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An Intercontinental Array— A Next-Generation Radio Telescope

New techniques permit construction of a radio telescope with extreme angular resolution.

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The history of radio astronomy has been one of steadily increasing angular resolution. The very first radio telescopes, built in the 1930's, could barely distinguish between cosmic sources tens of degrees apart in the sky. Today the largest paraboloids, such as the new 100-meter German telescope near Bonn, operating at short centimeter wavelengths, achieve angular resolutions of the order of 1 arcminute, comparable with the resolution of the unaided human eye. Larger dishes can be built, at very great cost, but then it is difficult to achieve the precision necessary to operate at short wavelengths.

For this reason, radio astronomers long ago turned to interferometers (*1*) to achieve high angular resolution. Contrary to early expectations, radio interferometry has produced angular resolution far superior even to the best results of conventional optical astronomy. This is due mainly to the more tractable behavior of the earth's atmosphere at radio wavelengths than at optical wavelengths.

The 1960's saw the development of sophisticated multielement synthesis arrays (*2, 3*) with which complete radio images of celestial objects could be obtained, rather than just the crude estimates of angular dimensions obtained with simple interferometers. This technique was pioneered at Cambridge, England. The Very Large Array (VLA) (*4*) now under construction in New Mexico, which will consist of 27 antennas located on three arms of a wye whose legs are each 21 kilometers long, will be the culmination of this technique and will map small areas of the sky with an angular resolution better than 1 arcsecond.

Even the VLA, however, will not resolve the most compact regions of cosmic radio emission. To do so requires very long baseline interferometers (VLBI's) with dimensions approaching the diameter of the earth. In these VLBI systems (*5*) the signals at two widely separated antennas are recorded on magnetic tape and later correlated to form the interferometer.

The VLBI systems attain angular resolutions better than 1 milliarcsecond, and have permitted unprecedented resolution in the investigation of galactic nuclei, quasars, stars, pulsars, and the interstellar molecular masers. Perhaps not unexpectedly, the microstructure of these objects has turned out to be extraordinarily complex. Moreover, unlike the extended radio sources, the more compact regions have angular structures which are often variable on time scales as short as 1 month or less.

Although sub-milliarcsecond astronomy is only in its infancy, many new areas of research are already being opened. These include the following phenomena.

1) ***Quasars and galactic nuclei.*** The limited data available so far suggest complex multicomponent structures which vary rapidly as a result of motions and variations in the size or intensity (or both) of the components. In some cases the component size is extremely small, corresponding to a light-month or so in linear dimension ($\sim$5000 astronomical units). The relation between these compact radio nuclei and the more extended sources of emission is unclear, but there is growing suspicion that a compact nucleus is a manifestation of an extremely high energy source which powers the entire radio source. Understanding the sources of energy in extragalactic radio objects has been one of the outstanding problems in astrophysics for the past two decades, and the ability to explore the seat of energy conversion with sufficient angular resolution is certain to shed new light on what many consider to be fundamentally new physics.

2) ***Interstellar molecular masers.*** Compact variable radio emission has been observed in celestial sources of OH (18 cm) and H_2O (1.3 cm) radiation. These extremely bright regions have linear dimensions of only a few astronomical units or less. It is widely believed that the radio emission from these hydroxyl and water vapor clouds arises as a result of stimulated emission from ions or molecules which are pumped by interstellar ultraviolet or infrared radiation, or by collision with neutral molecules. Other molecular masers are likely to be discovered, and research on these interstellar masers is providing exciting new knowledge of the interstellar medium.

3) ***Stars, novas, supernovas, x-ray sources.*** Several varieties of stellar objects, including novas and supernovas, are relatively powerful sources of radio and x-ray emission and have recently been the subject of intense investigation by astronomers (*6*). The ability to resolve these radio sources, which may have stellar dimensions, offers a new tool for studying stellar phenomena. So far only one radio star, Algol, has been observed with a resolution of about a nanoradian or a milliarcsecond (*7*). Every 69 hours the optical brightness of Algol suddenly drops by a factor of 3 for a period of a few hours, the result of the periodic occultation of the small bright star by a larger but fainter one. Further high-resolution observations may reveal the origin of the radio emission and its relation to the binary star pair.

Although the early two-element long baseline interferometer experiments of the late 1960's have now expanded to include

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three, four, or even five stations giving up to ten simultaneous interferometer baselines (*8*), it has not been possible to synthesize satisfactory pictures of complex sources. Even though the resolution of these VLBI systems is 10^3 to 10^4 times better, their "image" quality does not approach that of the smaller aperture-synthesis arrays, whose resolutions are 1 to 10 arcseconds.

Now, however, it should be possible to construct a true image-forming system with sub-milliarcsecond resolution by using eight to ten radio telescopes as part of an intercontinental very long baseline array (VLBA). In this article we discuss a possible system of this type. Before considering the outstanding problems facing the implementation of such a system, we give a brief review of interferometry and, in particular, of very long baseline, independent-oscillator, tape-recording systems.

Interferometry and Aperture Synthesis

Two radio telescopes are equipped with identical radio receivers sensitive only to one wavelength. As the earth rotates, the distant cosmic source has different radial velocities with respect to the two telescopes. The "signals" received by the respective telescopes will thus experience different Doppler shifts. The two output signals, differing somewhat in frequency because of the Doppler shifts, are combined in a nonlinear device, thus producing a "beat" at the difference frequency between them. This beat is a signal which is quasi-sinusoidal in time, and it is generally called a fringe by analogy with the optical fringes of the Michelson interferometer.

While the fringe has been considered here as a function of time, it can also be visualized as a function of the position of the source, which changes with the rotation of the earth: as the earth rotates the fringe pattern sweeps over the cosmic source to generate the time-varying output of the interferometer.

The general theory of an interferometer, taking into account the detailed characteristics of the telescopes and of the cosmic sources, has been discussed by Swenson and Mathur (*1*). A suitable approach is to consider the cross-correlation of the signals from the two telescopes, assuming that they are observing an extended cosmic source whose radiation is statistically stationary and spatially incoherent. It may be assumed that the signals are quasi-monochromatic—that is, that the telescopes are sensitive only in frequency bandwidths small compared with the center frequency. In this way it can be shown that the response of the interferometer to a cosmic source is the convolution of the fringe pattern of the interferometer and the spatial brightness function of the source (*1*).

During a short interval of time the output of the interferometer is nearly sinusoidal with time. In another sense, the convolution of the source and the fringe pattern is a nearly sinusoidal function of a spatial variable over a small interval in hour angle. This function can be interpreted as one term of a Fourier series representing the brightness of a cosmic source of finite extent. If a sufficient number of samples can be accumulated—that is, if a sufficient number of terms in the Fourier series can be measured—a brightness map of the source can be constructed by summing the series. As the output fringes from the interferometer possess both amplitude and phase at each fringe frequency, the map will be unique. The period of a given term in the Fourier series corresponds with the baseline length projected onto the celestial sphere at the location of the cosmic source. For the general case of a two-dimensional source, the period will be measured in the direction of the projected baseline; a two-dimensional Fourier series is needed to represent such a source.

To summarize, if one can arrange a sufficient number of interferometers situated geographically so as to determine the necessary terms of an appropriate two-dimensional Fourier series, one can synthesize a map of a cosmic source. The finest detail in the map will be determined by the longest baseline in the interferometer. In general, the baselines in the array will vary in length by discrete steps. If the steps are uniform, the size of the source that can be synthesized, in radians, is the reciprocal of the step size in wavelengths. These relationships are more or less approximate, depending on the exact organization of the array of interferometers.

It is not necessary that the geographical baselines occupy a two-dimensional array in order to determine the two-dimensional Fourier coefficients. The argument of each term in the series is determined by the projection of the corresponding baseline onto the celestial sphere at the location of the source. This projection is rotated and foreshortened as the earth turns, and in 12 hours each baseline turns through 180° on the sky. Except for sources on or near the celestial equator, a linear array of antennas observing a source for 12 hours produces a two-dimensional array of projections on the celestial sphere and thus permits two-dimensional synthesis of the source. The equatorial source represents a degenerate case; to map it, a two-dimensional geographical array is needed.

Such an array of telescopes produces source maps by fairly straightforward processes of observation and data processing. However, in order to produce unambiguous maps, the phases as well as the amplitudes of the fringes (Fourier series terms) are needed. This, in turn, requires that accurate phase reference signals be available at each antenna. Phase reference signals are customarily transmitted as local oscillator signals, which are used in the frequency converters of the superheterodyne receivers of the telescopes. Intermediate-frequency or baseband signals containing the astronomical information are then transmitted from the telescopes to a central location for combining or "correlating." Most existing synthesis arrays use coaxial cables or waveguides for transmitting the phase reference signals, with a resulting limitation of baseline length to a few kilometers. A few interferometers operate with microwave radio link connections between telescopes; here the baseline lengths can be increased to tens of kilometers while preserving phase stability by use of sophisticated two-way transmission techniques.

Independent-Oscillator, Tape-Recording Systems

For baselines longer than, say, several hundred kilometers, the transmission of phase reference signals by cables or microwave links is extremely expensive. Moreover, variations in temperature, pressure, and atmospheric composition cause strong fluctuations in the phase of signals disseminated by either cable or microwave-link systems, and the elaborate phase-correcting schemes that are being used on shorter baselines would be difficult to implement on baselines of continental length. Thus, very stable, independent local oscillators are used at each end of a baseline to establish the necessary phase relationships between the two telescopes. Atomic frequency standards (*9*) are generally used; rubidium vapor or hydrogen maser systems are the most common, the latter being capable of an accuracy of 1 part in 10^{14} over a period of days. Such systems are adequate for the most demanding applications attempted to date—wavelengths as short as 1 or 2 cm and baselines comparable with the diameter of the earth. It may be said that the availability of atomic frequency standards eliminates the timekeeping problem as a deterrent to high-resolution radio astronomy.

One major remaining problem is the transmission of the output signals of the telescopes to a common location for multiplication (or correlation). In order to obtain sufficient power from the cosmic source, bandwidths of at least several megahertz are generally desired, so that broad-band communication channels of very high quality are required. The medium used currently is the magnetic tape recorder. The data are recorded on tape at the radio telescopes, along with precise time marks. Then the tapes are shipped to a central location where they are played into a "processor," which adjusts the two data streams to be precisely synchronous and then multiplies them together to produce the fringes of the interferometer. The processor may be in the form of a large general-purpose computer, a special-purpose digital computer (*10*), or an analog device (*11*). In any case, processing is an extremely complex operation, both in principle and in practice. The necessity for a high degree of time synchronization between magnetic tapes recorded and played back on different tape transports is a complicating factor. It would be desirable to eliminate the tape recorders and to correlate the data streams at the same time they are observed, if a suitable broad-band communication medium could be developed. Some suggested approaches are discussed below.

Since many of the compact, complex cosmic radio sources are variable in time, a number of baselines must be used simultaneously to accumulate sufficient data to synthesize or model two-dimensional pictures before the source structure changes. With a single correlator, the time required to correlate the data from an observation with N telescopes is at least $N(N-1)/2$ times that required for the initial observations. In many cases weeks of correlator time are required to process days of observations. Multistation correlators are being developed to allow tapes from several stations to be processed simultaneously. Processing then is much more rapid.

Most VLBI observations have utilized only the amplitudes of the interference fringes. Although the fringe phase is in principle recoverable from the output of the correlation process, in practice the difficulty of calibrating the phase and the various phase instabilities in the system generally have rendered the phase values unreliable or incapable of interpretation. It has become almost customary, therefore, to assume that VLBI observations contain no phase data and that an observer must learn to interpret the fringe amplitudes alone in terms of the properties of cosmic sources.

The absence of fringe phase means that half of the potentially available information from an observation is not obtained. Moreover, the phase data are necessary if one is to produce a unique map of a source, measure the precise position of a source (the astrometric problem), or measure the precise length and orientation of the interferometer baseline (the geodetic problem). Thus, efforts to develop reliable phase-recovery methods are under way.

3C 273 Models 2.8 cm
(VLBI amplitude data)

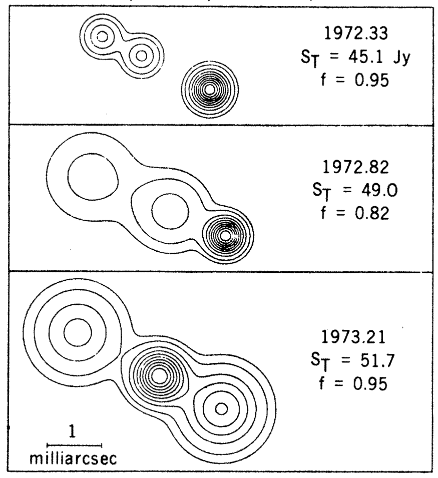

Fig. 1. Map of the distant galaxy 3C 273 made by fitting the data from a transcontinental three-station VLBI to a model (*21*). The wavelength is 2.8 cm. Abbreviations: S_T, total flux (in janskys); f, fraction of total flux arising from compact components.

The principal such difficulty is the inhomogeneous structure of the earth's atmosphere. As the cosmic radio waves emitted by a source must pass through different parts of the atmosphere, they suffer different cumulative phase delays in reaching the individual telescopes comprising an interferometer. The parameters of the atmosphere affecting the phase delay are the water vapor density, the air density, the free-electron density, and the magnetic field intensity, all of which are inhomogeneous and time-variable in essentially unpredictable ways. Some of these parameters can be monitored by sensors external to the interferometer antennas (integrated water vapor, electron, and air density) (*12*). The magnetic field can probably be assumed to be well enough known from standard models.

Problems of atmospheric phase are not unique to VLBI's. Conventional aperture-synthesis arrays, such as the VLA, need elaborate atmospheric-sensing equipment and sophisticated computer software. Only a start has been made toward accounting for these effects in VLBI's, mainly by investigators interested in geodetic measurements (*13*), but it appears that the phase problem will ultimately yield to this approach even though it is complex and expensive. With baselines greater than about 10 km there is an additional problem of baseline variation caused by solid earth tides and motion of the celestial pole. All these effects can, to a large extent, be accounted for by frequent observations of a group of unresolved reference sources (*14*). This is analogous to the technique used in x-ray diffraction work, in which a massive atom is incorporated into a molecule under study to provide a phase reference.

Thus, it is possible now to believe that, given adequate instrumentation, straightforward Fourier synthesis of source structure can be accomplished at angular resolutions of the order of 10^{-4} arcsecond.

Image Forming

In a carefully designed multielement array, an image may be formed by means of a conventional Fourier transformation. If, however, the antennas are not optimally placed or there is an insufficient number of intermediate baselines, a distorted picture of the source results. In particular, the response to a point source may contain numerous sidelobes, whose strength may, in extreme cases, be comparable with that of the main beam.

Procedures to minimize the effect of these sidelobes have been of considerable concern to radio astronomers who wish to minimize the number of antennas in an array. In current VLBI work the problems are even more difficult, for two reasons: (i) because relatively few antennas are used, and because these have not generally been placed at optimum locations, the sidelobes may be numerous and strong, and (ii) because there is generally little or no phase information, a formal Fourier transformation is not possible.

Thus, most VLBI observations have so far been interpreted by attempting to find simple geometric models that fit the data (Fig. 1). Generally, a graphic inspection of the data is the basis for a first guess, and then an iterative method is used to determine the parameters of the source model that best fit the data. If the source is only barely resolved, then only an estimate of the diameter, or perhaps the major and minor axes of an elliptical model, may be given. If better resolution is obtained, the separation and orientation of the best-fitting double-component model may be estimated. But if the data require more complex structure than a simple two-component model, the solution is difficult. Most model-fitting procedures are very sensitive to the first guess, and unless this is close to the true brightness distribution, generally the solution will not converge. Also, even if a satisfactory solution is found it is usually not unique, and in the multiparameter model one parameter may often be dependent on the value assumed for another.

It is encouraging to note, however, that model-fitting (*15*) applied to the early low-resolution interferometric data, while oversimplified, was successful in crudely describing the brightness distribution. The later, more complete data have greatly improved both the resolution and quality of the maps, but for the most part are not in disagreement with the early models.

Very Long Baseline Array

Extensive studies of conventional arrays have been made (*16*) and the technique of configuration studies is well established. For transcontinental or intercontinental arrays an additional consideration is the desirability of placing individual antennas at convenient sites—for example, at existing observatories.

The "beam pattern" of the array is a direct way to visualize its performance. The beam pattern of an antenna is the Fraunhofer diffraction pattern of the aperture of the antenna. An ideal array is defined as one in which all the necessary Fourier series components are present to permit a complete synthesis of the source with the amount of detail permitted by the longest baseline available. A "minimum redundancy" (*17*) array of eight elements, operating at a wavelength of 2 cm, with the longest baseline spanning North America along the 40° parallel of latitude, can map a source to a resolution of 10^{-3} arcsecond. By weighting, or de-emphasizing the longer baseline components when summing the Fourier series, the power level in the sidelobes can be reduced to a few percent of that in the main beam at the expense of somewhat degraded resolution. As the existence of sidelobes in the synthesized beam pattern tends to corrupt or distort the synthesized map of the source, it is desirable to keep sidelobe levels as low as possible, although, as the pattern is known quite accurately, it is possible to remove sidelobe effects to some degree in the post-observational data processing (*18*). This is often done in conventional arrays having fewer than the desirable number of spacings. With an east-west one-dimensional array such as that shown in Fig. 2, the source must be tracked for about 12 hours in order to synthesize a complete source map. Such a one-dimensional array has very poor angular resolution in the declination coordinate for sources at low declination, say within 20° of the celestial equator. Nonetheless, the relative economy of construction, the simplicity of data analysis, and the large number of sources available above 20° declination have been deciding factors in the design of previous arrays of lesser resolution (*19*).

Reasonable beam patterns are obtained with seven or eight elements, spaced across the continental United States and mostly located at existing radio astronomy observatories. The beam shape is improved if the antennas are located at ideal locations, but it is not clear whether the improvement justifies the additional expense and difficulty of establishing and operating new and possibly remote observing sites. Additional elements in Hawaii, Alaska, Puerto Rico, and Europe would greatly improve the angular resolution and sky coverage at the cost of logistical complication. Figure 2 shows the station locations and Fig. 3 the beam pattern of an array of telescopes located mostly at existing observatories in the continental United States, plus one in Hawaii and one in Europe.

The linear array can map sources only above, say, 20° declination. The two-dimensional array required for cosmic sources near the celestial equator cannot be optimized in the minimum redundancy sense. Since the number of baselines varies approximately as the square of the number of telescopes, the logistical and data-processing problems are also much larger for equatorial sources. The angular resolution

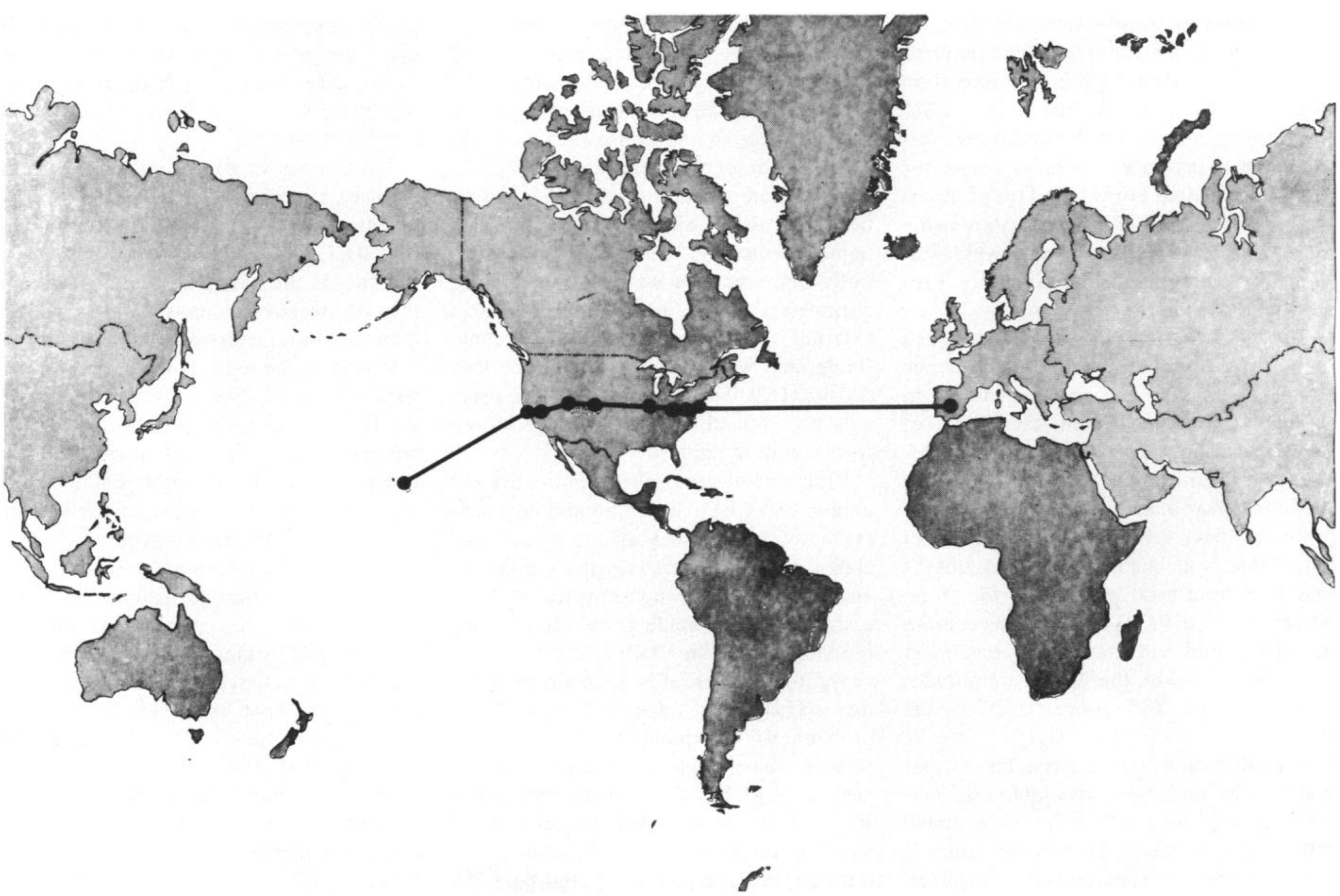

Fig. 2. Antenna locations for a possible array: Nanjemoy, Maryland; Charlottesville, Virginia; Green Bank, West Virginia; Danville, Illinois; Boulder, Colorado; Salt Lake City, Utah; Big Pine, California; Palo Alto, California; Madrid, Spain; and Hilo, Hawaiian Islands.

obtainable with various-sized VLBA's at various wavelengths is summarized in Table 1.

The telescopes comprising an array significantly influence its performance. For best results each should be able to track a cosmic source for as long as it is above the horizon. Thus, telescopes with altitude-azimuth mountings are to be preferred over those with equatorial mountings.

The best angular resolution is obtained at the shortest possible wavelength. Telescopes designed specifically for an array should be capable of operation at wavelengths as short as 1 cm. Existing telescopes designed for longer wavelengths will be useful for studies of somewhat larger sources, or where the wavelengths are dictated by spectral characteristics of the source rather than by the desire for maximum angular resolution.

Data Transmission

Transmission of the cosmic signals from the separate telescopes to the correlator is a major problem. At present the magnetic tape recorder is universally used (*10, 11*). Its attendant logistical problems will increase enormously in a VLBA, but the method is feasible, given adequate coordination and logistical support. The video tape recorders now available can record bandwidths of about 4 megahertz. Newer recorders now becoming available are suitable for bandwidths up to 50 Mhz. If the turnaround time at the processor could be held to a few days, 1 month's tape supply would probably suffice for the operation of the array.

Real-time processing could be achieved by electrical or radio transmission of the telescope output data to the processor. Ordinary telephone-quality channels have inadequate bandwidths. The microwave and coaxial-cable television distribution network is better, but the bandwidth is still too narrow for good sensitivity. For many applications, however, the television networks would be attractive.

It is already the practice among most VLBI experimenters to organize the telescope output into television format to permit the use of video tape recorders. Synchronization and other "housekeeping" data are easily included. Intercontinental connections could be made by satellite or by tape recorder, although the latter method would negate some of the benefits of real-time correlation. The monetary cost of a dedicated, broad-band communication system for VLBI's is much greater than that of a tape system. Thus, this communication medium remains an uncertain possibility.

A geostationary communication satellite, at the present state of the art, is capable of accommodating the telescope outputs of an eight- or ten-station VLBA. Each site would have a transmitter and antenna to send data to the satellite, which would then transmit all the data simultaneously to the receiving station at the processor. A group of radio astronomers from Canada and the United States have scheduled an experiment for 1976 to test the use of a communication satellite for two-station VLBI observations with real-time correlation (*20*). Because the correlator will be located at one of the telescopes, a delay line must be provided to equalize the time delays between the telescopes and the correlator. The delay line must have the exceptional characteristics of a 0.27-second delay and a 10-Mhz bandwidth.

The large and uncertain costs of the television network and satellite methods of data communication suggest that, at least as an interim measure, the tape-recorder method should be implemented. With careful organization and scheduling, an eight- or ten-element VLBA can be operated successfully with tape recorders.

Operation of a VLBA

Present-day observations with long baseline interferometers are generally ad hoc experiments requiring the cooperation of many observatories and an even greater number of investigators. The organization of a major multielement experiment involving the simultaneous scheduling of major radio telescopes, each having other commitments, and the processing of the data, one interferometer pair at a time, is a difficult logistical task. The preparation and planning of a 5-day experiment involving four elements begins 4 to 6 months beforehand, and the data processing and analysis may take 6 months to 1 year afterward.

The operation of a full-time, dedicated array of eight to ten elements, however, may not be as difficult as it may at first appear. Conventional arrays of this number of antennas are already being routinely operated, and the 27-element VLA is under construction. In principle, the magnetic tape from each antenna of an intercontinental VLBA has data that are not different from the real-time signal coming

Table 1. Resolution obtainable with VLBA's of various sizes at various wavelengths. The resolution, $\theta \sim \lambda/d$, where λ is the wavelength and d is the length of the maximum baseline of the array.

Maximum baseline	d (km)	θ (milliarcsec) at		
		λ = 1.3 cm	λ = 6 cm	λ = 50 cm
Within the United States	3.9×10^3	0.7	3.2	54
United States–Hawaii	7.0×10^3	0.4	1.8	31
Europe–United States–Hawaii	10.2×10^3	0.25	1.2	10

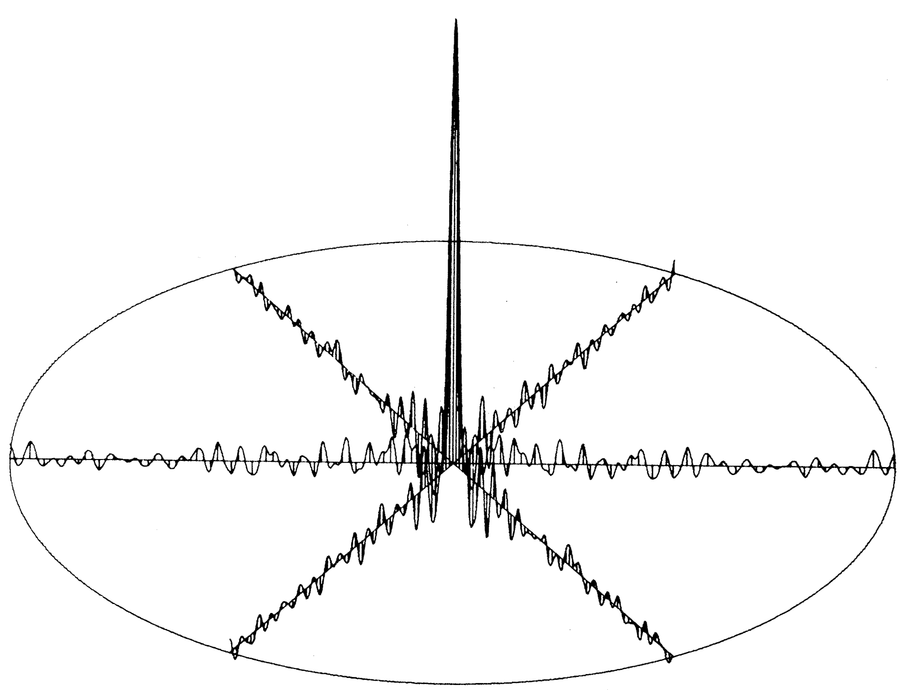

Fig. 3. Beam pattern of the array of Fig. 2 for a source at declination 45°. Angular beamwidth is proportional to wavelength: at a wavelength of 2 cm it is 1 milliarcsecond or 5 nanoradians. The vertical scale is linear in power.

via cable or waveguide from each antenna of a conventional array, and it may contain, in addition to the cosmic radio data, the other information necessary for the complete analysis of the data.

Transportation and handling of a huge number of magnetic tapes each day represents a formidable task. But with proper coordination and planning for the transportation of magnetic tapes and the use of a multistation playback system, incoming data can be correlated and analyzed with only a few days delay. Similar tasks are handled routinely by the National Aeronautics and Space Administration in evaluating the data that arrive each day from tracking stations throughout the world.

Summary

It is difficult to estimate accurately the cost of constructing a large scientific instrument that involves many techniques. On the other hand, most of the component parts of the VLBA consist of antennas and electronic systems that already exist or are being fabricated. The kind of 25-m antennas being constructed for the VLA will cost about $900,000 each and will work at wavelengths as short as 1 cm. A multifrequency radiometer, hydrogen maser frequency standard, small control computer, control building, and wide-band instrumentation recorder bring the cost to about $1.5 million per element, or $15 million for a ten-element array using tape recorders. A multistation playback facility, with ten recorders and enough correlators to handle all interferometer pairs simultaneously, together with the necessary computers to control the processor and reduce the data, may add $5 million. The total cost is thus about $20 million at current prices, including an adequate supply of magnetic tape. This is comparable to the cost of existing large radio telescopes and arrays.

An array that used a geostationary communication satellite to transmit the data to a real-time correlator would cost $30 million to $50 million more, but this is still within the price range of other space astronomy projects.

It is thus feasible to construct at reasonable cost an intercontinental very long baseline array which has sub-milliarcsecond resolution. This would complement the Very Large Array now being constructed (*4*), which is much more sensitive to objects of low surface brightness. This next step would permit the study of the universe with unprecedented angular resolution.

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22. A committee of radio astronomers has been formed to consider the establishment of a VLBA. Its members include J. J. Broderick, B. F. Burke, B. G. Clark, T. A. Clark, M. H. Cohen, W. C. Erickson, M. S. Ewing, K. I. Kellermann, S. H. Knowles, J. M. Moran, B. Rayhrer, A. E. E. Rogers, D. B. Shaffer, I. I. Shapiro, and G. W. Swenson. We acknowledge the advice and assistance of this group, particularly B. G. Clark, M. H. Cohen, and D. B. Shaffer; however, this article should not be regarded as an output from that committee. We also acknowledge valuable assistance from A. T. Moffet, D. H. Rogstad, and W. Hammond. The National Radio Astronomy Observatory is operated for the National Science Foundation by Associated Universities, Inc.

Spatial Configuration of Macromolecular Chains

Paul J. Flory

The science of macromolecules has developed from primitive beginnings to a flourishing field of investigative activities within the comparatively brief span of some 40 years. A wealth of knowledge has been acquired, and new points of view have illumined various branches of the subject. These advances are the fruits of efforts of many dedicated investigators working in laboratories spread around the world. In a very real sense, I am before you on this occasion as their representative.

In these circumstances, the presentation of a lecture of a scope commensurate with the supreme honor the Royal Swedish Academy of Sciences has bestowed in granting me the Nobel Prize for chemistry is an insuperable task. Rather than attempt to cover the field comprehensively in keeping with the generous citation by the Royal Academy of Sciences, I have chosen to dwell on a single theme. This theme is central to the growth of ideas and concepts concerning macromolecules and their properties. Implemented by methods that have emerged in recent years, researches along lines I shall attempt to highlight in this lecture give promise of far-reaching advances in our understanding of macromolecular substances—materials that are invaluable to mankind.

These polymeric substances are distinguished at the molecular level from other materials by the concatenation of atoms or groups to form chains, often of great length. That chemical structures of this design should occur is implicit in the multivalency manifested by certain atoms, notably carbon, silicon, oxygen, nitrogen, sulfur, and phosphorus and in the capacity of these atoms to enter into sequential combinations. The concept of a chain molecule consisting of atoms covalently linked is as old as modern chemistry. It dates from the origins of the graphic formula introduced by Couper in 1858 and advanced by Kekulé, Loschmidt, and others shortly thereafter. Nothing in chemical theory, either then apparent or later revealed, sets a limit on the number of atoms that may be thus