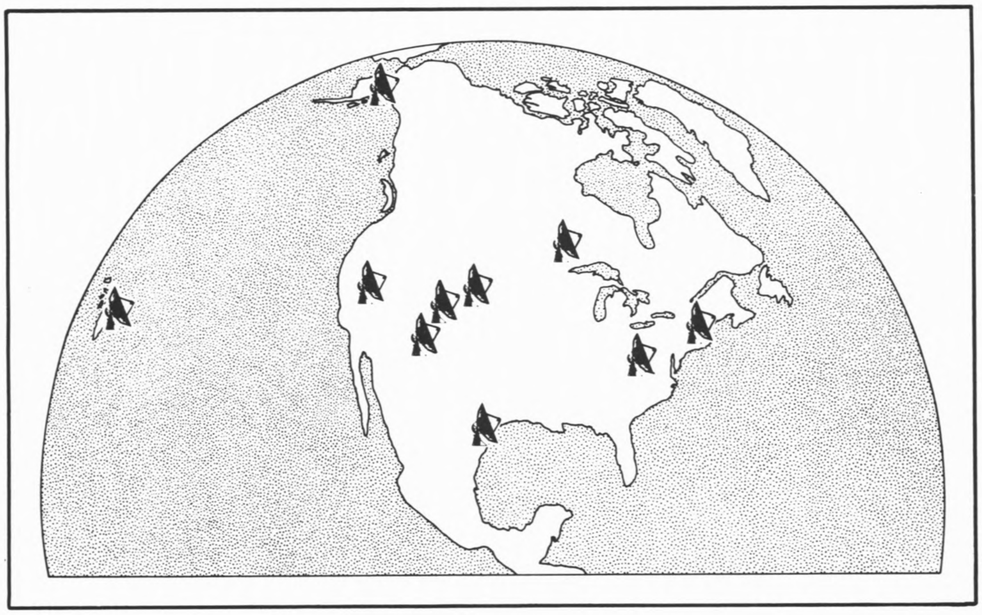
THE VERY LONG BASELINE ARRAY RADIO TELESCOPE



VLBA

NATIONAL RADIO ASTRONOMY
OBSERVATORY

- A PROGRAM -

FOR THE

VERY LONG
BASELINE ARRAY
RADIO TELESCOPE

MAY 1982

NATIONAL RADIO ASTRONOMY OBSERVATORY

prepared in collaboration with the
CALIFORNIA INSTITUTE OF TECHNOLOGY

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THE VERY LONG BASELINE ARRAY

Contents

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, rivalling the best optical telescopes under the most favorable observing conditions. But many of the newly discovered galactic and extragalactic objects 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) yielding an angular resolution of a few tenths of a milliarcsecond. The VLBA will make possible unprecedented high resolution radio pictures of cosmic objects including quasars and galactic nuclei, the galactic center, interstellar molecular masers, stellar radio sources, pulsars, and other exotic objects which are at the forefront of astrophysical research. The VLBA will complement and extend 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, supernova remnants, and the planets). The universe contains both extended and compact objects, and the two instruments will allow a full exploration of galactic and extragalactic radio astronomy.

This proposal is the result of studies and discussions in the radio astronomy community based on the experience, successes, and frustrations from 15 years of Very Long Baseline Interferometer (VLBI) experimentation, and on experience gained from the construction and operation of the VLA.

Section I summarizes the design and performance specifications of the VLBA, and Section II discusses the scientific applications. The operation and management is discussed in Section VI, and the cost of construction and operation is described in Section VII. Sections III, IV, and V describe the Array configuration, the antenna systems, and the central playback facility respectively, and are more technical than the other sections.

At the time of a preliminary study made in 1977, a number of problem areas were identified, particularly 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 powerful self-calibration techniques currently being used at the VLA and in VLBI to form images without the need to have absolute calibration of antenna 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 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 recording techniques should allow up to 24 or more 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 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 and performance are well understood.

VLBI is the only technique available, in any part of the spectrum, which can give images of astronomical objects with over 100 times better angular resolution than conventional optical or radio telescopes. The VLBA represents a practical limit to the resolution that can be currently achieved from the surface of the Earth. Significantly higher resolutions are possible through VLBI techniques, 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 developed among the Western European countries, in Canada, and in the USSR. The first of several dedicated VLBI antennas is already under construction near Bologna, Italy. Other VLB programs are being discussed in Japan, Australia, and China, and it will be important to explore ways in which to further exploit international cooperation to extend the VLBA to truly global proportions.

The work described in this volume has been carried out over a period of several years by a group of scientists and engineers from NRAO and Caltech consisting of:

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In addition, we have profited from discussions, calculations, and written contributions from many people including: J. Broderick (VPI & SU), T. Clark (NASA), D. Heeschen (NRAO), H. Hinteregger (MIT), S. Knowles

(Naval Res. Lab.), K. Knight (Phoenix Corp.), D. Shaffer (Phoenix Corp.), J. Spencer (Naval Res. Lab.), P. Thaddeus (Inst. for Space Studies), A. Whitney (MIT), and others in the radio astronomy community.

Liaison with the Canadian Long Baseline Array (CLBA) design group has been primarily through its chairman, E. Seaquist, as well as J. L. Yen (Univ. of Toronto), N. Broten, D. Fort, and T. Legg (National Research Council of Canada).

The details of the engineering studies which form the basis of this report can be found in 84 NRAO internal reports which are referred to in the text and listed in Appendix I. These reports will be edited and made available in a separate volume.

Green Bank, W. Va.
May 1982

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 equal in size to the entire United States. The Very Long Baseline Array (VLBA) represents an improvement in resolution of two to three orders of magnitude over the most powerful instruments operating in other parts of the spectrum and will permit for the first time detailed studies of some of the most challenging and least understood astrophysical phenomena.

Perhaps the most fundamental problem in astronomy is the source of energy in quasars and galactic nuclei, and the manner in which the energy is transported to distant radio-emitting lobes. The VLB Array will give the very high resolution images which are needed to understand the central "engine" in these exotic objects, as well as the weaker sources found in nuclei of ordinary spiral and elliptical galaxies. Of particular interest will be the apparent faster-than-light motion observed in quasars and radio galaxies; these are difficult to explain and perhaps challenge our fundamental concepts of physics and cosmology. The VLBA will permit the frequent multi-wavelength observations necessary to follow their evolution with time.

More than half of all extragalactic objects observable at centimeter wavelengths are too small to be studied with conventional radio arrays and optical telescopes, but their structure will be revealed with the VLBA. There are more than 100,000 extragalactic sources alone which can be observed with the VLBA, and most of these are probably variable on time scales of a few months. The VLBA will make it possible to follow their evolution in detail. Complementary observations made with the VLBA and the VLA, as well as the new generation of optical and X-ray telescopes, will have a profound impact on our understanding of quasars and galactic nuclei, and their cosmological evolution.

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 can be studied in detail with the VLBA. 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 VLBA is of the order of an Astronomical Unit, and the high linear resolution available for these sources will yield further insight into the nature of their more powerful extragalactic counterparts.

The intense line emission from molecular maser sources, found in regions of star formation and in the envelopes of highly evolved stars, is particularly interesting. The VLBA will be able to explore the temperature, density, magnetic field, and dynamics of galactic maser sources on scales as small as one 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 with the VLBA. The VLBA will, in addition, make possible direct trigonometric measurements of distances on galactic and even extragalactic scales. These measurements will be of fundamental importance to all areas of astronomy.

The VLB Array will be used for a broad range of problems in physics and geophysics, as well as for astronomy and astrophysics. Terrestrial applications include precision geodesy, crustal dynamics (tectonic plate motions), polar motion, precise clock synchronization and the determination of time. Other applications include accurate tests of relativistic bending 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 to about one second of arc, not by the telescopes, but by irregularities in the earth's atmosphere. At radio frequencies, the atmospheric fluctuations in the path-length of the incoming signal 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 (VLA) gives, for the first time at radio wavelengths, images of high sensitivity and dynamic range with angular resolution equal to or better than that given by optical telescopes. Although previous radio arrays have approached the resolution of the VLA, it is the unique combination of resolution, speed, sensitivity, frequency coverage, and dynamic range (image quality) that makes the VLA so powerful, and has already resulted in a number of new 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 have 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.

VLBI observations 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, such as the superluminal radio sources. But as is typical of major new scientific techniques, the VLBI observations have raised more new unanswered questions than answers to old ones. Extraordinarily high resolutions have already been obtained, but the results, like pre-VLA radio astronomy, are limited by poor image quality, low sensitivity, and inadequate frequency flexibility. These limitations are due to the use of too few antenna elements which are inappropriately situated, operate poorly at short wavelengths, have restricted sky coverage, are poorly instrumented, are unavailable much of the time, and are often inadequately coordinated and operated.

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

Discussions to combine VLA and VLBI technology to develop a very high-resolution aperture-synthesis telescope began in the early 1970's, less than five years after the first VLBI observations were made in Canada and the

United States. In 1974 the NRAO organized a workshop to plan toward the orderly development of a dedicated VLB Array in the United States. At this time a three-phase plan was prepared:

a) to coordinate and improve the operation of the existing radio telescopes for VLBI research;

b) to build a new radio telescope in the midwestern part of the country to fill in the gap between the concentration of radio telescopes on the east and west coasts, and to be the first antenna of a new dedicated VLB Array; and

c) to design and construct a dedicated VLB Array.

It was agreed at this time that the work in each of these three areas would be coordinated by Caltech, the Univ. of Illinois, and NRAO respectively. A semi-popular article describing the VLB Array was published by Swenson and Kellermann in 1975 (Science 188, 1263). In 1977 four reports were issued under the general title "VLB Network Studies":

I. Cohen, M. H. ed. "A VLB Network Using Existing Antennas", Calif. Inst. of Technology.

II. Swenson, G. W., Cohen, M. H., Kellermann, K. I., and Rogers, A. "Interim Report on a New Antenna for the VLB Network", Univ. of Illinois.

III. Kellermann, K. I. ed. "An Intercontinental Very Long Baseline Array", NRAO.

IV. Swenson, G. W. "On the Geometry of the VLB Network", Univ. of Illinois.

The first of these studies led to the formation of the U.S. VLB Network and the Network Users Group (NUG) which, although informally organized, has been remarkably successful in scheduling approximately 80 days per year for

VLB observing, in establishing priorities for the further development of VLBI instrumentation at the participating observatories, and in coordinating VLBI activities in the U.S. and with European observatories. Recently, the more formally organized VLBI Consortium has been formed to take over these activities.

The second study led to the submission of separate proposals by the Universities of Iowa and Illinois to the NSF for the construction and operation of the Mid-West Telescope for VLBI. Neither of these proposals was funded.

Volume III described the design, construction, and operation of the dedicated VLB Array. In January 1980, Caltech convened a group of about 15 scientists to participate in the further development of the VLB Array concept. The result of this study was issued in September 1980 (M. H. Cohen, ed. "A Transcontinental Radio Telescope", Calif. Inst. of Tech.). During 1980, the NRAO design study was also further developed, and in October 1980, a workshop was held in Green Bank to gain further input from the Network Users Group. As part of the workshop, the annual NUG meeting was held in Green Bank and the approximately 70 participants unanimously endorsed the concept of the dedicated "VLB Array". The result of the second NRAO Design Study was issued in February 1981 (The VLB Array Design Study, NRAO).

The NRAO and Caltech design studies both explored in depth the configuration of the proposed VLBA, record and playback systems, front end and feed designs, operations and management, as well as evaluating the cost of construction and operation of the Telescope. Many of the same people participated in both design studies which differed primarily in the separate approaches appropriate to the two organizations in the management and operation of the VLBA.

The VLBA has been discussed extensively within the radio astronomy community and has been selected by the Astronomy Survey (Field) Committee as the number one priority for new starts for major ground-based instruments for astronomical research.

C. Design, Performance and Operation

The VLBA will be operated by the NRAO 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 most of the visible sky, and will have sufficient sensitivity to observe a very wide variety of high-surface-brightness phenomena.

The Array itself will consist of ten elements, eight of which are located within the continental USA. Two are in more remote locations, probably one in Alaska and one in Hawaii. The locations of the individual Array elements will be chosen to optimize the dynamic range (image quality) 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, as experiments warrant, 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.

The VLBA elements will use 25m high-efficiency steerable paraboloids, designed to work well at wavelengths at least as short as 7 mm. Multiple low-noise receivers are used to provide the flexibility to observe over a wide range of wavelengths from 7 mm to 90 cm, including all of the commonly used radio astronomy band allocations at centimeter and decimeter wavelengths, the VLA frequencies, the NASA Deep Space Network frequencies, the spectral line of hydrogen (21 cm), the four ground state OH lines (18 cm), the excited OH line (5 cm), the H_2O line (1.3 cm) and the SiO line (7 mm).

At the longest wavelengths of 50 and 90 cm, prime-focus GASFET amplifiers are used to give moderate system temperatures at very low cost. The receivers operating from 2 cm to 20 cm are located at the secondary focus and use GASFET amplifiers cooled to 20K to give good sensitivity and reliable performance. At 1.3 cm and 0.7 cm, maser preamplifiers will be used at the secondary focus to give state-of-the-art low system noise temperatures. The observing frequency 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 VLBA is maintained by independent, stable, hydrogen maser oscillators. 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 VLBA can operate in the coherent 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 is applied with the VLBA 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 VLBA is sensitive only to sources of high surface brightness. The effective r.m.s. fluctuation in brightness temperature in each synthesized beam area is approximately 2 x 10^8 K, 10^7 K, or 10^5 K for observing times of 1 sec, the typical coherence time of a few hundred seconds, and the full 8 hour synthesis, respectively.

TABLE I-1

SENSITIVITY AND RESOLUTION OF THE VLBA

Frequency (GHz)	Feed	Efficiency	Rcvr	System Temperature		τ(sec)	Sensitivity (mJy)			
				K	Jy		σ	σ_c	σ_A	θ
.325	PF	0.31	GASFET (a)	65	990	100	850	85	0.8	24
.611	PF	0.47	GASFET (a)	55	640	200	550	38	0.5	13.5
1.4/1.7	SF	0.58	GASFET (c)	29	220	1200	225	5	0.18	5.4
2.3	SF	0.69	GASFET (c)	31	230	1000	200	7	0.18	3.5
5.0	SF	0.69	GASFET (c)	37	260	500	220	10	0.19	1.6
8.4	SF	0.71	GASFET (c)	40	290	280	260	16	0.23	0.9
10.7	SF	0.70	GASFET (c)	45	320	230	300	20	0.26	0.75
15	SF	0.67	GASFET (c)	65	490	160	320	23	0.20	0.54
22	SF	0.61	Maser	45	380	110	350	32	0.31	0.35
43	SF	0.35	Maser	75	1040	60	900	110	0.8	0.20

PF: Prime Focus
SF: Secondary Focus
a: Ambient Temperature
c: cooled to 20K
τ: Typical tropospheric or ionospheric coherence time
σ: Single baseline in 1 sec
σ_c: Single baseline in coherence time, τ
σ_A: For 8-hour coherent observation with entire Array
θ: Synthesized beam size, FWHM milliarc seconds.

The Operation of the VLBA will be controlled from the Array Operating Center which is connected to each of the elements via leased telephone lines. The VLBA will be operated under a preplanned program which is controlled by a central computer, which also monitors a number of test points in each antenna and receiver 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 the 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 VLBA is properly functioning. The full IF signal will be recorded on high-density digital recordings and shipped to the Operations Center for later correlation and analysis. The tape recorders available at each site will 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. 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, a central Service Center where a larger group of engineers, technicians, and mechanics are stationed, will be utilized. To a large extent, however, it is planned to replace complete modules in the case of failure as such replacements can be easily performed by the local site personnel. Defective modules will be returned to the

Service Center for repair. This procedure requires a somewhat larger than normal inventory of spare parts, but reduces travel and personnel costs.

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 with full polarization capability and up to 32 continuum delays. Alternatively, 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 VLBA will profit from the extensive experience gained from the VLA and from VLBI research.

Figure I-1 shows an overview of the entire VLBA. Individual sections are shown and described in more detail in Section IV.

D. Cost Summary

Construction and Operating Costs are summarized in Tables 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 given in 1982 dollars. Construction can be completed about 56 months after initial funding is available.

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 later be added expensive instrumentation and software.

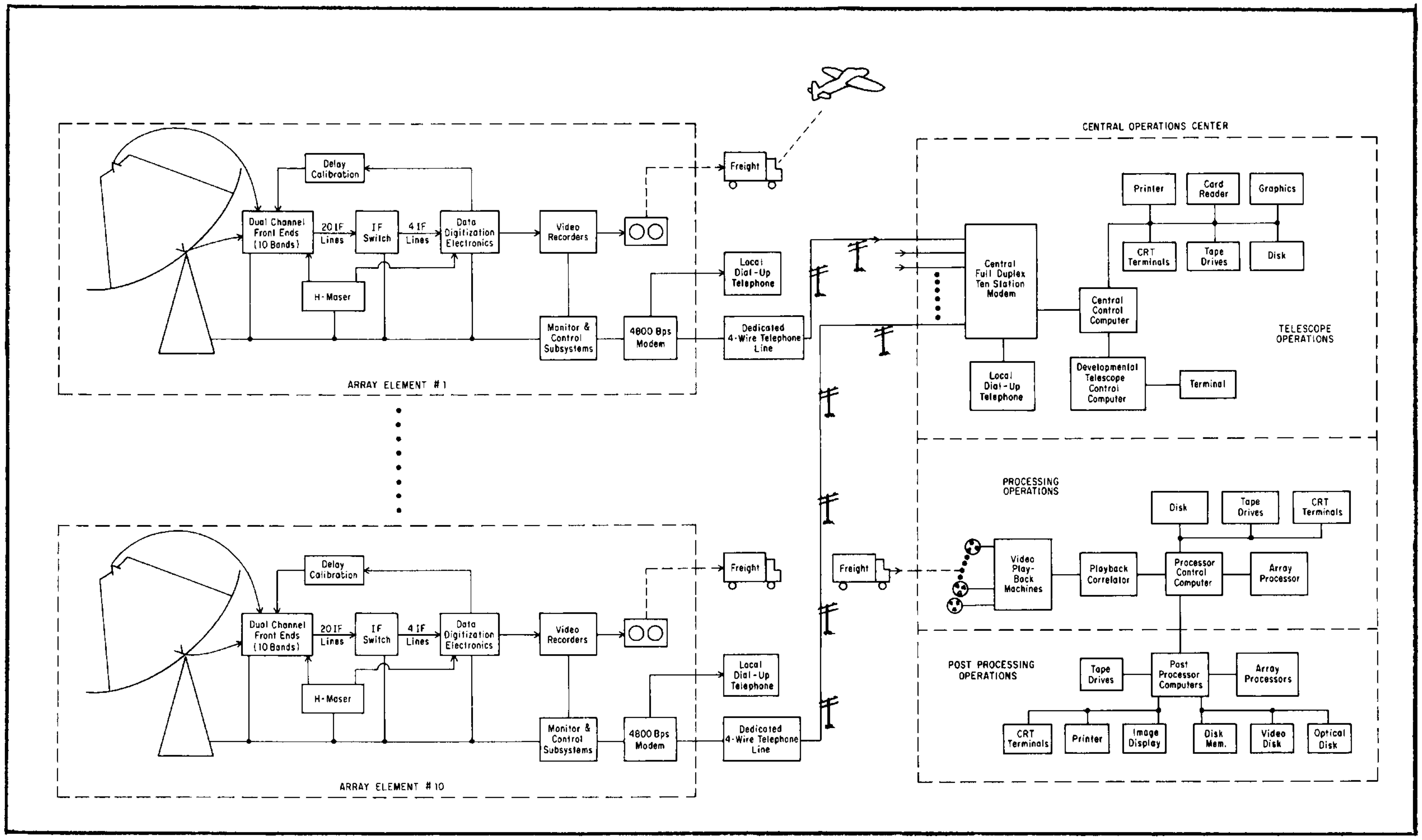

Fig. I-1. Block Diagram of VLBA.

TABLE I-2

CONSTRUCTION COST SUMMARY ($K)

Antenna Elements	17,170
Station Electronics	10,170
Site Development	2,550
Central Control and Processing Center	7,264
Spare Parts, Tapes, Test Equipment, etc.	3,415
Engineering and Design	2,060
Project Management	2,000
Contingency	6,000
TOTAL CONSTRUCTION COST (1982)	50,729

Our estimate of operating cost is based on the costs required to run the VLA and other NRAO sites, with the cost of unusually large items such as shipping, communication, and travel taken into account. The estimated operating budget is about twice the current level of U.S. support for VLBI astronomical research. 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 SUMMARY ($K)

Personnel Compensation	2,100
Materials, Supplies and Services	580
Shipping, Utilities, Travel, Communications	970
New Operating Equipment	500
ANNUAL OPERATING COST (1982)	4,150

II. SCIENTIFIC GOALS

Cosmic radio sources have angular sizes that range from a fraction of a milliarcsecond to several degrees, with a correspondingly large range of surface brightness. Therefore 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 that of 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 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.

Although many exciting pioneering discoveries have already been made with VLBI systems, the continental network of existing telescopes is inadequate for many reasons.

1) There are too few antennas.

2) The antennas are not optimally located, so that the image quality is poor.

3) There are too few close antenna spacings, so that the maximum source dimensions are restricted.

4) The maximum antenna spacing is only 4000 km, so that the resolution is limited.

5) There are inadequate north-south spacings so the resolution and beam shape in this direction are poor, particularly for sources which are not at high northern declination.

6) The existing antennas are not concentrated at dry sites and the observations often suffer from poor weather conditions.

7) The existing antennas do not work well at short wavelengths, further limiting the available resolution.

8) The existing antennas, particularly the better ones, are in demand for a wide variety of other research programs and are available for only limited periods for VLBI. This especially restricts systematic programs requiring repeated observations.

9) The sensitivity is limited due to narrow bandwidths and often poor receivers.

10) There is little or no polarization capability on most antennas, and the wide variety of different antennas being used makes polarization measurements difficult.

11) The process of correlating the magnetic tapes is awkward and requires many passes through existing correlators.

12) There is an inadequate number of frequency channels in the correlator systems for spectroscopic studies.

13) Only a limited number of frequencies are available on each antenna. Receiver changes generally are difficult and time consuming, and so are done only infrequently.

The VLB Array will be a true image forming instrument with sub-milliarcsecond resolution which eliminates all of the above restrictions. The linear resolution of the VLBA is a parsec and an Astronomical Unit on extragalactic and galactic scales respectively, so that a wide range of important new investigations will be possible. The high resolution radio images 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. A unique property of the VLBA will be its ability to study the evolution of individual objects. More conventionally, astronomers have pieced together evolutionary histories by observing many objects assumed to be basically similar but at different phases of their life-cycle. With repeated VLBA observations, however, it will be possible to follow the evolution in specific galaxies and quasars as well as the galactic radio sources.

In the following pages we summarize briefly the currently important areas where the VLBA 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 led to its construction, but from the unexpected discoveries which often 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 VLBA 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 weeks to 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 VLBA is expected to give major new insight into the manner in which matter is accelerated to relativistic energies, focused, and transported to the extended radio lobes as far as a million light years away.

While one of the prime areas of study for the VLBA will be distant quasars, BL Lac objects, and other active galactic nuclei, nearby galaxies such as M81, M82 and M87, Seyfert galaxies and N-galaxies will also be studied. Systematic observations of large complete samples of objects will be possible, and for the first time it will be possible to make cosmological studies requiring observations of weak sources.

Radio and optical observations of quasars and extended radio galaxies show evidence of dramatic cosmological evolution. The compact radio sources appear to be more uniformly distributed in space, but high resolution maps of weak distant sources are necessary to investigate how their properties change with cosmic epoch. The relation between the compact and extended radio sources and the reason for their apparently different cosmic evolution are not understood. Observations of compact sources with the VLBA will complement observations of extended sources made with the VLA in tackling this problem.

Finally, ordinary spiral and elliptical galaxies frequently contain compact radio nuclei. The new VLBA will enable us to follow in detail the evolution of these objects. Already some remarkable results have emerged from the crude VLBI maps of quasars and active galactic nuclei. Structures as small as 10^{16} cm are found in some objects, large double radio galaxies often contain asymmetric jets in their nuclei which are aligned with the large scale structure, and apparent superluminal component motion appears to be a common phenomenon (e.g. Kellermann and Pauliny-Toth 1981).

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 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. The fixed component models are not supported by the recent multi-element observations, but the situation is clearly more complex than the simple model of two components separating with superluminal velocity (e.g. Pauliny-Toth 1981, Pearson et al. 1981).

Instead, the observations reveal a complex elongated structure which resembles the jets seen with the VLA on larger scales. An example of superluminal motion is shown in Figures II-1 and II-2. This shows maps of the quasar 3C 273 made at five different epochs. The knot in the jet is moving with an apparent speed of 9.6c. The features appear to move and change in brightness, but the resolution and quality of the radio pictures are inadequate to obtain more than a few picture elements across the 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. Also, at present, individual components may only be followed for a very limited period. At first the resolution is inadequate to separate the components and, after a few years, the components fade from view. The VLBA will have the resolution, sensitivity, frequency flexibility, and dynamic range to be able to study, in detail, the kinematics of individual components throughout their evolutionary history.

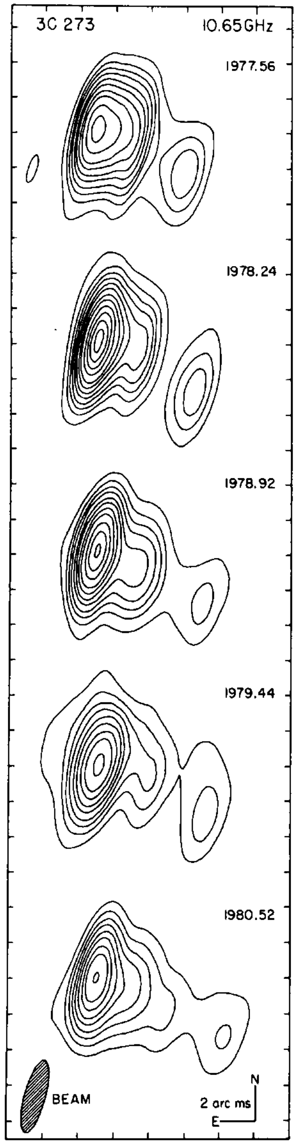

Fig. II-1. Change in structure of 3C 273 between 1977 and 1980 (taken from Pearson et al. 1981).

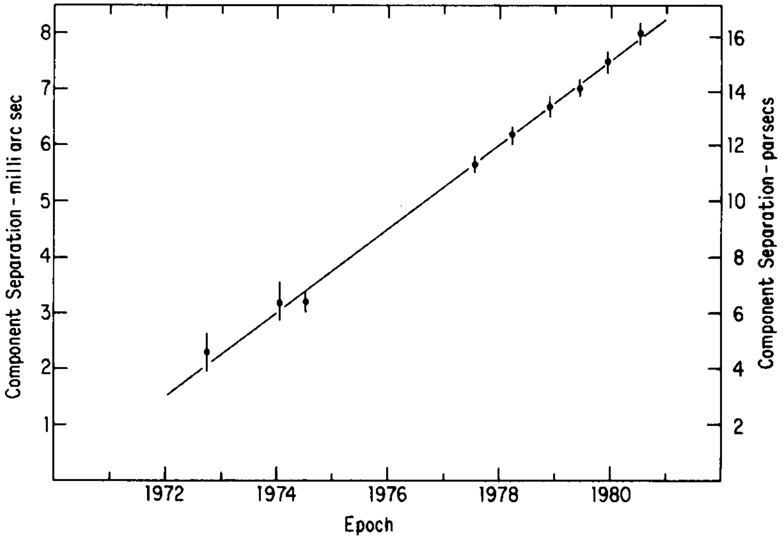

Fig. II-2. Component separation in 3C 273.

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 VLBA along with the flexible frequency coverage and dedicated nature of the instrument will permit the complex pattern of motion to be observed. In addition, polarization observations which will be possible with the VLBA 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 due to the finite signal travel time from radiating material which is moving nearly along the line-of-sight at velocities close to the speed of light. But it is difficult to understand the large fraction of sources which show superluminal velocities, as this implies a highly specialized geometry with nearly all sources pointed toward the Earth. The evidence for widespread highly relativistic bulk motions in quasars and radio galaxies is exciting and the detailed study of material moving with nearly the velocity of light, which will be possible with the VLBA, will have a profound impact on our understanding of extragalactic phenomena.

A large fraction of the nuclear radio emission regions appear as one-sided jets. One of the most important questions in extragalactic astronomy is: Are there two mechanisms for producing jets - one symmetric and one asymmetric; or is there only one universal symmetric mechanism? Asymmetric structure is found even in the nuclei of objects which have large-scale symmetry. Thus the basic ejection process appears to be symmetric but relativistic beaming and differential light travel times might cause an apparent asymmetry. One of the best studied examples of an asymmetric jet is found in the galaxy NGC 6251 where VLBI observations of the 2 pc core show it to be well aligned with the 200 kpc jet and the extended radio lobes over one Mpc away. The existing VLBI observations are sufficient to show the elongation, but no detail in the central core. With the VLBA the central component can be seen with the same clarity as the present observations of the larger jet shown in Figure II-3.

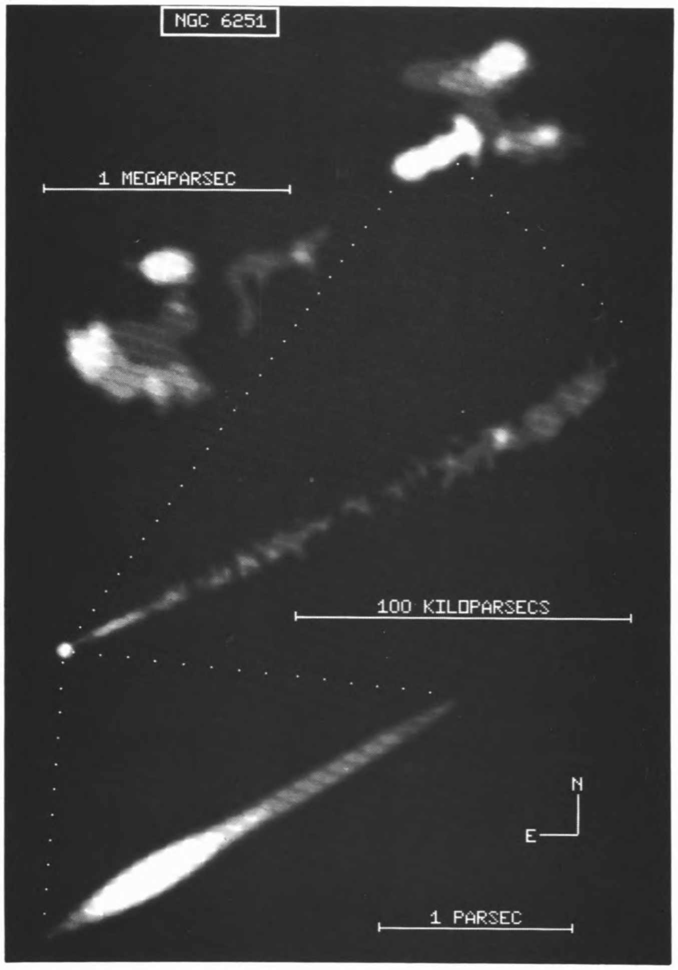

Fig. II-3. The radio source associated with NGC 6251 showing the location of nuclear and outer jets relative to the extended lobes. The large scale image and outer jet come from observations made with the Cambridge 1/2-mile and 5-km telescopes respectively; the image of the inner jet comes from 4-station VLBI observations. Images are based on data given in Readhead et al., Nature 272, 133.

The compact central radio components of double radio galaxies also have asymmetric jet-like structure which is well aligned with the outer components (Linfield 1981). Thus the directivity required to explain the shape and orientation of extended radio sources is established by the central object, and this directivity must be maintained for periods $\gtrsim 10^7$ years. The fact that the collimation mechanism maintains a constant direction while producing a radio source with energy $\sim 10^{61}$ ergs suggests that the long term stability of the orientation is the result of gyroscopic action of a massive black hole.

Figure II-4 illustrates another object which has been extensively studied with VLBI techniques, the radio galaxy NGC 1275 (3C84), which has a wide range of structure with features as small as 2 x 10^{17} cm at

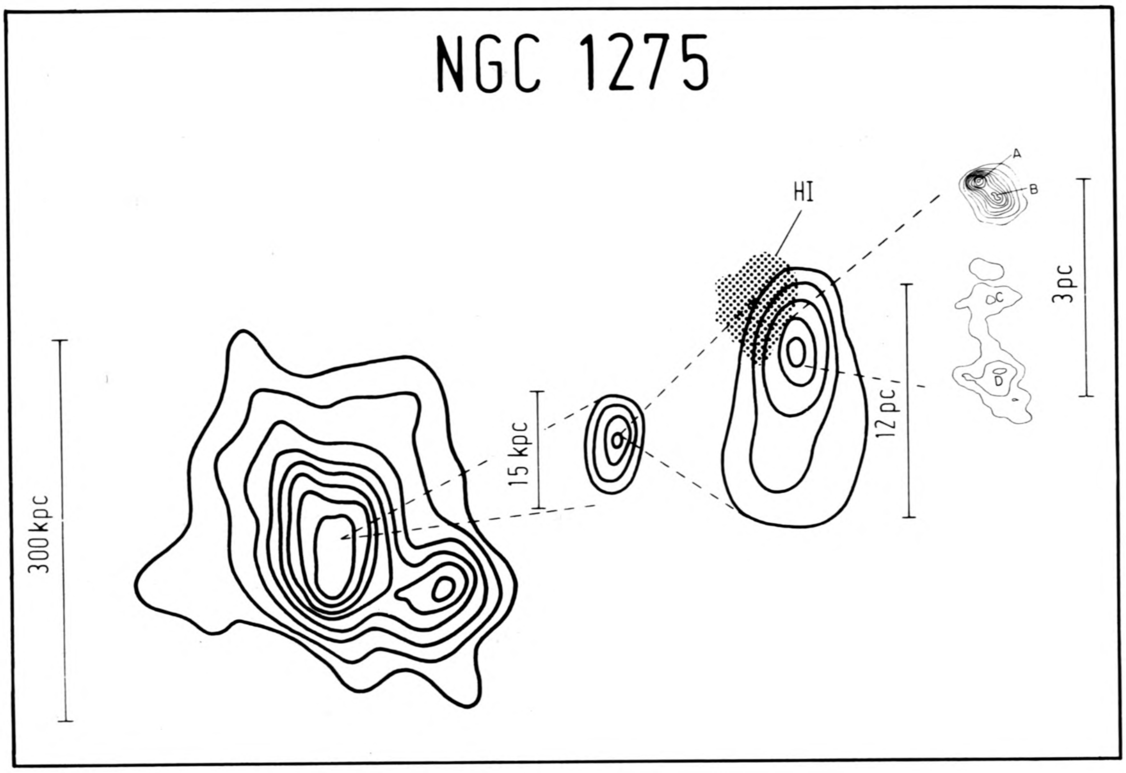

Fig. II-4. Schematic illustration of the radio emission from NGC 1275. Taken from Kellermann and Pauliny-Toth (1981) and Readhead et al.(unpublished).

1.3 cm. This is the shortest wavelength at which a VLB map has been made, but NGC 1275 is the brightest object in the sky at this wavelength. The VLBA will allow a wide variety of objects to be studied at 1.3 cm and at even shorter wavelengths. Observations at the shortest wavelengths are important not only because this gives the best resolution, but the opaque sources that are observed at 3 and 6 cm can be probed more deeply at shorter wavelengths where they become transparent. Moreover, for $\lambda \lesssim 1$ cm, unlike at longer wavelengths, there is significant correlation between radio and optical flux density variations. High resolution radio observations at these wavelengths will reveal radio features that vary synchronously with the optical variations, but the present capability at these wavelengths is very limited.

Low-frequency variable sources are also of great interest, since the brightness temperatures implied by the variations appear to violate the inverse Compton limit of 10^{12} K. In some of these objects there is structure on angular scales from less than 10 to more than 100 milliarcsecs. No serious attempt to map these objects can be made using present VLBI facilities, since uniform coverage from a few hundred kilometers to many thousands of kilometers and very high dynamic range are essential.

Many of the bright extragalactic radio sources are associated with objects that have bright optical emission lines. Although the radio continuum and the optical line emission arise in different regions, they are however related. In the Seyfert galaxy 3C 120, for example, the galaxy rotation axis, as determined by the velocity distribution of the emission lines, is parallel to the nuclear jet detected by VLBI on a scale 1000 times smaller. There is no way to directly measure structure in the optical band at the resolution necessary to determine the morphology on the sub-parsec scale. But the combination of radio morphology measured with the VLBA, studies of radio, millimeter and optical flux density variations, polarization, and spectral line observations will play an important role in determining the nature of the central engine.

Of particular interest will be the stimulated radio recombination lines which arise whenever a region of ionized gas is located between the observer and a source of background continuum radiation such as from a quasar or active nucleus. Unlike the spontaneous radio recombination lines observed in galactic HII regions and nearby galaxies where the maximum brightness temperature is only of the order of 10^4 K, the stimulated recombination line intensity may reach 10 percent of the continuum flux density. Because of their broad bandwidth, stimulated recombination lines have, until now, been difficult to detect. But recently radio lines have been observed (in emission) in the Seyfert galaxy OQ208 at $z = 0.0767$ and (in emission and absorption) from the quasar 3C 245 at $z = 1.030$ using modern broadband spectrometers, and it is expected that this will be a fruitful field for future research.

High resolution maps of stimulated radio recombination lines will provide unique information on the following:

(1) The thermodynamics (temperature and density) of the ionized gas in active galaxies and quasars on a scale of 1-10 pc.

(2) The kinematics of active nuclei. The rate of mass outflow (or infall) from a central object is directly measurable. With multi-epoch maps one should be able to follow nuclear activity in detail.

(3) The decomposition of the emission line region into discrete spatial and velocity components. If the line profile is a superposition of clumps, then the properties of these clumps (size and density) can be determined.

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 be used to 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-4) 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

For galactic sources the VLBA will have a characteristic resolution 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 (HII regions) and in the envelopes of highly evolved (IR) stars (Reid and Moran 1981). The very high brightness of the masers allows VLB observations to probe the dynamics and magnetic fields in these regions on a scale of 10^{13} to 10^{18} cm.

H_2O masers form around young O and B stars, some of 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 ionized regions around the young stars. They provide a sensitive probe of these highly disturbed clouds.

Studies of OH masers complement those of H_2O masers. Observations of OH masers determine the dynamics and physical condition 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 usually coincide with ultra compact HII regions. OH masers contain magnetic fields of the order of a few milligauss which cause the spectral features to exhibit Zeeman splitting. Proper motions of individual features obtained from synthesis maps made with the VLBA can be combined with radial velocities to provide three-dimensional velocity vectors for many components, from which the overall kinematics may be derived. In addition, observations of Zeeman splitting give the 3-dimensional magnetic field vectors throughout these regions, which give some insight into the manner in which the magnetic field affects cloud collapse and star formation.

The ability to study the dynamics of maser regions with VLBI is demonstrated in Figure II-5 which shows a schematic model of the outflow in the Orion KL nebula obtained from H_2O VLBI observations made over a two-year period. The spectrum contained low velocity features within ± 20 km/sec of the molecular cloud velocity and high velocity features extending out to ± 100 km/sec. During the two-year observing period, the position of many features changed linearly with time with rates up to 0.02 arcsec/yr,

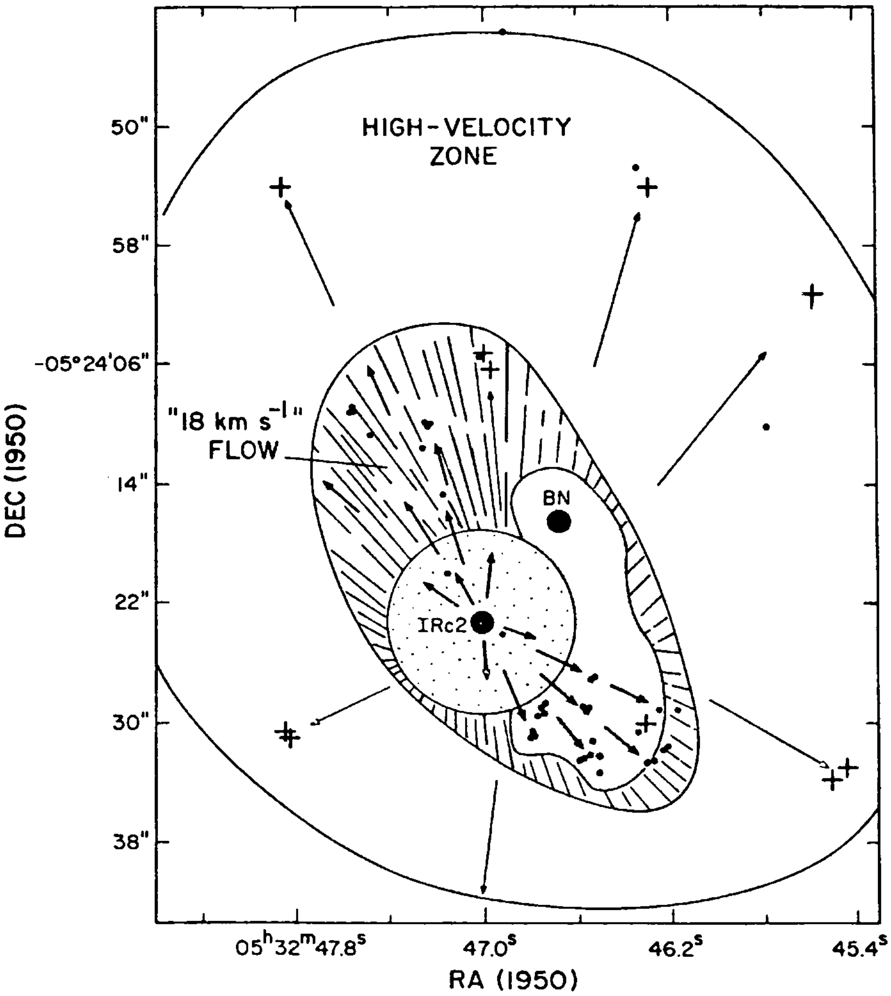

Fig. II-5. Schematic model of the Orion KL nebula showing the low and high velocity zones. Black dots are the H_2O low velocity maser features and crosses denote the high velocity H_2O features. Taken from Genzel et al. (1981a).

corresponding to transverse velocities of up to 50 km/sec. The pattern of velocities clearly indicated a symmetric outflow and was used to derive the distance (480±80 pc), velocity centroid (10 km/sec), and expansion velocity (18 km/sec) for the region within $\sim 10^{17}$ cm of the center of the explosion.

OH, H_2O and SiO masers are also found associated with late type stars, most of which are evolved stars in the red giant or supergiant phase of evolution. These stars have high mass loss rates and generate circumstellar envelopes in which masers occur. These stars 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 molecular species, so the masers occur at different levels in the envelopes. Therefore, studies of all three species provide valuable and complementary information on the kinematics, geometry, and magnetic fields (in the case of OH masers) in the circumstellar envelopes.

Some masers are associated with late-type stars whose evolutionary state is unusual and probably short-lived. The SiO masers appear to reside close to the stellar photosphere, while the H_2O masers occur farther out in the circumstellar envelope, and the OH masers exist at the greatest distance from the central star. Stars such as VY CMa and IRC+10420 are exceptionally luminous, possibly exceeding 10^6 $L_\odot$. VY CMa may be a pre-main sequence object surrounded by a circumstellar disk of dust and gas. IRC+10420 displays spectral characteristics of an F-type supergiant. Since it is the only known stellar maser whose central star is much hotter than the usual M-type maser star, it seems that in IRC+10420 we are observing a transient horizontal excursion across the HR diagram.

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 less than 0.1 to 100 milliarcsec and are scattered over fields having diameters of from $0\farcs01$ to 30". The ratio of the total source size to the individual component size is generally quite large, i.e. up to 10^4. Individual H_2O features typically have a lifetime of several years, but significant variations are observed on time scales of a few days. OH masers have considerably longer lifetimes than the H_2O masers, and the stellar OH masers appear to be much larger than those associated with HII regions.

Stellar Objects

In recent years both thermal (free-free) and non-thermal continuum radio emission from a variety of stellar objects have 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. However, crude VLBI pictures of the Galactic Center, the radio star β Persei, and the exotic object SS 433 have already emerged.

Free-free radio emission has been detected from approximately two dozen early-type stars and from an equal number of peculiar stars (protoplanetary nebulae, symbiotic stars, and the like). The radio fluxes, interpreted as arising in a spherical envelope produced by a stellar wind, give moderately accurate mass loss rates which are of great interest in the study of the evolution of these objects. Moreover, some of the peculiar stars are large enough in angular extent that they can be resolved by the VLA, and a study of the structure of the envelopes is beginning.

The expected size (at 6 cm) of the envelopes of the early stars is in the range 0.02 to 0.10 arcsec and is beyond the reach of present instruments. Sensitive high resolution observations are required to study these shells. The most important question is the geometry; there is tentative evidence from optical data that the ejection is into a plane. Knowledge of the geometry of the wind is crucial to an understanding of the mass loss mechanism and the mass loss rate. Observations with the VLBA also offer the possibility of a direct determination of the temperature gradient in the wind, by resolving the envelope at several wavelengths. This quantity is important in the discussion of the energy balance of the wind, and can be obtained in no other way.

There are many other non-thermal stellar radio sources throughout the Galaxy. Some, e.g. Cyg X-3, are at times very bright, but there are many more which are much fainter, and the quiescent flux is always weak. The sensitivity and flexibility of the VLBA make possible observations of many galactic radio stars, especially during their active periods. These variable sources have many quasar-like properties, and the ability to examine their structure and evolution with up to a million times better linear resolution will be important in attempts to understand the nature of the non-thermal stellar radio sources as well as their extragalactic counterparts.

Of particular interest will be the newly discovered exotic objects such as SS 433 with its remarkable system of precessing relativistic jets. The VLA 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 these 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 VLBA will be able to trace the motion of the jets on a scale of 10^{14} 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 independently of any assumptions about the similarity of properties of nearby and distant objects. Without the VLBA, the sensitivity, resolution, and image quality are not sufficient to detect the faint receding component.

Also of interest will be the binary radio stars which have frequent flares. VLBI observations have shown that the radio emission from Algol (β Persei) is on the size scale of the binary (Roche lobe) system. But more detailed repeated measurements are needed to trace the evolution of the flares and to determine the physical mechanism for their emission. Accurate astrometric observations may permit the orbital motion, if any, of the radio source to be directly observed. At the longer wavelengths, the VLBA will also be able to detect flare stars. It is not clear whether the resolution will be sufficient to resolve the radio flare, but if it is, it will be possible to study the motion and evolution of the flaring region.

Finally, we note that the galactic center is an extraordinarily rich and interesting region containing thermal and non-thermal radio and IR emission regions, including a very compact non-thermal radio source. The overall dimension of this compact nucleus is ∿ 0.02 arcsec (200 AU), and 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 (Lo et al. 1981).

This compact radio source is interesting because it may be similar to the extragalactic compact radio sources found in nuclei of radio galaxies and quasars. Since the galactic center is only 10 kpc distant, the radio nucleus can be studied in great detail, while the nearest external galactic nucleus in M31 is 70 times further away. So far, however, our knowledge of the structure of the galactic center source is limited due to its a) low southern declination where existing antennas give a particularly poor beam, b) low flux density, and c) the uncertain effects of interstellar scattering.

The two dimensional configurations of the VLBA 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 a few AU. Because this source is known to vary on time scales of a month or less, repeated observations will provide insight into the extraordinarily interesting activity which is going on at the center of our Galaxy.

The Interstellar Medium

The discovery of pulsars has led to the detection of irregularities of the thermal plasma density in the interstellar medium on a typical scale of a solar diameter (3 x 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 are not understood. They may be associated with abrupt gradients due to interstellar shocks, or 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 VLBA 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 phenomenon is very wavelength dependent, the broad wavelength coverage and flexibility of the VLBA will be particularly important in studying the interstellar plasma.

The effect of interstellar scattering (seeing) sets a limit to the effective resolution of the VLBA. At frequencies above 1 GHz, interstellar seeing is not important for Galactic latitudes greater than about 10 degrees, but at lower frequencies the resolution is limited for an increasingly large part of the sky.

Small clouds of neutral hydrogen are also found in the interstellar environment and the VLBA 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 VLBA 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 is 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 VLBA will give distances throughout the galaxy, by the more straightforward observations of parallax with a precision considerably better than $0\overset{''}{.}001$. The ability of the VLBA 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. Even at the distance of the Virgo cluster, proper motions of a few hundred km/sec can be observed in a few years.

Because the compact radio sources, in general, have a complex distribution of brightness, they must be accurately mapped with the VLBA when used as a basis of astrometric observations. Simple interferometry with only a few elements is inadequate for this purpose.

One type of H_2O maser source contains clusters of hundreds of "spots" whose relative motions are kinematic in origin and nearly random. The distance to such sources can be determined by statistical parallax methods, that is, by comparison of dispersions of the radial and proper motions. The distances to the masers in Orion and W51 at 0.5 and 7 kpc, respectively, have been measured with an accuracy of about 20% (Genzel et al. 1981b).

Since relative component positions, accurate to 10 micro arcseconds or better (across a 10 arcsec field) are possible, distances to masers throughout the entire galaxy can be determined with accuracies of ∿ 10%. It is important to emphasize that parallax distances are independent of the conventional complex hierarchy of distance indicators presently used in astronomy, and the fractional accuracy is nearly independent of distance. The application of these techniques to many distant and faint sources including extragalactic ones will require the high sensitivity and dynamic range of the VLBA at 22 GHz.

D. Geodesy and Geophysics

Observations of cosmic radio sources made with VLBI systems may give, with great precision, the instantaneous length and direction of the vectors connecting the elements of the array. This information may be used for a variety of geodetic and geophysical applications. These include monitoring changes in the distances between the major plates of the earth's crust, and distortions within these plates. The precise measurement of variations in the speed (UT1-UTC) and direction (pole position) of the earth's rotation vector, and of the constants of precession and nutation, will allow improved understanding of the earth's interior and of the causes of these various motions.

Major continuing programs are underway at the Haystack Observatory, the Goddard Space Flight Center, MIT, JPL, as well as the National Geodetic Survey to exploit the VLBI technique for these purposes. Repeatability of the order of a few centimeters has already been obtained in measuring transcontinental distances, and accuracies equivalent to a few tens of centimeters have been achieved in the measurement of variations in the speed and direction of the earth's rotation vector.

One source of error in the VLBI geodetic measurements is the variation with wavelength and time in the angular structure of the target sources. The VLBA could provide the detailed updated maps needed to fully interpret observations made with any dedicated geodetic VLBI systems that rely on observations of extragalactic sources to provide a fundamental reference frame. In addition, the astronomical observations themselves may provide, as a by-product, valuable geodetic data even though not designed for this purpose. It is further anticipated that from time-to-time there will be specific geodetic programs which will exploit the sensitivity, frequency coverage, dynamic range, and broad geographical distribution of the VLBA.

E. Other Applications

Other applications of the VLBA are in interplanetary spacecraft navigation and precise tests of the theory of general relativity by measuring the deflection of radio signals by the gravitational field of 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.

F. System Requirements

The scientific problems described above require an instrument capable of sub-milliarcsec resolution with a large dynamic range (i.e. low sidelobes), and sufficient sensitivity to study the weak continuum emission from the nuclei of galaxies, quasars, stellar objects, and the weaker molecular masers. Operation at a number of wavelengths between millimeter and meter wavelengths is desired for various continuum problems, and it is necessary to cover the spectral line of neutral hydrogen at 1.4 GHz

(21 cm), the four ground state OH maser lines near 1.7 GHz (18 cm), the 6 GHz (5 cm) excited OH maser line, the H_2O maser lines near 22 GHz (1.3 cm) and the SiO line at 43 GHz (7 mm). We also want the capability to observe in the 3.8 and 13 cm wavelength bands which have become the standard for the worldwide network of geodetic VLBI observations, and which are available on the NASA Deep Space Network (DSN) Antennas. Operation at long wavelengths, near 1 meter, is needed to adequately study phenomena of lower surface brightness, and to provide continuity with the resolution of the VLA at short centimeter wavelengths. Dual polarized receivers are needed for polarization studies, and the correlator must have sufficient capacity to handle the four polarization cross-products. Good long term phase stability ($\Delta f/f \lesssim 10^{-15}$) is needed for astrometric measurements.

Flexibility is required to easily change frequency and to permit operation over a range of bandwidths for a variety of spectral line and continuum observations. Reliability is important to minimize system down time and maintenance costs at the remote sites, and the system must be capable of being used by scientists not necessarily skilled in advanced techniques of radio interferometry.

Previous 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. This requires maximum antenna spacings $\gtrsim$ 5000 km at the shortest operating wavelengths. Minimum spacings $\lesssim$ 100 km are needed to study the lower surface brightness features, and to unambiguously map larger fields-of-view.

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 possible wavelengths. Practically, the shortest wavelengths that may be used with good performance and reliability are 1.3 cm and 7 mm. Even shorter wavelengths are desired for greater resolution, but although it may be possible at some later time to instrument the VLBA at millimeter wavelengths, we have not provided initially for this capability.

Short wavelength observations are important not only because they give the greatest possible resolution, but also to probe the dense cores of active galactic nuclei, which are opaque at the longer wavelengths. Also at millimeter wavelengths, the flux density variations are more closely correlated with those observed at optical wavelengths. The capabilities of the existing VLB Network are very limited at 1.3 cm, and nearly non-existent at 7 mm.

Current VLBI observations, for the most part, are limited to the stronger sources and only begin to investigate the broad range of milliarcsecond phenomena. Sufficient sensitivity is needed to allow objects studied to be selected because of their astrophysical interest, and not primarily on the basis of their brightness. The ability of the VLA to do this is one of its greatest strengths, and a comparable sensitivity is needed on the milliarcsecond scale. Some specific examples of the need for sensitivity at the mJy level are:

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

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

c) 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, as are the stimulated radio recombination lines.

d) 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 on some baselines. So even for strong sources, high sensitivity is required to map the lower surface brightness regions.

e) The dynamic range of self-calibrated maps is very sensitive to signal-to-noise ratio, and so for the weaker sources, good image quality requires the best possible sensitivity.

f) For many applications, in particular the study of very weak sources, it will be necessary to use nearby reference sources to obtain long coherent integration times and thus reach the full sensitivity limit of the Array. 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.

For spectroscopic measurements, typically 256 to 1024 frequency channels are used in conventional single dish spectrometers and at the VLA, and a comparable capacity is needed in the VLBA. Broad bandwidths, flat frequency response, and good (spectral) dynamic range are required to observe broad weak features such as found in the stimulated recombination lines. For some "worst case" maser sources, the field of view must reach 30" with a resolution ~ 0.0001 arc sec. With 256 frequency channels, up to 10^{13} separate picture elements may need to be examined from a single 8-hour observation, and this puts extraordinary demands on the image processing system, the mass storage capability, and the ingenuity of the observer.

To meet the requirements of resolution, good image quality, sensitivity, and flexibility, we have adopted a ten-element transcontinental array of 25 meter antennas. Each antenna is equipped with a low noise radiometer and feed system which allows the remote selection of observing frequency, polarization and bandwidth. Reliability is insured by partially redundant sub-systems and adequate spares. Detailed system specifications for the array elements are outlined in Chapters III and IV and for the Playback System in Chapter V.

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III. ARRAY CONFIGURATION

The number and location of the individual antenna elements are the most critical factors which determine the image quality of the array, although there are many possible configurations with the same number of antennas which give similar performance. In this section we discuss the criteria determining the number of antennas and their location. We first give a brief non-technical discussion of the method of aperture synthesis.

A. Interferometry and Aperture Synthesis Technique

If the United States were totally covered with antennas, then analysis of the outputs of all of the interferometer pairs would give the same result as would be obtained from one huge antenna the size of the entire country. However, in any practical system there will be only a small number of antenna pairs or interferometer baselines, and the instantaneous coverage of the aperture is incomplete.

As seen from a distant source, each interferometer baseline is projected onto a plane perpendicular to the line of sight, and the projected baseline changes continuously as the Earth rotates. Over the course of a day, as the projected baselines change, the equivalent effect of many antennas is synthesized by using only a small number of antennas and being patient while the Earth turns. This is called "Earth-rotation synthesis" or "aperture-synthesis", and is the basis for all radio interferometers and arrays, including the VLA.

The baseline coverage of a simple interferometer pair can be conveniently shown on a diagram as in Figure III-1, which shows one California-to-Massachusetts baseline as a vector. As seen by an observer far above the North Pole, the tip of the vector traces out a circle as the Earth rotates. At lower declinations the circle is seen obliquely and becomes an ellipse. The elliptical track starts when the source rises in California and ends when it sets in Massachusetts. For sources near the equator, each ellipse degenerates into a straight line. In an N-element array there are N(N-1)/2 separate interferometer pairs. The VLBA will have 10 antennas and 45 elliptical tracks like those in Figure III-1, one for each baseline.

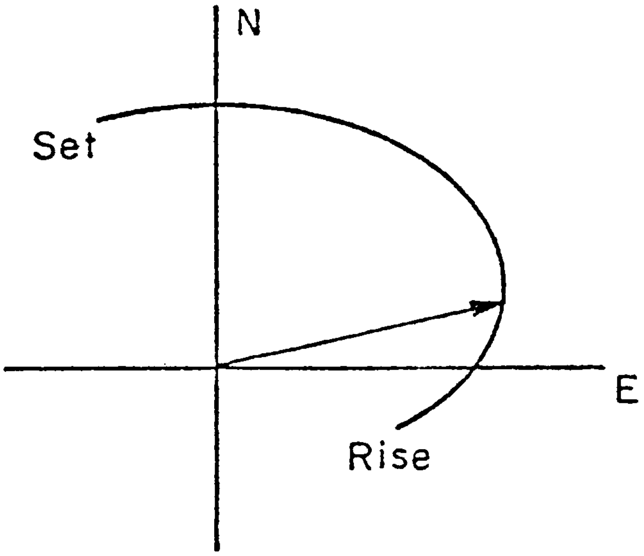


Fig. III-1. Baseline from California to Massachusetts seen from a fixed point in the sky.

At any moment the output signals from two antennas located at opposite ends of the baseline differ in frequency because of the different Doppler shift introduced by the rotation of the Earth. The resultant "beat" signal is quasi-sinusoidal in time and is called "fringes" by analogy with the optical fringes of a Michelson interferometer. The longer (in wavelengths) the baseline, the more closely spaced are the fringes and the greater the angular resolution.

The instantaneous output of a two-element interferometer is one component of the Fourier transform of the angular brightness distribution of the radio source. The two dimensional source image is constructed by properly adding many Fourier coefficients from the different interferometer configurations. The longest spacings determine the resolution; the shortest spacings roughly determine the maximum source dimension which can be mapped; and the sidelobe level or dynamic range is determined primarily by the uniformity of coverage between the shortest and longest spacings. Errors or uncertainties are introduced by gaps in the Fourier or (u,v) plane coverage, receiver noise, and by systematic errors in gain and phase calibration at each antenna element. Methods of compensating for missing antenna spacings (CLEAN), and correcting for errors in the amplitude and phase response of each antenna (self-calibration) are extensive and constitute a major area of current research in radio astronomy image processing. Errors due to random receiver noise are a function of the gain of each antenna and the receiver noise temperature, and are reduced in proportion to the number of antennas and the square root of the observing time.

The measurement of interferometer phase on very long baselines is particularly difficult. The use of modern hydrogen maser frequency standards essentially eliminates errors due to the use of independent local oscillators. But 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 determine baselines with a repeatability of a few centimeters, the measurements must be continually updated to correct for diurnal variations 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 (UT1) and in the wobble of the axis of rotation.

A much more critical problem is the effect of fluctuations in tropospheric water vapor content which introduces errors in the interferometer phase and which limits the quality or dynamic range of all aperture synthesis instruments. In Section IV-D we review further the effect of phase fluctuations and methods which may be used to measure the tropospheric water vapor content, and in Section V-D we discuss the "closure-relations" which lead to the very powerful self-calibration techniques.

B. Performance Goals

We list in this section the main design goals of the VLBA and their implication for the antenna configuration.

High Resolution. We want the resolution to be as high as practical. This requires long physical baselines and the shortest possible wavelengths.

Field-of-View. Compact radio sources often have an angular size many times larger than a single picture element (pixel). Particularly, at long wavelengths the low surface brightness regions may cover a relatively large region. In order to map these larger features, minimum antenna separations should not exceed about 200 km. Maser sources associated with IR stars require even shorter spacings.

2-Dimensional Configuration. The VLBA should give high quality 2-dimensional images at low declinations, and reasonable images at least down to

$\delta = -30$ degrees. This is important not only because the Galactic Center at $\delta = -28$ degrees is of great interest, but because half of the sky lies in the range $-30^\circ < \delta < 30^\circ$. This requires a 2-dimensional distribution of antennas.

Image Quality. The dynamic range or image quality (sidelobe level) depends primarily on the uniformity of the aperture coverage. A major disadvantage of the existing network of telescopes is that their geographical distribution gives a poor coverage of the Fourier transform plane, and hence poor dynamic range.

A uniform distribution of antenna spacings will give the highest quality image. Reasonably uniform coverage is particularly necessary for short or "snap-shot" observations which do not make use of the earth's rotation. Although the "snap-shot" performance is very limited compared with the full synthesis capability of the VLBA, it is the only practical means of observing very large samples for statistical studies.

To some extent the antenna configuration may be "centrally condensed" to facilitate the study of sources having a few bright features together with relatively extended structure. A centrally condensed aperture will also enhance the potential of the VLBA for augmenting its spatial frequency coverage through the use of multiple frequencies (space-frequency synthesis) (Swenson and Mathur 1969). For a given number of antennas a "centrally condensed" configuration gives a smaller minimum spacing and can be used to observe larger sources than a uniform distribution but with a small degradation in image quality.

C. Practical Constraints

Low Cost. The cost of construction and operation must be kept as low as possible consistent with meeting the scientific goals. This means the smallest possible number of antennas. Where practical, antennas should be located at or near existing observatories or other suitable technical or university facilities, to minimize site development and operation costs. Simulation of potential configurations suggests that three or four out of ten antennas may be located primarily on the basis of convenience, and if the remaining six or seven are optimally located, then the resulting performance is only slightly degraded compared with an "optimumly configured" 10-element array.

Proximity to the VLA. The "center" of the VLBA should be located close to the VLA to exploit the very great sensitivity available by using the VLA and the VLBA together. This configuration optimizes the distribution of baselines between the VLA and each of the VLBA elements. By choosing the VLBA element locations appropriately, it is also possible, to a limited extent, to fill in spacings intermediate between the VLA and VLBA and thus to fully extend the capability of both instruments.

Dry Sites. It is desirable that as many antenna elements as possible should be located at high dry sites, such as found in the desert southwest, to minimize the effect of tropospheric water vapor fluctuations which distort the image quality. Most of the antennas currently used for VLBI are concentrated on the East Coast and in Europe where the atmospheric water content is substantially higher.

Ease of Access. Each antenna should be near a major transportation center to facilitate shipping of magnetic tapes and spare parts, as well as travel for maintenance and repair.

Radio Interference. In bands in which the radio astronomy assignment is shared with active services, signal strengths in the vicinity of a site should not exceed the harmful thresholds discussed in Appendix II.

U.S. Territory. In order to minimize the problem of management, shipping, and travel, it is desirable to locate the antenna elements on United States territory. For this reason we have fixed the maximum east-west extent of the VLBA with elements in New England and Hawaii to give a total extent of 8000 km. An antenna in Alaska gives good north-south resolution, but the performance is limited for southern hemisphere sources. A site in Alaska may also present substantial environmental and logistical difficulties. Puerto Rico gives good performance for sources in the southern hemisphere, but the logistics will still be more difficult than for a continental site. A location near the Arecibo Observatory would facilitate the operation and maintenance of a Puerto Rico site, but the tropospheric conditions there are much poorer than on the southwest side of the island.

Baselines to Mexico and South America give even better enhancement to the north-south resolution (Mutel 1982), but will be more difficult and expensive to operate. For this reason we have considered only Alaska, Hawaii, or Puerto Rico in addition to the continental locations. But other locations, particularly in Mexico, will be explored further.

Even with all of the elements constrained to U.S. territory, it will still be possible, for specialized experiments, to use foreign telescopes to extend the performance of the VLBA. In this way the advantages of the more remote locations are achieved and, at the same time, the uncertainties for everyday operation are minimized.

D. Number and Location of the Antennas

The ratio of maximum to minimum spacings in the VLBA is 8000/200 or 40 to 1, so at least 10 antennas (45 spacings) are needed for uniform coverage. Actually, the situation is somewhat worse since, in order to get good 2-dimensional images, the antennas must be distributed in the north-south as well as east-west direction. Also, there is some redundancy or near redundancy, and not all the interferometer pairs give really independent spacings. To an extent, these limitations are balanced by the advantages of a "centrally condensed" array, but it is clear that 10 antennas are needed to satisfy the various needs.

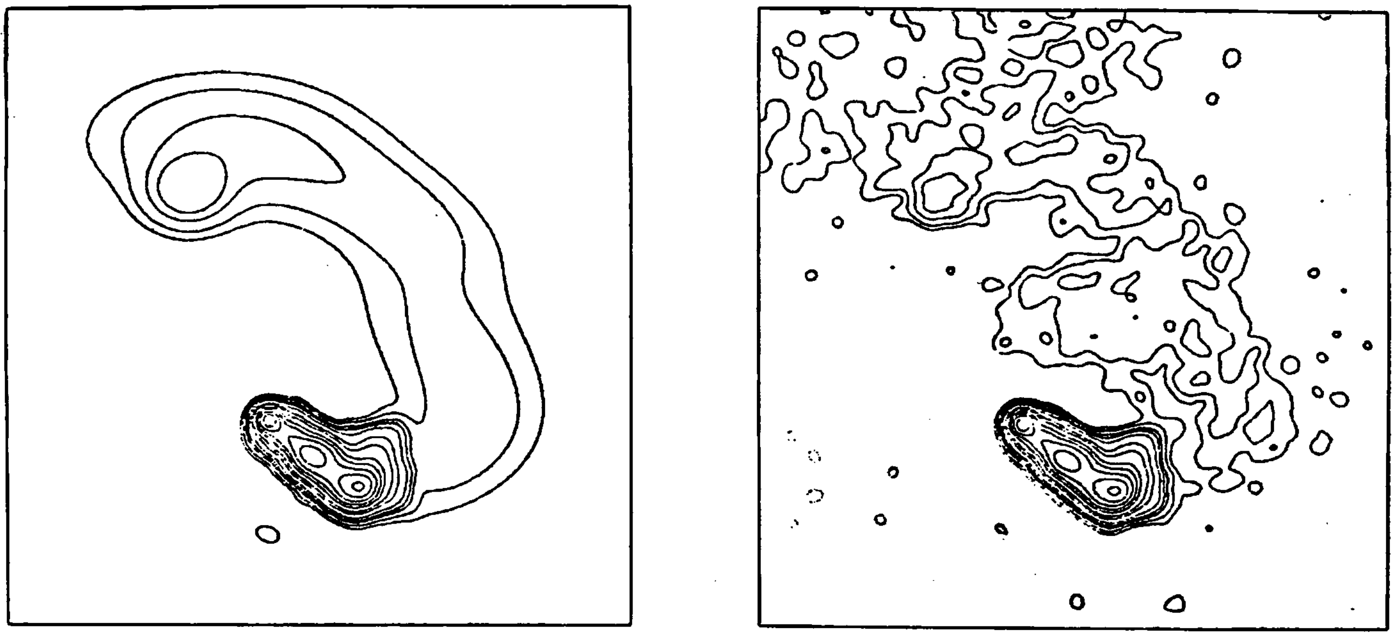
For comparison, in each configuration of the VLA the ratio of maximum to minimum spacing is about 40 to 1 using 27 antennas. But in the VLA the overall range of resolution can be varied by an additional factor of 40 by moving antennas. Clearly, this option is not possible in an instrument of transcontinental dimensions.

Ideally, one would like to have a continuous coverage of spacings from the 35 km maximum dimensions of the VLA to the 8000 km extent of the VLBA. This would require 13 or 14 antennas. To an extent the Multi-Telescope-Radio-Linked-Interferometer (MTRLI) at Jodrell Bank in the U.K. provides spacings between 10 and 130 km with a 6-element array. But the MTRLI operates well only at long wavelengths ($\lambda \gtrsim 18$ cm); at short wavelengths only 3 antennas are used. Moreover, while outside observers have used the MTRLI, the operation does not normally provide for visiting users, and in any case the instrumentation is not fully compatible with that of the VLBA. Nevertheless, to a limited extent, information on radio source structure corresponding to interferometer scales of 35 to 100 km will be available from the MTRLI and from a range of spacings between those covered by the VLA and the VLB Array. Therefore, in order to reduce the cost, we have not tried to completely fill in the range of spacings down to those of the VLA. although the power of the two instruments would be substantially enhanced if this range of spacings were fully covered.

We have studied the performance of the VLBA from simulated observations of test sources with various possible configurations. One artificial test source is shown in Figure III-2a. It is derived from VLBI observations of 3C 147 made with a 7-element array at 327 MHz (Simon, private communication), but contains more structure than could be deduced from those observations. Figures III-2b, c, d show the images reconstructed from hypothetical observations made with 8, 10, and 12-element arrays respectively. Each array has a minimum spacing of 200 km and a maximum spacing of 8000 km, and a suitably good configuration for the number of antennas. The test source was assumed to be at $\delta = 64°$.

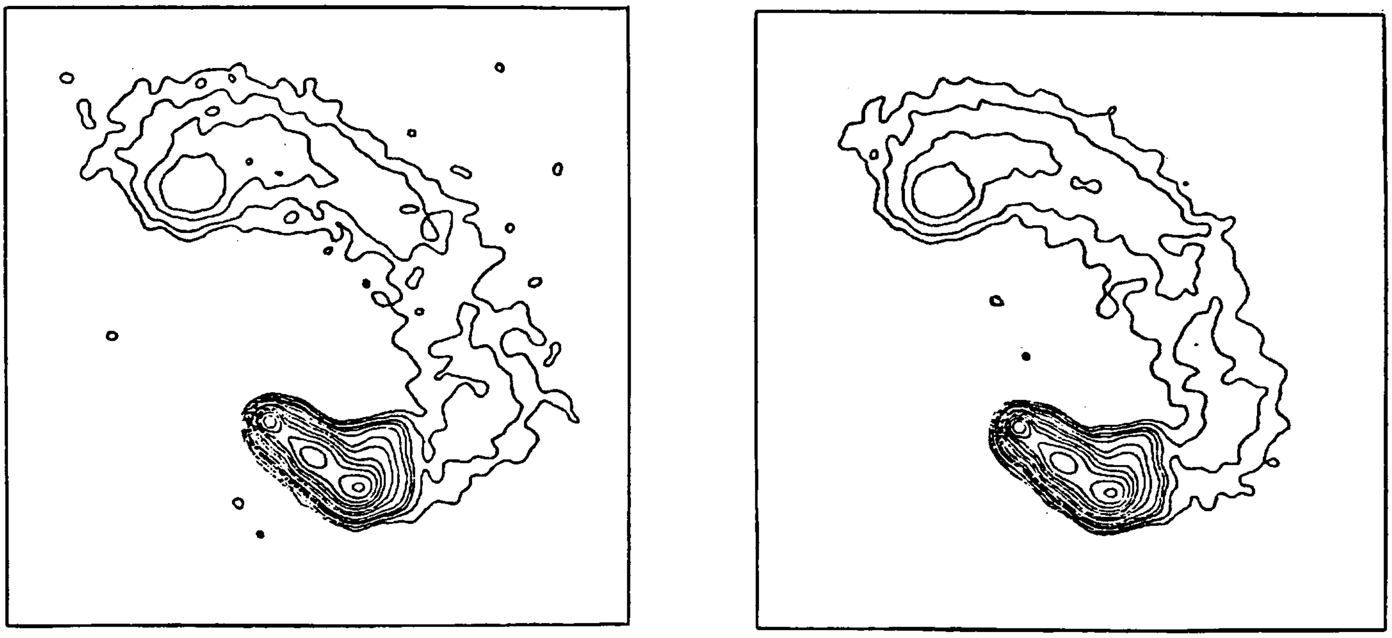
Figure III-2 shows a dramatic improvement in image quality in going from 8 to 10 stations, and a further, but less striking improvement with 12 antennas. In actual practice, however, if a 12-station array were built, the extra antennas would be used primarily to "fill-in" smaller spacings. This would not substantially effect the image quality of this particular test source, but would improve the quality of the image for sources 2 to 4 times larger. Figure III-3 shows the same comparison, but with the test source located at $\delta = -18°$. Here the 8-element array is wholly inadequate and completely misses the larger scale structure.

We have examined many of feasible 10-element arrays which meet the conditions given in Sections II-B and II-C. The various possible configurations were evaluated by several methods, none of which are free of subjective judgments, of selection criteria, or of dependence on variations in reduction techniques. Each candidate array was first evaluated by direct examination of the corresponding transfer functions at several declinations. This method requires subjective judgments since it does not provide a



a. The model

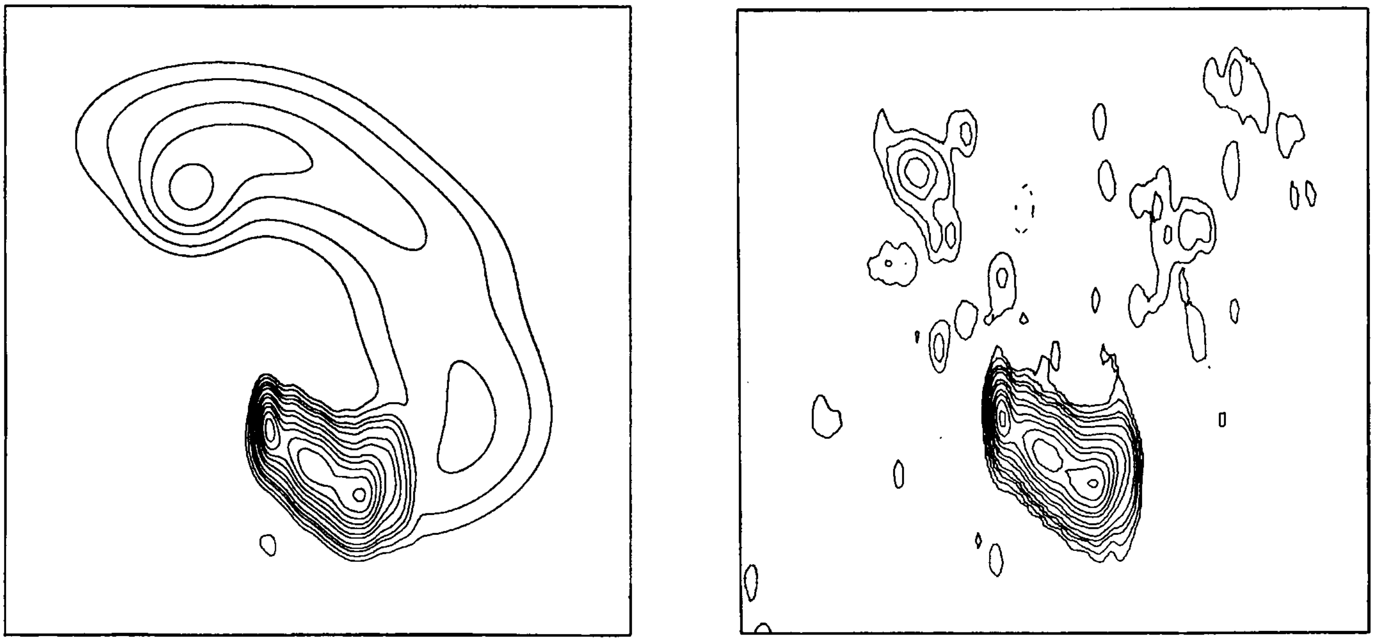
b. 8-station map



c. 10-station map

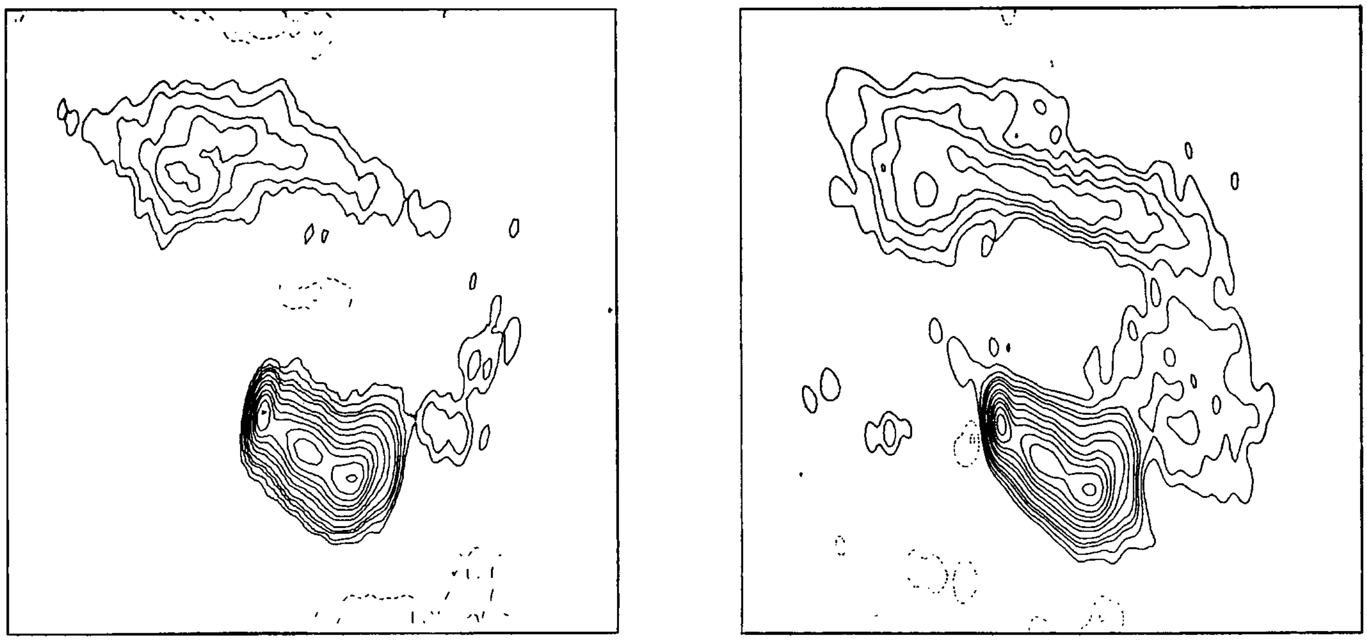
d. 12-station map

Fig. III-2. A comparison of three different arrays for a source at 64° declination. Fake data with realistic noise have been generated from the model shown in "a".



a. The model

b. 8-station map



c. 10-station map

d. 12-station map

Fig. III-3. Same as for Fig. III-2 but for a source at declination -18°.

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. The best arrays were then 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 here 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 were generated.

One of the best configurations we have found is shown in Figure III-4 and corresponding transfer function is given in Figure III-5. A more extensive description of the potential configurations studied will be made available in a later volume. Further study is needed, however, and a final choice of the configuration must await detailed studies of the individual sites. The actual performance is not likely to differ significantly from that shown in Figure III-5.

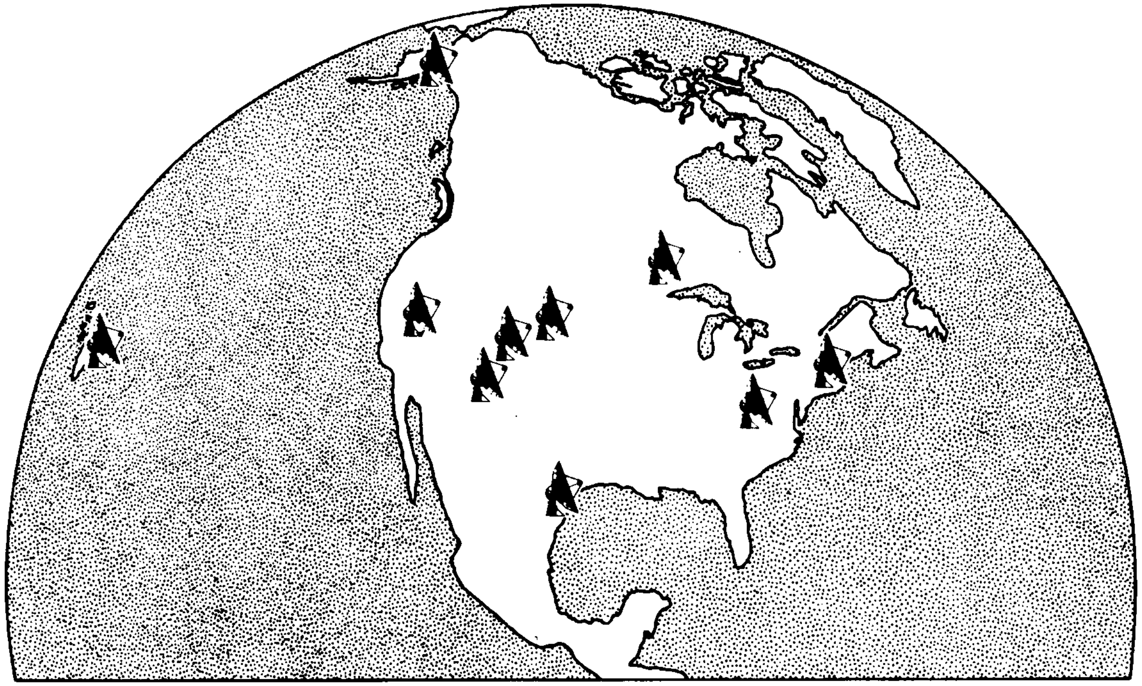


Fig. III-4. A map of one possible VLBA configuration.

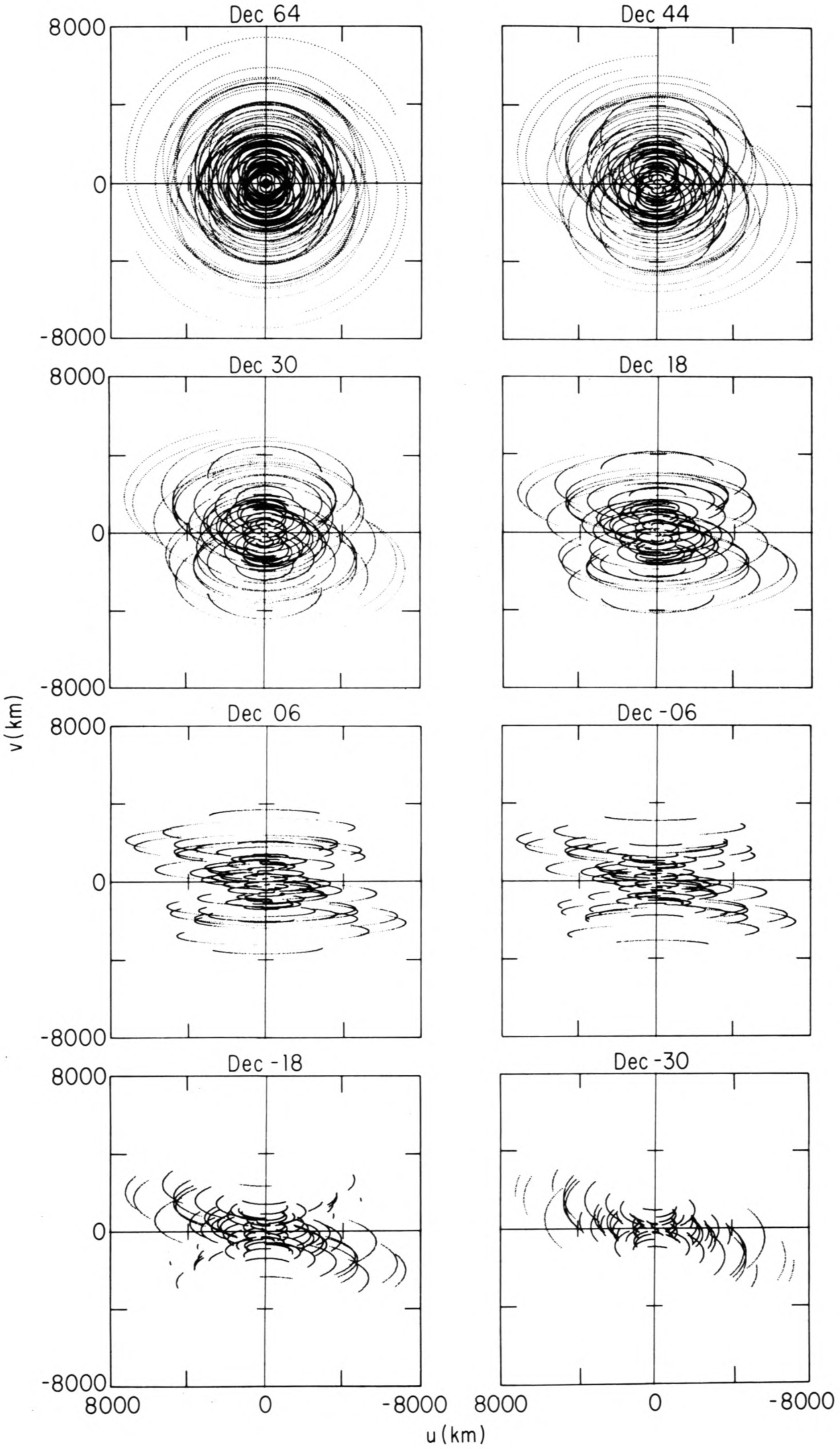


Fig. III-5. Transfer functions corresponding to the array shown in Figure III-4. Declinations are centered in bands, each of which contains 10% of the sky.

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IV. THE ARRAY DESIGN

A. Antenna Elements

The largest possible antennas are desired as elements in order to obtain the best sensitivity. This is especially true for the VLBA where the bandwidth is limited by the IF transmission system. Good sensitivity is needed not only for the obvious reason to study the weak sources, but because numerical simulations show that the quality of results obtained from self-calibrated data are very sensitive to noise (Linfield, 1981). 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 becomes difficult, due to greater surface irregularities, larger pointing errors, and smaller primary antenna beam. A good choice of size for the elements of an array operating at centimeter wavelengths appears to be in the range 15 to 40 meters, where the cost per unit area has a broad minimum. 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. First, 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 at least several decades, the receiver systems may be replaced after only 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 up to now decreased with time. It is therefore appropriate to build initially 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 we plan 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 recent escalation), and performance of such antennas is well known. It is clear that the antenna elements required for the VLBA will not present any technical difficulties or significant cost uncertainties.

The elements used for the VLBA must operate under a wide range of environmental conditions ranging from tropical to sub-arctic. Because of the relatively great importance attached to the shorter wavelengths, we have specified that the antennas perform well at least at frequencies as high as 43 GHz (7 mm). This requires an r.m.s. surface accuracy 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. The performance of these antennas is understood in detail, and where necessary, design modifications can be introduced. The cost, including necessary modifications, can be well-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. Improvement in the performance of the E-Systems antenna design has been achieved by shielding and insulating parts of the structure (e.g. von Hoerner, 1981), and further improvements are possible by 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 VLBA antennas will not be raised and transported, so a wheel-and-track construction, with a broader support structure, can be used for superior performance. The wheel-and-track design allows a wider separation of the elevation bearings than does the compact VLA design, so the thermal and wind induced pointing errors are reduced. Also by using a geometry of a space frame, similar to that of geodesic domes, for the reflector structure, the gravitational deflections can be reduced. The new design has a surface accuracy better than the specification and should allow some operation at shorter millimeter wavelengths. It is simple in geometry and light in weight. The entire structure consists of only two types of steel pipes;

hence, fabrication costs are minimized. An artist's conception of the proposed VLBA wheel-and-track antenna element is shown in Figure IV-1.

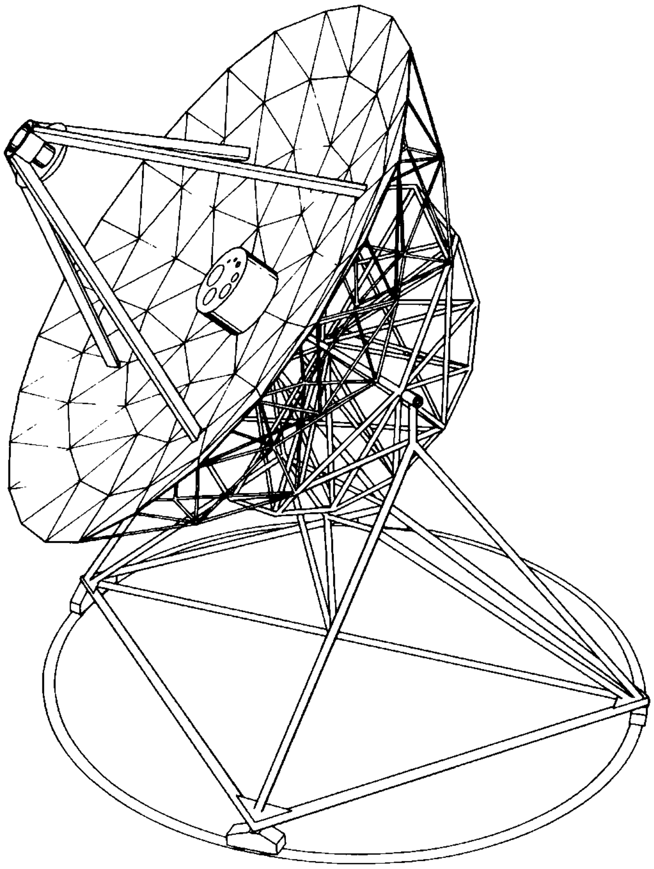

Fig. IV-1. Artist's conception of proposed wheel-and-track antenna element.

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 reduced even further.

It is possible that one or more existing antennas, currently being used for radio astronomy research, could be used as one of the ten VLB Array elements. Such use, however, would have to be on a full-time basis. Otherwise, the gap in the (u,v) plane coverage caused by the missing element would, in general, result in a substantial degradation of the image quality.

The availability of existing radio telescopes as dedicated elements of the VLB Array, the potential impact to U.S. "single-dish" radio astronomy research, as well as the cost-performance tradeoffs of modifying and operating these antennas is a complex problem. With a few exceptions, the existing antennas operate well only at longer wavelengths, and even the best ones will require expensive modifications to meet the performance specifications of the VLBA elements. The inclusion of existing antennas as part of the VLB Array will also make it more difficult to calibrate the gain and polarization response of the Array due to the different characteristics of the individual elements.

Many of the existing radio telescopes in the United States are 20 or more years old and have complex drive and control systems; and a further difficulty will be the increased cost of maintenance and remote operation of these older antennas compared with antennas of a more modern design.

The use of specific existing antennas in the VLB Array needs to be studied further and will be reported in more detail in a subsequent report.

B. Feed Arrangement

To meet the scientific requirements, a choice of ten wavelength bands is planned. A versatile feed system allows operation of the antenna at

325 MHz (90 cm), 611 MHz (50 cm), 1.4/1.7 GHz (18/21 cm), 2.3 GHz (13 cm), 5 GHz (6 cm), 8.4 GHz (3.8 cm), 10.7 GHz (2.8 cm), 15 GHz (2 cm), 22 GHz (1.3 cm) and 43 GHz (7 mm).

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 that at the VLA, is proposed for all receivers, except for the ones at 325 MHz and 611 MHz, which will be located at the prime focus. Frequency changes will simply require rotation of the subreflector about the main reflector axis, as is done on the VLA.

The 325 MHz feed will probably be located near the primary focus at the edge of the subreflector, and the 611 MHz feed will be permanently mounted in the middle of the subreflector. The subreflector drive mechanism and the feed legs will be designed to allow the subreflector to be driven to position the 611 MHz feed close to the primary focal point so that defocussing losses are less than 5 percent.

The proposed shaped Cassegrain geometry and feed layout is shown in Figure III-2. A large subreflector of diameter 3.18m is used to keep the feeds and feed circle as small as possible. The geometry is optimized so that aperture blockage due to the subreflector and feed system are equal. The feeds are arranged in a circle of radius 85 cm around the main reflector axis, with the secondary focal point being 1.67m in front of the main-reflector vertex. The larger than usual subreflector will reduce

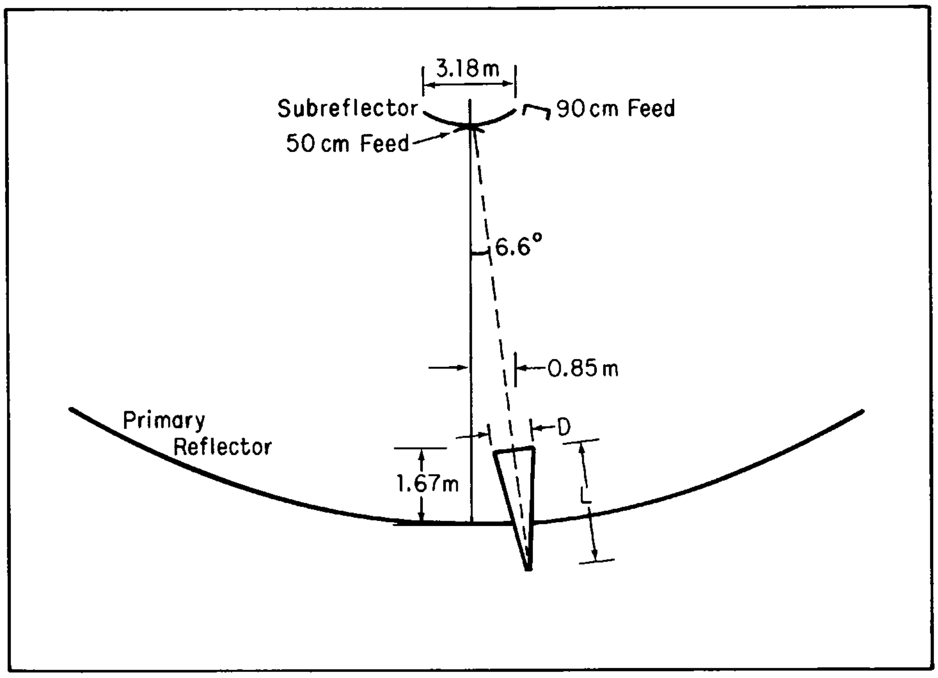

Fig. IV-2a. Proposed Cassegrain geometry, the length, L, and opening, D, of each feed horn is given in Table IV-2.

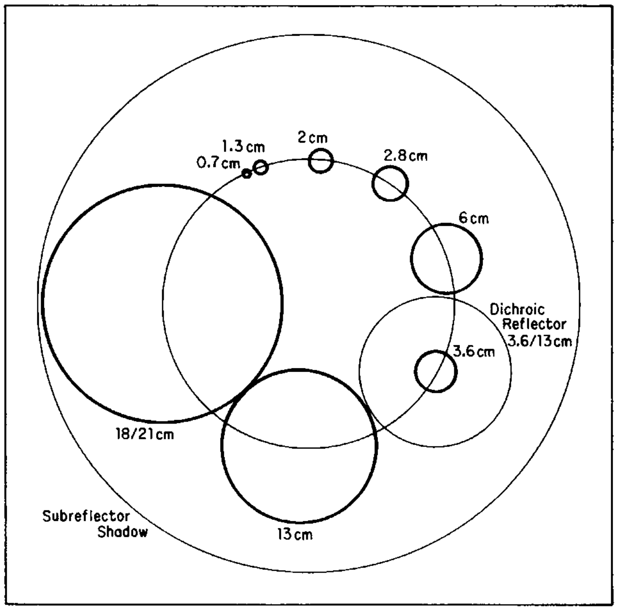

Fig. IV-2b. Proposed Cassegrain feed layout.

diffraction losses 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 small 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 sidelobe level resulting from the use of a larger subreflector does not deteriorate the performance of the Array significantly.

The Feed Elements

The prime focus 325 and 611 MHz feeds will be either Clavin or crossed double dipole type. Since a circle approximately 0.5 m in diameter in the middle of the subreflector is shadowed by the subreflector itself, the 611 MHz feed can be permanently located in this area without significantly effecting the performance of the Cassegrain feeds.

A single feed covers the 1.4 and 1.7 GHz bands. It will be a hybrid-lens feed of the same type used for the VLA, but scaled to provide the smaller aperture needed to illuminate the subreflector which subtends an angle of ±13.1°.

The feeds for the 7 frequency bands from 2.3 GHz to 43 GHz will be corrugated horns all scaled exactly according to wavelength from the same design. This approach has the advantage of low risk, since the design of corrugated horns is well established. The corrugated horn has high performance in terms of spillover efficiency and cross polarization. Table IV-1 summarizes the electrical parameters of the corrugated feed horn proposed for the Array. The outside length, L, and outside diameter, D, for each feed is given in Table IV-2.

TABLE IV-1

FEED HORN PARAMETERS

Horn Aperture	6.04 λ
Horn Length	19.2 λ
Corrugation Depth	0.25 λ
Corrugation Width	0.2 λ
Corrugation Period	0.25 λ
Number of Corrugations	76
Taper (Subreflector Edge)	14 db
Aperture Phase Error	0.2 λ
Spillover Efficiency	93%

TABLE IV-2

FEED HORN DIMENSIONS

ν(GHz)	1.4/1.7	2.3	5	8.4	10.7	15	22	43
D(cm)	142	90	41	24	19	14	9	5
L(cm)	228	256	119	71	56	41	27	16

All horns have their apertures in the same plane. The 22 GHz and 43 GHz horns feed into the same cryogenic dewar requiring the 43 GHz feed to be stretched to the same length as the 22 GHz feed using single mode circular waveguide. All other Cassegrain feeds will feed directly into their own dewars allowing the orthomode junction to be cooled for best noise performance. Circular polarization will be obtained by using a quarter-wave waveguide phase shifter of the VLA L Band type for the lower frequency bands and quasi-optical quarter-wave plates of the Green Bank type at the higher frequency bands. The Cassegrain vertex room will be designed to provide convenient access to the higher frequency dewars which will be approximately 3.8m above floor level.

Dual frequency operation will be provided for the 2.3 GHz and 8.4 GHz feeds using a combination of dichroic and ellipsoidal reflectors. If dual frequency operation between frequency bands higher than this is needed, there is room around the feed circle to provide for additional reflectors.

Feed System Performance

The main reflector will have a surface accuracy of 0.45 mm and a reasonable goal for the subreflector is about 0.12 mm giving a combined surface r.m.s. accuracy of 0.46 mm. The VLA shaped geometry produces uniform illumination of the primary from an 11.5 dB illumination taper on the edge of the subreflector. The VLA main reflector deviates from a parabola by 0.97 cm rms. The VLBA antenna will be more strongly shaped to produce uniform primary illumination from a 14 dB subreflector taper, and the deviation from a parabola will be about 1.2 cm rms. This will result in a gain loss of 9% at 610 MHz, which is acceptable.

Table IV-3 shows the expected performance for all bands. The low phase efficiency for the 325 MHz feed results from its off-axis location. This

TABLE IV-3

ANTENNA PERFORMANCE

Frequency	E_{surf}	E_{illum}	E_{diff}	E_{spil}	E_{block}	E_{phase}	E_{misc}	E_{total}
325 MHz	.97	.78	1.0	.78	.86	.63	.95	.31
611 MHz	.91	.78	1.0	.78	.86	.95	.95	.47
1.4/1.7 GHz	1.0	.95	.90	.85	.86	.98	.95	.58
2.3 GHz	1.0	.99	.93	.93	.86	.98	.95	.69
5 GHz	.99	.99	.95	.93	.86	.98	.95	.69
8.4 GHz	.98	.99	.98	.93	.86	.98	.95	.71
10.7 GHz	.96	.99	.99	.93	.86	.98	.95	.70
15 GHz	.92	.99	.99	.93	.86	.98	.95	.67
22 GHz	.84	.99	.99	.93	.86	.98	.95	.61
43 GHz	.50	.99	.99	.93	.86	.98	.95	.36

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.

can be improved by manually mounting the feed in front of the subreflector whenever 325 MHz is scheduled. The feasibility and cost of an automatic mechanism to move the 325 MHz feed in and out of position will also be investigated.

The spillover efficiencies given in Table IV-3 are reasonable goals for the prime focus feeds. The 1.4/1.7 GHz feed spillover is estimated from VLA experience and the spillover efficiencies for the corrugated horns are taken from Thomas (1978).

The subreflector support structure should be designed to minimize blockage. A total blocked area of 7%, including the blockage of the 3.18m diameter subreflector is a reasonable goal. With this much blockage, the worst first sidelobe level should be approximately -15 dB.

The circular polarization performance of the antenna will be degraded by the asymmetric geometry, so that measurements of circular polarization will require accurate self-calibration of the instrumental circular polarization.

C. Front End Systems

We have considered several types of low-noise front ends to satisfy the sensitivity requirements. These are traveling wave masers (TWM), reflected wave masers (RWM), upconverter-maser systems, and cooled or uncooled GASFET amplifiers.

Ruby maser systems are the lowest noise microwave amplifiers available, although they are expensive and the tuning rate is limited by the superconducting magnet. Maser/upconverter receivers offer maser-like receiver temperatures with wider bandwidth and tuning range than masers alone. NRAO has implemented an upconverter/maser receiver for the 140-foot telescope at Green Bank which achieves system temperature in the range 30 K to 60 K between 4.6 and 25 GHz. The system employs three upconverters and a single K-band maser mounted on a 4.5 K closed cycle refrigerator. The four frequency bands have instantaneous bandwidths of 300 to 500 MHz and tuning ranges of 2.5 GHz to 7 GHz.

Table IV-4 shows a comparison of receiver temperatures for upconverter/K-band maser type receivers, masers, and cooled or uncooled GASFET amplifiers. Although the low noise temperature and versatility of the upconverter/maser receiver is attractive, the complex hardware implementation is expensive and has the further disadvantage of high operating cost because of the need for skilled personnel to operate and maintain such a system. Additionally, the limited tuning speed and bandwidth preclude using rapid frequency switching for space-frequency synthesis (see Section III) at all but the 18/21 cm and 13 cm frequency bands.

We have examined carefully the cost-performance-reliability tradeoffs of different receiver possibilities (Moore 1982) and propose a receiver complement which consists of uncooled GASFET amplifiers near the prime focus for 90 cm and 50 cm, cooled GASFET amplifiers at the Cassegrain focus for six receivers between 21 cm and 2 cm and reflected wave ruby masers for the two shortest wavelengths of 1.3 cm and 0.7 cm. The proposed receiver system is reliable due to the simplicity of design and a high degree of modularity. The resultant commonality of spare parts will reduce operating costs and the initial acquisition cost will be lower than for a system featuring redundant sub-systems to achieve reliability. The expected performance at each wavelength band is summarized in Table IV-5.

GASFET amplifiers operating at 2, 2.8, 6, and 18/21 cm have already been built at the NRAO. Amplifiers at 50 and 90 cm have been built at Caltech, and at 3.8 and 13 cm at the University of California, Berkeley. These

TABLE IV-4

NOISE TEMPERATURE FOR VARIOUS TYPES OF RECEIVERS AT THE VLBA FREQUENCIES

Frequency (GHz)	Receiver Noise Temperature (Kelvin) GASFET at 300 K		GASFET at 20 K		Upconverter/ K-band Maser	Ruby Maser		Additional* Noise (Kelvin)
0.33	40	(30)	10	(7)				40**
0.61	45	(30)	10	(7)				25**
1.4/1.7	50	(40)	12	(9)	5	3		20
2.3	60	(50)	15	(11)	5	2		20
5	90	(70)	20	(17)	5	3		20
8.4	130	(110)	30	(20)	10	3.5		20
10.7	170	(140)	35	(25)	10	4		20
15	280	(170)	55	(40)	15	9		25
22	470	(200)	130	(60)	10	10	(2)	35
43	---	(800)	---	(200)		35	(5)	40

* Noise due to atmosphere, antenna spillover, and feed losses.

** Including galactic noise outside the galactic plane.

( ) Values in parentheses for GASFET's are 1986 projections. For the 22 and 43 GHz masers, the parentheses refer to traveling wave masers with superconducting slow wave structure, as opposed to the currently used reflected wave maser.

TABLE IV-5

PROPOSED FRONT END SYSTEM

Frequency (GHz)	Instantaneous Bandwidth MHz	Front End Type	Physical Temp (°K)	Receiver Noise Temp (°K)		Antenna Noise Temp* (°K)	1986 System Noise Temp (°K)	Notes
				1981	1986			
0.33	30	GASFET	300	40	30	40†	70†	Prime
0.61	60	GASFET	300	45	30	25†	55†	Prime
1.4/1.7	400	GASFET	20	12	9	20	29	Cassegrain
2.3	250	GASFET	20	15	11	20	31	Cassegrain
5	1,200	GASFET	20	20	17	20	37	Cassegrain
8.4	800	GASFET	20	30	20	20	40	Cassegrain
10.7	1,000	GASFET	20	35	25	20	45	Cassegrain
15	1,000	GASFET	20	55	40	25	65	Cassegrain
22	120	Maser	4	10	10	35	45	Cassegrain
43	70	Maser	4	35	35	40	75	Cassegrain

* Noise due to atmosphere, galactic background, antenna spillover and feed losses.

† Including galactic noise away from the galactic plane.

have been shown to give good low-noise performance and high reliability. Amplifiers at 90, 50 and 1.3 cm will also be built for the VLA so that relatively little new development work remains in this area.

We have elected to use the less expensive room temperature GASFETs at 50 and 90 cm since, at these wavelengths, the improvement expected from cooling is less than at the shorter wavelengths, particularly at 90 cm where the galactic background noise contributes significantly to the overall system noise temperature.

In order to obtain the minimum possible downtime for any observing frequency, each of the 6 GASFET front ends will be packaged on a separate closed cycle refrigerator. Cooled dual-polarization waveguide transitions will be integrated into the dewar to minimize the added noise due to loss between the feed and GASFET amplifiers. This technique of cooling the dual polarization transitions has been successfully used by other radio astronomy observatories over relatively narrow bandwidths. NRAO is currently supporting development of a wide band dual-polarization transition which is ideally suited for the wider fractional bandwidth needed by the 18/21 cm GHz front end.

At 1.3 and 0.7 cm there is a significant improvement in using maser amplifiers. Due to the importance which is attached to observations at the shortest wavelengths, where the available resolution is greatest and the coherence time limited, maser amplifiers are necessary to achieve the desired sensitivity. The masers proposed for these bands are Reflected Wave Masers of the type already developed by NRAO/JPL and in use on several radio telescopes with system temperature in the range 35 K to 60 K at 1.3 cm and 90 K at 0.7 cm (including radome losses at Haystack).

The two maser receivers will be mounted in a single 4 K refrigerator. Since the 22 and 43 GHz feeds are close together, this will not result in a loss in performance due to long input lines. The use of a common 4 K refrigerator and dewar will result in a cost saving of approximately $50 K per antenna. We are proposing that the 43 GHZ front end be single channel due to lower maser gain, higher pump power requirements and lack of a suitable low-noise second stage. The 22 GHz maser will be dual channel.

Figure IV-3 shows the proposed receiving system components that will be in the vertex cabin. The IF output frequency bands will lie in the range 250-1500 MHz. Since 9 frequencies are dual polarization and 43 GHz is single, there will be 19 IF outputs. These signals will go to an IF switching matrix to connect the front ends in use to the 4 IF input IF processor which is located in the vertex cabin to avoid sending broadband data down long cables to the control room.

A phase calibrator consisting of frequency pickets with 5 MHz spacing will be used to calibrate the delay through a complete receiver channel. A solid state noise source will be coupled into each feed horn with nearly equal intensity at the two polarizations. This will allow the system to be used as a noise adding radiometer for periodic gain and pointing calibration.

Cryogenic System

The front end system proposed for the VLBA requires one 4 K refrigerator and six 20 K refrigerators per antenna. The loss of any one refrigerator still permits the VLBA to operate at the other wavelengths. This feature is important since skilled cryogenic support is not always available at each site.

We are proposing to use CTI Model 350CP refrigerators; these have a 3W load capability and similar reliability as the larger CTI Model 1020 unit used at the VLA and other observatories. The 3W load capability is sufficient and

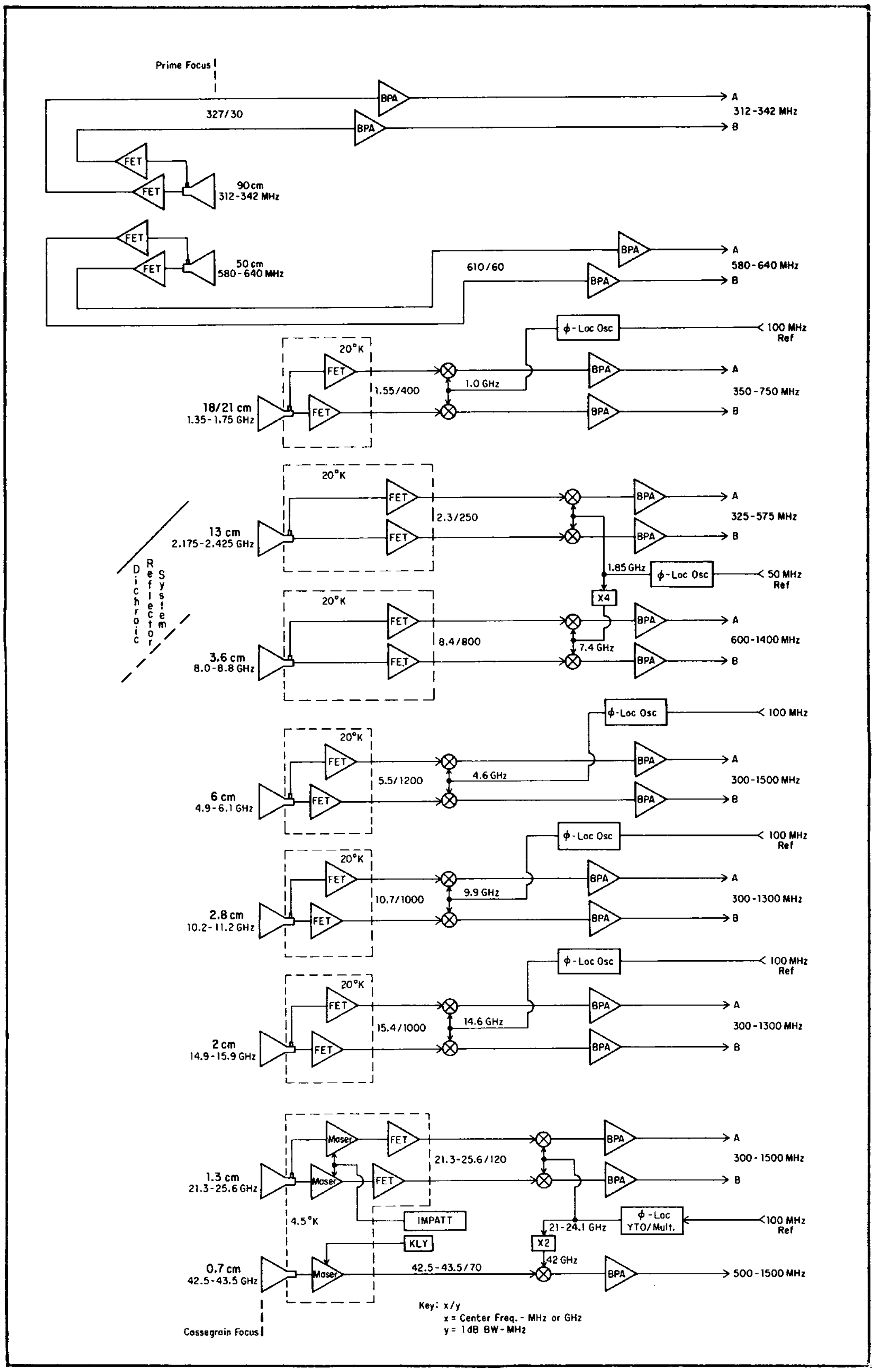

Fig. IV-3. Block diagram of 10-band front end system.

the smaller unit is significantly cheaper than the 1020 unit. We also propose to use three CTI 1020 style compressors to drive the six 20 K front ends. If one compressor fails, at least four of the six front ends can be kept cold; electrically controlled valves can be used to interchange compressors and receivers to keep the required frequencies operational.

The 4 K refrigerator used to cool the two masers would use the JPL/NRAO Joule-Thompson circuit on a CTI 1020 refrigerator. This system is now marketed by CTI and Cryosystems, Inc. The reliability of these 4 K systems is close to that obtained with the 20 K systems.

D. Local Oscillator System and Phase Calibration

The requirement to operate at wavelengths shorter than 1 cm and with long coherent integrations for maximum interferometer sensitivity places severe requirements on the stability of the frequency standard(s) used as independent local oscillators. The statistics of the stability of frequency and time standards is best expressed as the 2-sample Allan variance, $\sigma^2 y(\tau,\tau)$, and Figure IV-4 shows a comparison of the square root of the Allan variance for various state-of-the-art frequency standards.

Geodetic or astrometric work, as well as phase-reference mapping applications at short centimeter wavelengths require phase stabilities $\lesssim$ 20 degrees per hour or a few parts in 10^{15} frequency stability over this time scale. We also want a long coherence time to maximize the signal-to-noise ratio.

Coherence time is related to the observing frequency and to the Allan variance of the frequency standards. Rogers and Moran (1981) have investigated this relationship and calculated the loss of coherence with increases in integration time and observing frequency for the case of a two-element interferometer utilizing two active hydrogen masers, or two rubidium frequency standards (Figure IV-5).

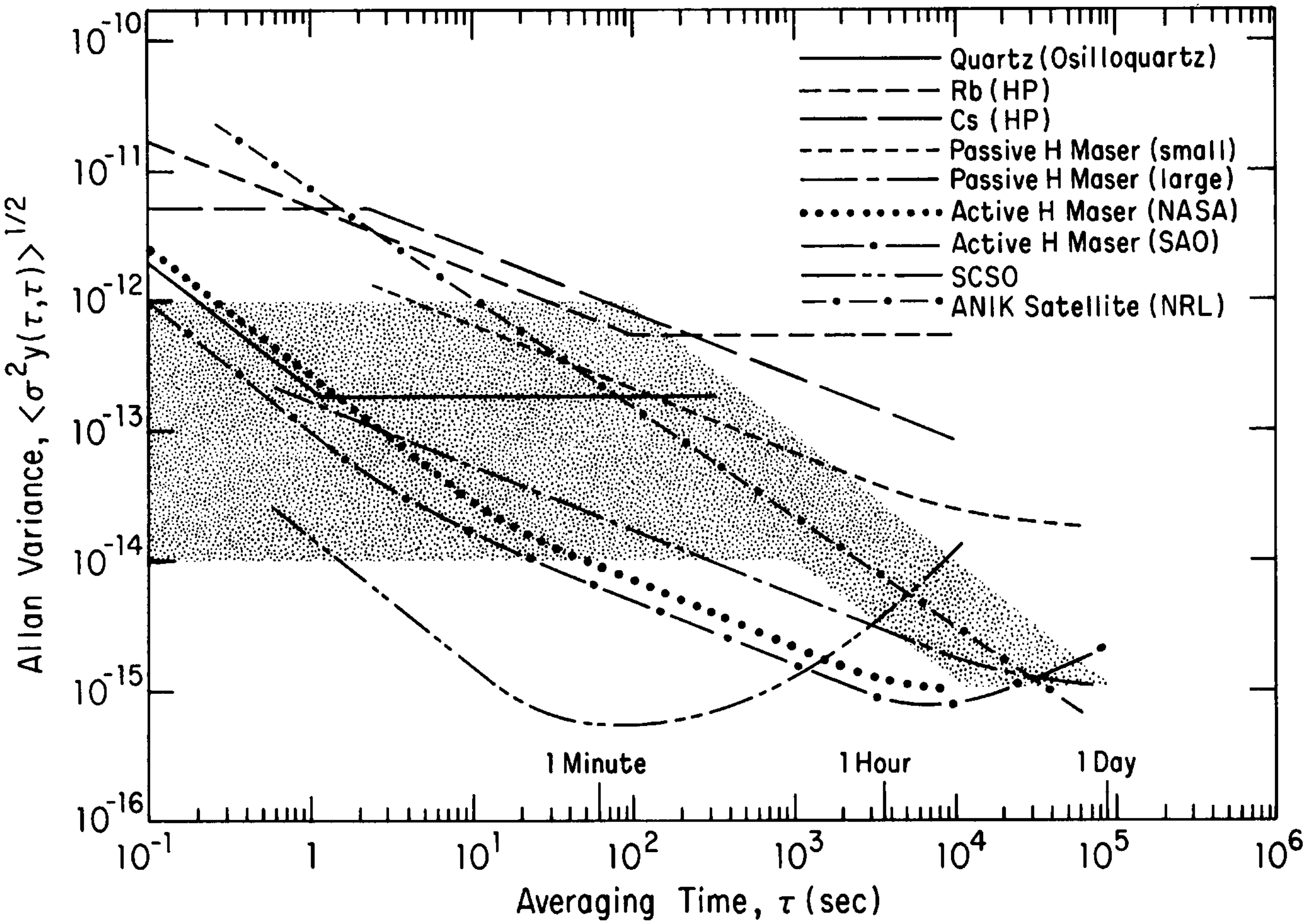

Fig. IV-4. Allan variance of various frequency standards. The data for quartz, Rb, and Cs standards are taken from manufacturer's specifications and the remainder from unpublished measurements. The estimate of atmospheric stability, shown shaded, is taken from Rogers and Moran (1981).

It is clear that at the present time only hydrogen masers can provide the required stability for the VLB Array.

Ionospheric and atmospheric phase fluctuations add an additional loss of coherence. Ionospheric fluctuations dominate at wavelengths longer than about 15 cm, while atmospheric fluctuations, due mainly to tropospheric water vapor, limit coherence at shorter wavelengths. Rogers and Moran have attempted to estimate the Allan variance of the atmospheric fluctuations and their results are plotted in Figure IV-4. From this it is seen that for coherent integrations less than 10^4 seconds (about three hours), interferometers employing active hydrogen masers will be limited by ionospheric

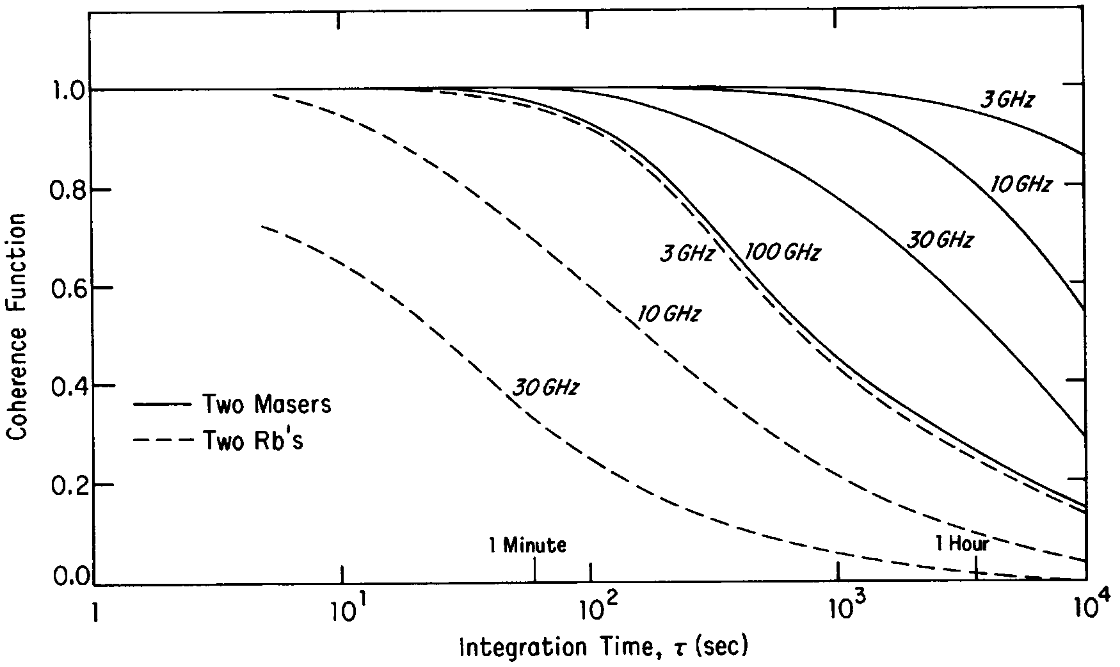

Fig. IV-5. Coherence estimates for Rb and Maser frequency standards as a function of frequency and integration time. Taken from data given by Rogers and Moran (1981).

and atmospheric fluctuations and not by the performance of the frequency standards.

Currently, active hydrogen masers are in widespread use in VLBI for radio-astronomy, astrometry and geodesy. The newer units developed at NASA/Johns Hopkins Applied Physics Lab (NR) and at the Smithsonian Astrophysical Observatory (VLG-11) are a significant advance both in performance and in field reliability. Oscilloquartz S.A. in Switzerland has developed an active hydrogen maser and is currently building several units for customers in Europe. Sigma Tau Standards Corporation of Tuscaloosa, Alabama is developing, with Air Force support, a small, active hydrogen maser which has the potential for considerable cost reduction with, it is hoped, only a modest reduction in performance from that of the large units. In addition, Hughes Research Laboratories, Malibu, California is developing a space qualified hydrogen maser for use on one of the NAVSTAR Global Positioning Satellites.

In the past there has been concern about the use of hydrogen masers in VLB interferometer systems because of initial cost, difficulty in maintenance or repair, and susceptibility to environmental effects which limit long-term (> 3 hour) stability. With all of the development activity noted above, these disadvantages have been, and will continue to be, reduced in importance. In particular, the reliability of hydrogen masers is now such that units are regularly used at field locations for geodesy and radio-astronomy VLBI with few problems. At present the cost of these devices remains high, however.

Another device under development is the Superconducting Cavity Stabilized Oscillator (SCSO) which can give an order of magnitude improvement in phase stability over an active hydrogen maser for integration times up to several hundred seconds. However, the SCSO is not stable over longer time scales and must be locked to another frequency standard in order to be useful for long coherent integrations. The SCSO is a laboratory device at present which is inherently susceptible to mechanical shock and vibration and must be cooled to temperatures below 1.5 K. As such, the real cost, performance, and reliability in the field have not been demonstrated. A single SCSO is being evaluated at Owens Valley Radio Observatory (OVRO) and is expected to give valuable information on their suitability as a frequency standard for independent oscillator interferometers. The cavity for this particular experimental device was developed at Stanford University and the receiver is being developed by the Jet Propulsion Laboratory for OVRO.

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. 1979) and ANIK-B (Cannon et al. 1980) satellites with encouraging results. In addition, the European Space Agency ECS satellite has been 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 (van Ardenne, et al. 1981). One problem in implementing a geostationary satellite phase link is the motion of the satellite which introduces phase shifts into the phase link. However, this can be satisfactorily canceled by using a two-way link.

The satellite transponder oscillator is not coherent with the VLB frequency standard, but its effect can be removed from the system by employing two tones in each link (van Ardenne et al. 1981), or determining the round trip link delay and subtracting the received and appropriately delayed transmit phases at each station (Clark 1981). The problem of differential dispersion in the up and down link frequencies can be mitigated by employing one of the newer satellites with the 14/11 GHz link frequencies. The problem of atmospheric phase fluctuations remains, however.

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 straightforward, the cost of acquisition and maintenance of the necessary ground station is not negligible.

For these reasons we consider a hydrogen maser at each array element as the only method at present of obtaining a satisfactory 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.

The hydrogen maser will be used to derive reference frequencies of 50 MHz and 100 MHz. These frequencies will have spectral purity and frequency stability comparable to that of the traditional 5 MHz output. The first local oscillator frequency for each radiometer will be fixed tuned and derived from microwave oscillators phase locked to the 50 MHz or 100 MHz standard frequency. The one exception is the 1.3 cm LO which will be generated with an indirect frequency synthesizer. A 1.3 cm YIG tuned oscillator (YTO) phase locked to harmonics of a 100 MHz reference signal will enable conversion of the 4 GHz maser tuning range into the 1 GHz IF band in steps of 0.9 or 1.1 GHz. The 7 mm LO will be derived from the 1.3 cm YTO with a doubler integrated into the 7 mm mixer. The mixer will be biased for starved LO operation, so that the LO power available from the YTO and doubler will be sufficient. The 3.6 cm LO will be derived from the 13 cm phase locked oscillator with a X4 multiplier. This will insure a constant phase relationship between the 13 cm and 3.6 cm signals. Only low order frequency multipliers or phase locked oscillators (where large frequency multiples are required) will be employed in order to control the oscillator phase noise, which increases as the square of the frequency multiplication. All of these techniques are presently employed in various NRAO receivers used successfully for VLBI experiments up through K-band frequencies.

The prime focus receivers will be the tuned RF type. These signals will be fed directly to the record terminal.

Tropospheric Phase Fluctuations

Even with a perfectly stable local oscillator system, phase errors are caused by the variable propagation delay introduced by variations in the tropospheric water vapor content at short wavelengths ($\lambda \lesssim 10$ cm) and by the electron content in the ionosphere at long wavelengths. Tropospheric phase fluctuations typically increase as the baseline increases, up to a few tens of kilometers. At greater separations, the antennas look through essentially independent atmospheres, and the phase variations only slowly increase as the baseline length is further increased.

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 antenna site.

A variety of techniques can be used to reduce and, for some applications, even substantially eliminate the effect of tropospheric phase 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" or "hybrid-mapping" techniques (see Section V-D).

For astrometric and geodetic measurements, it is particularly necessary to understand and reduce the effect of tropospheric phase fluctuations; and even for radio astronomy imaging where "self-calibration" is used to restore the image, it is important to maximize the coherence time to optimize the sensitivity and image quality as well as to reduce the required amount of post-processing computing.

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; the latter 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^{-3}) precipitable water vapor.

The amount of precipitable water vapor along the line of sight can be determined by using a microwave radiometer to measure sky brightness in the water vapor emission line at 22.235 GHz (e.g. Moran and Rosen, 1981). Experiments made in Green Bank and at the VLA generally show a correlation between 1.3 cm atmospheric brightness temperature and interferometer phase fluctuations, but the correlation is not sufficiently good to completely remove the tropospheric phase fluctuations from the interferometer data. 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, at the Green Bank interferometer, and by VLBI observers, and it is expected that the delay due to the wet component of the atmosphere can be measured to an accuracy of a few millimeters. Higher accuracy is obtained with differential phase measurements using a nearby reference source ("phase-referencing") since the water vapor content is closely correlated over directions only a few degrees apart.

E. 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 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.

Real-time transmission of the broadband IF data is possible even over very long baselines by using satellite repeaters. 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.) These plans are not being pursued, however, because of the high cost and uncertain availability of a suitable satellite.

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 recording system. Moreover, unlike many other satellite applications, there is no real need for "instantaneous" data transmission. The delay of a few days in receiving magnetic tapes at the Operations Center is only a minor inconvenience to the observer, although it clearly makes it more difficult to spot system malfunctions. 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 digital recordings will remain the most likely IF transmission system.

We have considered a variety of recording media such as optical disks, and have concluded that of the techniques presently available or projected for the near future, only magnetic tape recordings meet the requirements of data storage density, cost, and reusability.

The need to record a bandwidth of at least 50 MHz (100 Mbps) for up to 24 hours ($\sim 10^{13}$ bits) with a minimum of operator intervention puts difficult requirements on the VLBA recording system. The MkI VLBI Recording System, which was in use roughly between 1967 and 1975, recorded (360 kHz) 720 kbps 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 4 Mbps data. The newer MkIII System uses an instrumentation recorder to give data rates of up to 112 or 224 Mbps by simultaneously recording twenty-eight 4 or 8 Mbps tracks. But only about 13 minutes of 112 Mbps data can be recorded on a standard 9200 ft reel of 1 inch instrumentation tape, since the bit density is only comparable to that of the earlier MkII recordings. 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 MkIII System or the older 2 inch and 1 inch video recorders used previously, and permits 4 hours of data to be recorded on a small cassette.

However, neither the VCR MkII System nor the MkIII system as it is currently used provide a satisfactory medium for a full-time multi-element array. The MkII VCR System, although inexpensive and reliable, allows only a narrow 4 Mbps band to be recorded for 4 hours on a single cassette. The MkIII System, in contrast, records 112 or 224 Mbps, but the greater bandwidth is achieved only at the expense of greatly increased tape consumption. Frequent operator intervention is then necessary, and the cost of the magnetic tapes and transportation to and from the Processing Center becomes prohibitive.

There are several ways in which the broad bandwidth of the MkIII System can be combined with the long-playing-time of the VCR. An attractive possibility is to use broadband video or digital recorders which are not yet available commercially but are being developed by at least one manufacturer. It appears, however, that the absence of industry-wide specifications will limit the availability of these devices in the near future, and in any case, the cost is expected to be very high.

Another approach which is under development at the Caltech Jet Propulsion Laboratory and the Haystack Observatory, and which was explored earlier at the NRAO, is to write narrow, 1-mil-wide tracks on a MkIII instrumentation-type recorder, rather than the normal 25-mil-wide tracks. Then, up to 20 (or perhaps even 36) passes, each writing 28 tracks, should be possible using head stacks fabricated with these 1-mil-wide heads. By using 12,000 foot reels of tape instead of the currently used 9,200 ft reels, 20 passes will allow six hours of uninterrupted recording at a bandwidth of 50 MHz (100 Mbps). Even with a bandwidth of 100 MHz (200 Mbps), 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.

Alternately, we have considered using a more efficient coding scheme to increase the bit rate of the VCR and using multiple VCR's at each antenna to obtain an overall bit rate comparable to that of the MkIII System. By building an automatic cassette changer, continuous unattended operation for up to at least 24 hours is possible with a modified multiple VCR System. Additionally, the use of better recording schemes on the MkIII instrumentation recorder is a possibility. The coding scheme being developed for the VCR's and 3-position modulation are both being considered.

In Table IV-6 we summarize the projected construction and operating costs of four possible record systems including enhanced MkIII systems, VCR based systems, and broad band digital recorders. The X12 and X20 MkIII modifications are being developed at Haystack and JPL respectively, and we therefore propose to explore at the NRAO the multiple cassette system. We believe that this system may be the least expensive to build and operate, and also, at this time, it involves the least extrapolation of currently used techniques. However, the anticipated improvements in the enhanced MkIII recorder and in other wideband recorders offer great promise if the proposed tape density enhancement can be realized. The broad band digital recorders of the type being developed in industry (e.g. Ampex AVRX recorder) may also be attractive. But because of the high cost of tape and recorders as well as the lack of industry-wide standards, we have not considered this system in detail at the present time.

We propose to record four independent IF channels, each with a normal maximum bandwidth of 12.5 MHz (25 Mbps). By using a pulse-width-modulation digital coding instead of the conventional MkII bi-phase code, a data rate of 12.5 Mbps on a single cassette will be possible, and extensions to 16 Mbps may eventually be obtained. Each antenna will require eight recorders

TABLE IV-6

RECORD SYSTEMS

Recorders	MK II	MK III	Ampex AVRX	Moving Head MK III (X12)	Moving Head MK III (X20)	Moving Head MK III (X36)	VCR 12.5 M Bit MK II (X8)
Unit Price	$800	$35 K (c)	$140 K (f)	$35 K (c)	$35 K (c)	$35 K (c)	$26 K
Head Price	$ 75 (a)	$15 K (c)	$ 12 K (f)	$3.5 K (e)	$ 7 K (g)	$3.5 K (e)	$600
Data Rate Mbps	4	112	106	112	112	112	100
Record Time (hr) (per reel/cass.)	4	0.33	1-1/2	4	7	12	4
Gigabits/reel, cass.	52	120	570	1,600	2,600	4,800	180
Pounds/10^{13} bits (h)	110 (i)	1,380 (j)	55	81 (j)	50 (j)	27 (j)	32 (i)
10^6 bits/sq. in.	10	0.8	20	10	18	30	37
Ave. head life (hrs)	2,000 (b)	15,000 (e)	1,000 (f)	15,000 (e)	15,000	15,000 (e)	2,000 (b)
Ave. tape life (No. passes)	300 (b)	500 (e)	1,000 (f)	500 (e)	500 (g)	500 (e)	300 (b)
Cost of record/playback system (including spares) for entire VLBA ($K)	Not Considered	Not Considered	5,956	3,116	2,556	2,000	1,496
Tapes and shipping container 60 day supply ($K)	"	"	2,025	1,308	780	425	561
Maintenance cost/yr ($K)	"	"	2,200	103	103	103	158
Total replacement and shipping cost/yr ($K)	"	"	260	276	170	92	153
TOTAL CONST. COST ($K)	"	"	7,981	4,424	3,336	2,435	2,057
TOTAL OPR. COST ($K) ($yr^{-1}$)	"	"	2,460	379	273	195	311
Hours between tape change (Number of record racks)			3 (2)	16 (4)	21 (3)	24 (2)	48 (2)

a) NRAO b) Panasonic c) Honeywell d) 3M e) Haystack f) Ampex g) JPL

h) 10^{13} bits $\sim$ 24 hrs @ 100 Mbps i) 0.6 lbs/reel j) 13 lbs/reel each operating at 12.5 Mbps to keep up with the total 100 Mbps data rate output of the samplers. Lower sample rates can be handled by dropping recorders off line or by increasing the number of bits per sample.

Eight recorders will produce up to 48 four-hour tape cassettes per day per antenna. To reduce the bookkeeping required to keep this many tape cassettes straight and to reduce operator intervention to a minimum, we propose to develop a Data Acquisition Rack (DAR) using 8 video cassette recorders in an integrated rack assembly (see Figure IV-6). This DAR will have a rack-based automatic cassette changer plus a rack-based cassette storage area, all under control of a central microprocessor. The tape storage area will be a dismountable bin which can be shipped, cassettes in place, to the correlator for processing. A similar rack-based playback system at the processor will complement the antenna record system requiring only insertion of the cassette-loaded bin to process one day's worth of observations for a given antenna. Cassette changes, recorder operations, data synchronism, and monitoring the quality of each recording, etc. will all be done under microprocessor control requiring a minimum of operator intervention.

The sampler outputs at any antenna will be recorded on the various tape recorders in 10,000 bit data blocks with each block having its own time code and check sum encoded. By breaking the data into such blocks, the four IF bands can be multiplexed among all 8 recorders. Thus, one-eighth of any IF's data will be recorded on any given machine. Such an arrangement will require little digital circuitry to implement and to unscramble the multiplexing. Also, a failure of one recorder will then result in loss of 1/8 of each IF's data rather than eliminating a large percentage of one IF's data, yielding a more graceful recorder system failure sequence.

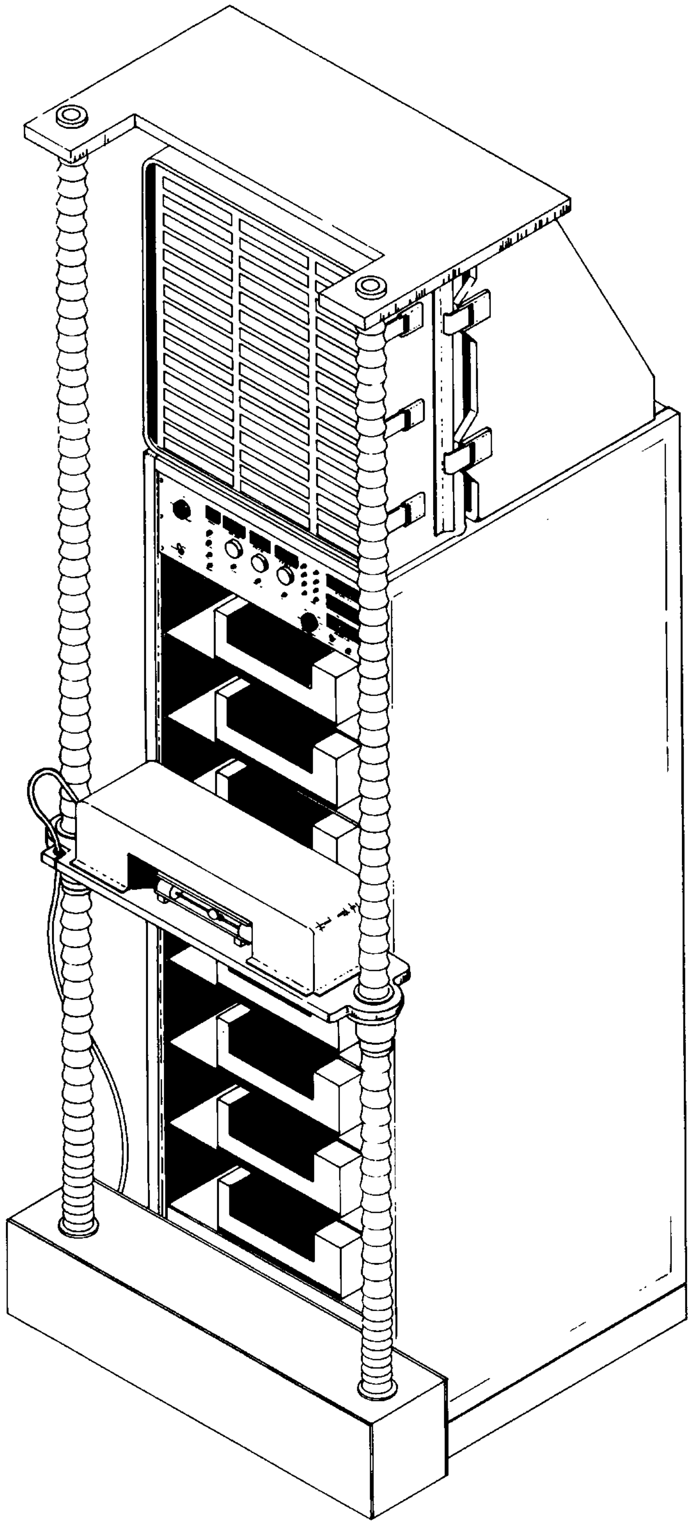

Fig. IV-6. Data Acquisition Rack Assembly.

Unlike the front ends, the loss of the DAR would bring down an entire VLBA element. Therefore, we have provided for a spare DAR complete with tape recorders, tape changer, and electronics. For most of the time, the spare record system can be expected to be operational, and thus unattended operation is possible for up to 48 hours. Alternately, for limited periods, both recorders may be used, allowing a total bandwidth of 100 MHz to be sampled at 200 Mbps for greater sensitivity. In this double bandwidth mode, twice as much magnetic tape is consumed, so it is practical to use this mode only when unusual sensitivity is required, such as at short wavelengths where the coherence time is limited.

The IF recording system will allow 1-bit (2-level) sampling of up to four 25, 12.5, 6.25, 3.12, 1.56, 0.78, 0.39, 0.19, or 0.10 MHz bands. For continuum observations the sampling is done at the Nyquist rate to give an rms noise of $(\pi/2)\ T_J\ (2B\tau)^{-1/2}$ per interferometer pair, with T_J being equivalent to the system noise temperature in janskys, B the bandwidth, and τ the integration time. In the spectral line mode, for channel bandwidths of 6.25 MHz or less, the sensitivity can be increased by a factor of 1.16 by oversampling.

Conversion of the four IF signals from the Vertex Cabin into a bit stream, suitable for input to the recorder, is done by the Data Digitization Electronics (DDE). The DDE consists of an IF Processor, four IF to Video Converters, a Sampler, Delay Calibrator, Time of Day Clock, RS232 Distributor, and 5 MHz Distributor. The design is based on the MkIII System, modified for fewer converters with wider bandwidths, and with the data formatting and quality monitoring assigned to the recorder electronics.

The IF and DDE systems are designed to be independent of the specific recording device used so that future developments in this area can be most easily exploited. Specifically, it is compatible with the MkIII-type instrumentation recorder, where each of the 4 IF bit streams must be multiplexed across all 28 recorder tracks. This results in greater reliability and lower cost than the conventional MkIII System with its 14 video converters (Lacasse 1981).

Figure IV-7 shows the IF Processor which has four IF inputs in the band from 300 MHz to 1500 MHz. Each of these inputs is frequency translated, with 10 kHz resolution, such that the lower edge of the band of interest is at 500 MHz. This section of the DDE is best implemented in the Vertex Cabin, to avoid sending wideband signals through long lengths of cable and then having to deal with the resulting frequency dependent cable attenuation.

As a result of the frequency agility of the IF Processor, the Video Converters can be relatively simple. Primarily, they frequency translate the outputs of the IF Processor to baseband, using fixed 500 MHz oscillators, and single sideband networks. The Video Converters also provide IF level setting attenuators, and selectable output bandwidths. Video, IF, and LO power levels are monitorable.

The sampler produces one-bit, 2 level samples of the filtered, baseband data at a maximum rate of 50 Mbps. The sampling clock is derived from the 5 MHz reference using phase-lock techniques; oversampling is easily accomplished for the narrow bandwidths. Both the sampled data streams and the sampling clock are transmitted to the recorders. A Time-of-Day Clock output is also transmitted to the recorders.

The Delay Calibrator in the DDE is the same as that used in the MkIII System with the exception that it also includes a self-contained counter and

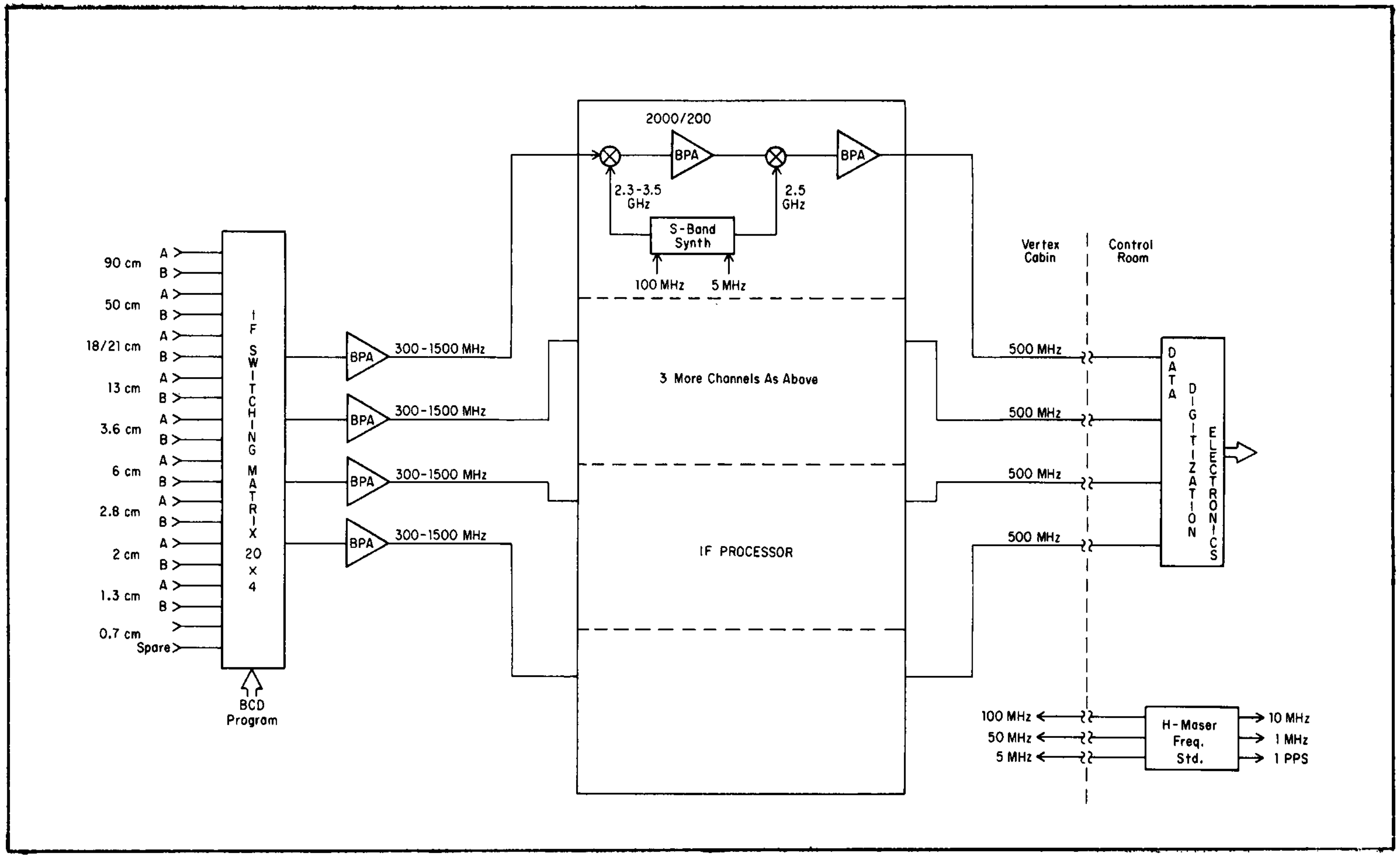

Fig. IV-7. Block diagram of IF Switching Matrix, IF Processor, and Data Digitization Electronics.

communicator module. The Delay Calibrator provides a 5 MHz reference to the Vertex Phase Calibrator System, and also measures the round trip delay in the 5 MHz reference cable.

Communication to the host computer is implemented as in the MkIII System: each module includes a RS232 transceiver which is assigned an address on a RS232 link. A module responds according to a well defined protocol when it is addressed. Thus, all significant functions in the DDE are remotely controllable and/or observable.

F. Control and Monitor System

The overall concept of the Control and Monitor System is a central control center linked by telephone lines to control and monitor each antenna. Typical categories of information required or supplied by an antenna along with typical data rates are given in Table IV-7. The data rates are comfortably low, of the order of a few hundred bits per sec; an antenna can be controlled and monitored with a 2400 bps telephone line with a large margin for future growth and error correction. The low data rate also allows low cost buffering of data in a memory for operation during a communication failure. In addition, data processing at the antenna will further reduce the data rate requirements. For example, instead of sending an antenna position every 10 seconds, a position and duration of observation can be sent to a local computer which then updates the antenna at the required rate.

The distribution of computing power between central control and antenna is an interesting but not particularly crucial question. It would be possible to give the central computer direct control and monitor capability of every bit at the antenna with minimal data processing at the antenna. This

TABLE IV-7

TYPICAL CONTROL AND MONITOR DATA RATES

CONTROL

Function	Bits	Update Period	Bit Rate (bps)
Antenna Pointing	48	10 s	4.8
Local Oscillators	48	10 s	4.8
Receiver Control	24	1 s	24
Tape Control	12	10 s	1.2
	TOTAL Control Bit Rate		34.8 bps

MONITOR

Function	Bits	Update Period	Bit Rate (bps)
Servo Error	16	1 s	16
Receiver Total Power - 4 channels	64	1 s	64
Monitor Data	512	100 s	5
Fringe Verification	10^6	10^4 s	100
	TOTAL Monitor Bit Rate		185 bps

minimal data processing would include error checking, immediate action for some severe out-ot-limits conditions, equatorial to azimuth-elevation coordinate conversion, and memory-buffering of the data link in the event of a communications failure. However, the system which is favored is one with a small computer at each antenna linked through commercial computer-network software to the central computer. The local computer program would be loaded via the phone link from the central control computer. This system has the advantage of great flexibility and the use of proven computer-network software.

A block diagram of a proposed remote system is shown in Figure IV-8. The data-sets are general purpose analog and digital input and output units which link to the local computer via a single serial-transmission twisted-pair cable. Each data-set is located close to the equipment it commands and monitors to minimize wiring. Units similar to those used on the VLA or a CAMAC adaptation will be used. The IF data verification buffer is a 2M bit RAM memory which is loaded with data while observing a strong source; the memory is then unloaded through the telephone link (taking 7 minutes at 4800 bits/sec) and correlated with similar data from another antenna to verify system coherence.

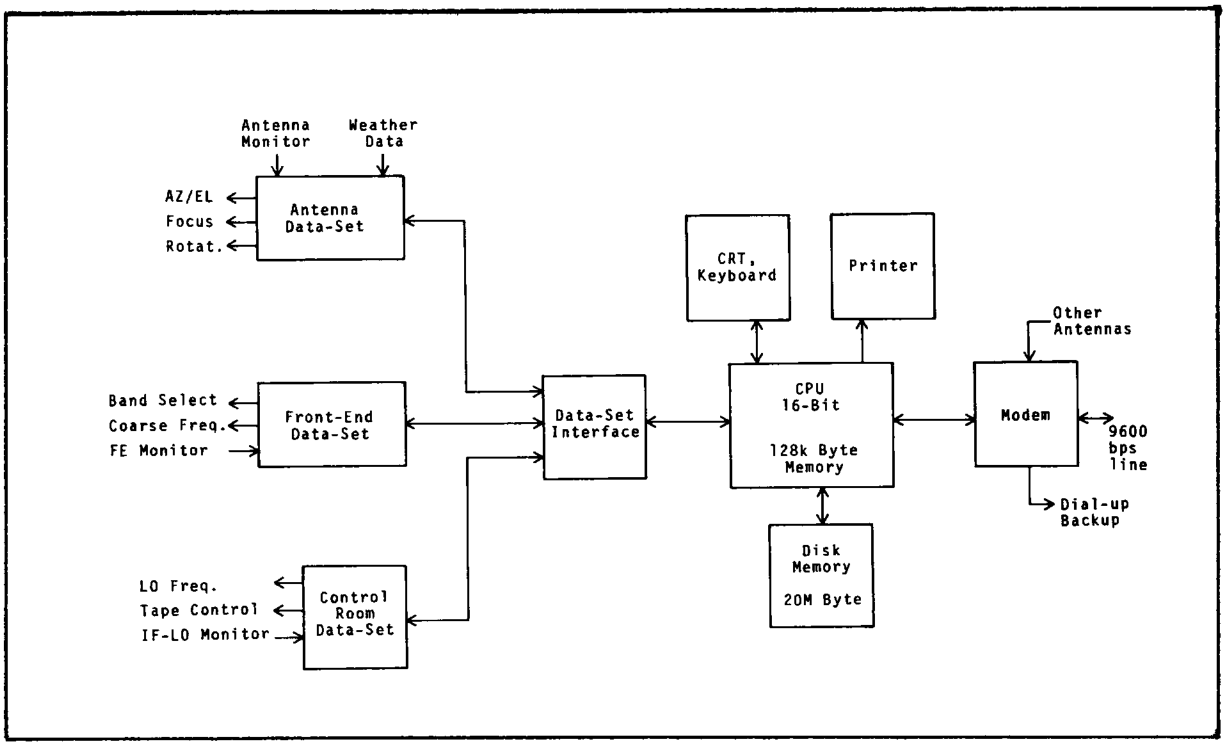

Fig. IV-8. Antenna Control and Monitor System

The antenna computer is in the LSI 11/23 class and will have a 16-bit processor with 128k byte memory, CRT display, slow printer, keyboard, and two 10M byte disks. The communications modem will be of an advanced type which allows error checking and automatic switch-over to a dial-up line in the event of failure of the dedicated line.

A dedicated 4-wire communications line with 9600 bps capability in each direction is proposed. As many as three antennas may share one leg of the link, so three 2400 bps data channels and a voice link may be simultaneously used. A dial-up line to each site for about 3 hours per day would cost the same amount and would not have the reliability or capacity of the dedicated 4-wire line.

The central control computer must perform the functions of communications to all antennas, presentation of CRT displays, monitoring of data, and correlation of fringe verification data. The latter includes model-calculation, fringe rotation, and delay. The proposed computer is in the PDP-11/44 class and includes 512k byte memory, two 128M byte disks, two 1600/6250 bpi tape drives, tele-typewriter, printer, card reader, 3 graphics and 9 text CRT's and commercial software for its operating system, communications, and higher-level languages. A duplicate telescope control computer is also included at the operations center to facilitate software development. The software development for control and monitor software is estimated to take 16 man-years.

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V. THE PLAYBACK SYSTEM

The heart of the VLBA is the Playback System which includes a set of tape recorders to simultaneously play back the IF signal recorded at each station, controls to adjust the relative timing of the data streams so that the samples of the same wavefront are being played back at the same time, fringe rotators to remove the differential Doppler effects among the various stations, (the interference "fringes"), and the correlator proper, which multiplies together each pair of IFs at several different time offsets ("lags"). Conversion of the correlation function into an image of the radio source is done in the Post-Processing Facility which consists of a medium to large scale general purpose computer(s) combined with specialized hardware and software.

A. Tape Playback System

The playback system can be, like the record system, based on consumer-type video cassette recorders. Rack-based playback stations, each with 8 playback recorders, a rack-wide automatic cassette changer, and a central cassette storage bin will be required to service the antennas of the Array. The cassette bin, which holds one day's worth of observational results for one antenna at 100M bps sampling, will be loaded into a playback rack where cassette shuttling, recorder operation, recorder time synchronism, etc. will be controlled by a central micro-processor. Since the order of the cassettes in the bins will have been under software control at each antenna, little bookkeeping will be required to keep the large number of cassettes produced by the Array in their proper order. Twenty such racks will be provided at the processor to allow processing of data from 10 antennas at a 200M bps data rate in one pass. Up to fourteen of these racks will be used for the normal 100M bps continuum operation.

Although 160 recorders will be required at the processor, the modular rack design should make the operational process at the correlator reasonable. The inexpensive nature of the cassette recorders will also make provision of spares, both at the rack level and at the individual recorder level, economical.

The playback cassette units can be modified to play back at a speed 10 to 15% higher than the record speed, allowing some processing time edge over the observing time. This edge will help reduce tape backlogs which might accumulate because of correlator delays and inefficiencies. Except for this possible modification to the cassette recorder servo electronics, there will be no difference between an antenna recorder rack and a playback rack.

The only additional equipment required at playback time is a buffer, to remove the mechanical variation in the playback rate, and a delay control, so that the bits are removed from the various tapes in synchronism. The interface to the correlator proper is four bit streams per recorder rack at a 25 Mbit/sec rate, with relative timing (among the racks) controlled by the correlator. Double bandwidth operation is organized as two 50 Mbps streams.

B. The Correlator System

The playback correlator system consists of several logically separate (but not necessarily physically separate) subsystems. They are:

(1) The bit stream handlers (one per station)

2) The baseline handlers (one per baseline)

3) The channels

4) The hardware controllers

5) The computer system.

Although the correlator is a relatively straightforward design and construction project, the tape recording system is much less so. It is inevitable that modifications will be made in it based on field experience. It is very desirable to have the correlator itself independent of such changes, so a well designed interface between the tape system and the correlator system is necessary. The concept of having the playback system provide four bit streams at 25 Mbit/sec each and having validity bits with well-defined properties would lead to an interface sufficiently simple that the independence could be maintained. This is important since the correlator can be built in its entirety from the beginning, giving substantial saving in money over having to build a prototype correlator system which will surely be necessary for the recording system to get the initial field experience.

1. Correlator Specification

The correlation function must be determined at a number of lags for two reasons. First, the proper delay is not known exactly *a priori* because of clock errors at the stations or because of imperfect knowledge of the location of the radio source, and, second, the correlation function is related (by a Fourier transform) to the frequency structure of the incoming radiation (that is, the correlation function measured at a number of "lags" can be used to synthesize a multichannel spectrometer).

Relatively modest requirements arise from the first reason. In a full time array, with frequent real-time coherence checks and more-or-less continuous reduction of the recorded data, the unknown clock errors can be held to less than 0.3 microseconds at all times. Such internal accuracy, within a continuous VLB "run" is already common. An additional allowance of 0.4 microseconds allows for an uncertainty in the location of the source of radiation by 1". Measurement of positions to greater accuracy than 1" is very easy on several existing radio telescopes; however, the source may be somewhat extended and present an uncertainty as to where within its boundaries the very compact object of interest might lie. Also, there are some objects of interest to VLB techniques in which the compact emitting regions are spread over an area of order 1" in size.

As discussed in Section VI, it will sometimes be useful to use the Array with radio telescopes other than the dedicated ones, to obtain either higher resolution, better coverage of the transfer function at long wavelengths, or to obtain greater sensitivity. In this case it is necessary to provide more than 10 stations in the playback correlator. The cost of an additional station of recording apparatus is relatively small, and, as discussed below, the additional correlators are needed anyway for spectroscopic studies. For continuum observations it is possible to increase the number of playback stations to 14 for little increase in cost. For double bandwidth continuum observations (100 MHz), the Playback System will be limited to 10 stations. Likewise, because of the stringent spectroscopy requirements, the spectrometer specifications are for a 10 station correlator. If a spectrometric experiment requires more than 10 stations, the experimenter must sacrifice spectral resolution, or must play the tapes three times to get all possible combinations.

It is easy to formulate scientifically reasonable experiments which require unreasonable capabilities in the correlator system, and a compromise is necessary. The minimum desired for astronomical spectroscopy is approximately 512 channels per baseline (powers of two are natural for implementations of Fourier transforms).

For both spectroscopic and continuum observations, it is often important to measure the polarization properties of the incoming radiation. This is done by causing two of the bit streams from each station to come from the same frequency band, but from different receivers with orthogonal polarizations. Two bit streams from two different stations have four cross-products. These products are, in effect, linear combinations of the four Stokes parameters characterizing the radiation. Provision must therefore be made in the correlator for calculating these four cross-products.

For spectroscopic observations we may wish to swap this polarization capability for additional channels in a single polarization. This is most effectively accomplished by having several different modes of operation for the line system. The correlator should support at least the following modes:

TABLE V-1

CORRELATOR MODES

A) Two bands, two IFs per band, full polarization processing.

B) One band, full polarization processing (two bit streams are idle)

C) Four bands, no polarization processing.

D) Two bands, no polarization processing (two bit streams are idle).

E) One band (three bit streams are idle).

The specifications for the correlator may be summarized as follows:

Number of stations: 14 normal continuum operation (91 baselines)
10 double bandwidth operation (45 baselines)
10 expanded spectrometer channels (45 baselines)

Number of bit streams per station: 4

Bit rate per stream: 25 Mbps in normal mode, 50 Mbps in double bandwidth mode (100 or 200 Mbps aggregate rate)

Polarization processing: All four cross products of two pairs of bit streams (but see below).

Simultaneous delay range: 1.28 microsec normal continuum or 0.64 microsec double bandwidth (32 channels at 40 ns/channel or 16 channels at 20 ns)

Integrator dump rate: Selectable from 0.1 to 30 seconds.

Output data rate: 100,000 channels x baselines x rate.

The number of frequency channels in the spectrographic mode is variable, according to the mode and preselected bandwidth.

Because the IF's are recorded at the antennas with identical local oscillators, a simple correlator would produce an output varying at the natural fringe rate of each interferometer baseline, which can be as high as 100 kHz for baselines and frequencies planned for the Array. This rapid fringe variation is removed by translating the frequencies in the IF band from one element of each baseline to compensate for the motion of that element relative to the other as the earth rotates. Prior to correlation, one of the two bit streams which comprise a baseline pair is multiplied by a three-level approximation (+1, 0, -1) to a sine wave, produced by a programmable rate generator. To avoid introduction of additional noise in this frequency translation, it is necessary to generate two frequency-translated bit streams by multiplying by two sine waves in quadrature, in effect implementing a single-sideband frequency conversion.

It is not sufficient to merely control the relative delays of the bit streams, because of their discretely sampled nature. Each bit has a time error of up to a half a sampling interval. The two bit streams involved in a particular baseline therefore can have an error of up to one bit time, whereas the required accuracy is half a bit time. Therefore, each baseline must have a "vernier" bit, to delay one bit stream by plus or minus one bit time, to give the optimum delay.

The correlator proper is probably controlled most conveniently by one or more fast, bit slice microprocessors. These in turn must be controlled by, and pass data to, a more general-purpose computer, which will do the necessary geometric calculations to provide fringe rates and phases, format the data in convenient forms for post correlation processing, pre-average the data and display "first-look" fringes or spectra, and provide hardware diagnostics.

The geometric calculations are not particularly onerous, but must be done with care. To track fringes accurately on a long baseline at 43 GHz requires an accuracy of about 38 bits. To attain this requires calculations about 42 bits of precision. There is no problem in attaining this in any modern minicomputer. Also, tracking fringes smoothly on a long baseline requires that the fringe function generator parameters be updated at least every 0.1 seconds. Calculating the geometry of the fourteen station array will take only a few percent of the time on any modern minicomputer, if the calculation is properly organized.

The data handling is a bit more severe in its requirements. Output data rates of up to 400 kBytes/second may be encountered. This carries the strong implication that input data rates will be at least as great. (In a well ordered world computers perform data reduction, not data expansion.) To handle this, and to resolve gracefully the inevitable bus contention problems, the computer should be specified with an aggregate I/O bandwidth of at least 2 MBytes/sec. This puts the computer into the size of a moderate minicomputer. For instance, a DEC PDP-11 is not sufficiently powerful, but a small VAX would probably be acceptable.

Perhaps the most computation intensive chore of the correlator computer is to convert from lag spectrum to cross-correlation spectrum in the spectral line case. There are several array processors on the market which can do Fourier transforms of the requisite length at the rate of about 500,000 output points per second, which should be sufficient for any case implied by the specifications above.

2. Correlator Design

The correlator specified above is a rather large one, at least in terms of correlators currently on line. The only correlator system of this size in current use is the VLA system which has 373,242 correlation products operating at a 100 Mbps clock rate. A larger correlator was prototyped for the NASA SETI project, but the full system is not being produced. One conservative approach is to design the correlator using the VLA technology and philosophy. Since it has been done, and works well, one can set out to design a correlator of this size with reasonable confidence that it will work when complete. Other designs have not been attempted in this size, and so will require more extensive design and prototype work.

It is obviously unprofitable to construct a correlator from standard MSI integrated circuits. A crude estimate of integrated circuit counts indicates that the correlator would be comprised of roughly half a million devices. Connecting, powering, and testing such a multitude would be very expensive, even if the devices themselves cost nothing.

Rough cost estimates indicate that the correlator cost is nearly proportional to integrated circuit package count, and only weakly dependent on the cost of the integrated circuits themselves. It is therfore clearly most economical to maximize the degree of integration, even at the expense of developing custom chips.

An alternative approach is to base the correlator design on the Caltech/JPL Block II VLB Processor which is currently being developed. This system uses a large number of relatively slow speed correlators, each operating at 8 Mbps. The economics of the Block II design for a large correlator improve considerably with the state-of-the-art in Very Large Scale Integration technology (VLSI). In fact, a 30 to 50 percent compression of the correlator chip count is now feasible with the recent introduction of a larger capacity Programmed Aray Logic (PAL) chip, and we anticipate that a custom gate array in the range 4,000 to 10,000 gates will be available in the near future.

An even higher level of integration is being sought in a development program recently initiated by Caltech and JPL to produce a complete 16-channel correlator/accumulator on a single VLSI silicon chip. The clock rate is expected to be 16-20 MHz. This development will draw on the substantial expertise developed in Caltech's "Silicon Structures" project, under the leadership of Prof. Carver Mead.

Another, very innovative, approach is planned for the large correlator on the Nobeyama interferometer array in Japan. In this design, the incoming bit stream is Fourier transformed into individual frequency channels, and the channels are then multiplied together and accumulated to give a correlated power spectrum, just what you want for the spectral line case. For use as a continuum processor, one would generate, say, spectral channels of width 780 kHz which are narrow enough that the possible clock errors and delay range do not reduce the amplitude of the fringes.

One can then do a Fourier transform back into lag space, to be able to discard lags not of interest. A complete design of such a device has not been made, so the cost and operating properties are not well known. The implementation is critically dependent on a few hardware devices at the forefront of technology, especially fast parallel multipliers for implementation of the Fourier transform on the incoming bit stream. The device count for this approach is attractively low, but with current commercially available devices, each device must be built of several integrated circuits, leading to a package count comparable to that of other approaches.

Since the only "demonstrated" design of a correlator of this size is the VLA correlator, we have based our cost estimate for the VLB Array on a recirculating correlator of this type; that is, the correlators are run at their maximum feasible rate, and the data coming from the tape playback systems at a lower rate are processed (recirculated) several times to extract more information. There are several ways to use recirculators, and it is not clear which will be most advantageous. The approach suggested here is to use a separate recirculator for each of the four 25 MHz bit streams. In the continuum mode, the correlator can perform four operations in the time taken for the recirculator to refill with new data. These could be to compute the polarization parameters of the radiation. That is, if there are two left-hand polarized IFs, LA and LB, and two right-handed, RA and RB, a single section of the correlator could compute the four products from two antennas (1 and 2) RA1*RA2, LA1*LA2, RA1*LA2, and LA1*RA2. These four products carry the intensity and polarization information at the band ("A") from which these two IFs arise.

In the double bandwidth mode only two of these products can be computed. The second pair would be produced in the section of the correlator that would normally produce the band "B" products. As in the spectral line mode the correlator is restrained to 10 stations, so that the 91 baselines are reconfigured into two 45 baseline sets. The second of these sets provides processing for the band "B" products.

In the spectroscopic mode, the number of channels varies with the width of the signal which is to be analyzed. This ranges from 256 channels for analyzing a 12.5 MHz band up to 4096 channels per baseline for analyzing bands narrower than 0.78 MHz. For comparison, for line emission by the water vapor masers, 12.5 MHz corresponds to a velocity range of 160 km/sec. For line emission by the OH masers, 0.78 MHz corresponds to about 140 km/sec. The number of available frequency channels per band, n, in this design is shown in Table V-2 for each of the modes of operation described in Table V-1.

TABLE V-2

CORRELATOR SPECIFICATIONS

Sample Rate Mbps	Band width kHz	Mode A		Mode B		Mode C		Mode D		Mode E	
		n	kHz	n	kHz	n	kHz	n	kHz	n	kHz
25	12.5	32	391.	64	198.	64	198.	128	98.	256	49.
12.5	6.25	64	98.	128	49.	128	49.	256	24.	512	12.
6.25	3.12	128	24.	256	12.	256	12.	512	6.	1024	2.
3.12	1.56	256	6.	512	3.	512	3.	1024	1.5	2048	0.76
1.56	0.78	512	1.5	1024	0.76	1024	0.76	2048	0.38	4096	0.19
0.78	0.39	512	0.76	1024	0.38	1024	0.38	2048	0.19	4096	0.10
0.39	0.19	512	0.38	1024	0.19	1024	0.19	2048	0.10	4096	0.05
0.19	0.10	512	0.19	1024	0.10	1024	0.10	2048	0.05	4096	0.02

C. 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.
2) Mapping including conversion of visibility data to images by sorting, Fourier inversion, self-calibration, and image restoration.
3) Analysis.

The hardware requirements necessary to implement these tasks are not easy to estimate. On the one hand data analysis techniques, particularly 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. But present experience indicates that this trend will be insufficient to offset the expansion in the complexity of algorithms which are being developed. As examples, we note:

1) There has been two orders of magnitude increase in the complexity of problems on which the CLEAN algorithm is being used since its introduction in the early 1970's; in the same period the computing cost per cpu cycle has gone down only by a factor of 10.

2) Algorithms to provide an error analysis of CLEAN maps, (or results of other restoration algorithms) are not being implemented because of the excessive requirements on computer time.

3) Self-calibration (see Section V-D) has only recently become a routine part of synthesis mapping, and the requirements are increasing because sources of greater complexity are being analyzed and because the increased sensitivity of telescopes makes it possible to decrease the time constant for the self-calibration averaging.

4) Other restoration algorithms such as maximum entropy, optimum deconvolution method, and regularization are likely to come into use. These can require more computer power than CLEAN.

5) It will be desirable to include the fringe fit in the self-calibration loop particularly for weak or very large sources. This would require considerably more computer time than the usual self-calibration algorithm.

6) Completely new techniques, such as space-frequency synthesis on a source of varying spectral index, are being considered.

We have attempted to estimate the data processing requirements of the Array by extrapolating practices in current use with the MkII and MkIII systems, as well as experience gained at the VLA. We consider separately continuum and spectroscopic applications.

1) Continuum mapping. In the current VLBI systems the premapping analysis is done partially in the on-line correlator computer and partially in a general purpose computer. These steps require about one minute per baseline on an IBM 360/65 for one hour of MkII data, or about twelve hours for a ten element (45 baseline) array and 12 hour track. The MkIII system requires about an order of magnitude more time for fringe fitting, but this can be reduced considerably with the use of an Array Processor and suitable improvement in algorithms.

To determine the time requirement for mapping, a VLA data set using 10 antennas with 35,763 data points was processed with the standard VLA self-calibration (Schwab 1980), mapping, and CLEAN programs. This is approximately the amount of data in 12 hours of 1-minute integrations. Programs were run on the MODCOMP CLASSIC, VAX 11/780, and IBM 360/65 computers and the execution times are typical of any modern super minicomputer with an array processor. At an average time of 30 minutes per pass, approximately 5 hours of computing time are required to map a source assuming 10 iterations of the self-calibration process.

For some types of observations, e.g. small diameter continuum sources dominated by a point component, an intelligent correlator can make at least an order of magnitude reduction in the data rate by using delay and fringe rate windowing. This is important because it enables a lot of good science to be done with an insignificant post-processing load. However, unless the majority of VLBA observing is of this type, this will not significantly change the post-processing requirements.

On the contrary, for wide-field mapping and for work on weak sources where the *a priori* position of the compact feature is not known better than a few tenths of an arc second, the post-processing requirements are increased by more than an order of magnitude over the estimate given above.

2) *Spectral line mapping*. Spectroscopic imaging adds another dimension to the mapping problem. Pre-mapping steps of pre-averaging; calibration of clock drifts, phase, and bandpass; velocity tracking; editing; and production of a preliminary fringe-rate map would currently require about 48 hours on an IBM 360/65 for a ten-element array, 12 hour tracks, and 256 spectral channels.

Estimates of computing requirements for spectral line mapping are based on the continuum case and the assumption that time for map-making and CLEANing is 256 times that for continuum work. This indicates about 2.5 days of post-processing for a 12-hour observation of a moderately complex source. However, the extreme (but real) case of a large H_2O source with a broad range of velocity features can provide over 100 GBytes of data in a one-day observation. This exceeds the maximum output ever expected from the VLA by a factor of about 30, and sets almost impossible requirements on the post-processing system. It is not realistically possible to fully analyze this kind of observation.

The maximum correlator output data rate in the spectral line mode is 400 kBytes per sec, or 14 GBytes in a 10-hour observation. We have specified a maximum storage of 10 GBytes, which can handle most H_2O and OH line programs, but still cannot store an entire observation at maximum correlator output rate. This data would still have to be written on tape and re-read for full processing.

3) 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 CLASSIC, VAX-11/780 and IBM 360/65 computers. 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 for the reduction of VLA, VLBI and other astronomical data. 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 more than offset 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 4 VAX-11/780's each with an array processor and 4 megabytes of main memory will be required to handle all of the post-processing needs. The system includes six high density tape drives, 10 GBytes of directly accessible storage on non-removable disks and an additional 10 GBytes on removable disk packs without the need for tape I/O. A further increase in the mass storage may be possible using optical disks. Image displays, a video disk to store images, CRT's (10 text and 4 graphics), and 2 line printers are also included. A possible post-processing computer configuration is shown in Figure V-1.

The proposed system is equivalent to about one-half of the currently available VLA post-processing hardware. It allows for a reasonable amount of reprocessing of data, and assumes that the typical observer is likely to have visibility data in the computer for about three days, that there is one moderate H_2O user, two easy line users, two wide field continuum mapping users and any number of continuum users with less complex data. We further assume that there will be a significant use of outside post-processing systems by some users. There are now ten large systems being used in the universities to reduce VLA data, and it may be anticipated that this practice will continue. In order for external computing systems to be easily used, the software must be "exportable".

Software requirements are traditionally even more difficult to estimate than hardware needs. To an extent, much of the post-processing software needed for the VLBA has already been developed as a result of work at NRAO, Caltech, and Haystack with the MkII and MkIII VLBI systems, and in particular from the extensive post-processing package for the VLA. This is nicely

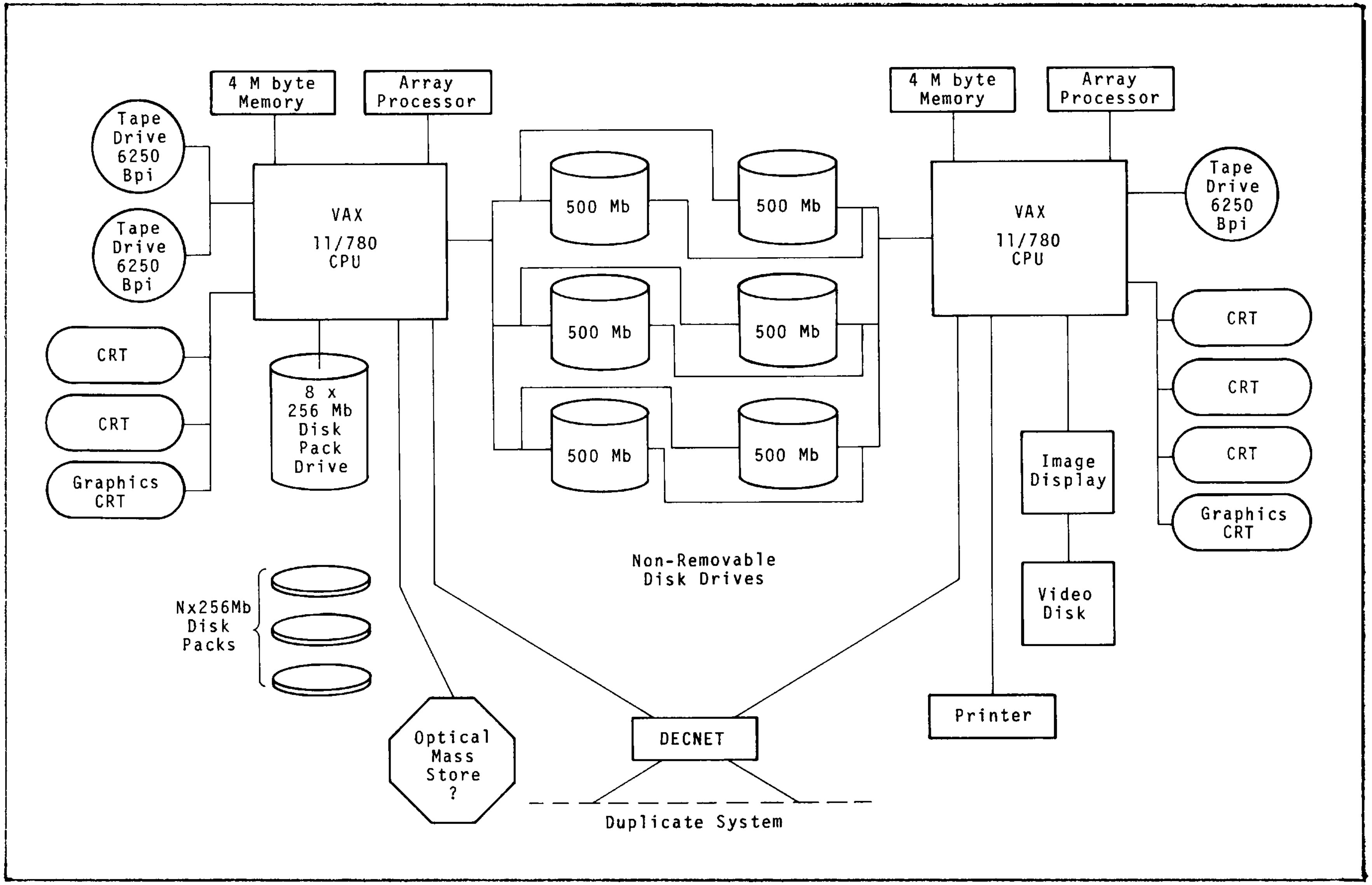

Fig. V-1. Block diagram showing post-processing system.

illustrated in Section III by the use of existing software to construct and compare images made from artificial and real data sampled with various possible VLBA configurations. Nevertheless, we have allowed for a further 10 man-years to write the specialized programs which we now foresee will be needed to exploit the capabilities of the VLB Array.

Software development is a continuing task. To minimize operating costs and to improve long term flexibility it is necessary to have an environment in which one can easily write high level and well structured software. This requirement is met by the VAX-type systems provided they have plenty of memory space and provided that the software for the specialized hardware is well modularized.

D. Image Reconstruction

A variety of techniques are used to reduce and even substantially eliminate the effect of ionospheric and tropospheric phase fluctuations. As described earlier, 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" or "hybrid-mapping" techniques.

The development of the self-calibration procedure has resulted in a major new tool for aperture synthesis which allows for the first time the construction of high resolution radio images, essentially free of tropospheric phase distortion. The technique is particularly important for VLB interferometers, where the tropospheric fluctuations above each antenna are completely independent, and where the small fringe spacings make it difficult to calibrate by the conventional phase-referencing technique (Readhead and Wilkinson 1978, Cotton 1979, Readhead et al. 1980, Schwab 1980, Rogers 1980, Cornwell and Wilkinson 1981).

Self-calibration is possible only when the number of measured fringe visibilities, N(N-1)/2 is substantially greater than the number of antennas, N-1, with unknown phase error. In this way, in an N element array, a fraction, (N-2)/N, of phase information is determined. A variety of algorithms have been devised which exploit the finite size and positiveness of radio sources to produce an image, even in the complete absence of phase data on the individual interferometer baselines. Similarly, a fraction, (N-3)/(N-1), of the total visibility amplitude information is available from an N element array with no knowledge of the gains of individual antennas. Figure V-2 shows the fraction of phase and amplitude data which can be obtained from an uncalibrated array of N elements. We see from Figure V-2 that in the VLBA about 80% of the amplitude and phase data can be regained by self-calibration of the complex gain of each antenna element. This gives an image roughly equivalent to that obtainable from a fully phase-stable 9-element (36 baseline) array.

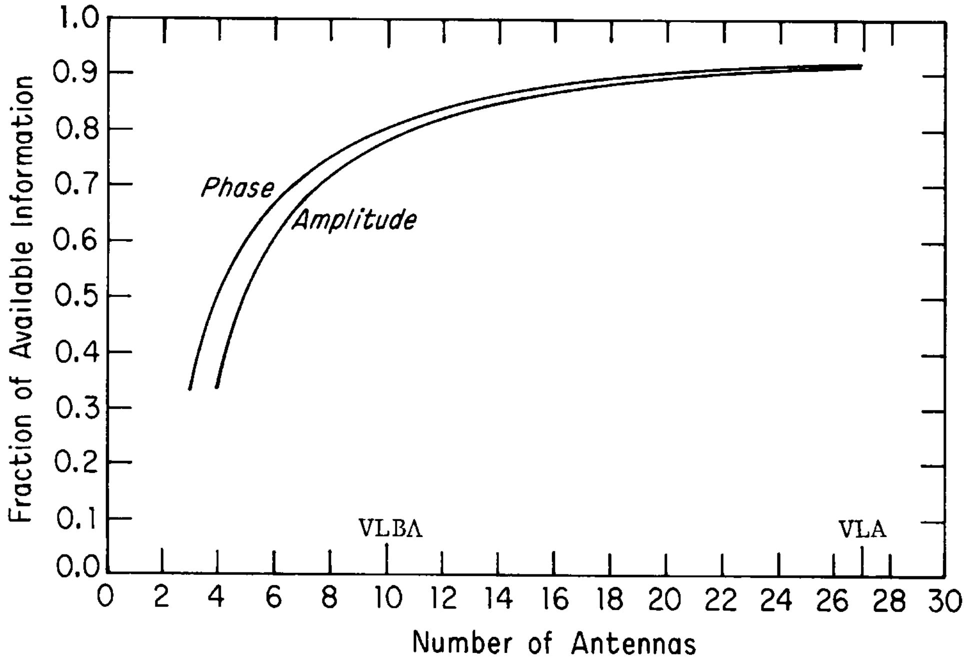

Fig. V-2. Fraction of amplitude and phase data obtained from self-calibrated data.

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 ∿ 20 minutes at 3 cm. Thus, in the case of the VLBA, self-calibration is effective only when the fringe amplitude on the individual baselines is greater than ∿ 100 mJy, and in the case of 43 GHz greater than ∿ 0.5 Jy. 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, Schwab 1982).

Nevertheless, even with existing algorithms, any moderately strong nearby compact reference source may be mapped using "self-calibration" techniques. The phase derived from these maps may then be used to calibrate the measured phase on a nearby unknown source too weak to be detected in a single coherent integration period. In this way the effective integration time may be extended to the whole 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 several degrees of any arbitrarily selected source position.

When calibrated in this manner, the VLBA is able to exploit the complete power of the aperture synthesis technique to reach sources far too weak to be observed on a single interferometer baseline during a typical coherence time of 10 to 20 minutes. The effective rms noise level of the self-calibrated VLBA shown in column 10 of Table I-1 is between a few hundred micro Jy and 1 milli Jy.

It must be noted, however, that while self-calibration can make a dramatic improvement in image quality in the presence of large measured phase errors, it is of no help in astrometric and geodetic observations where the true phase is used to derive the desired quantities of position and baseline. For these types of observations, phase referencing combined with measurements of the water vapor content must be used (See Section IV-G).

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VI. OPERATION OF THE VLB ARRAY

The VLB Array will be operated by the NRAO as a national facility, open to all qualified scientists from the United States and abroad. The Array will be operated in a manner similar to other NRAO facilities. That the various elements of this telescope system are geographically widely spread will introduce operational complexities but will not alter the basic concept of NRAO as a multi-site observatory. 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 VLBA operating staff, in much the same manner as for the VLA. To the user, the VLBA will be used in a similar manner as the VLA, and bear little resemblance to the current VLBI type of operation.

Ordinarily, the observer will not need to be at the VLBA 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 may wish to be present when the data are played back, and he will participate in the "post-processing" stage of analysis and image formation. In order to exploit favorable weather conditions for short wavelength observations, and to minimize the impact of equipment failures, scheduling will remain flexible. Once a program is approved, the VLBA staff will assume the responsibility for its successful completion within some reasonable period, but without a specific date and time being assigned in advance. This approach has been successfully used at other synthesis telescopes and optimizes the scientific productivity of the instrument. It is particularly appropriate for the VLBA as many of the sources of interest are variable, and there will be frequent proposals to observe them on short notice.

The normal operation of the VLBA is conveniently divided into five areas:

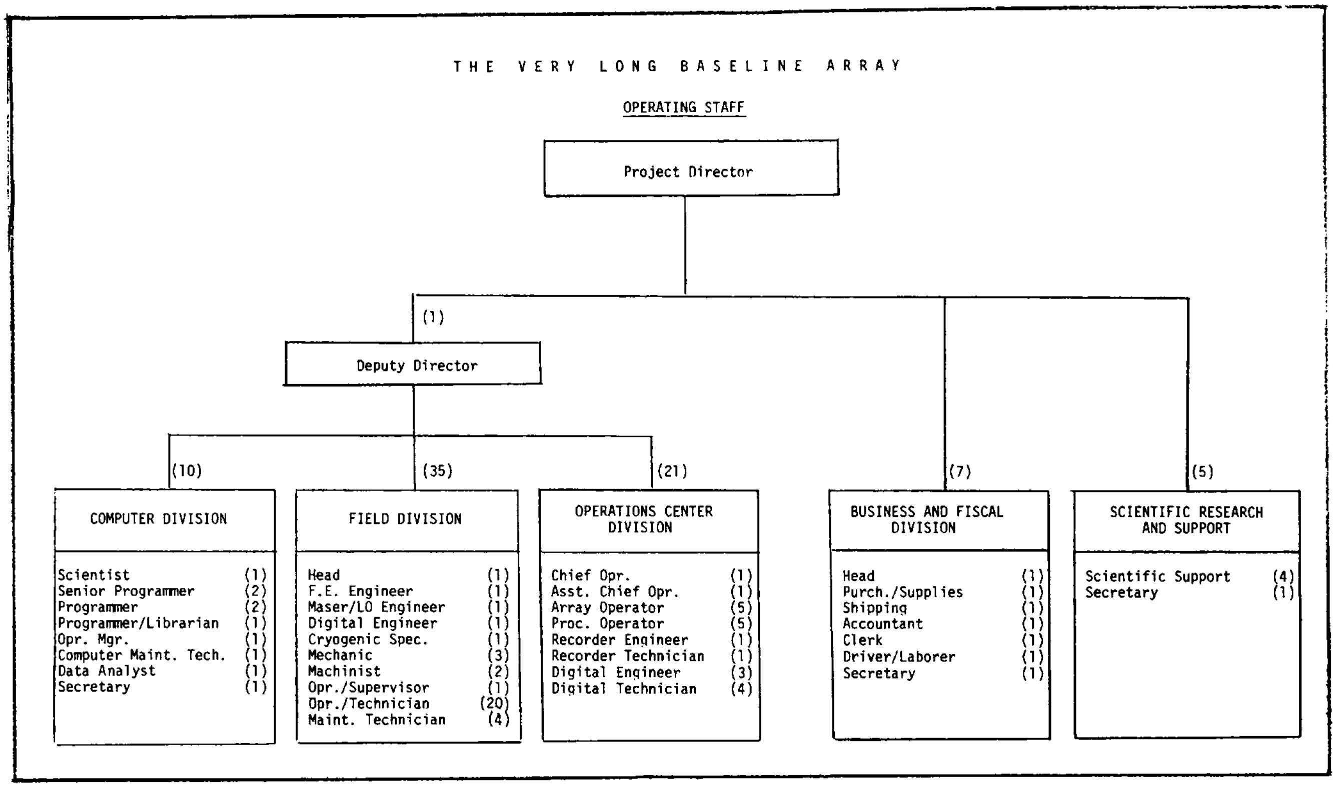
1) The operation of each telescope system under the control of an Operations Center;
2) Shipping the magnetic tapes to and from the Playback Center;
3) Routine maintenance and repair of malfunctioning equipment;
4) The correlation of the magnetic tapes in the multi-station processor to form each of the interferometer pairs;
5) Image formation and analysis.

Figure VI-1 shows an organizational chart for the VLBA operating staff. A total of 80 people are needed to operate the VLBA. These are divided among the Array Operations Center (AOC) and the various field stations. A small scientific group located at the AOC will have the responsibility for the 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 VLBA 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

Fig. VI-1



THE VERY LONG BASELINE ARRAY

OPERATING STAFF

COMPUTER DIVISION	
Scientist	(1)
Senior Programmer	(2)
Programmer	(2)
Programmer/Librarian	(1)
Opr. Mgr.	(1)
Computer Maint. Tech.	(1)
Data Analyst	(1)
Secretary	(1)

FIELD DIVISION	
Head	(1)
F.E. Engineer	(1)
Maser/LO Engineer	(1)
Digital Engineer	(1)
Cryogenic Spec.	(1)
Mechanic	(3)
Machinist	(2)
Opr./Supervisor	(1)
Opr./Technician	(20)
Maint. Technician	(4)

OPERATIONS CENTER DIVISION	
Chief Opr.	(1)
Asst. Chief Opr.	(1)
Array Operator	(5)
Proc. Operator	(5)
Recorder Engineer	(1)
Recorder Technician	(1)
Digital Engineer	(3)
Digital Technician	(4)

BUSINESS AND FISCAL DIVISION	
Head	(1)
Purch./Supplies	(1)
Shipping	(1)
Accountant	(1)
Clerk	(1)
Driver/Laborer	(1)
Secretary	(1)

SCIENTIFIC RESEARCH AND SUPPORT	
Scientific Support	(4)
Secretary	(1)

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, etc.). 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 transferred to the correlators some days to a week later. The output of the correlators and fringe fitting routines is then analyzed in a manner similar to 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.

A. The Operations Center

The heart of the VLBA is the Operations Center which has the responsibility for the control of each of the antenna elements and for playback of the magnetic tapes. It also provides the necessary post-processing facilities and services for image formation and for further analysis of the data.

The daily scheduling of the VLBA 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 Telescope Operators are on duty at all times. One is responsible for the control and operation of the antenna 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 Telescope Operators will also, when necessary, provide assistance in the operation of the off-line computing and image formation systems. A technician will be on duty or on call at all times in the case of instrumental failures at the Operations Center. Emergency repairs are kept to a minimum at the Operations Center with the use of self-checking circuits in the correlator, and by having available a sufficient number of spare playback racks.

Assuming that the VLBA 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. In planning the computing facilities and necessary staff, we have profited from the experience gained from the VLA operation. The techniques for 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 VLBA will exploit the full power of the instrument.

The staff for the Computer Section has two responsibilities. In addition to the development and maintenance of software, they are available to aid and advise the guest investigator in the use of the VLBA facilities. In particular, the Operations Manager supervises the flow of data, and has general responsibility for the operating of all computing facilities. A Data Analyst is available to work with each user to assist in the various stages of analysis. We also anticipate that many users will wish to continue their data analysis at one of a number of university facilities which are now becoming available, and the VLBA computer group will aid the user in transporting his data to other centers. They will also act as a clearing house for the interchange of new software developed among the university community.

The Operations Center also contains the engineering and technical staff which supports the operation of the Center and field sites, does maintenance, and develops new procedures and instrumentation.

B. Operation, Maintenance, and Repair at Observing Sites

Data are recorded at each of ten VLBA 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 telescopes, 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 each day.

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 a few kilometers or 1000 kilometers away.

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 has operated unattended for several days under computer control, or was 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 system operator at all present.

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

At each of the VLBA elements, a local staff averaging 2 full-time equivalent 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 person will work each day changing tapes and preparing them for shipment, performing routine inspection and preventive maintenance and servicing of operational equipment. A second person or locally available help will be on call for unscheduled first-level repair of malfunctioning equipment. For antennas located at or near other radio astronomy facilities or where there are other sources of technical support, only one full-time person will be required in support of the VLBA element. It is planned that a second full-time equivalent position will be used to support local help, so the work load can be shared among a number of different individuals.

Each of the local staff will be a trained technician proficient in the maintenance of analog and digital instrumentation. For preventive maintenance and minor 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 available at a Service Center 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. In general, complete modules will be replaced by the field personnel, and the defective unit will be returned to the Service Center for repair and calibration. These procedures may have to be modified, however, in the case of the most distant sites in Alaska and Hawaii, where stocks of spare parts may exceed those at continental sites.

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 one 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. The Data Acquisition Rack operates with only a small loss of signal-to-noise ratio in case of a VCR failure, and a complete spare DAR is available at each site in case of malfunction of the automatic cassette changer. Failure of an individual VCR is easily repaired by replacement with a new VCR.

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 Telescope operation.

Based on operating experience at the VLA, it is estimated that routine maintenance and servicing of each antenna will require the following support per year:

Antenna structural and mechanical	234	man-hours
Antenna servo cleaning and testing	12	" "
Antenna heating and air conditioning	12	" "
Cryogenics servicing	80	" "
Receiver system servicing	110	" "
TOTAL ROUTINE MAINTENANCE AND SERVICE	448	man-hours

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

Antenna structural and mechanical	137	man-hours
Antenna servo and drives	67	" "
Antenna electrical	52	" "
Antenna heating and air conditioning	15	" "
Cryogenics systems	160	" "
Receiver repair and modification	640	" "
TOTAL UNSCHEDULED REPAIR	1071	man-hours

System failures fall into one of two categories: critical components or modules that put the whole element out of operation, and those that only result in some system degradation such as the loss of one frequency or polarization, the monitor system, or the hydrogen maser. We have used experience gained with failure rates of various modules on the VLA to estimate the reliability of the VLBA system. The expected down time is very dependent on the access time to repair or replace malfunctioning modules or components. Assuming a mean access and repair time of 24 hours (VLB Array Memo No. 82), it is expected that all ten antennas will be operating with full capability for about 50% of the time and with degraded performance for 75% of the time.

C. Control, Monitor, and IF Data Distribution

The operation of the VLBA 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 VLBA element computers is via an enhanced 9600 baud leased telephone line. Observing programs originate at the Operations Center 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 VLBA 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 pair.

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 50 MHz (100 Mbps) bandwidth, a total of 48 cassettes per day per antenna will be required which, together with their shipping bin, weigh a total of about 50 lbs. At the 100 MHz (200 Mbps) bandwidth, twice this number are used, while for some spectral line observations, one bin of cassette 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 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. Location of Operation and Service Centers

The location of the central site will be determined by a number of factors. An obvious possibility is at the VLA site which is close to the geographic center of the array. Since much of the maintenance and support procedures at the VLBA will require staff and facilities comparable to those at the VLA, it may be attractive to operate and maintain both instruments from a common location, with a single large pool of technical staff. In this way, highly specialized, but infrequently used test and maintenance equipment may be kept to a minimum and required travel can be rotated among a larger group of people. Moreover, we have already noted the similar nature of the VLA and VLBA Post Processing, and considering also the many scientific problems that will use both instruments, it is clear that the VLBA and VLA Post Processing needs may be most effectively supported by a single group of scientists and programmers.

On the other hand, analysis of expected antenna down times shows that the overall VLBA performance is heavily dependent on the time required to repair critical components, and if this exceeds, on the average, 2 days, then it will be difficult to keep all ten elements operating at full capability. Thus the time required to travel between the Service Center and array elements, as well as the shipping time required to replace defective modules, needs to be kept to a minimum. This suggests that the Service Center be close to a major center of transportation. Similarly,the time and cost required to ship magnetic tapes between the antenna elements and the Playback Center also needs to be kept to a minimum, again suggesting a location near an urban transportation hub.

We are also aware of the important intangible benefit of co-locating observers, engineers, programmers, and other scientific and support staff, as well as the attraction of a centrally located university environment.

E. Use of Other Antennas with the VLBA

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 fur 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. The increased sensitivity is particularly important in studying weak short-term transient phenomena such as nova outbursts and flares in galactic stellar radio sources, and in using weak reference sources to calibrate the atmospheric phase instability, clock, and fringe rates.

As discussed in Section III, it is planned to locate one of the VLBA elements 50 to 100 km from the VLA. This allows a choice of the following operating modes dictated by the needs of the particular scientific investigation.

a) The VLBA and the VLA may be used independently on separate scientific programs.

b) One element of the VLBA can be used in conjunction with the VLA to effectively double the resolution of the VLA. At the same time, one VLA antenna then becomes available to replace the "borrowed" VLBA antenna, since the VLA correlator system is only able to handle a total of 27 antennas.

c) One VLA antenna can be used together with the VLBA to form an 11-element array with significantly improved performance for larger sources, and only slight degradation of the normal VLA performance.

d) The entire VLA and VLBA may be used together for investigations which require a wide range of angular resolution.

Other U.S. Antennas. Other antennas such as those at the Haystack Observatory, in Green Bank, and at the Owens Valley Observatory may also be used to further improve the sensitivity and image quality at long wavelengths.

Antennas from the NASA Deep Space Net with their sensitive radiometer systems are also used for VLBI, and 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.

Baselines between the VLBA 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.

Canadian Antennas. Canadian astronomers are developing plans for a "Canadian Long Baseline Array" (CLBA). As it is currently conceived, the CLBA will be a linear array of 8 dishes, with a shortest operating wavelength of 1.3 cm. The CLBA will have less resolution than the VLBA and, due to the linear configuration and northerly location, will not perform well over the southern half of the visible sky. Because of the somewhat closer regular spacings of the antenna elements, the CLBA will give a better quality image at high declinations for sources intermediate in size between those appropriate to the VLA and VLBA.

Combined, the VLBA and CLBA will have a substantially improved sensitivity and image quality due to the greater number of antennas and their broad geographic distribution. Although there are no plans for a formal combination of these proposed two national facilities, continuing informal discussions between the design groups in both countries should insure the compatibility of instrumentation and future opportunity for close collaboration.

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. Together with the Jodrell Bank Multi Element Radio Linked Interferometer (MTRLI), these facilities are complementary to the VLBA and when used in conjunction with the VLBA, allow a more detailed investigation of intermediate size sources than is possible with the VLA and VLBA.

A dedicated 32m VLB antenna is currently being built near Bologna, Italy, and a second one is planned for Sicily. Although considerably smaller than other European antennas which have been used for VLBI, the Italian antennas will not be in great demand for other research programs and are expected to be available for use with the VLBA to the benefit of both European and American observers. We have been cooperating closely with Italian scientists and engineers in the planning and development of the Italian VLBI system and anticipate future fruitful collaboration.

Use of the VLBA 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. We shall continue to share our plans and progress with our foreign colleagues, by the distribution of technical reports, and where appropriate, continue to provide aid and advice in the development of new instrumentation.

It is clear that the global telescope system that will be possible by combining the VLBA with antennas in Europe, Asia, Australia, and the rest of North America not only provides a scientific instrument of extraordinary power, but an exciting opportunity for fruitful international collaboration as well.

Literature Cited

Swenson, G., 1980, VLB Array Memo No. 24.

VII. COST ESTIMATES

Although the VLBA is a complex sophisticated system, it 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 (1982).

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 1982 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 price for a VLA type antenna modified to meet the specifications discussed in Section III-C has been determined from the known VLA costs 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 $585 K made necessary by the various modifications which are required, and $115 K for tooling costs.

In this way we estimate a total cost of $17,490 K for ten antennas, delivered over a two year period.

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 partially 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 used the cost of modified VLA type antennas. We anticipate, however, that the Array will be built using the wheel-and-track antenna concept, and we have therefore included the $950 K necessary for the full engineering design of this new antenna. However, the total cost of design plus fabrication of the 10 wheel-and-track antennas should not exceed the $17,490 K estimated cost of the modified VLA antennas, and is expected to give improved performance at the shorter wavelength. In addition to the basic antenna structure, the non-manufacturer supplied items in Table VII-1 are added.

TABLE VII-1

ADDITIONAL ANTENNA COMPONENTS ($K)

1)	Feed mounting ring (vertex room cover) and feed support towers	12 K
2)	Subreflector and support structure	22
3)	Focus and subreflector rotation mount	25
4)	Electrical installation	4
	TOTAL Auxiliary Antenna Equipment	63 K

To this must be added a non-recurring engineering and tooling cost of 90 K.

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

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

Because most of the individual receiver elements (e.g. cooled FET amplifiers, 1.3 and 0.7 cm masers) have already been developed or are part of on-going programs at the NRAO, we anticipate that only a further $150 K of non-recurring engineering and prototyping will be required to develop the complete 10 band low noise receiver system.

4. Hydrogen Maser. We have obtained cost estimates for hydrogen masers from three potential suppliers. One supplier offered no quantity discount and did not consider selling the physics package alone. A second supplier estimated a 25% cost saving if 10 units are procured at the same time, and a

TABLE VII-2

FEED SYSTEM ($K)

Prime Focus Feeds		
327 MHz	2 K	
610	2	
SUBTOTAL		4 K
Secondary Focus Feeds		
1.5 GHz	13 K	
2.3	11.7	
5.5	3.6	
8.4	1.8	
10.7	1.8	
15	1.5	
22	1.5	
44	1.5	
SUBTOTAL		36.4 K
Polarizers		8
S/X Band Dichroic		10
Windows, Waveguides, etc.		4
Measurement and Test		20
TOTAL Feed System (per ant.)		82.4 K
Non-recurring Engineering and Development		
Materials		150 K
Labor		110

TABLE VII-3

FRONT END COSTS

Cryogenic Costs		Materials $ K	Labor (Man Months)	
20° K Cryogenics				
Refrigerators	6x6 K	36 K		
Compressors	3x8 K	24		
4° K Cryogenics				
Refrigerator and Compressor		50		
Helium Lines				
4 K and 20 K Systems		20		
Total Cryogenics				130 K
300° K Front End Costs				
327 and 610 GASFETS Dual Pol.	4x1 K	4 K	2	
Weatherized Package	2x0.5 K	1	2	
Buffer Amplifiers	4x0.25 K	1	2	
Assembly		16		
Total 300 K Front Ends				22
20° K Front End Costs				
Dewar, Input Lines, etc.		20 K	6	
GASFET Amplifiers at 1.5, 2.3, 5.5 8.4, 10.7 and 15 GHz 6 frequencies x 2 Polarizations		12	6	
Mixer/IF Amplifiers (12)		12		
Local Oscillator System		20	9	
Assembly		56		
Total 20 K Front Ends				120
4° K Front End Costs				
Dewar, Input Lines, etc		20 K	6	
Dual Channel Masers 22, 43 GHz		20	12	
Solid State and Klystron Pumps		20		
Local Oscillator System		10	6	
Mixer/IF 4x2.5 K		10		
Assembly		64		
Total 4 K Front Ends				144
Miscellaneous				
System Noise Calibration		15 K		
Phase Calibration		15		
Power Supplies, etc.		10		
Total Miscellaneous				40
TOTAL FRONT END SYSTEM PER ANTENNA				456 K

further reduction of $75 K per unit if the receiver/synthesizer system is omitted. The third and lowest estimate is based on a formal quotation for purchase of one unit in 1982 either with or without the receiver system, but this is from a supplier that has not yet produced a commercial grade product.

We have also considered developing the maser oscillators in house, but have rejected this as being impractical. However, since we are able to build the receiver/synthesizer system for about 1/2 of the cost of a commercial supplier, we intend to purchase the "physics package" alone from an outside supplier. We estimate the cost of the hydrogen maser oscillator in Table VII-4 below.

TABLE VII-4

Hydrogen Maser Physics Package	210 K
Receiver-Synthesizer (Materials)	18
Receiver-Synthesizer (Labor)	22
TOTAL Hydrogen Maser (per ant.)	250 K
Receiver Development	30 K

5. The Record System. The cost of the data acquisition system is based on using modified Video Cassette Recorders and automatic Cassette Changer. One spare rack each complete with changer, recorders and electronics is included at each station. Although only one record rack per station is required for normal operation, the second recorder allows for uninterrupted operation in case of failure of the electromechanical cassette changer, or in special cases to record with twice the normal bandwidth.

The data acquisition system consists of the IF system, the Data Digitization Electronics, and the Record Racks. The cost is summarized in Table VII-5 below.

TABLE VII-5

COST OF DATA ACQUISITION SYSTEM

IF Switching Matrix	5 K	
IF Processor	36	
IF to Video Converters	13	
SUBTOTAL IF SYSTEM		54 K
Sampler	2 K	
RS232 Distributor	1	
Delay Calibrator	3	
Rack, Power Supplies, Connectors, etc.	10	
5 MHz Distributor	2	
Assembly (8 man months)	21	
SUBTOTAL DATA DIGITIZATION ELECTRONICS		39
20 Video cassette recorders	16 K	
2 Data Acquisition Racks with electronics and spares	43	
Assembly and integration (0.25 man yrs.)	7	
SUBTOTAL RECORDER RACKS		66
TOTAL DATA ACQUISITION SYSTEM (Per. Ant.)		159 K

We estimate that the non-recurring engineering and development cost of the Record/Playback Rack as $130 K.

6. Control and Monitor System. Each antenna element has its own minicomputer system which receives control information from the Array Control

Computer and transmits data to monitor the front end and record system performance as well as meteorological data. The cost of the Array Control Computer is given in Section VII.B.2. The per antenna cost is shown in Table VII-6 below.

TABLE VII-6

COST OF TELESCOPE CONTROL AND MONITOR SYSTEM

Telescope Control Computer (Includes 128k byte memory, two 10M byte disks, tele-typewriter, CRT, and manufacturer's operating system and communications software)	30 K
Interface Equipment to Antenna and Receiver (Three data-sets and serial interface to computer)	5
Fringe Verification Buffer (256k byte memory)	3
Communication Equipment - Modems	5
Dedicated Test Equipment	5
Spare Computer Parts	6
Installation Cabling ($1,000) and 1/2 man-year check-out labor	16
TOTAL PER ANTENNA	70 K

7. <u>Site Development</u>. The following items are included at each of the Array Stations.

a)	Site acquisition and grading	5 K
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 $70 per sq. ft.	98

c)	Telescope foundations. Cost varies from site to site depending on terrain, etc.	50 K
d)	Emergency generator. 30 KVA to stow antenna and keep cryogenics running.	20
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 $30 per foot including typical excavation and grading costs.	12
f)	Electrical power installation. 400-ft from commercial power. Underground installation at $15 per ft.	6
g)	Water supply and disposal system	10
h)	Furniture	6
i)	Maintenance equipment including small 4-wheel drive vehicle with snow plow, tools, service elevator.	35
j)	Fence (approx. 1200 sq. ft.) @ $12 per sq. ft.	12
k)	Soil Tests	6
ℓ)	Design Fee (Engineer-Architect)	25
	TOTAL SITE DEVELOPMENT (per site)	285 K

Of this amount, 30 K is needed for site selection and the initial predevelopment activities.

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

a)	Test equipment and miscellaneous tools	35 K
b)	Water vapor radiometer and other meteorological sensors.	35
c)	Timing equipment. Rubidium clock and timing receivers.	40

d) Test and Installation of all station feed and electronic systems. 10

TOTAL OTHER EQUIPMENT (per antenna) 120 K

B. Operations Center

1. The Playback Processor consists of the control computer, the tape playback system, and the correlator. The cost estimate in Table VII-7 is based on the VLA type recirculating correlator.

TABLE VII-7

PLAYBACK PROCESSOR (K$)

Computer System		
CPU with 2 Mbyte Memory, 100 Mbyte Disk, 800/1600 BPI Type Drive, Operations Software	$ 180 K	
2 Tape Drives 6250 BPI	67	
Array Processor, 64 K Word Memory	73	
4 Text, 1 Graphics Terminals	10	
Cabinets, Power, Furniture	10	
Software Development (3 man years)	96	
Installation (0.1 man years)	4	
Subtotal Computer		440 K
Tape Playback Unit		
22 Playback Racks	429 K	
218 Video Cassette Recorders	175	
Assembly (2 man years)	64	
Subtotal Tape Playback Unit		668
Correlator System		
Correlator Hardware	530 K	
Support Hardware	200	
Design (3 man years)	96	
Assembly (2-1/4 man years)	72	
Subtotal Correlator System		898
System Integration (2 man years)		64
TOTAL PLAYBACK PROCESSOR		2008 K
Engineering and Design (∿ 2 man years)		60 K

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 station computers will be through the Central Array Control Computer. An extra Telescope Control Computer is included at the Operating Center for programming support. Cost of the Control System is:

Array Control Computer	204 K
(Includes 512k byte memory, two 1600/6250 bpi tape drives, two 122M byte disks, teletypewriter, printer, card reader, 2 graphics and 8 text CRT's, and manufacturer's software for operating system, communications, and FORTRAN)	
Communication Equipment - Modems	15
Telescope Control Computer (For software development)	35
Software (16 man-years)	512
TOTAL Control and Monitor System Central Control	766 K

Post-Processing. Post-processing requirements are outlined in Section V-C 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:

4	VAX-11/780 with 2 Mbyte memory, accelerated I/O	850 K
4	Additional 2 Mbyte memory	72
	Disks and Controllers (10 G Bytes instantaneous, 10 G Bytes removable)	936
4	Array Processors	310
2	I^2s Image Displays	110
2	Printers	30
14	CRT terminals (10 text, 4 graphics)	30
6	High Density Tape Drives	170
	Optical Disk	40
	Video Disk	20
	DECNET System (incl. software)	32
	Misc.	50
	TOTAL Post-Processing Hardware	2650 K
	Post-Processing Software Development (10 man years)	320 K
	TOTAL POST-PROCESSING COST	2970 K
	Initial system specification and development	60 K

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. 20,000 sq. ft. are required at $80 per sq. ft. which includes design fee and utility service connections at an existing operating site. Site development is $50 K.

CONTROL BUILDING	1650 K

4. Magnetic Tapes. At the normal continuum bandwidth of 50 MHz, 42 tapes per day are used at each station. For most spectroscopic applications, the number of tapes used will be very much less, while for some continuum observations, two recorders will be used to increase the bandwidth. We have allowed for a 60 day supply of tapes at an average of 42 tapes per day to arrive at a cost estimate of tapes and shipping bins.

MAGNETIC TAPES AND BINS	450 K

5. Other Operating Equipment. Funds are allocated for general and digital test equipment and for a precision Cs flying clock.

OTHER OPERATING EQUIPMENT	200 K

6. Spare Parts. 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 or whose failure will not bring down an entire antenna system (e.g. a single receiver module) will be stocked primarily at the Service Center. We estimate the following costs for spare parts to keep all 10 antennas fully operational for more than half of the time, and for more than 75 percent of the time with some system degradation possible (i.e. loss of one frequency).

TABLE VII-8

SPARE PARTS INVENTORY

Antenna structure and servo	330 K
Cryogenics	160
Receiver	700
Hydrogen Maser	200
Playback System	125
Computers	50
TOTAL SPARE PARTS	1565 K

VLB ARRAY

COST SUMMARY (K$)

Per Station Systems		
Antenna	1654	
Aux. Antenna Equipment	63	
Feeds	82	
Front Ends	456	
Data Acquisition System	159	
Control and Monitor System	70	
Frequency Standard	250	
Site Development	255	
Other Equipment	120	
Total per station	3109	
SUBTOTAL 10 STATIONS		31090
Central Laboratory		
Control System	736	
Playback Processor	2008	
Post-Processing (incl. software)	2970	
Building and Site	1650	
Operating and test equipment	200	
Spares	1565	
Tapes and bins	450	
SUBTOTAL CENTRAL LABORATORY		9579
Engineering and Design		
Antenna	950	
Aux. Antenna Equipment	90	
Feeds	260	
Control	30	
Front End	150	
Record System	130	
Site Evaluation	300	
Frequency Standard	30	
Processor	60	
Post-Processing	60	
SUBTOTAL ENGINEERING AND DESIGN		2060
PROJECT MANAGEMENT		2000
CONTINGENCY		6000
TOTAL		50729

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 complete prior to initial 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 VII-1.

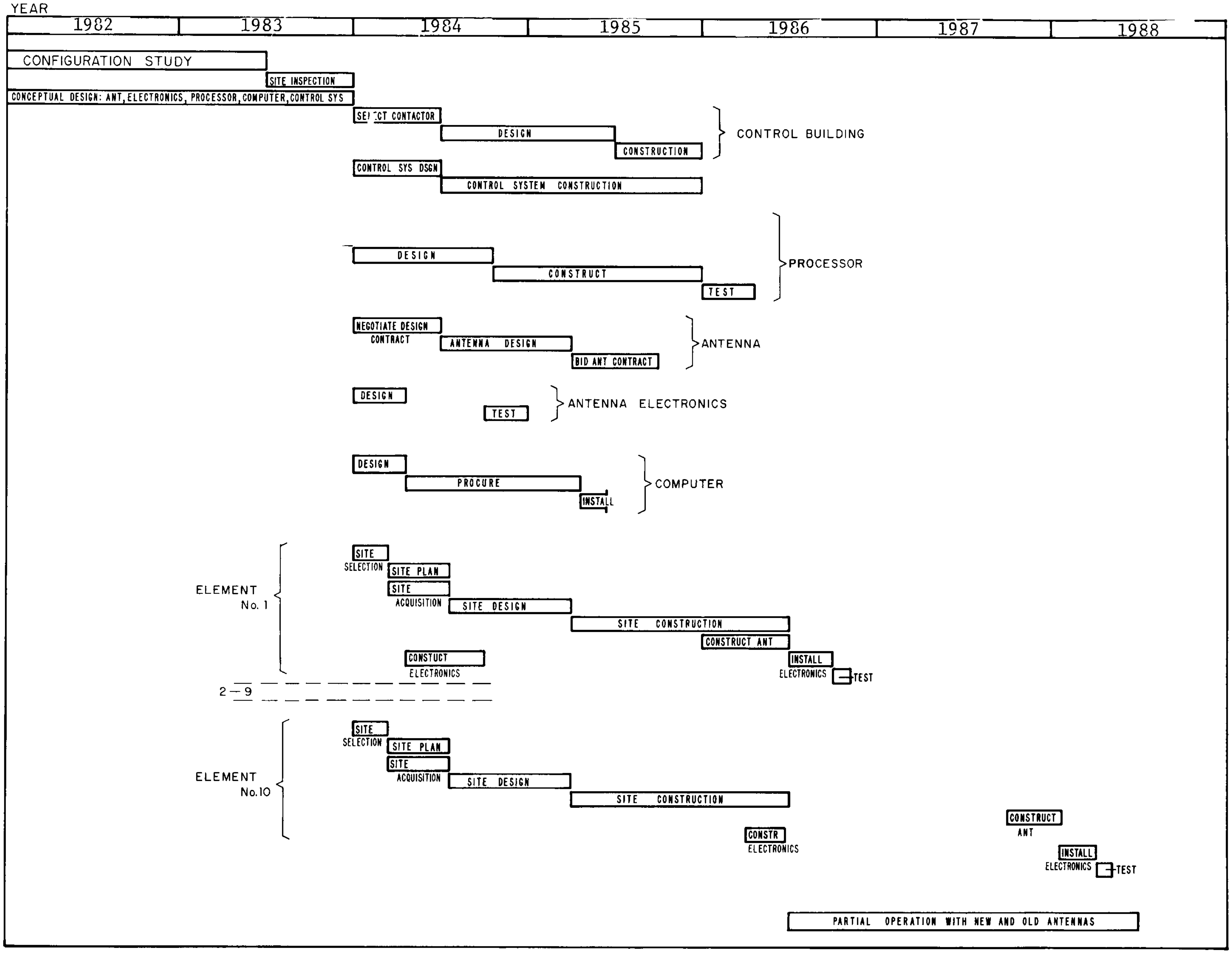
D. Operating Cost

Our estimate of the annual operating cost is based primarily on the operating costs for similar items at the VLA with particular attention to 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).	$2100 K

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 to five days between any points in the USA including Alaska and Hawaii. The cost for a 50-lb surface shipment is between $5 and $20 depending on distance. Air shipment to Hawaii and Alaska costs $60 for each 50-lb. parcel. Assuming 50-lbs. per day in each direction between each of the 10 Array Stations and the AOC at an average of $23 per 50 lbs for 300 days per year is about $140 K. International shipments add another $30 K. Additional shipping costs between the Service

VLBA CONSTRUCTION PLAN



Centers and the sites, shipments from suppliers, and shipments of data to visiting observers is estimated to add another $30 K.

Total Shipping Costs	$ 200 K

Travel. It is anticipated that major repair tasks will require dispatch from a Service Center of 1 or 2 technicians or mechanics and that each site will require such service approximately 8 times per year. Assuming four days of travel per repair job at $50 per day and $800 per trip gives $120 K. Additional travel to support guest investigators, professional meetings, visits to suppliers, etc. will cost $60 K.

Travel	$ 180 K

Communications. The 9600 baud enhanced leased lines from the AOC to each site, including Alaska and Hawaii, required for the communications link for control and monitoring, as well as real time fringe verification, is estimated at $156 K per year. This may be reduced, particularly on the Hawaii and Alaska circuits if satellite linked facilities become available at lower cost. An additional $34 K is estimated for conventional telephone service.

Communications	$ 190 K

Utilities. Each site uses about 60 KVA and the AOC about 150 KVA, corresponding to a total average power consumption of about 600 KW. The average cost of electrical power in the United States is $0.07 per KWH, giving a power cost of $400 K per year.

Utilities	$ 400 K

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 replacements such as mechanical and electrical equipment are estimated to cost $70 K per year, electronic parts $120 K, computer service $240 K, and miscellaneous business supplies and publications costs $150 K.

Materials and Services	$ 580 K

New Equipment. $500 K 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 the operation.

New Equipment	$ 500 K

TABLE VII-9

SUMMARY OF ANNUAL OPERATING COSTS ($K)

Staff (80 people)	$2,100
Shipping	200
Travel	180
Communications	190
Utilities	400
Materials and Supplies	580
New Equipment	500
TOTAL Operating Cost	$4,150

APPENDIX I

MEMORANDA AND REPORTS

1	VLBA Design Study	5/22/80	K. Kellermann
2	Antennas for the VLB Array	6/09/80	J. Findlay
3	A 25-m Radio Telescope Design for the VLB Array Project	7/07/80	W-Y. Wong
4	VLBI Array Computer Usage	7/03/80	W. Cotton J. Benson
5	Sensitivity of a Partially Coherent Array	8/01/80	B. Clark
6	VLBA Cost Estimates	4/16/80	M. Balister
7	Proposed Receiver for the VLB Array	8/14/80	M. Balister
8	Cost Estimate for the Wong Antenna	8/14/80	W-Y. Wong
9	Balsa-Wood-Core Test Plates	7/17/80	W-Y. Wong
10	Notes on Visit to ASULAB	7/09/80	K. Kellermann
11	Digital Data Transmission System	7/24/80	S. Weinreb
12	VLBA Design Study	8/08/80	W. Horne
13	Site Development Program	8/21/80	G. Peery
14	Antenna Construction Program	8/22/80	K. Kellermann
15	Antenna Design Details	7/24/80	W-Y. Wong
16	Masers and VLB Array	8/15/80	M. Balister
17	VLB Array - Comments	8/15/80	A. R. Thompson
18	Computer Usage	8/28/80	W. Cotton J. Benson
19	Computer Needs	8/28/80	C. Walker R. Burns
20	Construction Plan	8/29/80	H. Hvatum

21	Preliminary VLA Spectral Line System	6/01/75	A. Shalloway
22	A Possible Feed System for the VLBA Antenna	8/26/80	P. Napier
23	Alternative Data Communication Systems	9/01/80	G. W. Swenson, Jr.
24	Automatic VLBI Observing	9/01/80	G. W. Swenson, Jr.
25	Self-Calibration with a Low SNR	6/03/80	F. Schwab
26	VLBA Receiver	5/20/81	M. Balister
27	Size of Antenna Elements for the VLB Array	7/16/81	K. Kellermann
28	Tape Recording Systems for the VLB Array	7/16/81	K. Kellermann
29	Multiple Processor Sites for the VLB Array	7/24/81	K. Kellermann
30	A Single Carrier Satellite LO System	8/01/81	B. Clark
31	Questions to be Addressed	10/19/81	K. Kellermann
32	Planning Committee	10/21/81	K. Kellermann
33	VLBA Working Groups	10/26/81	K. Kellermann
34	VLB Array - Review of Design Study	10/26/81	K. Kellermann
35	Questions to be Considered for the VLBA	10/29/81	K. Kellermann
36	Distribution List	11/02/81	H. Hvatum
37	VLBA Proposal	11/02/81	H. Hvatum
38	Critique of Feb. 1981 VLBA Design Study	11/13/81	R. Hjellming
39	Remarks on the VLBA Report	11/10/81	B. Clark
40	Report on 11/16/81 VLBA Meeting	11/17/81	K. Kellermann
41	Possible Array Funding Plan	11/25/81	K. Kellermann
42	Correlator	12/04/81	B. Clark

42	Dec. 18, 1981 Meeting	12/16/81	K. Kellermann
44	Recording Systems	12/17/81	R. Escoffier
45	Dec. 18 Meeting Notes	12/23/81	K. Kellermann
46	Draft of Configuration Section	12/31/81	C. Walker
47	Data Storage Requirements	12/31/81	C. Walker
48	Receiver Block Diagram & Test Equipment Budget	1/04/82	C. Moore
49	Studies of Array Dynamic Ranges	12/01/81	R. Linfield (Cal Tech)
50	Cost Estimate-Antennas	12/04/81	W. Horne
51	Monitor and Control Chapter	1/12/82	S. Weinreb
52	Front End System	1/11/82	M. Balister
53	Suggested Numbers of Spare Modules for the VLB Array	1/07/82	A. R. Thompson
54	Agenda, Meeting Jan. 26, 1500 EST	1/19/82	K. Kellermann
55	Hardware Cost Estimate for Receiver Section of H-Maser Frequency Standard	1/20/82	R. Mauzy
56	Recording System - Draft #2	1/20/82	R. Escoffier
57	Data Digitization Electronics	1/20/82	R. Lacasse
58	Front End Alternatives	1/21/82	C. Moore
59	Feed System	1/11/82	P. Napier
60	Alternative Data Digitization Electronics	1/22/82	R. Lacasse
61	Playback Correlator System	1/26/82	B. Clark
62	Local Oscillator System	1/15/82	S. Weinreb C. Moore
63	Front End System - Further Comments	1/19/82	C. Moore
64	Recording System - Draft #3	1/27/82	R. Escoffier
65	H Maser Cost Estimate	1/28/82	C. Moore

66	General and Digital Test Equipment	1/28/82	R. Lacasse
67	Preliminary Cost Summary - Construction	1/29/82	K. Kellermann
68	Correlator Cost	1/29/82	B. Clark
69	Spare Parts	2/04/82	K. Kellermann
70	Agenda for Feb. 9th VLBA Meeting	2/05/82	K. Kellermann
71	Cost Estimates - Construction (First Draft)	2/05/82	K. Kellermann
72	Post Processing Requirements	2/03/82	R. Ekers
73	Correlator Design	2/04/82	M. Ewing (Cal Tech)
74	Cost Estimate - Construction (Second Draft)	2/12/82	K. Kellermann
75	Correlator System - Condensed Version	2/16/82	B. Clark
76	Comments on S/X Receivers and Recording System	2/08/82	A. Rogers Hinteregger (Haystack)
77	Additional Comments on Local Oscillator System	2/03/82	C. Moore
78	Recording System - Draft #4	2/22/82	R. Escoffier
79	Notes on the Planning Committee Meeting, 2/16/82	3/01/82	K. Kellermann
80	VLBA Element Operating Probability Using VLA Reliability Data	3/05/82	J. Campbell
81	Frequency Protection for the Transcontinental Radio Telescope	3/01/82	A. R. Thompson
82	Global Fringe Search Techniques for VLBI	4/01/82	F. Schwab
83	VLBA Meeting	4/15/82	K. Kellermann
84	A Design Study for a Dedicated VLB Array	5/01/82	R. Mutel R. Gaume

APPENDIX II

FREQUENCY PROTECTION

1. Harmful Interference

Very long baseline interferometry is less sensitive to interference than other observing techniques used in radio astronomy. Three effects of the long antenna spacings help to suppress the response to interference.

(i) The sidereal motion of cosmic sources gives rise to very high fringe frequencies, and signals from transmitters that do not show this motion are highly attenuated in the data analysis.

(ii) The time delay differences for signals that do not arrive from the direction of observation can substantially decorrelate unwanted signals.

(iii) The spacings of the antennas are large enough that an unwanted signal is unlikely to be simultaneously present at a harmful level at two antennas unless it originates in a satellite.

Thus it can generally be assumed that the interference to VLBI systems does not produce correlated components at the correlator inputs. The mechanism by which the performance of the radio telescope is degraded is the addition of uncorrelated power at the antennas which effectively increases the noise level. The harmful limit for such interference has not yet been studied in detail, but is estimated to be approximately 20 dB below the system noise power in a receiving channel. In estimating the flux density corresponding to this harmful limit, the probability of interference from satellites should be included. It is therefore appropriate to consider a sidelobe gain of +10 dB which typically occurs 7.6° from the main beam. The harmful flux density, S_I, is then given by

$$S_I = \frac{4\pi k T_s B f^2}{10^3 c^2} \ \mathrm{Wm^{-2}}$$

where $k = 1.38 \times 10^{-23}$ $\mathrm{JK^{-1}}$, T_s = system noise temperature (K), B = receiving bandwidth (Hz), f = observing frequency (Hz) and $c = 3 \times 10^8$ $\mathrm{m\ s^{-1}}$.

2. Observing Bands and Frequency Allocations

Table AII-1 lists the ten frequency ranges over which the VLBA will be tunable. It also lists the U.S. allocations to radio astronomy within these tuning ranges, the sharing services and the allocations in adjacent bands in cases where air-to-ground or space-to-earth transmissions may occur. The final column of Table 1 gives the estimated harmful interference levels, S_I, calculated from the formula above. The bandwidth, B, is that of the radio astronomy band, or 100 MHz, whichever is the smaller. Note that the levels are 28 to 41 dB higher than the corresponding values for single-antenna systems given in CCIR Report 224-5 (CCIR 1982). All except two of the VLBA tuning ranges contain bands that are allocated to radio astronomy within the U.S., and the primary mission of the instrument can be accomplished within these bands.

The two tuning ranges without a radio astronomy allocation are 2200-2300 MHz and 8400-8500 MHz. Both of these contain allocations to deep space communications, and VLBI observations have been made in these deep space bands for over a decade without serious interference. This practice arose because the large antennas and sensitive receivers that were developed for deep space projects were from time to time available for radio astronomy. The VLBI geodetic program that has been developed within NASA makes use of the deep space bands, and it would clearly be useful to include within the VLBA the capability to compare the positions of the antennas with those of antennas in the geodetic network.

The VLBA will have the capability of recording up to 100 MHz of input signal bandwidth for limited periods, and up to 50 MHz for general operation. There are numerous options in the way this can be used. For example, the system can record a full 100 MHz of continuous input bandwidth, or two 50 MHz bands at the same center frequency with opposite polarizations. The IF sections of the receiving system contain filters to select bandwidths that decrease by factors of two from 100 MHz down to 100 kHz. Each of the tuning bands of the VLBA listed in Table 1, except for the two with deep space bands, contains from 3.9 MHz to 1000 MHz of spectrum with primary allocation to radio astronomy. The flexibility provided by the IF filters will therefore make it possible to observe entirely within the radio astronomy bands, or to extend outside of them to obtain enhanced sensitivity as the spectrum usage permits. The narrow receiver bandwidths will be used mainly for spectral line observations in the lines that radiate by maser action. The most important of these are lines on those of the OH radical at 1612, 1665, 1667, and 1720 MHz, H_2O at 22.235 GHz and SiO at 43 GHz. All of these are provided with some degree of frequency protection.

Some points specific to certain observing bands should be noted. The lowest frequency band will probably present the greatest difficulty with regard to interference. The 322-328.6 MHz band has an international allocation to radio astronomy that is not implemented within the U.S. Nevertheless, general experience indicates that parts of this band may be usable for radio astronomy, depending upon the antenna location. Should further tests show the interference level in this band to be unacceptable, the 406.1 to 410 MHz band may be a viable alternative. However, this shared band is heavily used in some areas by the fixed communications service. The low frequency band of the VLBA is the least critical to the overall success of the project, and the investment in receiving components is relatively small because the input stages are operated at ambient temperature and the feed structures are simple.

In the 4950-4990 MHz band, protection to radio astronomy is provided in the vicinity of certain observatories, several of which are amongst sites considered for VLBA telescopes.

In the 10.6-10.7 GHz band there is sufficient bandwidth allocated to radio astronomy on a primary-shared basis to allow use of the full 100 MHz recording bandwidth. As development occurs in the 10.6-10.68 GHz band, the service sharing with radio astronomy is expected to be mainly the Digital Electronic Message Service (Moffet 1981). It is understood that under the proposed FCC rule making currently in progress radio astronomy will receive no protection in this band in the vicinity of the 100 most populous U.S. cities. The proposed limit on the e.i.r.p. in the 10.6-10.68 GHz band is +40 dBW, which requires an antenna gain of 43 dB (FCC 1981). In the unlikely event that a VLBA antenna were situated within the main beam of such a transmission (which would probably be an internodal link), the separation required to avoid interference at the harmful level estimated in Part 1 of this Appendix is 70 km. The separation required for the lower transmitting gain likely to be used for node-to-user communication is estimated as 45 km.

In the 15.35-15.4 GHz and 23.6-24.0 GHz bands, radio astronomy shares only with passive services so the full recording bandwidth can certainly be used. There should also be no problem in the 42.5-43.5 GHz band since none of the sharing services involve transmission from aircraft or from space.

REFERENCES

CCIR, Characteristics of the Radio Astronomy Service and Interference Protection Criteria, Report 224-5, Recommendations and Reports Vol. II, Geneva, 1982.

FCC, Third N.O.I., Implementation of the Final Acts of the World Administrative Radio Conference, FCC 81-323 29672, general Docket 80-739, 1981.

Moffet, A. T., Analysis of the Electromagnetic Compatibility of the Digital Electronic Message Service and the Radio Astronomy Service in the 10.6 to 10.68 GHz Band, Owens Valley Radio Observatory, Calif. Inst. of Technology, Pasadena, 1981.

TABLE AII-1

RADIO ASTRONOMY BANDS AND HARMFUL LIMITS WITHIN THE VLBA TUNING RANGES

VLBA Tuning Range	U.S. Radio Astronomy Allocation (1,2)	Sharing Services in R.A. Band	Adjacent Bands with Air-To Ground or Space-to-Earth Transmissions	Harmful Interference Levels (3)
				(dB Wm^{-2})
310-340 MHz	322-328.6 MHz (F)	FIXED, MOBILE	225-328.6 MHz, MOBILE 328.6-335.4 MHz, AERO. RADIONAV.	-161
or				
390-420 MHz	406.1-410 MHz (PS)	FIXED, MOBILE	403-406 MHz, MET. AIDS 410-420 MHz, MOBILE	-161
580-640 MHz	608-614 MHz (P)			-156
1350-1750 MHz	1300-1400 MHz (F)	RADIOLOC., AERO. RADIONAV.		
	1400-1427 MHz (P)		1350-1400 MHz RADIOLOC. MOBILE	-145
	1610.6-1613.8 MHz (S)	AERO, RADIONAV.		
	1660-1660.5 MHz (PS)	AERO. MOB.-SAT.		
	1660.5-1668.4 MHz (P)			
	1668.4-1670.0 MHz (PS)	MET. AIDS	1670-1690 MHz MET. AIDS, MET. SAT.	
	1718.8-1722.2 MHz (F)	FIXED, MOBILE	1710-1850 MHz MOBILE	
2175-2425 MHz	(4)			
4900-6100 MHz	4950-4990 MHz (F)	FIXED, MOBILE	4800-4900 MHz MOBILE	-130
	4990-5000 MHz (P)		5000-5250 MHz AERO. RADIONAV.	-137
8000-8800 MHz	(5)			
10.2-11.2 GHz	10.6-10.68 GHz (PS)	FIXED		-120
	10.68-10.7 GHz (P)		10.7-11.7 GHz FIXED SAT.	-127
14.9-15.9 GHz	15.35-15.4 GHz (P)		15.1365-15.35 GHz MOBILE, Space Res. 15.4-15.7 GHz AERO. RADIONAV.	-118
21.3-25.3 GHz	22.01-22.21 GHz (F)	FIXED, MOBILE (6)		
	22.21-22.5 GHz (PS)	FIXED, MOBILE (6)	22.5-22.55 GHZ MOB., BROADCAST SAT.	
	22.81-22.86 GHz (F)	FIXED, MOB., INTER-SAT., BROADCAST SAT.		
	23.07-23.12 GHz (F)	FIXED, MOB., INTER-SAT.		
	23.6-24.0 GHz (P)		23.55-23.6 GHz MOBILE 24.0-24.05 GHz AMATEUR SAT.	-113
42.5-43.5 GHz	42.5-43.5 GHz (PS)	FIXED, FIXED SAT. MOBILE (6)	40.5-42.5 GHz BROADCAST SAT.	-106

(1) From FCC Second, Third, and Fourth N.O.I., Implementation of the Final Acts of the W.A.R.C., Geneva, 1979. General Docket No. 80-739

(2) Protection status: (F) = Footnote, (PS) Primary shared, (P) Primary exclusive or shared with passive services, (S) Secondary.

(3) From formula in text.

(4) Deep Space Band 2290-2300 MHz

(5) Deep Space Band 8400-8450 MHz

(6) Except aeronautical-mobile.