VLBI
NETWORK STUDIES III

AN
INTERCONTINENTAL
VERY LONG BASELINE ARRAY

National Radio Astronomy Observatory

May 1977

PREFACE

Very Long Baseline Interferometry (VLBI) is only a decade old, but current research already covers a wide variety of topics including the tantalizing apparent faster-than-light motions found in some quasars and radio galaxies, methods of earthquake prediction, interplanetary spacecraft navigation, and precise tests of General Relativity.

Many of the newly discovered exotic astrophysical objects are extremely small. Interstellar molecular masers, pulsars, X-ray binary stars, the extremely powerful energy sources which are hidden deep inside quasars and galactic nuclei, all appear as unresolved "points" to ordinary radio and optical telescopes, but can be studied in great detail with VLBI techniques. Many important scientific discoveries have already been made, but the full potential of this new technique for research in astronomy as well as in geophysics has yet to be fully exploited.

Most of the previous effort has been the result of the ad hoc cooperation of a few individuals and institutions. In an effort to reduce the numerous practical difficulties of simultaneous scheduling of many radio telescopes and their non-uniform instrumentation, U. S. radio astronomers and observatories have organized a VLB Network which has simplified the procedures for multi-station VLBI observations using existing antennas (Cohen et al. 1977).

But still there are many limitations with an array consisting mostly of existing radio telescopes which have poor performance at short wavelengths, unsuitable locations, and often inadequate instrumentation and support. New, modern antenna elements are needed, together with the instrumentation and personnel necessary to link them into a true multi-frequency image forming array having sub milli-arcsec resolution. In this report we describe a dedicated Very Long Baseline Array of intercontinental dimensions. This array, which will study cosmic radio sources of high surface brightness (e.g. quasars, galactic nuclei, pulsars, compact galactic and extragalactic hydrogen clouds, radio stars, and interstellar molecular masers) with unprecedented angular detail, will complement the VLA, which has lower resolution but very much greater sensitivity to radio sources of lower surface brightness (e.g. giant radio galaxies and quasars, extended galactic and extragalactic hydrogen and molecular clouds, and the planets). The universe contains both types of objects, and both instruments are needed for a full exploitation of galactic and extragalactic radio astronomy.

Although the resolution of a VLB Array is greater than for conventional instruments by more than a factor of a hundred, it can use much of the instrumentation and techniques developed for the VLA (the antenna elements, the radiometers and other electronics, as well as some of the post-observation image formation techniques) with a considerable economy of design and operation. The basic difference is in the i.f. signal distribution by magnetic tape recordings instead of waveguide. Thus, even though we are discussing a major new scientific instrument with dramatic new capabilities, the component parts are all familiar and are based on established procedures and techniques. Nevertheless, many difficult decisions and questions remain. What is the optimum location of the antenna elements, taking into account the desirability of minimizing the number of new sites which must be developed? How can we best reduce the distorting effect of the atmosphere on the resulting images? And, perhaps the most difficult question: What is the best way to manage and operate a complex system whose elements extend halfway around the world? These problems, as well as the development of the needed reliable and automated instrumentation, are being studied at a variety of laboratories, and are discussed in this report. The report includes a plan for the orderly construction of a VLB Array, starting with the construction of a single antenna element in the midwest to be used initially together with existing radio telescopes (e.g. Swenson et al. 1977). Many variations of the Array and its development are possible, and this report is being distributed at this time in the hope of encouraging further discussion and study.

Many people including D. Backer (Univ. of Calif.), J. Broderick (VPI & SU), B. Burke (MIT), B. Clark (NRAO), T. Clark (NASA), M. Cohen (Caltech), W. Erickson (U. of Md.), M. Ewing (Caltech), K. Johnston (NRL), S. Knowles (NRL), J. Moran (Smithsonian), A. Niell (JPL), I. Pauliny-Toth (MPIfR, Bonn), B. Rayhrer (NRAO), A. Rogers (MIT), D. Shaffer (NRAO), G. Swenson (U. of Ill.), and S. Weinreb (NRAO) have contributed extensively to this report.

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I. SUMMARY

A. Introduction

For many years it was widely accepted that because radio telescopes operate at such long wavelengths, their angular resolution was fundamentally poorer than that of optical telescopes.

Actually, this is not the case, for two reasons. First, the resolution of large optical telescopes is limited not by their size, but by irregularities in the earth's atmosphere, to about one second of arc. At radio frequencies, the fluctuations in the length of the path of the incoming signal through the atmosphere are small compared with the length of radio waves, so that the effect of atmospheric irregularities is much less important.

Second, the radio signal or the optical signal must be coherent, or in phase, over the entire dimensions of the telescope. Coherent radio waves are much easier to manipulate than coherent light signals, so that radio telescopes can operate much closer to the theoretical limit of resolution than conventional optical telescopes.

The history of radio astronomy has been one of the successive solution of the variety of technical problems which limit the resolution, and today radio interferometers approaching the diameter of the earth give a resolution three orders of magnitude better than are obtained with conventional optical instruments. In this report we describe an extension of this Very Long Baseline Interferometer (VLBI) technique to the construction of a new kind of radio telescope - The Intercontinental Very Long Baseline Array, which with its dramatic resolving power and image forming ability will make possible a wide range of new astronomical and geophysical studies.

The proposed image forming radio telescope array of intercontinental dimensions will permit many exciting astrophysical and terrestrial phenomena to be studied with unprecedented detail.

The nuclei of radio galaxies and quasars, where vast supplies of energy are repeatedly and explosively generated in a volume of space a few light years or less across surely hold the key to the problem of the origin and evolution of radio galaxies and quasars, but existing instruments have not yet been able to unravel their complex nature. Speculation on the source of enormous energy currently centers around accretion on massive black holes hidden deep in the nuclei of galaxies or quasars, but whatever its nature, an understanding of the energetic phenomena which occurs in quasars and in the nuclei of galaxies will surely have an important influence on future astrophysical research. The study of these exotic regions and the similar, but smaller and less luminous nuclei of nearby elliptical and spiral galaxies, as well as the Galactic Center, will also be important in understanding the relation between galaxies and quasars, and the phenomena which causes the powerful radio emission.

The unexpected dramatic discovery of apparent faster-than-light motion in some radio galaxies and quasars challenge our fundamental concepts of physics and cosmology and a more detailed study of this phenomena may have profound implications.

Within our own Galaxy, clouds of interstellar water vapor and hydroxyl ions have been observed to act as giant interstellar masers. Their angular dimensions appear exceedingly small, and observations with sub milli-arcsec resolution give important insight into stellar origin and evolution.

Very compact clouds of neutral and ionized hydrogen in our own and in other galaxies have already been observed, and their more detailed study will add to our understanding of the interstellar medium.

Many stellar radio sources, including binary stars, pulsars, X-ray stars, and flare stars appear as "point sources" to conventional radio telescopes, or arrays, but they can be studied in detail with an array of intercontinental dimensions.

In addition, a variety of terrestrial phenomena, including the direct measurement of earth tides and continental drift, accurate global clock synchronization, and the possibility of earthquake prediction have already been explored using VLBI techniques and considerable improvement is expected with the Intercontinental Array. Other areas where great progress is anticipated include precise tests of General Relativity, and interplanetary spacecraft navigation.

Already, Very Long Baseline Interferometry using existing radio telescopes throughout the U.S.A., Europe, Africa, and Australia has resulted in many exciting new discoveries. But there are a number of important limitations which have prevented the full exploitation of this technique, so that in general only a measure of the over-all angular extent or a crude estimate of the angular structure of compact celestial objects has been obtained.

This situation is similar to that of conventional interferometry until the mid-1960's when the construction of the multi-element Cambridge one-mile telescope, the Westerbork Synthesis Array, and more recently the Cambridge 5-km array allowed the complete imaging of cosmic radio sources with a resolution of a few arc seconds over the northern part of the sky. The development of the VLA will permit rapid multi-frequency observations over most of the sky visible from the northern hemisphere with considerably greater resolution and sensitivity than is currently available, and will thus largely eliminate the problems of ambiguous results, lengthy observations, poor sky coverage, and limited choice of frequencies previously associated with interferometer observations. The full potential resolution and sensitivity of conventional interferometry will be achieved with the VLA.

In the same way, a fully dedicated Very Long Baseline Array will remove many of the problems now associated with Very Long Baseline Interferometry and will permit the true imaging of galactic and extragalactic sources of radio emission with an angular resolution better than one milli-arcsec. Specific improvements expected over currently available VLBI systems are:

a) More nearly optimum location of antenna elements, permitting better image formation as a result of the more uniform spacing of the interferometer pairs and inclusion of appropriate necessary redundancy to permit the calibration of the phase of the instrument.

b) Use of better antennas to permit operation at wavelengths at least as short as one centimeter to achieve better resolution, and to allow observations at the 1.3 cm water vapor line; and to allow for the tracking of sources over the entire visible sky (necessary for good image formation).

c) Sufficient logistical support to allow observations and analysis by a single scientist or small group of scientists. Presently, experiments require the recruiting of a large number of collaborators to carry out the tasks required at each observing site. Associated data reduction and analysis currently involves such considerable effort on the part of the astronomer, that there is inadequate time to pursue new scientific ideas.

d) Operation under a single management will allow coordinated direction, instrumentation, and operation. Presently-organized experiments involving various observatories involve the use of non-standardized equipment and procedures, as well as considerable difficulty in scheduling experiments which may involve three or more major telescopes. This problem of accommodating the needs of VLBI observations is becoming increasingly difficult in view of the rapidly increasing number of experiments and the number of scientists involved, as opposed to the continuing demands on the instruments for other areas of radio astronomy. Presently about one quarter of the observing time on the large radio telescopes at NRAO, OVRO, and Haystack is spent on VLBI. The simultaneous scheduling on a specific observing frequency, for example, at NRAO, Haystack, Bonn, ARO, and OVRO causes considerable disruption of the various operations, scheduling, and routine maintenance procedures normally in effect at these observatories. As a result, these important multi-station programs are possible only once or twice a year, and then only at considerable impact to the normal operation of each observatory.

B. The Array

The instrument described in this report is conceived as a multi-element Intercontinental Array to be operated as a national or international facility open to all qualified scientists from the U.S.A. and abroad. Many of the phenomena associated with compact radio galaxies and quasars, with pulsars, and with the interstellar molecular masers are variable. Thus it may be expected that for some fraction of the time, the Array will monitor a selected number of such objects, and also do a variety of systematic geodetic and astrometric observations, which are not only of interest in their own right, but are necessary for the calibration of the instrumental performance. The remainder of the time will be available for a wide variety of experiments. The Array we discuss here is a ten-element tape-recording array with 8 of the elements located in North America, one in Hawaii, and one in Europe. This instrument is capable of a resolution of about 0.5 milli-arcsec at its shortest operating wavelength of 1.3 cm.

Its total dimensions cannot be significantly increased without the use of antennas in space.

The system uses the now well-established techniques of independent-oscillator-tape recording-interferometry (commonly known as Very Long Baseline (VLB) Interferometry), along with instrumentation and data processing methods being developed for the Very Large Array (VLA).

Each of the individual antenna sites is operated and maintained by a local staff of three or four engineers and technicians who are also responsible for organizing the transportation and documentation of incoming and outgoing magnetic tape. A person is generally required at each telescope during normal operations to change magnetic tapes. Otherwise, each antenna element is capable of operation without any site personnel present. For many common types of observing programs, a single data tape will last several days and for periods of this length unattended operation may be possible.

The actual operation of the instrument may be controlled by a central Operations Center with direct access to the antenna elements via telephone lines. Information on the operational status of each antenna element as well as meteorological data is sent to the Operations Center for evaluation and possible change in the observing program.

Each antenna and receiving system is controlled by a small on-line computer, which points the telescopes, sets the observing frequency, records meteorological and radiometer data, monitors the performance of the receiver and recording systems, and handles communication with the Operations Center.

The data from each antenna is recorded on magnetic tape, and each day the tapes from the previous 24 hours of observing are sent to the Operations Center by appropriate commercial and in-house transportation. At the Operations Center they are sorted and correlated with each other by simultaneously playing back all 10 tapes. The data streams from the tapes are pairwise correlated (a total of 45 pairs) and the results stored on ordinary computer-readable magnetic tape. This data, which is in many ways analogous to the output of the VLA Synchronous Computer, is then available to the experimenter for further analysis, either using the facilities of the Operations Center or those at his home institution, and using either standard or specially developed software.

The process of correlating the magnetic tapes is done at rates ranging from one-half real time to up to 16 times real time depending on the particular experiment. For spectral line observations, in particular, which require relatively small bandwidths, a full day's worth of data can be processed in a little over one hour.

The maximum sensitivity of the Array at full bandwidth is about 1/3 that of the VLA for the same observing times. At centimeter wavelengths approximately half of all extragalactic sources are compact and are suitable for study with this Array; the other half are resolvable with the VLA. The number of sources increases approximately linearly with decreasing flux density, so that at any flux density level about 15 percent of all sources which are observed with the VLA can probably be mapped with this instrument. The amount of work to be done on the radio galaxies and quasars alone is very great. For the galactic sources the estimates are less certain, but there are already about 100 known OH and H_2O maser sources which can be studied with this Array. A large number of stellar sources and pulsars will also be available for study. Both the galactic and extragalactic sources are time variable, and so repeated observations not only of their flux, but of their brightness distribution as well (or in the case of pulsars, position), are necessary. For galactic objects such as pulsars and radio stars, repeated measurements of position will be required to determine their proper motion and distance. Thus there is essentially unlimited work to be done with the instrument without consideration of new types of sources which are likely to be discovered.

C. Cost Summary

The component parts of the Intercontinental Array are similar or identical to VLA components, or are available commercially. Thus, although we are discussing a unique and powerful new scientific instrument, there are no major new conceptual design or engineering problems to be solved, and the construction cost can be reliably estimated, aside from an uncertain rate of inflation.

The construction costs have been determined from present VLA costs in the case of the antennas, receiver, and data processing system; and from current prices for the tape recording system. It is believed that the costs given in Table I.1, below, do represent a good estimate of the actual cost in 1977 dollars of constructing the Array. The operating cost is based on estimates of the VLA operating cost but also the cost of unusual items such as replacement of recorder heads, shipping of magnetic tapes, etc. The construction costs discussed here are, as in the case of the VLA, for the entire operating system with radiometers and computers (including software).

Table I.1

Cost Summary

Array Antenna Systems	$ 9,960,000
Array Electronic and Computer Systems	6,860,000
Array Site Development	1,000,000
Processor System and Computer	4,937,000
Magnetic Tapes	720,000
Project Management	1,000,000
Contingency 10 percent	2,300,000
Total Construction Cost	$25,817,000
Annual Operating Cost	$2,780,000

Construction and operation of the Intercontinental Array as an extension to the VLA would require a continuation of the current VLA funding level for another two years and an increase of about 1/3 in the operating cost.

II. SCIENTIFIC APPLICATIONS

The excitement and major contributions of new scientific instrumentation lie not only in the increased capability to solve the scientific problems which led to their construction, but even more so in their unexpected discoveries which may uncover whole new areas of research.

This is especially true in radio astronomy where, as a result of the rapid succession of exciting new discoveries, radio telescopes are generally working in areas that were unknown at the time of their conception. For example, when the 140-ft telescope was planned in the late 1950's, quasars, interstellar molecules and molecular masers, hydrogen recombination lines, compact synchrotron sources, pulsars, and Very Long Baseline Interferometry itself were all unknown. Yet in recent years more than 75 percent of the observing time on the 140-ft telescope has been devoted to these areas.

Particularly in the case of an Intercontinental Array, with its great flexibility and high resolution image forming capability, it is difficult to anticipate the research topics which will be important in five to ten or more years. Although we may fully expect that much of the observing time of this instrument will be spent on problems which will arise as a result of its own discoveries, it is of interest to outline what currently appear to be relevant research topics which span most areas of current interest in astronomy and astrophysics, as well as a variety of geophysical topics.

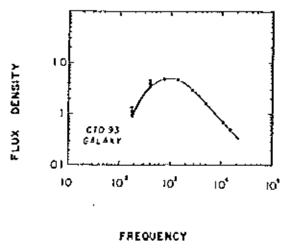
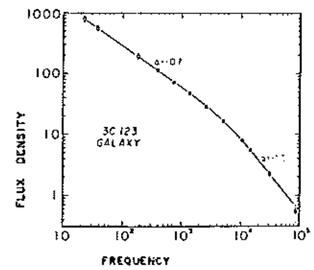
A. Radio Galaxies and Quasars

The radio emission from galaxies and quasars is generally believed to be due to "synchrotron" radiation from relativistic particles moving in weak cosmic magnetic fields.

These extragalactic radio sources may be conveniently divided into two categories: extended and compact. Their properties are briefly summarized in Table II-1. Figure II-1 illustrates the spatial relation between the two.

Table II.1

Properties of Compact and Extended Radio Sources

	COMPACT	EXTENDED
ANGULAR SIZE:	$<< 1''$	$\gtrsim 1''$
LINEAR SIZE:	1-10 parsec	10-100 kpc
STRUCTURE:	Complex	Complex
SPECTRA:		
VARIABILITY:	Yes	No

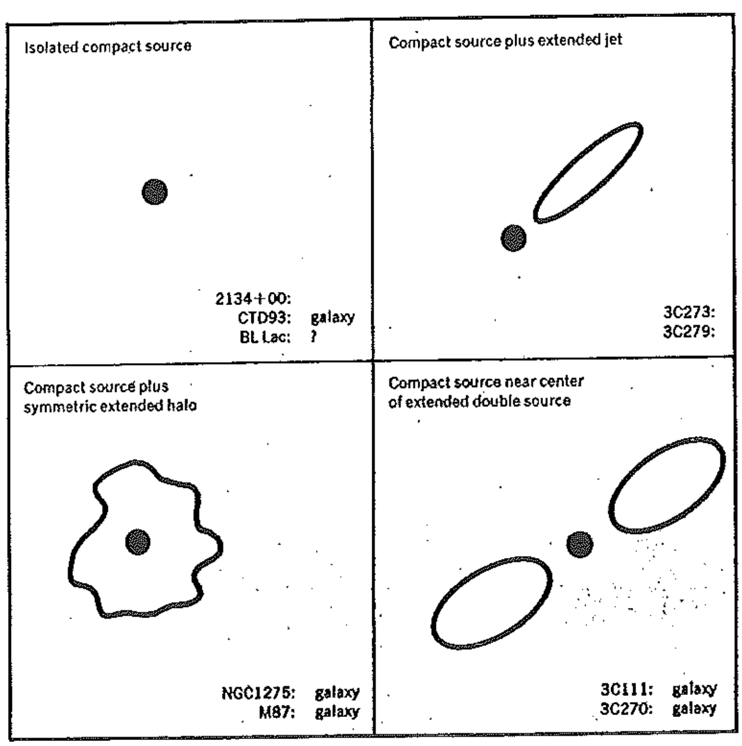


Fig. II-1. Schematic illustration showing the spatial relation between extended and compact radio sources. The closed circles represent compact components with dimensions of the order of a milli-arcsec and the open regions represent the extended components with dimensions of the order of one arcminute.

For the extended clouds of relativistic particles, the observed radio emission is the sum of the synchrotron radio radiation from the individual electrons. For these sources the radio spectrum reflects the distribution of particle energies. Radio interferometry and aperture synthesis observations have shown that the extended sources are quite complex and usually contain two or more components which may be separated by millions of parsecs. Often a galaxy or quasar can be identified which lies near the centroid of radio emission. Because the relativistic particles and magnetic fields occupy such large volumes of space, the energy requirements are tremendous. The source of this energy and the process by which the energy is converted into relativistic particles and extensive well organized magnetic fields is not understood and represents one of the basic problems of modern astrophysics.

It is generally believed that the powerful energy sources lie in the optically identified galaxy or quasar, and in particular, deep within the galactic nucleus. High resolution observations made with the NRAO, Westerbork, and Cambridge arrays have detected very compact radio sources located between the double extended components, and coincident with the identified galaxy nucleus or quasar. Many otherwise normal spiral, elliptical, and irregular galaxies also contain weak compact radio nuclei.

The VLA, with its ability to form images quickly of small regions of the sky with angular resolution of the order of 0.5 arc sec will be a powerful new tool for examining the extended sources with great detail and sensitivity, and will be able to isolate a much larger number of compact sources than is presently known. In these compact radio sources, absorption by the relativistic electrons is important and causes a peak in the spectrum. Sources exhibiting such spectral peaks in the decameter to short centimeter regions must be very small, with dimensions ranging from 0.1 to less than 0.001 arcsec . In some sources, the radiation may be due to electrons acting collectively (coherent radiation); these components could be even smaller. Because of their very small size, the VLA cannot resolve the compact sources, and indeed these will serve as "point" sources to calibrate the amplitude and phase response of the VLA. In order to study the spatial structure of these compact sources, an array of intercontinental dimensions is required.

Presently available high resolution observations of the compact sources using long baseline interferometry between existing radio telescopes in the

U.S.A., Canada, Europe, and Australia, and Africa have shown that like the extended sources, the spatial distribution is remarkably complex, but on a scale of size differing by a factor of up to a million. But, because of the insufficient number of antennas, and the absence of phase information, it has not been possible to construct a unique image of a compact radio source from the interferometer data. Figure II-2 illustrates several maps formed by various

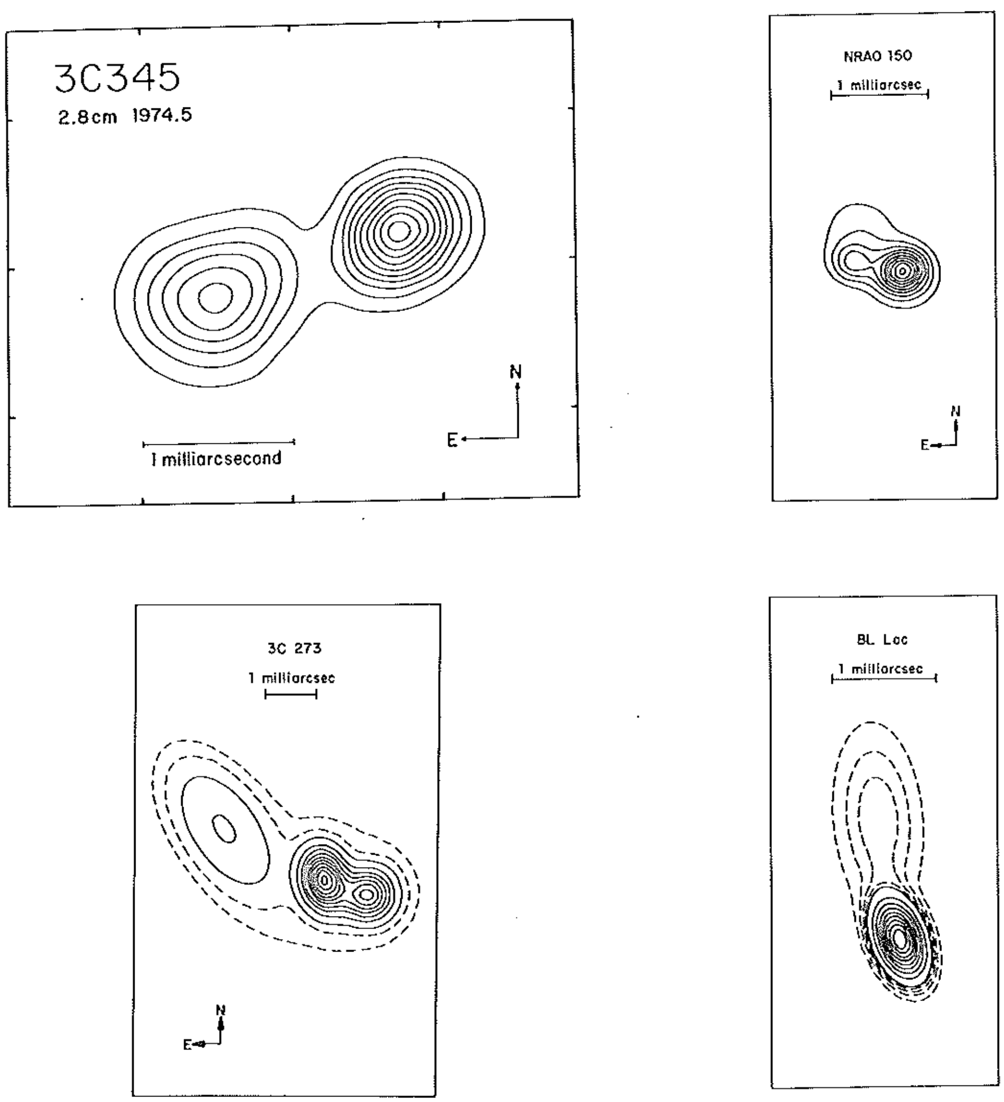


Fig. II-2. Brightness distribution of the radio sources BL Lac, 3C 345, NRAO 150, and 3C 273.

imaging techniques. Although these maps are not unique, they are believed to represent the main features of the source.

One of the best studied sources is the nucleus of the galaxy NGC 1275 which has a complex brightness distribution. The 2.8 cm contour diagram of NGC 1275, shown in Figure II-3, represents the complex distribution of radio surface brightness derived from model fitting intercontinental observations

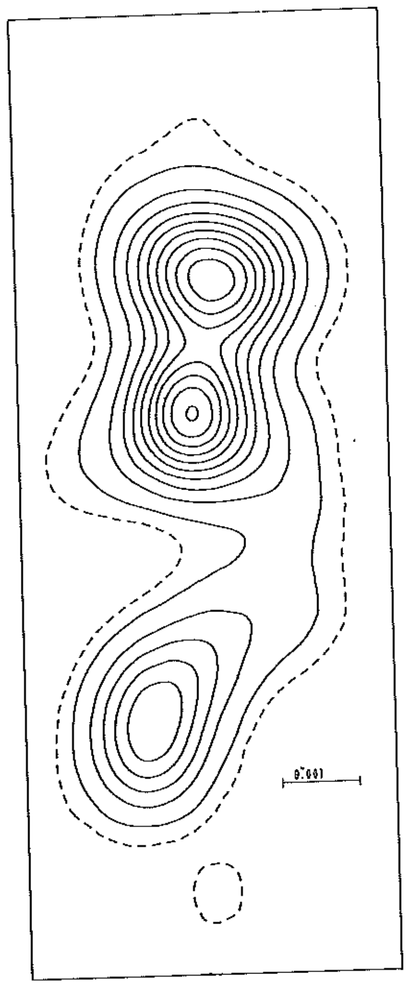


Fig. II-3. Contour map of the structure of the nucleus of NGC 1275. Contours are drawn at 10 percent contour levels. The dotted line represents the 5 percent contour.

(Pauliny-Toth et al. 1975). The over-all extent of the radio nucleus at short centimeter wavelengths is about 6 milli-arcsec or 3 parsecs, and it is oriented along position angle ∿ -7 degrees. This is the same direction as the greatest extent of the optical filaments which extend more than 50 kpc from the galactic nucleus. At decimeter wavelengths the radio nucleus is dominated by a source about 0.1 arcsec (500 pc) long and elongated in the same direction. There are also several extended radio components associated with NGC 1275. These have angular dimensions of 30 arcsec (5 kpc) and 5 arcmin (50 kpc) and are also elongated along the same direction as the nuclear components, implying a preferential direction which is effective over a wide scale of distance and time.

The compact centimeter wavelength component of NGC 1275 is unique only in that it is sufficiently large that it can be resolved into a number of picture elements, and at the same time sufficiently strong so that there is a reasonable signal-to-noise ratio at each point in the map. Given greater sensitivity as well as more complete (u,v) coverage, it will be possible to map many other galactic nuclei and quasars in even greater detail than has been done for NGC 1275.

The relation between the compact radio nuclei and the giant radio galaxies and quasars is not understood, but it is widely recognized that the radio nuclei may be the energy source for the more extended components. The common existence of the nuclei and their apparent alignment with the extended components means that a more thorough investigation with both the VLA and a VLB Array is essential to an understanding of the origin of radio galaxies and quasars.

Most extragalactic radio sources which have been studied can be modeled by simple two- or three-component configurations, with component separations as small as ∿ 0.6 milli-arcsec. The corresponding linear dimensions are as small as one parsec or less.

One of the smallest radio sources which has been observed in detail is the nucleus of the galaxy M87 (Virgo A) which has an angular size of 0.25 milli arcsec corresponding to a linear extent of only a few light weeks (Kellermann et al. 1977). The nucleus also has several larger components. Observations at shorter wavelengths are required to resolve these smallest radio components, and more extensive observations over a wide range of wavelengths are necessary to map the structure in more detail.

An even smaller component with dimensions $\lesssim$ 1300 A.U. has been found in the nucleus of the nearby spiral galaxy M81 (Kellermann et al. 1976). This is the smallest extragalactic object which has been observed. The Irregular galaxy M82 and several nearby elliptical galaxies also have radio nuclei which have been observed with VLBI techniques, and with the greater sensitivity and image forming ability of a VLB Array, many more will be located and studied.

For most compact radio sources, the intensity varies on time scales of a few weeks to a few months, and this is generally interpreted as the result of repeated energetic events which release expanding clouds of relativistic particles. In general, the radio source structure varies as well, although detailed repeated observations have been systematically made on only a few sources. For about half of those sources where sufficient data exist, (3C 120, 3C 273, 3C 279, and 3C 345), the separation of the radio components appears to increase with time, and changes in angular separation up to a factor of 10 within a few years have been observed (e.g. Kellermann and Shaffer 1976). Assuming a cosmological origin of the redshifts ($H = 50$ km sec^{-1} Mpc^{-1}, $q_o = 0.04$) the corresponding linear velocities are well in excess of the velocity of light, with typical velocities between 5c and 10c.

The apparent velocity of separation is not always constant. Small accelerations and decelerations are observed, although the position angle joining the components remains constant. In one case, 3C 120, two distinct sets of separating doubles have been observed, with both moving along the same position angle.

Interpretation of this apparent faster-than-light motion in terms of a stationary set of variable intensity sources does not appear possible. Since the observed component separation at any given epoch is independent of wavelength, refractive effects or variations in the synchrotron opacity are also unlikely. A variety of phase velocity effects have been suggested, but these are unconvincing since they require preferential geometries which are unlikely to be found in about half of the observed sources.

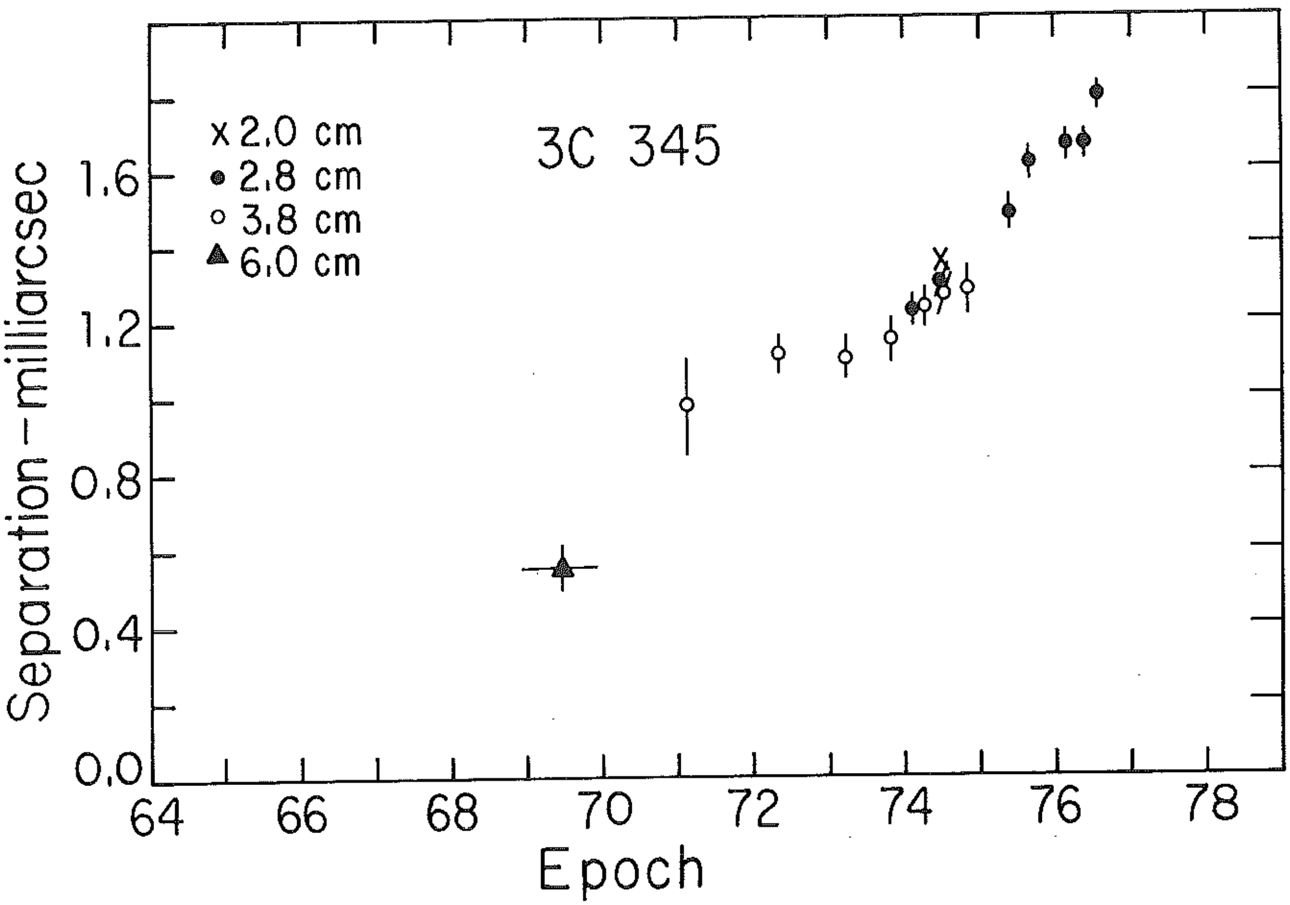


Fig. II-4. The separation of the components of the quasar 3C 345 as a function of time measured at several wavelengths.

The apparent faster-than-light motion in radio galaxies and quasars has important implications to the theory of radio sources, and has rekindled interest in the non-cosmological interpretation of the redshift. Frequent systematic observations over a wide range of wavelengths are needed to further investigate this unexpected and remarkable phenomena.

Compact radio nuclei and extended sources coexist in many radio galaxies and quasars. In the few cases where the structure of the compact nuclei of extended sources has been studied, the nuclei appear to be aligned with the extended components, although the linear dimensions and ages differ by a factor of 10^5 or more. This is illustrated by the structure of the radio galaxy 3C 111 illustrated in Figure II-5.

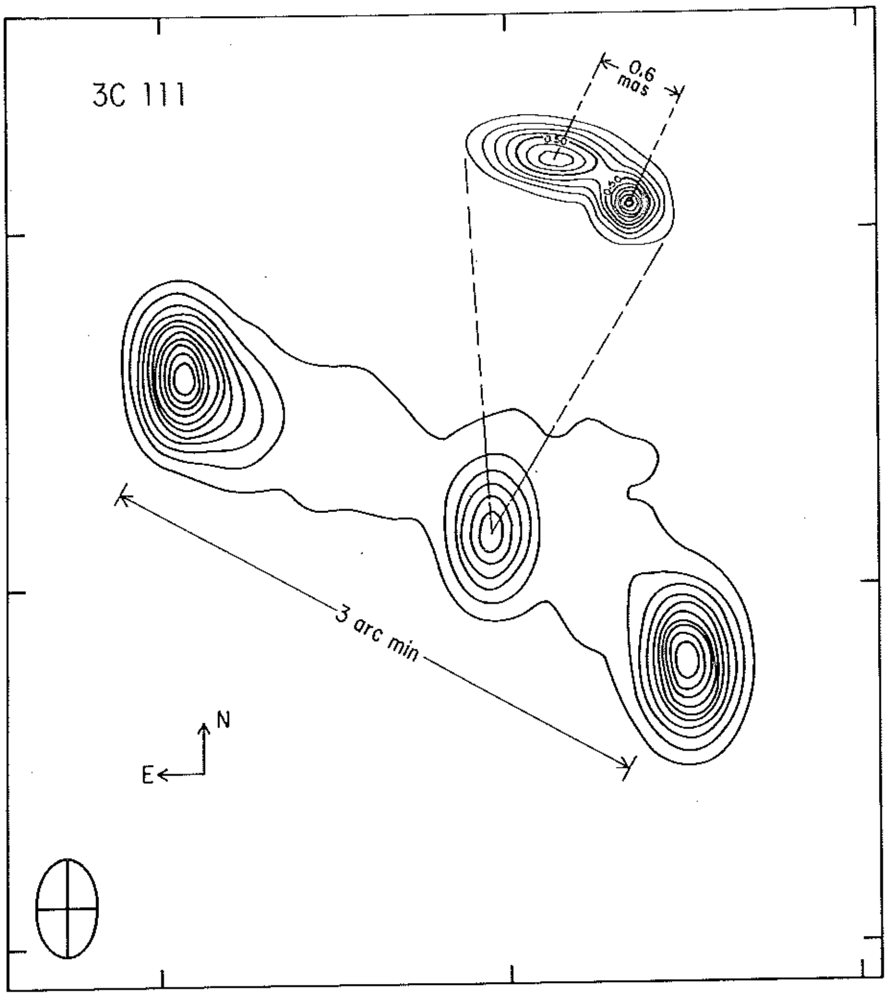


Fig. II-5. Contour diagram of 3C 111 showing the extended 3 arcminute source as observed with the Westerbork Array, and the compact radio nucleus observed by VLBI.

B. Galactic Sources

1. Molecular Masers.

In recent years more than 30 molecules have been detected in interstellar space. Most of these are in thermodynamic equilibrium, but in the case of clouds of OH (hydroxyl), H_2O (water vapor), S_iO (silicon monoxide) and CH_3OH (methyl alcohol) stimulated emission can be important, and these clouds appear as giant interstellar masers. These masering sources are found in HII regions associated with regions of early star formation, or with IR stars which are in later stages of evolution.

The spectra of the maser sources generally contain a large number of features or components having widths of about 1 km/s or less and spread over a range of typically 5 to 50 km/s. The components have apparent sizes ranging from 0.1 to 100 milliarc sec and are scattered over a field having a diameter of from 1" to 10". The ratio of the total source size to the individual component size is generally quite large, i.e. $10^1 - 10^4$.

About 100 OH and H_2O maser sources have been detected, and many of these have been observed with VLBI techniques. The OH emission from the relatively nearby IR sources have the largest angular sizes. Many are completely resolved by baselines of a few hundred kilometers (Moran et al. 1977). The H_2O emission features are very time variable and have the smallest angular sizes (Burke et al. 1972). Some are only partially resolved by transcontinental or even intercontinental baselines. The highest resolution VLBI observations, made in 1976, by scientists from the USA, Australia, and the USSR using baselines up to 12,000 km, show that some H_2O features are smaller than one astronomical unit.

Since both the spectrum and spatial appearance of maser sources change with time, observations at periodic intervals with the VLB array will be necessary. The mechanism causing the changes in the spectral profile and spatial structure is not known. There are at least two types of variation. The first is a slow quasi-periodic variation in which the spectral shape remains relatively constant but the total flux changes. This is characteristic of stellar-related OH and H_2O sources such as R Aquilae. The microwave flux for these sources varies in phase with the infrared flux. This variation is almost certainly due to a change in the pump power. The periods range from 200 to 1000 days, and appear to be proportional to the separation of the components in the 1612 MHz OH spectrum. The second type of variation is random fluctuations affecting individual features or groups of features. This could be caused by turbulence in the source which changes the path of amplification or by a lighthouse effect whereby the maser, if narrowly beamed, chances to sweep across the earth's direction. Many of the strongest OH sources such as W3(OH) are quite stable, having changed little in the ten years since their discovery. However, most of the H_2O sources associated with HII regions change drastically over periods of about 100 days while significant changes are sometimes noticeable over periods of only 10 days.

There is perhaps a third type of variability typified in the behavior of V1057 Cygni, an early type star. This source disappeared in about 1 year suggesting that OH masering is a phenomenon that perhaps lasts only about one year in the life of an early type star.

A widely discussed model concerned with the geometry of the maser sources is the so-called hot spot model, which predicts that the observed component size is about 1 to 2 orders of magnitude smaller than the actual maser size. This theory can probably be verified in the case of the IR related objects by synthesis observations at several points during their variation cycle to see how the images change.

2. Stellar Objects.

In recent years radio emission from a variety of stellar objects has been studied. These include novae, supernovae, X-ray sources, binary stars, and flare stars. Observations with conventional interferometer systems with resolutions better than one arc second shows the radio emission from these objects to be unresolved. Since the radio emission is both weak and transient, it has been difficult to arrange for observations with sufficiently sensitive VLBI systems.

In the case of the eclipsing binary system, β Persei, more commonly known as Algol, flares of sufficient strength have occurred to permit VLB interferometry which has resolved the radio source and shown the radiation to come from a region of about 0.1 AU in extent (Clark et al. 1975, Clark et al. 1976). This may be compared with the size of the individual stars of 0.03 AU and the separation of 0.2 AU of the two components.

The sensitivity and availability of the VLB Array make possible observations of all these objects,at least during active periods. Of particular interest will be the determination of the time variation of size of the variable sources associated with the explosive novae, supernovae, and flare stars. In the case of the binary stars, the radio brightness may be compared with the binary system. Highly accurate astrometric observations, which will be made possible with the VLB Array, may permit the orbital motion, if any, of the radio source to be directly observed.

(a) Extrasolar planets. The ability to make highly accurate differential position measurements may make possible for the first time the direct establishment of the existence of planets or low mass companions around nearby stars. The widespread existence of other planetary systems is widely accepted, although has never been observed. The small angular separation between a star and its satellites, even at a distance of a few parsecs, and the large luminosity ratio make the direct optical resolution impossible. The measurement of slight irregularities in the motion of nearby Barnard's star has been explained as the result of the gravitational perturbations caused by an orbiting planet. More recent analysis of the observational data, however, discredits these claims, so that there is now no convincing direct evidence of any planetary system.

Provided that radio emission from the star can be observed during an active period, differential angular displacements of only a few micro-arcsec (corresponding to a few degrees of phase) should be possible.

(b) Pulsars. Observations of pulsars with an array of transcontinental dimensions are of interest for three reasons: the direct measurement of distance by trigonometric parallax, the measurement of proper motion, and studies of scattering by the interstellar medium.

At 20 cm, phase measurements accurate to $\pm$ 10° would yield by trigonometric parallax distances accurate to about 5 percent for pulsars up to 1 kpc distant. Sixty pulsars are known which are estimated to be closer than 1 kpc. By combining the directly measured distance of pulsars with their dispersion measure, it will be possible to determine the column density of thermal electrons. This can then be used to calibrate the distance vs dispersion measure relation, to get better distance estimates to the more distant pulsars, to allow a better description of the space density of pulsars, and to tie HI absorption features into velocity models of our galaxy. Deviations from a simple parallax-electron column density "law" will provide knowledge of the large scale uniformity of the tenuous HII medium.

The measurement of pulsar proper motions to an accuracy of $\pm$ 1 km/sec requires a relative position accuracy of 1 milli-arcsec and a baseline of five years for distances up to 1 kpc.

Measurements of this accuracy (or even somewhat poorer) allow us to locate pulsar birthplaces, where a distributed supernova remnant may be found. The proper motion, combined with the position of an observed remnant, yields the ages of the remnant and of the pulsar, which are important parameters for testing theories of neutron star evolution and of supernova remnant emission.

(c) Flare stars. A VLBA operating at decimeter wavelengths might have sufficient sensitivity to detect a number of flare stars. It is not clear whether the resolution will be sufficient to resolve the radio flare, but if it is, it will be possible to study the motion and evolution of the flaring region. It may also be possible to determine the distance of the flare star by measuring the trigonometric parallax.

3. The Galactic Center

The Galactic Center is an extraordinarily rich and interesting region containing thermal and non-thermal radio and IR emission regions as well as a very compact non-thermal radio source. The over-all size of this compact radio nucleus is $\sim$ 0.02 arcsec (200 AU), but there is a smaller core $\lesssim$ 0.001 arcsec (10 AU) which contains about 25 percent of the total flux density.

It seems likely that this source is similar to, but smaller and less luminous than the compact radio sources found in the nucleus of other spiral and elliptical galaxies, radio galaxies, and quasars. Because it is so close, the Galactic Center source provides an unparalleled opportunity to study radio nuclei, which may play a key role in understanding the source of energy of the powerful radio galaxies and quasars. So far, however, our knowledge of the structure of the Galactic Center source is limited due to its a) low southern declination, resulting in poor (u,v) coverage, b) low flux density, and c) the uncertain effects of interstellar scattering.

C. The Interstellar and Intergalactic Medium

The discovery of pulsars has led to the detection of irregularities of the thermal plasma density in the interstellar medium on a typical scale of a solar diameter (3×10^{11} cm). Although the spatial scale of these inhomogeneities suggests a stellar corona origin, their general distribution, given our knowledge of the density of the stars, demands that they exist throughout the tenuous interstellar gas. The origin and stability of the irregularities is not understood at the present time; they may be associated with abrupt gradients due to interstellar shocks, acoustic or hydromagnetic waves driven by cosmic rays, and isotropic turbulence in the "hot" component of the interstellar medium. Along a few lines of sight, it is possible to associate the observed effects with turbulence in intervening HII regions. The kinetic energy involved in these irregularities may represent a significant term in the energy budget of the interstellar medium, particularly if it can be shown that larger irregularities exist on spatial scales octaves above 3×10^{11} cm.

Initial research on interstellar scattering concentrated on defining observables and measuring their radio frequency and dispersion measure dependences. While in most cases the frequency dependences of scattering parameters follows that expected from dimensional arguments, the dispersion measure dependences do not follow the expected patterns assuming a uniform medium of irregularities. The apparent brightness distribution of compact radio sources dilated by interstellar scattering is an important parameter to be studied to extend our knowledge of interstellar scattering (e.g. Readhead and Hewish 1972, Vandenberg et al. 1973, Mutel et al. 1974).

The main questions are:

(i) What is the shape of the irregularity spectra of thermal plasma density along various lines of sight in the interstellar medium?

(ii) How does the "amplitude" of the scattering vary along any line of sight, from the solar system?

(iii) Are there secular changes in the scattering?

An Intercontinental Array would provide information concerning these questions. Studies of the apparent brightness distribution of strong pulsars, distant OH/H_2O maser sources in our galaxy and in other galaxies, low-latitude compact extragalactic radio sources, radio stars, objects behind dense HII complexes (e.g. Cygnus X and the Gum nebula) and differential position measurements of the above objects at the frequencies are all important. Since scattering will result in a "limiting diameter", it will be interesting to study the minimum diameter vs galactic (super galactic) coordinates, and for galactic objects vs distance.

Interstellar Neutral Hydrogen. Information on the fine scale distribution of neutral hydrogen in interstellar space will be obtained by 21 cm absorption observations of compact extragalactic sources. This technique has been used for some years to study hydrogen clouds with a resolution somewhat better than a minute of arc, to reveal structures as small as 10^{17} cm. Very long baseline interferometer absorption measurements can increase the resolution by two to three orders of magnitude, and features on a scale of a tenth of an arcsec (< 100 AU) have already been detected (Dieter et al. 1976). The Intercontinental Array will permit a detailed mapping of these remarkably small irregularities in the distribution of interstellar hydrogen.

Neutral Hydrogen in Galaxies. Recent spectroscopic observations have disclosed narrow 21 cm absorption lines in several galaxies and quasars. High resolution absorption line observations can show the distribution of neutral hydrogen in external galaxies with a resolution corresponding to a few tens of parsecs. The very narrow neutral hydrogen absorption lines found in galaxies such as NGC 1275 are of particular interest, and it may be expected that the high resolution observations will give some insight to the remarkably small velocity dispersion. This is particularly true of the 3C 286 quasar absorption line which has a half width of only 8 km sec^{-1} compared with a recession velocity of about 200,000 km sec^{-1}. As in the case of the optical absorption lines found in quasar spectra, the absorption may be caused either by an intervening galaxy or by relativistically ejected gas from the quasar.

Very Long baseline interferometer observations which have already been made of the neutral hydrogen absorption in front of 3C 286 indicate that the line is composed of two components having a velocity difference of ~ 3 km sec^{-1} (Wolfe et al. 1976). This tends to support the hypothesis that the absorption is due to an intervening galaxy, but more complete mapping of the absorption features in 3C 286 and other quasars are needed to better determine the distribution of the absorbing gas.

D. The Solar System

Solar observations have been made with the NRAO, Hat Creek, and Westerbork interferometers, and show fine structure on a scale $\lesssim 1$ arcsec. Although so far no successful milli-arcsec observations have been made, it is believed that very small structures exist in the chromosphere ($\ell \sim 10$ to 100 meters in flares). It would be extremely important to observe the radio emission from such regions since they are where solar flare particles are accelerated. This would require about 0.1 milliarc sec resolution. However, scattering in the chromosphere and corona will probably smear such fine detail. Nevertheless, solar observations with the VLB Array are an exciting, but unproved possibility.

The only known small diameter intense source in the solar system is Jupiter. Since it radiates only below 40 MHz, the addition of a meter wavelength receiving facility would be required to study the small scale Jovian emission, and in particular to make measurements of its position relative to extragalactic sources. In this way it would be possible to determine the position of the source relative to the planet and Io, and find out how it moves under planetary rotation and satellite revolution.

A main problem in isolating other meter wavelength planetary sources is terrestrial interference. A VLB Array operating at meter wavelengths would be effective in detecting other planets, since the interference at each site is essentially uncorrelated.

E. Astrometry

Positions of many radio sources are already known to 0.1 arcsec or less, better than the FK4 optical system. The ability to measure angular coordinates to an accuracy of a milli-arcsec opens up an exciting range of astrometric problems, including studies of parallax and proper motion, galactic structure and rotation, and earth motion. In order to obtain fundamental positions to this accuracy, the full determination of all the physical parameters of the Earth's spin in an inertial coordinate system (rotation or UT.1, precession, nutation, and polar motion) and of the deformation of the Earth's surface (Earth tides, continental drift, and other crustal rearrangements) must all be determined. This requires extensive observations with a multi-element array.

The direct measure of extremely accurate fundamental source positions is for the present of limited value in radio-optical comparisons since positions of the optical counterparts of radio sources are not known better than a few tenths of an arc second. This situation will be improved only when optical or infrared interferometry at low-light level becomes available, or perhaps with the Space Telescope.

Of more immediate interest is differential astrometric work including the measurement of parallax and proper motions. In this way it will be possible to obtain a direct measure of distance and proper motion for sources up to several kpc or more for the Galactic Center, molecular maser sources, pulsars and other various radio stars .

Some applications of parallax and proper motion determinations have already been discussed in Section II.B.2.

F. Terrestrial Experiments

The time delay and its derivative (fringe frequency) of the signals received at each end of an interferometer depend on the source-baseline geometry and are extraordinarily sensitive to small changes in either the source coordinates or the interferometer baseline. Thus the accurate measurement of the differential delay and the interferometer fringe frequency or phase can be used in principle to determine source positions to a small fraction of a fringe spacing ($\lesssim$ 0.0001 arcsec) or baseline coordinates to a fraction of a wavelength ($\lesssim$ 1 cm). This in turn permits a variety of geodetic and geophysical effects such as crustal motions, earth tides, polar motion, and earth rotation to be measured with unprecedented accuracy.

In practice, the accuracy is limited by uncertainties in propagation through the earth's atmosphere and ionosphere and the interplanetary medium, by uncertainties in the rates of the independent local oscillators, and in the synchronization of the clocks. A further problem is the difficulty in separating the effects of changes in the length and direction of the interferometer baseline and of source coordinates.

Nevertheless, VLB interferometer experiments have already been used to determine the vector separation between two antennas thousands of miles apart to within ten cm, and to determine source coordinates to an accuracy better than .03 arc sec (Shapiro et al. 1974). This is equal to or better than what can be achieved with conventional techniques; and improvements of two orders of magnitude or more are expected with refined techniques. The continuous monitoring of the apparent position of a selected number of sources using redundant baselines will be required to calibrate the Intercontinental Array, and at the same time will provide valuable terrestrial data as well.

The measurement of source coordinates to an accuracy better than 1 milli-arcsec will permit a more accurate measurement of UT-1 and polar motion. Variations in the coordinates of the pole are caused principally by torques exerted on the earth's equatorial bulge by the sun and the moon. Variations in the rotation rate (UT-1) may be caused by changes in the moment of inertia and by dissipation of energy by tides raised by the sun and moon in the solid as well as the fluid portions of the earth. Variations in the rate of rotation of the earth are also believed to be caused by variations in atmospheric circulation, core-mantle interaction, and other causes as well. Highly accurate measurements of the earth's motion made possible by an Intercontinental Array will permit the investigation of these phenomena in great detail.

The position of the earth's pole also shifts relative to the crust in a complicated manner reflecting not only lunar and solar forces and the earth's non-rigid inelastic nature, but possibly also displacements of the crust associated with earthquakes and other tectonic activity. A complete global picture of these crustal motions are of great interest to geophysicists concerned with earthquake prediction, continental drift, and earth tides.

If the Array proves capable of centimeter or better baseline accuracy, it will be of interest to measure solid-earth tides and, in particular, ocean loading effects on the magnitudes and phases of the various frequency components of the tidal responses of the earth. Distinguishing the tidal contributions to the baselines reliably will require measurements to be made frequently compared to the periods of these various components: semidiurnal, biweekly, monthly, semiannually, etc. This monitoring function will be necessary anyway to separate tidal from tectonic motions as well as for the phase calibration of the Array.

G. Operation at Meter and Millimeter Wavelengths

The basic array as it is currently conceived operates between wavelengths of $\sim$ 1 cm and 50 cm. Operation at both longer (meter) and shorter (millimeter) wavelengths is necessary for several important scientific investigations.

Meter Wavelength Operation. Radio emission from flare stars and pulsars is most intense at long wavelengths. VLB observations of flare star emission will discriminate against terrestrial interference and permit reliable observations of their spectral characteristics, and possibly parallax.

Millimeter wavelength operation. The smallest compact radio nuclei and quasars ($\theta \lesssim 10^{-4}$ arc sec) will be self-absorbed at centimeter wavelengths, and they radiate most strongly at millimeter wavelengths. Moreover, with terrestrial baselines, only at millimeter wavelengths is it possible to resolve these very small sources, which exist for only a few weeks during the initial phase of a quasar and radio galaxy nuclear flare.

H. Other Applications

Tests of Relativity. As a result of its ability to obtain precise astrometric measurements, the VLB Array will permit the measurement of the relativistic "light" bending of a radio source passing the limb of the sun to better accuracy than previously obtained. The best existing measurements, made with cable or radio linked interferometers have an accuracy of about 0.01 arcsec or about 1 percent. The use of VLB techniques, while potentially promising, has so far not improved on this value due to the uncertainties imposed by coronal bending and atmospheric phase fluctuations (Counselman 1974).

With the multi-baseline VLB Array operating simultaneously at two or more wavelengths, it is expected that the experimental errors can be greatly reduced, and the accuracy improved by at least several orders of magnitude. In fact, the VLB Array is sufficiently sensitive to the bending effect that, even 90 degrees away from the sun, the angular displace at centimeter wavelengths amounts to about 10 fringes. Indeed, all position or phase measurements made with the Array will have to be "corrected" for this effect.

Applications to the Space Program. Long baseline interferometer techniques have also been used in locating the relative position of the Apollo Lunar Surface Experimental Package (ALSEP) transmitters on the moon's surface, to measure the moon's motion about its center of mass, to track the motion of the Apollo Lunar Rover Vehicle (LRV) and in spacecraft navigation. The operation of a VLB Array with continuous updating of baseline parameters and the parameters describing the earth's motion will have important application to lunar and planetary exploration programs.

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III. BACKGROUND

A. Historical Summary

The first radio telescope of Karl Jansky barely had sufficient angular resolution to distinguish one region of the sky from another. With the use of shorter wavelengths and the construction of ever larger antenna systems, the angular resolution of radio telescopes has steadily increased, so that today the most advanced steerable paraboloids have a resolution of about one arc minute, or comparable to that of the unaided human eye. Although larger precision telescopes can be built, the cost becomes prohibitive and it does not appear economically feasible to obtain resolutions better than about 0.1 arcmin in this way.

For this reason, radio astronomers long ago turned to interferometry which has grown from the simple two-element interferometers of the 1950's to the sophisticated multi-element aperture synthesis arrays of the 1970's.

The spacing of conventional radio interferometers has rapidly increased from a few hundred meters to a few kilometers; a spacing sufficient to give angular resolutions of a few arcsec at short centimeter wavelengths. In principle, the dimensions may be increased without limit, but then the cost of the cable or waveguide needed to distribute the signals between the antenna elements and the central processor becomes very great. For very large distances, of course, natural obstacles such as rivers, mountains, and eventually oceans, as well as the cost of obtaining the "right-of-way" limits the dimensions of interferometers with directly connected elements.

In order to obtain longer baselines and higher resolutions, Australian and British radio astronomers pioneered the use of microwave radio links to connect antennas up to 100 km apart and obtain resolutions about one arc sec by 1960. For some years it appeared that this was adequate to resolve the finest detail found in the discrete radio sources.

It was not until the mid-1960's that several new results independently indicated that there are a large number of very compact radio sources with dimensions $\ll$ 1 arcsec . These were:

a) The discovery of interplanetary scintillations suggesting angular structure considerably less than one arc second.

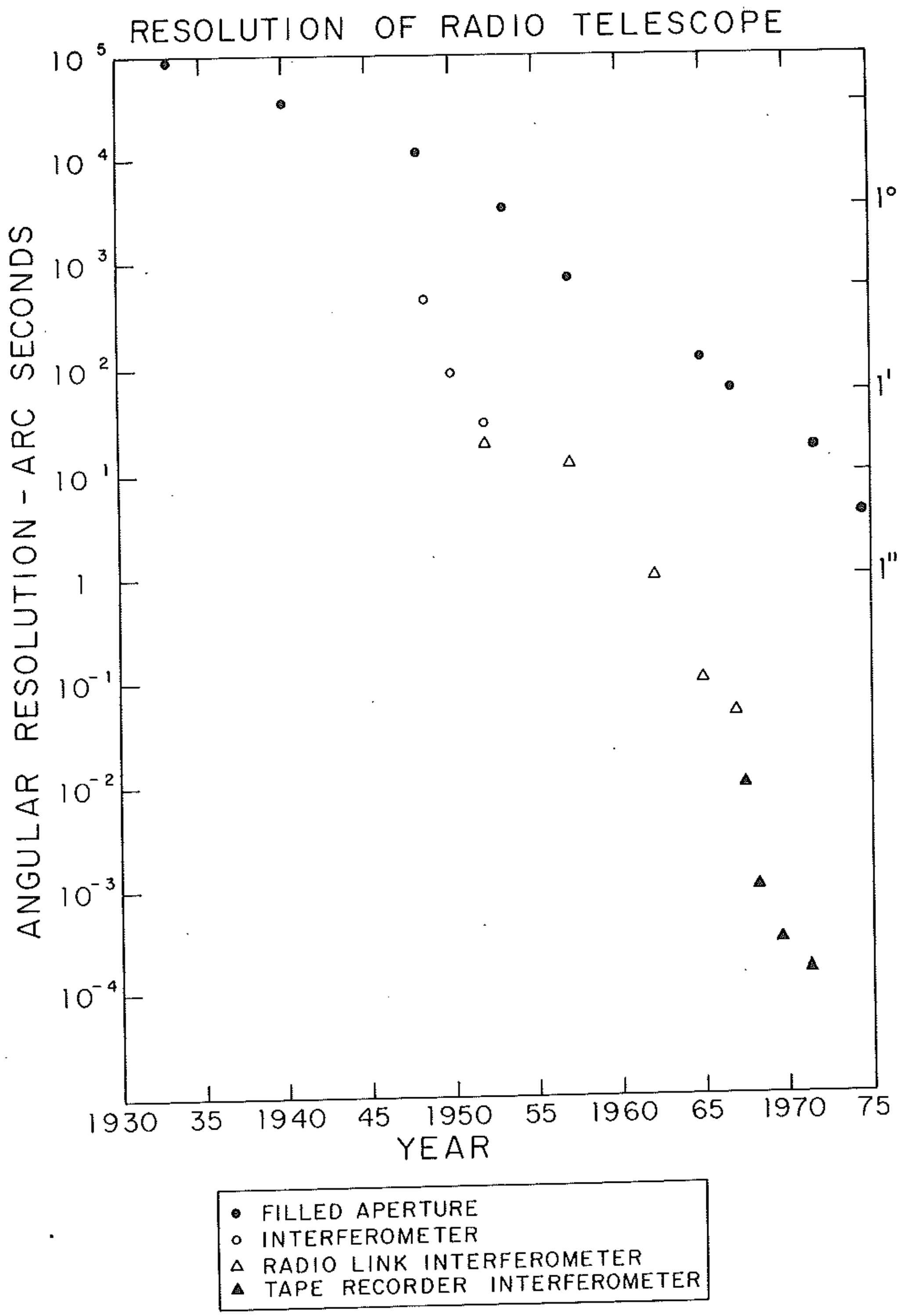

Fig. III-1. Graph showing the improvement in angular resolution of filled aperture radio telescopes and for various interferometer systems.

b) The realization that because of synchrotron self-absorption many radio sources appeared unusually weak at long wavelengths. Self-absorption implies a very high brightness temperature corresponding to angular sizes of one thousandth to one hundredth of an arcsec.

c) The discovery of remarkably rapid time variations in some quasars and radio galaxies suggesting small linear sizes, thus angular dimensions well under one thousandth of an arcsec.

Resolutions of this order can only be achieved using transcontinental and intercontinental baselines whose dimensions are too great to practically cover with direct electrical or radio connections. Techniques were then developed to use high speed tape recordings located at widely spaced radio telescopes. The tape recordings were then transported to a common center for correlation to reproduce an interference pattern in the sky. Accurate atomic frequency standards were used to provide a phase reference at the remote telescopes and to synchronize the tape recordings to the required accuracy of one microsec (Bare et al. 1967, Broten et al. 1967).

Ironically, such a scheme had been considered as early as 1950, when it was thought that the discrete radio sources were active stars with stellar dimensions, but the technology necessary to record and reproduce the radio signals with the required accuracy and precision had not yet been developed. Since, until 1965, it appeared that the one arcsec resolution available from modest interferometer baselines of a few tens of miles was adequate, these ideas were not pursued in the study of radio galaxies and quasars; and the first use of tape recording interferometers was to study the intense long wavelength bursts from the planet Jupiter (Carr et al. 1965). By the mid-1960's, however, the widespread availability at modest cost of precision atomic frequency standards and high-speed tape recorders made possible the much more sensitive recordings required to study the compact short wavelength emission from radio galaxies and quasars.

Even while the first sensitive tape-recording interferometers were being developed, the discovery of maser emission from interstellar hydroxyl (OH) and later waver vapor (H_2O) extended the technique to a whole new class of astrophysical phenomena. Shortly after, very long baseline interferometry was extended to study the newly discovered pulsars, interstellar scattering, and more recently, the radio emission from X-ray binary stars, compact clouds of hydrogen in our own and other galaxies, and the nuclei of spiral and elliptical galaxies, as well as our own Galactic Center. From the beginning, the application of long baseline interferometry to tests of General Relativity and to various terrestrial phenomena were also realized.

B. Interferometry and Aperture Synthesis

The general theory of interferometry is described in several references (e.g. Swenson and Mathur 1968, Fomalont 1974) and is only briefly summarized here. In a simple two-element interferometer, the rotation of the earth causes a distant cosmic radio source to have a different radial velocity as seen from each end of the interferometer. The output signals from each of the two antennas, which differ somewhat in frequency because of the Doppler shift, are combined in a non-linear device, thus producing a "beat" at the difference frequency. This beat signal is quasi-sinusoidal in time and is generally called "fringes" by analogy with the optical fringes of a Michelson interferometer. The fringe function may also be visualized as a pattern in the sky 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 longer (in wavelengths) the baseline, the more closely spaced are the fringes and the greater the angular resolution.

The instantaneous output of a two-element interferometer is the value of the Fourier transform of the angular brightness distribution of the radio source for the argument corresponding to the instantaneous projection of the baseline on the celestial sphere. By combining the output of many interferometers to find a sufficient number of coefficients of the Fourier series, it is possible to construct the two dimensional image of the source. This is the principle of aperture synthesis, and the Fourier transform is generally referred to as the "visibility function."

As the earth rotates, the projected spacing of the interferometer changes and sweeps out an elliptical track in the Fourier transform plane. In this way just a few interferometer pairs, even if lying on a straight line, can cover a portion of the Fourier transform plane sufficiently well to permit the reconstruction of the source image. The locus of points in the (u,v) plane is given by

$$\frac{u^2}{a^2} + \frac{(v-v_o)^2}{b^2} = 1$$

where

$$a^2 = (B_x^2 + B_y^2),\ b^2 = a^2 \sin^2 \delta,\ v_o = B_z \cos \delta,\ \delta = \text{declination}$$

and B_x, B_y, B_z are the components (in an earth-based coordinate system) of the baseline vector connecting the two array elements comprising the interferometer under consideration. A number of interferometer baselines must be used to make a satisfactory two dimensional picture. There are $N(N-1)/2$ interferometer pairs present in an N element array.

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, it is possible to synthesize a map of a cosmic source. The scale of the finest detail in the map will be determined by the longest baseline in the interferometer. If the baselines in the array vary in length by discrete uniform steps, the size of the largest source that can be unambiguously synthesized is, in radians, the reciprocal of the step size in wavelengths. The sidelobe level depends on the specific geometry, but in general is a fraction of the order of (1/number of elements) for a well designed array.

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 Visibility (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.

C. Independent-Oscillator-Tape-Recorder Systems

For baselines in excess of a hundred or so kilometers, the transmission of phase reference signals by cables or microwave links is extremely expensive. Moreover, variations in temperature, pressure, and atmospheric composition cause large 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 are generally used, rubidium-vapor or hydrogen-maser systems being the most common. The latter is capable of accuracies of one part in 10^{14} or better over periods of days. This means that at a frequency of 10 GHz (10^{10} Hz) the phase of two independent oscillators will differ by less than one cycle after 10^4 seconds (3 hours) of operation.

A second difficulty which arises on such long baselines 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 MHz are generally desired, so that broadband communication channels of very high quality are required. The medium used is the magnetic tape recorder. The data are recorded on tape at the radio telescopes, along with precise time marks provided by the atomic frequency standard (atomic clock). The tapes from each antenna are transported 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, or an analog device. This technique is generally referred to as Very Long Baseline Interferometry or VLBI.

A number of baselines must be used to synthesize satisfactorily a two dimensional picture. Since the compact radio sources are generally variable, all of the observations must be simultaneous or nearly simultaneous. This

* The required accuracy is about half the reciprocal of the bandwidth, or about 100 nanoseconds for a 4 MHz bandwidth.

complicates the data transmission problem, since the data from an N-telescope array requires N(N-1)/2 times as much correlation time as observing time if done one baseline at a time. To process in (equivalent) real time there should be a many processor "inputs" as recording stations.

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 due to local oscillator imperfections, atmospheric turbulence, and the uncertainties in the length and orientation of the baseline generally have rendered the phase values unreliable or incapable of interpretation.

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 do a straightforward Fourier synthesis of a source, or to measure the precise position of a source (the astrometric problem), or to measure the precise length and orientation of the interferometer baseline (the geodetic problem).

A principal 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 time delays in reaching the individual telescopes comprising an interferometer. The parameters affecting the phase delay are the density, pressure, and temperature of tropospheric water vapor which dominate at short wavelengths, the temperature and pressure of the "dry" component, and the free electron density and magnetic field strength in the ionosphere which are important at longer wavelengths. These are all inhomogeneous and time-variable in essentially unpredictable ways.

D. VLBI Systems

The first independent-oscillator-tape recorder interferometer used in radio astronomy was developed to study the intense decameter wavelength bursts from the planet Jupiter. Since the relatively narrow bandwidths of only a few kHz were used, simple audio tape recorders were sufficient and adequate time synchronization was provided from WWV transmission.

At least five broadband VLBI systems have been operated since 1967. Each of these systems is described briefly in Table III.1 and is discussed further below, along with the MK III system currently being developed.

Table III.1

VLBI Systems

System	Type	Recorder Type	Bandwidth	Correlator
NRAO MK I	D 1 bit	Computer	330 kHz	GPC or SP
Canadian	A	TV	4 MHz	SP
DSN	D 1 bit	Computer	24 kHz	GPC
Jodrell Bank	D 1 bit	Instrumentation	<7.5 MHz	SP
NRAO MK II	D 1 bit	TV	2 MHz	SP
MK III	D 1 bit	Instrumentation	50 or 100 MHz	SP

D - Digital
A - Analogue
GPC - General Purpose Computer
SP - Special Processor

NRAO MK I System: The MK I system was developed at NRAO to provide sufficient bandwidth and sensitivity for studying the stronger compact extra-galactic sources. Three minutes of data are recorded on ordinary computer-readable tape. Originally three record terminals were constructed, but additional units have been built by the NASA Goddard Space Flight Center. Processing is possible with any large general-purpose digital computer, but processing time can be excessive - taking from three minutes (with an IBM 360/95) to one hour (with an IBM 360/50) for a pair of three minute tapes. Recently a special purpose correlator for the MK I tapes has been built at the Haystack Observatory.

The MK I system was widely used throughout the USA and in Sweden, Australia, and the USSR. It is still used by the MIT-Goddard group to study source structure and for a variety of geophysical and astrometric observations. It is the most reliable system which is currently in use.

Canadian System: Unlike the MK I system which used relatively inexpensive standard computer tape drives, the Canadian system used more complex and costly video recorders to obtain greater bandwidth than allowed by the NRAO system. Recently, the original recorders have been replaced by more modern and considerably less expensive recorders.

DSN System: Each of the NASA Deep Space Network sites is equipped with a variety of data recording systems, and it has proven relatively straightforward to use this equipment for VLBI. Although the bandwidth is much smaller than the systems especially built for VLBI, the DSN system has the advantage of availability at worldwide sites with good communication and transportation links. To some extent the very low noise receivers and large antennas at the NASA DSN sites compensate for the narrow bandwidth. The NASA system has been used to monitor the angular extent of sources between California, Australia, and South Africa, and for geodetic measurements between California, Australia, and Spain.

Jodrell Bank System: The Jodrell Bank system is based on a multi-track instrumentation recorder, although only a few tracks are used at any one time. Because of its complexity, however, it has received little use. A few experiments have been successfully completed, but no results are published.

NRAO MK II System: Another system developed at the NRAO, the MK II, has enjoyed the most widespread use. A total of 19 record systems are in existence as shown in Table III.2. The MK II system uses a modified helical scan video tape recorder to record digital data which is then played back at a real time rate on a special processor. The system is limited to a data rate of 4 Mbits/sec and records only one speed so that observations such as those of molecular masers or strong continuum sources which do not require the full bandwidth capability waste tape and cannot be replayed faster than real time.

At the present time there are only two MK II processors in operation located at NRAO in Charlottesville, Va. and at Caltech, and all MK II tapes must be brought to one of these processor systems for analysis. The NRAO processor has been recently expanded to allow the simultaneous cross correlation of three tapes, which speeds up the processing of multi station experiments by up to a factor of three. The correlator has been rebuilt to allow 288 simultaneous frequency channels to be processed and a hard wired Fast-Fourier

Table III.2

Observatories Having VLBI Terminals

Organization	Location	Antenna diam(m)	Wavelengths(cm)	Record System
NRAO (2)	Green Bank, W. Va.	43, 94	1.3, 2, 2.8, 3.8, 6, 13, 18, 21, 50	MK I, MK II, MK IIC
Univ. of Iowa	Iowa City, Iowa	18	18	MK IIC
NEROC (Haystack)	Westford, Mass.	37	1.3, 2, 3.8, 13, 18	MK I, MK II
Caltech (OVRO)	Big Pine, Calif.	40	1.3, 2.8, 3.8, 6, 13, 18, 21, 50	MK I, MK II
Naval Res. Lab.	Md. Point	26	1.3, 2.8, 6, 18	MK II
Onsala Space Obs. (2)	Onsala, Sweden	20, 26	1.3, 3.8, 6, 18	MK I, MK II
Max Planck Inst. fur Radio Astr.	Bonn, Germany	100	1.3, 2, 2.8, 6, 13, 18, 21, 50	MK II
NASA (2)	Goldstone, Calif.	26, 64	2, 3.8, 13	MK II , DSN
"	Tidbinbilla, Aust.	26, 64	3.8, 13	MK II , DSN
"	Madrid, Spain	26, 64	3.8, 13	MK II , DSN
Crimea Astr. Obs.	Semeis, USSR	22	1.3, 2.8, 6	MK II
Harvard College	Ft. Davis, Tex.	26	2.8, 6, 18, 50	MK II
Univ. of California	Hat Creek, Calif.	26	6, 18, 21	MK IIC
NAIC	Arecibo, P. R.	305	13, 21, 50, 75	MK II
NRC Canada	ARO, Canada	46	1.3, 2.8, 75	Canadian, MK IIC
Univ. of Illinois	VRO, Danville, Ill.	31	13, 18	MK IIC

Number of terminals shown in parentheses.

Other Observatories Which Have Been Used In VLBI Observations

Nuffield Radio Astr. Lab.	Jodrell Bank, U.K.	76	50, 21, 18	MK II
Austr. N.R.A.O.	Parkes, Australia	64	18, 6	MK I
Neth. Found. for Radio Astr.	Dwingeloo, Neth.	26	18, 21	MK II
CRAAM, Mackenzie Univ.	Itapetinga, Brazil	14	1.3	MK I

Transform device has been added to the output of the Processor, to reduce the time consuming analysis of spectral line data previously carried out in a large digital computer.

One of the weakest features of the MK II system is the Ampex VR660C video tape recorder used in the record and playback terminals. Considerable difficulty has been experienced in keeping the recorders properly aligned, and due to the repeated mechanical failures, extensive maintenance has been required to keep these recorders in operating condition. A recent development has been the modification of the IVC 825 video recorder, manufactured by the International Video Corporation, to permit recordings which are compatible with those made on the VR660C. This is the same video recorder which is currently used in the Canadian analogue system, and so joint multi-station observations between U.S. and Canadian observatories are now possible without the need to transport the U.S. recording equipment to Canada. This hybrid system, which is known as the MK IIC appears to be more reliable than the original MK II, and a number of the newer terminals which are being constructed are based on the IVC recorder. The NRAO Processor has been modified to allow any combination of Ampex and IVC recorders to be used.

MK II Processors are also being built in Sweden and Bonn, Germany, but only the Bonn Processor will have a spectral line capability similar to that at the NRAO.

The MK III VLB System: A prototype next generation VLB Record-Playback system using a wideband instrumentation recorder is currently being developed at the NRAO and Haystack Observatory, and may be expected to come into widespread use in the late 1970's. For continuum observations the MK III VLB System has nearly an order of magnitude greater sensitivity than the currently used MK II System, while for spectroscopic work the MK III system gives higher spectral resolution and faster processing time. As it is currently conceived, the MK III System satisfies all of the requirements of a dedicated VLB Array. Nevertheless, as the MK III design continues, the prototype tested, and the system is used for VLB observations with existing antennas, the design specifications are likely to be modified to improve the performance still further.

Wide bandwidth digital recordings may be obtained using a multitrack instrumentation recorder in two ways, both of which involve a modest data rate of $\sim$ 4 Mbits on each track. In the "parallel" recording method chosen for the MK III system, the entire video band is divided into 28 equal segments, and each narrow-band slice is written on a different track. This gives the system considerable flexibility since portions of the receiver IF's can be recorded with each pair of tracks derived from the upper and lower sideband outputs of one of 14 IF to video converters. Each converter has an individual frequency synthesizer allowing the selection of a center frequency from 100 to 500 MHz in 10 kHz steps.

The data might also be written in "serial" form instead, so that when it is played back a single high-speed bit stream is reconstructed which represents the entire video bandwidth. The serial mode requires the use of high speed ECL logic and has the advantage of potential compatibility with the VLA digital system. The parallel mode requires 28 times as many correlators and fringe rotators, but uses lower cost common TTL logic.

The cost of implementing the two modes is roughly comparable. The parallel mode was chosen for the MK III system for the following reasons:

1) Reliability. Failure of a single channel does not affect the data from other tracks, whereas in the serial mode all of the data may be lost.

2) The available bandwidth may be more readily divided into several parts to accommodate different polarizations, different spectral lines, or for bandwidth synthesis where the r.f. signal is spread out over a frequency range many times greater than the recorded r.f. bandwidth.

The Mark III System can record up to 112 Mbits/sec (and possibly 224 Mbits/sec) and down to 250 Kbits/sec. The system used the 28 track EIA standard for one-inch-wide tape. Each track is recorded with NRZM code (a flux reversal represents a "one" and no flux change represents a "zero") at linear density of 33,000 bits/inch in odd-parity 9-bit bytes to guarantee a transitionless run of no more than 16 bit-cells long. Each track is structured into frames of 22,500 bits with a sync word of 4 successive even-parity bytes of 8 ones followed by a zero. The sync word is followed by a sync block containing the BDC coded time. All tracks are similarly encoded and recovery of the data from one track in no way depends on any of the other tracks.

A Honeywell 96 recorder has been selected for the basic MK III tape transport. All of the record-playback electronics are being designed by Haystack and NRAO to avoid the use of the rather more expensive manufacturer's electronics. Each of the record systems will be equipped with a single channel of playback electronics which will "scan" all 28 tracks in a "read-after-write" mode to check the quality of the digital data recording. At a fully equipped MK III record station a small on-line computer will be utilized to control the operation including the setting of bandwidths and local oscillator frequency, to record the atmospheric water vapor content, system noise temperature, and source antenna temperature, and to monitor the performance of the radiometer and record system. A Hewlett-Packard HP21MX computer has been selected for use at the NASA operated sites which will use the MK III VLB system for a variety of geodetic studies.

The cost of a complete MK III record system is expected to be about $90,000. It is expected that a considerably less expensive, but fully compatible, recording system can be constructed using simpler less expensive tape transports, 14 record tracks, and manual rather than computer controlled operation. Such a system can be used at smaller observatories to collaborate with the larger, better-equipped facilities with recording bandwidths up to 28 MHz. Data taken with the MK II system can also be cross-correlated with MK III data by first transcribing the MK II data to MK III tape. We note, however, that even the cost of a fully instrumented MK III record system is less than that of the typical cryogenically-cooled parametric amplifier which is in common use on major radio telescopes.

The maximum recording speed of the Honeywell 96 recorder is 240 inches per second which gives 8 Mbits per track on each of 28 tracks, or a total of 224 Mbits or 112 MHz total bandwidth. At this rate a full 16 inch reel of tape (12,000 feet) lasts for only 10 minutes so that the consumption of magnetic tape is very great. It is anticipated that such high recording rates will be used only when the coherence time is limited, such as when observing at very short wavelengths, or when observing very weak sources.

The fastest playback speed planned is 120 inches per sec, so that data recorded at 240 inches per second will require approximately twice real time to replay. Data recorded at slower speeds than 120 inches per second will be replayed faster than real time. This will be of particular advantage to spectral line observations, where only relatively narrow bandwidths are required.

The MK III system will be equipped with filters to record bandwidths of 4, 2, 1, 0.5, 0.25, or 0.125 MHz per track. For spectral line work only one, or at the most a few, tracks will be used at a time, and the recording will shuttle sequentially through each record track. Thus, at a bandwidth of 125 kHz, or a recording speed of 7½ ips, a single one track pass will last for 5 hours and 20 minutes, and the full 28 tracks for more than 6 days. Data recorded at this rate can be played back at a rate 16 times real time, and broader band data at a proportionally slower rate.

The prototype MK III correlator system, currently being constructed at the Haystack Observatory, will contain 8 complex delay channels on each of 28 tracks on three baselines. Data will always be played back at 120 ips, and so all delay lines, fringe rotators, etc. will always operate at a clock rate of 4 MHz. When used in the single track spectral line shuttle mode, 112 independent frequency channels are available for each of 3 baselines, or the complete 336 channels if only one baseline at a time is processed. Even greater spectral resolution can be obtained at the cost of increased processing time by repeatedly replaying the tapes.

Recordings at speeds of 120 ips (33.3 kbits/inch or 4 Mbits/sec) on up to 7 simultaneous tracks have been demonstrated at the Haystack Observatory using a Honeywell 7600 tape transport. The observed error rates varied between 5×10^{-6} (5 mil track width) and 2.5×10^{-8} (25 mil track width) with no noticeable degradation after replaying the same tape many hundreds of times. This is quite acceptable for VLB data recording, and suggests that up to 50 or 100 tracks (200 to 400 Mbits) might be ultimately accommodated on a 1 inch tape. No tests have yet been made at 240 ips record speed.

Two prototype MK III record systems are expected to be in operation by mid 1977, although only a fraction of the full 28 tracks will be implemented at that time, and by 1978 MK III record systems are expected to be available at several NASA sites, at the Haystack Observatory, as well as the two being constructed at the NRAO. As part of the PPME program (III.D.5), NASA may provide MK III terminals at several other radio observatories as well. The prototype MK III Processor at the Haystack Observatory should be in partial operation in 1977. Although a lengthy period is expected before reliable multi-station MK III operation is achieved, by 1978 preliminary high sensitivity observations will be possible using existing antennas equipped with MK III systems.

E. Current Scientific Programs

Figure III-2 shows the locations which have been used in VLBI experiments. In the past these have been ad-hoc experiments arranged jointly between individuals at two or more locations. However, several somewhat more formal programs have now been organized in an effort to minimize many of the technical and logistical problems discussed above, or to achieve specific program goals.

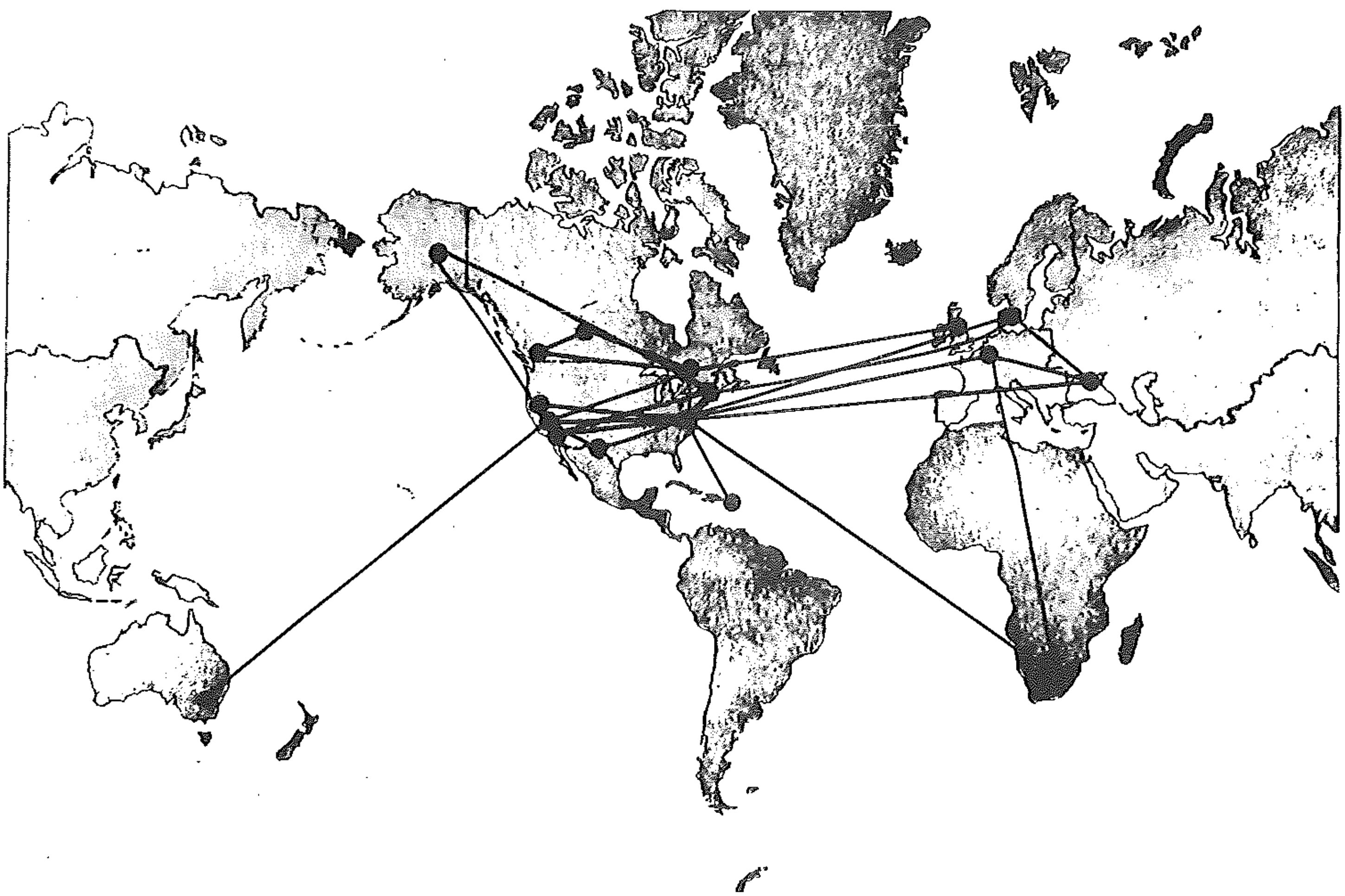

Fig. III-2. Map showing the location of radio observatories which have been used for VLBI observations. The lines connecting the locations show the most commonly used baseline.

1. Interim VLB Network with Existing Telescopes

In order to obtain the large number of simultaneous baselines required to synthesize complex variable compact sources, a number of critically located telescopes are made available for long baseline interferometry at specific pre-assigned times. It is hoped that these telescopes will be outfitted with uniform instrumentation to facilitate obtaining reliable well-calibrated data. Although these antennas are not generally optimally located, have limited sky coverage, are unsuitable for work at short wavelengths, and subject to scheduling conflict with other research programs, many important programs can be carried out. In particular, for work at relatively long wavelengths, ($\lambda \gtrsim 10$ cm) the structural limitations are less important, and complex and costly cryogenic amplifiers are not necessary. At these wavelengths the techniques necessary to synthesize moderately high resolution images may be investigated and developed, and a number of interesting astronomical programs may be pursued as well.

Key observatories in the United States which have agreed to cooperate in scheduling and in providing the necessary instrumentation in this VLB Network are the Haystack Observatory (MIT), the Maryland Point Observatory (NRL), the Vermillion River Observatory (Univ. of Ill.), the Harvard Radio Astronomy Station (Harvard), the Owens Valley Radio Observatory (Caltech), the Hat Creek Observatory (Univ. of Calif.), and the NRAO. Although the available facilities and supporting personnel differ widely, a number of Network programs have been successfully run, including two seven-station (21 simultaneous baselines) experiments.

A more complete report of the "VLBI Network Using Existing Telescopes" is given in the report by Cohen (1975).

2. UT1-Polar Motion Measurements - NASA

The 64-m antennas in Spain (DSS-63), Australia (DSS-43), and California (DSS-14) have been outfitted with simultaneous S-band/X-band reception capability. MK II recording systems and Hydrogen masers are available and the MK III system will be installed when it is available. Regular observations are being made which will determine UT1, polar motion, and time and frequency synchronization. The baselines and source positions are also determined in 24 to 30 hour runs. Models for other parameters, such as solid earth tides, precession, and nutation, will be improved upon. A full catalog of sources with fringe amplitudes 0.2 Jy has been obtained with positional accuracy better than about one arcsec in order to facilitate this program.

3. <u>Space Navigation - NASA</u>

Differential position measurements of spacecraft relative to cosmic sources will be used for spacecraft navigation. Although initially the observations will be made with only a single 64-m antenna at each site, later, if necessary, pairs of antennas at each complex will be used to overcome variations in the ionosphere and troposphere.

4. <u>Astronomical Radio Interferometric Earth Survey (ARIES) - NASA</u>

The development and construction of several transportable 4- to 9-m antennas with Hydrogen maser frequency standards having cryogenic X-band receivers are planned. One or more antennas will have dual S/X band capability. These portable stations will be used to do tectonic deformation monitoring and geodetic surveying over regional areas spanning about 1000 km. The baseline accuracy is expected to be better than 5 cm in all three dimensions. One or more 9-m antennas with dual S/X capability will be used for transcontinental and intercontinental baseline measurements. Regular observations have been made during the past two years using one fixed antenna at Goldstone and a portable antenna at several locations in California.

5. <u>Pacific Plate Motion Experiment (PPME) - NASA</u>

The relative motion of the American and Pacific plates is of considerable interest in studying earthquake dynamics along the San Andreas Fault, and in the Alaskan region. NASA plans to use VLB interferometer techniques to accurately measure the baselines between stations located in Alaska, Hawaii, California, Massachusetts and, if possible, Japan. Accuracies of a few centimeters in the measurement of the baselines and polar motion, and 100 to 200 μsec in the variation of the earth's rate of rotation (UTI) are anticipated.

The ARIES and PPME projects are both part of the NASA Plate Tectonic Motion Program and are intended primarily for studying earth physics by observation of distant extraterrestrial radio sources. The Intercontinental Array, by contrast, is conceived as an instrument to investigate the cosmic sources themselves, although, as explained earlier, many geophysical problems as well will be studied.

In particular, regular observations extending over a long period will answer such questions as: Are plate motions continuous or episodic? What are the relevant time scales? How do plate motions relate to polar motion, variations in Universal time, or to earthquakes. The technical requirements of the present earth physics projects are similar to those of the Intercontinental Array. The development at the Haystack Observatory of the broadband record-playback system of the type needed in the Array, is being supported by NASA as part of the PPME program. Other NASA supported programs aimed toward the commercial development of hydrogen masers, and the investigation of the atmospheric delay on the interferometer phase will also contribute to the development of the Array.

F. VLBI Activity at NRAO

The MK I VLBI System was developed at the NRAO during the period 1965 to 1967 and was extensively used from 1967 to 1971 by the NRAO, Caltech, and MIT groups. A special purpose processor for the MK I System has since been built at the Haystack Observatory, and the System has been further developed and improved by the MIT-NASA group who have continued to use it extensively for a variety of geodetic, astrometric, and astronomical studies.

The MK II VLBI system was also developed at the NRAO together with the Leach Corporation (Clark 1973) and came into use in the early 1970's. Initially 7 record units were built by NRAO and the Leach Corporation; by the end of 1976, 19 MK II or MK IIC units were in operation throughout the world. These later units have either been built at the NRAO or by following detailed designs made available by NRAO.

Because of the heavy demand on the Charlottesville MK II Processor, it has been expanded to permit data from three stations (3 baselines) to be replayed simultaneously. This speeds up the playback procedure by up to a factor of three. The correlator has also been expanded to give 288 interferometer frequency channels for the processing of spectroscopic data. A FFT device has been added to the Processor to give a real time display of the fringe spectrum and to greatly reduce the required time on the off-line 360/65 computer.

The two station CIT/JPL Processor has recently come into operation for continuum data analysis. Expansion to three or four stations is expected later in 1977, but no spectrosocpic capability is planned.

In 1976 NRAO built a new MK II record terminal which uses either the compatible IVC 825A video recorder or the older VR 660C recorder, and later assisted the VRO, the Univ. of Iowa, and the Hat Creek Observatory in building similar systems. The Astro-Electronics Laboratory (AEL) at Caltech intends to construct MK II Format units for several other observatories. The NRAO Processor has been modified to process any combination of tapes recorded on the IVC or Ampex machines, and similar modification and expansion of the Caltech processor is planned.

During the past few years the Charlottesville VLB Processor has changed from an experimental operation to a major facility which has served experimenters from all over the world. Until recently, visiting experimenters were for the most part expected to operate the Processor by themselves, but due to the growing demand for time and the complexity of the operation, three trained operators are now available to operate the system nearly full time. The visiting investigator is thus relieved of the tedious chore of replaying the magnetic tapes, and he is free to evaluate the data and do further analysis. The operation of the NRAO MK II VLB Processor is now much like that of the NRAO telescopes and includes the defrayment of visitor travel costs and the use of the NRAO 360/65 computer for the later stages of data reduction.

NRAO has also made available to the Harvard Radio Astronomy Station at Fort Davis, Texas, a MK II record terminal, atomic frequency standard, local oscillator system and 6 and 2.8 cm front ends. This has enabled the use of the Fort Davis antenna as part of the VLB Network by a variety of users. The 140-ft radio telescope has been equipped with low noise radiometers at all of the VLBI frequencies in use. Operation of the telescope is nearly automatic and is supported by an extensive engineering and operations staff. The VLB user need only provide general supervision, so that only a single observer is needed on the site. The 140-ft is the main observing station in the VLB Network observations, having been used for nearly all Network observations as well as for a wide variety of ad hoc VLB observations. For the past 3 or 4 years approximately 25 percent of the observing time on the 140-ft antenna has been devoted to VLBI research.

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IV. IMAGE FORMATION

Given an array of radio telescopes which sample some portion of the Fourier transform plane, two problems remain in reconstructing an image from the observed data. These are the uncertainties in the measurement of the amplitude and phase of the fringe visibility, and the incomplete sampling of the Fourier transform, both of which may lead to high sidelobe levels.

The uncertainties in the measurement of fringe amplitude, due to errors in the calibration of the individual antenna elements, are expected to be about 1 percent, exclusive of noise, using conventional techniques. Frequent observation of "calibration" sources which are unresolved at least on the shorter baselines, in any case, gives a calibration which is independent of the individual "single dish" measurements. As described below, pulsars provide the necessary "point" sources for amplitude as well as phase calibration. Moreover, if the array contains redundant interferometer spacings, then there is an additional check on the calibration. One percent amplitude errors, or phase errors of 0.1 radian will lead to sidelobe levels of the order of 20 db weaker than the main beam. Provided that there is proper instrumentation at each element, and adequate care is taken, amplitude calibration is not expected to be a serious problem.

A. The Phase Problem

We give below the main problem areas and techniques which may be used to minimize the uncertainties in the phase measurements. The practical limits to the measurements of interferometer phase are shown in the "sigma-tau" diagram (Figure IV-1) which gives the frequency stability of various frequency standards as well as that expected from the atmosphere under "good" and "poor" seeing conditions.

1. Local Oscillator Frequency Standard

The earlier VLBI observations used Rubidium vapor frequency standards to derive the local oscillator reference. These are limited in stability to 1 part in 10^{11} or 10^{12}. This restricted their use to relatively long wavelengths or short integration times, and excluded the possibility of measuring the fringe phase.

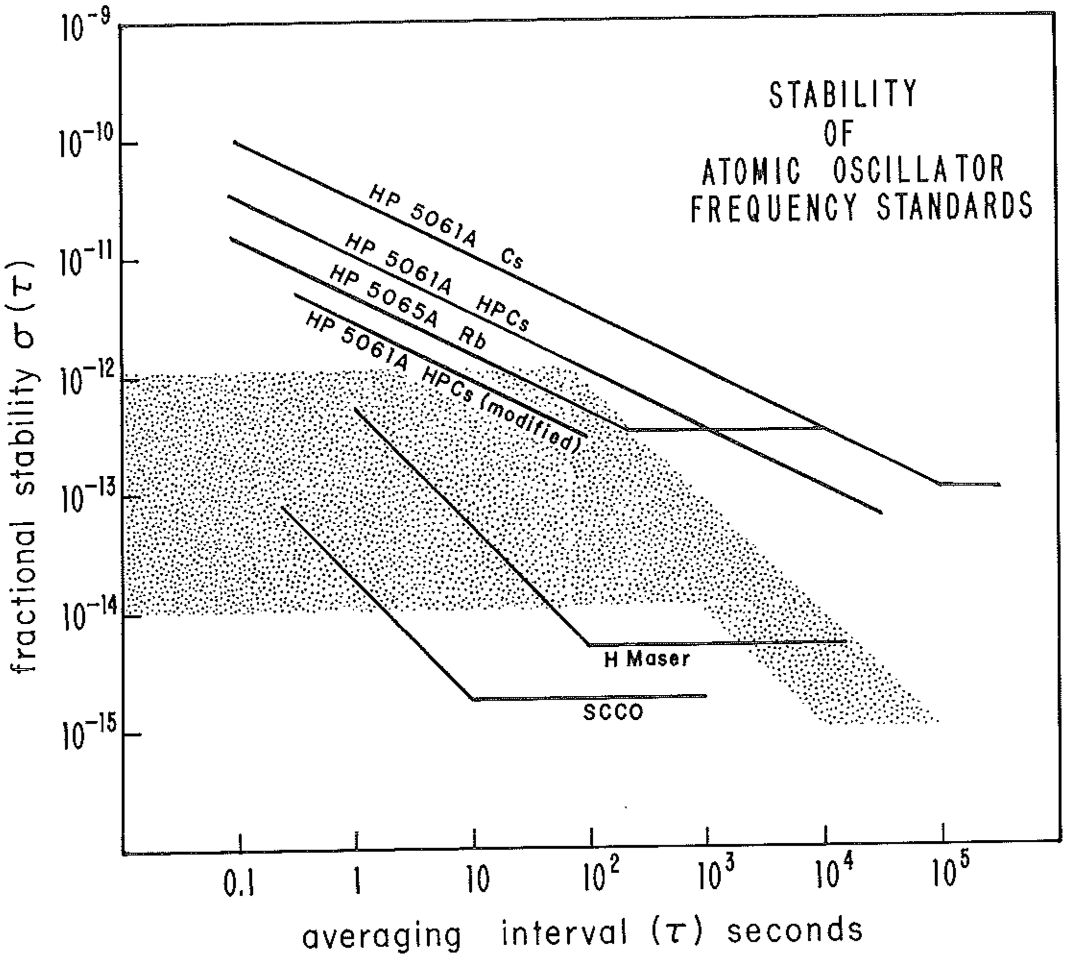

Fig. IV-1. Diagram showing the stability of typical atomic frequency standards used for VLBI observations. (σ-τ) plots are given for the Hewlett-Packard 5061A Cesium tube standard, the 5065A Rubidium tube standard, the newer 5061A HP (high performance) Cesium standard, a 5061 HP modified for improved short term stability, and a super cooled cavity oscillator (SCCO) The shaded area indicates the range of fluctuations due to the atmosphere under typical conditions.

Many current experimenters are using Hydrogen maser frequency standards with stabilities better than a part in in 10^{14}. Newer units now coming into operation have a stability of 3 parts in 10^{15}, and stabilities better than a part in 10^{15} have been claimed. This means that even when multiplied up to 30 GHz (1 cm) it takes 10^4 seconds ($\sim$ 3 hours) for two such oscillators to drift out of phase by one cycle. Thus, with frequent reference to calibration sources, the hydrogen maser provides adequate stability for use as an independent local oscillator.

In the past, hydrogen masers have suffered from poor reliability, high cost, and relative lack of availability. Several of the newer designs including those developed at the NASA Goddard Space Flight Center and the Smithsonian Astrophysical Observatory have demonstrated the required reliability. Their cost remains high, but is expected to be reduced if a sufficient number are manufactured.

Cesium tube frequency standards are much less expensive than hydrogen masers, very much more reliable, and less sensitivie to the environment. But they exhibit a much higher short term noise than hydrogen masers or Rubidium standards, which has made them unsuitable for a local oscillator reference. Newer high performance units , now commercially available, offer much reduced phase noise, making them more attractive for VLB work, and several special low noise units have recently been fabricated for the U.S. Naval Observatory. It is possible that a Cesium tube standard, when phase locked to a very stable crystal or rubidium oscillator, can provide adequate frequency stability for VLBI and at much lower cost than hydrogen masers. Tests of various oscillator systems, including the HP 5065A rubidium standard and the high performance HP 5061A Cs standard, are being made at the NRAO and the Naval Research Laboratory (Johnston et al. 1976) to evaluate their suitability for use in VLBI.

Other types of atomic oscillators, including the Rubidium maser, sub-millimeter and optical masers, and trapped ion masers, are under development and may give comparable, or even better performance to the hydrogen masers, at reduced cost and complexity (e.g. Hellwig 1974). Another new development is the super cooled cavity oscillator (SCCO) which is capable of extremely great short term stability, at relatively low cost, and with great reliability. NRAO will continue to investigate precision standards and, in particular, the Cesium tube standards in search of a lower cost device. A SCCO system is being procurred at Caltech to evaluate as a VLBI local oscillator reference. For the present, however, the hydrogen maser must be chosen as the frequency standard. Although the cost of masers is high, they are the only devices which meet performance requirements for the VLBA. The hydrogen maser may be augmented by a commercial Cesium standard to provide an accurate long term fundamental time and frequency reference against which the hydrogen maser will be compared. A Loran tracking receiver will provide a continuous check of station time and provide an independent external reference.

Hydrogen masers, or other atomic frequency standards generally provide a high level r.f. output at 5 MHz or 100 MHz. This must be multiplied to the operating frequency (up to 22 GHz) and the multiplier must not contribute significantly to the final phase noise. NRAO has developed such a multiplier which is commonly used in VLBI experiments at the 140-ft and elsewhere.

Even with perfect local oscillators, drifts in receiver phase are also important, particularly if these are correlated with antenna position. However, these can be calibrated using an injected calibration signal. A suitable "phase calibrator" consisting of a tunnel diode pulse generator has been designed at the Haystack Observatory (Rogers 1975) and is in routine use by the MIT-NASA VLBI Group. In this system the 5 MHz signal derived from the hydrogen maser is used to generate pulses at one microsec intervals and produces spectral lines with a spacing of 1 MHz which are then coupled into the front end. The phase calibration is then extracted by multiplying the recorded data with the quadrature components of a three-level representation of a sine wave.

A similar devide is being designed at NRAO, which will include more broadly spaced spectral features to verify that the local oscillator frequency and receiver sidebands are correctly set.

Long baseline interferometer systems need not have independent local oscillators. As is discussed further in Section V.E.2, a joint US-Canadian group is planning to use a synchronously orbiting satellite to transfer a local oscillator reference from one end of an interferometer baseline to another. If successful, this technique can be used for the worldwide distribution of phase reference.

2. Atmospheric and Ionospheric Path Fluctuations

A good hydrogen maser oscillator multiplied up to local oscillator frequency has a combined maser-multiplier phase noise which may be less than that of the atmosphere. Thus the main limitation to the performance of a VLB Array is the propagation delay introduced by the atmosphere at short ($\lambda \lesssim 10$ cm) wavelengths and the ionosphere at longer ($\lambda \gtrsim 10$ cm) wavelengths. These problems are not unique to VLBI. Experience has shown that for baselines of greater than a few kilometers, the path to the individual antennas goes through essentially independent atmospheres. As the separation of an interferometer pair is increased, the atmospheric phase fluctuations increase rapidly within spacings up to a few km, and then increase only very slowly as the spacing is further increased.

The typical path delay through the atmosphere is about 2 meters at the zenith. About 75 percent of this is due to dry air, and the rest to water vapor, which varies considerably in direction and with time as a result of fluctuations in the atmospheric water vapor content.

The total atmospheric path length may be estimated from surface measurements of temperature, pressure, and humidity, and the expected delay through the atmosphere is closely correlated with the precipitable water vapor along the line of sight. The theoretical electrical delay is 6.1 cm per gm cm^{-3} precipitable water vapor.

Methods to experimentally measure the delay and apply corrections to the observed interferometer phase have been under active study since 1967 at NRAO with reference to the performance of the VLA. A number of infra-red hygrometers have been built which measure the absorption due to atmospheric water vapor in a path along a line of sight pointed at the sun.

A potentially much more powerful technique has been developed which uses microwave radiometers to measure the atmospheric water vapor emission at the 22.235 GHz (1.3 cm) emission line. Since these radiometers can be mounted on each interferometer antenna element and pointed toward the radio source being observed, they are sensitive to spatial as well as to temporal inhomogeneities.

Tests conducted with the NRAO 3-element interferometer in Green Bank show a high degree of correlation between the water vapor radiation measured with the 1.3 cm radiometer and the observed interferometer phase fluctuations. However, the ratio of the two effects appears to vary with time in a way which is not understood. Thus, so far, it has not been possible to use the measurements of water vapor to correct the interferometer phase. Efforts to better understand the water vapor measurements is in progress at several places and it is hoped that more sophisticated radiometers that perhaps measure the integrated water profile by multi frequency observations may prove more reliable than the single measurement of peak emission used in the past.

3. Uncertainty in Baseline and UT.1

The separation between two points in the USA can be determined to an accuracy of only a few meters by using conventional survey techniques. This corresponds to a few hundred wavelengths at an operating wavelength of a few centimeters. Moreover, tides in the solid Earth will cause diurnal fluctuations of 10 to 20 cm, and over a period of years crustal motions may accumulate at the rate of a few centimeters per year.

The rate of rotation of the earth (UT.1) is not constant and at any given time the direction of the baseline relative to an inertial frame is uncertain by 10 to 30 milli-arcsec. Uncertainties in the rates of precession and nutation of the Earth's axis, and the wander of the axis will also cause significant errors to accumulate over periods of a few months or more.

4. Calibration

In principle, the baseline constants, UT.1, and the effect of the atmosphere and ionosphere can be determined from the interferometric observations of calibration sources. Even if there were no desire to investigate these phenomena for their geophysical interest, they must be evaluated if accurate interferometer phases are to be measured. To a large extent the various terms are interdependent, and to solve for one requires the evaluation of all parameters.

In order to accurately measure the absolute phase on each interferometer pair, we must know a) the differential path length to a few tenths of a millimeter (including errors in the baseline and in the differential delay through the atmosphere and ionosphere), b) the instantaneous orientation of the baseline to considerably better than a milli-arcsec (including uncertainties in precession, nutation, and UT.1), and c) the relative phase of the independent local oscillators.

This is a formidable, if not impossible, task. However, in practice the problem is greatly simplified if the interferometer phase is measured relative to a nearby unresolved (constant phase) source. If the calibration source and the source of interest are separated in the sky by an angle θ, then the effect of the uncertainty in the various interferometer parameters are reduced by a factor of the order θ (θ expressed in radians).

The technique of calibrating an interferometer by observation of a suitably chosen grid of sources, plus the more frequent calibration of the variable terms (in particular atmospheric fluctuations) is fundamental to modern radio synthesis instruments. It is used to some extent in all currently operating arrays, and is crucial to achieving the full potential of the VLA or a VLB Array.

An important restriction on the sensitivity of the Array is that each interferometer pair be able to measure with reasonable signal to noise ratio a nearby calibration source during an interval which is not long compared to the time required to obtain each individual measurement of the fringe visibility function. Using 85-ft telescopes and VLA type radiometers, it can be estimated that at 6 cm, on the average, there will be one compact source within one degree of arc of any chosen position which will be strong enough to give an SNR of 5 ($\pm$ 12° of phase) in 10 minutes integration time (using the full bandwidth of 50 MHz).

The pulsars are excellent calibration sources. Since they will be unresolved on even the longest earth based interferometer baselines, they can be used to calibrate the absolute scale of fringe amplitude, the length and orientation of the baseline, and UT.1. There are too few pulsars that can be seen with 85-ft antennas to allow them to be used as reference sources for calibration of atmospheric phase fluctuations, and they will have a measurable proper motion. This means that the Array must use both the weak "point" source pulsars and the stronger, more numerous extragalactic sources many of which will be partially resolved with an Intercontinental Array.

A very powerful constraint on the effect of instrumental phase as well as amplitude fluctuations is obtained if there are redundant interferometer baselines. The Quasi Uniform Array described in Section V.B below allows the calibration of the longer interferometer spacings in terms of the shortest spacing, since each interferometer pair is equal in length to the sum of two shorter interferometers, which in turn can successively be divided down to the basic unit spacing. The relative interferometer phase may thus be determined on all baselines at all times, and used to reconstruct the true source image independent of any instrumental or atmospheric phase variations or uncertainties or changes in the baseline or UT.1. The only restriction is that the source be unresolved or only slightly resolved on the shortest baseline which is a necessary condition in any case (see Section III.A). In this way only the absolute phase, or position, of the source is missing; all the necessary phase information necessary to reconstruct the source image is preserved.

Since there are more interferometer pairs than there are antenna elements (for more than three antennas), it is not necessary that all of the interferometer baselines can be derived as a sum of smaller baselines. If there are N antennas, then there are $M = N(N-1)/2$ interferometer pairs or M measured phases compared with only (N-1) relative phase variations due to changes in electrical path length over each antenna or to local oscillator variations.

In general there will be K redundant baselines or (M-K) independent visibility phases. One of these may be taken as arbitrary and the others referred to it. This arbitrary visibility phase contains information on the position of the source, but is not needed for reconstruction of the brightness distribution. Thus there are a total of $M = N(N-1)/2$ measured phases, (M-K-1) unknown visibility phases, and (N-1) unknown instrumental phases. Provided that $(N-K) \leq 2$, it is then possible to solve for the unknown visibility phases.

For example, in an 8-element array ($N = 8$), there are $M = 28$ measured interferometer phases. If there are at least 6 redundant baselines ($K = 6$), then it is possible to solve for 21 of the 22 visibility phases, and 7 of the 8 instrumental phases.

Even in the absence of redundant baselines, some phase data may be obtained from the so-called "phase closure" relations. In a multi-element array the vector sum of the phases measured on any three legs formed by three antennas is independent of local oscillator fluctuations or variations in the atmospheric or ionospheric path length above each antenna, but does contain information about the visibility phases which may be used to restrict the solutions found from the use of amplitude data alone. If the source contains an unresolved or slightly resolved component so that the visibility phase is nearly constant on the longer baselines, then the true visibility phase on each of the shorter baselines may be determined from the phase closure triangle involving a pair of longer baselines. The unresolved component may be thought of as a reference source to which all interferometer phases are referred. The use of "phase-closure" without the need for calibration of each interferometer phase was pointed out by Jennison in 1958 and was discussed further by Rogstadt (1967). It has been used by Rogers et al. (1974) to help interpret data from a three station VLBI experiment, and has been further developed by Fort and Yee (1976) and by Wilkinson et al. (1977).

The calibration of interferometer phase using a nearby reference source requires that the antenna elements be rapidly alternated between two sources on a time scale short compared with variations in the atmospheric and ionospheric instabilities as well as with variations in the phase of the independent local oscillators. The need to frequently move the antennas can be eliminated if there are two antennas located at each site so that the source and the reference source may be observed simultaneously and the relative interferometer phase directly measured independent of any instrumental variations common to the two sources. To use this method, the relative separation of each pair of antennas must be accurately determined, generally by instrumenting them as a conventional connected interferometer. The connecting baseline is then calibrated in the usual way by observing a grid of sources of known position.

Although several such dual VLBI and even triple VLBI (3 antennas at each of two sites) have been carried out, the additional cost of implementing two antennas at each of the VLBA sites seems unnecessary, except if possibly it is later decided to extend the observations to millimeter wavelengths by building a second antenna at each site. Although alternating between the source and reference source is both time consuming and inconvenient, it appears adequate to obtain well calibrated phase data, particularly if there are a sufficient number of redundant baselines.

The fraction of time that will have to be spent in observing calibration sources, and in determining the baseline and rate of earth rotation is not clear and may very well be of the order of half of the total observing time.

Figure IV-2 shows the phase observed at 18 cm on a $1.3 \times 10^6\ \lambda$ baseline on the source CTD 93. The NRAO 140-ft and NRL 85-ft antennas were used as elements of the interferometer.

B. Image Restoration from Imperfect Data

In a properly designed multi-element array, an image may be formed by means of a conventional Fourier transformation. If, however, there is insufficient sampling of the transform plane because of inopportune placement of antennas or there is too much noise in the measured visibility amplitude or phase, the reconstructed source image is distorted. 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.

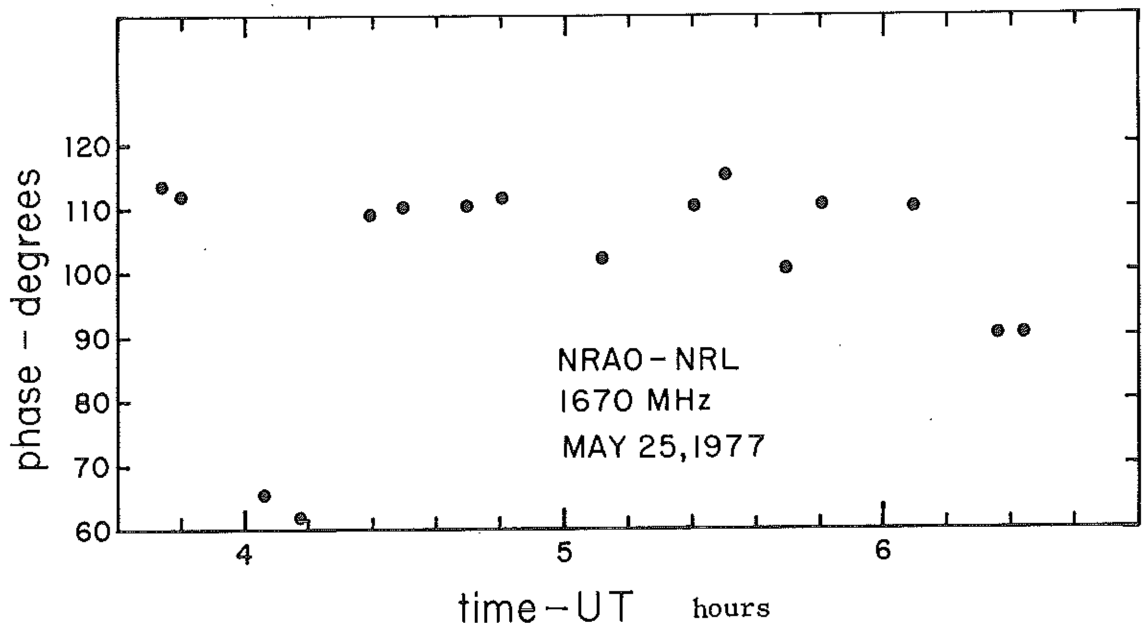

Fig. IV-2. The phase of the source CTD 93 observed on the NRAO-NRL baseline at 18 cm.

Procedures to minimize the effect of these sidelobes has been a subject of considerable concern to radio astronomers who wish to minimize the number of antennas in an array. In the case of present VLBI work, the problems are even more difficult, for two reasons.

a) First, because relatively few antennas are used, and because these have not generally been placed at optimum locations, the sidelobes may be numerous and strong.

b) Secondly, because there has been generally little or no phase information, a formal Fourier transformation of the observed fringe visibility has not been possible. VLBI workers have resorted to a variety of "tricks" to get the most information from a limited amount of data. Many of these techniques were developed earlier to deal with conventional interferometry which in previous years suffered from many of the same limitations of present VLBI - i.e., incomplete data with little or no phase information.

1. Model Fitting

The most straightforward, and so far most widely used, technique for interpreting VLBI data is "model fitting," i.e. an attempt to find the simplest geometric model which satisfies the observed interferometer data. The general procedure is to examine the extrema of the fringe visibility function on each interferometer track and from their location and amplitude to estimate the over-all dimensions, the orientation of the major axis, and the number of components of the source. This "first guess" is then used as input to an iterative procedure which varies the parameters of the model to find the best fit to the observed visibility amplitudes.

The procedure is simplified by assuming that the source can be divided into a relatively small number of discrete (usually gaussian) components and, by analogy with the more extended sources, has a fairly well defined line of symmetry. In detail, probably neither of these assumption is correct, but in most instances the limited data available so far can be represented with such simple source models.

If there are more than three components, or the components do not lie along a straight line, it is frequently difficult to find, by inspection, a satisfactory model to start the model fitting procedure. Another major difficulty is that the final model is sensitive to the "first guess" and unless this guess is close to the true brightness distribution, the solution may not converge. Also, even if a satisfactory solution is found, generally it is not unique, and often one parameter may be dependent on the value of another.

It is encouraging to note, however, that model fitting, applied to the early conventional interferometric data, while oversimplified, was successful in crudely describing the brightness distribution. The later, more complete data obtained with multi-element synthesis arrays have greatly improved both the resolution and quality of the maps; but for the most part, the early models are not in disagreement with the new maps.

Bates (1969a,b) and Napier (1972) have pointed out that the location of the complex zeros in the (u,v) plane may be used to determine all of the one dimensional source brightness distributions which can give the observed fringe visibility amplitudes. Frequently many of these can be excluded because they contain negative brightness and are thus physically impossible. If both the visibility amplitudes and phases are measured, but the phases are relatively inaccurately determined, the location of the complex zeros can be used to reduce the errors (Bates and Napier 1972).

There is no direct extension of the complex zero theory to two dimensions, but the one dimensional procedure can be applied along many straight lines in the (u,v) plane (Napier and Bates 1974).

2. Direct Fourier Transform

In arrays in which accurate amplitudes and phases are measured over the appropriate portion of the (u,v) plane, the source image may be reconstructed by direct Fourier inversion. In order to minimize the amount of computational time, the data are generally interpolated into a rectangular grid so that Fast Fourier Transform (FFT) techniques may be used.

If the (u,v) plane is incompletely sampled, it is necessary to assume some value of the visibility function at those grid points where it is not measured. This may be done by interpolating from nearby points or more simply by assuming a value of zero. In either case, this distorts the image by adding sidelobes. The Maximum Entropy Method (MEM) derives the brightness distribution which is the most random (i.e. has the maximum entropy) and is consistent with the observed data. The method has been demonstrated to be successful but the additional computational times appear excessive (i.e. Rogers 1975b).

Another method which has been recently used is the CLEAN technique in which sidelobes are removed by comparing the image obtained by direct inversion (DIRTY MAP) with the array response to a point source (DIRTY BEAM) to form the CLEAN MAP. The method works well if the source can be represented by a small number of discrete components, but phase data is required (Hogbom, 1974). Fort and Yee (1976) and Wilkinson et al. (1977) have combined the CLEAN technique with the use of phase closure to derive high resolution maps of compact radio sources.

Methods of efficient image reconstruction are being actively investigated by various VLBI workers and as part of the VLA design. The goal, of course, is to make maximum use of the available data and to introduce a minimum of distortion by the inversion process.

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V. THE ARRAY

A. Resolution and Sensitivity

The astronomical problems described in Chapter II suggest an instrument capable of sub-milli-arcsec resolution with reasonably low sidelobes. Sufficient sensitivity is needed to study weak continuum emission from the nuclei of radio galaxies, quasars, stellar objects, and the weaker molecular masers, particularly on the longer baselines where the sources are partially resolved, and also to give in a few minutes or less sufficient signal-to-noise on an adequate number of calibration sources. Enough flexibility is required to permit operation over a variety of bandwidths for spectral line and continuum observations. Operation at a number of wavelengths between about 1 and 50 cm are desired for various continuum problems, and specifically for the H_2O and OH maser lines at 1.3 and 18 cm and the 21 cm line of neutral hydrogen.

The limited very long baseline interferometer data available has already demonstrated that the compact radio sources have complex structure which is remarkable similar to that found in the extended sources, except of course for a factor of 100,000 difference in angular and linear size. Thus, to adequately map these complex sources, an image forming array with low sidelobes is necessary. Several theoretical arguments based on the existence of high frequency spectral cutoffs, rapid variability, as well as direct observations on intercontinental baselines has demonstrated that resolutions of a few tenths of a milli arcsec are required to resolve the smallest features found in radio galaxies and quasars at centimeter wavelengths. Intercontinental VLBI observations at 1.3 cm and 18 cm indicate that most, if not all, H_2O or OH features are larger than a few tenths of a milli-arcsec. At 1 cm, the maximum baseline needed to reach this resolving power is about 10,000 km.

This is also the maximum practical baseline which can be used from the surface of the Earth. Beyond this, the curvature of the Earth greatly reduces the time of common visibility for the more distant antenna pairs with little increase in the actual separation. Thus, unlike conventional arrays, there is a fairly well defined maximum size, which cannot be increased without the more costly and complex procedure of placing antennas in space or on the moon. Fortunately, this limiting size appears adequate to investigate a wide range of astrophysical problems.

At least a few hundred picture elements are required per image, and so the spacing increment must be about 5 percent of the over-all length. To keep sidelobes below 10 percent, the minimum number of antenna elements needed is about 10.

A sensitivity of several milli flux units is desired for several reasons.

a) It is expected that nuclear radio emission will be found at this level from most radio galaxies and quasars, and a number of normal galaxies as well.

b) A reasonable number of stellar objects can be observed at this level.

c) The interferometer fringe amplitude can drop to one percent or less of the total flux density in parts of the (u,v) plane, so even for strong sources, high sensitivity is required to completely map the source.

d) Calibration of the interferometer phase will require frequent reference to one or more nearby calibration sources, without spending an unreasonable fraction of the time. A signal-to-noise ratio of at least 5 to 1 is necessary to measure the phase to $\pm$ 12 degrees. Counts of radio sources made at centimeter wavelengths show that at a level of 0.1 Jy flux units there are about 1000 compact sources per steradian. This means that on the average there will be about one reference source $\gtrsim$ 0.1 Jy within one degree of any source; and the phase of the reference source can be measured to an accuracy of about 10° in one minute integration time.

e) A sensitivity which is comparable with that of the VLA is desirable so that the two instruments may more naturally complement each other. For example, the structure of compact ("point") sources discovered with the VLA can be studied with the Intercontinental Array.

The sensitivity of a digital interferometer system is proportional to the number of bits which are correlated. This in turn is proportional to the product of the observing time and the bandwidth (bit rate). The length of the integration time is limited by the coherence of the independent local oscillators or the atmosphere and ionosphere. For short centimeter wavelengths this is perhaps a few tens of minutes, so high data rates of about 100 Mbits/sec are necessary to achieve a sensitivity comparable with single dish radio telescopes or directly connected interferometer systems.

Table V.1 shows the sensitivity which will be achieved using VLA type antennas and radiometer systems together with one-bit digital data recordings using a modern multi-track instrumentation recorder. Although the actual coherence time may be less than one hour, frequent reference to unresolved sources can be used to extend the integration time to many hours in the same manner as is done in conventional aperture synthesis arrays.

Table V.1

Sensitivity*

r.m.s. Noise Fluctuation per Interferometer Pair (mJy)

B \ τ	1^{min}	$20^{min\dagger}$	$1^{hr.}$	$10^{hr.}$
4 MHz	70	16	9	3
56 MHz	18	4	2.5	1

Minimum Detectable (5 σ) Brightness Temperature (10^{6}°K) for Single Interferometer

B \ τ	1^{min}	$20^{min\dagger}$	$1^{hr.}$	$10^{hr.}$	
4 MHz	3000	670	400	100	Continental baseline ∿4000 km.
56 MHz	1000	220	100	25	
4 MHz	6	1.3	1	0.2	Shortest baseline (∿ 175 km) in 8 element array.
56 MHz	1.5	0.3	0.2	0.05	

* 25 meter antenna
efficiency 50%
T_s = 50°K
1 bit samples - 28 track instrumentation recorder

† Maximum time for 12,000 ft. tape (16 inch reel) at 120 ips (112 Mbits/sec). The same sensitivity is achieved in 10 minutes at 224 Mbits/sec (240 ips).

Average distance of nearest compact phase reference source with S $\gtrsim$ 0.1 f.u. (SNR = 5 in one minute with BW = 56 MHz) is about one degree, more or less independent of wavelength.

Efforts at the direct measurement of phase are complemented by the accurate determination of the differential delay of the incoming wavefront. Normally, this is done with an accuracy of the order of the reciprocal bandwidth. Although the instantaneous bandwidth will be limited by the recording medium to 50 to 100 MHz, the effective bandwidth can be increased by varying the local oscillator frequency to synthesize a bandwidth as large as the receiver bandpass (Rogers 1970). The local oscillator system must therefore be capable of being rapidly varied in frequency over about 10 percent while maintaining phase coherence at the different frequencies.

Although the Intercontinental Array will generally operate as a self-contained instrument, for several purposes joint operation with other telescopes will be desired. This includes extensions to north-south baselines, a tie-in with the global NASA network, or a transcontinental link for "local" geodetic VLB programs such as ARIES (see section IIID). The Intercontinental Array record system should be compatible with the record systems in use at NASA and at other radio observatories.

1. Spectroscopy

Studies of molecular line sources also require high sensitivity. Although a few sources are exceptionally strong, many sources of interest, such as those associated with stars, are rather weak and require fairly sophisticated receivers if the antenna diameter is 25 meters. System temperatures of $\sim$ 50 K or better are necessary, since for spectroscopic work the sensitivity cannot be improved by increasing the bandwidth.

The required range of interferometer spacings are:

1612 MHz (OH/IR sources)	100-800 km
1665/1667 MHz "	100-5000 km
22235 MHz (H_2O)	100-9000 km

It is not clear whether spacings of $\sim$ 100 km are best obtained with short spacings on a tape-recorder array, or a radio linked extension of the VLA.

Very wide bandwidths are not needed for spectral line work. Even in the isolated cases where it might be useful (e.g. the W49N H_2O source is about 20 MHz wide or the 1665 and 1667 OH transitions could be observed simultaneously), the number of correlator channels required to give adequate resolution becomes prohibitive and time multiplexed systems seem preferable.

It is always desired to record only the necessary bandwidth, both for economy of magnetic tape, and to speed up the playback procedure.

The recording system should also be able to handle several channels of data. Examples of this are:

1. different polarizations;
2. different molecular transitions;
3. synthesized wide bandwidth.

2. Pulsars

Pulsars are weak, have steep spectra, short duty cycles, frequency dispersed pulses, and time variable pulse strengths. These all pose special problems for their inclusion in programs on the Intercontinental Array.

The sensitivity to pulsed radiation is lower than to continuum radiation by the square root of the duty cycle (assuming the system is blanked during the interpulse period).

There are many known pulsars which could be observed by an Intercontinental Array. For the wide bandwidths planned, even at high frequencies, dispersion smearing of the pulse is significant, e.g. at 1400 MHz at 50 MHz bandwidth the dispersion smearing is 5 ms for a dispersion measure of 30 pc/cm^3; at 600 MHz with 10 MHz bandwidth it is 12 ms. This is appreciably long compared with typical pulse widths and would degrade the signal to noise if the only signal enhancement technique were blanking the correlator during the off pulse. However, a posteriori dedispersed pulse reconstruction is possible (e.g. Erickson et al. 1972). This method would require modification to the correlators to have the zero frequency fringe rate channels augmented with ones at multiples of the pulse repetition frequency.

It is also possible to significantly improve the sensitivity to pulsars, by running in a "burst mode" where up to 25 (duty cycle^{-1}) times the nominal bandwidth is sampled and put into temporary storage for recording during the off-pulse period. This provides a further increase in sensitivity by a factor of (duty cycle)$^{-1/2}$.

B. Array Configuration

The criteria for the design of radio telescope arrays has been discussed extensively. Generally, it is desired to maximize the number of interferometer baselines and the (u,v) coverage, using the minimum number of antennas (e.g. Mathur 1969).

In discussing transcontinental or intercontinental arrays, there are, however, additional constraints which are not present in conventional arrays. In the latter case the antennas generally may be placed at whatever location will optimize the geometric configuration. In a VLB Array the antenna locations must be at geographically "accessible" locations, avoiding mountains, oceans or lakes, etc. Also, unlike conventional arrays, it is difficult or impossible to transport antennas from one location to another. For convenience of operation, wherever feasible, the antenna elements should be located near already existing radio astronomy facilities, and these sites must be on politically stable territory.

Moreover, when the individual antenna elements are spread over a significant fraction of the earth, the time of mutual visibility of a celestial radio source is less than it would be if all the antennas were located at one site. Thus on the longer baselines, each interferometer pair covers a smaller fraction of the (u,v) ellipse than a similarly oriented smaller interferometer, and more interferometers (or more antennas) are required for a given density of (u,v) coverage. In other words, an Intercontinental Array cannot make full use of earth rotation synthesis, and so such an instrument must have a better instantaneous beam than the corresponding "small" array.

It is well known that in order to obtain a good beam with low sidelobes over the whole sky, a two-dimensional array is necessary. A one-dimensional or linear array oriented in the East-West direction can also have low sidelobes with 12 hours of observing, but only at high declinations does it give good resolution in the North-South direction. 12 hours of tracking on the interferometer baselines which extend more than a few thousand kilometers is possible only over a limited range of declinations.

The two dimensional array is less efficient in that it requires a considerably larger number of antennas to synthesize a given beam, even in that part of the sky where the linear array works well. For a given number of antennas and maximum resolution, the linear array gives the lowest sidelobes in the northern sky, at the expense of poor north-south resolution near the equator. Below the equator the sidelobes become large, since the tracking time is limited. A two-dimensional array with the same number of antennas and which has the same resolution gives an intermediate sidelobe level over the whole sky.

For arrays with no more than 8 to 10 antennas, it appears difficult to construct a good two-dimensional array. For this reason the major existing conventional arrays have an East-West linear configuration and use 12 hours of earth rotation to synthesize a beam. These are

a) the 3-element Cambridge one mile interferometer,

b) the 12-element Westerbork one mile array,

c) the Cambridge 8-element 5 km array.

In spite of the restrictions imposed by the poor performance near the equator and at southern declinations, each of these instruments has, as a result of its high resolution, low sidelobes, and relatively high sensitivity, given major astrophysical results which were not achieved with the simpler interferometer systems of comparable resolution, such as the OVRO and NRAO interferometers which were not designed for synthesis observations. Only the very much more complex and costly 27-element VLA can satisfactorily synthesize a good beam over most of the visible sky.

For similar reasons a linear East-West configuration is attractive for a VLB Array. However, as has already been noted for transcontinental and inter-continental baselines where the mutual visibility is restricted to less than 12 hours, more antennas are needed to achieve a comparable sidelobe level, thus negating some of the advantages of the simple East-West array.

Even among East-West arrays, there are several major classes of configurations from which to choose. Among these are

a) an exponential spacing array,

b) a uniform spacing array,

c) a minimum redundancy array (e.g. Moffet 1968).

1. <u>Exponential Spacing</u>

With an exponential spacing, a wide range of (u,v) coverage is possible. Indeed with only seven antennas plus the VLA , all spacings up to 4000 km are available to within a factor of two. This will permit the size of any source or its components to be determined, but there may be an inadequate number of intermediate spacings on any scale to determine in detail the source structure.

2. <u>Uniform Spacing</u>

A uniform spaced array has the advantage of being easily extended and having enough redundant spacings to significantly facilitate the problem of maintaining adequate phase calibration. The beam pattern of such an array is well known and gives low sidelobes.

The disadvantage of using uniform spacing is that with N antennas there are only N independent interferometer spacings, compared with a total of N(N-1) interferometer pairs, so a relatively large number of antennas is needed.

3. Minimum Redundancy Array

The minimum redundancy array gives the most number of interferometer spacings per antenna element (cost) and is thus attractive for a VLB Array. Table V.2 shows the maximum number of separate spacings, K (in multiples of the unit spacing) in column 2, which may be obtained with N antennas (column 1) and with each multiple up to maximum included. The total number $M = N(N-1)/2$ of spacings is given in column 3, and the quantity $(M-K)$ = the number of redundant spacings in column 4.

Table V.2

Spacings in Minimum Redundancy Array

N	K	M	(M-K)
2	1	1	0
3	3	3	0
4	6	6	0
5	9	10	1
6	13	15	2
7	17	21	4
8	23	28	5
9	29	36	7
10	36	45	9
11	43	55	12

4. Quasi Uniform Array

The minimum redundancy and uniform spacing arrays represent the extreme limits of maximum number of spacings per interferometer, and maximum redundancy respectively. The quasi uniform array has an even number, N, of antennas; $N/2 + 1$ are equally spaced with a separation $\sim s_o N/2$ where s_o is the unit spacing. The remaining antennas are placed between the two end antennas described above to form N/2 interferometers of spacing s_o. All spacings between s_o and $N^2 s_o/4$ appear in the array of steps of length s_o.

This array contains sufficient redundancy so that the phase of each interferometer of length $s_i = n_i s_o$ may be related to that on the shortest spacing s_o.

5. Comparison of Different Array Configurations

In an 8 element transcontinental array, the minimum element spacing is between 50 and 250 km depending on the particular configuration. A minimum spacing of $\sim$ 50 km is desirable to provide continuity with the range of resolution available with the VLA; but it is not possible to do this and also to provide the desired redundancy unless the number of antennas is increased. Spacings in the range 50 to 250 km may be more easily obtained by an extension of the VLA or by a specially built radio linked array.

A schematic illustration of exponential, uniform, minimum redundancy, and quasi-uniform spacing are shown for linear arrays of 8 elements in Figure V-1.

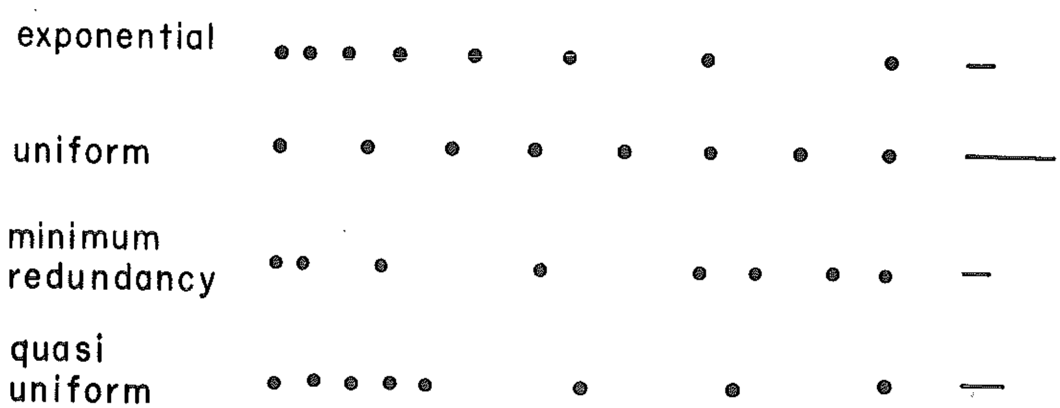

Fig. V-1. Schematic illustration showing the relative spacing for four 8 element arrays with exponential, uniform, minimum redundancy, and quasi uniform spacing. Each array has the same overall length. The solid line indicates the length of the minimum spacing for each configuration.

6. Real Arrays.

As has been already noted, the implementation of a real Transcontinental or Intercontinental Array requires consideration of geographic convenience as well as the desired baseline configuration. In general, if the radio source to be studied has a total angular extent θ, (radians), then the minimum incremental spacing is $\sim 1/\theta$ wavelengths, and the individual elements may deviate from their ideal location by an amount $\sim 1/\theta$ wavelengths (somewhat less than the unit spacing - a few hundred kilometers) without seriously degrading the reconstructed brightness. If, however, the redundancy of interferometer pairs is used to reconstruct the visibility phase on the longer spacings, then the allowed deviations are less, since the phase errors accumulate.

A variety of real Transcontinental Arrays have been investigated. Figure V-2 illustrates the (u,v) coverage and beam shape of a possible 8-element array with 6 of the antennas located at existing radio observatories. Other possible configurations, including extensions to intercontinental and to north-south baselines, are illustrated in the Appendix.

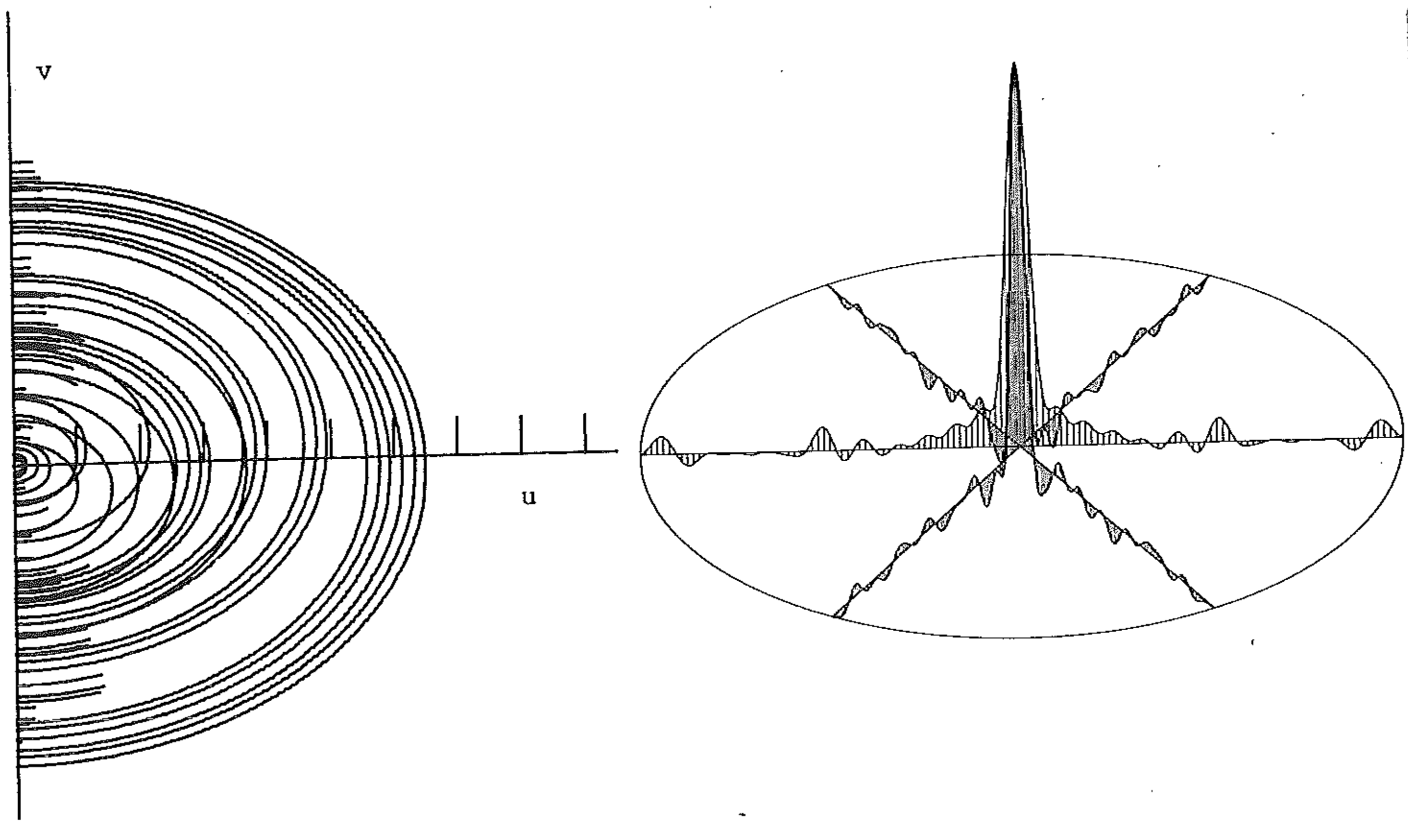

Fig. V-2. (u,v) coverage and beam shape for an 8-element array with antennas located at Md. Point, Md.; Charlottesville, Va.; Green Bank, W. Va.; Wichita, Kan.; Boulder, Colo.; Salt Lake City, Utah; Big Pine, Calif.; and Palo Alto, Calif. The tick marks correspond to a 2 milliarc sec length in the projected interferometer baseline. The half power beamwidth at 1.3 cm is 0.7 milliarc sec.

7. North-South Baselines

A significant improvement in the (u,v) coverage at low declinations may be obtained by adding one or two antennas in Puerto Rico, Mexico, Canada, Alaska, or other locations within the U.S. (Figure V-3). In general, the southern locations give better coverage below the equator and the northern locations for sources near to, but north of, the equator. The uniform spacing array gives the most uniform extension of the u,v plane when North-South baselines are added. Although adding North-South baselines will improve the (u,v) coverage, it is difficult to have the necessary redundancy to aid in phase calibration.

8. Intercontinental Baselines

Although an eight-element transcontinental array gives an unprecedented resolution with low sidelobes, the resolution still is inadequate to study the most compact structure found in the short wavelength radio outbursts already being investigated in a preliminary way with existing intercontinental VLB interferometer systems.

An extension to Europe improves the resolution by more than a factor of two, but this is too large an increase for a single step without a significant increase in sidelobes. A northerly location for the European station gives a greater duration of common visibility for northern sources and consequently greater (u,v) coverage. This is, however, at the expense of less uniform coverage and less (u,v) coverage at southern declinations.

An extension to Hawaii is interesting in that it is a more modest step from the transcontinental baselines, and gives nearly a factor of two improvement in resolution. An Intercontinental Array including Hawaii plus Europe gives an increase of 2.5 in resolution over the transcontinental array and a lower sidelobe level than either the Hawaii or Europe additions alone.

The uniform spacing array gives the most uniform coverage of the (u,v) plane when the resolution is extended. The addition of a single antenna separated from the original array by an amount equal to the array size will double the resolution while retaining all multiples of the unit spacing and enough redundancy to determine the visibility phase on all baselines.

The quasi-uniform array may be extended in a similar way, with all multiples of (N/2) times the unit spacing represented in the extended array. In the case of the 8-element quasi-uniform transcontinental array plus Europe and Hawaii, all spacings between 250 km and 4000 km at 250 km intervals are represented, plus approximately uniform coverage of the range 4000 to 8000 km. There is, in addition, a baseline about 10,000 km in length, but the duration of common visibility on this baseline is short, except for sources near the north pole.

9. Baselines in Space

An Earth-based array with over-all dimensions $\sim$ 10,000 km will give sufficient resolution to attack a wide variety of astrophysical problems. In particular, all incoherent synchrotron sources stronger than about 1 Jy can be resolved with terrestrial interferometers, since inverse Compton scattering puts an upper limit of $\sim 10^{12}$ K to the maximum brightness temperature of such sources. Longer baselines are, however, probably required to resolve the fainter sources found in many galactic nuclei, if these have brightness temperatures comparable to the stronger compact sources. Baselines necessary to resolve these sources require antennas in space. Also, observations of the stronger sources with sufficiently high resolution, may strain current theories if brightness temperatures significantly in excess of 10^{12} K are found in extragalactic radio sources. In any event, coherent radio sources such as pulsars and molecular masers do exist, and terrestrial interferometers may have inadequate resolution to study them.

Space-borne antennas with dimensions sufficiently large for VLB interferometry are expensive, but the costs are likely to be significantly reduced in the 1980's with the advent of the Space Shuttle. A proposal to use one of the early shuttle flights to put an antenna in space for earth-space VLB interferometry has been submitted to NASA (Burke 1976). A satellite-borne antenna which forms interferometer pairs with several ground-based antennas not only has greater resolution than a purely Earth-based system, but due to the orbital motion of the satellite, the coverage of the (u,v) plane is considerably more uniform.

10. Possible Choice of Configuration

Because preservation of phase information is so important in reconstructing an unambiguous source image, the redundancy provided by the quasi uniform array appears worth the loss in the number of independent baselines provided by the minimum redundancy array. An example of the possible locations for such an array is given in Table V.3.

Eight of the antennas are located in continental U.S.A., with the overall length and spacing chosen to allow some antennas to be located near existing radio astronomy facilities. These locations may be varied by about 50 or 100 km without affecting the performance of the array. But a detailed simulation of the performance, including the effect of noise is needed to determine the maximum allowable deviations from the ideal array, while still permitting the use of redundant baselines to calibrate the phase and amplitude.

For the antennas not located at existing radio astronomy installations, the exact choice of location will depend on the ease of access and operation. The two overseas antennas are located in Hawaii and Madrid, Spain, and give reasonably uniform spacings between 4000 and 8000 km at intervals of 1000 km.

Table V.3

Array Configuration

Number	Location	Longitude	Latitude
1	Madrid, Spain	3°11'	40°25'
2	Md. Point, Md.	77 14	38 22
3	Green Bank, W. Va.	79 50	38 26
4	South Central Ohio	∿81 30	∿38 30
5	South Central Indiana	∿85 30	∿38 30
6	South Central Illinois	∿88 00	∿38 30
7	Central Kansas	∿99 30	∿38 30
8	Central Utah	∿111 00	∿38 30
9	San Francisco, Calif.	122 24	38 30
10	Mauna Kea, Hawaii	155 28	19 50

Only one antenna of the array (near Madrid) is not located on U.S. soil. However, the U.S.A. already has three major antenna systems operating near Madrid for the NASA Deep Space Network and Manned Space Flight Network, and it is anticipated that no problems will be involved in locating a VLBA antenna at the same site.

With configurations of this type, the shortest spacing is several hundred km, leaving a gap of about a factor of 10 between this and the maximum VLA dimensions. Although this gap can in principle be filled by adding more antennas to the VLB array, a more practical approach would appear to be radio-linked extensions to the VLA.

Table V.4

VLB Array Resolution

Maximum Baseline	d(km)	θ ∿ λ/d milliarc sec. λ=1.3 cm	λ=2 cm	λ=3.8 cm	λ=6 cm	λ=13 cm	λ=18 cm	λ=50 cm
USA	3.9×10^3	0.7	1.1	2.0	3.2	6.8	9.5	25
USA, Hawaii	7.0×10^3	0.4	0.6	1.1	1.8	3.8	5.3	15
USA, Europe	8.2×10^3	0.3	0.5	1.0	1.5	3.2	4.5	12
USA, Europe, Hawaii	10.2×10^3	0.25	0.4	0.8	1.2	2.6	3.6	10

C. Antenna Elements

As in any multi-element radio telescope array, the largest possible antennas are desired as elements in order to obtain the best signal-to-noise ratio. This is especially true where the bandwidth is limited by the i.f. transmission system as it is for a VLB Array.

However, as the size of the elements is increased, the cost increases rapidly, and operation at short wavelengths is sacrificed. The optimum size for the elements of an array operating at decimenter and centimeter wavelengths appears to be in the range 15 to 40 meters. The 25-meter antennas which have been designed for the VLA operate well at short centimeter wavelengths and are also well suited for a VLB Array. Since a large number are already being built for the VLA, the cost is well determined, and there is a considerable saving in cost as a result of mass production techniques. These antennas are also designed to require a minimum of routine maintenance.

The main restrictions imposed by the use of these antennas is their relatively small collecting area compared with many of the antennas currently used for very long baseline interferometry (i.e. the NRAO 140-ft, ARO 150 ft., Caltech 130-ft., Haystack 120-ft., Goldstone 210-ft., Arecibo, 1000 ft., and Bonn 328 ft.) and their inability to operated at wavelengths shorter than about one cm.

Larger antennas are more expensive. Operation at shorter wavelengths can be achieved either by improving the antennas at increased cost, or by constructing smaller antennas of greater accuracy at comparable cost. The latter solution, however, would probably give unacceptably small collecting area for work at decimeter and centimeter wavelengths.

As in the case of the VLA, compromise between scientific need and economy dictates an antenna of about 25 m diameter. But because of the greater importance of shorter wavelengths for VLB work*, every effort should be made to improve the short wavelength performance over that of the VLA type antennas. Alternately, it may prove more economical to duplicate the VLA type antennas for operation at wavelengths of one centimeter and longer, and to construct additional smaller precision antennas at each site for operation at millimeter wavelengths. This latter approach has several advantages. They are:

* Compact sources are generally stronger at short wavelengths, and the shorter wavelength operation is necessary to increase the resolution with a physically limited baseline.

1) Receivers do not need to be changed when changing between millimeter and centimeter wavelength observing.

2) Simultaneous centimeter and millimeter wavelength observations are possible, permitting the cmλ fringes to be uses as a phase reference to coherently integrate the mmλ fringes well beyond the normal coherence time.

3) Simultaneous observations of two sources are possible.

4) The second antenna may also be used as a communications antenna in a satellite uplink when using a geostationary satellite as a data link for real time analysis of the data (see Section V.E.2)

5) The over-all cost is less than improving the accuracy of a 25-meter antenna.

6) The addition of the millimeter wavelength facility can be delayed until mmλ VLBI becomes practical.

Use of Existing Antennas:

The cost of an individual antenna element is approximately one half that of a completely equipped interferometer element. Thus, in principle, considerable cost could be saved if the Intercontinental Array could effectively use already existing radio telescopes.

The major instruments, such as the 140-foot, Haystack, and ARO telescopes, which have been involved in most of the previous VLB activity, are, however, heavily committed to other tasks, and even now sufficient time for desired interferometer work is difficult to schedule. Not surprisingly, scheduling of multi-station VLB experiments using these antennas is becoming increasingly difficult as the demand on their time increases.

Other obvious candidates such as the antennas at Michigan, Hat Creek, Fort Davis, Onsala, and the NRAO 85-ft. antennas suffer from the following problems, which also apply to a lesser extent to the major instruments above.

a) They are not optimally located.

b) They are inadequate for operation at short centimeter wavelengths. Operation near 1 cm is necessary to study the sub-milliarc sec structure if the baselines are restricted to 10,000 km, which is the maximum for which reasonable common sky coverage can be obtained. 1 cm wavelength operation is also required for the important H_2O observations.

c) Most of these antennas are equatorial mounted and are limited to < 6 hours hour angle, whereas ± 7.5 hours are needed to get the 12 hours of tracking for good (u,v) coverage even on U.S. baselines. If the baseline is extended to Europe, then ± 10 hours is necessary (usable only at high declination).

In other words, there are some half dozen 85-foot antennas at various sites around the United States which we anticipate will not be heavily used by the end of the decade. But for just the same reasons that they are not in demand for conventional uses, their effectiveness as elements of a dedicated long baseline array are limited.

The antennas which do work moderately well at short wavelengths can be expected to be in great demand for a wide variety of uses, particularly if the anticipated improvements of the Haystack and 140-foot antennas are made.

For many special purposes, however, joint operation between the dedicated array and existing telescopes may be anticipated. This includes experiments which require a greater range of interferometer spacings (e.g. north-south spacings) than otherwise available, particularly at decimeter wavelengths, and experiments requiring the extreme sensitivity obtained from the larger antennas such as the NRAO 140-ft., Haystack 120-ft., ARO 150 ft., Bonn 100-meter, OVRO 130-ft., and the very well-equipped NASA 64-m telescopes in California, Spain, and Australia.

D. Choice of Frequency and Radiometers

Modern radio astronomy covers a wide range of frequencies corresponding to a variety of astrophysical problems. In addition to the desire to cover a large part of the radio spectrum, there is also an important technical consideration: for a given array size and collecting area, the resolution is greatest at the shortest wavelengths, while the sensitivity to low surface brightness regions is maximum at longer wavelengths.

1. Spectral Line Observations

At the present time there are three spectral lines (or groups of lines) of interest to a VLB Array. These are the hydrogen (21 cm), hydroxyl (18 and 5 cm), and water vapor (1.3 cm) lines, and any VLB Array must be able to cover these wavelengths. The $J = 1 \rightarrow 0$ transition of the SiO maser near 43 GHz and the 23 GHz lines of methanol as well as other yet undiscovered lines may also be important.

2. Continuum Observations

These wavelengths are also suitable for continuum observations, although even more wavelengths are required to achieve the variety desired both to a) obtain a range of resolution and brightness sensitivity, and b) investigate the spectral behavior of the compact radio sources.

At least two wavelengths are desired between 1.3 and 18 cm and one longer than 21 cm. These are two obvious choices for the pair of intermediate centimeter wavelengths. These are:

(a) VLA wavelengths. In addition to 1.3, 18, and 21 cm, the multifrequency VLA receiver operates at 6 cm (basic frequency) and 2 cm. For essentially the same reasons that went into choosing the 1.3, 2, 6, 18, 21 cm combination for the VLA, this combination is attractive for a VLB Array. Furthermore, with similar radiometers in the VLA and VLB Array, the cost and effort of development are eliminated, and the maintenance effort for both systems, including spares, may be combined at considerable increase in efficiency of operation.

The relatively high system temperatures of the VLA receivers at 2 cm (∿ 350°K) and 1.3 cm (∿ 500°K) are probably inadequate for a VLB Array where the shorter wavelengths are particularly important to investigate the most compact time variable structure. With the addition of a one stage parametric amplifier, however, the system noise temperature can be reduced below 100°K at relatively low cost. Improvements in cooled mixers may also reduce the system noise with no increase in cost or complexity.

(b) NASA wavelengths. Two of the prime operating wavelengths of the NASA Deep Space Network are at 3.8 and 13 cm where extremely low system noise temperatures of ∿ 25 and ∿ 15 degrees respectively have been achieved. If the VLB Array had the capability of operating at these wavelengths, it could take advantage of the low receiver noise and large collecting areas of the NASA antennas in joint operations between the Array and DSN antennas. For a given cost and complexity, however, the 3.8-13 cm set does not differ from the 2-6 cm pair for operation of the Array by itself. The Array radiometers at either set of wavelengths can use masers, parametric amplifiers, cooled mixers, or a combination of these at a trade-off between sensitivity and cost. Since it is unlikely that more than a very small fraction of time will be available on NASA antennas, it does not appear particularly useful to have 3.8 or 13 cm as the prime operating wavelength. Secondary radiometer systems could be made available, however, if there is sufficient interest in joint operations with NASA antennas.

On the other hand, a 2 cm capability already exists at the NASA Goldstone tracking station and a 1.3 cm system is being developed. So even without modification of the basic VLA design, there will be several frequencies compatible with NASA operations.

(c) Other Wavelengths. One frequency at medium decimeter wavelengths is also desired. The relatively limited work which has been done so far at decimeter wavelength has demonstrated the presence of complex angular structure on a scale ∿ 10 times greater than commonly seen with cm wavelength VLBI (e.g. Purcell 1973).

An attractive alternate to the VLA radiometer system is the wideband receiver system currently being developed for the NRAO 140-ft and 300-ft antennas, and which may later be installed on the VLA. This radiometer uses a very low noise maser amplifier operating in the range 18 to 26 GHz plus parametric upconverters to cover the range 5 to 18 GHz at the secondary focus and 500 MHz to 5 GHz from the primary focus. System noise temperatures, exclusive of the atmospheric contribution, are expected to be ∿ 30 K over the entire range.

E. IF Data Transmission

In a conventional radio telescope array, the i.f. data from each antenna element is transmitted by cable, or in the case of the VLA by low loss circular waveguide, to a common point where the signals from each element are correlated with each other. For longer distances up to a hundred km or so, microwave links using up to two relays have been used. For very long baselines extending to intercontinental distances, the data is recorded at each element on magnetic tape which is then physically transported to the correlator.

In principle, any of these modes of i.f. transmission is possible in a dedicated very long baseline array, with the decision being based on the relative cost effectiveness.

1. Direct Transmission

The cost of a transmission facility of the type being used in the VLA appears prohibitive. At over $50 per meter, it would cost more than $200 million dollars for the waveguide alone, and many times this for the installation.

Long distance data transmission facilities capable of transmitting data rates ranging from a few kHz to a few MHz are available through conventional commercial facilities, although the cost is large. It may be anticipated that by the 1980's the cost of large bandwidth long distance data transmission will be significantly reduced with the installation of transcontinental waveguide or fiber optics systems. However, the desired bandwidth, which is equivalent to about 10 commercial TV channels, is very great. The cost of leasing commercial data transmission facilities will probably remain unacceptably large.

On the other hand, only a modest bandwidth of a few kHz is sufficient to examine the performance of the instrument and for the remote control of the antenna elements. In particular, this bandwidth gives adequate sensitivity to "see" interference fringes on strong sources, and so could be used to monitor the performance of the instrument in "real-time."

2. Radio Link via Synchronous Satellite

Long distance transmission of wideband data is also possible via a synchronously orbiting satellite which acts as an active relay. Each array location then requires a transmitter and antenna to send data to the satellite, which then retransmits all the data simultaneously to the receiving station at the correlator.

The simultaneous transmission of about ten chennels each of 100 to 200 MHz bandwidth is possible. Currently operating systems such as the Intelsat IV-A satellites which handle most of the intercontinental communications have a bandwidth of 500 MHz. Intelsat V, scheduled for launch in 1979, will have a total capacity of 2.3 GHz. Presently available microwave communication satellites typically operate in the wavelength range 2-7 cm where the available bandwidths are limited both by technical considerations and the need to conserve space in the electromagnetic spectrum. Communication satellite systems capable of much larger bandwidths which operate at millimeter wavelengths are, however, being considered. These systems, which may become available in the 1980's, offer excellent prospects for the transmission of multi-channel large bandwidth data required for the real time operation of a dedicated Intercontinental Telescope Array.

In order to test the feasibility of using a geostationary satellite as an i.f. data link for VLBI, NRAO in collaboration with the Naval Research Laboratory, the University of Illinois, and the National Research Council of Canada is using the joint US-Canadian Communications Technology Satellite (Hermes) as a data link for a Green Bank-Algonquin Park 2.8 cm interferometer (Yen *et al*. 1977). As part of this experiment, NRAO has developed a 20 Megabit, 270 millisec digital delay line to compensate for the Earth-satellite-Earth propogation time.

The i.f. data is transmitted from the 140-ft antenna in Green Bank to Algonquin Park where it is correlated with the (delayed) signal from the ARO 150-ft. antenna to form a real time long baseline interferometer of spacing $30 \times 10^6 \lambda$ or a resolution about 0.003 arcseconds.

Figure V-4 shows a block diagram of the interferometer system. The signal received at each telescope is sampled by a clock pulse derived from the atomic frequency standard, and then is organized into a format for further processing, together with additional time signals and housekeeping data. At Station No. 1 these binary signals are encoded into diphase code which phase-mudulates a 150 MHz carrier derived from the hydrogen maser oscillator. This carrier is multiplied to 14.0525 GHz for transmission to the satellite, which translates it to 11.8855 GHz and retransmits it to the communications antenna at Station No. 2.

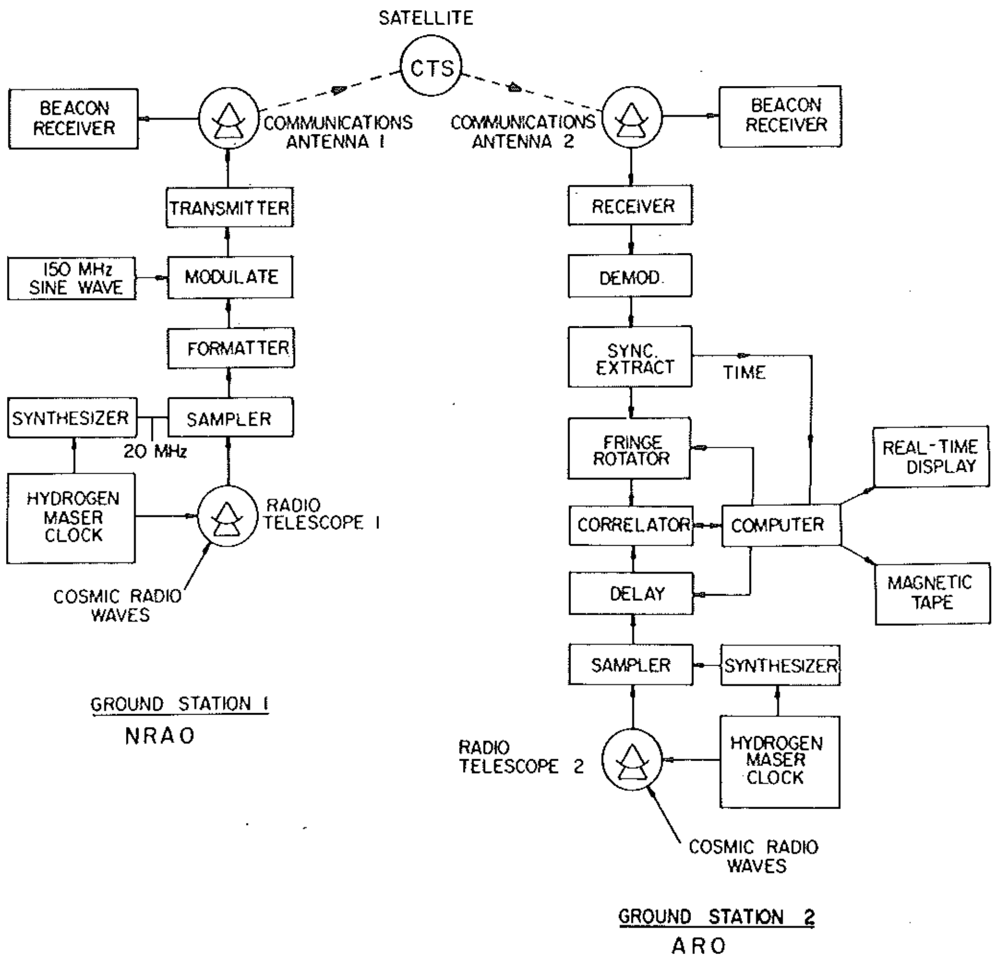

Fig. V-4. Block diagram showing satellite-linked VLBI system used between Green Bank (Station 1) and Algonquin Park (Station 2).

The received phase-modulated signal is then demodulated and decoded by reference to a clock pulse phase-locked to the clock rate of the incoming data stream from Station No. 1. The binary signal is then delivered to the delay and correlation system for combining with the binary signal from telescope No. 2.

The 5-1/2 million-bit delay line delays the local 20 megabit per second data stream for a maximum of 270 milli sec. It contains 5500 shift registers of 1024 bits each and a small but fast 32 K-bit read/write memory which is used as a first in - first out silo. Shift registers and memory operate in the 16 bit parallel mode, to reduce the bit rate to 1.25 M-bit per second. This achieves a compromise between power dissipation in the shift registers and complexity in the backplane wiring. The memory writes at the rate of the Station 2 clock and reads at the rate received via the satellite, which compensates for the motion of the satellite. This also serves to align the two data streams to an accuracy of 1 bit. The amount of delay is set by control circuitry which detects sync characters embedded in the link data and compares them with a 1 second pulse from the local clock. Multiplexers select the amount of delay to be used to within 16 K-bits and the memory resolves the delay to 1 bit. Two separate counters keep track of each bit of the local and remote data streams, provide write and read addresses for the memory and set the multiplexers. The amount of delay can be modified by as much as ± 26.2 milli sec under program control.

The control computer calculates the geometric delay and relative Doppler shift for the two stations. After both data streams are aligned in time a three level digital fringe rotator reduces the natural fringe rate to a rate near zero. Cross correlation is then performed in a 64-channel digital correlator with a total delay range of 3.2 microseconds. Data are accumulated in the correlator for 100 millisec , read into the control computer and further accumulated for one second. Then the 64 complex numbers are stored in a core memory buffer. After sixty such samples, the whole buffer, along with all other necessary information, is dumped onto magnetic tape. These data are intended for detailed post-experiment analysis. In addition, each minute of data is analyzed on-line to provide a CRT display of fringe amplitude vs delay and residual rate. The fringe amplitude, delay and residual rate are also printed out at this time.

Currently the satellite is used to transfer only the wideband i.f. data. Modifications to the system are now being made to allow a local oscillator phase reference to be transmitted as well. This will eliminate any residual phase errors due to the use of independent local oscillators, so that the determination of the interferometer fringe phase will be limited only by variations in atmospheric path length. Since only a narrow band transmission is required, a permanently operating oscillator link can be implemented, independent of the much more costly wide band i.f. data link.

3. Tape Recordings

In view of the presently great cost of real time wide band data links, it is anticipated that at least in the initial stage the Intercontinental Array will use high speed tape recordings to transfer the i.f. signal to the central processor. Other data storage media, such as the Laser Mass Memory System offered by Precision Instruments Company, are being investigated, but it appears that at the present time their capacity is inadequate or the cost is excessively high.

Tape recorders suitable for high data rates have already been developed for various applications including data acquisition from orbiting satellites. Data rates of up to a few hundred megabits per second appear possible using multi-track instrumentation recorders capable of recording several megabits per track and up to 42 or perhaps 56 tracks on one inch magnetic tape.

The disadvantage of the high speed recorders is the large amount of magnetic tape which is needed at the full bandwidth. For many experiments, however, such as observations of molecular masers or strong continuum sources, considerably smaller bandwidths may be used with correspondingly less consumption of magnetic tape.

When data is recorded at bandwidths less than the maximum, it may still be played back at the maximum data rate with a corresponding reduction in processing time. For example, 24 hours of data recorded at 7 Mbits (3.5 MHz bandwidth) may be played back in about 1 1/2 hours. On the other hand, when recording at full bandwidth of 112 Mbits (56 MHz) at 120 inches per second, each tape lasts only 20 minutes, so that 72 tapes per day are needed.

(a) Recorder requirements. There are several requirements that one needs to impose on the tape recording system. First, it needs to have a bit density as high as technically possible and economically feasible in order to keep the volume and cost of tapes within reasonable limits.

One further requires that tape speed be variable over a large range. This cannot be done in the Mark II system, resulting in wasteful oversampling when bandwidths smaller than maximum bandwidth are observed.

Further one needs to be able to play back at a greater speed than one records. This may not be possible when recording is done at maximum speed but certainly is a requirement for reduced record speeds. Mark II reproduction is in real time and processing is much slower than real time, which makes it unacceptable for an array operating nearly full time. An infinite backlog would build up.

Furthermore, tapes recorded on one recorder must play back on another recorder (which may be of different brand) without significant degradation. To insure compatibility, all tape recorders need to write a standard format, and must be tested according to standard test procedures.

All record terminals must have a read-after-write feature allowing bad recordings to be detected at record time, and not allow faulty recording to go undetected until processing several days later. The Mark II system does not have read-after-write which has resulted in failures which could only be detected at the time of processing.

The recorders need to be reliable. This is usually measured in MTBF (Mean Time Between Failures), a figure often not available. It basically means that the recorder should have few and well designed moving components, few servo systems, conservative design, field proven electronics, and good protection against dust.

(b) Linear bit density and coding. The maximum attainable linear bit density is a function of the coding and the size of the reproduce head gap. The commonly used Manchester codes (used in MK II) do not offer maximum bit density, but they have the advantage that they have no DC or low frequency components. The Miller code, developed and patented by Ampex Corporation, offers higher bit density, again with no D.C. components. The highest bit density is achieved with NRZ code. NRZ is not self-clocking and may have a DC component which is difficult to recover from tape. An "enhanced" or "augmented" NRZM (ENRZM) code takes advantage of the high bit density of NRZ and eliminates DC frequency components. It also provides an error count but is not self-clocking and therefore requires a bit synchronizer (tracking oscillator) at playback time. This code inserts an odd parity bit after an even number of bits which is detected at playback time and then stripped off to reproduce the original data. A bit transition is thus assured within the recorder bandwidth, at least 1 transition every 16 bits. The cost is a reduction to 8/9 of recorder bandwidth since the recorder bit-rate is 9/8 of the data rate.

With reproduce heads having a gap of 20μ inches, the following bit densities can be obtained with error rates of better than 1 in 10^7:

Code	Linear bitrate
Disphase (Manchester)	16.7 k bpi
Miller	28 k bpi
ENRZM	33.3 k bpi

(c) Track density and reproduce heads. For compatibility reasons, track allocation must comply with industry standards. Applicable standards are the IRIG and EIA standards.* 14 tracks per inch is most widely used but offers only low bit density. 28 tracks and 42 tracks per inch have recently become standards. Both 28 and 42 tracks are attractive for VLB systems. Other nonstandard densities such as 18, 32, 46 tracks are offered by some manufacturers, and multitrack heads of up to 130 tracks per inch have been reported.

Error rates increase with increased track density and so does the amount of record and playback electronics. Error rates of 1 error in 10^7 to 10^9 bits have been demonstrated with ENRZ coding on 14 track per inch systems. The error rate is a steep function of the S/N ratio and it is difficult to project error rates for 28 and 42 track systems.

Heads are either made with Alfesil or Ferrite tips. Alfesil heads have a lifetime of 1000 h at 120 ips and Ferrite heads 2000 to 4000 h. Ferrite heads show a low production yield, are expensive, and are not offered by all recorder manufacturers.

(d) Tape velocity and tape packing. Most instrumentation recorders on the market are equipped with IRIG specified tape velocities of 120, 60, 30, 15, 7 1/2, 3 3/4, 1 7/8 ips. Above 120 ips the tape tends to be lifted off the heads and take-up and supply reel problems become severe. Bell and Howell and Honeywell have added 240 ips for their recorder, and Emerson-Orion with their unique design offers 150, 300 and 600 ips. The maximum bandwidth which can be recorded per track is 2x(tape speed/120 ips) MHz.

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* IRIG = Inter-Range-Instrumentation Group
EIA = Electronics Industries Association

Instrumentation tape recorders on the market will accommodate 10 1/2, 14, and in some cases, 16-inch reels. A 16-inch reel contains 12,000 feet of tape and a 10 1/2 inch reel contains 4600 feet. Table V-5 shows data rate, record time, and cost per recording hour for 1 tape unit with 28 tracks and 33.3 kb/inch. The magnetic tapes are reusable for at least one hundred times so the actual operating cost for tape is less than one percent of the numbers give in Table V.5.

Table V.5

MK III Tape Recordings

ips	Approx. Data rate Mb/s	Recording Time per 16" reel	Tape cost 16" reel $/h
1 7/8	1.56	$21^h\ 20^m$	4
3 3/4	3.125	$10^h\ 40^m$	8
7 1/2	6.25	$5^h\ 20^m$	17
15	12.5	$2^h\ 40^m$	37
30	25	$1^h\ 20^m$	75
60	50	40^m	150
120	100	20^m	300
240	200	10^m	600

Table V.6 list a variety of recorders suitable for VLBI use. A number of these have been evaluated at the Haystack Observatory while on loan from the manufacturers. NRAO has purchased two Honeywell Model 96 tape transports for the construction of a prototype MK III wideband record system as described in Section III.D.

Table V.6

Recorders Suitable for VLBI

Recorder	Type	No. Tracks	Tape Size Inches	Density Mb/inch^2	Linear Density kb/inch	Max Data Rate Mb/sec	Max Record Time at 4 Mb/sec	Variable Speed	Cost Thousands $
AMPEX VR660C*	TV	1	2	0.65	6.2	4	3H	No	8
IVC 825*	TV	1	1	1.33	17	12	1H	No	5.5
AMPEX 5800*	TV	1	1	0.83	8	8	1H	No	5
SABGANO SABRE 3	I	14	1	0.47	33	56	2H	Yes	35
AMPEX FR-2000	I	28	1	0.93	33	112	3H	Yes	37
RCA HDMR 240G	I	82	2	1.4	20	240	23H	Yes	100
B&H VR 3700B	I	14	1	0.47	33	56	3H	Yes	37
ORION TITAN GW 300	I	42	1	0.7	17	400	1.5H	Yes	75
HONEYWELL 76	I	28	1	0.93	33	224	7H	Yes	11†

* Limited data rate. Suitable for present type of VLBI with limited sensitivity, but not desirable for high sensitivity.

† Tape transport only.

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VI. PLAYBACK SYSTEM

The equipment which accepts the tapes recorded at the remote telescopes, reproduces the digitized IF signals in time synchronism, and completes the playback processing consists of the following items:

a. The playback tape transports.

b. Electronics for decoding the recorded data.

c. The electronic deskewing mechanism and tape transport controller.

d. The lobe rotators and IF delay lines.

e. The digital correlator and its internal memory.

f. A small, on-line computer to calculate the lobe rotator phase, setting time delays, and to format data for output. particularly for spectral-line observations, it will Fourier transform the cross correlation function to obtain the cross power spectrum.

The items above comprise the essential components of the playback system. The astronomy which can be done with such a minimal system is already extremely limited even with the current two and three-element interferometers; with a full Array it would be impossible to proceed without another item.

g. A medium scale scientific computing center, which runs standard programs to make the Array, as much as possible, an image forming device.

The first two items are covered elsewhere. We shall consider here the remaining items.

A. The Processor

The special purpose processor performs several operations. These are:

1. Electronic Deskewing

In any tape transport, there will be a track-to-track skew which is produced by skewing of the tape between its mechanical guides or by local stretching or wrinkling of the tape due to flutter instabilities, and by differences between the recording and reproducing systems. In a well-designed transport, this skew amounts to only a few microns, perhaps one bit at the density of interest. This could be easily removed in a device with a few bits of memory per track. However, the single track bit rate is very convenient to work with, and it may be convenient to combine the track-to-track deskewing with the larger deskewing between tape drives, resulting from the finite bandwidth of the tape positioning servos. This last can be made as small as a few tens of microns. A buffer of 256 bits (available as a single integrated circuit) per track generously covers both sources of skew. The buffers involved are of the "fifo" or "first in, first out" type, in which bits are clocked in at the top of the buffer, and slightly later, asynchronously removed at the bottom.

2. Lobe Rotator

It is possible to rotate the phase of one of the local oscillators at each of the array elements in such a manner to cancel the geometric delay-rate term in the phase of the product of the two bit streams. Such a construction would result in a modest saving in the equipment necessary in the playback processor. However, this arrangement is more susceptible to human and mechanical error than the technique currently employed in the digital tape recorder interferometers now in use, which provides phase compensation during processing.

A lobe rotator is a single-sideband mixer which mixes one of the IF signals with the predicted fringe function, and thus produces the IF signal output from a hypothetical telescope which lies stationary on the incoming wavefront, rather than moving with the rotating earth. Building a single sideband mixer when the signal is a bit stream, rather than an analog voltage, is a more complex process and requires additional hardware. The traditional single-sideband mixer consists of two mixers, fed by local oscillator signals in phase quadrature. The output of one of the mixers is phase shifted by 90° and added to the output of the other mixer. Only the sideband for which this 90° phase shift cancels the 90° phase shift in the local oscillator will be transmitted; the other is cancelled. The quadrature mixers can readily be constructed for the one-bit digitized case, with only a few percent loss in signal-to-noise ratio, by using a three-level approximation (-1,0,+1) to the appropriate sinewave local oscillator. However, phase shifting and adding are operations which cannot readily be implemented on a one-bit digitized IF signal. A more complex formulation is necessary. These operations must be postponed until after the correlation is done. This means that both of the bit streams from the quadrature mixers must be correlated, doubling the number of correlators required.

3. Digital Correlator

With the very wide bandwidth contemplated for the Array, a single correlator can receive radiation from only a very narrow strip of the sky; signals from outside this strip become completely decorrelated because their path delays to the array elements differ from those commanded by the playback processor and implemented in the deskewing buffer. With a 50 MHz bandwidth, signals are seriously decorrelated by a delay error of 10 nanoseconds. Such an error would be introduced by a baseline error of 3 meters, or, on an earth-radius baseline, by an error in the cannonical position of the source of 0.1 seconds of arc, or an inaccuracy of 7 millisec in the estimation of UT1. This is obviously unacceptable, and correlation must be done for many delays adjacent to the cannonical delay.

In the MK III System, the broadband i.f. signal is divided into 28 relatively narrow bands each 2 MHz or less wide. With an 8 channel correlator for each track for every baseline, the correlation can be easily handled with standard low cost TTL logic, or by CMOS circuits which are becoming increasingly more popular and readily available. With this arrangement, observations over about a 30" strip at full bandwidth are possible. Unlike a real time array, the field of view can if necessary be increased by reprocessing. The number of elementary correlator channels in the playback processor is (28x8 = 224 channels per baseline) times (45 baselines) times (2 sine and cosine components), or 20,160 elementary correlators if the lobe rotation is implemented in the processor, and half this number if it is done at record time. This compares interestingly with the interim VLA continuum correlator system which consists of 5632 elementary correlators operating at a 100 MHz clock rate.

For spectral line observations requiring 2 MHz or less over-all bandwidth, (1 track) 112 frequency channels are available. If a greater number of tracks are recorded, the number of frequency channels is proportionally reduced. But unlike real time arrays, the resolution may be increased by repeatedly replaying the tapes with different time delays. A practical limit would require 16 replays giving 1792 frequency channels with a processing time equal to the record time. The resolution may also be increased by increasing the number of correlator channels per track from 8 to 16 or 32. This requires a total of $\sim 10^5$ correlators, which is still less than planned for the VLA spectral line system. As in the case of the VLA, custom-built LSI chips would probably be desirable and economical to implement.

Recorded on each tape, along with the IF information, will be the time and various other digital information necessary for calibrating the array, and for making sure that the information is valid. This information can be recorded at the beginning of each block of data and must be separately decoded and processed. For communication compactness, a buffer is provided for this information in the tape transport controller.

B. <u>The On-Line Computer</u>

The tasks which the on-line computer needs to perform are as follows:

1) The delay must be updated at about 50 ms intervals. This is sufficiently slow so that a simple, special purpose, hardware interpolator can be built. One would then initialize this interpolator with a starting delay and delay rate every 5 seconds or so.

2) The phase must be updated at about one microsecond intervals, and a special-purpose interpolator must be built to do this. This can either be initialized ten times a second with the initial phase and phase rate, or it may be initialized every three seconds with initial phase, phase rate, and rate-of-change of phase rate.

3) The correlator must be read and written to computer compatible tape at reasonable intervals. This interval will vary from about five seconds (to save output tape) to about 0.2 seconds (for mapping components of sources far from the phase tracking center). This includes, for spectral line observing, performing the Fourier transform to convert the cross correlation function to the cross power spectrum.

4) Various adjunct information recorded on the tape along with the IF data, such as noise temperature, and various system monitor points, must also be formatted into the output, for later editing and calibration.

None of these tasks are very onerous, and any of a large variety of modern minicomputers could handle the job satisfactorily. The only constraint is that some calculations must be carried to precision of about 38 bits, and the computer must have a convenient and reasonably fast provision for handling operants of this length. This does not seriously restrict the choice of minicomputer.

The prototype MK III Processor being developed at the Haystack Observatory uses an HP 1000 Model 30 computer with a 64K memory and 47 MByte disk. This has a sufficient capacity to handle up to 6 interferometer baselines. More baselines can be handled with faster versions of this computer and by using multiple computers.

The on-line computer must be equipped with a reasonable set of peripherals -- line printer, keyboard terminal, small moving head disk for program storage, tape transports for writing data, and a hardware FFT device. The last is used for calculating cross power spectra, and need be only moderately fast -- 10 ms for a 256 point complex transform is adequate.

The programming costs of the computer will be comparable with its hardware cost. The NRAO Mark II system on-line processor system currently has about six man-years of effort in its computer program. A comparable effort has been spent on the Caltech MK II Processor, and considerable software for the Haystack MK III Processor has already been developed. This experience, plus that of the VLA, will contribute significantly to the on-line software of a VLB Array, but a further three to five man-years of programming effort will be necessary to produce a first-rate, on-line program.

5) A general-purpose computing system. It is clear that some off-line capability beyond the elementary displays provided with the on-line computer is absolutely necessary at the location of the playback processor. There are three options open.

a. The playback processor could be located near a pre-existing computer center, with free easy access to the computer.

b. The playback processor could have a dedicated small-scale computer system with sufficient capacity to perform all routine computational chores, but without the high-performance peripherals necessary for producing publishable graphics, and without the operating system features necessary to make programming easy and convenient enough to accumulate a large software system. Users wishing displays different from a few standard options would take their data to a more general purpose (modern) computer center.

c. The playback processor could have a dedicated medium scale computer system, capable of conveniently doing special purpose displays and phenomonological analyses of the observations as well as the straightforward data reductions.

The choice of one of these options depends strongly on the amount of computing to be done in connection with the Array. It is difficult to determine this -- since the Array will offer capabilities which have not yet been sufficiently explored to be able to estimate the computer time required. The best we can do here is to examine one or two difficult problems, and estimate the amount of computing involved. Estimates will be in terms of the computation time in a 32 bit computer with one microsecond cycle time (about the speed of the IBM 360/44 - rather less than an IBM 360/65, which for many purposes is a 64 bit computer).

The first sample problem is a twelve hour observation of a water vapor maser source. There are 256 frequency channels, and the total bandwidth is 3 MHz. The object has a total extent of 2", so that the extreme features have a fringe rate (relative to the center of the field) of 0.2 Hz, on an earth radius baseline. The cross-power spectrum must therefore be sampled to a 2 Hz rate to avoid supression of the fringes from the distant features. There are therefore (86400 sampled spectra) x (45 baselines) x (256 channels per spectrum) = 10^9 complex numbers to be handled. A reasonable amount of processing is to produce preliminary maps in frequency/fringe rate space, at perhaps 20 hour angles, in order to identify components for further analysis. Then, a strong point feature is used as a phase reference, and its phase subtracted from all sources. A complete map in frequency and two spacial coordinates is an inordinate computing load, and is also unnecessary, since most of this three-dimensional space is empty. One would therefore select, say 40 components, isolate them by appropriately matched filters in frequency and fringe frequency, and make spacial maps of these frequency components. The rough estimate of computer time necessary for this operation is given below:

a. Preliminary maps. (20 maps) x (256 frequency channels) x (256 fringe frequency channels) x (45 baselines) = 6×10^7 numbers to input and process. Each number is complex multiplied eight times, and the time is taken as the multiply time (28 microseconds) times a factor of four for the logic and control instructions. Time = 13^h.

b. Fitting a smooth function to the reference feature. There are (86400 points to be fitted) x (45 baselines) = 4×10^6 points to be handled. Each must go through about 8 complex multiplies, again with a factor of four for other instructions. Time = 1^h.

c. Feature extraction and phase referencing. The entire set of data must be processed; each point is subjected to about one real multiplication (extraction in frequency by matched filtering) and one complex multiplication. Time = 42^h.

d. Mapping of features. (40 features to be mapped) x (256x256 maps) = 2.6×10^6 points to be handled, each point with perhaps 12 complex multiples. Time = 1^h.

Total time = 57 hours. This complicated problem thus runs about five times slower than the observing time, on a computer of this size. The time could be cut somewhat by the addition of such peripherals as a hardware Fourier transform device.

The second problem we shall consider is the case of a source of overall extent 0."1 x 0."05 , observed at 5 GHz. The coverage of the Array extends to 10^8 wavelengths, and the synthesized beam is thus about 0."002. However, the observations were made without phase coherence, so that the brightness is to be reconstructed without the use of phases. First, the data are averaged for a reasonable time. The first stage of integration is done in the playback processor, where it is read out at one second intervals. It can then be averaged coherently to two minutes. At this point we have, from twelve hours observations (360 two-minute intervals) x (45 baselines) = 15,000 numbers. Then we fit, by least squares, these numbers to the visibility function of a model of point sources specified every half beam in the 0."1 x 0."05 source area. The number of steps in this calculation is (number of input points = 15,000) x (number of output points = 5,000) x (number of interations for convergence ∿ 30) = 2 x10^9. Each operation involves a table lookup, a complex number times a real number, and a complex addition. Allowing the usual factor of four for logic and control instructions, the running time of this program is about 45 hours. The previous operation of coherent averaging to two minute intervals requires (43,200 seconds outputs) x (45 baselines) = (2x10^6 operations), only half an hour.

These two rather difficult problems are thus solved with a ratio of computer time to observation time of about five. We can conclude, since such difficult problems will probably occupy only a small percentage of the array's time, that the cannonical computer is too small by a factor of about two. The dedicated Array computer would thus be in the range of an IBM 370/158, a Univac 1108 or a Xerox Sigma 9 or a CDC Cyber 172. If the Array is to share a computer with an established computer center, the main system would need to be substantially larger. Perhaps the most attractive option is to provide a fast but unsophisticated and inexpensive computer for the main mathematical processes, and to share a large computer center, in which logically complex but not very time consuming processes are programmed, which provide the interactive and display capabilities needed to make the VLB Array maximally productive. This unsophisticated computer could be as inexpensive as a Datacraft/4/VS, an Interdata 7/32, or a Modcomp IV. In this case, the Array would use a substantial percentage of the general computer center, but not all of it.

VII. OPERATION OF THE ARRAY

The Array is expected to be operated as a national or international facility, and as such is open to all qualified scientists from the U.S.A. and abroad. Unlike the present ad hoc VLBI observations, there will be no need for the observer himself to obtain and coordinate observing time on a number of telescopes simultaneously. Nor will it be necessary for him to provide the excessive scientific and technical manpower currently required to simultaneously observe with a number of widely separated radio telescopes or to perform the routine tasks associated with the acquisition and distribution of magnetic tapes and the process of cross correlating the tapes. These functions will be handled by the Array operating staff, much in the same manner as for the VLA.

The operation of the Array is conveniently divided into two parts: the operation of each of the N = 10 individual antenna elements to record data on magnetic tape, and the correlation of these magnetic tapes in the multi-station processor to form each of the $N(N-1)/2 = 45$ interferometer pairs.

It is anticipated that the operation of the Array will be under the control of an Operations Center, which also contains the correlators and computers necessary to analyze the data. The operation of the individual antenna elements and the on-line monitoring of the performance of each element will be, at least in part, done from the Operations Center via commercial telephone lines.

The tapes containing the recorded data are shipped via a combination of air and ground transport from each element to the Operations Center. The incoming magnetic tapes contain all the data needed for the reduction and calibration of the interferometer (i.e., the i.f. data, meteorological data, the water vapor radiometer output, day, time, frequency, antenna location, source coordinates, system noise temperature, and if necessary the antenna temperature of the source being investigated). This is similar to the data used in a conventional radio telescope array, except that instead of being transmitted via cable or radio link (or in the case of the VLA by waveguide) in real time,it is recorded on magnetic tape and is inputed to the correlators delayed by some days to a week. The output of the correlators is then analyzed in essentially the same manner as the data from a conventional real time array.

The fact that the i.f. transmission system (the magnetic tape) involves a significant time delay has no fundamental effect on the output of the array, except possibly that the "observer" is not able to monitor the output of the instrument in real time, and so modify his program based on what he "sees" at observing time. This is not expected to be a significant factor, as, indeed, the currently operating arrays at Westerbork and Cambridge do not display their output at observing time and, in fact, frequently run completely unattended, supervised by only the control computer.

A major restraint in the scheduling of programs is the required sensitivity (bandwidth) which determines length of time a single reel of magnetic tape lasts. The required number of tapes ranges from about 2 per day for an 0.125 kHz bandwidth (adequate for many spectral line problems) to 720 per day for a 50 MHz bandwidth. A bandwidth of $\sim$ 100 MHz may be possible, but then 1440 tapes per day are needed.

Of course, the tapes are reusable, and reuse more than 100 times even under non-ideal field conditions is possible. Careful scheduling is required to balance narrow bandwidth programs which do not use much magnetic tape and which can be correlated much faster than real time, with large bandwidth problems which will be correlated somewhat slower than real time.

Assuming that the average bandwidth will be 16 MHz and that the tapes can be recycled in one month, then a supply of 7200 magnetic tapes is needed to operate the array.

The routine remote operation of 10 widely separated antennas will require a high degree of reliability. The major components at each site are the antenna and multifrequency radiometer. Since these will be very nearly identical to their VLA counterpart, it is expected that the experience in operating the VLA can be directly carried over to the VLB Array. The VLA antennas have been specifically designed for a minimum of routine maintenance, and of course the whole VLA concept is predicated on a long mean time between failures for individual elements.

In order to keep the operating staff to a minimum, the operation of each antenna element must be automated, so that local staff are needed only for routine maintenance and for changing magnetic tapes. This required level of automation is neither novel nor difficult. The fact that the individual elements are distributed over thousands of kilometers is inconvenient, but not excessively so. The VLA and other arrays do not have operators at each antenna element, but rely on a central operator to monitor and control the status of each element through the central computer and electrical links. Except for maintenance, it makes no fundamental difference in operations if the elements are spaced by 21 km or 1000 km.

Examples of automated remotely operated antenna systems already exist. NRAO has for some years routinely operated a 45-foot antenna at a site 35 km from the Observatory as part of a 4-element interferometer system. At the University of Illinois Vermilion River Observatory, a 120-ft antenna operates unattended for several days under computer control, or can be operated via a small portable terminal which can be connected at any telephone in the country or abroad. Small unattended antenna systems are also operated at difficult arctic and antarctic sites as part of satellite communications systems.

A. The Antenna Stations

Each interferometer element consists of the following:

a. 25-meter Cassegrain antenna.

b. 1.3, 2, 6, 18, 21 cm Cassegrain radiometers plus 50 or 75 cm prime focus radiometer; or two wide band maser-upconverter-mixer receivers covering the range 500 MHz to 26 GHz.

c. Precision frequency standard and stable local oscillator chain.

d. i.f. amplifiers, clippers, samplers, formatters.

e. 2 wide bandwidth multi-track instrumentation recorders;

f. Small computer for control of telescope, radiometry, sampling of meteorological data, and communication with Operations Center.

g. Receivers for the reception of standard time transmissions (WWV, Loran, Omega, etc.).

h. Equipment for sampling meteorological data, including, if desirable, 1.3 cm water vapor radiometers.

It is expected that for the most part the individual elements will operate unattended, with the antenna being controlled either by preprogrammed instructions in the on-line computer, remote commands from the Operations Center, or a combination of both.

A small staff consisting of one engineer and two or three technician-operators will be required at each site. This staff will be responsible for the routine maintenance of the antenna and electronics, as well as the transport and documentation of incoming and outgoing magnetic tape.

Although the antennas and radiometers operate unattended, regular human intervention appears necessary to change magnetic tapes, unless some means is found for storing up to 10^{12} or 10^{13} bits without changing the storage medium. It is planned to use two tape transports at each site, with automatic change-over between transports when the end of a tape is reached. This allows a) twice the record time without intervention, b) continuous recording, and c) a spare recorder so that in case of failure it is still possible to operate with a slightly reduced duty cycle. For periods of extended wide bandwidth operation, it will probably be necessary to supplement the "local" staff with one or two part-time "aids" to change magnetic tapes.

The need to change magnetic tapes as often as three or even six times per hour is probably the most awkward part of operating the Array. This process may be greatly simplified by developing a special tape changing device to replace the human operator. Such machines are already in use at large computing facilities, but no comparable device has yet been developed for use with instrumentation recorders. The development and construction of a special tape changer would probably add about $1,000,000 to the initial cost of the array, with the resulting saving of about $250,000 per year in operating costs due to the reduced manpower requirement. Although we are continuing to investigate the feasibility of an automatic tape changer, our estimates for capital and operating costs are based on the presence of human tape changers.

B. Operations Center

The Operations Center contains ten tape transports (plus spares) to read the magnetic tapes recorded at each of the ten antenna sites. The i.f. data from each antenna is then correlated with each of the other antennas to produce the 45 interferometer pairs. The on-line computer also averages and outputs the interferometer fringe amplitude and phase at intervals of 0.2 to 10 seconds and normalizes the data using the system temperature measured at each antenna at record time.

The Operations Center also controls the operation of each of the antenna elements using commercial telephone lines to connect each of the telescope elements with a computer at the Operations Center.

It is expected that the Processor will be operated nearly continuously, much in the same manner as NRAO operates a radio telescope, and a staff of operators will be required to do this. In addition, engineering, programming and scientific staff will be required to support the operation and to develop new procedures and instrumentation. The current NRAO MK II Processor operates in this manner.

It is anticipated that a considerable effort will be spent by both the Array staff and visiting users in post-processing, that is, in the use of a general purpose digital computer to transform the on-line output to useful maps. Because of the similar nature of this work to that of the VLA, it may well be useful to combine such facilities at a common location.

C. Operation Using Non-Array Antennas

It is expected that from time to time the Array will be operated jointly with one or more "outside" antennas in order to provide North-South baselines or to obtain greater sensitivity than possible with 25 meter antennas. It is anticipated that there will be a number of major observatories equipped with either fully compatible MK III recording systems of equivalent bandwidth, or at least compatible narrow band systems.

In these cases there will be fewer correlator inputs than antennas, and it will be necessary to have multiple passes through the Processor. Possibly an additional correlator input will be added to be used for joint work with outside antennas or otherwise as a spare.

VIII. CONSTRUCTION OF THE ARRAY

The concept of an Intercontinental Radio Telescope Array is based on proven concepts so that no major design and development is necessary. However, there are several areas where a detailed engineering design and prototype development are required, and other aspects which need to be studied in more depth before the full potential of the Array can be achieved.

The Array consists of two major components: a) the antenna elements and b) the processing center. Each of these will be developed gradually and independently, and at each phase the power and versatility of the instrument is increased.

Construction of the Processor will occur in three phases:

1) a minimal 3-station (3 baseline) processor;

2) a 5-station (10 baseline) system adequate to handle the anticipated load of experiments with existing antennas in 1980;

3) a 10-station (45 baseline) system necessary to handle the nearly full-time operation of the Array.

Construction of the Array elements will also occur in three phases:

1) the use of existing antennas with improved instrumentation;

2) the construction of the first array element in the central U.S.A.;

3) the construction of the full array.

Each of these development areas is described below in more detail.

A. The Interim VLBI Network

The synthesis of images at wavelengths $\lambda \gtrsim 10$ cm may to an extent be achieved using existing radio telescopes, but with enhanced sidelobe levels. Although, for the reasons outlined in Section I-C, this does not approach the scope of the work that can be carried out with a "Dedicated Array," many interesting astronomical problems can be explored, and new methods or data recording and analysis attempted. Good receivers already exist at 18 cm at all Network stations, but low noise receivers at shorter wavelengths are also needed, together with hydrogen maser frequency standards, and VLBI recording equipment, including, when available, the MK III system. Furthermore, provision must be made to allow for routine operation of these telescopes without the need for the observing scientist to be present at each telescope. The acquisition of all data necessary to accurately and quickly deduce the fringe amplitude from each interferometer pair is also required, and procedures for automatically doing this are being developed at the NRAO and Caltech. Further exploitation of existing antennas is anticipated through the Interim VLB Network (Cohen 1975).

B. Construction and Operation of a First Array Element

The Interim VLB Network of existing antennas is concentrated on the East and West Coasts, and VLBI observations with these antennas suffer from the missing intermediate baselines. Some improvement is obtained with the use of the antennas at the University of Iowa and the University of Illinois, but these antennas are limited to long wavelengths, and in the case of the Illinois antenna the hour angle range is restricted.

An important improvement to the U.S. VLB capability will be achieved with the early construction of the first Array element, equipped with complete Array instrumentation including a low noise multi-frequency receiver, MK II and MK III record terminal, Hydrogen maser, on-line computer and remote operation. This will give valuable experience in the routine operation of minimally supported dedicated VLB acquisition elements.

In addition to evaluating the Array prototype station, this antenna would fill the "hole" in presently available interferometer spacings, and permit a wide variety of continuum, OH, and H_2O experiments in conjunction with existing East and West Coast antennas. Further study of the optimum location is necessary, taking into consideration baselines formed with existing Network antennas as well as its inclusion as part of the final dedicated array. Figure VIII-1 shows the (u,v) plane coverage for a new midwest antenna located in a) Illinois, b) Iowa, and c) Colorado, together with some existing antennas.

The first new Array element should be constructed in a timely fashion in a midwestern location. Low noise ($\sim$ 30 K) multi-frequency receivers covering the range 500 MHz to 5 GHz, and 8 GHz to 26 GHz are currently being developed for the 140-ft. telescope and could be duplicated for the new antenna to provide a versatile VLB system capable of operating together with existing receiver systems at other observatories. If necessary, much of the needed instrumentation including a hydrogen maser, local oscillator system, MK II and MK III record systems could be obtained from existing and presently planned NRAO equipment. The requirements for the first dedicated Array element are discussed in more detail in the report by Swenson, et al. 1977.

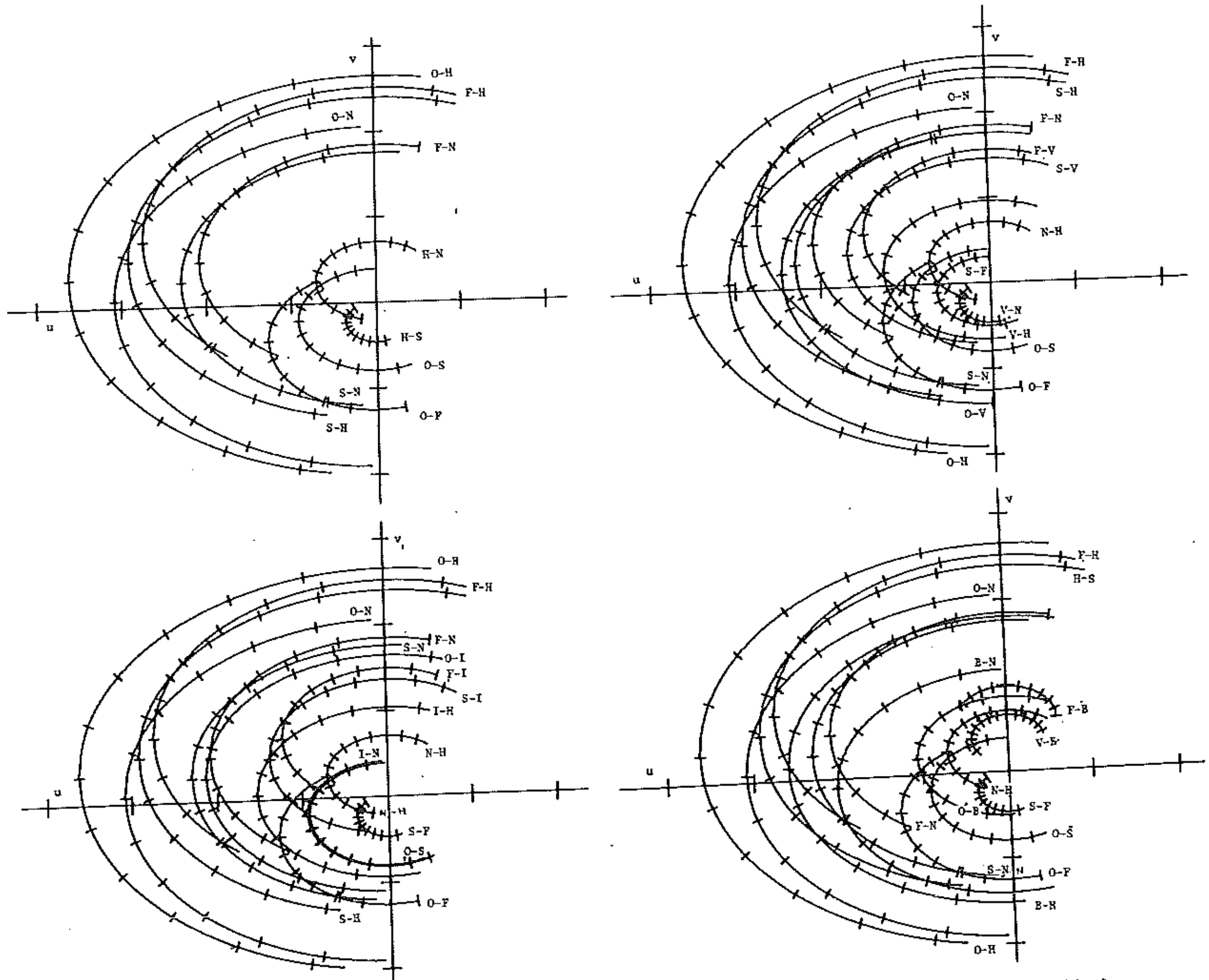

Fig. VIII-1. a) (u-v) tracks of five element Array with antennas at Haystack (H), NRAO (N), Owens Valley (O), Socorro (S), and Fort Davis (F); b) same as (a) plus VRO (V); c) same as (a) plus Iowa (I); d) same as (a) plus Boulder (B).

C. Real Time Satellite Data Link

In collaboration with the Canadian National Research Council, the University of Illinois, the University of Toronto, and the U.S. Naval Research Laboratory, NRAO is participating in a joint experiment using the Hermes synchronously orbiting satellite to transfer wideband i.f. data over a distance of 900 km from the 140-ft. telescope in Green Bank to the Algonquin Park 150-ft. telescope. This program has demonstrated the feasibility of using satellite links for real time VLB interferometry. During 1977 the satellite will be used to provide a phase stable local oscillator reference between the two telescopes to permit the measurement of fringe phase as well as amplitude. Should this technique prove practical, it will be possible to provide a permanent satellite-borne phase reference at relatively low cost since only a narrow band communication channel is necessary.

D. Other Studies

Other areas of study which will continue and which will contribute toward the evaluation of instrumentation and techniques for the VLB Array are:

a) the evaluation of atomic frequency standards and other stable oscillators;

b) study of methods of measuring atmospheric water vapor to provide phase corrections;

c) study of methods of image restoration, with particular reference to incomplete (u,v) coverage and/or poor phase data;

d) the measurement of visibility phase on transcontinental and intercontinental baselines using phase reference sources and/or a satellite-borne reference; and the investigation of the effect of signal-to-noise ratio and baseline redundancy on the use of phase closure;

e) detailed study of individual antenna locations with regard to geographic properties, transportation, and proximity to local support facilities;

f) the investigation of the feasibility of other recording media such as laser etchings and video disks;

g) the further evaluation and utilization of satellite-borne data links and as a coherent reference for the measurement of interferometer phase;

h) the evalutation of the use of large deployable antennas in space to extend VLBI baselines and to obtain more uniform (u,v) coverage.

REFERENCES

Cohen, M. H. ed. 1977, VLBI Network Studies I. A VLBI Network Using Existing Antennas, Calif. Inst. of Tech., Pasadena, Calif.

Swenson, G. W. et al. 1977, VLBI Network Studies II. Interim Report on a New Antenna for VLBI Network.

IX. EQUIPMENT DESIGN AND COST ESTIMATE

Like the VLA, a Very Long Baseline Array is a system composed of reasonably well understood techniques and equipment whose cost can be reliably estimated. No new uncertain structural engineering is involved. Somewhat under half of the cost is in the antenna elements, and since they are nearly identical to those currently being built for the VLA, their cost is well determined. The remaining cost is in receivers, tape recording devices, frequency standards, computers, and other electronic equipment. Unlike construction items, inflation of the cost of electronic equipment and computers is much less than in "heavy construction", and, in fact, past experience indicates that for a given specification the cost of these items may actually decrease with time.

Each of the major items is discussed below and the total capital and operating costs are summarized in Table IX.1.

A. Antenna Elements

The cost of the VLA antennas ranges from about $600,000 in 1977 to $700,000 in 1980. Taking into account the estimated loss incurred by the manufacturer, the additional cost of small quantity purchase of steel and other components, and the increased cost of erection due to union labor and lack of the VLA erection facility, we estimate the construction cost of additional antenna elements to be between $800,000 and $900,000 depending on the number of antennas which are built. This cost estimate and the performance specification for these existing antennas are felt to be considerably more precise than would be possible for a new design.

Dual polarization VLA type Cassegrain feeds are priced as shown in Table IX.1.

Table IX.1

Antenna Feeds

18-21 cm	$17,700
6 cm	9,800
2 cm	6,300
1.3 cm	6,100
Total (including Mount)	$48,000

B. Radiometers

Two radiometer systems are being considered.

VLA front ends. The basic receiver is similar to the 5-band (21, 18, 6, 2 and 1.3 cm) VLA receiver whose price is well determined. It is anticipated that the basic VLA receiver will be modified in several ways as follows.

a) The addition of low noise parametric preamplifiers at 1.3 and 2 cm to reduce the system temperature at those wavelengths to ∿ 50 K. The parametric amplifier including pump oscillator cost $15,000 per stage or $30,000 for each receiver for the two bands.

b) It is possible to omit one of the two receiving channels at each antenna at some loss in sensitivity for polarization measurements only. This results in a savings of $35,000 per antenna for the basic receiver, or $65,000 per antenna including the 1.3 and 2 cm preamplifiers. There have so far been no measurements of the polarization structure of compact sources, so it is not clear at this point whether or not the resulting effective reduction of ∿ 2.5 in sensitivity for polarization measurements will significantly affect the performance of the instrument.

c) The basic VLA receiver does not operate at wavelengths longer than 21 cm. The addition of a 50 cm prime focus receiver will add an additional $14,000 to the cost of each receiver.

MK II Receiver. A next generation of wide band low noise receivers is currently being developed for use on the 140-ft. and 300-ft. telescopes and possibly the VLA as well. In this receiver a maser amplifier which is tunable from 18 to 26 GHz is used together with parametric up-converters to give continuous coverage from 5 to 26 GHz at the secondary focus and 500 MHz to 5 GHz at the prime focus with a system noise temperature ∿ 30 K at all wavelengths exclusive of the contributions from the atmosphere, or the non thermal galactic background. Very low noise temperatures are also expected at millimeter wavelengths using cooled varactor mixers and a 22 GHz maser r.f. amplifier.

Since these receivers are still being developed, the cost is somewhat uncertain, but it is expected to be close to that of the VLA type receivers. Until a working model of this radiometer is available and its cost more accurately known, we will use the price of the VLA radiometer in the cost estimate.

Frequency Standard. At the present time, there is no commercial source of hydrogen maser frequency standards. Existing units which cost between

$120,000 and $220,000 including engineering costs, are being produced on a semi-commercial basis by NASA and at the Smithsonian Astrophysical Observatory. It is estimated that if purchased in quantity, they can be obtained at a cost of $150,000 per unit.

C. Tape Recording System

The cost of the recording system is based on the cost of the MK III Recording System, as given in Table IX.2.

Table IX.2

Recording System

2	Honeywell Model 96 tape transports	24 K
2	Sets of record heads (lifetime 300 hours)	24 K
	Recorder Electronics	10 K
14	Converter-synthesizer modules (125 kHz, 250 kHz, 500 kHz, 1 MHz, 2 MHz, 4 MHz)	23 K
	Clock module	2 K
	IF distribution module	2 K
	Format controller module	2 K
	Dual decoder module	1 K
	5 MHz distribution module	1 K
	ASCII communicators	6 K
	Power supplies, rack, bins, and other hardware	7 K
	Total	102 K

A new development of "half-speed heads" with a headgap of 12 to 15 μ inch allows recording of 4 Mb/sec at 60 ips (or possible 8 Mb/sec at 120 ips). This would reduce the frequency of tape changes and the amount of tape required by a factor of two. We are working with several manufacturers to investigate this further.

We are also investigating the cost and feasibility of constructing a device for the automatic changing of tapes to allow for complete unattended operation.

D. Control and Communication

The on-line computer at each of the antennas, in addition to controlling the operation of the telescope, is used to monitor the operation of the telescope element including antenna control voltages, position control, receiver and local oscillator performance, and meteorological data. These tasks are similar to those done by the VLA control and monitor system, except that the (out-of-spec) flags and other data will be communicated to the Operations Center via leased telephone lines. The control of the telescopes from the Operations Center is also via these same lines.

The cost estimate of the control and communications system is based on the equivalent VLA system plus the cost of modems at both ends to transfer digital data at 1200 kilobits/sec. Ordinary telephone quality lines are adequate for all necessary data transfer.

E. Playback Processor

The playback system consists of the correlator and the on-line computer. The cost summarized in Table IX.3 is based on the use of commercially available IC's, However, over half of the processor cost is in the (28 x 8 x 45 x 2 = 20,160) correlators, and as in the case of the VLA, custom designed LSI circuits could significantly reduce the cost with a potential cost saving of more than half a million dollars.

Table IX.3

Playback Processor

Correlator		480 K
12	Honeywell Model 96 tape transports (including two spares) (12 K each) with playback heads (12 K each) and playback electronics (16 K each)	
45	Correlator modules @ 1 K per track (28 per baseline)	1260 K
	Power supplies, bins, racks, etc.	40 K
	Total Correlator	1780 K

F. Computer System

Two computing systems are required: a) the on-line processor control and initial data reduction system, and b) the off-line image forming system.

Table IX.4

The On-Line Computer

	Computer modules (each with 64 K memory), disk, console, software (HP Series 1000 Mod 30, Modcomp II or equivalent)	300 K
2	1600 bbi tape transports for output data	22 K
	Card reader	4 K
	Fast serial printer	9 K
2	CRT terminal, interface	10 K
2	Decwriter	4 K
	FFT device, interfaced	88 K
	Software development	150 K
	Total	587 K

The total cost of the playback system is then:

Correlator	1780 K
Computer System	587 K
Total	2367 K

The Processor will be developed in 3 stages as described in Section VIII.

The cost of the off-line computer to be associated with the playback processor will be estimated under two different assumptions. The first assumption is that an existing computer center is available and readily utilizable. The scale of the services proveded are about that which would be supplied by use of the existing NRAO IBM 360/65 system, using about one-third of its resources. In addition, one would run computationally bound programs in a dedicated small scale computer system consisting of the following items:

CPU with floating point, etc.	$77,000
256 K Bytes memory	57,500
Card reader	4,500
Line printer	17,200
Disk storage, 100 M Bytes	51,000
Magnetic tape, three drives, 800/1600 bpi, 75 ips	54,500
Four CRT terminals, interface	16,600
Total	$278,300

The second cost estimate is for a totally stand-alone system which would enable the Array to operate independently of any existing computer system. Primarily because of operating and maintenance costs, it then becomes profitable to invest in a large computer system rather than a small, fast system like the one above. The following items are included:

64 bit CPU with 512 K bytes of 1 microsecond memory		790,000
5 magnetic tape drives		125,000
Disk storage, 700 M Bytes		235,000
Card reader, punch		85,000
Line printer		60,000
Communications processor and terminals		75,000
	Total	1,370,000

In both cases, about ten to twenty man-years of programming (200 K) would be required to construct an initial system capable of invoking the various techniques which have been used in VLB observations so far. Developments beyond this stage will certainly be extensive, but should not properly be charged to the capital cost of the Array. The array operations, since they are dependent on a continuing development of new techniques over the first few years, will require a relatively large programming staff. This includes systems programmers for the on-line and off-line computing systems, 2 programmers to develop new reduction and analysis programs, and 2 scientific aides to handle the day-to-day reduction of data.

G. Site Development

Some of the Array elements will be at existing observatories. Others will require new sites and the total cost will depend on the number of new sites which need to be developed at an approximate cost of $150,000 each. This includes

a) acquisition of land;
b) roads;
c) power;
d) control building (1200 sq. ft.);
e) furniture, benches;
f) water well;
g) maintenance equipment;
h) emergency generator.

At existing sites, the additional cost will be that of the control building and furniture at a cost of about $50,000.

Since about half of the Array elements will be at existing observatories, the average cost of a site development is $100,000.

Table IX.5

Cost* of Intercontinental Array

EACH ELEMENT			
Antenna Structure	$900		
Feeds (dual polarization)	48		
Focus and polarization mount	35		
Cassegrain subreflector	9		
Dichroic reflector (2/6 cm dual frequency)	4		
Total each Antenna Structure		$996	
ELECTRONICS			
On-line computer (terminal, disk, software, etc.)	70		
5 frequency dual polarization receiver	130		
Low noise parametric or maser amplifier for 1.3 and 2 cm	60		
50 cm prime focus receiver	14		
2 tape recorders with electronics	102		
Hydrogen maser	150		
Local oscillator and i.f. system	35		
Control and communication	25		
Test equipment	50		
Engineering, Design, Inspection, Administration and Installation	50		
Total Electronics		$686	
Site Development, power, buildings, roads, etc.		100	
Total Cost of each Array Element		$1,786	
Total Cost of 10 Elements			$17,860
Processor System			2,367
Stand-Alone Computer (including software)			1,570
Magnetic Tape (7200 reels each 12,000 ft.)			720
Project Management			1,000
Contingency (10 percent)			2,300
TOTAL COST OF 10-ELEMENT ARRAY			$25,817

* Thousands of Dollars.

H. Operations

The major part of the operating costs are in the salaries of staff, shipment of tapes and equipment, and in the replacement of expendable items such as magnetic tapes, recorder heads, etc.

The basic staff at each site will be an engineer and two or three technician-operators. The engineer will have the over-all responsibility for the operation, maintenance, and performance of the antenna, computer, and electronics. He is assisted by the on-site technicians.

For those antenna elements at existing radio observatories, the operations will be supported at least in part by the local Observatory staff. This, of course, does not change the real cost of operating the Array, and we have included the staff salaries as part of the Array Operating Cost, independent of the antenna location.

Although the operation of each antenna site is to a large extent automatic and remotely controlled, human intervention will be required to change tapes unless some device is developed to change tapes automatically. Narrow bandwidth experiments (including all spectroscopic observations) require only infrequent tape changes (perhaps one per day) and this can be done by the site engineer or technician with little interference to their other duties. For experiments requiring rapid tape changes, additional personnel will be required. No particular skills are required for this task.

From time to time major preventive or emergency maintenance to the antenna or electronics will be required which is beyond the capability of the limited on-site personnel. It is anticipated that the "Central Service" personnel which will be involved in these tasks will be normally based at the VLA site, and will be part of the VLA operations staff. Thus, they will be familiar with all instrumentation and techniques. The actual number of such personnel involved in VLB Array operations at any given time will range from zero to perhaps 5 or 6. These will not always be the same people, and we have budgeted for an average of two people involved in service activities.

The scientific staff is responsible for the calibration, testing and evaluation of the instrument, for liaison with other observers, and for the implementation of new techniques of data evaluation. In this they are supported by the programming staff and technical staff.

Table IX.6, below, gives a breakdown of the total staff requirements.

Table IX.6

Staff Requirements

Scientists	3
Engineers	12
Technicians	24
Programmers	6
Central Service	2
Secretary	1
Clerk	1
Total Staff	53

The major replacement item is the cost of replacing recorder heads. At the present time, 28 track ferrite heads cost $12,000 and are guaranteed for 3000 hours. Maximum head wear occurs at a tape speed of 30 or 60 ips. At faster or slower speeds, head wear is less and so we might expect an average of 4,000 or 6,000 hours of use, or about $300,000 per year for the 10-element array. The playback system will always run at 120 ips, and will operate for only a fraction of the time, since much of the data will be recorded at slower speeds and playback will be faster than real time. The total annual cost of replacement for recorder heads is thus estimated as $400,000 per year. It may be anticipated, however, that in the future, head life will be significantly lengthened, and due to their production in greater numbers, their cost substantially reduced.

Estimates for the transport of magnetic tapes, and the lease of communication facilities are based on current costs. It is anticipated that future costs of the communications facilities will be reduced as digital data transmission systems become more common in the 1980's.

The cost of other replacement items, new equipment, and other operating funds are based on experience with NRAO instruments and estimated VLA operating costs.

Table IX.7

Operations Budget

Staff	$1,200,000
Supplies	620,000
Shipping	300,000
Travel	50,000
Communications	90,000
New Equipment	350,000
Computer Maintenance	90,000
Antenna Spares	80,000
Total Cost	$2,780,000

APPENDIX

A number of different Array configurations have been studied in an attempt to optimize the (u,v) coverage over a wide range of declination and with a minimum of new sites introduced. Figures A-1 to A-7 show the (u,v) tracks covered by various configurations for declinations -30, 0, +30, and +60 degrees.

Figure A-1 shows a basic 8-element transcontinental array with elements at Md. Point, Md.; Charlottesville, Va.; Green Bank, W. Va.; Wichita, Kansas; Socorro, N. Mex.; Tucson, Ariz.; Big Pine, Calif.; Palo Alto, Calif. We refer to this as the Basic Array.

Figures A-2 through A-7 show an extension of the Basic Array to include other telescopes in order to improve the north-south coverage and/or to extend the baseline to intercontinental dimensions.

Figures A-8 through A-10 show the beam pattern for the basic 8-element array with additions in Hawaii and Spain to increase the resolution. Figure A-11 shows the beam shape at zero declination for an 8-element array which extends over a wide range of latitude as well as longitude.

These illustrations are only representative of the many configurations which have been studied, and intended only to illustrate the type of u,v coverage and beam shapes available with various practical configurations. Many other configurations are possible and considerably more study will be necessary to arrive at an optimum solution. The typical resolution at $\lambda = 2$ cm is 1 milli-arcsec for the transcontinental configurations and 0.4 milli-arcsec for the intercontinental configurations.

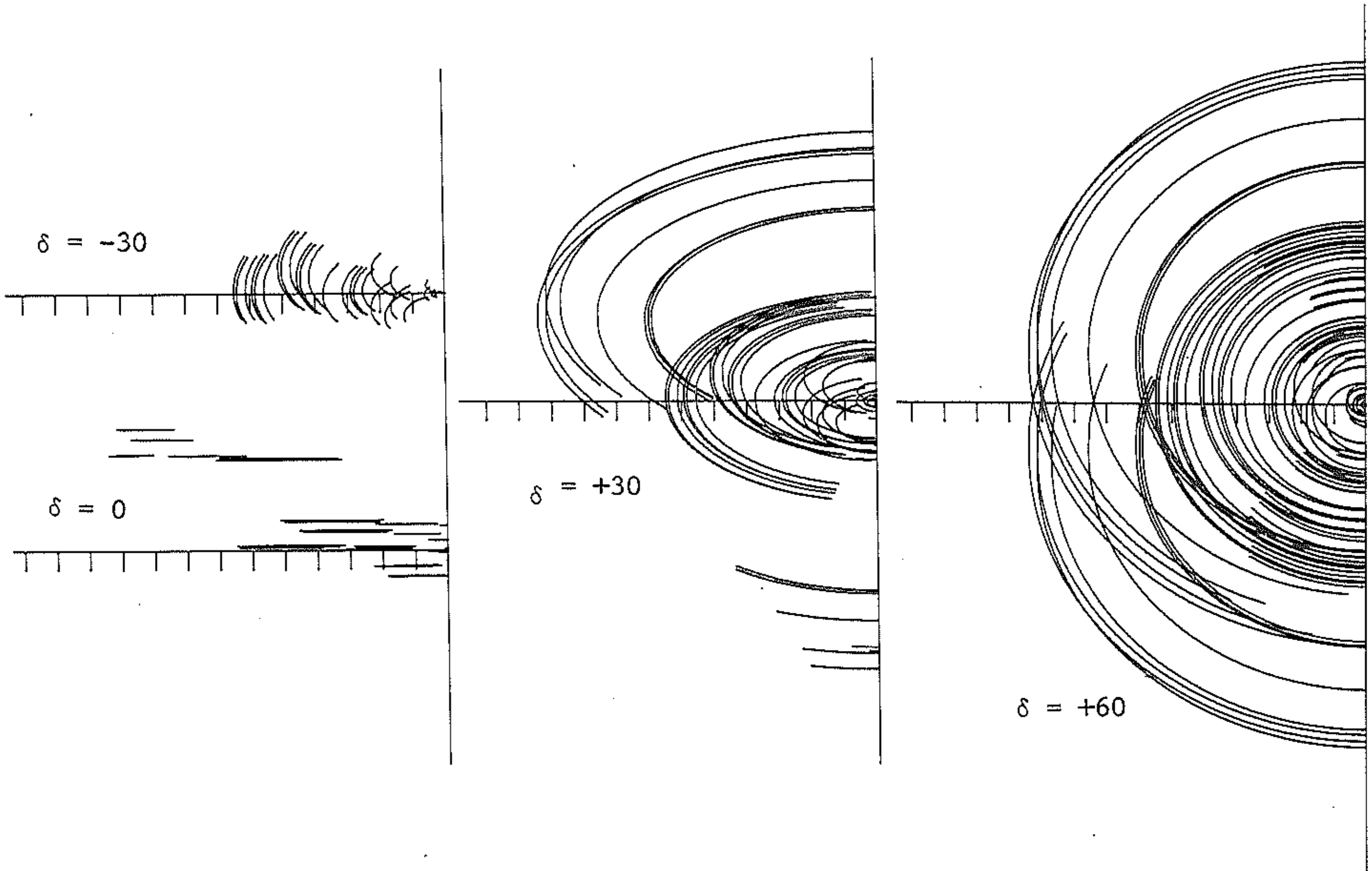

Figure A-7. As in Figure A-1 plus elements in Madrid and Iceland.

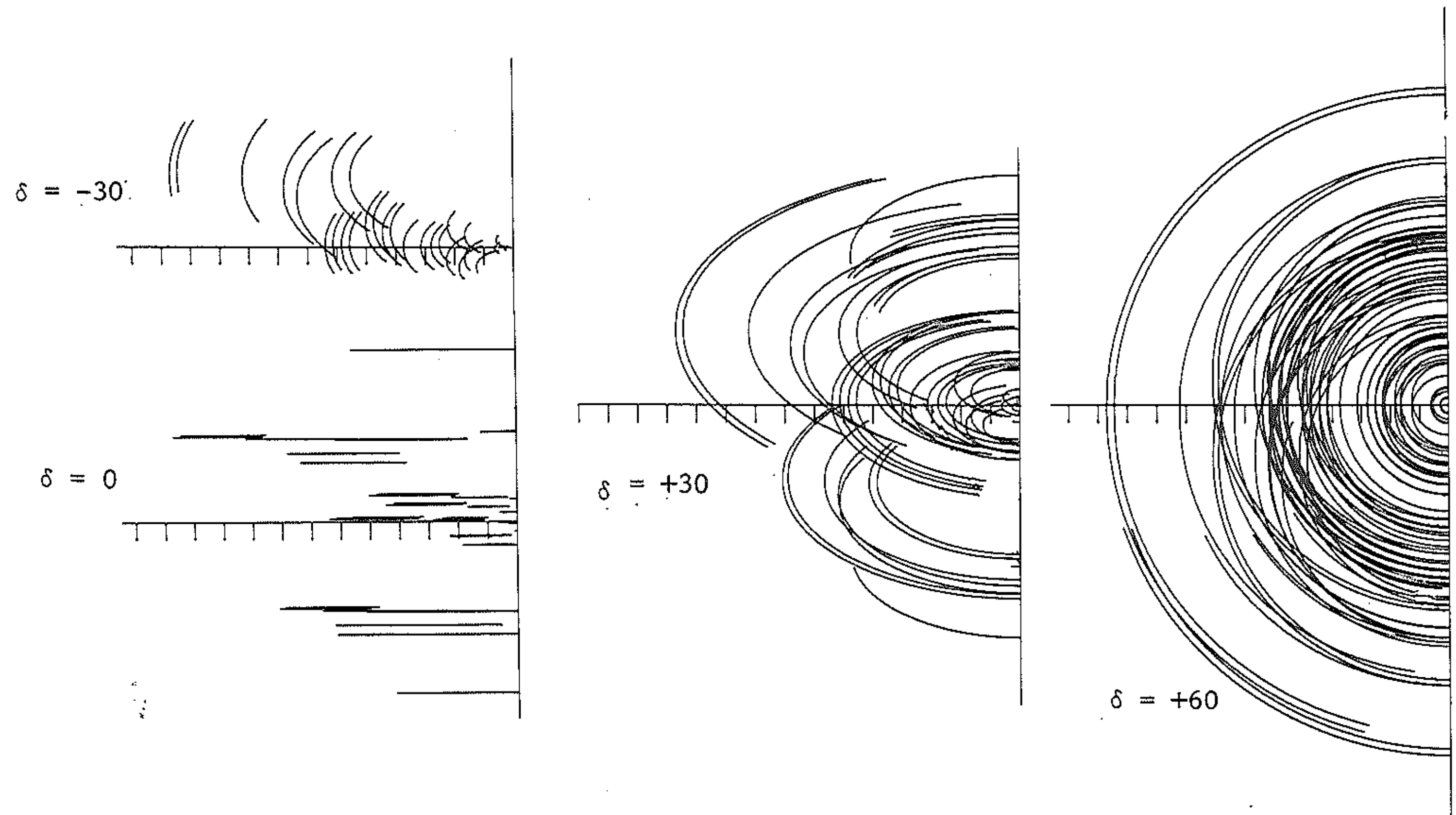

Figure A-6. As in Figure A-1 plus elements in Hawaii and Alaska.

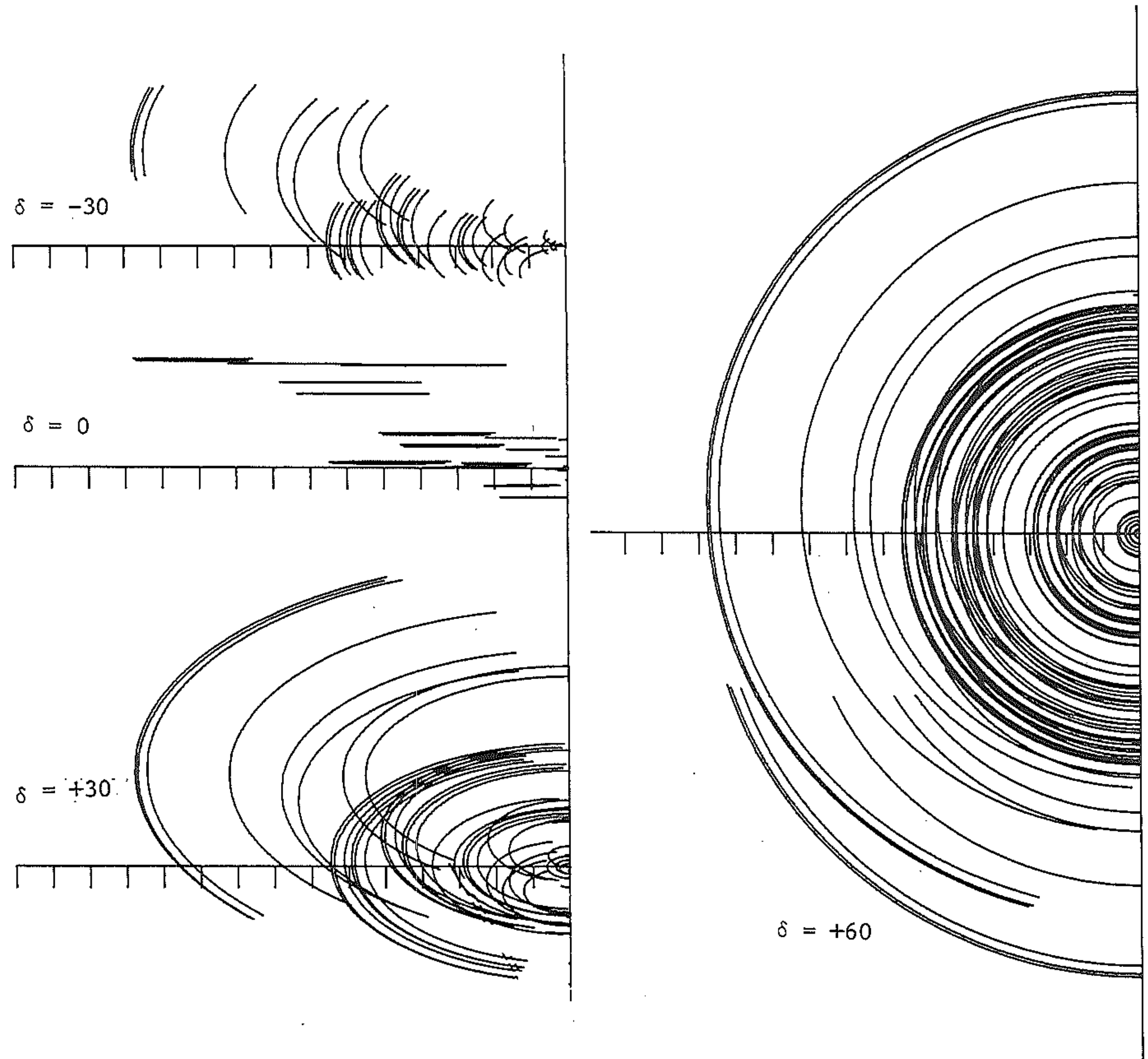

Figure A-5. As in Figure A-1 plus an element in Hawaii.

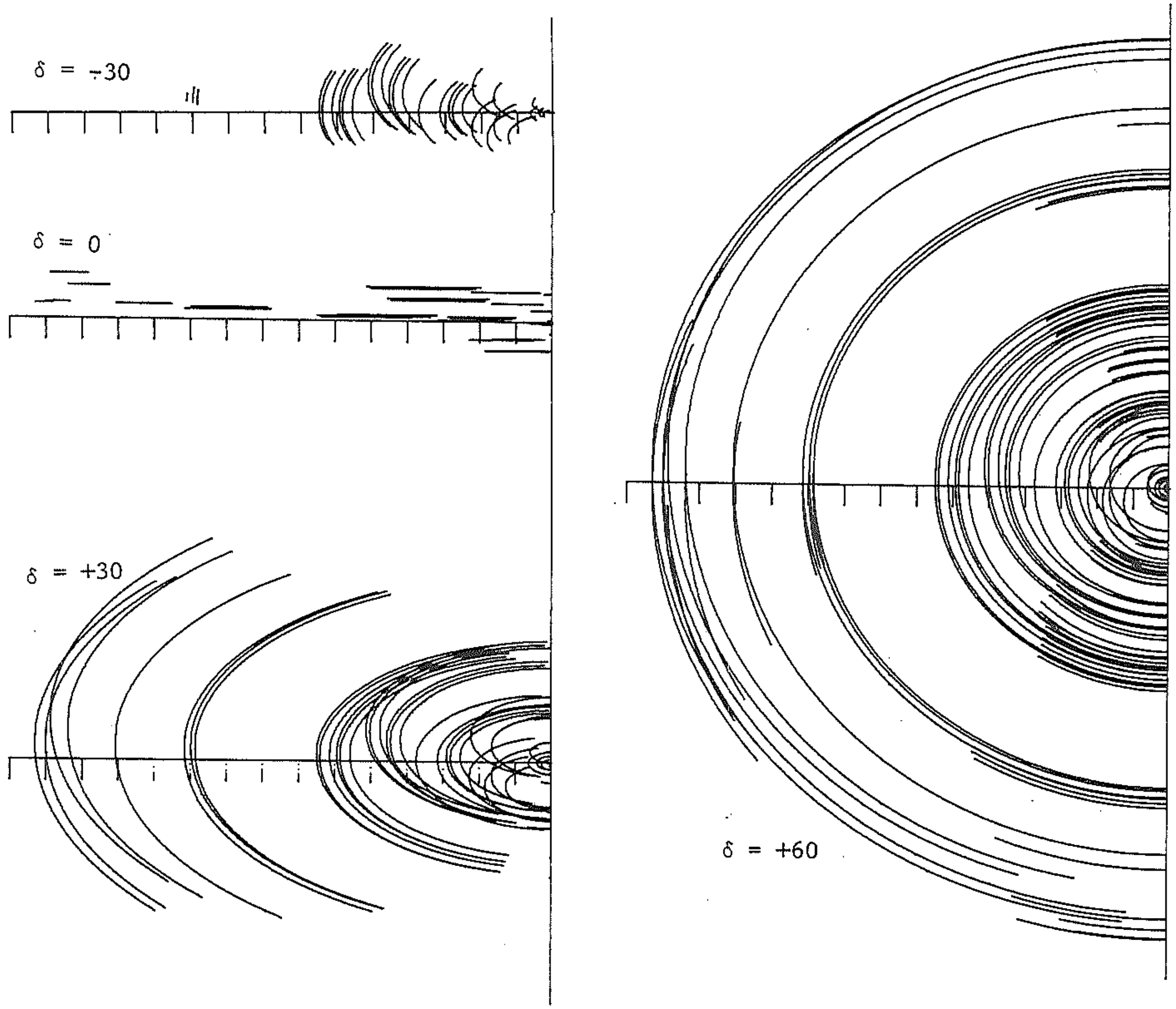

Figure A-4. As in Figure A-1 plus an element in the Azores.

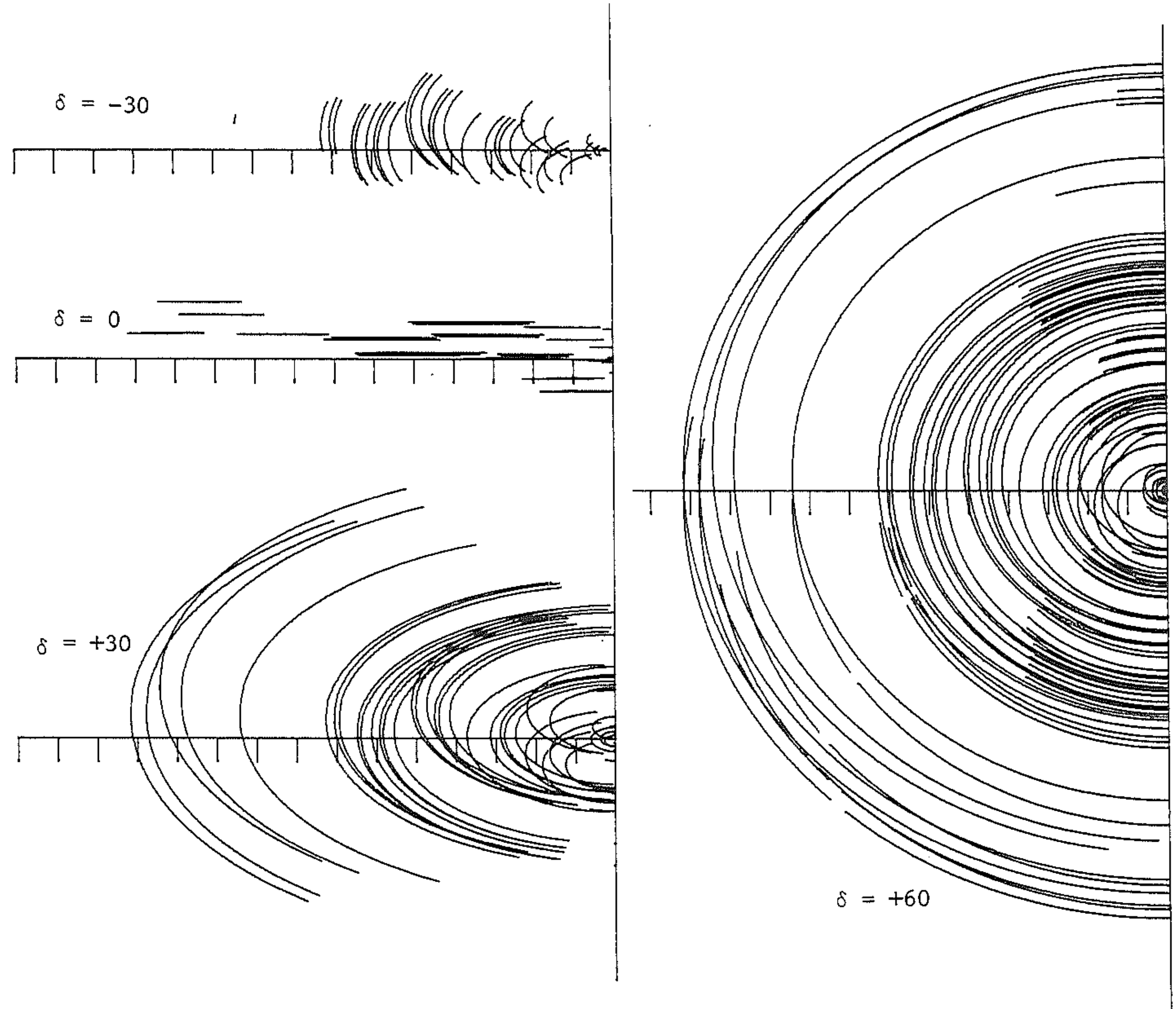

Figure A-3. As in Figure A-1 plus an element in Madrid, Spain.

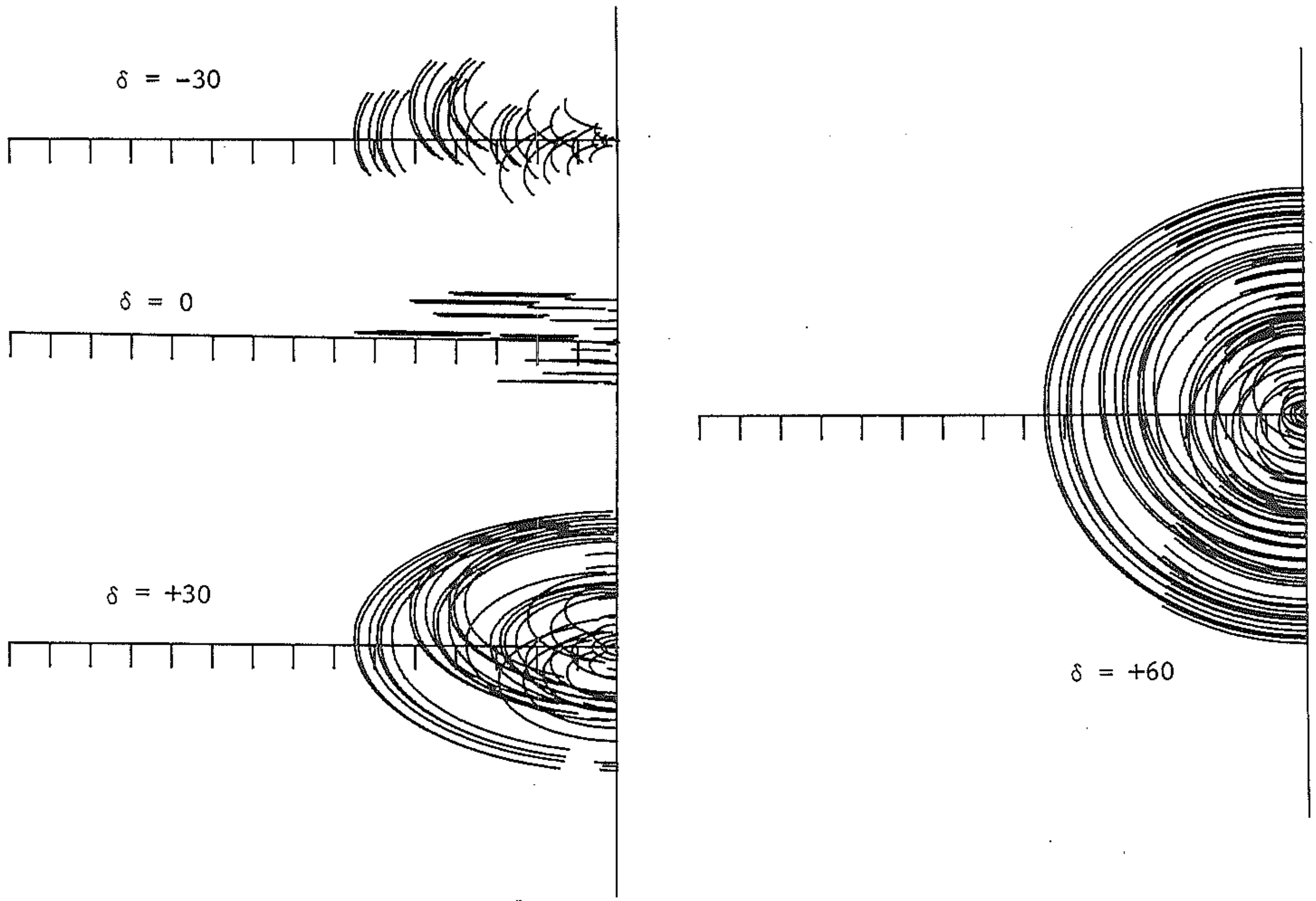

Figure A-2. As in Figure A-1 plus elements in Ann Arbor, Mich. and Fort Davis, Tex.

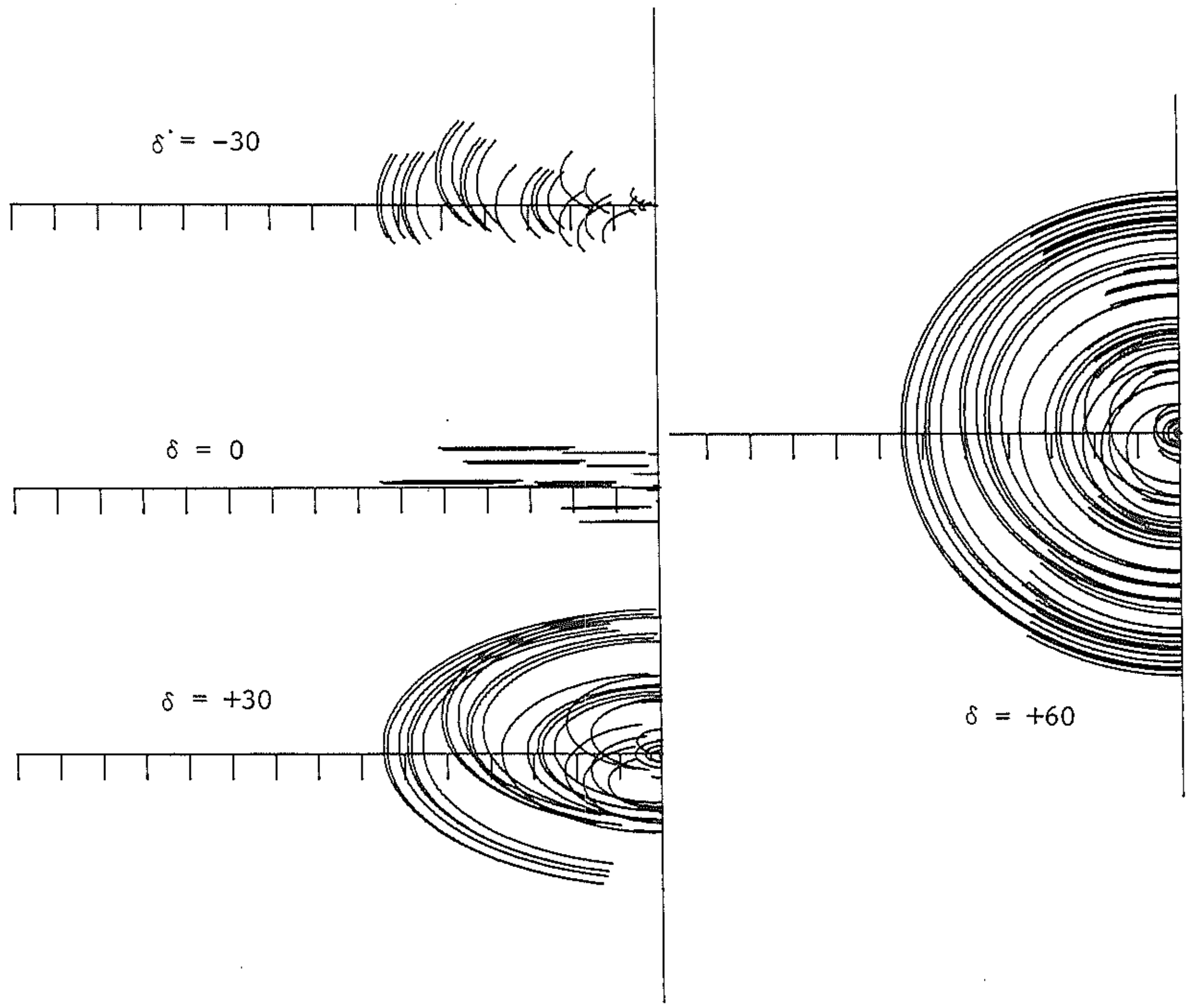

Figure A-1. Tracks in the (u,v) plane covered by an array of antennas with antennas at Md. Point, Md.; Charlottesville, Va.; Green Bank, W. Va.; Wichita, Kan.; Socorro, N. Mex.; Tucson, Ariz.; Big Pine, Calif.; and Palo Alto, Calif. The (u,v) tracks are shown for declinations of -30, 0, +30, and +60 degrees assuming an elevation limit of 10 degrees at each element. The horizontal and vertical axes are the conventional u and v axes of the projected interferometer baseline as described on page III-5. The tick marks represent a projected baseline length of 2 milli sec light travel time.

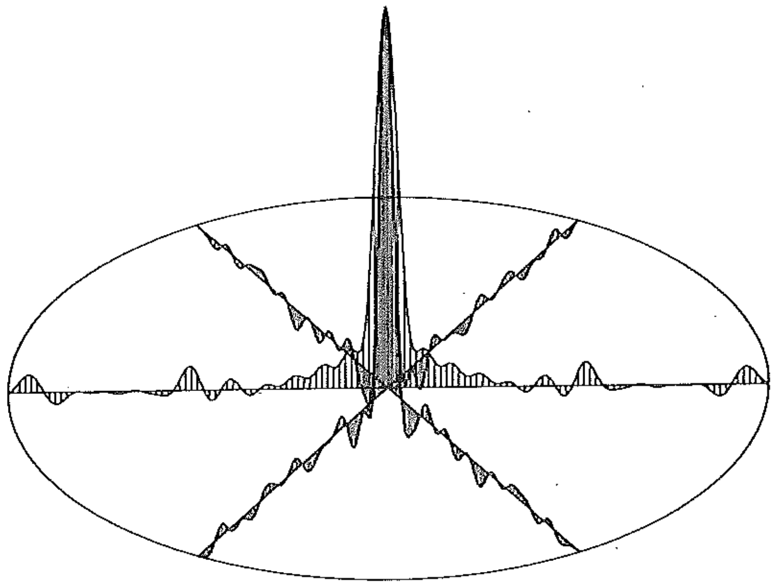

Figure A-8. Beam pattern at δ = 45 degrees for an 8-element transcontinental array for the configuration described in Figure A-1.

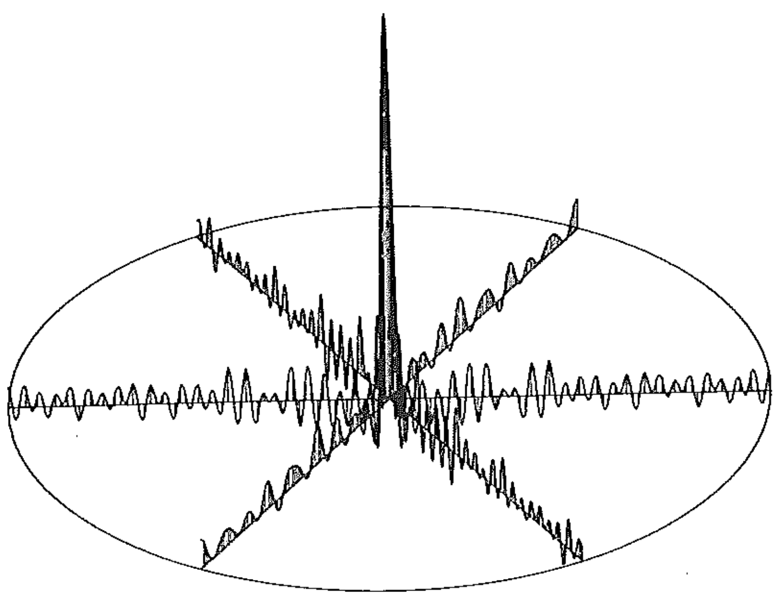

Figure A-9. Beam pattern at δ = 45 degrees for the basic transcontinental array plus one element in Madrid, Spain.

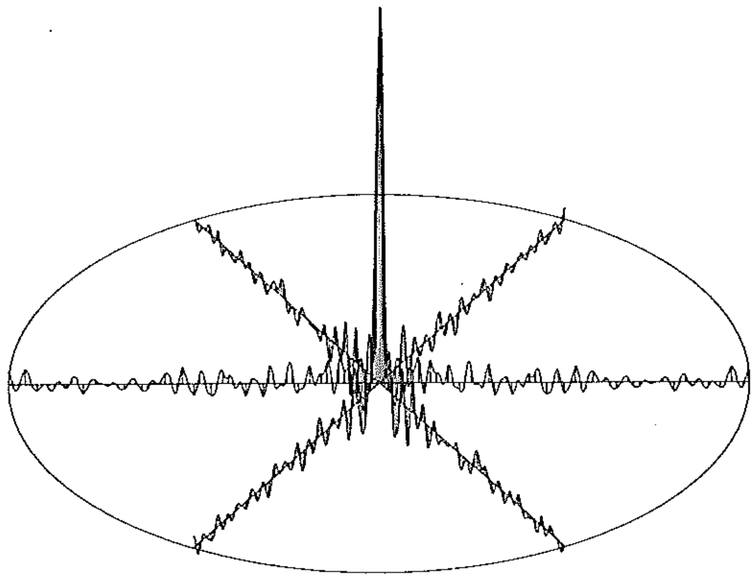

Figure A-10. Beam pattern at δ = 45 degrees for the basic transcontinental array plus elements in Hawaii and Madrid, Spain.

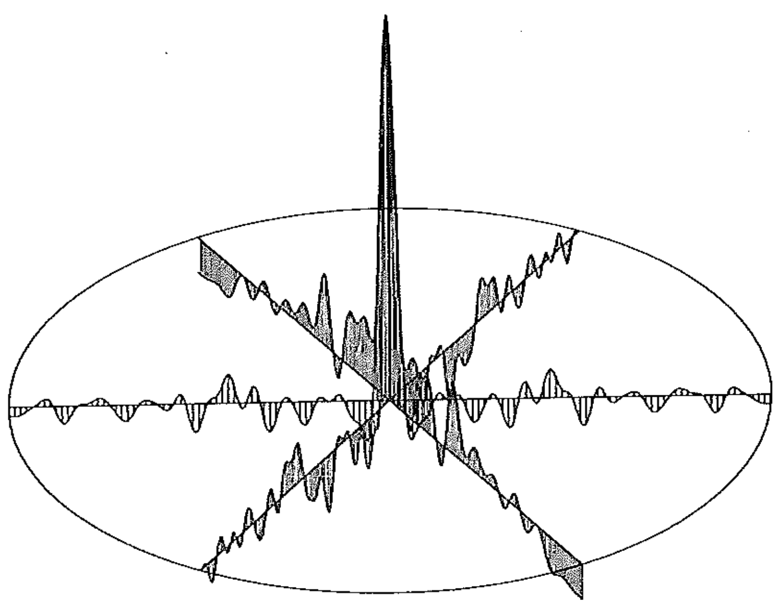

Figure A-11. Beam pattern at δ = 0 for an 8-element transcontinental array with antennas located at Md. Point, Md., Green Bank, W. Va.; Danville, Ill.; Big Pine, Calif.; Mexico City, Mexico; Penticton, B. C., Canada; Ft. Davis, Texas; and Fairbanks, Alaska.