and sent by commercial transport to the VLBA Operating Center in New Mexico, where it will be simultaneously played back and correlated with tapes from each of the other antennas. The processor system will allow for up to 20 playback recorders, so that additional antenna systems in the United States and other countries can be used to enhance the sensitivity and resolution of the VLBA. This processor, which is being developed at the California Institute of Technology, will contain about 50,000 complex digital correlators and will provide playback rates of at least up to 256 megabits per second (bandwidths up to 128 MHz) in the continuum mode. For spectroscopic applications, the received bandwidth can be subdivided into as many as 512 frequency channels with channel bandwidths as narrow as 125 Hz. An attached fringe processing computer will generate the frequency channels by Fourier transformation of the measured delay function and will perform other routine normalization and calibration tasks (*14*).

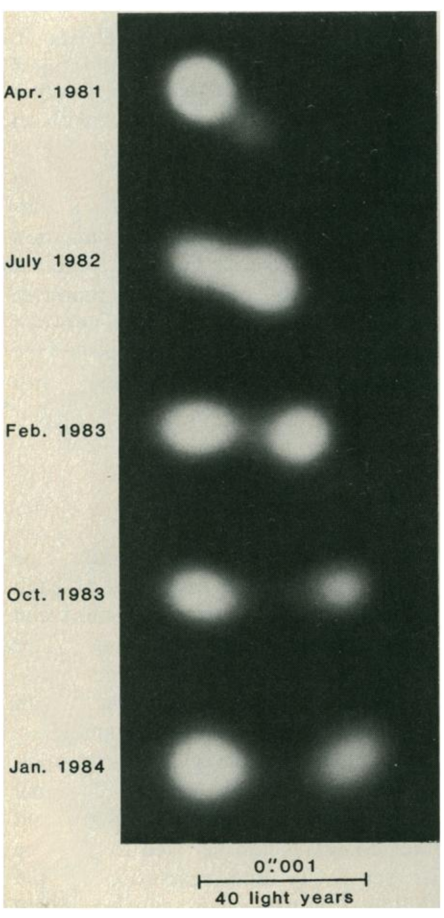
## Image Formation

The image of a radio source obtained by Fourier transformaton of the measured visibility is the true brightness distribution convolved with the synthesized beam pattern, which is the response of the array to a source of infinitesimal angular dimensions. The beam pattern is determined mainly by the range of spatial frequencies covered in the observations (see Fig. 1D) and is derived easily. It is desirable that the beam pattern should have a well-defined main beam with a minimum of sidelobes. This constrains the distribution of the baselines and was a major consideration in selecting the antenna sites. However, with only ten antennas there are sidelobes with amplitudes of the order of 5 percent of the synthesized main beam. Because the pattern of the residual sidelobes is accurately known, their effect on the radio image can be effectively reduced by numerical computation with an algorithm known as CLEAN. In this process the radio image is analyzed into a set of beam patterns (including sidelobes), and then the image is reconstructed with a clean beam (that is, one without sidelobes) (Fig. 4).

The effect of tropospheric and ionospheric irregularities on the signal phase is more serious because the resulting fluctuations are not predictable and are often too rapid to remove by using a separate calibration source, especially at short centimeter and millimeter wavelengths. However, adaptive calibration techniques have been developed that use preliminary images contaminated by phase errors to estimate the unknown phases by iterative procedures. For $N$ antennas there are many more measured interferometer phases, $N(N-1)/2$, than unknown relative antenna phases, $N-1$; because of this, the procedure converges rapidly. Several practical algorithms now exist under the names of "hybrid mapping," "self-calibration," or "adaptive-calibration" (*15*). However, the atmospheric effects are mitigated at the expense of increased computing time because the procedures require many iterations of the basic mapping processes. These procedures are presently in use at the VLA, and the two instruments will largely share the same software and computing facilities.

## Operation

The operation of a radio telescope with elements dispersed over 8000 km presents a number of problems. With the present ad hoc VLBI activities, each antenna is operated by the local resident



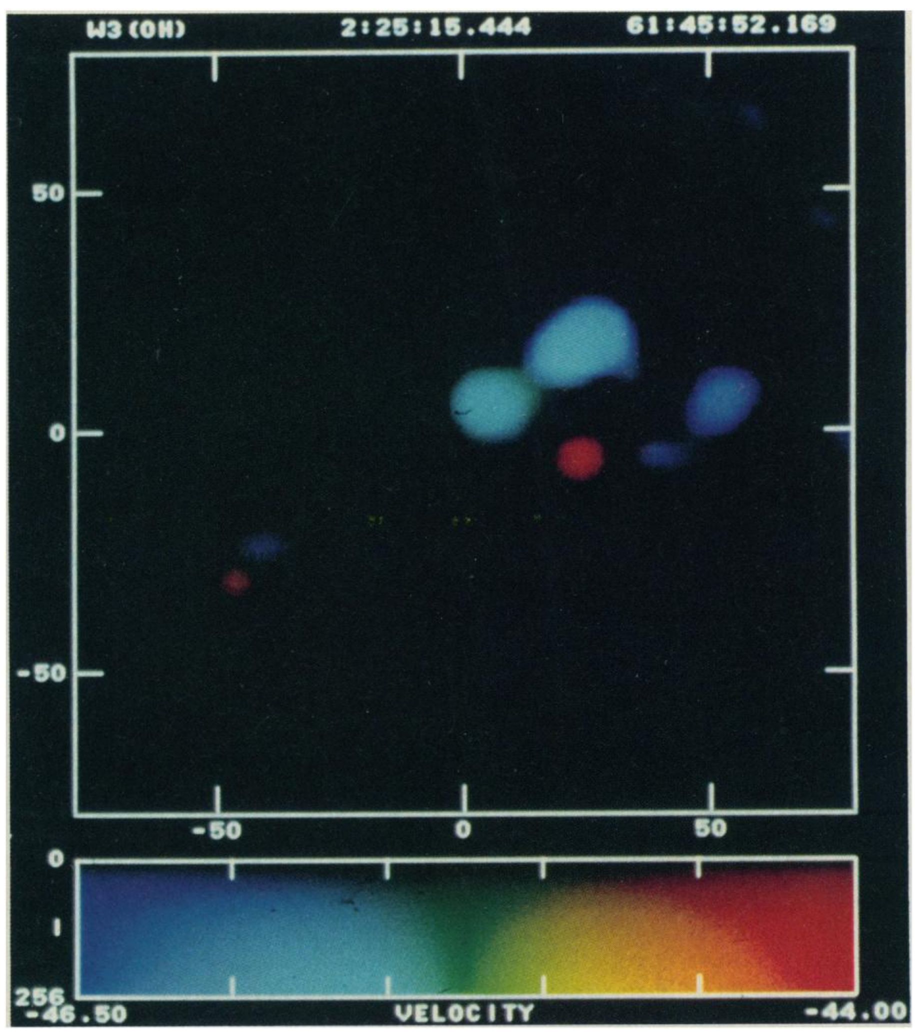




Fig. 6 (left). Five images of the quasar 3C345 showing the increase in separation of 21 light years during a 2.75-year period, or an apparent average expansion velocity of about 8$c$ (*17*). Fig. 7 (right). Image of the OH maser in the envelope of a newly formed star in the constellation Cassiopeia. The colors indicate Doppler velocities of recession increasing from blue to red. Each spot is a maser source emitting radio radiation equivalent to a black body heated to $10^{11}$ K. This image was formed from an eight-station VLBI observation with antennas in Massachusetts, West Virginia, Texas, Illinois, Maryland, California (two), and Canada (*18*).

staff who carry out a prearranged observing program. All the elements of the VLBA will be controlled from an Operations Center in Socorro, New Mexico. This location was chosen to simplify the combined operation with the VLA, including some sharing of personnel and equipment.

Normally, each antenna will be unattended, but a technician-operator will be available at each site for inspection, routine maintenance, and the simpler unscheduled repairs. The local staff will also update the operating systems at the local control computer, change the data tapes, and ship them to the Operations Center and will be responsible for security, emergency intervention, and routine start-up and shut-down procedures.

The Operations Center will provide for major maintenance and repair requiring personnel with special skills, special equipment, or major replacement parts. However, because there are plans to build much of the electronics in modular units and to replace complete modules in the case of failure, most such replacements can be performed easily by the local site personnel. Defective modules will be returned to the Operations Center for repair. This procedure, although requiring a somewhat larger than normal inventory of spare parts, will reduce travel and personnel costs. The modular packaging was used in the design of the VLA and has proved to be highly practical.

The VLBA will be operated by means of a preplanned program under the control of a central computer that will simultaneously monitor the performance of the antennas and receivers as well as the meteorological conditions at each site. An array control operator will be present at all times at the Operations Center to intervene when necessary and to carry out various bookkeeping tasks. From time to time brief samples of the received signal at each antenna will be sent to the Operations Center via telephone lines and correlated in nearly real time to check that all components of the VLBA are functioning properly.

For special experiments, additional antennas such as the VLA and antennas in North America, Europe, Japan, and Australia may be included to increase even further the resolution, sensitivity, and image quality of the array. Of particular importance will be the dedicated VLBI antennas now being constructed in Italy and an array of four to nine elements under discussion in Canada.

These global systems will approach the best practical resolution obtainable from the surface of the earth, but even higher resolution will be possible from space. Plans already exist for a joint European Space Agency–NASA project to orbit a 15-m radio telescope known as QUASAT to operate together with the VLBA and other terrestrial arrays. QUASAT will give a further increase in baseline length over the VLBA by a factor of about 3 (Fig. 5). But perhaps more important, it will be the first step toward larger and more distant antennas in space that will permit even further improvement in resolution.

## Research with the VLBA

Completion of the full VLBA, which will give high-quality radio images with unprecedented angular resolution, is planned for 1990. When completed, the array will allow detailed studies of the tiny energetic cores of galaxies and quasars, as well as pulsars, radio stars, interstellar molecular masers, and other compact sources of radio emission. In addition to astronomical studies, the array will be of importance in geodetics, crustal dynamics, and space navigation.

VLBI observations made with existing radio telescopes have already given a glimpse into the heart of quasars and galaxies, but the nature of the central energy source still remains a mystery. With the VLBA it will be possible to see in detail the dynamics of the energy generation process. Of particular interest will be the apparent faster-than-light motions resulting from the explosive ejection of relativistic material from quasars and galactic nuclei (*16*) (see Fig. 6).

Even within our own galaxy, there are various compact radio stars of interplanetary dimensions that are unresolved by conventional radio telescopes but can be studied with the VLBA. One of the most important problems in galactic astronomy is understanding the life cycle of stars. Clouds of OH, $H_2O$, and SiO are often found in regions where stars are formed and in the atmospheres of very old stars. They are excited by the stellar radiation and act as interstellar masers. High-resolution radio pictures made with the VLBA will be used to probe the dynamics and magnetic fields in these regions on a scale of $10^{13}$ to $10^{18}$ cm and to give information on the birth and death of stars (see Fig. 7).

Hydroxyl radical masers contain magnetic fields of the order of a few milligauss that cause the spectral features to exhibit Zeeman splitting. Observations of this splitting reveal the three-dimensional magnetic field vectors throughout these regions, which give some insight into the manner in which the magnetic field affects cloud collapse and star formation. The high resolution of the VLBA will also extend the range of direct distance measurements by trigonometric parallax. Observations of proper motions will be possible both throughout our galaxy and in other galaxies. This will open up an exciting range of astrometric solutions to the important problems of the structure and rotation of the galaxy.

One type of $H_2O$ maser source contains clusters of hundreds of bright spots whose relative motions are nearly random. The distance to such sources can be determined by statistical parallax methods, that is, by comparison of dispersions of the radial velocity and angular motions. The distances to the maser sources in Orion and W51 (1,600 and 23,000 light years, respectively) have already been measured by this technique with an accuracy of about 20 percent (*19*). With the VLBA it will be possible to make similar measurements on a larger number of objects, including $H_2O$ masers in nearby galaxies, thus extending this relatively direct distance measurement by a factor of about 100. This will have major implications for cosmology because knowledge of the correct scale of the universe will lead to a better understanding of its mass, energy content, age, and eventual evolution.

The VLBA will also be used for a broad range of problems in physics and geophysics as well as for astronomy and astrophysics (*20*). Because the spacing of the interferometer fringes depends on the separation of the antennas, precise analysis of the received signals makes it possible to measure the antenna separations with great accuracy. This measurement has a variety of applications to geodesy and crustal dynamics (plate tectonics). VLBI techniques have already been used to measure transcontinental distances to an accuracy of a few centimeters (*21*), and systematic measurements made over a period of time may well detect the small changes in separation among the various VLBA elements that are due to motions within the earth's crust. Tides in the solid earth amount to several tens of centimeters each day, and the ability to make systematic measurements of their effect will lead to a better understanding of the interior of the earth. In particular, measurements of this type may lead to the predictions of earthquakes and the detection of continental drift over time spans of several years.

Because the directions of the baselines connecting the individual elements can also be determined from the celestial observations, the VLBA may also be used to locate the instantaneous position of the Earth's rotation axis and the wandering of the poles. Accurate determination of the rate of the earth's rotation (time) and a better evaluation of the rate of its slowing down will also be possible.

The VLBA can also be used to measure with great accuracy the relativistic bending of radio signals as they pass close to the sun. Classical optical measurements of stars near the limb of the sun made during times of solar eclipses provided one of the first experimental demonstrations of general relativity. But even now, it is difficult to measure the bending of starlight with an accuracy better than 10 percent. Radio measurements made with connected element interferometers have already given an order of magnitude improvement in accuracy, and the much greater resolution of the VLBA will lead to further improvements. Indeed, the sensitivity to relativistic effects will be so great that even position measurements made 90° away from the sun will need to be routinely corrected for relativistic bending.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# Science and Technology in India


J. S. Rao


India has, throughout history, had a fair share of discoveries in medicine, mathematics, astronomy, metallurgy, and other scientific fields. A great surgeon who lived more than 2000 years ago is said to have used 500 different instruments and accomplished miracles in plastic surgery. The zero was first used in Indian mathematics. The earliest mention and description of various planets and other phenomena in the sky are found in Vedic texts, where the sun, worshipped as the source of energy to our planet, was given the central position in our solar system. Great observatories were built, making possible the tabulation of lunar and solar calendars. On the outskirts of New Delhi is an iron pillar that has stood for more than 1500 years without rust or blemish.

India, once a rich and prosperous country, fell prey to incessant invasions, and its people, weighed down by the opulence of their rulers, were impeded in their quest for innovation. During the period of industrial revolution, when the Western countries flourished with discoveries of science, India was struggling to gain independence. Railways and textile mills were brought to India in 1850's, yet not a single locomotive or textile mill was built there until independence was won in late 1940's.

Independent India's first Prime Minister, Pundit Jawaharlal Nehru, realized the importance of science, particularly its end application to society. He once said (*1*): "What is planning if not the application of science to our problems?" Science and technology have received major emphasis in all 5-year plans in India during the last three decades. Despite the problems that exist in a developing democratic country of large population, there has been considerable progress. For example, (i) the Indian farmer, through a green revolution, made the country self-sufficient in food and even produced exports in small quantities; (ii) the average life-span of an Indian has more than doubled since India's independence; (iii) development of basic heavy industry has placed India today among the ten largest industrialized nations in the world; (iv) India has designed and built nuclear power plants; (v) space programs have been undertaken with emphasis on applications such as long distance telecommunications, community television, and remote sensing of Earth resources and meteorological parameters; (vi) a permanent manned station has been established in Antarctica for scientific studies; and (vii) in the last decade, India has nearly tripled its oil production.

The infrastructure for R&D has had to be totally developed by the government, and a scientific policy resolution was made as early as in 1958. A chain of 42 national laboratories was established under the Council of Scientific Industrial


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