Radio Interferometry at One-Thousandth Second of Arc

Intercontinental interferometer base lines are used to refine our knowledge of compact radio sources.

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The angular resolution of large optical telescopes has always been limited, by atmospheric turbulence, to about 1 second of arc. At this resolution the stars look like points, and structure cannot be measured. This situation was ended when Michelson built the first stellar interferometer, which circumvented some of the turbulence limitations. At radio wavelengths the comparable limit for a telescope is set by the mechanical difficulties inherent in building large structures and is about 1 minute of arc, roughly the same as the limit for the unaided human eye. This resolution is inadequate for many purposes, so the higher-resolution interferometer has also been adapted to radio astronomy. This work has progressed rapidly in the last few years, and now the resolution at radio wavelengths is of the same order of magnitude as the highest ever attained with optical instruments, despite the fact that wavelengths in the two regions differ by a factor of 10^5.

In one simple form, the interferometer consists of two telescopes separated by a distance d. Both telescopes collect radiation ("signals") at wavelength λ from an astronomical source. The two signals are brought together and continuously multiplied. If they are coherent, then the product has regular maxima and minima ("fringes") as the earth rotates, since the rotation changes the relative path lengths and hence the relative phase of the quasi-sinuosoidal signals that are being multiplied. The fringes may also be thought of as the "beat" arising from the fact that radiation from the source is received with slightly different Doppler shifts at the two elements of the interferometer. If the two signals are incoherent, there are no fringes; partial coherence results in a relative fringe amplitude between zero and unity. The degree of coherence, or the fringe visibility γ, depends on the separation of the telescopes and the angular diameter of the source, θ. If the source acts as a point source ($\theta \ll \lambda/d$), γ will be unity; if the smallest component is large enough ($\theta \gg \lambda/d$), γ will be zero. More generally, γ is the Fourier transform of the brightness distribution of the source, a result first derived by Michelson (*1*), although the idea of measuring stellar diameters with an interferometer originated 20 years earlier with Fizeau (*2*). The resolution of an interferometer, therefore, is an angle of the order of λ/d radians in the direction parallel to the base line. All sources smaller than this look alike, and further discrimination is obtained only by decreasing λ or increasing d (or both).

Michelson and Pease, in 1920, were able either to measure or to get limits for the diameter of several stars by using an optical interferometer mounted on the 100-inch (254-centimeter) telescope on Mount Wilson (*3*). Their greatest mirror separation was 6 meters, which, with $\lambda = 5750$ angstroms, gave $\lambda/d \sim 0.02$ second of arc. The technique was apparently very difficult, for during the following half century it has not been successfully extended.

In a simple radio interferometer, the radio-frequency signals are amplified and then fed to a common point for direct multiplication and recording of the amplitude and phase of the fringes. However, it is difficult to transmit the full bandwidth of the received signal at frequencies commonly used in radioastronomy and maintain the required phase stability. It is often the practice, in many radio interferometers, to use a superheterodyne receiver and beat the signals down to some lower, intermediate frequency, generally around 30 megahertz. The output of the interferometer is the product of the coherence of the signals from the radio source and the coherence function of the instrument—essentially the relative coherence of the local oscillators at the two elements. Coherence in the local oscillators, as well as the return of the intermediate-frequency signal, can be conveniently achieved through the use of conventional coaxial cable lines between the two elements. However, for base lines of more than a few kilometers, this becomes impractical and the cost is prohibitive.

In the early 1950's, Hanbury Brown proposed a new type of interferometer which is capable of operation over much longer base lines (*4*). In this system the *phase* of the signals is ignored and only the *intensities* are brought together for multiplication, as the intensity fluctuations still carry information about the coherence. For this reason the instrument became known as an "intensity" or "post-detection" interferometer. Extreme phase stability is no longer required, but a severe price is paid in the signal-to-noise ratio, as it is usually much worse than in the Michelson system. The first measurements on the radio sources Cassiopeia A and Cygnus A were made in 1952 (*5*), and the technique was extended to optical wavelengths in 1956 (*6*). Due to its poor signal-to-noise ratio, use of the technique in radio astronomy has been limited, although a large stellar intensity interferometer operating at 4385 angstroms has been recently put into operation in Australia. The mirrors can be separated by as much as 188 meters to give a resolution better than 0.001 second of arc (*7*).

Long-baseline radio observations with a Michelson interferometer have been made over a period of years by Henry Palmer and his associates at the University of Manchester in England, over distances up to 134 kilometers. By using microwave radio links to carry the local oscillator reference signal and the intermediate-frequency signals, they extended their base lines until, by 1965,

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they were operating with $d/\lambda = 6 \times 10^5$ (127 kilometers at $\lambda = 21$ centimeters) (*8*). In 1966 and 1967 the wavelength was decreased to 11 centimeters ($10^6\ \lambda$) and, for a few sources, to 6 centimeters ($2 \times 10^6\ \lambda$) (*9*).

During the course of the Manchester observations it became clear that there were many radio sources, mostly quasars and a few galaxies with bright nuclei, which contained components having angular dimensions of considerably less than a tenth of a second of arc. At that time there was also strong inferential evidence that many of the same sources were probably very much smaller, with diameters as small as 0.001 second of arc, or less. The three lines of evidence bearing on this were as follows.

1) *Radio-frequency spectra.* The presence of a low-frequency cutoff in the spectra of sources with small components, as interpreted in terms of synchrotron self-absorption, requires angular diameters on the order of 0.01 to 0.001 second of arc.

2) *Secular variations in flux.* Such variations, for some radio sources, have periods of the order of a year. This means that the source cannot be significantly greater than 1 light-year in diameter. On the basis of such variations and the great distance implied by the red shifts, angular diameters of less than 0.001 second of arc are predicted.

3) *Interplanetary scintillations.* Only radio sources of very small angular diameter scintillate when they are observed through the solar wind.

In order to directly resolve these very small sources, interferometers with much longer base lines than those then being used were required. However, straightforward extension of the conventional interferometer seemed to present great difficulties, basically related to the communications link between the elements. Already the 127-kilometer-baseline interferometer with elements at Jodrell Bank and Malvern involved an elaborate radio link, including a relay station. Perhaps an even more difficult problem was the equalization of the arrival time of the signals at the two ends of the interferometer through use of conventional cable or acoustical delay lines; several radio astronomy groups therefore began investigating methods of using independently operated radio telescopes as elements of a widely spaced interferometer through separate recording of the signals at each end of the interferometer. Carr, May, Olsson, and Walls (*10*) were apparently the first workers to successfully use interferometry based on correlation of separate tape recordings of the outputs of the two telescopes. They used this method to study the Jovian dekametric bursts in 1965. The intensity of these bursts was extremely high, and adequate sensitivity was obtained through use of an intensity interferometer, so there was no requirement for coherent local oscillators at the two ends of the base line. More recently, Gubbay and Robertson (*11*) have used a similar technique to measure the fringe visibility of extragalactic source 3C 273 over a 13-million-wavelength base line. Although 3C 273 is one of the strongest extragalactic sources and extremely low noise receivers were used, the inherent low sensitivity of the intensity interferometer permitted only marginal detection of the interference fringes.

By using WWV (the radio station operated by the National Bureau of Standards) as a frequency reference, Brown, Carr, and Block (*12*) were able to use independent recordings to make narrow-band Michelson interferometry measurements on the bursts from Jupiter. This method is inadequate, however, for studying the much weaker emission from extragalactic sources, where much greater oscillator stability and larger bandwidths are required.

For this purpose two wide-band systems were developed, one in the United States and one in Canada (*13, 14*). In both, two highly stable rubidium-controlled oscillators are used, one at each telescope, as independent time and frequency standards. In these oscillators the hyperfine transition of Rb^{87} at a frequency of 6.83468517 gigahertz is used to stabilize the output of a 5-megahertz quartz crystal oscillator. This is done by passing the light from a rubidium lamp through a rubidium vapor cell placed inside a microwave cavity. The cavity is excited at the rubidium transition frequency by a signal derived from the 5-megahertz oscillator. Light from the rubidium lamp acts as an optical pump, raising the rubidium atoms in the vapor cell to an upper energy state. When the radio-frequency signal corresponds exactly to the hyperfine transition frequency, some atoms are de-excited by stimulated emission. The atoms then reabsorb the rubidium light, causing a slight decrease in the intensity of the light falling on a photoelectric detector placed on the other side of the cell. When the radio frequency drifts slightly from the resonance frequency, the current in the photocell changes, producing a signal which is used to control the frequency of the oscillator and bring it back to the resonance frequency.

When independently operated systems are used as elements of an interferometer, there are two requirements on frequency stability. First, the relative phase of the two local oscillators must be stable to within about a radian over the period of integration. Greater phase changes will cause a loss of correlation. Second, the relative time at the two stations must be known to within some fraction of the reciprocal bandwidth, to align the two records for correlation. The R-20 (*15*) rubidium frequency standard used in the U.S. system has a typical stability of about 1 part in 10^{11}, so that at a frequency of 1400 megahertz the phase may be expected to rotate through a whole cycle in about 1 minute. A linear drift in phase, however, is not important, as it is equivalent to a fixed-frequency offset and only shifts the interference fringe frequency (the fringe rate). In practice, integration times of several minutes, at frequencies up to 5 gigahertz, have proved feasible (*16, 17*). It should be noted that the stability requirement is independent of the length of the base line. If the system works in a laboratory test, it will work when the elements are separated by thousands of kilometers. We therefore referred to our system as a "VLB" (very-long-baseline) interferometer.

As for the second requirement, accurate timing, two clocks, controlled by frequency standards, having a relative accuracy of 1 part in 10^{11} may be expected to have a relative drift of about 1 microsecond per day. The most direct means of synchronizing the two clocks, of course, is to synchronize them while they are both at the same location and then carry one to the remote site. Often, however, it is difficult to transport these units by commercial transportation while they are operating. An alternative procedure is to synchronize both clocks with the network of cesium standard clocks which has been established around the world (*18*). In most cases this means that a clock has to be carried a few hundred kilometers. A simpler and less expensive, but less accurate, method is to make use of the widely spread Loran-C navigational stations which broadcast time references at a frequency of 100 kilohertz. At present there are a number of separate chains

Table 1. Long-baseline-interferometer configurations

Telescope location and antenna diameter (m)	Separation between antennas (km)	λ (cm)	d/λ	ψ* (second of arc)	References
NRC† (45.7)–Ottawa‡ (18.3)	183	66.9	2.7×10^5	0.25	(*14*)
NRC (45.7)–Penticton§ (25.6)	3074	66.9	4.6×10^6	.015	(*22*)
Green Bank‖ (42.7)–Maryland Point¶ (25.9)	226	49.2	4.6×10^5	.15	(*13*)
Green Bank (42.7)–Arecibo** (304.8)	2600	49.2	4.7×10^6	.015	(*27*)
Green Bank (42.7)–Haystack†† (36.6)	845	18.0	4.7×10^6	.015	(*21, 24, 31*)
Green Bank (42.7)–Hat Creek‡‡ (25.9)	3500	18.0	1.9×10^7	.0035	(*17, 25, 26, 31, 34*)
Haystack (36.6)–Hat Creek (25.9)	4033	18.0	2.2×10^7	.003	(*31, 34*)
Green Bank (42.7)–Onsala‖‖ (25.9)	6319	18.0	3.5×10^7	.002	(*17, 26, 31*)
Haystack (36.6)–Onsala (25.9)	5600	18.0	3.1×10^7	.002	(*31*)
Hat Creek (25.9)–Onsala (25.9)	7719	18.0	4.3×10^7	.0015	(*31*)
Green Bank (42.7)–Onsala (25.9)	6319	6.0	1.1×10^8	.0006	(*17*)

*ψ = angular resolution on a strong source = $\frac{1}{3}\lambda/d$. †Algonquin Radio Observatory, Ontario (National Research Council), ‡Defense Research Telecommunications Establishment, Ontario, § Dominion Radio Astrophysical observatory, Penticton, British Columbia. ‖ National Radio Astronomy Observatory, Green Bank, West Virginia, ¶Maryland Point Observatory, Md. (Naval Research Laboratory), **Arecibo Ionospheric Observatory, Puerto Rico (Cornell University), ††Haystack Microwave Facility, Mass. (Lincoln Laboratory), ‡‡Hat Creek Radio Observatory, California (University of California), ‖‖Onsala Space Observatory, Sweden (Chalmers University of Technology).

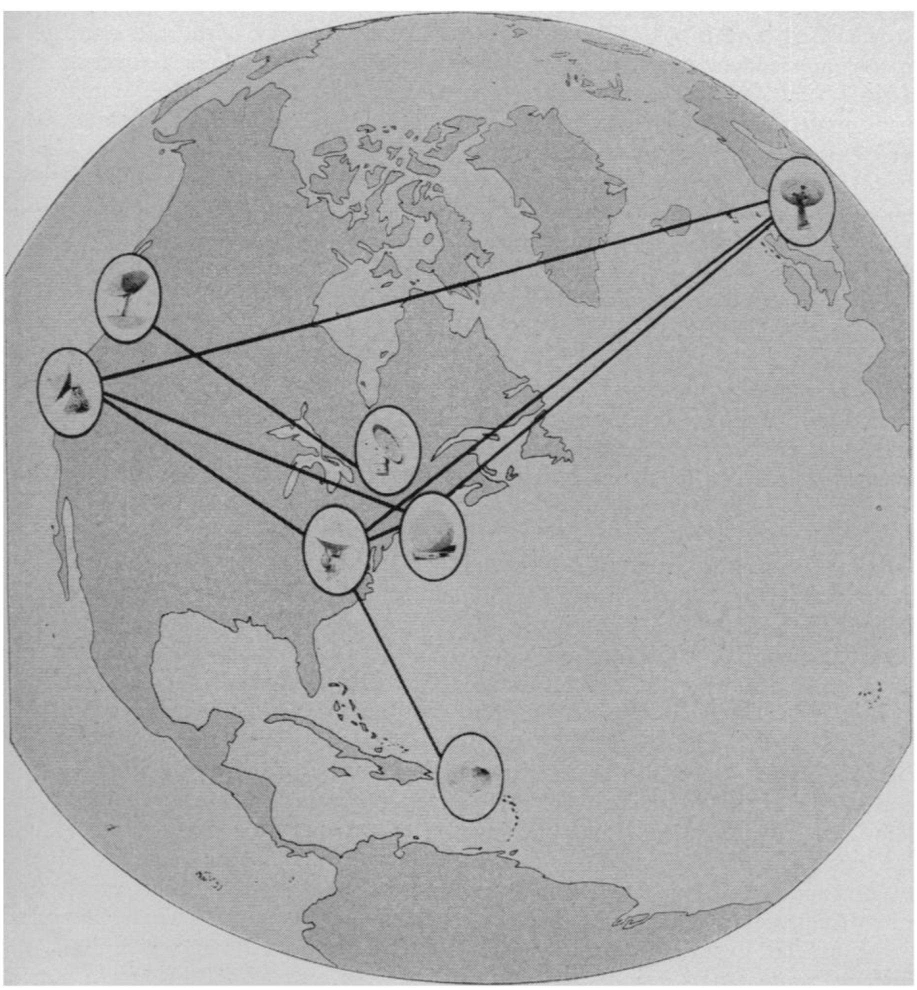

Fig. 1. Diagram showing the various baseline configurations used in the long-baseline-interferometer observations. Details of the individual base lines are given in Table 1. The relatively short base lines between the National Radio Astronomy Observatory (Green Bank) and the Maryland Point Observatory and between the Algonquin Radio Observatory (Ontario) and the Defense Research Telecommunications Establishment (Ottawa) are not shown.

each of which consists of a master station and several "slaves," which are synchronized with the master. Signals from each of these stations can usually be received at distances up to about 2000 kilometers or more under favorable propagation conditions. Due to the uncertainty of the propagation times between transmitter and receiving sites and to the low signal-to-noise ratios, it is difficult to obtain a precision better than a few microseconds.

In both the U.S. and the Canadian VLB systems, the intermediate-frequency signals are recorded on magnetic tape and transported to a common site for subsequent correlation. In the Canadian system the data are recorded in analog form on a modified videotape recorder, originally manufactured for television use. Accurate time signals from the atomic clocks are placed on the records and are used to synchronize the tapes at "playback."

In the U.S. system the data are recorded in digital form. The intermediate-frequency signal is first clipped, so that only the sign of the voltage is preserved, and the one-bit samples are recorded on the magnetic tape. This results in a degradation of the signal-to-noise ratio by a factor of $2/\pi$ (*19*), but provides great efficiency in the storing of information. The sampling rate is determined by the atomic clock, so that each bit represents a precisely defined interval of time. The two tapes are correlated bit-by-bit in a digital computer so that there is no requirement for continuous synchronization of the recorders or of playback units, but only for the assignment of a time to the first bit of each bit stream. The initial time synchronization is obtained by one of the methods discussed above. Although alignment in time to within a fraction of the reciprocal bandwidth (to about 1 microsecond with the 350-kilohertz bandwidths used so far) is required, initial timing errors many times greater than this can be tolerated, since successive time delays can be entered in the computer until the correct value is found. Once this is found, succeeding tapes can be processed more quickly, as the relative clock error over a few hours is less than 1 microsecond.

Timing errors arise not only from imprecision of the clocks at the two stations but also from uncertainties in the geocentric coordinates of the individual telescope elements and the astronomical position of the source. Such errors can also cause a shift in the fringe frequency, as do the offsets in the frequency of the standard oscillators. Thus the data analysis program must look for fringes over a range of frequencies. Furthermore, the effect of any oscillator instability is to broaden the frequency spectrum of the interference fringes, so, in the final analysis, the fringe amplitude is taken as the integral of the observed output over a range of frequencies centered on the expected frequency.

In the system used so far, the sampling rate is 720 kilohertz, which is sufficient for intermediate frequencies up to 350 kilohertz. The recording speed is 150 inches (380 centimeters) per second. This gives about 3 minutes of observing time on a full reel of tape. The reduction of a pair of tapes takes about an hour in an IBM 360/50 computer.

The Canadian system is much more economical of magnetic tape and of computing time. It also has a broader bandwidth, but future models of the digital system will probably take advantage of video-type tape drives to get larger bandwidths also. The broad bandwidth is an advantage for continuum observations because the signal-to-noise ratio is proportional to its square root. It is, however, of no consequence in spectral line observations, since all the energy is in a very narrow band. In the digital system, most of the computing time is taken up by the multiplication; in the Canadian system this is an analog operation, and thus a lot of computer time is saved. It appears, however, that comparable savings could be realized with a digital system, by performing the multiplication in a special-purpose digital correlator.

Results

The first successful trials of both VLB systems were made in the spring of 1967. The Canadian group used, as interferometer elements, the 150-foot dish at the Algonquin Radio Observatory, Ontario, and the 60-foot dish of the Defense Research Telecommunications Establishment near Ottawa, 183 kilometers away (*14*). The U.S. group used the 140-foot dish at the National Radio Astronomy Observatory, Green Bank, West Virginia, and the 85-foot dish at the Maryland Point Observatory of the Naval Research Laboratory, 226 kilometers away (*13*).

Since these first tests, extensive observations have been made over longer baseline configurations and at several other frequencies. Most of these configurations, with telescope locations, are described in Table 1 and shown schematically in Fig. 1.

The best resolution reached so far is about 0.0006 second of arc, achieved on the Green Bank–Onsala base line at a wavelength of 6 centimeters. This is about the angle subtended by a postage stamp in Sweden, as seen from Green Bank. It is comparable to the highest resolution ever achieved at optical wavelengths (*7*).

The observations to date completely confirm the expectation of very small angular sizes for some radio galaxies and quasars. Also, while the VLB was being constructed, it became known, from conventional interferometry, that certain galactic OH-emission regions were very small, indeed less than 1 second of arc in diameter (*20*), and so they were among the first objects to be investigated (*21*). These objects sometimes have components that are less than a hundredth of a second of arc in diameter, separated from each other by about a second of arc. The line emission from each of these components is confined to a very narrow band, in some cases less than 1 kilohertz. One source, W3, still shows strong fringes, as observed over the Hat Creek–Onsala base line, at a wavelength of 18 centimeters and contains a very small component with an angular diameter of about 0.0045 second of arc (*22*), corresponding to a linear diameter of only about 8 astronomical units, less than the diameter of Jupiter's orbit. The brightness temperature of this particular component is about 10^{13} degrees Kelvin.

The radiation from these small intense OH regions is often strongly circularly and linearly polarized, and perhaps variable as well (*23*). These regions have been the subject of great interest and much investigation (see *23*).

The most extensive data on the extragalactic sources are from the Green Bank-to-Haystack (*24*) observations, which had an angular resolution ψ of ~ 0.015 second of arc at a wavelength of 18 centimeters. Fringes were observed on 26 sources, as follows: 18 quasars (NRAO 140, 3C 119, 3C 147, P1055 + 01, P1127-14, P1148-00, 3C 273, 3C 279, 3C 287, 3C 286, 3C 309.1, P1510-08, 3C 345, 3C 380, P2203-18, 3C 446, CTA 102, 3C 454.3); two Seyfert galaxies (3C 84, 3C 120); one radio source in a blank optical field (CTA 21); and five radio sources which have not been identified (P0202 + 14, NRAO 150, NRAO 530, 3C 418, P2127 + 04).

Six sources show fringes on the Green Bank–Hat Creek base line at a wavelength of 18 centimeters (*17, 25, 26*) ($\psi \sim 0.0035$). These are CTA 21, 1127-14, 3C 273, 3C 279, CTA 102, and 3C 454.3. These sources still yield detectable fringes on the Green Bank–Onsala base line (*17*), with a resolution of 0.002 second of arc.

At 6 centimeters ($\psi \sim 0.0006$ second of arc), seven sources (3C 84, 3C 120, 3C 273, 3C 279, 3C 345, 3C 454.3, and 4C 39.25) showed fringes over the same base line. In order to determine directly the radio spectra of these small components, observations are being made over the Green Bank–Arecibo base line at a wavelength of 49.2 centimeters ($\psi \sim 0.015$ second of arc) (*27*).

Interpretation

In most cases the observed fringe visibility, γ, is reduced below unity. This indicates either relatively simple structure, with an angular size $\theta \sim \lambda/d$, or complex structure with a fraction γ of the total flux coming from one or more unresolved components having $\theta < \lambda/d$.

The visibility as a function of spacing may be determined by observing with several different telescopes at different separations, or by making observations at different times of day, thus allowing the rotation of the earth to change the projection of a single base line on the plane of the sky, or by a combination of the two methods. In both cases the base line may cross the line of emission from the source at several different angles, and information is thus obtained about the brightness distribution in different directions.

The visibility curve of the quasar 3C 286—an example of a source with simple structure—is shown in Fig. 2. If 3C 286 has a circular gaussian brightness distribution, then the half-power diameter is 0.029 second of arc. The triangle is a point measured at 69.6 centimeters by Broten *et al.* (*16*); it shows that the gross structure of 3C 286 is independent of wavelength.

A more interesting object in the well-known quasar 3C 273, whose visibility function at 18 centimeters is shown in

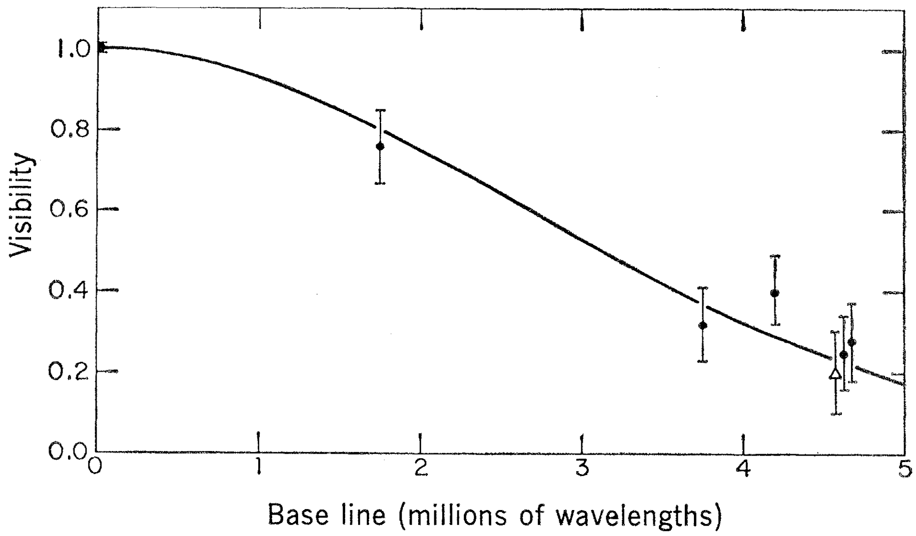

Fig. 2. Visibility function of the quasi-stellar source 3C 286. (Circles) Data points measured at wavelength of 18 centimeters (*24*); (triangle) data point measured at wavelength of 67 centimeters (*16*). The curve is the visibility function of a Gaussian source with a half-power width of 0.029 second of arc.

Fig. 3. From lunar occultation measurements it is found that 3C 273 has two major components (*28*). Component A, which is associated with the optical jet, is about 20 seconds of arc in extent and is completely resolved by the long-base-line observations (that is, no part of the fringes is due to component A because it is too big). The small component, which is coincident with the bright quasi-stellar object, is very complex and has at least three major subcomponents. The fringe visibility curve, shown in Fig. 3, indicates that there is a component (B) which is resolved between zero and 7×10^6 wavelengths. This component contains about half the flux at 18 centimeters and has a diameter of about 0.02 second of arc. The rest of the source is unresolved out to 35×10^6 wavelengths and has a diameter less than 0.003 second of arc. The complex radio spectrum of this small source, shown in Fig. 4, indicates that it is itself made up of several subcomponents each of which becomes optically thick at a different wavelength. One of these subcomponents is partially resolved by the 6-centimeter Green Bank–Onsala observations at 103×10^6 wavelengths. The corresponding diameter is about 0.002 second of arc. The rest of the source is unresolved and therefore has a diameter less than 0.0006 second of arc.

It is generally believed that these compact sources radiate by the synchrotron emission process, which occurs when ultrarelativistic electrons spiral in a magnetic field. At sufficiently low frequencies such a source becomes optically thick, and the radio-frequency spectrum shows a maximum flux when the optical depth is about unity. The frequency at which the optical depth becomes unity (the "cutoff frequency"), the angular size of the source, the strength of its magnetic field, and the peak flux density are related; any three of these parameters uniquely determine the fourth.

Sources of angular diameter greater than about 0.1 second have a very low cutoff frequency, in the range where radio astronomy observations are not easily made. The ability to measure angular sizes in the range 0.001 to 0.01 second thus makes it possible to calculate the value for the magnetic field in extragalactic sources. In cases where such calculation has been possible, the magnetic field is found to be of the order of 10^{-4} gauss.

The discovery of rapid intensity variations in some of these sources was a great surprise, and has been very puzzling. It was a surprise because of the very short time scale of the observed radio-frequency variation, often only a few months. The usual assumption that the linear dimensions of the source cannot greatly exceed the distance traveled by light during the time of the variation gives a maximum dimension and a maximum value for the magnetic field strength. The minimum energy, in terms of relativistic particles, is, then, very large—greater than 10^{58} ergs, or more than 10^8 times the energy released by the most powerful supernovae explosions (*29*). It is difficult to understand the magnitude and frequency of the observed outbursts in such a small volume of space. The situation is even more severe if one considers the inverse Compton radiation expected from such small sources, for which the intensity of the radiation field apparently exceeds 1 erg per cubic centimeter, and it has been suggested that some of these difficulties would be eliminated if the relativistic electrons were expanding at relativistic velocities. The size and the age of the source might then be much greater than the values deduced from the simple travel-time-of-light argument (*30*), and so the required energy would be significantly reduced. The VLB measurements, however, directly confirm the belief that the dimensions of several extragalactic sources are extremely small. The size of one component of the quasar 3C 273, for example, which radiates at a rate of more than 10^{45} ergs per second, is less than 4 light-years. The variable radio source in the Seyfert galaxy NGC 1275 is only about a light-year across. Continuing measurements of the size, during periods of high activity, will define the dynamics of the expansion and the law of variation of the magnetic field, and may specify boundary conditions within which further theoretical speculation must occur. Such observation will also show whether succeeding outbursts occur in precisely the same volume of space or are spatially separated. These observations are not beyond our present capabilities and require only modest increases in resolution over the best now attainable.

Further Applications

Many sources remain unresolved when observed over the longest base line so far used, and it is important to increase the resolution. The present techniques are nearing a limit, however. The Green Bank–Onsala distance is more than 1 earth radius. The maximum base line is, of course, 2 earth radii, but at base lines much greater than 1 radius the problems of looking near the horizon, with very little sky visible from both places at once, may make the experiment more trouble than it is worth. The wavelength of operation can probably be reduced to a few centimeters—that is, reduced by a factor of 2 or 3. At still shorter wavelengths, however, the performance of both antennas and radiometers is degraded, and there may also be problems of atmospheric phase instability. Thus we can expect an improvement in resolution by a factor of about 3 or 4 over the next year or so. The base line then will be about 300 × 10^6 wavelengths long, and the resolution limit will be nearly 10^{-4} second of arc. This will give a resolution of 1 light-year at a distance of 500 megaparsecs, which should be sufficient for studying some variable sources in detail. Still higher resolution can be obtained when we have a terminal in space or on the moon.

The VLB experiments to date have only touched on many potential applications. The technique was originally developed as a means of measuring angular diameters through the use of two widely separated telescopes, but it is easily adapted to simultaneous operation of many independent telescopes at different sites. When n telescopes are used, they provide $n(n-1)/2$ independent base lines, so the efficiency of data collection (but not of data reduction) goes up rapidly with the number of stations. The earth's rotation alters the projected base lines, so observations at different times of day can provide a variety of spacings and orientations.

Multiple-station observations have already begun. In January 1968 four telescopes, located in West Virginia, Massachusetts, California, and Sweden, respectively, were used simultaneously to observe the OH source W3. Fringes were obtained on all six independent base lines (*31*). We can envision, for the near future, many radio observatories scattered about the world, cooperating, through simultaneous observation, to provide crude maps of compact radio sources, with resolutions better than 0.001 second of arc. The cost of such a network is relatively small, since existing radio telescopes are used and it is only necessary to provide a stable oscillator and high-speed tape recorder for each antenna.

Other major improvements in the VLB systems will come from the use of more stable oscillators, such as hydrogen masers, for improved phase stability. Improved sensitivity, expected to be achievable through the use of larger bandwidths and low-noise receivers, will allow study of many more sources. The greater oscillator stability would allow a whole new range of phenomena to come under study. These phenomena relate to very accurate determinations of position and time; some of the possibilities have been discussed by Gold (*32*) and by McDonald (*33*).

The simplest application of the technique, one we are already of necessity making, is clock synchronization at remote locations. The data reduction program automatically shifts the magnetic tapes until maximum coherence is obtained, and this gives the error in one clock (relative to the other) to within a fraction of the reciprocal bandwidth. At present this is a fraction of a microsecond, an accuracy comparable with that obtained by other means, but the error will get smaller as broader-band systems are introduced.

One cannot tell, from a single measurement, whether the error is due to the clock, to errors in the assumed locations of the telescopes, to errors in the assumed angular direction of the radio source, or even to a magnetic storm seriously disturbing the ionosphere over one antenna and not over the other! When we strive for even greater precision, other subtle complications arise, including delays due to normal day-to-night atmospheric changes, refraction, relativistic time dilation due to the difference in the earth's rotational velocity for clocks at different latitudes, and earth tides. Ultimately the stability of the base line, of the angular position of the sources, and of the earth's rotation will enter the picture.

These three sets of parameters, of course, are of very great astronomical and geophysical interest. It is clear that they are interrelated in complex ways, and their unraveling will require patient observations of a grid of radio sources. It seems likely that an improved system would enable us to achieve the following: (i) clock synchronization to within 10^{-8} second; (ii) measures of the length of a day to within 10^{-4} second; (iii) baseline determination to within better than 10 centimeters; (iv)

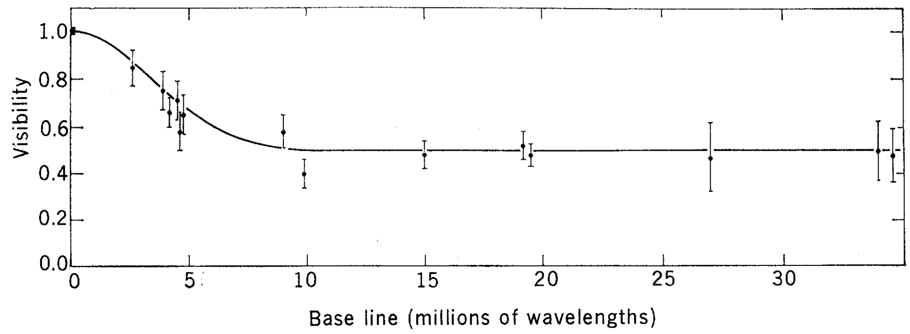

Fig. 3. Visibility function of the quasi-stellar source 3C 273. The curve is the visibility function of a source with half the flux in a "halo" of half-power width 0.023 second of arc and half in an unresolved "core."

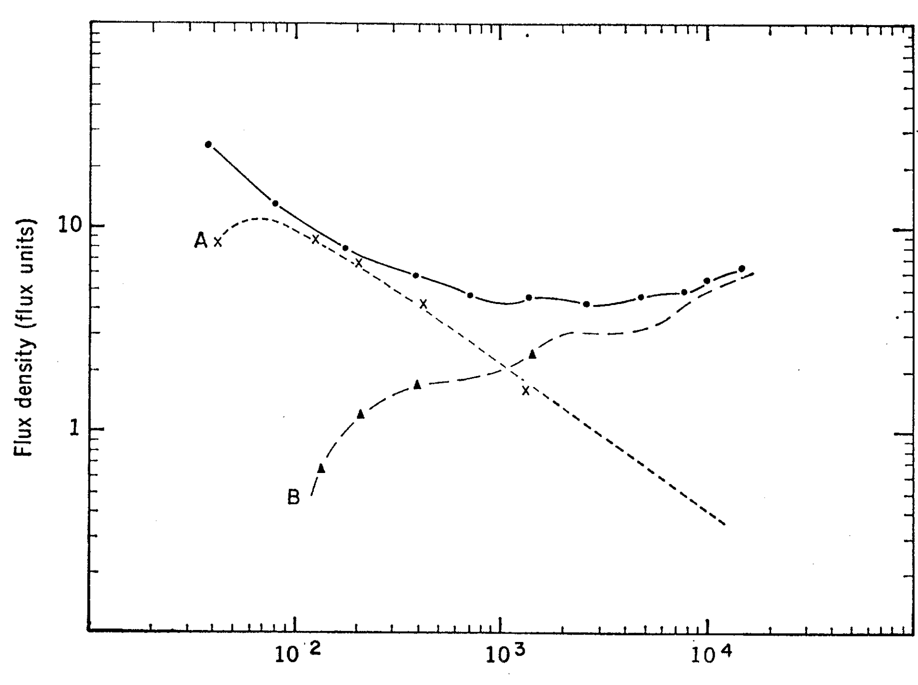

Fig. 4. Radio-frequency spectrum of quasi-stellar source 3C 273.

determination of angular position to within 10^{-3} second of arc.

Accurate measures of the length of a day, and its variation, are of great interest in geophysics, since there are several short-period variations in the rotation rate and in the axis direction which could be studied if such measures were available.

Measurements of distances to within better than 10 centimeters, and their changes across continents and oceans, will tie together the various geodetic systems. Tides in the solid earth and the continental drift can probably be measured directly.

Highly accurate measurements of the positions of radio sources may be very important in astronomy. Some understanding of the origin and mechanism of the sources may be gained through knowledge of the precise relationships between radio and optical features and between different radio components. Measurements of the change in the relative positions of various components will give insight into the dynamics of the multicomponent sources. In particular, proper-motion measurements for the small-diameter OH-emission regions would open up a new and broad field. The motions of the region as a whole could be studied in great detail, as well as the motion of the individual emission centers within a given region. Galactic motions as small as 100 kilometers per second should be detectable within 1 or 2 years.

Positional accuracy to within 0.001 second of arc will also make possible the accurate measurement of the bending of radio waves by the gravitational field of the sun. Such bending, the classical test of general relativity, is only marginally detectable at optical wavelengths during the time of a total solar eclipse. The VLB technique can improve the accuracy of the measurement by more than two orders of magnitude and should make possible a more definitive test of general relativity.

Summary

Atomic oscillators provide sufficient stability to allow use of independent radio telescopes as a coherent interferometer; the data collection is synchronized at the two ends and recorded on magnetic tape for later processing. The required timing accuracy is a fraction of the reciprocal bandwidth, and the phase must be stable to within a radian over several minutes. These requirements are independent of the length of the base line.

Such very-long-baseline interferometers have been operated at various wavelengths down to 6 centimeters and at various base lines up to 7719 kilometers. The highest resolution so far achieved is about 6×10^{-4} second of arc.

Several dozen extragalactic radio sources have been studied with these systems. Most of the sources have several components of different diameter. The observations agree with the synchrotron theory of emission for these sources, which allows calculation of magnetic field from observations of diameter and radio spectrum. Fields of about 10^{-4} gauss have been deduced in this way. The variable radio sources all have very small diameters, generally smaller than the resolution limit when observed over the longest base line used to date. Some OH emission regions in the galaxy also have extremely small angular diameters, and are also being studied.

It will be possible to make a wide variety of geophysical and astronomical investigations with future versions of VLB systems. These investigations will include very precise clock synchronization; accurate measurements of the earth's rotation rate and axis, and of their variation; accurate distance measurements; studies of earth tides and continental drift; highly accurate measurements of the position of radio sources; proper-motion studies; and tests of general relativity.

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