LONG-BASELINE INTERFEROMETRY

Radio telescopes separated by many thousands of kilometers can be operated in pairs to obtain very high angular resolution, suitable for studies of quasars and hydroxyl-line emitters, for geodesy, and for a test of general relativity.

BERNARD F. BURKE

THE RAPID DEVELOPMENT of electronic technology has given man the ability to control electrical events in the time domain with extraordinary precision, just as the mechanical revolution of the last century improved, by orders of magnitude, our power to control linear dimensions of physical objects. Perhaps the only failure in the analogy is quantitative; linear dimensions are now controllable to parts in 10^8, whereas time sequences can be generated and measured to parts in 10^{14}. The modern radio equivalent of Michelson's stellar interferometer is an interesting example of the revival of old mechanical principles in new electronic forms. The first motivation for building radio interferometers was the same as Michelson's: the angular resolution of sources of electromagnetic radiation. The principal difference lay in the limitation of the conventional techniques, for angular resolution of stars in the visible region of the electromagnetic spectrum is limited to a second of arc or so by the irregular refracting properties of the atmosphere, and the diffraction limit of a few minutes of arc for conventional radio telescopes is set by the size of the federal budget.

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Radio interferometers currently in use have baselines of several thousand kilometers (that is, many million wavelengths). For example, the 140-foot (43-meter) telescope at Green Bank, W. Va (shown in figure 1) has been paired with a telescope in Sweden to give a baseline of 110 million wavelengths.

Angular resolution of these arrays is a thousandth of a second of arc or less, so that radio astronomy now has the resolution available for accurate work on quasars and the 18-cm hydroxyl-line emitters. Nearer home, these interferometers could be useful in geodesy (accurate measurement of intercontinental distances) and for synchronizing worldwide time standards. A test of general relativity is available, too, because the gravitational deflection of quasar radiation passing near the sun should be detectable.

Interferometer geometry

The radio interferometer shown in figure 2 differs from the optical form only by its use (usually) of a single receptor. In the optical interferometer the entire interference pattern is displayed in the image space. The radio interference pattern is usually displayed only by motion of the radio source through the reception pattern of the system, in the object space. The two voltages, e_1 (t) and e_2 (t), received by the two antennas, are effectively multiplied at the receiver, and if the two antennas are pointing at a source with dimensions small compared to the primary beamwidth of the individual antennas, the signal at the receiver varies quasi-sinusoidally as the source moves through the interference pattern. The exact geometry is shown in figure 3, which shows the celestial sphere about the earth, with the baseline connecting the two antennas extended to show its intersection with the celestial sphere. The interference fringes lie along small circles about this axis, and as the earth rotates the interference pattern sweeps across the radio source that is being observed. The fringe frequency varies during the day (unless the source is at the celestial pole), and goes through zero frequency, repeating the fringe pattern in a mirror-image representation, after the radio source has travelled tangent to the fringe pattern.

A Fourier transformer

Celestial sources of radio noise come in great variety. Some, like the Crab Nebula, are supernova remnants that can be observed; some are radio galaxies, like Cygnus A, that emit radio noise from a much larger volume of space than the visible galaxy occupies. Some, like pulsars and quasars, are entirely new classes of object, and we would like to understand what they are. In addition there are, apparently, celestial masers that emit line radiation from either hydroxyl radicals (OH) or water molecules or both. In

RADIO TELESCOPE at the National Radio Astronomy Observatory, Green Bank, W. Va. This 140-foot (43-meter) dish has been part of long-baseline systems that include radio telescopes in Massachusetts and Onsala, Sweden. —FIG. 1

all cases the angular sizes are so small that interferometric techniques have been needed to show their structure. The radiation is, in general, polarized, so we have to specify the brightness distribution as a set of four functions $B_i(\alpha,\delta)$ $(i = 1, 2, 3, 4)$ where the angles α,δ are usually taken as the right ascension and declination, although linear coördinates centered on the sources are generally a good approximation.

The essence of the interferometric technique is that it is essentially a Fourier transformer, and the fringe amplitude and phase at any given orientation determine a point on the Fourier transform

$$b_i(u,\nu) \underset{}{\overset{\text{FT}}{\rightleftharpoons}} B_i(\alpha,\delta)$$

The variables u and ν are simply the projection of the baseline on a plane perpendicular to the line of sight, measured in units of the observing wavelength λ. So $u = 2\pi\ (x'/\lambda)$ and $\nu = 2\pi(y'/\lambda)$ where x' and y' are the projected coördinates. The rotation of the earth, therefore, allows us to sample part of the Fourier-transform plane even when the antennas are fixed on the earth, because the projected baseline length and its orientation change. A complete Fourier transform can, therefore, be built up by moving the antennas along a straight track, accumulating a family of transforms at each spacing. A striking use of this technique has been made by the Cavendish group under Sir Martin Ryle,[1] which has published a number of maps of sources, at wavelengths of 21 cm and 75 cm, derived from observations with its one-mile (1.6-km) interferometer. One of the most striking of these, Tycho's supernova,[2] is shown in figure 4, and it is easy to visualize the expanding shell in which the radio noise is produced.

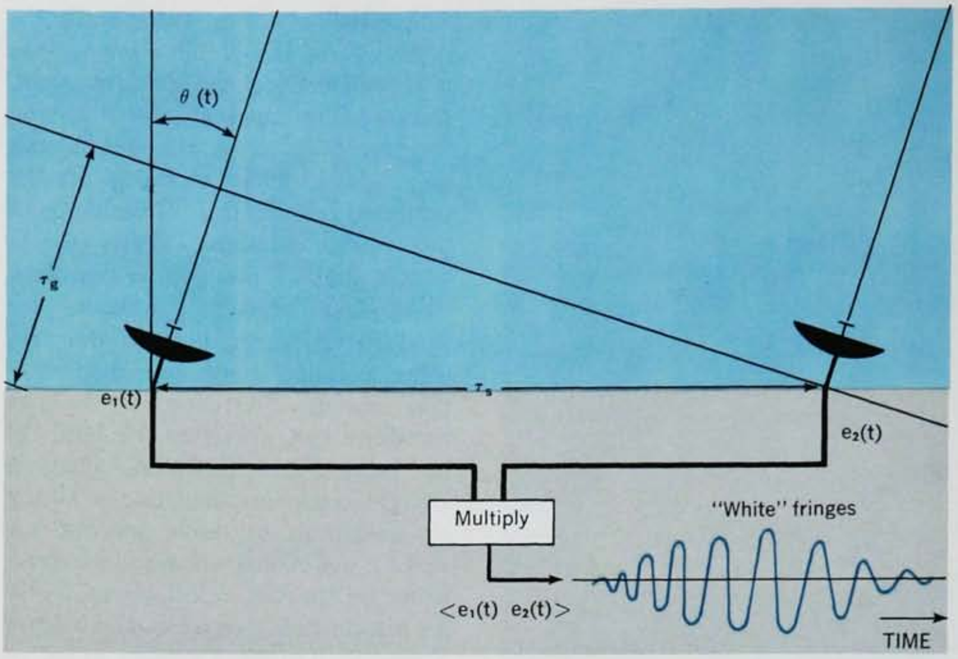
Alternative descriptions

The operation of an interferometer is conventionally described in terms of the alternating constructive and destructive interference of a pair of waves, but there are other ways of describing the action of the system. For example we can make a logically equivalent derivation of the interference pattern by noting that the two elements of an interferometer are located at different places on the earth's surface. Thus the earth's rotation results in different apparent Doppler shifts at the two antennas, and the interference pattern is simply the result of the beat between the two signals.

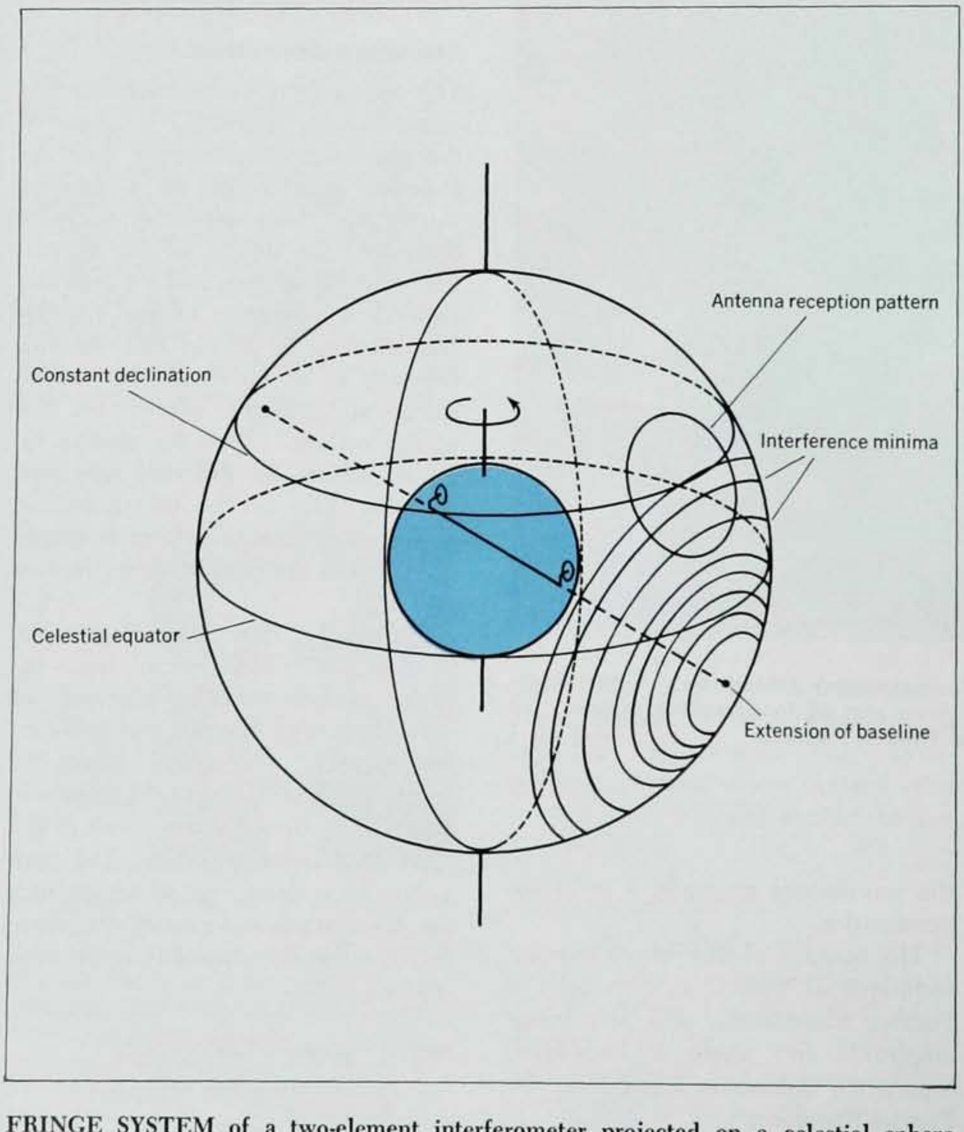
Yet another description is possible, because the travel time of light between stations provides a system of natural units to describe the radio interferometer. The relative phase delay ϕ between the received signals in figure 2 can be written in terms of the received frequency ω and the geometric time delay, τ_g, which in turn can be written in terms of the angle $\theta(t)$ and the light travel time between stations, τ_s

$$\begin{aligned} \text{received power} &= 2P_0 \exp[j\theta] \\ &= 2P_0 \exp[j\omega\tau_g] \\ &= 2P_0 \exp[j\omega\tau_s \sin\theta(t)] \end{aligned}$$

The receiver, however, usually re-



TWO-ELEMENT INTERFEROMETER shown schematically. The two antennas receive voltages $e_1(t)$ and $e_2(t)$, respectively, which are effectively multiplied at the receiver. A quasi-sinusoidal signal, perhaps the "white-fringe" pattern as shown, appears as the source moves through the interference pattern. —FIG. 2



FRINGE SYSTEM of a two-element interferometer projected on a celestial sphere to show the relationship of the interferometer baseline with the reception pattern of the two antennas and the track of a star at constant declination. —FIG. 3

ceives a finite bandwidth, so that the output of the receiver is

$$P(\tau_s \sin\theta) = 2P_0 \int_{-\infty}^{\infty} G(\omega) \left\{ \exp[j\omega\tau_s \sin\theta] \right\} d\omega$$

So the envelope of the fringe pattern is the Fourier transform of the bandpass of the receiver. The wider the bandpass, the smaller the range of τ_g for which the interference pattern shows what is familiar in optics as the "white-fringe" pattern shown in figure 2. Thus the interferometer can be used to measure the relative time delays between the two signals, and the wider the pass band of the receiver, the more precise the time-delay measurement will be.

The long-baseline technique

The operation of a radio interferometer is absolutely dependent on phase stability, which must for most purposes be maintained to within a few electrical degrees, and this becomes difficult as the separation between antennas increases. The development of highly stable atomic frequency standards, however, has brought a revolution in interferometry, and the new system is contained conceptually in figure 5. After amplifying the signal at each antenna, the received voltage (not the power!) is recorded at each station, with time control derived from the frequency standard. The signal is converted from its initial frequency by a superheterodyne receiver to video, phase locking the local oscillator to the atomic standard. The cables connecting the antennas to the receiver are no longer necessary, because the signals can be multiplied later when the two records are brought together. There is no longer any limitation on the separation of the stations, and the length of the observations will be limited by the stability of the time standard.

Two different groups, one associated with the US National Radio Astronomy Observatory and Cornell University, and the other with the National Research Council of Canada, began work on completely different recording concepts. The American group developed a digital system, in which the incoming signal is clipped, sampled and recorded directly on magnetic computer tape for later processing by a digital computer. The Canadian group chose to record the analog signal directly on video tape, using an adapted TV tape recorder whose sweep was controlled by the atomic standard. The tapes were then multiplied together by analog circuitry. Both groups were primarily concerned with measuring the radio sizes of quasars.

At the same time, the MIT–Lincoln Laboratory group had become increasingly involved with conventional interferometry of the emission sources of 18-cm line radiation from the hydroxyl radical.[3,4] These emission sources were clearly peculiar, for the line radiation is strongly polarized (usually circular), exhibits narrow lines only 1 or 2 kHz wide, and is strikingly intense with peculiar intensity relations between hyperfine components. The radiation was usually found near an H II region, where one ordinarily would expect the dilute interstellar gas to be ionized, and one such example (illustrated in figure 6), is the H II region known to radio astronomers as W3 and to optical astronomers as IC1795. The OH emission was shown to be coming from the small region shown in the figure. The fine structure of a single hyperfine component, the $F = 1 \rightarrow 1$ line at 1665 MHz, is shown in figure 7. The appearance is markedly different in right and left circular polarization. Evidently the source is composed of a number of emitters travelling at slightly different velocities, as shown by the frequency scale, which has been converted to equivalent Doppler velocity.

In early 1967 our MIT–Lincoln Laboratory group had extended its conventional interferometer baseline to 10 km, or 74 400 wavelengths,[5] (fringe spacing 3 seconds of arc) with a radio link between the Lincoln Laboratory's 120-foot (37-meter) "Haystack" antenna and the 60-foot (18.5-meter) Agassiz telescope of Harvard College Observatory. At that time there had been no positive results from the other experiments, and it looked as though the OH-line experiment might actually be easier to perform because the narrow line width of 1 kHz would require an initial timing error of only a millisecond or so. We joined forces with the NRAO–Cornell group, and as so often happens in science all experiments were giving positive results within a remarkably short time.

In late April 1967 the Canadian group reported a successful test at 410 MHz between stations 183 km apart,[6] rapidly followed by a test across Canada, between the 150-foot (46-meter) dish in Algonquin Park and the 85-foot (26-meter) dish at Penticton, B. C., a separation of 3074 km, or 4.6 million wavelengths (0.044 seconds).[7] In early May the NRAO group successfully tested their system over a short baseline, between Green Bank, W. Va. and the NRAO 85-foot telescope at Maryland Point, with an observing frequency of 610 MHz and a separation of 226 km.[8] In late May 1967 the NRAO recording

MAJOR PARTICIPANTS IN RADIO-TELESCOPE COLLABORATIONS

Green Bank–Arecibo

NRAO	Claude Bare Barry Clark Kenneth Kellerman
Cornell	Marshall Cohen David Jauncey

Algonquin–Penticton

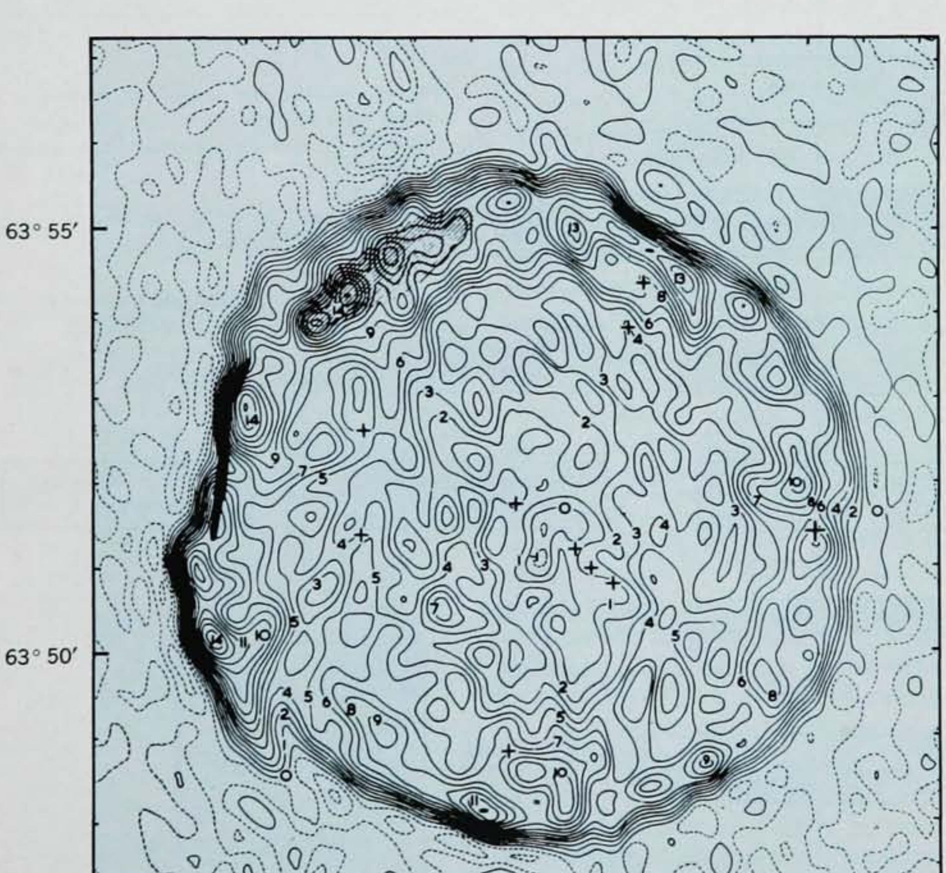
NRC	Norman W. Broten T. H. Legg Jack Locke C. W. M. Leich R. S. Richards
Toronto	Alan Yen
Penticton	R. M. Chisholm John A. Galt

Haystack

MIT–Lincoln Lab	James Moran Alan Rogers
MIT	Alan Barrett Bernard Burke
Lincoln Lab	John Ball Joe Carter Patricia Crowther

Other participants

Chalmers	O. Rydbeck B. Harisson B. Hoglund
Berkeley	D. D. Cudaback



TYCHO BRAHE'S SUPERNOVA. The remnant of this supernova was observed by aperture synthesis at 1407 MHz with the one-mile interferometer at the Mullard Radio Astronomy Observatory, Cambridge. (From J. E. Baldwin, ref. 2.) —FIG. 4

system and the MIT–Lincoln Laboratory rf system was operated between the Haystack antenna at Westford, Mass. and the 140-foot (43-meter) dish of the NRAO at Green Bank, this time at 1665 MHz and a separation of 845 km, or 4.7 million wavelengths.[9] At the time we could claim to be second in the race, but holders of the world's record baseline (in wavelengths) by 100 000λ!

Worldwide network

The network of stations has now extended across much of the earth, and figure 8 shows the stations that have participated so far.[10] The system is still expanding, and will soon include the 210-foot (64-meter) telescope of CSIRO Radiophysics at Parkes, Australia, and the 72-foot (22-meter) dish of the Lebedev Institute in the USSR. The longest baseline on the map in figure 8 must be computed two ways —in kilometers, the Hat Creek, California to Onsala, Sweden line is longest with a separation of 7719 km, and at the observing wavelength of 18 cm this separation is 43 000 wavelengths, or a resolution of 0.0015 seconds.

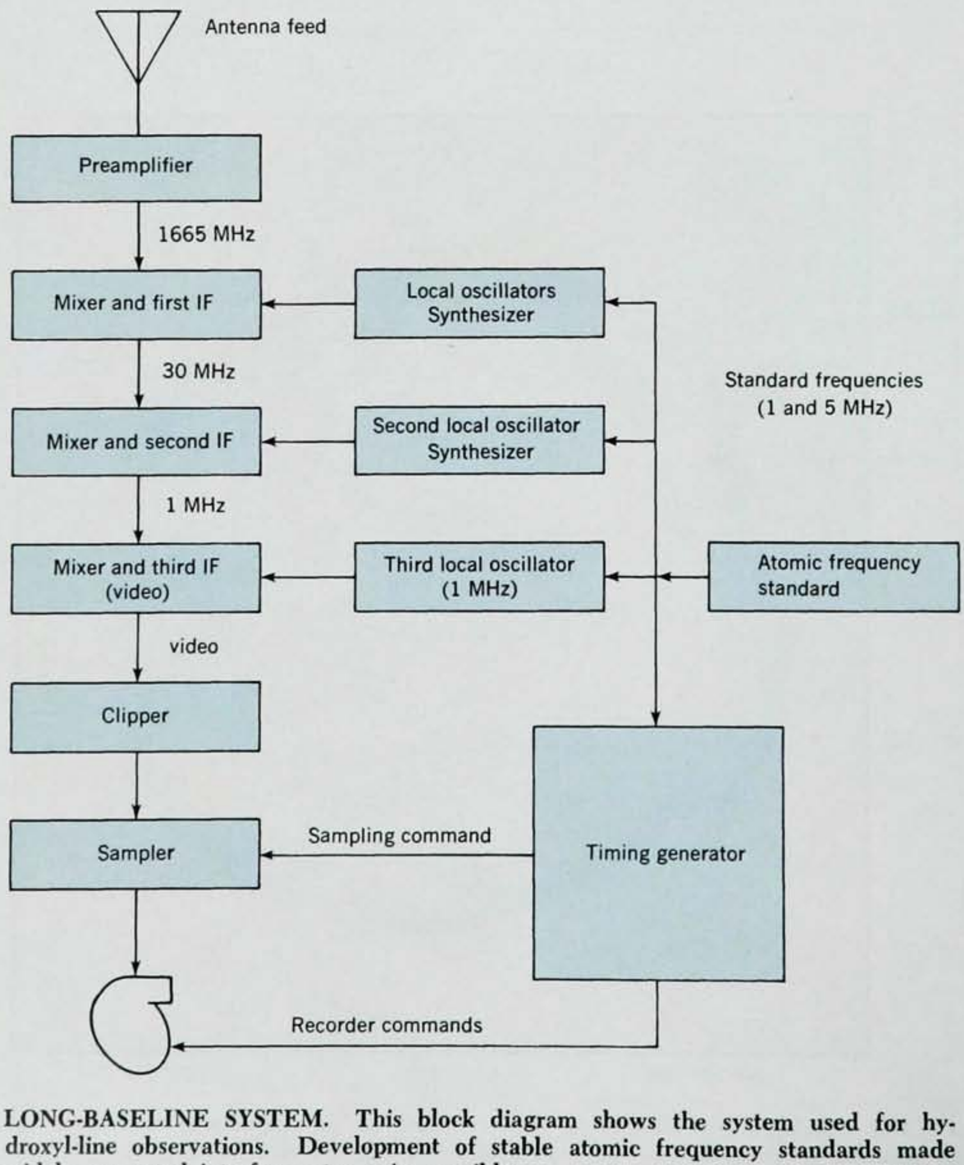
The longest baseline in wavelengths is Onsala–Green Bank, with a separation of 110 million wavelengths, corresponding to a fringe spacing of 0.0006 seconds of arc. There are three active groups at present: the Canadian group and the NRAO–Cornell group, who have concentrated on continuum sources, and the MIT–Lincoln Laboratory group, who have concentrated on the OH-line emitters. The Chalmers University, the University of California at Berkeley and Cal Tech have participated in many of the experiments as major partners.

The present network is much too fragmentary to synthesize a complete aperture as large as the earth, but the limited tracks through the Fourier-transform plane that we obtain still provide reasonable ideas about the appearance of the quasars and interstellar masers. The simplest Fourier transform of all is probably the delta function, whose Fourier transform is a perfectly flat spectrum from zero to infinity. Consequently, if the source is very small compared with the resolution of the system, it will show a fringe amplitude that is the same size for all interferometer spacings. On the other hand, if the source is a reasonably symmetrical disk the Fourier transform will drop off in amplitude when the interference-fringe spacing is of the same order of magnitude as the angular size of the disk.

The exact form will depend on the precise brightness distribution, but generally speaking all reasonable models—a uniformly bright disk, a gaussian brightness distribution, and a parabolic brightness distribution—exhibit remarkably similar Fourier transforms with only a small scale factor, generally less than two. The best information on the exact shape lies in the wiggles in the tail of the distribution, and these are often lost in the noise; nevertheless, even a size estimate that is within a factor of two is useful. (A small game of angular-size-manship can be played by adopting a gaussian model, whose characteristic dimension, the half-brightness width, is smaller than the size of the equivalent uniform disk.)

The study of quasars

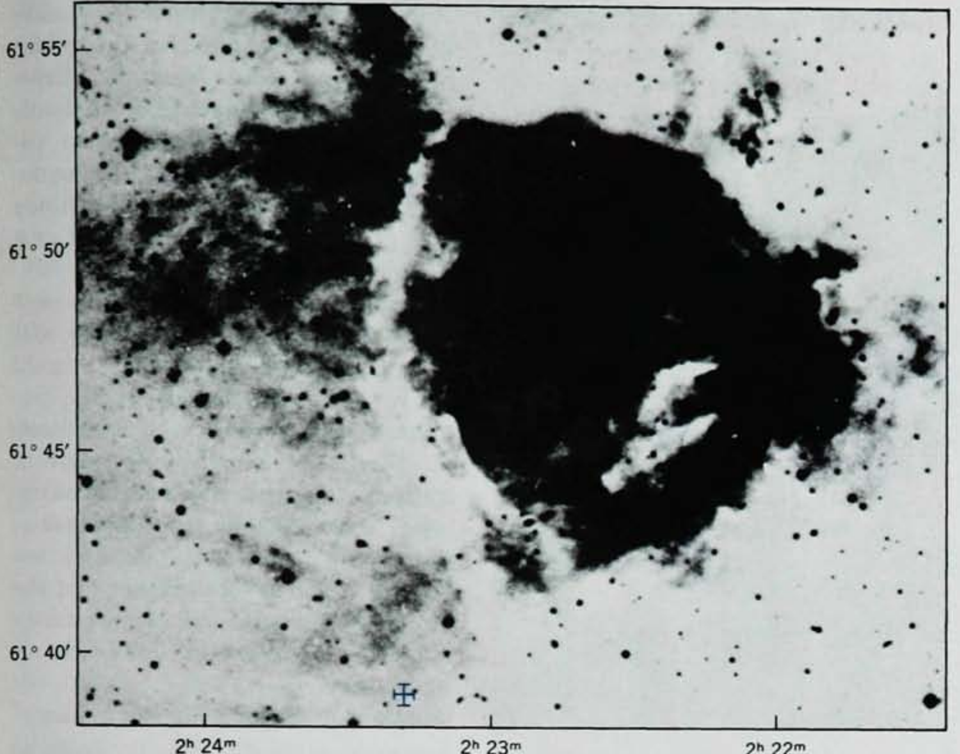
The data for the most celebrated quasar, 3C273, are summarized in figure 9, which includes principally data taken by the NRAO–Cornell group at 18 cm.[10] 3C273 has a gross structure, shown in figure 10, that was first measured by using the moon as an occulting disk. The optical object is composed of the quasar proper plus a thin jet extending 20 seconds of arc from the quasar. There is a radio counterpart for each part: a long thin radio envelope around the jet (designated 3C273A) and a compact radio source on the quasar (3C273B). The "B" source was not resolved by the occultation measurements, but its general features can easily be seen in figure 9 by mentally Fourier transforming the fringe visibility in the crude manner described. The visibility decreases by half in a properly quasi-gaussian manner over the first 5 million wavelengths, and then stays constant to at least 35 million wavelengths. The source associated with



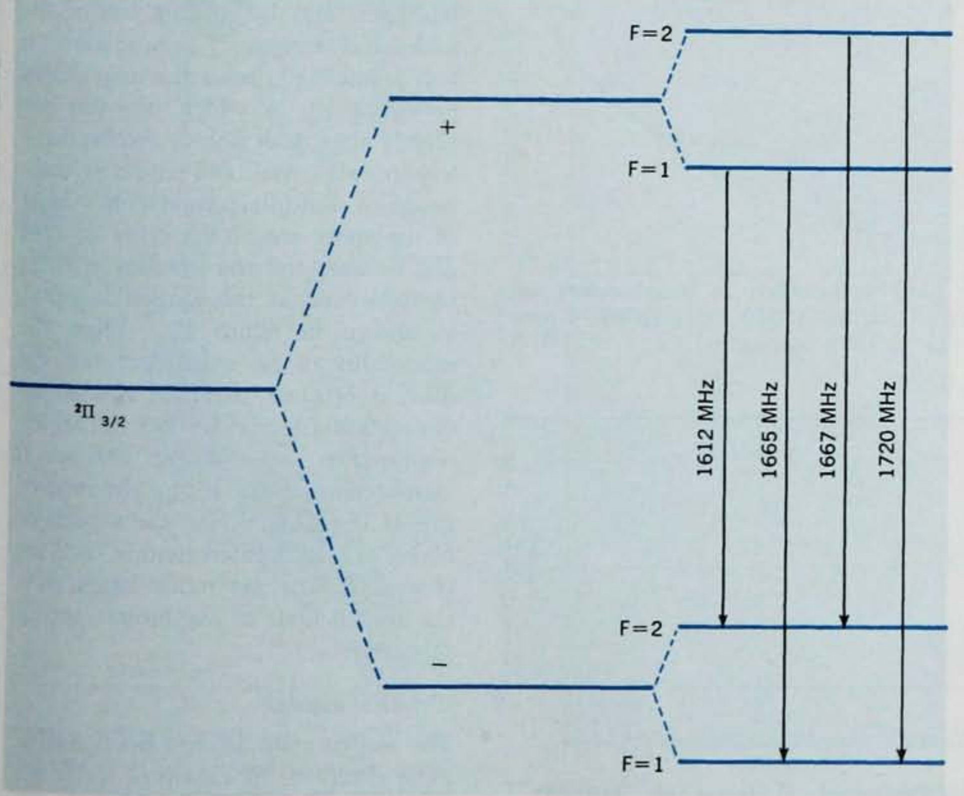
LONG-BASELINE SYSTEM. This block diagram shows the system used for hydroxyl-line observations. Development of stable atomic frequency standards made widely separated interferometer pairs possible. —FIG. 5

the quasar proper must, therefore, have at least two components, shown in the inset of figure 10. There is a compact core, of angular size much less than $(3.5 \times 10^7)^{-1}$ radians, or 0.005 sec, surrounded by a halo perhaps 0.04 sec in extent. The latest observations at 6 cm show finer substructure, of the order of 0.001 sec or smaller.

What do we learn about the size of the radio part of a quasar? Here, of course, there is a slightly embarrassed hesitation, because nearly everyone (except Fred Hoyle and Geoffrey Burbidge) agrees that, because of the large red shift of most quasars, they must be at cosmological distances. If this is so (and the Cambridge–California advocati diaboli turn out to be wrong) then 3C273 is at a distance of about 1.5×10^9 light years, and so the compact part of the radio noise is coming from a region less than 10 light years across, whereas the radio halo is approximately 300 light years in extent. This is still not enough evidence to unravel the knotty problem of what the quasar is, nor can we explain the sources of energy needed to maintain the prodigal energy output. The first looks at 3C273 and other quasars, however, show that the radio noise is often coming from a combination of extended envelopes and compact regions, suggesting explosive events that occur repeatedly in each object.



OPTICAL EMISSION from the H II region known to radio astronomers as W3 and to optical astronomers as IC 1795. Hydroxyl-line emission detected by radio interferometers comes from the region shown as a small colored cross at $2^h\ 23^m\ 20^s$. (Photograph from the Mt Wilson–Palomar Sky Atlas.) —FIG. 6



GROUND-STATE HYPERFINE STRUCTURE of the hydroxyl radical. The four transitions are the fine structure of a single hyperfine component. —FIG. 7

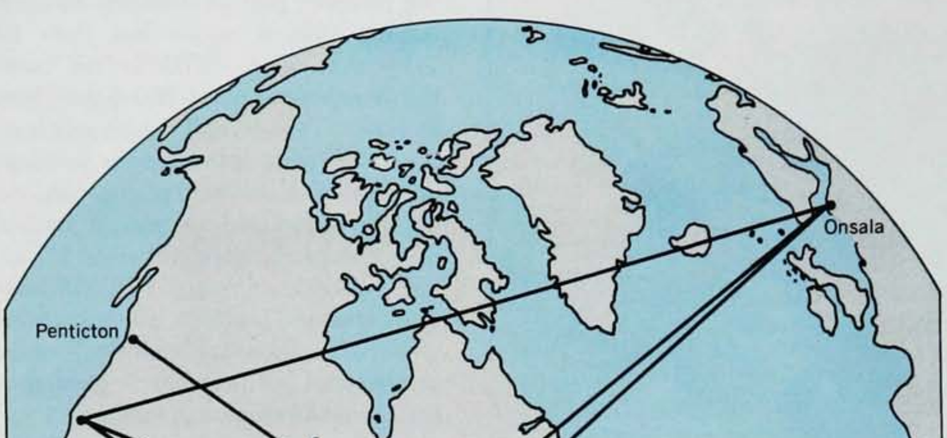
Hydroxyl sources

In contrast to the vast energy release and elusive nature of the quasar that intrigue us by the dramatic scale of the phenomenon, the sources of 18-cm hydroxyl-radical line emission offer an example of the unexpected order that appears in unlikely places in the universe. Ordinarily one thinks of emission from the tenuous gas clouds between the stars as arising from purely thermal, quasi-equilibrium processes, but a quick review of the properties of the hydroxyl emission shows that this is not necessarily so.

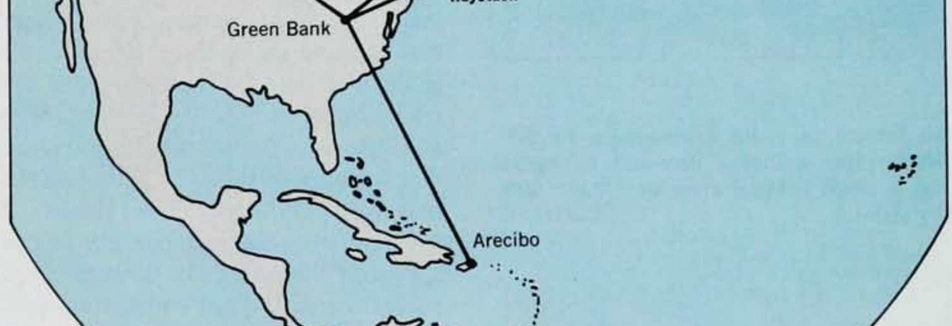
The structure of the ground state of the hydroxyl radical is shown in figure 7. The major splitting, the lambda-doublet interaction, arises because in the $2_{\pi_{3/2}}$ ground state, the total electronic angular momentum along the molecular axis, 3/2, actually corresponds to two degenerate states —symmetric and antisymmetric combinations of the two possible orientations (+ and −) of the electronic angular momentum. The degeneracy is removed by interactions with neighboring electronic states, and there is a further interaction between the proton and the electronic magnetic moments, giving four states. The four allowed transitions are shown in figure 7, the strongest being at 1665 and 1667 MHz.

The expected emission from the interstellar medium was not seen, but the discovery was made, at Harvard and at Berkeley, that the lines were to be found near associations of very young stars, apparently associated with the ionized gas, the H II regions, surrounding the youngest and hottest stars. The radiation was orders of magnitude stronger than expected, and the relative line strengths of the hyperfine components sometimes differed by a factor of 100 or so from the expected values that one would complacently derive from the usual angular-momentum matrix elements. There were other anomalies as well. The lines exhibit strong polarization, usually circular; they are extraordinarily narrow, suggestive of thermal broadening in a very cold gas (10–20 K), and yet, as it turns out, they exhibit such high surface brightness that the gas would typically have to be at a temperature of 10^{12}–10^{13} K if the emission mechanism were thermal!

The observations have been made largely by the MIT–Lincoln Laboratory–Chalmers University–Berkeley consortium, and considerations similar to those described for the quasar observations were used to derive models from the limited Fourier-transform information. There is an additional complication in processing the data, because the fringe amplitude and phase must now be derived as a function of frequency as well. Typically, each hyperfine component is split into many individual lines, and a typical example is shown in figure 11 for both polarizations. The frequency cöordinate has been replaced by the equivalent Doppler shift in km/sec, for these lines undoubtedly arise from different gas aggregations moving at their own peculiar velocities. (One might expect that the structure could be interpreted mostly by Zeeman effect, but all such attempts have failed.)



WORLD-WIDE NET OF STATIONS that have participated in long-baseline experiments. Hat Creek to Onsala is the longest baseline (7719 km); Onsala–Green Bank is the longest in terms of wavelengths (11×10^7 wavelengths). —FIG. 8



RELATIVE AMPLITUDE OF FRINGES (measured in terms of "visibility") from quasar 3C 273 for different baseline lengths. The variation of resolution with baseline length shows a difference of response from the 0.02-sec halo and the unresolved core. —FIG. 9

The H II region W3, also known to astronomers as IC1795, is shown in figure 6, and the line radiation shown in figure 11 was known to come from within a very small region off to one side, shown by the cross.[4] By observing the fringe variation for various baselines, and by making use of the additional frequency information, it was possible to derive the map shown in figure 12, in which one can see plainly that each line is coming from a particular spot and is often composed of multiple components. Most of the spots are of the order of 0.01 deg in size, and the smallest of them was resolved at the longest baseline, as shown in figure 13. From the model fits to an equivalent uniform disk, it is clear that the size is between 0.004 sec and 0.005 sec, which corresponds to a linear size of 6 astronomical units at the distance of this H II region.[11] All the sources of emission are located within a 2-sec circle, an area not much larger than the seeing limit of the largest optical telescopes.

Celestial maser?

The explanation of the phenomenon must surely lie in a form of maser action, but the detailed working drawings for the cosmic maser have not yet been produced. If a suitable pumping mechanism can be found to invert the state populations, then the high specific intensity, narrow line width, and most probably the polarization as well, would correspond to well known phenomena of man-made masers. Ultraviolet pumping from the nearby bright blue stars is possible, but there are energetic difficulties. As one ultraviolet photon is needed for each radio photon, the ultraviolet pump is relatively ineffective. Proposals have been made for pumping by infrared radiation,[12] but the detailed workings have not been generally agreed upon.

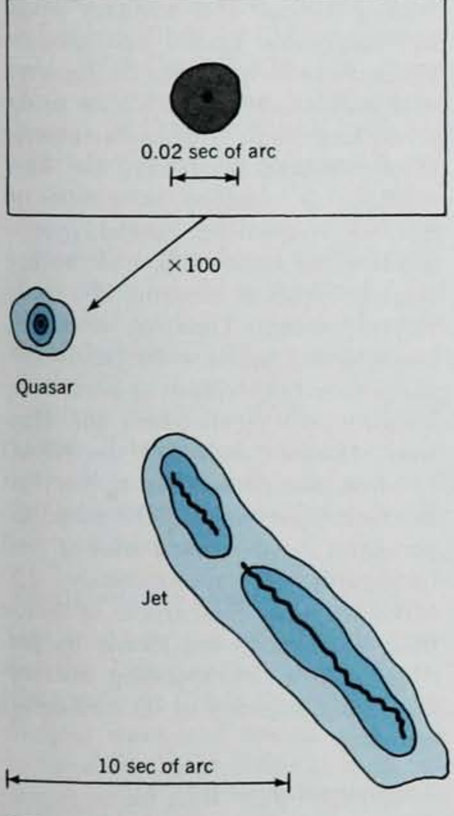
Even if one accepts the maser principle as a physical explanation, the geometry of the maser is not known. Even though the apparent size is very small, the true dimensions of the maser could be large. If very distant background-continuum sources of small angular size are being amplified by the maser, the incident plane wave on the maser region would emerge also as a plane wave, and hence the image would contain no information about the actual size of the maser. On the other hand, if the maser is of small angular size and serves to amplify the cosmic radio background, then the apparent size is the true size of the maser.

The apparent sizes of the sources are quite comparable to the dimensions of the solar system, and the temptation is very strong to identify the masers with stars in the earliest stages of formation. Such stars would presumably emit strongly in the infrared, because they should be heavily mantled with the interstellar dust that is found wherever star formation is occurring, and the conditions should be favorable for forming large quantities of OH. As the observed components in figure 12 have substructure comparable in size to the orbit of Jupiter or Saturn, visible changes should occur in a time of a year or so, and observations are being planned to observe such changes.

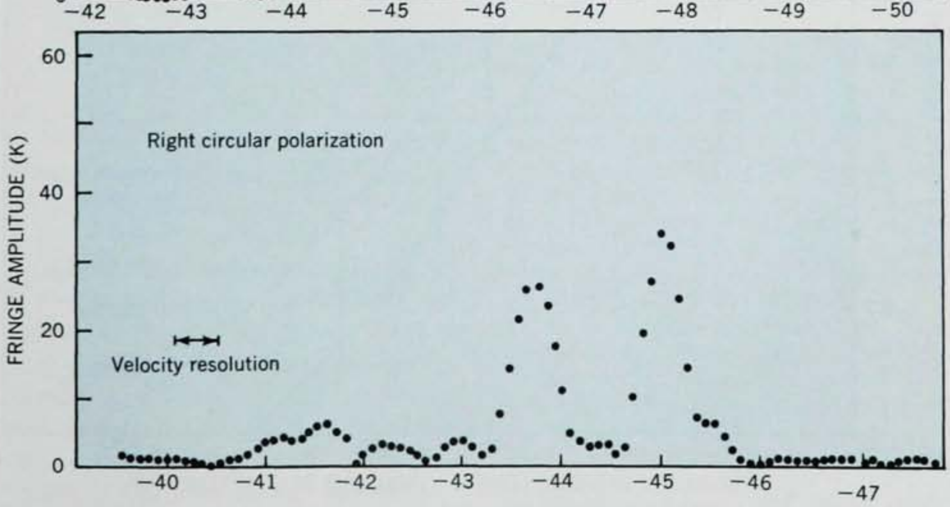
As a physical tool

Interferometers have been used for many purposes other than the realization of high angular resolution, and it is not surprising that the radio interferometer has similarly wide-ranging applications. If the position of the radio sources were known, it is clear that the interference pattern would be useful for finding the spacing between the antennas. One only need count fringes. The ultimate accuracy, one might expect, would be of the order of a wavelength, and the 18-cm observation, in principle, would allow one to determine distances on the surface of the earth with centimeter accuracy. Such a measuring capability would have powerful applications to geodesy, and proposals have been made by Irwin Shapiro,[13] and by Thomas Gold and Gordon MacDonald,[14] to use this new measuring instrument to look for continental drift directly, to study the motion of the axis of rotation of the earth, and by observing the fluctuations in the rotation of the earth, both to infer motions within the earth's mantle and core and to study seasonal changes in ocean currents and the earth's atmosphere.

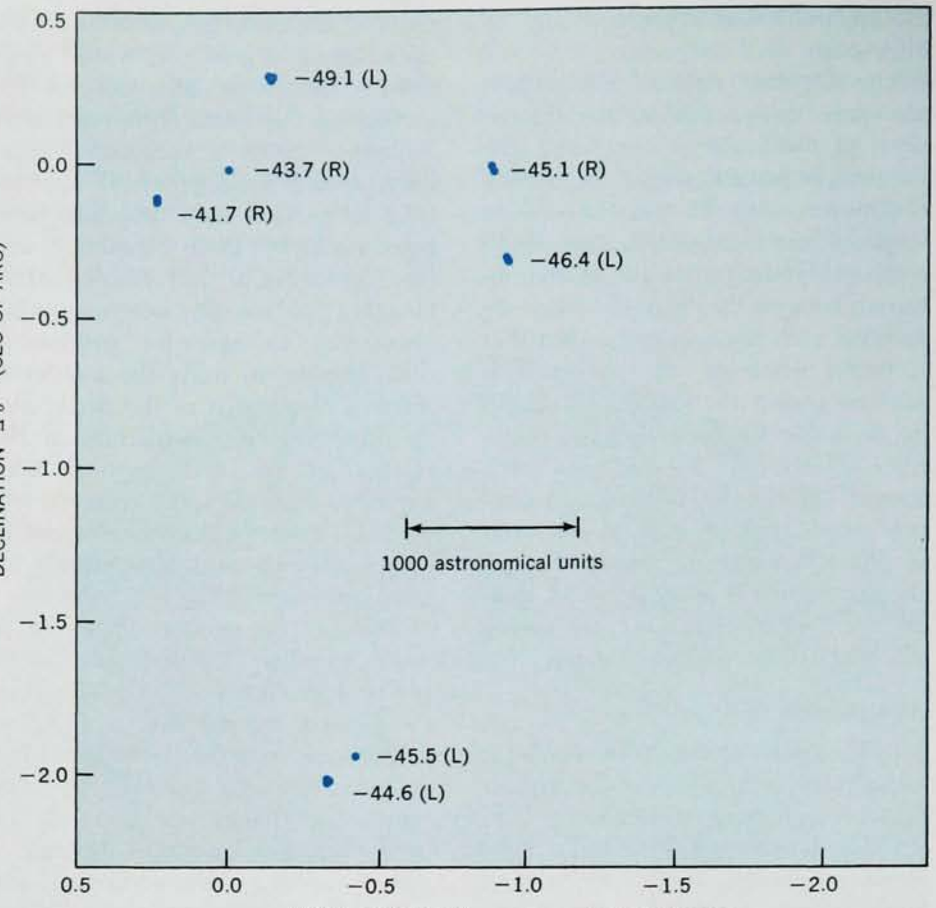
The uses for geodesy have had to wait, however, for the solution of practical problems. The positions of the quasars are not known with sufficient accuracy a priori; the individual antennas heave up and down by many centimeters twice each day with the earth tides, and the earth's atmosphere and ionosphere cause additional, and uncertain, time delays in the system. Direct counting of fringes, although possible in principle, is not a feasible method yet, because even the excellent stability of hydrogen-maser frequency standards is not quite good enough. (At 18-cm wavelength, a



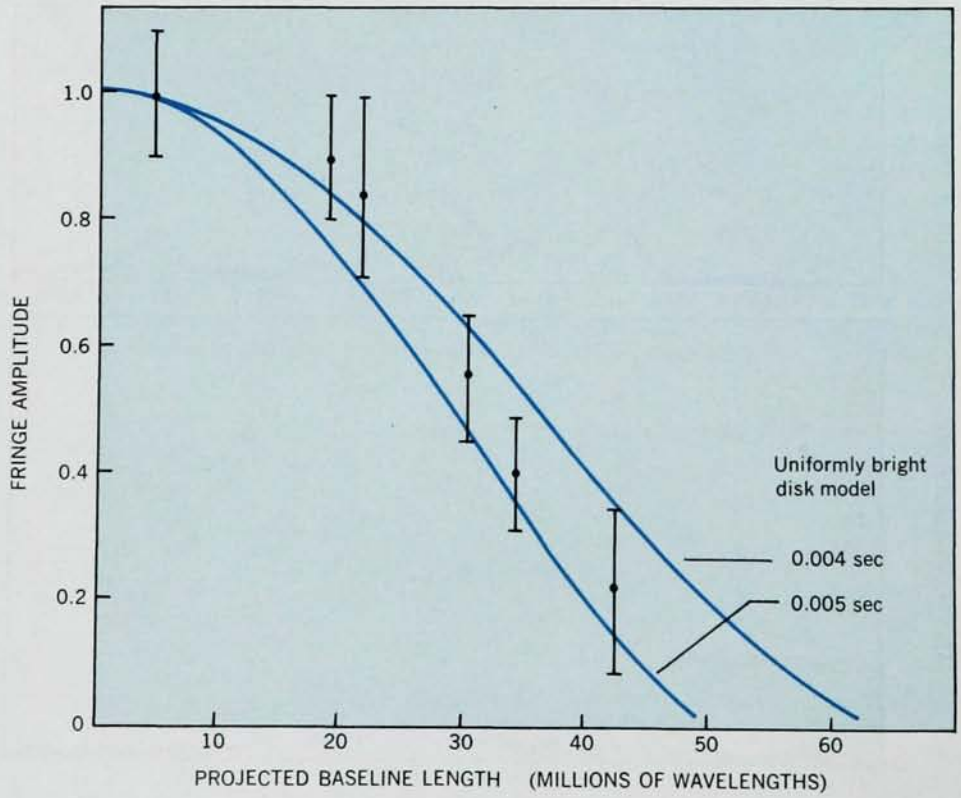
GROSS STRUCTURE of quasar 3C 273 was first determined in radio emission by using the moon as an occulting disk. In both radio and optical observations a long thin jet extends from the quasar proper. —FIG. 10



VELOCITY SUBSTRUCTURE of the 1665-MHz hydroxyl line emitted by the source, shown in figure 6, associated with the H II region W3. —FIG. 11



INDIVIDUAL SOURCES of hydroxyl emission in W3. Each line in figure 11 comes from a particular spot (often composed of multiple components) here labeled with the velocity (in km/sec) and "L" or "R" for left or right polarization. (From J. M. Moran and others, ref 12.) —FIG. 12



THE SMALLEST FEATURE in figure 12, with a uniform-disk model for comparison. The angular size of this feature is between 0.004-sec and 0.005-sec, which represents a linear size of 6 astronomical units. **(From ref 12.) —FIG. 13**

frequency standard with guaranteed stability of 2 parts in 10^{14} will drift in phase by 2π in 12 hours.)

A joint program now under way within the MIT–Lincoln Laboratory groups has been approaching the problem by avoiding extreme dependence on the stability of the frequency standards. The present group comprises Irwin I. Shapiro, H. H. Hinteregger, C. Knight, C. Whitney and myself of MIT, and Joe Carter, Alan Rogers and James Moran of Lincoln Laboratory.

In essence, the method makes use of the time-comparator aspect of an interferometer, discussed on page 55. The wider the receiving bandwidth, the shorter the correlation time of the pair of signals received at the two antennas, and in the limit of infinite bandwidth the time delay τ_g could be determined exactly. The recording bandwidth of the digital systems used by the MIT–Lincoln Laboratory–NRAO–Cornell consortium is, alas, only 360 kHz, and even the analog system used by the Canadian group has only a 4-MHz bandwidth. The ability to compare time delays directly with available signal-to-noise ratios, then, would be some fraction of a microsecond, corresponding to a physical distance of perhaps several tens of meters. This accuracy would be comparable to the best geodetic measurements, but it can be improved with only a minor modification to the receiving system. Rather than observe at a constant frequency, the local oscillator is switched to a series of discrete frequencies spread, over a much wider bandwidth, and the first stage amplifier is electronically tuned in synchronism. Thus one effectively synthesizes a much wider bandwidth, and a recent experiment at 3-cm wavelength operating between the Haystack 120-foot dish and the NRAO 140-foot instrument has shown that the technique works. The initial experiments have worked over a total bandwidth of approximately 120 MHz; a time comparison of better than one nanosecond should be possible, with a corresponding distance-measuring accuracy of 30 centimeters or better.

The new astrometry

The use of this new tool will not be possible until the entire system of radio sources, geodetic location, and atmospheric phase shift is solved simultaneously. The measured time delay during the day, for a given source, is of the form

$$\tau_g = A + B\cos(\omega t + \phi)$$

Thus only three observables, A, B and ϕ, can be derived. These in turn are functions of the orientation of the baseline of the interferometer (two unknown angles), the unknown length of the baseline and the unknown time difference between the atomic clocks at each station. As there are six unknowns and only three observables, a single-source observation is clearly not enough. With three sources, however, there are nine observables and ten unknowns; because we are free to choose the origin of the coordinates the right ascension of one source can be chosen, reducing the number of unknowns to nine, and the system can be solved. Naturally more sources should be chosen in order to overdetermine the system, and this effort is still under way, occupying impressive quantities of computer time. In effect all of classical meridian astronomy is in the process of reconstruction, and our expectation is that orders-of-magnitude improvement over the traditional optical techniques will result.

One problem that deserves special mention is the classical test of general relativity, by observations of the deflection of light by the gravitational field of the sun. The sun passes close to two of the most intense quasars, 3C273 and 3C279. The two sources are separated by only 4.5 deg, so the measurement of the deflections can be made differentially. The accuracy of the long-baseline technique should make a meaningful test of general relativity possible, because the deflection is 1.76 sec at the limb of the sun. Last fall the first observations were made by the MIT-Lincoln Laboratory group; the results have not yet been fully analyzed, and the experiment is scheduled to be repeated this year.

The uncertainty principle

One final note can be made concerning the long-baseline interferometry technique. As the amplitude of the incident wave, and not its power, is recorded by the receivers at each station, it would seem that, in the single quantum limit, the observer could observe incoming photons separately at each antenna without destroying the interference pattern (which now is detected in the computer, rather than on a screen). This echo of the arguments between Niels Bohr and Albert Einstein can be easily set to rest, although for entirely new reasons.[15] Before recording the amplitudes, it is essential to interpose an amplifier between the antenna and the recorder.

The simplest amplifier to consider is the maser, and it is well known that a maser cannot be free of noise, because it works through the coefficient for induced emission, the Einstein B. For every Einstein B, there is an Einstein A, and hence the system must generate its own noise. It can be shown that this occurs just at the single-photon limit, and it is an expression of the uncertainty relation

$$\Delta\phi \approx \Delta\eta\Delta t$$

Thus the interference pattern is not destroyed, but rather is retained; Nature chooses to mask the arrival of individual photons by adding noise to the system.

The future

The experiments that have been carried out so far have demonstrated convincingly that the technique of long-baseline interferometry can improve the resolution and angle-measuring ability of the astronomer by orders of magnitude. Whether the future instrumentation is analog or digital, it is clear that the present recording techniques are somewhat cumbersome. The analog systems using video tape fill a hefty reel of magnetic tape in half an hour, while the digital systems use a pair of 2400-foot computer reels in three minutes. A truly high-density information-storage system would aid future systems greatly. A more direct need is for wider-band recording. Perhaps existing video recording bandwidths will prove to be sufficient for a while, but a system with a 100-MHz bandwidth would allow the study of much fainter objects. The usefulness of such a wide-band system would, however, be strongly dependent on more efficient information-storage systems.

Hydrogen masers are stable enough for most of the experiments being discussed at the present time. There is the possibility of turning the system around and using the observations of strong sources to synchronize clocks at various locations with high precision. The role of the atomic frequency standard would then be simply that of a flywheel, with the requirement of constant rate being much more important than absolute frequency accuracy.

A principal lack from the astronomers' and geophysicists' point of view is the small number of large paraboloids available for ambitious programs. The explorations so far have been able to proceed fruitfully with only a few hours of observing time on existing great radio telescopes of the world. But full exploitation of the possibilities will require more stations with radio telescopes of at least 26-meter diameter scattered at strategic locations around the world. Such a worldwide net is only a glimmer of hope, but such a network should be high on the list of scientific priorities.

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