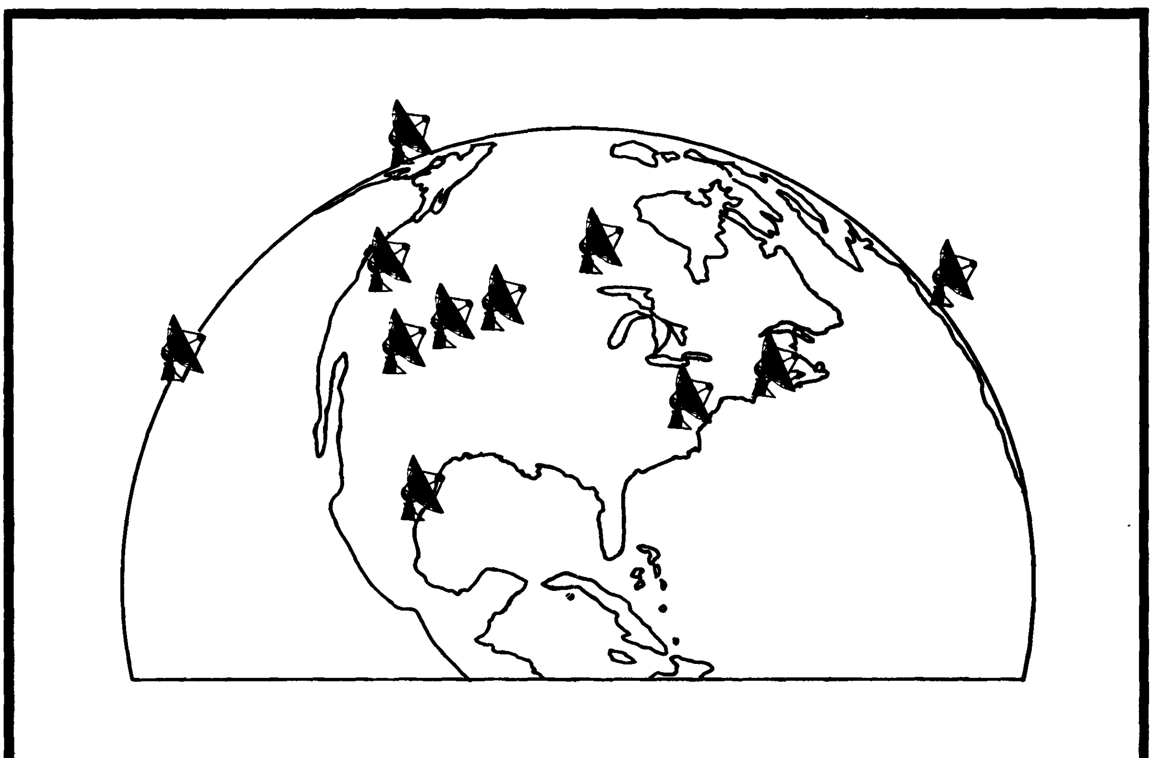
THE VERY LONG BASELINE ARRAY DESIGN STUDY



NATIONAL RADIO ASTRONOMY OBSERVATORY

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VERY LONG

BASELINE ARRAY

DESIGN STUDY

FEBRUARY 1981

VLBA

NATIONAL RADIO ASTRONOMY OBSERVATORY
OPERATED BY ASSOCIATED UNIVERSITIES, INC.,
UNDER CONTRACT WITH THE NATIONAL SCIENCE FOUNDATION

VLB ARRAY DESIGN STUDY

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PREFACE

The history of radio astronomy has been one of ever increasing angular resolution. The VLA, with its dramatic high resolution image forming capability, has made possible the detailed study of cosmic radio sources with a resolution better than 1 arc second, rivaling the best optical telescopes under the most favorable observing conditions. But many of the newly discovered galactic and extragalactic phenomena are very much smaller. They appear as points to conventional radio and optical telescopes and require even higher resolution.

In this report we describe the design of an image-forming Very Long Baseline Array (VLBA) with an angular resolution of a few tenths of a milliarcsecond which will make possible unprecedented high resolution radio pictures of quasars and galactic nuclei, interstellar molecular masers, X-ray stars and stellar supernovae remnants, pulsars, and the Galactic Center. It is not possible at any other wavelength, with any instrument, existing or planned, to obtain the resolution necessary to study and understand these exotic objects which are at the forefront of astrophysical research.

The VLB Array will complement the VLA, which has lower resolution but very much greater sensitivity to radio sources of lower surface brightness (e.g., extended galaxies and quasars, galactic and extragalactic hydrogen and molecular clouds, supernovae remnants, and the planets). The universe contains both extended and compact objects, and both instruments are needed for a full exploitation of galactic and extragalactic radio astronomy.

The organization of this report largely follows that of an earlier version distributed in 1977, except that much of the background material is not repeated here and the reader is referred to the earlier document for this information (Kellermann 1977). The present report is the result of studies and discussions in the radio astronomy community based on the experience, successes, and frustrations from over a decade of VLBI experimentation, and on experience gained from the construction and early operation of the VLA. At the time of the 1977 study, a number of problem areas were identified, in particular relating to the difficulty of phase calibration and the need for a large staff to change magnetic tapes as frequently as several times per hour at each of ten or so remote sites. Since that time advances have been made in a number of technical areas and these are reflected in the present report.

Of particular importance are the self-calibration techniques currently being used at the VLA and in VLBI to form images without the need to measure individual interferometer phases; and various procedures have been developed to exploit these techniques. Also, reliable low-noise GASFET and maser amplifiers have come into use on radio telescopes, largely eliminating the need for costly difficult-to-maintain parametric amplifiers.

Meanwhile, the MkIII VLBI system is now in use at a number of observatories; the feasibility of broadband VLBI using magnetic tape recordings has been established, and recent developments in high-density recordings should allow four to eight hours of uninterrupted recording of broadband data, without the need for operator intervention. Unattended computer-controlled antenna operation has been successfully demonstrated at several facilities and hydrogen maser frequency standards, while still expensive, are now sufficiently reliable to permit long periods of uninterrupted operation.

Although the development of a radio array with dimensions comparable with the size of the Earth represents a dramatic technical achievement and offers major new scientific capabilities, it thus does not contain any new or untried instrumentation or concepts. Rather, instrumentation and techniques developed for the VLA are combined with the independent oscillator, tape-recording procedures used for Very Long Baseline Interferometry to produce a reliable state-of-the-art instrument whose cost is well understood.

In order to develop accurate cost estimates, and to realistically evaluate the requirements for effective management and operation, we have assumed, for the purpose of this study, that the Array is built, managed and operated by the NRAO. More specifically, the Operations Center is assumed to be co-located with the VLA both to take advantage of the increased scientific potential offered by combining both instruments with very similar instrumentation and maintenance requirements. Other arrangements are feasible, but we have not yet studied them in any detail. Although it is expected that, in practice, at least some of the VLA and the new VLB Array staff will be combined, our budget estimates reflect the entire cost to the NRAO of building and operating the VLB Array.

Our plan for operation and management of the Array is not the only one possible. Interest in developing a VLB Array is very broad, and studies similar to this one have been made by Caltech-JPL (Cohen 1980) and in Canada (Legg 1979). During the course of these studies there have been continual exchanges of ideas among the groups. Not surprisingly, the final design concepts are not very dissimilar, particularly in the case of the Caltech-JPL and NRAO studies, and the possibility for a joint development and operation of the Array by two or more interested groups needs to be carefully considered.

The VLB Array represents a practical limit to the resolution that can be currently achieved from the surface of the Earth. Considerably higher resolutions are still possible, but this will require the more difficult to use millimeter wavelengths, or the construction and operation of sensitive radio telescopes in space.

VLBI is inherently an international science. It is not uncommon to find scientific papers with authors from three to five countries having disparate cultures and political systems. Indeed, there are cases where co-authors of VLBI papers do not even share a common language. Major VLBI projects are being discussed among the Western European countries, in Canada, and in the USSR. The first of several dedicated VLBI antennas is already being started near Bologna, Italy. More modest VLB projects are being considered in Japan, Australia, and China, and it is important to explore ways in which to further exploit international cooperation to produce an array of truly global proportions.

This report is based on the studies done at NRAO by the following group: J. Benson, M. Balister, B. Burns, B. Clark, W. Cotton, J. Findlay, B. Hjellming, W. Horne, H. Hvatum, K. Kellermann, P. Napier, G. Peery, F. Schwab, A. Shalloway, C. Walker and W-Y. Wong. We have also benefited from contributions, discussions and criticisms from M. Cohen (Caltech), K. Johnston (NRL), P. Thaddeus (Inst. for Space Studies), M. Reid (Center for Astrophysics), J. Moran (Center for Astrophysics), D. Shaffer (Phoenix Corp.), G. Swenson (U. of Ill.), S. Knowles (NRL), B. Rayhrer (JPL), and others in the radio astronomy community.

The details of many of the engineering studies can be found in a series of NRAO internal reports which are referred to in the text and listed in Appendix I, and the reader is referred to these.

Green Bank, W. Va.
December 1980

Literature Cited

Cohen, M. H. ed. 1980. A Transcontinental Radio Telescope, Calif. Inst. of Tech.

Kellermann, K. I. ed. 1977. An Intercontinental Very Long Baseline Array, National Radio Astronomy Observatory.

Legg, T. H. ed. 1979. A Canadian Very-Long-Baseline Array, National Research Council of Canada.

I. SUMMARY

A. Introduction

This report describes the design and operation of a radio telescope array which has a resolution equivalent to that of a single antenna covering the entire United States. This represents an improvement in resolution of two to three orders of magnitude over other instruments, and will permit for the first time detailed studies of some of the most challenging and least understood astrophysical phenomena.

Probably the most fundamental problem in extragalactic astronomy is to understand the source of energy in quasars and galactic nuclei, and the manner in which the energy is transported to distant radio lobes. The VLB Array will provide the only way of obtaining high resolution images of the central "engine" in quasars and active galaxy nuclei, as well as the nuclei of ordinary spiral and elliptical galaxies. Of particular interest will be the apparent faster-than-light motion observed in quasars and radio galaxies which challenges our fundamental concepts of physics and cosmology. The VLB Array will permit the detailed frequent multi-wavelength observations necessary to follow the complex structural changes which occur in these sources.

More than half of all extragalactic objects observable at centimeter wavelengths are unresolved with conventional radio arrays and optical telescopes, and their structure can be studied only with the VLBA. There are more than 10^5 extragalactic sources alone which can be observed with the VLBA, and most of these are probably variable on time scales of a few months.

Within the Galaxy, a variety of stellar objects including novae, supernovae, binary stars, flare stars, and X-ray sources are transient radio sources of interplanetary dimensions which will be studied in detail with the VLB Array. Unique objects such as SS433 and the Galactic Center are of special interest and have many similarities to the compact radio sources in active nuclei and quasars. For galactic objects, the characteristic resolution of the VLB Array is of the order of an Astronomical Unit, and the high linear resolution available for these sources may give further insight into the nature of their more powerful extragalactic counterparts.

Of particular interest is the intense line emission from molecular maser sources which are found in regions of star formation and in the envelopes of highly evolved stars. The VLB Array will be able to explore the temperature, density, magnetic fields, and dynamics of maser sources on scales as small as an A.U. and give unique information on the birth and death of stars. Also of great interest are the compact galactic and extragalactic absorption clouds of hydrogen which can be mapped only with the VLB Array. The Array will, in addition, make possible direct trigonometric measurements of distances on galactic and even extragalactic scales. Such measurements are of fundamental importance to all areas of astronomy.

Although the array is intended primarily for galactic and extragalactic research, there are also a variety of terrestrial applications relating to precision geodesy, the direct measurement of Earth tides, and plate motions, polar motion, precise clock synchronization and the determination of time (UT.1). Other applications include accurate tests of relativistic light bending, interplanetary spacecraft navigation, and possible advance warning of earthquake activity.

B. Historical Background

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 ordinarily 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 wavelength of radio waves, so that the effect of atmospheric irregularities is much less important.

Second, to form clear images, signals must be coherent, or in phase, over the entire dimensions of the instrument. Coherent radio waves are much easier to manipulate than coherent light signals, so that radio telescopes of very large size can be built and operated close to the theoretical limit of resolution.

The recently completed Very Large Array gives for the first time at radio wavelengths resolutions equal to or better than optical telescopes with high sensitivity and dynamic range. Although previous radio arrays have approached the resolution of the VLA, it is the unique combination of resolution, sensitivity, frequency coverage, and dynamic range (image quality) that makes the VLA so powerful, and has already resulted in a number of exciting discoveries which have led to a better understanding of the nature of extended radio sources.

The development of Very Long Baseline Interferometry using independent local oscillators and tape recording IF systems has removed the need for the physical or electrical connections between the elements and has allowed the baselines to increase to nearly the diameter of the Earth. During the past 15 years the VLBI technique has been continuously refined. Oscillator stability has increased by four orders of magnitude, essentially eliminating any limitations introduced by using independent oscillators. Meanwhile, improvements in digital-tape-recording technology has given an increase from $\sim 10^8$ bits to $\sim 10^{11}$ bits on a single reel of tape, and a further improvement of at least an order of magnitude is anticipated shortly.

Already VLBI systems using existing radio telescopes throughout the USA, Canada, Europe, South America, Africa and Australia have increased the resolution by some three orders of magnitude over conventional connected arrays, and have resulted in many exciting new discoveries. But not atypical of new scientific techniques, the VLBI observations have raised more new questions, rather than answered old ones. Although extraordinarily high resolutions have been obtained, the results are limited by poor image quality, low sensitivity, and inadequate frequency flexibility due to the use of too few antenna elements which are inappropriately situated, inadequately operate at short wavelengths, have restricted sky coverage, are poorly instrumented, and whose operation and management are inadequately coordinated.

The proposed VLB Array addresses all of these restraints to combine HIGH ANGULAR RESOLUTION, SENSITIVITY, DYNAMIC RANGE, and FREQUENCY COVERAGE to give an image-forming instrument with very powerful scientific potential.

C. The Array

The VLB Array will be operated as a national facility open to all qualified scientists from the USA or elsewhere. It is designed to give high resolution and good dynamic range over more than half of the sky observable from mid-northern latitudes, and will have sufficient sensitivity to observe a very wide variety of high-surface-brightness objects.

The Array itself will probably consist of ten elements, eight of which are located within the continental USA, one in Alaska, and one in Hawaii. In addition, provision is made to use up to four additional antennas such as one of the DSN tracking stations, the 100m antenna in Germany, the Italian VLB antenna, the Arecibo 1000-ft antenna, antennas located in Canada, and in particular from 1 to all 27 elements of the VLA. The locations of the individual Array elements are chosen to optimize the dynamic range while at the same time retaining the convenience of placing as many of the elements as possible at or near existing radio astronomy facilities. Particular attention has been given to providing a reasonably smooth extension of VLA resolutions, and in organizing the operation to allow simultaneous use of the VLA and VLBA to give the broad range of resolution necessary to effectively study the variety of structural features found in cosmic radio sources.

Individual interferometer pairs of the VLBA have a sensitivity comparable to antenna pairs in the VLA; but the 10 baselines from the VLA to each of the VLB Array elements are some five times more sensitive, and together give moderately uniform (u,v) coverage to allow the study of very weak objects with reduced dynamic range.

Each of the Array elements is a 25m high-efficiency steerable paraboloid, designed to work well at wavelengths as short as 0.7 mm. Multiple low-noise receivers are used to provide the flexibility to observe over a wide range of frequencies from 327 MHz to 43 GHz, including all of the commonly used radio astronomy bands at centimeter and decimeter wavelengths, the VLA frequencies, the DSN frequencies, the spectral lines of hydrogen (21 cm), the four ground state OH lines (18 cm), the excited OH line (5 cm), the H_2O lines (1.3 cm) and the SiO line (43 GHz).

At the lowest frequency of 327 MHz a prime-focus GASFET amplifier is used to give a moderately low system temperature which is dominated by the galactic background. All other receivers are located at the secondary focus and use GASFET amplifiers cooled to 20K. At 1.3 cm and 0.7 cm, low-noise maser preamplifiers are required to give sufficiently low system temperatures. Frequencies can be changed rapidly allowing flexibility in observing programs, as well as minimizing the impact of receiver failures or poor weather conditions.

Phase coherence over the Array is maintained by independent stable hydrogen maser oscillators, so as in connected synthesis arrays, measurements of interferometer phase will be limited by tropospheric delay fluctuations, rather than by instrumental effects.

For strong sources the Array can operate in the incoherent mode and "self-calibration" or "hybrid mapping" procedures can be used to reduce the effect of the atmosphere and to form high resolution images. For weaker sources, nearby reference sources which have themselves been mapped using "self-calibration", can serve as phase references, thus maintaining coherence over the range of hour angles that the source is visible. In this way the full power of aperture synthesis techniques are applied to the VLB Array to achieve high resolution combined with high sensitivity and good dynamic range.

In Table I-1 we summarize the resolution and sensitivity at each wavelength under a variety of observing conditions. Because of the very high angular resolution, the Array is sensitive only to sources of high surface brightness. The effective r.m.s. fluctuations in brightness temperature in each synthesized beam area is approximately 2×10^8 K, 10^7 K, or 10^5 K in 1 sec, in a typical coherence time of a few hundred seconds, or in a full 8 hour synthesis respectively.

TABLE I-1

SENSITIVITY AND RESOLUTION

ν	feed	ε	Rcvr	T_s(K)	T_s(Jy)	τ	σ	σ_c	σ_A	θ
0.327	P	0.32	GASFET	65	990	100	850	85	0.8	24
0.61	S	0.42	GASFET	61	708	200	610	43	0.5	13.5
1.5	S	0.65	GASFET	31	232	1200	200	5	0.18	5.4
2.2	S	0.66	GASFET	33	243	1000	210	7	0.18	3.5
5.0	S	0.68	GASFET	36	257	500	220	10	0.19	1.6
8.8	S	0.68	GASFET	45	322	280	275	17	0.24	0.9
10.7	S	0.68	GASFET	50	358	230	310	20	0.27	0.75
15.0	S	0.64	GASFET	50	380	160	330	24	0.29	0.54
22.3	S	0.59	Maser	50	413	110	360	33	0.32	0.35
43.0	S	0.35	Maser	75	1040	60	900	110	0.8	0.20

ν : Frequency in GHz

ε : Aperture efficiency

T_s(K) : System Temperature, degrees Kelvin

T_s(Jy): Equivalent System Temperature, Jy

τ : Typical coherence time

σ : rms noise fluctuations on a single baseline in 1 sec, (mJy)

σ_c : " " " " " " " in coherence time, (mJy)

σ_A : " " " for 8 hour coherent observation with entire Array, (mJy)

θ : Synthesized beam size, FWHM milliarc seconds; Field of view is ∿ 50 times larger.

P : Prime focus

S : Secondary focus

The Operation of the Array will be controlled from an Array Operating Center which is connected to each of the Array elements via enhanced leased telephone lines. The Array will be operated under a preplanned program which is controlled by a central computer, and which also monitors a number of test points in each antenna and radiometer as well as local meteorological conditions at each site. An Array operator is available at all times at the Operations Center to intervene when necessary. From time to time brief samples of a narrow band IF signal from each antenna are sent to the Operations Center via the telephone lines and correlated in nearly real time as a check that the Array is properly functioning.

The full IF signal will be recorded on high-density broadband digital recordings and shipped to the Operations Center for later correlation and analysis. A number of tape recorders will be available at each site which can be automatically switched into operation to allow uninterrupted recordings for periods of up to 24 or more hours.

Normally each antenna element runs unattended except for changing tapes once or twice per day. Two or three technician/operators are available at each site, however, for inspection, routine maintenance, and the more straightforward unscheduled repairs of malfunctioning equipment. In addition to changing magnetic tapes, the local staff will be responsible for inserting operating programs and corrections at the local control computer, shipping and receiving magnetic tapes, for security and precautionary oversight, for emergency intervention and routine start-up and shut-down procedures. For major maintenance and repair requiring personnel with special training, special equipment, or major replacement parts, one or two Service Centers where a larger group of engineers, technicians, and mechanics are stationed, will be utilized.

The tape processing facility will be a flexible system allowing a wide choice of performance specifications. Depending on the chosen mode of operation, up to 14 tapes can be simultaneously correlated, or full polarization capability, or up to 32 continuum delays, or up to 512 frequency channels per baseline can be used with 10 antennas. It is proposed to build the processor using high speed recirculating correlators with a great economy of circuits and resultant improvement in reliability and maintenance over conventional correlator systems.

Post processing and image formation systems will be very similar to those of the VLA, and the software development for the VLB Array will profit from the extensive experience gained from the VLA.

D. Cost Summary

Construction and Operating Costs are summarized in Table I-2 and I-3 respectively. Construction costs are largely based on the cost of similar components at the VLA and other NRAO facilities, or which are being developed at NRAO or elsewhere. All construction costs are corrected for past escalation and are given in 1980 dollars. Construction can be completed about 56 months after initial funding is available.

TABLE I-2

COST SUMMARY

Antenna Elements	14,310K
Station Electronics	9,860K
Site Development	1,810K
Central Control and Data Center	5,015K
Spare Parts, Tapes, Test Equipment, etc.	1,390K
Project Management	1,620K
Contingency (15 percent)	5,100K
TOTAL Construction Cost (1980)	39,105K

It is important to note that the costs given in Table I-2 represent the cost of the entire operating system including electronics, computers, and software development. It is not limited to the "heavy construction" costs to which must be later added expensive instrumentation.

Our estimate of operating cost is based on the costs required to run the VLA and other NRAO sites, but include the cost of unusually large items such as shipping, communication, and travel. Adequate provision is made for continual upgrading and improvement of the instrument to keep it at the forefront of research for many years.

TABLE I-3

ANNUAL OPERATING COST

Personnel Compensation	1,782K
Materials and Services	1,030K
Shipping, Travel, Communications	372K
New Operating Equipment	500K
Management Fee	100K
Annual Operating Cost (1980)	3,784K

II. SCIENTIFIC GOALS

Cosmic radio sources have a wide range of angular size and surface brightness, ranging from a fraction of a milliarcsecond to several degrees. Correspondingly there is no one particular type of radio telescope which is suitable for all areas of radio astronomy research. For the large scale low-surface brightness sources, the filled aperture instruments provide the needed sensitivity and moderate angular resolution. But even for the largest antennas the resolution is only of the order of a minute of arc, or comparable to the unaided human eye. Higher resolution is obtained by using arrays to increase the instrument dimensions at the expense of sensitivity to extended low surface brightness features.

The VLA combines high sensitivity with a resolution and image quality equal to that of optical photographs made with the largest telescopes under the best seeing conditions. It is ideally suited to study in a detail not previously possible, a wide range of cosmic radio sources. But the very high surface brightness sources which are associated with the compact energetic objects remain unresolved by the VLA or other conventional radio telescopes, even when operated at the shortest wavelengths. They can be studied in detail only with an array of global dimensions.

The proposed Very Long Baseline Array will give the flexibility, frequency coverage, and image quality necessary to study galactic nuclei, quasars, molecular masers, radio stars, and other compact objects, in the same manner as is now obtained by the VLA objects of lower surface brightness. Although many exciting poineering discoveries have already been made using existing VLBI systems, the poor image quality and sensitivity, as well as the limited frequency coverage and lack of polarization capability has prevented a clear interpretation of the observations.

The VLB Array will be a true image forming instrument with sub milliarcsecond resolution, corresponding to linear scales of a parsec and an Astronomical Unit on extragalactic and galactic scales respectively. This will make possible a wide range of important investigations not possible with any other instrument in any wavelength band. The high resolution radio images, which will be of unprecedented quality, are not only of direct astrophysical interest, but will also make possible the measurement of precise positions, parallax, and proper motions. This will permit the direct measurement of distance on galactic and extragalactic scales, as well as studies of galactic structure and rotation.

In the following pages we summarize briefly the currently important problems where the VLB Array is expected to have great impact. However, as with other major new scientific instruments, the exciting new contributions will come not only from the increased capability to solve the problems which lead its construction, but from the unexpected discoveries which may uncover whole new areas of research.

A. Extragalactic Studies

One of the most fundamental problems in extragalactic astronomy is to understand the source of energy in quasars and galactic nuclei. It is widely speculated that black holes or other massive condensed objects play an important role, and the high angular resolution of the VLB Array will enable us to probe closer to the central engine than otherwise possible. On these size scales, the radio emission is variable on a time scale of months to a few years, so frequent observations are necessary to study the kinematics of these objects. Except for the occasional supernova, there is no other known phenomenon in extragalactic astronomy in which it is possible to follow the evolution on a scale of human lifetimes, and the VLB Array is expected to give major new insight into the manner in which electrons are accelerated to relativistic energies and how they are focused and transported to the extended radio lobes as far as a million light years away.

Nearly all BL Lac Objects, most quasars, and many radio galaxies contain compact radio nuclei. Compact radio sources are also found in other active galaxies as well as in apparently normal spiral and elliptical galaxies. Indeed, at centimeter wavelengths, half of all catalogued sources are compact and the VLB Array will be able to map them in the same way the VLA is used to study the more extended extragalactic sources.

When observed with current VLBI systems, quasars and galactic nuclei show a wide variety of structural forms ranging from simple doubles to assymetric structures containing a bright region plus a low surface brightness "jet-like" extension. But the resolution sensitivity, and image quality are insufficient to detect any but the most prominent features, and the observation of wisps and knots of the type seen with the VLA will require the full image forming capability of the VLB Array.

Unlike the extended tranparent sources which have nearly wavelength independent structure, the compact sources have a complex distribution of opacity and their structure varies dramatically with wavelength. Observations at the shortest possible wavelength are required to probe close to the center-of-activity. The low surface brightness jets are more prominent at the longer wavelengths. Flexible multi-wavelength capability is thus necessary not only to vary the resolution and field of view, but also to cover the wide range of surface brightness found in these objects. This capability will also be important in studying the so called "hot-spots" found in jets and extended lobes of radio sources which remain unresolved by the VLA.

In a few instances where the central component of an extended radio source is sufficiently strong to be mapped with current VLBI techniques, it is found to be assymetric and to be elongated along the direction connecting the brightest regions of the extended components. This allignment implies a preferred axis in each source which extends from a few light years or less to far out into intergalactic space, and which must last over time scales of at least 10^8 years. The VLB Array will give a dramatic new insight into the central regions of galaxies and quasars where the remarkable features observed with the VLA are focused and collimated.

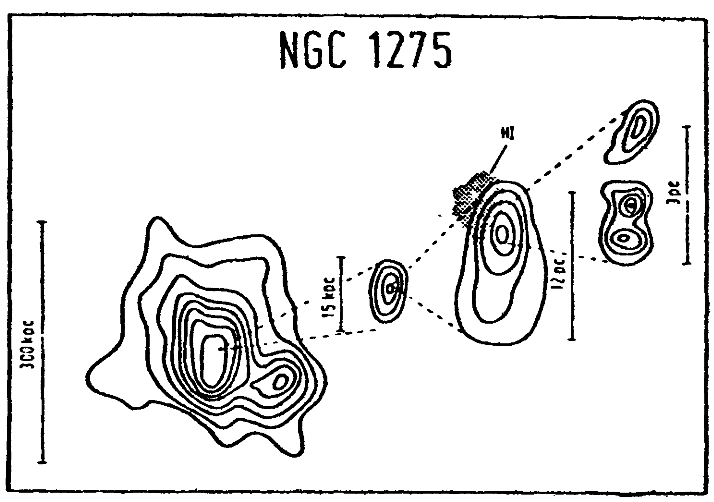
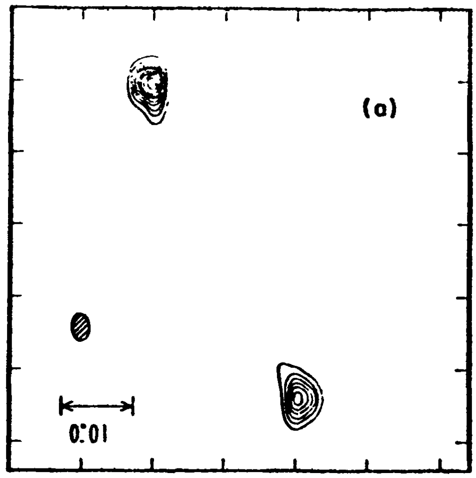


Figure III-1. Structure of NGC 1275 (3C 84) observed over a range of 10^5 in resolution.



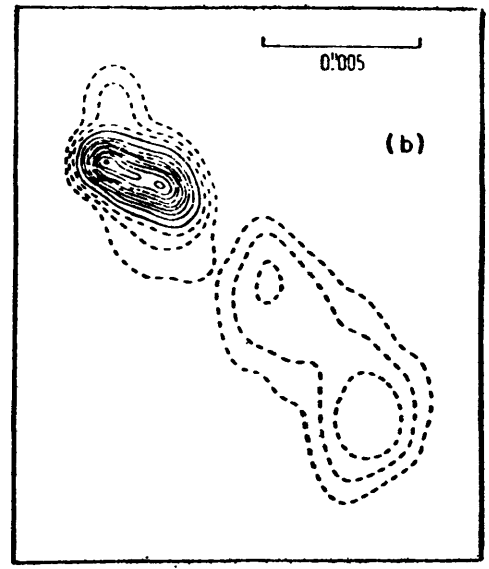


Figure III-2. Structure of the compact radio sources a) CTD 93 and b) 3C 273 as mapped with VLBI systems.

Observations of extended radio sources made over a wide range of flux density with conventional synthesis instruments show evidence for dramatic cosmic evolution. The compact radio sources appear to be more uniformly distributed in space, but high resolution maps of weak sources are necessary to investigate how their properties change with cosmic epoch. The sensitivity and resolution of the VLB Array will be sufficient to investigate weak compact sources at the largest observed redshifts, and to study the manner in which the apparent dimensions change with flux density and redshift. This will permit the geometry of space to be studied in the same way as for the extended sources, but it will be unaffected by the variation in the intergalactic medium with cosmic epoch.

Superluminal Sources. Perhaps the most exciting discovery to come so far from VLBI observations is the detection of apparent superluminal (faster-than-light) motion in several quasars and at least one galaxy. The early evidence for superluminal motion was based on very limited observations over a restricted portion of the (u,v) plane made with a simple two element interferometer. When first announced more than a decade ago, alternate less exotic interpretations were explored; and in particular explanations which invoked intensity variations in fixed components appeared attractive. Although stationary models are not supported by the recent multi-element observations, the earlier models of two components separating with superluminal velocity are also no longer tenable, (eg Pauliny-Toth 1981, Pearson et.al. 1981). Instead the observations reveal a complex elongated "jet-like" structure which may resemble the jets seen with the VLA on larger scales. The features appear to move and to change in brightness, but the resolution and quality of the radio pictures are inadequate to obtain more than a few picture elements across each source, and it is not possible to establish whether there are two or more plasmons moving along the same or different trajectories or if only one moves and the other remains stationary. Moreover we are currently able to observe changes only in the overall source size. The VLB Array will be able to study in detail the kinematics of individual components as a function of wavelength and time.

Although several sources, such as 3C 120, 3C 273, and 3C 279 have shown multiple superluminal events, the interpretation is confused because components appear to overlap in space and time. An individual component can be followed for only a few years since initially it is too close to central components, and later it is too faint to be distinguished against the glare of the younger more intense components. The higher resolution and better image quality of the VLB Array along with the flexible frequency coverage will permit the complex pattern of motion to be observed. In addition, polarization observations which will be possible with the VLB Array will show how the strength and direction of the magnetic field as well as the energy distribution of relativistic particles varies with time.

The observed superluminal motions are widely interpreted as evidence for relativistic bulk motions in quasars and radio galaxies. The detailed study of material moving with nearly the velocity of light, which will be possible with the VLB Array, will have a profound impact on our understanding of extragalactic phenomena.

Not all compact radio sources show superluminal motion. Some, in fact, appear to show no motion at all although their components may vary on a time scale much shorter than the characteristic lifetime deduced from their spatial extent and upper limit on component motion. This is also a puzzle since it requires multiple centers of activity.

Neutral Hydrogen in Galaxies. Recent spectroscopic observations have shown narrow 21 cm absorption lines in several galaxies and quasars. High resolution absorption line observations can investigate the distribution of neutral hydrogen in external galaxies and quasars with a resolution corresponding to a few tens of parsecs. The very narrow neutral hydrogen absorption lines found in galaxies such as NGC 1275 (see Fig. II-1) 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}. 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.

With the VLBA it will be possible to measure small proper motions of the absorbing cloud relative to the quasar, and perhaps in this way distinguish between these two possibilities.

B. Galactic Studies

On a scale of galactic dimensions the VLB Array will have a resolution of the order of an Astronomical Unit (10^{13} cm) which will make possible a wide range of new investigations.

Interstellar Molecular Masers.

One of the most important problems of galactic astronomy is to understand the life cycle of stars. Molecular masers provide information on the end points of this cycle since they are found in regions of star formation and in the envelopes of highly evolved stars. The very high brightness of the masers allows VLB observations to probe the dynamics and magnetic fields in these regions on 10^{13} to 10^{18} cm scales.

H_2O masers form around young O and B stars which have recently ignited and begun to blow away their remaining protostellar clouds. These stars are imbedded in molecular clouds and are usually in the vicinity of, but often not coincident with, infrared objects and compact HII regions. The masers are thought to occur in the boundary region between the undisturbed clouds and the stellar winds and ionized regions around the young stars. They provide a sensitive probe of these highly disturbed regions.

Studies of OH masers compliment those of H_2O masers. Observations of OH masers determine the dynamics of gaseous material with densities of 10^5 to 10^9 cm^{-3}, whereas the H_2O masers are found in regions with densities of 10^7 to 10^{11} cm^{-3}. In general, the OH and H_2O sources do not coincide on the sky, reflecting their association with different types, or evolutionary phases of forming stars. Unlike the H_2O masers, interstellar OH masers almost always coincide with compact HII regions. OH masers contain magnetic fields of the order of a few milligauss which cause the spectral features to be split into Zeeman pairs. Synthesis maps made with the VLB Array will be able to determine the strength and orientation of the magnetic field, and give some insight into the manner in which the magnetic field effects cloud collapse and star formation.

OH, H_2O and SiO masers are also found associated with late type stars which are thought to be evolved stars in the red giant or supergiant phase of evolution. These stars have high mass loss rates which generate circumstellar envelopes in which masers can occur and which are responsible for the return of a significant fraction of all material to the interstellar medium. The energy levels of the masing states differ considerably for the three species so the masers occur at different levels in the envelopes. Therefore, studies of all three species provide valuable and complimentary information on the kinematics, geometry, and magnetic fields (in the case of OH masers) in the circumstellar envelopes.

The spectra of maser sources contain features or components having widths of about 1 km/s or less and spread over a range of 5 to 500 km/s. The components have apparent sizes ranging from 0.1 to 100 milliarcsec and are scattered over a field having a diameter of from $0''.01$ to 30". The ratio of the total source size to the individual component size is generally quite large, i.e. $10 - 10^4$. Individual features typically have a lifetime of several years, but significant variations are observed on time scales of a few days.

The VLB Array is designed to provide full polarization capability, adequate spectral resolution and bandwidth, plus a sufficient angular resolution and field of view to adequately study the known maser transitions of OH, H_2O, and SiO at 18, 5, 1.3 and 0.7 cm.

Stellar Objects. In recent years continuum radio emission from a variety of stellar objects has been observed. These include novae, X-ray sources, binary stars, and flare stars. Since the radio emission from these objects is both weak and transient it has been difficult to map their spatial structure, but crude pictures of the Galactic Center, the radio star β Persie, and the exotic object SS 433 have already emerged.

The Galactic Center, which is an extraordinarily rich and interesting region containing thermal and non-thermal radio and IR emission regions, contains a very compact non-thermal radio source. The overall dimensions of this compact nucleus is ~0.02 arcsec (200 AU). There appears to be a smaller core ~0.001 arcsec (10 AU) in size which contains about 25 percent of the total flux density but the observations are distorted by scattering in the intervening medium.

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.

The two dimensional configurations of the VLB Array operating at the shortest wavelength will give, for the first time a good picture undistorted by interstellar scattering, of the heart of our Galactic System with a resolution of 300,000 km. Because this source is known to vary on time scales of a month or less, repeated observations will provide some insight into the extraordinarily interesting activity which is going on at the center of our Galaxy.

The sensitivity and availability of the VLB Array make possible observations of many galactic radio stars, especially during active periods. Of particular interest will be the determination of the time variation of the size of the variable sources associated with the explosive novae 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. At longer wavelengths, the VLB Array should have sufficient sensitivity to detect flare stars. It is not clear whether the resolution will be sufficent to resolve the radio flare, but if it is, it will be possible to study the motion and evolution of the flaring region.

The VLB Array will also play a crucial role in trying to understand the newly discovered objects such as SS 433 with its remarkable system of precessing relativistic jets. VLA observations already show the proper motion of the jets. The observations give, from the radio measurements alone, the three dimensional orientation of the jets and the axis of rotation, the velocity of the jets, as well as the distance of the source (Hjellming and Johnston 1981). But the VLA observations refer to dimensions of the order of a few tenths of a light year, or several orders of magnitude greater than the dimensions of the precessing optical jets. The VLB Array will be able to trace the motion of the jets on a scale of 10^{13} cm where the optical and radio jets are formed and collimated.

A very exciting possibility is the extension of this technique to measure directly the distance to relativistically moving radio components in quasars and radio galaxies. This may be possible because the effect of finite signal travel time from the receding and approaching parts of the source give the velocity from the observed component separations. The distance is then obtained in a straightforward way from the measured proper motions. Such observations made over a wide range of redshift would demonstrate directly the relation between redshift and distance and give the value of the Hubble constant and q_o independent of any assumptions about the similarity of properties of nearby and distant objects. Without the VLB Array, the sensitivity, resolution, and image quality are not sufficient to detect the faint receding component.

The Interstellar Medium. The discovery of pulsars has led to the detection of irregularities of the thermal plasma density in the intergalactic medium on a typical scale of a solar diameter (3×10^{11} cm). Although the spatial scale of these inhomogeneities suggest a stellar origin, they probably exist throughout the tenuous interstellar gas. The origin and stability of the irregularities is not understood. They may be associated with abrupt gradients due to interstellar shocks, acoustic or hydromagnetic waves driven by cosmic rays, or isotropic turbulence in the "hot" component of the interstellar medium. 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 above 3 x 10^{11} cm.

The irregularities in the interstellar medium can be studied by observing the apparent brightness distribution of compact radio sources dilated by interstellar scattering. The VLB Array will be able to map the apparent brightness distribution of distant OH/H_2O masers and low latitude continuum sources, particularly those objects which lie behind dense HII complexes. This will allow us to investigate the shape of the irregularity spectra of the plasma density along different lines of sight, and to search for possible secular changes in the scattering. Since the scattering phenomena is very wavelength dependent, the broad wavelength coverage and flexibility of the VLB Array will be particularly important in studying the interstellar plasma.

Small clouds of neutral hydrogen are also found in the interstellar environment and the VLB Array will be used to study the 21 cm absorption in front 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 ($\sim$ 100 AU) have already been detected. The VLB Array will permit a detailed mapping of these remarkably small irregularities in the distribution of interstellar hydrogen.

C. Astrometry and Distance Measurements

Distance and angular coordinates in the sky are among the most fundamental measurements in astronomy. The position of many radio sources are already known to 0.1 arcsec or less; better than the FK4 optical system. We have already mentioned the possibility of determining the distance of superluminal expanding sources. In addition the VLB Array will give distances throughout the galaxy, by the more straightforward observations of parallax with a precision $\lesssim 0''.001$. The ability of the VLB Array to measure angular coordinates to this accuracy will open 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, precission, 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. Because the compact radio sources, in general, have a complex distribution of brightness, they must be accurately mapped with the VLB Array when used as the basis of astrometric observations. Simple interferometry with only a few elements is inadequate for this purpose.

The distance to OH and H_2O masers may also be determined by the radio analogue of the classical statistical parallax method: That is by comparison of the radial velocities and measured proper motions. Measurements accurate to about 20% have already been made (Genzel et al, 1981). The VLB Array will allow these techniques to be significantly improved and extended to many other galactic as well as to extragalactic sources.

D. Other Applications

Very Long Baseline Interferometry has been applied to a number of terrestrial as well as to astronomical problems. These include:

1. Transcontinental and intercontinental distance measurements to an accuracy of 1 cm.

2. Accurate determination of the constants of precession and nutation of the Earth's motion.
3. The rate of rotation of the Earth (UTI-UTC)
4. Polar motion
5. Tidal deformations in the solid Earth
6. Global clock sychronization

Although the VLB Array is conceived primarily as an instrument for astronomical research it will have a major impact on several of the continuing geodetic programs of NASA, the US National Geodetic Survey, and the Naval Observatory. Firstly the VLB Array will be able to obtain the detailed maps needed to fully interpret observations made with the dedicated geodetic VLB systems. Secondly, the regular calibration of the VLB Array will provide, as a by-product, valuable geodetic and astrometric information, even without observations specifically designed for this purpose. In addition it is anticipated that there will be, from time to time, specific geodetic programs which will exploit the sensitivity, frequency coverage, dynamic range, and broad geographical distribution of the Array.

Other applications of the VLB Array are in interplanetray spacecraft navigation and precise tests of General Relativity by means of measuring the deflection of radio signal by the sun. In this latter respect it is interesting to note that the effect of relativistic light bending by the sun will be easily measured over the whole sky, and in fact all observations will need to be routinely corrected for this effect.

Literature Cited

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III. THE ARRAY

A. System Requirements

The scientific problems described in Chapter II require an instrument capable of sub-milliarcsec resolution with a large dynamic range (i.e. low sidelobes). Sufficient sensitivity is needed to study weak continuum emission from the nuclei of galaxies, quasars, stellar objects, and the weaker molecular masers, particularly on the longer baselines where the sources are partially resolved. It is also necessary to obtain, in a few minutes or less, sufficient signal-to-noise on an adequate number of calibration sources. Operation at a number of wavelengths between 7 mm and about 1 meter are desired for various continuum problems. We also want to cover the SiO, H_2O and OH maser lines at 0.7, 1.3, 5, and 18 cm and the 21 cm line of neutral hydrogen. Flexibility is required to permit operation over a variety of bandwidths for spectral line and continuum observations.

Very Long Baseline Interferometer observations have shown that the compact radio sources have complex structure containing multiple spatially separated components that change with time. Because of the wide range of opacity at any given frequency, there is a corresponding wide range of surface brightness, and the brightness distribution varies rapidly with wavelength. Thus to map these complex sources, an image-forming array with good dynamic range and flexible frequency coverage is necessary. Several theoretical arguments based on the existence of high-frequency spectral cutoffs, rapid variability, as well as direct observations on intercontinental baselines, have demonstrated that resolutions of at least a few tenths of a milliarcsec are required to resolve the smallest features found in radio galaxies and quasars at centimeter wavelengths. The observations show that most H_2O and OH features are resolved on baselines $\gtrsim$ 5,000 km, but minimum spacings of 100 km or less are required to obtain a field of view sufficiently large to study the maser sources.

There is a maximum practical baseline of about 10,000 km 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. Thus to obtain the highest resolution, we wish to observe at the shortest feasible wavelength which is 0.7 mm.

A sensitivity of several mJy is desired for several reasons.

a) Radio galaxies and quasars, as well as some normal galaxies have nuclear radio emission at this level.

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

c) Individual radio sources have a wide range of surface brightness, and the interferometer fringe amplitude can drop to a few 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 map the lower surface brightness regions.

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 of at least 5 to 1 is necessary to measure the phase to an accuracy of about 10 degrees. Counts of radio sources made at centimeter wavelengths show that there are about 1000 compact sources per steradian with a flux density $S > 0.1$ Jy. 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 degrees 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, and the structure of compact ("point") sources discovered with the VLA can be mapped with the VLBA.

f) Although a few molecular sources are exceptionally strong, many sources of interest, such as those associated with stars or located in external galaxies, are much weaker.

We have adopted a flexible multifrequency system. Operation at a relatively long wavelength is necessary to study lower surface brightness phenomena, and for this purpose we have included a prime-focus system at 327 MHz. Dual-frequency, dual-polarized feeds are used at the Cassegrain focus for all other wavelengths, allowing rapid remote selection of the wavelength bands.

B. Array Configuration

In order to produce high quality maps with the best possible resolution and dynamic range at minimum cost, we have considered the following constraints.

1) The resolution of the Array should be as high as possible within the geographic limitations.

2) The u-v coverage should be reasonably uniform.

3) The configuration should provide good two-dimensional images for all sources north of the galactic center at -28° declination.

4) The Array must contain enough elements so that self-calibration techniques (closure amplitude and phase) work well.

5) The cost of the Array, and therefore the number of elements, should be kept as low as possible consistent with providing the capability necessary to meet the scientific goals of the instrument.

6) The Array may be "centrally condensed" in the sense that the u-v coverage at short spacings might be more complete than at long spacings. This type of configuration facilitates the study of spectral distributions and observations of sources containing bright regions together with relatively extended structure.

7) The configuration should provide well distributed u-v coverage in "snap-shop" mode.

8) The Array should interact well with the VLA both when the VLA is used for its large collecting area and when information over a wide range of scale sizes is desired. In particular the baselines between the ten VLB Array elements and the VLA have a sensitivity which is greater by a factor of about 5 compared with the baselines between the VLB Array elements alone. To exploit this sensitivity these 10 baselines should be reasonably uniformly distributed.

9) The minimum spacing should be no greater than about 100 km. Thus the VLB Array will complement the existing Multi-Telescope-Radio-Linked-Interferometer at Jodrell Bank and probable future extensions of the VLA.

10) Redundant baselines should, where possible, be avoided. They can reduce the number of unknowns but they also reduce the total available information. Although the redundant information can be useful when dealing with uncalibrated data, self-calibration techniques do not require the redundancy, and the quality of the images appear to be improved when the amount of independent visibility data is maximized.

11) As many elements as possible should be at high, dry sites for the best possible performance at high frequencies.

12) Existing observations will cost less to develop and maintain than new sites and should be used where practical.

13) The sites should, if possible, be near major transportation centers.

14) For purposes of this report, the sites are confined to U.S. territory.

The constraints suggest that the Array should have the following characteristics.

1) Hawaii should be used in conjunction with a station in New England, Florida, or Puerto Rico to give maximum resolution in the East-West direction.

2) Alaska should be used to give maximum North-South resolution.

3) The main concentration of stations should be in the Southwest to take advantage of the southern latitude, the high dry sites, and the proximity to the VLA.

4) Sites at or near the VLA, the Owens Valley Radio Observatory, Green Bank, and the Haystack Observatory should be included where feasible in order to take advantage of local engineering and technical support.

5) The element nearest the VLA should be located roughly 100 km from the center of the VLA in order to partially fill the gap between the resolutions of the VLA and the VLB Array when both instruments are used together. The specific location of this element will depend in part on future expansions of the VLA.

6) The Array should consist of a minimum of 10 elements. With a minimum spacing of 200 km and a maximum spacing of 8000 km, 40 ideally distributed baselines are required for complete (u,v) coverage at high declinations. About three times as many baselines are required for similar coverage at low declinations. These represent lower limits on the number

of baselines needed for uniform coverage since ideal distributions are not possible to obtain given the geographic constraints. However, the number of required baselines is reduced because the maximum North-South coverage possible in the U.S. is about 4000 km (Z baseline component) and because a centrally condensed configuration with relatively sparse coverage of the long spacings is acceptable. Ten to twelve elements, providing 45 to 66 baselines appear to be sufficient, at least at high declinations. More elements, including antennas at sites outside the USA, might be added at a later date to reduce the minimum spacing, fill holes in the u-v coverage at longer spacings or extend the resolution. Similarly, at the longer wavelengths, existing radio observatories may be used with the Array to further improve the image quality.

We have evaluated the Array performance as a function of the number of antennas and cost. Table III-1 gives parameters of arrays of between 6 and 16 elements. The columns are the number of array elements (N), the number of baselines (B), the minimum spacing (in km) for an ideal zero redundancy array (not possible) which provides complete coverage to 8000 km for high declination sources ($d = 8000/B$), the percent of the total phase information which is contained in the closure phases (P), the percent of the total amplitude information which is contained in the closure amplitudes (A), the incremental improvement (over N-1 stations) in the amplitudes and closure phases ($\Delta I = (n-1)^2/(N-2)^2$ where the total information from an array is taken to be the sum of all amplitudes and phases [$2\ N(N-1)/2 - (N-1)$] and the incremental cost (ΔC) assuming 3.3 million dollars per element plus 7.0 million dollars for the operations center.

The parameters given in Table III-1 provide no clear break point that sets the number of elements needed, although with less than nine stations the percentage of the total visibility information contained in the closure parameters becomes unsatisfactorily low. For purposes of this report we consider 10 element arrays. Nine elements is probably the lower limit for a tolerable configuration, but the field of view is considerably reduced. Eleven or more elements would significantly improve the performance of the array. This improvement may not justify the cost of an additional new element at this time. However, at the long wavelengths, some existing antennas can be used in conjunction with the ten new ones to improve the dynamic range. But to do this the 10 new antennas must be located away from the existing sites.

Proposed array configurations may be evaluated by several methods, none of which are free of subjective judgments, of controversial selection criteria, or of dependence on variations in reduction techniques. The primary method used in this study was to first make direct examination of u-v plots (transfer functions). This method requires subjective judgments since it does not provide a quantitative comparison of arrays. However, it is computationally fast and it allows the investigator to apply complex criteria in judging arrays and in deciding which arrays to examine further. Final candidate arrays are compared by the much more involved procedure of calculating the dynamic range in CLEAN maps produced using artificial data with calibrated amplitudes and phases. The dynamic range is defined as the ratio of the highest signal peak on the map to the greatest difference between the map and the model (convolved with the clean beam) for which the artificial data was generated (e.g. Cohen 1980). Other possible techniques involving calculation of sidelobe levels in the dirty beam or application of quantitative selection criteria to transfer functions have not been used. After selecting a tentative configuration, maps were made using standard Fourier inversion and CLEAN techniques.

Table III-2 gives the locations of the elements of the Array D2 which is used for cost estimates in this report (D2 is an internal bookkeeping number used here as a convenient label to distinguish this array from other configurations that we have studied). The D2 configuration meets the criteria set forth earlier in this section, but minor changes are needed, such as moving the element at the VLA about 100 km to better complement the VLA in joint observations and moving the Brownsville station inland out of the path of hurricanes. It is likely that the ongoing configuration studies will produce a final array somewhat superior to Array D2; but major improvements are unlikely so this array provides a good test of the costs and capabilities of a 10 station array. Table III-3 gives the dynamic ranges obtained with Array D2 on a test source (see Figure III-3) at declinations centered in bands, each of which contains 10% of the sky. To facilitate comparison of configurations evaluated in the Caltech study, we have used the same test source "Daisy", but our dynamic ranges were determined using longer tracks, a lower loopgain, and more CLEAN steps than were used in the Caltech study. Dynamic ranges for the Caltech Array 13, calculated using our procedure, are also shown in Table III-2. The differences between our results and those derived at Caltech and the variations in the results in four runs at dec 44° demonstrate the dependence of the technique on minor details of the analysis. In particular, we note the variations in apparent dynamic range resulting solely from the effect of noise.

A map showing the locations of the elements of Array D2 is shown in Figure III-1. The transfer functions of the array at the declinations at which the dynamic ranges were calculated are presented in Figure III-2. The transfer functions of the array, showing only the baselines to the VLA, are shown in Figure III-3. The fake source "Daisy" used to evaluate the dynamic ranges is shown in Figure III-4 along with the CLEAN map produced using a conventional Fourier inversion with full amplitude and phase data in the presence of random noise appropriate to a source of 0.5 Jy. Figure III-5 shows a CLEAN VLA map of M87 together with a map reproduced from appropriately scaled, artificial data generated from hypothetical observations with Array D2.

We have also evaluated the improvement in resolution and image quality expected from several possible additional or complementary array elements. Figure III-6 shows the transfer function of Array D2 plus elements in Edmonton and Newfoundland, Canada (Figure III-6a); in northern Italy (Figure III-6b); in Japan (Figure III-6c); in Puerto Rico (Figure III-6d), and in Australia (Figure III-6e).

TABLE III-1

ARRAY PERFORMANCE AS A FUNCTION OF THE NUMBER OF ELEMENTS

N	B	d(km)	P(%)	A(%)	ΔI(%)	ΔC(%)
6	15	533	67	60	56	14
7	21	381	71	67	44	12
8	28	285	75	71	36	11
9	36	222	78	75	31	10
10	45	178	80	78	27	9
11	55	245	82	80	23	8
12	66	121	83	82	21	8
13	78	102	85	83	19	7
14	91	88	86	85	17	7
15	105	76	87	86	16	6
16	120	67	88	87	15	6

TABLE III-2

ARRAY ELEMENT LOCATIONS

Array D2	
	Location
1.	Island of Hawaii
2.	Anchorage, Alaska
3.	Big Pine, California
4.	Very Large Array, New Mexico
5.	Santa Fe, New Mexico
6.	Boulder, Colorado
7.	Grand Forks, North Dakota
8.	Brownsville, Texas
9.	Green Bank, West Virginia
10.	Westford, Massachusetts

TABLE III-3

Dynamic Ranges[1]

Declination	Array	Dynamic Range
64	Array D2	252
44	"	238[2]
	"	184
	"	204
	"	214
30	"	180
18	"	162
6	"	120
-6	"	93
-18	"	97
44	Array 13[3]	224
-6	"	73

1. Derived for test source Daisy of Cohen 1980 (see Figure III-4) using a total flux of 20 Jy for the test source and using a rms noise of 0.2 Jy in each 10 min data point. CLEAN was used with a loopgain of 0.2 for 5000 iterations. The dynamic range given in column 3 is the value appropriate to a 0.5 Jy source.

2. Four runs of the programs with the only difference due to the use of a random number generator in simulating noisy data.

3. Array 13 of Cohen 1980. The dynamic ranges given in Cohen 1980 for Array 13 are 205 at dec 44° and 66 at dec -6°.

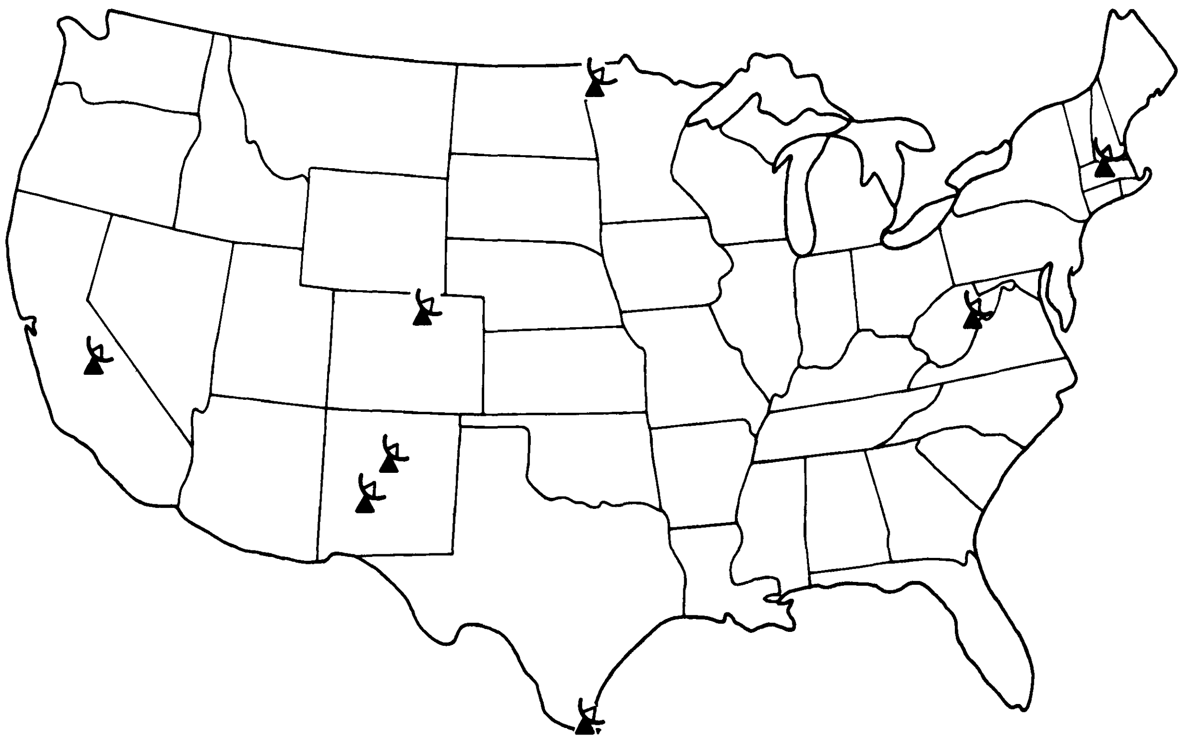


Figure III-1. A map showing the locations of the elements of Array D2 within the continental United States. There are also stations in Anchorage, Alaska and on the Island of Hawaii.

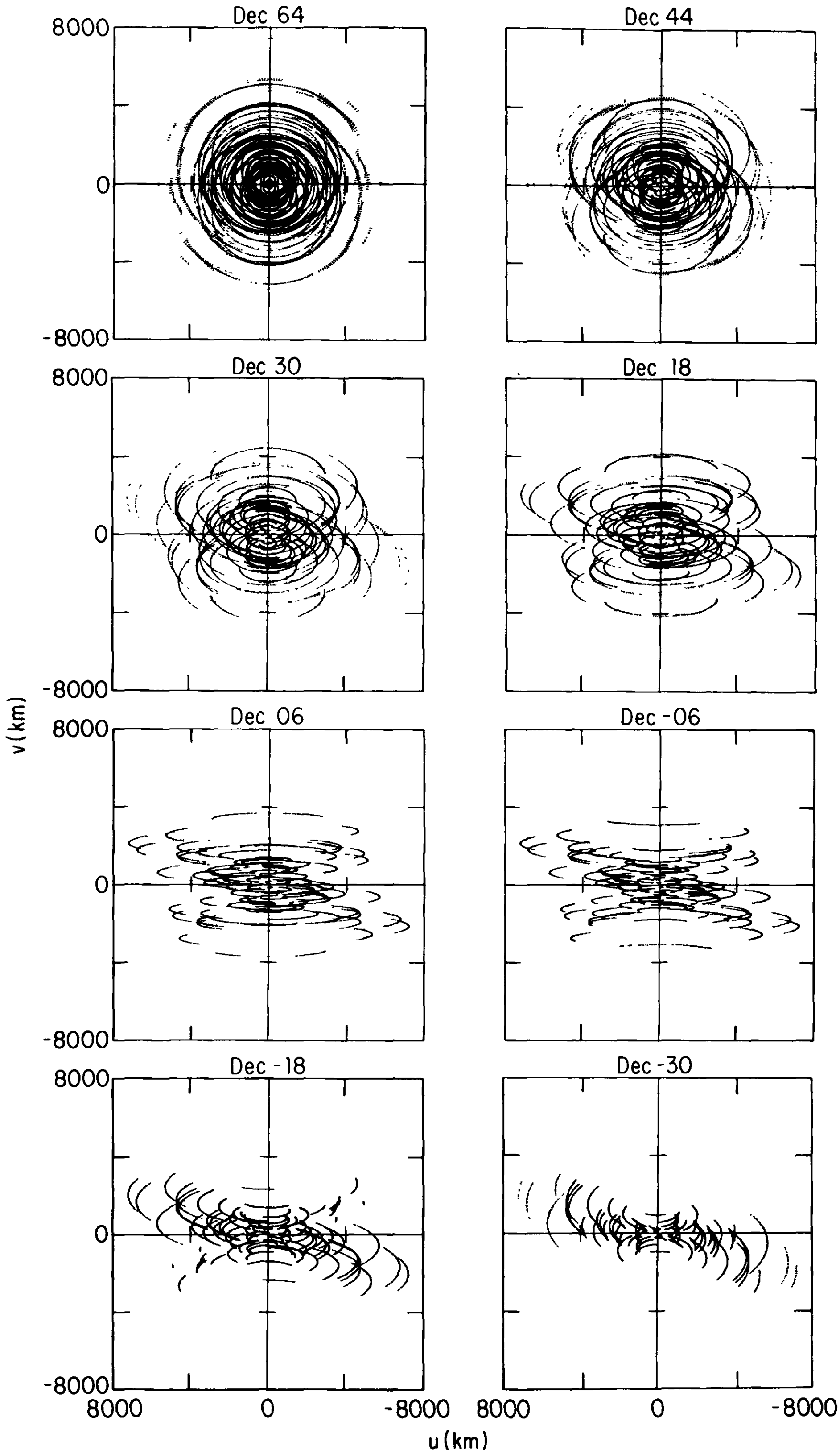


Figure III-2 Transfer functions for Array D2 at declinations centered in bands, each of which contains 10% of the sky.

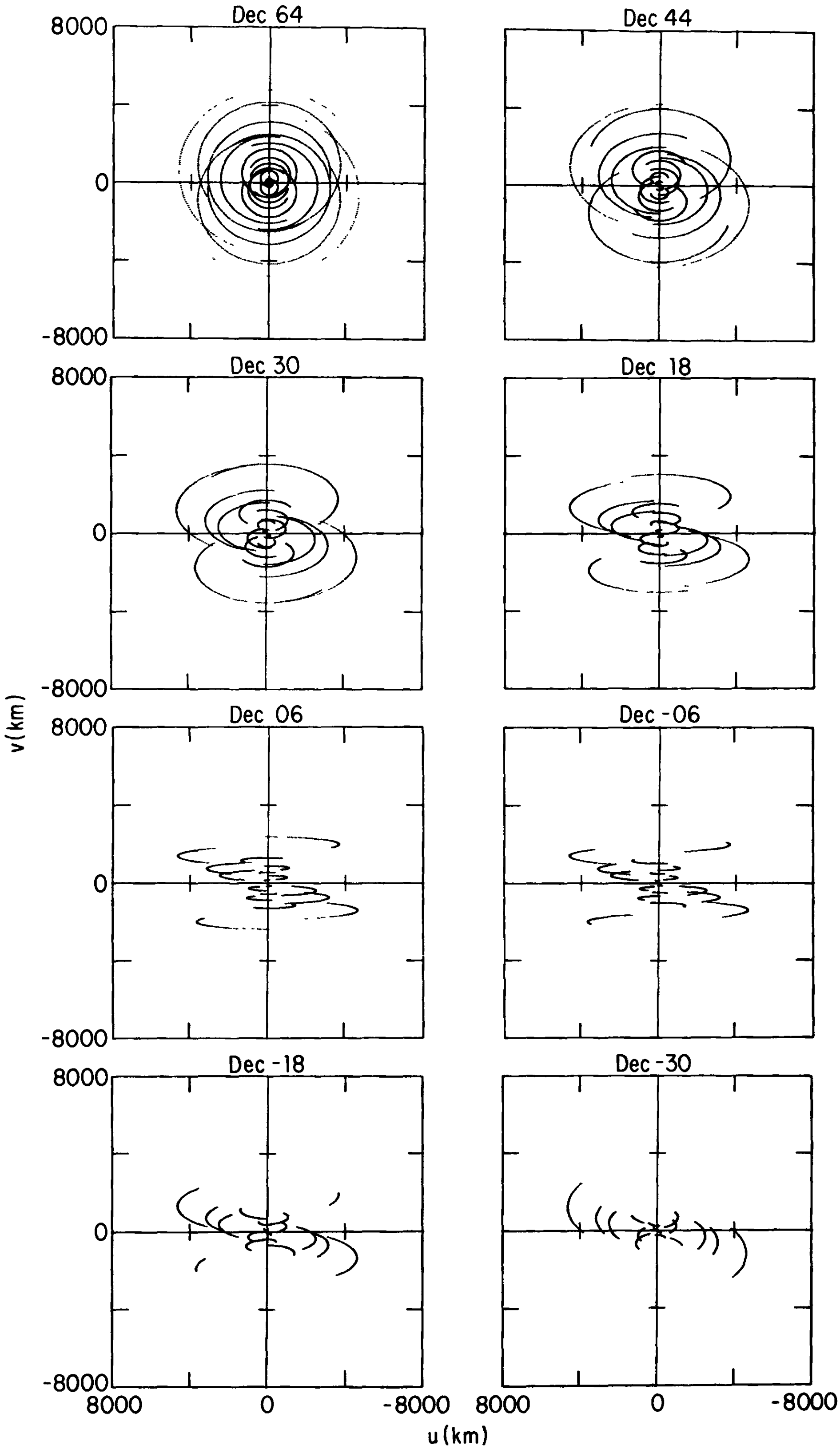


Figure III-3 Transfer functions for Array D2 showing only the baselines to the VLA. When the Array is used with the VLA, these baselines will have about five times the sensitivity of the others.

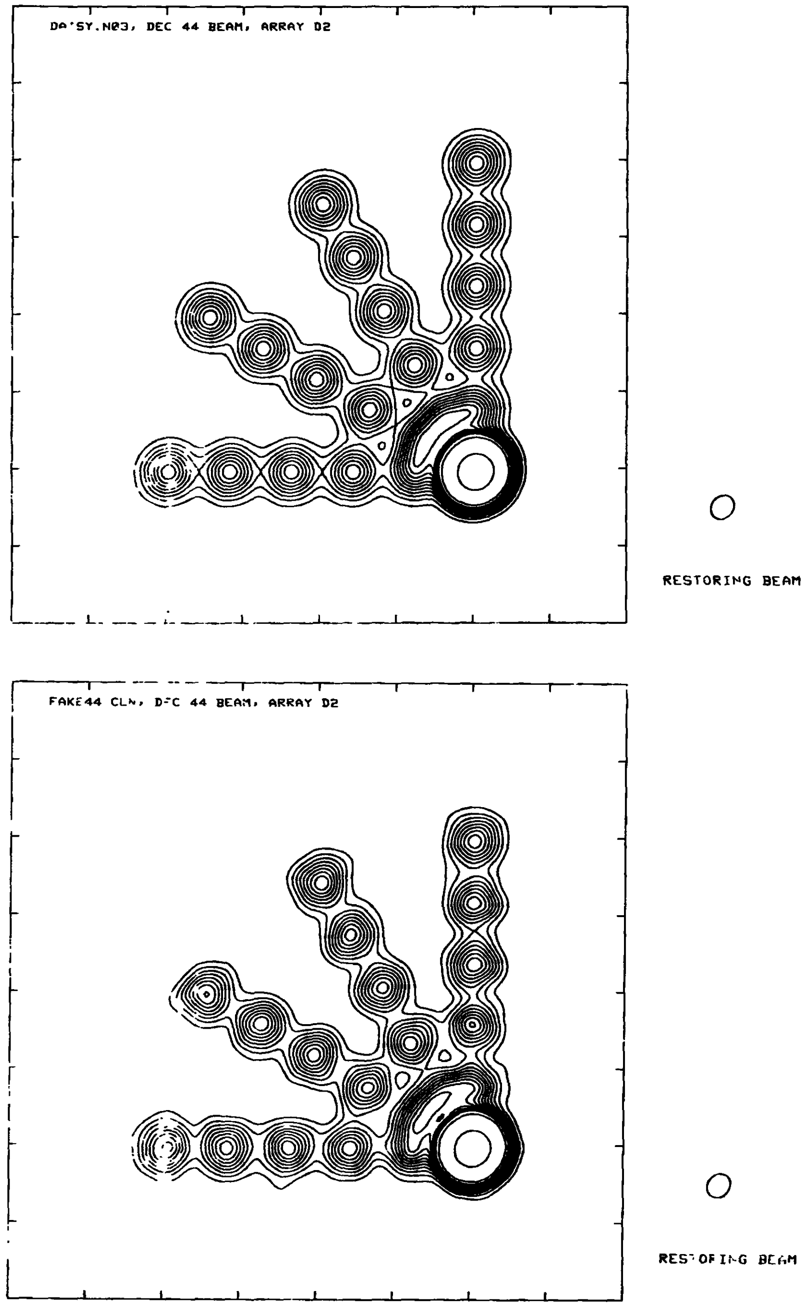
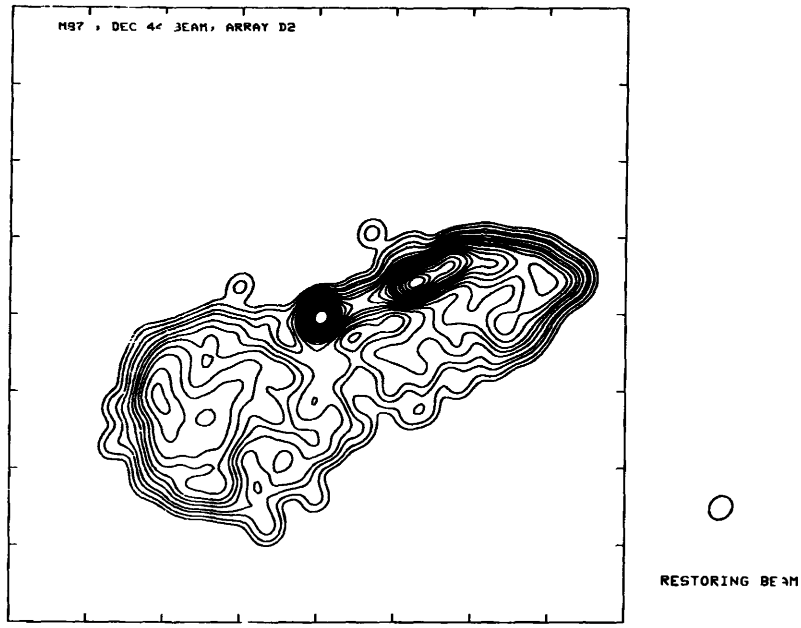


Figure III-4 a) Test source Daisy (Cohen 1980) convolved with the CLEAN beam of Array D2 for observations at 44° declination. The contour levels are -1.0, -0.5, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 10.0, and 50.0 percent of the peak.

b) A CLEAN map of Daisy made with artificial data generated from hypothetical observations with Array D2. Noise has been added to the data to simulate real observations of a source with a total flux of 0.5 Jy. The contour levels are the same as in (a).



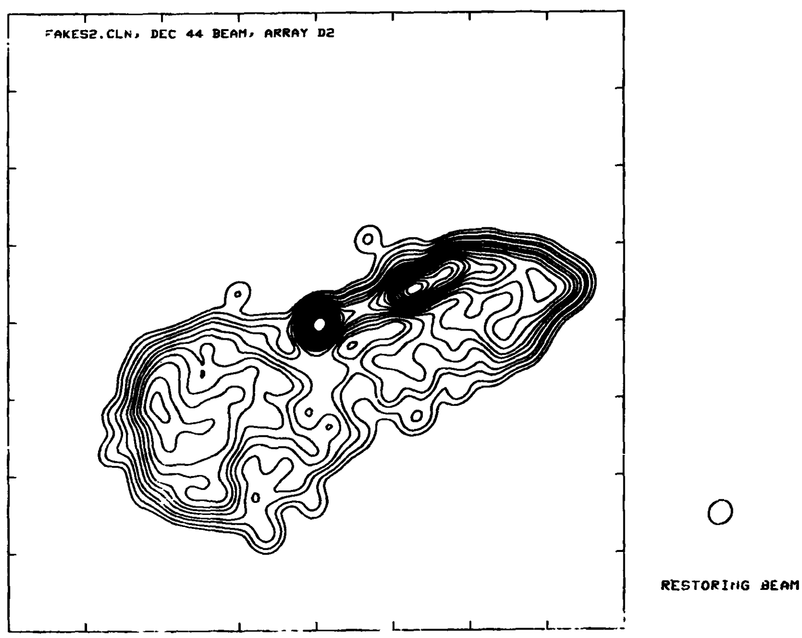


Figure III-5 a) A test source based on the 600 highest map cells in a VLA map of M87 which has been convolved with the CLEAN beam of Array D2 for observations at 44° declination. The test source is scaled down to a hypothetical size appropriate for VLBI observations. The contour levels are -1, -0.5, 0.5, 1, 2, 3, 5, 7, 9, 12, 15, 20, 25, 30, 35, 40, 50, 60, 70, and 80 percent of the peak.

b) A CLEAN map of the M87 test source made with artificial data generated from hypothetical observations with Array D2 at a declination of 44°. Noise has been added to the data to simulate real observations of a source with a total flux of 15 Jy. The contour levels are the same as in (a).

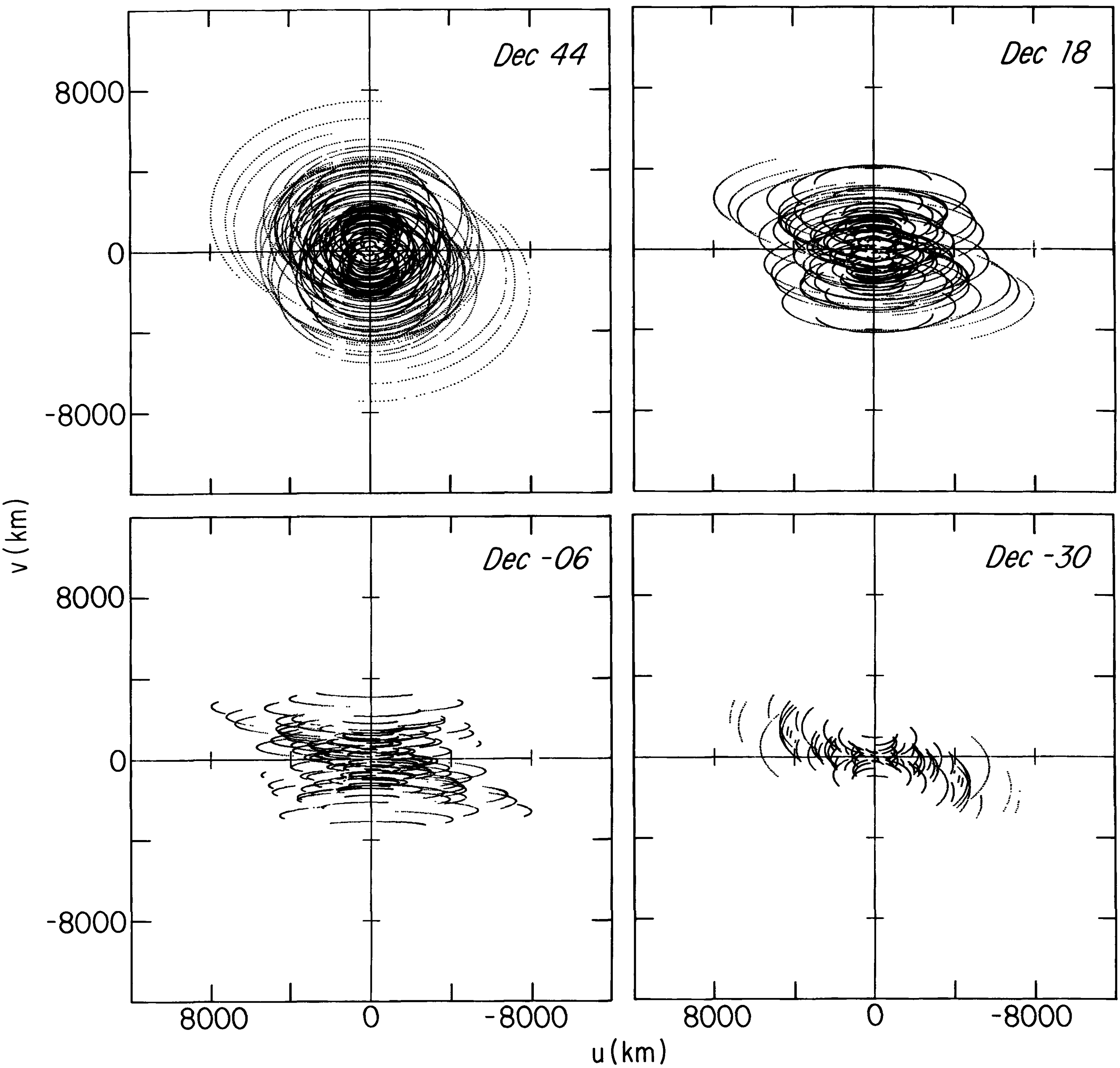


Figure III-6a **The transfer functions for Array D2 plus Edmonton and Newfoundland.**

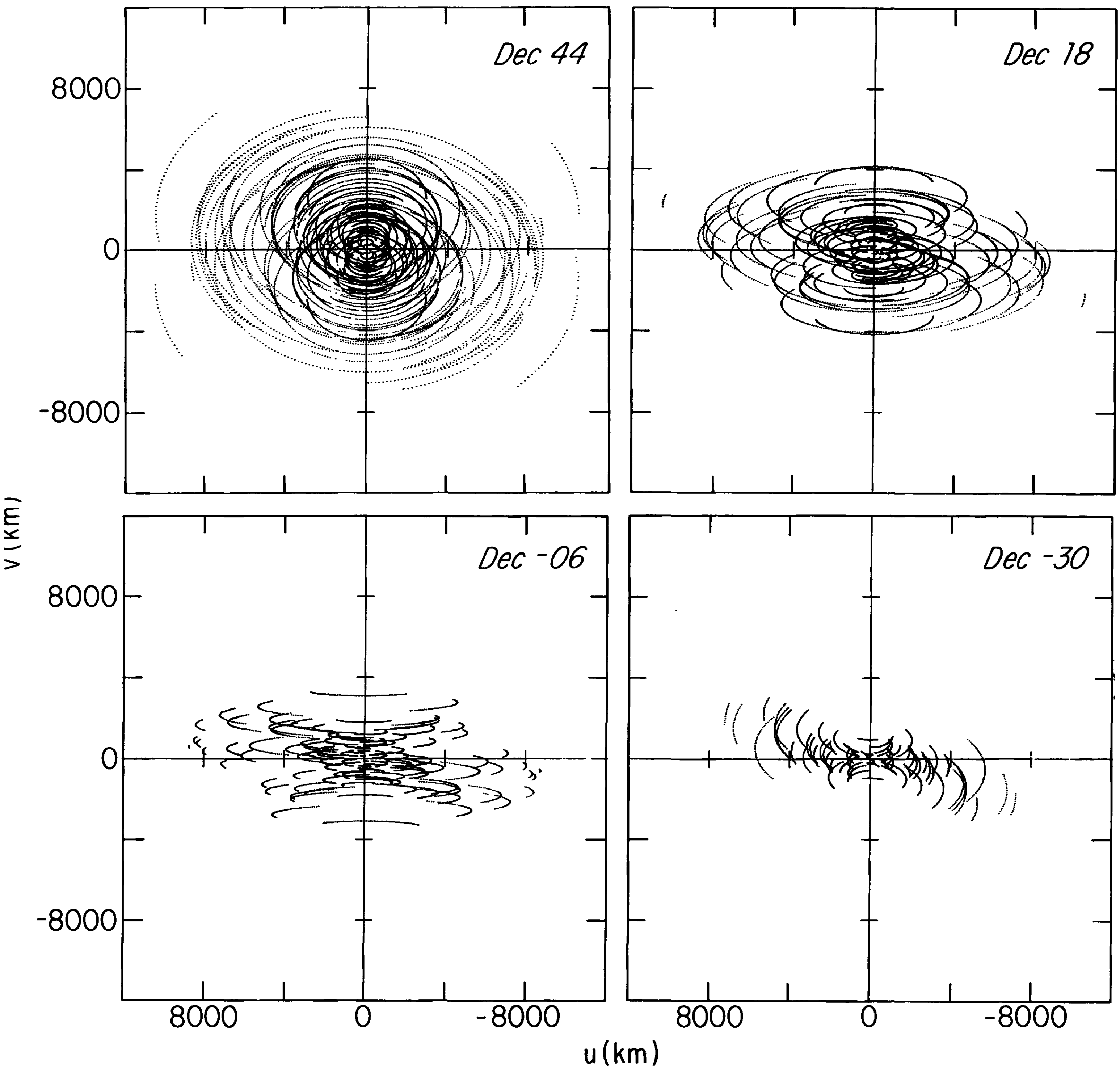


Figure III-6b **The transfer functions for Array D2 plus Italy.**

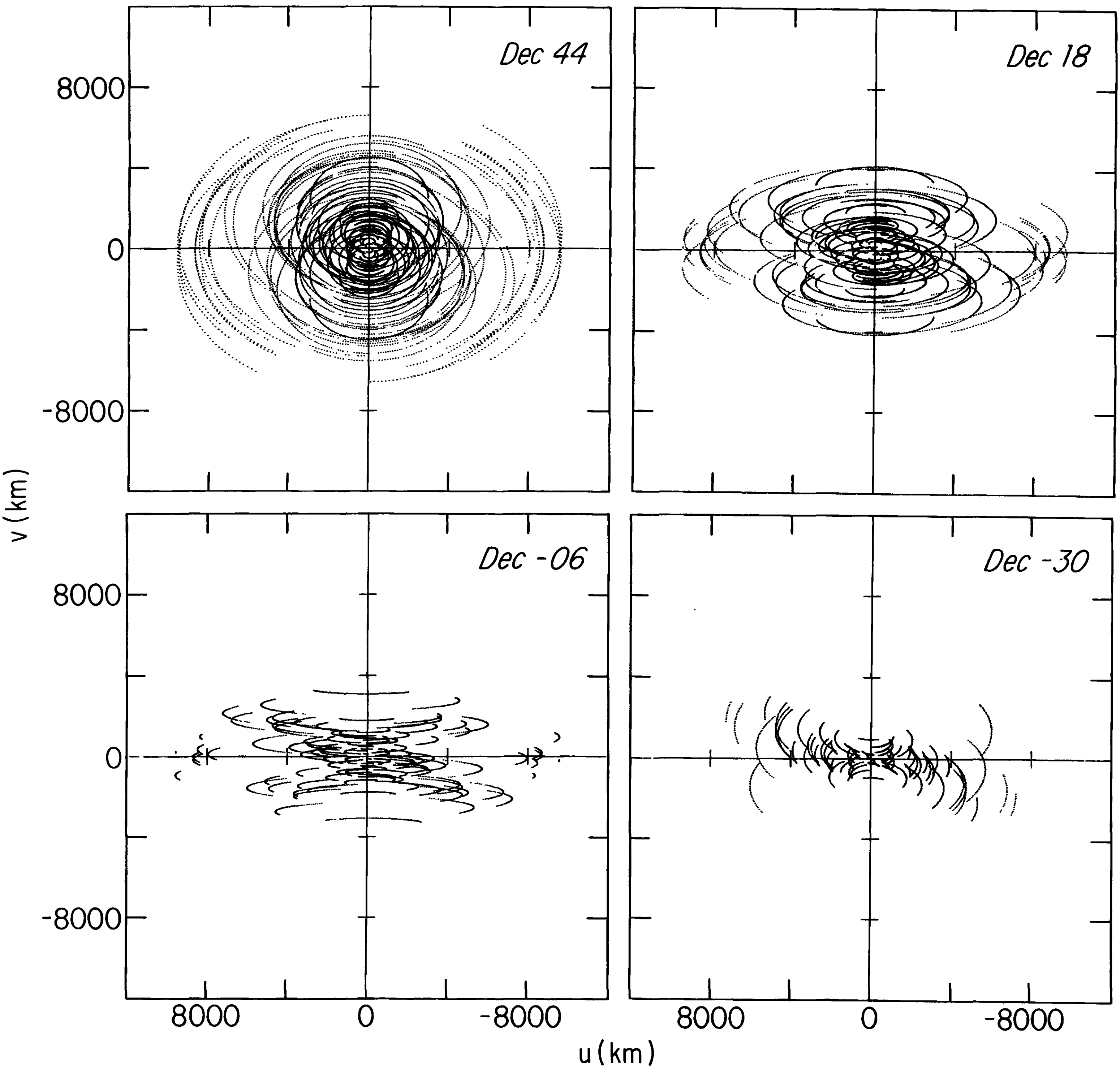


Figure III-6c   The transfer functions for Array D2 plus Japan.

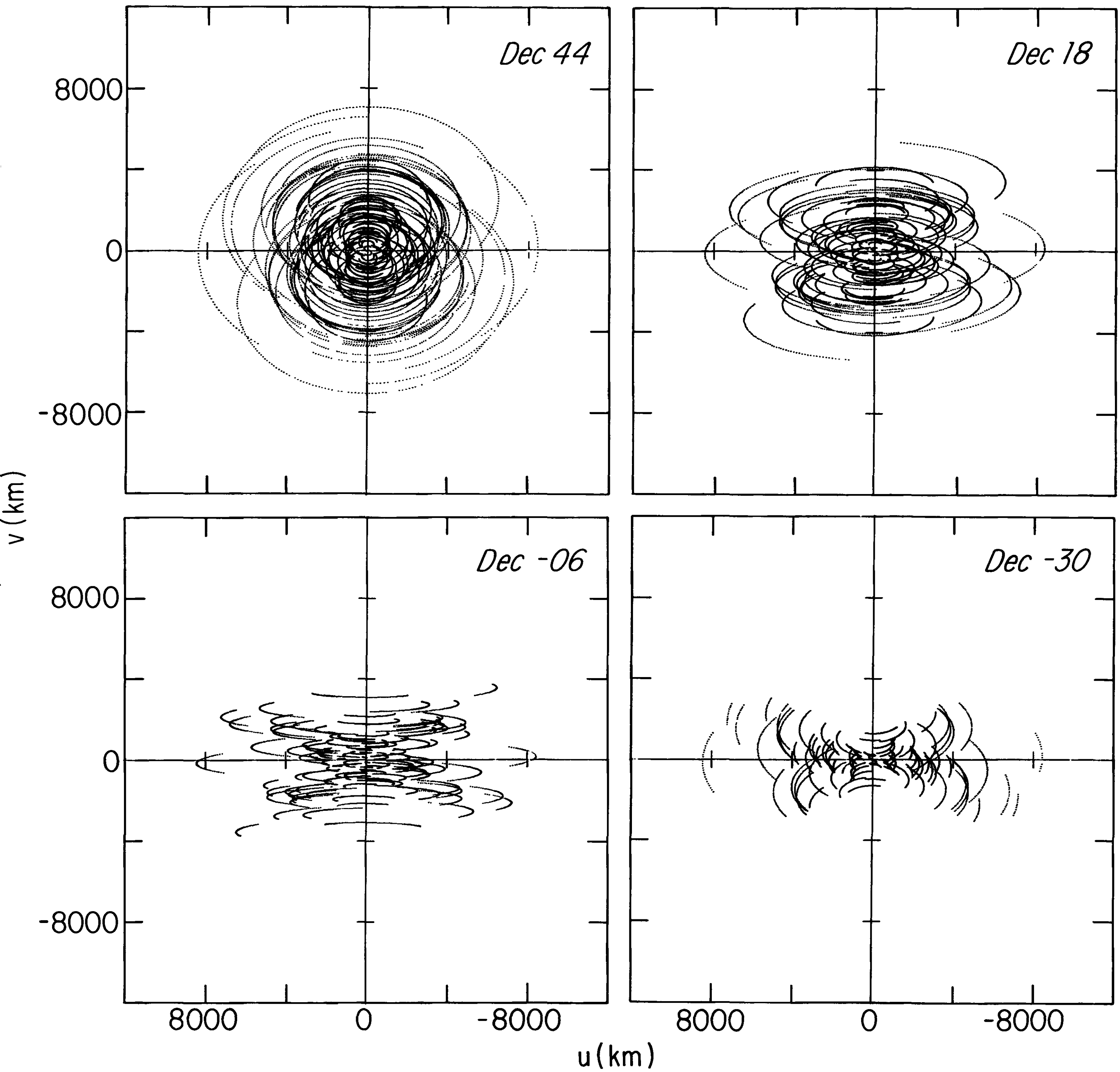


Figure III-6d The transfer functions for Array D2 plus Arecibo.

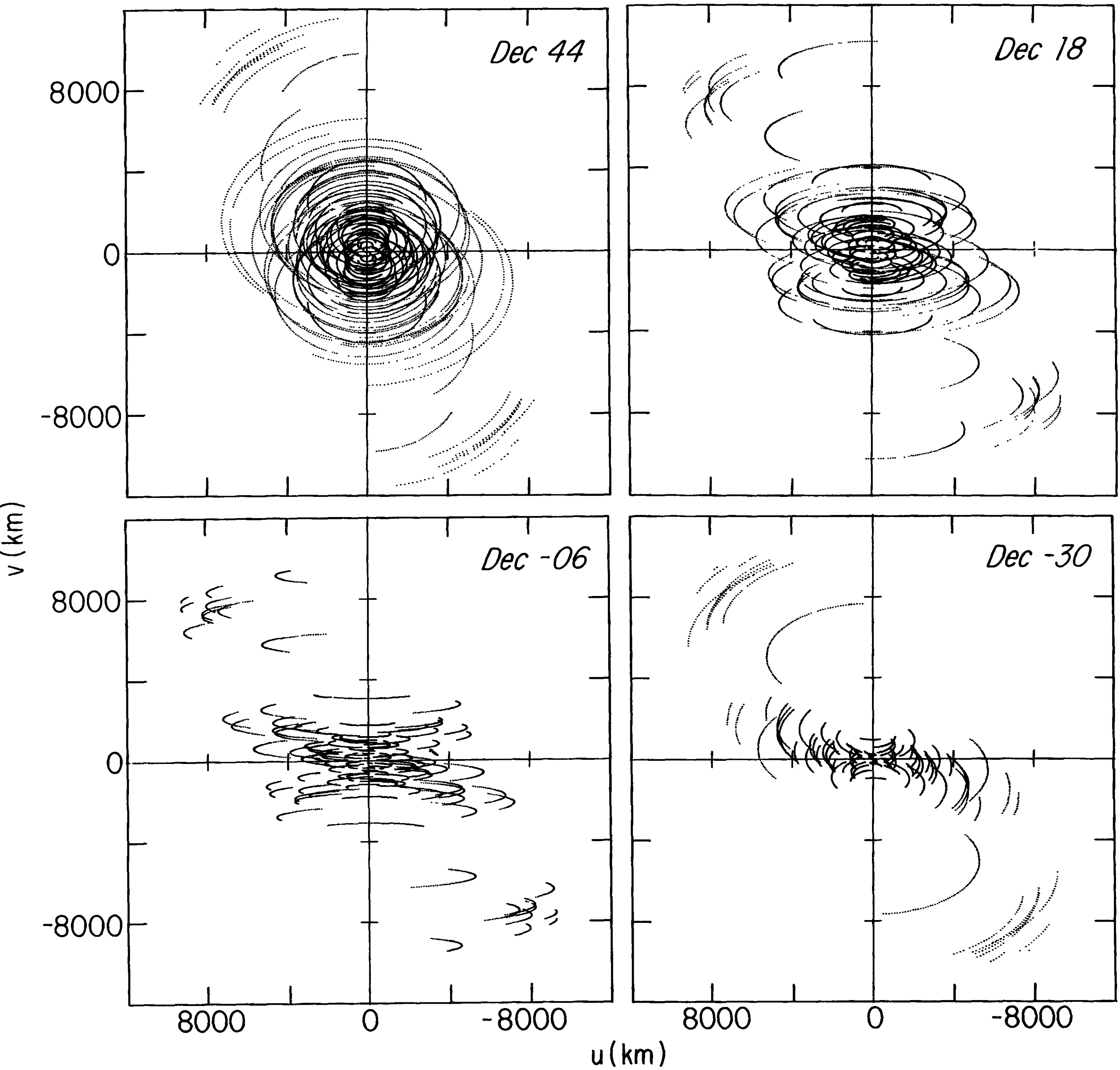


Figure III-6e   The transfer functions for Array D2 plus Tidbinbilla, Australia.

C. Antenna Elements

The largest possible antennas are desired as elements in order to obtain the best sensitivity. This is especially true where the bandwidth is limited by the IF transmission system as it is for a VLB Array. Good sensitivity is not only needed for the obvious reason to study the weak sources, but numerical simulations show that the results obtained from self-calibrated data are very sensitive to noise. This is because even for moderately strong sources the signal-to-noise ratio can become low in portions of the (u,v) plane.

However, as the size of the elements is increased, the cost increases rapidly, and operation at short wavelengths is sacrificed, due to increased surface irregularities, larger pointing errors, and smaller antenna patterns. The optimum size for the elements of an array operating at decimeter and centimeter wavelengths appears to be in the range 15 to 40 meters. We have adopted a size of 25m as the best compromise between collecting area, cost, pointing accuracy, and short wavelength performance, and because antennas of this size are commonly produced in industry.

It is probably possible to obtain a slight improvement in sensitivity at the same cost by using a somewhat smaller antenna and more sophisticated radiometer systems. We have elected not to do this for three reasons. One, the more sensitive receivers will be more difficult to maintain at the remote sites; second, we recognize that while the useful lifetime of the antenna is several decades at least, the receiver systems may be replaced after 5 to 7 years; third, the cost of antenna structures increases with time due to inflation, while for a given performance specification, receiver costs have decreased with time. It is therefore appropriate to initially build a somewhat larger antenna than the one corresponding to the antenna-radiometer combination which gives maximum sensitivity for a given cost.

Many antennas similar to the elements which will be used for the VLBA have been built in the past. In particular, considerable experience has been gained in the procurement and construction of the VLA 25m antenna elements, and the cost (including the effect of past escalation) and performance of such antennas is well known. It is clear that the antenna elements required for the VLB Array will not present any significant technical difficulties or cost uncertainties.

The elements used for the VLB Array must operate under a wide range of environmental conditions ranging from tropical to sub-artic. Because of the relatively great importance attached to the shorter wavelengths, we have specified that the antennas perform well at a wavelength of 43 GHz (7 mm). This requires an r.m.s. surface error of 0.45 mm ($\lambda/16$) and non-repeatable pointing errors of less than 10 arc seconds. We have paid particular attention to reducing the non-random non-repeatable pointing errors, as in practice these often limit the precision of any measurements, rather than surface irregularities or repeatable structural deformations. The antenna will have a Cassegrain configuration, which has a number of advantages over prime focus systems. 1) It gives low spillover temperatures so that low noise receivers can be exploited to obtain maximum sensitivity; 2) it will permit the simultaneous installation of multiple-feed radiometer systems which can be remotely switched; 3) it will allow the use of a non-parabolically shaped main reflector to raise the aperture efficiency to $\sim$ 70% at wavelengths where surface irregularities are negligible. A more detailed discussion of the antenna requirements is given in a report by Findlay (1980).

We have considered two approaches to the design of the VLBA elements. In the first case we have started with the E-Systems VLA design. This is the most conservative approach. Twenty-eight of these antennas have been fabricated for the VLA. Considerable experience is being obtained with their operation, and the performance will be understood in detail, and where necessary, design modifications can be introduced. The cost can be accurately estimated based on VLA costs.

The primary limitation of the VLA antennas has been the uncertainty in the pointing due to thermal distortions under the extreme conditions which can occur at the 7000 ft semi-desert site in New Mexico. Thermal effects are expected to be less severe at the other VLBA sites, but our pointing requirements are more demanding than at the VLA. Further improvement in the performance of the E-Systems antenna design can be achieved by shielding and insulating parts of the structure, restructuring the pedestal, strengthening the yoke arm and "feed support" legs, and fabricating more accurate surface panels.

As an alternate approach, we have considered a new design (Wong, 1980). Unlike the VLA antennas, the VLB Array antennas are stationary, so a wheel-and-track concept can be used for superior performance and possible lower cost. The wheel-and-track design allows a wider separation of elevation bearings than the VLA compact design, so the thermal and wind induced pointing errors are reduced. Also by using a geometry of a space frame similar to that of geodetic domes on the reflector structure and the equal-softness concept on the supporting part, the gravitational deflections are minimized. The new design has a surface accuracy better than the specification. It is simple in geometry and light in weight. The entire structure consists of only two types of steel pipes. Hence, the new design gives a considerable cost saving.

Several kinds of surface plates are being considered, including plates with stretched aluminum skin and reinforcing ribs as in the VLA structure, and plates with fiberglass-epoxy-honeycomb core as in the 100-m Effelsberg dish. Two inexpensive fiberglass-epoxy-balsa-wood-core sandwich plates have been built for evaluation. Should this approach be proven acceptable, the antenna cost could be even further reduced.

D. Feed Arrangement

A versatile feed system is required which will allow operation of the antenna at 327 MHz, 610 MHz, 1.4-1.7 GHz, 2.2 GHz, 5-6 GHz, 8.85 GHz, 10.7 GHz, 15.4 GHz, 22 GHz and 43 GHz. The design which we have considered has three main features:

(1) Remote Operation. Since it is important to minimize the operating manpower at the antennas and to permit rapid frequency changes, radiometer changes must require a minimum of hardware changes on the antenna. An offset Cassegrain reflector geometry, similar to the VLA, is proposed with all receivers, except for the one at 327 MHz located at the secondary focus. Frequency changes will simply require rotation of the subreflector about the main reflector axis, as is one on the VLA. The reflectors will be shaped for high efficiency. The 327 MHz feed will be located at the primary focus. It can be located on axis if the subreflector is removed, or off axis, at the edge of the subreflector, with reduced performance.

(2) Large Subreflector. A much larger than usual subreflector of 3.66m diameter is proposed. This will reduce subreflector diffraction loss at the lower frequencies and allow all feeds to be smaller, simpler to design, and less expensive. The reduced feed size will allow the feeds to be

arranged in a smaller circle around the main reflector axis so that the circular cross polarization problem, present in the VLA antennas, is reduced. Also, because of the smaller feeds the subreflector will not be in the near field of the feeds. The increase in side-lobe level resulting from the use of a larger subreflector does not deteriorate the performance of the Array significantly.

(3) Dual-Frequency Feeds. Since 8 frequency bands must be accommodated at the Cassegrain focus, dual-frequency feeds are used to make more efficient use of space. Simultaneous dual-frequency observations will also be possible in the 1.5/5 GHz, the 2.2/8.4 GHz, the 10.7/22 GHz, and 15/43 GHz bands.

The high-performance dual-frequency feeds recently developed by JPL (e.g. Williams and Withington 1979) is suitable for these frequency ranges. The JPL and VLBA subreflectors subtend very nearly the same angle ($32\overset{\circ}{.}7$ and $30\overset{\circ}{.}5$ respectively) so that an almost identical design, scaled for frequency, can be used. This dual-frequency feed works on the principle that when the length of a horn of fixed flare angle is made sufficiently long, the increasing phase error in the horn aperture prevents the radiation pattern from getting any narrower and the beamwidth of the horn is determined only by the flare angle. If a dual-frequency horn is operated in the "beamwidth saturation" mode at both frequencies, its radiation patterns will be very nearly the same at both frequencies.

For the 610 MHz feed it is proposed to use a single ring of helices each having a total of 15 turns. This feed arrangement is chosen because, for a given aperture diameter, an annular aperture distribution has the narrowest beamwidth of any circularly symmetric distribution. This is therefore the smallest possible feed, although the spillover efficiency is somewhat low.

The 327 MHz feed at the prime focus will probably be a conventional scalar feed which would normally give an aperture efficiency of approximately 50%. If it is located 1.83m off axis at the edge of the subreflector, a gain loss of 2 dB can be expected and coma aberration will increase the first sidelobe level by 10 dB. Thus the overall efficiency will be about 32 percent at this frequency.

Figures III-7 and III-8 show the proposed Cassegrain geometry and feed layout.

System Performance. The shaped reflector system will provide uniform illumination in the aperture of the main reflector with a -14 db illumination on the edge of the subreflector, and will keep the low frequency feeds to a manageable size. The shaped main reflector should not give significant gain loss at 327 MHz. For this reason the difference between the shaped main reflector and its best fit parabola should not exceed 1.8 cm rms (for the VLA this difference is 0.97 cm rms). The main reflector will have a surface accuracy of 0.45 mm ($\lambda/16$ at 43 GHz). A reasonable goal for the subreflector accuracy is 0.12 mm, giving a combined surface rms of 0.46 mm, so that there is no significant loss of gain due to the subreflector irregularities.

Table III-4 shows the aperture illumination efficiency, the surface accuracy efficiency, the fraction of the energy lost due to subreflector diffraction with a -14 dB illumination on the subreflector, and the fraction of the feed energy incident on the subreflector across the range of observing frequencies.

A reasonable goal for total blocked area, including the subreflector support legs and the blockage of the 3.66 m diameter subreflector is 7%. This gives a blockage efficiency of .86 in a uniformly illuminated reflector.

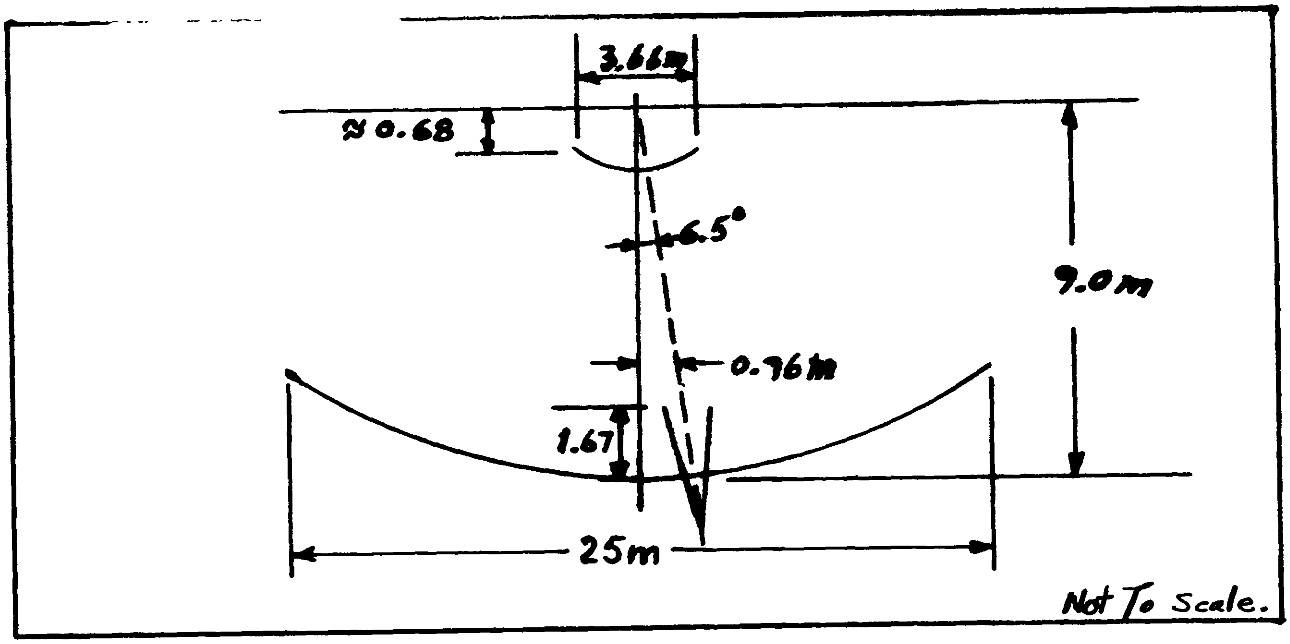


Figure III-7 Proposed Cassegrain Geometry

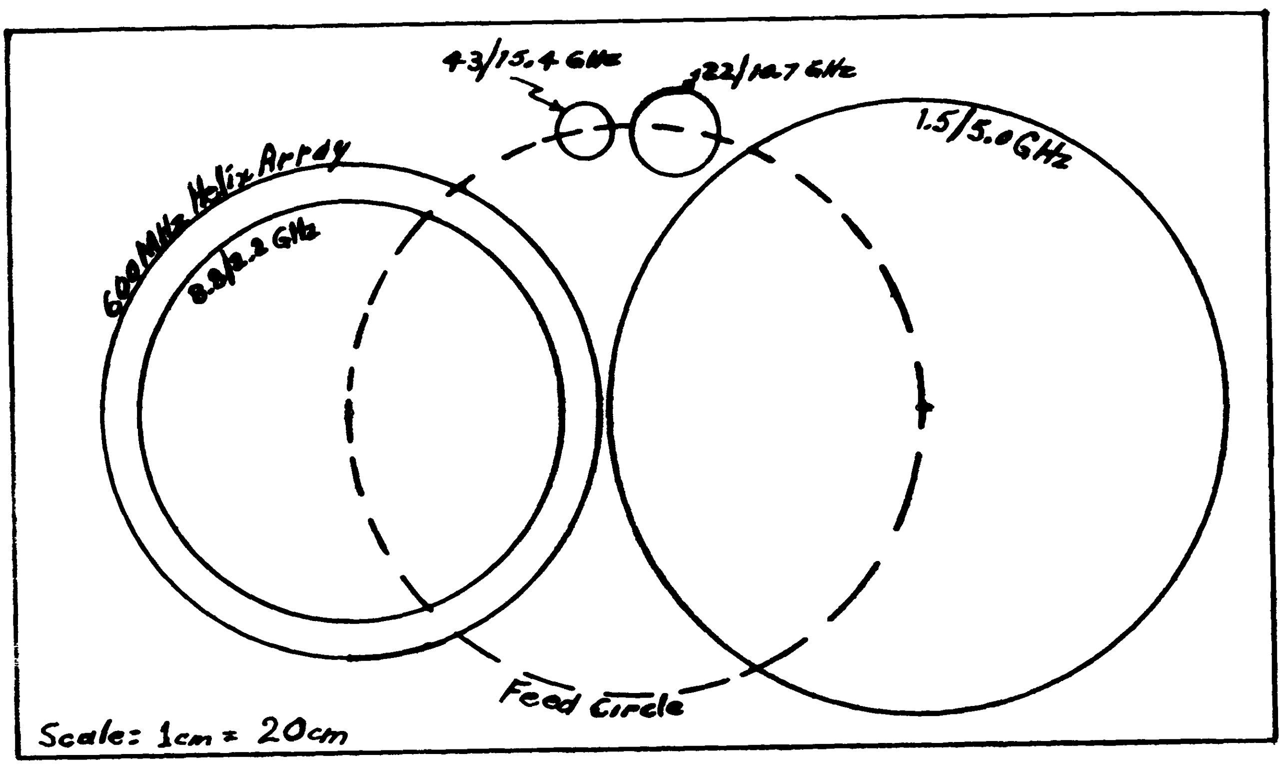


Figure III-8 Proposed Feed Layout

The nominal phase center of the Cassegrain geometry, as shown in Figure III-7, is 1.7 m in front of the main reflector vertex. Since the dual frequency horns have their phase centers at their throats, it will be necessary to refocus the subreflector. With a Cassegrain magnification of 5.2, this should not result in significant loss of phase efficiency.

A 25 m circular aperture with uniform illumination and 3.7 m diameter circular blockage at its center has a first sidelobe level of -13.7 dB. The VLA antennas have sidelobes of this level. However, for the VLB Array, this high first sidelobe level is not expected to be a problem.

Since the feeds of this VLBA antenna are somewhat closer to the main reflector axis than they are on the VLA antenna, the instrumental circular polarization present on the VLA antennas will be slightly reduced. A separation between the circularly polarized beams of 0.047 beamwidth can be expected. In general this should not be a problem since most compact sources will be confined to the antenna axis. At 43 GHz pointing problems will cause a circular polarization uncertainty of approximately 3%, but it may be possible to eliminate this by self-calibration of the data.

TABLE III-4

PREDICTED FEED PERFORMANCE

Frequency	E_{surf}	E_{illum}	E_{diff}	E_{spill}	E_{block}	E_{phase}	E_{misc}	E_{total}
610 MHz	1.0	.95	.87	.64	.86	.98	.95	.42
1.5 GHz	1.0	.98	.92	.90	.86	.98	.95	.65
5.0 GHz	.99	.99	.96	.90	.86	.98	.95	.68
8.4 GHz	.90	.99	.97	.90	.86	.98	.95	.68
10.7 GHz	.96	.99	.99	.90	.86	.98	.95	.68
15 GHz	.92	.99	.99	.90	.86	.98	.95	.65
22 GHz	.84	.99	.99	.90	.86	.98	.95	.59
43 GHz	.50	.99	.99	.90	.86	.98	.95	.35

E_{surf} = Surface accuracy efficiency

E_{illum} = Aperture illumination efficiency

E_{diff} = Subreflector diffraction efficiency

E_{spill} = Feed spillover efficiency

E_{block} = Blockage efficiency

E_{phase} = Phase efficiency

E_{misc} = Efficiency due to miscellaneous effects, e.g. VSWR efficiency, loss in the feed and its window.

E. Front End Systems

We have considered two types of low-noise front ends to satisfy the sensitivity requirements. These are upconverter-maser systems and cooled or uncooled GASFET amplifiers. Table III-5 shows a comparison of the performance of different types of front ends at the various frequency bands.

TABLE III-5

RECEIVER NOISE TEMPERATURES FOR VARIOUS TYPES OF FRONT-ENDS AS A FUNCTION OF FREQUENCY (VALUES IN PARENTHESIS ARE 1986 ESTIMATES)

FREQUENCY	RECEIVER NOISE TEMPERATURE			ADDITIONAL NOISE*
	GASFET @ 300K	GASFET @ 20K	UP-CONV -MASER @ 4K	
0.33	40 (30)	10 (7)	-	35
0.61	45 (30)	10 (7)	-	31
1.4 - 1.7	50 (40)	12 (9)	5	22
2.2	60 (50)	15 (11)	10	22
5-6	90 (70)	20 (14)	10	22
8.8	130 (110)	30 (20)	10	20
10.7	170 (140)	40 (25)	10	25
15	280 (170)	70 (40)	15	32
22	470 (200)	130 (60)	10	40
43	- (800)	- (200)	(30)	45

* ADDITIONAL NOISE DUE TO TRANSMISSION LINES, ANTENNA LOSSES, AND ATMOSPHERE.

The most sensitive and versatile radiometer systems currently being used in radio astronomy use parametric upconverters working into a maser amplifier. NRAO has recently installed a flexible upconverter maser on the 140-ft telescope. Evaluation is not yet complete, but initial tests indicate that the goal of achieving system temperatures in the range 30 to 50 K between 4.5 and 26 GHz will be achieved. But although the upconverter-maser system has low receiver noise and nearly continuous frequency coverage, they are expensive and require skilled personnel to maintain and operate. We have therefore chosen to use GASFET amplifiers as the first stage of most of the radiometers. Recent work at NRAO and Berkeley in developing cooled GASFET amplifiers for 1.4-1.7 GHz and 4.5-5.0 GHz has shown that these amplifiers are capable of good low-noise performance and high reliability. About 25 of the 4.5-5.0 GHz amplifiers have replaced parametric amplifiers in the VLA front ends and they have been operating for many months without a single failure.

It is expected that room temperature GASFET's will be used at 327 and possibly at 610 MHz, since at these wavelengths the improvement expected from cooling is less than at the shorter wavelengths. This is particularly true at 327 MHz where the galactic background noise dominates the system temperature.

At 22 GHz and 43 GHz there is a significant improvement in using maser amplifiers. A 4°K maser system based on the NRAO masers covering 22 GHz and 43 GHz is proposed which gives improvement of at least a factor of two over the cooled GASFET amplifiers. The 1.4 cm masers which have been constructed at the NRAO have a nominal tuning range from 18 to 26 GHz, but it is expected that these can be modified to work over the range 15-23 GHz. This would reduce the system temperature at 15 GHz by at least a factor of two over the cooled GASFET system.

Due to the importance which is attached to the observations at the shortest wavelengths where the available resolution is greatest, and the deteriorating performance of the GASFET amplifiers at these wavelengths, we feel that maser amplifiers will be necessary to achieve the performance goals.

Table III-6 summarizes the radiometer systems at each of the Array wavelengths.

TABLE III-6

RECEIVER CONFIGURATION

	FRONT END TYPE			T_R		SYSTEM TEMPERATURE		
	GASFET		MASER					
FREQUENCY	300K	20K	4K	1980	1986	1980	1986	NOTES
0.33	X			40	(30)	75	(65)	Prime
0.61	X			45	(30)	76	(61)	Cassegrain
1.4-1.7		X		12	(9)	34	(31)	Cassegrain
2.2		X		15	(11)	37	(33)	Cassegrain
5-6		X		20	(14)	42	(36)	Cassegrain
8.85		X		30	(20)	50	(40)	Cassegrain
10.7		X		40	(25)	65	(50)	Cassegrain
15.4		X		70	(40)	102	(72)	Cassegrain
22			X	10		50		Cassegrain
43			X	50	(30)	95	(75)	Cassegrain

Cryogenic Systems

In the receiver developed by NRAO for the VLA, the front-end components for the four frequencies are installed in a large dewar and cooled to 20 K with a 10 W refrigerator. However, failure of the refrigerator or cryogenic components generally means a loss of all observing frequencies. Since for the VLB Array skilled personnel are not always available at each site, this could be a serious problem. We therefore propose that the cooled FET amplifiers be mounted in small dewars with small refrigerators run off a large common compressor. The dewars will be mounted on the dual-polarization transitions on the feeds so line losses are kept to a minimum.

The CTI Model 350 refrigerator has a 3 watt capability at 20 K and three of these units can be run from one 1020 type compressor. A spare compressor with automatic changeover, if a failure occurs, will be used to decrease down time for maintenance and increase reliability. We have also considered using six smaller refrigerators having a 1 watt capacity as this would give greater flexibility. But the long term reliability of the smaller refrigerator has not been established.

F. Local Oscillator System and Phase Calibration

In order to reconstruct an image from interferometer data, it is necessary to know the phase as well as the amplitude of the fringe visibility. The measurement of phase in a VLB Interferometer system is limited by the stability of the independent local oscillators and the fluctuations caused by variations in the phase delay due mainly to tropospheric water vapor above each antenna.

Local Oscillator System: 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. Currently, hydrogen masers are in widespread use and the newer units developed at NASA (Reinhardt and Rueger 1980) and at the Smithsonian Astrophysical Observatory (Vessot 1980) have stabilities of the order of a part in 10^{15} over time scales of one hour or so. Thus, even at the shortest wavelength of observation (7 mm), the independent frequency standard contributes only $\sim$ 5 degrees of phase noise in an hour, and so their stability at least for periods of a few minutes to a few hours is as satisfactory as conventional phase stable interferometers. Hydrogen masers have several disadvantages, however, which has led to concern about their use in VLB interferometer systems. These are:

1) They are not commercially available;
2) They are expensive;
3) They have, in the past, been unreliable and difficult to maintain;
4) For periods in excess of about 3 hours, environmental effects degrade the stability, so that the long term phase stability necessary for astrometric and geodetic measurements is not satisfactory.

A relatively recent development is the Super Cooled Cavity Oscillator (SCCO) which for periods $\lesssim$ 10 sec gives an order of magnitude improvement in stability. The SCCO, however, is not stable over long time scales, and it must be locked to a fundamental standard, such as a Cs tube oscillator to give good long term stability. Like the hydrogen maser, there is no commercial source of SCCO's, and their real cost, performance and reliability in the field have not yet been demonstrated. A single SCCO is being evaluated at the Owens Valley Radio Observatory and is expected to give valuable information on their suitability as a frequency standard for independent oscillator interferometers.

In an attempt to find a less expensive oscillator than the hydrogen maser, we have experimented with various combinations of stable crystal oscillators phase locked to stable Cs standards. Even with carefully selected units, we have been unable to approach the performance of the hydrogen maser.

We have also considered the use of a direct round trip phase link using a geostationary satellite. Several successful experiments have already been performed using the Hermes (Waltman et al. 1980) and ANIK-B (Cannon et al. 1980) satellites with encouraging results. In addition, the European Space Agency ECS satellite is being used by Dutch radio astronomers as part of a program aimed toward developing a phase-stable link to join radio telescopes in the UK, The Netherlands, Germany, Sweden, and Italy to form a truly phase stable array. A major problem in implementing a geostationary satellite phase link is the motion of the satellite which introduces phase shifts of up to 10^6 turns per day. However, it seems that this can be satisfactorily cancelled by using a two-way link (Waltman et al. 1980). It is expected that by using a real-time-local-oscillator link it will be possible to maintain the long-term stability necessary for a variety of astrometric and geodetic observations. We note, however, that a stability of the order of one part in 10^{15} can be achieved for an indefinite period even with independent oscillators by using two hydrogen masers at each element autotuned to each other.

The cost of a suitable satellite circuit is not well established, nor in fact is there a straightforward mechanism for the use of satellite transponders with one's own ground equipment. All of the experiments to date have used experimental satellites, and it is not clear if a satisfactory solution can be found to the full time use of a satellite phase link. We note also that all of the previous experiments have used radio telescopes already available at the site for the up and down links. While the requirements on the ground station to support a satellite phase link are not excessive, the cost and maintenance of the necessary ground stations is not negligible.

For these reasons we consider the hydrogen maser as the only proven cost effective method at present of obtaining a stable local oscillator system. We shall, however, continue to follow the progress of the Canadian-American ANIK-B and Dutch ECS experiments, and at the same time explore the cost and availability of other suitable satellite facilities.

<u>Phase Calibration</u>: Even with a perfectly stable local oscillator system, errors in the measured phase are introduced because of uncertainties in the length and orientation of the interferometer baseline, and by variations in the propagation delay through the atmosphere and ionosphere. Although the VLBI measurements themselves are able to determine baselines with a repeatability of a few cm, the measurements must be continually updated to correct for diurnal fluctuations of 10 to 20 cm due to tides in the solid Earth, crustal motions which may accumulate at the rate of a few centimeters per year, variations in the rate of rotation of the Earth (UT.1) and in the wander of the axis of rotation.

Additional phase errors are caused by the propagation delay introduced by the troposphere at short wavelengths ($\lambda \lesssim 10$ cm) and by the ionosphere at long wavelengths, which affects the phase stability of all interferometers. Typically the phase fluctuations increase as the baseline increases, up to a few tens of kilometers. At greater separations, the antennas are looking through essentially independent atmospheres, and the phase fluctuations only slowly increase as the baseline length is further increased.

The typical path delay through the atmosphere is about 2 meters at the zenith. About 80 percent of the delay 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 expected delay through the atmosphere is closely correlated with the precipitable water vapor along the line of sight which may be estimated from surface measurements of temperature, pressure, and humidity. Typically, the theoretical electrical delay is 6.1 cm/(gm cm^{-2}) precipitable water vapor.

The amount of precipital water vapor along the line of sight can be measured by using a radiometer to measure the atmospheric water vapor emission at 22.235 GHz (e.g. Moran and Rosen, 1980). Previous measurements made in Green Bank show a good correlation between 1.3 cm atmospheric brightness temperature and interferometer phase fluctuations on a given day, but could not be used to "predict" the interferometer phase from day to day. A more precise evaluation of this technique, using improved water vapor radiometers, combined with surface measurements of temperature, pressure, and humidity is being made with the VLA, with the Green Bank interferometer, and by VLBI observers. By mounting a water vapor radiometer on each antenna, so that it measures the sky brightness along the line of sight of the antenna beam, it is expected that the delay due to the wet component of the atmosphere can be measured to an accuracy of a few millimeters. Even higher accuracy should be possible with differential measurements between a reference source and any nearby position.

Reduction of the effects of tropospheric phase fluctuations is a major concern which limits the performance of aperture-synthesis instruments of all dimensions. It is particularly serious for VLBI systems, where substantially different meteorological conditions may exist at each site.

A variety of techniques are used to reduce and even substantially eliminate the effect of tropospheric fluctuations. These include the direct measurement of precipitable water vapor with microwave radiometers, phase calibration by the use of a nearby "point" reference source, and self calibration techniques which exploit the fact that when there are more than three antennas in an array the number of unknown phase errors is less than the number of measured interferometer phases.

In order to accurately measure interferometer phases, it is necessary to 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 millisecond (including uncertainties in precession, nutation, and UT.1), and c) the relative phase of the independent local oscillators.

In conventional interferometry the problem is simplified by using a nearby point source as a phase reference. But with the very long baselines used in the VLB Array, it will be difficult to find a sufficient number of strong unresolved sources.

Even without a "point" reference source, it is possible to "self calibrate" providing only that the number of measured fringe visibilities, N(N-1)/2 is much greater than the number of antennas, N, with unknown phase error. In this way, in an N element array, a fraction, (N-2)/N, of the phase information is determined. A variety of algorithms have been devised which exploit the finite size and positiveness of radio sources to produce images from uncalibrated phases and, if necessary, uncalibrated amplitudes as well. These procedures are referred to in the literature as "hybrid mapping" (Readhead and Wilkinson 1978, Readhead et al. 1980), "self calibration", or "adaptive calibration" (Schwab 1980), (Rogers 1980).

The main restriction of the self-calibration schemes currently in use with incoherent arrays is that they are limited to sources which are sufficiently strong that they give a reasonable signal-to-noise ratio on each baseline in a time less than the coherence time, which may typically be $\sim$ 20 minutes at 3 cm. Various new schemes are being investigated, however, which may lead to an effective sensitivity intermediate between the incoherent and fully coherent arrays (Clark 1980, Schwab 1980).

Nevertheless, even with a simple extension of current procedures, any moderately strong nearby compact reference sources may be mapped using "self calibration" techniques. The phase derived from these hybrid maps may then be used to calibrate the measured phase on an unknown source too weak to be detected in a single coherent integration. In this way the effective integration time may be extended to the full period of common visibility to achieve the full sensitivity of the entire array. With 25 m dishes and low noise radiometers, there is sufficient sensitivity to find a suitable reference source within one or two degrees of any arbitrary position.

G. The Record System

In a conventional radio telescope array, the IF 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 are recorded at each element on magnetic tape which is then physically transported to the correlator.

The MkI VLBI System, which was in use roughly between 1967 and 1975 allowed only a 330 kHz band to be recorded for 3 minutes on a standard reel of 1/2 inch computer tape. The MkII System uses video recorders and allows the recording of up to four hours of 2 MHz data. More recently, the MkIII System which allows a bandwidth of up to 56 MHz has come into operation. But only about 13 minutes of data can be recorded on a standard 9600 ft reel of 1 inch instrumentation tape since the bit density is only comparable to the earlier MkII recordings, and the increased bandwidth is achieved only at the expense of greatly increased tape consumption. Thus, although the bandwidth (sensitivity) of the MkIII tape recording system is comparable to a single IF channel on the VLA, the limited recording time restricts its use in a full time multi-element system such as the VLB Array.

However, another recent development is the use of the inexpensive consumer type video cassette recorder (VCR) which gives an order of magnitude improvement in bit density over the Ampex VR660 and IVC 825 MkII tape recorders used previously. Experiments have been made at NRAO and Haystack to use VCR heads to write narrow, 1-mil-wide, tracks on an instrumentation recorder, rather than the normal 25-mil-wide tracks. Up to 20 passes, each writing 28 tracks, should be possible using head stacks fabricated with these 1-mil-wide heads. Thus, by using 12,000 foot reels of tape instead of the current 9,600 ft reels, the multiple passes allow nearly six hours of uninterrupted recording at a bandwidth of 56 MHz (28 tracks, 4 Mbits per track at 135 inches per sec). Even with a bandwidth of 112 MHz (28 tracks, 8 Mbits per track at 270 inches per sec), three hours of continuous recording are possible. For spectroscopic observations, where much narrower bandwidths are used, many days of data can be recorded on a single tape. It is expected that by 1981 the feasibility of at least an order of magnitude improvement in MkIII bit density will be demonstrated, and that commercial 1 mil-track-head-stacks will become available.

Experience with the present MkIII System has shown that the best results are achieved with Professional Video Tapes (PVT) which appear to give the best signal-to-noise ratio with the commonly used ferrite heads. PVT's also appear to be more resistant to wear, and at least 1000 passes or 9 days of recording are possible at 56 MHz bandwidth before a tape becomes significantly worn.

We have also experimented with a thin tape which would allow a further increase of a factor of two in the number of bits recorded per unit volume of tape. But these tapes are designed for low speed audio use, and appear to give poor results on the instrumentation recorder.

Based on the proven performance of the MkIII tape recording system and the prospects for a big increase in recording time, we have tentatively adopted the MkIII System for the VLB Array and have used it in our cost estimates. The IF recording system will allow 1-bit (2-level) sampling of 4, 2, 1, 0.5, 0.25, 0.125 MHz per track and up to 28 simultaneous tracks. For continuum observations the sampling is done at the Nyquist rate to give an rms noise of $(\pi/2)\ T_J\ (2Bt)^{-1/2}$ per interferometer pair, with T_J being equivalent to the system noise temperature in Janskys, B the bandwidth, and t the integration time. In the spectral line mode, for track bandwidths of 2 MHz or less, the sensitivity can be increased by a factor of 1.16 by oversampling by a factor of two.

The MkIII recording system has been developed largely at the Haystack Observatory, and a detailed description of its design and operation is given in several reports.

A major disadvantage of the MkIII System is the expense of the multiple video converters necessary to obtain the 28 separate IF tracks. A simpler method might be to record a single broadband signal. Although no such systems are currently available, the anticipated development of digital TV is expected to make 40 MHz (80 Mbit) recorders commercially available in the near future, and other broadband digital recorders are being developed for various industrial and military applications.

We have also considered the use of a satellite-linked system to transmit the IF signal in real-time from each of the Array elements. The feasibility of using a geostationary satellite as an IF data link has already been demonstrated (Yen et al. 1977) and European radio astronomers have developed detailed plans for a dedicated VLB transponder to permit real time VLBI among 5 or more European radio telescopes. (Phase A Report on Satellite Linked VLBI, 1979, European Space Agency.)

At the present time the cost of a satellite with suitable capacity is greater than $\$10^8$, and is not cost effective compared with a tape recording system, particularly with the expected increase of an order of magnitude in tape bit density. Moreover, unlike many other satellite applications, there is no real need for "instantaneous" data transmission, and the delay of a few days in receiving magnetic tapes at the Operations Center is only a minor inconvenience. We shall continue to be alert for any new developments in this rapidly changing field of digital data transmission, but we anticipate that at least for the next decade, high density tape recordings will remain the most likely IF transmission system.

H. Control and Monitor System

Each of the Array elements will be controlled by a central computer through a local computer. Normally the observing program will originate with the central computer, and communications between the Array Operating Center and the individual site computers will be required for observations. In addition, routine logging information, including system performance at each of some 40 check points, and narrow band I.F. data for real-time fringe verification are routinely returned from each site to the Operating Center through the central computer.

The real-time fringe verifier is patterned after the MkIII fringe verifier but will have at least a 4 Mbit RAM memory and transmit data at a 9600 bit sec^{-1} rate. This will allow fringes to be detected on sources as weak as 2 Jy in a ten-minute integration.

Communications between the Array Control Computer and the Element Computers will be via a combination of 9600 baud enhanced leased telephone circuits and normal dial-up lines. In the event of partial communications failure, a limited form of operation will still be possible in a manual mode, with the operators entering the observing program directly through each of the local computers.

The Array control computer will be a PDP 11/44 type system with a 512K byte memory, disk, storage, CRT terminal, line printer, DEC writers and 1600 bpi tape transport. At each antenna, the local computer will be in the LSI-11/23 class with 128K byte memory. An additional LSI-11 will be located in the Array Operating Center to be used by technical support personnel for ongoing development. The LSI 11/23 is supported by remote diagnostics which should facilitate repair in the field.

For the computer/telescope interface we plan to use either CAMAC or other similar serial system such as the NRAO designed interface used at the VLA. This will reduce the number of wires required between the various parts of the antenna and the instrumentation.

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IV. THE PLAYBACK SYSTEM

Once observations are completed and the recorded tapes from all stations are collected at the Array Operations Center, the first step in the analysis sequence is to correlate the raw data. This will be done on the VLBA Processor. This Processor consists of the instrumentation tape decks and their associated electronics to play back the recorded data; a large, flexible correlator to provide the cross-correlation functions from each antenna pair; a mini-computer to control the operation of the processor; and output devices (6250 BPI tape drive and large capacity disks) to hold the correlated data. The correlated data from each baseline will typically be averaged from 1 to 30 seconds depending on frequency and the field of view required to map the source. A block diagram of the processor is given in Figure IV-1.

The correlated data are analyzed with the post-processor equipment which consists of some specialized hardware/software to do on-line fringe fitting whenever possible, and a general purpose computer(s) with an attached array processor which is used to arrive at the final product (e.g. maps, source positions, etc.). The Playback Processor is described in Section IV.A and the Post Processing Computer System in Section IV.B.

A. The Playback Processor

1. Video Playback System. The video tapes from each station will be played back on tape drives with 28-track reproduce heads, preamplifiers and phase equalizers. The Honeywell Model 96 tape drive has been used satisfactorily in the MkIII system. One recorder is needed for each station in the Array. The data is played back at an 8 Mb/sec sampling rate regardless of the recording rate used at the telescope. Assuming that most data will be recorded at a sampling rate of 4 Mb/sec or slower, the

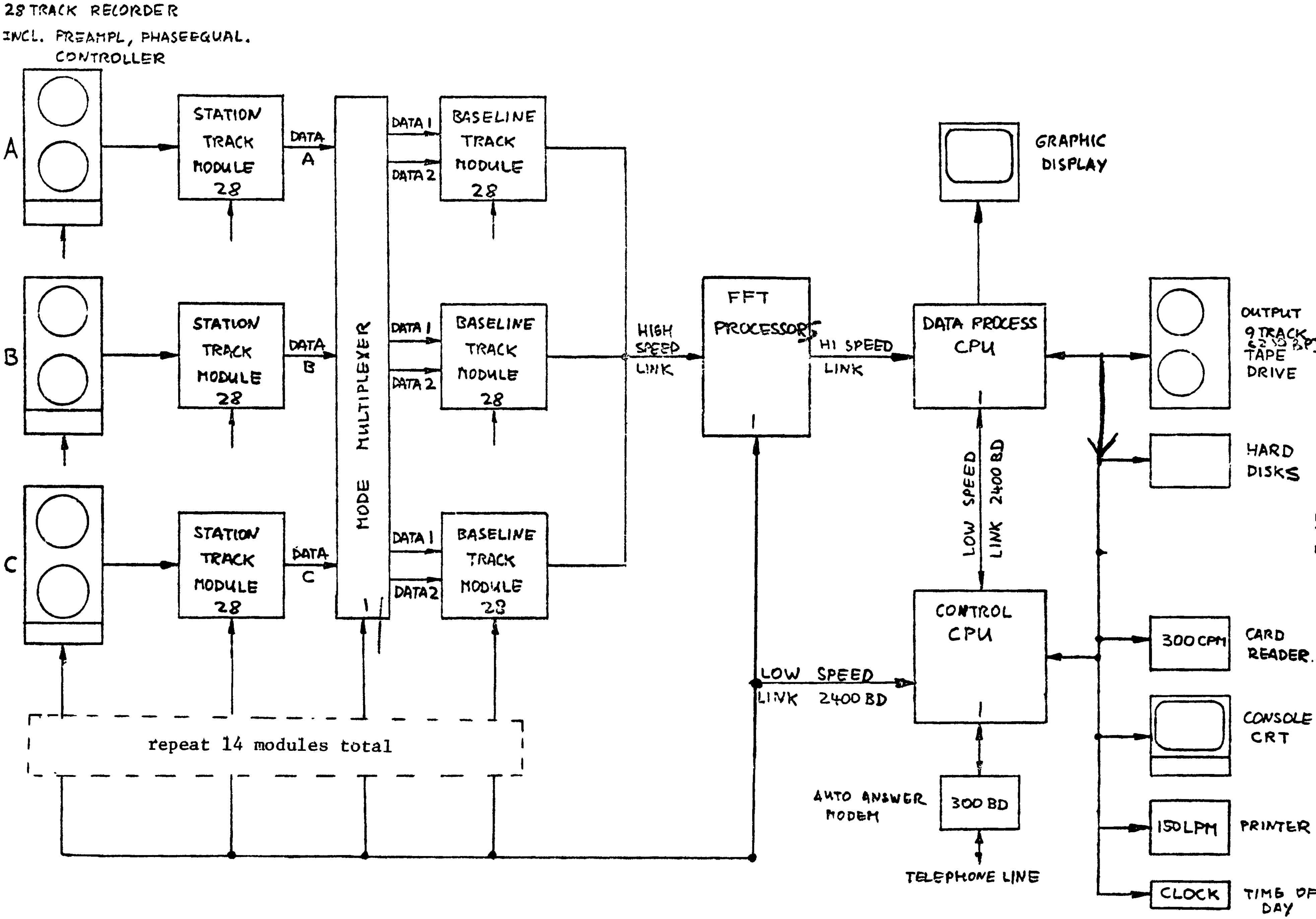

Figure IV-1. 14-Station VLB Array Processor.

Processor will be able to correlate faster than real time. This is necessary in order to allow for processor overhead due to time lost changing tapes, maintenance, and other logistical problems in handling the large flow of data in and out of the system. Also, this allows for some observations in which the data are recorded at double the normal sampling rate (which doubles the usable bandwidth) for higher sensitivity, and provides a reasonable amount of time for certain experiments, such as those involving "double-quasars", which require multiple passes through the processor due to their large angular extent.

2. Correlator Requirements. A wide range of considerations go into the specifications of the VLBA correlator as continuum and spectral line observations each have distinct requirements. These requirements are discussed separately below, however, as is shown the number of correlator channels needed for continuum and spectral-line work are not very dissimilar and a flexible correlator design can serve the needs of both.

Continuum observations. In order to estimate the correlator requirements for continuum observations, we have assumed a "standard" observing configuration involving a 10-station array recording a 28 MHz bandwidth in each of two orthogonal circular polarizations. This can be accomplished with current MkIII recording capability by recording 14 tracks of 2 MHz bandwidth in RCP and 14 tracks of 2 MHz bandwidth in LCP. This requires that the telescope be equipped with two receivers for each observing frequency. The processor yields correlation functions containing the full information available in the recorded signals, by cross correlating the four combinations of the two polarizations recorded for each antenna pair (designated RR for RCP x RCP, RL for RCP x LCP, etc.). The correlator should yield a delay-lag range of ±1 to ±2 seconds to allow for clock uncertainties and a field-of-view of $\pm 0\overset{''}{.}5$ to $\pm 1''$ to be analyzed in one processing pass through the video tapes. Thus the minimal size for the correlator for this "standard" observing configuration is

45(baselines) x 14(tracks/polarization) x 4(correlator polarizations) x 8(1/4μs complex lags) = 20160 complex lags.

In order to allow for the convenient use of "non-standard" configurations (such as including European or Canadian stations and/or the VLA or other US antennas in the Array), even more correlator channels are needed to avoid time consuming multiple passes.

Spectroscopic needs. Spectral line observations offer an extra dimension of information compared to continuum observations, but this also adds considerably to the processing and post-processing burden. It is difficult to define a "standard" observing/processing system since the needs of absorption-line studies differ substantially from those of maser-line studies; also observations of different molecules and transitions are usually not similar. Rather than consider a single "standard" observation, we will describe two examples of the more common spectral-line experiments, OH and H_2O synthesis experiments.

The ground state of the OH molecule has four transitions near 1.6 GHz. It is important to obtain synthesis maps of the emission in all transitions simultaneously in order to precisely register the maps with each other. At present this can only be accomplished by time multiplexing the data which reduces sensitivity and introduces frequency aliasing problems. One of the most important uses of the VLB Array will be to conduct and efficiently process multiple-track line synthesis experiments. In order to properly characterize a spectral line, at least three resolution elements are required over the width of a line. A number of spectral channels, N, required for this type of experiment is, therefore, 3 x (Bandwidth) x (No. of tracks) / linewidth.

The H_2O maser case differs from the OH maser in that there is only one transition; however, multiple 2 MHz bands are needed to cover the emission which is spread over a frequency range of up to 20 MHz. In Table IV-1 we list the number of channels, N, and the parameters used to determine them for typical OH and H^2O maser observations.

TABLE IV-1

CORRELATOR REQUIREMENTS FOR SPECTROSCOPY

Molecule	Frequency (GHz)	No. of Tracks Recorded	linewidth (kHz)	track bandwidth (kHz)	N	Comments
OH	1.6	4	1.5	62.5	500	for 4 transitions in 1 polarization, or 4 polarizations in 1 transition.
H_2O	22.2	4	50	2000.	480	known sources require from 1 to 14 tracks.

Thus 512 spectral channels per baseline appears to be the minimum requirement for many spectral line studies. Certainly there will be experiments, expecially for H_2O maser sources, where more than 4 tracks are needed to map the source. A limited number of such experiments can be accommodated in a processor with 512 spectral channels per baseline by multiple passes through the processor.

The 512 spectral channels per baseline can be obtained by Fourier transforming 1024 complex cross correlation lags. (The number of lags is twice the number of spectral channels because the transformed spectrum contains two sidebands whereas the observations are single sideband). Thus a 10 station (45 baseline) correlator would require 45 x 1024 = 46,080 complex delay lags to handle spectroscopic observations. In addition, a separate 512 channel (real lags only) autocorrelator is needed for each station to produce the "single-dish" spectra needed for calibration.

3. Correlator Design. The proposed VLBI correlator has 46,080 complex cross correlation lags and 5,120 real autocorrelation lags. In order to accommodate different types of continuum and spectral line programs, it can be designed to permit a variety of configurations as shown for example in Table IV-2.

TABLE IV-2

CORRELATOR CONFIGURATIONS

46,080 complex cross correlation delays
5,120 real auto correlation delays

Possible Continuum Configurations

No. Stations	Total BW(MHz)	BW per pol(MHz)	Polarizations recorded	Polarizations correlated	No. delays	delay range μsec
10	112*	56*	2	RR, LL, RL, LR	8	±0.5
10	56	28	2	" " " "	8	±2
10	56		1	RR or LL	32	±4
14	56	28	2	RR, LL, RL, LR	8	±1
14	56		1	RR or LL	16	±2

Possible Spectroscopic Configurations

No. Stations	No. Frequency Bands	Polarizations per band	Polarizations correlated	Frequency Channels
7	7	1	RR or LL	128
10	4	1	RR or LL	128
10	1	2	RR, LL, RL, LR	128
10	2	1	RR or LL	256
10	1	1	RR or LL	512
13	1	1	RR or LL	256

* Recorded at 8 Mb sec^{-1} (4 MHz per track).

The correlator is divided into station modules, a multiplexer and baseline modules. More stations may be added by increasing the number of station modules, and adding to the multiplexer.

Station modules: The station module contains all circuitry unique to a station including an autocorrelator, bit synchronizers, and decoders. There is 1 station module per track for each station, or a total of 14 x 28 = 392 modules for a 14-station processor.

Multiplexer: The multiplexer has to multiplex 14 lines per station module. There are a large number of different configurations possible and we will design this multiplexer for maximum flexibility.

Baseline modules: The baseline module contains the cross correlation for 16 lags and the fringe rotator (see Figure IV1). There will be one module per baseline track and 28 modules per baseline.

We have considered two ways in which the processor logic might be implemented. In the first method, the entire system runs at an 8 Mbit clock rate and uses standard low cost TTL digital logic. The Haystack MkIII Processor and the Caltech-JPL Block II Processor work in this way, but differ significantly in their architecture. In the Haystack design, the system is built up out of a number of baseline oriented modules, while in the JPL Block II design, more of the hardware is assigned to the "per station" modules, and so for a large number of stations it is cheaper to implement. The Processor described in this report is also station oriented, and follows a design described by Rayhrer, Reid, and Shaffer (1980).

It is also possible to implement the correlator using a high speed recirculating system. This is the system used at the VLA. By using 100K ECL circuits which are now readily available, each correlator can be made to operate at a 256 MHz clock rate. Thus up to 32 lags at

8 MHz can be obtained from a single correlator, giving a large reduction in the number of circuits with a corresponding decrease in the cost and improvement in reliability and service.

Since we have not yet done a detailed design of a high speed recirculating correlator, we have based all of our cost estimates on the design described by Rayhrer et al. but modified to allow for the increased number of stations and lags.

4. The Processor Computer. The computer system is divided into three parts--the FFT processor, the data process CPU, and the control CPU. The system is designed so that it will be able to handle the 14-station operation.

The FFT processor accepts data from the correlator, performs a fast Fourier transform and fractional bit shift correction in the spectral line mode and passes the cross-spectrum on to the data process CPU. For continuum observation, the FFT processor can be used to increase the SNR by transforming the correlation into a spectrum, doing the fractional-bit-shift correction, filtering the unwanted sideband and then transforming the spectrum back into its correlation function.

The FFT processor will have many fast hardware array processors capable of transforming 512 complex channels in 3 msec. A prototype model is currently being evaluated on the NRAO MkII processor.

The data process CPU is a general purpose minicomputer that will:

(1) block data for efficient tape usage,

(2) integrate data typically from 1 to 10 seconds,

(3) display "first look" fringes or spectra,

(4) perform hardware diagnostics.

The control CPU is quite flexible and will perform a number of different tasks. It will operate under a real time operating system with a number of peripherals. It will provide capabilities for program development, communication with the user, communication with the operator and controlling operation of the processor. Controlling the operation of the processor is divided into:

(1) Preparation to process data,

(2) Setting up the hardware parameters for each scan,

(3) Controlling and updating the processor during run,

(4) Monitor performance of the processor,

(5) Write log for each run.

B. Post-Processing

Post processing normally consists of two parts:

1) pre-mapping including fringe fitting to determine amplitude and phase on each baseline at frequent intervals, editing, averaging, and calibration; and

2) mapping including conversion of visibility data to images by Fourier inversion, self calibration, and CLEAN.

The hardware requirements necessary to implement these tasks are not easy to estimate. On the one hand data analysis techniques, particu-- larly in the area of image processing are rapidly evolving, and as more sophisticated algorithms are developed the computing requirements are continually increased. On the other hand the cost of computing power is decreasing with time, particularly with the introduction of large fast array processors.

For the purpose of this study the computing needs of the VLB Array are estimated from practices in current use with the MkII and MkIII

VLB systems, as well as at the VLA, and typical execution times on the MODCOMP IV, VAX-11/780 and IBM 360/65 computers. We consider separately continuum and spectroscopic applications.

1) Continuum post-processing. In the current NRAO VLB system all of the pre-mapping analysis is done in the IBM 360, while in the Caltech and Haystack systems the pre-averaging and some fringe fitting is done on the on-line correlator computer. These steps require about one minute per baseline on the 360 for one hour of data, or about twelve hours for a ten element (45 baseline) array and 12 hour track. This can be reduced considerably with the use of a suitable Array Processor.

To determine the time requirement for mapping, a VLA data set using 10 antennas with 35,763 data points was used in the VLA self-calibration mapping program (Schwab 1980). This is approximately the amount of data in 12 hours of 1-minute integrations. Programs were run on both the MODCOMP and IBM 360 computers. Typical execution times per pass are about 6 minutes for mapping 256x256 cells, 8 minutes to CLEAN 500 components, and 16 minutes to "self-calibrate". Thus at 30 minutes per pass approximately 5 hours are required to map a source assuming 10 iterations of the self-calibration program.

2) Spectral line post-processing. Pre-mapping steps of pre-averaging; calibration of clock drifts, phase, and bandpass; Earth motion; editing; and production of a preliminary fringe-rate map require about 48 hours for a ten element array, 12 hour tracks, and 256 spectral channels.

VLA spectral line software is not yet available so detailed estimates of computing requirements for mapping are based on the continuum case and the conservative assumption of that time for map making and CLEANing is 256 times that for continuum work. This gives 2.5 days per 12-hour observation.

Computing requirements. We have estimated the post-processing requirements in terms of the computing power of the DEC VAX-11/780 computer and the execution times of existing programs on the MODCOMP and IBM 360 computers as described above. It is assumed that the VAX has an array processor. We have chosen this method of presentation since the VAX computer is in widespread use not only for the VLA and VLBI but elsewhere as well. Obvious improvements will be made in the next few years including larger CPU's, CPU's with built-in array processors, optical disks, etc. It is expected, however, that the trend in more sophisticated processing techniques will balance the gains in hardware technology.

Assuming that the Array is used for spectroscopy about 20 percent of the time, we estimate that a total computing power equivalent to 3.5 VAX-11/780's with array processors and 2 megabytes of additional memory will be sufficient to handle all of the post-processing needs. The computing requirements are broken down as follows:

Continuum pre-mapping	1 VAX
Continuum mapping	0.5 VAX
Spectral line pre-mapping	1 VAX
Spectral line mapping	1 VAX

We emphasize that we do not actually propose such a configuration, but we have used this as a reliable convenient method of determining post-processing requirements in terms of existing procedures, techniques, and hardware.

Literature Cited

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V. OPERATION OF THE ARRAY

The Array is expected to be operated as a national facility, open to all qualified scientists from the U.S.A. and abroad. 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 technical and logistical support currently required to simultaneously observe with a number of widely separated, independently operated radio telescopes or to perform the routine but demanding 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, in much the same manner as for the VLA. To the user, the VLB Array will be used in a similar manner as the VLA, and bear little resemblance to the familiar VLBI type of operation.

Ordinarily, the observer will not need to be at the Array Operations Center during his observations, although he may choose to monitor the progress from remote terminals linked to the Operations Center via commercial telephone lines. More likely, however, the investigator will choose to be present when the data are played back, or to participate in the "post-processing" state of analysis and image formation. In order to exploit favorable weather conditions for short wavelength observations, and to minimize the impact of equipment failures, once a program is approved, the Array staff assumes the responsibility for its successful completion within some reasonable period, but without a specific date and time being assigned in advance. This approach which has been successfully used at other synthesis telescopes appears

VLB ARRAY

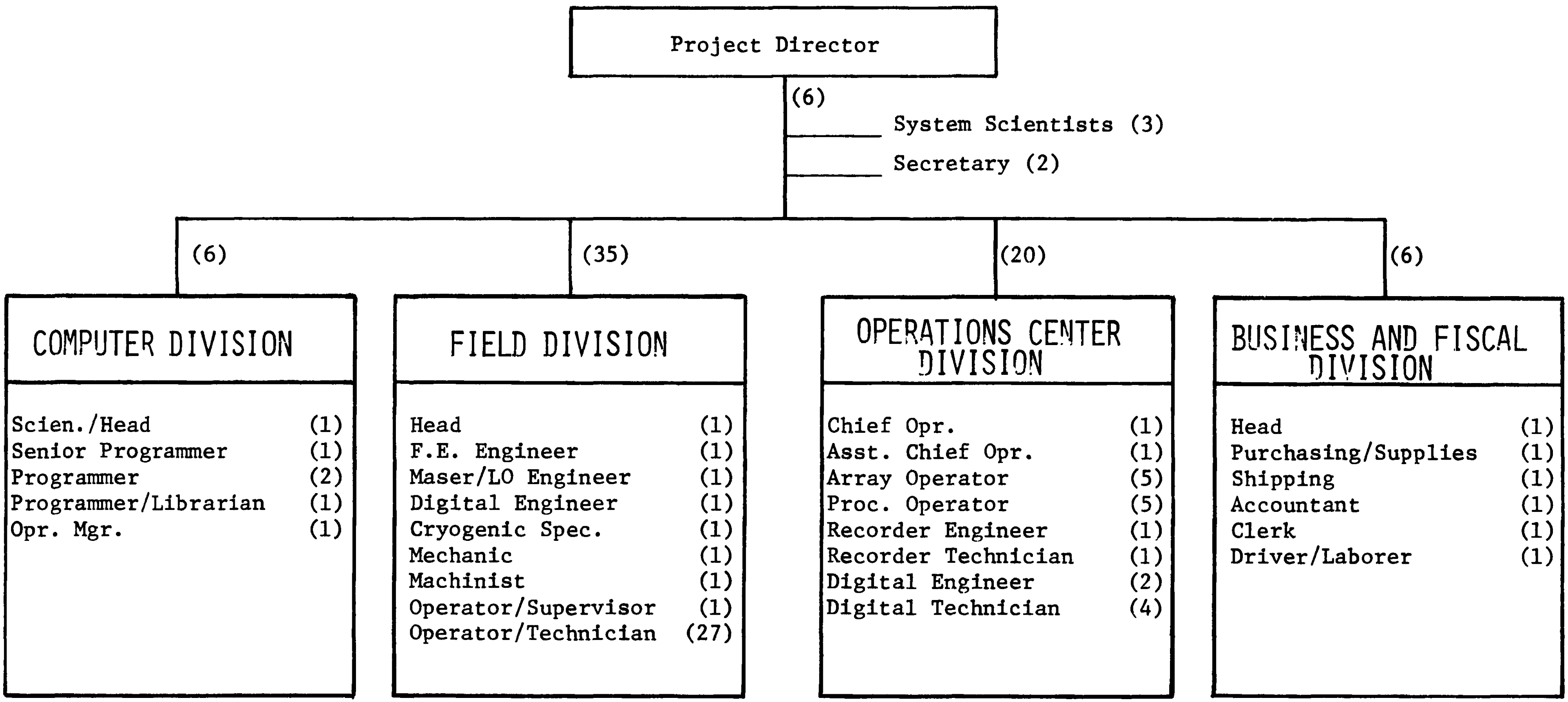


Fig. V-1

preferable to the conventional "take-your-chances" procedures used at most optical and radio telescopes.

The normal operation of the Array is conveniently divided into the following parts:

1) The operation of each of the ten elements under the control of an Operations Center;
2) Shipping the magnetic tapes to the Playback Center;
3) The correlation of the magnetic tapes in the multi-station processor to form each of the interferometer pairs;
4) Image formation and analysis.

Figure V-1 shows an orgizational chart for the Array operation. A total of 73 people are needed to operate the Array. These are divided among the Array Operations Center and the various field stations. A small scientific group located at the AOC has the responsibility for the Array management including the selection and scheduling of the scientific programs, supervision of the data analysis and continuing software development, liaison with the guest observers, and for introducing new techniques and procedures. In addition, it is expected that other NRAO scientists will be using the instrument for their own scientific work, and will in the course of doing this provide further scientific input as well as instrumental and software development.

The operation of the Array will be under the control of the Array Operations Center, which also contains the playback facility, 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 done from the Operations Center via leased 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 the conventional real time array to form the radio source image. The fact that the IF transmission system (the magnetic tape) involves a significant time delay has no fundamental effect on the output of the array, since due to the complex data analysis necessary, even in conventional synthesis arrays there is little opportunity for real time interaction between the observer and his data.

A. The Array Operations Center

The heart of the VLB array is the Operations Center which has the responsibility for the control of each of the antenna elements and, upon receipt, plays back the magnetic tapes, and provides the necessary post-processing facilities and services, to form images and for further analysis of the data.

The daily scheduling of the Array for operation and maintenance is under the supervision of a Chief Operator. He is assisted by an assistant chief, who assumes full responsibility when the chief is ill, on vacation, or otherwise away from the operating center.

Two Array Operators are on duty at all times. One is responsible for the control and operation of the array elements, and the other for the Playback Processor. To a large extent, however, they will work together to absorb unusual loads in either area when they arise. The Array Operators will also, when necessary, provide assistance in the operation of the off-line computing and image formation systems. A technicial will be on duty or on call at all times in the case of instrumental failures. Emergency repairs are kept to a minimum at the Array Center with the use of self-checking circuits in the correlator, and by keeping a sufficient number of spare playback recorders available at all times.

Assuming that the Array is in operation 360 days per year, a total of 8640 operating hours are possible. With a basic time of 2080 hours per man per year (52 x 40) less 248 hours vacation, holiday, and sick leave, 4.72 men are required for each of the two operator's positions. We have therefore allowed for a total of 10 Array Operators. In the case of multiple illness or vacation, the Assistant Chief and Chief Operators are also available for shift duty. This is the procedure which has been successfully in use at other NRAO telescopes for many years.

An important part of the Operations Center is the Post Processing Section. Beyond the initial steps of fringe fitting, the instrumentation and procedures will be, in most respects, similar to those at the VLA. Partly for this reason, and partly to make the most efficient use of the instrumentation and personnel, we consider it likely that the VLA and VLB array will be maintained and operated from a common location, although other arrangements are certainly feasible and need to be explored further. Although we have budgeted for the instrumentation and staff necessary to support the VLB Array, we expect that in practice both the facilities and personnel of the VLA and VLBA will be combined to the benefit of both operations.

In planning the computing facilities and necessary staff, we have profited from the experience gained from the VLA operation. The techniques of image processing of aperture synthesis data are rapidly evolving, and the continuing development of software for image processing at the VLA will insure that the VLB Array will exploit the full power of the instrument.

The staff for the Computer Section has two responsibilities. In addition to the development of software, they are available to aid and advise the guest investigator in the use of the Array facilities. In particular, the Operations Manager keeps track of the flow of data, and has general responsibility for the operating of all computing facilities, and system operation.

The Operations Center also contains the engineering and technical staff which supports the operation of the Center and field sites, as well as develops new procedures and instrumentation. As in the case of the Computer Section, the technical personnel will be closely integrated with VLA personnel to form a larger group of technical experts to supervise the routine maintenance and repair of unexpected failures of the antenna, electronics, and cryogenic systems at the Array sites.

B. Operation, Maintenance, and Repair at Observing Sites

Data are recorded at each of ten Array sites and are transmitted to the Array Operations Center primarily via commercial transport. Except for their remoteness from the Operations Center, the antenna elements perform in much the same manner as those of other synthesis arrays, such as the VLA. In order to minimize the cost of operations personnel, each site is remotely operated from the Operations Center. No operators are normally on duty at the individual antenna elements except to change magnetic tapes.

The 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 the maintenance, it makes no fundamental difference in operations if the elements are spaced by a few km or 1000 km.

Examples of automated remotely operated antenna systems already exist. NRAO routinely operates 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 to any telephone in the country or abroad (Swenson 1980). The synthesis arrays at Cambridge and Westerbork frequently operate for several days at a time with no operator at all.

The operation of the remote 45-ft antenna at NRAO gives some guide to the level of support and maintenance necessary to give reliable operation. Typically, two to four visits are made each week to the remote site. This requires about one full-time equivalent person, but the actual number of skilled personnel available is of course much larger.

At each of the VLB Array elements, a local staff of 2 or 3 people will be available for inspection, simple routine maintenance, and the more straightforward unscheduled repair of malfunctioning equipment. In addition, the local staff is responsible for changing magnetic tapes, insertion of operating programs and corrections at the site control computer, shipping and receiving magnetic tapes, for security and precautionary oversight, for emergency intervention, and for routine start-up and shut-down procedures. Normally one man will work a forty hour week changing tapes and preparing them for shipment, performing routine inspection and preventive maintenance and servicing of operational equipment. The second man is on call for unscheduled first-level repair of malfunctioning equipment. At those antenna sites which are located close to other radio astronomy facilities, it is expected that further help, when necessary, will be obtained locally. For the more remote sites, we have allowed a third person to insure the smooth operation of the facility. From time to time this third person may be called upon to support one of the other Array stations in the case of prolonged illness or other heavy work load. For antennas located at or near existing NRAO sites in Green Bank, Socorro, and possibly Hawaii, only one additional person will be required in support of the VLBA element, although in practice the work load may be shared among a number of people.

Each of the local staff will be trained technicians proficient in the maintenance of either analogue or digital instrumentation. Preventive maintenance and minor repair are performed by these site personnel. For major maintenance and repair requiring personnel with special training, special equipment or major replacement parts, one or two Central Service Centers where larger groups of engineers, technicians and mechanics are stationed will be utilized. Examples of personnel which will come from one of the Service Centers are certified welders, millwrights, hydraulic technicians, cryogenic technicians, servo technicians, and electrical technicians. It is anticipated that a typical repair task would require dispatch from the Service Center of one or two technicians or mechanics, and that each site will require such service approximately eight times per year. In these instances the local personnel will assist the specialists from the Service Centers.

The major portion of spare-parts stocks are located at the Service Centers, with only small components whose failure rates are large, being maintained at each field site. These procedures may have to be modified, however, in the case of the Alaska and Hawaii sites, where stocks of spare parts will exceed those at continental sites. Personnel level in Alaska will be increased in order to provide more skills and to reduce or obviate expensive travel from a Service Center. The Service Centers will probably be located at the AOC in New Mexico, and for the support of the East Coast facilities, in Green Bank or Charlottesville.

In order to reduce downtime due to failures, considerable redundancy is built into all critical systems. For each frequency there are two independent radiometers, so except for observations of polarization, the observations can continue at any frequency if a radiometer fails. Likewise, multiple refrigerators are used so that a failure does not shut down all frequencies. Two compressors, remotely switchable, provide continuous operation in the case either one malfunctions. Four tape recorders are in normal use at each site, permitting 16 to 24-hour operation without intervention. But satisfactory observations can continue with fewer recorders in operation, with more frequent attention from site personnel.

Thus the repair of most failures can be delayed until normal working hours, or when necessary until expert help is dispatched from a Service Center with only minimal impact on the Array operation.

Based on early operating experience at the VLA, it is estimated that routine maintenance and servicing at each antenna will require the following number of man-hours per year in the following categories:

Antenna structural and mechanical	234 man-hours
Antenna servo cleaning and testing	36 " "
Antenna heating and air conditioning	24 " "
Cryogenics servicing	80 " "
Receiver system servicing	110 " "
TOTAL routine maintenance and service	484 man-hours

Unscheduled repair of damaged or malfunctioning equipment is estimated to require the following support:

Antenna structural and mechanical	148 man-hours
Antenna servo and drives	70 " "
Antenna electrical	54 " "
Antenna heating and air conditioning	24 " "
Cryogenics systems	160 " "
Receiver repair and modification	640 " "
TOTAL unscheduled repair	1096 man-hours

C. Control, Monitor, and IF Data Distribution

The operation of the Array is, at all times, under the control of an operator at the Operations Center. Communication between the central control computer and each of the individual Array element computers is via an enhanced 9600 baud leased telephone line. Observing programs originate at the AOC and are normally sent well in advance to the observing sites. But changes in the program made necessary by equipment failures or by poor short wavelength observing conditions at one or more sites may be made at any time.

In order that the Array Operator be informed of the complete status of each array element, some 40 points are continually monitored and returned to the Operations Center. These include monitoring of antenna position control and servo errors, receiver and local oscillator systems, and meteorological data.

In addition, the communications system is capable of providing a narrow band quasi "real-time" IF data link to give periodic on-the-air surveillance of the fringe pattern from each antenna both as a check on the system performance and to monitor atmospheric phase fluctuations.

The main IF signal at each antenna is recorded on magnetic tape and sent once per day to the Operations Center. In the normal continuum mode with a 56 MHz bandwidth, approximately four tapes per day will be required which weigh a total of about 50 lbs. At the 112 MHz bandwidth, twice this number are used, while for spectral line observations, one tape may last many days.

For shipments of the order of 50 to 100 lbs. per day, we have found that United Parcel Service (ground) and United Parcel Blue Label Service (air) is by far the most inexpensive and at the same time quickest method of transport, with "door-to-door" service of two days anywhere in the country, including Alaska and Hawaii.

D. Use of Other Antennas with the VLB Array

For many applications, other antenna elements can be used together with the Array to even further increase its resolving power, dynamic range, or sensitivity. For this reason the playback processor allows up to 14 input stations with a possibility for further expansion.

The VLA. A particularly common mode of operation will be in conjunction with the VLA allowing observers to study individual sources over a broad range of resolution. Moreover, for each of the ten baselines between the VLBA elements and the VLA, the sensitivity is improved by a factor of 5 compared with each of the VLB Array baselines alone. This allows the mapping of weaker sources than otherwise possible, although because of the limited number of interferometer pairs, the dynamic range is reduced. The increased sensitivity is particularly important in studying weak short-term transient phenomena such as novae outbursts and flares in galactic stellar radio sources, and in using weak reference sources to calibrate the atmospheric phase instability.

Canadian Antennas. Canadian astronomers are currently developing plans for constructing a number of antennas in Canada dedicated to

VLB observations. As it is currently conceived, the Canadian antennas do not have the extensive instrumentation necessary to allow them to be fully utilized in connection with the VLB Array, nor the personnel support to allow reliable uninterrupted operation. It is not unlikely, however, that if the Canadian Array can be developed on a time scale comparable to that of the US Array, there will be an ensuing dialogue which will result in compatible instrumentation, as well as modification of the antenna locations in both arrays to achieve the optimum overall performance when both antenna systems are used together.

European Antennas. An active VLB program is carried out at a number of European radio telescopes. Because of the large collecting areas at Jodrell Bank, Westerbork, and Bonn, and because of their relatively close spacings, this array of antennas is particularly sensitive to faint lower surface brightness features, and when used in conjunction with the proposed US VLB Array is able to map these features by using the high surface brightness components as a phase reference. Taken alone, any one of these antenna elements provides a high sensitivity extension to the VLB Array. Although the overlap with the VLBA is small at low declinations, at higher declinations a European element adds significantly to the resolution, particularly the MPIfR 100m telescope near Bonn with its excellent performance at short wavelengths.

A dedicated VLB antenna is currently being built near Bologna, Italy and a second one is planned for Sicily. Although considerably smaller than the other European antennas, the Italian antennas will not be in demand for other research programs and are expected to be available for use with the VLB Array to the benefit of both European and American observers. This will relieve the pressure on the general purpose instruments at Bonn, Jodrell Bank, and Westerbork which will be used only for observations which require the increased sensitivity.

Europe is also developing plans for the use of the synchronous satellite, LSAT, to be used as a real time broadband data link in lieu of magnetic tapes. LSAT can "see" the East coast of the United States and could be used to transmit IF data across the Atlantic and thus avoid expensive transatlantic shipments.

Arecibo. Baselines between the VLB Array elements and the Arecibo antenna give the greatest instantaneous sensitivity, but due to the restricted sky coverage at Arecibo, the Fourier Plane coverage is limited. Nevertheless, the improvement in sensitivity of more than an order of magnitude will be important for certain specialized observations.

Other U.S. Antennas. Three of the probable Array element locations are near the Haystack 120-ft antenna, the NRAO 140-ft antenna, and the OVRO 130-ft antenna. If these Array antennas, or the one near the VLA, are located more than 50 or so km from the above observatories, then the short baselines established between the array antenna and "local" observatories will provide a valuable range of resolution, intermediate between the VLA and VLB Array. The ten new elements can then be used together with existing antennas at the longer wavelengths to improve the image quality, particularly at low declinations.

Japan. A new 45-m antenna is being constructed in Japan which is expected to work well at wavelengths well below 1 cm, and when used in conjunction with the VLB Array will give a higher resolution than possible with the Array alone.

USSR. Several new 64-m diameter antennas are being completed in the USSR, which will provide a valuable high sensitivity extension to the Array.

DSN Antennas. Antennas from the NASA Deep Space Net with their sensitive radiometer systems are frequently used for VLBI. To allow for the use of DSN antennas, or the NGS POLARIS antennas for geodetic as well as astronomical observations, we have included radiometers at the standard NASA S and X-Band wavelengths.

Use of the VLB Array in conjunction with other antennas requires compatible instrumentation and a mutually satisfactory mechanism for the scheduling of observations. For those antennas outside the United States, formal agreements may be desirable. Preliminary discussions have already begun, and it may be hoped that the VLBA instrumentation will become accepted as the international standard which other facilities will match.

VI. COST ESTIMATES

The VLB Array is a complex sophisticated system which is based on well understood techniques and instrumentation whose cost can be reliably estimated. No new sophisticated structural engineering is involved; designs exist for most of the electronic systems, and in many cases prototypes are already in operation on existing radio telescopes. Nevertheless, further design and engineering will be required to ensure that all sub-systems take advantage of the latest advances in the art, particularly in the rapidly evolving digital field. Indeed experience has shown that the instrumentation will continually be modified and improved, and allowance for these improvements forms a crucial part of the operating budget.

In this chapter we describe the total construction and operating costs. We also include in this chapter a preliminary construction plan. All costs are given in thousands of dollars (1980).

A. Array Elements

Estimates for the construction and acquisition of new equipment is, in part, based on the cost of similar instrumentation in use or being fabricated for the VLA or other NRAO telescopes with allowances for escalation to 1980 as well as required design changes.

1. The Antenna Elements. Twenty-eight antennas have been built and are now in operation at the VLA. The cost of antennas 26-28 delivered in 1980 is $697,483 each. The price for a VLA type antenna modified to meet the specifications discussed in Section III-C has been determined from this base with the following corrections:

a) The increased cost of steel and labor due to price escalation since the original contract.

b) The increased erection costs due to the use of Union labor and lack of the NRAO supplied erection facility.

c) Shipping costs of structure to the site.

d) Manufacturer's loss on VLA antennas and profit allowance.

e) Shielding and insulating of pedestal structure.

f) Strengthening of "feed" legs.

g) Strengthening of yoke structure.

h) Higher accuracy surface panels.

In addition, there is a one time only engineering cost of $480,000 made necessary by the various modifications which are required.

In this way we estimate a total cost of $12,920 K for ten antennas, if all ten antennas are purchased at the same time. If, on the other hand, the antennas are contracted, one at a time, then the total cost is increased to $16,800 K, due to the loss of quantity discounts.

We have not yet completed the cost analysis of the new wheel-and-track design. The cost of this antenna is reduced due to the simplicity of the structure, that is, fewer joints and fewer members are used. But this may be offset by the need to adopt a new design concept. There is also an increased engineering and design cost, but this is small if it is amortized over 10 antennas.

For our budget calculations we have assumed the use of modified VLA type antennas and a quantity discount to arrive at a unit cost of $1,290 K. To this must be added the non manufacturer supplied items in Table VI-1.

TABLE VI-1

ADDITIONAL ANTENNA COMPONENTS

1)	Feed mounting ring (vertex room cover) and feed support towers	10K
2)	Subreflector and support structure	18K
3)	Focus and subreflector rotation mount	15K
4)	Electrical installation	3K
	Total each antenna	46K

2. Feed System. The cost of the 10 band feed system is given in Table VI-2.

TABLE VI-2

FEED SYSTEM

Secondary Focus	
Dual Frequency Feeds	
1.5/5 GHz	20K
2.4/8.8 GHz	20K
15.4/43 GHz	20K
10.7/22 GHz	12K
Single Band Feed	
600 GHz	6K
Prime Focus Feed	
327 MHz	1K
Total Feed Systems per Antenna	$79K

3. Front End System. The cost of parts and labor for the multi-frequency front end system is summarized in Table VI-3.

TABLE VI-3

FRONT END COSTS

		Materials $K	Labor (Man Months)	
Cryogenic Costs				
20°K Cryogenics				
Refrigerators	3 x 5K	15K		
Compressors	2 x 6K	12K		
4°K Cryogenics				
Refrigerator and Compressor		50K		
4°K and 20K He lines				
6 lines (one spare)		12K		
Total Cryogenics				89K
300°K Front End Costs				
327 and 610 GASFETS Dual Pol.	4x1K	4K	2	
Local Oscillator	2x0.5K	1K		
Mixer IF Amplifier	4x0.25K	1K	2	
Labor		11K		
Total 300K Front Ends				17K
20°K Front End Cost				
Dewar, input lines, etc.		10K	6	
GASFET Amplifiers at 1.4-1.7, 2.3-2.7, 8.8, 10.7 and 15 GHz				
6 frequencies x 2 Polariz		12K	6	
Mixer/IF Amplifiers (12)		12K		
Local Osc. System		15K	6	
Labor		51K		
Total 20K Front Ends				100K
4°K Front End Costs				
Dewar, input lines, etc.		20K	6	
Dual channel masers 22,43 GHz		20K	12	
Solid state pumps		20K		
Local oscillator system		20K	6	
Mixer/IF	4x2.5	10K		
Labor		68K		
Total 4K Front Ends				158K
Miscellaneous				
System Noise Calibration		15K		
Phase Calibration		15K		
Power supplies, etc.		10K		
Total Miscellaneous				40K
TOTAL FRONT END SYSTEM PER ANTENNA				404K

4. Hydrogen Maser and Local Oscillator System. There is currently no commercial manufacturer of hydrogen masers, although two semi-commercial sources are available.

The Smithsonian Astrophysical Observatory (SAO) has developed and sold a number of its VLG-10 and VLG-11 series masers at a price which has increased from about $100K five or six years ago to $315 currently. Masers based on the NASA NR design are being fabricated at the Johns Hopkins University, Applied Physics Laboratory, but their cost is even greater.

A program to commercially fabricate the NASA NR hydrogen masers is currently being developed at AUSULB, Oscilloquartz of Neuchatel, Switzerland. Two prototypes have already been fabricated and a decision is expected in early 1981 on whether to fabricate and market some of these masers commercially. If so, the first units are expected to be available by 1983 at an estimated cost between $100K and $150K.

In a production run of 10 units, the cost of the SAO maser is reduced to $233K each. A further saving is realized if the receiver/synthesizer system for providing a high level signal which is phase locked to the maser is developed and constructed at NRAO. This was the procedure followed in the procurement of the VLG 10 (later upgraded to VLG 11) maser which has been successfully operated at the 140-ft antenna for a number of years.

The net cost for each one of ten masers obtained in this way is estimated to be $180K. The final price could be lower, if Oscilloquartz does decide to commercially fabricate hydrogen masers. However, for our budgetary estimate we have used $180K based on the cost of the SAO maser with NRAO electronics as this is the least expensive of any maser currently available.

5. The Record System. The cost of the data acquisition system is based on the current cost of the MkIII VLB record system. Two of these have been fabricated at the NRAO and a larger number at the Haystack Observatory. Their cost is well established. A total of four tape transports is included to allow 24 hours of uninterrupted operation without operator intervention. The cost of the recording system including fabrication and testing is given in Table VI-4.

TABLE VI-4

COST OF DATA RECORDING SYSTEMS

4 Honeywell Model 9600 Tape Transport (12K each)	48K
4 Sets of Heads (12K each)	48K
4 Sets of Record Electronics	20K
IF to Video Converter Modules	40K
ASCII Communications Module	14K
IF Distribution Module	9K
Format Control Module	9K
Phase and Delay Calibration	18K
5 MHz Distribution Module	2K
Power supplies, racks, bins, and other hardware	9K
Total	217K

6. Control and Monitor System. The local computer at each site samples some 40 monitor points on the antenna and in the front end and recording systems as well as meteorological data, and communicates this information to the Array Control Computer. The local computer also serves to receive the observing program from the control computer,

control the antenna, tape recorder, and electronic systems. For these purposes we plan to use two small minicomputers, in the class of an LSI 11/23, or one such system with complete spares. No significant downtime is expected from malfunctions of the local computer systems. Cost is as follows:

2	LSI-11/23 CPU	54K
	Interface and Communication	19K
	CRT	7K
	DECWRITER	2K
	Hard Disk	18K
	Total Station Computer	100K

7. Site Development. The following items are included at each of the Array Stations.

a) Site acquisition — 5K

b) Control building, including environmentally controlled area for instrumentation and computers, tape storage, shipping area, office space, maintenance area, and toilet. 1400 sq. ft. at $55 per sq. ft. — 77K

c) Telescope foundations. Cost varies from site to site depending on terrain, etc. — 40K

d) Emergency generator. 30 KVA to stow antenna and keep cryogenics running. — 20K

e) Roads. Road requirements will vary from site to site but is taken to average 400 ft. A 12' wide road for light traffic can be constructed for $25 per foot including typical excavation and grading costs. — 10K

f) Electrical power installation. 400-ft from commercial power. Underground installation at $12.50 per ft. — 5K

g) Water supply and disposal — 5K

h)	Furniture	4K
i)	Maintenance equipment including small 4-wheel drive vehicle with snow plow, tools, etc.	15K
	Total Site Development (per site)	181K

8. Other Site Equipment. The following additional items are required at each antenna element.

a)	Test equipment. Specialized test equipment will be designed and installed at each antenna to facilitate remote diagnostics.	50K
b)	Water vapor radiometer and other meteorological sensors.	35K
c)	Timing equipment. Rubidium clock, crystal oscillator, and timing receiver.	20K
d)	Test and Installation of all feed and station electronic systems.	10K
	Total Other Equipment (per antenna)	115K

B. Operations Center

1. The Playback Processor. We have not yet made a detailed analysis of the cost of the high speed recirculating correlator. The cost estimate shown in Table VI-5 is based on a design by Rayhrer, Reid, and Shaffer (1979). The high speed version would have a similar cost, except that the cost of the correlator modules (800K in the R^2S design) is likely to be reduced.

TABLE VI-5

COST ESTIMATE
PLAYBACK PROCESSOR

Correlator		
15 tape recorders (incl. heads, electronics) at 24K	360K	
14(stations) x 28(tracks) = 392 station modules at $150	59K	
3200 16 lag (complex) correlator modules at $250	800K	
Combiners and multiplexer	100K	
Cabinets, bins, racks, etc.	1K	
Total Correlator		1320K
Computer System		
32 Kbyte Control computer CPU	20K	
64 Kbyte Data pre-process computer CPU	43K	
Array Processor	100K	
Disk 1.3 Mbyte	10K	
9-Track Tape Drive	13K	
CRT	4K	
Graphics Terminal	5K	
150 LPM Printer	9K	
Card reader	7K	
Modems	4K	
Total Computer System		215K
Labor		
System Scientist	2 man-years	
Electronics Engineer	5 man-years	
Electronics Technician	6 man-years	
Programmer	6 man-years	
Labor		540K
TOTAL Playback Processor		2075K

2. Computing Equipment.

Processor Controller. The cost of the on-line computer which controls the Processor and handles some of the preliminary fringe fitting is included in the cost of the Processor.

Array Control Computer. Control of the Array and communications with the LSI-11/23 station computers will be through the Central Array Control Computer which will be in the PDP-11/44 class. An extra LSI-11/23 is included at the Operating Center for programming support. Cost of the Control System is:

PDP 11/40 w 512 Kbyte memory, disk, 9-track tape drive, CRT, Graphics terminal, DECWRITER, 150 LPM Printer, Card reader, modems	150K
LSI-11/23 system	53K
Software Development (16 man-years)	512K
Total Array Control Computer	715K

Post Processing. Post processing requirements are outlined in Section IV-B in terms of the DEC VAX-11/780 system. Post processing software will depend largely on procedures already developed for the VLA and existing specialized VLBI software. An additional 10 man-years of programming effort is assumed. Cost estimates are given below:

3 VAX-11/780 with 2 Mbyte memory, disks, and 9-track tape drives	670K
Additional 2 Mbyte memory	35K
Additional Disks	150K
3 Array Processors	270K

3	Printers	30K
	CRT terminals	30K
3	High Density Tape Drives	100K
	Optical Disk	40K
	Video Disk	40K
	Grey Scale Display	50K
	Misc	50K
	Total Post-Processing Hardware	1465K
	Post-Processing Software Development (10 man-years)	320K
	TOTAL Post Processing Cost	1785K

3. Control Building. The control building houses the Playback Processor, the Array Control System, the computer for data reduction, electronic laboratories for development and maintenance, storage area for magnetic tapes and spare parts, office space for visitors and staff, and shipping area. 8000 sq. ft. are required at $55 per sq. ft.

Control Building	440K

4. Magnetic Tapes. At the normal continuum bandwidth of 56 MHz, 4 tapes are used per day at each station or 40 tapes for the entire Array. Broadband recordings at 112 MHz require twice as much tape, while continuum observations of strong sources and spectral line observations consume less tape. Taking 40 tapes per day to be the average, a forty day supply costs 400K.

Magnetic Tapes	400K

5. Spare Sparts. The major portion of spare parts stock will be located at the Service Centers with only small components whose failure rate is fairly high being maintained at each field site. Those parts

whose "mean time between failure" is greater than one year will be stocked only at one or both Service Centers in order to minimize the capital investment. We estimate the following costs for spare parts in order to support and maintain operation with no serious downtime.

TABLE VI-6

SPARE PARTS INVENTORY

Antenna structure and servo	275K
Cryogenics	35K
Electronics	580K
Computer	100K
Total Spare Parts	990K

TABLE VI-7

COST SUMMARY

Array Elements			
Antenna Structure			
Antenna, servo, drive	1292K		
Feeds and feed mounting structure	79K		
Focus and subreflector rotation mount	45K		
Cassegrain subreflector and support	15K		
Total each antenna structure		1431K	
Electronics Systems			
4K front end systems	212K		
20K front end systems	135K		
300K front end systems	17K		
Control computer, communications and monitor equipment	100K		
Power supplies	10K		
Record system (4 recorders)	217K		
Hydrogen Maser	180K		
Other site equipment	115K		
Total electronics each antenna		986K	
Site Development		181K	
TOTAL Cost of One Array Element		2598K	
10 Array Elements			25980K
Playback Processor			2075K
Central Array Control Computer System (incl. software)			715K
Post-Processing Computer (incl. software)			1785K
Control Building			440K
Magnetic Tapes			400K
Spare parts, Test equipment, etc.			990K
Project Management			1620K
Contingency (15 percent)			5100K
TOTAL Cost of Ten-Element Array			39105K

C. Construction Plan

Construction of the Array is estimated to require 56 months from the date of initial funding. This schedule assumes that adequate conceptual design of the antenna and electronics systems and some prototyping has been completed prior to funding, the Array configuration is determined, and preliminary site inspection completed. Partial operation can begin 30 months after the start of construction. The pacing item is the antenna construction; 21 months are needed between the time funding is available and the start of construction of the first antenna.

A preliminary construction schedule is shown in Figure VI-1.

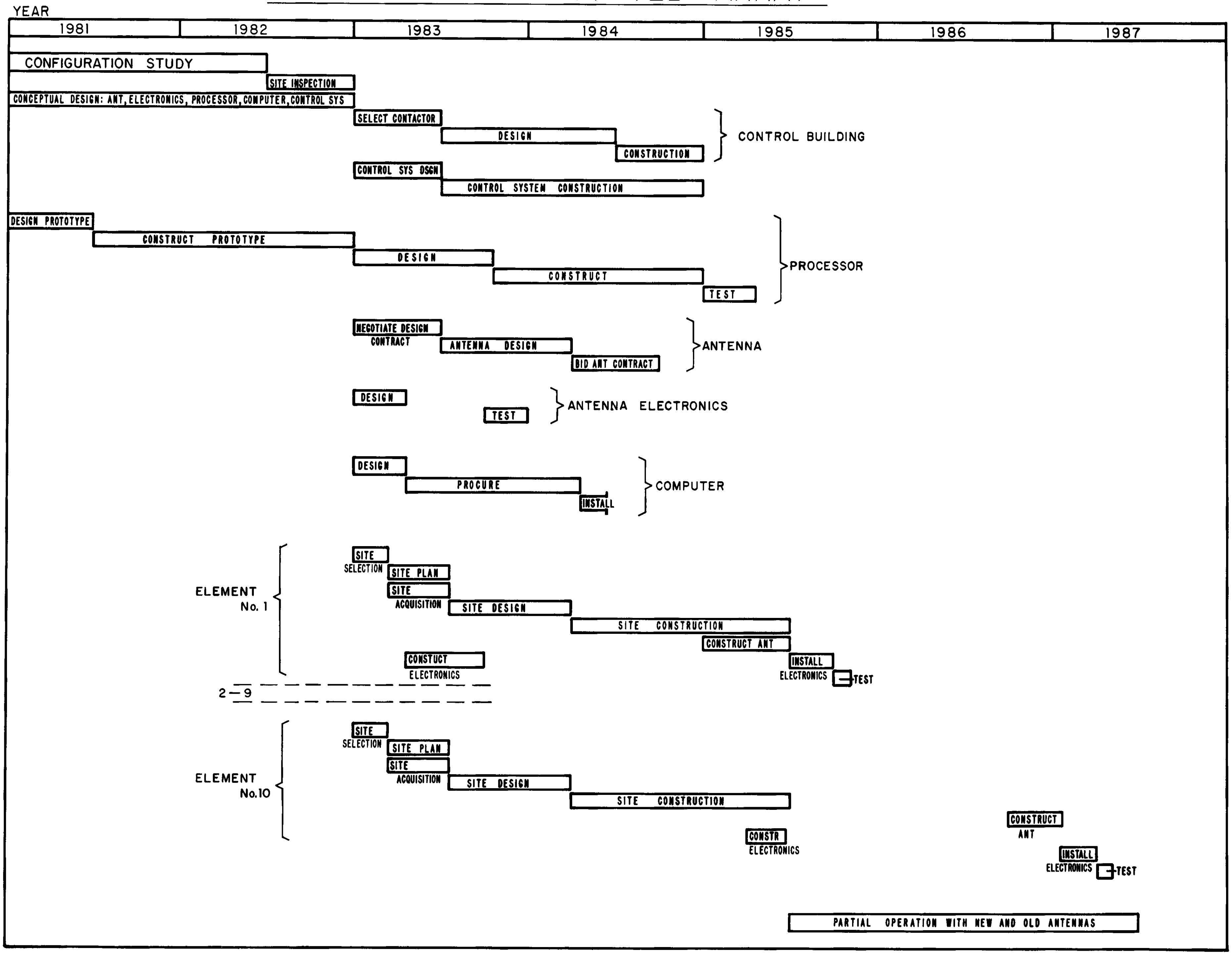
D. Operating Cost

Our estimate of the annual operating cost is based largely on the operating costs for similar items at the VLA with particular attention to the replacement of expendable items such as magnetic tapes and recorder heads, shipment of magnetic tapes and equipment, and travel between the Service Centers and Array sites. The Operating Cost is summarized as follows.

Personnel Compensation (including benefits). 1782K

Replacement of Recorder Heads. Ferrite recorder heads currently available are guaranteed for 3000 hours use. With down time for maintenance, bad weather, moving between sources, etc., and considering the increased lifetime at the low recording speeds appropriate to spectroscopic observations, a mean lifetime of over 4000 hours (166 days) is estimated. Thus 2 head stacks per year at each of 10 stations (20 head stacks) are needed at 12K per set or 240K. At the Playback facility an

CONSTRUCTION PLAN VLB ARRAY



average of 11 transports will be in operation, as tapes are processed from non-Array stations as well. 22 Playback Only heads at 7K = 154K.

Total Recorder Heads 394K

Shipping. Inexpensive shipping of magnetic tapes is available by UPS and UPS Blue Label (air). Convenient door-to-door pick-up and delivery is guaranteed in two days or less between any points in the USA including Alaska and Hawaii. The cost for a 50-lb shipment is between $5 and $47 depending on distance. Assuming 50-lbs per day in each direction between each of the 10 Array Stations and the AOC at an average of $20 per 50 lbs for 300 days per year is $120K. International shipments add another $20K. Additional shipping costs between the Service Centers and the sites, shipments from suppliers, and shipments of data to visiting observers is estimated to add another 30K.

Total Shipping Costs 170K

Travel. It is anticipated that typical repair tasks will require dispatch from a Service Center of 2 or 3 technicians or mechanics and that each site will require such service approximately 8 times per year. There are eight antenna sites not at Service Centers. Assuming three days of travel per repair job at $50 per day and $300 per trip gives 43K. Additional travel to support guest investigators, professional meetings, visits to suppliers, etc. will cost 75K.

Travel 118K

Communications. The 9600 baud enhanced leased lines are available at $0.54 per mile per month. Including Alaska and Hawaii, the communications link for control and monitoring, as well as real time fringe verification, is estimated at 54K per year. This may be reduced, particularly on the Hawaii and Alaska circuits if satellite linked facilities become available at lower cost. An additional 30K is required for conventional telephone service.

Communications	84K

Utilities. Each site uses about 30 KVA. At $0.05 per KWH, $11K per year are required for power at each station. 20K is allowed for the AOC.

Utilities	130K

Other Materials and Services. Material and supplies required to service the antenna elements including both consumable items such as oil, greases, paint and tools, and replacement items such as mechanical and electrical equipment are estimated to cost 56K per year, electronic parts 100K, tape replacement 150K, computer service 100K, and miscellaneous business supplies and publications costs 100K. The tape costs are estimated on the basis of 1000 passes per tape lifetime. With 15 minutes per pass and 500 passes at record time, this is 125 hours, or 5 days per tape. Thus 60 tapes per station, or 600 tapes per year are required. Professional video tapes in 12,000 foot lengths cost $250 per tape.

Materials and Services	506K

Other Operating Equipment. 500K per year are needed to continuously upgrade computer and electronic systems to keep the Array performing at the state-of-the-art and to expand the power of the Array. This ability to react quickly to new scientific discoveries or to technical advances is important, and is a crucial part of all NRAO operations.

Other Operating Equipment	500K

TABLE VI-8

SUMMARY OF ANNUAL OPERATING COSTS

Staff	1782K
Record Heads	394K
Shipping	170K
Travel	118K
Communication	84K
Utilities	130K
Other M&S	506K
New Operating Equipment	500K
Management Fee	100K
Total Operating Cost	3784K

VLB ARRAY

Memoranda and Reports

No.	Author	Title
1	K. I. Kellermann	Outline of Study
2	J. W. Findlay	Antennas for the VLB Array
3	W-Y. Wong	A 25-m Radio Telescope Design for the VLB Array Project
4	W. D. Cotton and J. M. Benson	VLB Array Computer Usage
5	B. G. Clark	Sensitivity of Partially Coherent Arrays
6	M. Balister	VLBI Cost Estimates
7	M. Balister	Proposed Receivers for the VLBI Array
8	W-Y. Wong	Cost Estimate for the Wong Antenna
9	W-Y. Wong	Balsa-Wood-Core Test Plates
10	K. I. Kellermann	Notes on Visit to ASULAB
11	S. Weinreb	Digital Data Transmission System
12	W. Horne	Notes on VLBA Design Study
13	G. Peery	Site Development Program
14	K. I. Kellermann	Antenna Construction Program
15	W-Y. Wong	Antenna Design Details
16	M. Balister	Masers and VLBI Array
17	A. R. Thompson	VLB Array - Comments
18	W. Cotton and J. Benson	Computer Usage
19	R. C. Walker and B. Burns	Computer Notes
20	H. Hvatum	Construction Plan
21	A. Shalloway	Preliminary VLA Spectral Line System
22	P. J. Napier	A Possible Feed System for the VLBA Antenna
23	G. W. Swenson, Jr.	Alternative Data Communication System
24	G. W. Swenson, Jr.	Automatic VLBI Observing
25	F. Schwab	Self-Calibration With a Low SNR