– A Proposal For –

A VERY LARGE ARRAY RADIO TELESCOPE

Volume III

January 1969

National Radio Astronomy Observatory*

Green Bank, West Virginia

*OPERATED BY ASSOCIATED UNIVERSITIES, INC., UNDER CONTRACT WITH THE NATIONAL SCIENCE FOUNDATION

Contents

Volume III

Chapters 1 - 9

SUMMARY

This report and its technical appendices describe the design work which has been done on the VLA since publication of the original proposal in January 1967.

The basic concept of the VLA remains unchanged. It is an instrument which will obtain radio "pictures" with 1" resolution, high sensitivity, and low side-lobe levels in 8 to 14 hours observing time. The most important change that has been made in the proposed array is a reduction in the number of antennas from 36 to 27. This produces a decrease in sensitivity of a factor of 1.8, an increase in peak side-lobe levels from -20 dB to -15 dB, and a considerable reduction in cost. It is believed that this is a more reasonable compromise between cost and performance than is the original 36-element array.

The only other major change in specifications is a reduction of the bandwidth from 50 MHz to 35 MHz. This produces a decrease in sensitivity of a factor of 1.2, but greatly eases the problem of the IF distribution system.

The VLA, as now proposed, consists of an array of twenty-seven 25 m antennas, arranged on a wye-shaped configuration of railroad tracks. Each arm of the wye is 21 km long. The initial operating wavelength of the array is 11 cm, which gives 1" resolution.

The cost of the array is $32,318,000, and construction time is five years from time of authorization. Other wavelengths and spectral-line capability can be added at any time, as can additional antenna elements if lower side lobes or greater speed becomes desirable.

Chapter 1

INTRODUCTION

A proposal for a Very Large Array Radio Telescope (VLA)[1] was published by the National Radio Astronomy Observatory (NRAO) in January 1967. It consisted of two volumes: Vol. I, The VLA Concept, and Vol. II, The System Design, describing a large radio telescope system for research in radio astronomy. During the two years which have elapsed since the publication of the VLA Proposal, further studies of the VLA concept have been made, and several technical subsystems and components which were considered unique or critical to the successful operation of the planned array have been designed, prototyped, and tested. Many radio astronomers, both from the U.S. and abroad, have discussed, criticized, and commented on the original proposal, and the direction of the work reported here was strongly influenced by these discussions. In particular, the recommendations by the ad hoc Advisory Panel for Large Radio Astronomy Facilities[2] were taken into account.

Although the basic concept of the Very Large Array remains unchanged, some of its performance specifications were slightly modified when it was found that the original performance goals were either unwarranted or could only be achieved by undue costs and/or unreasonable technical efforts. For example, the maximum acceptable peak side-lobe level within the field of view was relaxed from -20 dB to -15 dB, and this change was a main contributing factor in the reduction from 36 to 27 antennas.

The VLA was originally conceived as a high-resolution instrument for continuum observations. This does not, however, in any way preclude its use as a high-resolution array for the observation of spectral lines. The array

---

[1] Vol. I - PB 173912, Vol. II - PB 173913, Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia.

[2] The ad hoc Advisory Panel for Large Radio Astronomy Facilities (the Dicke Committee) was convened by the National Science Foundation in Washington, D. C., July 24-28, 1967, to consider five proposals for design and construction of large radio telescopes. The VLA was one of those considered.

configuration for spectral-line operation has been studied (Chapter 3) and experiments with spectral line observing techniques have been made with the Green Bank three-element interferometer.

The VLA effort has been concentrated to the following general areas.

1. Operation of the Green Bank interferometer

The Green Bank three-element array has been under computer-controlled operation since July 1967, and many of the techniques which will be used in the VLA have been successfully tested. In particular, the operation of a portable 42-foot antenna element together with the three-element array over baselines comparable to the size of the VLA (11 km and 35 km) has shown that sufficiently phase-stable operation to form a synthetic beam can be achieved even in the relatively hostile Green Bank climate. It is, therefore, clear that a 1" pencil beam at 11 cm wavelength is entirely practicable (Chapter 2).

2. Configuration studies

In the original VLA proposal an array consisting of 36 elements uniformly spaced along three arms of a "wye" was proposed. During the continuing studies of the configuration an optimization procedure was developed. Using this technique, a new configuration with nonuniform spacings between the antenna elements along the arms of the wye has been found. This configuration, which requires 27 antenna elements, gives a full sky coverage pencil beam with a -15 dB peak side-lobe level within the field of view, except for a narrow strip of a few degrees near $\delta = 0$ where the peak side lobe increases to about -14 dB.

The performance of a reduced version of the VLA consisting of one of the three arms with 12 antennas has also been investigated. Although the performance of this "sub-VLA" falls considerably short of the goal for the full VLA, it performs very well at higher declinations. Its overall performance for continuum observations is at least equal to other proposed or existing arrays for radio astronomy and could be regarded as a first step towards the full VLA (Chapter 3).

3. Site evaluation

Three areas in the southwestern part of the United States were originally selected as possible candidates for the VLA site. During the past two and a half years water vapor content in the atmosphere has been studied at these sites, and recently an extended program observing the water vapor content as well as its correlation over distances comparable to the size of the VLA has been started (Chapter 4).

4. Hardware development

Many of the critical and unique components and subsystems which are essential for the successful performance of the VLA have been further developed. Engineering prototypes of some of these have been built to prove the feasibility of the design. Examples of such components are:

(1) The local oscillator system of which a working prototype now exists.

(2) The basic elements of an IF distribution and delay system.

(3) A two-frequency (2695 MHz and 8085 MHz) dual circular polarization feed.

Other components similarly developed, such as low-noise parametric amplifier front-ends (2695 MHz), are in successful use on the three-element Green Bank array (Chapter 6).

The conceptual design of the antenna element and the mobility system has been brought to a conclusion. The efficient, low-cost antenna structure, the carrying vehicle, and the track system are described in Chapter 5.

Studies of the VLA computer system and its tasks are described in Chapter 7.

5. Maintenance and operation

The problem of maintaining a large and complex system with 27 antennas, with all its electronic equipment with minimum downtime for maintenance and repairs, requires a well-planned maintenance program. Several possible approaches to this problem have been studied, and a solution is recommended in Chapter 8. It is assumed that the array should be in full working condition at least 90% of the available time (24 hours a day, 7 days a week).

6. Cost and Schedules

Funding and time schedules for the detailed design and construction of the VLA (and sub-VLA), together with estimates of the operating costs of the VLA facility, are presented in Chapter 9. It should be stressed, however, that the sub-VLA must not be regarded as a cheaper substitute for, but rather as a step towards, the full array.

With the publication of this report, the work on the VLA has been brought to a point where detailed design, prototype, and construction would be the next logical steps. Pending authorization for the VLA or some modified version of it, no design and study work beyond the completion of this report is planned.

The work presented here has mainly been an internal NRAO effort. During certain phases of the work help has been sought from industry and academic institutions as well as individuals in the form of study contracts and consultation arrangements. Continuous support has been given by radio astronomers both in the U.S. and abroad, and it is believed that the VLA, as it has been described here, represents a major and entirely feasible step forward in instrumentation for radio astronomy.

Chapter 2

OPERATION OF THE NRAO INTERFEROMETER SYSTEM

A. The Three-Element Interferometer System

The NRAO three-element interferometer system, after a complete rebuilding of the receivers at the time the third antenna was added, has been in operation since July 1967. Although the number of antennas and correlators is of a completely different order than the VLA, it operates in an analogous fashion and some insight into VLA operation may be obtained through a description of the Green Bank instrument.

The three antenna elements are 85-ft antennas of a standard Blaw-Knox design. One is fixed in location, and the other two may be moved to one of a set of seven observing stations. The observing stations lie along a line at azimuth 242° from 85-1, the fixed antenna. Six of the stations are at 300 m intervals from 1200 m to 2700 m from 85-1. The seventh is located on the same line 1900 m from 85-1. The 21 possible configurations given by this arrangement provide baselines (the distance between pairs of antennas) in steps of 100 m from 100 m to 900 m, and in steps of 300 m from thence to 2700 m, as well as a baseline of 1900 m. A set of nine configurations will provide all of these possible baselines.

The three-element interferometer operates completely under computer control. The observer punches a card which specifies the source (by name, right ascension, and declination), and the time at which he wishes the observation to end. The small on-line computer, after checking the card for a variety of errors, then performs the whole task of observing. The antennas are slewed to the requested position, pointed at the source coordinates (corrected for the effects of precession, aberration, and nutation if so requested by the observer) to an accuracy of about 1 minute of arc rms error (by means of an interpolation formula describing the pointing corrections of each antenna; after each move, the constants in the interpolation formula are redetermined--a process requiring about 16 hours of observations of strong sources of well-known positions). The computer switches the step variable delay line to the proper value for the source position and hour angle and collects data from each of the three correlators by means of a multiplexed A to D converter. It then fits a theoretical fringe pattern to the correlator output and displays the fitted amplitude and phase on a teletype (in distinction to the VLA, the Green Bank interferometer does not employ lobe rotators, and fringes at the natural rate appear at the correlator output). The computer also records the information for later processing in a general purpose computer, along with various information monitoring the behavior of the instrument. In addition, it performs checking of various monitor points in real time and notifies the operator if the quantities monitored are not within their proper range. Various subsidiary services may be requested of the on-line computer on the observation request card. Some small facility for modifying the parameters of the request card through the computer teletype is provided. Except under unusual conditions, the system requires no human intervention to complete the observation.

A very similar operation is envisioned for the VLA. The chief difference apparent to the user would probably be that, because of the complexity of the possibility of running the array as several sub-arrays and of retrieving data lost because of a malfunction, etc., there will probably have to be some rather complex program which can prepare a detailed observing program from a somewhat more general description of the data desired. This program may be run well in advance so that one may avoid the complexity of interfacing this program to the program which does the actual observing.

The Green Bank interferometer also utilizes the polarization system proposed for the VLA: Information about the linear polarization brightness distribution of the source is determined by measurements with opposite circular polarization on the two antennas of the interferometer. At present, the front-ends are switched between the two ports of the feed to measure, for instance, the LL coherence, then the LR coherence, then the RL coherence. Linearly polarized radiation may be resolved into a coherent sum of the two circular polarizations, and, unlike randomly polarized radiation, gives a non-zero coherence in the LR and RL measurements. This system has the following advantage over a linearly polarized system: That, for the linear system, the corresponding measurements require not only, say, E-vector vertical and E-vector horizontal, but E-vector at 45°. This latter may be produced by combining vertical and horizontal, which is difficult to do with proper gain and phase, or by physically rotating the feed, which consumes time better spent observing.

The instrumental polarization of the Green Bank system is about 3%, which is slightly higher than would be expected for a linearly polarized system (the instrumental polarization can be made much less for any one interferometer pair by properly orienting the feeds). The calibration of the instrumental polarization and the interpretation of the results in terms of the source polarization have proceeded about as expected. Although the instrumental polarization is slightly higher than expected for a linearly polarized system, there is no evidence that the nonrepeatable variations in instrumental polarization are sensibly larger than for the latter case.

Accuracy of amplitude measurements with the three-element interferometer is about 3%, estimated from the measurement of ratios of the amplitudes of point sources, taken at various places in the sky. This accuracy is attained only after corrections have been made for dispersion and length error effects in the step variable delay lines and for the effects of atmospheric absorption. The accuracy appears to be limited by (1) small errors in antenna pointing, (2) nonreproducibility and difficulty of determination of the delay line effects, and (3) the variation of atmospheric absorption.

A greater difficulty in using the interferometer as a synthesis instrument lies in calculating the phase corrections to reduce the measured quantity to a given coordinate system on the sky. Various instrumental effects have been identified and removed in the course of the past year and a half. The principal--though not the only--remaining difficulty lies in atmospheric effects, which, being nonreproducible, cannot be removed. These effects are due to a nonuniform structure in the refractivity above the instrument and are analogous in effect to optical "seeing." However, the optical seeing arises in density fluctuations with a typical scale of a few centimeters and a path difference of a few microns, whereas the radio effect arises in fluctuations in water vapor content with a typical scale of about a kilometer and a path difference approaching a centimeter.

The refractivity of water vapor may easily be calculated from well-known formulae: The water vapor content of the atmosphere contributes an additional path of from 6 to 20 cm (water droplets are much less important because the high dielectric constant of liquid water causes the electromagnetic wave to avoid the centers of the drops; the path per molecule of water induced by droplets is about 10 times smaller than for vapor).

That the water vapor distribution has structure of a few hundred meters size has been determined by meteorologists, by observing the readings of a hygrometer towed behind an airplane; however, little is known about the statistics of this structure or its relation to other meteorological parameters.

To further study this structure, the NRAO has built infrared hygrometers, which determine the total amount of water vapor between the hygrometer and an infrared source outside the atmosphere, usually the sun. A discussion of these instruments is given in an internal report by Wesseling (1968). They have indeed demonstrated that there are fluctuations in total atmospheric water vapor of the right order of magnitude to explain the short term phase variations observed with the three-element interferometer. An attempt has been made to confirm our belief that all of the phase fluctuation is due to the water vapor by observing a radio source close to the sun with the three-element interferometer and at the same time measuring the total water vapor in front of each dish with an infrared hygrometer near the dish, observing the sun. The results so far have been inconclusive, chiefly because of weather when the attempts were made, as the infrared hygrometers require a very clear day for consistent operation.

The 11 cm phase variations seen on the longer (> 1.2 km) baselines with the three-element interferometer amount to 3° to 7° rms, varying with the seasons as the total atmospheric water content varies. For all but very weak (< ∿ 0.1 flux unit) or very low surface brightness (< ∿ 200° K) objects, this phase fluctuation is the chief cause of uncertainty in the reconstructed brightness distribution--more important than either noise or the amplitude uncertainties.

Because of the relative slowness of an interferometer with only three-correlator outputs, the three-element interferometer has been used to a large extent for problems involving the fitting of models with only a few parameters, or where reasonable but stringent assumptions may be made about the brightness distributions, rather than for a wide field, clean beam supersynthesis.

However, a clean beam supersynthesis, in the classic sense, of both brightness and polarization characteristics, has been undertaken on a few sources to examine the technique. Although reductions are not yet complete, the problems arising have simply been in determining an accurate calibration of instrumental gain and phase over all the sky rather than any problems fundamental to the technique.

Utilization of model fitting techniques with the three-element interferometer, and possibly also for a more complex interferometer array, will probably continue for two reasons. First, additional information can be added to the solution fairly conveniently, such as restricting it to a certain region of space, or requiring the brightness distribution to be everywhere positive. This latter condition, though it makes a significant improvement in the data, causes the fitting process to be nonlinear and thus to yield answers whose uniquity and precision cannot easily be determined. Second, the use of a model fitting procedure rather than a direct Fourier inversion gives somewhat more freedom in weighting, namely that the phase may be less heavily weighted than the amplitude, since--because of atmospheric and other effects--the phase has a higher uncertainty than the amplitude on sources strong enough that the measurement accuracy is limited by other instrumental effects than receiver noise.

B. Future Plans - Spectral Line Work

Two major changes to the interferometer instrumentation are planned during the next two years. The first is the incorporation of dual-frequency, dual-polarization front-ends with a dual-channel delay and correlator system. Four front-ends will be utilized to provide left- and right-hand circular polarization at frequencies of 2695 and 8085 MHz. Any two of the four front-end outputs can then be selected for processing by the dual-channel back-end system. This will provide observations in single polarization simultaneously at both frequencies or single-frequency, full-polarization observations at a much more rapid rate than the present system.

The second major addition that is planned is the addition of spectral-line equipment to the system. At the present time a high degree of interest in hydrogen-line observations has been expressed. A set of 1420 MHz front-ends, a 3 x 128 channel cross-correlator system, and some observing stations at spacings less than 100 m are planned. Construction will begin when funds and manpower are available.

An exploratory-tutorial attempt to detect the 2702.8 MHz Hα recombination line was made in October 1968. The present three correlators were used at three different IF frequencies, each with 250 kHz bandwidth, between 85-2 and 85-3 antennas at 900 m spacing. The LO frequency was adjusted so that the line would appear in the central IF band. A complete analysis of the data has not been performed. However, initial examination of the data does not show the line and it is doubtful that it was detected. This is due to: (a) the low expected line-to-continuum ratio (1 to 2%) at this frequency with a degenerate paramp; (b) the fairly long antenna spacing; and (c) gain variations between the three IF channels which are a function of delay-line setting. The measurement pointed out some of the problems in spectral-line interferometry and a future attempt at 100 m spacing is planned.

C. The Long Baseline, Phase Stable Interferometer

NRAO has also operated an interferometer between one of the 85-ft antennas and a 42-ft portable antenna. The 42-ft antenna is of a rather simple design in order that it may be easily disassembled and reassembled in another location. Because of the simplification of the design, it has rather restricted sky coverage-- ± 2 1/2 hours either side of the meridian, declination 0° to 66°. It is connected to the three-element interferometer by a microwave link, which returns the IF signal to the control building, phase controls a local oscillator at the 42-ft antenna, and provides a voice link with the control building to the 42-ft antenna operator.

The 42-ft portable antenna has been used on two baselines of lengths 11 and 35 km, primarily in a program to investigate the problems of phase stable interferometry with baselines comparable with those in the VLA. The portable antenna operated at 11 km baseline from November 1967 to August 1968. It has been at the 35 km baseline since September 1968, but various instrumental problems connected with the longer baseline were not completely removed until November 1968, so that there is not yet any completely reduced data from this baseline.

Some preliminary investigations of radio source sizes, using only the measured amplitudes, have already been published (Basart, Clark, and Kramer,

1968) and a considerable extension of this work is in hand. Careful investigations of the phase behavior of the instrument are also underway.

The problems which arise in understanding the phase behavior of this interferometer may be placed into two groups--those which are intrinsic to the long baseline and those which arise from the nonidentical nature of the two antennas. The latter corrections have proved to be most troublesome.

The largest of the corrections, though one quite easy to handle, arises from the fact that the polar and declination axes are separated by 32 feet on the 85-ft antenna, but only by a few inches on the 42-ft antenna. This causes the interferometer phase to obey a slightly different equation than in the case for which the mathematics are usually developed, the case of point antennas. A more serious correction arises from the fact that the optical axis of the 42-ft paraboloid does not intersect the declination axis. This means that the phase center of the antenna is moved forward or back with small changes in the declination pointing. A similar up-and-down motion of the phase center is caused by thermal expansion. Since the two antennas comprising the interferometer are of different sizes, the amount the antenna expands is different at each end, raising or lowering one phase center relative to the other. Thus, the instrumental phase may be expected to be a function of temperature. A similar consideration may occur, even in the case of identical antennas if the insolation or wind is different at the two antennas, which may on occasion be the case when the baselines exceed several miles. It would not be too surprising if a temperature difference of 5° C occurred in the two antennas under partly cloudly skies with little motion of the clouds. The differential expansion between two 25 m steel antennas under these conditions is 1.5 mm or 5° of 11 cm phase. Similar phase increments may be generated by the leaning of the antennas due to differential heating.

The flexure behavior of the two dissimilar antennas is likely to be quite different, so that the phase may not follow the simple baseline parameter rules, but may have terms which must be computed from an analysis of the antenna structure or empirically derived from observation.

A further difficulty arises from the large elevation difference between the two ends of the interferometer. We have assumed that the meteorology is the same at the two places and that the phase delay in the lower antenna is simply the path difference times the refractivity measured at the interferometer control building at the lower end of the interferometer. In addition to the systematic decrease of refractive index with height, there is a systematic difference in weather at the remote telescope, located on a high and exposed ridge.

These difficulties, and the uncertain positions of the radio sources under investigation, have precluded the absolute phase calibration of the instrument, which is made yet more difficult because of the very restricted portion of the sky visible to the 42-ft antenna. However, even without the absolute calibration of the phase, we may conveniently discuss the phase stability of the instrument. This quantity is what limits the eventual usefulness of the instrument, as the calibration problems can in time be solved and, indeed, if the whole sky were available to the instrument, could fairly easily be solved.

It is convenient to discuss the phase stability of this interferometer in two realms: First, in the short term realm variations shorter than about two cycles per hour (wavelength smaller than 8 km with a 10 mph wind), and second, a long-term realm extending to times long compared to the interval between phase calibration. In the short-term realm most of the corrections discussed above may be ignored because they change too slowly to enter into the measurements. The short-term phase variation is estimated by observing a strong source, so that the signal to noise ratio is very high, and calculating the variance of the phase during a 30-minute interval. The distribution of these estimates is shown in Fig. 2-1a for data taken in February 1968 with the 42-ft interferometer on the 11 km baseline. (The quantity plotted in the figure is not the variance but the square root of the variance, the rms phase deviation.) The estimate of the deviation is nearly Poisson distributed, which implies that the large part of the deviations occur with time scales comparable to the length of the interval. The true rms deviation is about 5°.

A similar distribution obtained at the same time with the three-element interferometer operating with a baseline of 2.1 km is shown in Fig. 2-1b. This distribution is appreciably more peaked than a Poisson distribution,

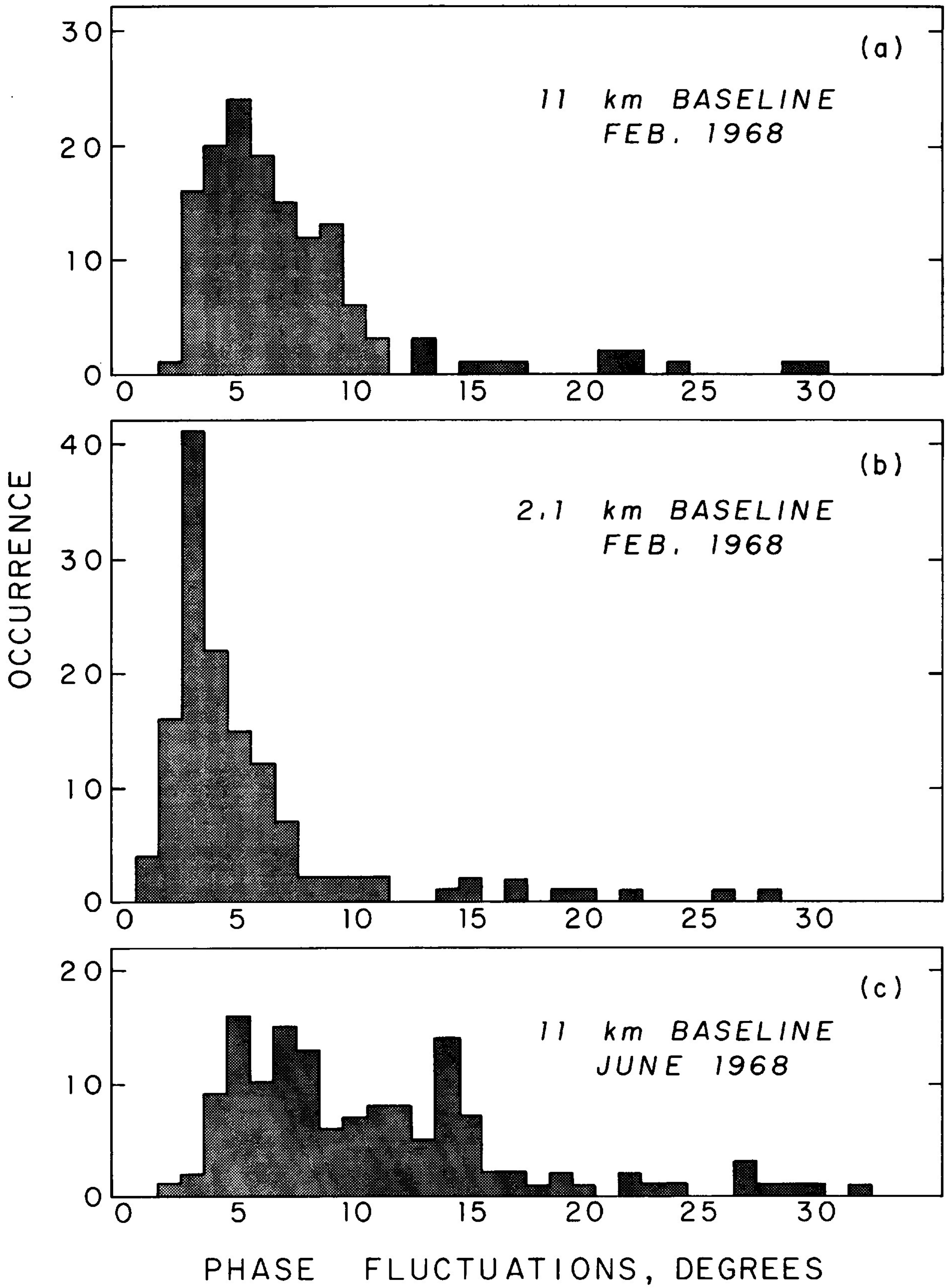


Fig. 2-1. Histograms of short-term phase fluctuations.

and thus indicates that short-term variations contribute more to the deviations than is the case for the 42-foot interferometer data. The distribution indicates an rms deviation of about 3.2°. The rms phase deviations in this time scale are thus worse on the 11 km baseline by about a factor of 1.5 relative to the 2.1 km baseline. It is believed, however, that an appreciable part of the phase deviations on the 11 km baseline are due to a timing error internal to the interferometer equipment, which has since been discovered and corrected. Although the exact incidence of this timing error at the time of the observations is not known, an estimate of its occurrence indicates that it generates a spuriously large rms (∿ 10°) in perhaps one-third of the observations plotted in Fig. 2-1a. In this case, the true rms for the 11 km baseline may be as low as 4°, only 1.3 times the rms of the 2.1 km baseline.

In any event, it is clear that the rms phase deviation rises much more slowly than directly proportional to baseline for baselines longer than 2 km.

The effect of greater water vapor concentration is shown in Fig. 2-1c, which is a collection of data observed, reduced and compiled in the same fashion as that of Fig. 2-1a, but taken in June when the integrated water vapor content was much higher. The greater dispersion of these data must reflect the increased atmospheric phase variations in the summer when the atmospheric water vapor content is relatively high.

The second, long-term, realm of phase variations has been investigated by noting the reproducibility of the phase at the same sidereal time on two adjacent days when it may be hoped that most of the effects mentioned above have returned to the same values they had on the preceding day. In this case, the same source measured on successive days may differ in phase by up to about 60°. To what extent this difference is due to the instrumental effects mentioned above and to what extent it is a genuine change in the atmosphere is not yet known. In any event, this can probably be reduced by at least a factor of two by calibrating the instrument and atmosphere more often than once per day. Thus a long-term phase stability of ± 30° deviations, that is, about 15° rms, should be attainable even in the mountainous meteorology of the Green Bank area.

To summarize, we may say first that the Green Bank interferometer instruments are doing front-line astronomical research but not a large amount of clean beam synthesis because of the slowness of a three-correlator instrument for that problem. Second, the Green Bank interferometers have already demonstrated the instrumental stability and atmospheric behavior necessary to synthesize a low side-lobe 8" beam, and in addition have demonstrated that a beam of 2" beam width (and probably 1" also) can be generated without beam broadening due to atmospheric or instrumental phase effects.

REFERENCES

Basart, J. P., Clark, B. G., and Kramer, J. S. 1968, Publ. Astron. Soc. Pac., 80, 273.

Wesseling, K. H. 1968, "A Continuously Recording Infrared Hygrometer, and Results of an Interferometer-Hygrometer Correlation Experiment," NRAO Electronics Division Internal Report No. 78.

Chapter 3

THE ARRAY CONFIGURATION

A. Introduction

The problem of designing the configuration for the VLA is basically different from that of designing conventional phased arrays. Although extensive work has been done on the latter problem (e.g. Lo and Lee, 1966), no attempts have been made at evolving a technique for designing correlator arrays operating in the supersynthesis mode. The transfer function of the correlator array is the autocorrelation function of the array configuration. However, the configuration to be considered is the projection of the actual configuration on a plane normal to the direction of the source. Thus each baseline contributes a point to the transfer function in the spatial frequency plane (the u-v plane) which is determined by the length and orientation of the effective baseline as seen from the source. The east-west and north-south components (u and v, respectively) of the effective baseline are given by (Rowson, 1963)

$$u = B_2 \sin\,(H-h) \tag{3-1}$$

$$v = B_1 \cos\delta - B_2 \sin\delta\,\cos\,(H-h) \tag{3-2}$$

where B_1 and B_2 are, respectively, the components of the baseline parallel to and perpendicular to the earth's rotation axis (in wavelengths), h is the hour angle of the baseline pole (it is the point at which an extension of the baseline in a direction closest to the north intersects the celestial sphere), and δ and H are, respectively, the declination and hour angle of the source. The transfer function, W(u, v), can be computed by computing the u and v corresponding to each pair of antennas and each value of H for which a measurement will be available. (The details are given in VLA Proposal, Vol. I). The normalized beam (power) pattern of the array, B(x,y), for a rectangular sampling grid is given by

$$B(x,y) = \frac{1}{C} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} W(u,v)\, e^{-j2\pi(ux + vy)}\, du dv$$

$$= \frac{1}{C} \sum_{k=-K}^{K} \sum_{\ell=-L}^{L} W_{k,\ell}\, e^{-j2\pi(k\Delta ux + \ell\Delta vy)} \tag{3-3}$$

where

$$C = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} W(u,v)\, du dv = \sum_{k=-K}^{K} \sum_{\ell=-L}^{L} W_{k,\ell} \tag{3-4}$$

Equations (3-1) through (3-4) point out two features of the correlator supersynthesis array design problem. Firstly, due to tracking, the beam pattern is a very complicated function of the array configuration, in contrast to the simple relationship between the beam and configuration of a nontracking, linear, phased array. Secondly, the beam depends also upon the declination of the source, the hour angle range for which the source is tracked and the latitude of the array site. Thus the design of a correlator supersynthesis array involves many more parameters than that of the linear phased array. Lo and Lee (1966) have summarized the extensive research that has gone into the design of linear phased arrays. No satisfactory technique of design has yet been found and the problem is still being investigated by numerous people. In the design of correlator arrays the simplest case is that of a linear correlator array used for instantaneous observation of a source at the zenith. Moffet (1968) has applied the theory developed by Leech (1956) for designing minimum redundancy correlator arrays. But it has been pointed out by Moffet (1968) and earlier by Bracewell (1962) that there is no two-dimensional analog to the minimum redundancy linear array. The operation of the array in the supersynthesis mode further complicates the design. Thus it appears that an analytical approach to the design will, at best, be extremely difficult. The VLA configuration design has, therefore, been carried out entirely by the use of a large digital computer.

The VLA is designed to operate in four configurations corresponding to resolutions of 1", 3", 9", and 27". The field of view (defined as the distance between the main beam and the grating lobe) is to be 120 times the resolution. At the smaller resolutions the primary dish pattern limits the field of view. At higher resolutions the field of view is limited by the bandwidth used. The array is required to produce a beam with no side lobes greater than -15 dB throughout the field of view.

Moreover, this beam characteristic is to be achieved within a total observing time of 14 hours and over the entire sky north of declination -15°. (These performance specifications are less stringent than those originally adopted in VLA Proposal, Vol. I.)

In this chapter a computerized optimization technique, termed pseudo dynamic programming (Mathur, 1969) is described and is applied to the VLA configuration problem. It is shown that the above performance specifications can be met by a 27-element array. The suggested configuration and its performance are discussed. The question of the necessary bandwidth is investigated and some results on the performance of the array in the 1"- and 3"- resolution modes with a bandwidth of 35 MHz are given. An important aspect of the array, the deterioration in performance when one or more antennas become inoperative, is discussed. In addition, we describe a smaller array, the sub-VLA, which can be considered as the first step in the construction of the VLA. This would be a linear array comprising one arm of the wye, built at the VLA site and capable of being expanded to the full VLA.

The use of complementary arrays for the VLA, in which the source is observed with two different array configurations and the results combined is discussed in the appendix.

B. Pseudo Dynamic Programming

The computer has been extensively used in the design of linear phased arrays (for example, see Skolnik, et al, 1964). The basic techniques used are (a) random arrays, (b) empirical approach, and (c) perturbation approach. Although the problem of correlator arrays is mathematically very different from the linear phased arrays, the same computer techniques can be used to design correlator arrays. In the random array approach, one evaluates the performance of various randomly chosen configurations and finds out the best configuration. Obviously such a configuration cannot be termed optimum in any sense and one cannot obtain a final array design by this method. In the empirical approach one tries out various geometrical forms such as circles, radial arms, etc., and various distributions of elements such as uniformly spaced, tapered, etc., and chooses the best one. In a perturbation approach one starts with a reasonable configuration selected by some means and perturbs the positions of each element about its initial value. The effect of the perturbation on the performance is observed and a new set of element positions is found on the basis of this study.

The optimization technique termed pseudo dynamic programming combines the empirical approach with a modified perturbation approach. In this technique the position of an antenna is optimized over a given set of pre-specified positions. During the optimization (which is carried out for a given declination and hour angle range) the positions of the remaining antennas of the array are kept fixed. The optimum position is the one that gives the array with the best performance. All the antennas are optimized in this way, one after another, and after each optimization one gets a configuration which is better than (or at least as good as) the preceding configuration. After optimizing all the antenna positions once, one can start with the first antenna again and go through a second loop of optimization; this procedure can be continued until a configuration is arrived at whose performance cannot be substantially improved by further optimization. Before considering the application of this optimization technique in detail, the choice of the criterion of optimization and the choice of the pre-specified optimizing positions should be discussed.

1. The criterion of optimization

The ultimate criterion of performance of the array is the side-lobe level in the beam pattern. However, computation of the beam pattern of the array requires a considerable amount of computer time (of the order of 13 minutes) even with the use of the Cooley-Tukey algorithm. It is, therefore, impractical to compute the beam at each stage in the optimization procedure. The transfer function can be computed relatively quickly. Since the size and structure of the side lobes are determined by the number and distribution of unsampled cells (holes) in the transfer function, a good criterion of optimization will be a count of the holes with some weighting that takes into account the distribution of holes. It has been found that a count of the holes with a Gaussian weighting that tapers down to 15 dB at the edge of the transfer function works as a reasonably good criterion. The relationship between the weighted holes and the side lobes in the beam pattern is shown in Fig. 3-1. The peak and mean side lobes for a variety of transfer functions are plotted in this figure as a function of the actual holes and the weighted holes. The close correspondence between the peak side lobes and the weighted holes is brought out clearly. Therefore, the weighted holes have been used as the criterion of optimization in the design.

2. The choice of the basic wye-configuration

As mentioned earlier, the optimization is carried out over a prespecified set of positions. The choice of these positions is very important since the optimization program can only find the best out of the available positions. An exhaustive empirical study of the array configuration (Hogg, 1966; Chow, 1966; Hogg, 1967) has shown that the requirements of expandable resolution and large sky coverage of the VLA can best be met by arranging the antennas along the arms of an equiangular wye with one arm at an azimuth of 5° and with arm length of 21 km for 1" resolution. For the optimization work, therefore, the wye has been chosen as the basic configuration. The design has been carried out for an array of resolution 10" and field of view 20'. As mentioned in the VLA Proposal, Vol. I, the performance of the array remains the same for any other combination of field of view and resolution so long as their ratio remains the same. For the 10" resolution the arm length is 2100 m. With 42 stations on each of the arms (50 m apart), the prespecified set of positions used in the optimization consist of 126 positions on the wye.

It should be pointed out that pseudo dynamic programming does not lead to a unique configuration which could be termed the "optimum". The final configuration obtained depends largely on the starting optimum configuration. In the absence of an analytic solution the truly optimum configuration of N antennas which can occupy any of P possible locations can be found by analyzing all the possible ${}_{P}C_{N}$ configurations, where

$$ {}_{P}C_{N} = \frac{P(P-1)\,(P-2)\ldots(P-N+1)}{N!} $$

The best of these configurations will be truly optimum over the P locations. However, the use of the technique on a multitude of configurations and

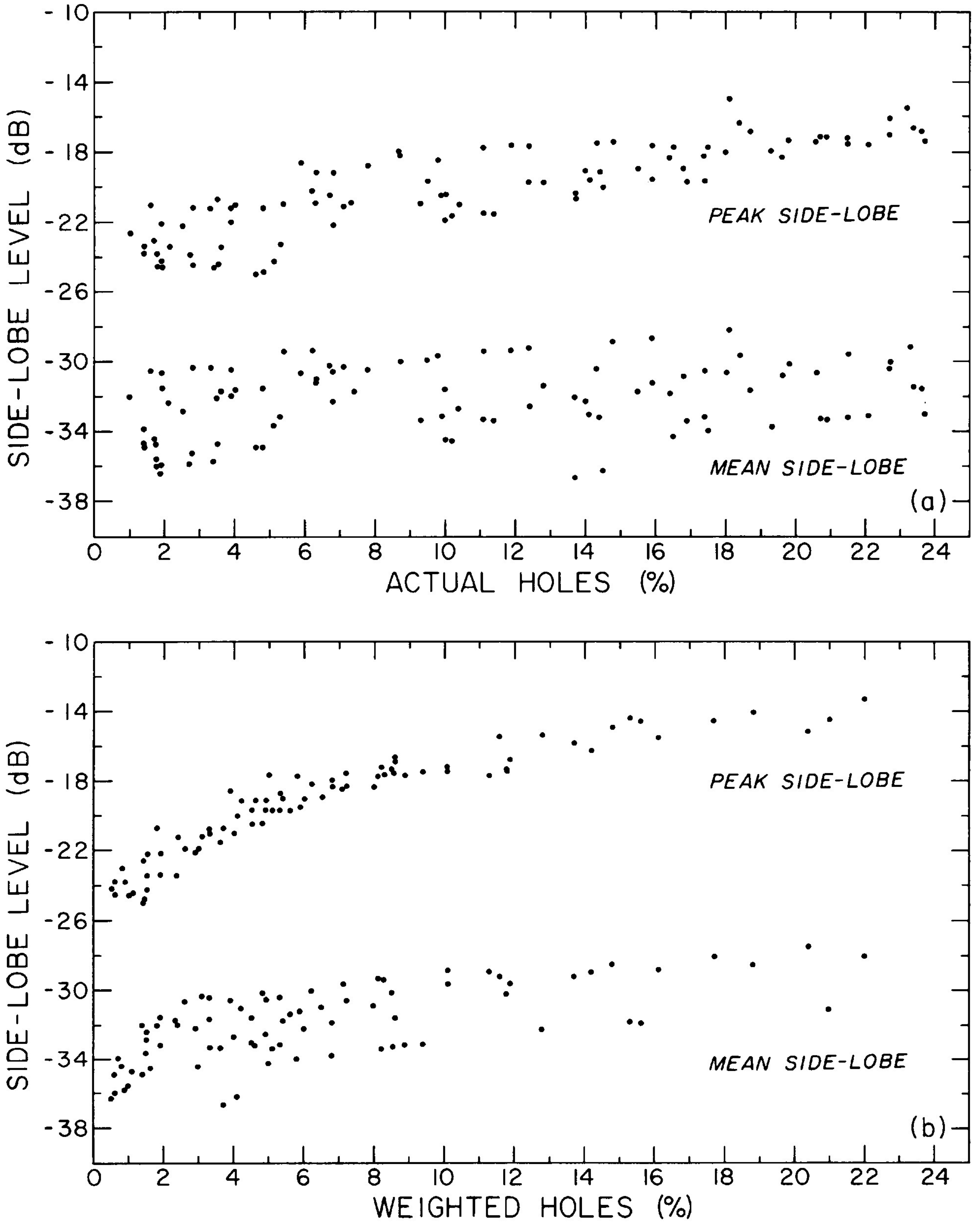


Fig. 3-1. Relation between side lobe levels and holes in the transfer function.

declinations has led to the conclusion that the final configuration obtained by this technique, even though not truly optimum, has a performance which does not depend much upon the starting configuration. A typical case is illustrated in Fig. 3-2. Here the decrease in weighted holes as a function of number of antennas optimized is plotted for two different starting configurations. The performance of the starting configurations are quite different but after two runs of optimization, one gets arrays with nearly the same performance. It is interesting to note that for each of the curves of Fig. 3-2 the optimization program considers about 6000 configurations, compared to the total possible number $_{126}C_{30} \simeq 10^{28}$! In every case it was found that the weighted holes go down roughly exponentially as more and more antennas are optimized and that generally no more than two runs of optimization are required to arrive at the final configuration. A great deal of confidence in the pseudo dynamic programming technique is also gained by applying this technique to the design of a linear, nontracking correlator array. It is known that the optimum configuration is the minimum redundancy array discussed by Leech (1956). The pseudo dynamic programming technique arrived at the optimum configuration as given by Leech in two runs of optimization.

C. The Recommended Array

1. The number of antennas

In order to get an estimate of the number of antennas as needed in the array the pseudo dynamic programming has been applied in a modified form. A smaller array consisting of 15 antennas was first optimized at a declination of 0°. Since the elliptical tracks in the u-v plane degenerate into straight lines for sources at the equator, it is very difficult to achieve a good filling of the transfer function. It is, therefore, logical to assume that an array that performs well at $\delta = 0°$ is likely to perform well at other declinations also. Additional elements were then added to the array, one at a time, on locations which were found to be the best at 0° by the optimization program. The peak and mean side-lobe levels of the increasingly larger arrays found in this manner are plotted in Fig. 3-3 as a function of the number of antennas for

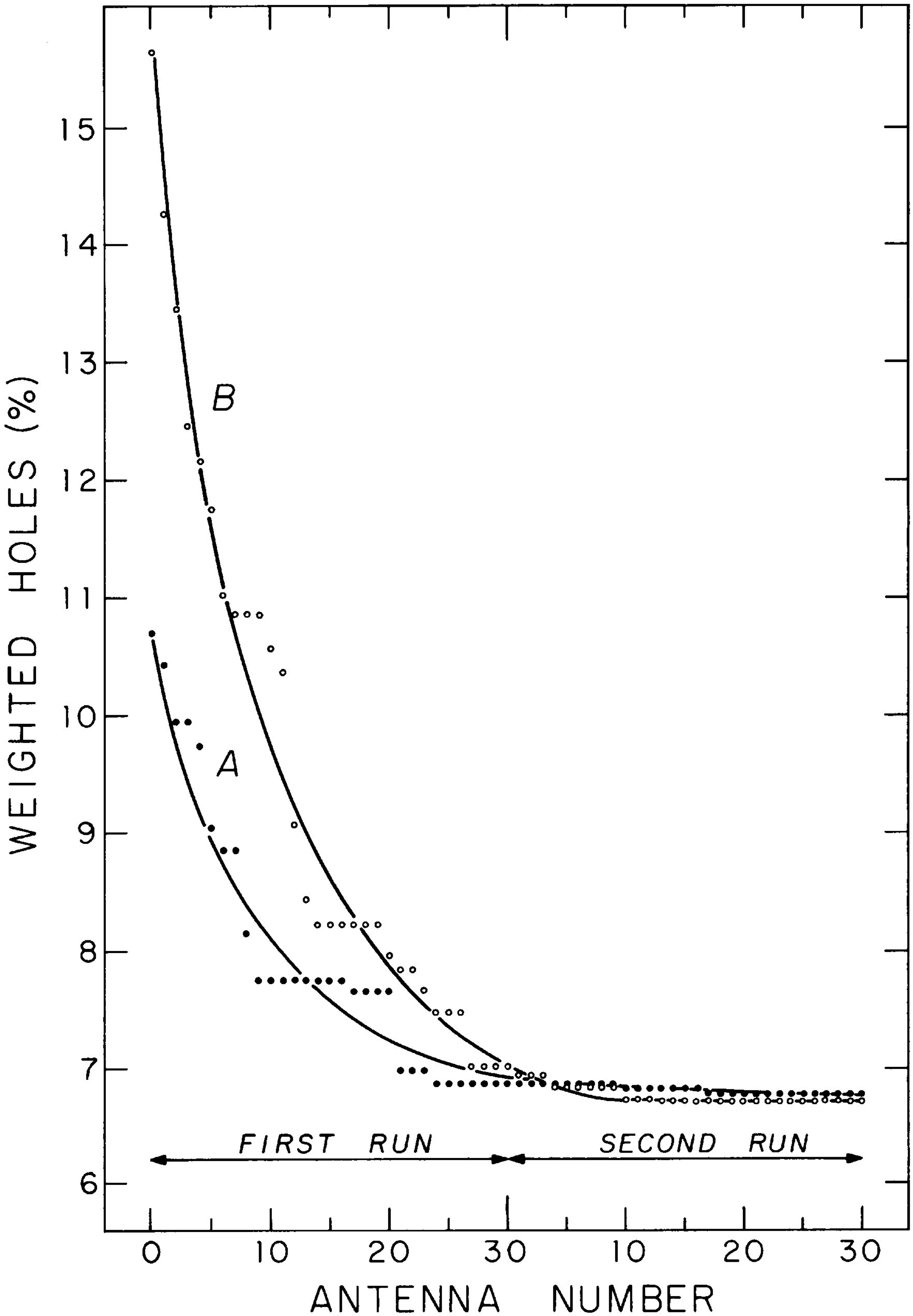


Fig. 3-2. Some results of optimization of a 30-element array. The starting configuration in each case was a wye with uniformly spaced antennas. (A) arm length 2000 m (B) arm length 1500 m.

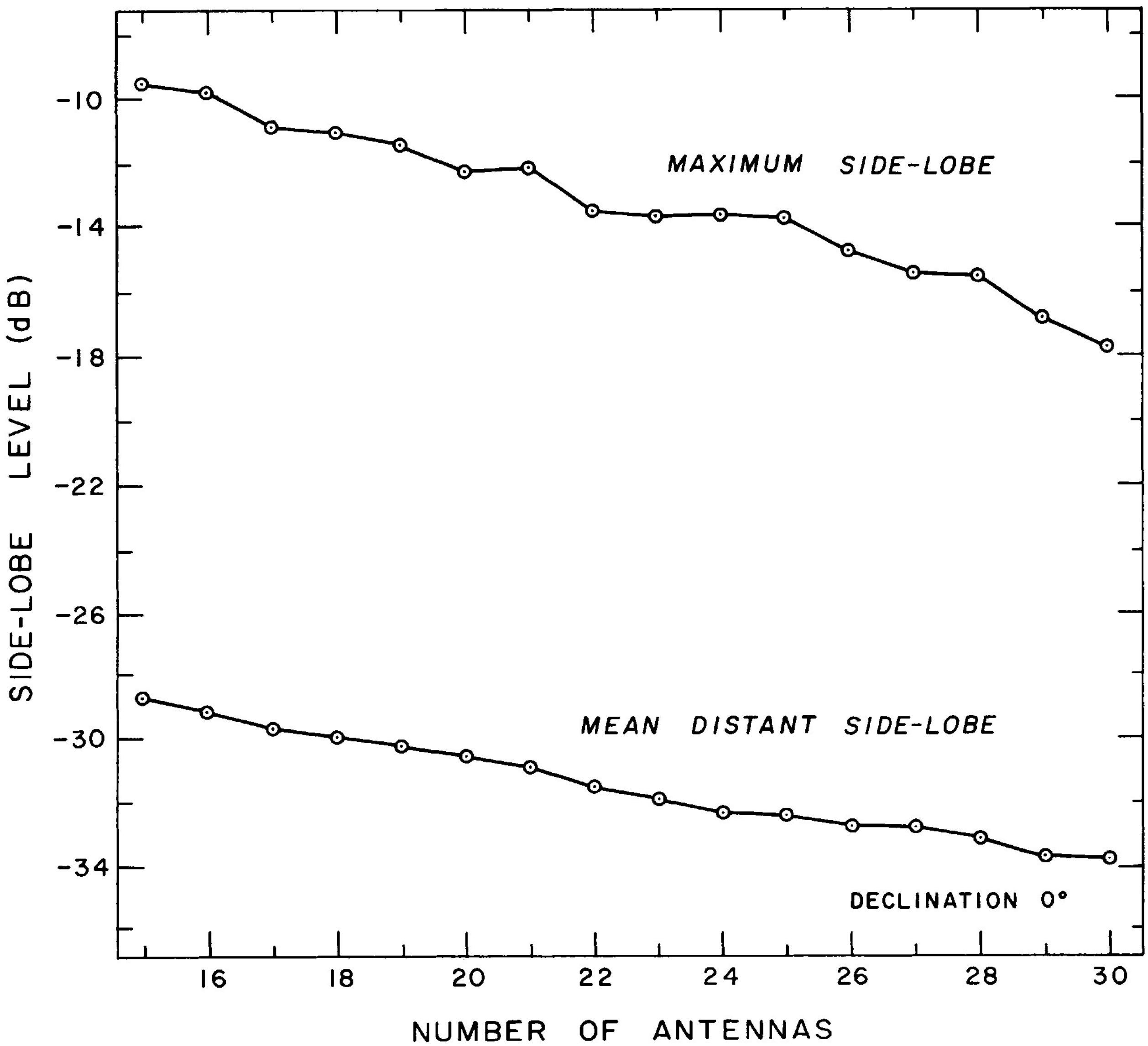


Fig. 3-3. Performance of arrays of increasing number of antennas.

$\delta = 0°$. It was found that this method of enlarging the array produced a configuration which was very good at $\delta = 0°$ but very poor at some other declinations. It, therefore, became necessary to go back to the smaller array and evaluate the performance at a number of declinations at the intermediate stages. Whenever it appeared that the array was becoming superior at $\delta = 0°$ at the cost of performance at other declinations ($\delta = -15°$ and $+20°$ were checked for this purpose) antennas were added at positions which were optimum for $\delta = -15°$ or $+20°$ rather than 0°. In this way an attempt was made to meet the sky coverage requirement of the VLA at all intermediate levels of the work. In Fig. 3-4 the performances of arrays thus obtained with N = 27, 33, and 39 are shown as a function of declination. At each declination the tracking time is either 14 hours or the time for which the source is at least 5° above the horizon, whichever is less. The arrays for the same number of elements in Fig. 3-3 and Fig. 3-4 do not have the same configuration or performance.

The final choice for the number of antennas for the VLA was made, keeping in view the performance available from optimized arrays of various sizes as indicated in Figs. 3-3 and 3-4, the increase in array cost per decibel improvement in side-lobe level and the general VLA specifications for side-lobe level, sky coverage, and sensitivity. It was decided that the smallest number of antennas that would be needed to meet the performance goals of the VLA is 27. With each antenna a 25 m dish, the sensitivity provided by the array would also be adequate.

2. The final configuration

Having decided upon the number of antennas the next step was to find the configuration that would lead to the best possible performance over the entire region of sky which is of interest. For this purpose a great deal of effort was invested in further optimizing the 27-element array whose performance is shown in Fig. 3-4. It was found that although the peak side lobe at $\delta = 0°$ could be further suppressed by perhaps 1 dB this invariably led to raising the peak side lobes at other declinations to undesirable levels. It was found that the area under the curve of

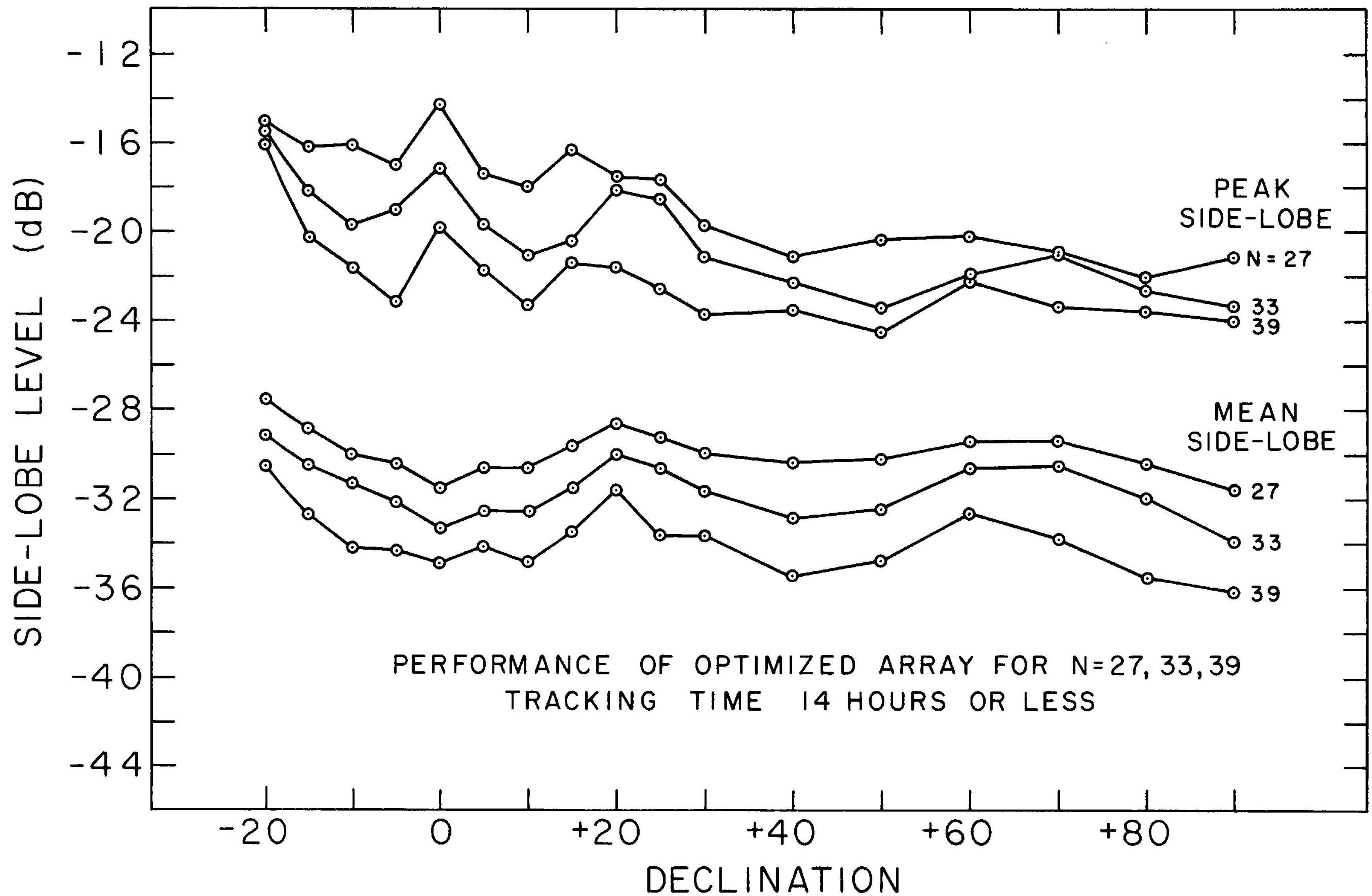


Fig. 3-4. Side lobe levels of arrays of 27, 33, and 39 elements as a function of declination.

peak side lobe vs declination remains more or less constant and any suppression at one declination leads to a rising level at another. Generally, the side-lobe levels were high at declinations around +20° and -15°. So a system was designed for further optimization. It is clear that in the performance of the array at any one declination, the different antennas have a different measure of importance. The relative importance of various antennas for $\delta = 20°$ (and also $\delta = -15°$) was found by computing the transfer function of the array with the antenna under question removed. By comparing the weighted holes for the different cases, the less critical ones were found, that is, those whose removal would hurt the performance at $\delta = 20°$ the least. These antennas were then optimized for $\delta = 0°$ in the hope of suppressing the 0° side lobe without raising the 20° side lobe. Application of a variety of techniques of this nature led to a large number of 27-element array configurations to choose from. The final choice was made keeping in view the relative importance of various declinations (and ranges of declinations) in the VLA application.

The array finally chosen is shown in Fig. 3-5 in the 1" resolution mode. Its performance is plotted as a function of declination in Fig. 3-6. The details of the various parameters are given in Table 3-1. In Table 3-2 the observing stations needed on the three arms for the four resolutions are given. The 1", 3", and 9" configurations are related to each other by a scaling factor of 3. However, for the 27" configuration a scaling factor of 3 leads to some adjacent observing stations which are too close in view of the 25 m dish size. These stations have been changed appropriately. In all, 100 observing stations will be needed. The transfer function and beam for declinations of -15°, 0°, and 20° are shown in Figs. 3-7, 3-8, and 3-9.

In Fig. 3-10 the peak and mean side-lobe levels have been plotted as a function of declination for four arrays: (a) the final 27-element array described above, (b) the 36-element "supplemented wye" array described in the VLA Proposal, Vol. I and Vol. II, (c) a 27-element uniformly spaced array with 9 equispaced antennas on each arm, and (d) the best 27-element symmetrical array. The last one has all three arms identical and was

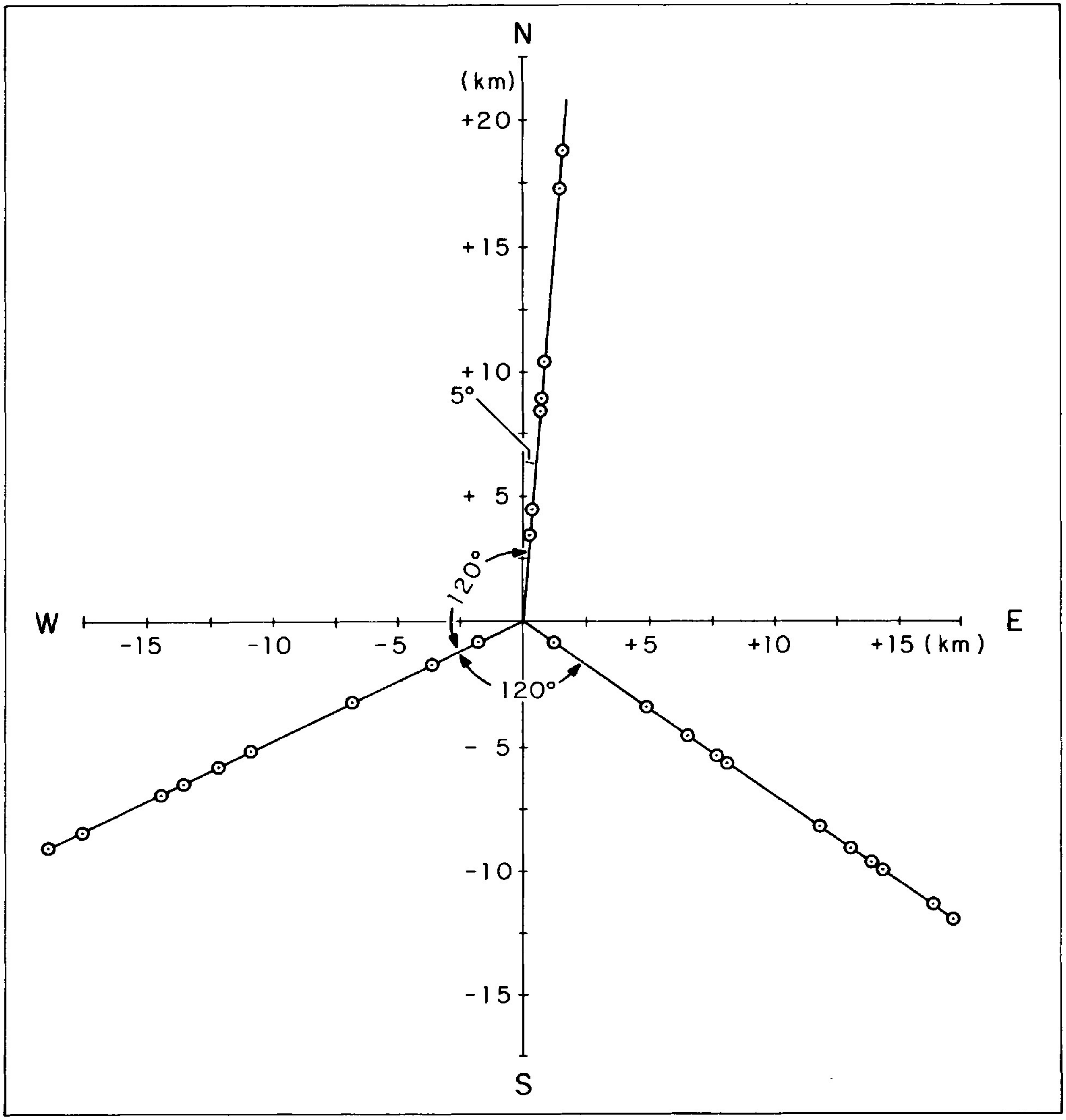


Fig. 3-5. The array configuration.

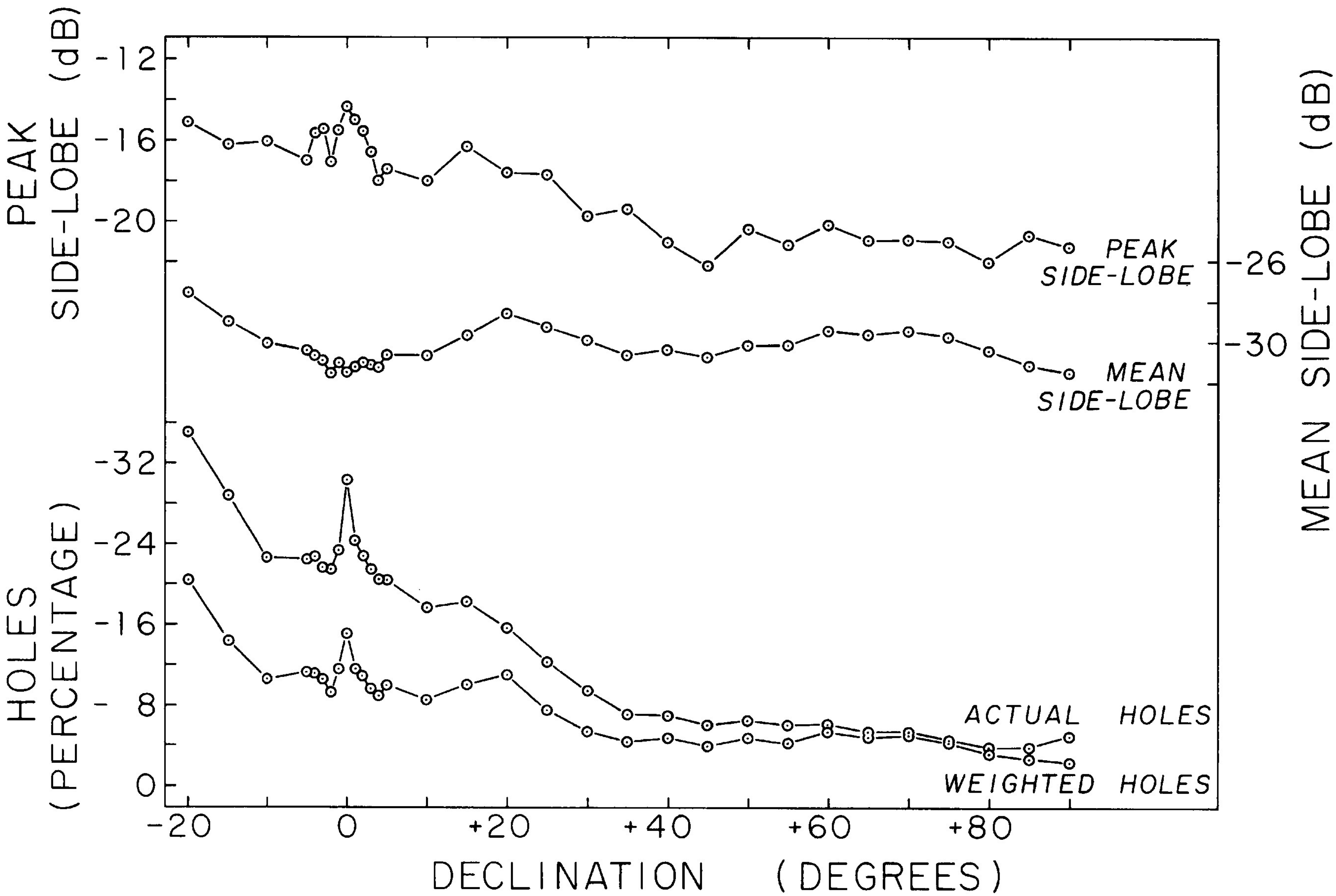


Fig. 3-6. Performance of the 27-element array as a function of declination.

TABLE 3-1

Performance of the 27-Element VLA

Declination (Degrees)	Tracking Time (Hours)	Unsampled Cells (Percentage)		Forward Gain*	Half-Power Beamwidth (Seconds)	Peak Sidelobe Level (db)					Mean Sidelobe Level (db)					
		Actual	Weighted			Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Overall Mean
-20	9.21	35.08	20.40	260	10.6 x 6.3	-15.6	-15.1	-16.1	-16.8	-18.5	-20.8	-23.1	-25.1	-26.7	-28.0	-27.5
-15	9.76	28.76	14.28	262	11.1 x 11.3	-16.2	-16.6	-17.6	-18.9	-19.4	-21.4	-24.0	-26.0	-28.0	-29.5	-28.9
-10	10.26	22.73	10.54	281	10.6 x 12.7	-16.1	-17.7	-19.3	-18.1	-18.9	-23.7	-25.8	-27.4	-28.9	-30.5	-30.0
-5	10.74	22.67	11.40	283	10.6 x 12.2	-17.0	-17.5	-17.3	-17.5	-17.0	-23.2	-25.4	-27.6	-29.3	-30.9	-30.4
-4	10.83	22.88	11.27	286	10.6 x 11.8	-16.1	-17.7	-15.6	-18.0	-17.9	-23.5	-25.1	-27.1	-29.5	-31.2	-30.6
-3	10.92	21.86	10.55	292	10.5 x 11.6	-15.4	-17.3	-17.4	-17.4	-16.9	-23.8	-26.1	-27.8	-29.8	-31.4	-30.9
-2	11.01	21.49	9.44	295	10.6 x 11.3	-17.1	-18.5	-18.3	-17.5	-18.0	-23.6	-25.8	-28.2	-30.0	-32.1	-31.4
-1	11.10	23.62	11.86	290	10.4 x 11.4	-16.3	-16.3	-16.9	-17.4	-15.5	-23.4	-24.3	-27.5	-29.9	-31.7	-31.0
0	11.19	30.43	15.34	274	10.0 x 12.3	-15.7	-16.7	-14.9	-17.5	-14.3	-23.2	-25.0	-27.9	-30.3	-32.1	-31.5
1	11.29	24.37	11.90	287	10.6 x 11.5	-17.8	-17.3	-17.8	-17.7	-14.9	-24.0	-24.7	-27.5	-30.2	-31.8	-31.2
2	11.38	22.98	11.14	300	10.5 x 11.8	-18.0	-17.7	-17.0	-17.6	-15.5	-23.9	-26.0	-27.9	-29.9	-31.6	-31.0
3	11.46	21.43	9.86	292	10.5 x 11.3	-16.6	-17.3	-16.9	-17.4	-17.8	-24.3	-25.8	-27.9	-30.0	-31.7	-31.1
4	11.55	20.65	9.09	290	10.4 x 11.3	-18.9	-18.0	-18.3	-19.1	-18.9	-24.4	-26.2	-28.1	-30.0	-31.8	-31.2
5	11.64	20.58	10.08	292	10.4 x 11.4	-19.2	-17.8	-19.4	-17.8	-17.4	-24.0	-25.9	-28.0	-29.3	-31.1	-30.6
10	12.09	17.96	8.57	298	10.4 x 11.2	-18.0	-18.4	-20.0	-19.8	-19.3	-25.1	-26.4	-28.1	-29.4	-31.2	-30.6
15	12.55	18.41	10.11	297	10.0 x 11.2	-16.3	-18.3	-19.4	-18.7	-20.0	-23.1	-25.4	-27.3	-28.6	-30.1	-29.6
20	13.02	15.90	11.31	309	9.7 x 11.0	-17.6	-17.7	-18.0	-19.6	-19.2	-22.8	-25.1	-26.2	-27.9	-28.9	-28.5
25	13.53	12.38	7.84	323	9.9 x 10.8	-17.7	-18.8	-20.2	-20.8	-21.1	-24.5	-26.2	-27.2	-28.9	-29.5	-29.2
30	14.00	9.49	5.76	339	9.9 x 10.6	-19.7	-19.8	-20.4	-22.5	-22.6	-24.5	-26.7	-28.2	-29.4	-30.2	-29.9
35	14.00	7.30	4.47	344	9.8 x 10.6	-19.4	-23.0	-21.8	-22.7	-22.1	-26.3	-28.2	-29.2	-30.2	-30.8	-30.6
40	14.00	7.14	4.77	350	9.8 x 10.5	-21.1	-21.7	-22.2	-22.9	-21.9	-26.4	-28.5	-28.8	-29.8	-30.6	-30.3
45	14.00	6.24	4.14	343	9.9 x 10.5	-22.6	-22.2	-23.2	-23.5	-23.5	-28.0	-28.5	-29.7	-30.1	-31.0	-30.7
50	14.00	6.68	4.77	351	9.9 x 10.4	-20.4	-21.4	-22.2	-22.9	-22.3	-26.1	-27.2	-28.8	-29.7	-30.4	-30.1
55	14.00	6.11	4.58	348	9.9 x 10.4	-21.2	-21.4	-21.1	-22.8	-22.6	-27.0	-27.4	-28.5	-30.0	-30.2	-30.1
60	14.00	6.23	5.51	353	9.9 x 10.3	-20.8	-20.2	-21.4	-21.9	-21.9	-26.4	-26.9	-28.4	-28.9	-29.6	-29.4
65	14.00	5.49	4.92	354	9.9 x 10.3	-20.9	-21.5	-22.3	-21.1	-22.8	-27.3	-26.6	-28.4	-29.2	-29.8	-29.6
70	14.00	5.37	5.14	357	9.9 x 10.2	-21.6	-20.9	-22.4	-22.0	-21.2	-26.4	-26.4	-27.8	-29.1	-29.6	-29.4
75	14.00	4.55	4.32	365	10.0 x 10.2	-22.3	-21.0	-21.7	-22.5	-22.4	-26.7	-26.8	-27.8	-29.6	-30.0	-29.7
80	14.00	3.92	3.30	371	10.0 x 10.3	-22.9	-22.5	-22.0	-23.4	-23.2	-28.2	-28.9	-28.5	-30.3	-30.6	-30.4
85	14.00	3.99	2.64	380	10.1 x 10.3	-20.7	-22.8	-23.3	-24.3	-23.5	-26.4	-28.0	-29.4	-31.0	-31.3	-31.1
90	14.00	4.81	2.29	380	10.3 x 10.3	-21.2	-24.1	-22.8	-24.7	-24.6	-28.8	-30.2	-30.1	-31.3	-31.7	-31.5

Note: The zones are square annuli, lying at the following distances from the center of the main beam: Zone 1, 23".4 - 42"; Zone 2, 42" - 79".2; Zone 3, 79".2 - 153".6; Zone 4, 153".6 - 303"; Zone 5, 303" - 600". For fields of view other than 20', these numbers should be multiplied by the appropriate factor.

*This is the gain in sensitivity over a two-element interferometer integrating for one minute.

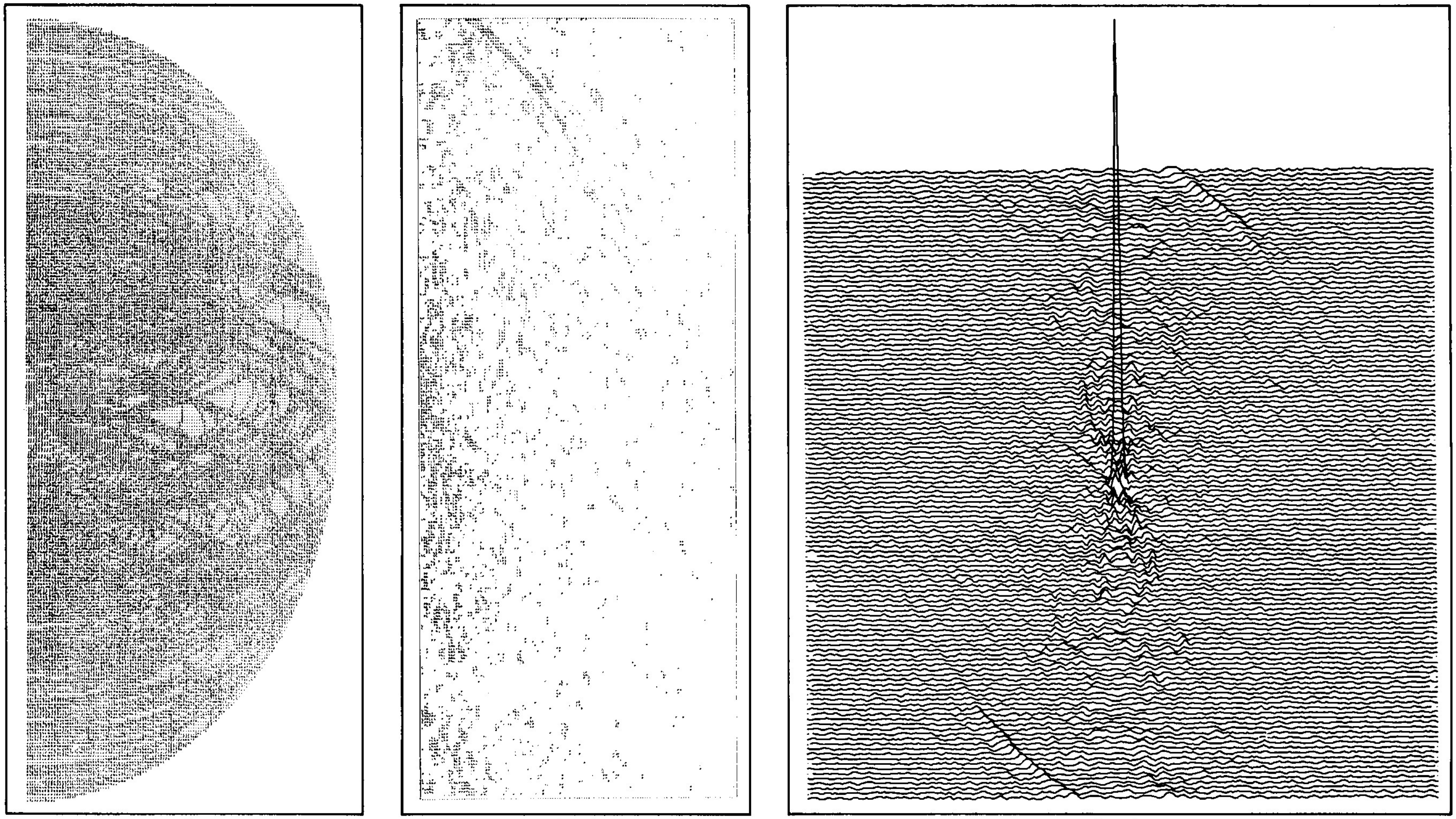
TABLE 3-2

LOCATIONS OF OBSERVING STATIONS FOR THE VLA

(All distances are in meters from the center of the Wye)

North Arm				South-East Arm				South-West Arm			
1"	3"	9"	27"	1"	3"	9"	27"	1"	3"	9"	27"
3500.00	1166.67	388.89	129.63	1500.00	500.00	166.67	55.56	2000.00	666.67	222.22	74.07
4500.00	1500.00	500.00	166.67	6000.00	2000.00	666.67	222.22	4000.00	1333.33	444.44	148.15
8500.00	2833.33	944.44	314.81	8000.00	2666.67	888.89	296.30	7500.00	2500.00	833.33	277.78
9000.00	3000.00	1000.00	388.89	9500.00	3166.67	1055.56	340.00	12000.00	4000.00	1333.33	444.44
10500.00	3500.00	1166.67	500.00	10000.00	3333.33	1111.11	370.37	13500.00	4500.00	1500.00	500.00
17500.00	5833.33	1944.44	648.15	14500.00	4833.33	1611.11	537.04	15000.00	5000.00	1666.67	555.56
19000.00	6333.33	2111.11	703.70	16000.00	5333.33	1777.78	592.59	16000.00	5333.33	1777.78	592.59
				17000.00	5666.67	1888.89	629.63	19500.00	6500.00	2166.67	722.22
				17500.00	5833.33	1944.44	666.67	21000.00	7000.00	2333.33	777.78
				20000.00	6666.67	2222.22	740.74				
				21000.00	7000.00	2333.33	777.78				

Total number of observing stations = 100



(a) (b) (c)

Fig. 3-7. The performance at $\delta = -15°$. (a) The transfer function. (b) The beam pattern. This is a 10' x 20' plot of the beam. Blanks represent power level below -25 dB. Integers represent side lobe level in dB. Letters A through P represent side lobe levels -10 through -25 dB, respectively. (c) Calcomp plot of the beam pattern. The full 20' x 20' beam is plotted. Cross sections in right ascension are plotted at declination intervals of 9".4.

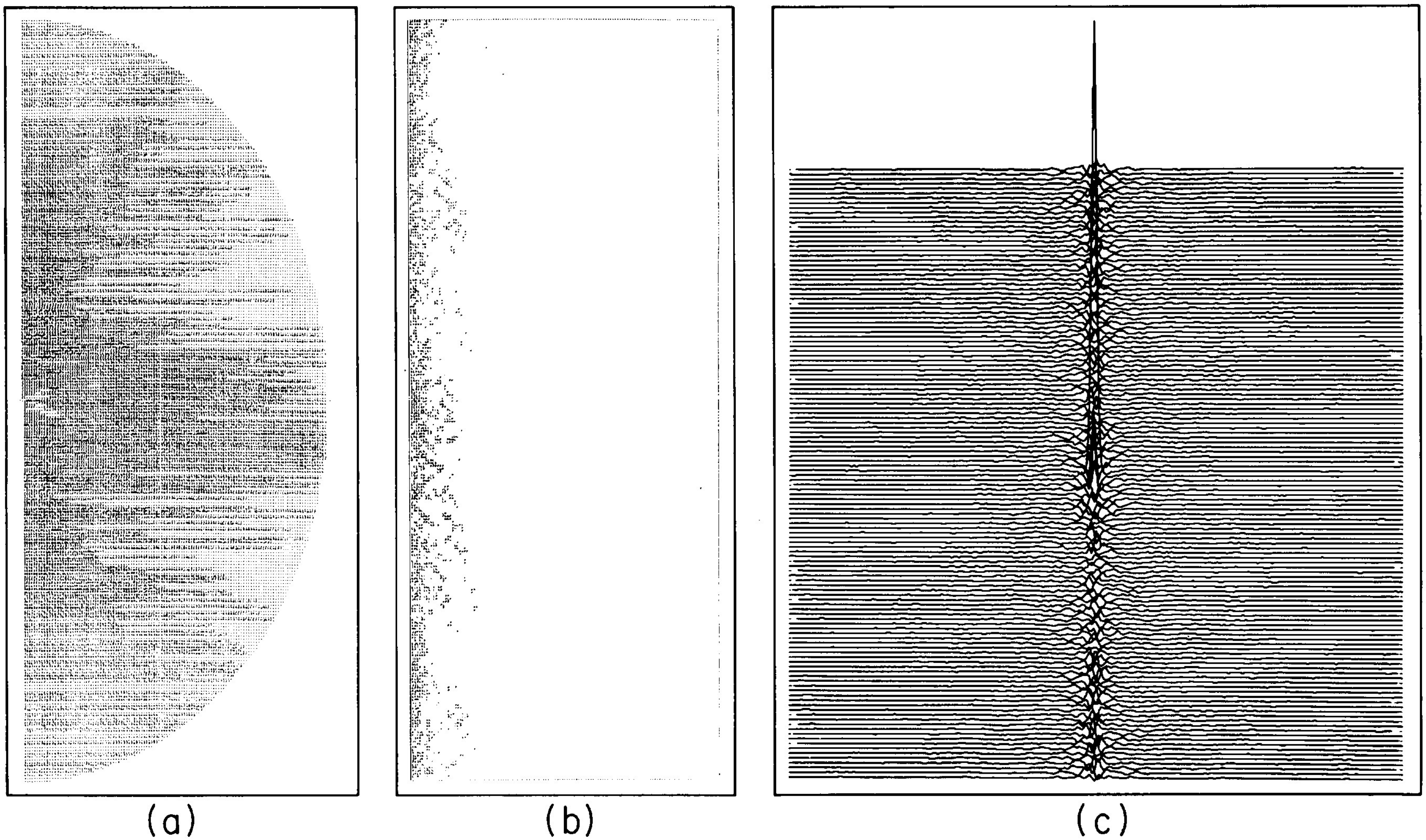
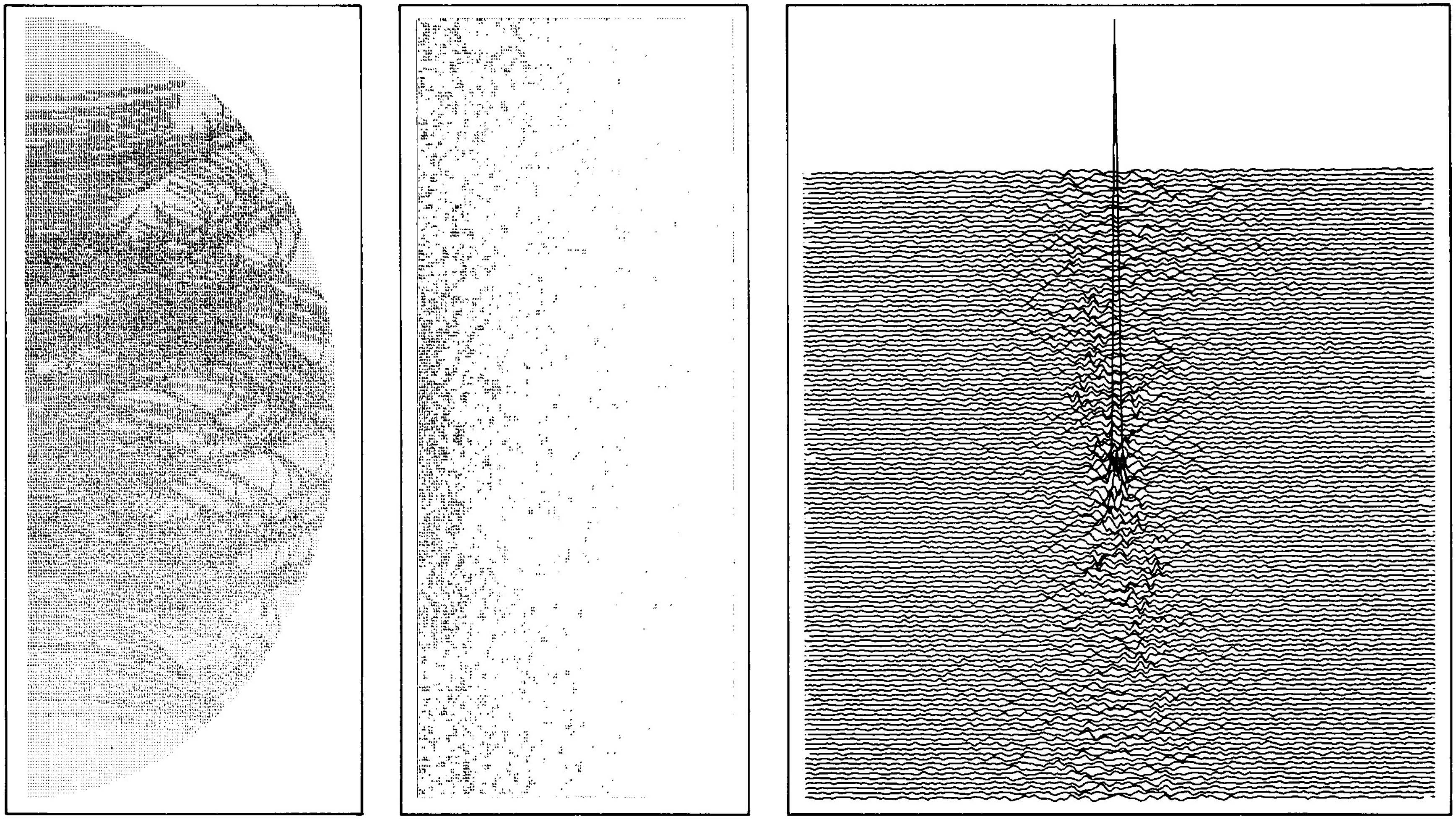


Fig. 3-8. The performance at $\delta = 0°$. The method of plotting is the same as in Fig. 3-7.



(a) (b) (c)

Fig. 3-9. The performance at $\delta = 20°$. The method of plotting is the same as in Fig. 3-7.

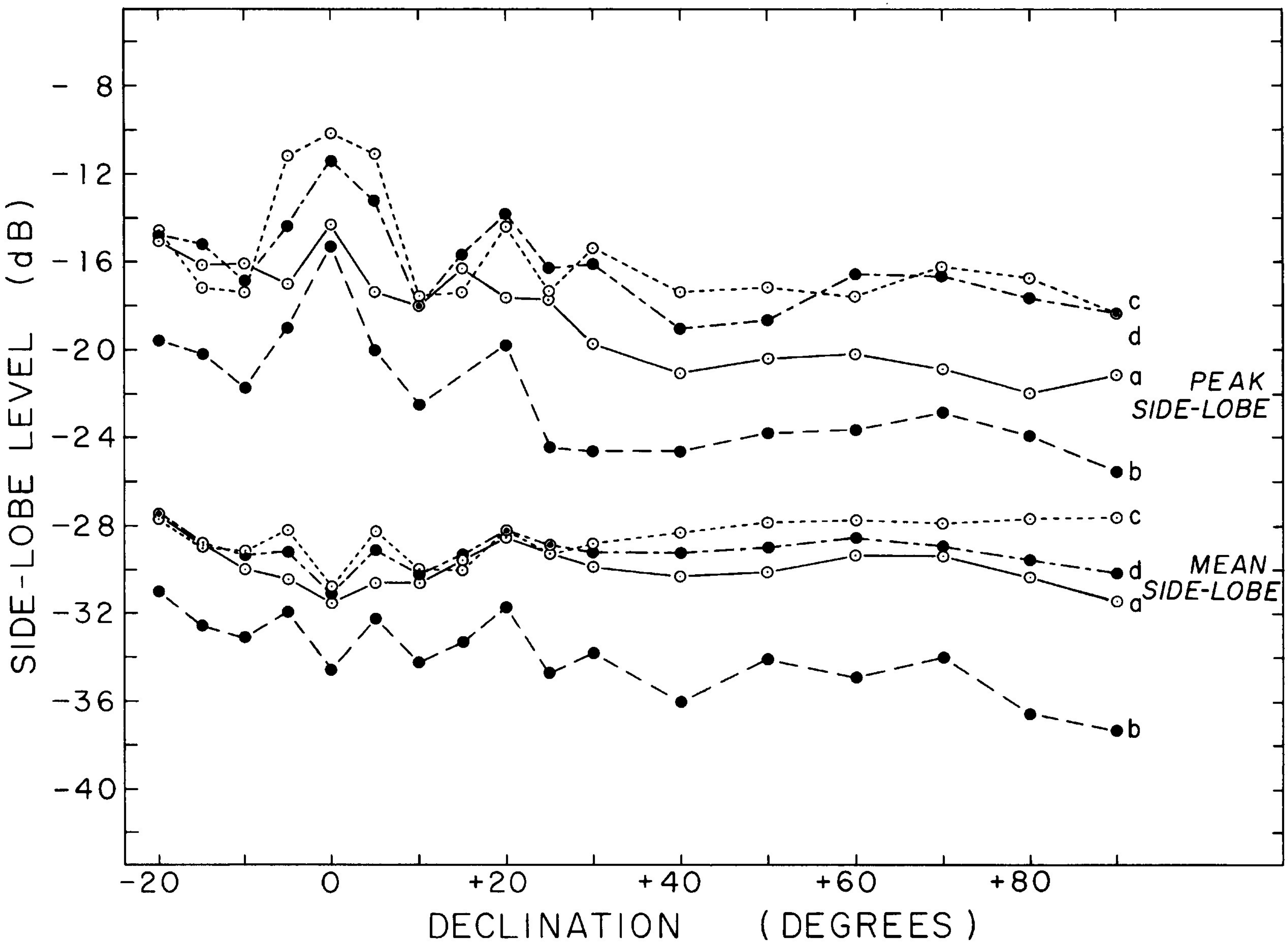


Fig. 3-10. A comparison of performance of several arrays. (a) Final 27-element array. (b) 36-element supplemented wye as in proposal. (c) 27-element uniform wye. (d) 27 element symmetrical wye (optimized).

optimized by making relative changes in antenna positions on one arm, but keeping the three arms identical. It is seen from Fig. 3-10 that the 27-element arrays having symmetrical arms are considerably inferior in performance to the array (curve a) in which the three arms are unsymmetrical. It is, therefore, worthwhile to adopt the unsymmetrical configuration.

D. Bandwidth Effect

1. The role of the bandwidth

The use of a rectangular sampling grid in the u-v plane leads to a beam pattern that is repetitive, that is, there are grating lobes which are identical to the main beam and are separated from it by a distance (defined as the field of view) which is the reciprocal of the size of the grid used for sampling the u-v plane. These grating lobes are to be distinguished from the side lobes which arise due to insufficient sampling of the cells in the u-v plane. (The grating lobes will be reduced in size due to the smearing effect of integrating over one-minute intervals along the elliptical tracks). The design of the array, discussed in the preceding sections, is based on the occurrence of grating lobes at 20' from the main beam. The configuration is designed to give a resolution of 10" and the sampling of the cells (based on a 20' field of view) is adequate to keep the side lobes within the acceptable limits. The grating lobes, which can be a source of confusion, are effectively suppressed by the dish pattern which is about 17' (25 m dish at 11 cm wavelength). If the array is contracted to be operated in the 27" resolution mode, the sampling would be even better for the same field of view, and, consequently, the side lobes smaller. However, when the array is expanded to provide higher resolution (3" and 1") it is necessary to analyze the performance in more detail. This can be done in one of two ways. (i) One can increase the grid size correspondingly, thus keeping the sampling the same. This would result in preserving the beam shape and side-lobe structure. However, there would be a change in the scale, that is, the grating lobes would move in closer. With a fixed field of view to resolution ratio of 120, the grating lobes would occur at 6' and 2' for the

3" and 1" resolutions, respectively. The primary dish pattern will not be able to suppress the grating lobes effectively and there will be greater possibility of confusion. (ii) Alternately, one can keep the sampling interval the same. This would keep the distance of the grating lobes unchanged and they would still be effectively suppressed by the primary dish pattern. But now the sampling will be much poorer, resulting in greater side lobes. The use of a wide bandwidth in the IF system is aimed at improving the sampling and thus reducing these side lobes to within the acceptable limits.

In the one-dimensional analysis of a correlator interferometer an exact equivalence exists between monochromatic operation with directional antennas and wideband operation with isotropic antennas (Swenson and Mathur, 1969). Thus in a plane containing the baseline, the response of the interferometer can be restricted to a small angular width of the sky either by the use of large dishes or by the use of a wide bandwidth. Alternately, one can look at the wideband interferometer as a spatial frequency filter which passes a band of spatial frequencies. This band is centered at the spatial frequency corresponding to monochromatic operation and lies along the effective baseline in the u-v plane. The width of the band is directly proportional to the length of the baseline and to the IF bandwidth (MacPhie, 1967). Thus by using a wideband IF system one can improve the sampling in the u-v plane and thereby reduce the side lobes. The bandwidth effectively produces a "smearing" in the transfer function.

2. The choice of the bandwidth

In order to determine the necessary bandwidth one must compute the transfer function for 1" configuration using a sampling interval corresponding to the 17' primary dish pattern and including the effect of bandwidth smearing. The number of cells in this transfer function is so large that it will require a matrix of the order of 2000 x 2000 points to store it for the purpose of beam determination by Fourier transformation. This is beyond the capacity of the IBM 360/50 computer and so a detailed analysis of the bandwidth effect is not feasible. However, it is possible to consider two cross sections of the beam and to study the effect of bandwidth on them. For the beam cross sections in right ascension (east-west) and declination (north-south) we have

$$B(x,0) = \frac{1}{C} \sum_{k=-K}^{K} \left[\sum_{\ell=-L}^{L} W_{k,\ell} \right] e^{-j2\pi k\Delta u \cdot x}$$

$$B(0,y) = \frac{1}{C} \sum_{\ell=-L}^{L} \left[\sum_{k=-K}^{K} W_{k,\ell} \right] e^{-j2\pi \ell\Delta v \cdot y}$$

In order to determine these cross sections, one needs to perform only a one-dimensional Fourier transformation. For the cross section in right ascension, for example, one determines the weighting of each of the cells on the u-axis. The k^{th} cell will have a weighting determined by the number of times a value of u lying between $k\Delta u$ and $(k+1)\Delta u$ is encountered (irrespective of the value of v). After computing the weighting of the cells for all possible antenna pairs and each minute of the observing time, a one-dimensional Fourier transformation is carried out to determine the beam cross section. It should be noted that in this method of computation it is not possible to use the Gaussian taper given to the transfer function in the earlier analyses. The weighting in this case is governed entirely by the number of minutes of integration time given to each cell. It should be remembered, therefore, that the side lobes obtained can be further reduced by analysing the entire transfer function in a computer of appropriate size.

The effect of bandwidth smearing is taken into account in the following way. After the value of u is computed for a particular baseline at a particular time, all cells lying in the range of u from $(1-\alpha)u$ to $(1+\alpha)u$ are given an increment of $(2\alpha u)^{-1}$. Here α is the fractional IF bandwidth B/ν_o.

A computer program was written to carry out these computations and to determine the beam cross sections in right ascension and declination. It used a sampling interval corresponding to a 17' field of view. The one-dimensional Cooley-Tukey algorithm was used for Fourier transformation. The program was checked for any errors in two ways. Firstly, it was used to compute the beam cross sections for a 10" resolution array with zero bandwidth. These were compared with the cross sections computed by the regular beam program which was used in all the design studies. Although this latter program computes less points on the beam, there was complete agreement in the values at points computed by both the programs. Secondly, the program was used to compute the beam of a linear, uniformly spaced, nontracking array with zero bandwidth. The beam of such an array can be computed relatively easily by a simple formula. Again, there was complete agreement between the values obtained by the two methods.

The extent to which side lobes are suppressed by bandwidth for the 27-element VLA configuration considered in section C are shown as a function of bandwidth in Fig. 3-11. Three declinations, -15°, 0°, and 30°, are considered. In each case the peak and mean side lobes in the outer half of the field of view are plotted for cross sections in declination and right ascension for two configurations corresponding to 1" and 3" resolution. It is clear that although increasing bandwidth causes decreasing side lobes, the rate of decrease has an exponential form.

It was decided, on the basis of the curves plotted in Fig. 3-11, that an IF bandwidth of 35 MHz would provide adequate side-lobe suppression for the higher resolution modes.

Some typical results of the use of a 35 MHz bandwidth are shown in Fig. 3-12. Here the peak and mean side lobes in 1' intervals of the beam are plotted for four declinations, -15°, 0°, 30°, and 60°. The zones indicate one-minute intervals of the beam. Both cross sections are plotted for the 1" and 3" arrays.

It is seen that, with the exception of $\delta = 0°$, the peak side lobes do not exceed -16 dB for any of the configurations or declinations in the two cross sections considered. The beam cross section in declination for $\delta = 0°$ is very poor. The reason is again the fact that the elliptical tracks degenerate into straight lines parallel to the u-axis at $\delta = 0°$.

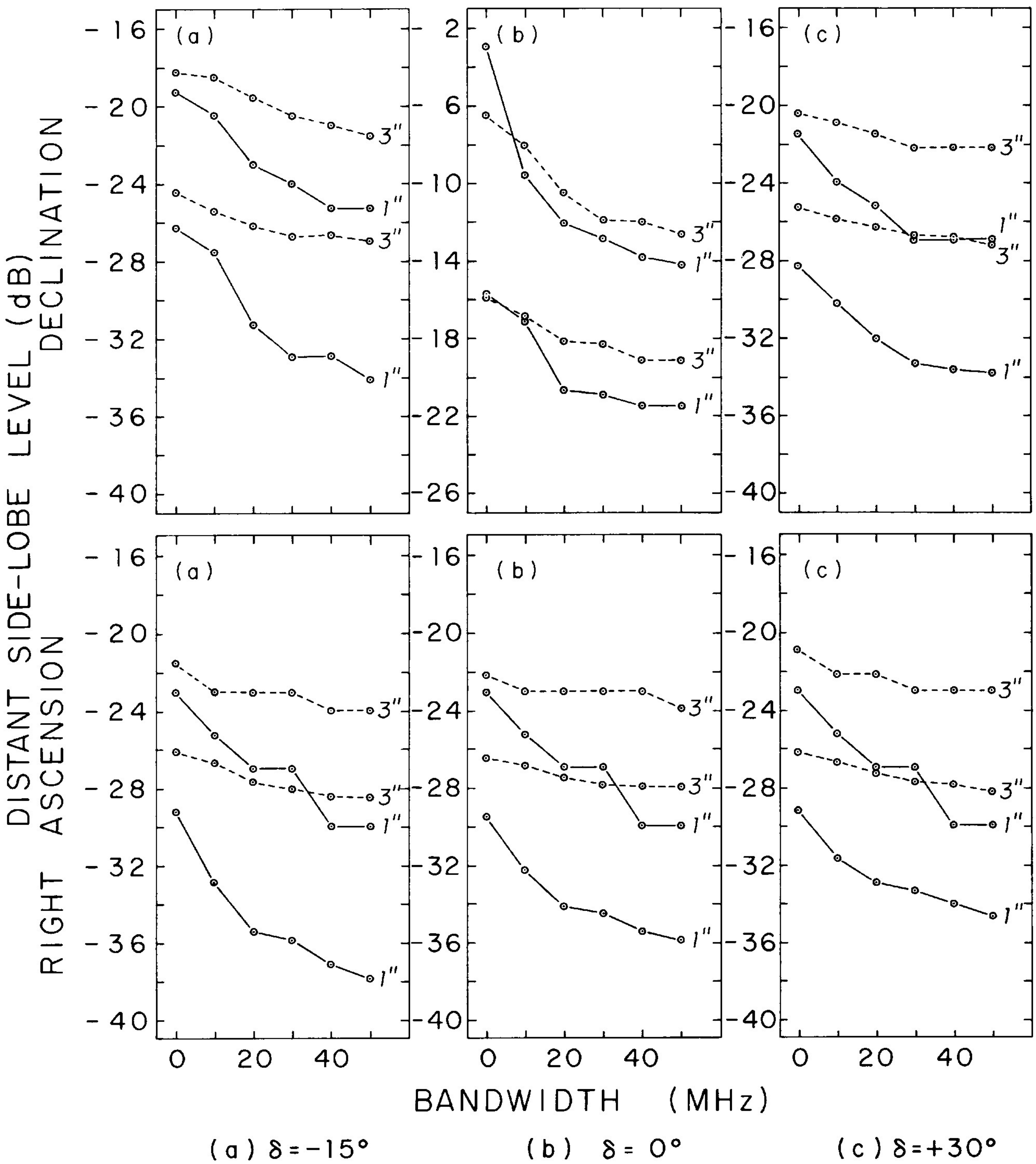


Fig. 3-11. Peak and mean side lobe levels as a function of bandwidth.

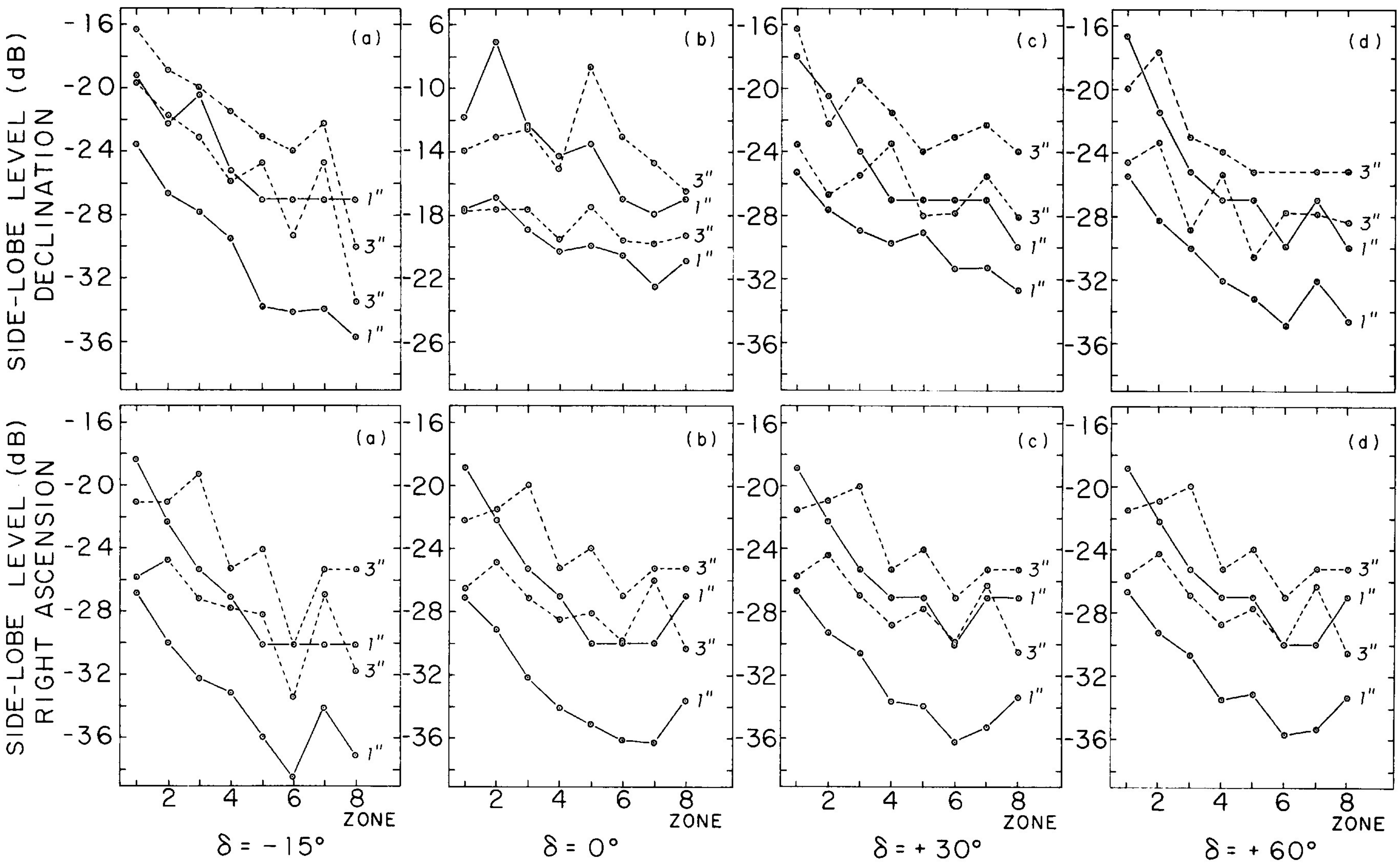


Fig. 3-12. Peak and mean side lobes for the 27-element array using a 35 MHz bandwidth. The zones are 1' intervals across the beam. The total field of view is 17'.

This results in a beam which is very good in right ascension but has large side lobes in declination. The region near $\delta = 0°$ has been analyzed in greater detail and the results are presented in Fig. 3-13 for the 1" and 3" arrays. It is apparent that in a region of the sky in the range of $\pm$ 3° the beam cross section in declination has side lobes in excess of -14 dB for the 1" and 3" resolution modes.

E. Effect of Antenna Failure

In the operation of an instrument of the size of the VLA, having 27 fully steerable 25 m diameter antennas located as far away as 21 km from the central control building and involving highly complicated electronics, it is realistic to expect that not all of the antennas will operate all of the time. A variety of mechanical and electronic troubles can cause one or more antennas to become inoperative during parts of the observation. It is important to assess the effect of this kind of failure on the performance of the array. Since the effect is different for different down times, a detailed study of antenna failure will involve a large amount of computation. This has not been carried out at this time. However, a limited study has been made to get an idea of the extent of deterioration in performance due to the failure of a few antennas.

For the purpose of this study the performance at 0° declination has been considered. The performance has been evaluated for configuration in which 1, 2, 3, or 4 antennas are inoperative during the entire observation. Fig. 3-14(a) shows the deterioration in performance at $\delta = 0°$ as a function of the number of antennas inoperative. This represents an upper limit to the deterioration in performance since the antennas chosen were those that effect the performance at $\delta = 0°$ the most. A typical degradation in performance at $\delta = 30°$ is shown in Fig. 3-14(b). It is seen that the performance, though much degraded, is still within the acceptable limits.

This limited study of the effect of antenna failure indicates that the observing need not be stopped even if as many as four antennas become inoperative, although it may become necessary to change to a new observation program at, for example, a different declination.

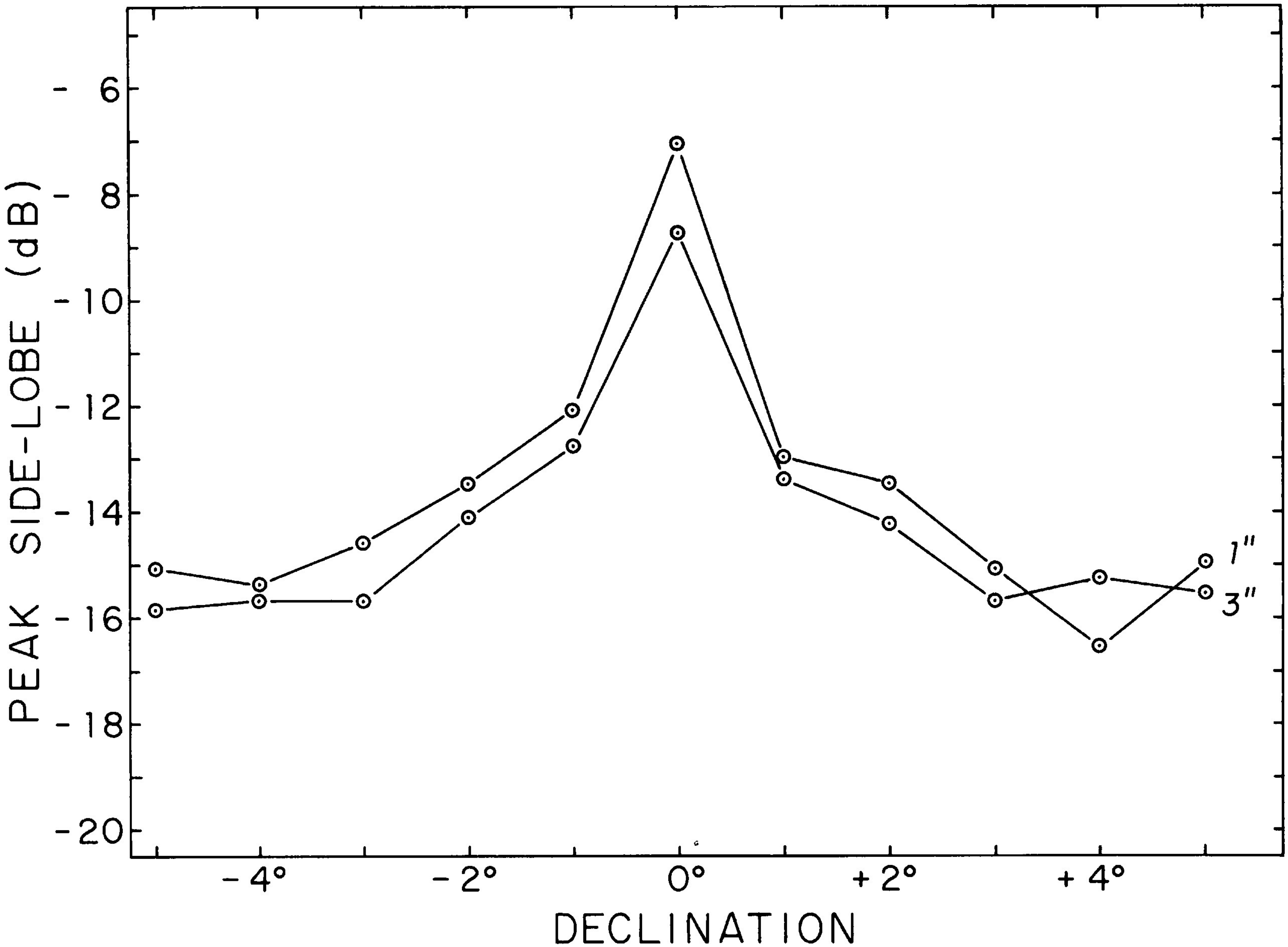


Fig. 3-13. The performance near $\delta = 0°$. The beam cross section in declination is considered.

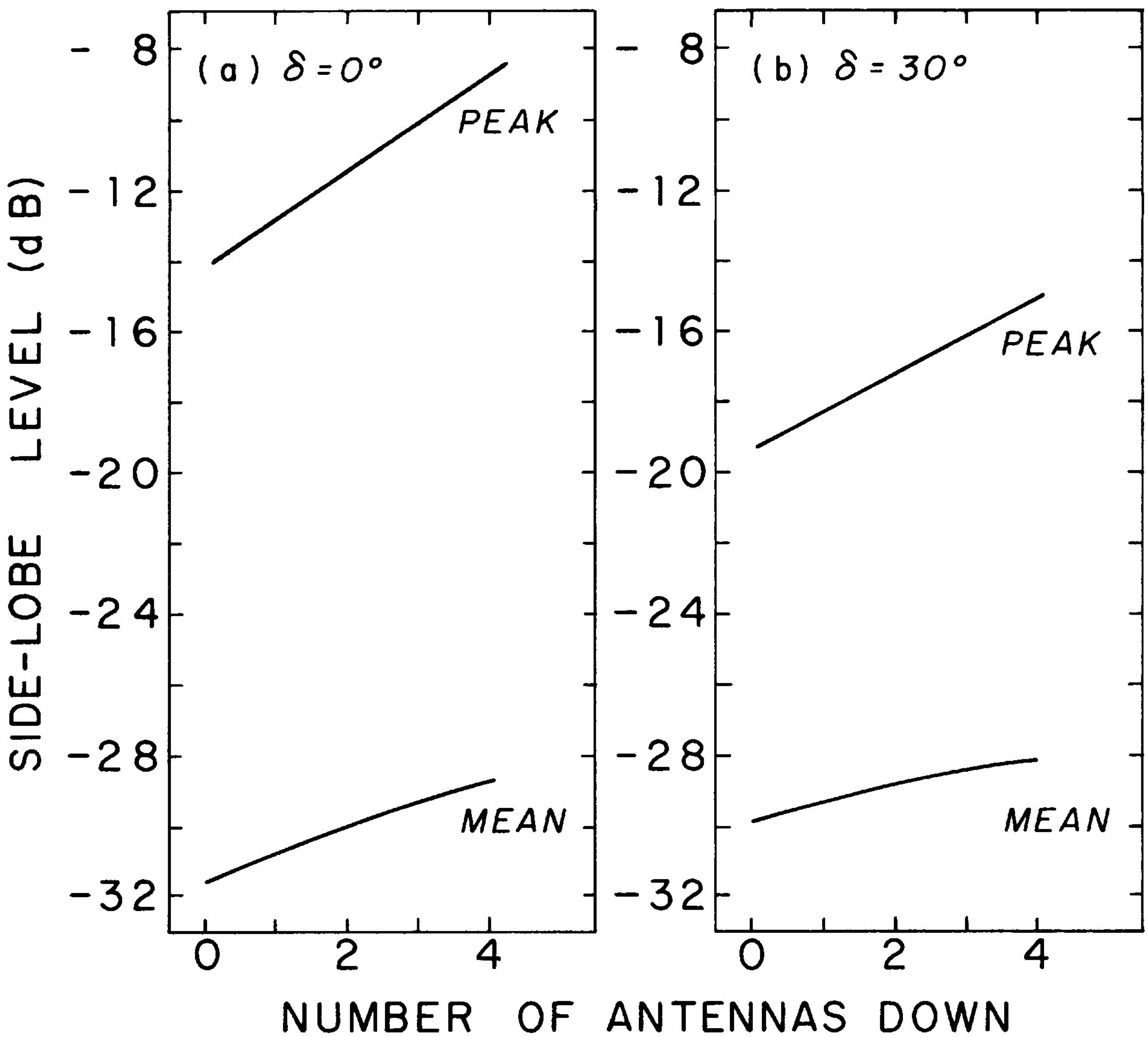


Fig. 3-14. Deterioration in performance due to antenna failure.

F. The Sub-VLA

In this section some arrays which can be considered as the first step in the construction of the VLA are evaluated. In each case the sub-VLA is a twelve-element array which will be capable of some very useful radio astronomy and will be expandable to the full VLA at a later stage. Arrays for two types of applications have been considered - continuum observation and spectral line observation.

1. Continuum array

For continuum observations arrays have been considered with the same parameters as the VLA, viz, operating wavelength of 11 cm and field of view 20'. Various configurations of the 12 antennas over various arms of the wye were analyzed. A two-arm or one-arm configuration cannot, obviously, provide the full sky coverage specified for the VLA. Limited optimization has accordingly been carried out for a declination of 40°. The performances of a few configurations are summarized in Table 3-3. The tapered configurations in this table refer to an element location following the law $d_n = k.n^{1.5}$ where k is adjusted to make the arm length 2100 m. The minimum redundancy array uses the configuration

•1•2•3•7•7•7•7•7•7•4•4•1•

The dots represent antennas and the figures in between represent the relative spacing. This configuration is based on Leech's work (Leech, 1956), and this has all the spacings from 1 to 50. If used with a field of view to resolution ratio of 50 at δ = 90° it will produce a transfer function with no holes. However, the figures in Table 3-3 correspond to the case in which the unit spacing is chosen to give an overall array length of 2100 m and a field of view of 20'. The peak and mean side lobe at δ = 40°, 60°, and 80° are indicated. For declinations 0° and lower the peak side lobes are in excess of -5 dB. The antennas are assumed to track the source for the entire time the source is above the horizon. The results given in Table 3-3 show that the minimum redundancy array is not necessarily the best configuration when the aim is to synthesize an aperture designed to map a large field of view at a high resolution.

TABLE 3-3

Performance of 12-Element Sub-VLA For Continuum Observations

		Sidelobes(db)					
		δ = 40°		δ = 60°		δ = 80°	
Arm of Y	Element Arrangement	Peak	Mean	Peak	Mean	Peak	Mean
S-E and S-W	Tapered, 6 on each[1]	-15.0	-25.2	-14.6	-26.2	-13.7	-26.1
North only	Minimum Redundancy[2]	- 9.1	-24.2	-12.9	-26.3	-14.3	-28.9
	Tapered[2]	- 9.0	-23.3	-13.4	-24.9	-16.8	-25.9
	Optimized[3]	- 9.9	-24.1	-13.5	-25.6	-15.0	-27.1
S-E only	Minimum Redundancy[2]	-10.3	-26.2	-16.5	-28.9	-10.6	-27.5
	Tapered[1]	-11.1	-24.9	-18.2	-26.9	-15.5	-27.0
	Optimized[3]	-11.6	-25.9	-17.0	-27.7	-18.0	-28.0
S-W only	Minimum Redundancy[2]	- 9.8	-26.9	-12.0	-27.7	- 9.8	-27.2
	Tapered[1]	-12.2	-25.1	-18.3	-27.0	-14.8	-27.0
	Optimized[3]	-11.8	-26.0	-17.5	-28.0	-16.8	-28.0

[1] Tapered spring is given by $d_n = k_n^{1.5}$ with k chosen to make arm length 2100m.

[2] The minimum redundancy array is based on Leech's work and has all baselines from one to fifty times the unit spacing.

[3] Optimized at δ = 40°. Element distances from center are (in meters)

North arm: 100,200,250,525,600,1250,1325,1500,1550,1950,2075,2100.

S-E arm: 50,150,200,700,875,900,1325,1475,1700,1775,1850,2100.

S-W arm: 0,50,100,200,500,900,1125,1325,1500,1850,2075,2100.

2. Spectral line array

Arrays operating at 21 cm wavelength for hydrogen-line work have now been studied. The field of view is taken as 35', and the resolution required is of the order of 1'. The arm length is, therefore, of the order of 700 m. Emphasis has been placed on the equatorial region of the sky. Several types of arrays were considered using the wye as the basic configuration. Although only a limited amount of work has been done, it is sufficient to give an idea of the order of magnitude of the side lobes to be expected from a 12-element array used for hydrogen line work. Some optimization was carried out at $\delta = 0°$, both on the wye and over an elliptical area of a size appropriate for a 1' circular beam at $\delta = 0°$. The latter optimization was very time consuming since each antenna was optimized over almost 1000 stations. However, it brought out the interesting result that even though the antennas were free to occupy any position on an elliptical area, their final positions were close to, or on, the wye. This lends strong support to the choice of the wye as the basic configuration. The performance of three different configurations over a range of declinations is summarized in Table 3-4. These figures are merely indicative of the order of magnitude of side lobes, and it appears likely that more comprehensive optimization will lead to considerably better performance.

As a result of these limited studies it is felt that a smaller array can be designed which will be capable of future expansion to the full VLA. Such an array could be a very useful instrument for both continuum and spectral line studies. If such an approach is to be adopted for the construction of the VLA, further configuration studies will be needed to determine how best to use a smaller number of antennas.

REFERENCES

Bracewell, R. N. 1962, "Radio Astronomy Techniques", Handbuch der Physik, ed. S. Flügge (Springer-Verlag, Berlin), 54, 42.

Chow, Y. L. 1966, "The T and Y Correlation Arrays", NRAO VLA report.

Hogg, D. E. 1966, "A Summary of VLA Array Plan Studies", NRAO VLA report.

Hogg, D. E. 1967, "A Summary of Computed Beam Patterns for Single Arrays", NRAO VLA Scientific Memorandum No. 2.

TABLE 3-4

Performance of 12-Element Sub-VLA For Hydrogen Line Work

	Declination (degrees)	Observing Time (Hours)	Sidelobe Level (db)	
			Peak	Mean
1. Arbitrary; 4 elements on each arm at distances 175, 350, 525, and 700m from center	-15	9.76	-11.7	-21.5
	-10	10.26	-12.7	-22.3
	- 5	10.74	- 7.2	-20.9
	0	11.19	-10.7	-23.4
	5	11.64	- 7.1	-21.0
	10	12.09	-12.7	-22.8
	20	13.02	-10.0	-20.8
	30	14.07	-11.9	-21.5
2. Arbitrary; 4 elements on each arm at distances 50, 125, 225, and 425m from center	-15	9.76	-12.5	-22.7
	-10	10.26	-13.2	-22.3
	- 5	10.74	-11.3	-22.6
	0	11.19	- 8.7	-22.3
	5	11.64	-10.6	-22.6
	10	12.09	-12.8	-22.3
	20	13.02	-14.3	-22.7
	30	14.07	-15.6	-23.6
3. Optimized at $\delta = 40°$. Distances from center: N: 125, 150, 300, 400 S-E: 200, 275, 400, 450 S-W: 25, 200, 400, 450	-15	9.76	-10.0	-21.9
	-10	10.26	-12.4	-23.2
	- 5	10.74	-12.0	-23.2
	0	11.19	-10.2	-23.5
	5	11.64	-12.7	-23.4
	10	12.09	-13.7	-23.3
	20	13.02	-12.3	-22.2
	30	14.07	-15.0	-23.5

Leech, J. 1956, J. London Math. Soc., 31, 160.

Lo, Y. T., and Lee, S. W. 1966, IEEE Trans. Ant. Prop., AP-10, 22.

MacPhie, R. H. 1967, "The Use of Space-Frequency Equivalence in Long Baseline Interferometers", VLA Scientific Memorandum No. 3, NRAO.

Mathur, N. C. 1967, "Complementary Array Configurations for the VLA", VLA Scientific Memorandum No. 5, NRAO.

Mathur, N. C. 1969, "A Pseudo Dynamic Programming Technique for the Design of Correlator Supersynthesis Arrays", to be published in Radio Science (March).

Moffet, A. T. 1968, IEEE Trans. Ant. Prop., AP-16, 172.

Rowson, B. 1963, Mon. Not. Roy. Astron. Soc., 125, 177.

Skolnik, M. I., Neuhauser, G., and Sherman, J. W. III. 1964, IEEE Trans. Ant. Prop., AP-12, 35.

Swenson, G. W., Jr., and Mathur, N. C. 1969, Radio Science, 4, No. 1.

APPENDIX

Complementary Arrays

The basic idea of complementary arrays is to observe a source with two different array configurations in order to get more spatial frequency components of the source with a given number of antennas. The operation involves more observing stations and more time (since not only is the observing time doubled but considerable time is spent in changing the configuration). A study of complementary arrays for the VLA was made following the publication of the VLA Proposal, Vol. I and Vol. II, and before the development of the optimization program using the pseudo dynamic programming technique. The results have been given in detail elsewhere (Mathur, 1967) and will be briefly reviewed here.

The objective of studying complementary arrays is twofold: (i) to find the minimum number of antennas needed to achieve a desired performance, and (ii) to find the best performance that can be achieved by using the VLA (as designed for operation in the single array mode) in two complementary array configurations. The study was carried out using the empirical approach. The transfer functions corresponding to two array configurations were computed and superposed to find the transfer function that the complementary arrays would yield. Ideally, the holes of the transfer function of one configuration would be filled by the other configuration with no redundancy. Practically, it is neither possible to fill all holes nor to avoid redundancy. One can proceed with the design in two ways.

(a) One can study the locations of the holes of the transfer function of one configuration and try to design another configuration that will fill these holes. With a good feeling for the location of the elliptical tracks corresponding to various baseline lengths and orientations, one can find out the antenna locations that will be needed to fill a given collection of lobes. However, the availability of only a limited number of antennas makes this procedure hopelessly difficult for the size of transfer functions encountered in the VLA.

(b) An alternate approach is to try out various pairs of configurations and find out which is the best. This is a purely empirical approach and is the one that was used in the absence of a better method.

Various element arrangements, such as uniform, tapered, and other distributions, were tried. Also, attempts were made to use different arms of the wye in the two configurations to find those that achieved the greatest degree of complementarity. The pairs of configurations that had the highest degree of complementarity were found to depend on the declination, the tracking time, and the number of elements. The broad conclusions of the study were

(i) The performance of the 36-elemented supplemented wye given in the VLA Proposal, Vol. I, could be achieved by 24 elements when used in complementary array configurations.

(ii) If 36 elements were to be used in complementary array configurations, the peak side lobe, even at $\delta = 0°$, could be pushed down below -22 dB.

(iii) The use of two configurations for observing a source with a smaller number of antennas does not reduce the observing time needed with each configuration.

It should be emphasized that the complementary array study was made using an empirical approach before the development of an optimization technique. If the VLA is to be used in two complementary configurations, then more detailed studies will have to be carried out. The pseudo dynamic programming can be applied to this problem also and should lead to useful results.

Chapter 4

THE ARRAY SITE

A. Introduction

A number of sites in the southwestern United States have been evaluated from the standpoint of engineering and construction criteria; these conclusions were discussed extensively in the VLA Proposal, Vols. I and II. During the past two years, the work has involved observations of the total water vapor content in the atmosphere above these sites in order to evaluate the feasibility of phase measurements over baselines of the order of 20 km.

Earthbound interferometric observations of radio sources at centimeter wavelengths and with interfereometer baselines of the order of 1 km or longer are significantly disturbed by changes in the refractive index of the air. Several agents are known to cause changes in the refractive index of the atmosphere at centimeter and decimeter wavelengths, notably the ionosphere, dry air pressure and temperature effects, water vapor, and liquid water in clouds and rain.

B. Limitations to Phase Stability of an Interferometer

1. The ionosphere

Mathur (1967) calculated the effect of the ionosphere for various interferometer baseline lengths at a wavelength of 11 cm, and concluded that ionospheric effects are negligible compared to errors introduced by the troposphere except under highly disturbed ionospheric conditions, when they can be as large as the tropospheric errors.

2. Dry air pressure and temperature changes

Of the two, the pressure variations are small and have a very large horizontal scale, and thus should not be a significant disturbing factor. With regard to temperature variations, a dry air temperature variation of 10° C extending vertically over the lower 3 km of the atmosphere causes a phase error of approximately 20° at 11 cm wavelength. The Handbook of Geophysics (1960) gives ground-level temperature variations and scale sizes under a number of meteorological conditions; information from it is in Table 4-1. The phase fluctuation resulting from differences in air mass are considered unimportant because of the large horizontal scale compared to the VLA array. Phase fluctuations due to the disturbed atmosphere (weather fronts, squall lines, and thunderstorms) could certainly be serious; however, the conditions occur only a small percentage of the time. Land breezes may well be the most significant dry air contributor to phase fluctuations for short periods of time.

Table 4-1

Dry Air Temperature Variations

Local Condition	Horizontal Scale (km)	ΔT (°C)	Resultant Phase Fluctuations at 11 cm (degrees)
Difference in air mass	160-1600	3-22	6-44
Weather fronts	16-160	3-22	6-44
Squall lines	8-80	3-17	6-34
Thunderstorms	8-23	3-17	6-34
Land breeze	3-8	1-6	2-12

3. Water vapor fluctuations

J. Waters (1967) has calculated the effect of a change in the amount of water vapor on the interferometer phase at 11 cm wavelength. At this wavelength the conversion factor is 200° phase retardation per centimeter precipitable water vapor in the propagation path. The conversion factor is temperature dependent, but it is accurate to 5 or 10% under most condiitons. Fig. 4-1 is a hygrometer recording showing the precipitable water vapor in the atmosphere over Charlottesville on a typical summer day. The trace on the left may be converted to millimeters of water vapor using the superimposed horizontal scale. Time is the vertical scale, one hour (1500 EDT to 1600 EDT) being marked. The trace on the right is an enlargement (approximately a 5 times scale) used to see more clearly the small-scale variations in water vapor. From the trace on the left, it can be seen that fluctuations of as much as 3 mm of precipitable water may occur over time spans of only a few minutes. This corresponds to a 60° change in phase delay at 11 cm. Long-term water vapor fluctuations can be even bigger than this, but have time scales on the order of hours. Such long-term fluctuations can be calibrated and subtracted from the interferometer measurements by observing calibrator radio sources.

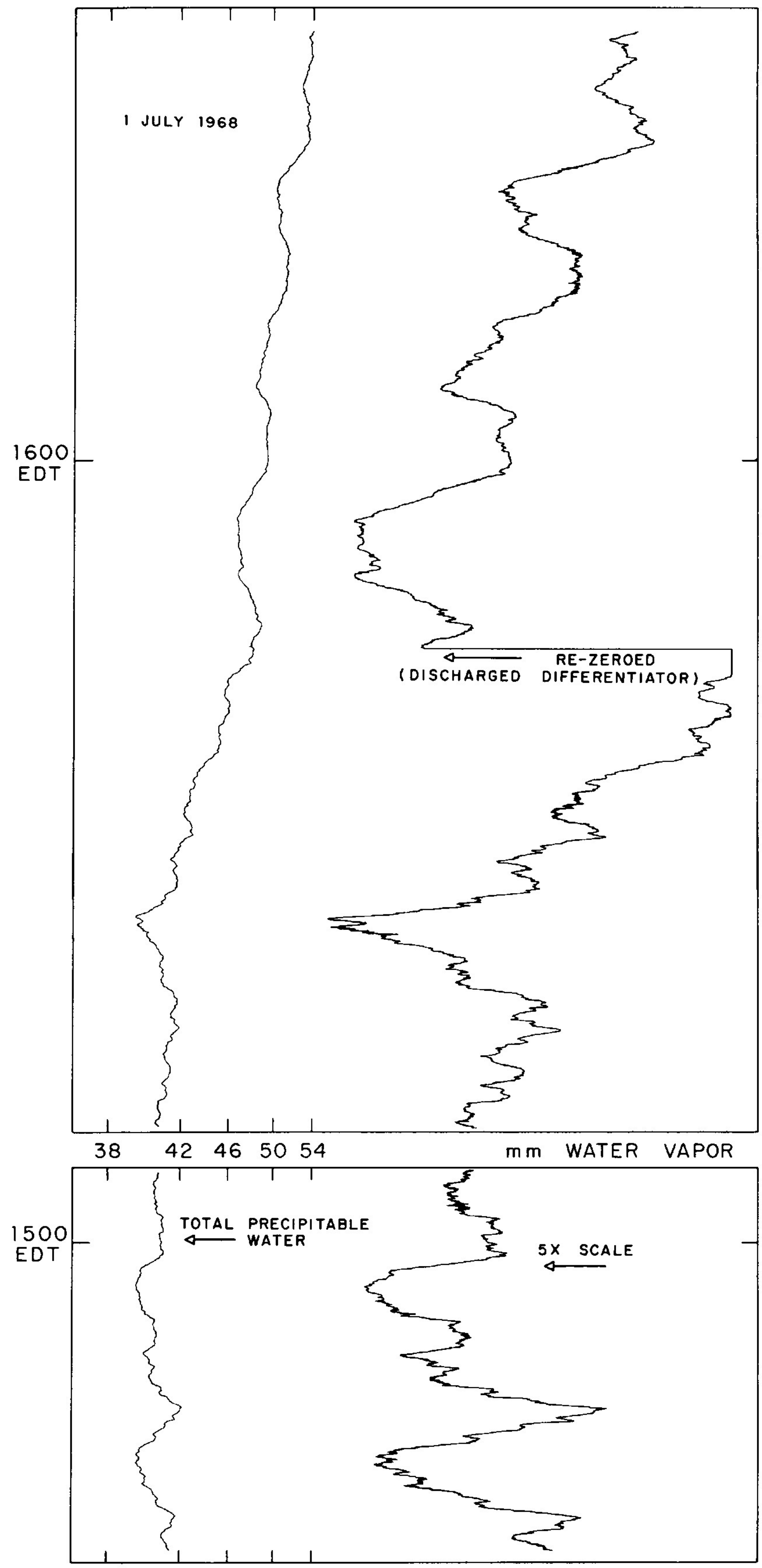


Fig. 4-1. Typical water vapor fluctuations for a summer day at Charlottesville, Virginia.

Short-term water vapor fluctuations (with time spans less than the minute) are usually small, which is due in part to the integrating effect of the telescope beam cross section. The residual effect will be averaged out in the receiver's time constant, or in the worst case cause a small reduction in apparent source flux.

The intermediate term phase fluctuations with time scales up to one hour are of the greatest concern in interferometric radio astronomy observations. Not only do they change too quickly to be calibrated out, but they also disturb the long-term calibrations.

4. Liquid water in clouds and rain

Liquid water droplets of sizes much smaller than the wavelength couple inefficiently with the electromagnetic wave and produce only small changes in effective dielectric constant. Meinke, et al. (1962) state: "If the total amount of water vapor in moist air would condense in the form of liquid water droplets, the part of the effective dielectric constant due to water would drop to 10% of its original value." However, an extremely wet cloud with 10 g/m^3 of liquid water, 1 km thick, contains 1 cm of precipitable water which will still cause 20° of phase retardation. Generally, large air motions and temperature gradients exist in clouds which also contribute to a change in the refractive index. Measured deviations in the refractive index of clouds from the surrounding air, in N units, range from 0 to 20 (as given in the Handbook of Geophysics). A 1 km thick cloud with a difference in the refractive index of 10 N units will cause a phase error of 30°.

C. Influence of Water Vapor Variation on an Interferometer

Of the four factors which can cause errors in the apparent interferometer phase observed for a radio source, the water vapor fluctuations seem to be the most important for observations at 11 cm on clear days with baselines about 1 km length. In order to show this more clearly, a special observation was made in which the outputs of the Green Bank interferometer (see Chapter 2) and a hygrometer were compared.

In this experiment the interferometer tracks a radio point source of known position at a time when the source is within a few degrees of the sun (near-occultation). A hygrometer is located near one of the antennas and tracks the sun. The phase of the interferometer output is constant (tracking interferometer) if no disturbing factors are present. Any variation in phase is caused at least in part by the change in the water vapor distribution over the two paraboloids in the direction of the source. The spectral hygrometer also records changes in the water vapor distribution over the two paraboloids in the direction of the source. The spectral hygrometer also records changes in the water vapor distribution, but receives energy only in the line of sight to the sun. Thus if the radio source is near the sun, the hygrometer will detect the same large-scale water vapor fluctuations that are producing phase delays in the radio signal reaching the nearby antenna.

Fig. 4-2 shows the results of such an observation made on October 12, 1967. The interferometer baseline was 1.9 km, and the sun-source separation was approximately 2°. In the figure the plotting symbol A indicates fringe amplitude, and the letter P indicates fringe phase (0 to 360°) in 3° increments. The letter H indicates water vapor measured by the hygrometer and converted to phase delay (0 to 360°) in 3° increments. One set of information points is plotted every minute of time. Points of the H and P plots are interconnected with a solid line. A dashed line indicates loss of hygrometer data due to the passage of clouds over the hygrometer.

The correlation between the observed interferometer phase fluctuations and the fluctuations in the hygrometer output is not perfect, although readily evident. This is to be expected, since there is no measurement of the water vapor fluctuation over the second telescope. There is strong correlation between P and H, for example, between LST 1227 and LST 1236. Both interferometer phase (P) and water vapor measured by the hygrometer (H) exhibit the same type of variation. The fluctuation in interferometer phase was about 20°, compared to the predicted phase fluctuations of 25° shown by the hygrometer output. (This has been derived from the observed fluctuations of 0.12 cm in precipitable water vapor, assuming 1 cm of water vapor causes 200° of phase retardation.)

The experiment strongly suggests that the water vapor fluctuations are indeed the principal limitations to the phase stability of a radio interferometer operating over intermediate length baselines at a wavelength of 11 cm. Therefore, a useful criterion in the selection of a site for the VLA is the amount of water vapor in the atmosphere over the site and the nature of the fluctuations in the water vapor.

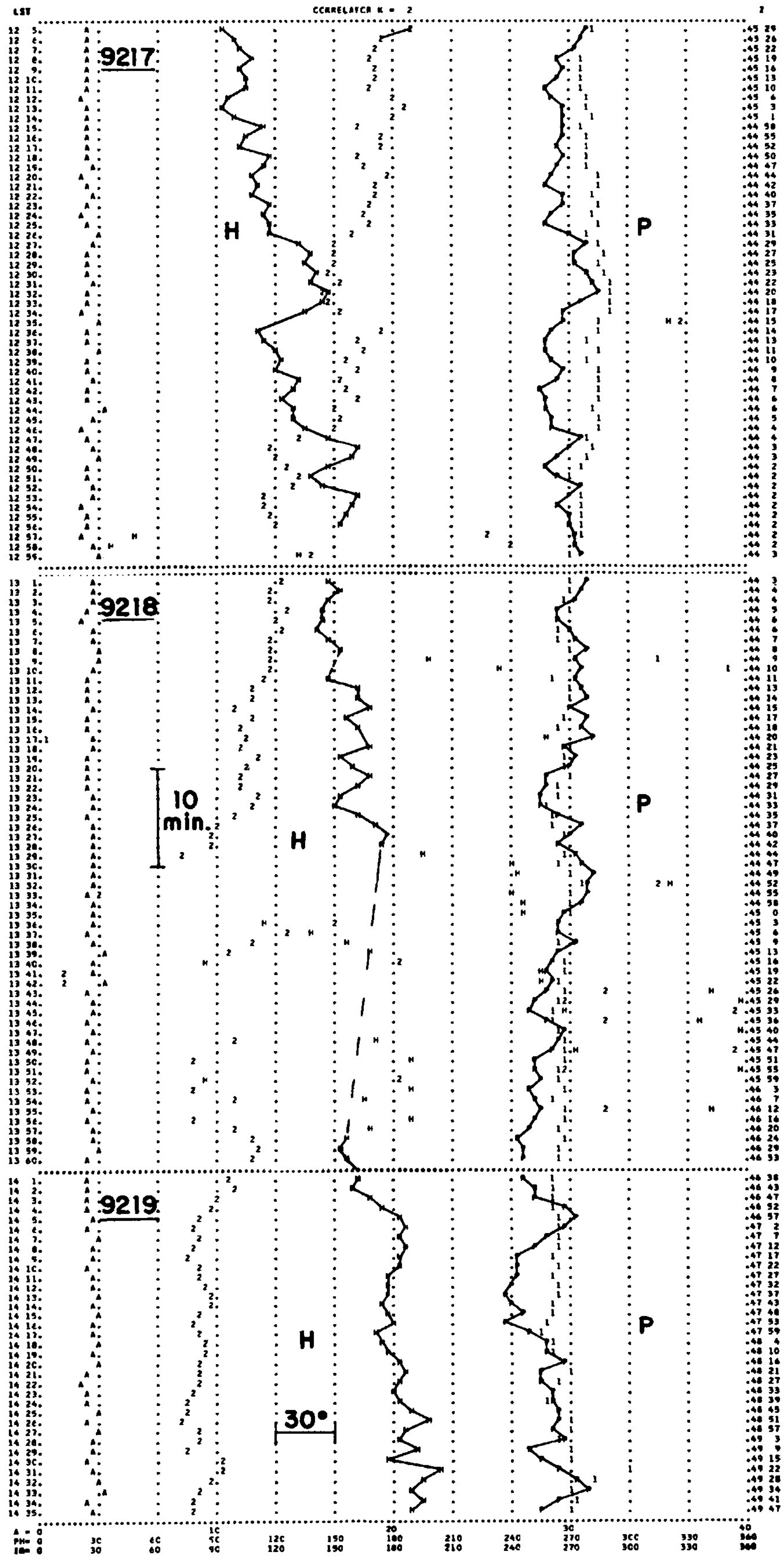


Fig. 4-2. Record of a near occultation interferometer hygrometer experiment.

D. Site Observations

A measurement and analysis program was initiated in order to acquire quantitative data on the amount of precipitable water vapor in the atmosphere above the sites under consideration for the VLA. The first phase of this program started in June 1966, when three hand-held spectral hygrometers were put into daily use at locations near the Y-15, Y-23, and Y-27 sites. These electronic hygrometers operate by sensing relative atmospheric absorption of sunlight at two infrared wavelengths (880 nm and 935 nm) to measure the water vapor in the total atmosphere between the instrument and the sun. With these instruments, a measure of the total precipitable water in the atmosphere between the sun (at noon) and the site was recorded and reported on a monthly schedule. Zenith angle corrections were applied to all data before it was plotted.

Fig. 4-3 is a graph of the mean precipitable water vapor by month for the 30 months data has been collected at the three sites. The site Y-15 has the smallest amount of water vapor, with the other two having equal amounts. All three show a strong annual variation, with the maximum water vapor occurring in July and August. The amount of water vapor over any of the three sites is less than or, at worst, equal to the amount over Green Bank, at comparable times of the year. Since successful phase-stable interferometry has been done at Green Bank, it may be concluded that it will be possible at any of these three sites as well.

In order to completely evaluate the sites and to enable the selection of the best site, it is necessary not only to know the total amount of water vapor over each site but also the scale of the water vapor variations, both in time and space, since these contribute to the limitation of the phase stability. Therefore, a second phase in the study of the atmosphere over the possible VLA sites was begun late in 1968 which will give information on the scale of the water vapor variations. The hygrometers used in these experiments are semi-automatic instruments operating on the same principles as the hand-held instruments. The hygrometer is mounted on a polar telescope drive that tracks the sun during measurement. The hygrometer is described by Wesseling (1968).

Three of the continuously indicating hygrometers were equipped with recorders and the necessary electronics for eight hours of unattended

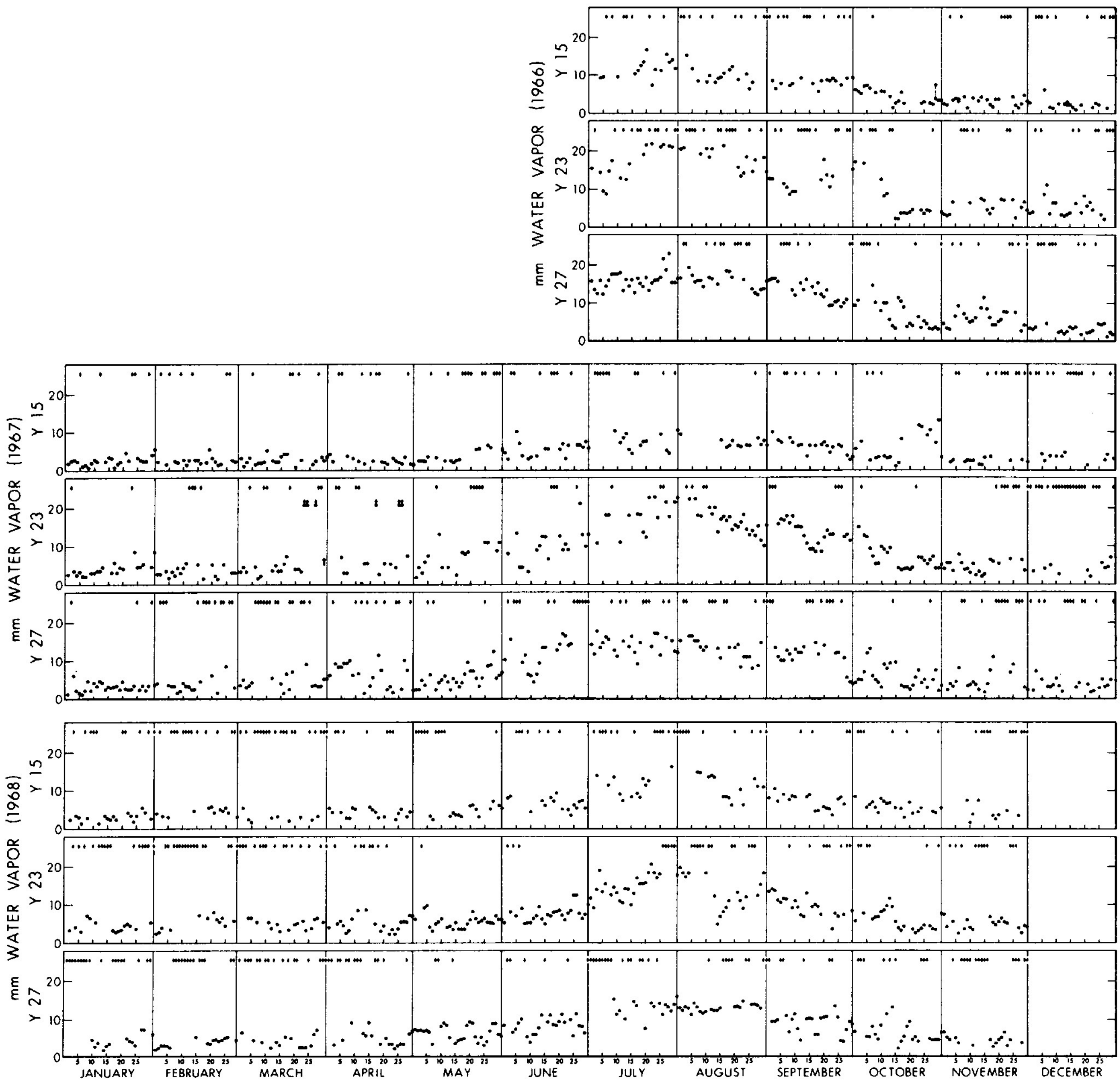


Fig. 4-3. Seasonal variation in water vapor over three western sites.

operation, and were installed adjacent to site Y-23 on stations with 1.6 km and 27 km separation.

The electrical output of each hygrometer is recorded on magnetic tape along with timing signals from radio station WWVB, which allows cross correlation between instruments to within one second. An operator attends each instrument every morning to reset the solar tracking drive and change the magnetic tape. The tapes are returned to the NRAO at Charlottesville for data reduction and interpretation. Operation of the three stations was begun in November 1968.

A preliminary analysis of data recorded on clear days in early November 1968 from site Y-23 has been made. Of most interest is the water vapor fluctuation over a baseline of 27 km, since this is the distance over which the atmosphere must be stable in order that the synthesis of a 1" beam be successful. Therefore, the outputs of these hygrometers were differenced and the rms fluctuations were computed. In the three days of observation, the rms differences over a period of one hour near noon between the outputs of two hygrometers separated by 27 km were 0.13 mm, 0.20 mm, and 0.13 mm, which would produce phase fluctuations in an interferometer of that baseline operating at 11 cm of only 3°, 4°, and 3° rms, respectively. Under conditions such as this, synthesis of an 1" beam clearly would be possible.

The observations at Y-23 will be continued in order to study the nature of the water vapor fluctuation under a variety of conditions. In addition, facilities for a similar installation are complete at site Y-15, and plans call for the instruments to be moved there in early 1969. Another series of observations with these instruments is planned for the Owens Valley Observatory (California Institute of Technology) during 1969.

REFERENCES

Mathur, N. C. 1967, "Ionospheric Effects at 11 cm Wavelength," VLA Scientific Memorandum No. 9.

Meinke, H. 1962, F. W. Gundlach: Taschenbusch der Hochfrequenztechnik, 2nd edition.

USAF Handbook of Geophysics, 2nd edition (1960).

Waters, J. W. 1967, "Atmospheric Effects on Radio Wave Phase, etc.", VLA Scientific Memorandum No. 8.

Wesseling, K. H. 1968, "A Continuously Recording Infrared Hygrometer, and Results of an Interferometer-Hygrometer Correlation Experiment," NRAO Electronics Division Internal Report No. 78.

Chapter 5

THE ANTENNA ELEMENT

A. Introduction

In the period between the submission of the VLA proposal in January 1967 and the present, extensive investigation and development have been performed of the antenna concept and configuration and the mobility system. The VLA proposal contained a suggested configuration which served as an outline in presenting the performance requirements in a request for proposals for the design of a prototype antenna element. This request was sent to a number of interested and competent firms in May 1967 and led to the receipt of proposals from five companies. An examination of these proposals revealed a wide divergence in the designs proposed and suggested the pursuance of further development of the configuration of the antenna and the mobility system. The purpose of further development of the configuration was the elimination of study programs during the antenna design stage, the resolution of areas of indecision in the request for proposal, and the translation of the performance requirements into physical and mechanical specifications. It was decided to continue the antenna element development and the mobility system study as an in-house effort, utilizing the aid of experienced consultants in the performance of portions of the work.

The Rohr Corporation was chosen as one of the consultants to assist the NRAO in the antenna element development because of its large and varied experience record in the design, shop fabrication, and erection experience in the antenna field. A prime consideration in the choice of this consultant was Rohr Corporation's experience in large-scale production of complex manufactured equipment in their shops, which, in NRAO's opinion, uniquely qualified them to make recommendations in the areas of designing an antenna which offered economies in production, field alignment, and field assembly.

Another consultant, the Systems Development Laboratory, was chosen to assist NRAO in the development of the mobility system and transport vehicle because of its experience in structural and heavy mechanical equipment as well as its knowledge and experience in antenna design.

These two consultants completed their work in the fall of 1968, and the results of their studies form the basis for the recommendations which NRAO makes to the antenna element and transport system to be used in the VLA.

B. The Antenna Structure

1. The reflector surface

In reviewing existing designs of antenna surfaces, it was found that practically all previously built antennas of the same approximate diameter as the proposed VLA antenna use 252 panels for the reflector surface. This number evidently developed due to the ease in making smaller panels, reluctance to develop manufacturing and inspection tools for larger panels, and experience that panel tolerance could be held closer for the smaller size panels. As additional telescopes were procured by various organizations in numbers of only one or two, it was not economically feasible to develop a new set of manufacturing and shop checking tools for just one telescope. For the panel system developed for the VLA, the tooling charges are estimated at $120,000 which, while a sizable charge for one antenna, when distributed over 27 antennas does not represent a significant cost and is offset by savings in panel manufacturing costs, panel installation and alignment costs, and the number of supporting members required.

The surface panel system developed for the VLA is based on the use of aluminum solid surface panels. (This selection is covered in the earlier VLA proposal.) In the early stages of their study, the Rohr Corporation (1968) confirmed this selection based on lower initial costs, increased reliability, and reduced maintenance. A study of the panel manufacturing problems indicated that stretch forming of the panel skins would be required for panels larger than approximately 6 ft x 10 ft, but that panels of the 6 ft x 10 ft size could be manufactured economically without stretch forming to a tolerance of 0.025 in rms. Optical alignment of panels on present antennas of comparable size is achieved economically to a tolerance of 0.010 in rms. For the VLA it is proposed to assemble the antenna in an assembly bay and to use a contour tool with the reflector pointed at zenith. The reflector would rotate in azimuth, and surface panels would be adjusted until they contact the contour tool, thus shortening the alignment time to two to three hours. A tolerance of 0.025 in rms is considered feasible with this method of alignment and has been used in the error budget estimate.

The proposed panel configuration shown in Fig. 5-1 will have adjustment provisions at the four corners so that adjustment may be made from the top surface, will have a maximum size of 10 ft 6 in x 6 ft 0 in, will have a skin surface of 0.050 in thick aluminum sheet which will be painted for diffuse reflectivity, and will weigh approximately 1.6 lb/ft^2. The reflector surface will consist of 120 individual panels.

2. The reflector backup structure

The study of the reflector backup structure revealed that in order to best support the panels and to minimize structural deflections a structure consisting of 24 radial ribs, 3 circular bracing trusses, and a dual ring girder system was advisable. The dual ring girder system supports the elevation wheel structure, an 8 ft x 8 ft x 8 ft equipment room at the vertex, the feed cone at the vertex, and transfers the reflector loads to the top of the yoke arms. The elevation wheel structure is located at the center of the backup structure so that only a single drive rack is required and that distortion due to off-center driving is not induced. The elevation wheel supports the elevation counterweight and eliminates the need for an additional counterweight structure which would not contribute to the stiffness of the backup structure. A rotating elevation shaft is used which simplifies alignment of the declination bearings and which, being a part of the dish structure, contributes to the stiffness of the reflector. Table 5-1 shows the surface

Table 5-1

Surface Accuracy Error Table Primary Reflector

1σ rms - inches	Panel Mfg. Tol.	Panel Align. Tol.	Gravity Load Declination Zen. to Hor.	Windload Deflection 25 mph	Ice Load Deflection 0.1 cm	Thermal Load Deflection $\Delta t = 5°C$
Surface panels	0.025	0.025	0.007	0.020	.002	.003
Structure	-	-	0.050	0.020	.006	.013
Σ 1σ - inches	0.025	0.025	0.057	0.040	.008	.016
$1\sigma^2 \times 10^{-6}$	625	625	3250	1600	64	256
Σ $1\sigma^2$			0.006422 in^2			
RSS - 1σ			$\sqrt{0.006422\ in^2}$ = 0.080 in 1σ (2 mm rms)			

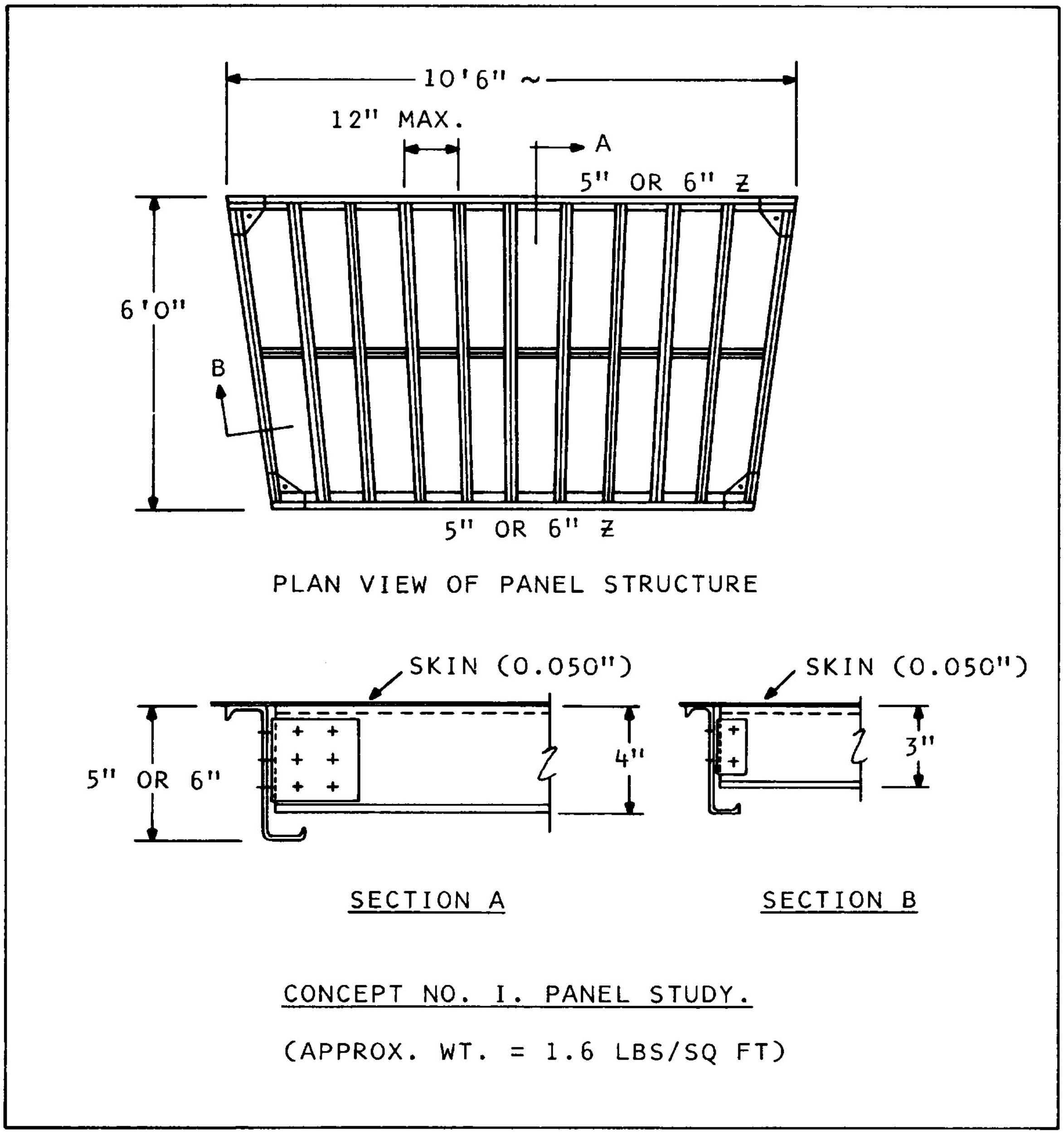


Fig. 5-1. A typical panel configuration.

accuracy of the reflector and its backup structure, including manufacturing tolerance, alignment tolerance, and the influence of the various operating load conditions.

3. The yoke and alidade

The proposed yoke and alidade configuration, as shown in Figs. 5-2 and 5-3, make possible the use of the large diameter elevation wheel, the location of both elevation and azimuth drive components in one enclosure, and the use of an inverted king post design for the azimuth bearings. The elevation bearings, being located at the top of the yoke arms, are easily adjusted to secure proper alignment of the elevation axis.

The large diameter elevation wheel, which provides for increased rigidity of the central section of the reflector structure, also reduces loads on the elevation drives due to the large reduction ratio available in the elevation wheel and increases the drive stiffness. The yoke and alidade structure, being of welded steel plate manufacture, will lend itself to economical shop fabrication and can be fabricated in modules which will minimize the amount of field welding and alignment.

The location of all drive components in a dust-proof enclosure, as shown in Figs. 5-2 and 5-3, at the base of the yoke and alidade component will assure protection from the elements and thus reduce maintenance, provide convenient access for servicing, and place all drive components, including servo electronic controls, in one enclosure. This enclosure travels with the azimuth motion and is accessible from a fixed platform directly underneath.

The inverted king post, shown in Figs. 5-3 and 5-4, is a unique development resulting from this study. The azimuth bearings rotate around a fixed inverted king post which is mounted on top of a rigid space-frame steel pedestal to become an integral, rigid extension of the pedestal structure. The king post houses two small diameter bearings spaced vertically 5 ft apart Typically, when the single bearing approach is used, the azimuth bearing system for antennas represents one of the more complex and expensive components. The concept developed for the VLA antenna using small diameter azimuth bearings is economical, does not contain long lead time components, is easily maintainable, and assures the attainment of the necessary rigidity to meet the system performance requirements. The absence of torsional windup in the

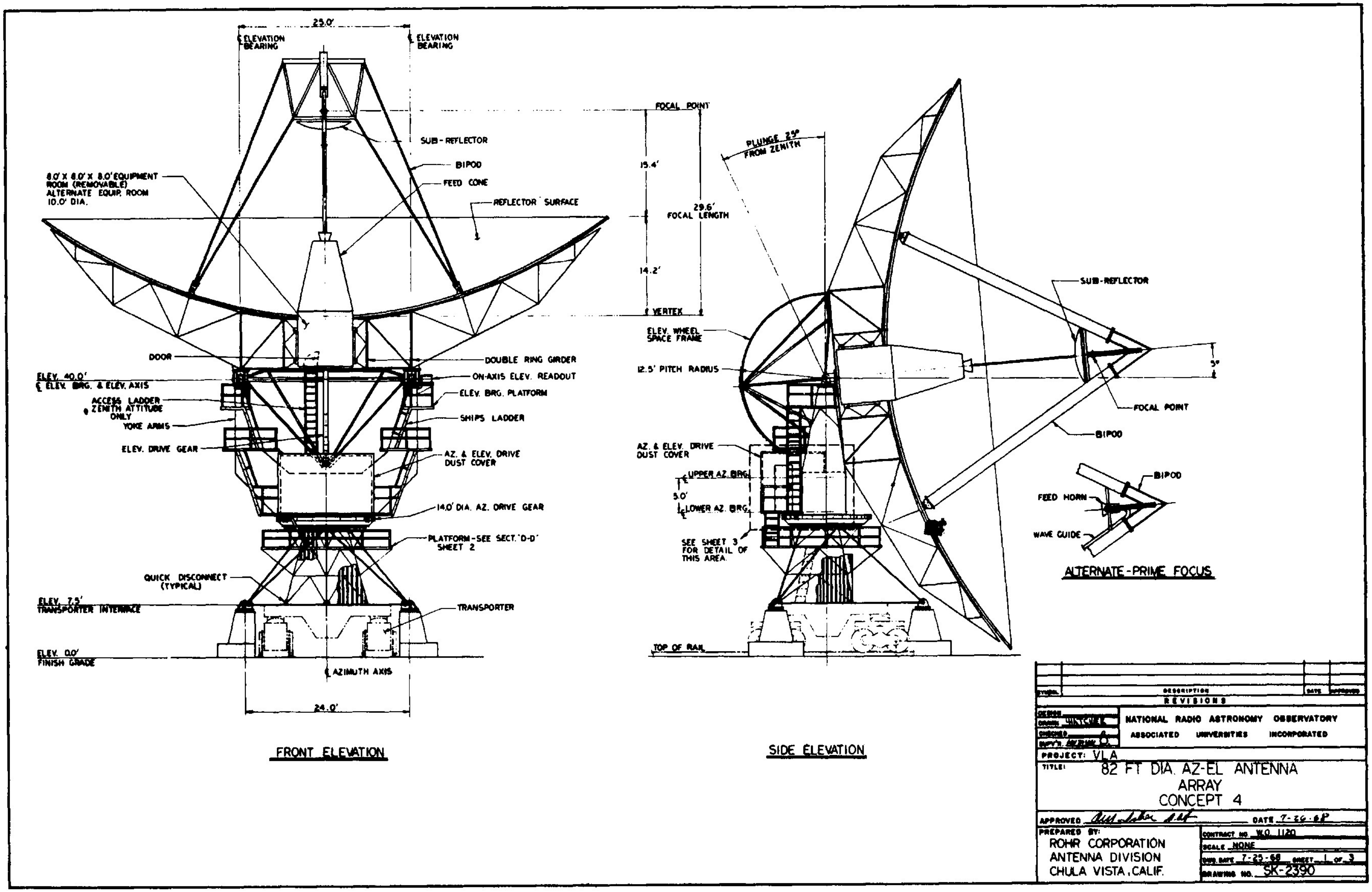


Fig. 5-2. The VLA antenna element.

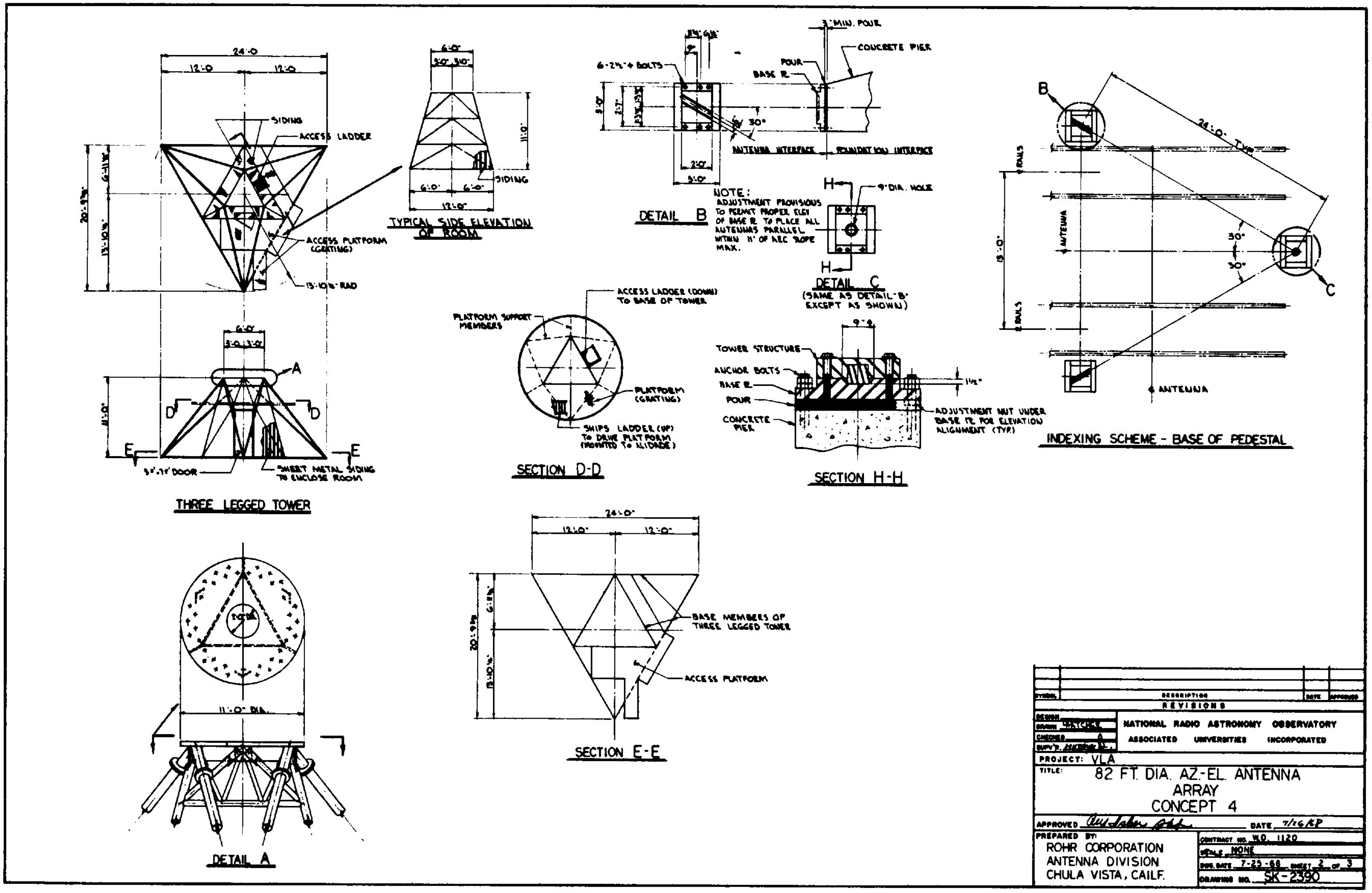


Fig. 5-3. Details of the antenna tower and foundation.

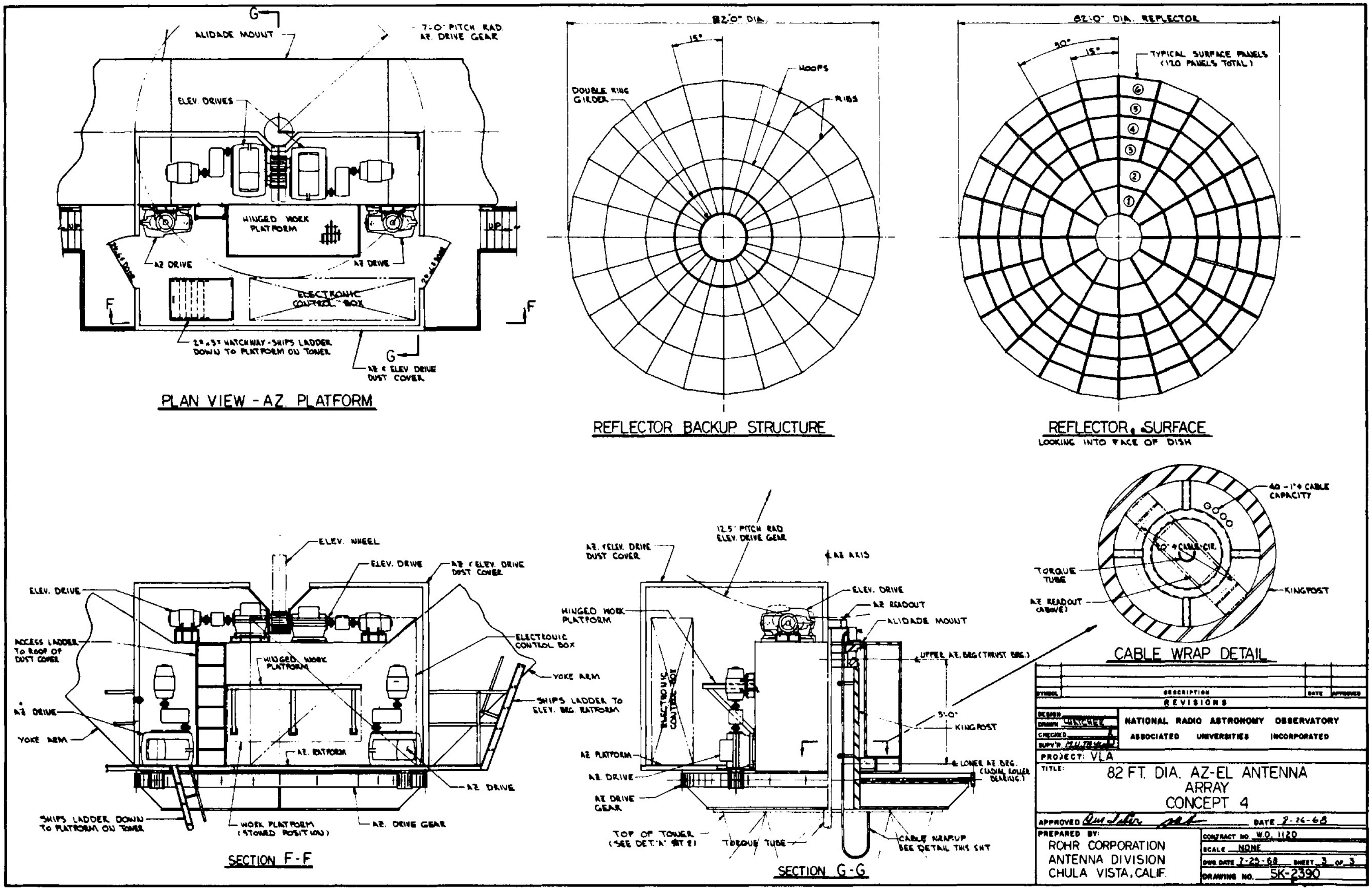


Fig. 5-4. Antenna element details.

king post is unique in this design. The load path for azimuth moment is reacted by the azimuth bull gear bypassing the king post, thereby making the use of a relatively small diameter king post and small diameter azimuth bearings possible.

4. The antenna pedestal

The proposed antenna pedestal is a three-legged, open space frame structure. The three-legged structure has advantages over a four-legged structure in that it reduces the number of foundation pads at each station (there are 100 stations proposed for the VLA), increases the width clearance between legs for the transporter by 0.16 times the diameter of the foundation envelope, and decreases the time required for disconnecting and reconnecting each time the antenna is moved.

Another major advantage of the three-legged pedestal is in the ease of indexing and alignment of the azimuth axis of the antenna in both the vertical and azimuth directions. In order to reduce the position control load on the computer, it is considered advisable to position the vertical axis of all antennas parallel rather than perpendicular to local gravity. Taking the center of the wye as the control location will require an 11' of arc tilt of the vertical axis to local gravity at the extreme stations on the three arms of the wye. This tilt amounts to 1 in difference in elevation across a 24-ft foundation pad. The adjustment for the required difference in elevation will be made at the baseplate at the top of each foundation so that all antennas may be made identical and may occupy any station without adjustment of the vertical axis of the antenna. A tripod structure, being stable by nature, lends itself to this type of alignment more readily than would a four-legged or continuous base structure. The antenna is indexed in azimuth by locating slots in the tops of the foundation baseplates that are mated with keys in the antenna base, as shown in Fig. 5-5.

The indexing scheme shown in Fig. 5-5 will fit the antenna location about one point only (Detail C) while permitting a gradual change of the base dimensions through the slot-key arrangement incorporated in the other two support points (Detail B).

The centerline of the triangular base would then be permitted to shift as a function of temperature, and the cap screws connecting the antenna to

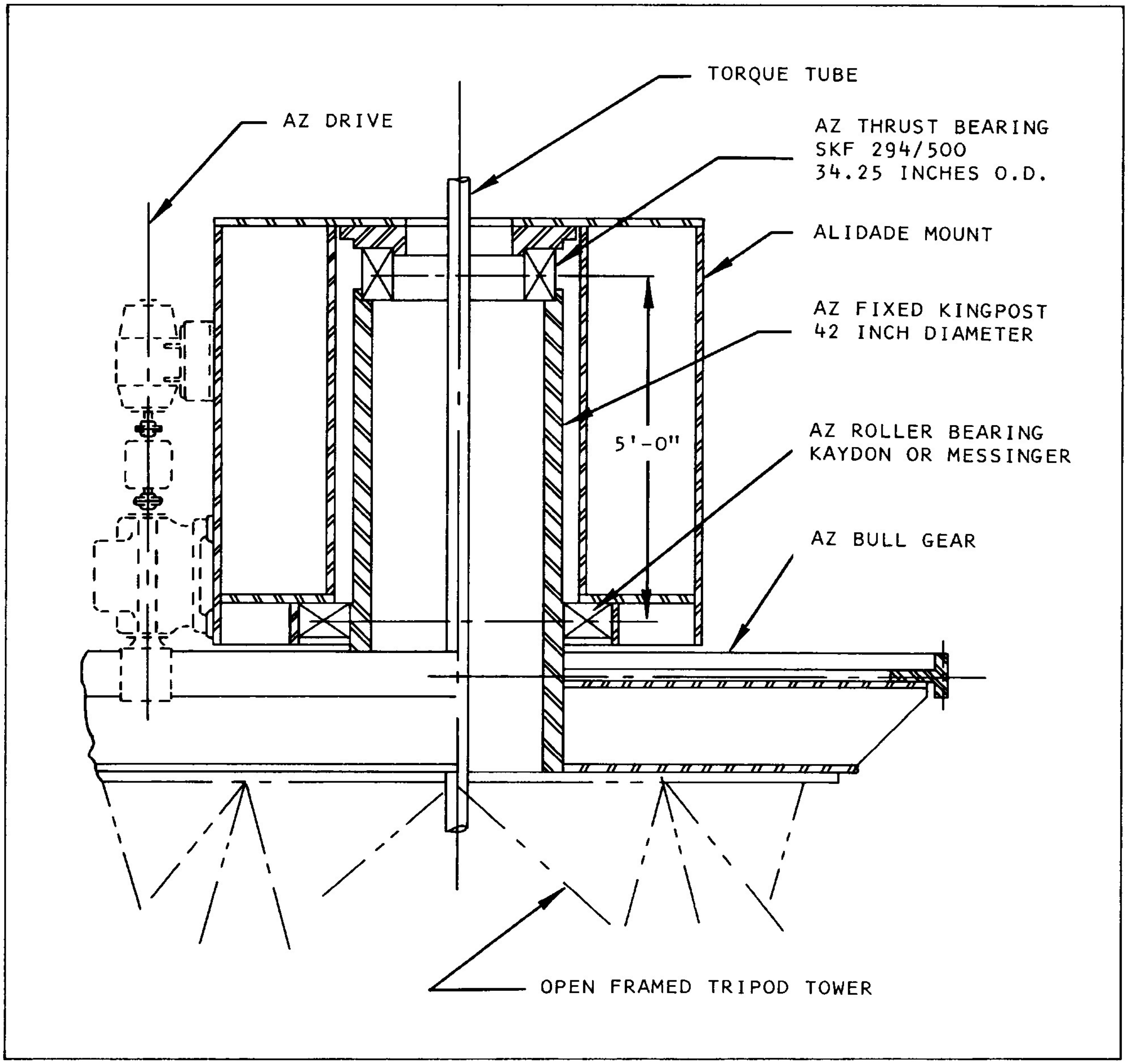


Fig. 5-5. Azimuth bearing and king post.

the foundation may have to be loosened and retightened from time to time to release the strain on the tower and foundation due to average seasonal temperature changes. The dimensional distances between the antennas would then also change very slightly, which may require some recalibration effort every time this adjustment is made.

A better approach, which has been considered but which is not shown in detail, would be to provide all three mounting pads with slot-key arrangements. The position of the slot-key pairs would be so that their centerlines would coincide with the centerline of the base triangle. This would assure a constant dimensional distance between the antennas, regardless of environmental temperature changes.

While traveling on the transport vehicle, the antenna is supported by a central tower which is braced to the main pedestal to prevent a change in structural geometry of the main pedestal during transport. Provision will be made for a lateral movement of the antenna of up to 1 in on the transport vehicle at the support points since the indexing keys on the antenna mate with the grooves on the foundation baseplates. The pedestal central tower will be covered and will form the exterior of an electronic equipment room.

The pedestal frame will be designed for modular fabrication and field erection time will be reduced. At the present time, it is proposed to use solid rod for the exterior frame members. Shop welded assemblies will be utilized at connection points to assure ease of assembly and minimum alignment time in the field. The pedestal base will contain adjustment features at each leg to make all antennas identical on a master foundation, so that any antenna may then be placed on any foundation and be properly aligned.

5. Drive and cable wrap

The antenna will be driven about each axis by two 3 hp DC-motors, having a maximum speed of 1750 rpm, by means of two gear trains per axis. The gear trains will have a reduction ratio of 785:1 in elevation and 1400:1 in azimuth. The total reduction between the gear train input shaft and the antenna axis output will be 31,500:1. The motors will be controlled through application of opposing biasing torques during tracking operation in such a way to eliminate backlash in the gearing. However, during "drive to stow" operation both motors on either axis will be controlled to apply torque in the same direction, and their power will then be additive.

The selection of an electric drive over an electrohydraulic drive was based on considerations of reliability, maintenance, and ease of maintaining a constant bucking torque. The two main drives will be controlled by electromechanical servo systems. The servos can be controlled by the central computer which calculates the position errors, or by local manual control. The azimuth and elevation drives will have fail-safe mechanical brakes and stow pins will be provided. (McVey [1969]; Rohr [1968])

A cable wrap system, designed to accommodate the desired azimuth coverage of ± 270°, will be provided. The mechanical arrangement is shown in Fig. 5-3 and will be driven by a torque tube which passes through the center of the king post and is rigidly attached to the alidade mount. The cable wrap is chosen over a slip ring arrangement since sufficient space is available, and an azimuth coverage of only ± 270° is required, which makes it relatively easy to design a feasible, well-functioning cable wrap arrangement, and any possible radio interference caused by a faulty slip ring contact can be eliminated.

6. The antenna foundation

The antenna foundation interfaces have previously been discussed in relation to the indexing of the antenna. The attachment to the foundation baseplate (which is considered to be a part of the foundation) will be by cap screws through the pedestal shoe. The release or connection of the antenna to the foundation will require the removal or installation of 18 screws.

The foundation will be either a concrete mat with three pedestals or three individual pile foundations with a concrete cap and pedestal. The selection of the particular type will be made after more extensive soil investigations and will be determined by the soil characteristics. A foundation spring constant of approximately 10^{10} ft lbs per radian is required in order to keep the pointing error due to foundation rotation below the maximum desired amount of 2.5". A silty or sandy silt foundation material will not meet this requirement with a mat foundation, while a sandy or gravelly soil will and is not considered a controlling factor in site selection since sites under consideration will meet foundation requirements by use of one of the foundation designs.

7. Mechanical and structural performance

The following are the characteristics of the telescope:

Type of mount	Elevation over azimuth-intersecting axis
Diameter	25 m
Focal length	9 m
f/D	0.36
Sky coverage	
Elevation limits	+ 5° to 125°
Azimuth limits	± 270°
Operational frequency	3 cm wavelength (10,000 MHz)
Surface accuracy	2 mm (0.080 in) - 1σ
	± 5 mm (± 0.20 in) - peak
Minimum solidity	100%
Axis alignment	
Azimuth axis to gravity vector	18"
Orthogonality elevation over azimuth	18"
Elevation axis to reflector axis	18"
Subreflector axis to reflector	18"
Feed cone - phase center	18"
Reflector panel manufacturing tolerance (1σ)	0.65 mm (0.025 in)
Panel gap	5 mm (0.2 in)
Man load	250 lb (on 36 in^2 of surface) (6 in x 6 in)
Counterbalancing	Underbalanced to return to zenith position
Pedestal	Built-in adjustment features. Lifting points for transport vehicle.

Readout errors

	Absolute	Nonrepeatability
Mounting and couplings (peak)	5"	2.5"
Encoder (17 bit)	12"	6"
Total RSS error peak	13" per axis	6.5"
Pointing direction	By NRAO computer	

Servo errors	7" per axis	
Servo loop bandwidth	0.5 Hz minimum; K_a = 2/s (minimum)	
Pointing errors (peak)	5' repeatable; 36" nonrepeatable (0.01°)	
Structural resonant frequency		
Reflector: Symmetrical mode	10 Hz	
Reflector: Antisymmetrical mode	10 Hz	
Azimuth and elevation locked rotor	2 Hz minimum	
System stiffness (minimum)	4.4×10^9 ft-lbs/radian	
Drive characteristics		
Azimuth velocity	20°/min	Slewing motion
Elevation velocity	20°/min	Slewing motion
Azimuth acceleration	$15°/min^2$	Scanning motion
Elevation acceleration	$15°/min^2$	Scanning motion
Scanning motion	0 to ± 5°/min	
Axis inertias (structural)		
Azimuth	1.8×10^6 lbs-ft/s^2	
Elevation	1.5×10^6 lbs-ft/s^2	
Cone of silence	± 2.5° zenith angle	
Environmental conditions		
Scanning	Wind gusting to 25 mph with 0.1 cm (0.04 in) ice	
Slew to stow position	Wind 60 mph with 1.0 cm (0.4 in) ice	
Slew to dump position	Wind 25 mph with 2 g/cm^2 (4 psf) snow	
Survive (stow position)	Wind 110 mph with 2 cm (0.8 in) ice or 10 g/cm^2 (20 psf) snow	

<u>Breaking</u>	
Operational	Any azimuth or elevation position
Stow - hold in 60 mph wind	Any position - for maintenance stow pin - zenith position
<u>On axis torque</u>	
60 mph wind - azimuth	720,000 ft-lbs
- elevation	720,000 ft-lbs
<u>Friction</u>	
Azimuth - breakaway	18,200 ft-lbs
- running	13,000 ft-lbs
Elevation - breakaway	18,200 ft-lbs
- running	13,000 ft-lbs
<u>Drive horsepower</u>	
Elevation	6 hp total
Azimuth	6 hp total
<u>Type of drive</u>	Electric motors bias drive
<u>Power requirements</u>	
Peak operating	40 kVA
Normal demand (25 mph wind)	19 kVA
<u>Environmental conditions</u>	
Ambient temperature	-30° C (-22° F) to + 50° C (+ 123° F)
Temperature differential	± 5° C (± 10° F) design requirement
Lightning protection	Electrical grounding system
Altitude	2500 m (8000 ft)
<u>Reflector structure equipment room</u>	8 ft x 8 ft x 8 ft. Removable equipment room located at the vertex of reflector.
<u>Pedestal equipment room</u>	11 ft x 11 ft triangular x 8 ft at the base, plus a 9 ft x 14 ft x 9 ft room enclosing the drives.
<u>Foundation parameters</u>	
Gravelly soil	
Depth to stratum of high bearing capacity	5 to 10 ft

Vertical dynamic modulus of elasticity of bearing material E_D	$\approx$ 17,000 psi
Subgrade modulus (K_s)	∿ 230 lb/in^2
Bearing pressure	Greater than 3000 psf
Mobility	Move in 25 mph wind; travel velocity 5 mph; 2% grade; survival 60 mph wind
Interchange ability	Time to disconnect $\leq$ 0.5 hr Time to connect $\leq$ 1 hr
Power available	440 V, 3 phase, 4 wire and 230-115 V, 3 wire
RFI	MIL-16910
Secondary support system	
Equipment load	750 lb
Type of feed	Cassegrain; prime
Blockage	$\approx$ 3.5%
Static deflection	4.8 mm (3/16 in)

8. Mechanical and structural parameters

	Elevation Axis	Azimuth Axis	Units
Weights (structural and mechanical)	150,000	300,000	lbs
Mass moment of inertia (structural)	1.5×10^6	1.8×10^6	slug ft^2
Motor to axis ratio	31,500	31,500	-
Friction torque (25 mph)			
Breakaway	18,200	18,200	ft-lbs
Running	13,000	13,000	ft-lbs @ max rate
Inertia torque at axis at $0.1°/s^2$	2,620	3,150	ft-lbs

	Elevation Axis	Azimuth Axis	Units
Axis drive torques			
Nominal rated torque at each motor	9	9	ft-lbs
Peak rated torque at each motor	18	18	ft-lbs
Rated hp drives total	6	6	
Drive system			
Reducer ratio	785:1	1400:1	-
Service factor used (life)	1.25	1.25	-
Number of reducer assemblies per axis	2	2	-
Axis stiffness	1×10^9 minimum	1×10^9 minimum	ft-lbs/rad
Stiffness at each reducer	0.71×10^6	1.14×10^6	ft-lbs/rad
Axis bearings			
Nominal diameter	17 in O.D.	34.25 in O.D.	
Type	Spherical rollers	Spherical thrust and cylindrical rollers	

An analysis of the maximum nonrepeatable pointing errors for various positions of the antenna with the maximum operating wind velocity of 25 mph revealed that for this antenna configuration the peak error occurs with the antenna horizon pointed and the wind blowing directly into the antenna. Tables 5-2, 5-3, and 5-4 show the contributing factors to this error about each axis and the resultant peak error.

Table 5-2

Worst Case - Wind Straight Into Reflector

Elevation Axis: θxx - Seconds of Arc

Component \ Error Source	Deadload Nonrepeat-ability	25 mph Windload Steady State $\alpha = 0°$; $\psi = 0°$	Alignment Errors (RSS) Nonrepeat-ability	Servo Errors	Ice	Thermals
Cassegrain assembly	1	0	< 2	-	4	15
Antenna mount	0	31	< 2	-	Negl.	4
Servo system	-	-	-	8.3	-	-
Encoder 17 bit	-	-	< 6	-	-	-
$\Sigma\ 3\sigma$	1	31	7	7	4	19
$3\sigma^2$	1	985	49	6.9	16	360

$RSS = \sqrt{\Sigma 3\sigma^2}$ $\qquad \sqrt{1480} = 38.5''\ 3\sigma$

Table 5-3

Worst Case - Wind Straight Into Reflector

Azimuth Axis: θyy - Seconds of Arc

Error Source / Component	Deadload Nonrepeat-ability	25 mph Windload Steady State $\alpha = 0°; \psi = 0°$	Alignment Errors (RSS) Nonrepeat-ability	Servo Errors	Ice	Thermals
Cassegrain assembly	0	0	< 2	-	0	0
Antenna mount	0	0	< 2	-	0	0
Servo system	-	-	-	8.3	-	-
Encoder 17 bit	-	-	< 6	-	-	-
Σ 3σ	0	0	7	8.3	-	
$3\sigma^2$	0	0	49	69	-	-

RSS = $\sqrt{\Sigma 3\sigma^2}$ $\sqrt{118}$ = 10.8" 3σ

Table 5-4

Resultant Space Pointing Error Vector

All pointing error values listed are in seconds of arc-3σ

Pointing Error / Antenna Axis	3σ	$3\sigma^2$	$\Sigma 3\sigma^2$
Elevation (θxx)	38.5	1480	1598
Azimuth (θyy)	10.8	118	
RSS = $\sqrt{\Sigma\ \sigma^2}$	$\sqrt{1598}$ = 40" ≅ 0.01° peak 3σ		

C. Mobility System and Transport Vehicle

1. The mobility system

The mobility system proposed for the VLA will operate on two parallel railroad tracks of standard gauge on each arm of the wye spaced at 15 ft on center. An early study of the antenna and its transport vehicle indicated that a track spacing of 15 ft would be sufficient to provide static stability under all operating conditions specified. All development work on the antenna and transport vehicle has been based on this track spacing. A dynamic analysis, which takes into account a reasonable track waviness spectrum, indicates that it may be advisable to increase the track spacing to approximately 18 ft in order to minimize dynamic wheel loads resulting from the swaying motion of the transport vehicle which is initiated by the wavy rail contour during full speed travel. This dynamic analysis however was based only on a lumped spring-mass system which did not include the flexibility of the antenna and the surge damping effects of the hydrostatic transmission proposed for the transporter. For the purposes of this report, the previously proposed spacing of 15 ft for the transport track will be used.

This track system serves the purpose of a roadway for the transport vehicle in transporting the antennas and for access to the complete system for maintenance and servicing. All observing stations will be located off the main track at a distance of 100 ft from the centerline of the main track and will be connected by a spur track at 90° to the main tract. This track system is shown in Fig. 5-6. By placing the observing stations off the main track, it is possible to move any antenna to any position on the arms without passing through a switch or interfering with an operating antenna. It is proposed that all service and maintenance vehicles be rail mounted and by installing cross-overs between the two tracks it will be possible to keep the outside track free for rapid movement of the service vehicles.

The proposed 90° cross links are preferred to the switch and turnout system previously proposed in order to reduce the number of switches on the mainline track, to reduce the amount of spur track from approximately 480 ft for the curved turnout to 120 ft for the 90° cross links, and to reduce the amount of land required for each of the 100 stations.

2. The transport vehicle

The VLA proposal submitted in January 1967 presented the reasons for using a rail-mounted transport vehicle and the advisability of using three vehicles when changing the array configuration. The reduction in number of antennas from 36 as previously proposed to 27 presently proposed does not reduce antenna moving requirements, as with 36 antennas a portion of the antennas would remain in position while with 27 antennas all antennas will be moved during a reconfiguration of the array. It was considered advisable to retain the requirement of three transport vehicles and to investigate the possibility of increasing the transport speed from the previously proposed 2 mph to 5 mph in order to reduce the reconfiguration time.

The concept study performed by Systems Development Laboratory concentrated on developing a basic design for the transport vehicle, defining the operations it would perform, the mechanisms required for the performance of these functions, and the investigation of the track requirements and other factors which would limit the transport vehicle performance in time. The basic functions of the transport vehicle are:

(a) To move the VLA antenna from one observing station to another.

(b) To remove or place this antenna from and onto the observing station foundation by raising or lowering the structure.

(c) To position the antenna during the installation or disconnection phase and to accomplish the transfer from main to spur track or vice versa.

(d) To serve as a service vehicle during maintenance or repair of an antenna.

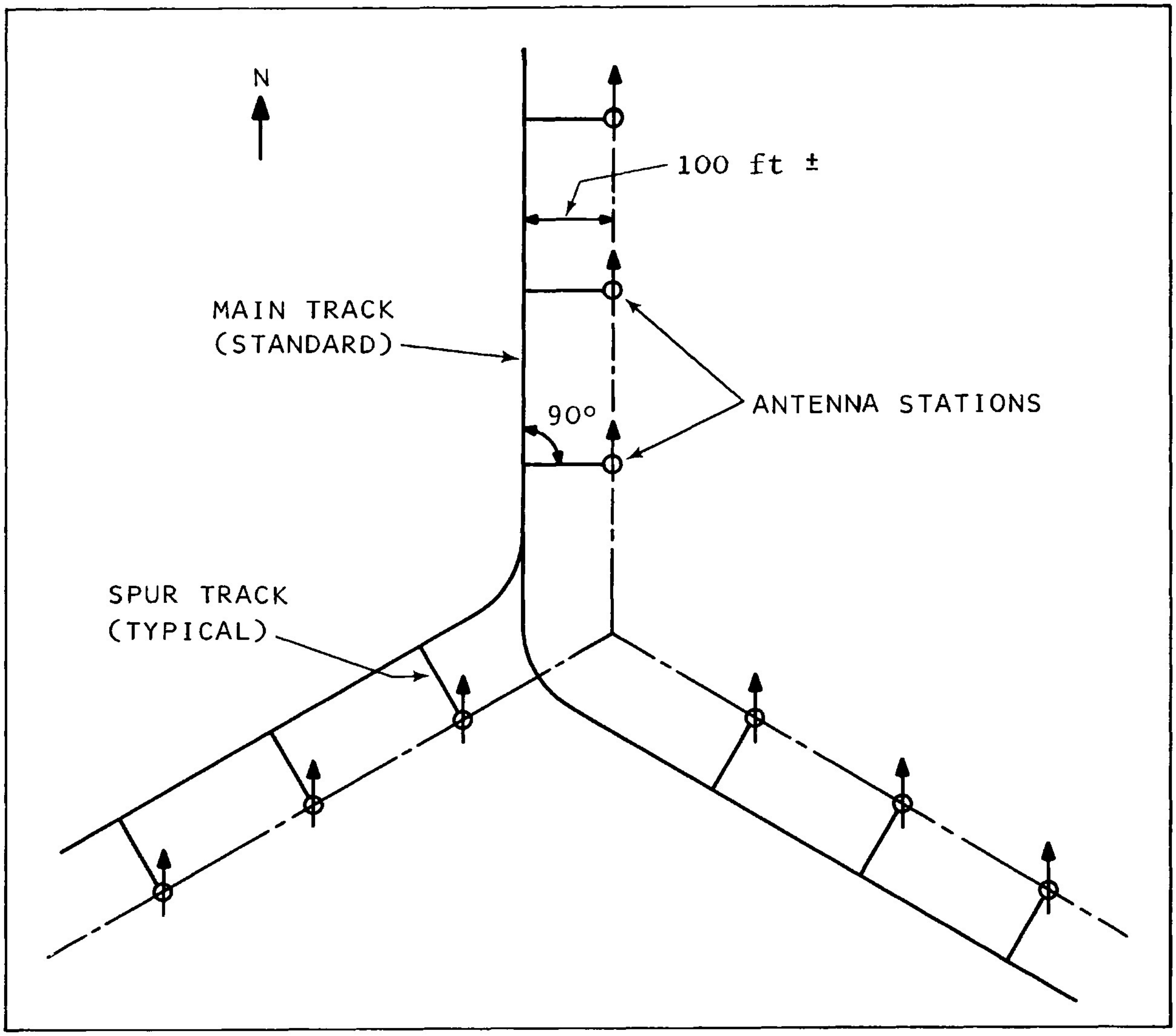


Fig. 5-6. Track and station layout at the center of the wye.

The requirements placed on the transport vehicle in the transport mode were that it should carry an antenna weighing 400,000 lbs, that it must be capable of moving up a 2% grade against a 25 mph wind at a speed of 5 mph while transporting the antenna, that it be stable against lateral or longitudinal forces created by a wind of 60 mph blowing in any direction, and that it provide for distribution of wheel loads to a track system which contains a random waviness spectrum. The concept as developed and shown in Figs. 5-7 and 5-8 uses a vehicle supported on four trucks using 16 wheels of standard 42 in diameter. Each truck is supported on four hydraulic cylinders which are hydraulically interconnected, thereby permitting cross flow between cylinders to equalize load on each of the four truck wheels. Driving force is provided by hydraulic motors via gear trains on each truck. These hydraulic motors are furnished motive power by two diesel driven hydraulic pumps delivering a total of 442 gallons/min. It is considered advisable to use two diesel units instead of one for added reliability since the unit may be used at reduced travel rates if only one unit is operating and there is a reduction in weight of approximately 2600 lbs using two units instead of one. An auxiliary diesel generator unit will be provided on the vehicle which will furnish electrical energy for controls, lights, booster pump operation, oil reservoir heater, and emergency power for operation of one antenna.

The operation of removing or placing an antenna from and onto the observing station is accomplished by use of the hydraulic suspension cylinders which, when placing an antenna on a foundation, elevate the transport platform to attain clearance, tilt the platform to the plane of the foundation pads, and lower the platform until the antenna mounting pads are in contact with the foundation and indexing is accomplished. The cylinders are then retracted and the transporter is removed. For removal of the antenna the reverse procedure is employed.

The operation of transferring the vehicle from the mainline tracks to the 90° spur tracks is accomplished by the hydraulic system of the transport vehicle. The transport vehicle is positioned at the center of intersection of the main and spur tracks to within an accuracy of about 0.5 in, the parking brakes are applied and four self-locking hydraulically actuated jacks are lowered onto foundation pads until the weight of the vehicle and

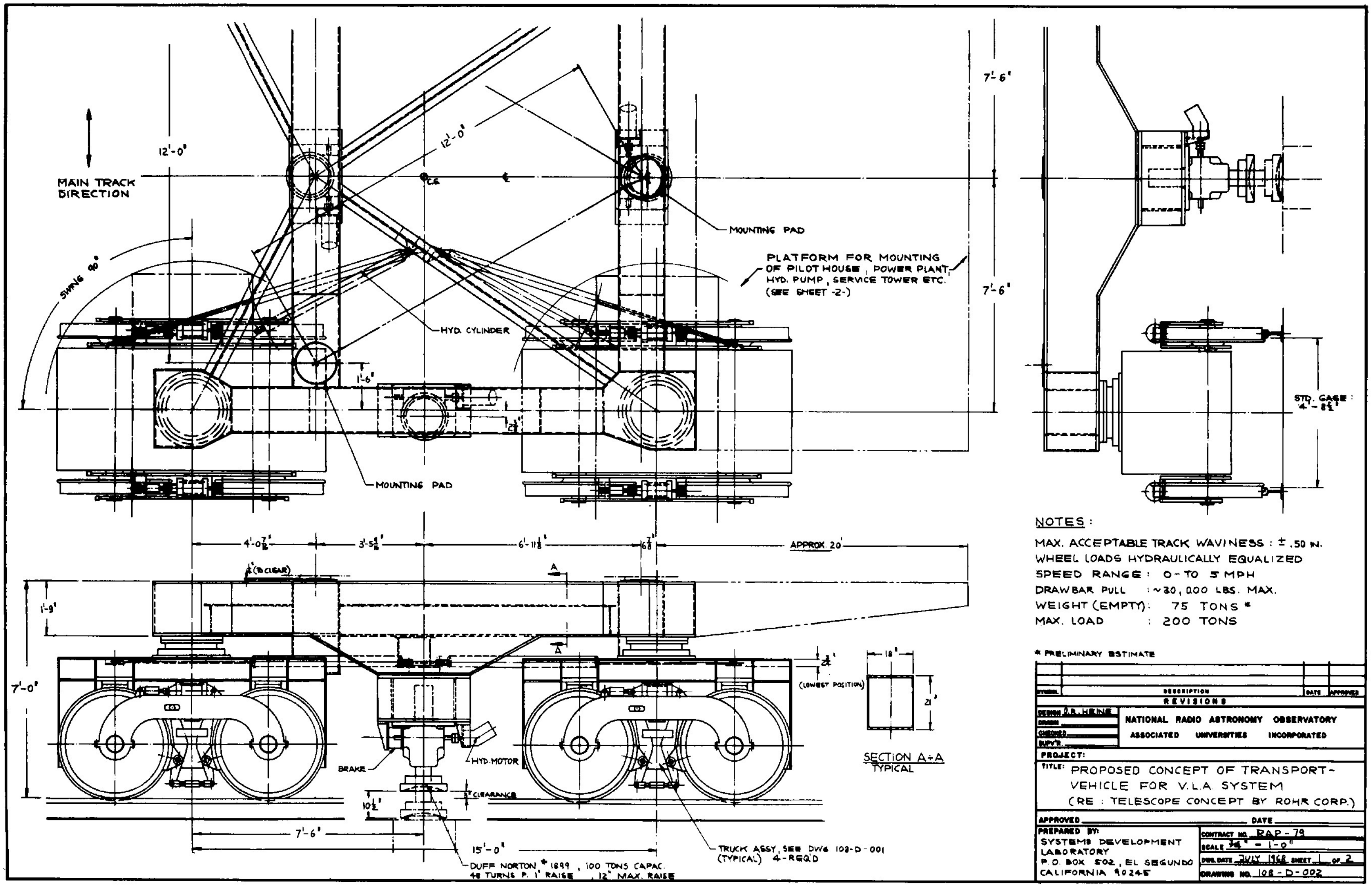


Fig. 5-7. The transport vehicle truck arrangement.

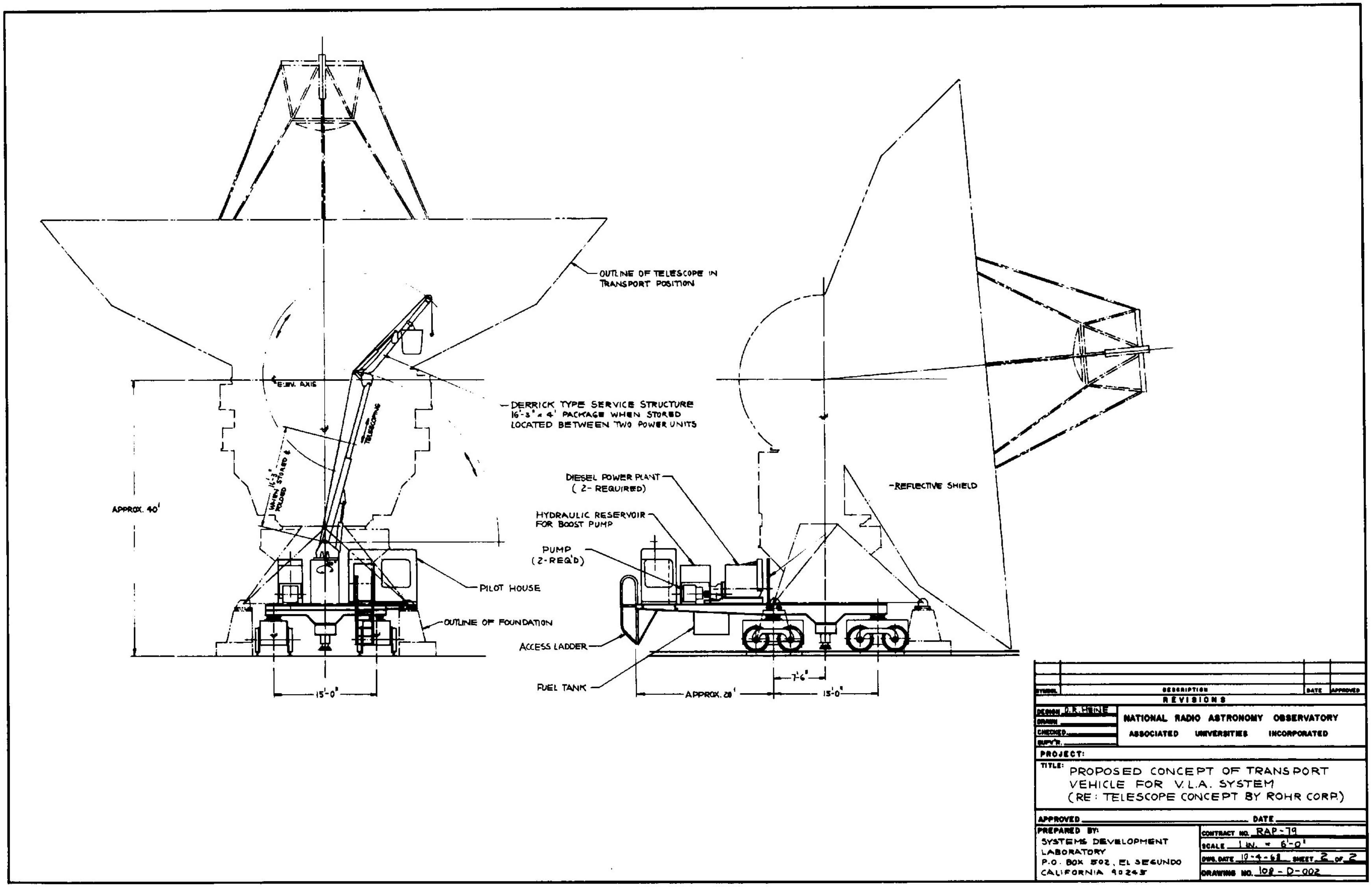


Fig. 5-8. The transport vehicle.

its antenna are on the jacks. The wheels of the tracks are then retracted by the hydraulic cylinders on the trucks to obtain clearance between wheel flanges and the top of the rails. All four trucks are then rotated 90° by means of hydraulic cylinders so that they are then in line with the spur track. The wheels are next lowered onto the spur track rail and the supporting jacks are removed.

The transport vehicle also serves as a service and maintenance vehicle and will be used to transfer components to the antennas. As previously mentioned, it will contain an auxiliary generator to furnish power for power tools and emergency operation of the antenna. Mounted on the antenna will be a light hydraulically operated crane boom which will have the capability of servicing either feed equipment at the vertex or the drive enclosure at the azimuth axis of the antenna. This boom is shown in Fig. 5-8. A summary of the main features of the transport vehicle are as follows:

Type of drive system	Hydrostatic
Power units	Dual diesel
Power required	413 hp max @ 1800 rpm
Type of pump(s) required (2)	Axial piston-variable-volume-remotely controlled
Flow required	442 GPM @ 2000 PSI
Pump speeds at full flow	860 rpm
Reduction gear required	2:1
Motor(s) required (4)	High-torque, low-speed radial piston
Motor speed range	0 to 260 rpm
Wheel speed at 5 mph	40 rpm
Drive-gear train(s)	4.15:1, One axle/truck
Vehicle speed at 25 mph wind	5 mph
Vehicle speed at 60 mph wind	2.6 mph
Vehicle speed, empty	7.85 mph
Efficiency of drive	67%

D. Antenna Feed

1. Introduction

The operation of the VLA requires simultaneous observations of both circular polarizations at two 100 MHz wide frequency bands centered at 2695 MHz and 8085 MHz. The axial ratio of the polarization ellipse should not exceed 1.05:1 within the receiving bands. This performance is not easily achieved. In April 1968 a contract to design such a feed and to build a prototype was awarded to the Defense Products Division of RCA.

The feed and its specifications are described in this section.

2. Feed design

(a) Input section. The input section configuration is shown schematically on Figs. 5-9 and 5-10. The basic feed horn is linearly polarized in orthogonal planes. The linear polarization is combined in these networks to form right- and left-hand circular polarizations.

(b) Moding section. The moding section of the feed is shown in Fig. 5-11.

Low-frequency signals are injected into the S-band ports (considering the system in a transmit operation). These signals will be supported in the TE_{10} mode only until section G in the flared section is reached where low-frequency mode generators are installed. The LSE_{12} (hybrid TE_{12} + TM_{12}) mode generated in this section combine with the dominant TE_{10} mode at the horn aperture to control the illumination taper and spillover.

High-frequency signals are injected into the x-band ports (considering the system in a transmit operation). The x-band port is a signal square waveguide input section fed by a dual mode transducer which provides orthogonal polarizations. A step discontinuity in the form of an abrupt increase in waveguide dimensions exists for these signals as they progress into the B section of the moding section shown in Fig. 5-11. This discontinuity generates the TE_{10} and LSE_{12} mode pair from the incident TE_{10} mode from the dual mode transducer.

These modes propagate through the dual-frequency section into the pyramidal horn. The pyramidal horn mode phase difference at the center frequency of the high-frequency band is 1.44π radians. The length of the dual-frequency section is adjusted to provide a $0.56\pi + 2\pi(n-1)$ radian mode phase

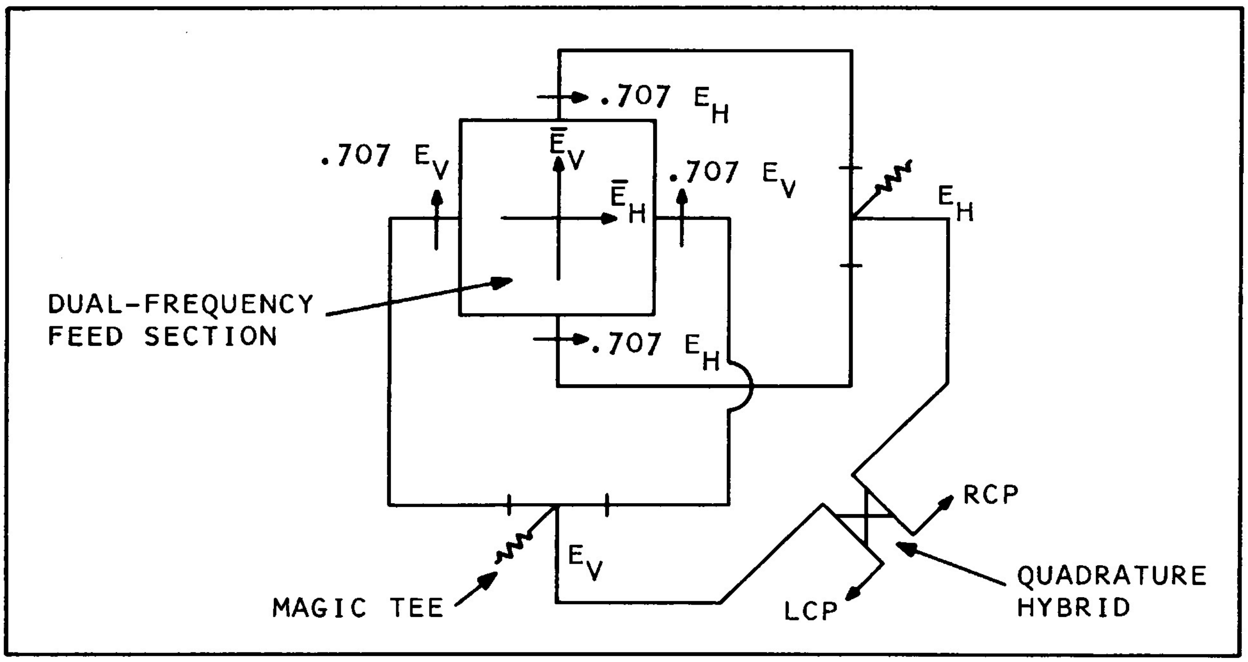


Fig. 5-9. Low frequency polarization network.

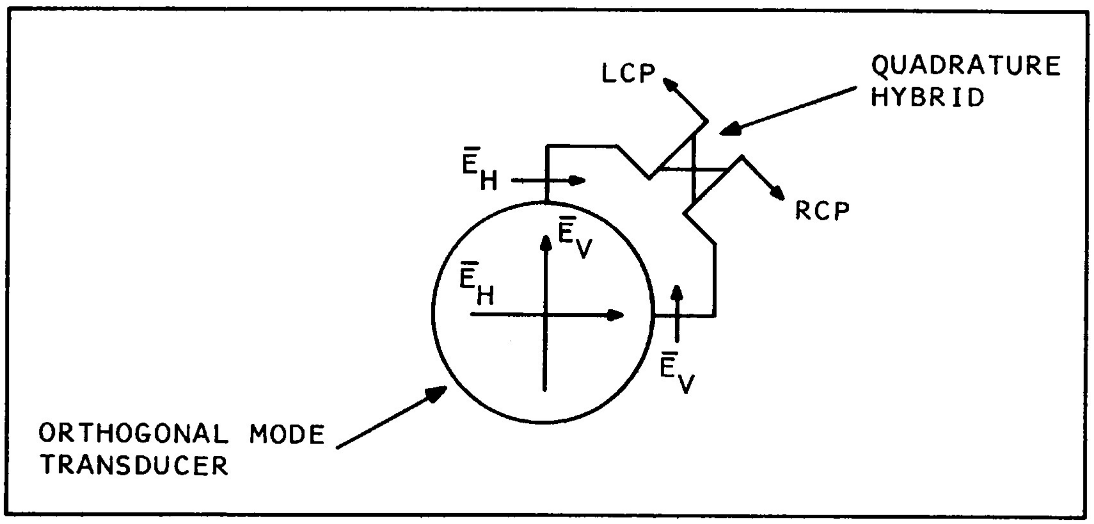
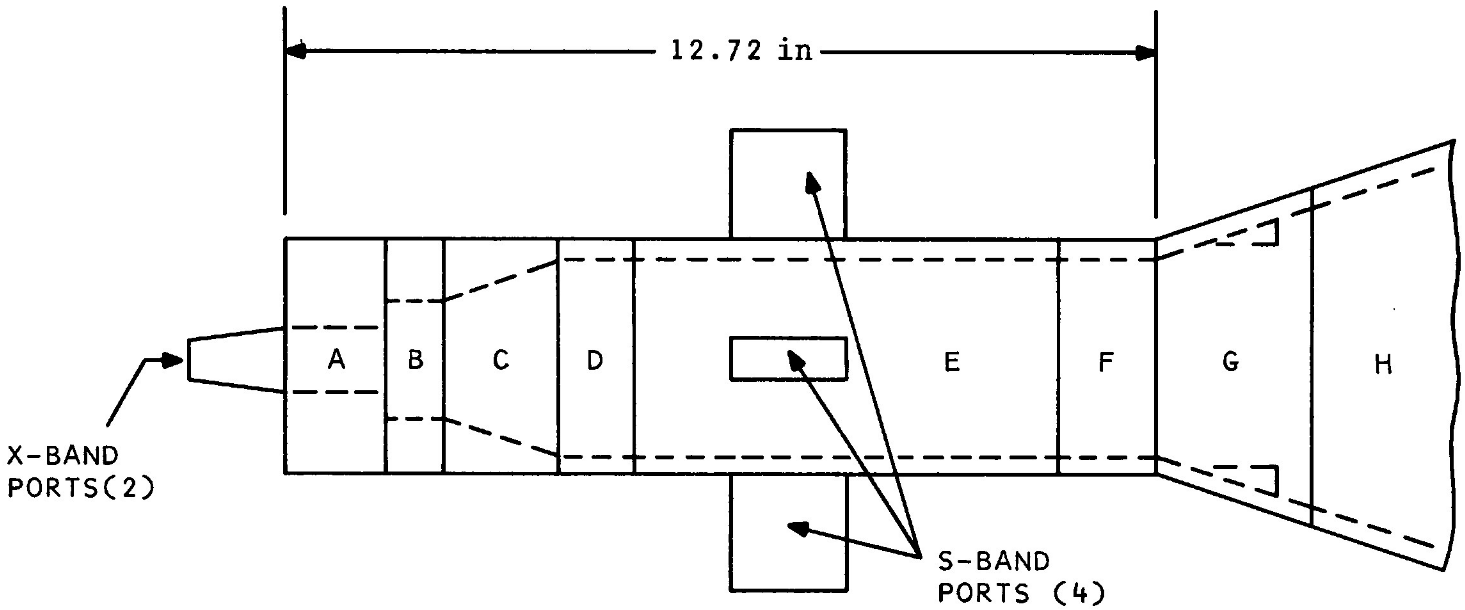


Fig. 5-10. High frequency polarization network.



A. X-BAND MODE FILTER

B. X-BAND MODE GENERATING SECTION

C. X-BAND TAPERED TRANSFORMER (S-BAND SHORT CIRCUIT)

D. PHASING SECTION

E. DUAL FREQUENCY FEED SECTION

F. PHASING SECTION

G. NEAR-FIELD HORN SECTION 1, WITH S-BAND MODE GENERATING RIDGES

H. NEAR-FIELD HORN SECTION 2

Fig. 5-11. The VLA feed moding section.

difference, thereby producing the required aperture mode phase difference at the high frequency. The side dimension of the dual-frequency section immediately following the step are chosen to support the LSE_{12} mode and suppress the TE_{30} mode.

(c) Horn section. The horn section shown in Fig. 5-12 is fabricated from aluminum honeycomb. The horn size is dependent upon the low frequency requirement and thus provides the necessary aperture to control the subreflector illumination at the low operating frequency band.

(d) Cassegrain subreflector. The subreflector is a hyperboloid in the standard Cassegrain configuration. The focal points, diameter, and position are shown in Fig. 5-13. The reflector will be remotely controlled for focal adjustments from the lower control room.

3. Antenna feed specifications

Type of feed	Cassegrain configuraion using a hyperboloidal subreflector in the near field of the primary feed and operating in a dual-polarization dual-frequency mode.
Frequency	2645 MHz to 2745 MHz and 8035 MHz to 8135 MHz
Polarization	Simultaneous right- and left-circular polarization with an axial ratio of the polarization ellipse not to exceed 1.05:1 at any frequency within the operating bands. The response of the antenna to a cross-polarized source at any point in the primary beam must not exceed -18 dB.
Port impedance	The VSWR of any output port must not exceed 1.15:1 within the operating bands.
Side lobes	The maximum near side lobe must not exceed -18 dB.

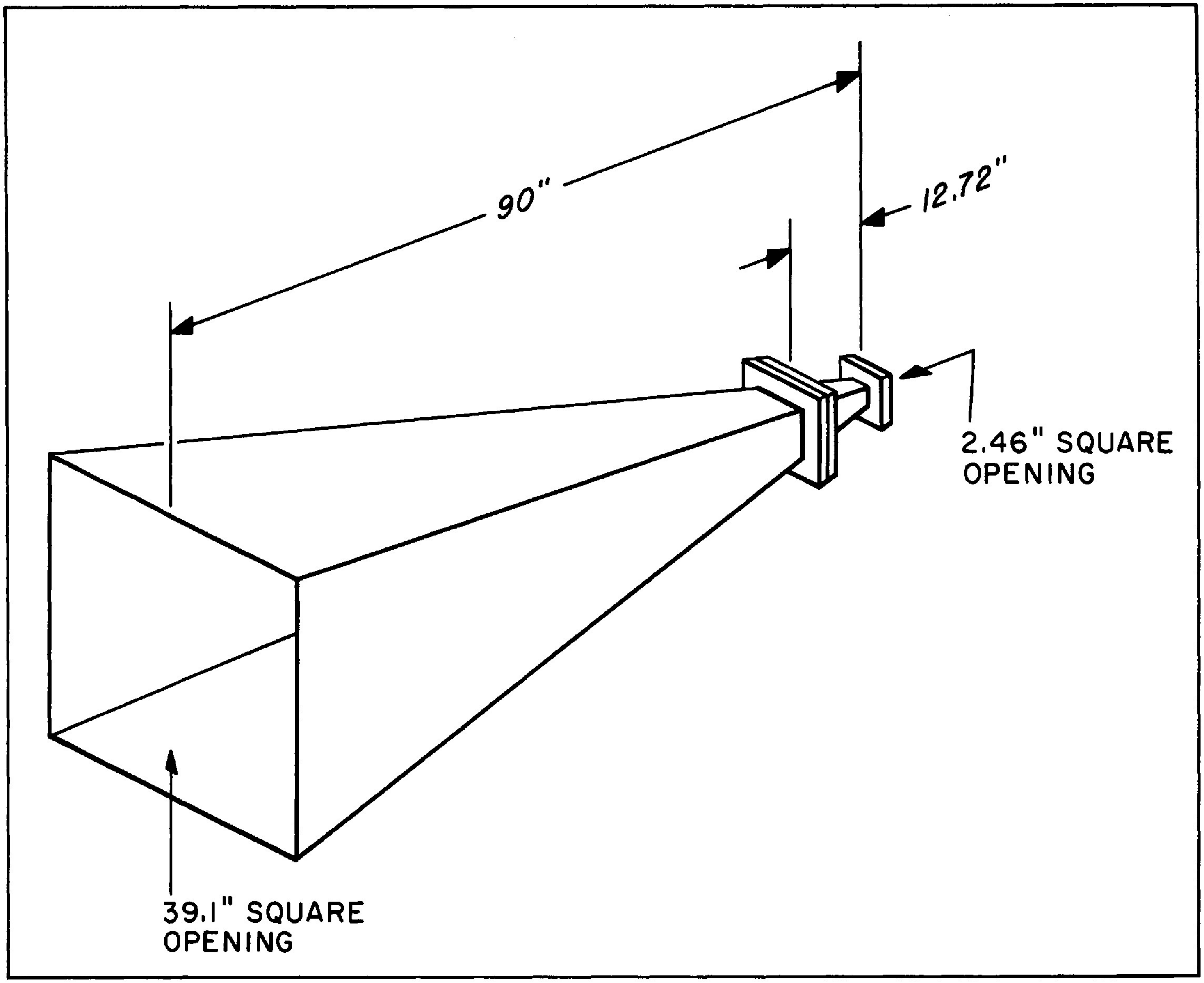


Fig. 5-12. The VLA feed horn section.

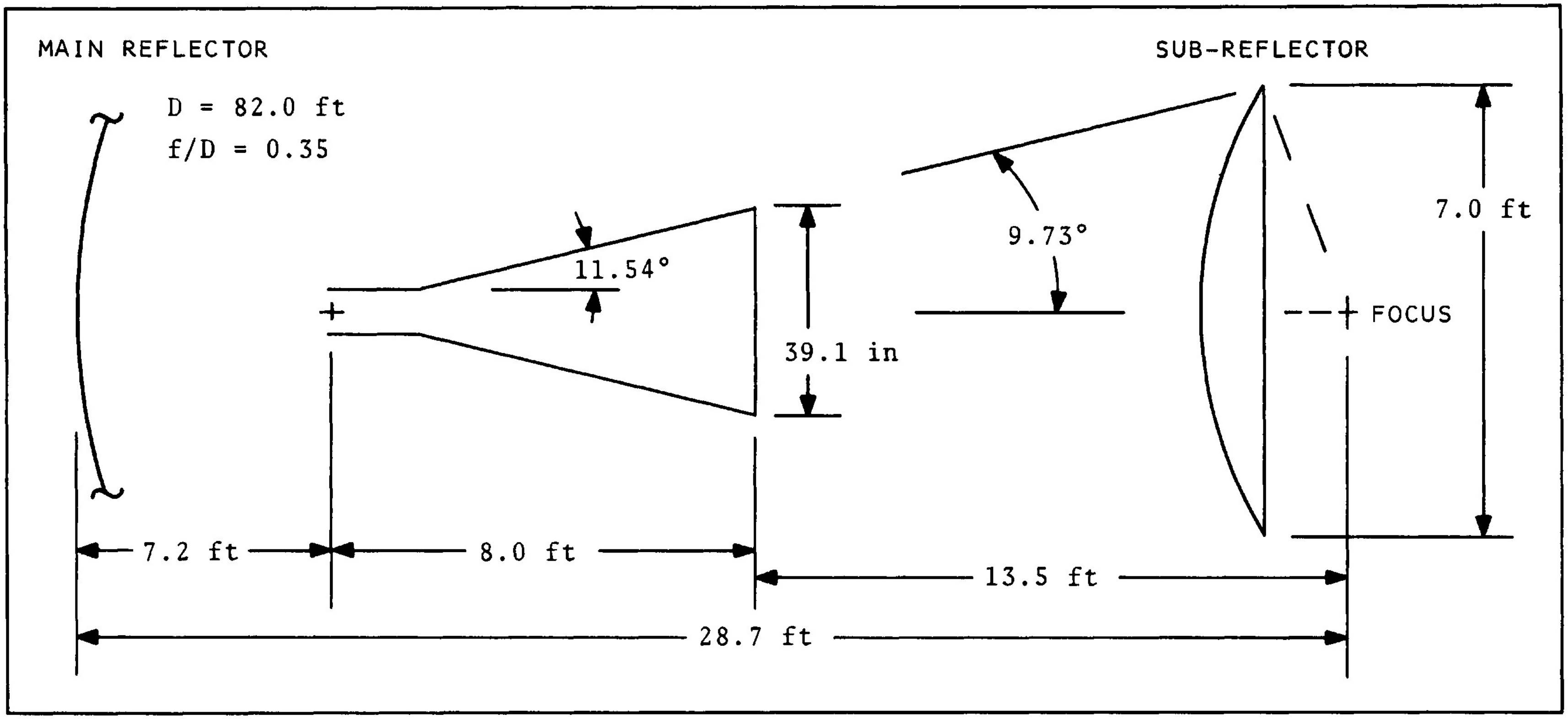


Fig. 5-13. The main dimensions of the Cassegrain feed geometry.

Noise temperature and aperture efficiency	Assuming receiver noise temperatures of 30° K at 2695 MHz and 50° K at 8085 MHz, the ratios of aperture efficiency to system noise temperature must be a maximum.

REFERENCES

Rohr Corporation Antenna Division, Final Report and Technical Specifications for VLA-W.O. 1120, August 1968.

McVey, E. S. 1969. "Report on the Specifications of the Servo Assembly for the Very Large Array (VLA) Prototype Antenna," VLA Antenna Memorandum No. 3.

Radio Corporation of America Report, Contract RAP-74, November 1968.

Chapter 6

ELECTRONIC SYSTEM

A. Introduction

A system design for the VLA electronics was presented in the VLA Proposal, Vols. I and II, in January 1967. The prime goal during the past two years has been to examine the feasibility of this system. In most cases this has required a combination of detailed design, component testing, and construction and test of a prototype subsystem. This work has been carried out both internally and through contracts with a university and industrial firm.

Three changes in the system specifications have occurred in the past two years. These are:

(1) The higher array frequency has been changed from 5390 MHz to 8085 MHz.

(2) The IF bandwidth has been reduced from 50 MHz to 35 MHz.

(3) The number of antennas has been reduced from 36 to 27.

The latter two changes have only recently been adopted and all work reported in this chapter is based on the former values. However, the effects upon the design are minor and are in the direction of easier requirements.

The electronics system can be divided into six subsystems. These are the local oscillator system, receiver front-ends, the IF transmission system, delay-lines, and a monitor and control system. Detailed design and prototype construction has proceeded on the first five of these subsystems and will be described in this chapter. No design work has been performed on the monitor and control system. This task is fairly straightforward and is best done after the initial design of the remainder of the system.

Two years ago the major question concerning the local oscillator system was whether the system analyzed in the VLA Proposal would perform reliably with adequate phase stability. Tests of the prototype show that it does perform according to the design specifications. The prototype would be adequate in the final system except for some microphonic components and a marginally-tolerable equipment temperature coefficient of 6° phase per °C at 8085 MHz. These deficiencies can be corrected by tighter component specifications, shock-mounting, or tighter temperature control. It has also been found that the three-loop system described in the Proposal requires a change to a four-loop system due to higher attenuation and lower sensitivity than considered.

The major problem concerning the IF transmission system has been prevention of distortion of 50 MHz bandwidth signals transmitted through up to 21 km of coaxial cable. A detailed design has been performed and shows that this problem can be solved. Critical components have been identified and developed and an 0.8 km repeater link has been tested. These tests have shown that amplitude uniformity with frequency is a problem. The present results would give 1.5 dB variation over 50 MHz at 21 km. This is tolerable and an integrated amplifier-equalizer will give better results. The repeater noise, cross-talk, and intermodulation distortion have been shown, theoretically, to be acceptable for the chain of 26 repeaters required for a 21 km baseline.

The VLA requirement for delay lines with 100 μs delay range, 50 MHz bandwidth, and 2 ns accuracy is difficult to meet. However, two different lines having the required delay range and bandwidth have now been developed. Methods of setting the lines with 2 ns accuracy have been investigated but have not yet been incorporated in either of the prototype lines. Both of the lines have components with unproven reliability, and further tests in this direction are needed.

The major question concerning the correlator units has been whether they can be produced with sufficient reliability, economy, and stability in view of the large numbers required (2520 for 36 antennas; 1404 for 27 antennas). Suitable units have now been constructed and tested. The use of Schottky-diode quad multipliers and the latest modular transistor operational amplifiers results in a small, inexpensive, repeatable and reliable correlator.

The reliability of the complex electronics system has been investigated, and one can make the following statements:

(a) The failure of most components in the array produces only a slight deterioration in performance.

(b) All electronics in the array will be solid-state. No klystrons TWT, high-voltage, or high-power components are used.

(c) Sufficient time is allowed in the construction schedule to allow prototyping of all components. High failure-rate or overly critical components will be weeded out before final construction.

(d) An adequate monitor system and modular construction is planned to allow quick detection and correction of faults.

B. Local Oscillator System

A system for distribution of local oscillator signals was described in the VLA Proposal. This system corrects for phase errors introduced in the long transmission path from the central control room to each antenna. The system was selected for reasons listed in the proposal after consideration of several alternative methods. A theoretical analysis of the phase stability of the system was also presented and adequate performance was predicted.

During the past two years, a portion of the proposed system has been constructed and tested. The system operated satisfactorily, as constructed, without changes from the original design. However, several areas that can be improved have been found and much knowledge about the system performance and reliability has been gained.

The system is particularly suitable for distribution of fixed-frequency local oscillator signals to several antennas located on a trunk line > 3 km in length. If any one of these conditions (i.e., fixed frequency, several antennas, > 3 km trunk) is changed, the system may not be suitable although the basic principle may still be applicable.

1. Prototype design and composition

The prototype system was constructed through a contract with the Research Laboratories for the Engineering Sciences of the University of Virginia. A complete description of the work is given in a summary report (see reference list at end of chapter).

The prototype system follows quite closely the design described in the VLA Proposal, and a detailed description will not be given here. Some minor changes or additions to the proposed design are:

(a) Change of IF frequency from 10 kHz to 355 kHz or 455 kHz to reduce oscillator noise problems.

(b) Incorporation of crystal filters in multiplier chains to reduce oscillator noise.

(c) Addition of tuners at each antenna coupling point to minimize effects of cable reflections.

The complete local-oscillator distribution system described in the VLA Proposal consists of a master oscillator (in the central control room), 9 launchers and terminators (along cable trunks), and 36 receivers (one at each antenna). One of each of these units was built in the prototype system. These units are outlined in heavy black lines in the block diagram shown in Fig. 6-1. A cable transmission path of 7 km was simulated with attenuators and variable phase shifters.

Photographs of the completed prototype system are shown in Figs. 6-2 and 6-3. A very rigid, well-shielded construction was required because of phase stability requirements and large signal-level differences in the system.

2. Test results

The prototype system was completed on November 13, 1967, and has been in continuous operation since that date. It was experimentally verified that the system reduces phase variations in the cable transmission line by a factor of ∿ 4500. (This is the ratio of line transmission frequency, 224 MHz, to loop offset frequency, 50 kHz.)

A typical phase stability record is shown in Fig. 6-4. This record shows the effects of varying the equipment temperature. The phase error has a temperature coefficient of 0.6 phase per °C ambient temperature change at 2695 MHz. Thus temperature control of ± 1° C would give ± 2° phase shift at 8085 MHz. This would be tolerable but can also be improved by a factor of 2 or 3 by more careful selection or specification of a few components. The temperature coefficients of various components are given in Table 6-1.

The prototype system operates satisfactorily for an antenna located at any distance from the master oscillator along 95 dB of simulated cable. This attenuation would be obtained from 6.7 km of 1 5/8 in cable plus 720 m of 7/8 in cable (used to loop the trunk line through each antenna). Some margin is needed to account for cable not laying straight in the trench, cable attenuation tolerance, and degradation of performance with age. Thus

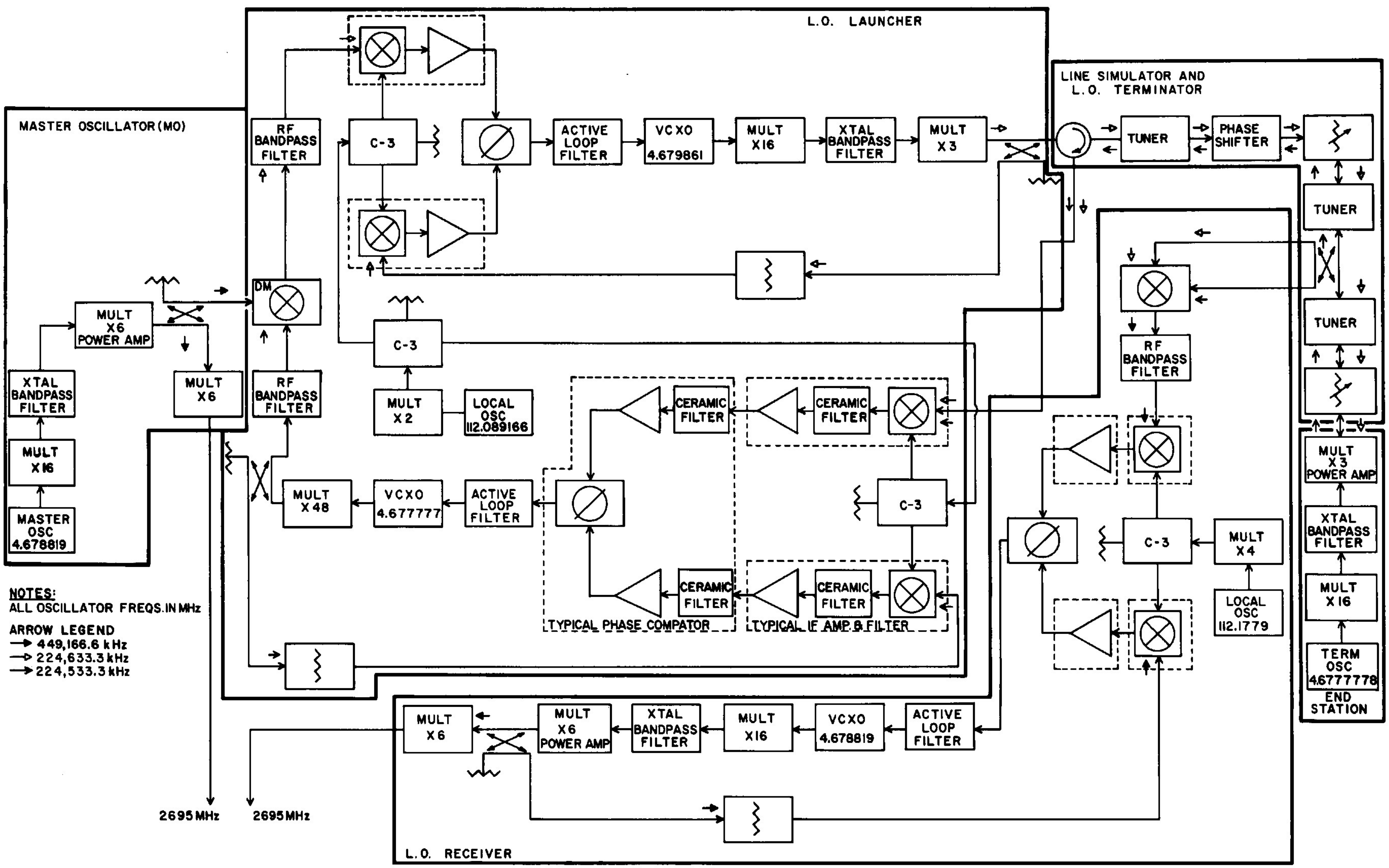


Fig. 6-1. Block diagram of the prototype local-oscillator system.

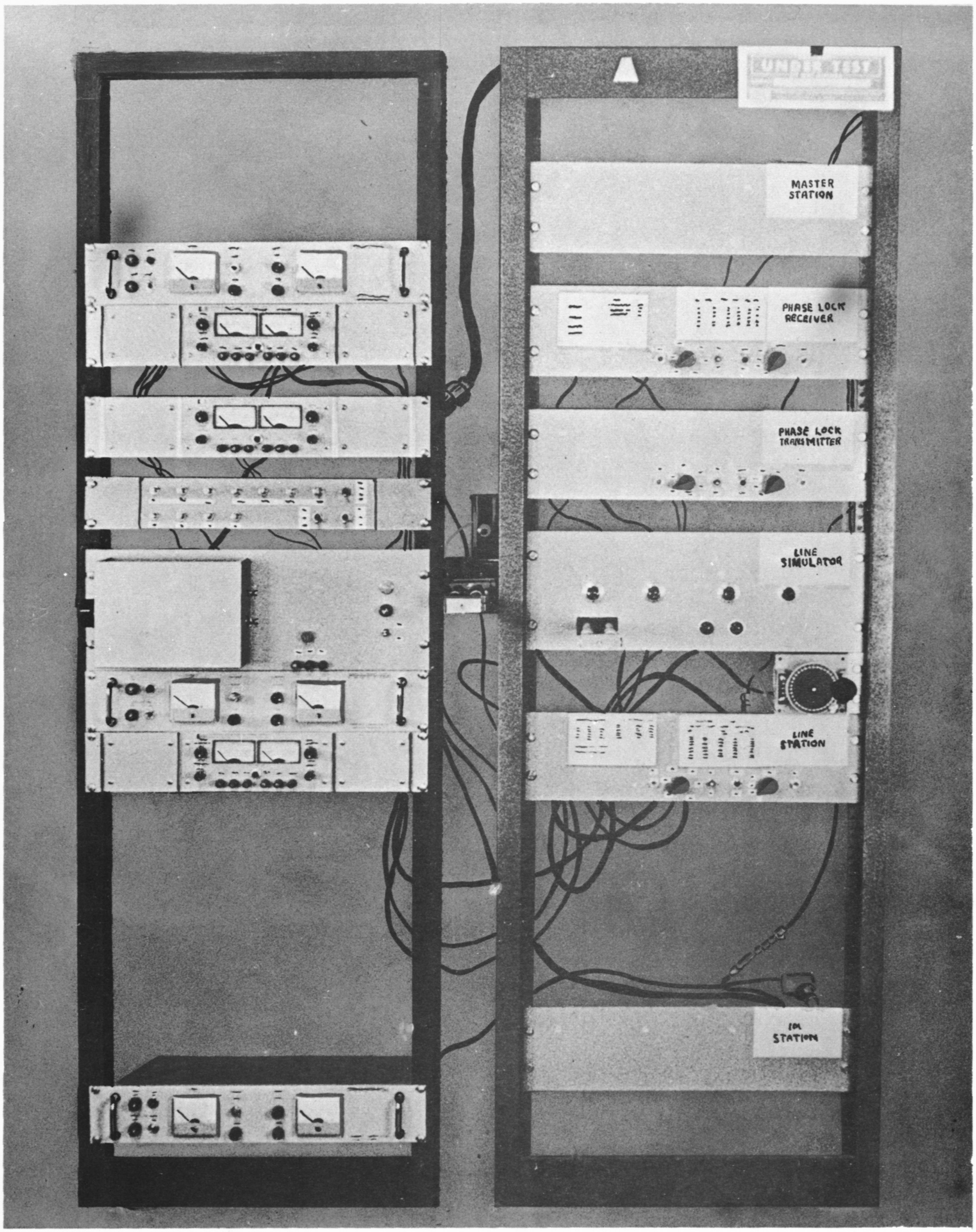


Fig. 6-2. Prototype local-oscillator system; front view of equipment rack.

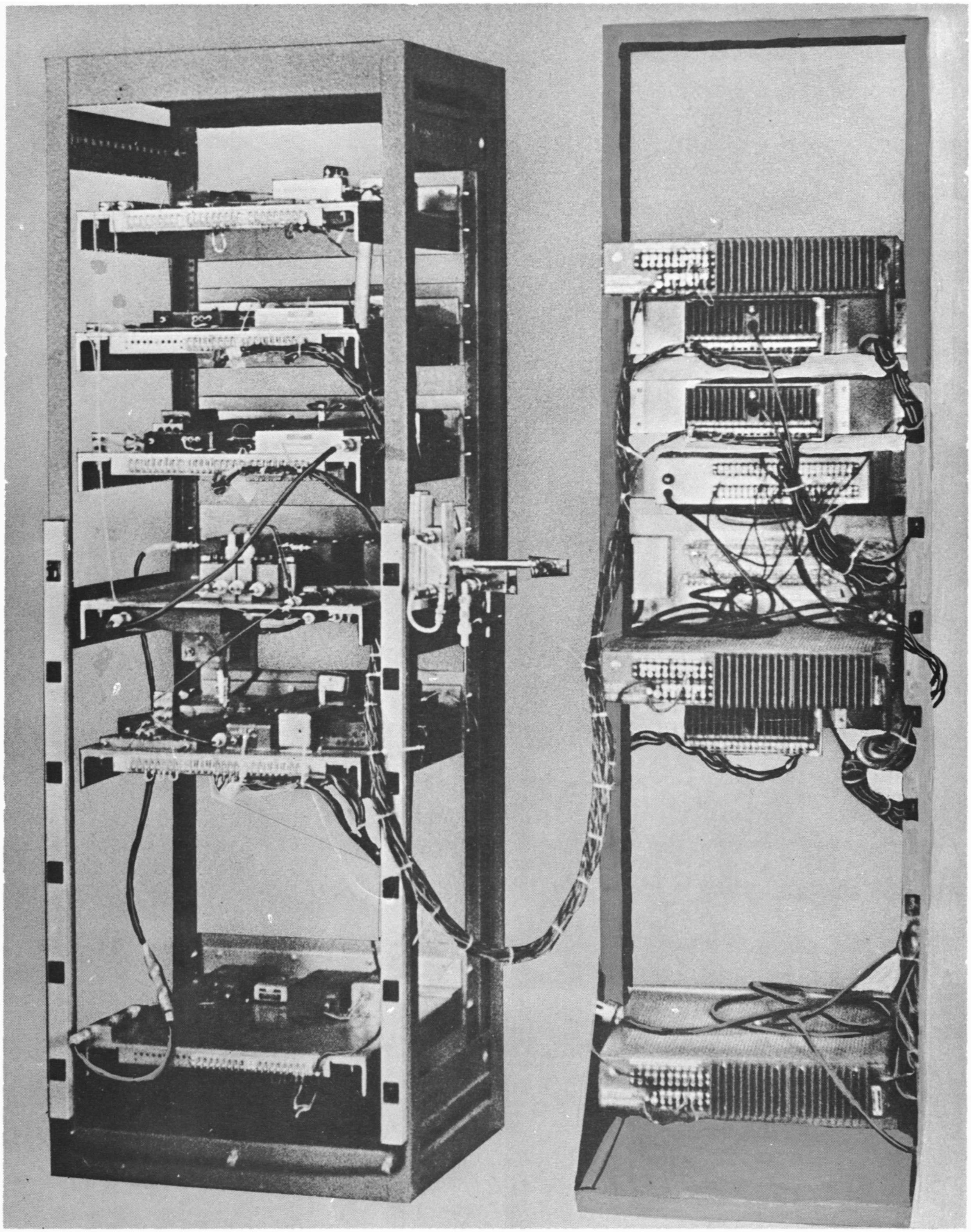


Fig. 6-3. Prototype local-oscillator system; rear view of equipment rack.

some improvement in the system noise performance or lower attenuation cable is needed if a three-loop system is to be used with 21 km trunk lines.

The system noise performance is indirectly limited by noise in the basic crystal oscillator circuits. This noise is reduced by higher lock-loop bandwidths. However, the higher loop bandwidths make the system more sensitive to thermal and amplifier noise. The oscillator noise can be reduced by some design changes and thus the system attenuation tolerance would be improved. This problem is discussed by Beazell (1968) in the University of Virginia Summary Report.

Three component failures have occurred in one year's continuous operation of the system; all were within the first 4000 hours. These are described in detail in the above-mentioned report. One of the failures could have been avoided by design changes; the other two appear to be random semiconductor failures.

3. Lobe rotation development

Three methods of accomplishing lobe rotation were investigated. The first two were done at the IF frequency of a phase-lock-loop as suggested in the original VLA proposal. The third is by voltage offsetting the phase-lock-loop.

The first two techniques are similar. A mechanical "phase shifter" was procured and tested in the system, and a single-side-band suppressed-carrier modulator was designed and tested. Both techniques depend on generating quadrature voltages from the reference signal and both are slightly sensitive to frequency changes of the IF. The system temperature coefficient was increased by a factor of six when the mechanical lobe rotator was used. This problem needs further investigation if the mechanical shifter is to be considered.

The third technique is by voltage offsetting the phase-lock-loop error. This technique is analogous to the serrodyne method of phase modulating a TWT. Since the phase detector is nearly linear over a full 360° of phase error, a linear phase analog voltage can be used. Also the ultimate LO phase is shifted a proportionally greater amount by the final LO multiplication. For operation at 2695 MHz, a 300° span of the phase detector was used, providing 1800° of continuous phase variation. At the end of the 1800°

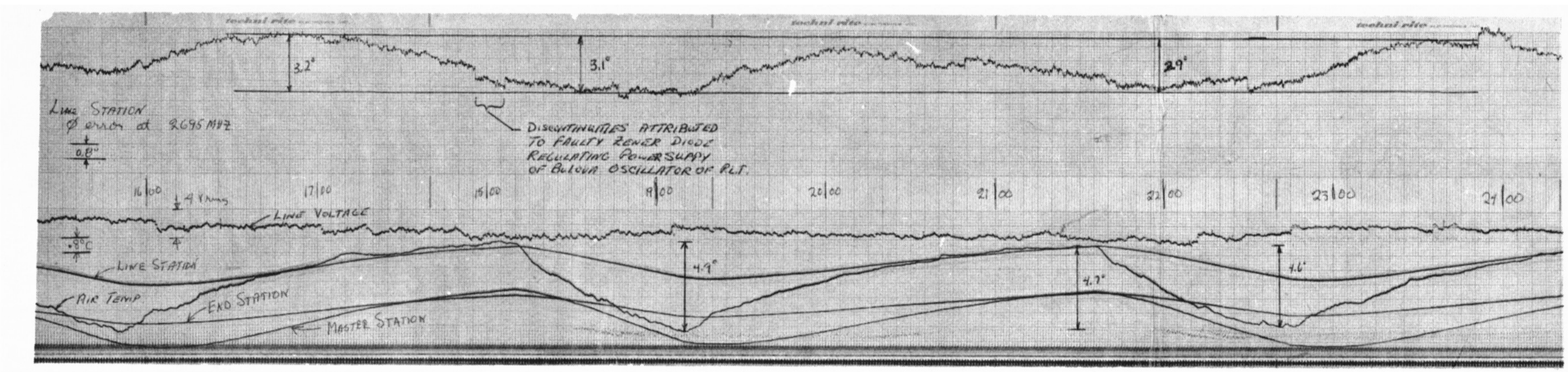


Fig. 6-4. Typical stability of the prototype LO system with 5° C of ambient temperature variations. The top curve is the phase error at 2695 MHz as measured between the master oscillator and an antenna receiver. The lower curves are line voltage and temperatures of various units in the system. This data was taken with a simulated 95 dB of cable loss between launchers and terminators and the receiver located at the center of this trunk; loop bandwidths of 100 Hz to 200 Hz were used.

of variation, a short-duration phase discontinuity occurs; it is not known at present whether this can be tolerated by the system.

Table 6-2 lists pertinent characteristics of the three methods.

4. Conclusions and recommendations

In general the operation of the prototype system has indicated satisfactory performance in supplying 2695 MHz phase stable operation. It is recommended, however, that a number of changes be incorporated in future units to assure at least equal or better capability of 8085 MHz. Tests have shown that the following improvements should be incorporated:

(a) Receivers. Two versions of mixers were used. The balanced transistor mixers in the launchers performed well but are subject to phase shift as a function of supply voltage change. It is recommended that these be replaced by the double-balanced-mixer FET preamp version used in the receiver.

It is also recommended that the entire receiver be redesigned mechanically to place the ceramic filters in closer proximity for an improvement in phase tracking as a function of temperature.

(b) Receiver local oscillator. Voltage control of the 112 MHz crystal oscillators would permit incorporation of automatic frequency correction due to LO and signal frequency drifts and therefore minimize the need for periodic adjustment of the LO frequency and eliminate the need for an oven stabilized LO. Ability to sweep the LO while observing the phase error output also would provide a highly convenient diagnostic capability and facilitate attaining minimum differential phase error between signal and reference channels.

(c) Crystal oscillator - multiplier chains. The 4.7 MHz oscillators have performed well within their specifications. However, to reduce oscillator noise effects, a redesign should include a higher oscillator frequency, a low-vibration crystal mount, a low IF noise oscillator circuit, and a low-noise amplifier following the oscillator.

(d) Final S- and X-band multipliers. Since the majority of the phase shift/temperature sensitivity was due to the final S-band multipliers, these and future X-band units should be carefully specified and designed for phase-stable operation.

Table 6-1

Temperature Coefficients of LO Systems Components

(Values are degrees phase shift at 2695 MHz per °C component temperature change.)

Component		k_t $\frac{Deg.}{°C}$
Micromega multiplier No. M6-2700		2.24
Applied Research multiplier No. 154-1		-0.76
10 dB attenuator Serial No. 03005		*
HP variable attenuator No. 218-11010		*
Easy match tuner		*
Receiver No. 1	Launcher	0.27
Receiver No. 2	Launcher	-0.58
Receiver No. 3	Launcher	-0.45
Receiver No. 4	Launcher	-0.21
Receiver No. 5	Line receiver	*
Receiver No. 6	Line receiver	*
Circulator		-0.53
Phase comparator No. 1 PLR		*
Phase comparator No. 2 PLT		*
Phase comparator No. 3 LSU		*
Loop filter No. 1 PLR		*
Loop filter No. 2 PLT		*
Loop filter No. 3 LSU		-0.265

* No detectable correlation

Table 6-2

Lobe Rotator Comparison

	Mechanical	SSBM	Voltage
Insertion loss	≌ 30 dB	≌ 30 dB	0
Linearity	Good	Poor	Good
ϕ repeatability	Best	Good	Good
Freq. sensitive	Yes	Yes	No
Drive servo	Yes	No	No
Data input	Shaft-angle	Sin ϕ + Cos ϕ	-
Continuous ϕ	Yes	Yes	No
Complexity	Maximum	Medium	Minimum
Reliability	Poor	Medium	Best
Cost	Maximum	Medium	Minimum

C. Front-Ends

The development of prototype front-ends was purposefully delayed until March 1968 since feasibility was certain and a later development would take advantage of advances in the state-of-the-art. During the summer of 1968 orders were placed for prototype parametric amplifiers, crystal mixers, an LO and a paramp-pump frequency-multiplier package. Components for operation at both 2695 MHz and 8085 MHz were ordered. These prototype components will be incorporated in the Green Bank three-element interferometer during late 1969. The present interferometer utilizes degenerate 2695 MHz paramps with synchronous pumps similar to the VLA prototypes on order.

At the present time only a few of these components have been received and some preliminary measurements have been reported by manufacturers. This report will describe some system design changes and refinements, the specifications of major components on order, and some preliminary data on these components.

1. System design

The major change in the front-end design from that discussed in the VLA Proposal is the adoption of single-stage paramps in lieu of two-stage units. Omission of the second-stage paramp will increase the system noise temperatures by 5° K to 8° K. However, only half as many paramaps are required and the phasing problems (due to synchronous operation needed with degenerate paramps) are simplified. A single phase-shift adjustment can be placed in the LO line; the two-stage paramp requires placing a phase adjustment in a paramp pump line where it is critical to gain stability.

A block diagram of the prototype 2695 or 8085 MHz front-end is shown in Fig. 6-5. The LO power is leveled by sensing the crystal current in one mixer; each paramp has its pump power leveled by sensing the varactor bias current. Dicke-switched operation (may be necessary for antenna pointing calibration) is achieved by removing paramp pump power and biasing the paramp into a no-gain, low-loss mode.

A three-port input circulator has been specified for the paramp. Sufficient isolation can be obtained in a carefully manufactured unit, and the noise temperature will be 15° K lower than with a four-port input circulator.

2. Paramp specifications

A contract was signed on June 18, 1968 with the Micromega Division of Amphenol for the development of the prototype parametric amplifiers. At the time of this writing, Micromega has reported that the 8085 MHz amplifier is meeting specifications and no problems are expected with the 2695 MHz amplifier. The pertinent specifications of these amplifiers are the following:

(a) General description. Two single-stage, uncooled, degenerate parametric amplifiers. One unit operates at a center frequency of 2695 MHz while the second unit operates at 8085 MHz. Each paramp will consist of an input three-port circulator, a varactor mount, and an output isolator.

(b) Gain and bandwidth. The gain, G, of each unit must be 14 dB $\pm$ 0.25 dB over a 100 MHz band centered at one-half the pump frequency. (The pump frequency is 5390 MHz for one unit and 16,170 MHz for the second unit.) The definition of gain of a degenerate paramp is ambiguous and is defined as follows for the 14 dB specification:

If the paramp input signal voltage has amplitude E at frequency $f_p/2 + f_1$ then the output amplitude is GE at signal, $f_p/2 + f_1$, and GE at idler frequency, $f_p/2 - f_1$. In these equations, f_p is the pump frequency, f_1 is a frequency between -50 MHz and +50 MHz, and G = 5 (14 dB). The insertion gain as measured with a crystal detector will be 17 dB since the

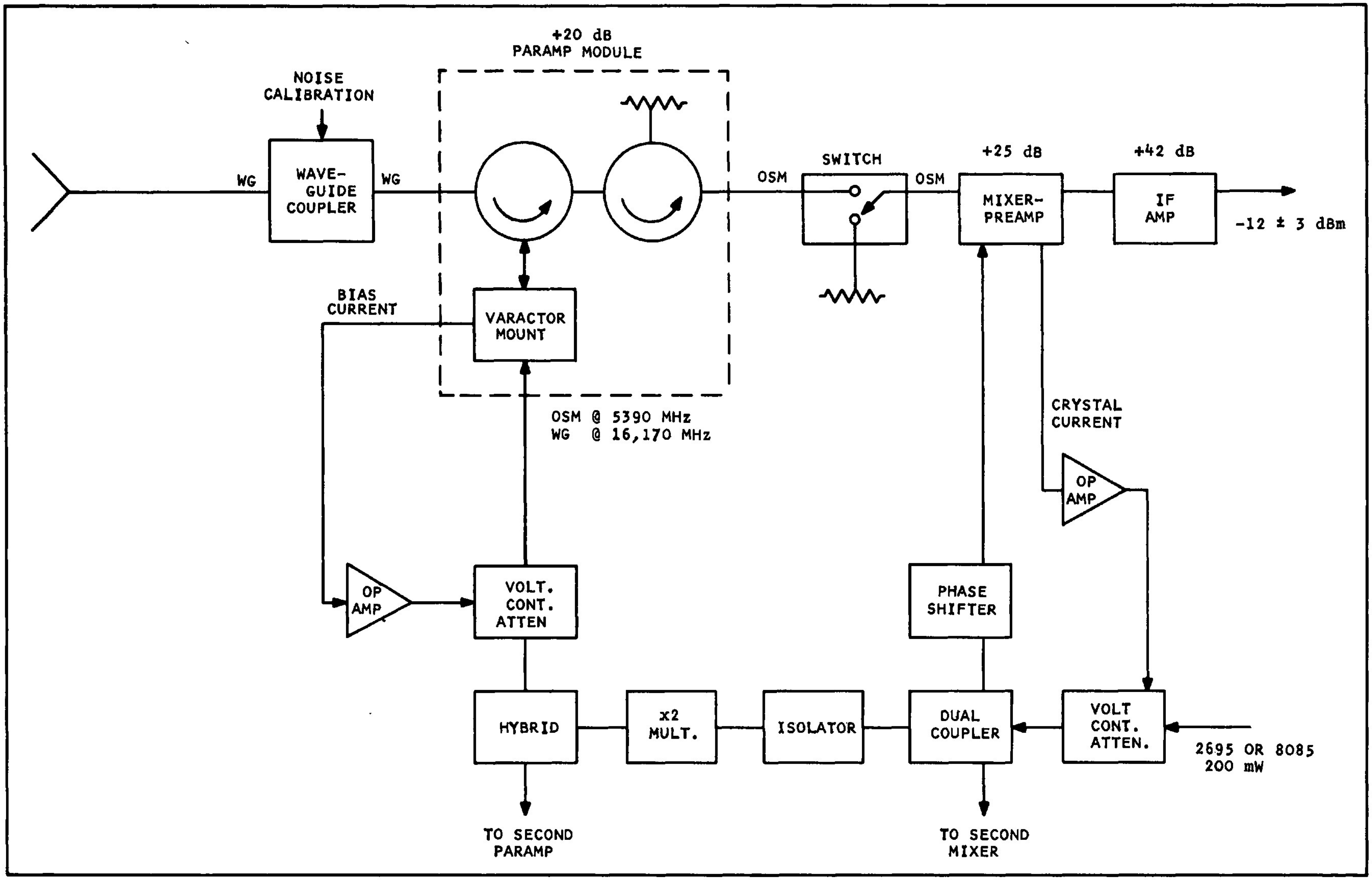


Fig. 6-5. VLA front-end block diagram. This block diagram is repeated four times in the dual-channel, dual-frequency configuration.

detector responds incoherently to signal and idler. The insertion gain as measured with a crystal mixer will be 20 dB since the mixer responds coherently to signal and idler (assuming the LO is at one-half the pump frequency, is coherent with the pump, and is phased correctly).

(c) Noise temperature. The double-sideband noise temperature must be less than 50° K for the 2695 MHz unit and less than 90° K for the 8085 MHz unit. This measurement applies to any frequency in the 100 MHz band and must be measured with a cryogenic termination with VSWR < 1.10 and noise temperature calibrated to within ± 2° K.

(d) Signal isolation. The input circulator must be a high-performance narrow-band unit having an isolation of > 35 dB over a 200 MHz band centered at the operating frequency. The amplifier gain must vary less than ± 1.5 dB as the input source or output load reflection coefficients are varied from -1 to +1.

(e) Pump isolation. The pump signal should be highly decoupled from the amplifier input and output ports. Specifically, the amplifier gain should not vary by more than ± 0.1 dB as the reflection coefficient at the pump frequency is varied from -1 to +1 at the amplifier input or output.

(f) Pump VSWR. The pump port of the amplifier must be matched without tuning screws to a VSWR less than 1.5. It is especially important that the pump is efficiently coupled to the varactor in the 8085 MHz unit so that a minimum amount of pump power is required.

(g) Bias. The amplifiers must be externally biased and a forward bias current between 0.1 μA and 2.0 μA must be drawn. This bias current is needed for a pump power control loop.

(h) Stability. The gain stability of the amplifier must be sufficient to meet the following requirements:

- (i) Less than ± 0.2 dB variation for ± 5° C temperature variation from 25° C.
- (ii) Less than ± 1.0 dB variation as the pump power is varied by ± 0.1 dB.
- (iii) Less than ± 0.1 dB variation if the amplifier is lightly tapped.

3. <u>Other front-end components</u>

Mixer-preamplifiers for 2695 MHz and 8085 MHz have been ordered from two different manufacturers. These units have tight specifications on noise temperature, isolation, and impedance match.

An all-solid-state LO and paramp pump source has been ordered from Applied Research Corporation. The unit contains an oscillator at 449 MHz (which would be phase-locked to a master oscillator through the LO system) and frequency multipliers to provide the following outputs:

2695 MHz - 2 outputs, 5 mW each
5390 MHz - 2 outputs, 20 mW each
8085 MHz - 2 outputs, 5 mW each
16,170 MHz - 2 outputs, 100 mW each

These outputs are needed for local oscillator and paramp pump sources in the dual-channel, dual-frequency system.

D. <u>IF Transmission System</u>

The further development of the IF transmission system has been conducted primarily through theoretical studies, component measurements, and prototype design within NRAO. This work will be reported in this section. At the present time, a small portion of the system is being constructed. Tests of this prototype subsystem are planned in the next few months; some initial results will be reported here.

1. <u>General system design</u>

The ITT Federal Laboratories system design study recommended a cable system for transmission of the VLA IF signals. A microwave-link system had been rejected early in the study, but it was decided in March 1967 that a short, internal study of a microwave link system would be worthwhile.

The results of this study are documented by Weinreb (1968). The advantages of the microwave-link system are:

(a) Approximately $500,000 lower construction cost.

(b) Greater flexibility with respect to location of observing stations except in the case of a closely spaced array.

(c) Ease of expansion to baselines longer than the planned 21 km.

(d) Potentially greater reliability because of the lack of a series repeater system.

The disadvantages are:

(a) A frequency allocation of 1800 MHz bandwidth is required.

(b) There is a danger of interference of the link into the receiving array and of external interference into the link.

(c) The array antennas tend to block the link and the link towers tend to block the array. This problem is especially acute at the wye center.

It would be very difficult to be certain that problems (b) and (c) were solved before the entire array was constructed. On the other hand, the cable transmission system can be debugged in a prototype stage and then will operate with little interaction with the site environment or other portions of the array. The cable system was chosen for detailed design and prototyping.

Two other types of IF transmission systems have been briefly considered. These are an optical transmission system and TE_{01} circular waveguide transmission. In both cases there are technical problems, which, so far, have prevented commercial application. The reliability of these systems is unknown and it does not appear prudent to use a new and unproven transmission method in a complex instrument such as the VLA.

2. Cable system design

The design of a cable IF transmission system requires the selection of cable type, frequency band, degree of multiplexing, and a modulation system. These choices must be made considering cost, reliability, repeater noise, intermodulation noise, cross-talk, phase nonlinearity, and amplitude distortion.

Studies of these factors are presented in the ITT final report and the following internal reports:

Weinreb, S. 1967, "Comparison of Modulation Systems for Transmission Through Dispersive Cables," VLA Electronics Memorandum No. 5.

Weinreb, S. 1967, "Prototype IF Transmission System," VLA Electronicss Memorandum No. 6.

Buhl, D. 1968, "Equalization and Signal-to-Noise Problems in the IF Transmission System," VLA Electronics Memorandum No. 7.

The following conclusions may be reached from these reports:

(a) The lowest cost system will utilize either 7/8 in or 1 5/8 in coaxial cable with transmission of 4 to 12 IF signals per cable in an octave band, with its low-frequency limit between 300 MHz and 1000 MHz. The above bounds define a broad minima of cost and the optimization within these bounds can be governed by other factors.

(b) The system selected for prototyping utilizes 1 5/8 in cable, 12 signals per cable, and a 1000 MHz to 2000 MHz frequency band. This choice makes equalization less critical (since a small percentage bandwidth is used for each signal), contains a minimum number of cables, and utilizes 1000 MHz to 2000 MHz transistor amplifiers which are readily available.

(c) The requirements defined by noise, phase linearity, cross-talk, and amplitude distortion are quite attainable. A repeater gain of $\sim$ 40 dB and repeater spacing of 800 m are dictated.

(d) A double sideband modulation system has the simplest terminal equipment and the highest tolerance to cable dispersion and attenuation variation with frequency. However, a single sideband system requires only 0.6 as much cable and appears to be quite feasible. A final decision will be made after prototype repeaters and modulators have been evaluated.

3. Status of prototype system

A prototype IF transmission system is described by Weinreb (1967), VLA Electronics Division Memorandum No. 6. A block diagram of the system is shown in Figs. 6-6 and 6-7.

The construction of the prototype system was begun in January 1968 (except for construction of cable equalizers, which began a few months earlier). The first task has been the evaluation of critical components of the system. The results of this evaluation have been good, and there is little doubt that the system is feasible. A brief description of the status of the critical components is as follows:

(a) Cable. Requests for quotations and technical data were sent to all potential manufacturers of 1 5/8 in cable. The cables of three responsive manufacturers were compared on the basis of cost, attenuation, reliability and ease of installation of connectors, and dispersion. One manufacturer of cable was chosen for prototype development primarily because it has a longitudinal dielectric. The longitudinal dielectric gives much less

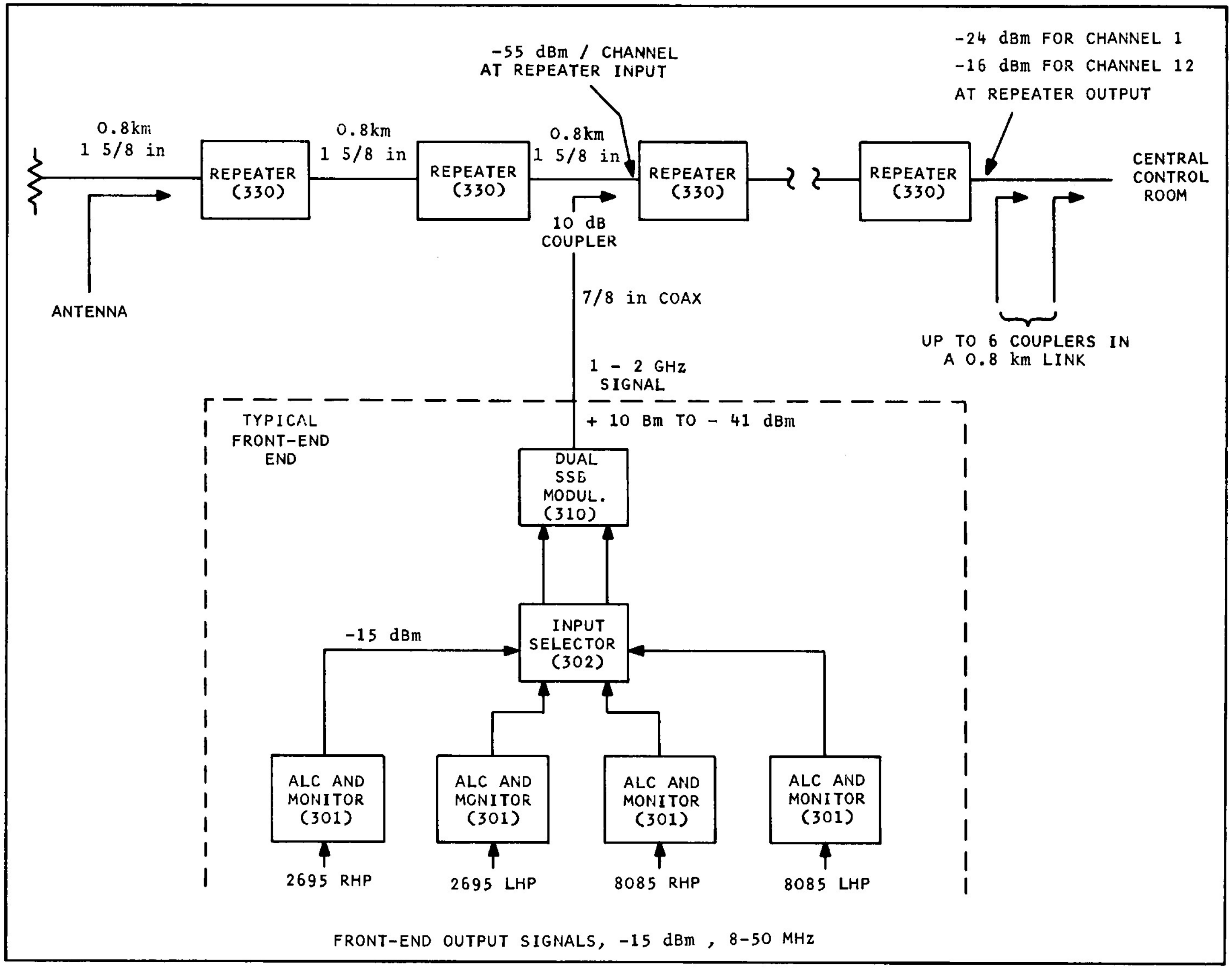


Fig. 6-6. Block diagram of front-end box and transmission line portion of prototype IF transmission system. Two of the four possible input signals (2695 MHz or 8085 MHz, right-hand or left-hand circular polarization) are transmitted as upper and lower sidebands of a carrier in the 1096 to 1904 MHz range.

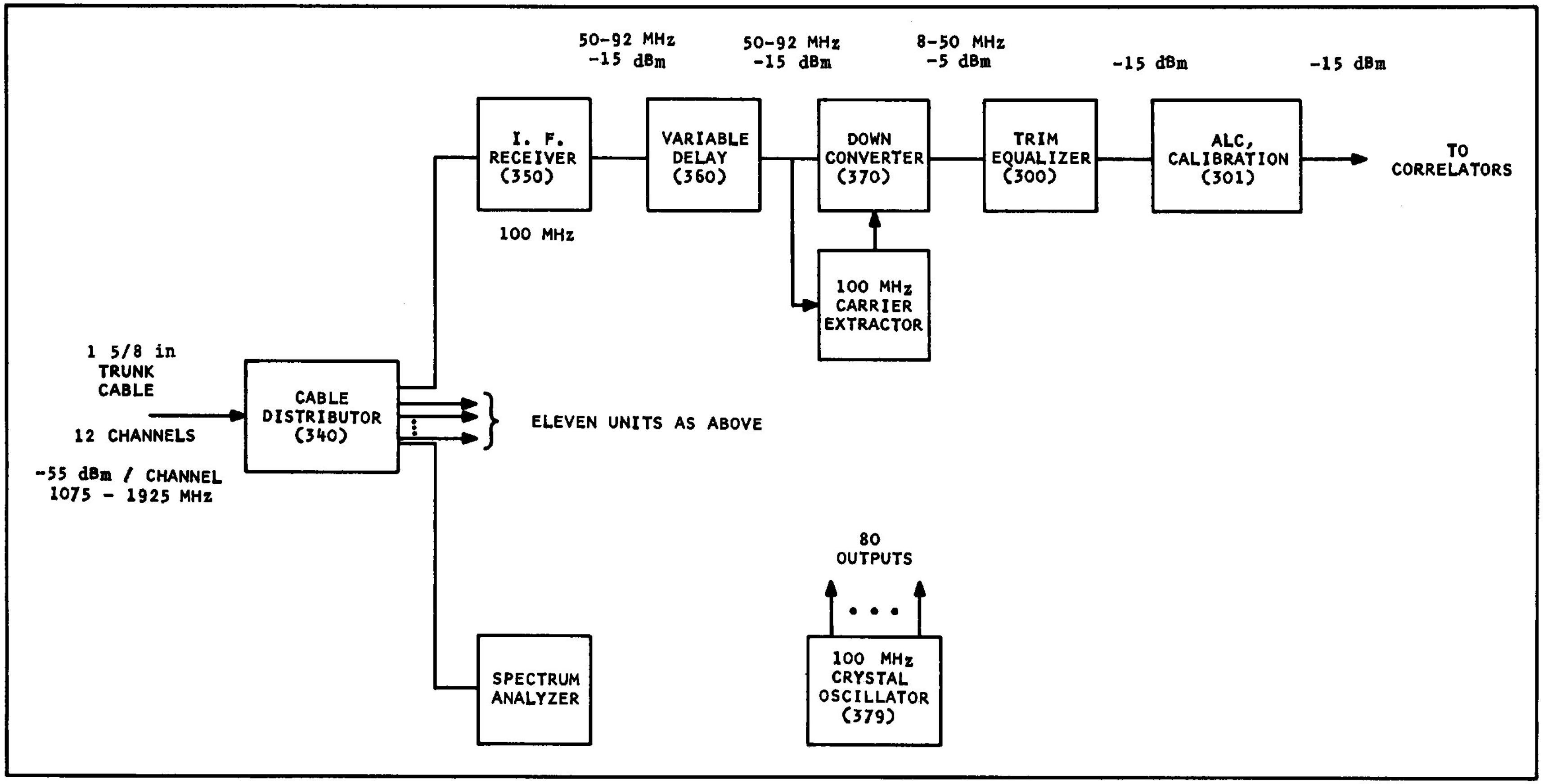


Fig. 6-7. Block diagram of central control room portion of the prototype IF transmission system. The IF receiver translates one IF signal from the 1000-2000 MHz region down to the frequency of the variable delay line. More detailed block diagrams are given in VLA Electronics Memorandum No. 6.

dispersion than helical-dielectric cable and lower loss than foam-dielectric cable.

At the beginning of 1968, the magnitude of the cable dispersion and its effect upon the transmission system were unknown. The dispersion problem is now understood because of cable measurements and the theoretical analysis presented by Weinreb (1967), VLA Electronics Memorandum No. 5. The measured dispersion of a 300 m length of 1 5/8 in cable is shown in Fig. 6-8; this amount of dispersion is tolerable in the proposed system.

(b) Repeater amplifiers. Specifications were sent to all manufacturers of 1 GHz - 2 GHz transistor amplifiers in March 1968. No manufacturer had an amplifier design available to meet the complete specifications. A small number of amplifiers, which were close to the specifications, were ordered to allow tests to proceed. At the same time, one manufacturer was contracted to modify an amplifier to meet our specifications. This amplifier has now been received and does meet specifications.

The next step in the repeater development will be to integrate the amplifier and equalizer into one unit.

(c) Equalizer. The attenuation of all coaxial cables varies approximately as $f^{0.5}$. This variation must be compensated in order to prevent amplitude distortion of the transmitted signals.

The design of cable equalizers in the video frequency range is readily available in the technical literature. However, no references have been found for attenuation equalizers in the UHF or microwave range where complex lumped-circuit element networks are not feasible.

A computer-aided design of a suitable equalizer was begun in June 1967. The basic network structure which has been used in the design and in prototype construction is shown in Fig. 6-9. The best results that have been obtained to date have been with a cascade of three sections of this network.

A test of 800 m of cable, with repeater amplifiers, and a three-section equalizer has been made. The amplitude variations with frequency are shown in Fig. 6-10. Within a 50 MHz band the peak-to-peak amplitude variations is 0.3 dB. A cascade of 26 of these repeaters would produce a 1.5 dB amplitude variation in a 50 MHz band, assuming that the variations

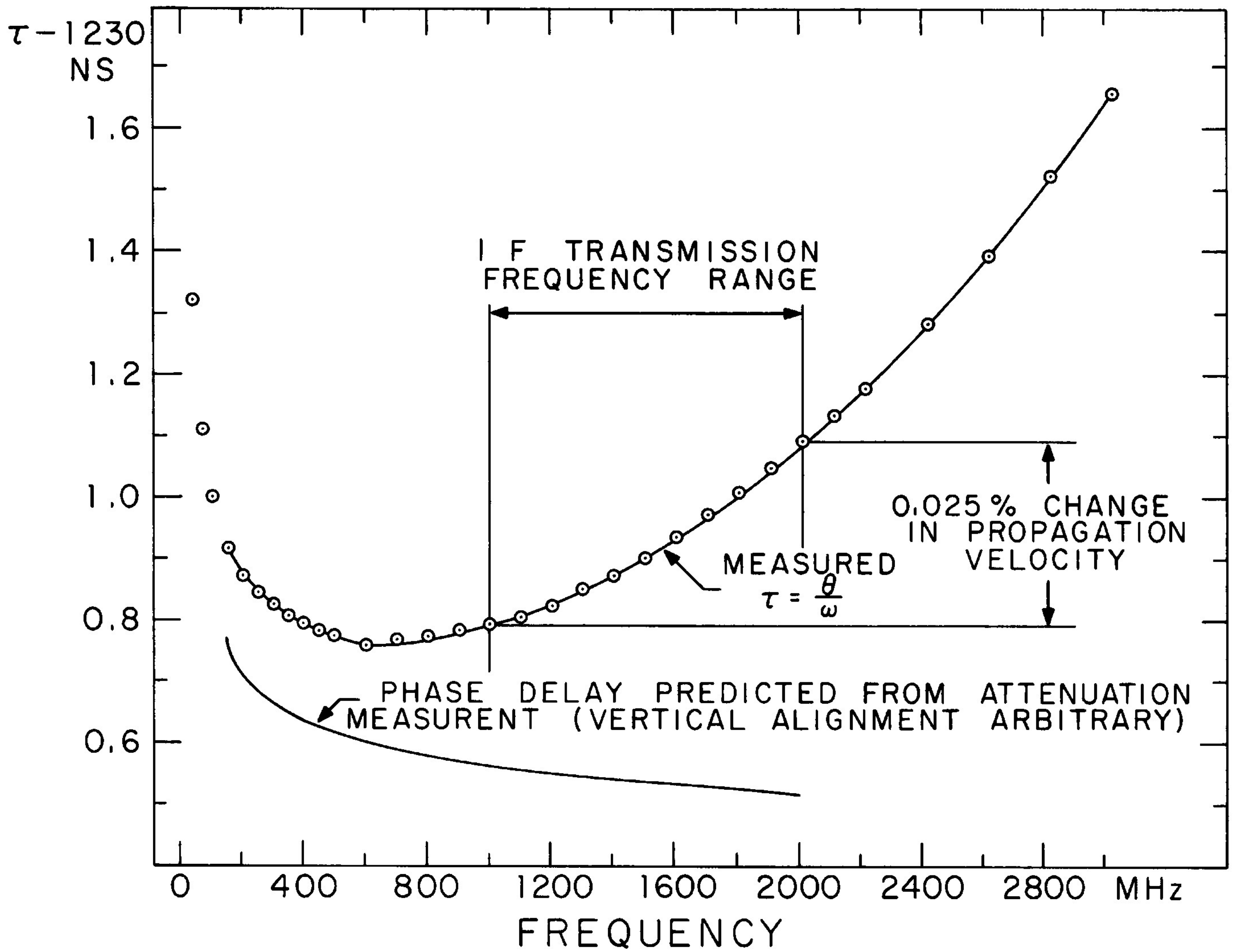


Fig. 6-8. Variation of propagation velocity (or delay time) of one manufacturer of 1 5/8 in coaxial cable. This variation changes the phase relationships between different frequency components in the IF signal and destroys the coherence of a pair of signals. However, the variation in the above cable is small enough to make the effect small and easily compensated. A second sample of identical manufacture gave the same variation to within 2 ppm.

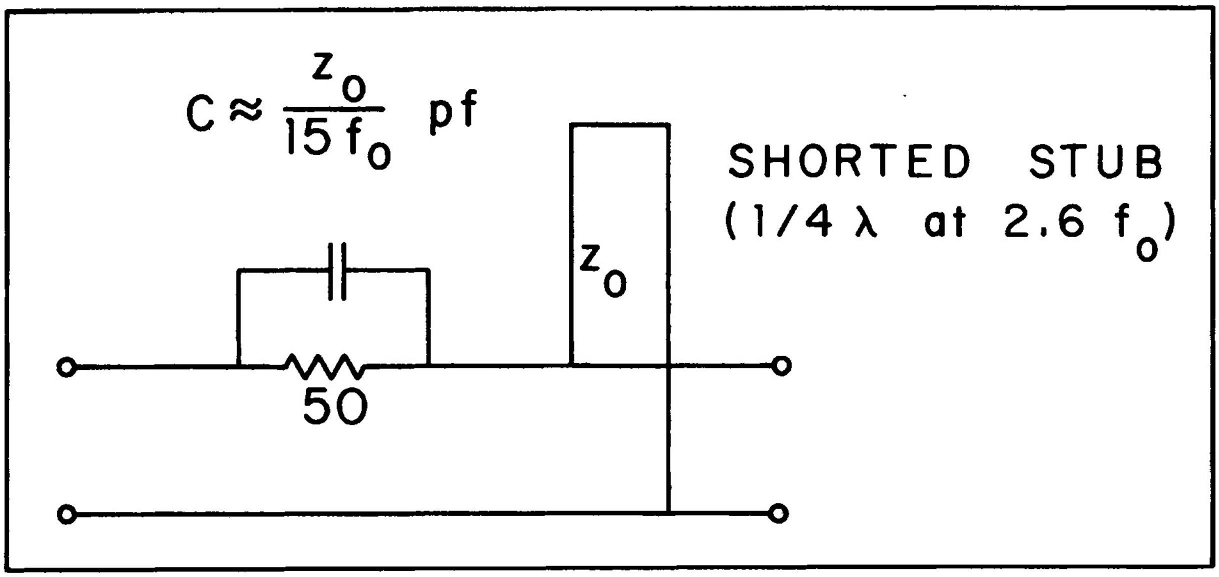


Fig. 6-9. Cable attenuation equalizer for an octave band starting at frequency f_o. The parameter, Z_o, is chosen for a particular length of cable that is being equalized. These equalizers have been constructed in strip-line and coaxial structures. Good results have been obtained with the coaxial structure. The equalizer is discussed in VLA Electronics Memorandum No. 7.

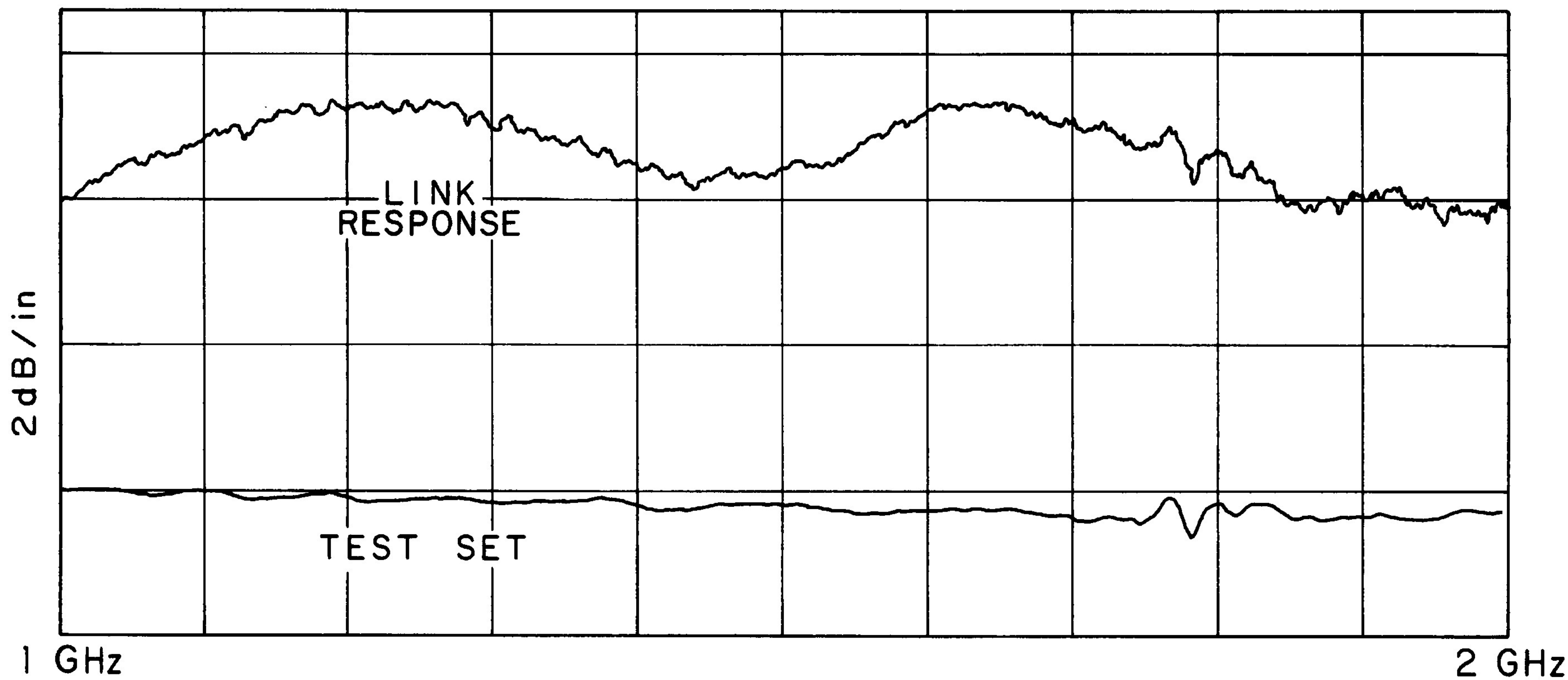


Fig. 6-10. Response of 800 m of transmission line cascaded with an equalizer and 1-2 GHz amplifiers. The lower curve is the test set frequency response.

added randomly. This would be tolerable, but it is felt that much better results can be obtained with better matching to the cable and integration of the amplifiers and equalizers.

Further tests of amplitude response, phase response, signal-to-noise ratio, and cross-talk on a 1.6 km link are planned.

(d) Single sideband filters. The simplest method of single-sideband modulation and demodulation involves the use of a sharp cutoff filter to remove the unwanted sideband. The required sharpness of the filter depends on the ratio of highest to lowest frequencies in the modulating signal. An IF band of 8 MHz to 50 MHz has been chosen as a compromise which allows a feasible sideband filter and yet does not lose too much bandwidth (i.e., the band between 0 MHz and 8 MHz is not used). (The change in VLA bandwidth specification to 35 MHz will change this band to 7 MHz to 35 MHz.)

A sharp cutoff filter tends to have a nonlinear phase response in the passband. The nonlinear phase will not be detrimental to the system if it is not too severe and can be matched from one IF signal to another.

Several filters have been evaluated with regard to sharp-cutoff response with phase match between filters operating at different center frequencies. A 14-section interdigital filter, having the response shown in Fig. 6-11, has been found to give satisfactory performance.

4. Future program

The work on testing of critical components described in the previous section is part of the development of a prototype IF transmission link. This link needs to be long enough so that any troublesome effects in the 21 km system can be detected in the prototype link. A link of the order of 5 km (6 repeaters) should be tested before construction of the final system.

Two theoretical studies should be performed. The first report should describe the degradation of signal-to-noise as caused by phase nonlinearity and amplitude variation. A method of pulse testing the system response should also be described.

The second theoretical study should relate the system reliability (as defined in Chapter 19 of the VLA Proposal, Vol. II - essentially fraction of available Fourier components) to the failure rate and repair times of

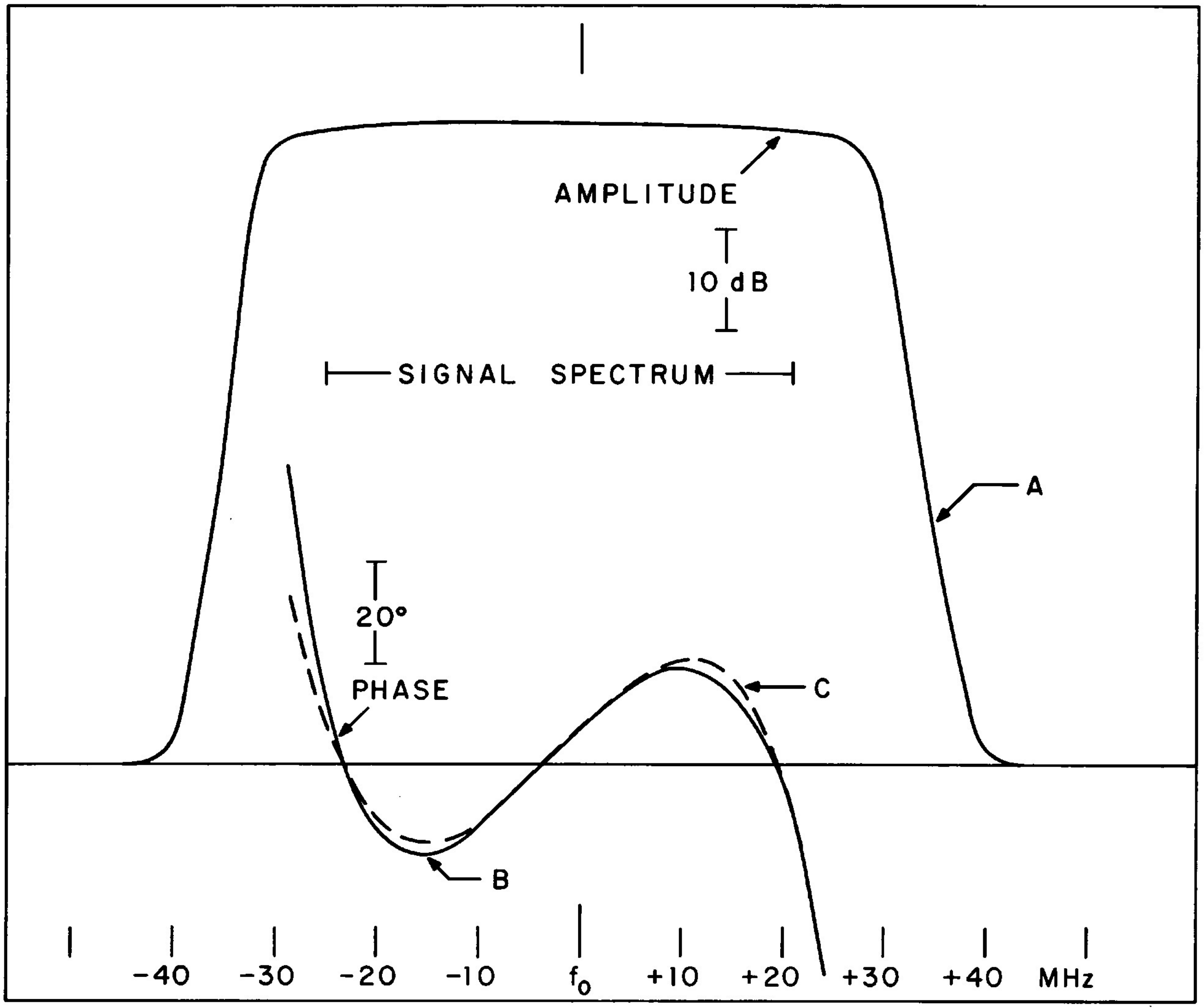


Fig. 6-11. Amplitude and phase match of a filter which is suitable for the IF transmission system. The amplitude response (A) provides ± 0.5 dB uniformity for the desired signal spectrum and > 43 dB rejection of adjacent channels. The phase response of two filters (B and C) at different center frequencies is matched to within 5° over the desired signal spectrum.

repeaters. This study will lead to recommendations concerning redundancies and fault correction techniques in the final system.

After the 5 km prototype link has been tested, final manufacturing prototypes of all elements of the system should be developed. These prototypes will correct for technical deficiencies in the first stage prototype and will contain the packaging and monitor facilities desired in the final system.

E. Delay Line System

The delay line development work has been performed by Microsonics, Inc., Weymouth, Massachusetts, and Andersen Laboratories, Bloomfield, Connecticut. Microsonics, Inc., has developed a delay line utilizing a sliding tap on a quartz wedge. The input and output transducers are mounted on a slider to provide delay variability. Andersen Laboratories' design approach is an optically-tapped delay line. It consists of a bar of quartz with the input transducer mounted on one end. The output signal is tapped by transmitting a light beam through the bar and detecting it with a photo-diode. The light beam and photo-diode are moved along the bar to vary the delay.

The VLA requires an electrically-variable delay line in which a digital command sets the value of delay. This feature was not required in either prototype line development and must be incorporated at a later date. Both manufacturers have investigated the problem and recommend a servo system which measures the actual delay of the line and corrects the errors between the measured and required delay.

At the present time the development work of both companies is nearly complete, and preliminary test data is available and will be reported here. A final report will be supplied by each company.

The desired specifications of the prototype delay lines are given in Table 6-3. Some minor variations from these specifications are in the contractual agreements with Microsonics and Andersen Laboratories.

Table 6-3

Prototype Delay Line Specifications

Delay range	The time delay must be variable from τ_o to τ_o + 150 microseconds where τ_o can be chosen by the manufacturer.
Frequency range	All specifications must be met over a frequency range of f_o - 25 MHz to f_o + 25 MHz where f_o can be chosen by the manufacturer.
Variability	The time delay must be manually variable over the specified range. A further extension of the contract may call for the design of a control system to allow the delay to be set to within $\pm$ 1 ns by application of electrical control signals. The manufacturer should perform an initial investigation of a means of meeting this requirement.
Stability	The delay stability must be $\pm$ 1 ns over a 24-hr period, assuming an environmental temperature variation of $\pm$ 2° C.
Insertion loss	The unit must include buffer amplifiers to provide an insertion loss of 0 dB $\pm$ 2 dB for all values of delay. The input signal level will be - 15 dBm $\pm$ 5 dBm from a 50 ohm source. The departure from linearity over this range of input signal level must be less than $\pm$ 0.1 dB.
Frequency effects	The variation of time delay with frequency to be less than $\pm$ 1 ns. The variation of insertion loss over the specified frequency range to be less than $\pm$ 0.7 dB.
Spurious signals	All spurious signals (in particular, spurious time delays and spurious harmonics) must be a minimum of 25 dB below the desired signal.

1. Quartz-wedge line

(a) Physical description. The quartz wedge is a 9 in x 16 in right-triangular shaped quartz section 1 in thick. The transducers are bonded into a small quartz slider which moves along the large triangular quartz section as shown in Fig. 6-12(a). The acoustic signal path is illustrated in Fig. 6-12(b). The signal path length can be varied from approximately 6 in to 30 in by moving the sliding tap.

(b) Mechanical assembly. Uniform pressure must be maintained between the sliding tap assembly and the quartz wedge to prevent large variations in attenuation as the tap is moved. The quartz wedge is clamped to a large aluminum plate. The lead screw assembly and the sliding-tap carriage are mounted between the quartz wedge and a guide rail as shown in Fig. 6-12(c). A two-speed gear assembly connected to the drive screw provides for coarse and fine control of the delay setting.

(c) Temperature control. The quartz exhibits a delay change with temperature of -80 ppm/°C. To maintain stability of the delay line, it is mounted in a temperature controlled package where the temperature is maintained constant within $\pm$ 0.01° C for ambient temperature variations of $\pm$ 2° C. A 250 W heater is used with a proportional type temperature controller.

(d) Electronics. The electronics consist of a driver amplifier and a post-delay amplifier. The driver amplifier is a two-stage transistorized amplifier with 17 dB gain over the frequency band of 30 MHz to 110 MHz. Connection between the amplifier output and the delay line transducer is made with 14 in of flexible cable. Matching networks located on the sliding tap match the transducer impedance to the cable impedance.

The post-delay amplifier is a four-stage transistorized amplifier with a maximum gain of 59 dB over the bandwidth of 20 MHz to 140 MHz. Low-noise transistors are used in the first three stages followed by a higher power driver stage. The second and third stages are manually gain controlled, which permits a 20 dB change in gain.

2. Quartz-wedge line -- preliminary test results

(a) Delay range. The time delay is manually variable from 45 μs to 210 μs.

(b) Frequency range. The center frequency is 65 MHz. The bandpass is flat within $\pm$ 1 dB from 40 MHz to 90 MHz.

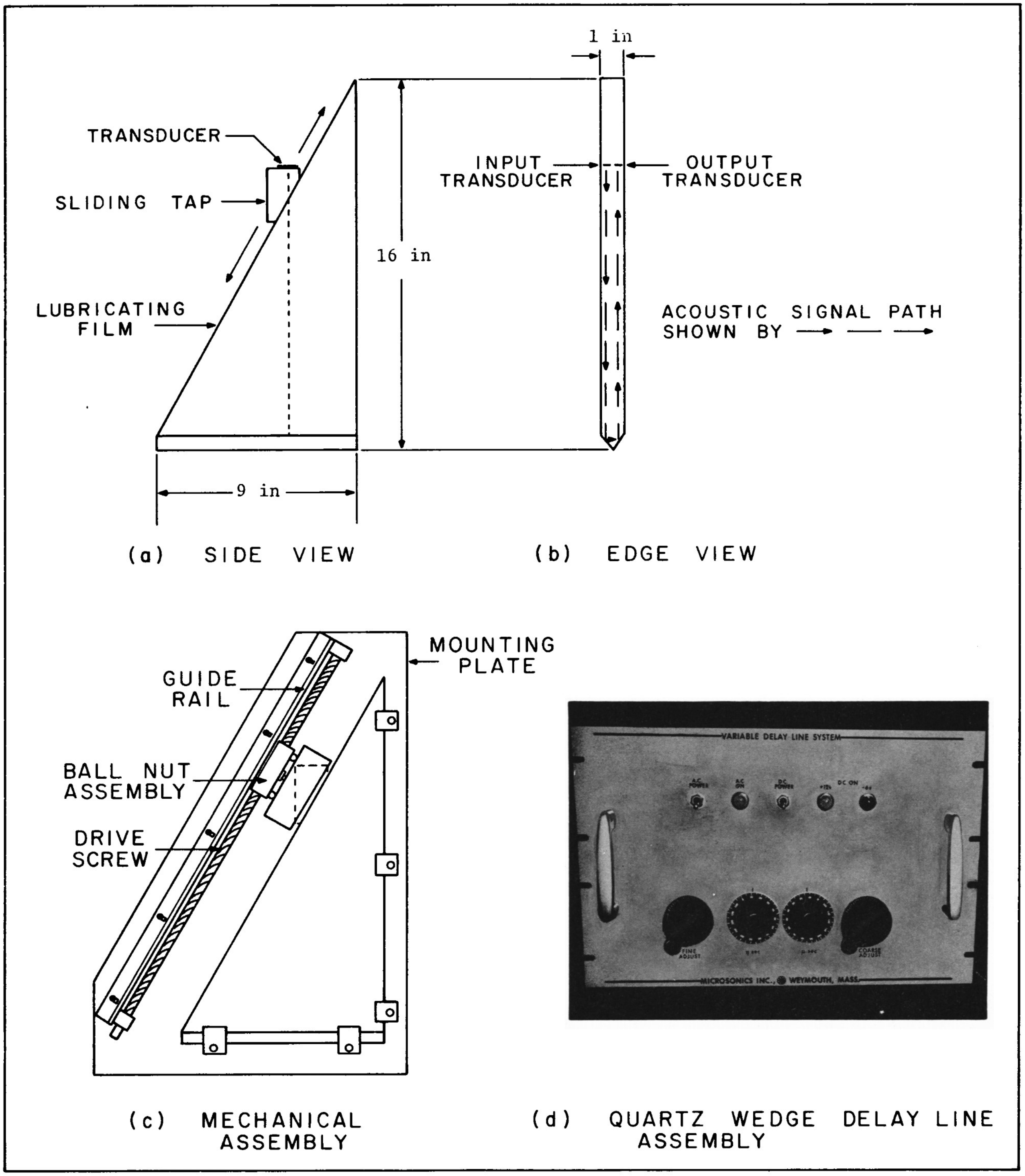


Fig. 6-12. Quartz-wedge delay line.

(c) Insertion loss. The insertion loss is 0 dB ± 2 dB for all values of the delay. The unit accepts an input signal level of -15 dBm ± 5 dBm.

(d) Frequency effects. The variation of insertion loss with frequency is less than ± 1 dB. Typical bandpass curves are shown in Fig. 6-13.

(e) Spurious signals. All spurious signals are greater than 25 dB below the -15 dBm output level. The noise level at the output is -45 dBm.

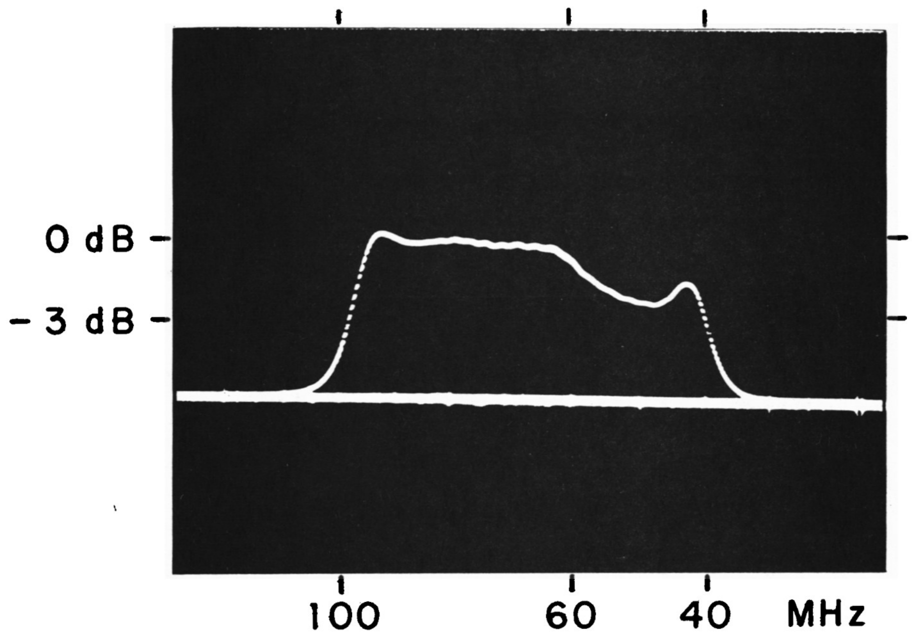
3. Optically-tapped delay line

(a) Physical description. The quartz bar used by Andersen Laboratories in the prototype delay line is 15 in long, 2 in wide, and 3/4 in thick. The input transducers are bonded to one end of the bar. The other end of the bar has a wedge-shaped termination to prevent reflection of the acoustic signal.

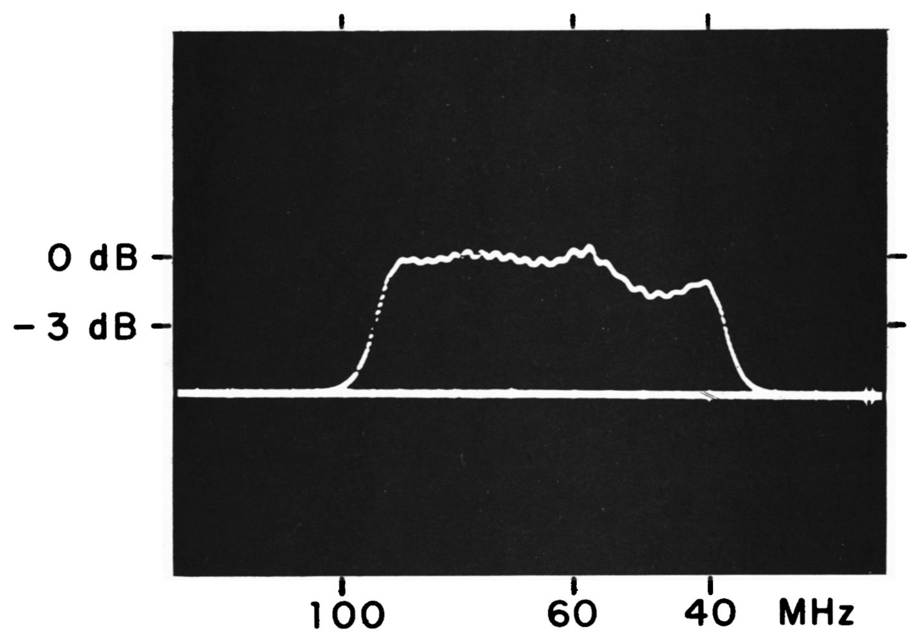
The output transducer consists of a laser light source, a lens system, and a photo-diode. The acoustic wave traveling along the quartz bar modulates the light beam transmitted through the bar. The arrangement of the components used in this delay line is shown in Fig. 6-14(a).

(b) Mechanical assembly. The angle at which the light beam interacts with the acoustic wave affects the output signal level. In this delay line the angle of incidence of the light beam is adjusted as the delay is increased to compensate for the reduction of the acoustic signal. The optical-tap components are mounted on a carriage assembly which is moved along the line to change the delay. The mirror assembly is rotated on a pivot to change the angle of incidence of the light beam. The carriage assembly is held in alignment by three circular guide bars. A lead screw is used to drive the assembly along the line. A multiple-speed mechanical drive assembly provides for manual control of the delay line setting. In the prototype line, the laser is mounted at the back of the delay line assembly and held in alignment with a rigid baseplate which interconnects the two assemblies.

(c) Optical readout assembly. The acoustic beam diverges as it travels through the quartz bar. It is necessary to have the laser beam interact with all of the acoustical energy available to optimize the conversion efficiency. To assure interaction of the acoustic and laser beams, the laser beam is expanded from a 1 mm spherical beam to a 1 mm x 6 mm rectangular beam with a lens system. The rectangular beam is transmitted through the bar and then converged back to a spot focused on the photo detector.



(a) MINIMUM DELAY - 45 μsec
MARKERS AT 10 MHz INTERVALS
FREQUENCY DECREASING LEFT TO RIGHT.



(b) MAXIMUM DELAY — 210 μsec
MARKERS AT 10 MHz INTERVALS.

Fig. 6-13. Quartz-wedge line - amplitude vs. frequency.

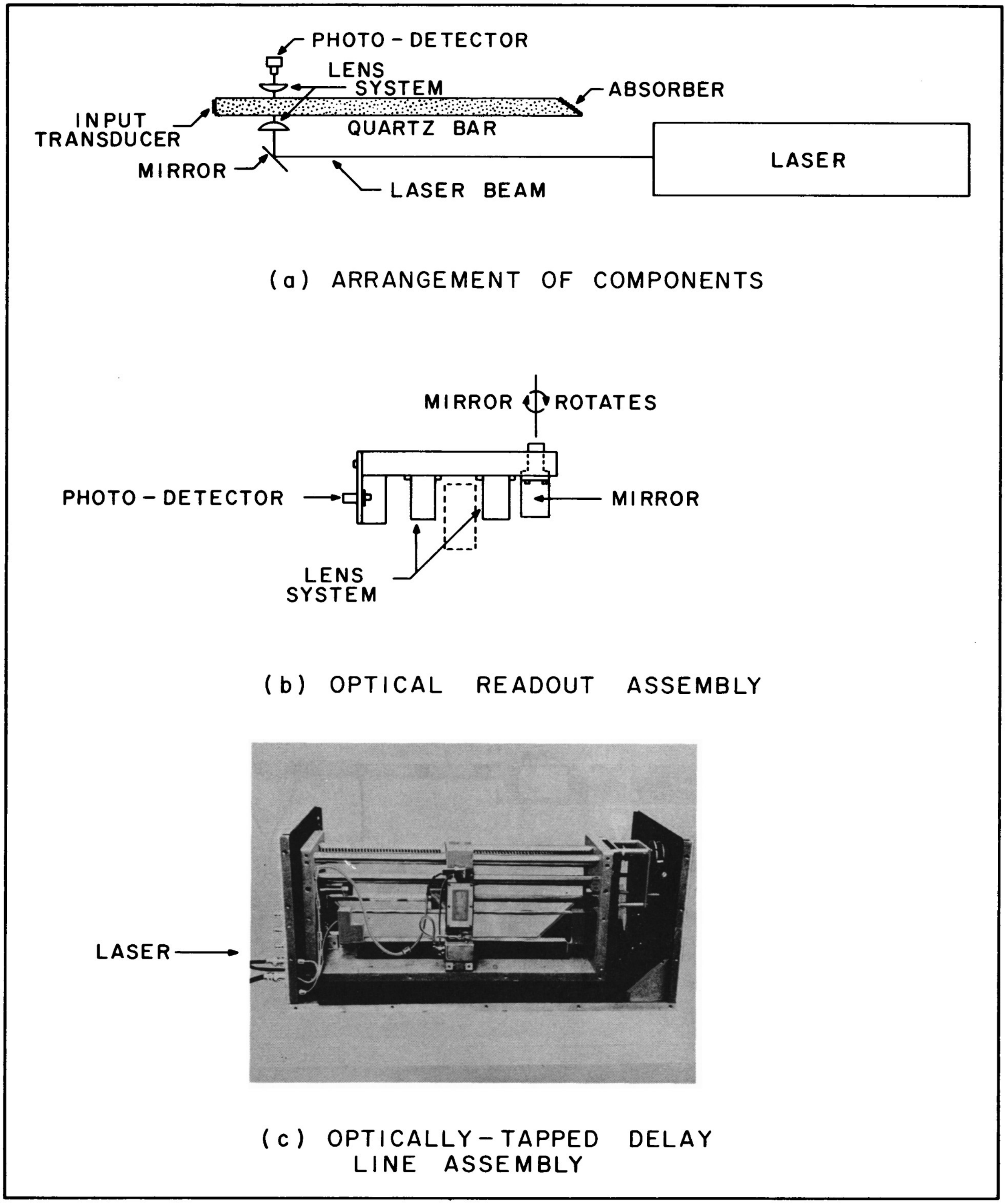


Fig. 6-14. Optically-tapped delay line.

(d) Temperature control. The quartz used in this delay line has a delay change with temperature of -74 ppm/°C. The temperature of the delay line is held at 40° C ± 0.1° C.

(e) Electronics. The electronics for the optically tapped delay line consists of a driver amplifier, a photo-detector preamplifier, and a post-delay amplifier. The driver amplifier and post-delay amplifier are packaged separately from the delay line assembly. The photo-detector preamplifier is mounted on the movable carriage to minimize the lead length from the photo-detector. This preamplifier is an Avantek Model AL5 with 25 dB gain.

The driver amplifier consists of a modular Avantek amplifier having 20 dB gain followed by an IFI M-5000 amplifier with approximately 28 dB gain. The Avantek amplifier is flat within 2 dB from 10 MHz to 250 MHz. The IFI amplifier has an output of 5 W maximum over the range of 200 kHz to 220 MHz.

The post-delay amplifier is a modular Avantek amplifier with 20 dB gain.

(f) Laser. The laser used in this delay line is a Spectrophysics Model 123, rated at 7 mW output and guaranteed for 2000 hours continuous operation.

4. Optically-tapped line -- preliminary test results

(a) Delay range. The time delay is manually variable from 2.5 μs to 92 μs.

(b) Frequency range. The center frequency is 70 MHz. The bandpass is flat within ± 1.5 dB from 45 GHz to 95 MHz.

(c) Stability. Over a 14-hr period the delay change was within 1.0 ns with ambient temperature variations in excess of ± 2° C.

(d) Insertion loss. The insertion loss is 0 dB ± 2 dB for all values of the delay. The unit accepts an input signal level of -15 dBm ± 5 dBm.

(e) Frequency effects. The variation in time delay with frequency is less than ± 3.5 ns. The variation of insertion loss with frequency is ± 1.5 dB. Typical bandpass curves are shown in Fig. 6-15.

(f) Spurious signals. All spurious signals are 25 dB below the signal level. The noise level at the output is -40 dBm.

5. Comparison of the delay lines

From the test data available to date, the quartz-wedge line exhibits a flatter amplitude response and a better signal-to-noise ratio over the

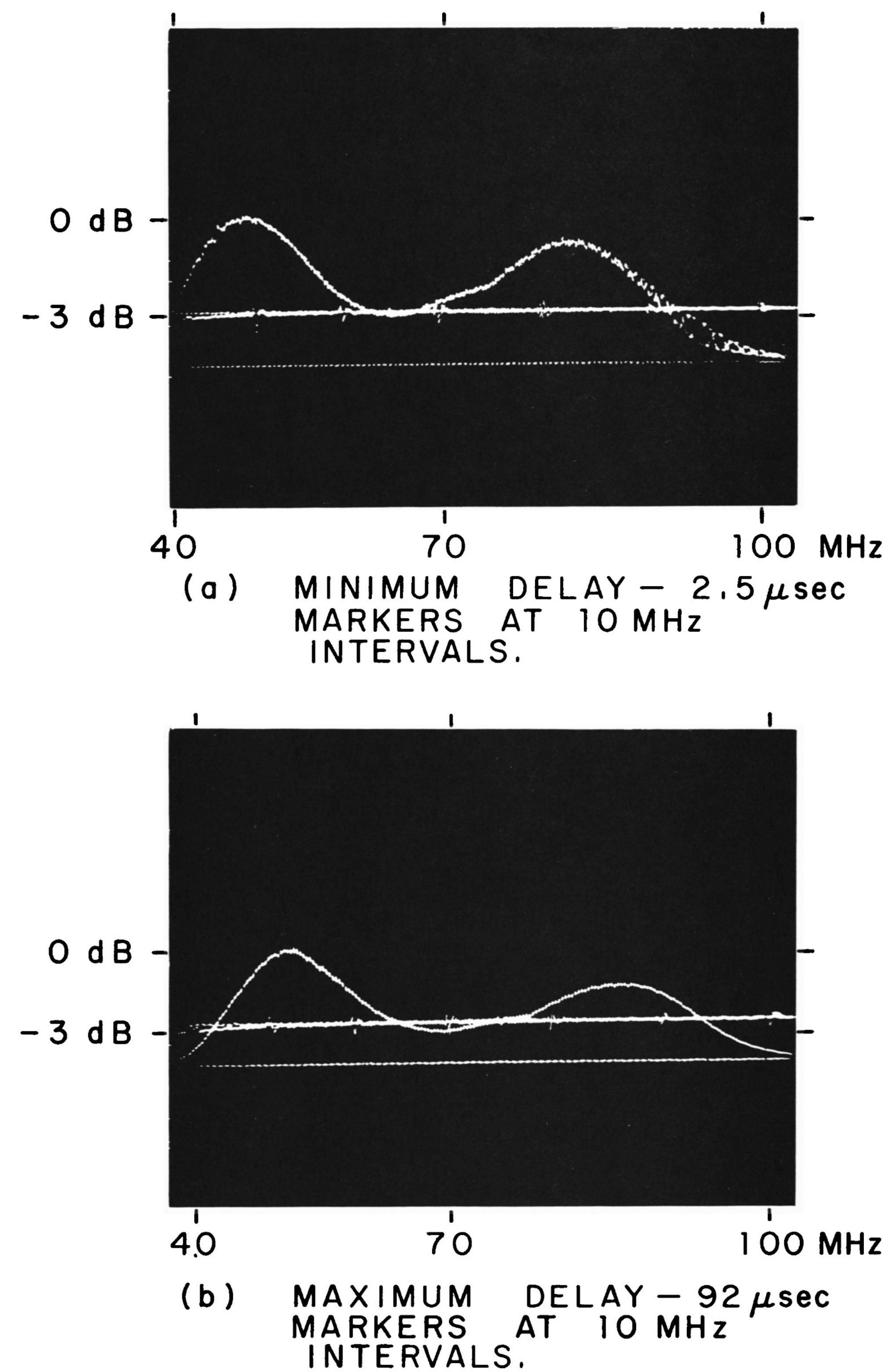


Fig. 6-15. Optically-tapped line - amplitude vs. frequency.

required frequency band than the optically-tapped line. The reliability of the delay lines has yet to be determined. It is estimated that the lubricating film used on the quartz-wedge line will last six months before relubrication is required. The laser and optical alignment are the most critical items in the optically-tapped delay line. Lasers are available with a guaranteed 10,000-hour life. Further tests will be performed, simulating actual use conditions, to determine which design is more reliable.

F. Correlator Development

Development of the VLA correlator has been performed by the NRAO at Green Bank, West Virginia. The development work has included design of a correlator test set, testing of several types of correlator components, design of an active bandpass filter, and design of the prototype correlator. The test set and some of the early design work are described by Rehr (1967) in VLA Electronics Memoranda Nos. 3 and 4.

The correlator test set provides two wideband (2 MHz - 50 MHz) noise-type signals which simulate the IF signals from a pair of antennas. The test set contains three noise sources. Two of these sources simulate the uncorrelated noise due to the individual antenna receivers. The third source simulates the correlated noise component of a radio source. Controls are provided which permit adjustment of the ratio of correlated to uncorrelated noise in the output signals.

In order to determine the optimum correlator design, several types were fabricated and tested. The results of these tests indicate that a correlator using balanced center tapped transformers and hot carrier diode detectors performs as well or better than the more complex transistorized versions.

Additional work is required to determine the optimum system for distributing the IF signals to each of the correlators. The control of the multiplexing system and the A-D converters and synchronization with the VLA computer must be studied.

1. Prototype correlator

The prototype correlator designed for the VLA consists of a multiplier, a bandpass filter, and an output amplifier and multiplexer as shown in Fig. 6-16. A brief description of these elements is as follows.

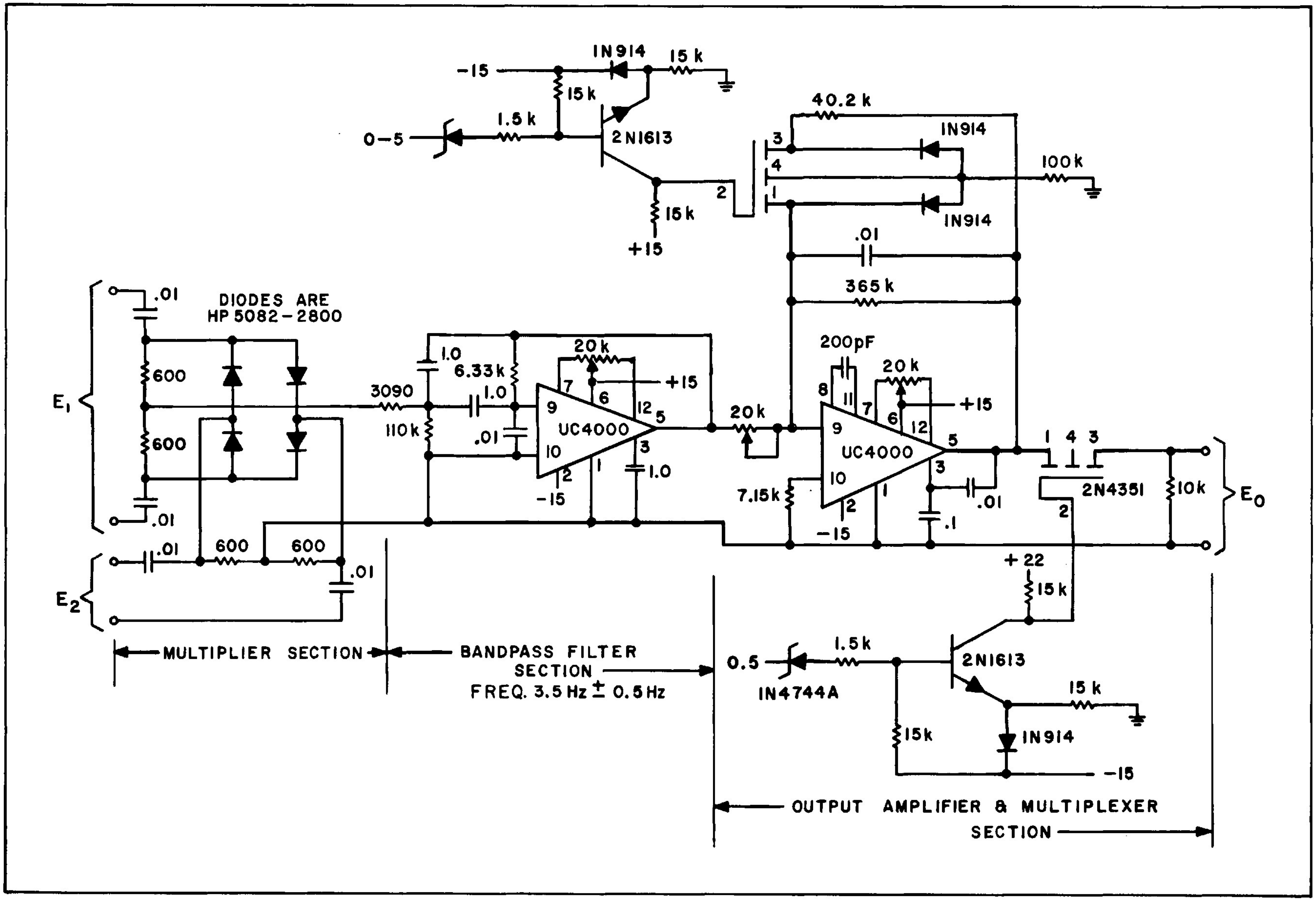


Fig. 6-16. Prototype VLA correlator.

(a) Multiplier. The multiplier accepts the two IF inputs and produces an output proportional to the correlated power input. The multiplier is a four-diode ring assembly, as shown in Fig.6-16. The diodes used are HP Hot Carrier Type 5082-2800. This multiplier produces an output of 1500 mV/mW of correlated power present at the inputs. With the total power to each input held constant at 1 mW, the output voltage change with correlated power is linear within 7% over the correlated power range of 0 dBm to -30 dBm.

(b) Active bandpass filter. It has been determined that if a narrow bandpass filter is used after the correlator, rather than a low pass filter, the number of samples per second of the correlator output required to maintain the same signal-to-noise ratio is substantially reduced. A multiple feedback active bandpass filter has been developed utilizing a Union Carbide UC4000 integrated circuit operational amplifier. Amplifiers have been constructed with center frequencies of 3.5 Hz and 0.5 Hz, having bandwidths of 0.5 Hz and 0.2 Hz, respectively. The component values are tabulated on the schematic, Fig. 6-16. The gain of the active bandpass filters varies from 20 to 100, depending upon the design center frequency.

(c) Output amplifier and multiplexer. The output amplifier provides an adjustable voltage gain of 1 to 5 to give a total gain of 100 from the output amplifier and the active filter. A controlled gain multiplication of 10 is also provided to give a total gain of 1000 when higher sensitivity is required. The output amplifier utilizes a UC4000 integrated circuit operational amplifier. The X10 gain control circuitry consists of 2N4351 field-effect transistor and the driver as shown on the schematic. High gain is provided with a 0 V gain control signal and low gain with +5 V signal.

The multiplexer utilizes a 2N4351 FET and is switched on with a +5 V sample signal and off with a 0 V sample.

The output amplifier and multiplexer has an output vs. input characteristic which is linear within 1% for both high and low gain settings over a range of outputs from -10 to +10 volts.

(d) Stability. Based on the UC4000 amplifier specifications, the calculated change in offset with time is 7.25 mV/24 hours and with temperature is 1.5 mV/°C under high gain conditions for the complete correlator. These drifts would be reduced by 10 with the low gain setting.

REFERENCES

Beazell, H. 1968. "VLA Local Oscillator Distribution Systems," Summary Report, Research Laboratories for Engineering Science, University of Virginia, Report IRDC-4783-101-684.

Weinreb, S. 1968. "Consideration of a Microwave Link IF Transmission System," VLA Electronics Memorandum No. 2.

Weinreb, S. 1967. "Comparison of Modulation Systems for Transmission Through Dispersive Cables," VLA Electronics Memorandum No. 5.

Weinreb, S. 1967, "Prototype IF Transmission System," VLA Electronics Memorandum No. 6.

Buhl, D. 1968. "Equalization and Signal-to-Noise Problems in the IF Transmission System," VLA Electronics Memorandum No. 7.

Rehr, John 1967. "VLA Correlator Design Studies," VLA Electronics Memorandum No. 3.

Rehr, John 1967. "A Test for VLA Correlator Design Studies," VLA Electronics Memorandum No. 4.

Chapter 7

COMPUTER SYSTEM

A. Introduction

Since the publication of the original VLA Proposal in January 1967, only a limited direct attack has been made on the computer problems for the VLA. This is because of the volatile nature of the computer market when the cost per unit computing power is rapidly declining, so that a study based on today's hardware might well be obsolete by the time the VLA construction begins. However, in June 1968, NRAO contracted with ARCON Corporation, Wakefield, Massachusetts for an independent assessment of the VLA needs described in Chapter 20 of the VLA Proposal, and a more thorough study of some of the machine-independent aspects of the software necessary to control, and to reduce the data from the VLA. Another, less important, goal of this study is to investigate the implementation of some of the more time consuming tasks on existing or announced machines whose characteristics are available today. This study contract is not yet complete, although several preliminary reports are available. The final report is expected in April 1969.

B. The NRAO Three-Element Interferometer Computer System

NRAO has increased its understanding of real-time computer systems considerably by their use as data reduction-recording systems on the 300-ft and 140-ft telescopes at Green Bank, and as a control and data reduction-recording system on the NRAO interferometer. Although little or none of the actual coding for the interferometer computer may be transferable to the VLA computer system, it has been instructive in several general points which may prove applicable.

The first of these general points is that the output of the receiver should not be regarded to be the analogue voltage coming from the various correlators but the digital numbers coming from the first stage reduction, because it is never contemplated to do any serious work with any other output, and because this stage will be the same regardless of the application made of the data. This implies that this first stage software is simply part of the receiver, and that the considerations of receiver design should apply to it in full. It should be constructed with care and economy of components, with timing synchronization, and all signal paths carefully worked out in advance; this program should have all of the permanence of a receiver and should only be changed infrequently and with care. This has the future advantage that, since the task is fixed and unvarying on both long and short time scales, the computer performing this task can run with a much higher utilization factor than is usually allowed in real time computers, since it can be arranged in advance that the various tasks never occur at the same time.

The second general point is that, after this rigid and fixed function first reduction, an extremely flexible set of programs is needed for the following reduction and map making. This is necessary both to produce "clean" maps with the bad data deleted and for efficient maintenance of the array. It may prove worthwhile to have a language interpreter, or even compiler in addition to the usual high level languages, to support a special computer language for the manipulation of VLA data. It should be immediately apparent the advantages it would bring to be able to say, for instance, "Examine the last week's data and report if telescope 17, receiver 1 varies in noise temperature by more than 3%," in words little more complicated than the English sentence. Once a provision for this is implemented, it adds little complication to include provisions for interpreting sentences like, "Discard data from correlators connected to telescope 17, receiver 1 when received IF power drops below 5 mW," or, "Make a map 2' on a side with grid spacing 2" of the data on 3C 55".

The existing three-element interferometer computer system does not fully embody these general points. The DDP-116 on-line computer is programmed in a rather more flexible mode than recommended here, partly because there is no other computer available at the interferometer control building to predigest the few variable formats one wishes to use, and partly because the extent that flexibility would add to complexity was not realized at the time. The software written for the NRAO IBM 360/50 computer in Charlottesville is not as flexible as one might wish. An interpretive language for data editing has been prepared, but it is much more primitive than that suggested for the VLA.

C. Updating of Chapter 20 of the VLA Proposal

In the course of the contract with ARCON, Chapter 20 of the VLA Proposal was re-examined in order to find the changes caused by the reduction of the number of antennas. The computing task described in Chapter 20 were re-evaluated assuming 27 antennas instead of 36, 1404 correlators (4 per antenna pair) instead of 1890 (3 per antenna pair). For most items, the contractor has assumed the numbers in Chapter 20, or simply applied a certain reduction factor corresponding to the reduced number of antennas and correlators. However, the data reduction loop has been examined in detail. For reasons to be explained below, this loop was recoded for a DDP-516 computer, in order that a specific bench mark program could be used for the estimation of time. The reduction of computing power is not as great as would be expected from the reduction in number of correlators, because the DDP-516 word length and command set differ from the 32-bit word length and eclectic set of commands used to make the estimates of Chapter 20.

The main result of this review can be best presented by repeating and expanding Table 20-2 of Chapter 20 (VLA Proposal, Vol. II).

Revision of Table 20-2, VLA Proposal, Vol. II

Computing Requirements
(Operations/second)

	Chapter 20	ARCON
On line functions		
Data reduction	6×10^5	5.4×10^5
Lobe rotator control	2×10^4	7.5×10^2
Antenna control	5×10^3	5.3×10^3
Delay switching	2×10^4	1.1×10^4
Receiver checkpoints monitoring	1×10^4	7.5×10^3
Logging and display	1×10^3	7.5×10^2
Timing loops	2×10^3	1.5×10^3
Asynchronous reduction		
Sort	3×10^5	2.2×10^5
Gain calibration	3×10^4	3.2×10^4

(Revision of Table 20-2, VLA Proposal, Vol. II - continued)

Fourier inversion	1×10^5	1×10^5
Map output and display	6×10^4	6×10^2
Total	1.1×10^6	9.2×10^5

The remaining point to be investigated thoroughly in this re-evaluation is whether the factor of 2 allowed in the estimates of Chapter 20 for the parts of the program not considered in detail and for future expansion is sufficiently large (a factor of 4 is usual for more general purpose real time systems).

D. Investigation of Alternate Configurations

In considering alternate configurations to the two 32-bit machines mentioned in Chapter 20 of the VLA Proposal, several configurations composed entirely of DDP-516 computers were investigated. This was done because both the contractor and the NRAO are quite familiar with this computer, since it is an integrated circuit version of the DDP-116. It also supplies a great deal of computing power for a low price, including a 0.96 μs memory cycle time, a 16-bit multiply and 32-bit add hardware. These investigations are informative because they indicate one of the cheapest ways of obtaining the required computing power; however, they may be unacceptable as actual configurations for the VLA computer system because, for lack of floating point hardware, the implementation of any high-level programming language is extremely inefficient.

Several configurations of from three to seven linked DDP-516 processors with varying peripherals, storage, and interconnections have been considered, with various distributions of the work load among the processors. Because so much of the cost of modern computer systems is in the peripherals and in the storage, which must be present in any case, these configurations cost less than the two large computers proposed in Chapter 20 of the VLA Proposal. Systems with several processors have the considerable advantage that the task of each computer may be made much more specific, and the degree of multiprogramming considerably reduced, which in turn greatly reduces the cost of the software.

Although the general order of magnitude of the computer task for the VLA is now fairly well understood, the computer configuration necessary to accomplish it is far from clear. We can at this time only mention the possibilities which we have partially investigated and which will be more fully evaluated during the study contract with ARCON. There are three of these, which all appear feasible, and the choice between them simply reduces to a problem of cost and, to a smaller extent, convenience.

First, it is possible to obtain all of the computing power needed for the VLA in one large processor which is programmed with a large variety of real time programs and is running an assortment of FORTRAN coded data reduction and management programs in an asynchronous background. In order for this to be the most efficient configuration, it appears that the data reduction work load would have to be considerably reduced through some analogue preprocessing of the signals from the correlators before the analogue to digital conversion.

Second, one may consider, as in Chapter 20 of the VLA Proposal, a configuration of two or three more modest, but still fairly capable computers. This allows some separation of functions and, if the various processors are of the same type, may actually reduce the cost of the software, despite the fact that two or three computers instead of one are to be programmed.

Third, a configuration of various small computers, completely dedicated to their fixed, time consuming but simple tasks, along with a single, moderate sized computer which provides the flexibility in data reduction and handling, appears very attractive. The cost of the processing units of a computer is very low for integrated circuit computers, and a machine which is completely dedicated to a simple, repetitive task is easy and inexpensive to program.

E. Software

Although a detailed and carefully prepared estimate of the software costs for the VLA computer configuration is not available, several things are now quite clear:

(1) Whichever computer is chosen, its software will have to be developed from a rather primitive starting point.

(2) The software will be complex and expensive, and it will probably take a large amount of time to develop it.

(3) There does not now exist a sufficiently detailed description of the computer task to allow a programming specialist to code the software. The development of these specifications is the first task of the software development and is a major part of the whole task.

(4) Many features of the VLA computer tasks are independent of undecided parts of the receiver hardware and of the choice of computer. These can be described verbally or in flow charts or in FORTRAN programs early in the VLA construction effort, decreasing the level of programming effort required at later stages.

(5) These items, as well as some of the computer dependent studies, should be done to more realistically choose the VLA computer system.

To sum up: Several configurations of computers which will perform the required tasks have been investigated, and these configurations are available at closely comparable prices. The closeness of the cost estimates lends additional confidence to the belief that they are complete and realistic, although possibly not representing the optimum cost for the VLA computer system.

REFERENCES

Final Report, VLA Computer Study Contract. G. Conant (ARCON Corporation). In preparation, expected April 1969.

Chapter 8

OPERATION AND MAINTENANCE

A. Introduction

The VLA is designed for continuous operation, 24-hours per day, seven days per week, although the actual utilization of the instrument will be somewhat less because of weather, equipment failure, and necessary maintenance. A well-planned maintenance program should permit the array to be in productive operation at least 90% of the available time, the remaining 10% of the time divided about equally between time lost because of weather, preventive maintenance, and equipment failure. This chapter discusses the maintenance philosophy, the necessary repair and maintenance facilities, and the organization of the maintenance program.

The development of this program is based on the experience gained in operating the Green Bank Observatory, particularly the three-element interferometer. A study contract with the Raytheon Service Company, Burlington, Massachusetts, who operates similar installations at many places in the world, assisted in the development of the general philosophy and provided detailed schedules and manpower needs.

B. Maintenance Philosophy

The upkeep of a large radio telescope system such as the VLA may conveniently be separated into three different areas.

1. Overhaul

At certain intervals, typically two to three years, a radio telescope needs to be overhauled. Examples of what is understood by overhaul are the following adjustments, repairs and replacements which periodically are being made on the three 25 m telescopes in the Green Bank interferometer: painting, adjustment of gears, oil changes in gear boxes, adjustment of surface panels, aligning of axes, cleaning and greasing of bearings, replacement of cables, replacement of brakes, etc. For the Green Bank interferometer some of these overhaul tasks have been done during the eight hours per week when the system is off for preventive maintenance, but the major jobs require a complete shutdown for one or more weeks. With only three telescopes, this is not a difficult problem, but with 27 antennas in the system it becomes completely unacceptable, if not impossible, to handle the overhauls in this manner. Based on the experience with the Green Bank interferometer a realistic time to perform those tasks which should be included in an overhaul is from three to five weeks. Thus, assuming one telescope at a time is being overhauled, it will take an average of 27 months or two to three years to cover all antenna elements. Therefore, one antenna is always in the overhaul mode, during which time it is not productive and, in order to maintain continuous operation with 27 antenna elements, an extra antenna is needed to accomplish a satisfactory overhaul program. The actual overhaul will take place in a centrally located facility where overhead cranes, jigs, templates, and other equipment are located. The same facilities are needed for the construction and testing of the antenna element on the VLA site and will remain for overhaul purposes.

2. Preventive maintenance

In addition to the periodic overhaul, a more frequent (once every eight days) inspection and preventive maintenance program is planned according to the experience from the operation of similar facilities at NRAO. For example, the NRAO computer (IBM 360/50), which is of the same order of size and complexity as the planned VLA computing facility, requires an eight-hour preventive maintenance period once every week. The computer is essential to the operation of the VLA, and the entire array will be down during this period. Each eight-hour period will be used for inspection and some limited preventive maintenance work on a few (two or three) antenna elements. Typical items in this maintenance category are inspection and minor adjustments of motors, drive gears, and air-conditioning equipment, certain checks (noise temperature, bandpass, gain, etc.) of the electronic components and tests of the monitor and control functions for the antenna elements. By performing preventive maintenance on three antenna elements every eight-day period all antennas will be covered in nine weeks and the procedure will repeat.

Certain maintenance can be done without disturbing the observations. Almost all track and foundation maintenance, work on the antenna transport vehicles and general work on the central building and laboratory complex are of this type.

3. Corrective maintenance

The overhaul and preventive maintenance program outlined above is designed to keep the system in good operating condition indefinitely. Occasionally equipment failures will occur and personnel and facilities for corrective maintenance must be available. An equipment failure detection system, based on the detailed monitoring (Table 8-1) of the performance of most subsystems of the VLA will assess the failures and help the operator to determine the importance of the failure before corrective maintenance is started. In a system consisting of many similar units working together, the breakdown of one unit is not necessarily fatal to the operation. For example, a failure of the input amplifier on one of the two frequencies on one antenna is obviously unimportant if the observer is interested in the other frequency only. Even the breakdown of one whole antenna element might not be of major concern if most of the observing (say ten hours of a 12-hour track) has been done and the antenna element in question does not contribute heavily to the total observation during the remaining observing time. In such a case, the observer would certainly decide to continue his observing and correct the failing component later. On the other hand, a failure in a central subsystem, the computer for example, is catastrophic and emergency repair must start immediately.

Many subassemblies, up to a whole antenna element with its electronics, will contribute to the final observation with different weights at different times, depending on the particular observing program. The assessment of the importance of any equipment failure is a complex bookkeeping task in which the observer will be aided by the computer which will display continuously the weighted condition of the total system.

Table 8-1

Typical Monitor Points

General (antenna)(6 points)

- AC power
- AC voltage
- Pedestal room temperature
- Vertex room temperature
- Gearbox oil pressure
- Oil level

Receiver Control (13 points)

- Polarization selection
- Frequency selection

(Table 8-1, continued)

Local oscillator	Elevation drive motor current
Power	Temperature
Phase lock	Elevation encoder reading
Signal level	Azimuth encoder reading
Front-end	Interlock condition
Pump power correction	Stow pin in-out
Mixer current	Azimuth error
Varactor current	Elevation error
Element temperature	Weather Monitor (5 points)
RF carrier power	Wind mean velocity
AFC carrier reading	Temperature
Antenna noise temperature	Precipitation
Servo Control (9 points)	Dew point
Azimuth drive motor current	Atmospheric pressure

C. Repair and Maintenance Facilities and Personnel

1. Introduction

A general maintenance program as it has been described above can be achieved in several different ways. One possibility would be to contract the entire operation to an outside company. (Several military and civil installations are maintained and operated this way.) On the other hand, the VLA installation could be handled entirely by VLA personnel and facilities. It is believed, however, that a combination of outside contracts and an internal VLA organization would be the most efficient and economical operation. The following guidelines seem reasonable:

(a) Jobs not directly affecting the operation of the VLA and not of a routine nature will be contracted outside.

(b) The computer maintenance will be done by contract personnel.

(c) The routine inspection of the railroad track will be done by site personnel. Major overhaul or replacing sections of track will be done by contractor.

(d) Sufficient personnel should be on the VLA site at all times to handle emergencies.

(e) Overtime will be used as need arises for emergency and routine repairs.

2. Maintenance and supporting facilities

Assuming a combination of internal maintenance capability and the use of outside contractors as suggested in the guidelines above, the following basic maintenance, shop, and supporting facilities will be needed:

(a) An antenna overhaul facility complete with cranes, scaffolding, jigs, templates for surface adjustment, optical devices for axis alignment and surface panel measurements, etc. It should give weather protection since overhaul of antennas will be a continuing operation. This facility will be needed for the construction of the antennas and should be retained as a permanent part of the installation.

(b) Several (one for each arm of the wye) transport vehicles capable of moving the antennas between observing stations and between an observing station and the antenna overhaul facility. This vehicle has been described in detail in Chapter 5.

(c) Other smaller vehicles for speedy transportation of tools, equipment and personnel on the railroad tracks between the central location and the antennas. Since the VLA uses standard gauge railroad tracks, the design and procurement of these vehicles are not a difficult problem.

(d) A laboratory with a screened room where faulty electronic equipment can be repaired and tested.

(e) Life sustaining and protecting facilities, such as cafeteria, dormitories, fire equipment, ambulance, and security guards.

(f) Supply and stock of spare parts.

3. Personnel

The manpower needs for the operation and maintenance of the VLA were discussed in Chapter 9 of the original VLA Proposal, and the estimated personnel in the scientific, administrative, housekeeping, and operations groups is still considered reasonable. These groups will normally be working standard hours, except for the operations group which will be working three shifts per day, seven days per week in order to keep the array operating continuously. The maintenance philosophy has, however, changed as outlined above. The basic difference being the concept of a periodic overhaul of the antenna elements. The personnel who perform the overhauls will be scheduled with adequate time to also do the preventive and the expected corrective maintenance. One advantage of this organization is that the overhaul crews will become very experienced in the behavior of all equipment and will therefore be uniquely qualified to do speedy and satisfactory corrective maintenance. Ideally this personnel category should always be available on the site, meaning three shifts. It is, however, possible to achieve an acceptable coverage of emergency repairs by using a two-shift operation. There will be a three and one-half hour gap in maintenance coverage between the end of one shift and the beginning of the next. This arrangement is a compromise between continuous maintenance coverage and the economies of a two shift system. Fig. 8-1 shows a sample schedule for the maintenance crews based on two-shift operation.

The total population of the VLA site is estimated to be 60, distributed among the different categories as shown in Table 8-2.

Table 8-2

VLA Resident Staff

<u>Administrative Group</u> (9)
- Site Director
- Site Superintendent
- Business Manager
- Clerical Staff (2)
- Secretary
- Switchboard Operator

<u>Scientific Staff</u> (4)
- Scientists (2)
- Engineering and Computer (2)

<u>Operations Group</u> (11)
- Operations Manager
- Operations Supervisor (lead man)
- Operations Crew (4)
- Computer Supervisor (lead man)
- Computer Crew (4)

<u>Maintenance Group</u> (20)
- Maintenance Manager
- Antenna Supervisor
- Electronics Supervisor
- Maintenance Crew (16)
- Instrument Man

<u>Building and Grounds</u> (16)
- Buildings and Grounds Manager
- Maintenance Crew (3)
- Machinist and Carpenter (2)
- Air Conditioning Crew (2)
- Housing and Cafeteria Staff (3)
- Security Guards (5)

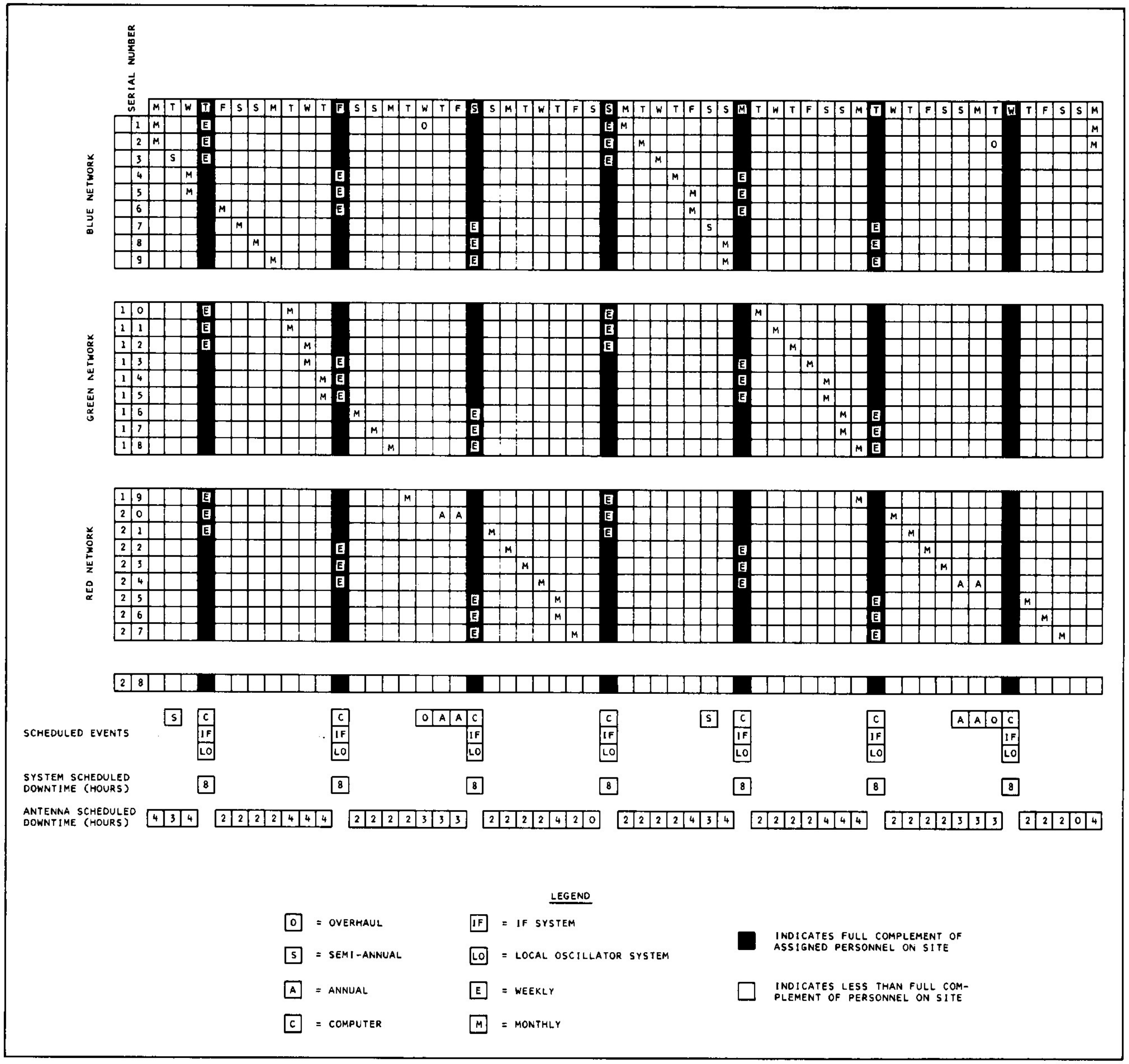


Fig. 8-1. Basic 8-week maintenance schedule.

Chapter 9

COST ESTIMATES AND TIME SCHEDULE

The 1966 cost estimates for the various elements of the VLA have changed for a variety of reasons, as listed below:

(1) Number of antennas, with associated electronics, has been reduced from 36 to 27.

(2) Experience gained from breadboarding various critical components.

(3) Advances in technology.

(4) Experience gained from operation of the three-element NRAO interferometer at Green Bank, West Virginia for approximately two years.

(5) Price escalation of technical components and construction costs.

(6) Refinements in various systems concepts, such as the track system, basic antenna design, transporter configuration, etc.

The cost estimates in Table 9-1 include all costs deemed necessary to procure a sub-VLA system (12 antennas on one arm of wye), and a complete basic VLA system (27 antennas, full wye, 100 observing stations, and electronic equipment for one frequency). The estimates are in 1968 dollars and do not include any contingency or price escalation. Again, the estimates provided are for site Y-15 and, of course, may have to be revised to reflect the particular site chosen.

All estimates are believed to be accurate to within ± 10%. Some contingency should be provided, however, to allow for the uncertainties of the estimates, incompleteness of the detail design, and vagaries of the market at the time of procurement. This is provided at a rate of 10% on major construction items only. In addition, price escalation during construction should be anticipated when funding is available.

Table 9-2 summarizes the current estimated cost of continuum research equipment for a second frequency and equipment to do spectral line work.

The anticipated total cost in 1968 dollars of the VLA, plus contingency and additional research equipment, is summarized in Table 9-3.

The estimated time schedule for design and construction of the VLA is shown in Fig. 9-1. As seen from the schedule, total time for completion is estimated to be about five years from the time funding is available.

An estimated commitment schedule, based on the above cost and time estimates, is shown in Table 9-4. The schedule assumes that design work

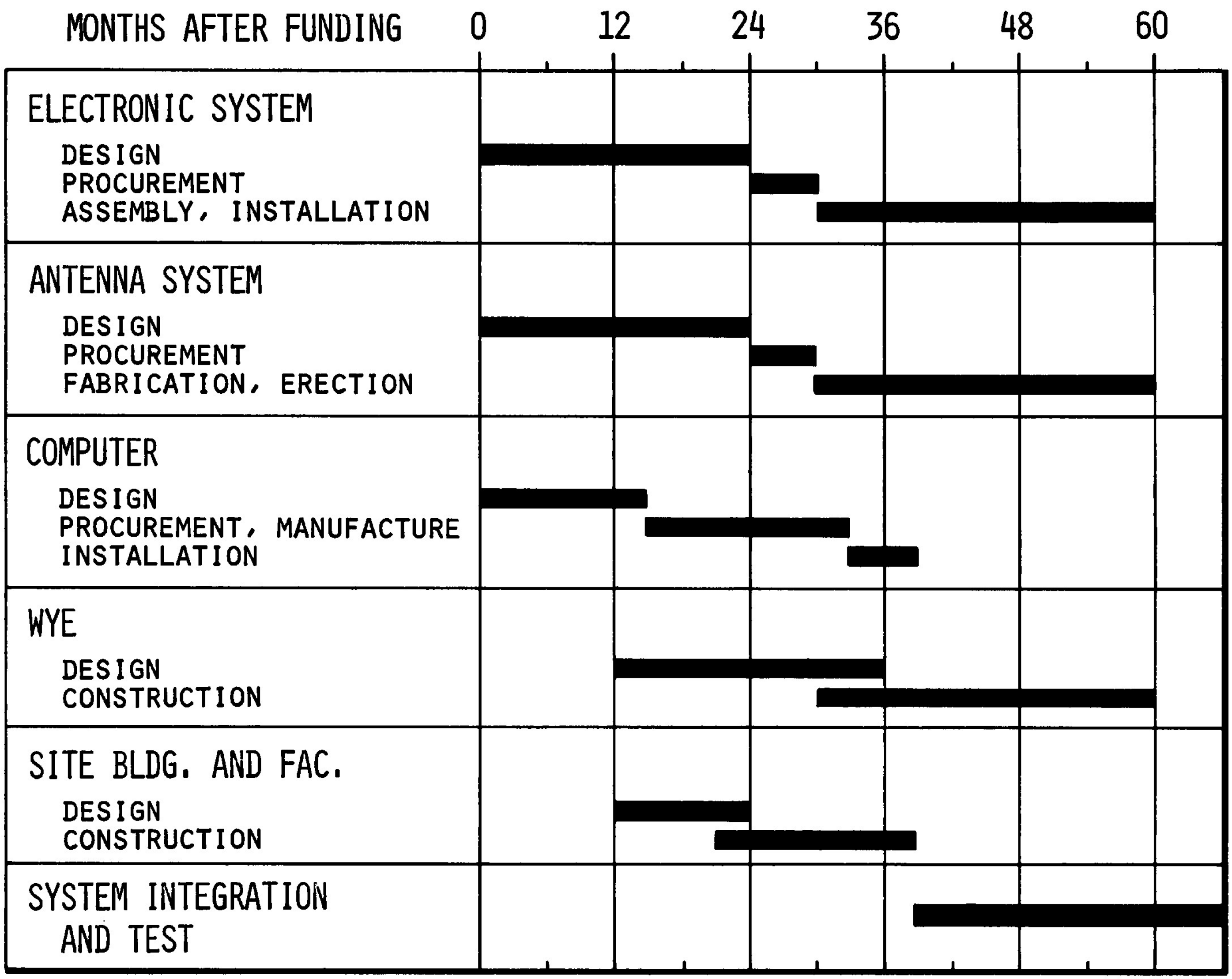


Fig. 9-1. Design and construction schedule - basic VLA.

prototyping and prototype evaluation will be completed in the second year after funding is available, and that major construction funds will be available starting at that time.

It should be noted here that constructing the basic VLA in steps (i.e., starting with the sub-VLA) will result in a higher overall cost at completion.

Operating costs of the completed array are still estimated at the amounts shown in the VLA proposal. This has been further substantiated by a Study Report prepared by the Raytheon Service Company during 1968.

Table 9-1

Cost Estimates
(1968 Dollars)

	Sub-VLA System Cost (Millions)	Basic VLA System Cost (Millions)
Electronic System		
Local Oscillator	$ .617	$ 1.331
Front Ends	.375	.753
IF and Delay	1.286	2.773
Correlators	.070	.179
Monitor and Control	.240	.338
System Integration	.300	.500
Miscellaneous	.277	.277
Subtotal	$ 3.165	$ 6.151
Antenna System		
Antenna	$ 5.809	$ 11.933
Transporter	.225	.556
Feed	.071	.126
Subtotal	$ 6.105	$ 12.615
Computer System		
Main Computer	$ 1.432	$ 1.521
Communications	.986	1.392
Programming	.300	.300
Subtotal	$ 2.718	$ 3.213

Table 9-1, continued

	Sub-VLA System Cost (Millions)	Basic VLA System Cost (Millions)
Site		
Buildings	$ 1.109	$ 1.109
Wye	2.899	7.665
Utilities and Facilities	1.465	1.465
Site Acquisition	.100	.100
Subtotal	$ 5.573	$ 10.339
Total	$ 17.561	$ 32.318

Table 9-2

Additional Research Equipment
(1968 Dollars)

Item	Sub-VLA Cost	Basic VLA Cost
Continuum Research Equipment	$ .988	$ 2.558
Spectral Line Equipment	1.166	2.623
Total	$ 2.154	$ 5.181

Table 9-3

Total Funds
(1968 Dollars)

Item	Sub-VLA Cost	Basic VLA Cost
VLA	$ 17.561	$ 32.318
Contingency	1.701	3.318
Continuum Research Equipment	.988	2.558
Spectral Line Equipment	1.166	2.623
Total	$ 21.416	$ 40.817

Table 9-4

Commitment Schedule
(Less Escalation)

Year	Sub-VLA Commitment (Millions)	Basic VLA Commitment (Millions)
1st Year	$ 1.930	$ 1.930
2nd Year	6.296	7.135
3rd Year	13.190	31.752
Total	$ 21.416	$ 40.817