THE VLA

A Proposal For

A VERY LARGE ARRAY RADIO TELESCOPE

Volume II

NATIONAL RADIO ASTRONOMY OBSERVATORY

– A Proposal For –

A VERY LARGE ARRAY RADIO TELESCOPE

Volume II

SYSTEMS DESIGN

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THE ANTENNA ELEMENT

CHAPTER 11

THE ANTENNA ELEMENT

A. Introduction

Approximately half of the capital investment in the VLA will be the cost of the antenna elements and the mobility system. A total of 36 elements will be needed to reach the desired combination of field of view and resolving power, and in order to obtain sufficient sensitivity each antenna element should have the collecting area of a 25 m paraboloid.

Many antennas similar to the elements which will be used for the VLA have been built in the past. The cost and performance capabilities of such antennas are well known, and it is clear that the antenna elements required for the VLA will not present technical difficulties of any significance. The problem will be to find an economical way to produce 36 units that can be moved over the 63 km of road or rail. One should, however, bear in mind that the number of elements required for the VLA is of the same order as the total number of similar antennas of approximately 25 m diameter in existence in the world today. The construction of the VLA antenna elements is, therefore, a large undertaking, and raises the possibilities of significant reductions in unit cost compared to previously built antennas. Three possible areas where a cost reduction could be accomplished are:

1. The design of the antenna elements

The amount of engineering that can be economically applied to the design of antennas which are built in quantities of one or two is necessarily limited. In the case of the VLA, however, a thorough engineering can be afforded. For example, a satisfactory engineering design can be obtained for about 3% of the estimated cost of the antenna elements and mobility system for the VLA. However, the reduction in construction cost expected as a result of this engineering effort is considerably more. To insure an optimum design, a prototype antenna element should be considered.

2. Construction

With a well engineered design it will be possible to let contracts for the construction of the different parts to manufacturers specializing in different types of construction. Surprisingly few parts of an antenna element require very high precision work. For example, the pedestal tower and the dish backup structure require only standard steel construction accuracies, meaning low cost. The rigidity required of these parts is part of the engineering problem and not the work of the manufacturer. The division of the construction work between several specialized manufacturers is also necessary for a reasonable completion schedule, which is estimated at approximately two years for 36 units.

3. <u>Assembly</u>

The antenna elements will be assembled on the VLA site using an assembly line approach. Since all the units will be movable, this should be easy to accomplish. It is contemplated that seven antenna elements will be in various stages of completion at the same time during assembly. Cranes, scaffolding, jigs, etc., will be positioned as needed at the seven assembly stations. This approach should result in a minimum assembly cost within a two year total construction and assembly time.

In the spring of 1966, a subcontract was let to The Defense Electronic Products Division of the Radio Corporation of America to study the antenna elements and the mobility system for the VLA. At the time, NRAO had completed a conceptual design which would satisfy the astronomical mission of the VLA (VLA Report No. 1). The purpose of the RCA study was (1) to determine the factors influencing the cost and performance of the VLA antenna element, and (2) to consider the design in sufficient detail to arrive at a reasonably reliable cost estimate for the system.

Since several of the performance specifications desirable for successful astronomical observations could be subject to changes without serious reduction in the overall usefulness of the instrument, RCA was specifically asked to make parametric studies of possible cost trade-off areas. Examples of such potential trade-offs are:

1. <u>Sky coverage</u>

Although a complete sky coverage is desirable from an astronomical point of view, some areas of the sky may be less important than others. For example, the usefulness of the first 5° of elevation coverage is limited by the earth's atmosphere, and an estimate of possible cost reduction if the antenna sky coverage is restricted in elevation is of interest.

2. <u>Environmental conditions for full accuracy</u>

The stiffness required for a certain surface accuracy of an antenna, as well as the size of an accurate gear and servo system, is dependent upon the wind loading of the structure. It is, therefore, of interest to know how the cost of the system is affected by the maximum wind for which full observing capabilities are required.

3. Time allowed for changes in the array configuration

The change-over time is unproductive from an astronomical point of view, and it is desirable to keep it as short as possible. The change-over time is directly related to the cost of the mobility system. As one extreme one can envision a highly sophisticated mobility system with a moving vehicle for each antenna element, all moving at the same time. As the other extreme, only one moving vehicle is available for all antenna elements, and only one antenna is moved at a time.

In the following sections of this chapter, the antenna element and mobility system problems are discussed in more detail. In Section B, the basic performance specifications for the antenna element are determined. In Section C the factors which influence the cost and performance of an antenna element are discussed in detail, and in Section D the antenna element proposed for the VLA is described. In Section E the construction problems are discussed and a possible schedule is indicated. Finally, in Section F the cost of the recommended system is discussed.

A large part of the discussion in these sections is based on the RCA study report.

B. Preliminary Performance Specifications

The basic performance specifications described in this section are determined by the astronomical requirements of the VLA.

The antenna element will consist of a 25 m diameter parabolic reflector (see Chapter 7) with a Cassegrain feed system. The Cassegrain antenna was chosen for two main reasons: (1) its low noise characteristics and (2) the convenient location of the electronic equipment in a large, easily accessible room behind the reflector vertex.

The main dimensions of the Cassegrain system are shown in Fig. 11-1. The system is designed for the VLA design wavelengths of 11.1 cm (2695 MHz) and 5.5 cm (5390 MHz). For observations of spectral lines, the antenna may be used as a prime focus instrument with the Cassegrain subreflector removed. Thus the change-over between the operating frequencies will be simple.

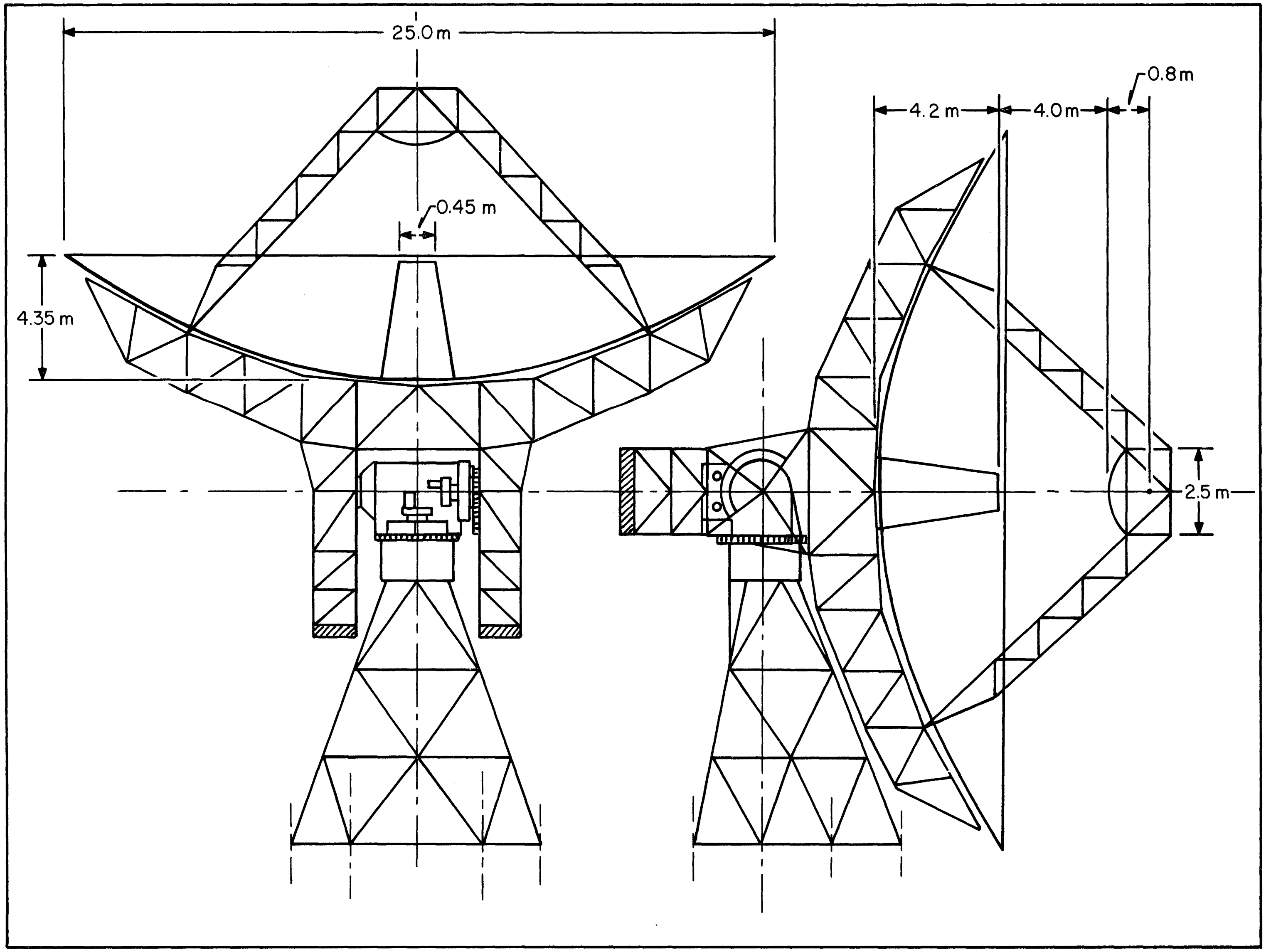

Figure 11 - 1. Bench mark antenna assembly.

High sensitivity is very desirable for any radio astronomical installation, and it is therefore important to build a system with the lowest possible noise temperature. It is possible today to produce reliable and inexpensive low noise amplifiers permitting a radiometer noise temperature of approximately 40°K, and even better amplifiers should be expected to be available a few years from now. The noise contribution from the antenna element may, therefore, be a significant part of the total operating noise temperature of the antenna, and antenna elements with low noise characteristics should be chosen for the VLA.

The main contributor to the antenna noise is the radiation from the ground which enters into the feed by spillover and far out side-lobes. In the Cassegrain antenna the feed spillover pattern is pointed towards the cold sky with a corresponding reduction in the noise temperature. Furthermore, the optimum Cassegrain antenna requires a smaller F/D ratio than the optimum primary focus system, and the complete feed arrangement, including the Cassegrain secondary reflector, is somewhat better shielded from the ground radiation.

The VLA will have an extensive electronics system located at each antenna (see Chapter 15). The important (and delicate) parts of the electronic equipment are the low noise input amplifiers and the phase stable (phase locked) local oscillator system. Both should be located as close as possible to the antenna feed, certainly close enough to avoid any rotary joints or flexing cables between these parts of the system and the feed. The Cassegrain antenna configuration provides a large and easily accessible room inside the backup structure directly behind the vertex of the reflector.

The shortest operating wavelength planned for the VLA is 5.5 cm (5390 MHz), and in order to assure satisfactory performance at this wavelength, the accuracy of the reflecting surface must be better than 2.5 mm rms, and the Cassegrain secondary reflector surface accuracy must be better than 0.5 mm rms. Furthermore, the pointing accuracy of the antenna element should be better than $\pm$ 0.01° ($\pm$ 36"), corresponding to 1/16 of the half-power beam width at 5.5 cm.

The reflector must be fully steerable with complete sky coverage with the exception of elevation angles below +5° where atmospheric conditions limit the usefulness of the antenna (see Chapter 6). The antenna element must also be able to track a celestial source and to move between points on the sky at a reasonable speed. A slewing speed of approximately 20°/min and scanning speeds adjustable between 0°/min and 4°/min will accomplish this.

Possible limitations of the antenna element operating accuracy caused by the environmental conditions must be kept to a minimum. An average loss of observing time because of wind, extreme temperatures, ice, snow, etc., of 5% or less is considered acceptable.

Finally, the antenna system must be able to survive any extreme weather conditions which may occur at the site.

C. Discussion of General Factors Which Influence Performance and Cost

There is a number of ways to achieve the performance outlined in the preceding Section B. The important factors that have to be considered in the choice of the recommended system are the following:

(1) Type of mount
(2) The wind environment
(3) Antenna reflector surface
(4) The reflector backup structure
(5) The servo drive system
(6) Mobility problems

In the following, these factors will be discussed in detail.

1. Type of mount

The use of equatorial mounts for astronomical observations is a natural development, since this arrangement minimizes the drive system requirements. For land-based or earth targets, such as are encountered with radar, an azimuth-elevation (Az-El) (or altitude-azimuth) type of arrangement has been typical. In shipboard application an X-Y (or elevation-traverse) type of mount is often encountered, where the lower axis is aligned parallel to the ship's roll axis, so that rotation about the lower axis can accommodate both ship's roll motions as well as target motions. Each of these mounts has special merit for certain specific purposes, and all have the same limitation due to "gimbal-lock" when the instrument is rotated about the upper (or outer) axis until the line of sight is parallel to the lower axis. Under this condition rapidly moving targets cannot be tracked as the instrument must rotate about the lower axis at a speed equal to the target angular velocity times the secant of the declination angle (elevation or traverse angle for Az-El and elevation-traverse type mounts, respectively), requiring an infinite velocity about the lower axis when the upper axis angle reaches 90°. As a result each type of mount has limited capability for tracking rapidly moving targets in a conical zone centered on the axis center line of the lower axis. For celestial use this is of little consequence for the equatorial mount, as the conical zone of limited tracking capability is aligned with the North Pole. On this basis, the equatorial type of mount would be the obvious choice; however, structural considerations as well as sky coverage and accuracy requirements introduce significant effects on total antenna costs.

As shown in Fig. 11-2, the Az-El mount requires only 90° of travel in the elevation axis and 360° of travel in azimuth to obtain full hemisphere coverage of the visible sky. The two axes can readily be made to intersect; adequate space is available for the structure, counterbalancing the elevation axis inherently results in balance of the antenna in both axes with no additional counterweight, and the minimum pedestal height is D/2.

The same antenna pedestal arrangement can be converted to an equatorial mount by inclining the former azimuth axis until it is parallel to the earth's axis. This provides good coverage of the northern sky for all positive declination angles, but much of the northern coverage is uselessly directed toward the ground, and the mount is very limited in coverage of negative declination angles. This mount also requires either complex limit stops or raising the minimum axes height above ground by approximately 20%, as shown in Fig. 11-3. With minor modifications to the antenna and pedestal structures, declinations from -10° to -15° could be obtained, while still maintaining intersecting axes. This axis and structural arrangement is inherently limited in sky coverage and is best suited to provide hemispheric coverage centered about the North Pole, providing unlimited hour angle coverage, but drastically limited negative declination angle coverage.

In somewhat similar fashion, the X-Y or elevation-traverse mount can be modified by tilting the lower axis until it is aligned parallel to the

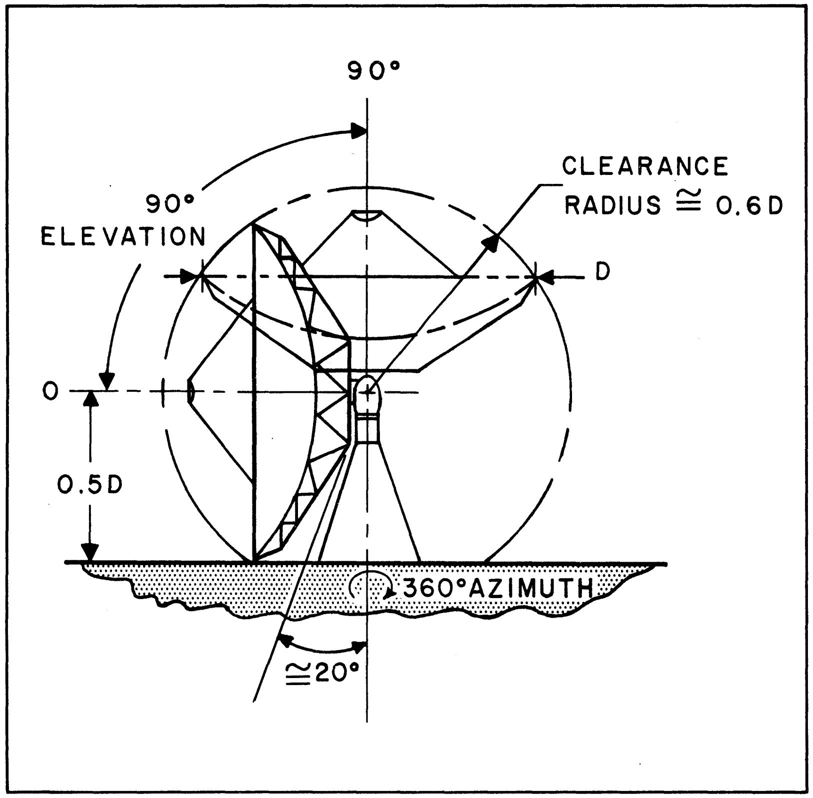

Figure 11 - 2

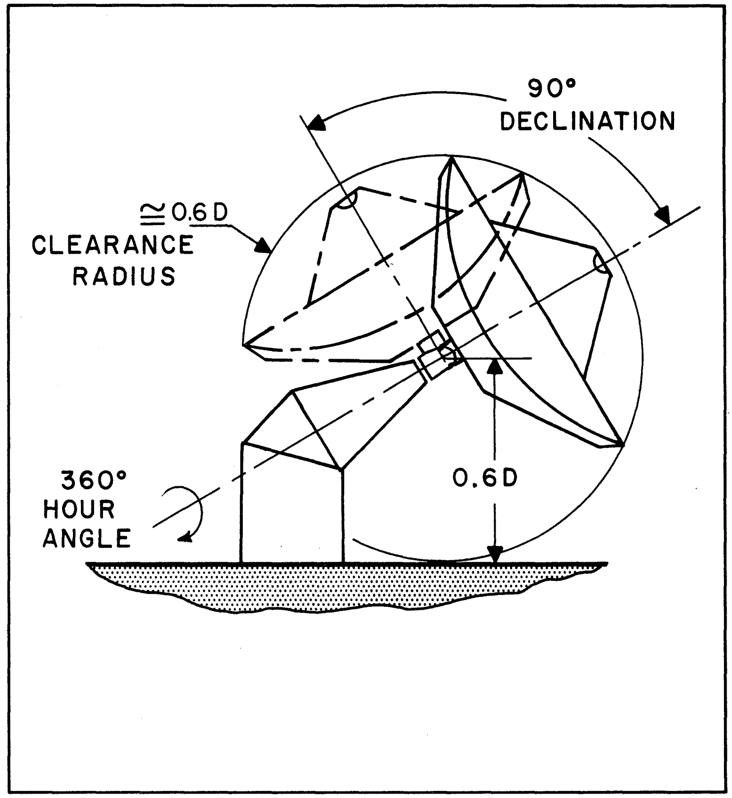

Figure 11 - 3

earth's polar axis, as shown in Fig. 11-4. This is the general arrangement used for the Cal Tech 90 ft interferometer at Owens Valley. As shown in the figure and in the table accompanying the figure, this arrangement is well adapted to providing unlimited declination angular coverage, but is inherently limited to approximately ± 4 hours of hour-angle coverages before the notch in the stationary structure becomes too large. At the higher hour-angle coverages this notch effect becomes so large that structural stiffness is not adequate to provide the required accuracy under wind load conditions.

Two different approaches have been used in the past to obtain greater angular coverage with equatorial mounts. Both approaches require use of non-intersecting rotational axes. One approach to an equatorial antenna mounting, built by D. S. Kennedy, has utilized a canted Az-El pedestal to obtain extended negative declination coverage, as shown in Fig. 11-5. The declination axis is moved slightly farther back from the vertex along the antenna axis to provide structural clearance by the reflector, and the hour axis and declination axis are offset by the distance X, which is approximately equal to 0.1 D and is required to obtain rotational clearances and space for structural supports. Full hemispherical sky coverage can be obtained at a cost which is not excessively high, but is significant. Much of the increased cost of this mount is hidden, as it arises from the awkward structural configuration, cramped space for drive components, and need for complex limit switches and stops which should be provided to avoid mishaps during operation. The more obvious cost increases are the increased pedestal and tower height; the need for counterweighting the reflector unbalance about the declination axis and in turn counterweighting the declination-rotating assembly (including the declination counterweight) about the hour axis. The second approach to an equatorial antenna mounting with large angular coverage is based on a version of the Hale telescope mount or "split-ring" type of mounting, and is shown in Fig. 11-6. This type of mounting has been successfully used by Blaw-Knox and Rohr for a number of radio telescope applications. For applications with full sky coverage, it is generally comparable in cost to that of the canted Az-El (Kennedy) type mounting. In comparison to the canted Az-El mount, the split-ring mount requires greater separation of axes, larger

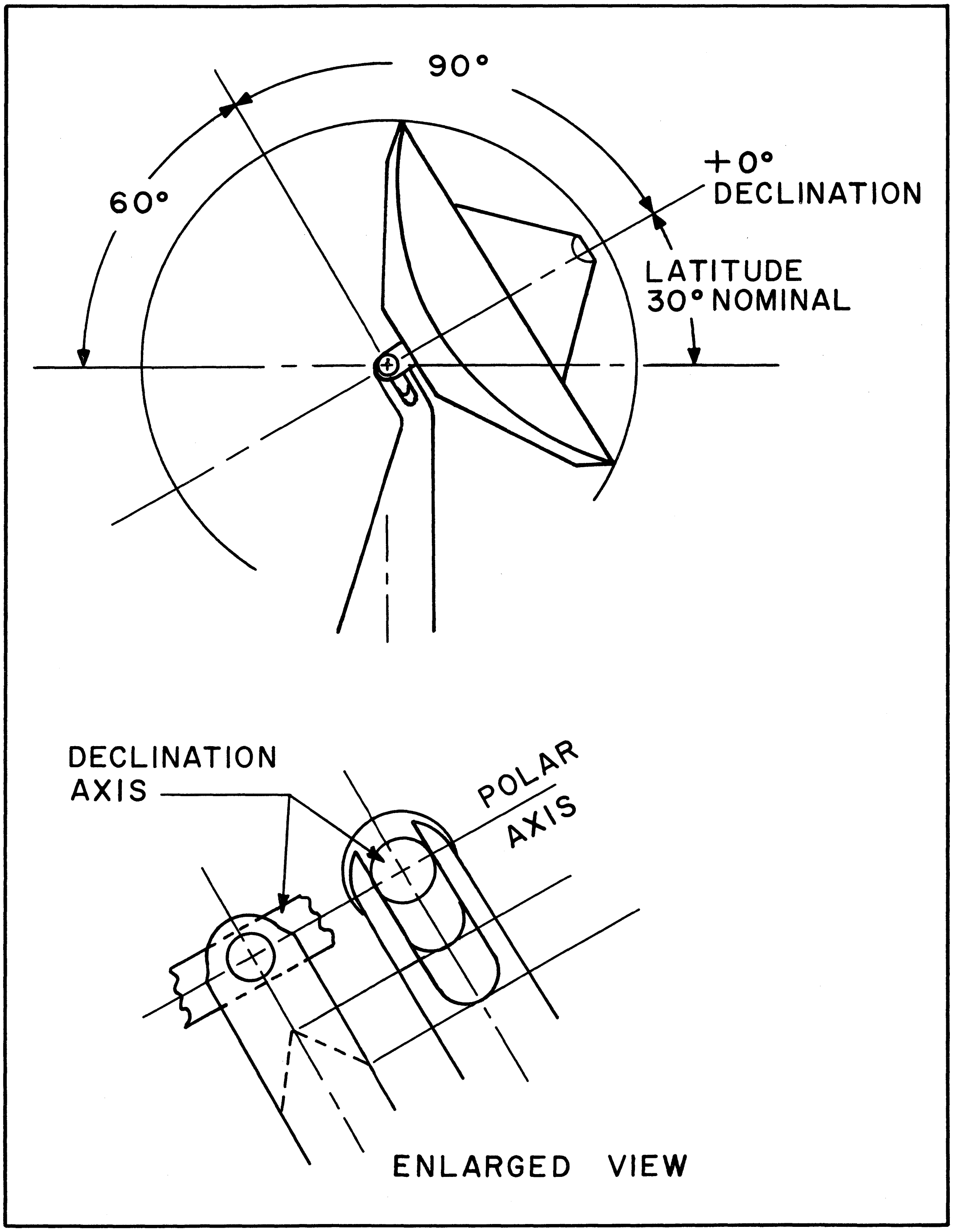
90°
60°
+0°
DECLINATION
LATITUDE
30° NOMINAL
DECLINATION
AXIS
POLAR
AXIS
ENLARGED VIEW

Figure 11 - 4

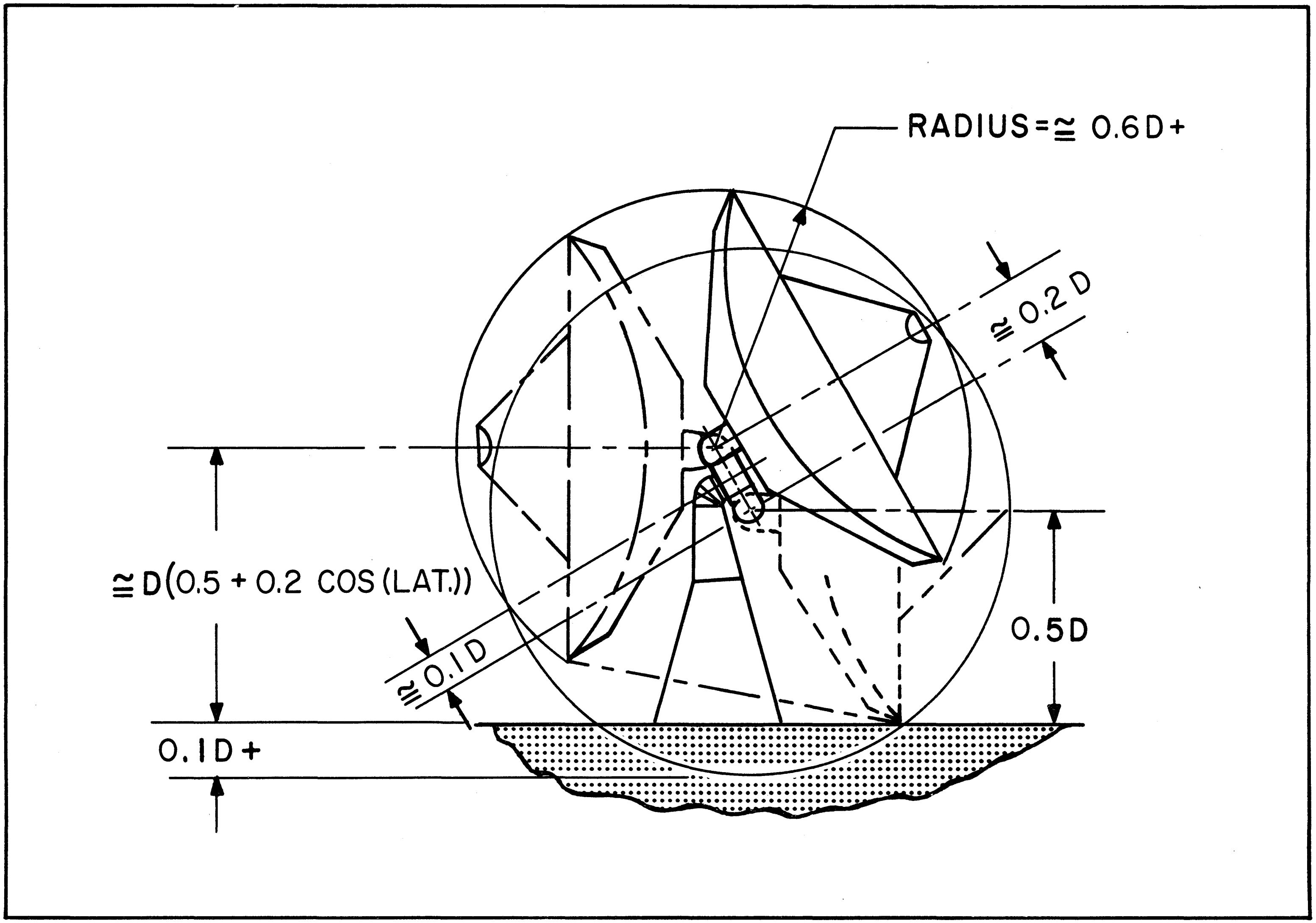

Figure 11 - 5

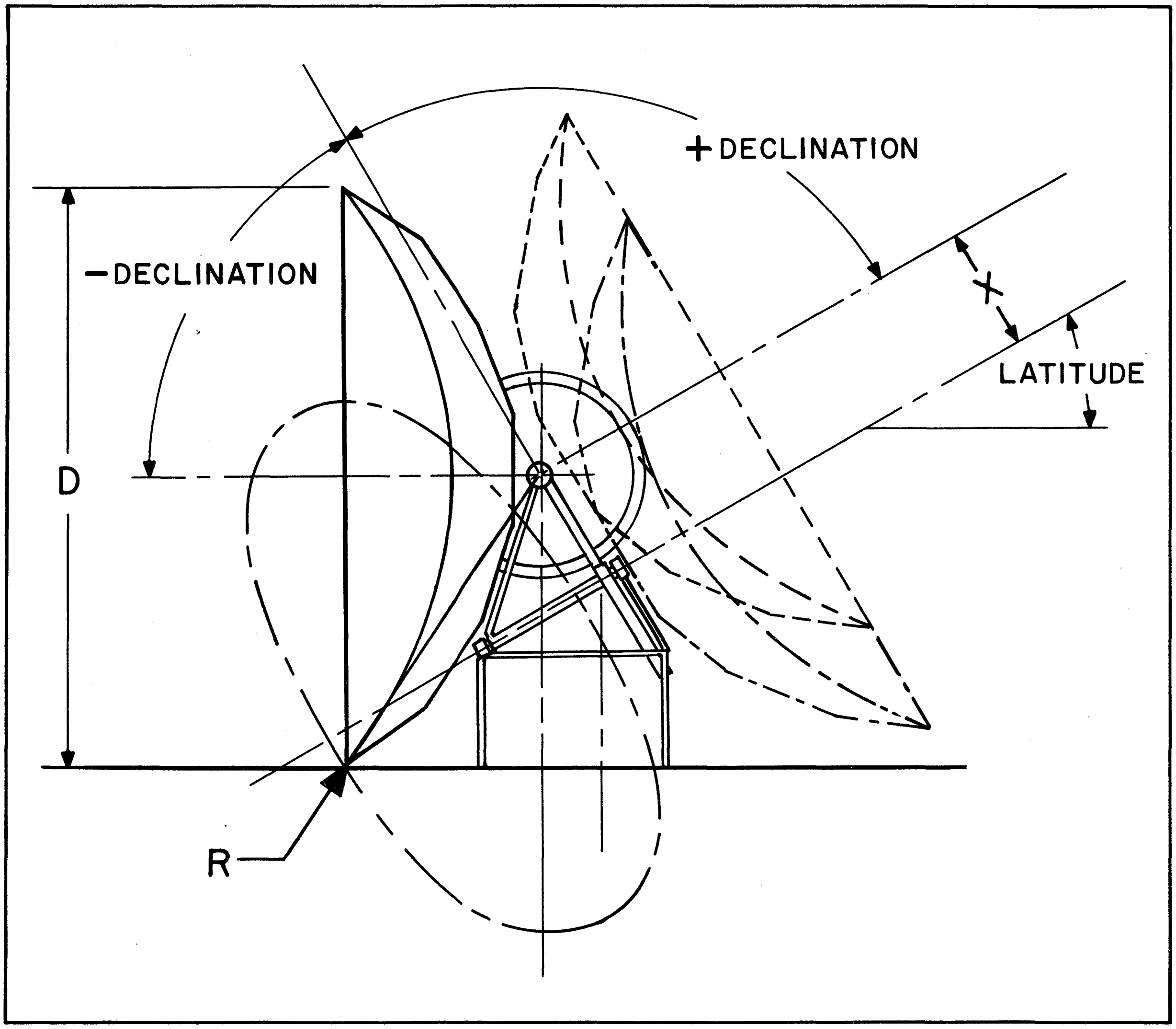

Figure 11 - 6

counterweights, and a greater total weight. However, the bulk of the split-ring structure can be relatively more economical on a per pound basis, as the major part of the structure can be unmachined, truss-type, steel structure, and the large-diameter, sectoral-shaped drive gears can be relatively crude because of their large diameter. It should be noted, however, that the precision of the large diameter gears cannot be increased, except at relatively large cost, and that enclosure and sealing of the gears is very difficult, if not impractical.

The following table sums up the properties of the different antenna mounts.

Table 11-1

	Position of Axes	Sky Coverage	Relative Cost	Remarks
Az-El	Intersecting	Full	1	
Tilted Az-El	Intersecting	HA Full δ +90 - -10	1	Insufficient sky coverage
	Offset	Full	1.25-1.30	
Tilted X-Y	Offset	HA ± 4h δ Full	1	Insufficient sky coverage
Split ring equat.	Offset	Full	1.25-1.30	

As the Az-El type of mounting appears to be significantly more economical than other mountings for a given angular coverage, further examination of the cost effects of minimum elevation angle is warranted for this type of mount. In order to minimize the variables being considered, the following table will be used to define a typical antenna assembly. The figures selected are typical for equipment in the 15 m to 30 m antenna diameter size and have been selected by comparison of existing field installations.

Typical Shape Factor for Antenna Pedestals

Antenna Size	"D" (15 m < D < 30 m)
Bearing and Gear Assembly Diameter	0.1 D
Dish Depth	0.18 D (F/D = 0.35)
Back Structure Depth	0.1 D
El Bearing to Az Bearing Distance	0.1 D

The major influence in structure weight and ultimate cost is structure height and distance between the center of gravity of the reflector (without counterweights) and the elevation axis.

Using the typical antenna geometry described in the table above, one arrives at the following cost factors as a function of the minimum elevation angle of the Az-El mount.

Table 11-2

Min Elevation	0°	10°	20°	25°	30°
Wind drag loading	1.00	0.96	0.91	0.88	0.70
Wind moment at ground	1.00	0.90	0.67	0.58	0.51
Counterweight	1.00	0.87	0.80	0.73	0.70
Tower structure weight	1.00	0.88	0.74	0.66	0.60
Pedestal cost	1.000	0.938	0.885	0.848	0.825

The figures in the table represent cost relative to the Az-El antenna with full sky coverage. In Fig. 11-7 the relative cost as a function of minimum elevation angle is shown for different telescope sizes. An examination of Table 11-1 shows that only the Az-El, the tilted Az-El with offset axes, and the split-ring equatorial mounts give the required sky coverage (Chapter 6), and of these three the Az-El mount with intersecting axes is clearly the least expensive antenna element. The atmosphere will limit useful observations to elevations above approximately +5°, and Fig. 11-7 indicates a further cost reduction possibility of the Az-El telescope by a slight restriction in elevation coverage.

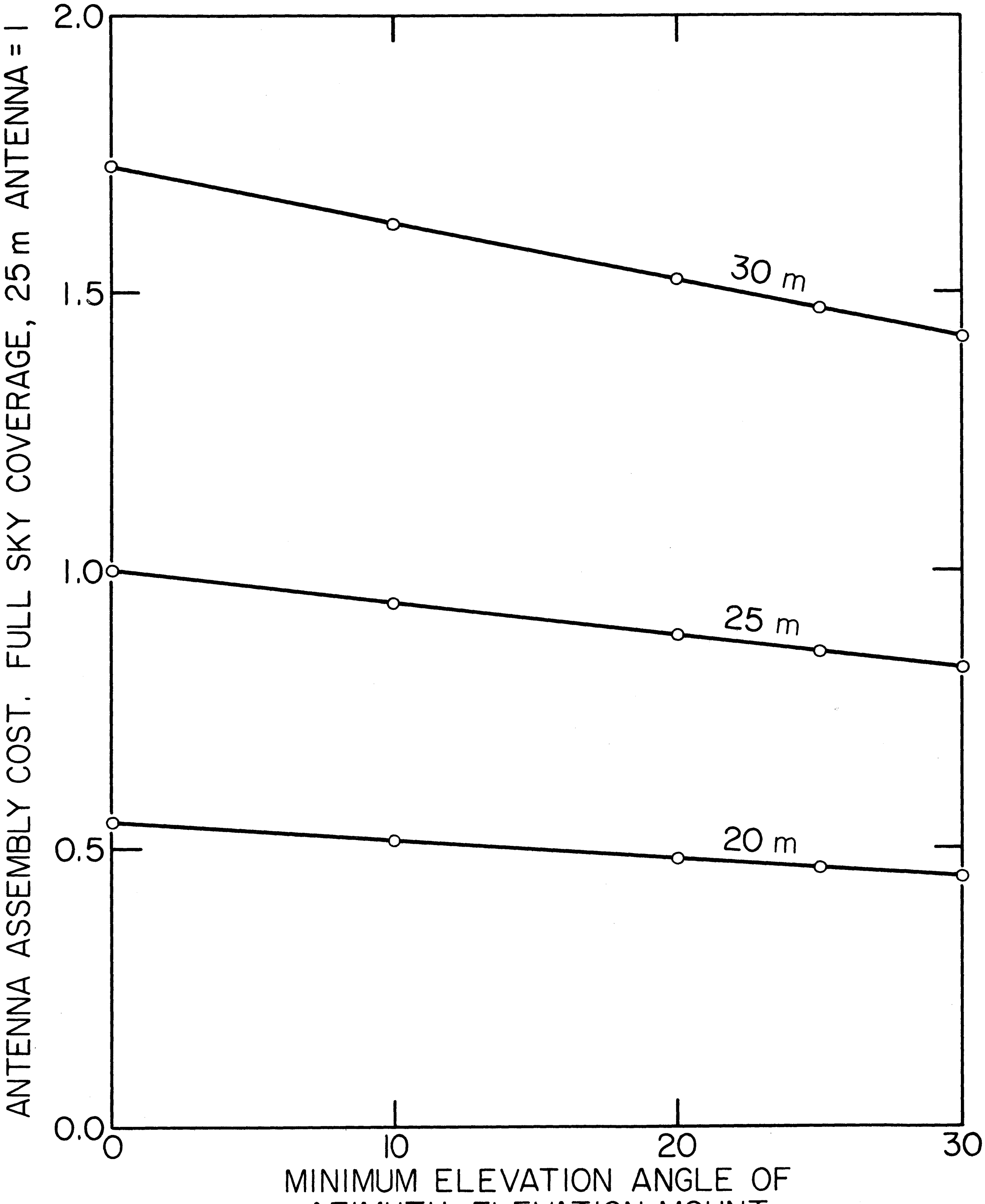
2.0
1.5
1.0
0.5
0.0
0
10
20
30
30 m
25 m
20 m
ANTENNA ASSEMBLY COST, FULL SKY COVERAGE, 25 m ANTENNA = 1
MINIMUM ELEVATION ANGLE OF
AZIMUTH-ELEVATION MOUNT

Figure 11 - 7

Fig. 11-8 shows comparative costs of the split-ring equatorial mount and the canted Az-El mount providing ± 6 hours travel in the lower axis and various amounts of extended south declination travel. The unit cost is not the total picture, however. Both of these mounts, for full sky coverage, weigh considerably more than the Az-El mount and result in conditions where the stowed antenna height is approximately 20% greater for the canted Az-El and 50% greater for the split-ring equatorial types of mounting.

Also shown are estimated relative cost of the tilted X-Y mount for various hour-angle coverages. This mounting is attractive, as it is comparable in weight, cost and stowed antenna height to the full coverage Az-El mount, being slightly lighter and cheaper for limited hour angle travel, but cost and weight increases rapidly beyond ± 4 hours of hour angle coverage.

The equatorial mounts have three principal system advantages:

(1) Sidereal tracking requires motion in only one axis

(2) Coordinate conversion of angle data is not required

(3) The antenna maintains a constant position relative to polarization angle of the target

For full sky coverage the Az-El mounting has a more compact, shorter load-path structure, resulting in the following advantages:

(1) Lower cost, weight and height

(2) Greater stiffness leading to higher potential servo bandwidth and providing greater resistance to wind disturbances

(3) Antenna gravity deflections are easier to control as gravity forces change direction only in the elevation axis

(4) Stowing means are easier to incorporate

From a mobility aspect, for full sky coverage, the Az-El mount has the following advantages:

(1) Antennas can be emplaced at any convenient azimuth or orientation and azimuth position reference obtained by changing encoder reference setting or by computer correction

(2) Antennas can be mechanically leveled to gravity vertical by levels on the turntable -- or by adding a clinometer, the azimuth axis

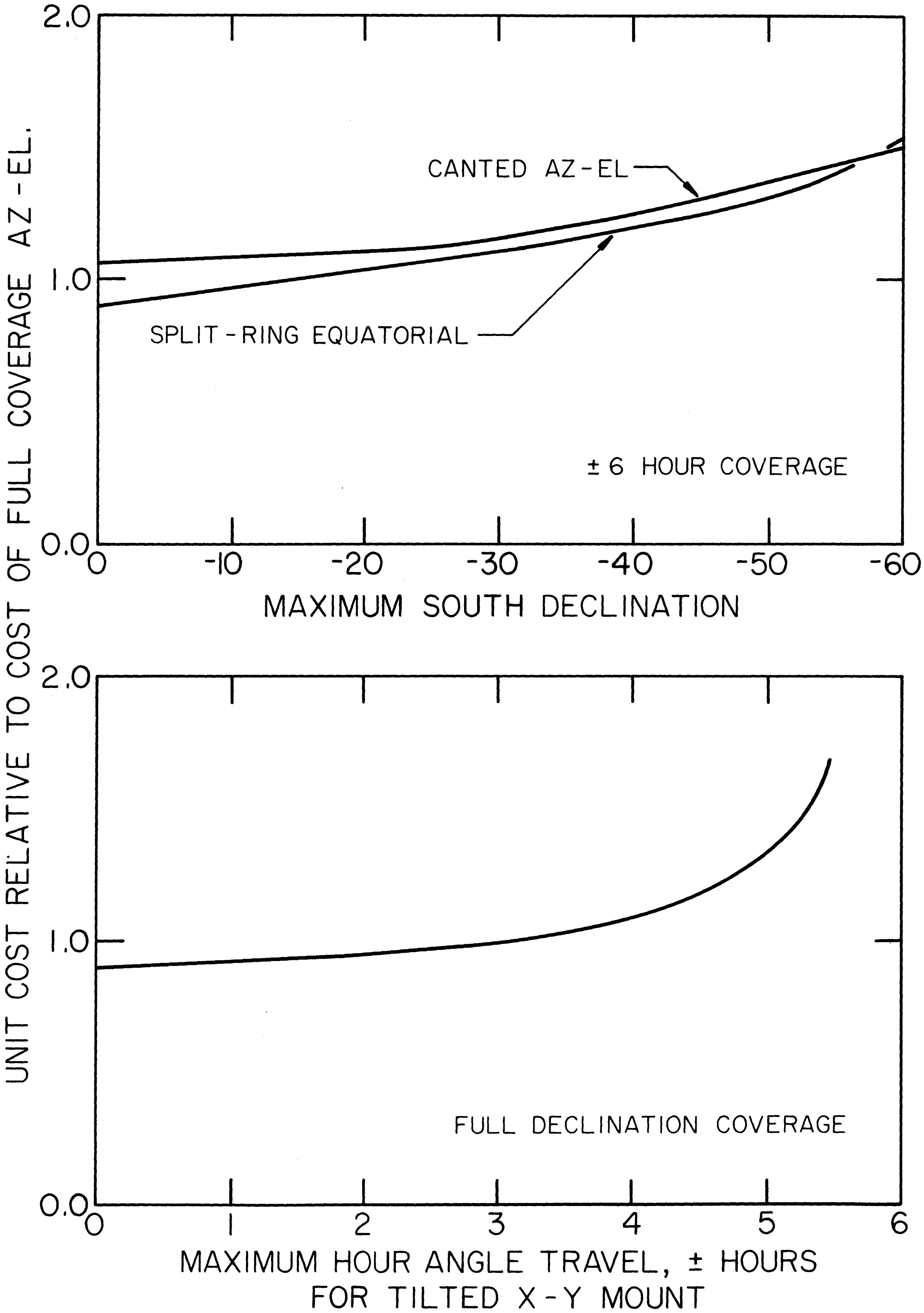
UNIT COST RELATIVE TO COST OF FULL COVERAGE AZ-EL.
2.0
1.0
0.0
CANTED AZ-EL
SPLIT-RING EQUATORIAL
± 6 HOUR COVERAGE
0
-10
-20
-30
-40
-50
-60
MAXIMUM SOUTH DECLINATION
2.0
1.0
0.0
FULL DECLINATION COVERAGE
0
1
2
3
4
5
6
MAXIMUM HOUR ANGLE TRAVEL, ± HOURS
FOR TILTED X-Y MOUNT

Figure 11 - 8

can be set off-level by any predetermined amount to position all azimuth axes parallel to each other

(3) Lower stowed antenna height during move, with lower wind loads and center-of-gravity, and permitting narrower roadbed

(4) Lighter weight on transport vehicle

(5) The shape and structure at the antenna base is relatively easy to interface with the mobility transport vehicle.

As mentioned above, the Az-El mount has a few small disadvantages compared with the equatorial mount.

(a) The difficulty of tracking a source through the zenith. The inability of the Az-El mount to permit tracking of a source through the zenith, and the excessive azimuth angular rates (and accelerations) needed for tracking sources close to the zenith, establishes a "cone of avoidance" around the zenith. It is easy to show, however, that the servo system needed for accurate operation under reasonable wind conditions will be able to perform satisfactory tracking as close as 2.5° from the zenith. Thus the cone of avoidance represents an insignificant amount of sky.

(b) The need for coordinate transformation. For a modern computer with the capabilities needed for the VLA for other purposes, the real time coordinate transformation is very simple and easy to accomplish. (The transformation information is common to all elements.)

(c) The need for a servo type drive system. A servo drive system will be more expensive than the simple drive arrangement needed for an equatorial telescope, but the increase in cost should be compared with the cost difference between an equatorially mounted antenna with full sky coverage and the Az-El mounted antenna element. (The servo system requirements will be described in Section C.5.)

(d) There is a certain inconvenience in tracking sources north of the zenith if it is not possible to "over travel" in elevation through the zenith to the celestial pole. Tracking a source will then require a negative azimuth rotation. This inconvenience is easily overcome by the VLA computer. It will only be necessary for the azimuth cable wrap-up to permit ± 270° motion in azimuth in order to avoid running into the limits while observing.

If a plunge feature were to be included as a requirement, it would complicate the location of the drive system, either by spreading the elevation bearings and mounting the elevation drive boxes below the elevation axle and mounting the azimuth drives beneath the turntable, or by inverting the elevation drive by hanging the elevation drive boxes on the counterweight arm and driving against a stationary elevation bull-gear attached to the turntable. Two items are of primary concern from a cost standpoint. First, the space available for drive components would be very limited and would require increased engineering effort to fit everything into the available space and still provide adequate structural stiffness for controlling wind deflections. Second, the tighter space limits would make it unlikely that standard commercial gear-boxes could be utilized. It is anticipated that extending elevation travel beyond zenith would result in cost increases as follows:

Elevation Travel	Engineering Cost $	Increase in Unit Cost %	Increase in 25 m Unit Cost $
0 - 120°	10,000	1.4	5,000
0 - 150°	30,000	4.0	15,000
0 - 180°	50,000	7.0	25,000

These are estimates based on three steps in which it is anticipated that the first 30° increase requires only increased difficulty in stowing, the next 30° requires modifying the elevation drive concept, and the last 30° requires modifying the azimuth drive concept.

2. The wind environment

A careful study of the environmental factors which affect the structural design of the antenna element shows that the wind is the most important single consideration. The required size and strength of the reflector back-up structure and the antenna pedestal are strongly dependent upon the maximum wind conditions during which observations take place.

In addition to the obvious requirement that the antenna element must have the strength to survive any wind condition that may occur at the

VLA site (100 mph seems to be a reasonable design figure), there are several factors which affect the performance and safety of the antenna element during operation:

(a) The overturning moment. When the antenna element is anchored at an observing station, the overturning moment which the antenna element must withstand will be determined by the survival conditions. It is when the antenna is being moved between stations that a chance for overturning is present at lower wind velocities. Fig. 11-9 shows curves giving the size of the pedestal base needed to prevent overturning of a 25 m antenna as a function of wind velocity. Two different pedestal configurations are considered. The effective pedestal base that has been selected for the VLA antenna element during transportation (distance between rail centers) is approximately 15 ft. As can be seen from the curves, this is more than adequate for safe transportation during any but the strongest winds.

(b) Vibration problem. Wind induced vibrations in antennas may lead to early fatigue failure of structural truss members. An analysis of this problem for tubular members leads to the conclusion that, if tubular members are used, the antenna structure should utilize members of large diameter. For example, a 10 ft long tube should have a diameter not less than 5 inches to ensure freedom from dangerous wind-induced vibration. However, it is of interest to note that transmission line towers and similar structures using relatively long, slender structural steel angles have been notably free from wind-induced vibration problems. Aerodynamic flow theory would also lead to the conclusion that angles and Tees, with asymmetrical cross-sections, should be less sensitive to wind induced vibrations than tubular members. Also considering economic factors, one may conclude that structural steel angles, Tees and z-sections are the best choice for antenna structural elements.

(c) Surface material. It is possible to reduce the wind forces on the antenna reflector by using a mesh surface, but for any mesh that would be an acceptable reflector at 5.5 cm wavelength, the wind force reduction will be negligible. For example, a mesh made of 2 mm (0.08 in) wire spaced 10 mm (0.4 in) apart would have transmission loss at 5.5 cm wavelength of less than 5%, and would reduce the wind load by approximately 50%. However, such a reflector screen would be hopelessly inadequate from a

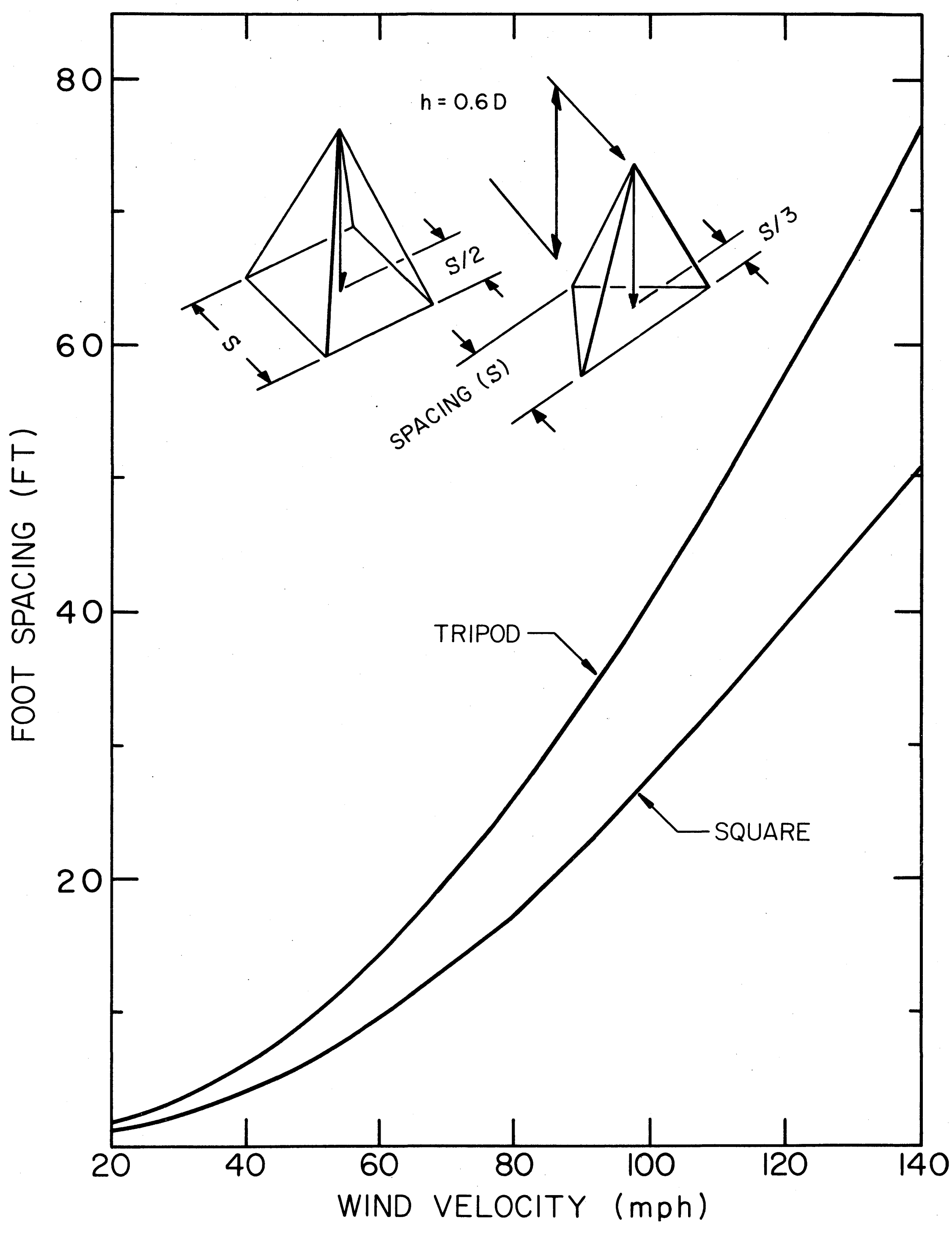
80
60
40
20
FOOT SPACING (FT)
h = 0.6 D
S/2
S
SPACING (S)
S/3
TRIPOD
SQUARE
20
40
60
80
100
120
140
WIND VELOCITY (mph)

Figure 11 - 9

structural point of view, and the use of larger wires would increase the wind load rapidly. One is therefore led to conclude that reduction of wind forces by using wire mesh surface material is impractical at the operating wavelengths planned for the VLA.

(d) Servo power and gear requirements. For a slow moving structure as the VLA antenna element, the amount of power in the drive machinery is almost entirely determined by the wind forces. An analysis of an antenna element gives the curves shown in Fig. 11-10. Curves for each of the three dish diameters 20 m, 25 m, and 30 m show the torque for the telescope axes caused by the wind.

In addition to the simple problem of providing the raw power needed to move the telescope against the wind forces, the pedestal stiffness, gear ratio, etc., enters into a complicated relation which in the end determines the servo accuracy. The antenna structure and servo system proposed for the VLA antenna element will give the following error budget for a 20 mph wind load.

Tracking Error Budget

*Wind Structural Error	26"
*Wind Gust Error	26"
Cogging Error	12"
Data Takeoff Error	7"
Antenna Droop	20"
Thermal Error (2 hours after sunset)	5"
Axis Orthogonality	5"
Alignment	10"
Deviation from Remainder of Elements	12"
Level	6"
RMS Error	48"

* 20 mph assumed to be a typical wind

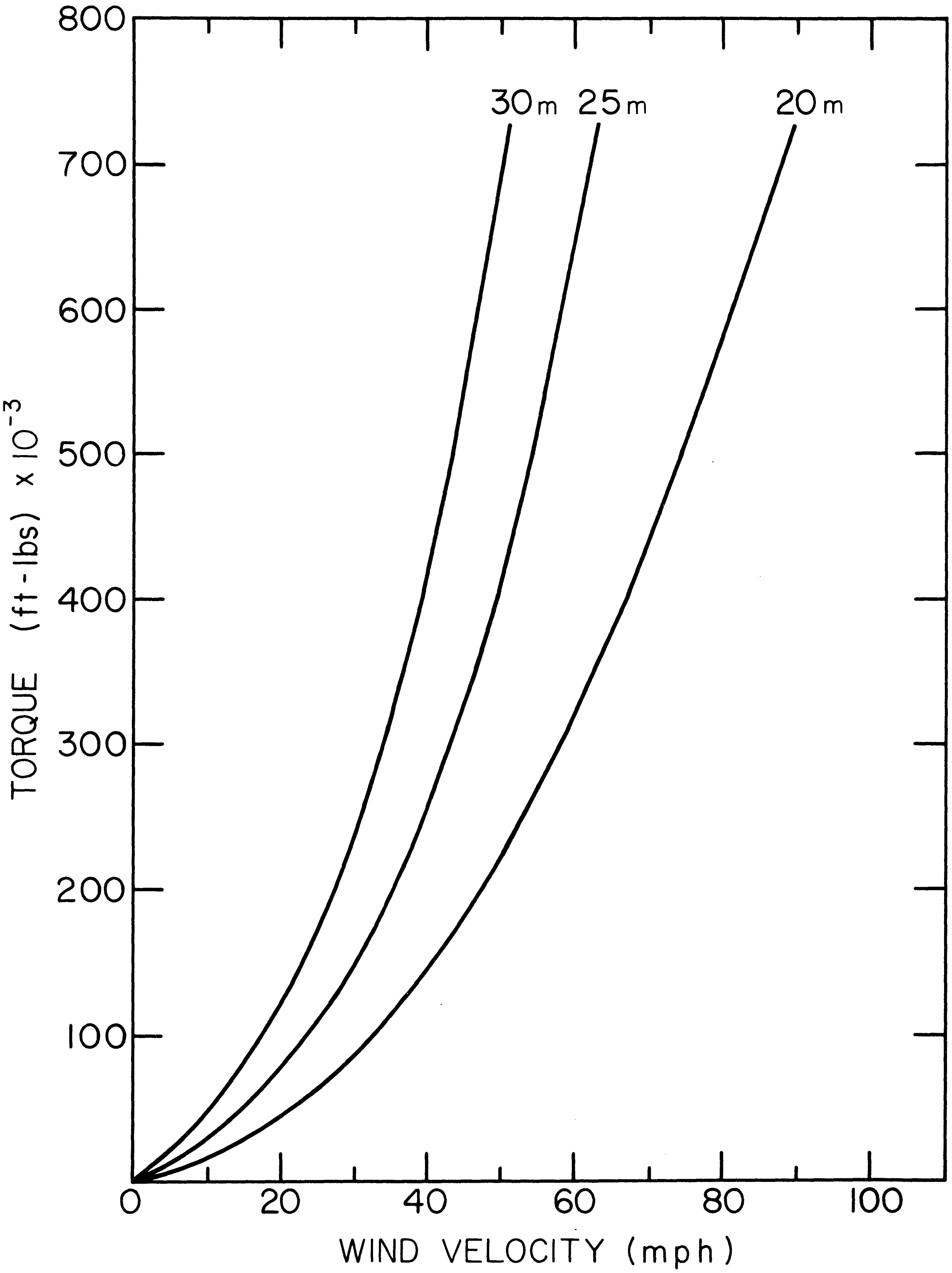

Figure 11 - 10. Wind torque for 20, 25, and 30 meter antennas. F/d = 0.35, X_v = 0.10.

The error budget presented above represents an estimate of possible errors. Considerable work is required in this area before an actual error budget can be established. Exact figures for alignment capability, actual wind velocity profile, and thermal effects all must be obtained be-before the error budget is realistic.

Since the wind load on the antenna element is such an important factor, it will be necessary to gain reliable knowledge about the actual wind conditions at the site which will be chosen for the VLA. In order to get an approximate estimate of the wind problem, typical wind conditions in the Y-15 site area have been evaluated. Table 11-3 shows a summary of the wind conditions.

From Table 11-3, it can be seen that the average wind exceeds 20 mph approximately 6% of the time for these sites.

An average wind velocity of 20 mph, as reported in the table, will usually be composed of three components.

(a) A steady wind component of approximately 10 mph

(b) A rms "average" gust component of approximately 10 mph

(c) Peak winds up to 30 mph

The analysis of the survival wind problem shows that, again in the Y-15 site area, there is a 0.997 probability that the wind will not exceed 100 mph in a given year. As a preliminary survival design figure, 100 mph should, therefore, be conservative enough.

3. Antenna reflector surface

The antenna surface was briefly discussed above (2) with the conclusion that the reflecting surface should be solid.

One of the most attractive and effective ways of obtaining an economical antenna reflector with surface accuracy of 2.5 mm rms is to utilize accurately contoured reflector surface panels, each supported on three or more adjustable mounting points by a structural frame. This approach permits the structural frame to be designed for strength and overall rigidity without requiring precision dimensional control in the structural members. The panels provide distributed local support for the precision reflecting surface and carry wind and gravity loads into the back structure through the adjustable mounting points. During field erection, the reflector

Table 11-3

Summary of Mean Wind Observations in Y-15 Site Area
by Weather Bureau, U. S. Department of Commerce

	Velocity (mph)	Percentage of Wind Speeds Hourly Observation of Wind Speed % of Time Wind at Velocity 0-3	4-7	8-12	13-18	19-24	25-31	32-38	34-46	Over 46	Average Speed
Y-15 Site Area	Jan.	21	41	23	10	3	1	.1	--	--	7.4
"	Feb.	17	37	25	12	5	3	.9	.2	--	8.8
"	Mar.	15	31	27	17	7	3	.5	.1	--	9.8
"	Apr.	10	29	28	19	9	3	.7	.1	--	10.7
"	May	11	31	29	19	7	2	.5	.1	--	10.0
"	June	13	33	30	16	6	1.6	.2	--	--	9.2
"	July	13	36	30	15	5	1.1	.3	--	--	8.9
"	Aug.	19	39	29	10	2.8	.7	--	--	--	7.6
"	Sept.	18	37	27	12	4	1	.2	--	--	8.2
"	Oct.	19	40	24	10	4	2	.2	--	--	8.0
"	Nov.	25	37	22	11	4	1	.1	--	--	7.4
"	Dec.	26	39	20	8	4	1	.2	--	--	7.0
"	Average	17	36	26	13	5	1.7	.3	.1	--	8.6
Nearby Area "A"	Average	17	29	47	22	6	2	.5	.2	--	12.0*
Nearby Area "B"	Average	13	24	43	16	5	1	--	--	--	9.0*
Nearby Area "C"	Average	26	34	21	13	4	--	--	--	--	

*Estimated

back-structure is assembled to practical tolerances, and each panel support point is individually adjusted to the required position. The support structure is an integral frame and does not rely on the panels for strength or rigidity. Therefore, at any time after the panels are installed, the final surface contour can be measured, and each panel individually adjusted for the best reflector contour. This approach separates the requirements for precision surface tolerances and high structural rigidity and permits economical optimization of each part of the reflector. Since (1) the surface panels involve considerable forming of thin sheets, (2) require local support of extended areas, and (3) represent a dead-weight on the back structure, it is desirable that the lightest practical material be used. Furthermore, since adjustments of the reflector may present an appreciable maintenance cost, it is desirable that the panels be relatively easy to maintain.

The panel design involves optimization of several design parameters which affect the cost of the back structure as well as the panels. In general, the surface panels should be as large as is economically feasible, since reflector back structure, panel attachment hardware, and panel installation and alignment costs increase in proportion to the number of panels required. Handling and shipping considerations generally limit panel sizes to 8 ft x 16 ft, with panels capable of being nested in stacks for economical shipment.

Three principal approaches to panel construction are presently available; honeycomb sandwich, framed-skin, and foam sandwich. The honeycomb sandwich construction utilizes two stretch-formed aluminum face sheets adhesively bonded to expanded aluminum honeycomb core material; the framed skin utilizes a single stretch-formed aluminum sheet supported by a fabricated aluminum frame structure, and the foam sandwich utilizes a fine wire mesh reflecting surface embedded in the front face sheet of a sandwich panel made by molding two fiberglass reinforced plastic sheets separated by urethane foam core material.

Aluminum honeycomb core material is available in a wide variety of foil thicknesses and cell sizes. The general ranges are summarized as follows:

	Military Grade	Commercial Grade
Foil Thickness - inches	.0007 to .006	.003
Cell Size - inches	1/8 to 3/8	1/4 to 3/4
Weight - lbs/ft^3	1.6 to 23.4	1.8 to 5.2
Maximum Core Thickness - inches	20	3
" " Width - inches	24	48 to 50
" " Length - inches	130	90 to 110

In general, the properties increase with increasing core density, irrespective of whether the density increase is derived from thicker foil or smaller cell size. The commercial grade has less choice of cell size, foil thickness, and core thickness, and is manufactured and inspected with less control, but has essentially the same average physical properties and is considerably lower in cost. Commercial grade honeycomb core is manufactured of 0.003 in gage architectural aluminum foil in 1/4, 3/8, and 3/4 in cell size. Core thickness is normally available from 1/4 to 3 in by 1/4 in increments, with cost varying almost in direct proportion to core thickness. The 3/4 in cell size provides the lightest weight and, with thicker cores, can yield adequate mechanical properties. It has a weight of .45 lbs/ft^2 and costs 0.75 dollars/ft^2 for 3 in thickness in quantities over 25,000 ft^2.

Aluminum sheet for panel facing is normally available in 1100, 3003, and/or 3004 alloys in the following maximum sheet sizes, width by length in feet:

	Mill Standard	Commercial Maximum	
Gage - inches	Flat	Flat	Coiled
0.014	2 x 6	4 1/2 x 12	5*
0.020	3 x 10	5 x 15	6*
0.025	4 x 12	5 x 15	6*
0.030	4 x 12	*8 x 15	8*
0.040	5 x 12	*8 x 16.67	8*

*5 ft in annealed sheet

There should be no difficulty in obtaining 0.030 in or thicker sheets in any desired alloy and temper in sheet sizes up to 8 ft x 15 ft. For the quantities involved, it is possible that 0.020 to 0.025 in sheet can be obtained in widths up to 8 ft on special order. Furthermore, it is feasible to stretch-form two thinner sheets of 4 ft x 15 ft material and assemble two sheets with an internal splice strip to form a single 8 ft wide panel. While this approach involves additional costs in the splice, costs of the face sheets are reduced. The net cost per ft^2 assembled panel should be comparable.

In order to minimize the number of different panels, the design should utilize rings of identical panels with each panel being sectoral in shape. Allowing for trim of stretch-formed face sheets and core material, maximum width would be approximately 7 ft with lengths up to 15 ft. Using front and back facing sheets of 0.016 in aluminum and 3 in core material, with adhesive applied at a controlled density of 0.1 lbs/ft^2, a panel weight can be derived as follows:

Face sheets (2) .016 (144) (.098)	=	.45	lbs/ft^2
Aluminum Core 3/12 (1.8)	=	.45	"
Adhesive	=	.1	"
		1.00	"
Allowance for edges and inserts	=	.05	
Total		1.05	lbs/ft^2

Costs of aluminum honeycomb sandwich panels of the general size required for the VLA vary from \$10 to \$20/ft^2 depending on size, shape, accuracy and quantity. A trade-off is involved between cost of back-structure and panel costs, as the lowest cost panels are obtained with sizes and shapes which require less trim and waste material, while lowest cost back-structure require panel sizes and shapes which require the least number of pick-up points and location of pick-up points on principal truss members in the back structure. The final design will require further study of this, as well as other areas, but for the present VLA trade-off study cost figures of \$21, \$15, \$12, and \$10.5/ft^2 for quantities of 1, 10, 40, and

100 antenna elements, respectively, appear to be the best probable value, considering reasonable allowance for trim and waste.

Framed skin panel construction requires use of thicker stretched skins, with 0.025 to 0.040 in material being fairly typical. The frame structure to support the stretched skin typically weighs in the order of twice that of the stretched skin, yielding panel weights from 1.1 to 1.8 lbs/ft^2. Both weight and cost vary with antenna size and surface accuracy, as economical back structures require use of larger panels for larger size reflectors. For the 25 m (82 ft) antenna, with 2.5 mm rms surface accuracy, a framed skin panel weight of 1.5 lb/ft^2 appears to be near optimum. Panel costs vary from \$10 to \$20/ft^2, depending on accuracy, size and quantity. For the 25 m antenna in quantitites of 1, 10, 40, and 100 costs appear to be in the order of \$18, \$13, \$10.5, and \$9/ft^2.

The foam sandwich panel construction technique with 2 in thick panels results in average panel weights in the order of 2.0 lbs/ft^2 for fine wire mesh surfaces and 2.6 lbs/ft^2 for stretched skins. Costs of complete panels with wire mesh surface in quantities of 1, 10, 40, and 100 are in the order of \$10, \$8, \$7, and \$6/ft^2, respectively.

The cost and weight per square foot for the three panel construction techniques are compared in the following table.

		Honeycomb Sandwich	Framed Skin	Foam Sandwich
Weight		1.05	1.5	2.0
\$/ft^2 -	Qty 1	21	18	10
"	Qty 10	15	13	8
"	Qty 40	12	10.5	7
"	Qty 100	10.5	9	6

Considering factors, such as possible problems with moisture absorption in either of the sandwich construction techniques, as well as weight effects on pedestal and mobility costs, it appears that the framed-skin technique is the best choice for the VLA antennas. While the weight of panels is nearly 50% greater than with aluminum honeycomb, the lower panel cost becomes a deciding factor.

4. The reflector back-up structure

The primary functions of the reflector back structure are: (1) to support and maintain alignment of the reflector panels, the hyperbolic Cassegrain reflector, and the feed and receiver system; (2) to resist loads from wind and gravity; and (3) to provide means for carrying the resulting loads into an axis of rotation to permit steering of the antenna. None of these three primary functions can be unduly compromised in an optimum antenna design, and a number of secondary factors must also be considered.

With typical reflector panels and wind velocities of 20 mph, the panel gravity loads and wind pressures are approximately equal at 1.5 lbs/ft^2. The structure must provide sufficient stiffness to resist these loads and its own gravity loads to an extent where maximum deflections do not significantly degrade the 2.5 mm rms surface tolerance requirement. In general, this limits the reflector edge deflections to $\pm$ 7.5 mm maximum.

Several reflector design approaches have utilized the reflector skin as a main structural element, while other approaches have relied extensively on ring-shaped space trusses or many circumferential ring trusses to form a more or less integral shell structure. These approaches have merit where operation is within a radome and gravity deflections are removed by self-compensation techniques.

For the VLA operating conditions a more direct structural approach with a stiff central hub structure carrying loads diametrically across the reflector appears more favorable for the following reasons:

(a) Gravity loads are accommodated along the shortest path

(b) Localized forces from wind gusts and nonuniform wind pressures from wind velocity gradients and eddies are resisted directly

(c) The reflector panels can be independently adjusted for best contour at any time

(d) The structural effects of the subdish supports and the support structure for the declination or elevation axis and counterweights can be more directly integrated with the reflector back structure to provide an overall structural unit with minimum deflections, weight and cost

The stiff central hub concept requires that the depth of the hub structure be a significant fraction (10% or more) of the reflector diameter in order to limit reflector edge deflections. Since the major part of the gravity load carried by the support structure is contributed by its own weight, there is no particular advantage to aluminum versus steel, except as total reflector weight affects the pedestal and mobility aspects. Therefore, the primary methods of reducing deflections lie in the design of the central area of the reflector structure and include such factors as the depth of structure, the degree to which the stiffness of other structural elements can be utilized, and the amount of self-compensation that can be designed into the structure.

Several related factors enter into the choice of the construction material for the reflector back structure. Aluminum has the advantage of lighter weight and lower maintenance costs, while steel has the advantage of a lower coefficient of thermal expansion. The deciding element, however, is cost, which is significantly lower for steel, both in material and fabrication cost.

5. The servo drive system

The power needed for the movement of the telescope is moderate. The following table shows approximate power (hp) needed for different wind conditions and telescope sizes.

Power Requirements for Various Operational Modes

Ant. Size	20 mph Wind 2.88°/min Track	20 mph Wind 4°/min	20 mph Wind 20°/min	35 mph Wind 20°/min	60 mph Wind 20°/min	87 mph Wind 20°/min
20 m	4.6×10^{-3}	0.076	0.38	1.09	3.32	7.1
25 m	0.01	0.145	0.725	1.95	6.40	14.0
40 m	0.017	0.25	1.24	3.08	9.15	19.2

In the design of the servo system, consideration should be given to both the hydraulic type and the electric type servo.

The prime reasons for selecting hydraulic drive systems for many tracking applications are:

(a) High continuous power applications
(b) Wide dynamic range
(c) High dynamic performance
(d) Low inertia/torque ratio
(e) Occasional need for short-duration, high-peak power
(f) Low RFI generation

An example of a practical selection of a hydraulic drive is the RCA high performance Missile Range Instrumentation Tracking Radar, "MIPIR," pedestal which has a maximum speed of 6 rpm, minimum of 60 x 10^{-6} rpm, response of 5 Hz, and wind capability to 60 knots with a 29 ft antenna. This 15 hp drive, with a 600:1 gear ratio, must be capable of continuous high-speed scanning.

Radio telescopes, on the other hand, require low power drive systems at very low speeds of approximately 10 times earth rate or 7 x 10^{-3} rpm. Using a typical motor speed of 1800 rpm for the 20°/sec slew speed, a gear ratio of approximately 30,000 is required. The low power and scan requirements minimize motor overheating and require no accumulator-type power storage. The antenna-to-motor isolation provided by the high gear ratio limits the acceleration requirements to that of the motor alone, and is insignificant for radio telescopes.

In conclusion, there is no power or dynamic requirement leading to the choice of a hydraulic drive. Thus the choice becomes a practical, not a technical or performance one.

Hydraulics have a unique set of problems which should be avoided if possible -- lower reliability, added complexity, and a tendency to leak. While an electric system can be reduced to power amplifiers and motor for small power drives, the hydraulic drive must remain a complex of relief valves, filters, case circulation system, power supplies, reservoirs, pressure switches, and a variety of safety switches, independent of the drive size. For the specific application of radio telescopes where the power ranges under consideration are in the order of 1 to 5 hp, it is estimated that the hydraulic system would cost 50% more than an equivalent electrical drive system. Furthermore, maintenance costs are estimated to be five to ten times greater with the hydraulic system, based on users field service experience.

RFI is a function of the servo power. AC servo motors and the associated control circuitry in the 1 hp range contribute little or no interference. Above this power range, silicon-controlled rectifiers, Ward Leonard systems, or amplidynes coupled to DC servo motors, are usually used. These have a much higher interference power, especially with SCR controllers. Noise of the type generated by motors and associated power generators has significant energy up to 1 MHz. Adequate isolation can be achieved using line filters and an insulating case around the motors and sensitive amplifiers.

6. The mobility system

The interface of the antenna tower with the transport vehicle and with the observing site foundations is of great importance and permits many variations and alternate approaches. Several economic factors must be considered in addition to a number of technical and practical factors. From an economic standpoint, it should be noted that the nominal VLA system involves 36 movable antennas, 99 observing sites, and n transport vehicles (n = from 1 to 36). On this basis, the relative weighting of costs are 3x for observing stations, 1x for antenna elements, and $\frac{n}{36}$ x for transport vehicles.

Economic effects of width of graded roadway, transport wheel loading, etc., must also be considered. From a technical standpoint, effects on angular travel limits and the effects on stability during transport and when anchored to the observing station foundations must be considered. From a practical standpoint, irregularities in the roadway and between individual foundation pads must be considered. Furthermore, considering that the antennas are to be moved repeatedly, it must be recognized that sooner-or-later a mistake may be made, and that the overall design should be as fool-proof as economically possible. Arrangements requiring prepositioning of antenna elements to provide clearance during moving or carefully sequenced operations, such as leveling a four-point foundation interface, should be avoided.

In order to provide for roadway and foundation irregularities and provide fool-proof mobility, three general solutions are possible. First, a three-point mounting for both transport and observing functions. Second, a four-point mounting for both transport and observing functions with two-points equilibrated by cross-connected hydraulic jacks, or equivalent. Third, a four-point mounting for both transport and observing functions, with two or more adjacent points spring-mounted to minimize effects of roadway irregularities. Obviously, the transport and observing functions can utilize different approaches, yielding nine possible combinations using these three approaches. However, the optimum solution can be quickly selected. A three-point mounting is preferable for the observing stations from the operating point of view, and in addition it requires a minimum number of supporting pads. One foundation pad is eliminated at each observing site (which carries a 3x weighting factor); and one interface pad and fine-leveling jack is eliminated at each antenna (which has 1x weighting factor).

The optimum solution for transport is somewhat less obvious. A three-point mounting would be more economical except for two factors. First, for equal spacing between the two roadway center lines, the square four-point mounting places the antenna center of gravity at the midpoint between roadway center lines and provides a restoring moment arm equal to one-half the roadway spacing; whereas, the triangular three-point mounting places the antenna center of gravity at the one-third point on roadway center line spacing and provides a restoring moment arm of one-third the roadway spacing. As a result, the triangular support arrangement provides a restoring moment arm equal to two-thirds that obtained with the four-point mount. Second, the wheel and roadway loading is one-third greater with the three-point mounting than with the four-point mounting, for the same number of wheels. For these reasons, the four-point mounting is generally more favorable for transport. However, for the smaller antenna a three-point mounting on a larger triangular spacing could be considered. The next question with the four-point mounting is whether to use a sprung vehicle or a cross-connected hydraulic jack arrangement (or equivalent) on two adjacent support points. The use of such a cross-connected arrangement increases costs over that of conventional springs, and, of more importance, reduces the potential restoring moment (in one direction) by 50%, as the two-equalized load points cannot provide a restoring moment about the axis normal to their centerline. Therefore, it is concluded that the optimum transport approach should utilize four-point mounting for the transport condition, with sprung wheels to accommodate roadway irregularities.

In addition to the above factors, and in view of the economic weighting factor of 1x for the antenna ssembly and $\frac{n}{36}$ x for the transport vehicle, it is concluded that the transport system should include lifting jacks as part of the transport vehicle, rather than as part of the antenna. Fine leveling jacks or adjustable spacers would be provided between the foundation pads and the antenna tower mounting feet for fine leveling, but the actual lifting or lowering operation to transfer the antenna from the transport vehicle to the foundation supports would be accomplished by motor powered jacks on the transport vehicle.

The most compact and economical arrangement for the antenna tower is shown in Fig. 11-11. This arrangement requires a minimum size tower with mounting centers spaced 28 ft on an equilateral triangle. The only significant disadvantage of this arrangement is the necessity of having one observing station foundation located between the two roadways. The advantages of this arrangement far outweigh this one disadvantage.

An alternate arrangement is shown in Fig. 11-12. This arrangement is best suited to triangular transport mounting-point spacing and locates the foundation points outside the two roadways However, the tower cost is considerably increased. As the side of the tower increases from 28 ft to 39 ft 5 in, at the same time the restoring moment arm decreases from 7 ft 8 in to 5 ft 1 in. Furthermore, the increased tower base dimension tends to cause interference with the reflector at low elevation angles and causes a reduction in elevation travel, or a considerable increase in the size and cost of the pedestal if the same elevation coverage is obtained.

Fig. 11-13 shows an arrangement with transport and observing foundation centers, both spaced on equilateral triangles which are rotated 180° relative to each other. This arrangement requires increasing

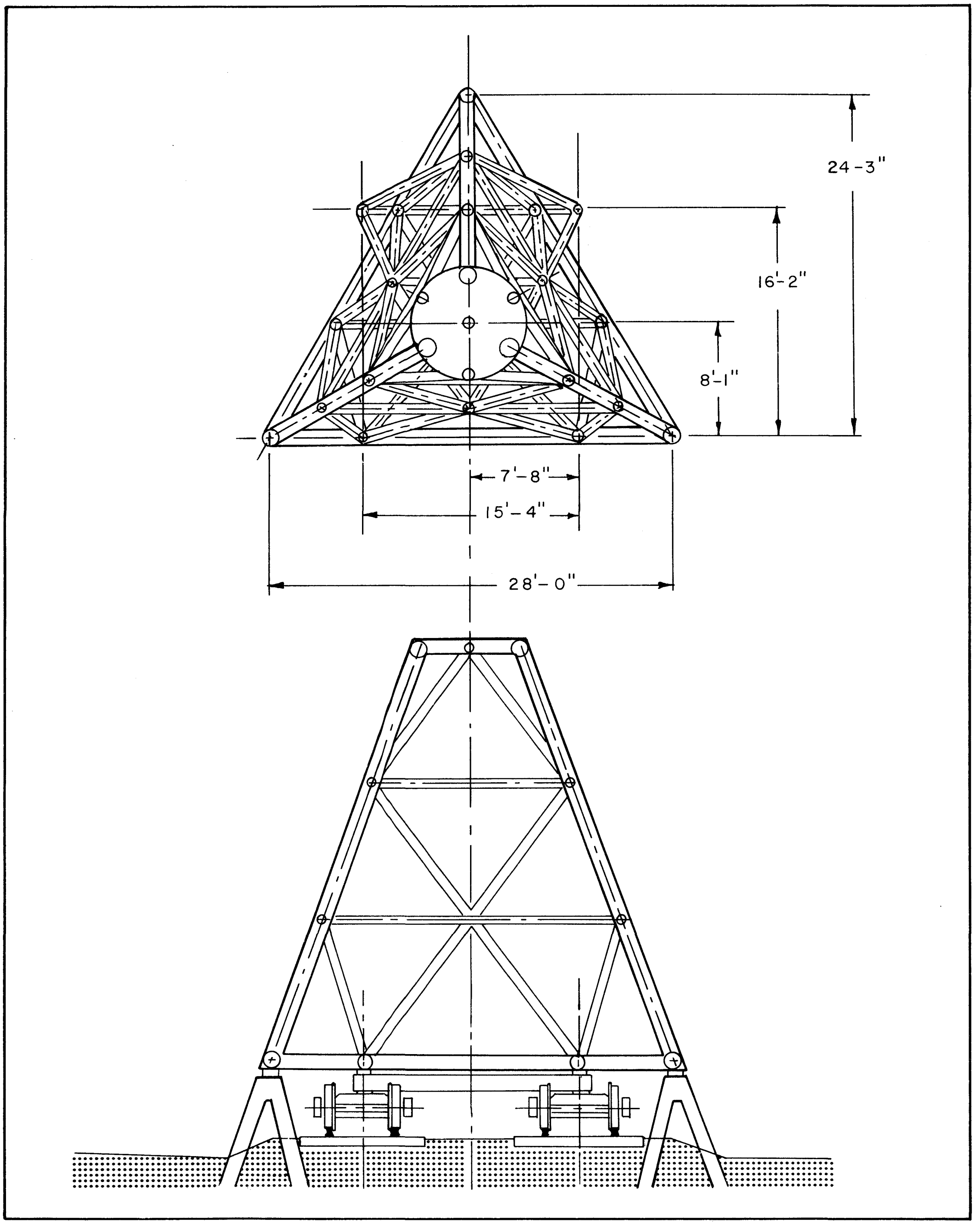

Figure 11 - 11. Bench mark tower-mobility interface.

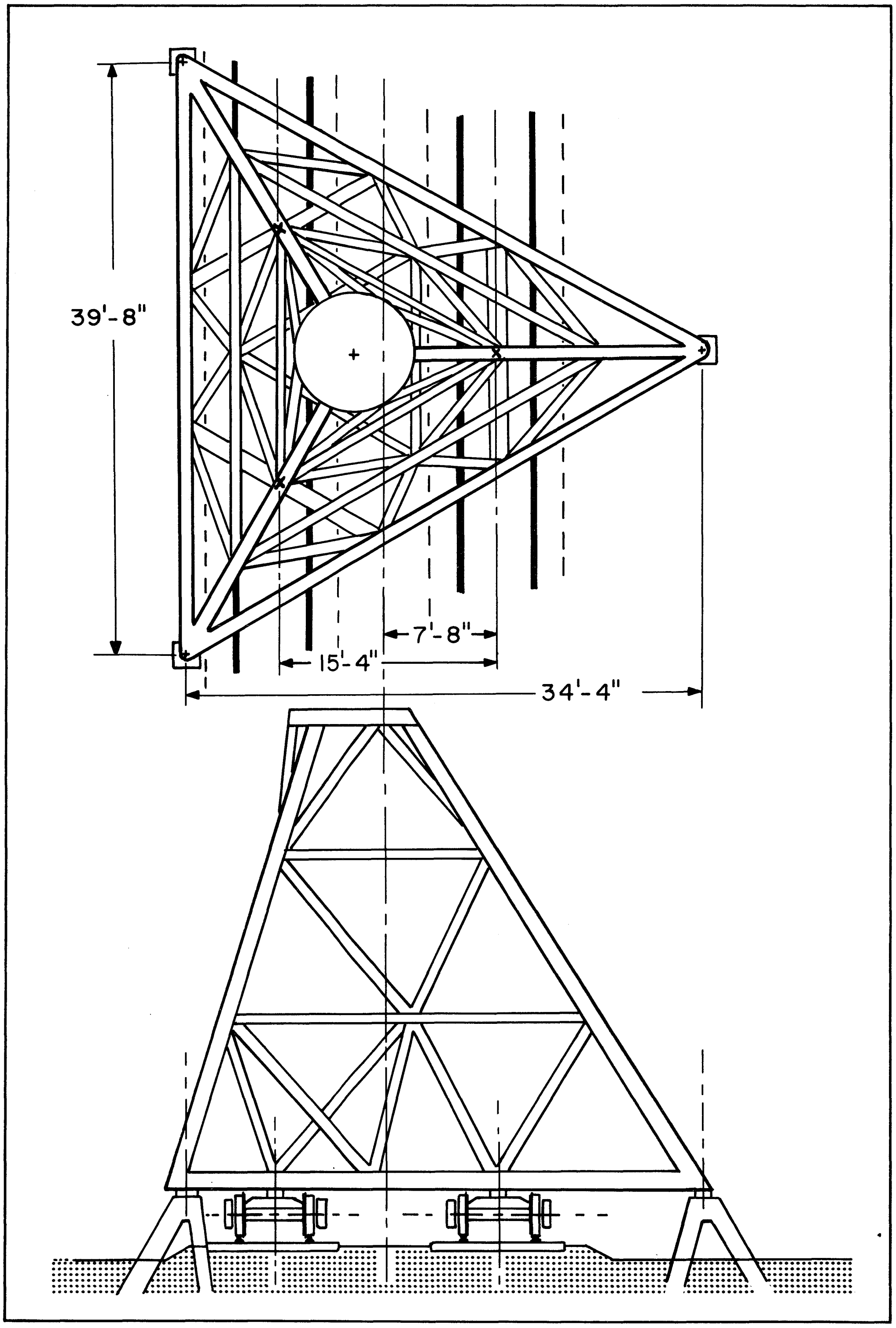

Figure 11 - 12. #1 Alternate interface.

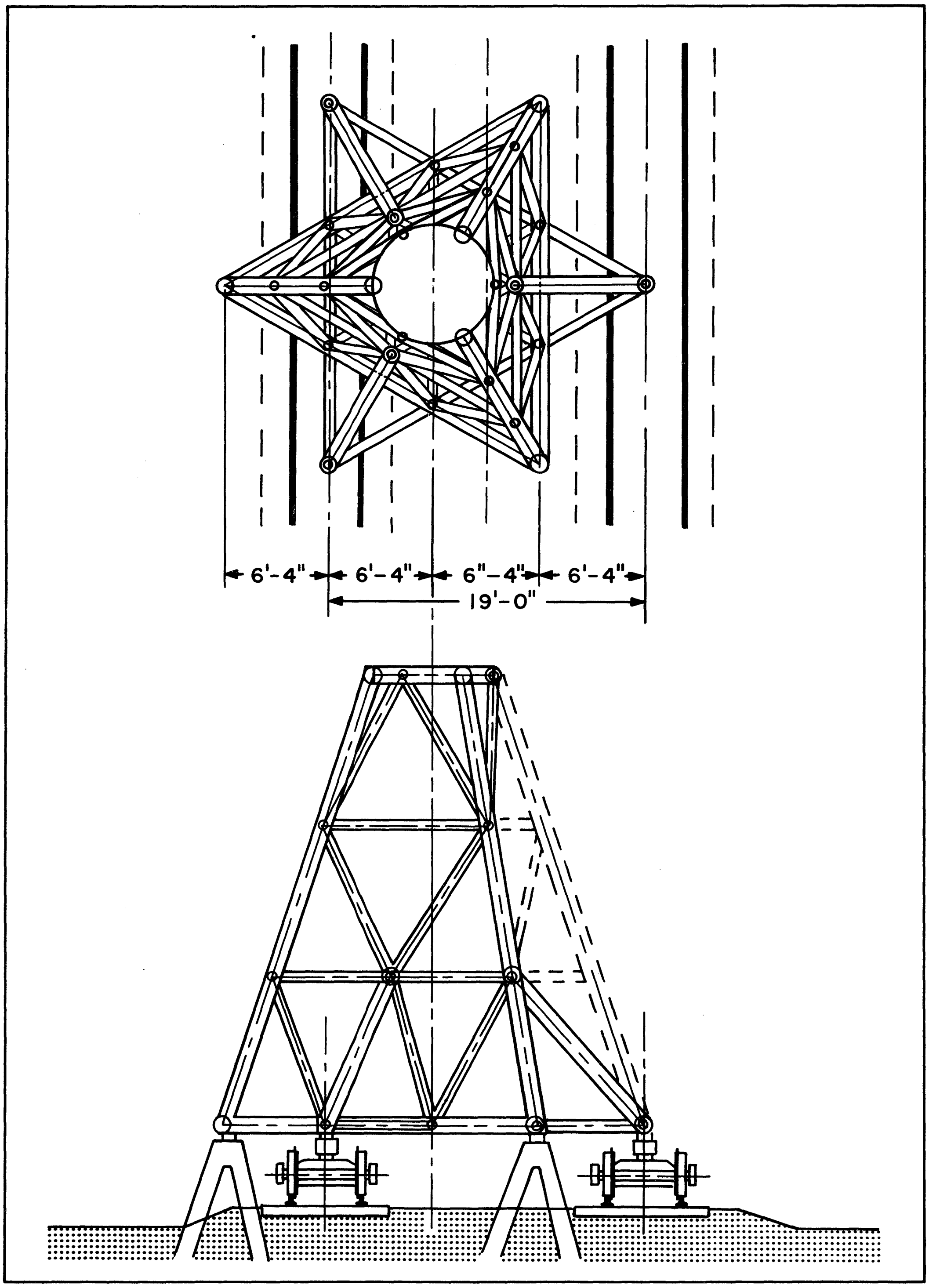

Figure 11 - 13. #2 Alternate interface.

the roadway center-line spacing to 19 ft and locates two foundation pads between roadways, but does provide a relatively large restoring moment arm of 6 ft 4 in even with three transport trucks and a tower 22 ft on each side.

Fig. 11-14 summarizes some of the above data in one figure, with all arrangements shown to the same scale for comparison purposes. Plan A, B, C, and D show the different alternates. All these alternates are based on providing zero clearance with a transport vehicle width of 10 ft 8 in and a 1 ft distance from foundation center line to the edge of the pad. Larger pads or clearances would require a slight increase in dimensions.

The mobility system suitable for moving the antennas will involve one of the following three schemes:

(a) Continuous track-type crawler vehicle (tractor)

(b) Pneumatic tires

(c) Rail systems

The continuous track-type crawler vehicles are very expensive, large, and require constant roadway rebuilding. This type equipment is generally suited to limited passage over unimproved roads. A track pressure of 10 psi is the usual design figure, which for 200 tons would require 280 ft^2 of track, which for any reasonable application is excessive. If the roadbed were gravel, concrete, or asphalt, this size would reduce somewhat. Rubber tired vehicles also have a size problem requiring from 30 to 50 wheels, depending on roadbed type.

Thus the large size and high maintenance costs associated with these wheeled vehicles prohibit their use. Rail then becomes the choice. Once the rail system is considered, the concept of mobility vehicle and roadbed layout become the major trade-offs.

The true measures of the effectiveness of the transport vehicle are cost, versatility, and simplicity of movement. In order to evaluate each alternate on a comparable basis, each will be constrained to fit the following general specification:

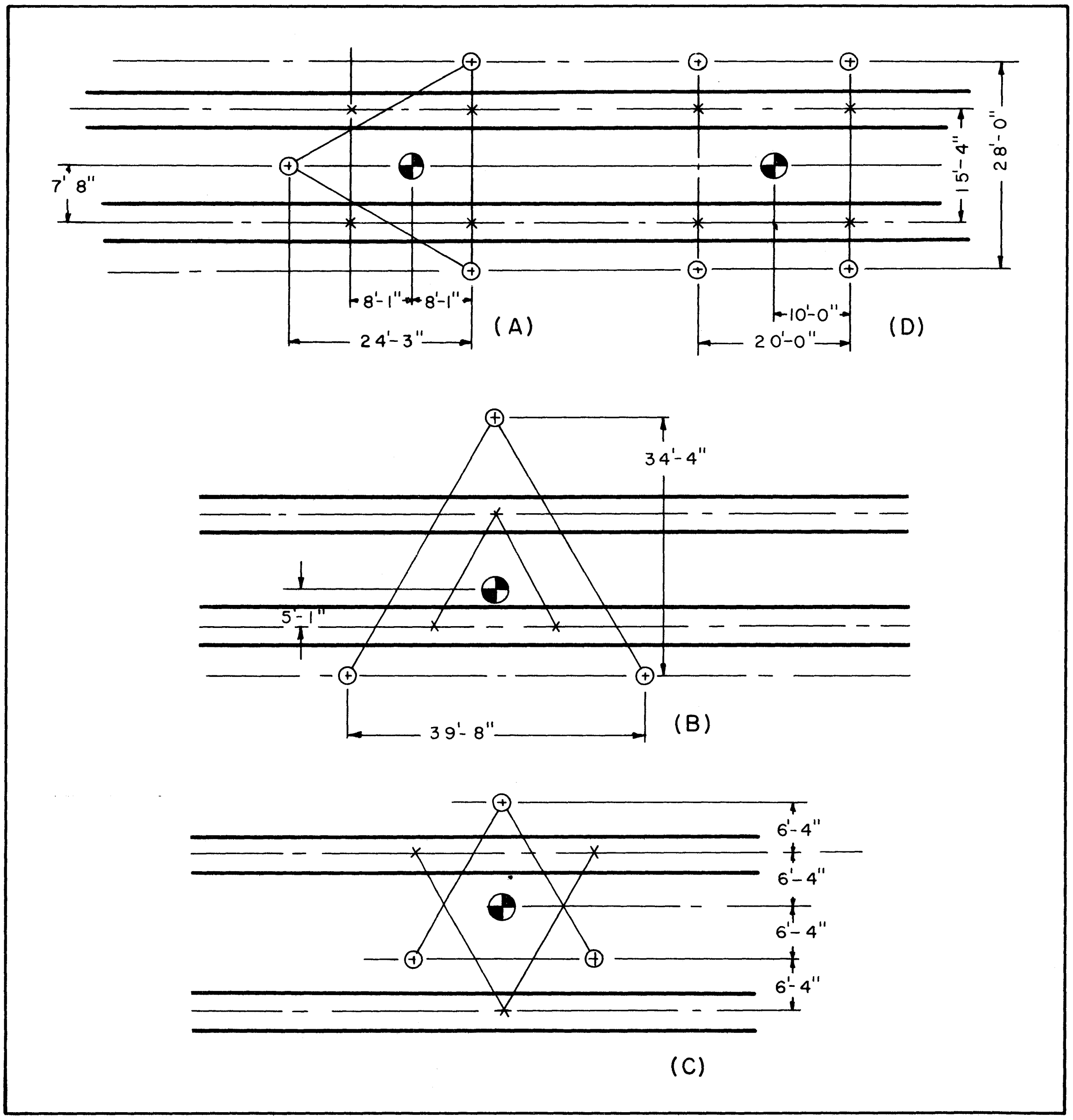

Figure 11 - 14. Comparison of tower-mobility interface alternates.

Transport Vehicle Specification

Operational Speed of Travel	2 mph
Maximum Speed	15 mph
Maximum Draw Bar Pull	18,000 lb
Velocity Control	Continuous from start to maximum speed
Vehicle Control Area	Enclosed to protect operator from rain and dust
Maximum Time to Engage Equipment	1/2 hour
Maximum Power Per Vehicle	50 hp

A wealth of equipment and experience is available in the rail and trucking industry which can be applied to the VLA mobility system. A properly designed transport system should incorporate as much of this equipment as possible. The use of standard equipment will minimize engineering costs by confining special design efforts to the interface between the equipments. A considerable number of alternates can be designed using standard parts or subsystems. The following alternates are some of the many considered.

(1) The transport vehicle is part of each antenna element. While this system provides the maximum utility, permitting movement of each antenna element within a minimum time, it is also the most costly. It is estimated that such an elaborate system will add in the order of $25,000 to the cost of each element.

(2) A semi-integral transport vehicle where trucks are permanently installed on each antenna on one track only. These trucks would be idler vehicles with no motive power. A motorized vehicle consisting of two trucks and a power source would occupy the other track and be common to all antennas on one arm of the Wye. This basic concept is well suited to a continuous track without turnout (see Chapter 12), as one track will remain clear for rail mounted traffic. Thus the continuous track which will remain clear to the most remote element will provide an all-weather road for logistics.

(3) A separate mobility system which will be shared among the 36 antenna elements composing the array. In considering the economics of

the various trade-offs, three separate transport vehicles will be used, one for each leg of the Wye. While more or less can be used, considering their maximum speed and redundancy for reliability, three seem a comfortable minimum.

This concept considers the use of a transport vehicle with four points of support. In general this method is suited for the turnout track layout if a single vehicle is considered, or for the continuous track layout with two separate vehicles, one for each track. The two-vehicle concept could consist of one power and one auxiliary vehicle or two power vehicles.

Alternate (3) is considered to be the most versatile and economical system for the VLA. In addition to being by far the lowest cost system, it makes an all-weather transport system for logistic purposes during observing periods when the antenna elements are mounted on the observing stations. In order to make the maximum use of this, the antenna pedestal towers will be designed with sufficient clearance between the tracks and the pedestal structure, to permit personnel and tool carrying vehicles to pass through without interference.

D. Recommended System

The previous discussions of the antenna element and the mobility vehicle lead to a recommended system for the VLA. In arriving at the recommended system, the governing criteria have been the astronomical requirement, cost of the system, and the flexibility.

The antenna element selected as the recommended system has a 25 m (82 ft) diameter main reflector with a 9 m focal length and utilizes an Az-El type of mount to provide complete sky coverage above + 5° elevation. The principal features of the antenna element are shown in Fig. 11-1. The antenna will use a Cassegrain feed arrangement with a 2.5 m diameter secondary reflector. The surface accuracies of the reflectors, 2.5 mm rms for the main reflector and 0.5 mm rms for the Cassegrain reflector permit good operation of the antenna at the shortest wavelength 5.5 cm, planned for the VLA.

The paraboloidal main reflector will utilize adjustable surface panels with stretched aluminum skins and aluminum support frames, weighing approximately 1.7 lb/ft^2. The panels are each nearly 14 ft long and are arranged in three concentric rings. The inner ring contains 24 panels with a maximum width of 55 in; the second ring contains 24 panels with maximum width of 94 in; and the outer ring contains 48 panels with maximum width of 65 in. Each panel will be individually supported from the back structure by six adjustable mounting points, located along the edge of each panel, and permitting adjustment of surface contour at any time after erection is complete.

The reflector support structure is selected to be welded construction, utilizing structural steel angles and Tees for the lowest fabrication and erection cost. The outer portion of the structure consists of 24 radial rib trusses, 24 ft in radial length, which are cross-braced at four radial intervals along their length by circumferential rings of cross-frames and diagonal braces for torsional stiffness. Additional cross-frames and bracings are necessary to support two panels per rib in the outer rows of panels. Four ribs at 90° intervals are reinforced to carry the added load of the hyperbola support structure, which is a tetrapod arrangement of welded truss construction.

The inner portion or hub structure is 8 ft deep and 27 ft in diameter and includes two circumferential ring trusses with diameters of 27 and 14 ft and the necessary radial and diagonal bracing members. The hub section also provides support for the feed-receiver subassembly and allows additional space for receiver components in the central portion of the hub. An air-conditioned room in this area will house the electronic systems.

Two support arms of structural steel truss construction, with large structural cross-sections, extend from the rear of the hub structure. These arms are integrated into the 14 and 27 ft diameter ring trusses of the hub and extend back on each side of the pedestal to support the two counterweights.

On the inner side of the "U" formed by the hub structure and counterweight support arms, and spaced on about 14-ft centers, are the two self-aligning roller bearings which support the elevation-rotating assembly. One counterweight support arm also supports the elevation sector gear, which has a 5 ft pitchline radius capable of 265,000 ft-lbs torque.

The antenna pedestal will be a compact structure of welded steel construction. The turntable provides a nonrotating elevation axle or trunnion shaft which supports the inner races of the elevation bearing on the 14 ft centers. The azimuth and the elevation drive gear boxes are supported on the rear vertical surface of the turntable. Each drive will include: two low-speed, high-torque commercial type gear boxes, a single high-speed gear box with dual gear trains, a spring-loaded anti-backlash device between the two input shafts, two 2 hp frame size, servo drive motors for tracking and scan, and two 5 hp motors for slewing and driving to stow in 40 mph winds. The turntable is supported at the bottom face on the inner-race of an 8 ft diameter turret-type bearing. The outer race of the turret bearing and the 10 ft pitch diameter azimuth bull gear are supported by a welded-steel stationary base, which is 8 ft in diameter and 4 ft high.

A cable twist arrangement for electrical circuits, direct-coupled digital-data angle indicators, and travel limit switches and stops, for each axis, will be used. Angular coverage of $\pm$ 270° in azimuth and from +5° to +90° in elevation will provide essentially full sky-coverage.

The pedestal assembly will be supported by a welded structural-steel truss-type tower of triangular cross-section, with three decks or levels of structure, shown in Fig. 11-11. The upper deck proves a transition in the structural cross-section from triangular to hexagonal to mate with the pedestal base. The bottom of the lower section provides three interface points for the observing site foundation, with center lines spaced at 28 ft on an equilateral triangle, and four interface points for transport, with center lines on 15 ft 4 in spacing in a square pattern

Tracking power requirements are small for each axis of the 25 m antenna and can be met by a 2 hp servo drive system coupled with an ancillary 5 hp drive system for slewing and stow. The combination of a low-power, low-noise linear servo system for tracking and a clutch-engaged induction motor drive system for slewing and drive-to-stow seems best from the system performance standpoint, and is one of the most economical systems investigated. Each motor will drive one pinion of the parallel preloaded gear system. The choice of a DC servo motor and DC amplifier is made to avoid RFI sources, such as would be obtained with SCR servo systems. In the low horsepower range, DC servo systems exist without the need for development. RFI insulation will be used around the motors to eliminate radiated noise.

Speed control and feedback should be incorporated to assure a wide bandwidth, high-gain torque response for accuracy in a wind. Digital feedback from the shaft encoder will provide the necessary sensitivity and resolution by eliminating data gearing, and should provide 17 bits of accurate data.

The total weight of the antenna element will be 140 tons (metric) (312,500 lbs), of which the reflector weight will be 30 tons (metric) (65,200 lbs).

The means of moving each element is chosen to be a separate vehicle which can be shared among the various elements. This choice is primarily dictated by the economics of the system. Each transport system is priced at approximately the same value, independent of being integral or separate with each element. As this total cost is significant, incorporating the transport vehicle into each element design will raise the total element cost approximately 10% to 20%.

The transport vehicles are combinations of components widely used throughout the transportation industry. Standard railroad trucks and 3/4 ton automotive trucks with railroad wheels are used. Auxiliary air compressors for brakes, hydraulic jacks for lifting the antenna element, and the associated structure complete the design.

The recommended transport system employs use of the two separate carriers, each having two railroad trucks. One of the vehicles would have a driven truck using a splicer drive arrangement. The other vehicle would use the two freight trucks and be transported to the site by a towing vehicle, as discussed before. In this arrangement, the antenna can be placed over the tracks with one hardpoint centered between tracks and two hardpoints on the outside. The split transport vehicle arrangement then allows the carriers to be driven under the elements so as to allow unrestricted movement of all antennas. To accomplish this, a 6 ft clearance will be provided between the rails and the tower. This approach does not limit the system should use of spurs be desired at discrete points as discussed in Chapter 12.

The arrangement provides for carrying personnel and some limited maintenance equipment to each site by vehicles adapted to rail travel without having to go around each antenna element. For heavier maintenance, crane or other equipment could be transported on a road paralleling the tracks; however, it is not expected that this need be a high speed, paved road. The initial construction road with compacted soil and gravel should suit the need, and, although maintenance would be somewhat higher than for a paved road, particularly after rainstorms, the initial savings appear to warrant considering this approach.

An artist's conception of the VLA antenna element and the mobility vehicle is shown in Fig. 11-15.

E. Antenna Element Construction and Erection

Following the detailed design of an antenna element with its mobility vehicle, it is recommended that a prototype unit be constructed and evaluated before the large quantity production is started. Such a prototype should, if possible, be built at the site chosen for the VLA, and in the cost schedules in Section F, it is assumed that the prototype will be one of the 36 elements of the array.

The antenna erection is a major phase of the VLA program. Considerable planning must be incorporated into this portion of the program to insure a synchronized flow of material with erection activity and checkout and test functions. Illustrations in this section depict the erection stages.

In applying the assembly line technique, it is proposed that during full production seven antennas will be at various stages of assembly, as shown in accompanying Fig. 11-16 through 11-22.

The antenna is decentralized into principal areas or stages for logical and economical erection sequence. The principal areas/stages are as follows:

Stage 1	Transport Vehicle Assembly
Stage 2	Tower Assembly
Stage 3	Pedestal Base

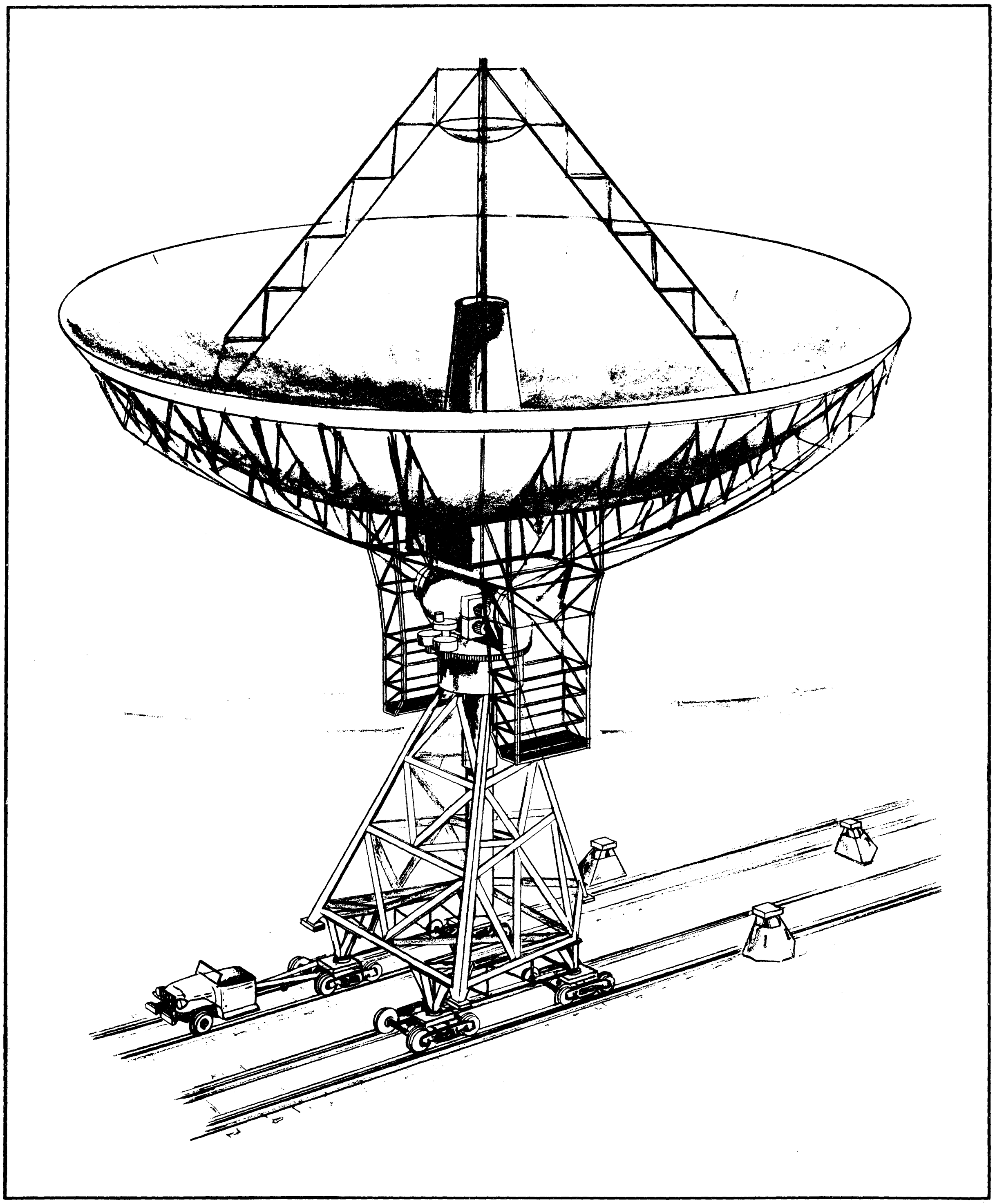

Figure 11 - 15. VLA antenna.

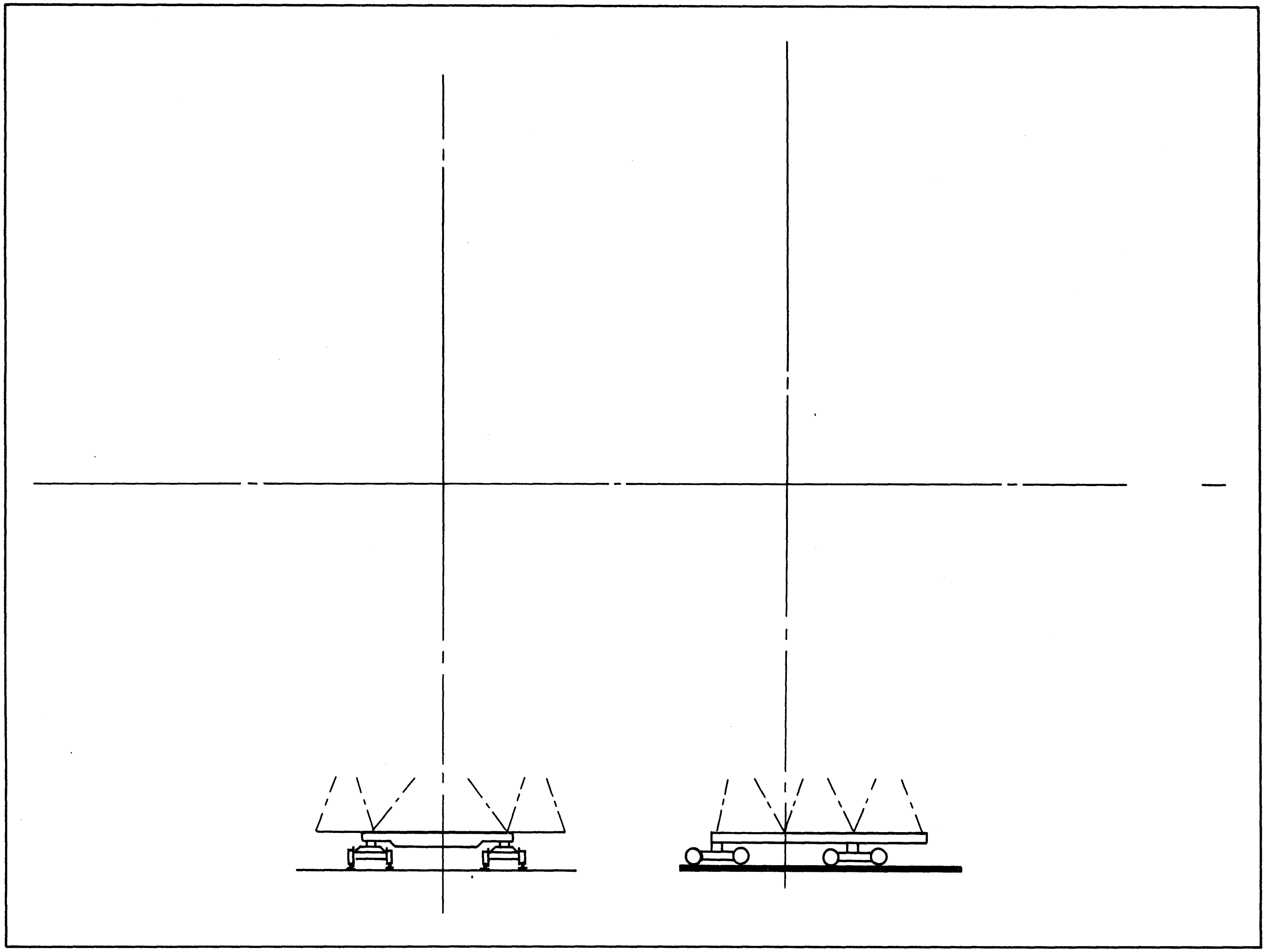

Figure 11 - 16. Stage 1. Antenna erection.

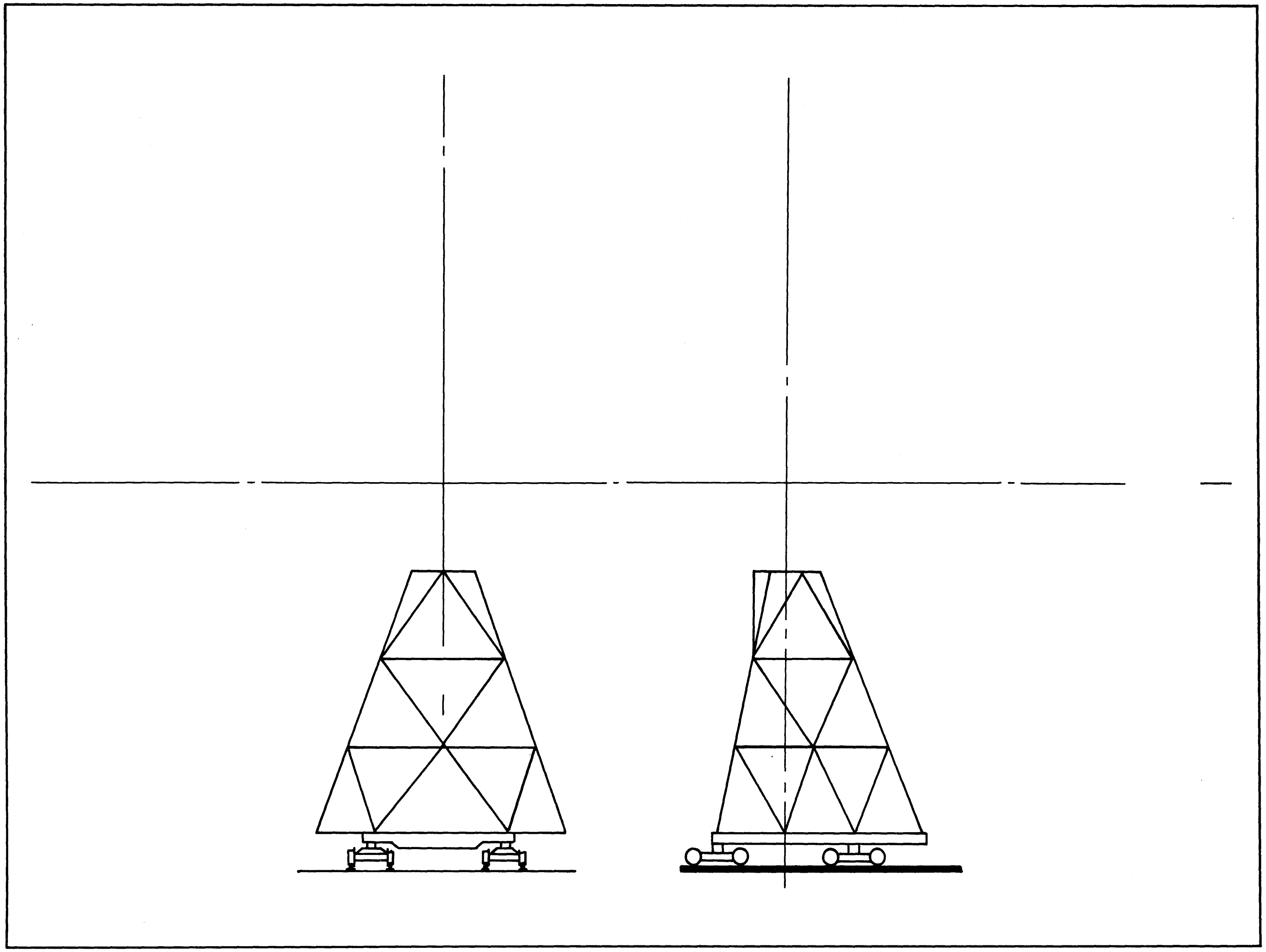

Figure 11 - 17. Stage 2. Antenna erection.

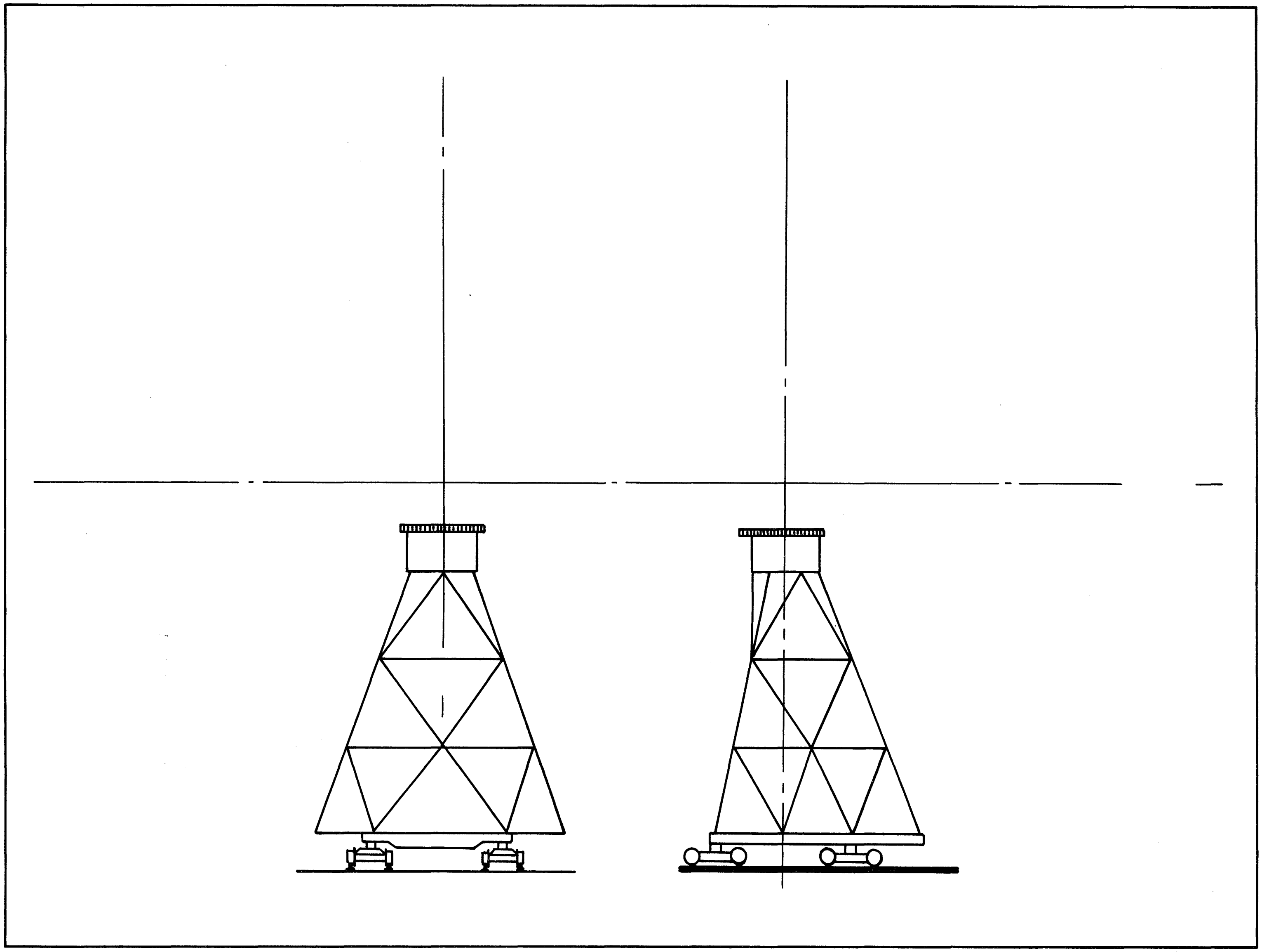

Figure 11 - 18. Stage 3. Antenna erection.

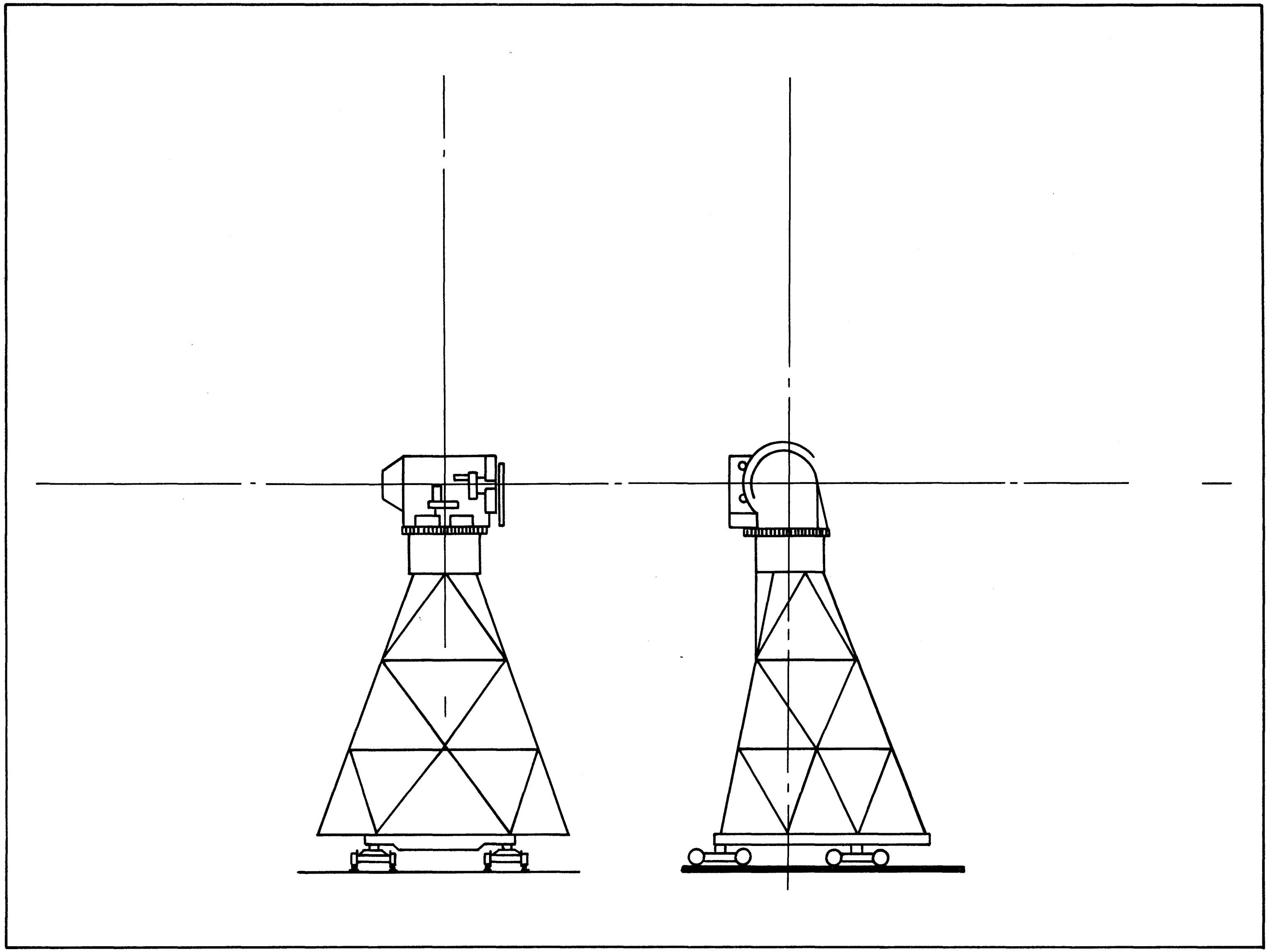

Figure 11 - 19. Stage 4. Antenna erection.

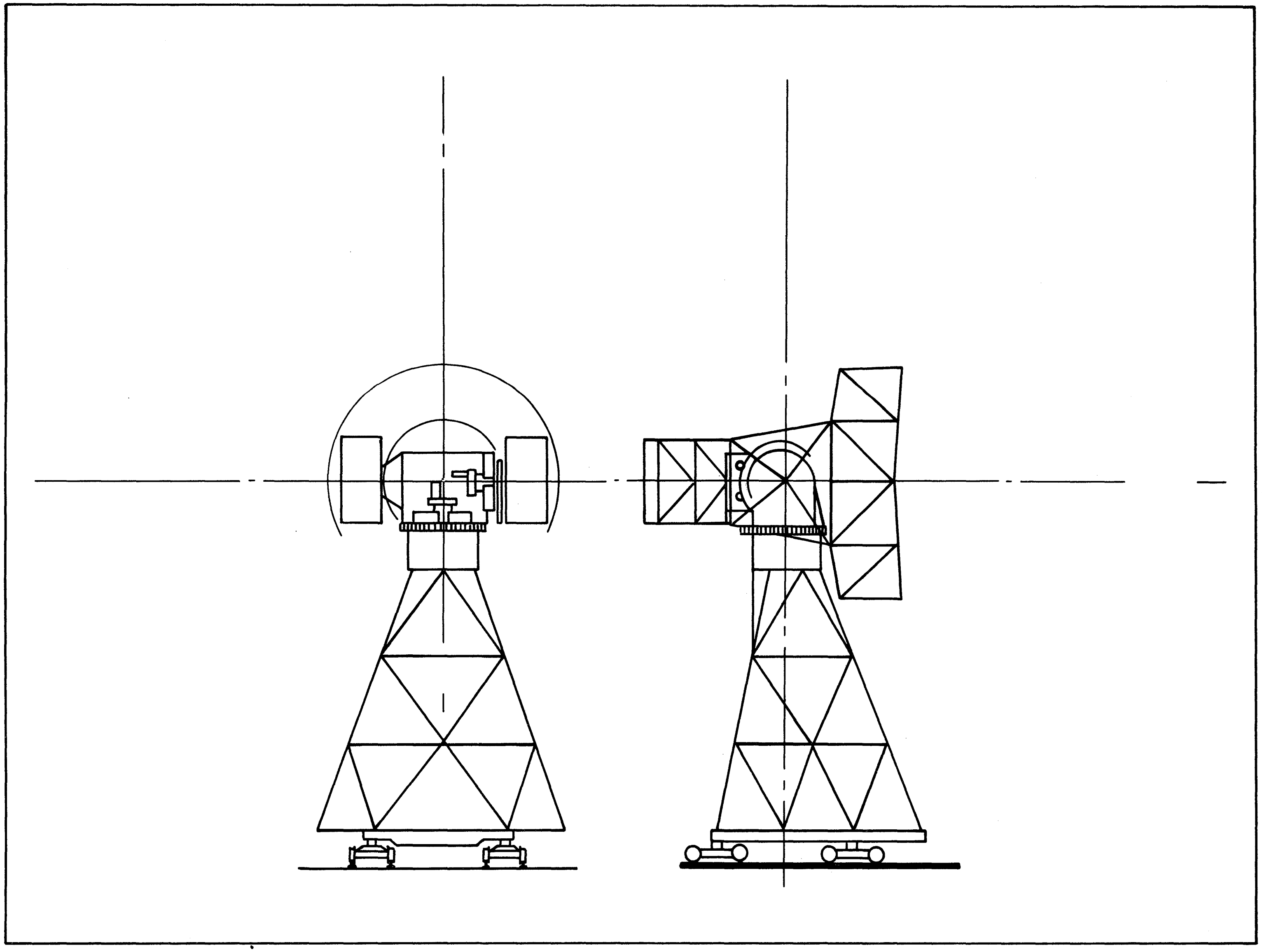

Figure 11 - 20. Stage 5. Antenna erection.

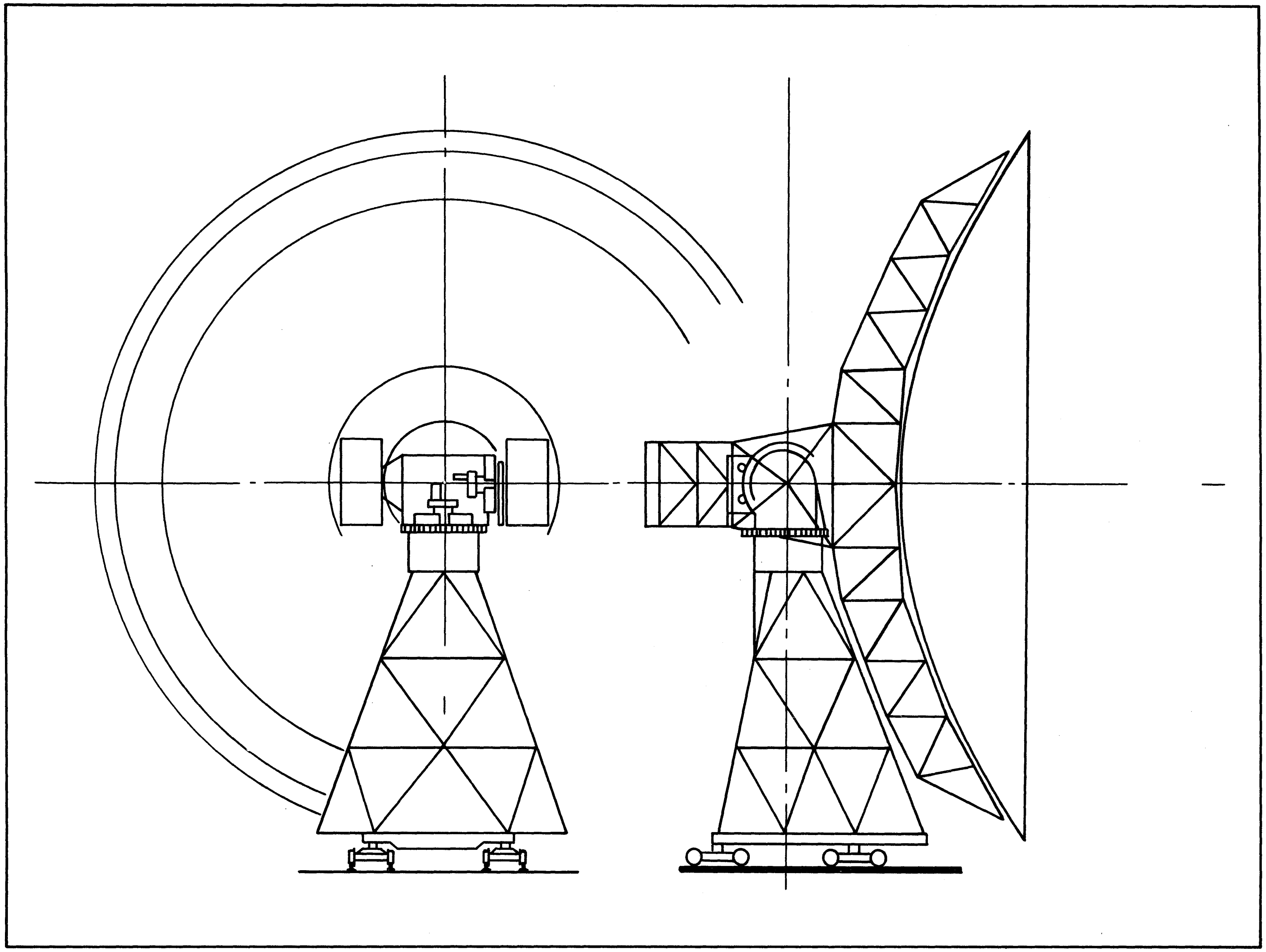

Figure 11 - 21. Stage 6. Antenna erection.

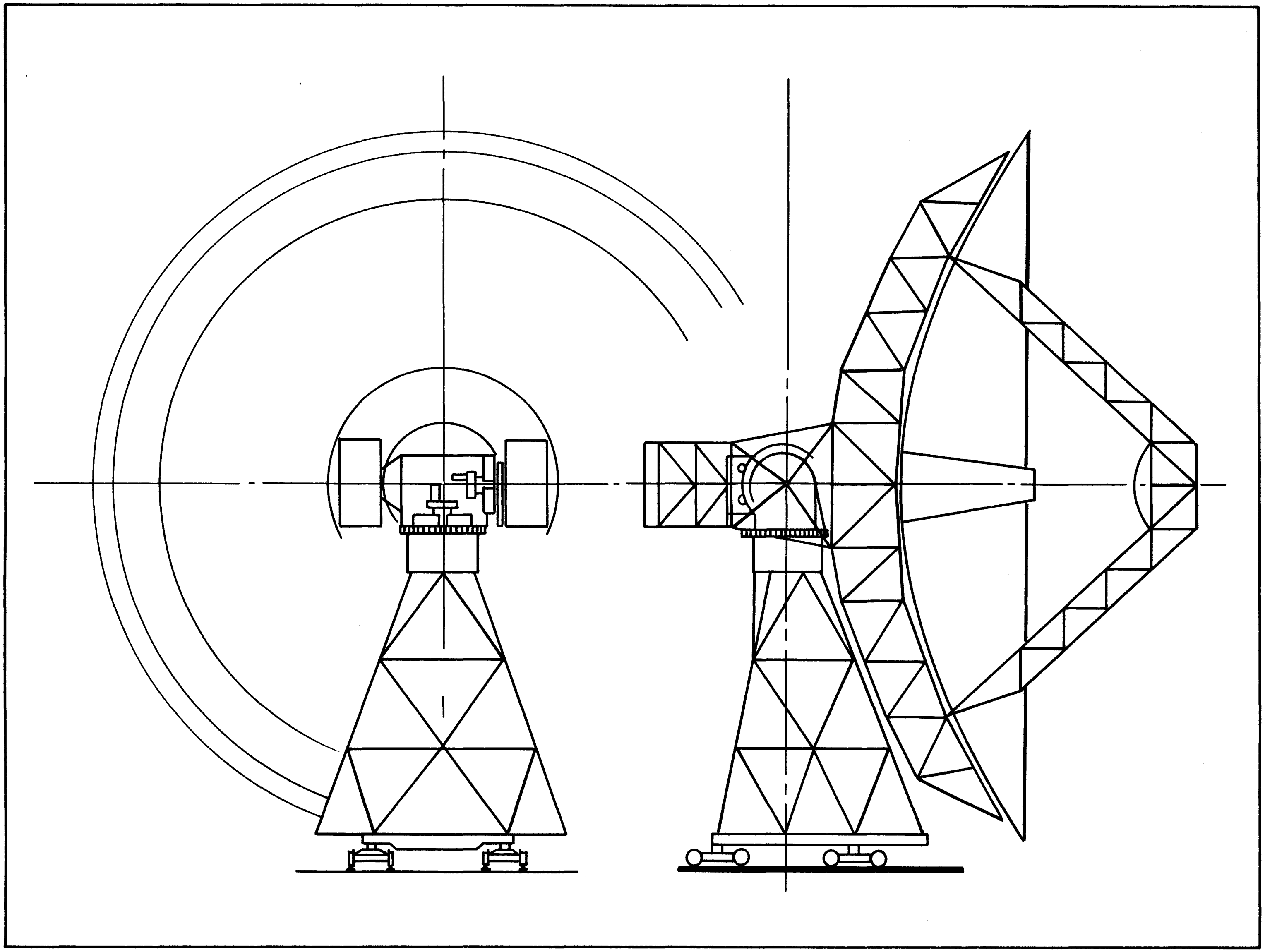

Figure 11 - 22. Stage 7. Antenna erection.

Stage 4	Pedestal Turntable
Stage 5	Counterweights
	Reflector Hub
Stage 6	Reflector Assembly
Stage 7	Feed Horn Assembly
	Hyperbola and Support Assembly
	Checkout and Test

Erection equipment would be crawler-type cranes, or a combination of crawler and gantry cranes.

Further study should be made to coordinate all activities in order to establish the most economical flow of manpower/materials/equipment and maximum use of available facilities.

Fig. 11-23 shows two possible arrangements of the construction area.

Fig. 11-24 indicates a possible design, construction, and erection schedule for the VLA antenna elements and the mobility system.

F. Cost Summary

The following two tables show the cost of the VLA antenna system consisting of 36 antenna elements (one prototype and 35 production units) and three mobility vehicles. The unit cost in the production unit cost summary assumes that a quantity of 35 units is purchased. The unit cost therefore shows the cost of adding one antenna to the system, provided it is ordered at the same time as the 35 elements.

The following is an explanation of the various items in the cost tables.

1. Reflector structure

Includes the complete reflector backup structure with feed support legs and counterweight. Panels are not included (see item 4). The room for electronic equipment located behind the reflector vertex is not included (see item 9).

2. Pedestal

Includes tower structure, gears and bearings. Does not include servo system (see item 3).

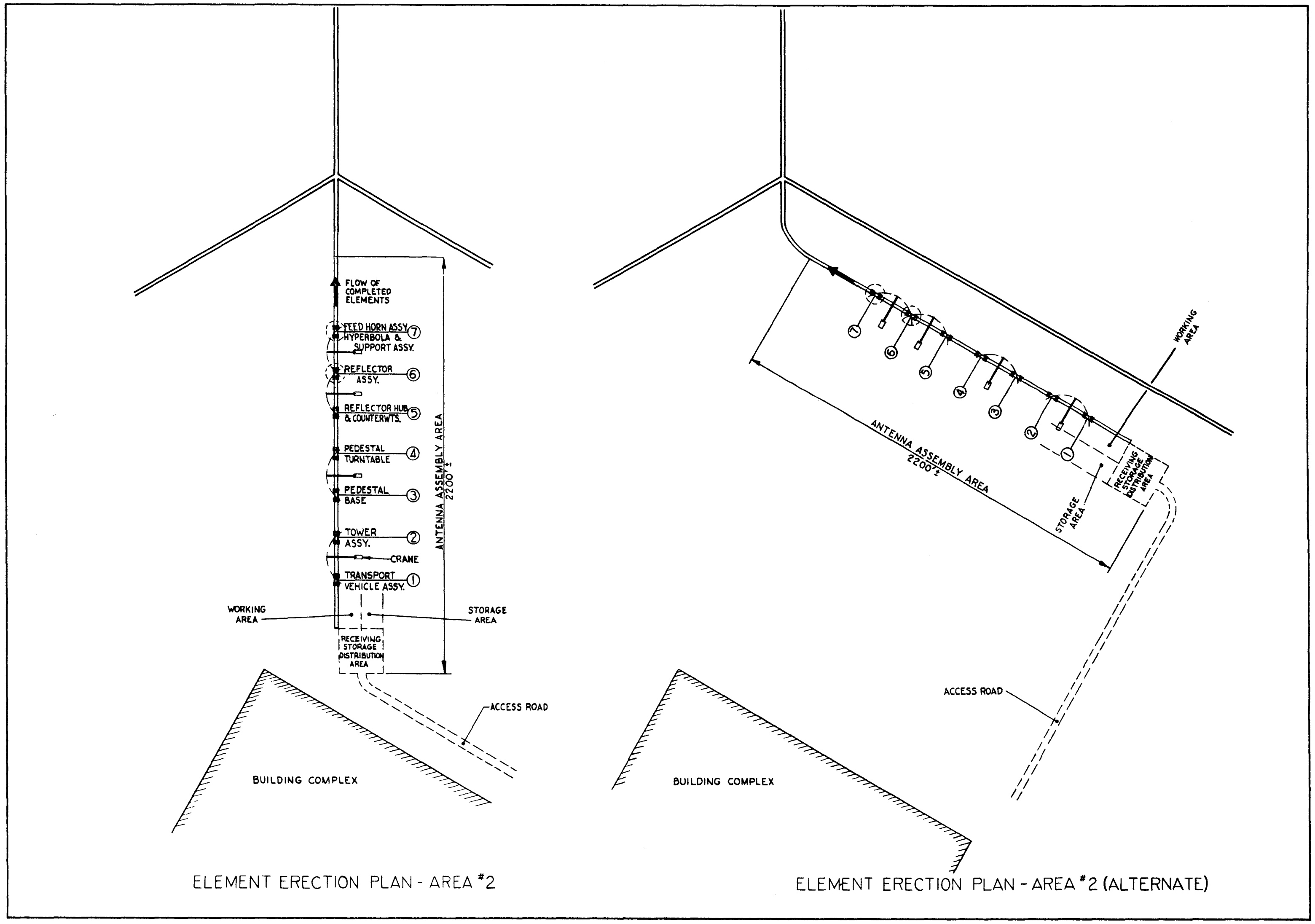

Figure 11 - 23. Element erection plan.

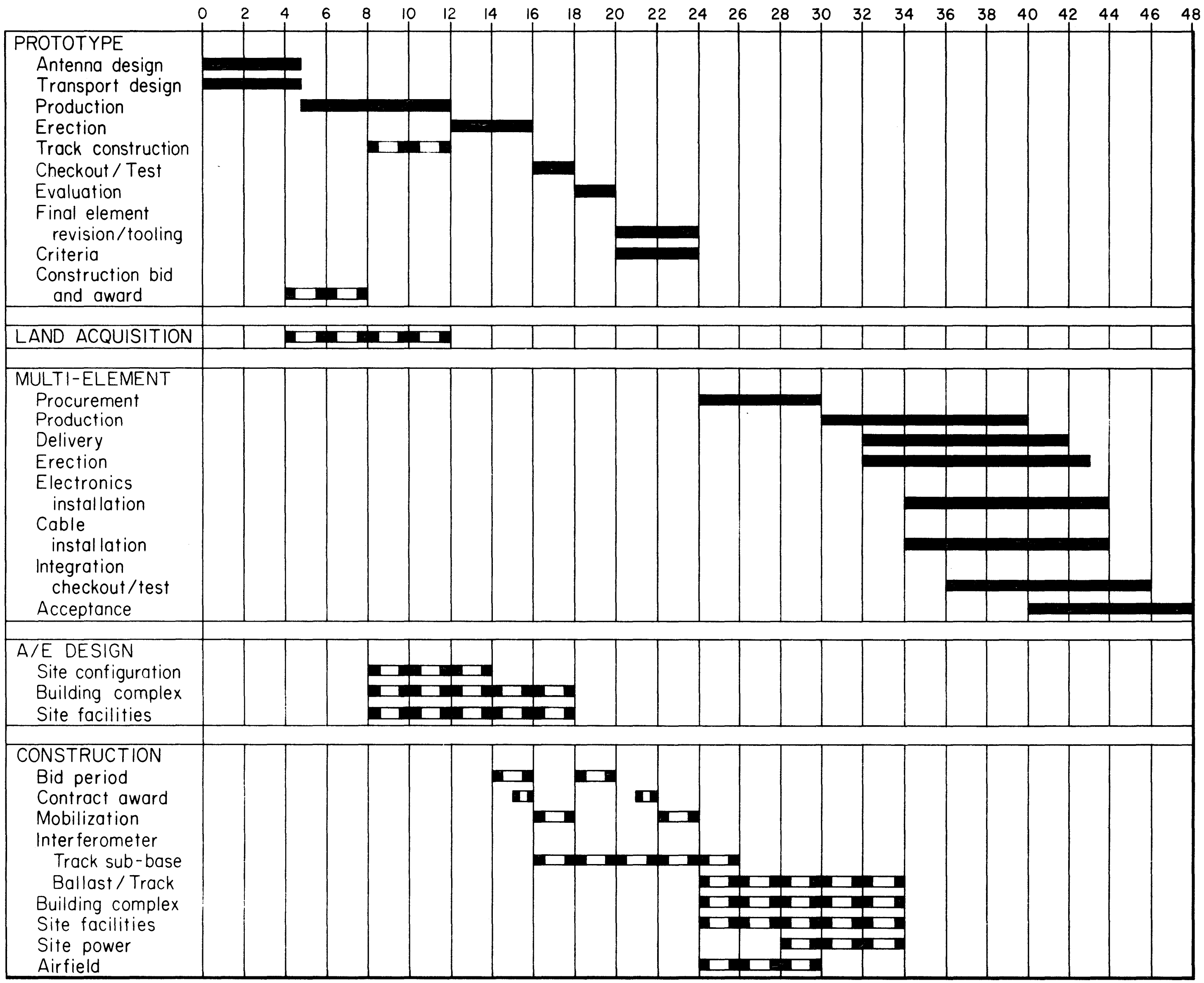

Figure 11 - 24. Program schedule.

3. Ancillaries

Includes servo system, digital angle encoders, brakes, platforms, hoists, ladders, etc. Includes the Cassegrain hyperbolic reflector.

4. Panels

Includes reflecting panels and tools for the manufacture of the panels. In the prototype unit $100,000 is estimated for tooling. These tools will also be used for production, but it is estimated that at least another set of tools will be needed for a quantity of 35 units, and $150,000 is included in the production unit cost for this.

5. Shipping

Includes shipping to VLA site. $50 per ton for the prototype unit and $25 per ton for the production unit has been assumed.

6. Field erection

7. Engineering

Includes engineering, drafting, technicians, field construction supervision, and travel and living applicable to the antenna element production program.

8. Handling, overhead

Includes all material handling, overhead, administration, profit, etc.

9. Electrical integration

The electrical integration includes:

(a) A temperature controlled room behind the reflector vertex for electronic equipment

(b) Junction boxes for cables (up to 15 one inch diameter cables planned)

(c) RFI filters and shield

(d) Cable windup for azimuth axis ($\pm$ 270°)

(e) Four runs of semirigid coaxial cable with rotary joints in azimuth and in elevation

(f) Provision for mounting and changing feeds

(g) Safety interlocks and limit switches

(h) All electric cables, switches, etc., for mechanical operation of the telescope

(i) Insulated equipment room in the pedestal

10. Engineering

Includes engineering, drafting, technicians, field construction supervision, and travel and living applicable to the electrical integration production program.

11. Handling, overhead

Includes all material handling, overhead, administration, profit, etc.

12. Transportation equipment

(a) For prototype: Includes one set of transport vehicle complete with hydraulic jacks and other ancillaries, 150 m of track and one turn-out with a 100 m extension, and one observing station.

(b) For production unit: Includes three complete mobility units.

13. Engineering

Includes engineering, drafting, technicians, field construction supervision, and travel and living costs applicable to the transport system production program.

14. Handling, overhead

Includes all material handling, overhead, administration, profit, etc.

Cost Summary Prototype Antenna

		One Unit $			
1.	Reflector Structure	93,000			
2.	Pedestal	128,000			
3.	Ancillaries	87,000			
4.	Panels	198,000			
5.	Shipping	10,000			
6.	Field Erection	100,000			
7.	Engineering	413,000			
8.	Handling, Overhead, etc.	298,000			
			1,327,000		
9.	Electrical Integration	81,300			
10.	Engineering	177,000			
11.	Handling, Overhead, etc.	63,000			
			321,000		
				1,648,000	
12.	Transport Equipment	75,000			
13.	Engineering	39,000			
14.	Handling, Overhead, etc.	33,500			
			147,500	147,500	
	Total Prototype Antenna				1,795,500

Cost Summary Production Unit

		One Unit			35 Units		
		$	$	$	$	$	$
1.	Reflector Structure	58,000			2,030,000		
2.	Pedestal	77,000			2,695,000		
3.	Ancillaries	56,000			1,960,000		
4.	Panels	60,000			2,100,000		
5.	Shipping	5,000			175,000		
6.	Field Erection	52,000			1,820,000		
7.	Engineering	12,600			441,000		
8.	Handling, Overhead, etc.	55,600			2,086,000		
			376,200			13,167,000	
9.	Electrical Integration	45,500			1,592,500		
10.	Engineering	4,000			140,000		
11.	Handling, Overhead, etc.	8,700			304,500		
			58,200			2,037,000	
				434,400			15,204,000
12.	Transport Equipment	41,400					
13.	Engineering	10,000					
14.	Handling, Overhead, etc.	8,150					
		59,550					59,550
							15,263,550
	Plus Prototype System						1,795,500
	Total - 36 Antennas						17,059,050

Chapter 12

SITE DEVELOPMENT

Chapter 12

SITE DEVELOPMENT

A. Introduction

The NRAO staff initially selected 29 possible site locations in the Southwestern United States based on their evaluations of small scale topographic maps. Further studies, both in the office and in the field, narrowed the number of typical desirable sites to three.

Limbaugh Engineers, Inc. of Albuquerque, New Mexico received the assignment from AUI to study these three sites in some detail and then submit their findings in an interim report. Based on this information, the NRAO staff would select two sites for further study. The interim report was submitted on August 1, 1966 and efforts since that time have been in further preliminary design and refinement of information and cost estimates for the sites designated Y-15, and Y-23. It should be noted that neither of these two sites is necessarily the final choice for the VLA. This chapter therefore represents a hypothetical solution to the site development problem.

This final Site Development Report is the result of the analysis by Limbaugh Engineers, Inc. of the many factors affecting the desirability of the Y-15 site and the Y-23 site for location of the VLA facility. The purpose is to provide sufficient preliminary engineering, design and cost analysis information so that the NRAO staff can make a final assessment of the sites and establish a firm order of preference.

The factors considered in this report for the evaluation of each site were as follows: (1) General Site Factors, (2) Geology and Foundation Investigation, (3) Topography and Drainage, (4) Railway Design, (5) Access Roads, (6) Aircraft Landing Field Design, (7) Water Supply, (8) Utilities, (9) Real Estate Ownership and Acquisition, (10) Preliminary Building Designs, (11) Sewage Treatment and Disposal, and (12) Cost Analysis of the items listed above.

Information contained in this report is a composite of published and unpublished information gleaned from various government and private sources as well as from educational institutions in the area. Original design work was performed in conformity with accepted engineering and architectural standards for the civil engineering work and the building complex. Field work was performed to obtain profiles of the Wye branches at the two sites, and a limited amount of test drilling was performed in order to obtain preliminary soils data for engineering designs.

B. General Discussion

1. General site factors

The general site factors consist of such items as exact location and access to the site. In addition, the site is described generally and the availability of commercial transportation in the area is discussed. Information is given on the surrounding towns and cities to give a brief picture of their desirability to the prospective scientists and technicians.

In the assembling of climatological data for each site, ten items were considered. These were: temperature, precipitation, wind, humidity, tornadoes, hail, dust, thunderstorms, sunshine and solar radiation. In some cases these items could be obtained from local stations having records of long standing. In other cases relatively short periods of record-keeping or sources from nearby areas were used and these are interpolated or rationalized for the area in question.

2. Geology and foundation investigation

Surface geological field investigations were made at the Y-15 and Y-23 sites during the summer of 1966. The purpose of these studies was to evaluate each area as to the stability of the soil types, the magnitude and effect of surface drainage, and the availability of sand, clay, gravel, and aggregate to be used in concrete and for construction purposes.

Subsurface soil investigations were carried out at each of the sites utilizing a truck-mounted auger unit equipped with a 4 in diameter, continuous flight auger. Disturbed samples were taken from the auger cuttings, and undisturbed samples were obtained using a 2.5 in I.D. ring sampler. Adjacent to each boring, a continuous measurement was made of the earth penetration resistance using a 2 in bullnose penetrometer with a standard 30 in free-fall hammer weighing 140 lb.

Laboratory tests performed on selected samples obtained during the drilling program included liquid limit, plasticity index, compressibility, dry density, and sieve analysis. A study was made as to the suitability of representative soils at the two sites to support footings at various depths.

3. Topography and drainage

In both the Y-15 site and the Y-23 site, the topography of the area lends itself to the installation of the Wye and it is only at the extremities of the Wye branches that the grades approach the 2% maximum allowable.

The finished grade of the Wye branches is generally above the existing ground and could act as a dam where it crosses the normal run-off flow pattern. The drainage design as noted on the profile exhibits is planned to accommodate this run-off in its existing channels. The Wye branches are not intended to act as dikes to retard, divert or hold run-off water, although in some sections this will occur during peak run-off from heavy precipitation.

In developing the drainage demands for both VLA sites many factors were considered which contribute to the determining of run-off volume and flooding in these areas, namely; topography; geology; climate; watershed size and shape; percolation and infiltration of the soil; altitude; vegetation; anticedent storms; base flow and precipitation. The maps utilized in the drainage studies were U.S. Geological Survey quadrangle sheets, aerial photographs and the state geologic maps covering both site areas. Precipitation and flood records were obtained from the U.S. Weather Bureau. Consultations were held with the U.S. Geological Survey Surface Water Division and Water Resources Division, Department of Commerce, Weather Bureau climatologists, State Highway drainage engineers and university hydrologists. Test borings, soils analysis and soils classification were made for each site. Site visitations were made to observe existing surface conditions and record historical flood data.

Each site is located in a somewhat remote region where, unlike much of the U.S., only sketchy climatological records have been recorded.

The precipitation records that have been kept are on the basis of total rainfall in 24 hr periods only and intensity data for any one period must be developed. All data interpretation was on the basis of a 50 year storm. No stream or gauging station records are available for either site area. Flood data for a major flood on the Y-23 site is available and was utilized. The Y-15 site has no flood record.

Formulations, design criteria, charts, graphs and technical data available in Design of Small Dams -- Bureau of Reclamation; Rainfall Intensity, Duration, Frequency -- U.S. Weather Bureau; Transactions -- American Society of Civil Engineers; Civil Engineers Handbook -- Urquhart and others were studied and analyzed for application to the site area.

Many formulas have been evolved to develop run-off volumes. Some of those considered were by McMath, Jarvis-Myers, Talbot, Manning, Bremmer, Dun, Pettis, and Potter. Some are utilized for only small areas; some for large watersheds; some for particular conditions; some for only certain parts of the country. The "C" coefficient in the various formulas is extremely important since it is dependent on the type of country in the drainage area and is an interpretive value generally made by observation. It is deceptive in that proper evaluation requires a very extensive detailed hydrological study for each application. Values of "C" for earth surface are varied by degree of saturation, compaction, surface irregularity, slope, character of subsoil and by presence of frost or snow or ice.

The Talbot formula, $a = C\sqrt[4]{A^3}$, (a is the area in square feet, C is the coefficient depending upon the type of country, A is the drainage area in acres) is one of the oldest and one of the most popular but it does not include some pertinent factors such as the intensity of rainfall; the velocity of flow; culvert slope; roughness; etc. The advantage of this formula is that it is quick and easy to use to give the drainage structure area directly, whereas most other formulas produce the run-off quantity and must utilize an additional formula such as Manning's to obtain the drainage structure area. While it is not possible to express all factors affecting run-off in one simple formula for all watersheds, consideration of all such variables is desirable. For small drainage areas the rational method, $Q = ciA$, (Q is discharge in cubic feet per second, c is the coefficient representing the ratio of run-off to rainfall, i is the intensity of rainfall in inches per hour for a duration equal to the time of concentration, and A is the area in acres) can be applied satisfactorily. Using this formula with proper weight given to the factors involved, a curve has been plotted for each site giving volume of run-off to area. In developing this curve for larger drainage areas use was made of run-off curves developed by the U.S. Geological Survey which cover both sites. These run-off curves combined with the frequency chart effect a continuation with the rational formula curves and have been used to determine predicted volume of run-off for a 50 year storm for both sites.

The culvert pipe sizes were developed using Manning's formula $Q = \frac{1.486}{n} Ar^{2/3} s^{1/2}$, (n = Roughness coefficient of the pipe, A = cross section of the pipe in square feet, r = mean hydraulic radius, s = slope of pipeline in feet per foot). Culvert pipe areas were computed on the basis of n = 0.0235 and s = 0.010 for both sites.

4. Railway

The railway section was developed to enable the 157 ton mobile radio telescope units to be transported to different locations on the Wye. The tracks will also serve to carry personnel and maintenance equipment to the units. Initially, at least, there will be no access road serving the Wye observation stations.

Fig. 12-1 shows the basic layout of the array. There are 33 observing stations along each arm, five of which are occupied in at least three of the four planned array arrangements. By-passes or turnouts are provided at these latter stations to obviate the necessity of moving these antennas each time the array is changed. Transfer of antennas from one branch to another branch is accomplished at the Wye apex where the tracks meet to form a typical railway junction.

The major railway crossing by highways will be accomplished with bituminous base course over railway ballast and covered with 2-1/2 inches

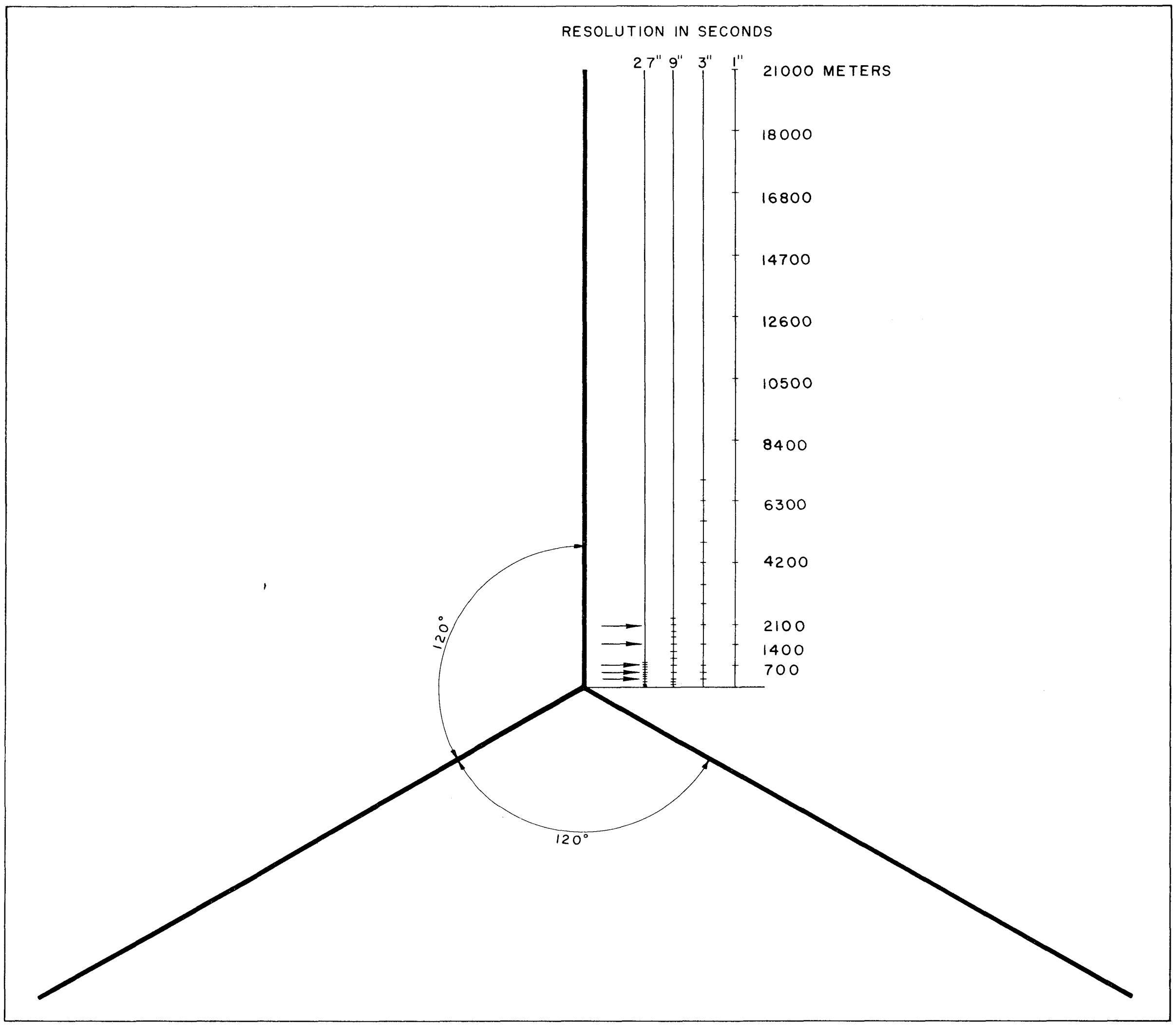

Figure 12 - 1. Locations of observing stations for the four array configurations. All arms of the wye are identical. Stations occupied in three or four configurations indicated thus ⟶.

asphaltic concrete surface. Minor railway crossing by roads will be accomplished by normal timber crossing methods. Railway crossings will follow A.R.E.A. practice and methods.

The design of the railway was based on the following criteria:

(a) Use standard gauge railroad track.

(b) Distance between center lines of double tracks to be 15 ft 3-1/2 in.

(c) Observation stations to be established at ends of spur tracks.

(d) Use #8 turnouts for by-passes.

(e) Trackage to support 157 ton radio telescopes in transit with minimum deflection.

(f) Radio telescopes to be supported in transit by four, four-wheel bogies.

(g) Each bogie wheel to have 25,000 lb maximum load.

(h) Maximum track grade allowable is 2%.

(i) Railway intersection to provide for movement of radio telescopes to each of the three branches.

(j) Maximum wind during telescope transport is 35 mph.

Each observation station has three foundations -- one for each leg of the radio telescope. One is centered between the tracks and the other two are outside of the tracks as in Fig. 12-2. The foundations are to prevent overturning of the units as well as to support them in a fixed position.

Each observation station will be enclosed with a 4 ft high open mesh stock fence. Two 15 ft long gates across the railway tracks will lock together at the center line when in closed position. Design criteria included the following:

(a) Radio telescope weight is 313,000 lbs.

(b) Foundations to support 100,000 lbs each.

(c) Foundations to resist 100,000 lbs overturning.

(d) One foundation to be centered between tracks and other two to be outside of tracks.

(e) Area to be enclosed with fence and gates.

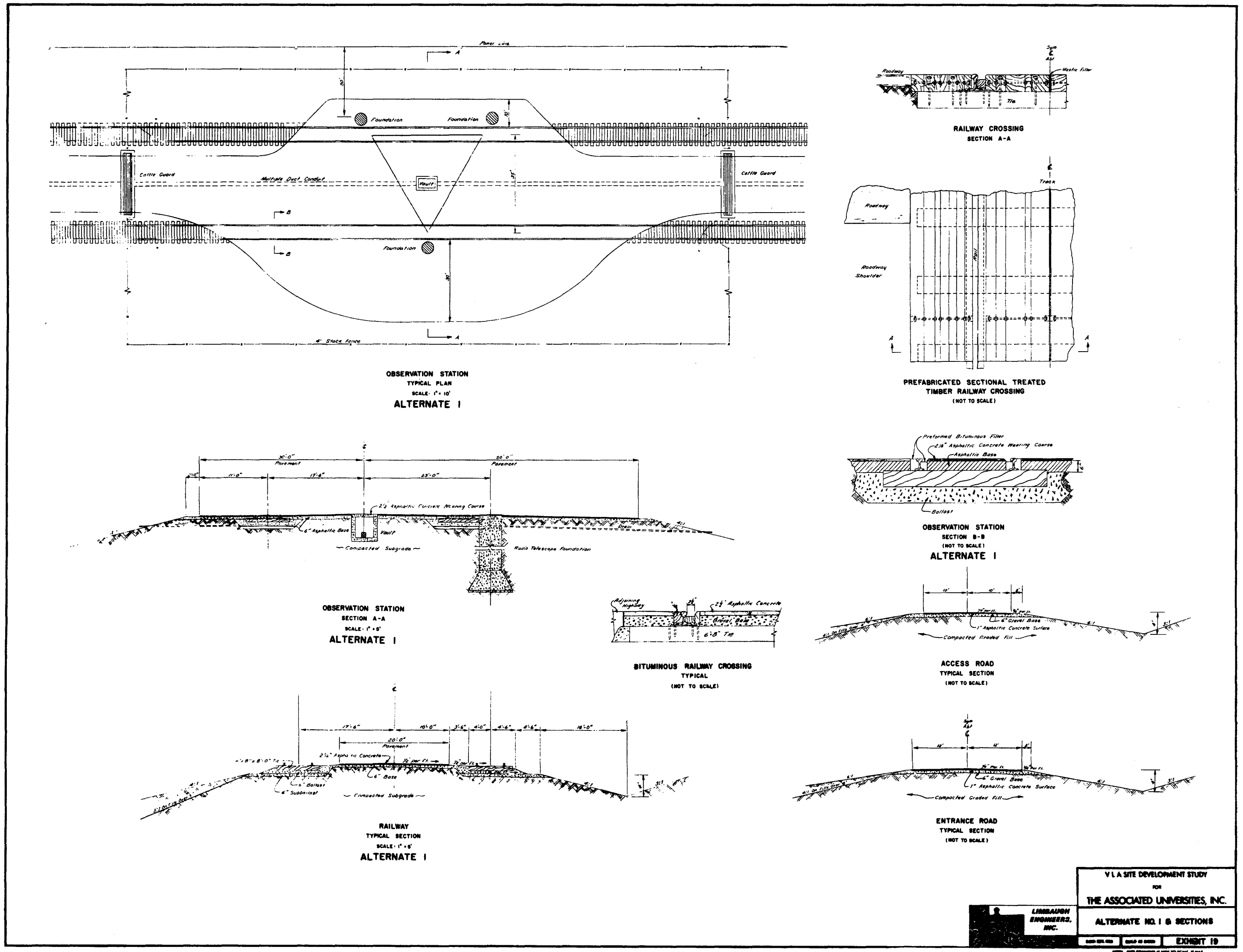

Figure 12 - 2. Alternate No. 1 and sections.

The staging area is developed to provide a location for field erection of the radio telescopes. The units will be erected on railway which is an extension of a spur track near the apex thus permitting access to the Wye. After the array becomes operational this staging area will be utilized for maintenance. The design criteria includes trackage, hard stand for crane operation, assembly and storage areas.

5. Access roads

The roads which serve the VLA sites are the entrance road, the access road to the airstrip and the access road to the Wye apex. The design of these roads is based on the following:

(a) All weather surface

(b) 45 mph speed

(c) Adequate drainage

(d) 300 ft sight distance

(e) 7% maximum grade

6. Airstrip

The airstrip for either site will be classified as a Basic Utility Airport and follows the FAA design criteria, Stage 11B. This type of Basic Utility Airport accommodates about 95% of the general aviation fleet and meets all general aviation needs except turbine-powered types, transport types and a few types of critical twin-engine aircraft.

7. Water supply

The water supply will be a "High Pressure Storage" system composed of a well, elevated storage tank, chlorinator and softener. Water supply requirements for the VLA sites are based on 5,000 gallons per day potable water and 50,000 gallons reserve for fire. Investigation of existing wells on each of the sites indicates that this demand can be met in each area both as to quantity and quality. Both sites are generally on alluvial deposits underlain with a ground water acquifer. The quality of the water is expected to be within allowable limits for flouride, chloride and sulfate content with the total dissolved solids not exceeding the satisfactory 500 ppm maximum. It should be noted that variations of the chemical characteristics of the water appear at both sites so that the degree of hardness may permit the zeolite water softening process to be omitted.

8. Utilities

The utility companies that would supply power to the sites were contacted to determine the availability and reliability of electric power. Both sites are served by cooperatives who expressed a desire to assist in determining the best alternates for supply.

This study was based on a normal load of 400 kw with a 90% load factor utilization. Demand load is considered as 800 kw. Based on this demand the buildings will be heated electrically. This will make unnecessary a natural or bottled gas supply source.

The telephone service in either area will be by the Bell System.

9. Real estate

A number of basic assumptions are made concerning the land acquisition necessary for the VLA.

The embankments or cuts for the runways between the observing stations will probably be less than 100 ft in total width. However, as there is some disturbing of adjacent land during construction and as the observing stations are on spur tracks that require approximately 150 ft additional width and as there is a power pole line along the spur side of the railway, it is anticipated that a strip 200 yds wide, the full length of the runway should be obtained.

This strip 200 yds wide is approximately 72.7 acres per mile or a total of 3,270 acres required for the railways. It is anticipated that the building complex area, access road to the site, utility line rights-of-way, sewage treatment areas and landing strip will require an additional 1,500 acres. This total of 4,770 acres will need to be acquired in some manner.

Land acquisition for such a facility is normally accomplished by one or more of the following methods:

(a) Perpetual easement - This is a lump sum, one time payment. It gives the right to use but not title. Usually 75% to 90% of the purchase price. Amount is based on the worth of land taken plus damages to the surrounding land.

(b) Term year leases - These are from 5 to 50 years with annual payments renewable at the AUI option.

(c) Open end lease - This is renewed each year at the option of the AUI, normally costs slightly more than the term lease.

(d) Purchase outright - This is the fee approach whereby the land is valued, as well as damages to surrounding land, and then purchased.

(e) Co-use agreement - This type of acquisition has been used when the surface of the land is not permanently changed, such as for missile ranges, drop areas, bombing ranges, etc. when the government only needs to use the land on specific days. It would not apply in this case.

It is assumed that the land acquired will not be fenced with the exception of small areas at the observing stations, and perhaps the building complex. It is also assumed that where fences are crossed by the facility, adequate gates or livestock guards will be installed to provide protection for the ranchers' operations.

The current land utilization at both sites is predominantly grazing. Sales of grazing land are usually in large size blocks of land at a price per acre which includes all improvements, all leased lands or grazing rights within the unit, and are usually between a willing seller and a willing buyer with no severance or other damages being involved in the transaction. The nature of taking small parcels from a larger tract for a special use such as the VLA will require, generally disrupts the normal operation of the parent tract, interrupts and complicates the continuity of its title, usually creates a nuisance, and in some cases causes a severance damage. In some instances a change in operation of the parent unit is made necessary as a result of the acquisition of the smaller parcel. As a consequence the acquisition of these types of small or irregular shaped and erratically located parcels generally are higher in price per acre than the market price of regular size, larger plots of grazing land. As a general rule, it has been noted that acquisition of rights-of-way for highway, utility lines, and railways usually costs from two to four times the per acre price found in normal ranch sales or leases.

There are numerous advantages to purchasing the land outright rather than leasing. When purchasing, all recurring costs associated with leasing are deleted. Assuming there will be an unwilling seller, it is much easier to exercise the right of eminent domain and put a sale price on the land than to determine a fair lease price.

10. Building complex

The building complex is composed of a Laboratory Building, Shops, Garage and Dormitory. These four units will house all the on-site support functions for the VLA. While the technical requirements, and therefore the physical configurations, will possibly change during the design stages it is felt that the total area is adequate as originally envisioned.

The Laboratory Building serves not only as the headquarters of the facility, but also as the Control Building, Office area, and has the Experimental Laboratory and Storage.

The Shops and Garage functions are combined into a common unit for equipment maintenance.

The Dormitory is for transient scientists involved with current observations and is not intended to house permanent personnel. However, the kitchen and dining hall facilities are to provide hot food to all, including permanent personnel, who might be on the site at meal times.

11. Sewage treatment

Sewage treatment by use of oxidation ponds or "lagoons" is a satisfactory method used in the area where sites Y-15 and Y-23 are located. Design criteria for these lagoons is based on the effluent from domestic use and is as established by the Ten State Standards with capacity for 50 people. This type of sewage treatment requires a minimum of maintenance and trouble which generally only consists of keeping the area clean from external debris, keeping plant growth controlled particularly along the berms, and maintaining correct depth of pond.

C. Facilities Considered Identical for Either Site

1. Building complex

The building complex is comprised of three main buildings located in a closely related plot, the axis of which lies on the north leg of the array. The buildings consisting of the following:

Laboratory Building:

Control and Electronics Equipment		10,000 ft^2
Offices and Director's Area		2,500 ft^2
Electronics Laboratory		3,000 ft^2
Storage		1,000 ft^2
	Total	16,500 ft^2
Supporting area: toilets, entrances, stairs, air handling equipment rooms		3,750 ft^2
	Total of building	20,250 ft^2

Shops Building, Garages, and Central Mechanical Plant:

Shops		9,750 ft^2
Garages		1,620 ft^2
Covered Vehicle Storage		2,300 ft^2
	Total	13,670 ft^2
Central Mechanical Plant		1,450 ft^2
	Total	15,120 ft^2

Dormitory: 7,900 ft^2

(a) Architectural

All buildings are single story, except the Dormitory and the electronics and Control portion of the Laboratory Building, which are two story.

An electrical equipment room is combined with the Shops and Garage Building and supplies electrical distribution to the individual buildings of the complex as well as housing the 500 kw emergency power unit.

Floors will be of concrete. Slabs on grade will be reinforced and poured over compacted fill. Structurally supported floors for the second floor of the Dormitory and for the second floor of the Electronics Equipment and Control Building will be reinforced concrete slab poured over corrugated steel forms supported upon steel framing members.

Roof construction will be long span steel joists supporting a light aggregate roof deck.

Roofing will be 20 year bonded, built-up roof with colored aggregate surfacing. Roofing will be installed over rigid insulation board.

Windows will generally be of fixed type (non-opening) to control dust and air conditioning. Vents and screens will be strategically located. All windows will be of steel. Glass will be 7/32 in crystal.

Interior finishes will be as follows:

Floor covering: Toilet rooms will be ceramic mosaic tile with coved base. Shop building, garages, mechanical rooms, and rough storage areas will have concrete floors. All other floors will receive vinyl-asbestos floor tile and vinyl cove base.

Doors: Exterior doors will be of metal for minimum upkeep. Steel roll-up doors will be used for vehicles. Interior doors will be label type where location requires label to satisfy code requirements. All other interior doors will be solid core wood, book-matched veneers.

Partition work will be of the movable type in the laboratory sections. Partitions around stairways and vertical chases carrying through two stories will be of 2 hr fire-rated construction. Masonry partitions will be plastered and all other partitions are of steel studs, with gypsum board facing.

Ceiling work will be of one-hour-rated construction, and will vary from plaster ceilings in toilet rooms, kitchen and mechanical rooms, to that of lift-out Tee-bar and acoustical board ceilings in offices, in dormitory rooms, and in laboratories where ceilings are required. All other buildings will be exposed structure, painted.

All spaces will be painted.

(b) Structural

Structure will be of two types. Skeleton steel frame will be used generally, with reinforced concrete spot footings and grade beam. Wall-bearing construction of brick and tile masonry, and with continuous reinforced concrete foundations will be used for the Dormitory, and for all locations where such is economical. Exterior walls will be of face brick, with structural tile backing reinforced. Where feasible to leave interior wall surfaces of exposed masonry, backing will be of concrete masonry units.

(c) Mechanical - Description of Systems

Laboratory Building

The office laboratory wing of this building will be air conditioned and heated by two multizone air conditioning units. Cooling will be provided by direct expansion cooling coils served by air cooled condensing units on mechanical room roofs. Heating will be provided by electric coils in the units. Humidity control will be provided at the units.

The Control and Electronic Equipment wing of this building will be air conditioned and heated by two single zone air conditioning units, one for each floor. Cooling will be provided by direct expansion cooling coils served by air cooled condensing units on the roof over the mechanical spaces. Heating will be provided by electric coils in the units. Humidity control will be provided at the units.

Shops and Garage Building

This building will be heated by electric unit heaters in the shop and garage areas. Exhaust ventilation will be provided in those areas requiring it. The office will be air conditioned by a through-the-wall, self-contained unit and heated by electric baseboard.

Dormitory Building

This building will be air conditioned and heated by a single zone air conditioning unit. Cooling will be provided by a direct expansion cooling coil served by an air cooled condensing unit on the roof. Electric zone coils will provide reheat for each zone during the cooling cycle. Heating will be provided by an electric unit pre-heat coil, the zone reheat coils and electric baseboard units in each dormitory room and along the window wall in the lounge and dining room. Exhaust ventilation will be provided for bathrooms and kitchen. Humidity control will be provided at the unit.

Equipment and Material

Condensing units will be air cooled, roof mounted, with low ambient temperature kits, Carrier or equal.

Heating coils will be electric blast coils for duct or unit installation, Indeeco or equal.

Air conditioning units will be blow-through multizone and draw-through single zone units with direct expansion cooling coils and electric heating coils.

Unit heaters will be electric, propeller fan type, horizontal discharge.

Baseboard heaters will be electric.

Refrigerant piping will be Type ACR copper tubing.

Fire protection for all buildings will be by means of a wet automatic system with alarm valve and water motor alarm. There will be a separate system for each building. Upright heads will be used in all shops and garages and pendant heads will be used in offices, laboratories, dormitory and other areas with finished ceilings.

(d) Electrical

The electrical work will include, but is not limited to, the following principal items:

480/277 V, 3 phase, 4 wire power distribution system to the various buildings of building complex.

Systems of power and light for each building in the building complex.

Parkway, road and floodlighting as required.

Telephone systems for the various buildings.

Grounding system.

The electrical work will comply with all applicable Federal and State building laws, codes, ordinances, and regulations relating to the building and public safety.

Distribution System

Electrical service for the building complex will be supplied by the utility company by overhead lines and from an outdoor transformer. The outdoor transformer shall have the following secondary characteristics: 277/480 V, 3 phase, 4 wire, full capacity neutral and frequency of 60 cps. The secondary of the 277/480 V, 3 phase, 4 wire transformer will distribute power to the main switchboard and from the main switchboard to power panel or load centers of the various buildings of building complex. Power distribution through the building complex will be

480/277 V, 3 phase, 4 wire. Motors 1/2 hp and larger will be served at 440 V, 3 phase. Receptacles and small appliances will be served from 480/120/208 V dry type transformers and panelboards.

Lighting systems will in general be 277 V fluorescent with 120 V lighting kept to a minimum except in the dormitory building.

The main switchboard will be 480 V and will be metal-enclosed, free-standing structure with General Electric Type "AK" draw-out air circuit breakers or approved equal.

The 2300 V main switchgear will be the metal-clad roll out fusible air switch type.

The motor control center will be totally enclosed, free-standing type of modular design with main horizontal bus and individual vertical bus runs. All units shall be plug-in type, full voltage, non-reserving, circuit breaker combination starters. Construction shall be NEMA, Class 1, Type B. Control devices shall be furnished as shown on the drawings.

Panelboards

(1) General lighting panelboards shall be GE Type NHB with main lugs or approved equal.

(2) General 120/208 V distribution panels shall be GE Type NLAB with main lugs only or approved equal.

Transformers shall be 480-120/208 V, 3 phase, dry type Class "H" insulation.

Bus ducts shall be totally metal enclosed, low impedence type.

All wiring shall be copper conductors with 600 V insulation, Type TW for conductor size #10 AWG and smaller, and Type THW for conductor size #8 AWG and larger, THW shall be used in all underground, and damp or wet areas. No conductor smaller than #12 AWG will be used except in the case of control circuits, where #14 may be used.

Conduits

All wiring shall be installed in rigid metallic conduit (hot dip galvanized after threading). Minimum conduit size shall be 3/4 in trade size. Flexible conduit shall be used for the final connection to rotating equipment and to transformers.

All fluorescent lighting fixtures shall be furnished with ETL, CBM approved instant start ballast. Ballasts shall be individually fused. All other fixtures types shall be as designated on the drawings.

The grounding system will be as required by the National Electrical Code or as specified. The grounding conductor shall not be smaller than #6 AWG copper nor larger than #4 AWG copper.

(e) Parking

The roadways and parking areas in the building complex area will be constructed of 1 in thick asphaltic concrete surface. The base course will be 6 in gravel compacted on prepared sub-grade. All methods, procedures and materials will meet the Asphalt Institute specifications.

(f) Landscaping

The landscaping will be simple and of indigenous nature to preserve the area surrounding the buildings in harmony with the site. Plants and trees native to the area will be used combined with a small sprinklered area of grass. The sidewalks will be of concrete and of 4 in thickness laid on prepared gravel bed.

2. Sewage treatment

Assuming a biochemical oxygen demand (BOD) of 0.20 lb per day per capita with a 20 day minimum retention period permits a 1/2 acre cell as ample size for the planned capacity of 50 personnel, two cells are designated for operational use and maintenance. Each cell will be 150 ft x 150 ft at the 5 ft level with sides sloping out at a 4:1 terminating on a compacted berm 5 ft above the normal ground. The total cell depth will be 8 ft and operating depth from 3 ft to 5 ft. An adjustable outlet pipe is located at the 5 ft level for overflow.

Only one cell will be used at a time, the second cell accepting effluent when maintenance is required on the first cell. Both cells are to be clay lined and no primary treatment is anticipated. Effluent flow from the building complex is through 6 in C.I. pipe, direction controlled by gate valves at the lagoon site. The lagoon area is to be enclosed by a cyclone fence with a gate and appropriate signs.

3. Underground cable trenches

The cables which extend to each observation station on the Wye will be laid directly in a trench at a minimum depth below ground level of 42 in. Manholes to give access to cable junctions will be 6ft x 4ft x 6ft deep, constructed of prefabricated reinforced concrete with a wood cover which can be locked.

The manholes will be spaced so that two manholes will be required between each observation station for the first 5 miles on each branch and 8 manholes between each observation station in the remaining 10 miles of each branch.

Both the multiple duct conduit and the manholes will be centered between the railway tracks. A manhole will be located at each spur and conduit will be branched here to supply a vault located at the center of the observation station. This vault will be 6ft x 4ft x 6ft deep. The cover of the vault will be wood and could be secured from access by a lock.

Existing overhead telephone and power lines will be conducted underground in suitable conduits where they cross the Wye branches.

D. Cost Estimate

The cost estimates for this study have been developed as "budget type" estimates for each site. It should be noted that the figures reported here are based upon slightly different array parameters than those finally adopted. In particular, the array lengths used here are 15 miles per arm, while the finally-chosen value is 13.1 miles. Further, the "spur" construction of the observing stations will not be used, and the total number of such stations has been increased from 61 to 99. The present tables are printed nonetheless, to indicate the manner in which the cost estimates were determined. In Chapter 10, Cost Analysis, the figures have been adjusted to reflect the most recent decisions regarding array parameters. These cost estimates cover all the physical facilities including land required, but excepting special laboratory and scientific equipment and apparatus, shop equipment, movable antennae, cables to observation stations, terminal boards, dormitory and office furnishings and similar items. These budget estimates are sufficiently detailed to be used as a basis for determining funds required later for design and construction of the project.

In order to determine the best possible unit cost estimates, the services of the C.L. Noe consulting firm specializing in cost estimating in the southwest were procured.

In addition to these services an independent determination of unit prices was made by one of the largest contractors in the area. While certain of the unit prices had considerable variances between these two sources, the total costs compared favorably within 5%. Individual item differences can be discounted because of the normal contractor tendency to unbalance bids.

Cost estimates have been prepared on the following:

1. Airstrip including drainage
2. Access roads including drainage
3. Water supply system
4. Sewage treatment system
5. Wye branches and spurs including drainage
6. Cable trenches
7. Foundations
8. Staging area
9. Power supply
10. Telephone system
11. Real estate
12. Buildings

The buildings have been broken down into plumbing, electrical, heating, air-conditioning, sprinkler system, structural, and general.

Some of the above items have not been prepared if they are identical for the two sites. These identical items follow the variable items.

The unit prices used in this report are based on existing material and labor costs in the Southwest as of 1966. It is expected that when the time schedule of request for funds, design, and tentative construction is set, that these figures will require adjustment to reflect costs expected during the construction period.

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Item No.	Item	Amount	Cost	Totals
1.	Airstrip			
	Clear & Grub	35 acres	700	
	Strip	90,000 yd^2	7,200	
	Excavation-unclassified	24,000 yd^3	18,000	
	Borrow	37,200 yd^3	27,900	
	Base	7,900 yd^3	25,675	
	Triple Surface Treatment	47,167 yd^2	21,225	
	CMP Culverts 36in	6 ea	19,200	
	" " 48in	3 ea	14,100	
				134,000
2.	Access Roads			
	Clear & Grub	5 acres	250	
	Strip	23,700 yd^2	1,422	
	Excavation	-	-	
	Borrow	18,120 yd^3	13,590	
	Base	1,800 yd^3	5,850	
	Asphaltic Concrete	8,000 yd^2	4,000	
	CMP Culverts - w/hw 30in	1 ea	1,225	
	Parking Area - Apex	225 yd^2	405	
				26,742
3.	Water Supply			
	Well & Pump	1 ea	7,565	
	Elevated Tank - 65,000 gal	1 ea	42,000	
	Chlorinator	1 ea	1,750	
	Zeolite Softener	1 ea	1,200	
	Galv. Steel Pipe - 2-1/2in	5,000 ft	8,750	
	A.C. Pipe - 4in	1,000 ft	1,850	
				63,115
4.	Sewage Treatment			
	Cells - 1/2 Acre - Clay Lined	2 ea	8,600	
	C.I. Pipe - 6in	3,000 ft	13,500	
	Valves	3 ea	525	
	Manhole	20 ea	5,500	
	6ft Cyclone Fence & Gate	1,600 ft	5,600	
				33,725

Y-15 Railway -- 15 Mile Branches

Item No.	Item	Amount	Cost	Totals
5.	Wye			
	Clearing & Grubbing	350 acres	7,000	
	Stripping	350 acres	91,000	
	Excavation-unclassified	1,116,198 yd^3	837,149	
	Borrow	67,133 yd^3	50,350	
	Channel Relocation & Dikes	-	2,000	
	Erosion Protection	-	2,000	
	Stock Fence	16,775 ft	20,969	
	Fence Gate	122 ea	14,640	
	CMP Culverts - w/hw 24in	86 ea	67,940	
	" " " 30in	30 ea	29,700	
	" " " 36in	37 ea	51,800	
	" " " 42in	28 ea	49,560	
	" " " 48in	18 ea	35,100	
	" " " 54in	2 ea	4,400	
	" " " 60in	4 ea	9,880	
	" " " 78in	2 ea	7,280	
	Conc. Box Culverts 10ft x 10ft	2 ea	22,400	
	Railway Ties	234,000 ea	760,500	
	" Spikes	3,780 keg	81,459	
	" Bolts	945 keg	30,429	
	" Tie Plates	468,000 ea	351,000	
	" Joint Bars	24,480 pr	94,248	
	" Rail	14,256 ton	1,639,440	
	" Ballast	192,456 ton	625,482	
	" Cattle Guard	64 ea	17,600	
	" Labor	475,200 ft	1,724,976	
	Railway Spur Ties	17,568 ea	57,096	
	" " Spikes	393 keg	8,469	
	" " Bolts	100 keg	3,220	
	" " Tie Plates	48,600 ea	36,450	
	" " Joint Bars	2,440 pr	9,394	
	" " Rail	1,376 ton	158,240	
	" " Ballast	15,900 ton	51,675	
	" " Turnouts - #8	122 ea	292,800	
	" " Crossovers	61 ea	183,000	
	" " Stops	244 ea	19,520	
	" " Switch Ties	122 set	95,160	
	" " Labor	49,410 ft	260,885	
	Existing Buried Tel. Cable	1 ea	100	
	" Overhead Tel. Line	1 ea	500	
	" " Power Line	3 ea	3,000	
	" Road Crossing - Major	1 ea	1,000	
	" " " - Minor	12 ea	8,400	
				7,817,211

Y-15 Railway -- 15 Mile Branches

Item No.	Item	Amount	Cost	Totals
6.	Cable Trenches			
	Cable Conduit & Trench*	249,000 ft	996,000	
	Manhole	349 ea	209,400	
	Vault	61 ea	42,700	
				1,248,100
7.	Foundations - Concrete	1,867 yd^3	74,680	
				74,680
8.	Staging Area			
	Clear & Grub	6-1/2 acres	130	
	Strip	6-1/2 acres	1,690	
	Excavation-unclassified	17,000 yd^3	12,750	
	Asphaltic Concrete - 2-1/2in	4,400 yd^2	4,180	
	Double Surface Treatment	22,300 yd^2	7,805	
	Base	4,445 yd^3	14,446	
	Gravel Surfaced Road	0.10 mile	1,500	
	Railway Tracks	800 ft	9,000	
				51,501
9.	Power Supply - Obs. Stations			
	2300 V Main Switchgear	1 ea	11,000	
	Station Switchgear	61 ea	122,000	
	Overhead Pole Line	45.5 mile	273,000	
				406,000
11.	Real Estate	-	83,000	
				83,000

* Note: The most recent design of the trenches does not include conduit. The cost of direct burial trench is estimated at $2.00/ft

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Item No.	Item	Amount	Cost	Totals
1.	<u>Airstrip</u>			
	Clear & Grub	31 acres	12,400	
	Strip	74,000 yd^2	11,840	
	Excavation-unclassified	77,669 yd^3	58,252	
	Borrow	-	-	
	Base	6,470 yd^3	21,028	
	Triple Surface Treatment	38,833 yd^2	17,475	
	CMP Culverts - w/hw 42in	1 ea	4,360	
	" " " 72in	2 ea	16,600	
	" " " 84in	3 ea	33,300	
				175,255
2.	<u>Access Roads</u>			
	Clear & Grub	32 acres	12,800	
	Strip	158,000 yd^2	18,960	
	Excavation-unclassified	24,400 yd^3	18,300	
	Borrow	172,400 yd^3	129,300	
	Base	12,000 yd^3	39,000	
	Asphaltic Concrete	53,500 yd^2	26,750	
	CMP Culverts 30in	1 ea	1,225	
	" " 42in	4 ea	8,920	
	" " 48in	4 ea	9,720	
	" " 54in	1 ea	2,750	
	Parking Area	225 yd^2	405	
				268,130
3.	<u>Water Supply</u>			
	Well & Pump	1 ea	15,130	
	Elevated Tank - 65,000 gal	1 ea	42,000	
	Chlorinator	1 ea	1,750	
	Zeolite Softener	1 ea	1,200	
	Galv. Steel Pipe - 2-1/2in	5,000 ft	8,750	
	A.C. Pipe - 4in	1,000 ft	1,850	
				70,680
4.	<u>Sewage Treatment</u>			
	Cells - 1/2 Acre - Clay Lined	2 ea	10,000	
	C.I. Pipe - 6in	3,000 ft	13,500	
	Valves	3 ea	525	
	Manhole	20 ea	5,500	
	6ft Cyclone Fence & Gate	1,600 ft	5,600	
				35,125

Y-23 Railway -- 15 Mile Branches

Item No.	Item		Amount	Cost	Totals
5.	Wye				
	Clearing & Grubbing		350 acres	105,000	
	Stripping		350 acres	175,000	
	Excavation-unclassified		1,096,460 yd^3	822,345	
	Borrow		1,391,217 yd^3	1,043,413	
	Channel Relocation & Dikes		-	5,000	
	Erosion Protection		-	20,000	
	Stock Fence		16,775 ft	20,969	
	Fence Gate		122 ea	14,640	
	CMP Culverts - w/hw	24in	1 ea	790	
	" " "	30in	37 ea	36,630	
	" " "	36in	78 ea	109,200	
	" " "	42in	78 ea	138,060	
	" " "	48in	99 ea	193,050	
	" " "	54in	30 ea	66,000	
	" " "	60in	64 ea	158,080	
	" " "	66in	18 ea	55,260	
	Conc. Box Culverts	8ft x 4ft	7 ea	30,450	
	" " "	8ft x 8ft	3 ea	21,450	
	" " "	8ft x 10ft	2 ea	16,400	
	" " "	10ft x 10ft	25 ea	280,000	
	Bridge - 400ft		1 ea	93,000	
	" - 200ft		1 ea	47,000	
	Railway Ties		233,486 ea	758,830	
	" Spikes		3,780 keg	81,459	
	" Bolts		945 keg	30,429	
	" Tie Plates		468,000 ea	351,000	
	" Joint Bars		24,480 pr	94,248	
	" Rail		14,256 ton	1,639,440	
	" Ballast		192,456 ton	625,482	
	" Cattle Guard		32 ea	8,800	
	" Labor		475,200 ft	1,724,976	
	Railway Spur Ties		17,568 ea	57,096	
	" " Spikes		393 keg	8,469	
	" " Bolts		100 keg	3,220	
	" " Tie Plates		48,600 ea	36,450	
	" " Joint Bars		2,440 pr	9,394	
	" " Rail		1,376 ton	158,240	
	" " Ballast		15,900 ton	51,675	
	" " Turnouts - #8		122 ea	292,800	
	" " Crossovers		61 ea	183,000	
	" " Stops		244 ea	19,520	
	" " Switch Ties		122 set	95,160	
	" " Labor		49,410 ft	260,885	

Y-23 Railway -- 15 Mile Branches

Item No.	Item	Amount	Cost	Totals
5.	Wye (continued)			
	Existing Overhead Tel. Lines	2 ea	1,000	
	" " Power Lines	2 ea	2,000	
	" Road Crossing - Major	1 ea	1,000	
	" " Crossings - Minor	13 ea	9,100	
				9,955,410
6.	Cable Trenches			
	Cable Conduit & Trench	249,000 ft	996,000	
	Manhole	349 ea	209,400	
	Vault	61 ea	42,700	
				1,248,100
7.	Foundations - Concrete	1,867 yd^3	84,015	
				84,015
8.	Staging Area			
	Clear & Grub	6-1/2 acres	2,600	
	Strip	6-1/2 acres	1,950	
	Excavation-unclassified	21,000 yd^3	15,750	
	Asphaltic Concrete - 2-1/2in	4,400 yd^2	4,180	
	Double Surface Treatment	22,300 yd^2	7,805	
	Base	4,445 yd^3	14,446	
	Gravel Surfaced Road	0.50 mile	8,000	
	Railway Tracks	800 ft	9,000	
				63,731
9.	Power Supply - Obs. Stations			
	2300 V Main Switchgear	1 ea	11,000	
	Station Switchgear	61 ea	122,000	
	Overhead Pole Line	48.5 mile	291,000	
				424,000
11.	Real Estate	-	51,000*	
				51,000*

* Additional amount of $48,470 per year is required for land lease.

VLA - Building Complex

Y-15 or Y-23

Item No.	Item	Amount	Cost	Totals
12.	Building Complex			
	Laboratory			
	Basement			
	Structure	5,800 ft^2	58,000	
	Finish	5,800 ft^2	15,950	
	Plumbing	5,800 ft^2	1,450	
	Heating & Air Conditioning	5,800 ft^2	21,750	
	Electrical	5,800 ft^2	11,600	
	Sprinkler System	5,800 ft^2	2,030	
				110,780
	First Floor			
	Structure	14,450 ft^2	130,050	
	Finish	14,450 ft^2	72,250	
	Casework	300 ft	18,000	
	Plumbing	14,450 ft^2	3,613	
	Heating & Air Conditioning	14,450 ft^2	54,188	
	Electrical	14,450 ft^2	32,513	
	Sprinkler System	14,450 ft^2	5,058	
				315,672
	Shops, Garages, Veh. Sta.			
	Shops			
	Structure	9,750 ft^2	97,500	
	Finish	9,750 ft^2	24,375	
	Plumbing, Heating & Air Conditioning	9,750 ft^2	19,500	
	Electrical	9,750 ft^2	19,500	
	Sprinkler System	9,750 ft^2	3,413	
				164,288
	Garages			
	Structure	1,620 ft^2	16,200	
	Finish	1,620 ft^2	3,240	
	Plumbing, Heating & Air Conditioning	1,620 ft^2	3,240	
	Electrical	1,620 ft^2	3,240	
	Sprinkler System	1,620 ft^2	567	
				26,487
	Covered Vehicle Storage			
	Structure	2,300 ft^2	12,650	
	Plumbing, Heating & Air Conditioning	2,300 ft^2	4,600	

VLA - Building Complex

Y-15 or Y-23

Item No.	Item	Amount	Cost	Totals
12.	Building Complex (continued)			
	Shops, Garages, Veh. Sta. (continued)			
	Covered Vehicle Storage (continued)			
	Electrical	2,300 ft^2	4,600	
	Sprinkler System	2,300 ft^2	805	
				22,655
	Central Mechanical Plant			
	Structure	1,450 ft^2	18,125	
	Plumbing, Heating & Air Conditioning	1,450 ft^2	2,900	
	Electrical	1,450 ft^2	2,900	
	Sprinkler System	1,450 ft^2	508	
				24,433
	Dormitory			
	Structure	7,900 ft^2	77,025	
	Finish	7,900 ft^2	33,575	
	Kitchen Equipment	-	8,000	
	Plumbing	7,900 ft^2	3,950	
	Heating & Air Conditioning	7,900 ft^2	27,650	
	Electrical	7,900 ft^2	13,825	
	Sprinkler System	7,900 ft^2	2,765	
				166,790
	Parking Area, & Roads	6,400 yd^2	14,080	
				14,080
	Landscaping & Sidewalks	-	5,000	
				5,000
	Power Supply			
	500 KW Generator	1 ea	60,000	
	480 V Main Switchgear	1 ea	8,400	
	Exterior Lighting	-	3,000	
				71,400
			TOTAL	921,585
10.	Telephone System	1 ea	3,000	
				3,000

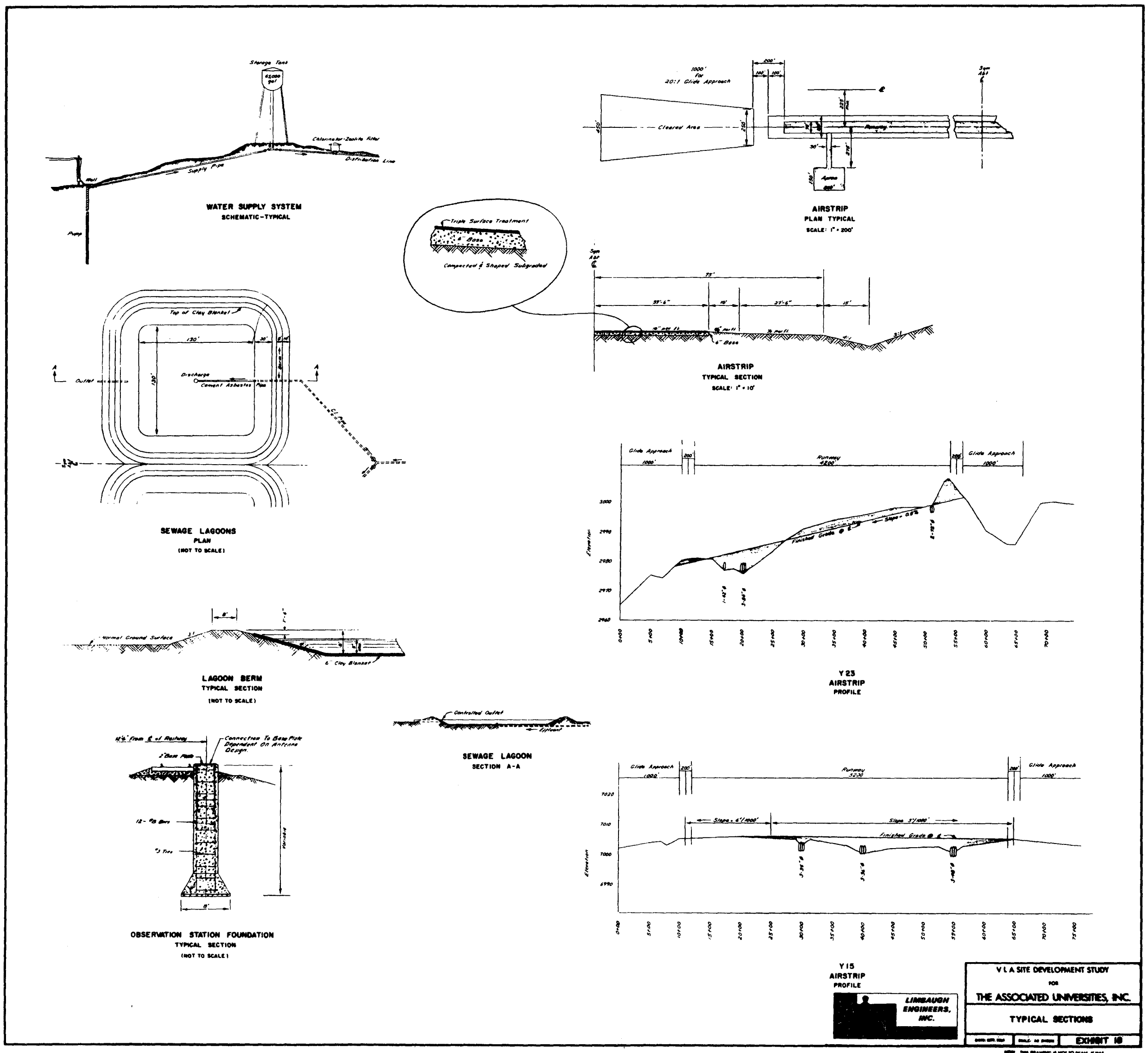


Figure 12 - 3. Typical sections.

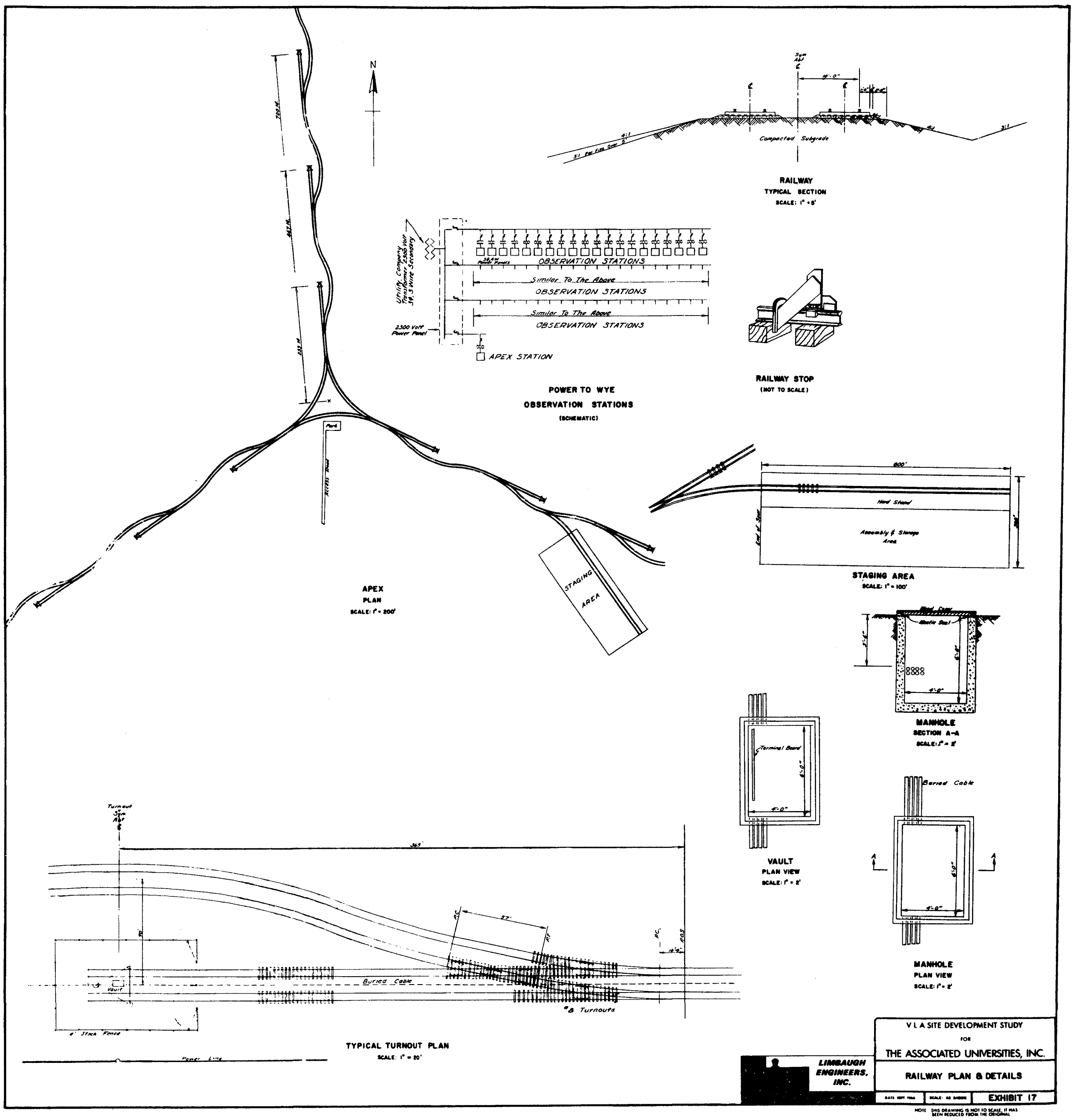


Figure 12 - 4. Railway plan and details.

Figure 12 - 5. Artist's conception.

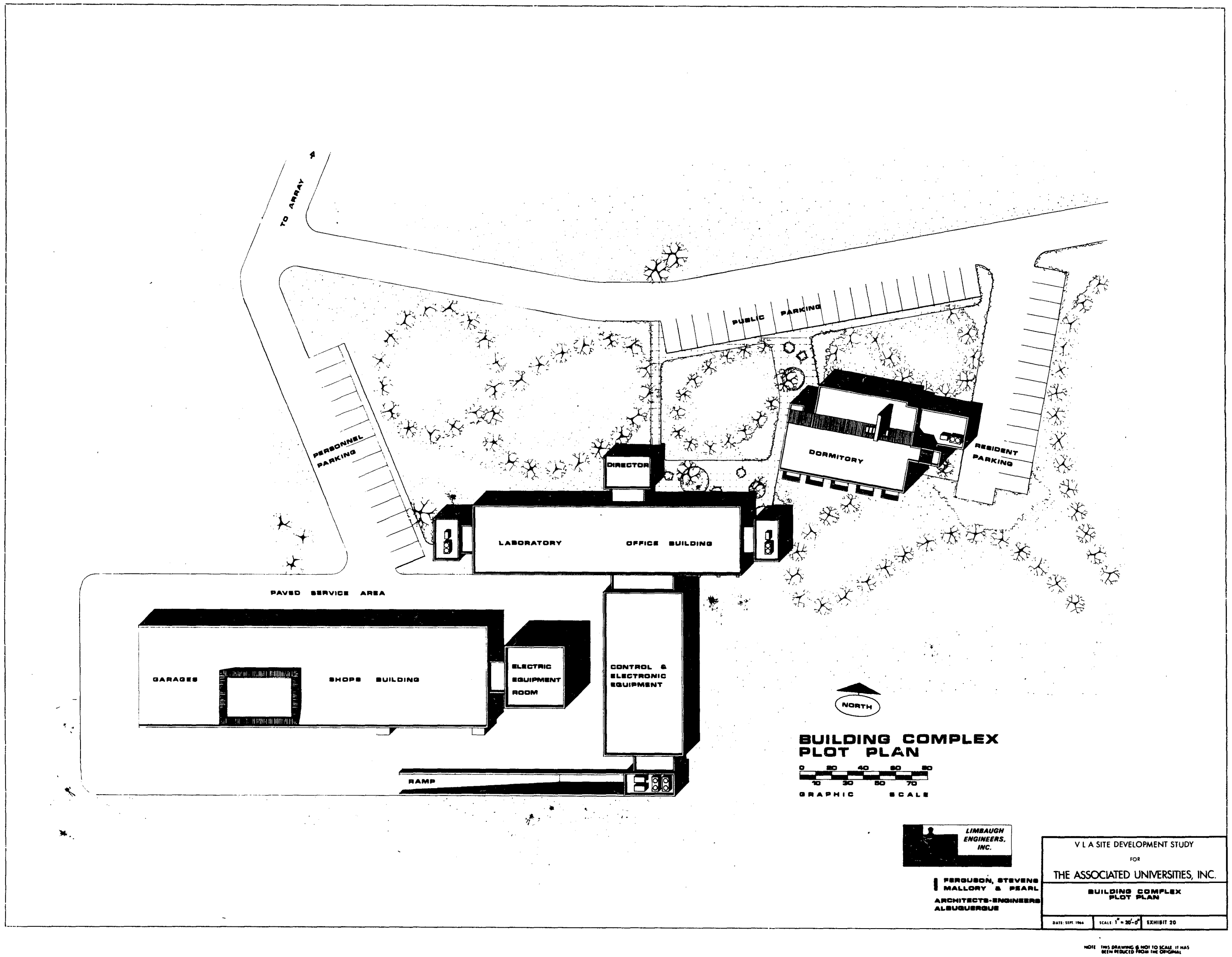


Figure 12 - 6. Building complex plot plan.

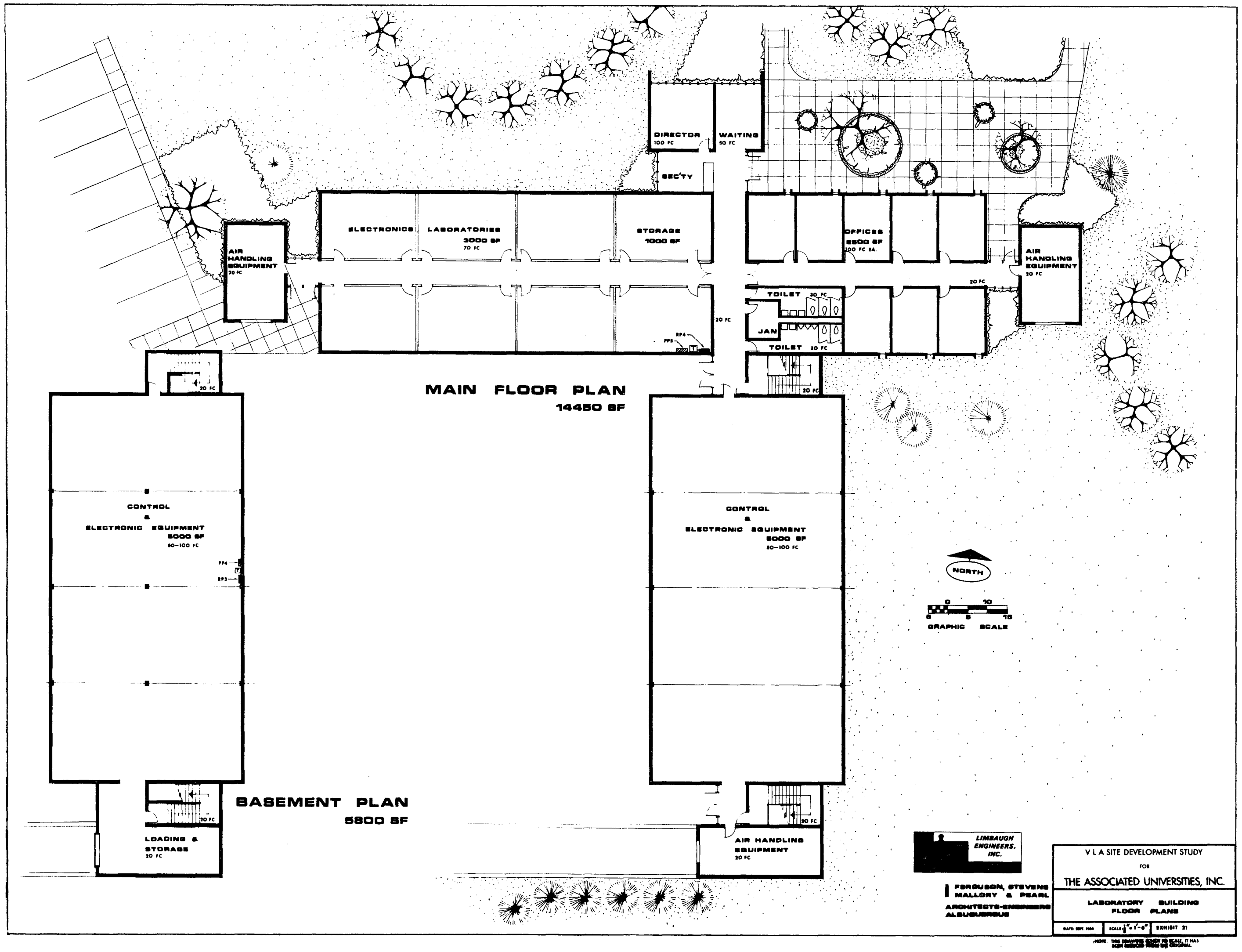


Figure 12 - 7. Laboratory building floor plans.

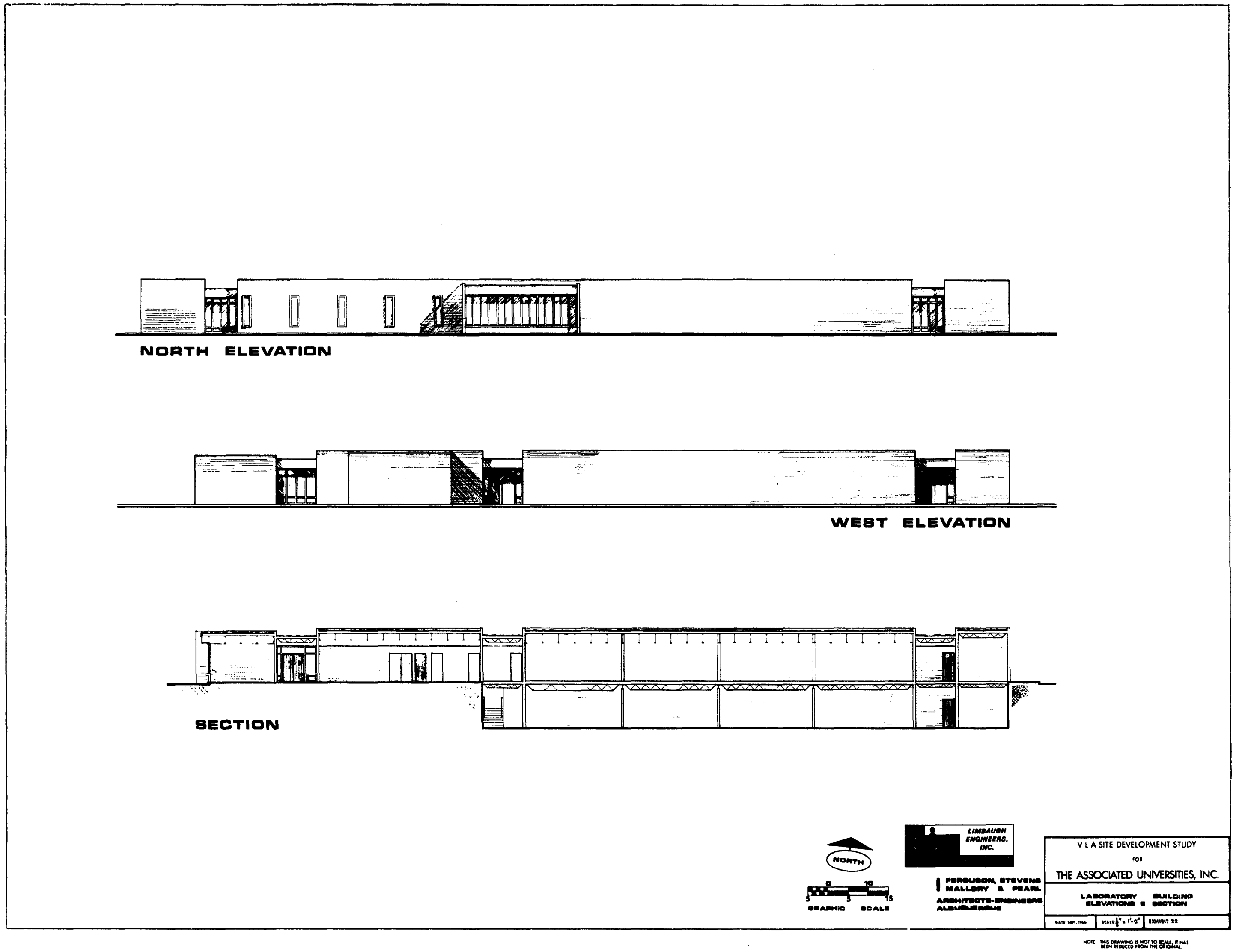


Figure 12 - 8. Laboratory building elevations and sections.

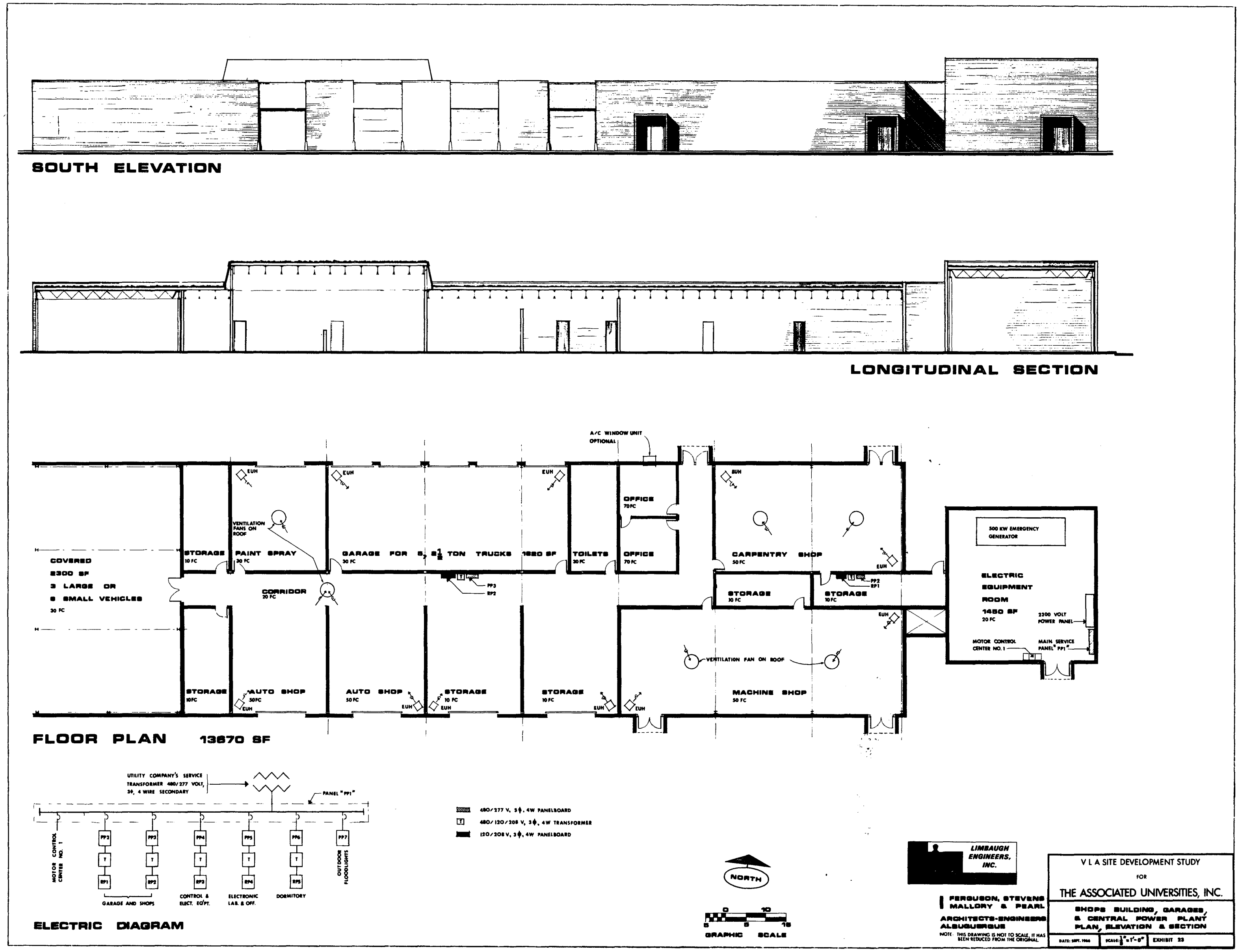


Figure 12 - 9. Shops building, garages and central power plant -- plan, elevation and section.

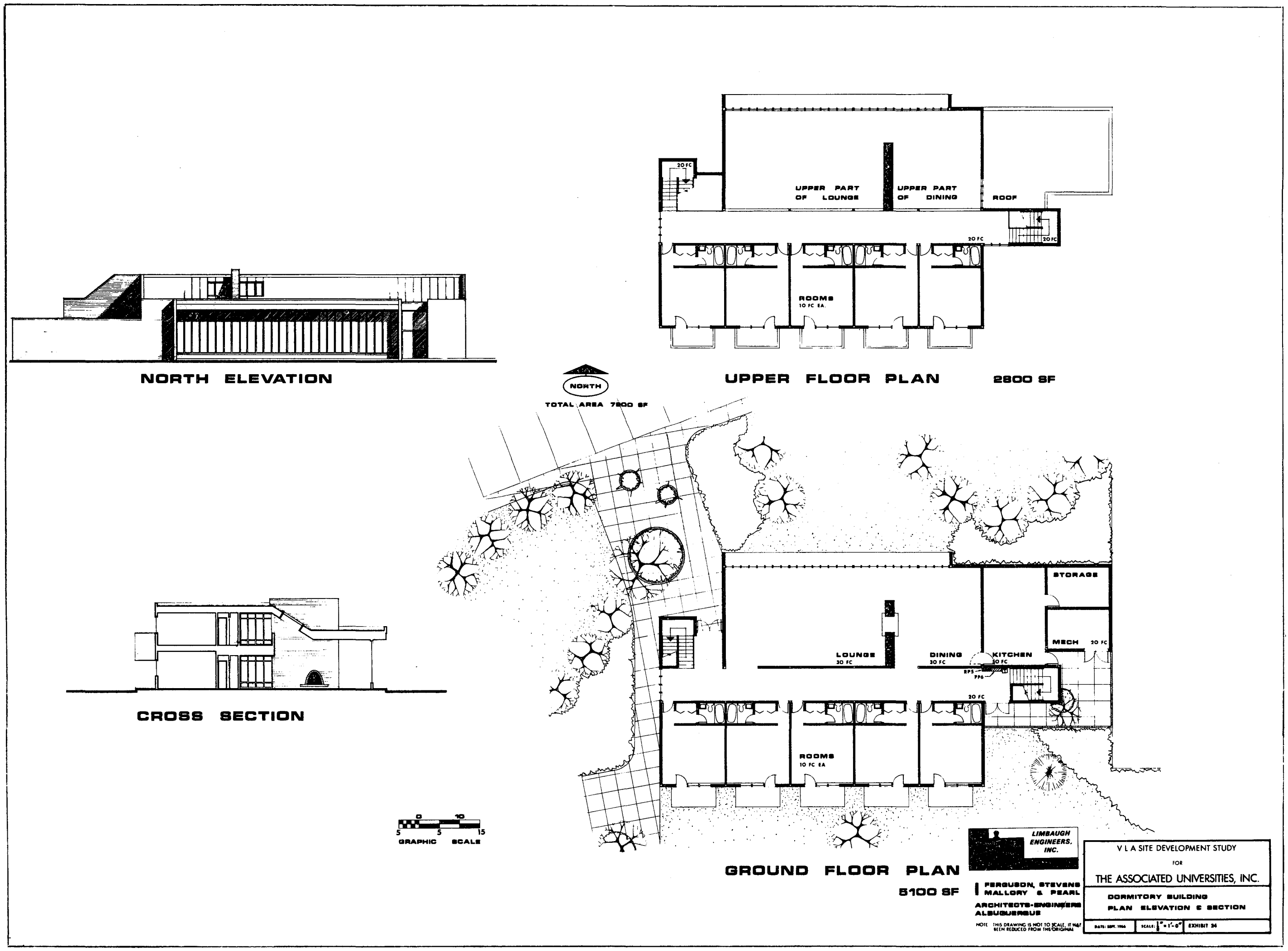


Figure 12 - 10. Dormitory building -- plan, elevation and section.

Chapter 13

ELECTRONICS SYSTEM

Chapter 13

ELECTRONICS SYSTEM

A. Introduction

The VLA is designed as a full-correlation, supersynthesis array. Such a designation implies two immediate requirements on the electronic system. First, cross correlations of the signal voltages between all possible pairs of antennas must be formed and second, this must be done continuously as the antennas track the source over a range of sky coverage up to the full range offered by the antenna mounts.

When such requirements are first examined, one is struck by the large amount of electronics equipment necessary for the proper operation of the array. A closer examination, however, reveals that the total electronics system consists of a relatively small number of unique system blocks which are multiplied many times throughout the system. The complexity of the electronics is then reduced to that of number rather than degree.

The VLA can be thought of as the superposition of roughly $\frac{1}{2}M^2$ two-element interferometers with a variety of baseline lengths and orientations, with the important distinction that only M antennas are required rather than M^2. The electronics system description and requirements will, therefore, be introduced by investigating the requirements for a single two-element interferometer.

B. Two Element Interferometer Theory

The block diagram of a two-element interferometer incorporating most of the important features of the VLA electronics is shown in Fig. 13-1. The system to be described is a double sideband, delay tracking, correlation interferometer with the following possible features:

1. Synchronously pumped degenerate parametric amplifiers
2. Phase locked local oscillator (LO)
3. Lobe rotation
4. Automatic gain control

The significance of each of these features will be brought out in the following discussion.

The power spectra of the signals of interest are shown in Fig. 13-2. The signal spectrum at RF is assumed to be composed of equal, symmetrically placed sidebands about the LO frequency ω_o. The bandwidth of the sidebands is $2\pi B$ (rad/sec), and is actually set by the action of IF filters. The center of each sideband is offset from ω_o by ω_1, the IF center frequency. The paramp pump signal p(t) is at twice the LO frequency and, in fact, is derived from it by means of a frequency doubler.

The signal voltages entering the antenna feeds at time t are s(t) and $s(t-\tau)$ (perfectly correlated except for the delay τ). The delay τ, arising from the source-baseline geometry, is given by

$$\tau = \frac{D}{c} \left[\sin d \sin \delta + \cos d \cos \delta \cos (H-h)\right] \tag{13-1}$$

and is seen to be a slowly varying function of H for a given source. In general, the degree of correlation between the two signals is determined by the details of the source structure and the resolution of the interferometer. What is assumed here is the case applicable to a point source of radiation.

All group and phase delays of signals are assumed to be only those shown by blocks in the diagram of Fig. 13-1. Thus, the phase of the LO signal at the mixer of antenna 1 is $-(\beta+\gamma)$ while that of the paramp pump is $-(2\beta+\phi)$. The IF group delay τ_n is inserted in the IF channel of antenna 1.

The double sideband signal s(t) entering antenna 1 is amplified by the degenerate paramp G_1. This signal is then mixed with the LO signal in a double sideband mixer which folds the input spectrum into a bandwidth B(Hz) as indicated in Fig. 13-2. This signal is transmitted to the terminal electronics where it is delayed by τ_n(sec). The level of the signal is adjusted by the automatic level control (ALC) unit by an amount which exactly cancels out any gain or loss variations in the signal path. This signal is then multiplied in the correlator with that which results from $s(t-\tau)$ in antenna 2 after similar processing.

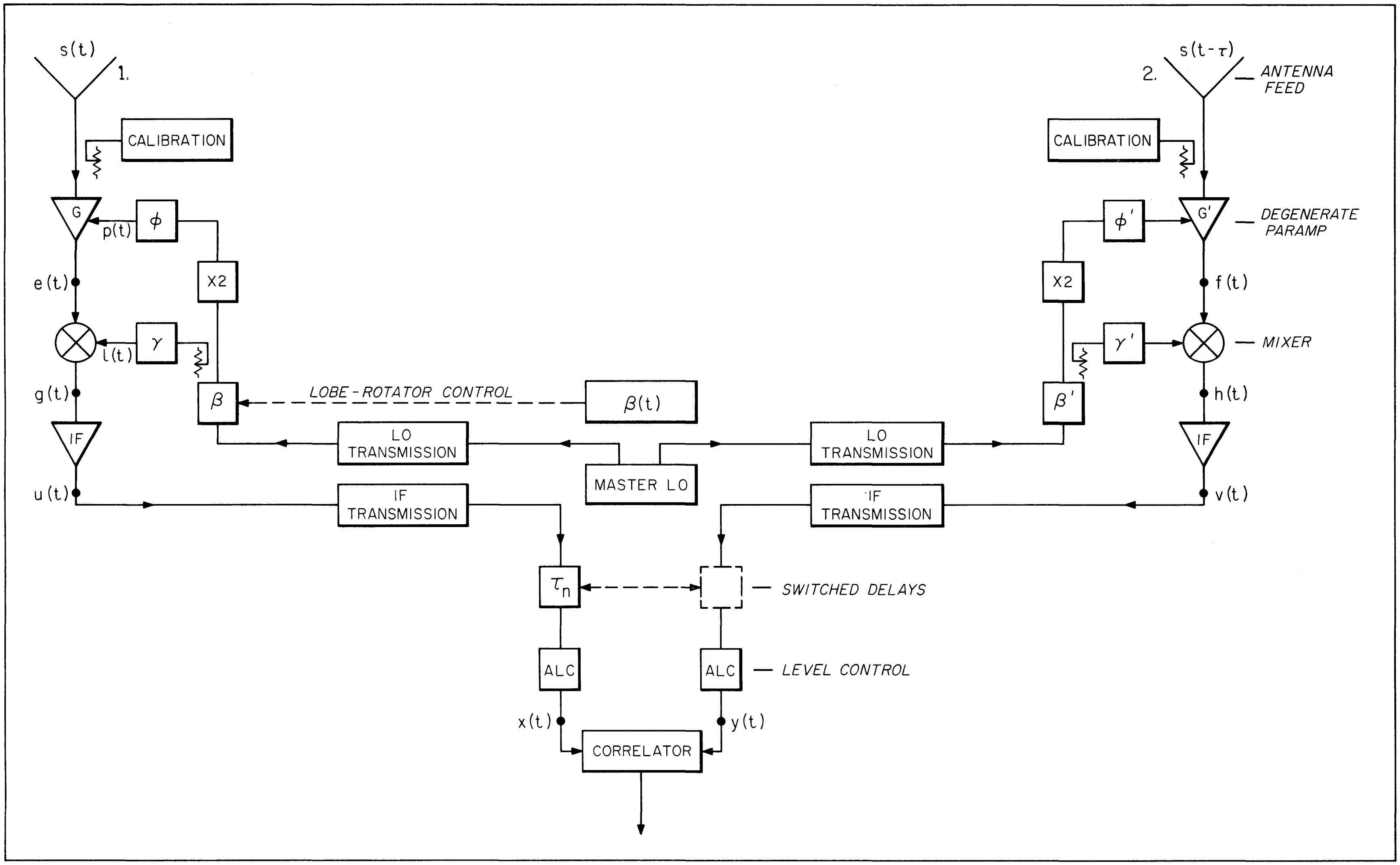

s(t)
1.
s(t - τ)
2.
ANTENNA FEED
CALIBRATION
CALIBRATION
G
p(t)
φ
G'
φ'
DEGENERATE PARAMP
e(t)
X2
X2
f(t)
γ
l(t)
γ'
MIXER
g(t)
β
LOBE-ROTATOR CONTROL
β(t)
β'
h(t)
IF
LO TRANSMISSION
LO TRANSMISSION
IF
MASTER LO
u(t)
IF TRANSMISSION
IF TRANSMISSION
v(t)
τn
SWITCHED DELAYS
ALC
ALC
LEVEL CONTROL
x(t)
y(t)
CORRELATOR

Figure 13 - 1

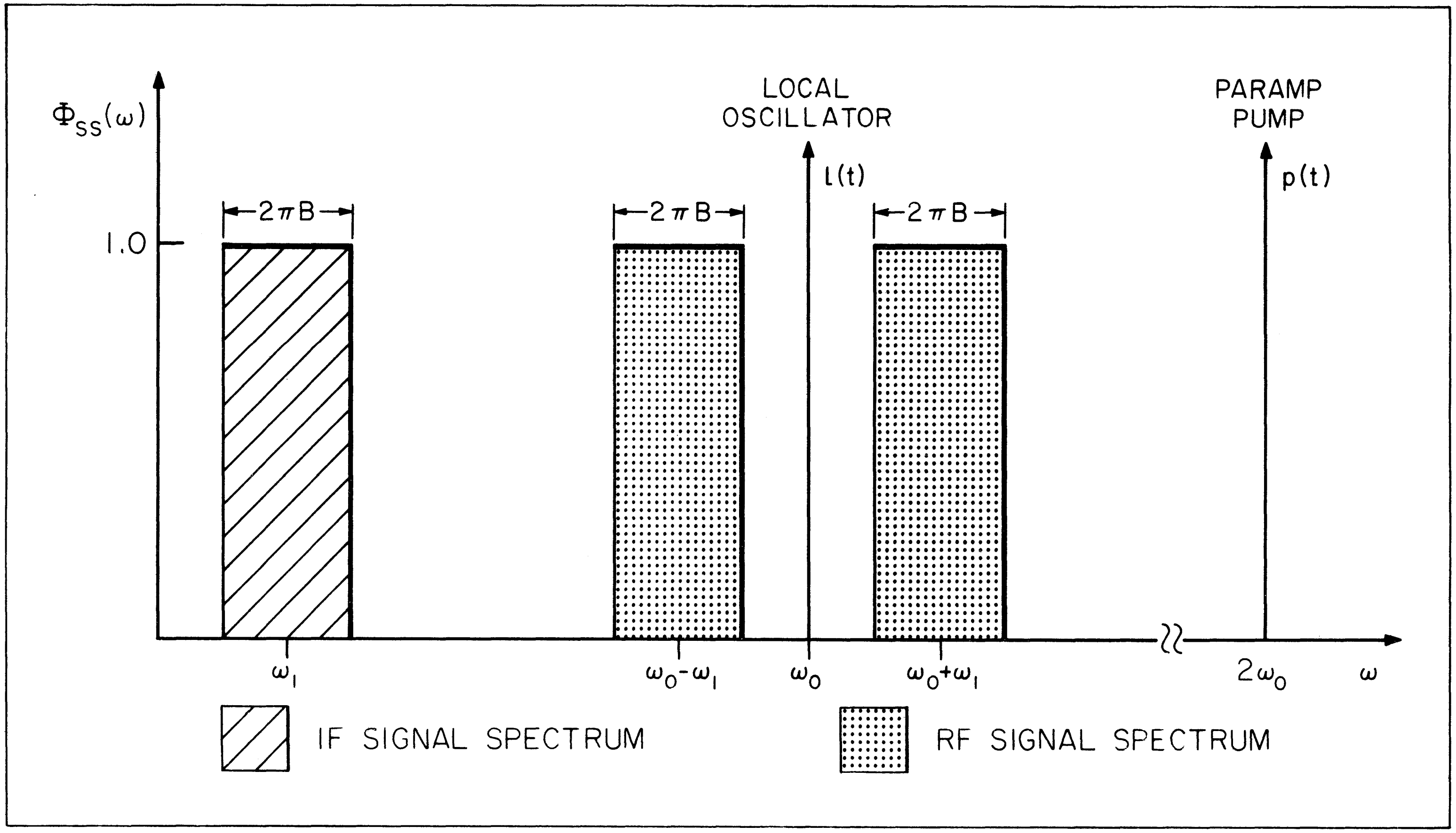


Figure 13 - 2. The signal spectrum.

In Section D it is shown that the output of the correlator is proportional to

$$B \cos \left(\frac{\Delta\phi}{2} - \Delta\gamma \right) \left[\frac{\sin \pi B(\tau - \tau_n)}{\pi B(\tau - \tau_n)} \right] \cos \omega_1 (\tau - \tau_n) \cos (\omega_o \tau + \Delta\beta + \frac{\Delta\phi}{2}) \qquad (13\text{-}2)$$

where $\Delta\phi = \phi - \phi'$

$\Delta\gamma = \gamma - \gamma'$

$\Delta\beta = \beta - \beta'$

Ideally the response of the interferometer to the point source would be simply $\cos \omega_o \tau$. As is obvious, the other terms in Equation (13-2) arise from the instrumental effects of the measuring apparatus, and it is one of the tasks in the electronic design to reduce these to either negligible or controllable amounts. Each of these instrumental terms will now be discussed.

1. $\cos (\frac{\Delta\phi}{2} - \Delta\gamma)$ - This factor arises due to improper phasing of the degenerate parametric amplifiers. By making ϕ and ϕ' adjustable phase shifters in the pump circuitry, the conditions for synchronous, phase-locked pumping can be achieved. That is, ϕ and ϕ' are set individually such that

$$\left. \begin{array}{l} \phi = 2\gamma \\ \phi' = 2\gamma' \end{array} \right\} \qquad (13\text{-}3)$$

and $\cos (\frac{\Delta\phi}{2} - \Delta\gamma) = 1$

2. $\frac{\sin \pi B(\tau - \tau_n)}{\pi B(\tau - \tau_n)}$ - This factor arises from the assumed rectangular bandpass of the correlated signals and is simply a measure of the loss in correlation between the two rectangular bandpasses when a delay setting error $\Delta\tau = \tau - \tau_n$ exists. For a bandwidth B an error of 1% in amplitude will result from a delay setting error $\Delta\tau$ when

$$\Delta\tau(\text{ns}) \cong \frac{80}{B(\text{MHz})}$$

3. $\cos \omega_1 (\tau-\tau_n)$ - Each sideband of the double sideband system actually produces an interference pattern $\cos \left[\omega_1(\tau-\tau_n) + \omega_o\tau\right]$ and $\cos \left[\omega_1(\tau-\tau_n)-\omega_o\tau\right]$ for the upper and lower sidebands, respectively. If, as is assumed here, the sidebands are equal and symmetric about ω_o, the sum of the two patterns gives

$$\cos \omega_1(\tau-\tau_n) \cdot \cos \omega_o\tau \ .$$

If the sidebands are not equal, the delay switching error $\omega_1(\tau-\tau_n)$ appears in the argument of the fringe term described in (4) below, giving rise to phase errors. In addition, any differential phase shifts in the IF channels will then also appear in the fringe term.

The effects of this term in producing an error in amplitude is always greater than that of the $\dfrac{\sin \pi B(\tau-\tau_n)}{\pi B(\tau-\tau_n)}$ term in (2) above. For a 1% error in amplitude, the delay setting error $\Delta\tau$ is approximately

$$\Delta\tau(\text{ns}) \cong \frac{22}{f_1(\text{MHz})}$$

where $f_1 = \dfrac{\omega_1}{2\pi}$.

4. $\cos (\omega_o\tau + \Delta\beta + \frac{\Delta\phi}{2})$ - This is the fringe term which exhibits the desirable feature of the double sideband system in that the switched delay τ_n does not appear in the argument. Thus the delay switching does not change the phase of the fringes. If the phase shifters ϕ and ϕ' are set according to (13-3), the fringe term becomes

$$\cos (\omega_o\tau + \Delta\beta + \Delta\gamma).$$

The terms in 1 through 3 above are instrumental factors which affect the amplitude of the fringe term. $\Delta\beta$ and $\Delta\gamma$ are then instrumental factors which introduce phase errors in the fringe term. It is primarily the <u>time variation</u> in the phase error that is of concern, whereas the amplitude error leads to a decrease in system sensitivity.

There are now several features of the block diagram which can be discussed with the aid of the discussions in items 1 through 4. In order to assure relatively error free, flexible operation of the interferometer, techniques must be developed for the following operational requirements.

1. Paramp phasing and synchronous pumping

The pump frequency must be derived from the LO frequency and the pump phases adjusted according to (13-3).

2. Phase stabilization

The variations in $\Delta\phi$, $\Delta\gamma$ with time must be kept small enough ($\sim 2^{\circ}$/hour) so that infrequent periodic calibrations will suffice to keep track of them. This is achieved mainly by the use of compensating networks and stabilization of the component's environment.

3. Phase-locked local oscillator

The term $\Delta\beta$ involves the differential phase shifts in a signal which must be transmitted from the central control station to the antennas, involving long transmission paths and varying environmental conditions. Generally the ability to stabilize $\Delta\beta$ sets the limit on the interferometers' capabilities. A separate phase locking loop must be incorporated in the design since the problem of simple stabilization becomes almost impossible for long baselines and varying environmental conditions. The phase-locked loop would either reduce $\Delta\beta$ to zero or maintain $\Delta\beta$ constant over the interval between calibrations.

4. Lobe rotation

It is very desirable, from the standpoint of the computer requirements for data reduction, that the fringe frequency be controllable. In particular, for very long baselines, the high natural fringe frequency and subsequent fast sampling rate require input data rates for the computer which become needlessly costly. One way to circumvent this problem is to employ lobe-rotation schemes which, for the interferometer under consideration, would consist of a variable phase shifter incorporated into β in addition to the phase locking loop. By computer control, the phase shifter could be varied continuously such that $\Delta\beta = -0.9\ \omega_o \tau$, for example. The fringe term would then be reduced to the form

$$\cos\ (0.1\ \omega_o \tau)$$

with a subsequent ten-fold reduction in the input data rate to the computer.

Another technique would be to vary β in such a way that

$$\Delta\beta = \omega_f t - \omega_o \tau$$

The fringe term would thus be reduced to

$$\cos\ \omega_f t$$

where ω_f = any desired constant. Thus the output of the correlator would be of constant frequency, considerably simplifying the data reduction process. All of the information regarding the source structure is still contained in the amplitude and phase of the fringe term.

5. Delay tracking

For the double sideband system, the effect of introducing IF group or phase delays asymmetrically exhibits itself only in the term

$$\frac{\sin\ \pi B(\tau-\tau_n)}{\pi B(\tau-\tau_n)}\quad \cos\ \omega_1\ (\tau-\tau_n) \tag{13-4}$$

which is a function of the group delay above. The slow variation in τ as the source is tracked across the sky can be compensated for by switching in fixed delay τ_n so as to keep $\Delta\tau = \tau-\tau_n$ small enough so that the delay dependent term (13-4) in the correlator output can be kept as close to unity as is required. For small $\Delta\tau$ we may set

$$\frac{\sin\ \pi B(\tau-\tau_n)}{\pi B\ (\tau-\tau_n)}\ \cos\ \omega_1(\tau-\tau_n) \cong 1 - \varepsilon_\tau$$

where

$$\varepsilon_{\tau} = 2\pi^2 \left[f_1{}^2 + \frac{B^2}{12} \right] (\Delta\tau)^2$$

For most purposes it is sufficient to insure $\varepsilon_{\tau} < 0.01$. For a computer controlled or monitored delay switching system, the effect of this error can be further reduced by data weighting in the computer.

6. <u>ALC control and calibration</u>

The amplitude of the fringe output of the correlator would ideally be constant for a point source. For a more complex source the amplitude of the fringes will change in a way which is directly related to the source structure. Thus it is imperative that no variations in amplitude are caused by instrumental effects unless they can be detected and calibrated to high accuracy. A gain variation of .04 dB gives a 1% error in amplitude. Stabilizing the gains and losses in the system to this degree is an unreasonable task to attempt, particularly when the effect of the delay switching system is considered. One technique which has proven useful is to limit the input to the correlator by an ALC circuit. This unit produces a constant level input to the correlator and as such exactly compensates for pure gain changes in the system. The ALC circuit, however, does not distinguish between gain changes and system noise temperature changes, and so an amplitude error is <u>introduced by the ALC</u> whenever the latter occurs. The total gain and system noise temperature can be monitored continuously by suitable calibration circuits and the information used to either correct the ALC action directly or to adjust the data in the computer. In addition there is an error introduced when strong sources (giving antenna temperatures comparable to system noise temperatures) are observed. These effects are easily accounted for in the computer if the source flux density is known.

The proper operation of the interferometer as described above sets certain requirements on the precision and stability of the electronic components. This in turn implies a certain environmental stability.

Such requirements will be discussed in this and the following chapters in terms of their effect on the design of the VLA electronics system.

C. VLA Electronics - System Description

The VLA electronics system is basically a simple extension of the two antenna interferometer electronics to an M-antenna system forming $\frac{1}{2}$ M (M-1) interferometer pairs. Except for some special problems introduced by the specific array configuration, the electronics design problems are identical in nature to those of the two-element interferometer.

The general system specifications for the array, which are pertinent to the electronics design, are as follows:

1. The array is to be capable of expansion to simultaneous operation at either of two frequencies or two polarizations. In the first instance, the two frequencies would be 2695 MHz (λ 11.1 cm) and 5390 MHz (λ 5.5 cm). For the dual polarization operation, there would be a choice of right and left circular polarization at either 2695 MHz or 5390 MHz. In all cases, the system is to be operated double sideband.

2. The bandwidth (IF) would nominally be 50 MHz. For special applications, selectable filters at IF would allow restriction of this to satisfy the specific requirement.

3. The LO system will provide phase-locked signals at each antenna suitable for use as mixer signals at both frequencies and as parametric amplifier pump signals with phase rotators for synchronous pumping purposes. In addition, the LO signals will have incorporated a lobe rotation scheme which will give a discrete set (35) of constant fringe frequencies out of the correlators.

4. The system will provide delay switching networks at IF which will allow delay tracking over the entire range of sky coverage offered by the antennas.

5. Three complete sets of correlators will be provided. Here a set is to mean $\frac{1}{2}$ M(M-1) for M antennas. Two sets will be required when dual frequency work is being done, and three full sets are required for the dual polarization operation.

6. System sensitivity

A $75^{\circ}K$ to $100^{\circ}K$ system noise temperature is perfectly feasible today. The requirement for extreme reliability may tend to degrade this figure, but state-of-the-art improvements in the reliability of presently available low noise parametric amplifiers will undoubtedly allow a design goal of $75^{\circ}K$ to $100^{\circ}K$ to be achieved for the VLA application. The reliability requirement is one of the chief reasons for the present choice of degenerate parametric amplifiers due to their inherent simplicity of design and ease of obtaining reliable pump power.

7. Monitor, control and calibration

For such a complex electronics system, automatic monitoring of the system is an essential requirement both for detecting failing or faulty components and for measuring certain system parameters which are required in the data reduction. In addition, many control functions must be performed during both normal operation and periodic calibration of the systems performance. These considerations lead immediately to the requirement for a somewhat complex, automated communications system which is predominantly under computer control and which extends throughout the array electronics system.

The VLA configuration has several features which must be taken into account in the design of the electronics system. These features may be summarized in the following statement: The VLA consists of a large number of antennas arranged more or less uniformly along 3 distinct lines with the individual elements either very close together or very far apart or both. The point is that where the antennas go, the electronics must go along and function as well in one configuration as another. In order to be successful under these conditions, the electronics design must be flexible, reliable and simple, all consistent with good economics. It will be seen in Chapter 16 that economy does not always follow from simplicity.

To summarize, the electronics system must satisfy the requirements of 1 through 7 above and, in addition, accommodate the following configuration features:

1. Large number of antennas (36)
2. Long baselines
3. Three distinct array arms
4. Array aperture can be expanded and contracted by a factor of 10 or more.

The VLA electronics system can be thought of as the combination of a large number of major and minor system blocks. The number of different kinds of system blocks is relatively small. These are categorized below.

Major System Blocks

1. Antenna Electronics
2. LO System
3. Data Transmission System
4. Delay System
5. ALC and Calibration
6. Signal division and Correlator Sets
7. A/D Converters and Computer Input

Minor System Blocks

1. Control System
2. Monitor System
3. Display
4. Test

It is the purpose of the remainder of this chapter to describe the requirements, general design and functioning of each of these system blocks and their interrelationships. In the following chapters will be found specific details on the design, operation, and cost of those portions of the major and minor blocks which present the most significant challenges to the electronics design engineer.

Fig. 13-3 is a simplified overall system block diagram, which shows the interconnections between the major system blocks and the number of blocks required for the system design under consideration.

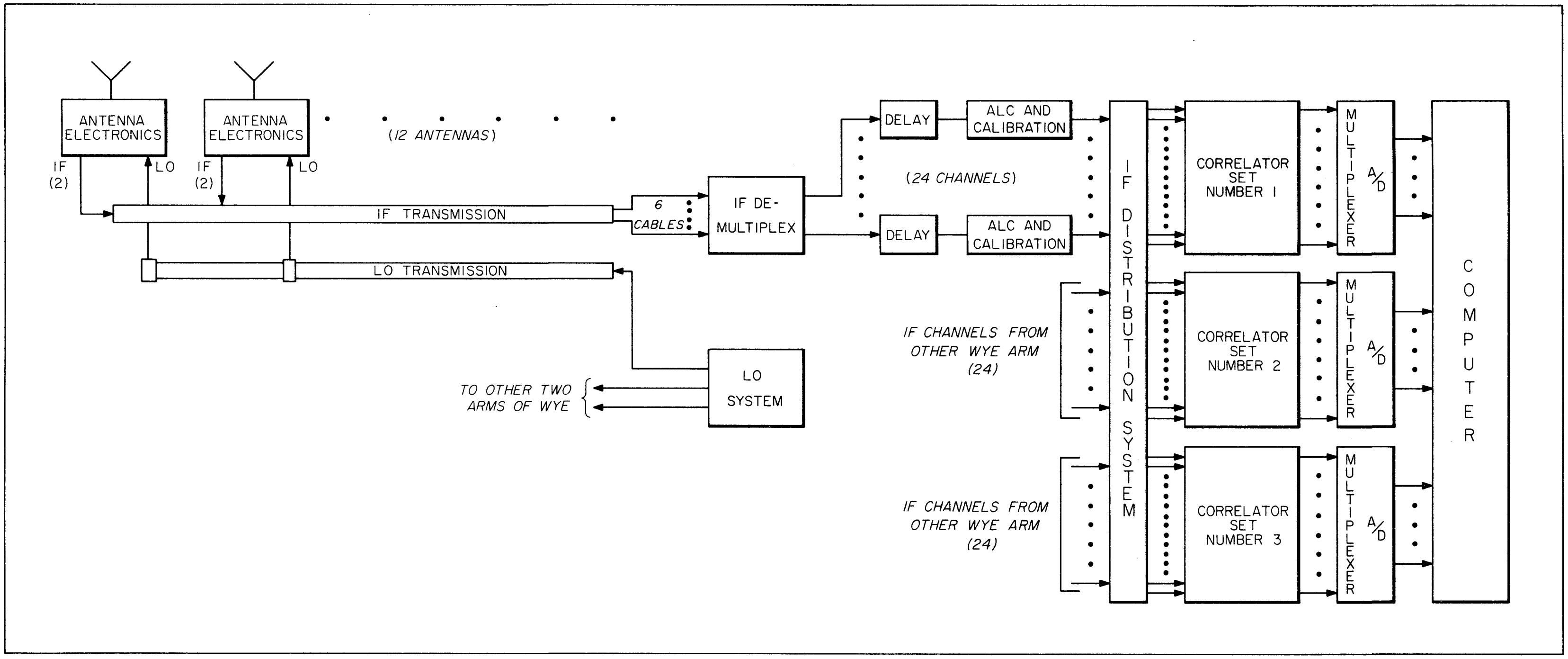


Figure 13 - 3. Simplified block diagram showing major system blocks.

Antenna Electronics (Fig. 13-4) - The antenna electronics block consists of the following circuitry:

1. Antenna feed assemblies

These will consist of three separate feeds, only one of which will be in place at a given time. One feed will be a dual frequency horn with a single polarization output at each frequency. The other two feeds will be single frequency with dual polarization (right and left circular) outputs. The latter will be designed for center frequencies of 2695 MHz and 5390 MHz. All feed assemblies will be of the Cassegrain prime feed type and will be fixed relative to the antenna reflector. Focusing will be achieved through motion of the Cassegrain sub-reflector.

2. Calibration and test circuitry

This circuit provides for two major tests and calibrations. A modulated noise tube signal inserted into the signal channel prior to the RF amplifiers provides for a continuous measure of system gain and noise figure. This information is needed to correct for the action of the ALC following a system noise figure change. In addition to the modulated noise tube, a swept-frequency oscillator signal can also be injected between observations in order to measure the symmetry of the double sideband system.

3. RF amplifiers

This item includes the low-noise degenerate parametric amplifiers (up to 4 at each frequency), their associated pump circuitry and phasing adjustments, and the final tunnel diode amplifiers in each channel. In addition, a ferrite switch is located between the two paramps in each channel. This switch will be used to provide a switched radiometer output from each antenna during calibration of the antenna pointing correction curves. In addition, it is useful during the phase adjustment of each paramp.

4. IF conversion

This includes the IF mixer preamp for each channel, LO input and the first stage IF driver amplifiers.

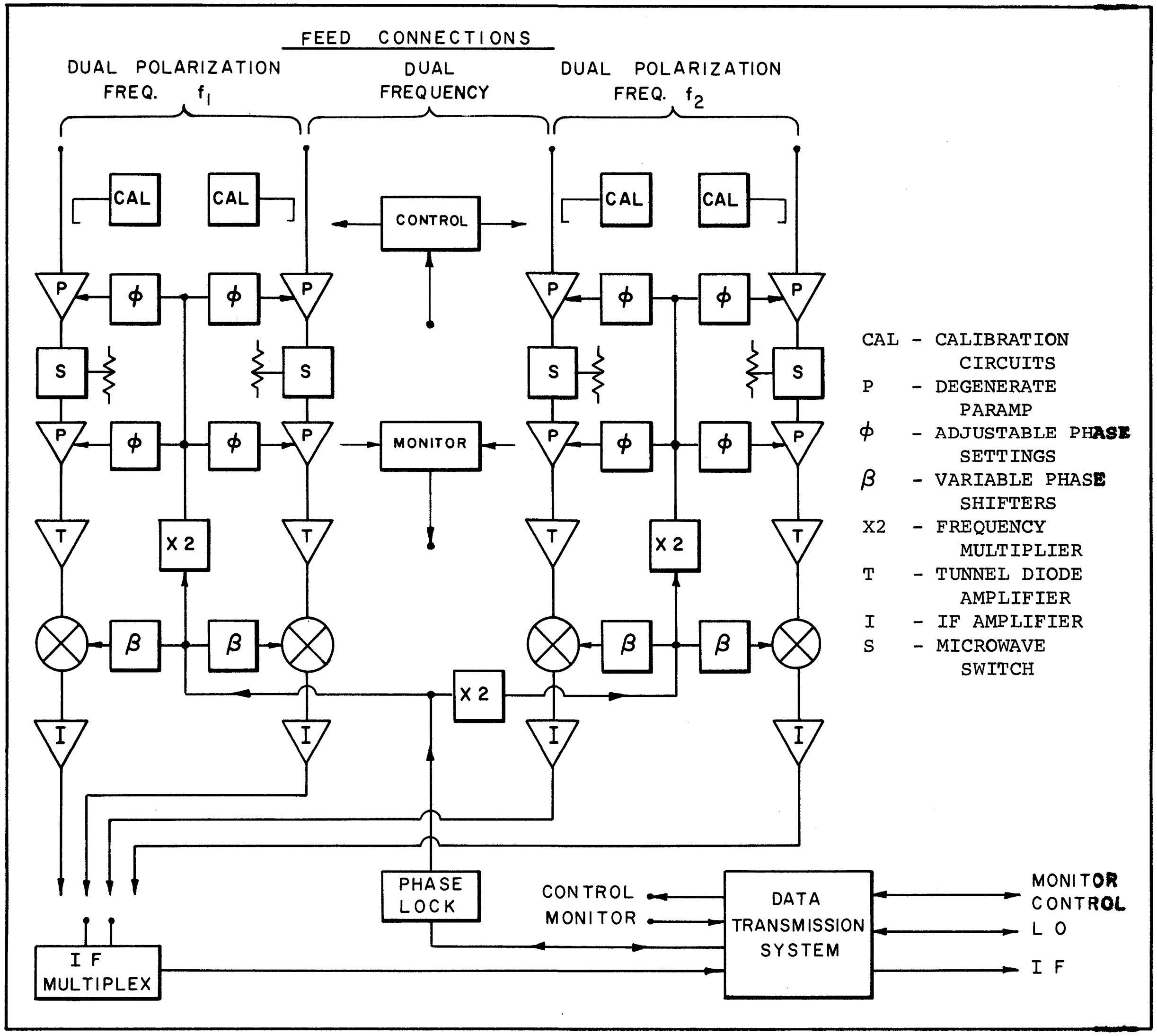


Figure 13 - 4. Antenna electronics.

5. Monitor and control

The monitor and control functions within the antenna electronics block will be summarized in a later section.

A block diagram and specifications for most of the antenna electronics block will be found in Chapter 15.

Local Oscillator System (Fig. 16-3a) - The two primary functions of the LO system are: 1) provide a phase-locked signal to each antenna electronics block to be used as mixer and paramp pump signals, and 2) phase modulate these signals in such a way as to generate a discrete set of constant fringe frequencies at the output of the correlators. The manner in which the first function is achieved is described in Chapter 14, The Local Oscillator System. The lobe rotation system will be described here.

Consider any two antennas, designated ℓ and m, of the array. Their location will be described by means of the distance vectors $\underline{r}_\ell$ and $\underline{r}_m$ joining some arbitrary origin (taken as the center point of the wye) to the phase centers of the respective antennas. From the same origin consider the unit vector $\underline{s}$ directed toward the source under observation. The delay of the source signals at the antennas with respect to that at the origin of coordinates is

$$\tau_\ell = -\frac{1}{c}\ (\underline{r}_\ell \cdot \underline{s})$$

$$\tau_m = -\frac{1}{c}\ (\underline{r}_m \cdot \underline{s})$$

The fringe term in the output of the correlator joining these two antennas will be seen to be (from Section B)

$$\rho_{\ell m} = \cos\left[\frac{2\pi}{\lambda}\ (\underline{r}_\ell - \underline{r}_m) \cdot \underline{s} + \beta_\ell - \beta_m\right]$$

assuming the term $\Delta\gamma$ has been calibrated out. If β_m and β_ℓ are held constant (no lobe rotation) then $\rho_{\ell m}$ will have the "natural" fringe frequency determined by the source motion $\dot{\underline{s}}$ and the baseline constants $(\underline{r}_{\ell} - \underline{r}_m)$ for these two antennas. However, if β_{ℓ} and β_m are phase shifters under computer control, then their settings may be continually adjusted so that

$$-\beta_{\ell}(t) = \frac{2\pi}{\lambda} \; (\underline{r}_{\ell} \cdot \underline{s}) - \omega_{\ell} t$$

$$-\beta_m(t) = \frac{2\pi}{\lambda} \; (\underline{r}_m \cdot \underline{s}) - \omega_m t$$

The "lobe-rotated" correlator output then reduces to

$$\rho_{\ell m} = \cos\, (\omega_{\ell} - \omega_m) t$$

Thus the correlator output is of constant frequency, independent of $\underline{r}_{\ell}$, $\underline{r}_m$, and $\dot{\underline{s}}$. A discrete set of M equally-spaced values ω_i, i = 1,2,...M, $(\omega_i \neq \omega_j)$ can then be selected to give a finite set of (M-1) frequencies $\omega_i - \omega_j$ for the $\frac{1}{2}$ M(M-1) correlators. The advantages of such a scheme are immediately obvious from the standpoint of the data reduction requirements on the computer. These considerations are discussed in Chapter 20, The Computer System.

<u>Data Transmission System (Fig. 16-3a)</u> - One of the major design problems for the VLA is the communication between the various electronic system blocks. There are three primary requirements, all of which require the transmission of signals along the arms of the wye between the individual antennas and the central processing facility at the center of the array. These are:

1. Transmission of the broadband (50 MHz) IF signals (2 for each antenna) from the individual antenna electronics blocks to the delay blocks.

2. LO transmission from the master LO to the antennas.

3. Transmission of all monitor and control data to and from the computer.

The major problems associated with this requirement arise from the large bandwidth of the IF signals and the large distances involved. The technique which seems most promising at present is a buried cable transmission system. Burying the cable is a definite requirement for phase and group delay stability of the transmission system.

Three buried cable designs have been considered. The first is the simple straightforward approach of using separate cables running to each antenna from the center of the array. For the full 1" array, however, this approach involves a vast amount of cable at a prohibitive cost. The second technique involves multiplexing many of the IF signals onto a single cable with separate cables for the LO distribution and the monitor and control signals. The third approach is to multiplex all signals transmitted along each arm of the wye onto a single cable. The latter two methods cut down on cable costs but add to the complexity of the system in addition to adding the cost of the multiplexing equipment. A trade-off between cost, complexity and reliability has to be made. The detailed discussion of this trade-off along with the recommended data transmission system block design is found in Chapter 16.

Delay System (Fig. 13-5) - The delay system must provide two delay units for each antenna (one for each IF channel). The operation of the delay units must be such that the difference between signal delays at the outputs of all delay units is approximately zero (less than approximately 1 ns for the 50 MHz bandwidth for a 1% amplitude error). Using the vector notation introduced under the section LO System above, the signal delay from the m^{th} antenna relative to the center of the array is

$$\frac{1}{c}\left(|\underline{r}_m| - \underline{r}_m \cdot \underline{s}\right)$$

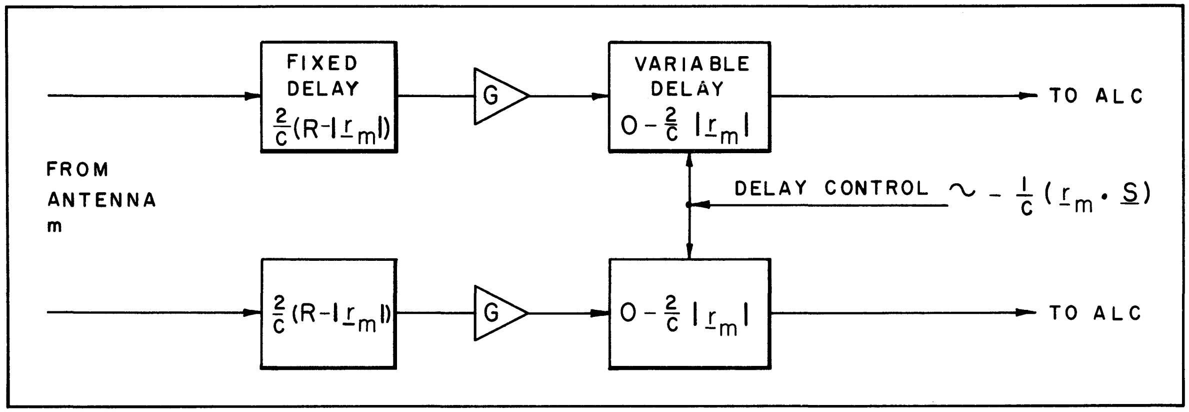


Figure 13 - 5. Delay unit (per antenna).

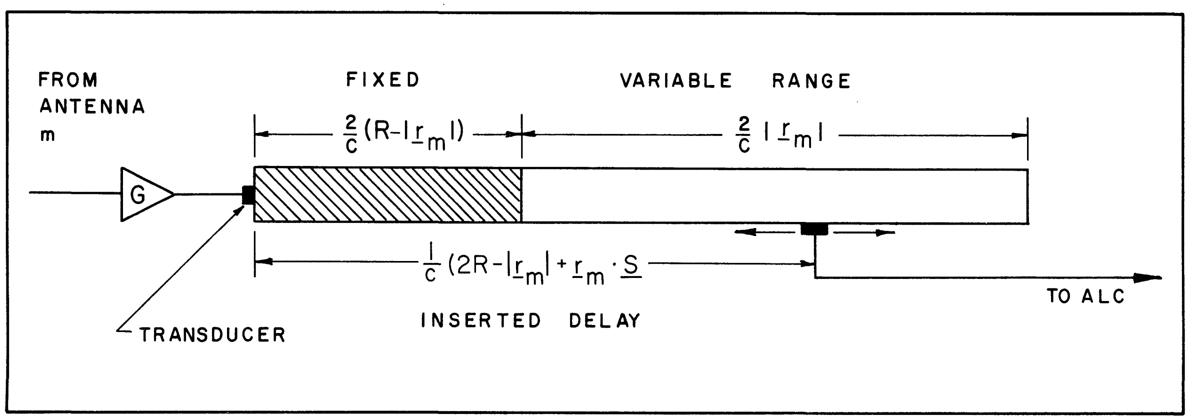


Figure 13 - 6. Application of single variable delay of total delay 2R/C.

where the transmission delay to the center (assuming free space transmission speed) has been included. By inserting a (necessarily positive) delay

$$\frac{1}{c}\,(2R - |\underline{r}_m| + \underline{r}_m \cdot \underline{s})$$

all delay unit outputs will have the same net delay $\frac{2R}{c}$ and the zero difference condition is satisfied. Here $R = |\underline{r}_m|_{max}$.

Note that all antennas require the same total maximum delay, $\frac{2R}{c}$, independent of their location within the array. This is not strictly true if the cable transmission velocity is significantly less than c, and if there is no antenna located at the center of the array. However, for the anticipated data transmission system and array configuration the difference is small. The proportion of the total delay which must be variable does however depend on the location of the antennas. Thus the total delay consists of a fixed part τ_f and a variable part τ_v where

$$\tau_f = \frac{2}{c}\,(R - |\underline{r}_m|)$$

$$0 \leq \tau_v \leq \frac{2}{c}\,|\underline{r}_m|$$

One approach to the design of the individual delay units would be to make them all identical. This would mean each unit is variable over its entire range of delay $\frac{2R}{c}$ in order to satisfy the condition for the outermost antennas $|\underline{r}_m| = R$ since

$$0 \leq \tau_v \leq \frac{2}{c}\,|r_m| \;.$$

For the closer antennas, a portion of the variable range would be used for the fixed delay, the remainder constituting the variable part as shown in Fig. 13-6. An advantage in this approach is that only one set of input-output transducers is required for each delay unit. The crucial question is whether or not a single variable delay of maximum delay $\frac{2R}{c}$ can be produced. For the 1" array this amounts to 140 μ sec. This question is further discussed in Chapter 17.

The operation of the delay unit then consists simply of computer control of the variable part of the delay unit for each antenna

$$\tau_{v,m} = \frac{1}{c} (\underline{r}_m \cdot \underline{s})$$

This control function computation is then identical to that which calculates the lobe-rotator setting for the m^{th} antenna

$$-\beta_m(t) = \frac{2\pi}{\lambda} (\underline{r}_m \cdot \underline{s})$$

ALC and Calibration (Fig. 13-7) - Variations in the total system gain in any single channel of the array will cause amplitude errors in the computed output of (M-1) correlators. Such gain variations are very difficult to control on an individual basis. This is particularly true for the variable delay unit. The very nature of most variable delay designs makes it extremely difficult to maintain a constant loss through it.

The ALC unit inserted in the IF channel cancels the effect of such gain and loss variations by maintaining a constant output power independent of the input power. This is done most simply by gain controlling the final IF drive amplifier prior to the IF division and correlators with an error signal derived from the amplifier output.

Unfortunately, the action of the ALC responds to noise figure changes in addition to gain changes, and thus introduces an error which can not be sorted out without the aid of additional information. The latter is furnished by the calibration circuitry. This unit responds to the modulated noise tube signal injected in the antenna electronics block. The calibration unit has as output the relative system noise figure and gain.

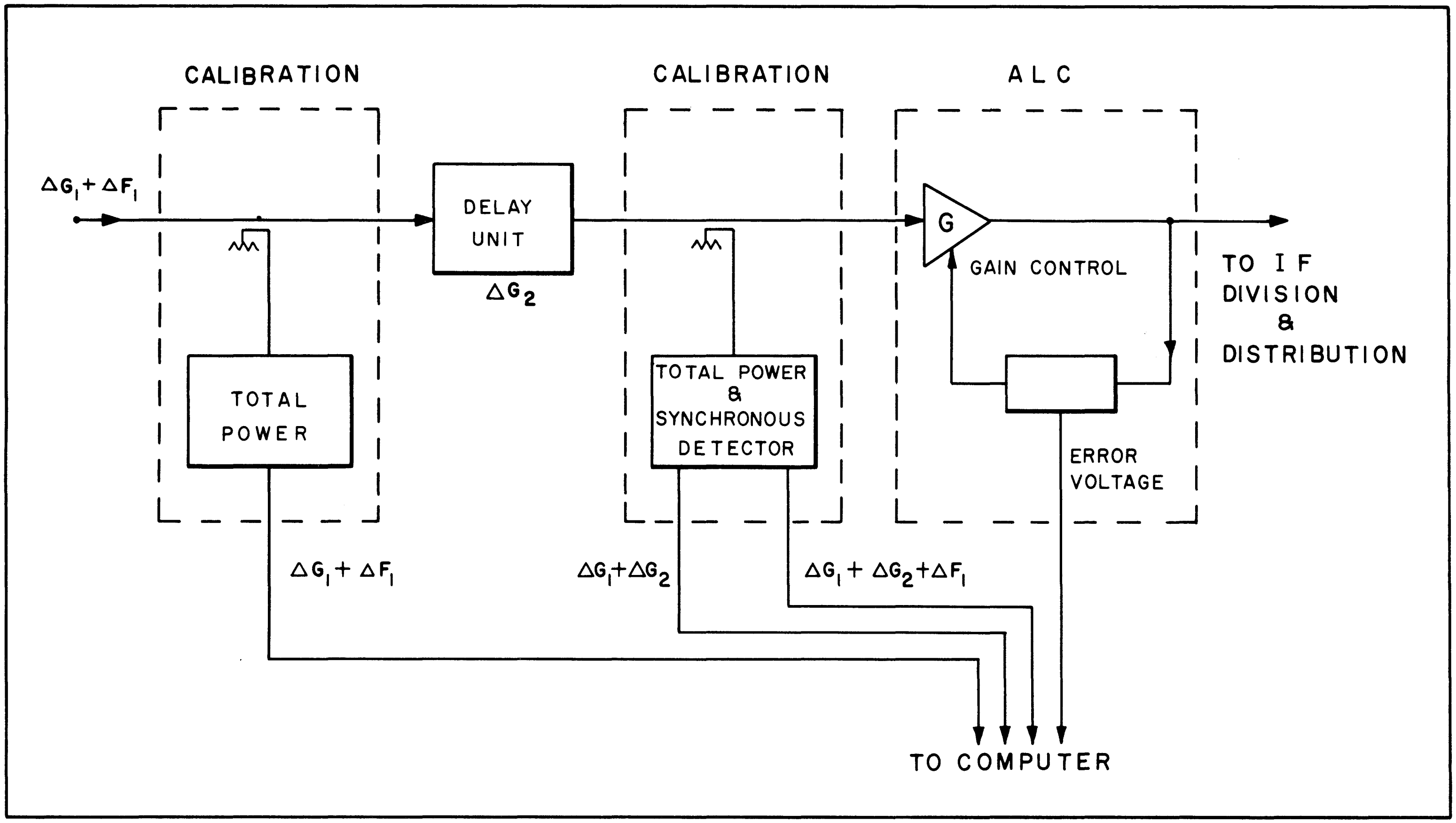


Figure 13 - 7. ALC and calibration units (per channel).

Further information relating to these units is found in Chapter 18.

Signal Division and Correlators (Fig. 13-8) - The signal from any given antenna must be correlated with that from the other M-1 antennas. Hence the signal from each antenna must be split into M-1 separate channels, fed into a distribution network which arranges these into pairs with the signals from the other antennas and then inputs these pairs into the $\frac{1}{2}$ M(M-1) correlators. The major problem for this block arises from the fact that the number of components required is now proportional to M^2 rather than M as in most previous blocks.

Thus economy of design is of paramount importance. In order to maintain a low unit cost necessitates minimizing the number of active elements in the design. The design and cost details for this block are discussed in Chapter 18.

A/D Converters and the Computer - The function of the A/D converters is to sample the correlator outputs and convert the data into digital form for input to the computer. A standard A/D converter of 11 to 12 bit resolution is sufficient to ensure that the "digitization noise" is always much less than the receiver thermal noise.

Minor System Blocks - There are several system blocks listed under this category which are, nevertheless, essential to the successful operation of the array. They are separated out simply because they do not appear in the signal-flow diagram of Fig. 13-3 showing what has been termed the major system blocks. The present category includes:

1. Control System
2. Monitor System
3. Display and Test

The specific monitor and control functions are discussed in Chapter 20, The Computer System. The display and test system must necessarily evolve from the detailed design of the other electronic system blocks and from the requirements imposed by maintenance and operating procedure considerations. Fig. 13-9 shows the general relationship of these minor system blocks to the rest of the electronics system.

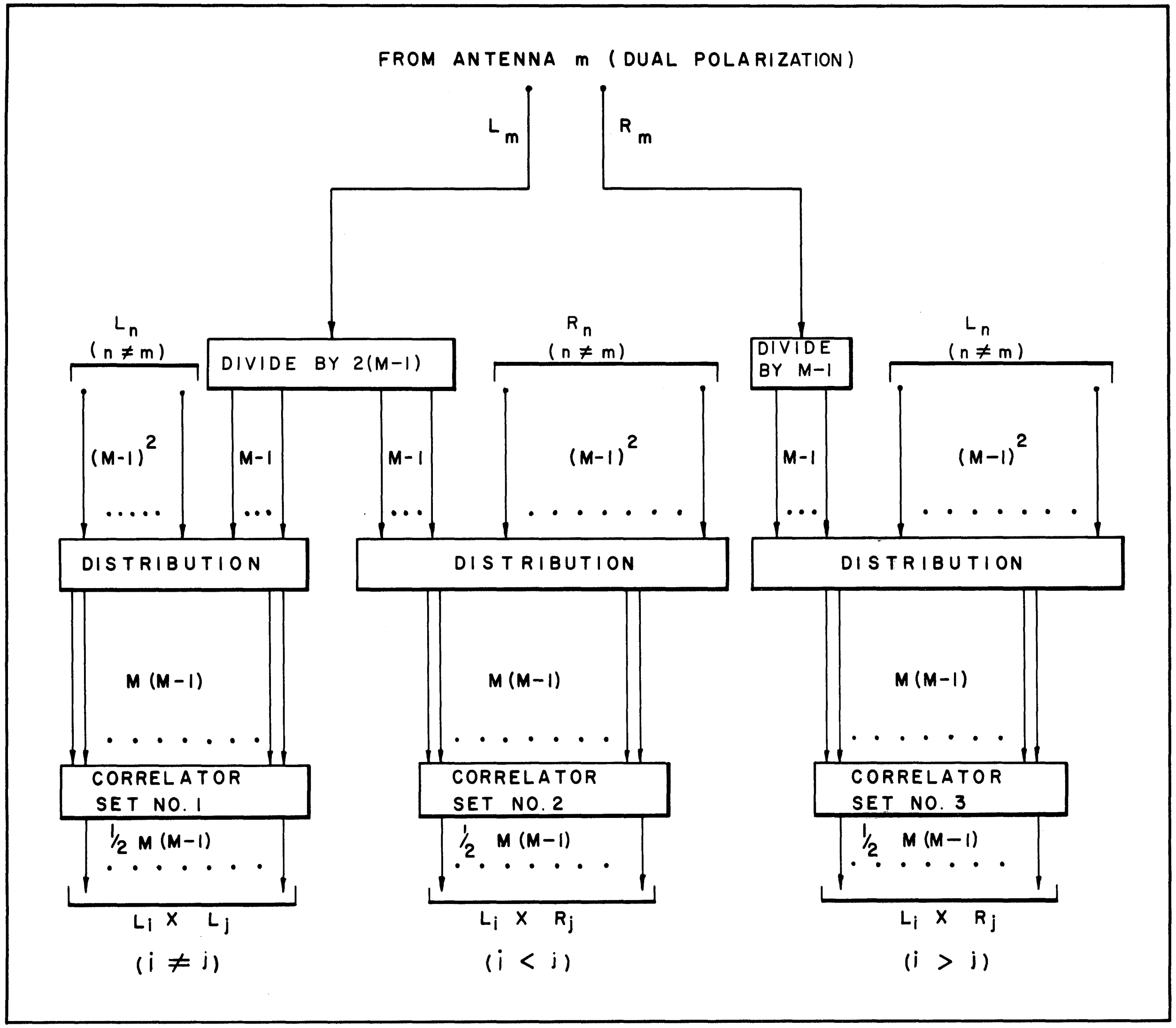


Figure 13 - 8. Signal division, distribution, correlators.

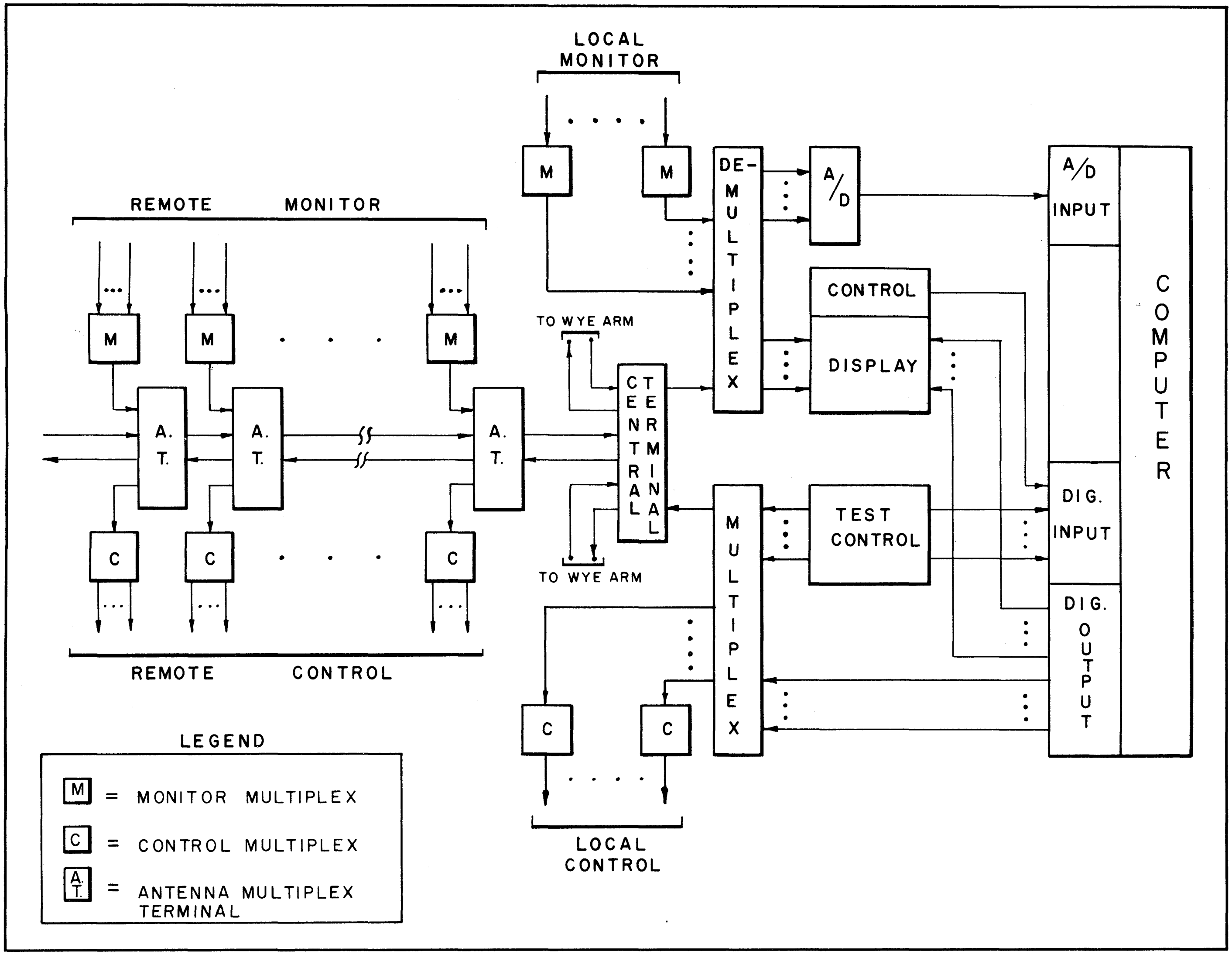


Figure 13 - 9. Minor system blocks (monitor, control, display and test).

D. Appendix - Analysis of a Double Sideband Interferometer Utilizing Degenerate Parametric Amplifiers

The Fourier transform-pair relating the cross-correlation function $\phi_{12}(\rho)$ and the cross-power density spectrum $\Phi_{12}(\omega)$ is

$$\phi_{12}(\rho) = \int_{-\infty}^{\infty} \Phi_{12}(\omega)\, e^{j\omega\rho}\, d\omega$$

$$\Phi_{12}(\rho) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \phi_{12}(\rho)\, e^{-j\omega\rho}\, d\rho$$

Extensive use will be made of the correlation function defined here as $\phi_{ss}^{I}(\rho)$ which is obtained by taking the Fourier transform of the (double-sided) IF spectrum shown in Fig. 13-2. Thus,

$$\phi_{ss}^{I}(\rho) = 4\pi B \cos \omega_1\rho \cdot \left(\frac{\sin \pi B\rho}{\pi B\rho}\right)$$

Referring to the block diagram of Fig. 13-1 and the discussion of Section B, the following signals and correlation functions are identified:

1. Paramp pump signals

$$p(t) = \cos\,(2\omega_o t - 2\beta - \phi)$$

$$p'(t) = \cos\,(2\omega_o t - 2\beta' - \phi')$$

$$\phi_{pp'}(\rho) = \frac{1}{2} \cos\,(2\omega_o\rho + 2\Delta\beta + \Delta\phi)$$

2. Local oscillator signals

$$\ell(t) = \cos\,(\omega_o t - \beta - \gamma)$$

$$\ell'(t) = \cos\,(\omega_o t - \beta' - \gamma')$$

$$\phi_{\ell\ell'}(\rho) = \frac{1}{2} \cos\,(\omega_o\rho + \Delta\beta + \Delta\gamma)$$

The cross correlation between the signal voltages at the antenna inputs (assuming completely correlatable noise voltages) is

$$\phi_{ss'}(\rho) = \phi_{ss}(\rho-\tau) = \int_{-\infty}^{\infty} \Phi_{ss}(\omega)\, e^{j\omega(\rho-\tau)}\, d\omega$$

$$\phi_{ss}(\rho-\tau) = 2 \cos \omega_o(\rho-\tau) \cdot \phi_{ss}{}^{I}(\rho-\tau)$$

The action of the degenerate parametric amplifiers can be analytically described by (see notation of Fig. 13-1)

$$e(t) = [1 + 2p(t)] \cdot s(t) \ ,$$

$$f(t) = [1 + 2p'(t)] \cdot s(t-\tau) \ ,$$

neglecting the gain factor. These expressions do not take into account the filtering action of the amplifiers. This will be taken into account by inspecting the form of the correlation functions. The cross-correlation between the paramp output signals is (unfiltered)

$$\phi'_{ef}(\rho) = [1 + 4\phi_{pp'}(\rho)]\ \phi_{ss}(\rho-\tau)$$

After filtering is taken into account, this reduces to

$$\phi_{ef}(\rho) = 4 \cos\left(\omega_o\rho + \Delta\beta + \frac{\Delta\beta}{2}\right) \cdot \cos\left(\omega_o\tau + \Delta\beta + \frac{\Delta\beta}{2}\right) \cdot \phi_{ss}{}^{I}(\rho-\tau)$$

The unfiltered mixer outputs are described by the cross-correlation function

$$\phi_{gh}(\rho) = \phi_{\ell\ell'}(\rho) \cdot \phi_{ef}(\rho)$$

The filtering actions of the IF amplifiers (which pass only the IF portion of the spectrum shown in Fig. 13-2) yields, as the cross-correlation between the amplifier outputs

$$\phi_{uv}(\rho) = \cos\left(\Delta\gamma - \frac{\Delta\phi}{2}\right) \cdot \phi_{ss}{}^{II}(\rho-\tau)$$

where

$$\phi_{ss}^{II}(\rho) = \cos\left(\omega_o\tau + \Delta\beta + \frac{\Delta\phi}{2}\right) \cdot \phi_{ss}^{I}(\rho)$$

The delay network is represented by the transfer function

$$D_n(\omega) = e^{-j\omega\tau_n}$$

The cross-power density spectrum at the output of the delay network is then

$$\Phi_{xy}(\omega) = D_n^*(\omega) \cdot \Phi_{uv}(\omega)$$

From this expression, the cross-correlation function $\phi_{xy}(\rho)$ is obtained by a Fourier transform yielding

$$\phi_{xy}(\rho) = \phi_{uv}(\rho + \tau_n)$$

Thus finally,

$$\phi_{xy}(\rho) = \cos\left(\Delta\gamma - \frac{\Delta\phi}{2}\right) \cdot \phi_{ss}^{II}(\rho+\tau_n-\tau)$$

The definition of $\phi_{xy}(\rho)$, is, for random signals x(t) and y(t),

$$\phi_{xy}(\rho) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} x(t) \cdot y(t+\rho)dt$$

Therefore the actions of the correlator (followed by a low-pass filter) may be approximated by

$$\phi_{xy}(o) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} x(t) \cdot y(t)\, dt ,$$

where the correlator is assumed to be a perfect multiplier and the filter a perfect integrator.

Thus the smoothed correlator output is given by

$$\phi_{xy}(o) = \cos\left(\Delta\gamma - \frac{\Delta\phi}{2}\right) \cdot \phi_{ss}^{II}(\tau-\tau_n)$$

or

$$\phi_{xy}(o) = 4\pi B \cos\left(\frac{\Delta\phi}{2} - \Delta\gamma\right) \cdot \cos \omega_1(\tau-\tau_n) \left[\frac{\sin \pi B(\tau-\tau_n)}{\pi B(\tau-\tau_n)}\right] \cdot \cos\left(\omega_o\tau+\Delta\beta+\frac{\Delta\phi}{2}\right)$$

which is the equation (13-2), to within a constant factor.

Chapter 14

LOCAL-OSCILLATOR SYSTEM

Chapter 14

LOCAL-OSCILLATOR SYSTEM

A. Requirements

The local-oscillator (LO) distribution system must provide high purity sinusoidal signals to mixers in the front-end boxes of each antenna. The difference in phase of any two of these LO signals must remain constant over an 8 hour period to within an rms error of 2° at 2695 MHz and 4° at 5390 MHz. The constant phase differences need not be known and the phase stability over periods longer than 8 hours is not important because these phases will be measured using astronomical radio sources at intervals no longer than every 8 hours. The preservation of phase stability between antennas which may be as far apart as 36 km (325,000 λ at 2695 MHz) is the major design problem in the LO distribution system.

The amplitude stability of the LO signal is not too critical for mixer conversion loss stability but is critical for paramp gain stability since the LO will be passed through a frequency doubler and used to pump the degenerate paramp. An LO amplitude stability of $\pm$ .02 dB per 8 hours is required; this can be met with a closed loop leveler system operating in the temperature controlled front-end enclosure.

Noise which is on the LO signal and is between 2 MHz and 50 MHz of the carrier can be a source of difficulty. Noise which is correlated between one antenna and another will cause spurious correlator outputs. With 8 hours of integration and 48 MHz of IF bandwidth, signals 60 dB below receiver noise are detectable. Assuming 50 °K receiver noise, 27 dB paramp gain, and 23 dB mixer LO rejection, a correlated noise of less than 5 °K is required (-111 dBm in 100 MHz bandwidth). This figure is easily provided if there is a phase-locked oscillator in each LO signal line with the loop bandwidth being much less than 2 MHz.

Assuming the same numbers as above, the uncorrelated noise on each LO signal must be less than 50,000 °K (-71 dBm in 100 MHz bandwidth) to cause less than 1% increase in receiver noise temperature.

B. General Design Approach

The phase stability requirement cannot be met with a simple distribution system; a round-trip phase correcting system must be utilized. For a simple cable distribution system, the temperature coefficient of the phase delay in the cable (typically 20 ppm/°C) would necessitate that the cable temperature be kept uniform to within .0016 °C. Temperature compensated cable would relax the temperature requirement by an order of magnitude but this is not enough. Furthermore, this cable is expensive and pressure variations will also cause difficulty.

If a simple air link is used with no phase correcting system, a uniformity of .03 N units in the index of refraction is required. (This requirement is a factor of 3 more stringent than the uniformity requirement in the atmospheric RF signal path from the astronomical source to the array since the scale height of the atmosphere is only about 1/3 the length of an arm of the array.) Furthermore, the spacing between receiving and transmitting antennas must be held constant to within .6 mm and multi-path will also cause phase instabilities.

Fortunately, phase correcting systems can be devised so that the phase stability required by the VLA can be achieved without requiring unusually stable components. The basic principle of all such phase correcting systems is illustrated in Fig. 14-1 and is explained in the caption of the figure. The basic point is that the phases of two signals can be compared only if they are in the same physical location. If we must measure the phase of widely separated signals, a round-trip measurement must be made and 1/2 the phase delay is assigned to each direction. Once the phase delay is measured, its variation can be corrected with a servo-controlled phase shifter or corrected for in the processing of data.

Many variations of the system shown in Fig. 14-1 have been investigated. The first conclusion is that in order to insure that the phase delays in the forward and return signals are identical, an identical signal path (cable or air-link) must be used. A means must then be devised for separating the forward and return signals. Directional couplers and circulators do not provide sufficient isolation to overcome the large differences in forward and return signals caused by cable attenuation. Time multiplexing and frequency multiplexing have been examined and frequency multiplexing has been chosen for the system proposed in this report.

The frequencies of forward and return signals must, of course, be close together so that the phase variations are nearly identical.

A second major question concerns the choice of transmission medium. The three choices which require serious consideration are laser beams, microwave air-links, and coaxial cables. Most of the effort and experience up to this time has been directed to coaxial cable distribution systems. A quite feasible coaxial cable distribution system will be presented in detail later in this chapter. The coaxial cable offers a well known and well controlled transmission medium and requires less electronic equipment than a microwave link system.

At the present time laser beam transmission methods do not have the proven reliability of a microwave air link or coaxial cable system. The transmitters, receivers, and optical properties of the atmosphere are currently active research areas and it does not appear prudent at this time to base the design of a complex instrument such as the VLA upon these techniques. However, further study of laser transmission methods both for LO and IF data transmission is planned. (An excellent review article on optical transmission research is given by S.E. Miller and L.C. Tillotson in Proc. of the IEEE, October 1966.)

C. The Proposed System

A coaxial cable round-trip phase correcting has been proposed by Dr. John Granlund of ITT Federal Laboratories. This system has four very important advantages:

1. The system provides a phase-corrected LO signal to each antenna with a single coaxial cable trunk line. A single cable to each antenna is not required as might be expected from examination of Fig. 14-1.

2. The phase correction is achieved without a requirement for servo-controlled phase shifters (with limited dynamic performance and range). The correction is achieved by mixing with a signal whose phase error is equal and opposite to the first signal.

3. The system must tolerate only one-way attenuation loss. Other systems, such as that of Fig. 14-1, must tolerate a round-trip loss between the master oscillator and the phase-measurement point.

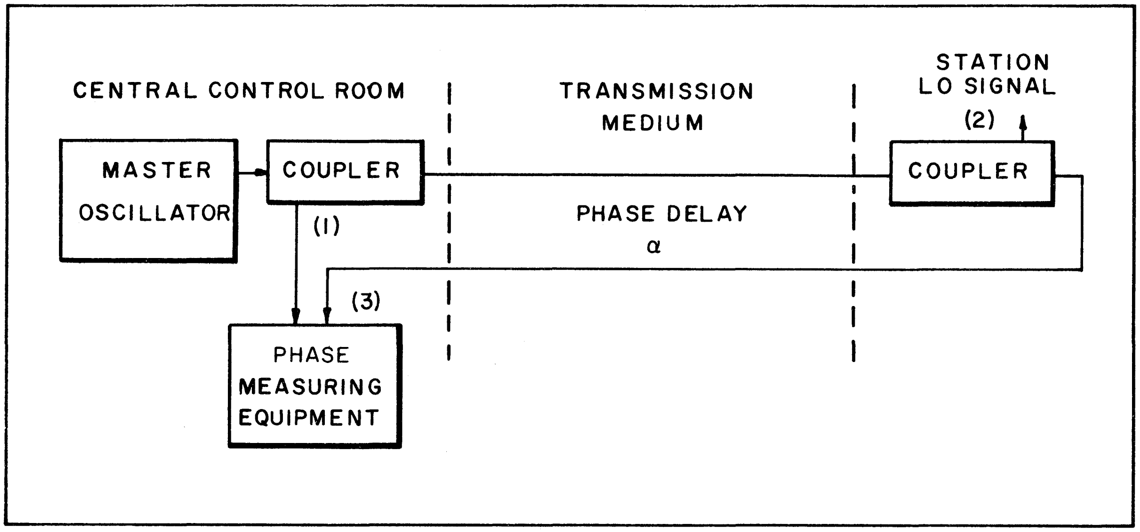


Figure 14 - 1. Round-trip phase measuring system. We wish to determine the phase delay, α, between point (1) and point (2). This is accomplished by measuring the phase delay, 2α, between points (1) and (3) and assuming that 1/2 of the delay has occurred in the (1)-(2) path.

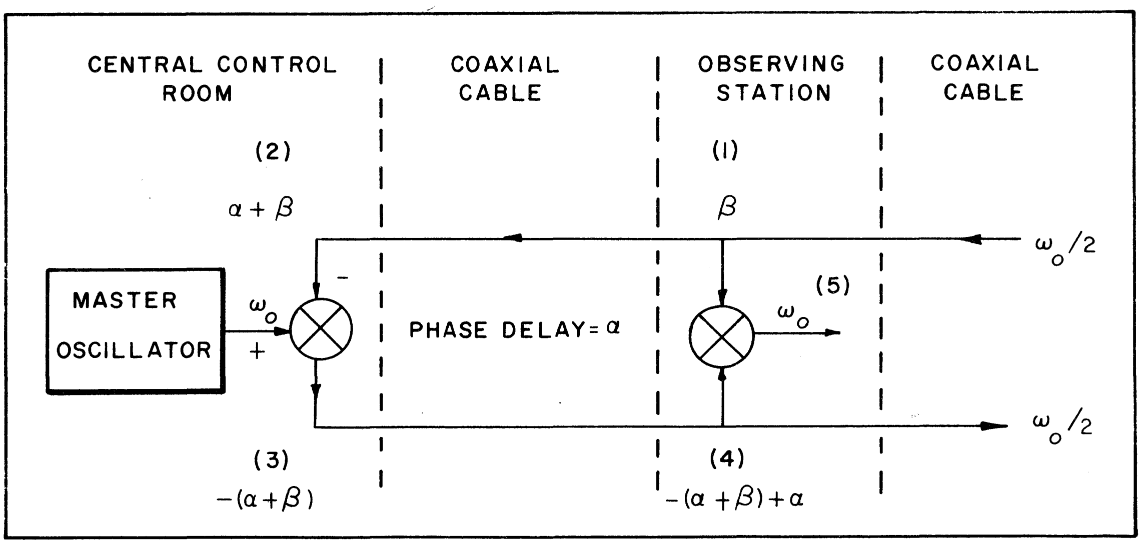


Figure 14 - 2. Principle of the proposed phase correction system.

4. The signals on the coaxial cable have approximate frequency $1/2\omega_{LO}/N$, where N is the frequency multiplication factor at each antenna. Most other systems that have been examined require signals of ω_{LO}/N and thus have $\sqrt{2}$ more cable attenuation.

The system, in its simplest form, is shown in Fig. 14-2. Assume that a signal at approximate frequency $\omega_o/2$ (where $\omega_o = \omega_{LO}/N$) is propagating towards the central control room. This signal has arisen from an oscillator at the far end of the trunk line and its exact frequency and phase are only of secondary importance. Assume that this signal has phase, β, at point (1) and $\alpha + \beta$ at point (2). At the central control room the signal is mixed with the master oscillator at frequency, ω_o. The difference frequency output will also be at a frequency of approximately $\omega_o/2$ and will have phase, $-(\alpha + \beta)$ at point (3). The reversal of the sign of the phase shift is fundamental to the operation of the system. The signal accumulates a further phase shift, α, to give phase, $-(\alpha + \beta) + \alpha = -\beta$ at point (4), the observing station. This signal is then mixed with the original signal (1), having phase $+\beta$. The upper sideband is kept and the result is a signal at frequency, ω_o, and in phase with the master oscillator independent of α and β.

In reality the forward and return signals shown in Fig. 14-2 would be carried on a single cable and directional couplers would be used at each observing station to extract the two signals. However, the isolation that can be obtained in the couplers is not sufficient and the forward and return signals must be further isolated by frequency offsetting then by $-\omega_a$ and $+\omega_a$ from $\omega_o/2$.

The proposed system is analyzed in Section E, where the effects of the frequency, ω_a, finite coupler directivity, imperfect mixers, cable reflection, and cable attenuation are investigated. The pertinent results are as follows:

1. The frequency offset, ω_a, causes a phase shift $2\omega_a\tau_g$ between the master oscillator and a station located at group delay, τ_g, from the control room. (Group delay is defined as $d\Theta/d\omega$ evaluated at $\omega_o/2$ and is approximately equal to the cable length divided by the propagation velocity.) For $2\omega_a = 2\pi \times 10^5$ and $\tau_g = 82$ μs (station at 21 km), this phase shift is 2960°. The absolute value of the phase shift is not important but the stability is important. In order to achieve 0.1°

phase stability at $\omega_o = 2\pi \times 448 \times 10^6$, ω_a must be constant to within 1.7 Hz and τ_g must be constant to within $(33 \times 10^{-6})\tau_g = 2.7$ ns. The first requirement is no problem and the second requirement can be met with 20 km of buried coax having .2 °C stability and 1.3 km of exposed cable having 30 °C temperature variations.

2. Non-ideal values for coupler directivity, cable reflection, and mixer unbalance (the mixer does not act as an ideal multiplier and produces output components which are squares of the input signal) cause spurious sidebands at $\pm 2\omega_a$ from ω_o and also a spurious signal at ω_o. The sidebands can be easily removed with a phase-locked oscillator loop (see Fig. 14-6); this loop is also necessary for power gain. The spurious signal at ω_o causes a phase error of .27° (at ω_o) assuming $\omega_o = 2\pi \times 448 \times 10^6$, coupler directivity = 35 dB, mixer unbalance = 26 dB, cable VSWR = 1.10, and a cable temperature variation of 10 °C over its entire length.

The above results indicate that quite tolerable phase errors can be obtained with readily obtainable components.

It is possible to operate the LO distribution over the entire 21 km arm length without any repeaters of any sort. This can be accomplished with 1-5/8 in cable, 100 watts of transmitter power, a distribution frequency, $\omega_o/2$, of $2\pi \times 112$ MHz and mixers with 7 dB noise figure. However, this does not appear to be the optimum arrangement.

The phase correction loop need not extend over the entire 21 km. At the end of each loop the master oscillator frequency, ω_o, is available and can be used as the input to a second loop. The number of loops, L, in an arm of the array can be traded against the frequency multiplication ratio, N.

The one-way attenuation at $\omega_o/2 = \omega_{LO}/2N$ in a single loop is approximately $660/LN^{1/2}$ decibels for 1-5/8 in cable. The amount of one-way attenuation that can be tolerated in a loop is calculated as follows:

Noise in 1 Hz bandwidth ----------	-174 dBm
Mixer noise figure ---------------	+ 20 dB
5 Hz bandwidth -------------------	+ 7 dB
Signal-to-noise ratio required for 0.5° phase error at ω_{LO} ----	38 dB + 20 log N + 10 log L
Coupling value -------------------	10 dB
Margin ---------------------------	10 dB
Required receiver power ----------	- 89 dBm + 20 log N + 10 log L
Transmitted power ----------------	+ 20 dBm
Maximum tolerable attenuation ----	109 dB - 20 log N - 10 log L

Thus, the following restriction is placed on L and N

$$\frac{660}{LN^{1/2}} \leq 109 - 20 \log N - 10 \log L$$

A table of solutions is as follows:

L	N	Distribution Frequency, $\omega_o/2$
1	$\geq$ 89	$\geq$ 15 MHz
3	$\geq$ 6	$\leq$ 224 MHz
$\geq$ 7	1	1347.5 MHz

In addition to the above discussion, the following factors must be considered in the choice of L and N:

1. The phase error in individual loops will contribute to mean square LO phase error, $\Delta\phi^2$, in the following way:

$$\Delta\phi^2 = LN^2 \left(a^2 + \frac{b^2}{N^2}\right)$$

where a^2 is the mean square phase error in a loop operated at very low frequency and $a^2 + b^2$ is the mean square phase error in a loop operated at $\omega_o/2 = 1347$ MHz. These constants which describe the error in a loop as a function of its operating frequency are not known at present. Assuming that b = 10a and using the cable attenuation restriction $L^2N \sim 60$, the value of L which minimizes $\Delta\phi^2$ is 3.

2. The reliability of the system is decreased as L increases. If an inner loop fails, the data from an entire line of antennas is lost.

3. Solid state components are more easily available and are less expensive at low frequencies; a distribution frequency $\leq$ 500 MHz ($N \geq 3$) is desirable.

4. A very stable multiplier for N = 6 was developed for the Stanford Linear Accelerator. Over 30 of these units have been constructed and very good phase stability information is available.

D. System Block Diagram

The discussion in the previous section has led to the system block diagram shown in Fig. 14-3 thru 14-6. Three loops (L = 3) are chosen along each arm of the Y. A frequency multiplication ratio, N, equal to 6 is required.

The system conveniently breaks into 3 units: LO Launchers, LO Terminators, and LO Receivers. Each of these units can be housed in a 7in x 19in x 18in volume and cost approximately $11 thousand each.

An important building block in each of the above units is the phase-locked amplifier (PLA) shown in Fig. 14-6. This unit provides phase-stable power gain, narrow band filtering, and electrically controlled phase shifting for lobe rotation purposes. The phase shift is performed at a low frequency (10 kHz) and can be accomplished with a synchro driven by a small stepping motor or by diode-switched all-pass phase shift networks.

The cost of the proposed LO system is tabulated in Table 14-1.

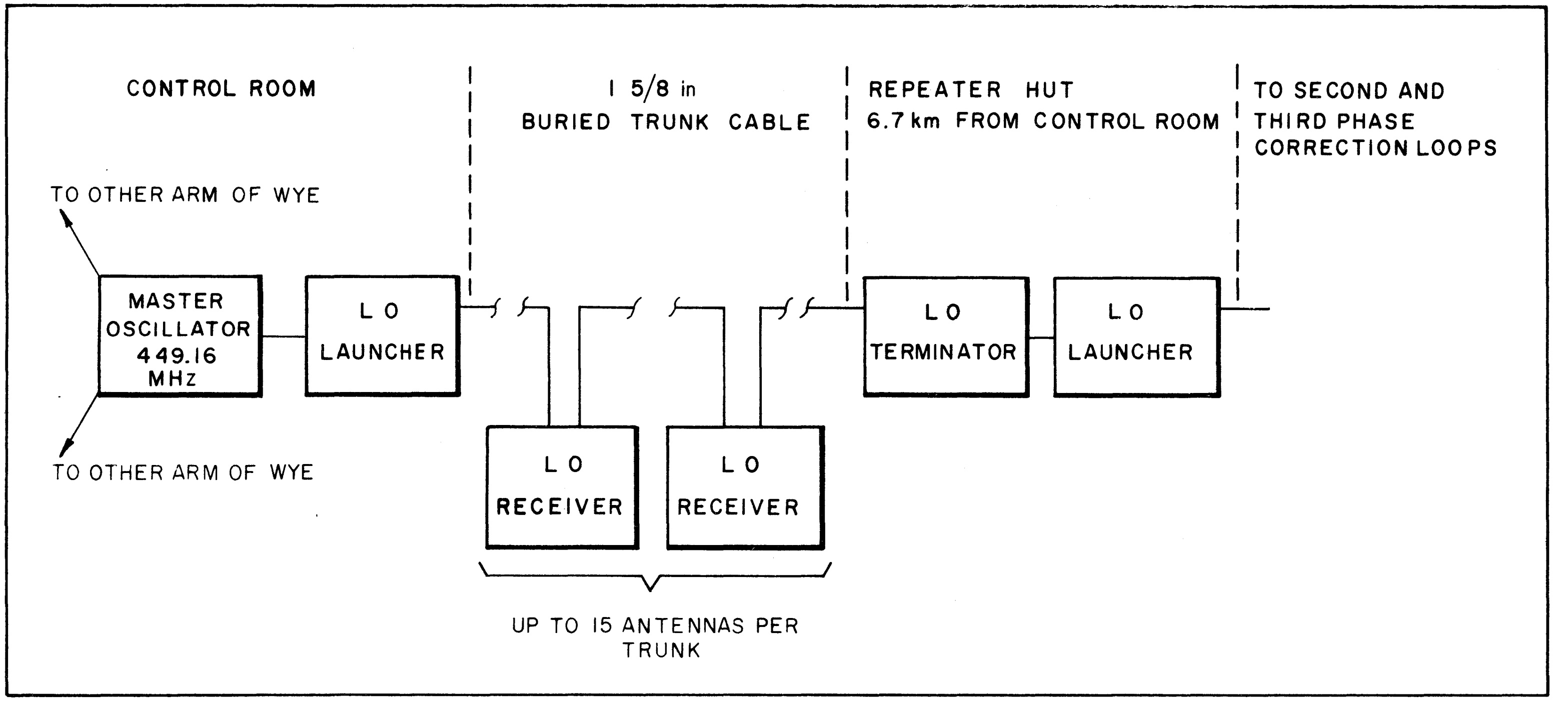


Figure 14 - 3. Master oscillator and one phase correction loop of the proposed Local Oscillator distribution system. Three loops, each 6.7 km long, are used on each arm of the WYE. The blocks are described in more detail in following figures.

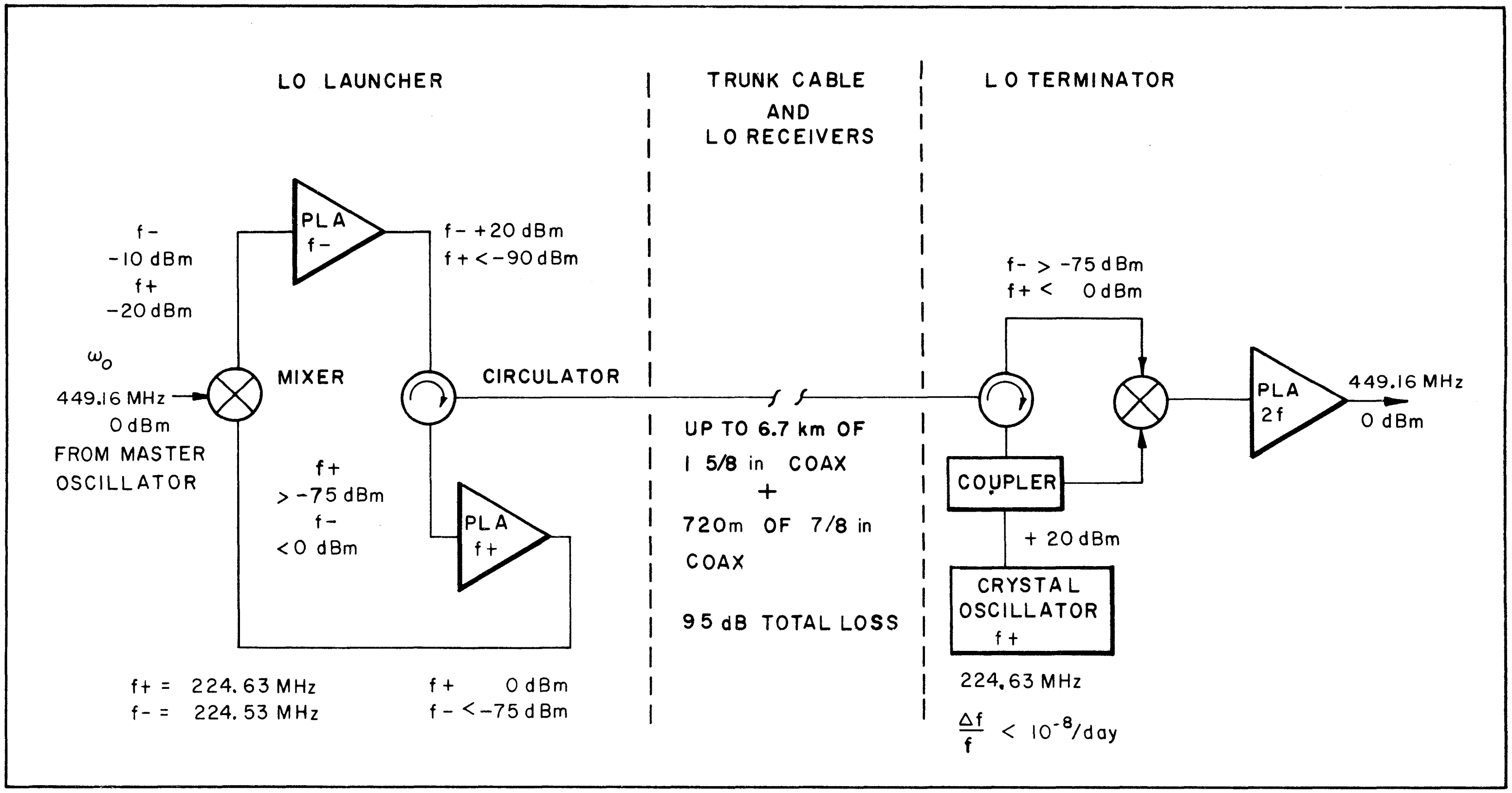


Figure 14 - 4. LO Launcher and LO Terminator units of the proposed Local Oscillator system. The blocks marked "PLA" are described in Figure 14 - 6. Nine Launchers and nine Terminators are required in the proposed system.

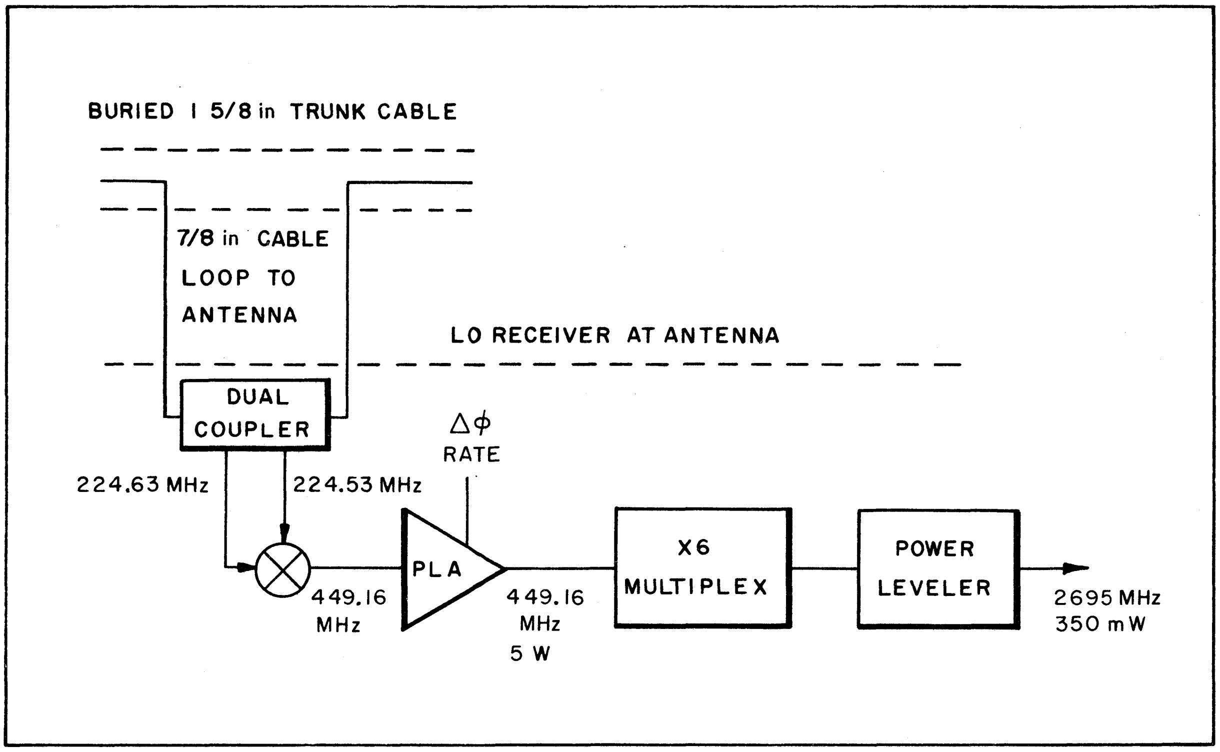


Figure 14 - 5. LO Receiver Unit. One such unit is required at each antenna in the proposed system. The receiver mixes the outgoing and return signals, amplifies and filters the sum frequency components, and multiplies and power levels the signal to provide 350 mW at 2695 MHz.

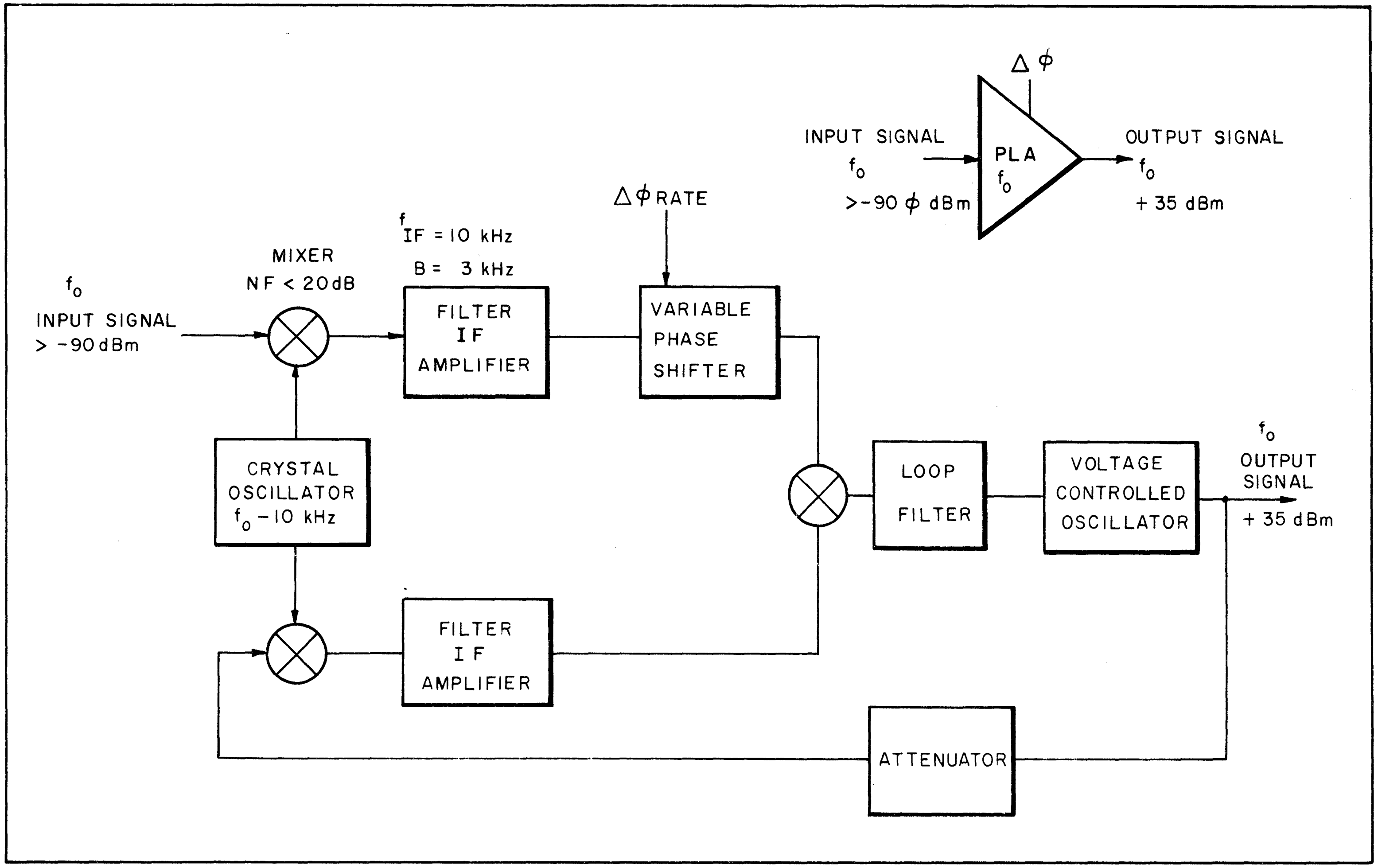


Figure 14 - 6. Phase-locked amplifier. The above configuration provides amplification, very-narrow band filtering, and phase-shifting. Units of this type are used in the proposed system at frequencies of 224.53, 224.63, and 449.16 MHz.

Table 14-1

LOCAL OSCILLATOR COST

Component	Average Unit Cost	Number Required			Total	Total Cost (Thousands)
		38 Receivers	11 Launchers	11 Terminators		
Directional Coupler	$ 200	76	22	22	120	$ 24
Crystal Mixers	200	152	66	88	316	63
IF Amplifiers	300	76	44	22	142	42
Crystal Oscillators (with oven)	300	38	22	22	82	25
Voltage Controlled RF Oscillator	500	38	22	11	71	36
Attenuators	100	152	44	11	207	21
Isolators	200	76	22	11	109	22
Circulators	200	0	11	11	22	4
Misc.	500	38	11	11	60	30
Variable Phase Shifter	1,000	38	0	0	38	38
X6 Multiplier	800	38	0	0	38	38
Power Leveler	500	38	0	0	38	19
Master Oscillator	10,000	0	0	0	1	10
Construction and Testing Cost - Including Overhead	3,400	38	11	11	60	204
G/A and Profit at 20%						115
Total LO Electronics						$691
63 km of 1 5/8 in Cable with connectors						465
4 km of 7/8 in Cable						12
Total LO Cost Excluding Cable Burial Cost						$1,168

E. Appendix: Analysis of The Proposed Local Oscillator Distribution System

The LO system described is analyzed in this appendix. The effects of cable loss, cable VSWR, coupler directivity, and imperfect mixers are considered.

The essential features of the proposed system are shown in Fig. 14-7. A return signal at a frequency ω_a higher than $\omega_o/2$ is injected into the far end of the trunk line. At the central control building this signal is beat with the LO reference signal to produce the outgoing signal at ω_a lower than $\omega_o/2$. At each observing station, the outgoing and return signals are extracted from the line and beat together. The station LO signal is the sum-frequency component of this beat.

Phases at various points in the system are shown in the bottom half of Fig. 14-7. The trunk line is split into two sections, each of which models transmission in one direction. A trunk line phase shift that is arbitrarily dependent on frequency is assumed so that the effects of dispersion in the portion of the line between the central control building and the observing station can be analyzed. If the group delay of the line is relatively constant over the band $2\omega_a$ wide occupied by the outgoing and return signals, the phase error between the station LO signal and the LO reference in the central control building is

$$\phi = \Theta(\omega_o/2 + \omega_a) - \Theta(\omega_o/2 - \omega_a) \simeq 2\omega_a \frac{d\Theta(\omega_o/2)}{d\omega} = 2\omega_a \tau_g(\omega_o/2)$$

in which $\tau_g(\omega)$ is the group delay of the portion of the trunk line under consideration.

Calculations of the changes in this phase error, due to temperature changes, will next be made for a trunk line consisting of 20 km of aluminum coax that is buried in a duct several feet below ground level and free to expand. The temperature change in the duct will be taken to be 0.1 °C per day, consisting primarily of a linear rise or fall due to the annual temperature variation at the VLA site. If it is desired to avoid the need for a separate phase correcting system to connect each antenna front-end box to its trunk line coupling point, the trunk line can be broken at each coupling point in use and extended by a loop up to the

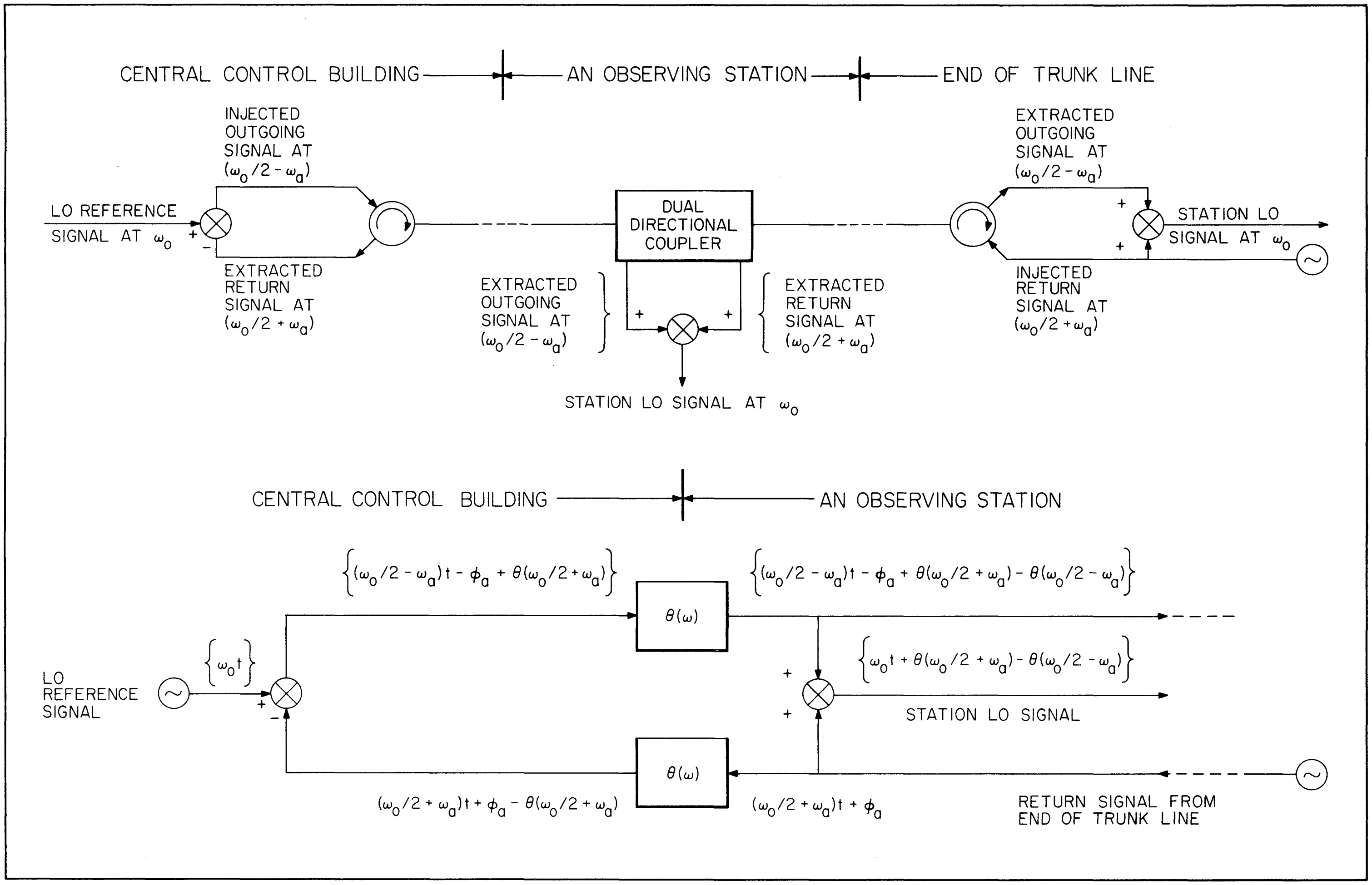


Figure 14 - 7. Phases and frequencies in the proposed system.

front-end box and back. This arrangement will be referred to as the looped trunk line. The total length of the loops will be taken to be

$$12 \text{ stations} \times 100 \text{ m/station} = 1.2 \text{ km},$$

the peak-to-peak temperature variation of the loops will be taken to be 30 °C, corresponding to the assumed daily temperature variation at the site, and the loops will also be taken to be aluminum coax. Since (30 °C x 1.2 km) is almost 20 times (0.1 °C x 20 km), the effects of temperature changes in the loops will far exceed the effects in the trunk line itself in the course of a day. Temperature compensated line should be considered for the loops, if they are used.

The daily line length changes for the assumptions that have been made are:

$$\Delta\ell_{\text{unbroken trunk}} = 24 \times 10^{-6} \text{ parts/part/°C} \times 2 \times 10^{6} \text{ cm} \times 0.1 \text{ °C} = 4.8 \text{ cm}$$

$$\Delta\ell_{\text{loops}} = 24 \times 10^{-6} \text{parts/part/°C} \times 1.2 \times 10^{5} \text{ cm} \times 30 \text{ °C} = 86.4 \text{ cm}$$

$$\Delta\ell_{\text{looped trunk}} \approx \Delta\ell_{\text{unbroken trunk}} + \Delta\ell_{\text{loops}} = 91.2 \text{ cm}$$

Assuming a group velocity equal to the speed of light in vacuum for the coax, and allowing 0.1° change in phase error, the frequency separation between outgoing and return signals should not exceed

$$2f_a = \frac{2\omega_a}{2\pi} = \frac{\Delta\phi(\text{radians})}{2\pi\Delta\tau_g} = \frac{c \times .1°}{\Delta\ell \times 360°}$$

$$\left.\begin{array}{ll} (2f_a)_{\text{unbroken trunk}} & = 1.74 \text{ MHz} \\ (2f_a)_{\text{looped trunk}} & = 91.4 \text{ kHz} \end{array}\right\} \quad \Delta\phi = 0.1° \text{ in one day}$$

If the sixth subharmonic of the LO injection frequency, about 450 MHz, is transferred over the trunk line as the LO reference frequency, the 0.1° change in phase error becomes a 0.6° change at the injection frequency, which is acceptable.

The effects of mismatch on the trunk line will be examined next. These effects are influenced by the directivities that can be achieved by the directional couplers at the observing stations and by the circulators at the ends of the line. They are also influenced by the degree of balance that can be held in the mixers shown in Fig. 14-7 and/or by the extent to which filtering can force one of the mixer arms to carry only the signal at $(\omega_o/2 + \omega_a)$ and the other arm to carry only the signal at $(\omega_o/2 - \omega_a)$. For example, if the mixers, circulators, and couplers are perfect, a double reflection is required to produce a phase error: The outgoing signal is reflected from a point in the trunk line beyond the observing station in question, reflected again from a point between the central control building and the observing station, and extracted by the directional coupler at the observing station with the main outgoing signal to cause an error in its phase. The same pair of reflections, in reverse order, do not affect the phase difference between the two versions of the return signal extracted at the observing station and at the central control building unless the phase of the transmission coefficient for the discontinuity nearer to the central control building is other than zero. But if it is, the same phase shift is incurred by the outgoing signal, since the discontinuity will be reciprocal, and the net effect of the two phase shifts will not appear in the phase error between the station LO signal and the LO reference in the central control building.

The situation that has just been described in which a double reflection is required to produce a phase error is a goal to be worked toward. Since each reflection can be expected to be weak, the resulting phase error should be very weak. Although the directional coupler at the observing station can always be matched to the trunk line to eliminate reflections from the line at one frequency and temperature, temperature changes in the line will then disturb the match, and the reflections will return. Before studying the effects of imperfections in the circulators, couplers, mixers, and filters, an estimate will therefore be made of the reflection coefficient and its changes with temperature for a long piece of trunk line -- long enough so that reflections from its far end are sufficiently attenuated by line loss as to be negligible.

The coaxial structure of Fig. 14-8 will be used as a model of the imperfect trunk line. It is axially homogeneous except that at random points along the line, the characteristic impedance changes abruptly between two nearly-equal values, producing reflection coefficients for waves originating at z = 0 of

$$\rho_k = r(-1)^k$$

and transmission coefficients

$$t_k = \sqrt{1 - r^2} \approx 1.$$

The reflection coefficients for waves originating at the right are the negatives of the reflection coefficients listed above, but they will not be needed, because triple, quintuple, etc., reflections will be neglected in comparison with the dominant single reflection from each discontinuity. The propagation constant on either section of line will be assumed to be

$$\gamma = \alpha + j\beta = \alpha + j\frac{\omega}{c} .$$

The transmission coefficient from the origin through the n^{th} discontinuity is

$$t = \left(t_1 e^{-\gamma z_1}\right)\left(t_2 e^{-\gamma(z_2 - z_1)}\right)\cdots\left(t_n e^{-\gamma(z_n - z_{n-1})}\right) .$$

which suggests that the transmission coefficients can conveniently be absorbed into the attenuation coefficient, α, of the line with good accuracy. The reflection coefficient for a wave entering at the left is then very nearly

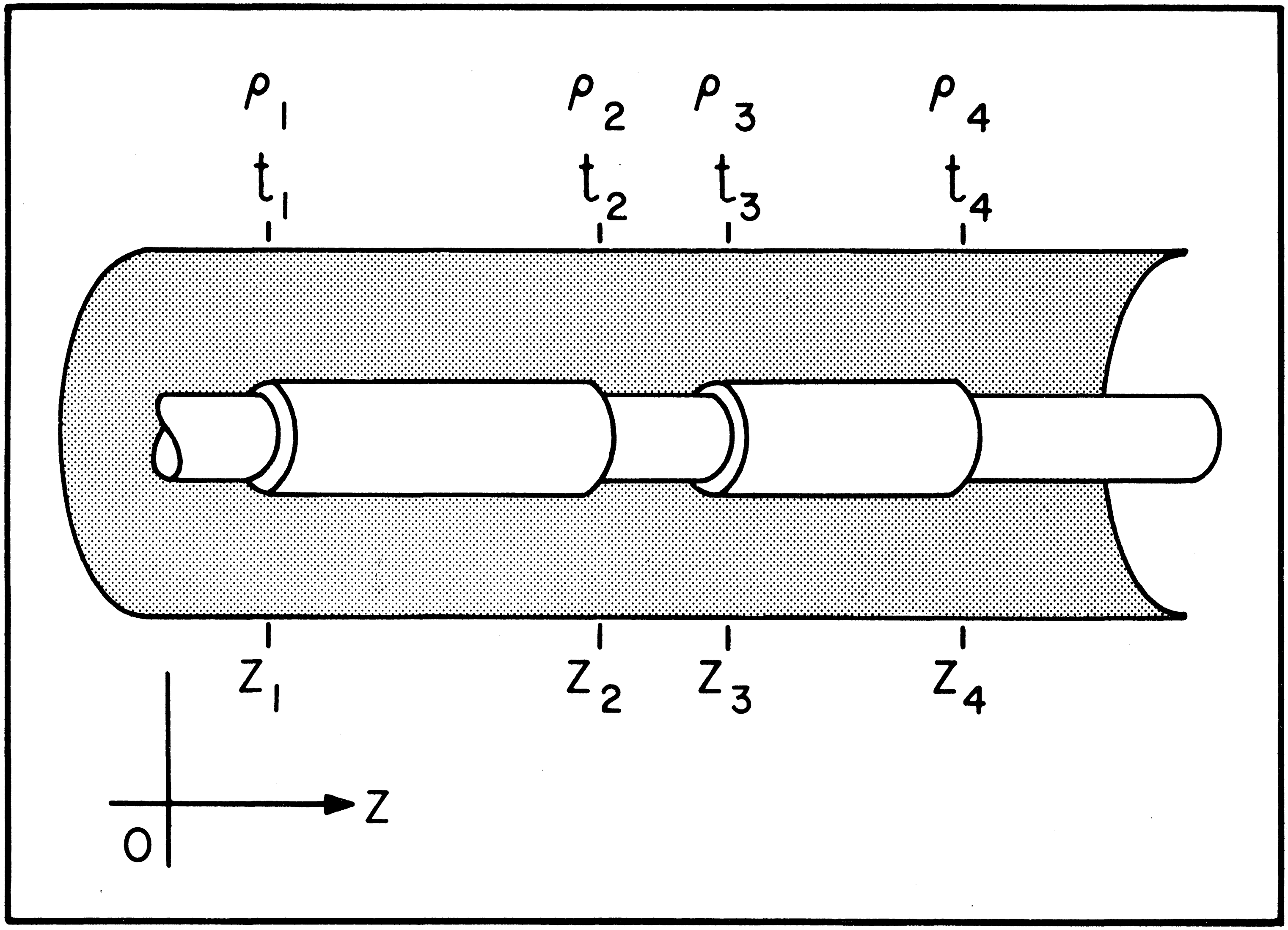


Figure 14 - 8

$$\rho = e^{-2\gamma z_1}\left[\rho_1 + t_1^2 e^{-2\gamma(z_2 - z_1)}\left[\rho_2 + t_2^2 e^{-2\gamma(z_3 - z_2)}[\rho_3 + \ldots]\right]\right]$$

$$\approx \sum_{k=1}^{\infty} \rho_k e^{-2\gamma z_k} = r \sum_{k=1}^{\infty} (-1)^k e^{-2\gamma z_k}$$

in which the approximations

$$\rho_k \approx \frac{\rho_k}{t_k^2} \text{ and } t_k^2\, e^{-2\gamma(z_k - z_{k-1})} \approx e^{-2\gamma(z_k - z_{k-1})}$$

have been used, and only single reflections have been considered.

The discontinuities will be assumed to fall at random with an average of n discontinuities per meter, the location of each discontinuity being independent of the locations of the rest, and n will be taken to be (wavelength)$^{-1}$ = 1/3 m^{-1} for a line signal frequency of 100 MHz. The discontinuities will then have a Poisson distribution. Under these circumstances, the phase of each contribution to the reflection coefficient of the line -- modulo 2π -- will be very nearly uniformly distributed and independent of the phases of the other contributions. And there will be many contributions of nearly the maximum size: For 1 5/8 in, 50 ohm cable at 100 MHz

$$\alpha = 0.225^{dB}/100\text{ ft} \times \frac{100^{cm}/m}{100^{ft}/100\text{ ft} \times 12^{in}/ft \times 2.54^{cm}/in \times 8.686^{dB}/neper}$$

$$= 0.850 \times 10^{-3}\ ^{nepers}/m$$

$$(= 1.2 \times 10^{-3}\ ^{nepers}/m \text{ at } 224\text{ MHz})$$

so that 1-neper length is 1,175 m, for an average of $\frac{1175}{3}$ = 392 contributions within 2 nepers of the same strength. According to the Central Limit Theorem, the reflection coefficient of the line will have very nearly independent, zero-mean, equal variance, Gaussian real and imaginary parts;

its magnitude will be Rayleigh-distributed, and its phase -- modulo 2π -- will be uniformly distributed. The squared magnitude of the reflection coefficient is

$$|\rho|^2 = r^2 \sum_{k,i=1}^{\infty} (-1)^{k+i} e^{-2\alpha(z_k + z_i)} e^{-j2\beta(z_k - z_i)}$$

In the average, only the terms for which i = K, so that $z_k - z_i = 0$, will remain. The mean squared magnitude of the reflection coefficient is

$$\overline{|\rho|^2} = r^2 \sum_{k=1}^{\infty} \text{Av.} \left\{ e^{-4\alpha z_k} \right\}$$

$$= r^2 \sum_{k=1}^{\infty} \frac{n^k}{(k-1)!} \int_0^{\infty} z^{k-1} e^{-(4\alpha + n) z_k} dz_k$$

$$= r^2 \sum_{k=1}^{\infty} \left(\frac{n}{4\alpha + n} \right)^k = r^2 \frac{\frac{n}{4\alpha + n}}{1 - \frac{n}{4\alpha + n}} = r^2 \frac{n}{4\alpha}$$

$$= 98\ r^2$$

for the 1 5/8 in, 50 ohm cable at 100 MHz.

A reasonable estimate of the VSWR of this cable "with fittings" is 1.05. This means that the VSWR is measured by driving the cable directly through a 50 ohm slotted line. And a reasonable estimate of the VSWR of the cable "without fittings" is 1.02. This means that the match between cable and slotted line can be adjusted, but the adjustment must remain fixed while a number of different cables are measured. VSWR = 1.02 is then representative of all of these measurements.

The identification

$$\text{VSWR} = 1.02 = \frac{1 + \rho_{rms}}{1 - \rho_{rms}}$$

$$\rho_{rms} = \sqrt{\overline{|\rho|^2}} = 9.9\ r = \frac{\text{VSWR} - 1}{\text{VSWR} + 1} = \frac{0.02}{2.02} = 9.9 \times 10^{-3}$$

$$r = 10^{-3}$$

will be made here. A 1 5/8 in, 50 ohm air dielectric cable has an inner conductor diameter of 0.707 in. The reflection coefficient $r = 10^{-3}$ for one discontinuity, which corresponds to a reduction of characteristic impedance from 50 ohms to 49.9 ohms, would be produced if the diameter of the inner conductor were increased by 0.00118 in or if the center of the inner conductor were displaced from the axis of the outer conductor by 0.0299 in. The validity of the model of the imperfect trunk line is corroborated by the fact that these numbers seem to be reasonable manufacturing tolerances.

The model will next be used to calculate the mean squared magnitude of the change in reflection coefficient when the temperature x meters down the line is increased by the small amount $T(x)$. When this happens, the length of an increment Δx of line located at x increases by

$$\frac{d(\Delta x)}{dT}\ T(x) = \left[\frac{1}{\Delta x}\ \frac{d(\Delta x)}{dT}\right]\ T(x)\Delta x \quad = \quad \Theta T(x)\ \Delta x,$$

in which $\Theta = \frac{1}{x}\frac{dx}{dT} = 24 \times 10^{-6}$ parts/part/°C is the temperature coefficient of expansion of aluminum. Evidently, the length of a section extending to a point z meters down the line increases by

$$\Theta \int_0^z T(x)\ dx$$

when the temperature change need not be the same at all points along the line. The resulting change in reflection coefficient is

$$\Delta\rho = r \sum_{k=1}^{\infty} (-1)^k e^{-2\gamma z_k} \left[e^{-2\gamma\Theta \int_0^{z_k} T(x)\,dx} - 1 \right]$$

$$\approx 2\gamma\Theta r \sum_{k=1}^{\infty} (-1)^{k+1} e^{-2\gamma z_k} \int_0^{z_k} T(x)\,dx$$

The approximation required for a tractable result gives a clue as to how small the temperature change must be. The mean square magnitude of this change is

$$\overline{|\Delta\rho|^2} = 4|\gamma|^2 r^2 \sum_{k,i=1}^{\infty} \text{Av.} \left\{ (-1)^{k+i} e^{-2\alpha(z_k + z_i)} e^{-j2\beta(z_k - z_i)} \right.$$

$$\left. \times \int_0^{z_k} T(x)dx \int_0^{z_i} T(y)\,dy \right\}$$

$$\overline{|\Delta\rho|^2} \approx \beta^2\Theta^2 r^2 \sum_{k=1}^{\infty} \text{Av.} \left\{ \left[\int_0^{z_k} T(x)\,dx \right]^2 e^{-4\alpha x_k} \right\}$$

in which the cross terms have been dropped as before because it has been supposed that their phases -- modulo 2π -- are uniformly distributed from one piece of coax to the next so that the ensemble average of each cross term is zero.

This expression can be simplified to give

$$\overline{|\Delta\rho|^2} = 4\beta^2\Theta^2 r^2 n \int_0^{\infty} \left[\int_0^{z} T(x)\,dx \right]^2 e^{-4\alpha z} dz$$

As it stands, this result could be used to calculate the rms change in reflection coefficient due to one temperature change in the buried trunk line and a different temperature change in the loops up to the front end boxes. The necessary integration is straightforward, but unfortunately laborious. However, this effort does not seem necessary for present purposes, so it will be avoided. Instead, a numerical result will be obtained for the case in which the temperature change is the same at all points along the line. If the temperature change is $T(x) = T_o$,

$$\int_0^z T(x)\, dx = z\, T_o$$

and

$$\overline{|\Delta\rho|^2} = 4\beta^2\Theta^2 r^2 n\, T_o^{\,2} \int_0^\infty z^2 e^{-4\alpha z} dz$$

$$= 4\beta^2\Theta^2 r^2 n\, T_o \frac{2}{(4\alpha)^3}$$

$$= \frac{\beta^2\Theta^2 r^2 n\, T_o^{\,2}}{8\alpha^3}$$

Substituting the previously calculated relation for r in terms of ρ_{rms} gives,

$$(\Delta\rho)_{rms} = \sqrt{\overline{|\Delta\rho|^2}} = \frac{\beta}{\sqrt{2}\alpha} \cdot \rho_{rms} \cdot T_o \cdot \Theta$$

This relation then gives the rms change in reflection coefficient, $(\Delta\rho)_{rms}$, due to a temperature change, T_o, in a coaxial cable having propagation constant, $\beta = 2\pi/\lambda$, attenuation constant, α, rms reflection coefficient, ρ_{rms}, and temperature coefficient of delay, Θ.

It will be noted that a temperature change of

$$\Delta T = \frac{\rho_{rms}}{\left[\frac{(\Delta\rho)_{rms}}{T_o}\right]} = \frac{\alpha\sqrt{2}}{\beta\Theta} = 23.9\ °C$$

would be required "on the average" to make the reflection coefficient change by an amount equal to its rms value if the rate of change remained constant as its initial value throughout the change. This suggests that the approximate expression that has been obtained will be quite accurate for the buried portions of the trunk line, but that for a long, completely exposed line it will be somewhat conservative. Since the exact expression is rather unwieldy, the approximation will be used in all cases.

If it were possible for a single reflection from the totally buried trunk line to add to the signal to produce a phase error, the rms change in that phase error in the course of a day would be

$$(\Delta\phi)_{rms} = \frac{1}{\sqrt{2}}(\Delta\rho)_{rms} = 1/4\ \beta r\Theta \sqrt{\frac{n}{\alpha^3}}\ T_o$$

$$= 1/4 \cdot \frac{2\pi}{3} \cdot 10^{-3} \times 24 \times 10^{-6} \sqrt{\frac{1/3}{(0.85 \times 10^{-3})^3}} \times 0.1$$

$$= 29.3 \times 10^{-6} \text{ radians} = 0.00168°$$

for the 1 5/8 in buried cable operating at 100 MHz as has been postulated. The change in phase error resulting from the desired double-reflection condition,

$$(\Delta\phi)_{rms} = \sqrt{1/2\ \overline{\left|\frac{d}{dT}(\rho_1\rho_2)\right|^2}}\ T_o$$

$$= \sqrt{1/2\ \overline{\left|\rho_1 \frac{d\rho_2}{dT} T_o + \rho_2 \frac{d\rho_1}{dT} T_o\right|^2}}$$

$$= \rho_{rms}(\Delta\rho)_{rms},$$

would be almost two orders of magnitude smaller. On the other hand, if the trunk line were totally exposed and subject to a 30 °C daily temperature variation, the daily change in phase error, hypothetically caused by a single reflection, would be

$$(\Delta\phi)_{rms} = 0.00168 \times \frac{30\ °C}{0.1\ °C} = 0.504 \text{ degrees}$$

If this phase change were associated with the station LO signal at 224 MHz, the change would reach an rms value of 6 degrees after frequency multiplication by 12 to the LO injection frequency. The actual phase change for a particularly unfortunate cut of cable might be 3 times greater, which would not be tolerable. But a directional coupler directivity of only 10 dB would reduce this hypothetical single-reflection phase change enough to make it again tolerable.

The joint effects of imperfections in the dual directional coupler and mixer at an observing station and the imperfect trunk line will be examined next. Let the waveforms of the outgoing and return signals on the trunk line be

$$e_o(t) = \text{Re}\left\{(\text{amplitude})\ e^{j(\text{phase})}\ e^{j(\omega_o/2 - \omega_a)t}\right\} \equiv \text{Re}\left\{E_o\right\}$$

and

$$e_r(t) = \text{Re}\left\{(\text{amplitude})\ e^{j(\text{phase})}\ e^{j(\omega_o/2 + \omega_a)t}\right\} \equiv \text{RE}\left\{E_r\right\}$$

respectively, so that the vector (analytic) signals are E_o and E_r. The sum-frequency product component of these two, $E_r\ E_o$ -- rather than the difference-frequency product component, $E_r E_o^*$ -- will be of interest. As shown in Fig. 14-9 there will be reflected versions of these signals traveling in the wrong directions on the trunk line. In accordance with the foregoing calculation, double reflections on the trunk line will be neglected. Although a 10- or 20 dB coupler will probably be used at a station near the center of the trunk line, considerations of absolute level will be deferred; Fig. 14-9 has been drawn to show, for example, a return port output voltage equal to the voltage of the return signal on the trunk line. The directivities of the coupler are of interest, however, The fraction D_r of the outward-traveling signal voltage also appears at the return port of the imperfect coupler, and the fraction D_o of the signal returning toward the central control building is intercepted by the outgoing port. Directivities

$$-20 \log D \approx 35 \text{ to } 40 \text{ dB}$$

can be expected for a coaxial directional coupler. The sum-frequency component of the mixer output would be proportional to the product of the two coupler outputs if the mixer were a perfect multiplier, but this would require that the mixer be balanced with respect to both inputs and that both inputs be small, tending to make the mixer noisy. In this analysis, the mixer gain will be normalized to make its desired output equal to the product of the inputs. The first-order mixer imperfections will be accounted for by including in its output the fractions U_r of the square of the return port output voltage and U_o of the square of the outgoing port output. It will be noted that both squares fall in the band of the station LO signal. Although a near-perfect multiplier could be built to maintain unbalances

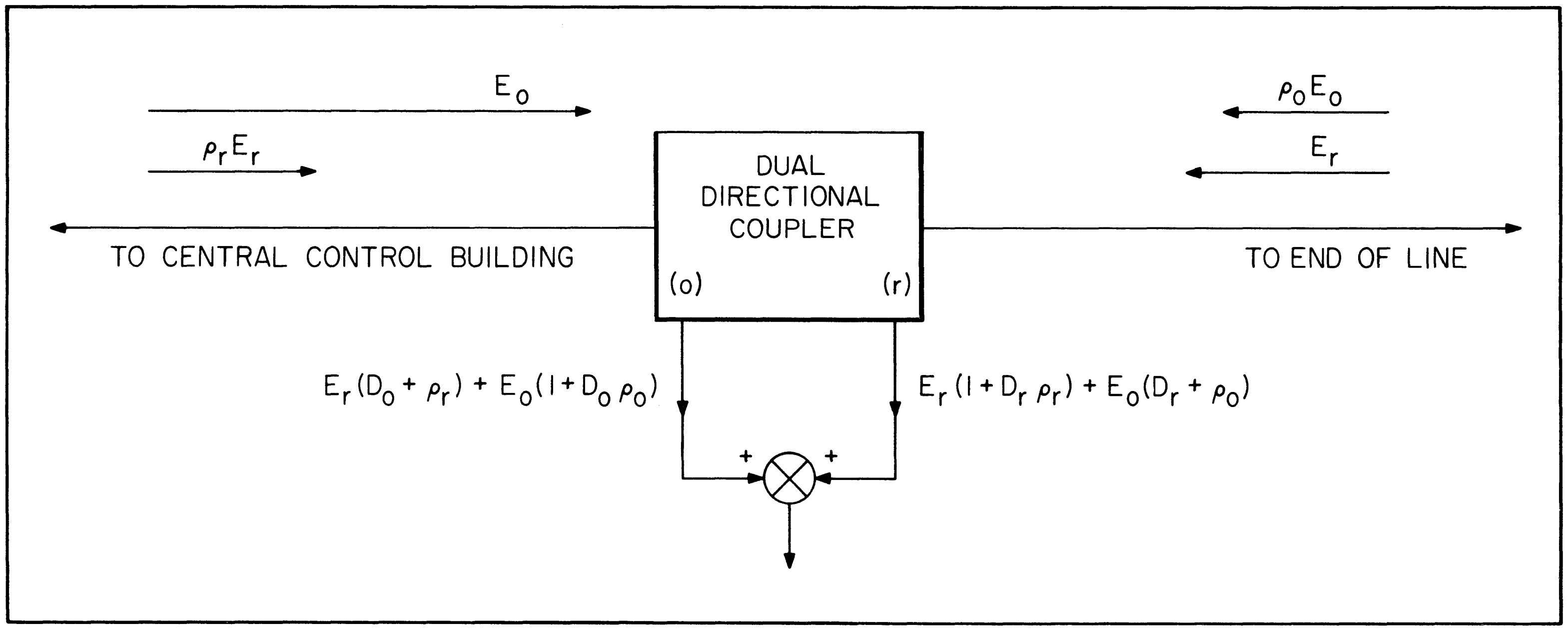
$$-20 \log U_r = -20 \log U_o = 20 \text{ to } 30 \text{ dB},$$

it would be quite noisy. Larger unbalances U_r and U_o may be necessary at the critical observing stations near the central control building and near the end of the line where mixer noise figure will be important.

In accordance with the assumptions that have been made, the sum-frequency component of the mixer output is

$$\begin{aligned} & E_r^2(1 + D_r\rho_r)(D_o + \rho_r) \\ & + E_rE_o[(1 + D_r\rho_r)(1 + D_o\rho_o) + (D_r + \rho_o)(D_o + \rho_r)] \\ & + E_o^2(1 + D_o\rho_o)(D_r + \rho_o) \end{aligned}$$

Terms due to perfect multiplier.



E_o
$\rho_r E_r$
$\rho_o E_o$
E_r
DUAL
DIRECTIONAL
COUPLER
TO CENTRAL CONTROL BUILDING
TO END OF LINE
(o)
(r)
$E_r(D_o + \rho_r) + E_o(1 + D_o \rho_o)$
$E_r(1 + D_r \rho_r) + E_o(D_r + \rho_o)$
+
+

Figure 14 - 9

$$+ E_r^2 [U_r(1 + D_r\rho_r)^2 + U_o (D_o + \rho_r)^2]$$

$$+ E_rE_o[2U_r (1 + D_r\rho_r) (D_r + \rho_o) + 2U_o (1 + D_o\rho_o) (D_o + \rho_r)]$$

$$+ E_o^2[U_o (1 + D_o\rho_r)^2 + U_r (D_r + \rho_o)^2].$$

Terms due to first-order mixer imperfections.

All of the terms shown here are in the band of the LO signal. The frequency of the cross terms is the LO reference, and the other terms are offset in frequency by $\pm 2\omega_a$. At the center of the trunk line where $|E_r| \approx |E_o|$, the leading cross term is E_rE_o and the leading offset terms are

$$E_r^2(D_o + \rho_r + U_r) \quad \text{and} \quad E_o^2(D_r + \rho_o + U_o),$$

each of which is of the order of (0.01 + 0.01 + 0.03) or 26 dB weaker than the leading cross term. For a 2- km run of 1 5/8 in coaxial trunk line, having a total attenuation of

$$0.225(^{dB}/100 \text{ ft}) \times 656 \text{ (100 ft)} = 147 \text{ dB},$$

the offset term proportional to E_r^2 will be 147-26 = 121 dB <u>stronger</u> than the leading cross term at the end of the line, and the offset term proportional to E_o^2 will be 121 dB <u>stronger</u> than the leading cross term at the central control building.

These calculations suggest that, except possibly near the center of the trunk line, a strong effort will be needed to remove the offset terms from the mixer output. Since the frequencies of these terms are close to the LO reference frequency, it is not practical to achieve even a majority of the ncesssary reduction by filtering in the LO reference frequency band. But it is practical to lock an oscillator to the desired cross term as shown in Fig. 14-6.

Both the "dirty" mixer signal and the VCO signal are heterodyned to a low enough frequency so that the mixer signal can be cleaned up by bandpass filtering. The two beats are then zero-beat to provide the VCO control signal. It is essential to filter out the strong offset terms and amplify before trying to lock the VCO to the cross term. Otherwise, the zero-beat due to the cross term would be too weak to drive the VCO. The VCO control signal should overload to prevent the VCO from seeking to lock at 0.98 ω_o. This is an unstable point of equilibrium, and at lower frequencies the VCO would be driven even further away from the desired lock frequency, ω_o. This requires that the VCO drift with no control signal should be small compared with 0.02 ω_o; it may be necessary to use a crystal oscillator for the VCO. Similarly, it will be desirable to use a crystal oscillator to provide the 0.99 ω_o offset; changing the frequency of the offset oscillator changes the frequency of the signal passing through the bandpass filter and hence the phase shift of the filter, which contributes directly to the phase difference between the VCO signal and the desired cross term from the mixer.

Having thus removed the offset terms proportional to E_r^2 and E_o^2, the remaining sum-frequency component of the mixer output is

$$E_rE_o\ [(1 + D_r\rho_r)\ (1 + D_o\rho_o) + (D_r + \rho_o)\ (D_o + \rho_r)]$$

$$+ E_rE_o\ [2U_r(1 + D_r\rho_r)\ (D_r + \rho_o) + 2U_o(1 + D_o\rho_o)\ (D_o + \rho_r)]$$

$$= E_rE_o\ [(1 + D_rD_o + 2U_rD_r + 2U_oD_o) + 2\rho_r(D_r + U_o + U_rD_r^2)$$

$$+ 2\rho_o(D_o + U_r + U_oD_o^2) + \rho_r\rho_o(1 + D_rD_o + U_rD_r + 2U_oD_o)]$$

$$\approx E_rE_o\ [1 + 2\rho_r(D_r + U_o) + 2\rho_o(D_o + U_r) + \rho_r\rho_o]\ ,$$

where the reflection coefficients have been regarded as the variables in the last expression, and only the leading terms in their coefficients have been retained. The phase error due to imperfect trunk line match, mixer, and coupler is determined by the portion of the coefficient in brackets,

$$C = 2\rho_r(D_r + U_o) + 2\rho_o(D_o + U_r) + \rho_r\rho_o$$

When the temperature of the line changes, the change in this coefficient is

$$\Delta C = (\rho_o + 2D_r + 2U_o)\,\Delta\rho_r + (\rho_r + 2D_o + 2U_r)\,\Delta\rho_o .$$

Taking the four temperature-dependent variables to have zero mean and to be statistically independent over an ensemble consisting of a batch of different trunk lines, the mean square change in the coefficient becomes

$$\overline{|\Delta C|^2} = \left[\overline{|\rho_o|^2} + 4|D_r + U_o|^2\right]\overline{|\Delta\rho_r|^2} + \left[\overline{|\rho_r|^2} + 4|D_o + U_r|^2\right]\overline{|\Delta\rho_o|^2}$$

In obtaining a numerical result, the following values will be used:

$D_r = D_o = D = .0178$ -- 35 dB coupler directivity

$U_r = U_o = U = .05$ -- 26 dB mixer unbalance

$\sqrt{\overline{|\rho_r|^2}} = \sqrt{\overline{|\rho_o|^2}} = \rho_{rms}$ -- cable VSWR = 1.10

$\sqrt{\overline{|\Delta\rho_r|^2}} = \sqrt{\overline{|\Delta\rho_o|^2}} = (\Delta\rho)_{rms} = 2.0$ angular degrees

-- cable temp. change = 10 °C

Under these conditions, the rms change in phase error is very nearly

$$(\Delta\phi)_{rms} = \sqrt{1/2\ \overline{|\Delta C|^2}} = (\Delta\rho)_{rms}\sqrt{\rho_{rms}^{\ 2} + 4|D + U|^2} = 0.29 \text{ degrees}$$

in the station LO signal at, say, 448 MHz. After frequency multiplication by 6 to the LO injection frequency, the rms change in phase error is 1.75°, and the 3 σ value, for a particularly unfortunate cut of cable is 5.2°. In spite of the fact that this value is barely acceptable, leaving no room for phase errors introduced in the frequency multiplier or in the mixing operation at the central control building; the conservatism of the assumptions made in this calculation may very well provide room for the additional phase errors. The major sources of this conservatism are as follows:

1. The entire 21 km of trunk line has been assumed to be exposed to the air, which then produces a 10 °C peak-to-peak daily temperature change throughout the trunk line.

2. The rate of change of reflection coefficient with temperature has been assumed to remain constant at its initial value throughout the day.

3. The mixer unbalance and coupler directivity leakage terms have been assumed to be in phase.

Nevertheless, the observing station system implied by this calculation requires a rather well-balanced mixer that may be uncomfortably noisy for some of the stations. An alternate system, to be described next, does not need a balanced mixer and should be no more costly to produce. For this system, the rms change in phase error, calculated as above with $U_r = U_o = 0$, is

$$(\Delta\phi)_{rms} = (\Delta\rho)_{rms} \sqrt{\rho_{rms}^{\ 2} + 4|D|^2} = 0.11°$$

which provides a 3 σ value of 2.0° after frequency multiplication by 6. Fig. 14-10 is a complete block diagram of the alternate system. Approximate frequencies at various points in the system are noted.

The signals entering the original mixer, M, have been offset in opposite directions so that the sum of their phases is preserved, but so that the squares of the signals do not fall in the band centered on ω_o. This eliminates the terms in the original mixer output due to first-order mixer imperfections.

Before closing the discussion of the observing station system, it is appropriate to examine the absolute levels at certain critical points. As a guide to this examination, let it be noted that the rms phase fluctuation of the sum of a bandpass noise and a tone in the band of the

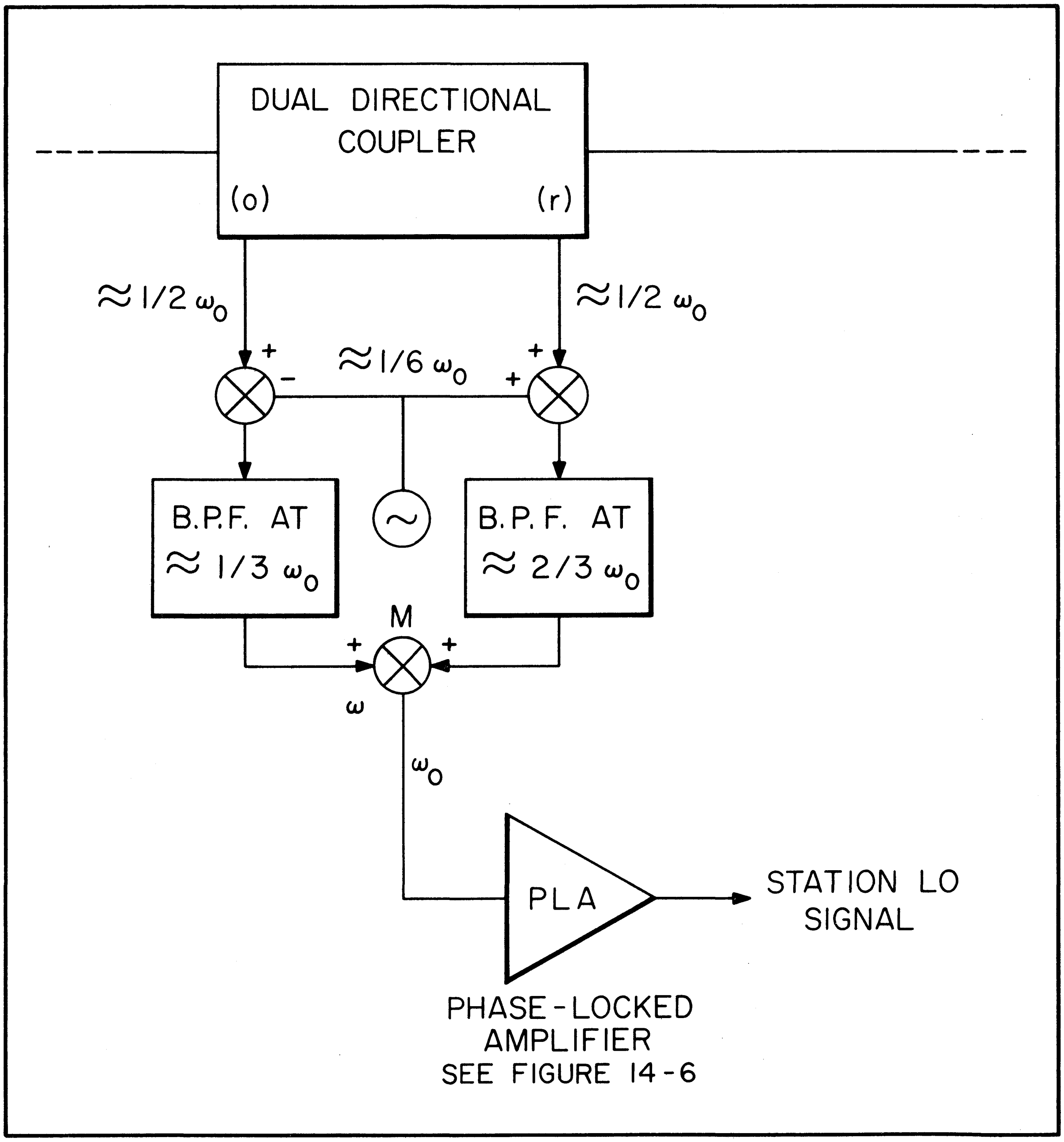

DUAL DIRECTIONAL COUPLER
(o)
(r)
≈ 1/2 ω0
≈ 1/2 ω0
≈ 1/6 ω0
B.P.F. AT ≈ 1/3 ω0
B.P.F. AT ≈ 2/3 ω0
M
ω
ω0
PLA
STATION LO SIGNAL
PHASE-LOCKED AMPLIFIER
SEE FIGURE 14-6

Figure 14 - 10

noise is

$$\phi_{rms} = \frac{1}{\sqrt{2\ SNR}} ,$$

so that an SNR of 54 dB is required to hold the rms phase fluctuations to 1/2 degree. After frequency multiplication of the locked oscillator output by 6 to the LO injection frequency, the rms phase fluctuations would be 0.5°. An SNR of 54 dB measured in the noise bandwidth of the VCO loop of Fig. 14-6 should therefore be sufficient. A loop noise bandwidth of 5 Hz, preferably much less than the lock and capture ranges of the VCO, will be used in the level calculation that follows. This figure is actually considerably larger than is needed; if SNR = 54 dB in 5 Hz, SNR = 0 dB in 1.25 MHz, so the bandpass filter at 0.01 ω_o can easily be arranged to deliver a signal stronger than noise to the VCO loop for best operation of the balanced demodulator.

The following is a sample level calculation for an observing station near either end of the 20 km trunk line:

KT	-204 dBW
Bandwidth (5 Hz)	+7 dB
KTB	-197 dBW
Noise Figure	+7 dB
FKTB	-190 dBW
SNR	+54 dB
Received Weaker Signal	-136 dBW
Line Loss at 112 MHz	+146 dB
Transmitted Signal	+20 dB

Evidently, 100 watt outgoing and return signals transmitted from opposite ends of the 1 5/8 in, 20 km trunk line at 112 MHz provide sufficient levels for LO distribution. Some power reduction may be achieved by narrowing the noise bandwidth of the VCO loop and by improving the noise figure of the amplifier connected to the weak signal arm of the directional coupler. In this regard, it will be noted that if the coupler directivity is only 35 dB, a 30 mW leakage signal from the near end of the line will emerge from the coupler with the weak signal. Amplification of the weak signal before mixing, to improve noise figure, would require a corresponding reduction of the leakage signal first, but the leakage signal can be attenuated 20 dB or so with a crystal notch filter without affecting the phase stability of the circuitry at signal frequency.

Chapter 15

RECEIVER FRONT-ENDS

Chapter 15
RECEIVER FRONT-ENDS

The receiver front-ends are a critical part of any receiving system. Fortunately, commercially available components and experience with the NRAO interferometer provide the hardware and know-how to do an excellent job in this area. Front-ends that are now on hand, operating at 2695 MHz, will probably meet all the requirements of the VLA. The front-ends will be given extensive tests and refinements, and similar units operating at 5390 MHz will be developed.

A. Requirements

The system which has been described in this report imposes the following requirements upon receiver front-ends:

(1) Three modes of operation must be provided: Dual circular polarization at 2695 MHz or 5390 MHz or single circular polarization simultaneously at 2695 MHz and 5390 MHz. The changeover time between these modes should be less than one hour per antenna.

(2) A double-sideband type of operation (input signals at both $f_{LO} + f$ and $f_{LO} - f$ appear in the IF at frequency, f) is desired because this type of system allows more accurate phase measurements.

(3) The input noise temperature should be as low as possible, consistent with reliability and cost.

(4) An IF bandwidth of 50 MHz is specified; the RF bandwidth should be a minimum of 100 MHz at 1 dB points.

(5) A phase stability of 2° rms over an eight hour period is desired in the front-end components (the LO has an additional 2° rms allocation). The phase match between front-ends should be within ± 10°. An amplitude stability of ± .1 dB per hour is desired.

(6) Provision for noise temperature, gain, and bandpass monitoring must be provided.

(7) A means should be provided for Dicke-switched radiometer operation of each front-end. This is required for pointing tests of each antenna.

B. The Proposed System

A block diagram of the proposed front-end operating at 2695 MHz is shown in Fig. 15-1. The 5390 MHz front-end will have an identical block diagram. A discussion of each block is as follows:

1. Dual circular polarization feed

Three feeds, one for each mode of operation described in the previous section, must be provided. All of the feeds should provide for a minimum of 60% aperture efficiency (assuming a perfect reflector and sub-reflector) and should produce a noise temperature of less than 10°K due to loss and spill-over. The feed VSWR should be less than 1.05 and the axial ratio of the polarization ellipse should be less than 1.02. Each feed should include a coupling probe (-33 dB coupling) to couple a calibration signal and a swept frequency signal into both polarizations. (It may be possible to use a single feed for all modes of operation; this will be investigated.)

2. Paramp, Stage 1 and Stage 2

Degenerate paramps will be used in the system; the effect of degenerate operation upon the system is discussed in the next section. Degenerate amplifiers are chosen because they have lower noise temperature (for double-sideband application) and are more stable since they are pumped by passing the LO signal through a frequency doubler; the resulting pump is more stable and reliable than klystron pumps used in non-degenerate paramps. The noise temperature specifications of the 2695 MHz and 5390 MHz amplifiers should be 40°K and 55°K, respectively. The gain of the cascaded stages should be 26 dB and the phase stability, phase match, and amplitude stability requirements stated previously should be met. A bandwidth of 150 MHz at 1 dB points is required.

3. Ferrite switch

A ferrite switch is incorporated between the two paramp stages to allow Dicke-switched radiometer operation. When this mode of operation is used, the varactor of the first paramp stage should be biased into conduction (it may be necessary to also remove pump power). The stage will then not amplify and will have about 0.5 dB loss, so that the switch is effectively at the receiver input. System noise temperatures of approximately 90°K at 2695 MHz and 110°K at 5390 MHz should be achieved with this mode of operation. (The switch was not placed at the first stage input

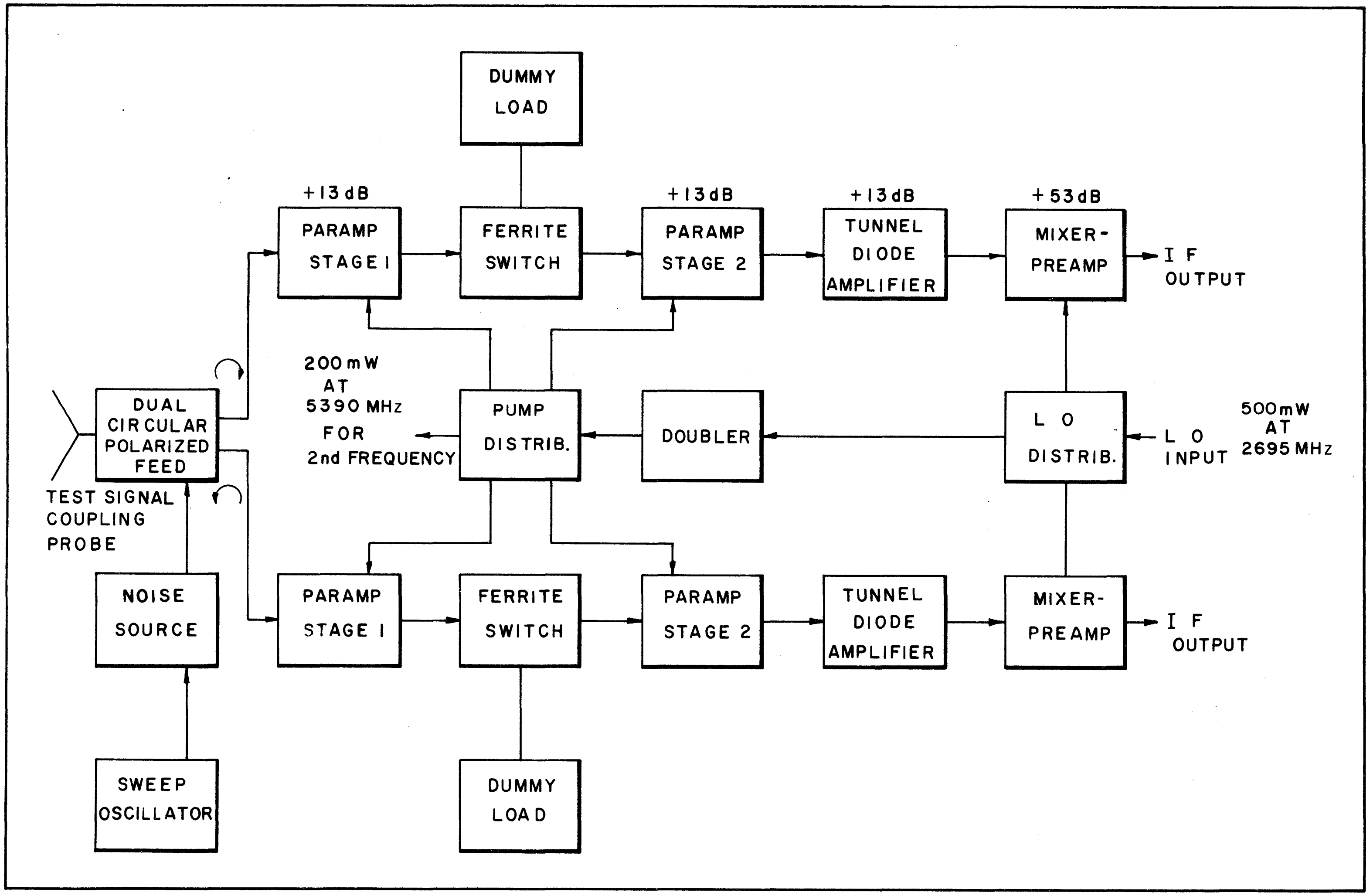


Figure 15 - 1. Front-end block diagram for 2695 MHz receiver. The 5390 MHz receiver is identical except no 2nd frequency output is provided from the pump distributor.

because it would increase system noise temperature in the normal mode of operation.)

The ferrite switch should have a maximum loss of 0.2 dB, an isolation of 20 dB, and a VSWR of less than 1.10.

4. Tunnel-diode amplifier

A tunnel-diode amplifier is used between the paramp and mixer to reduce mixer noise contribution to system noise temperature. The amplifier should have a maximum noise temperature of 450°K, a gain of 13 dB, and a bandwidth of 150 MHz at 1 dB points.

5. Mixer-preamp

This unit should have a maximun single-sideband noise figure of 9 dB, an RF to IF gain of 53 dB, and IF bandpass of 2 MHz to 50 MHz at 1 dB points, LO isolation of 15 dB, and an output capability of + 5 dBm at the 1 dB gain compression point. The normal output level, supplied to the IF transmission system is -10 dBm. The phase stability, phase match, and amplitude stability requirements previously stated should be met.

6. LO distributor

The LO distributor is a power divider network which provides 2 mW for each mixer and 496 mW (12 mW at 5390 MHz) to the pump doubler.

7. Frequency doubler

In the 2695 MHz front-end this unit provides at 300 mW output at 5390 MHz from a 496 mW input at 2695 MHz. In the 5390 MHz front-end a 100 mW output at 10,780 MHz is produced from a 200 mW input at 5390 MHz. The outputs should have built-in ferrite isolators.

8. Pump distributor

In the 2695 MHz front-end the pump distributor provides 25 mW to each paramp-stage and 200 mW for the 5390 MHz front-end. The pump-distributor in the 5390 MHz front-end provides 25 mW to each paramp-stage. The required phase adjustments (see next section), attenuation adjustments, and monitor crystals should be built into each pump distributor.

9. Noise source

This is a gas-discharge tube noise source with a diode-switch modulator at its output. The feed coupling probe should be adjusted to provide a 5°K calibration signal.

Table 15-1

Front-End Cost

Item	Per Frequency and Per Antenna	
	Quantity	Cost
2-Stage Degenerate Paramp (including testing)	2	$ 6,000
Ferrite Switch	2	800
Tunnel Diode Amplifier	2	2,000
Mixer-Preamp	2	1,400
Noise Source (with modulator and power supply)	1	800
Sweep Oscillator	1	600
Dual Circular Polarization Feed	1	3,000
Pump Distributor	1	1,000
Frequency Doubler	1	500
LO Distributor	1	400
Miscellaneous Racks, Cables, and Monitor Equipment	1	2,000
System Assembly and Testing Labor	300 hrs	1,200
Overhead at 125% of Labor	-	1,500
G and A and Profit at 20%		4,200
Total Per Frequency and Per Antenna, Dual Polarization		$25,400
Antenna Cables and Connectors		5,000
X38 (36 Antennas + 2 Spares) Single Frequency Total		$ 1,155K
38 Dual Frequency Feeds		$ 114K
X38 Electronics for 5390 MHz		$ 965K
Total Dual Frequency and Dual Polarization Front-Ends		$ 2,234K

10. Sweep oscillator

A simple tunnel-diode sweep oscillator should be built into each front-end and be capable of being turned on and off from the main control room; this will allow checking of the complete system bandpass. A power output of -50 dBm, sweep width of 150 MHz, and flatness of $\pm$ .5 dB are appropriate specifications.

A cost breakdown of the proposed system is presented in Table 15-1. The paramp cost of \$3,000 per two stage unit is based on a budgetary estimate from a large paramp manufacturer; the cost is low because a pump is not included, the paramp is degenerate, and the quantity is large.

C. Degenerate Paramp - Double Sideband Mixer System

The use of a degenerate paramp with a double-sideband mixer in an interferometric system is new to radio astronomy; the first such system (as far as we know) will be put into operation on the NRAO three element interferometer in February 1967. In this section, a theoretical analysis aimed at questions concerning phase stability and phase adjustment will be carried out. First a few words will be stated about degenerate paramps and why they were chosen.

All negative-resistance parametric amplifiers accept input power at three frequencies, commonly called the pump frequency, f_P, the signal frequency, f_S, and the idler frequency $f_i = f_P - f_S$. Power out of the amplifier at signal frequency comes from power into the amplifier at both signal and idler frequencies. If the gain at signal frequency is G, the conversion gain for idler input-signal output frequency is $(f_S/f_i)G$. This is unavoidable and no gain can result at signal frequency unless there is conversion gain at idler frequency. As a result of this, thermal noise coming from the idler termination (usually the varactor series resistance) at the temperature, T_i, is amplified and appears in the amplifier output. This noise adds a term $(f_S/f_i)T_i$ to the receiver noise temperature. For this reason, high pump frequencies are used in low-noise non-degenerate paramps.

In a degenerate paramp $f_P = 2f_S = 2f_i$, and hence $f_S/f_i = 1$. This would produce a very high noise temperature except that the idler termination is now made to be the antenna (i.e., the idler tank circuit is closely coupled to the input port) which presents a very low value (< 30°K) for T_i. In addition, in a double-sideband radiometer system with $f_P = 2f_{LO}$, useful signal is received at the idler frequency, and the noise temperature which must be used in S/N calculations is halved. However, the noise temperature contributions from varactor loss and circuit loss are approximately doubled in the degenerate paramp. The result of all this is that the degenerate paramp has an effective noise temperature which is equal to that of a non-degenerate paramp with idler noise removed.

At the present time noise temperatures of 40°K and 65°K can be obtained with degenerate and non-degenerate paramps, respectively. These figures could be reduced considerably (to of the order of 15°K and 25°K) by cooling the amplifiers to 20°K in a closed cycle cryogenic refrigerator. Although the reliability of cooled amplifiers and cryogenic refrigerators is improving, it does not appear prudent to propose these for the VLA at the present time.

The only other front-end which could be considered for the VLA is the low-noise crystal mixer. However, the lowest noise temperature which can presently be obtained is approximatey 250°K. This would reduce system sensitivity by a factor of four and is unacceptable.

We will now turn to the question of phase adjustment and phase stability of a two stage degenerate paramp followed by a double-sideband mixer.

The output of a degenerate paramp at frequency $f_{LO} + f$ (where $f_{LO} = f_P/2$) arise from input signals at frequencies $f_{LO} + f$ and $f_{LO} - f$ (just as a double-sideband mixer produces an output at frequency f from inputs of $f_{LO} + f$ and $f_{LO} - f$). The phase shift of the signal which changes frequency (i.e., the idler signal) is affected by the pump phase while the direct signal is not.

The situation becomes rather complex when two degenerate paramps are followed by a double-sideband mixer. An input signal at frequency $f_{LO} + f$ arrives in the IF output at frequency f through four paths:

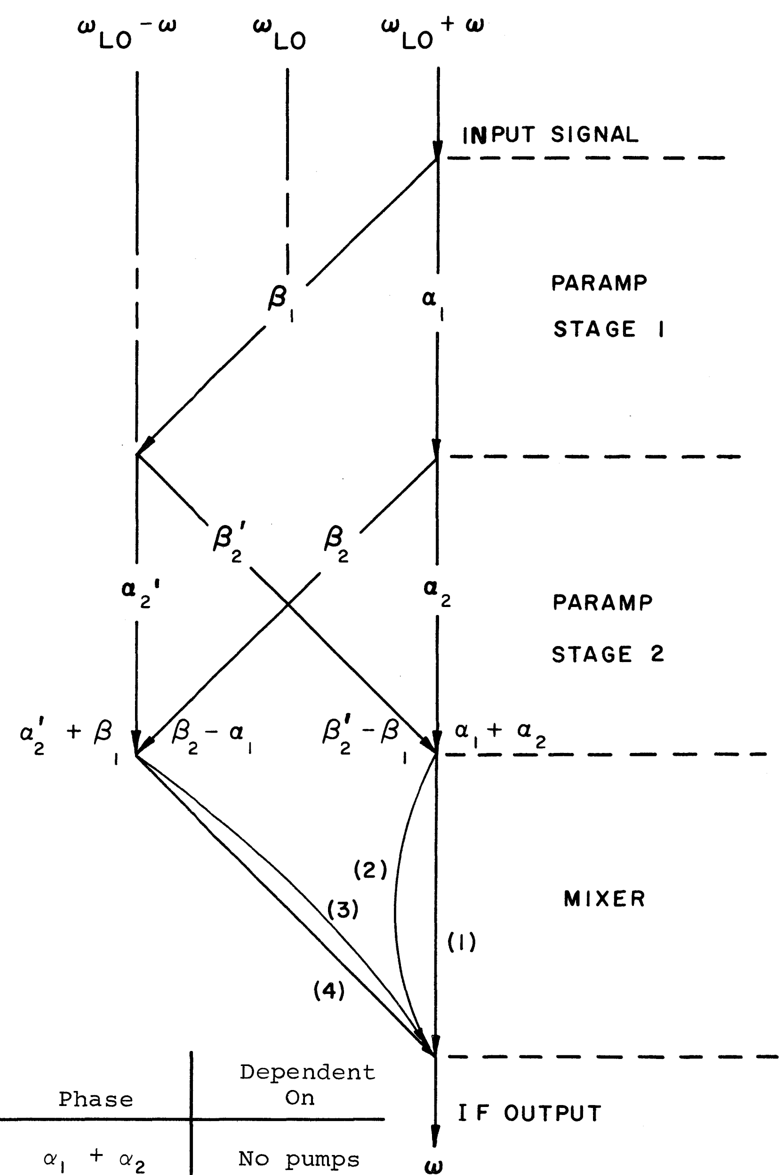
(1) Direct signal through both paramps and upper mixer sideband;

(2) Idler signal through first paramp (output at $f_{LO} - f$), idler signal through second paramp (output at $f_{LO} + f$), and upper mixer sideband;

(3) Direct signal through first paramp, idler signal through second paramp, and lower mixer sideband;

(4) Idler signal through first paramp, direct signal through second paramp, and lower mixer sideband.

The phase shifts, α and β, through different signal paths and the resultant output signal phases are given in Fig. 15-2. The β phase shifts are dependent upon pump phase while the α phase shifts are not. The IF output signal is given by:



Signal Path	Phase	Dependent On
(1)	$\alpha_1 + \alpha_2$	No pumps
(2)	$-\beta_1 + \beta_2'$	Both pumps
(3)	$\alpha_1 - \beta_2$	Pump 2
(4)	$-\beta_1 - \alpha_2$	Pump 1

Figure 15 - 2. Phase diagram of degenerate paramp, double-sideband mixer system.

$$
\begin{aligned}
&(1) \quad & A_1A_2 \cos\,(ft + \alpha_1 + \alpha_2) \\
&(2) \quad + & B_1B_2 \cos\,(ft - \beta_1 + \beta_2{}') \\
&(3) \quad + & A_1B_2 \cos\,(ft + \alpha_1 - \beta_2) \\
&(4) \quad + & B_1A_2 \cos\,(ft - \beta_1 - \alpha_2)
\end{aligned}
$$

where the A's and B's are the paramp voltage gains over the paths described by the subscripts in the phase angle diagram. These gains will be approximately equal.

Assuming that there are pump phase adjustments for each paramp and that $\alpha_2{}' = \alpha_2$ and $\beta_2{}' = \beta_2$ (this will be true if paramp 2 has a symmetrical bandpass), the phases β_1 and β_2 can be adjusted to put all four signals in phase. The correct settings are:

$$\beta_2 = -\alpha_2$$

$$\beta_1 = -\alpha_1 - 2\alpha_2$$

The IF output signal will then be

$$4A_1A_2 \cos\,(ft + \alpha_1 + \alpha_2)$$

This adjustment can probably be performed by adjusting the two phase shifters in a trial and error fashion to peak the IF output signal from a swept frequency input signal. The pump phase shifters must have very little loss variation with phase settings.

An independent adjustment of each phase shifter could be performed if the pump signal to one paramp can be removed without disturbing the phase relationship between the other pump and the LO. For example, if pump 1 is removed, only signals (1) and (3) will be present, and they can be phased with the β_2 adjustment (independent of α_1).

Turning now to the question of phase stability, assume that the pump phases are adjusted correctly and a phase shift of ψ occurs in the LO signal and a phase shift of $2\psi + \Theta$ occurs in each pump line. The 2ψ term arises, of course, from the doubling of the LO frequency, while the Θ term is the phase error occurring in the pump doubler alone. If these terms are included in the signal phase analysis, the IF output is:

$$4A_1A_2 \cos \Theta/2 \cos\,(ft + \alpha_1 + \alpha_2 - \psi - \Theta/2)$$

The conclusions are then:

(1) The effect of LO phase error is the same as if no paramp or a non-degenerate paramp was used. The LO phase shift of ψ causes a phase shift of ψ in the IF output. (Signal paths (3) and (4) contain some 2ψ terms which are reduced by a $-\psi$ term, so that all signal paths give a ψ phase error.)

(2) The pump doubler phase error, Θ, causes a $\Theta/2$ phase error, and a cos $(\Theta/2)$ amplitude error in the fringe visibility. (The pump doubler error behaves like LO phase error and not like IF phase error with respect to double sideband operation.) The pump doubler error does not occur in signal path (1) and cancels in signal path (2), but does appear in paths (3) and (4).

D. Front-End Physical Configuration

The mounting and housing of the front-end components on each antenna is of the utmost importance with regard to stability, system noise temperature, equipment serviceability, and quick changeover of feeds. The mounting of these components is often done as an after-thought when the antenna is complete; this often is the root of poor system performance.

A Cassegrain feed system has been chosen, among other reasons, to allow easy access for large amounts of equipment near the antenna focal point. The feed will be focused by moving the hyperbolic subreflector. No feed rotation is necessary since polarization measurements are accomplished with dual circular polarization feeds.

A sketch of a proposed front-end configuration is shown in Fig. 15-3. A temperature controlled equipment box with inside dimensions of 6' 4" long, 7' wide, and 7' high should be mounted at the vertex of the paraboloid. Up to six racks, weighing 1500 pounds. of equipment should be accommodated. A winch for handling racks up to 400 pounds should be located above the equipment box door.

The temperature control of the equipment box is very important. Air-conditioned air which is held to $\pm$ .5°C per day should be blown through the equipment racks. A very high air circulation rate should be maintained so that the temperature does not change as the antenna is tilted.

Conventional air-conditioners cannot be tilted and those with centrifugal compressors or thermoelectric cooling are very expensive in the size

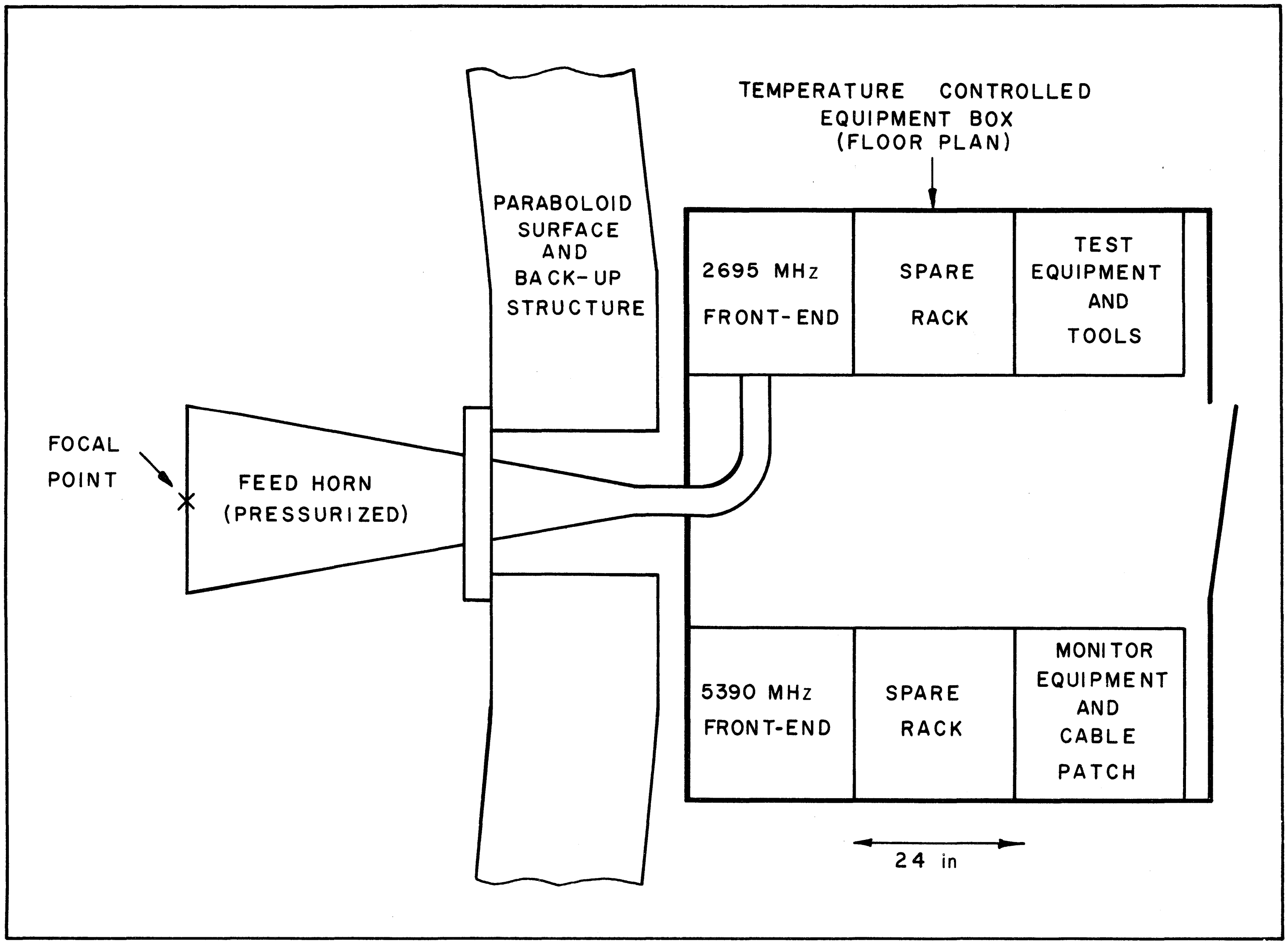


Figure 15 - 3. Feed and front-end equipment mounting configuration.

capacity that is required. A solution may be to mount the air conditioner below the azimuth axis and blow air through insulated conduit or to pipe a refrigerant to a heat exchanger at the box. This problem needs careful consideration in order to provide a stable and reliable system.

The equipment box should be well insulated. Metal boxes of this sort often have metal members which go from the outside wall to the inside. Comparison of the thermal conductivities of aluminum and good insulators indicates that the area of aluminum thru-members must be less than 1/10,000 of the insulation area if the insulation is to be effective.

The antenna feed is likely to be quite large (6 ft long by 2 ft diameter for 2695 MHz) and a convenient method must be devised for changing and storing feeds. It should be possible for two men to change a feed within one hour. With the arrangement shown in Fig. 15-3, the feed would be changed with the antenna pointed at zenith and feeds would be stored through hatches in the paraboloid surface. A simple boom may be helpful for handling of the feed.

The focal point can be located where it is mechanically most convenient (within limits) by changing the position and shape of the subreflector. It should be placed at a point so that the feed horn output is near the front-end equipment. Waveguide plumbing, with quick disconnect clamps, will be used between the feed output and first paramp. A maximum length of 5 ft is tolerable. (This will add approximately 1°K noise temperature at 2695 MHz and 4°K at 5390 MHz.) The position of the focal point cannot be decided until a preliminary design of the feed horns is made.

The cable run up the antenna must also receive some attention in the antenna design. Four lines of 7/8 in semi-rigid coax must be accommodated with rotary joints (no flexible jumpers) on the antenna axis. In addition, a cable tray to handle up to fifteen 1 in diameter flexible cables should be planned. Whenever possible, the cable runs (especially the coax) should be protected from extreme temperature changes and weather.

If spectral line operation is desired at 1420 MHz and 1667 MHz, a prime-focus equipment box may be necessary. The frequencies may be too low for a Cassegrain system, and it may be convenient to change over quickly from continuum to spectral line mode by removing the subreflector. The cost of the equipment box and cables is included in Chapter 21. If this mode of operation is desired, the antenna feed support structure must be made capable of accepting this box.

Chapter 16

IF TRANSMISSION SYSTEM

Chapter 16

IF TRANSMISSION SYSTEM

A. Introduction

The double sideband spectrum of the RF signal is converted in the individual receiver front ends to a single sideband spectrum at some intermediate frequency (IF) by the action of the mixer. (The folding of the RF spectrum on itself is actually accomplished by the degenerate parametric amplifiers.) This IF signal must then be multiplied with that from each of the other antennas after the appropriate delays have been accomplished. The problem of how each of the IF signals are transmitted to the central terminal for this further processing is the subject of this chapter. The local oscillator (LO) transmission was discussed in Chapter 14, and the monitor and control signal transmissions will be dealt with in Chapter 20, The Computer System.

The magnitude of the transmission problem is directly related to the following array and electronic system parameters:

1. Wye arm lengths

For the full 1" array, the average transmission distance is approximately 10 km.

2. M/3

The number of antennas in a given arm of the Wye determines the number of simultaneous signals which must be transmitted independently to the central terminal.

3. Simultaneous Operation

This parameter indicates the number of receiver channels per antenna which must operate simultaneously.

4. Bandwidth of the IF signal

This parameter determines the complexity and stability required of the transmission system.

5. Mobility

The transmission system must be adaptable to all array configurations.

Obviously the most severe requirement for the transmission system will be that imposed by the 1" array configuration, with antennas as much as 21 km from the central terminal. Therefore, the discussion of this chapter will center around that configuration.

B. Requirements

The specifications for the data transmission system will be set by the following requirements:

1. Two IF signal channels, each 50 MHz in bandwidth, are to be transmitted from each of 12 antennas (in a given arm of the Wye) to the central terminal. For the 1" array, each arm is 21 km long with antennas approximately equally spaced.

2. The deterioration in system signal-to-noise ratio due to the transmission system should be no greater than 1%.

3. The short-term (< 1/2 hour) stability of total delay through the transmission system should be better than ± 1 nsec. The long-term (< 24 hours) stability should be better than ± 5 nsec.

4. The maximum dispersion should be such that the relative phase deviation from linearity over the 50 MHz band is less than 1/10 revolution at any frequency.

5. The net variation in loss through the system should be less than 1 dB.

6. The system should provide equalization networks which will maintain the band shape over 50 MHz to within 0.5 dB at any frequency in the band.

7. The different IF bands transmitted will be isolated one from another to a degree that will guarantee that any cross-talk will result in less than a 0.1 S_{min} signal at the output of any correlator, where S_{min} is the rms noise level from any correlator after 12 hours averaging in the computer. In addition, the cross-talk will not introduce added noise greater than that set by the requirement in (2) above.

8. A failure in the transmission system should affect the smallest number of antennas possible, consistent with economical design.

C. Possible Systems

Three approaches to the solution of the IF transmission problem have been investigated. These are: (1) microwave air-link, (2) modulated laser beam-link, (3) cable transmission line. Applying the requirements of Section B to each of these, it was determined that a buried cable transmission system offers the most reliable, stable solution to the problem at hand.

There are several ways in which a cable transmission system can be employed for this application. These may be classified as:

1. Individual cable system

One cable for each IF signal to be transmitted. This would require 24 cables per arm of the Wye.

2. Partial multiplex

Two or more of the 24 IF signals multiplexed on each of a number of cables.

3. Full multiplex

All 24 signals multiplexed on a single cable. This would require 1,200 MHz bandwidth exclusive of guardbands.

A brief look at cable costs for the individual cable system (243 km per arm) is a convincing argument against this approach. The complexity and extremely large bandwidth of the full multiplex system is at least a first argument against it. Thus a partial multiplex system would seem to offer the most practical, economical solution.

In order to check this tentative conclusion, a study was made of the costs of a cable transmission system as a function of the degree of multiplexing. The basic considerations and specifications which were followed in the cost analysis were as follows:

1. The total cost of each system included only cable and repeater costs.

2. For the systems having a low degree of multiplexing, the cost of the LO system cables and repeaters were added. This is due to the fact that for the high-degree multiplex, the LO signal can be easily included, offering a savings which is not available for the low-degree multiplex systems.

3. For each system the repeater bandwidths were assumed to be one octave, which included 25 MHz guardbands between each 50 MHz signal band.

4. Three different cables were investigated, $\frac{1}{2}$ in, $\frac{7}{8}$ in, and $1\frac{5}{8}$ in diameter rigid coaxial line. For each system the best cable is determined by a trade-off between the large number of repeaters required

for the higher loss, small-diameter cable, and the higher cost of the larger diameter low-loss cable.

5. A range of costs for repeaters was used which, at the high end of the range, reflects a very pessimistic estimate based on single-unit development prices, while the low end of the range is felt to be realistic still, but takes advantage of buying in production quantities.

The results of the cost analysis are shown in Fig. 16-1, the band associated with each cable size showing the effect of the estimated range in repeater costs. The choice obviously lies with either the $\frac{7}{8}$ in or the $1\frac{5}{8}$ in cable. For the $1\frac{5}{8}$ in cable to become favorable in comparison with the $\frac{7}{8}$ in, a high degree of multiplexing must be selected.

In view of this complexity and the fact that the multiplexing equipment costs have not been included in this analysis (which will tend to raise the right portion of all curves), the $\frac{7}{8}$ in cable system is seen to offer the most economical system. A more detailed analysis of this cable, including multiplexing equipment costs, indicates that a system employing a four-signal channel per cable multiplexing scheme is the best tradeoff between complexity, reliability, and economy. The design and analysis of this system is discussed in the next section.

D. <u>Proposed System</u>

The choice of a multiplexed transmission system with four signal channels per cable leads to the following detailed specifications in addition to those listed in Section B.

1. The signals from two antennas will be multiplexed on a single cable.

2. Assuming 25 MHz guardbands and octave bandwidths for the repeater amplifiers requires the multiplexed transmission spectrum to cover the band from 300 to 600 MHz for minimum upper transmission frequency. The division of the transmission band for each pair of multiplexed antennas is shown in Fig. 16-2.

3. Six cables are required per arm of the Wye, distributed as shown in Fig. 16-3. The total cable required per arm is 65 km, which includes antenna cabling to the front end enclosure.

4. The number of repeaters required is set by the cable attenuation at the upper frequency (600 MHz) and the maximum usable gain in a

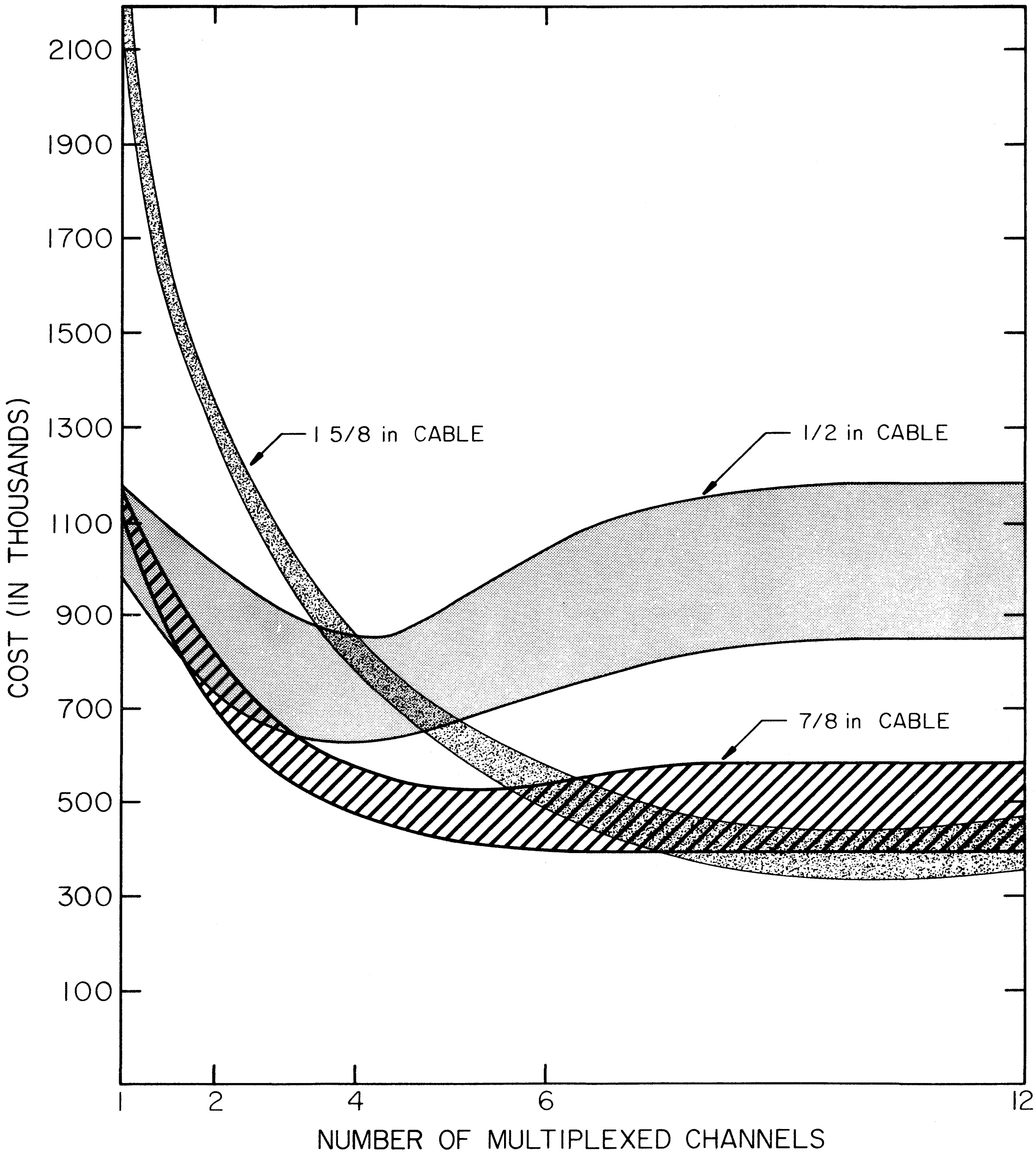
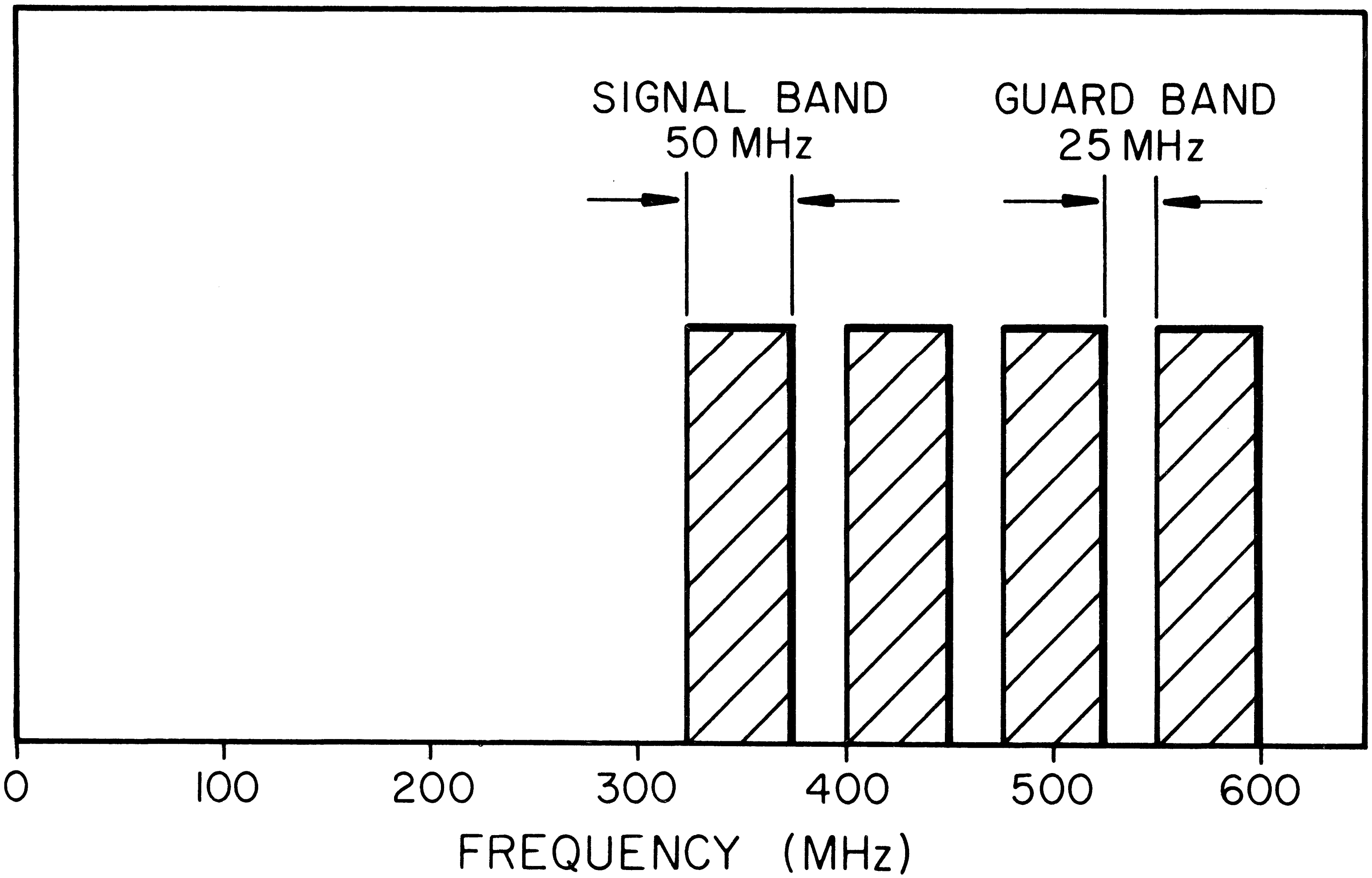


Figure 16 - 1. Cable and repeater costs for a 21 km arm with 12 antennas (includes LO cable).



SIGNAL BAND
50 MHz
GUARD BAND
25 MHz
0
100
200
300
400
500
600
FREQUENCY (MHz)

Figure 16 - 2

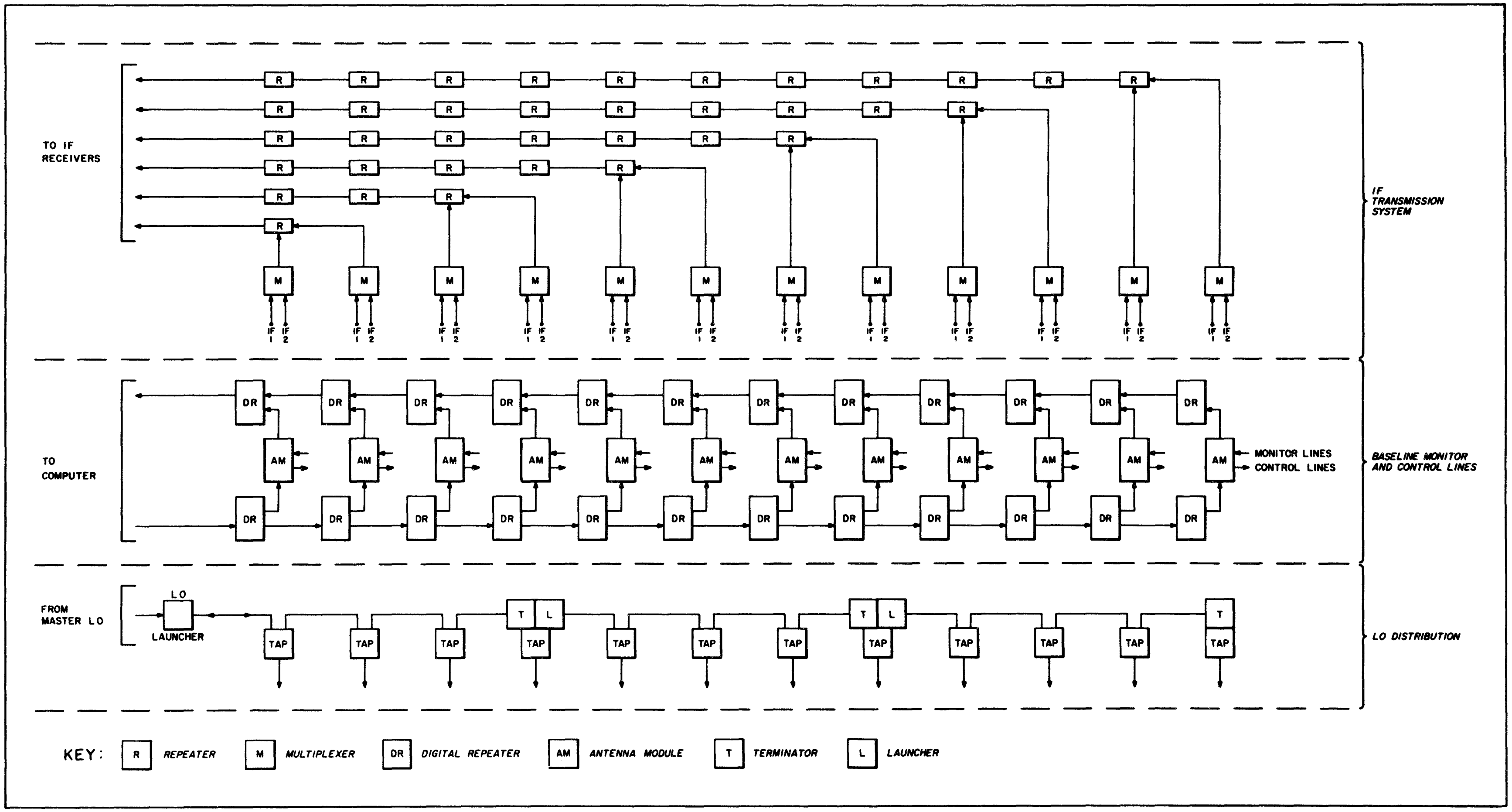


Figure 16 - 3A. VLA baseline transmission systems diagram (per arm of wye).

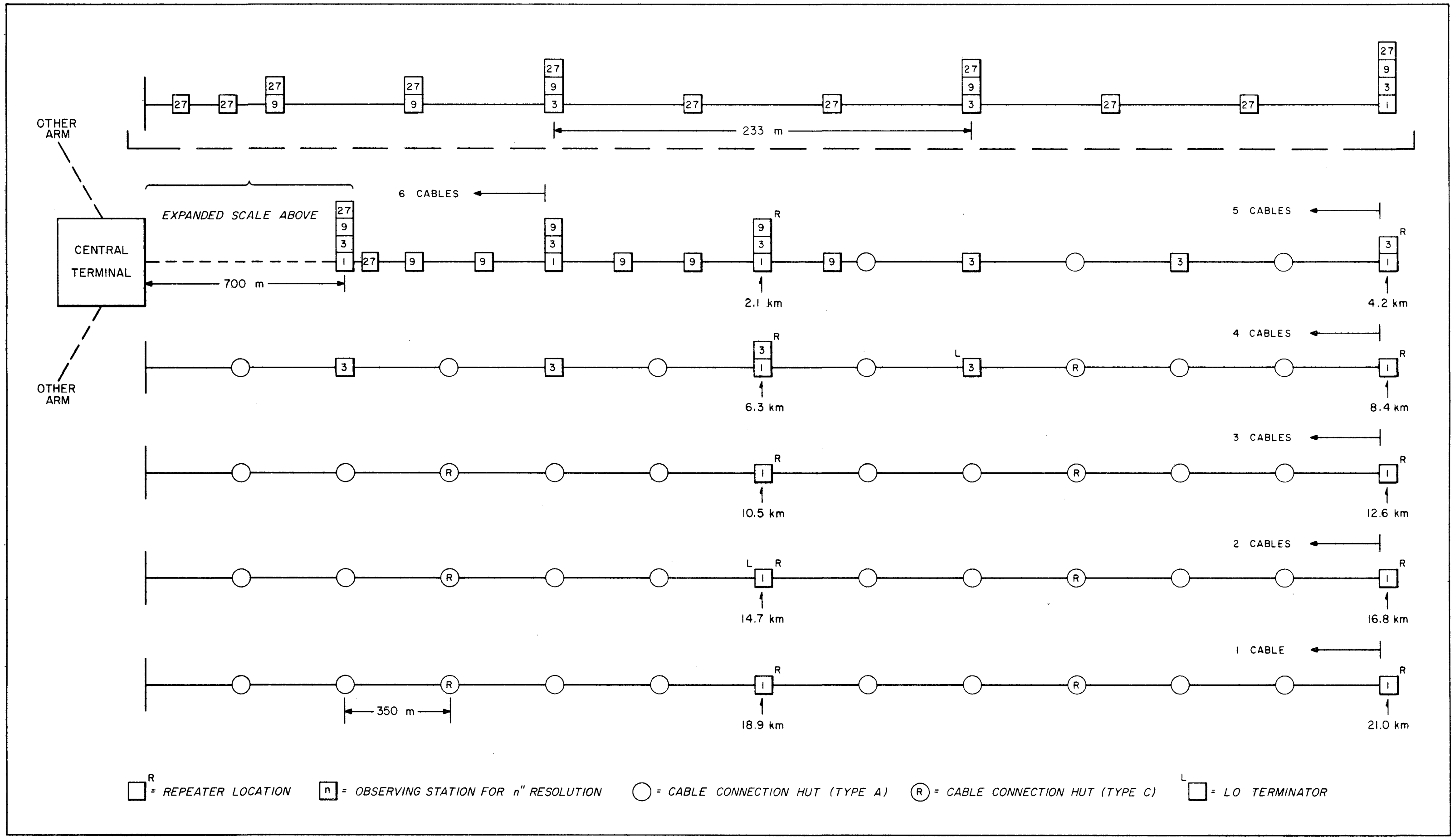


Figure 16 - 3B. Cable, repeater, hut and observing station locations -- one arm of wye.

repeater. The 600 MHz cable attenuation for air-dielectric, rigid $\frac{7}{8}$ in diameter coax is approximately 30 dB/km. At maximum spacing, the antennas are 2.1 km apart, giving 63 dB loss between antennas. If the repeater gain could be at least 63 dB, the repeaters could be located at each antenna observing station. For this application, such a high gain may not be practical, as will be discussed later.

5. If the repeater spacing is smaller than 2.1 km ($G < 63$ dB), additional equipment enclosures will be required between the antennas. These enclosures will require power and some environmental stability.

The stability requirements set forth in Item 3 of Section B are satisfied by direct cable burial to a depth of 3 to 4 ft. For a 3-ft burial depth, a daily surface temperature variation of 40°C would result in a transmission delay variation of less than 0.1 nsec. The peak-to-peak yearly component of the surface temperature variations at typical sites is probably less than 20°C. For the 3-ft burial depth, this would lead to a yearly variation of less than 30 nsec, which can be calibrated and compensated for on a regular basis quite easily. Therefore, a 3-ft burial depth is assumed for the IF transmission cable.

The burial cost (trenching only) is included in the cost analysis of the site development. It is assumed that the LO cable and monitor and control line(s) will be buried along with the IF cables.

The block diagram for a multiplexed antenna pair is shown in Fig. 16-4. The other antenna pairs are identical except for the number of repeaters required to reach the central terminal. A description of the block diagram follows.

1. At the antenna designated 1, signals are available from two RF channels A and B (either dual frequency or dual polarization). These signals are mixed with the 2695 MHz (or 5390 MHz) LO signals and converted to IF.

2. The action of the single sideband modulators then converts the signals to the 327-375 MHz and 402-450 MHz bands, respectively, and adds the 325 MHz and 400 MHz pilot tones.

3. Channel B is added to that of Channel A, and the resulting spectrum passed through the Broadband Amplifier G and its associated equalizer network. The output of Telescope 1 then is fed directly into

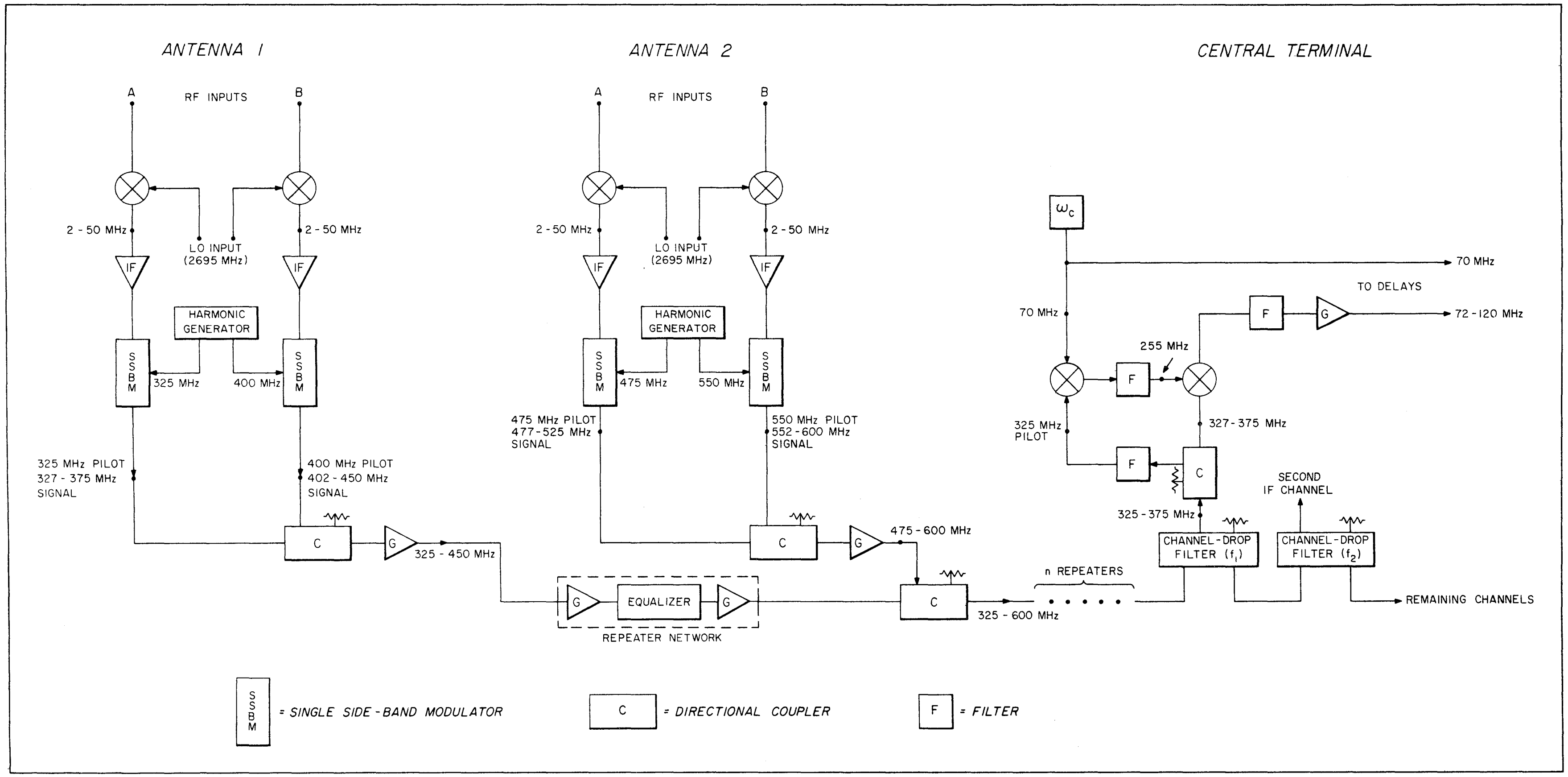


Figure 16 - 4. Four channel multiplexed transmission system.

the buried cable system leading to the antenna designated 2 (toward the central terminal). Prior to arriving at this next antenna, the signal spectrum is passed through a repeater network which restores the spectrum to its original shape.

4. The signals at Antenna 2 are processed in a similar way, with the exception of the offset frequency bands which are 477-525 MHz and 552-600 MHz, with pilot tones of 475 MHz and 550 MHz for Channels C and D, respectively.

5. The signals from Antenna 2 are added to those from Antenna 1 through a directional coupler.

6. The resulting four-channel spectrum is passed through a series of repeater networks and finally arrives at the central terminal. The signal is passed through a series of channel-drop filters which extract the individual channels.

7. Each channel is now processed separately as follows. The pilot tone associated with the given channel is extracted by a sharp notch filter and mixed with a 120 MHz reference in a single sideband mixer. The output of this mixer is then used as a mixer drive to convert the particular channel spectrum to the 70 MHz to 120 MHz band required for the variable delay line discussed in Chapter 17. The 120 MHz reference is preserved and used to bring the channel to the 2-50 MHz band prior to the calibration circuitry, ALC and correlator input.

Each multiplexed antenna pair is processed identically. The system appears at first glance to be somewhat complex, but it involves no serious design obstacles as far as can be determined at present. The IF transmission system will necessarily require a design proven through an extensive prototype development program. The economy of the multiplexed system, as compared with an individual cable system, demands a thorough investigation of the limitations of a system such as the one proposed here.

One of the critical components of the IF transmission system is the repeater network. The requirements and specifications of the repeaters and their effect on the system cost will now be discussed.

1. <u>Repeater gain</u>

This has been mentioned previously in terms of its effect on maximum repeater spacing possible. Referring to Fig. 16-3, the number of repeaters required (assuming 63 dB gain) for each cable is as follows:

Cable #1	11 repeaters
#2	9
#3	7
#4	5
#5	3
#6	2
Total	= 37 repeaters

These repeater networks are priced at $3,000 per unit, including the equalization network and packaging. A somewhat less stringent requirement on the gain (G = 33 dB) yields the distribution shown in Fig. 16-3 and summarized as follows:

Cable #1	21 repeaters
#2	17
#3	13
#4	9
#5	5
#6	3
Total	= 68 repeaters

For such a reduced-gain repeater, the price has been estimated at $2,000 per unit.

The reduced-gain unit is considered in spite of its higher total system cost as it will more likely allow the transmission system to meet the specifications and requirements outlined in Section B. The lower gain reduces the intermodulation of the multiplexed signals, thus reducing cross-talk. Associated with this is the overload problem in high gain amplifiers which increases the intermodulation index. The effect at the output of the correlators of cross-talk due to intermodulation is considerably reduced by the fact that the relative delays between the channels when the cross-talk occurs is not the same as when these two channels are multiplied in the correlators, since the two channels are processed through different delays after arriving at the central terminal. The delays will be proper only for a source on the horizon such that $\underline{r} \cdot \underline{s} = +1$.

2. Repeater noise figure

This specification is set by the requirement that the input signal power be 30 dB above the equivalent input noise power from the repeater amplifier for a 10 repeater (G = 63 dB) chain and 33 dB for a 20 repeater (G = 33 dB) chain. (These numbers refer to the Cable #1, of 21 km length.) A 10 dB noise figure repeater amplifier with a saturation level of + 23 dBm will satisfy the specifications, assuming a 100°K system noise temperature.

3. Repeater stability

In order that the requirement for a net gain variation of less than 1 dB be met, it may be necessary to put in a fairly weak AGC around the repeater amplifiers.

The repeater environmental stability will certainly be of some consequence in determining the final stability. For the 63 dB gain repeater, it was pointed out that the repeaters could be located at the antenna observing stations with other equipment in an environmentally controlled enclosure. For $G < 63$ dB, they must be located at other than an observing station occasionally.

Connected with this question is the one which arises because of the maximum cable lengths available from manufacturers. Normally the maximum length is 1000 ft (or about 330 m) for $\frac{7}{8}$ in rigid coax. If cable lengths of 350 m were available, only 6 separate lengths would be required between maximum spacings as shown in Fig. 16-3. At the juncture of each of these lengths, a connector hut or manhole is required to allow access to the cable for testing, and also to protect the connectors and cable from the weather and ground water.

In addition, a direct joint-to-joint connection in-line should not be made because of thermal expansion. The yearly variation of almost 15°C, which penetrates to the 3-ft burial level, would expand each 350 m length by 12 cm, sufficient to damage the cable. A cable connector manhole arrangement, such as is shown in Fig. 16-5, should guard against such effects, while affording ease of access and adequate protection from the weather.

Returning to the question of repeater location, it is apparent that if $G < 63$ dB, it should be such that any between-station repeater locations coincide with a cable connector hut or manhole. For the purpose

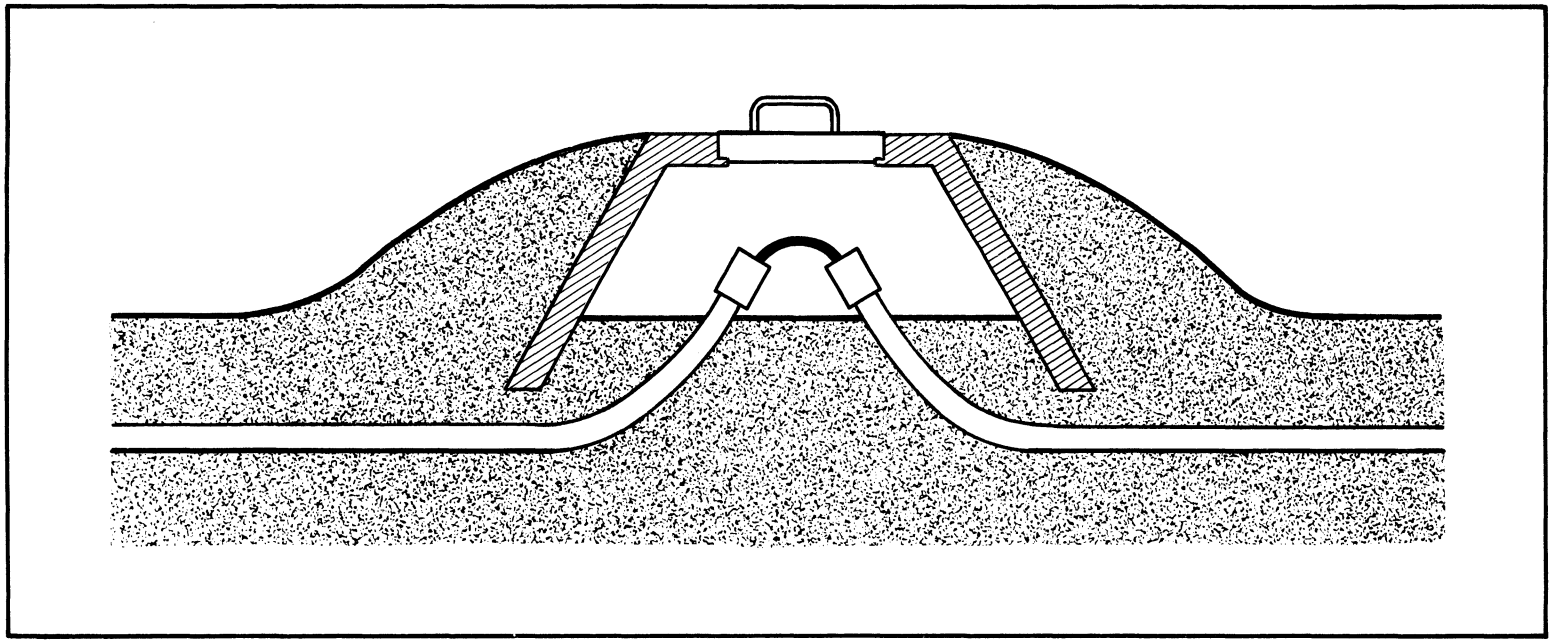


Figure 16 - 5

of estimating hut or manhole costs, the following designations will be made.

<u>Hut Type</u>

A - Not common with any observing station or repeater location (cable connector huts only).

B - Common with antenna observing station.

C - Common with a (possible) repeater hut, but not an antenna observing station.

Using the above designations and referring to Fig. 16-3, the distribution of hut types is as follows:

Type A	-	34
Type B	-	33
Type C	-	6

This assumes the 33 dB repeater. For the 63 dB repeater, the distribution is

Type A	-	40
Type B	-	33

For purposes of pricing, the cost of huts is estimated as follows:

Type A	-	$ 700
Type B	-	$ 2,000
Type C	-	$ 3,000

The breakdown of estimated costs for the data transmission system is given in Table 16-1.

Table 16-1

Pricing for IF Transmission and Delay
(Dual Frequency or Dual Polarization--36 Antennas)

A. Antenna Electronics

	Item	Antenna 1 Quantity	Antenna 1 Cost	Antenna 2 Quantity	Antenna 2 Cost
1.	325 MHz SSB Modulator	1	$2,000		
2.	400 MHz SSB Modulator	1	2,000		
3.	475 MHz SSB Modulator			1	$2,000
4.	550 MHz SSB Modulator			1	2,000
5.	Pilot Tone Generator	1	800	1	800
6.	Directional Coupler	1	100	2	200
7.	Amplifier-Equalizer	1	1,500	1	1,500
8.	Miscellaneous	1	500	1	500
9.	System Test & Assembly	1	1,000	1	1,000
	Subtotal		7,900		8,000
	G&A Profit at 20%		1,580		1,600
	Totals		9,480		9,600
	Cost per Antenna Pair				19,080
	Cost per Arm of Wye (6 x $19,080)				$114,480

B. Cables and Baseline Costs (per arm)

	Item	Quantity	Cost
1.	$\frac{7}{8}$ in Rigid Coax	65 km	$198,200
2.	Connectors (installed)	314	20,000
3.	Repeaters	37	111,000
4.	Huts: Type A	40	28,000
	Type B	33	66,000
5.	Cable Burial (supervision costs)	8 hrs/km	10,000
6.	System Test		20,000
	Subtotal		453,200
	Material Handling		20,000
	Cost per Arm of Wye		$473,200

C. Central Terminal Electronics

	Item	Unit Cost	Quantity	Cost
1.	IF Section			
	a. Preamplifier	$ 475	24	$ 11,400
	b. Filter	500	24	12,000
	c. IF Amplifier	475	48	22,800
	d. Variable Equalizer	2,000	24	48,000
	Subtotal	$3,925	24	$ 94,200
2.	Demodulator			
	a. Mixer	475	24	11,400
	b. Filter	500	24	12,000
	c. Phase Lock Loop (70 MHz)	1,200	24	28,800
	Subtotal	$2,175	24	$ 52,200
3.	Delay Section			
	a. 10 MHz Phase Lock Loop	1,200	24	28,800
	b. Phase Detector	100	24	2,400
	c. Resolver	530	24	12,720
	d. Delay Servo Control	800	24	19,200
	e. Variable Delay	2,500	24	60,000
	Subtotal	$5,130	24	$123,120
4.	Calibration and Monitor			
	a. Synchronous Det.	1,500	24	36,000
	b. Monitor Circuits	200	72	14,400
	Subtotal	$2,100	24	$ 50,400
5.	Miscellaneous			
	a. Packaging	1,500	24	36,000
	b. Test	1,000	24	24,000
	c. Subsystem assembly	2,000	24	48,000
	Subtotal	$4,500	24	$108,000
	Subtotal per Arm			$427,920
	G&A, Profit @ 20%			85,584
	Cost per Arm of Wye			$513,504

D. <u>Total Costs</u> (Sum of Items A, B, and C)

1.	Cost per Arm	$1,101,184
2.	Total for 3 Arms	$3,303,552

Chapter 17

DELAY LINE SYSTEM

Chapter 17

DELAY LINE SYSTEM

A. Introduction

The basic requirements for the delay line system have been described in Section C of Chapter 13, the Electronics System. In this chapter, the detailed requirements and specifications will be presented and a proposed design will be described. In addition, cost estimates are presented along with a discussion of the developmental program which needs to be undertaken in order to prove the feasibility of the proposed delay line system.

B. Requirements and Specifications

Each IF channel will require a separate delay line unit under the general design of Chapter 13. This requirement presumes the continuously variable, single unit delay which will be discussed later as the proposed design. If a discrete, stepped-delay system is used, some delay sharing between telescopes would be possible (saving approximately one-third in total cost for this type of design). At present, however, the latter type delay line is not considered to be competitive with the continuously variable, single unit design. Thus a total of 72 delay line units will be required. The requirements and specifications for each of these (identical) units follow.

1. Total delay

For the full 1" array, each delay unit requires a total delay of $\frac{2R}{c}$ = 140 μ sec, where R ≅ 21 km is the length of each arm of the wye. As was pointed out in Chapter 13, this includes the compensating delay for the transmission cable delay from each telescope.

The total delay requirement of $\frac{2R}{c}$ assumes a) that there is a telescope at the center of the wye and b) that the cable transmission speed is that of free space. Neither of these assumptions is true for the array under discussion. However, deleting the antenna from the center decreases the total delay requirement while the effect of the transmission speed $v < c$ increases the total delay requirement, and the two effects tend to cancel each other. Thus $\frac{2R}{c}$ is adopted as the total delay for the purpose of this discussion.

The delay unit must have a variable range which is dependent upon the location of the telescope with respect to the wye center. The remainder of the total $\frac{2R}{c}$ is that required for the fixed delay. Thus

<u>Variable delay range</u>

$$0 \leq \tau_v \leq \frac{2}{c} \quad |\underline{r}_m|$$

<u>Fixed delay</u>

$$\tau_f = \frac{2}{c} (R - |\underline{r}_m|)$$

2. <u>Bandwidth</u>

The design bandwidth for the array is $\sim$ 50 MHz. The bandwidth of the delay unit should exceed this by the order of 10-20% in order to keep the phase nonlinearities small over the signal bandwidth. The problem in achieving such a bandwidth differs markedly from one type of delay to another. For cables, there is no problem. For lumped constant lines, the bandwidth decreases markedly with increasing delay. For acoustic devices, the problem arises primarily in the transducer and is, therefore, quasi-independent of total delay.

3. <u>Delay resolution</u>

From Chapter 13 it is shown that for a signal bandwidth B (Hz) centered at f_1 (Hz), a delay error $\Delta\tau$ (sec) will give rise to a fringe amplitude error

$$e_\tau \simeq 2\pi^2 \left[f_1^2 + \frac{B^2}{12}\right] \cdot (\Delta\tau)^2$$

Thus, for $e_\tau \leq .01$, B = 50 MHz, f_1 = 25 MHz

$$|\Delta\tau| \leq 0.75 \text{ nsec.}$$

For a switched delay line system, the minimum delay step is therefore set at τ_1 = 1.5 nsec ($\Delta\tau$ ± .75 ns), and for a continuously variable line the delay setting accuracy should be equal to $\Delta\tau$.

4. Delay stability

The stability required (1 ns in 140 μs or approximately 1 part in 10^5) involves not only the delay line units themselves but the transmission delay in the cables from each telescope. The requirements are based on three different stability time scales:

(a) Short-term (< 1 hour)

(b) Long-term (daily)

(c) Extra-long term (seasonal)

The delay line units and transmission line cables must have short-term stability of the order of 1 nsec. The long-term stability will be measured by observations of calibration sources and corrected for in the computer, with some reduction in signal-to-noise ratio. The extra-long term effects apply primarily to the transmission cables and can be corrected for by periodic (say monthly) adjustment of the offset point in the delay line units themselves.

The temperature coefficient for the cable is approximately $10^{-5}/^\circ C$. By burying the transmission cable to a depth of 3 ft, the stability requirements will be satisfied except under conditions of a sudden heavy rain. By oven-controlling the temperature of the delay line units to $.01^\circ C$, the stability requirements are easily met.

To summarize, the following stability requirements are set for the combined cable plus delay line system:

(a) Short-term ± 1 ns

(b) Long-term ± 5 ns

(c) Extra-long term - measurable to ± 1 ns.

5. Loss variation

The delay unit is followed by the automatic level control (ALC) unit, and so loss variations are automatically compensated for. However, due to limitation in the linear dynamic range of the ALC unit, it is desirable to keep the loss variations to less than 1 dB.

6. Equalization

The function of the equalization networks is to compensate for three primary effects of the delay line units on the input signal spectrum. These three effects (not all independent) are:

(a) Loss

(b) Change in bandpass

(c) Introduction of phase nonlinearities

All types of delay lines introduce these effects to varying degrees. Items (b) and (c) are somewhat alleviated by use of the double sideband system with ALC. The main consideration in (a) is simply to provide sufficient gain prior to the loss so that no deterioration in S/N results.

The equalization requirement may be summarized in the following way. The transfer function of the delay unit is, in general

$$D(\omega) = e^{-\alpha(\omega)-j\sigma(\omega)}$$

where $\alpha(\omega)$ is the attenuation function and $\sigma(\omega)$ is the phase function of the network.

The linear term $\sigma_\ell(\omega)$ in $\sigma(\omega)$ is the only desired term, as it gives the delay. All other terms $\alpha(\omega)$ and $\sigma(\omega)-\sigma_\ell(\omega)$ give rise to the effects (a), (b), and (c) above. Thus, ideally the transfer function of the equalization network would be

$$E(\omega) = e^{\alpha(\omega)+j\left[\sigma(\omega)-\sigma_\ell(\omega)\right]}$$

Such a network will not in general be realizable. The approach for best achieving a low-distortion delay plus equalization network is to first attempt to make $\alpha(\omega)$ and $\sigma(\omega)-\sigma_\ell(\omega)$ as small as possible to begin with and then attempt to find a realizable network $E'(\omega)$ which best approximates $E(\omega)$.

7. Environmental control

The requirements will depend on the choice of the particular type of delay element. With the exception of a cable delay system, the stability requirements can be met by oven-controlling the delay units to approximately .01-.05°C.

The following table summarizes the requirements discussed above.

TABLE 17-1

Delay Line Unit Requirements

1.	No. of units	-	72
2.	Total delay per unit	-	140 μs
3.	Bandpass	-	50-60 MHz
4.	Delay setting accuracy	-	∿ 1 ns
5.	Loss variations	-	< 1 dB
6.	Equalization		
	(a) Loss	-	< 10 dB
	(b) Phase linearity	-	
	(c) Band shape	-	
7.	Environmental control	-	.01-.05°C

C. Possible Designs

There are three types of delay lines which, either individually or in combination, may satisfy the requirements set forth in Section B. These are the cable delay, lumped constant delay, and acoustic delay. Other types have been investigated but found to be unsuitable for this application in one way or another.

The cable delay has excellent characteristics except for cost, bulk, and loss. All but the first inferior characteristic could be compensated for. Table 17-2 gives the basic costs for two cable delay systems which represent different approaches using cables alone. System A utilizes RG 65-u, a slow-wave structure coaxial cable, while system B utilizes 1/2 in. rigid coax with transmission speed approximately 0.9 c. A switched delay system is implied; however, neither the cost of the switches nor the individual equalization networks has been included. Both systems are assumed to operate at base-band with an estimate of $300/60 dB for the amplifiers. The equalizer costs could easily exceed that of the amplifiers, particularly for system B.

TABLE 17-2

Two Cable Delay Systems

Characteristics based on total delay of 140 μs	System A RG 65-u	System B 1/2 in. heliax
Length	3200 ft	117,000 ft
Loss 2-50 MHz	300-1400 dB	133-660 dB
Cable cost	$ 8,000	$110,000
Amplifier cost	$ 7,000	$ 3,300
Unit cost	$15,000	$113,000
Equiv. rack space for 72 units	10 racks	360 racks
Cost for 72 units	$1.08 M	$8.14 M

System B need not be considered any longer. System A now becomes the one to beat by using other types of delay.

The lumped constant delay line may be a useful and relatively inexpensive component in a combination delay system, but it cannot do the whole job. This is primarily due to the fact that a maximum of only 1 or 2 μs delay is achievable for the 50 MHz requirement. Larger delays (or equivalently staggering many units) leads to severe reduction in bandwidth and large phase nonlinearities.

For the extremely large delays required, the acoustic delay line appears to be the only practical system. However, it is not possible to achieve the desired bandwidth at base-band. By converting the IF signal up to a frequency ω_c for which B represents the order of one octave bandwidth, this type of unit becomes practical. Thus $\omega_c \geq 75$ MHz. The glass acoustic line is very attractive due to its low temperature coefficient (.06 ppm/^{o}C) and is being used successfully in the Green Bank interferometer. However, it is primarily a low frequency device with high losses being encountered at about 70 MHz and above. The fused quartz line has a higher temperature coefficient, but operates quite nicely at frequencies well above 100 MHz. For a delay of the order of 100 μs and a 50 MHz bandwidth centered at 75 MHz, the quartz line has approximately 60 dB loss, with most of this taking place in the input-output transducers.

The signal dispersion of acoustic lines in general is quite low. One possible disadvantage is that the minimum delay for an acoustic line is of the order of 1 to 2 μ sec. For the proposed design in Section D, this will present no problem.

Two general design approaches will now be discussed. The first is the discrete stepped-delay configuration using a hybrid of all three types of delay elements. The second is a continuously variable single unit delay which, if proven feasible, offers many obvious advantages over the stepped-delay system.

Fig. 17-1 illustrates the basic principle of the stepped-delay system. The delay line unit consists of a binary set of fixed delays, each with its own equalizing and zero delay equivalent networks. Thus

$$\tau_n = 2\,\tau_{n-1}\ ,\ n = 2 \ldots N$$

and for a total delay $\sum_n \tau_n = 140$ μs with $\tau_1 \cong 1$ ns, N = 17. Except for cable, no single type of delay element can satisfy the requirements for all τ_n. Thus a hybrid system as shown in Fig. 17-2 is required with the following possible distribution of delay types among the τ_n.

Delay number n	Type of delay	Min-Max delay
1 - 7	Cable	1 - 64 ns
8 - 12	Lumped constant	.13 - 2 μs
13 - 17	Acoustic	4 - 65 μs

The lumped constant and acoustic elements are operated at some frequency ω_c above base-band as indicated in Fig. 17-2. This system suffers from several faults, most of which are connected with the fact that three different kinds of delay are utilized, with a requirement for three quite different types of equalizing networks. In addition,

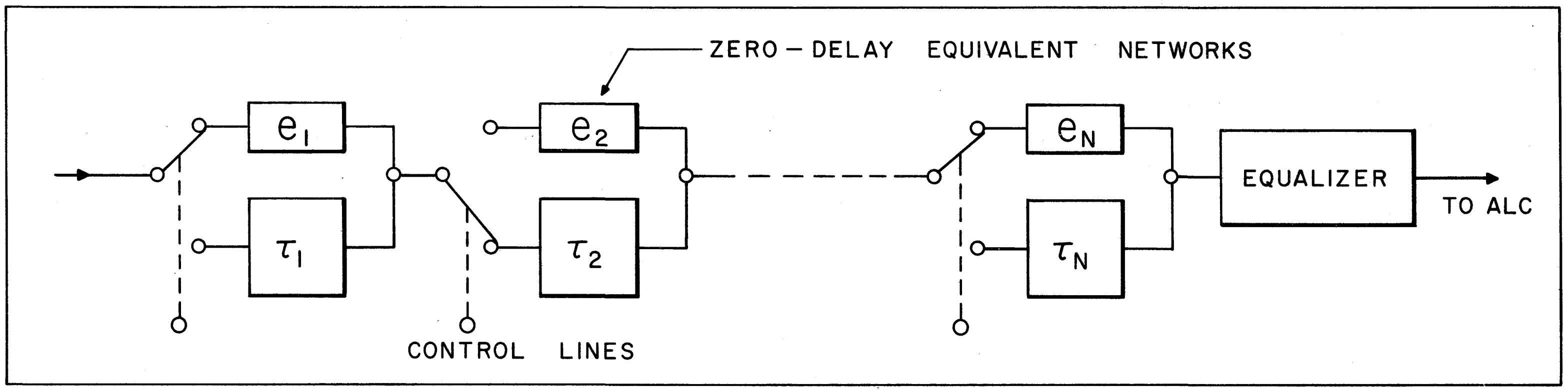


Figure 17 - 1. Stepped - delay unit.

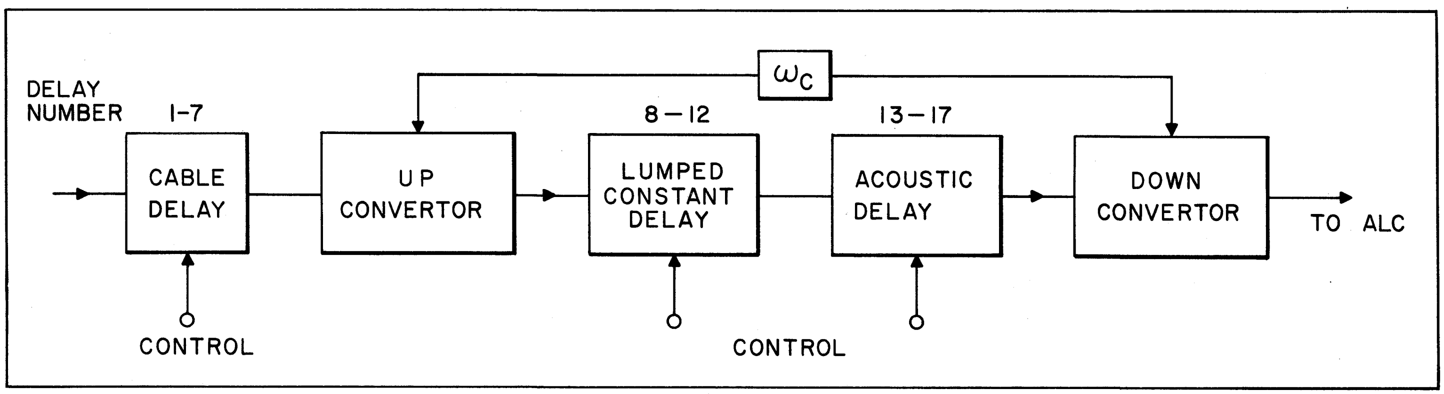


Figure 17 - 2. Delay type-distribution in stepped - delay unit.

the presence of 5 separate acoustic lines, each with transducer losses of the order of 60 dB, complicates matters.

The design which offers greatest promise for the application here is a continuously variable, single unit, acoustic line. The basic principle is outlined in Chapter 13. (See Fig. 13-6.) There is only the single set of input-output transducers and only a single equalization network. (The equalization requirement is set by the transducers rather than the delay material itself, and so remains constant.) The design details of such a unit are given in the next section, with a discussion of its feasibility, based on laboratory measurements of a prototype

D. Proposed Design

In the course of investigating the acoustic delay lines it was learned that Microsonics Inc. of Weymouth, Massachusetts, using fused quartz delay material, was in position to provide a bandwidth capability approaching the required 50 MHz. This material is temperature sensitive (85 ppm/^{o}C) and requires a well stabilized oven. In the course of discussions with Microsonics, it was learned that the company is in production with a variable acoustic delay line which would fit the VLA requirements extremely well, except for its bandwidth, which is somewhat less than the 50 MHz requirement.

The delay line is constructed as shown in Fig. 17-3 of a large triangular shaped wedge of fused quartz material used as the main delaying medium and a second small triangular wedge of the same material acting as the carriage for the two transducers used for input and output. The hypotenuses of the two triangles are in contact via a special lubricant.

The large quartz wedge has two 45^{o} beveled edges along the bottom forming two surfaces that are perpendicular to one another. A wave launched with the input transducer travels straight down to the bottom of the large piece of quartz, reflects from the beveled edges, and returns to the output transducer. Delay is varied by varying the position of the carriage on the hypotenuse of the large triangle using a lead screw mechanism. A critical factor is the lubricant between the

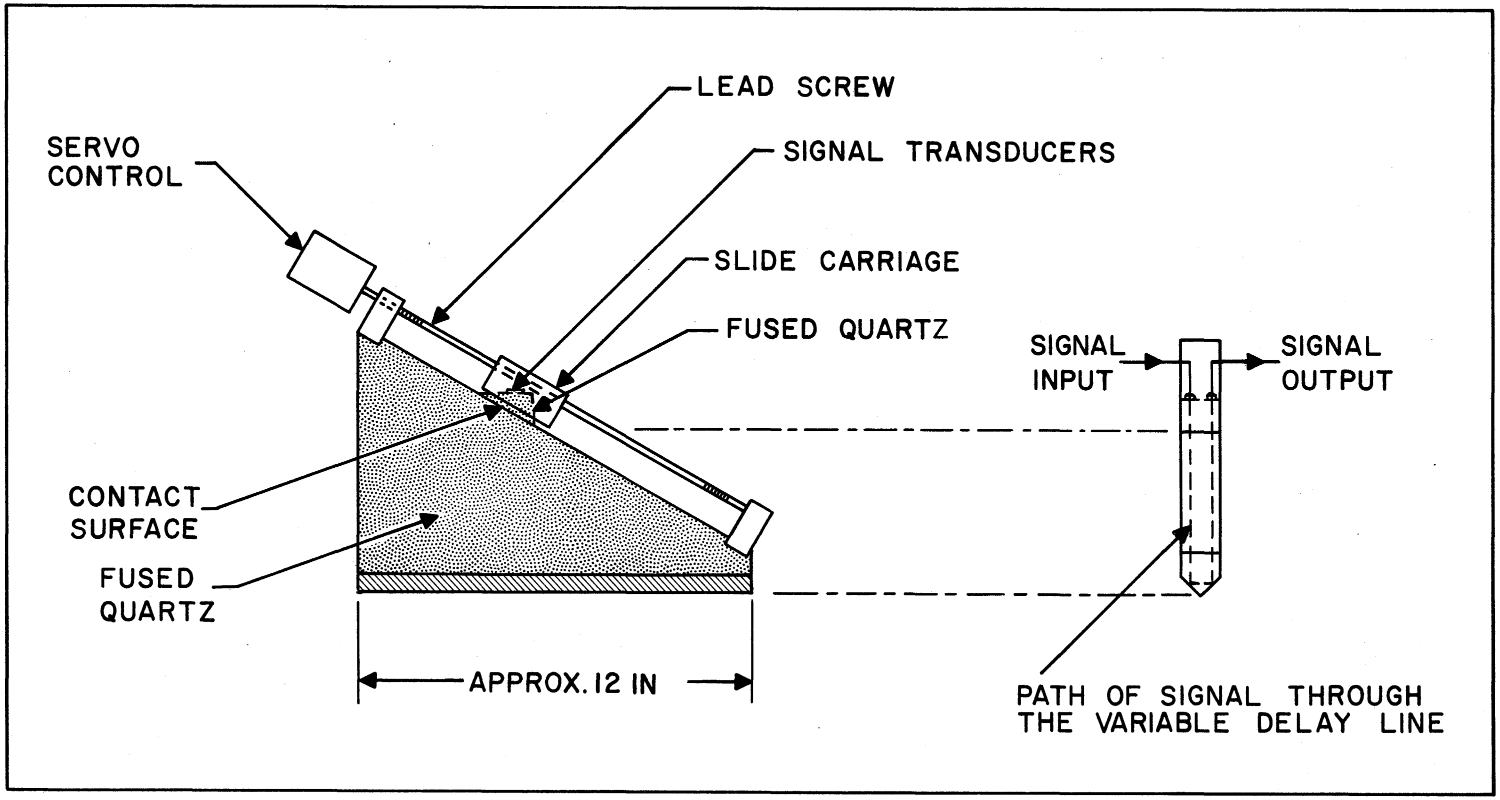


Figure 17 - 3. The variable delay line.

two acoustic materials, which is required not only to lubricate but to provide good impedance match between the two acoustic materials.

The total amount of delay in such devices can be varied anywhere from tens of μsec up to several hundred μsec. The lower limit of delay presents no problem in this situation, of course, because all receiving lines will undergo the same amount of minimum delay, and only the differences between the line delays are of importance. Thus it is possible to enter the delay line once, obviating switching and simplifying amplifier requirements considerably. A new problem arises now, viz the ability to set the delay to the required accuracy of 1 nsec.

Referring to Fig. 17-3, if the length of the hypotenuse is taken to be 12 in and the total variation 120 μsec, then a required resettability of 1 nsec requires a positioning accuracy of .0001 in. This degree of accuracy for mechanical positioning without feedback requires excessive precision and complex machinery. A reasonable alternative is to measure the actual delay electronically for a given delay setting and to correct this setting by a servo system until the required delay is achieved. Since delay dispersion of an acoustic delay line is extremely low, it is possible to measure the actual delay for signal frequencies by actually measuring the delay of an out-of-band pilot tone. Or, a second set of transducers can be used for the purposes of injecting a pilot in the signal band without interfering with the signal. The carriage is notched to place the pilot transducers in the same delay position relative to the signal. The latter appears to be the more desirable method of operating if the delay line is to be measured independently. Where a pilot is injected at each antenna location and the total delay of the system, including the delay line, is measured at the receiving point, then the first scheme, of course, is more practical.

Further work in the following areas needs to be carried out before this design meets the requirements for the VLA delay line unit:

1. Transducer bandwidth
2. Environmental control
3. Delay linearity

4. Delay continuity
5. Servo system - resettability - response time
6. Frequency conversion techniques
7. Pilot tone system

Fig. 17-4 is a diagram of the complete delay-line unit which is used as a basis for the cost estimates. Table 16-1 includes the details of anticipated cost for the delay line unit and for the total VLA system. The estimate for the quartz line itself is based on recent manufacturer's estimates for a unit with similar specifications to that required for the VLA unit.

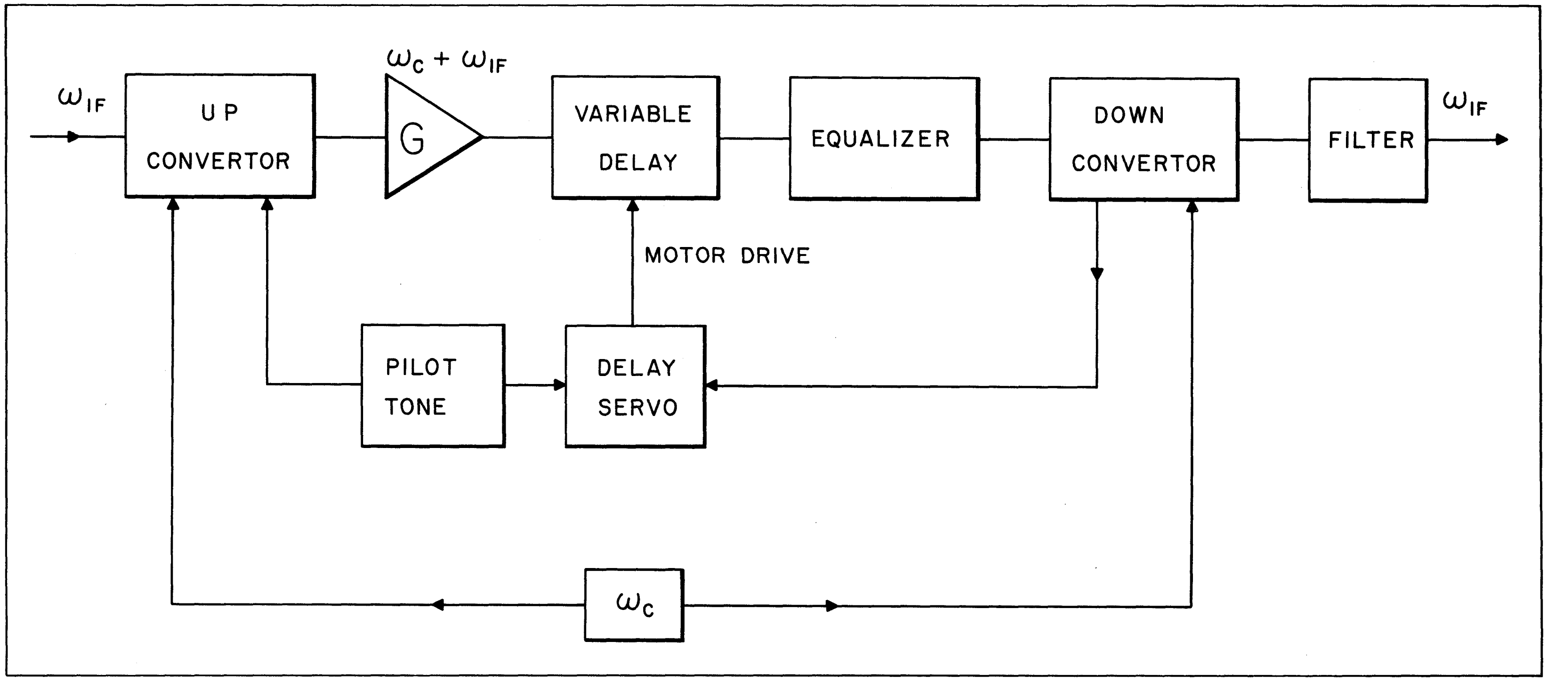


Figure 17 - 4. Continuously variable delay unit.

Chapter 18

CORRELATOR SYSTEM

Chapter 18

CORRELATOR SYSTEM

The term "correlator" as used in this proposal refers to a device which multiplies two IF signals and low-pass filters the resultant product signal. Every antenna in the array must be correlated with every other antenna; thus for 36 antennas $M(M - 1)/2 = 630$ correlators are required for single-frequency, single-polarization measurements. The correlator outputs are multiplexed into one or more A/D converters and are then transferred into a computer. Further filtering (or integration) is performed in the computer to produce a visibility amplitude and phase for each pair of antennas. This visibility function is then Fourier transformed to give the desired brightness temperature map.

More correlators are required for more extensive modes of operation of the system. For dual frequency operation, 1260 correlators are required. For linear polarization measurements assuming no circular polarization is received, 1890 correlators are required. (The correlations between the two polarizations on individual antennas are not of value.) Finally, for complete polarization measurements and maximum sensitivity (increased by $\sqrt{2}$ over 3 bank correlator system), 2520 correlators are required.

The large number of correlators that are required are the dominant factor in the design. The units must be inexpensive, small, and highly reliable. Fortunately, excellent, low-cost correlators have been designed by at least three radio astronomy organizations. Any one of these designs would probably be adequate for the VLA; prototypes will be constructed and an optimum design will be selected. A design which appears best at the present time is described later in this chapter.

Before proceeding to a proposed design, the correlator specifications will be discussed. After the proposed design is presented, the signal distribution system and automatic-level-control (ALC) loop will be discussed. Finally, cost figures will be given.

A. Specifications

The desired output signal, $A_{ij}(t)$, from each correlator is given by,

$$A_{ij}(t) = \int_{-\infty}^{\infty} x_i(t') \, x_j(t') \, h(t - t') \, dt'$$

where x(t) is the IF output of each antenna (after delay correction and automatic level control) and h(t) is the impulse response of the low pass filter following the multiplication of $x_i(t)$ and $x_j(t)$. The impulse response is large over only some finite time, τ, and it is sometimes convenient to think of $A_{ij}(t)$ as being the average of $x_i(t) \, x_j(t)$ over a period of time, τ,

$$A_{ij}(t) \sim \int_{t-\tau}^{t} x_i(t') \, x_j(t') \, dt'$$

The actual correlator output contains 3 components as shown in Fig. 18-1 and as discussed below:

1. Fringe output signal

This will be s sinusoid whose amplitude and phase are the desired fringe visibility components at the u-v spacing of the two antennas being correlated. The frequency of the sinusoid is artifically set by lobe rotators (see discussion in chapter 13) and will be fixed at discrete frequencies between 0.1 Hz and 3.6 Hz, dependent on the particular pair of antennas being correlated. For signals in this frequency range a low-pass filter cutoff frequency of 3.6 Hz and a computer sampling rate of 15 Hz are appropriate. (An optimum low-pass filter configuration and computer sampling rate will be determined in a future study.) The amplitude and phase of the sinusoid are determined after further filtering and integration in the computer.

2. Front-end noise

This is the unavoidable noise due to receiver front-end noise and the random nature of the signals received by the antenna. The rms value

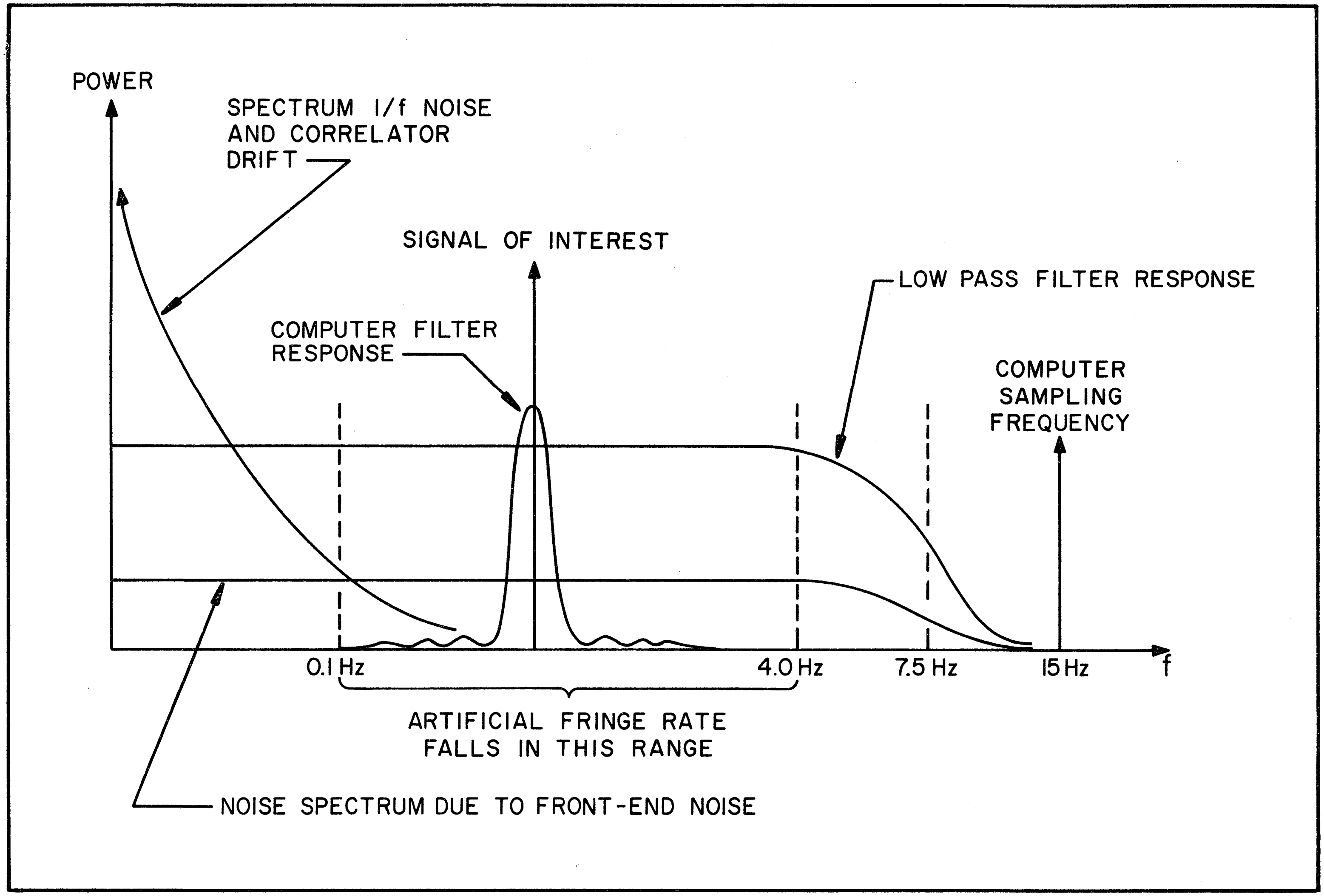


Figure 18 - 1. Power spectra pertinent to the correlator output signal, $A_{ij}(t)$.

of this noise, E_n, is given by,

$$E_n = \sqrt{\frac{2B_v}{B}} \; E_o$$

where B is the IF bandwidth (48 MHz), B_v is the noise bandwidth of the low-pass filter (approximately 5Hz), and E_o is the correlator output for two perfectly correlated IF signals assuming no saturation takes place. These values give $E_n = E_o/2200$. Thus, before computer integration, unity signal-to-noise is produced by a signal having a correlated component which is 1/2200 of the total system noise temperature (including antenna temperature).

3. Correlator noise

This is the noise (including DC drift) due to components within the correlator. The correlator should be designed so that this noise has negligible effect upon system operation. This requires that the correlator noise within the response of the computer-simulated band-pass filter be small compared to the front-end noise, i.e., the front-end noise and not correlator noise should limit the system sensitivity.

It is convenient to consider that correlator noise consists of broadband noise plus a 1/f noise (or drift). The broadband noise must have a value much less than the front-end noise; an rms value of less than $E_o/10{,}000$ will insure less than 4% degradation of sensitivity. The effect of the 1/f noise depends on the detailed shape of the computer simulated fringe filter. This question needs further investigation. Both the drift and 1/f noise have their largest effect on the 0.1 Hz fringe. In order to keep the power introduced by the drift at this frequency well below the front-end noise power, the drift rate must be less than $E_o/10{,}000$ per 8 hours.

No direct multiplication devices exist for signals in this frequency range. To the best of our knowledge, all multipliers which are fast enough make use of balanced square-law devices and are described as "quarter square" multipliers. If x_i and x_j are in inputs, $(x_i+x_j)^2$ and $(x_i-x_j)^2$ are produced and are subtracted to give $4x_ix_j$.

Table 18-1

Correlator Specifications

1.	Output Level and Scales	The unit must have an output level capability of ± 10 V into a 5000 ohm load. Two scales as selected by a relay must give a + 9 ± .5 V output for two perfectly correlated input signals. The second scale must give + 9 ± .5 V output for input signals which have 10% of their power correlated. The second scale should be selected by applying + 28 V to a control terminal.
2.	Input Levels	The inputs of the correlator will be Gaussian white noise signals at a level of 0 dBm into 50 ohms and a bandwidth of 1 dB points of 2 MHz to 50 MHz. The amplitude and phase variations with frequency in this band caused by the correlator should be less than ± .5 dB and ± 10°.
3.	Noise	With zero input signal the noise output of the correlator should be less than 1.0 mV rms in the band, .01 Hz to 3.6 Hz on the first scale. The noise may be 10 times greater on the second scale.
4.	Drift	With zero input signal or with two uncorrelated input signals held constant to within ± .01 dB, the output on the first scale should be 0 ± 1 mV for a 24 hour period with temperature variations of ± 1 $^{\circ}$C. The drift on the second scale may be 10 times greater. If the level of either input is changed by 0.1 dB, the output change should be less than 10 mV on the first scale.
5.	Non-Linearity	The output need not be linear with respect to the product of the inputs. However, the departure from linearity must not be greater than ± 20% for outputs up to ± 9 V and the output vs. input-product curve must be identical to within 2% for all correlators.

A common fault with this type of multiplier is the appearance of x_i^2 and x_j^2 terms in the output due to non-identical square-law devices. These terms cause a DC or slowly varying voltage in the correlator output. At any one input level the DC term can be removed with a gain adjustment on one square-law device. However, as the input level changes (due to gain or antenna temperature changes), a drift will appear in the correlator output. This drift will not have a serious effect unless it has frequency components near the artificial fringe frequency (between 0.1 Hz and 3.6 Hz).

The drift due to variations in x_i^2 and x_j^2 can be easily reduced by an ALC loop and by well balanced square-law devices in the multiplier. An ALC loop has been developed for the NRAO interferometer which holds an output level to within ± .01 dB for input level fluctuations of ± 4 dB. A loop similar to this will be incorporated in each IF cannnel of the VLA, and we will require that the correlator output change by less than ± E_o/10,000 for input level changes of ± .01 dB. This will require that the square-law devices be identical to within 5% which is easily met.

Some further requirements regarding phase and amplitude variations, input and output levels, and non-linearity are given in Table 18-1.

B. Proposed Design

Fortunately, the need for correlators quite similar to those required for the VLA has arisen at three radio astronomy organizations and some good designs have been developed. All of these designs are of the "quarter square" type but differ in the choice of non-linear elements and in the method of developing the sums and differences of the input signals. The designs are described briefly below:

1. A correlator utilizing field-effect transistors has been developed by the University of Bologna and was reported at the 1966 URSI conference in Munich. This unit utilizes the square-law relationship of drain current vs. gate voltage in a field-effect transistor. The sum and difference components are obtained with a transistor phase inverter. A schematic of the unit is shown in Fig. 18-2.

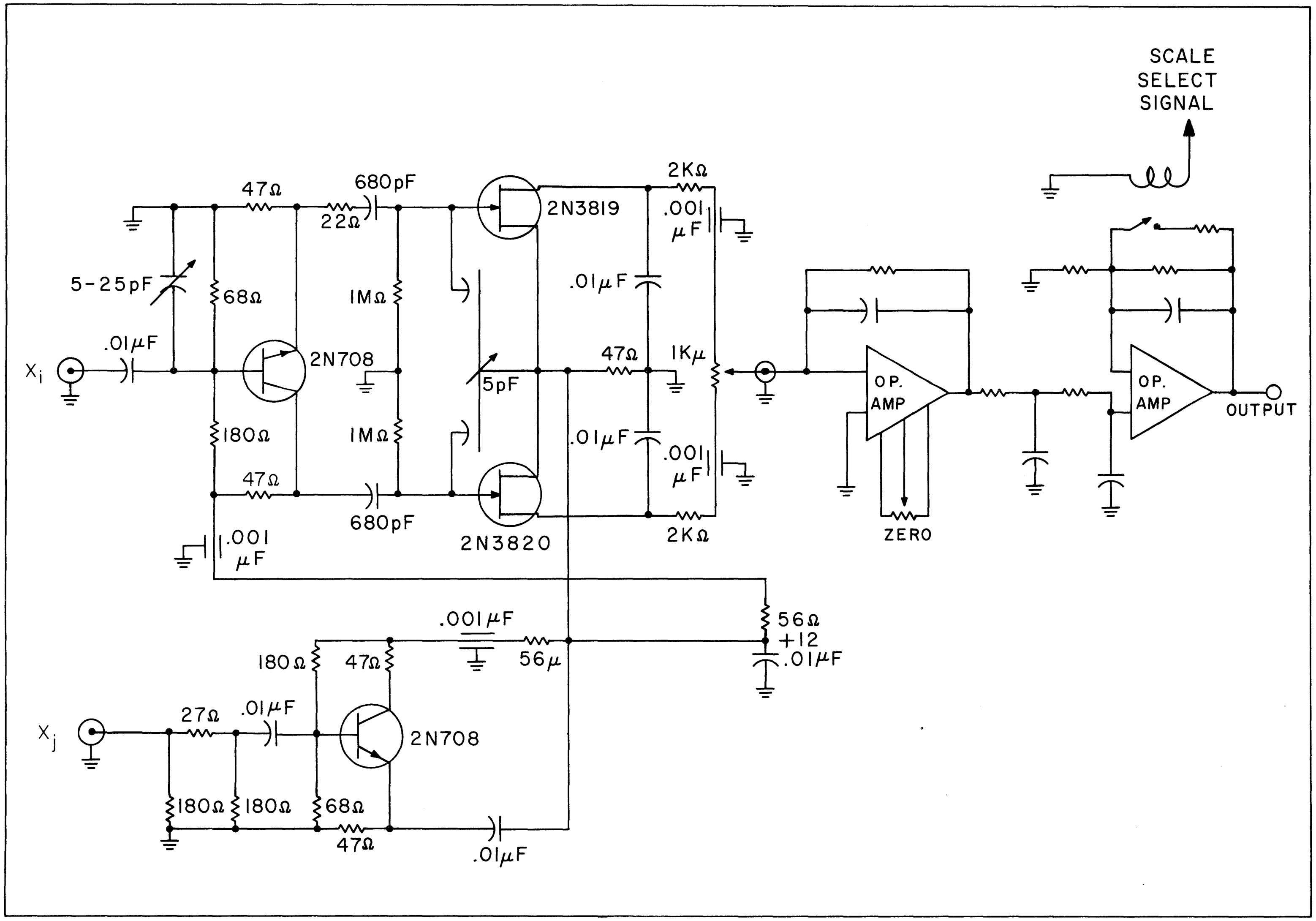


Figure 18 - 2. Correlator design based upon field-effect transistor design developed at the University of Bologna.

2. R.H. Frater of the University of Sydney has designed a correlator utilizing a differential pair of transistors. (This unit is described in Review of Scientific Instruments, Vol. 35, No. 7, pp. 810-813.) The non-linear element is the emitter to base diode in a transistor and the sums and differences are produced in the transistor differential amplifier.

3. At the NRAO a correlator has been developed utilizing hybrid transformers and semiconductor diodes in a full-wave balanced configuration. This unit does not have the required bandwidth but in other respects would meet the VLA requirements.

The first two of the above designs use transistor amplifiers to form sums and differences of the input signals; the NRAO correlator uses hybrid transformers. The hybrid must be well balanced over a bandwidth of 2 MHz to 50 MHz and the cost is uncertain at this time. The small quantity cost of the transformer hybrid used in the NRAO correlator is $190 and the volume occupied is approximately 2 in x 2 in x 1 in. It should be possible to greatly reduce the transformer-hybrid cost and volume; this will be investigated. However, it is fairly certain that a transistor "hybrid" will cost less than $10 and will occupy a volume of approximately 2 in x 1 in x 1/2 in. Furthermore, an integrated circuit "hybrid" meeting the required specifications is almost a reality. The RCA CA 3001 integrated circuit, containing 7 transistors and costing $4.40, will perform the hybrid operation (with 18 dB gain) but only has a bandwidth of 16 MHz. For the correlator proposed in this chapter, a transistor "hybrid" will be used.

A second point of departure in the three designs is the non-linear element. Field-effect transistors, emitter-to-base transistor junctions, and simple diodes are used. The last two are probably quite similar (except DC bias currents exist in the transistor junction), whereas the field-effect transistor has a different temperature characteristic and a different non-linearity curve. Not enough information is available at the present time to make this choice. A diode non-linear element correlator will be proposed. If it is later found that the field-effect transistor is better, the cost difference will be less than $5 per correlator.

Once the hybrid and non-linear element problems have been solved, the correlator design is quite straightforward. A proposed design is shown in Fig. 18-3. Two discrete-element modular operational amplifiers are used to provide voltage gain, low-pass filtering, a scale change, and a low output impedance. Integrated circuit operational amplifiers were not chosen because none having the desired input current drift and output voltage swing are available.

A multiplex switch has been included as part of the correlator to reduce the output signal wiring requirements. The outputs of all correlators in a sub-assembly can then be bussed together. A field-effect transistor is used as the switch because it has low leakage current (< .2 nA), low on resistance (< 80 ohm), and no offset voltage.

The correlator described in Fig. 18-3 has not been constructed. It represents the state of our knowledge at this time, contains the best features of the three designs that have been discussed, and should not differ appreciably in cost from the final design.

A cost breakdown is given in Table 18-2.

C. Mechanical Configuration, Signal Distribution, and ALC Loop

The mechanical configuration of the correlators must be integrated with the design of the IF distribution system and is a vital factor in the ease of maintenance of the system.

It was pointed out at the beginning of this chapter that the number of correlators that are required will be 630, 1260, 1890, or 2520, dependent on the mode of operation of the system and assuming 36 antennas are used. It is reasonable then, to split the correlators into identical banks of 630. These banks should be interchangeable and it should be possible to interchange banks quickly (through coaxial relays or diode switches) in the event of a failure. (In some modes of operation spare banks will be available; in the 2520 correlator mode of operation the loss of one bank will only deteriorate the sensitivity by $\sqrt{2}$.) In order to reduce the wiring associated with the correlator output line, a multiplex system and a A/D converter will be included in each bank.

The circuit shown in Fig. 18-3 can be packaged on a printed board which is 4 in x 2½ in x 1 in. Sixteen of these boards could be mounted

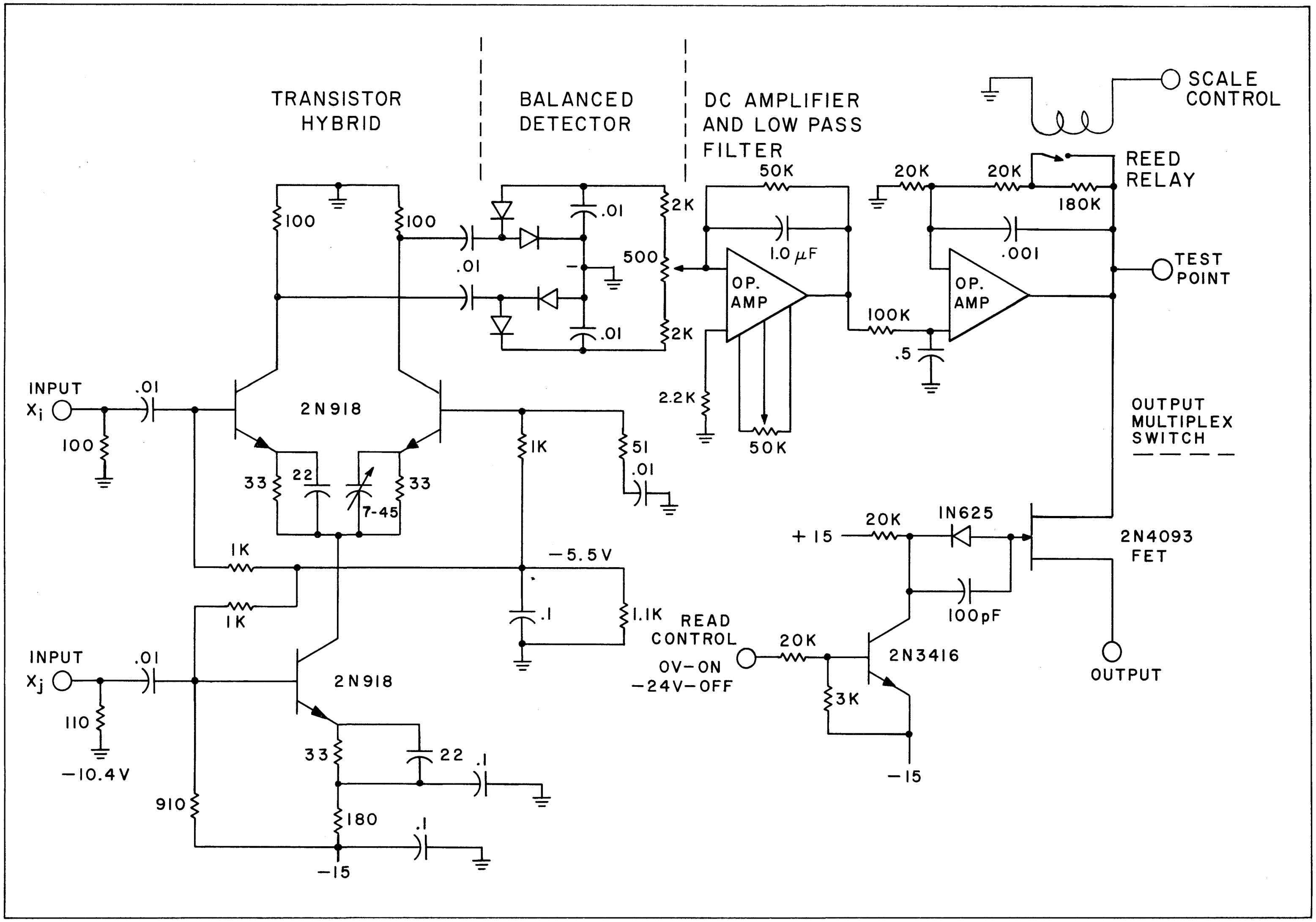


Figure 18 - 3. A proposed correlator design.

on a main board which is $4\frac{1}{2}$ in x 3 in x 18 in. The main board would contain signal distribution, power, and output signal wiring, and would be a plug-in assembly.

Each main board then contains a 4 x 4 correlator array, requires 8 IF input lines, and produces a single multiplexed output. These outputs would be connected to a 64 channel multiplexer located in the same cabinet. Sixteen channel-select lines, connected in common to each main board, will control the output switches on each correlator.

Each IF input to a main board must be distributed to 4 correlators. A means of accomplishing this is shown in Fig. 18-4. An integrated circuit video amplifier is used to provide power gain and isolation. The Sylvania SA-20 unit, priced at $12, can probably perform this task. The isolation requirement between channels is a minimum of 40 dB including all sources of coupling. The different lobe-rotation frequencies help in isolating correlators and it appears that there will not be a cross-talk problem. However, this question needs some closer investigation and prototype measurements.

The distribution circuit shown in Fig. 18-4 will also be used for distribution of each IF input up to 12 main boards. This is accomplished by paralleling 3 of the video amplifiers (with one 93 ohm input-terminating resistor) to give 12 outputs. The connections between the distribution amplifiers and main boards could be accomplished with RG-180B, .142 in coaxial cable. Seventy-two of these distribution amplifiers are required for each correlator bank.

A cabinet layout of a correlator bank is shown in Fig. 18-5. A two-bay standard 19 in panel width cabinet houses up to 1024 correlators, up to 100 distribution amplifiers, power supplies, an A/D converter with 64 channel multiplexer, and some monitor equipment. This correlator bank accepts as an input 72 IF signals, computer control signals for scale (1-bit) and multiplexer selection (10-bits) and produces a 15-bit A/D converter output every 110 μs (for 630 correlators sampled at 15 Hz).

One requirement which is not fulfilled by the mechanical design discussed here is the ability to use the correlators for spectral line measurements as discussed in Chapter 21. In this case it must be possible

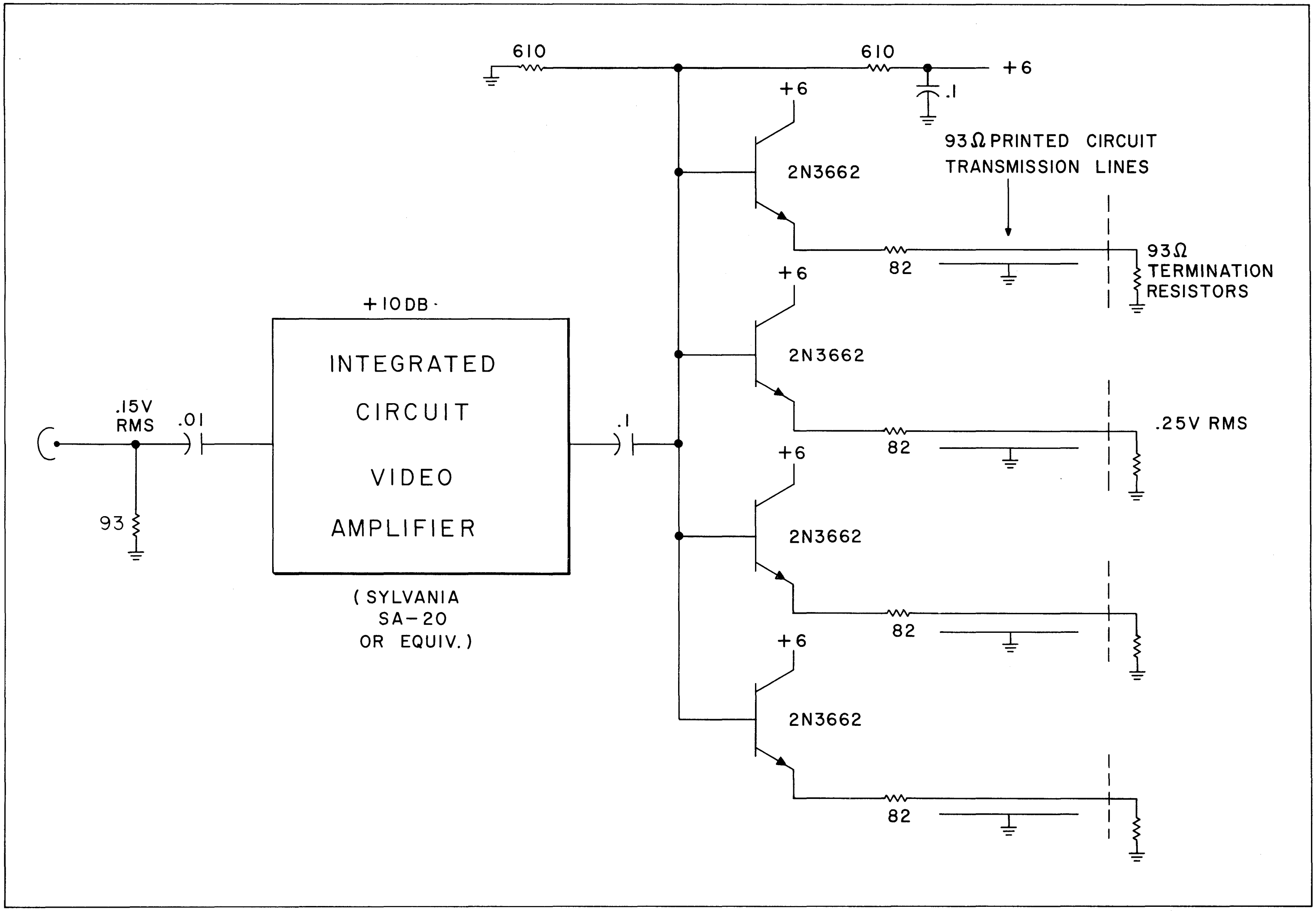


Figure 18 - 4. Distribution amplifier. Eight of these units are required on each 16 correlator sub-assembly.

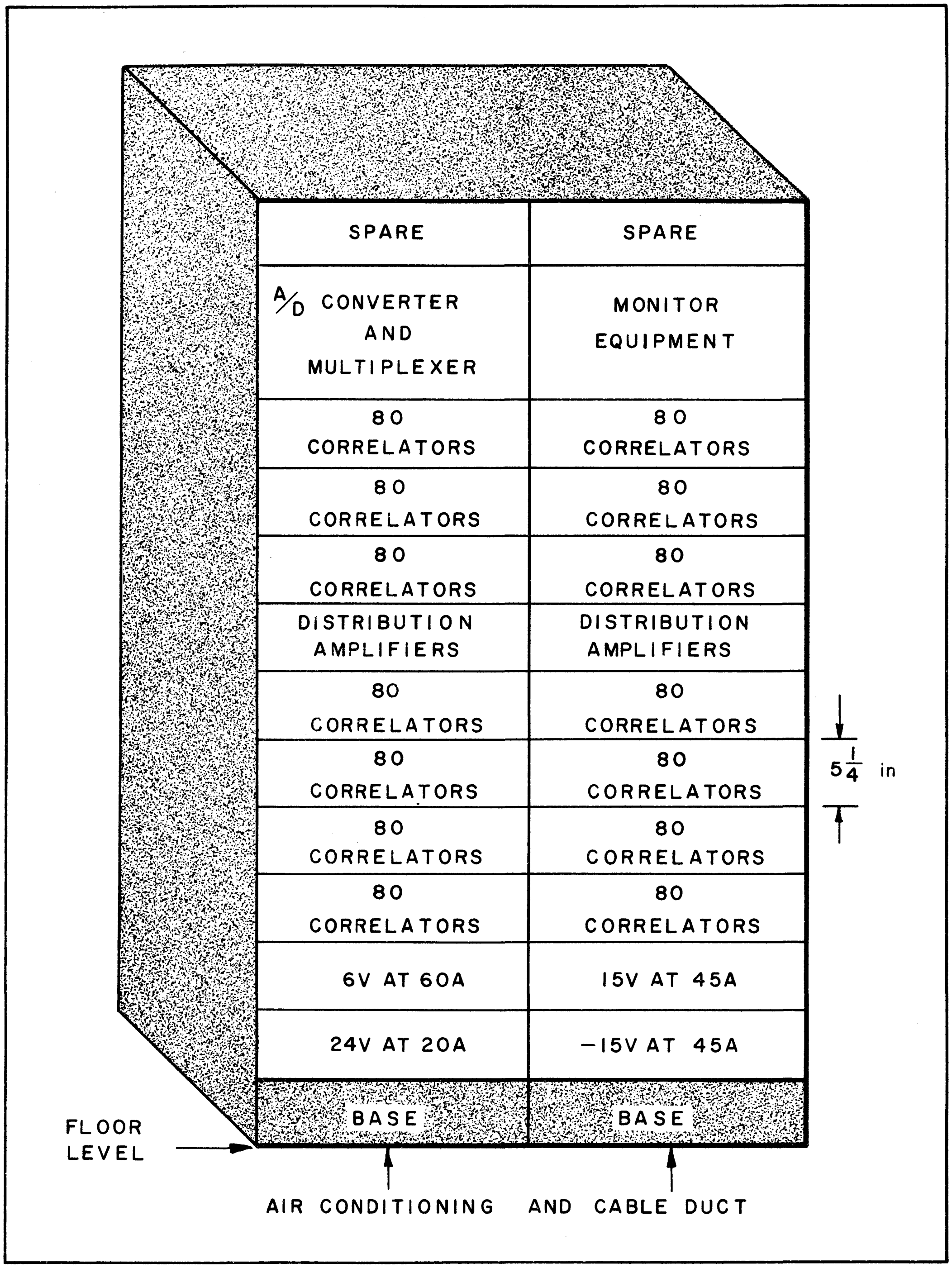


Figure 18 - 5. A cabinet layout of a bank of up to 1120 correlators with associated power supplies, distribution amplifiers, and A/D converter.

to use the correlator banks for calculation of 50 sets of 36 correlations between 9 inputs. This requires a different signal distribution than is presented here; it should be possible to devise a distribution system which serves both needs.

The ALC loop should proceed the splitting up of IF signals into correlator banks; 72 control loops are then required. The design is fairly straightforward; a design which is suitable except for the bandwidth requirement has already been developed and tested. A block diagram of level control loop is shown in Fig. 18-6.

D. Cost

The cost of an individual correlator is tabulated in Table 18-2. The cost is based on assembly, test, and procurement of parts by an outside contractor. The component pricing is based upon the circuit of Fig. 18-3; however, the price would not change by more than ± $5 if the circuit of Fig. 18-2 was used. The materials cost is based upon November 1966 quantity prices. It is expected that in the next few years the drop in materials cost will be offset by rising labor costs.

The overall cost of the correlator system is given in Table 18-3. The pricing of the ALC control loops is based on a material cost of $350 each, a direct labor cost of $240 each, and the same overhead costs as used in the correlator pricing.

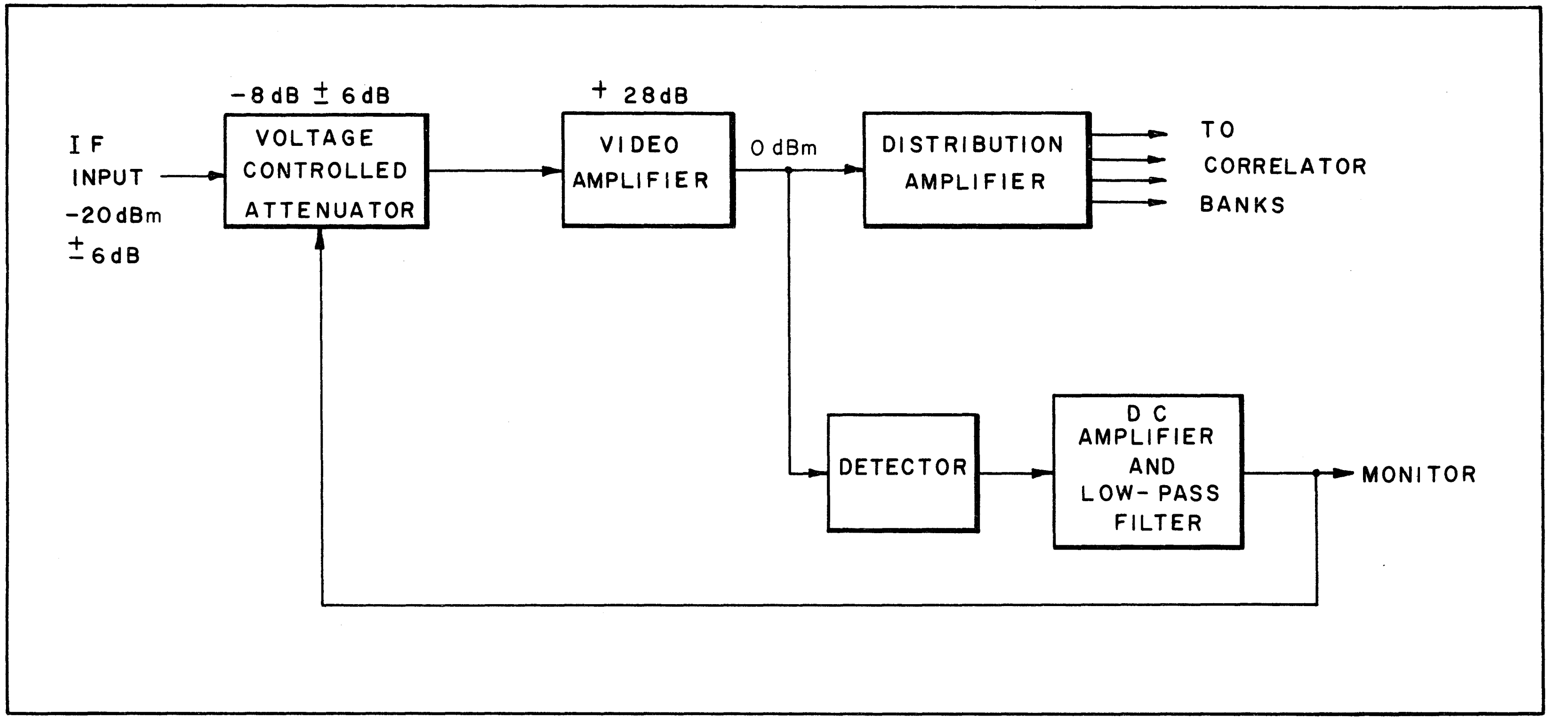


Figure 18 - 6. Automatic level control loop. A loop similar to the above has been designed for the NRAO interferometer and holds output power constant to ± .01 dB for input power variations of ± 4 dB. Balanced diodes are used in the voltage controlled attenuator.

Table 18-2

Correlator Unit Cost

Component	Typical Manufacturer	Quantity	Total Cost
Modular Operational Amplifiers	Analog Devices (Model 108)	2	$ 48.00
Field-Effect Multiplexer Switch	Amelco 2N4093	1	2.70
RF Transistor	RCA 2N918	3	4.50
Switching Transistor	GE 2N3416	1	.40
Detector Diodes	Sylvania	4	6.00
1N625 Diode	Texas Insts.	1	.20
Reed Relay	Dunn	1	2.50
Resistors, 1%	IRC	25	2.50
Mylar Capacitors	Good-All	2	.60
Ceramic Capacitors	Sprague	13	1.00
Potentiometers	Beckman	2	2.00
Variable Capacitor	Centralab	1	.80
Connector Board	----	1	5.50
Total Materials			$ 76.70
Labor for assembly and test 3 hours at $2/hour; 2 hours at $3.50/hour			13.00
Labor overhead at 125%			16.30
Subtotal			$106.00
General and Admin. expense and profit at 20% of Subtotal			21.00
Total Correlator Unit Cost			$127.00

Table 18-3

Correlator System Cost

Item	Cost
<u>Pricing of an 630 Correlator Bank</u>	
560 Driver Amplifiers at $25 each	$ 14,000
45 Correlator Sub-Assemblies at $80 each	3,600
Power Supplies: 15 V at 45 A -15 V at 45 A 6 V at 60 A 24 V at 20 A	3,000
Cabinets and Chassis Hardware	4,000
Cables and Connectors	2,500
Monitor Equipment	2,000
<u>Materials Cost Excluding Correlator Units</u>	$ 29,100
Labor for System Wiring and Testing: 1000 hours at $3/hour 400 hours at $5/hour 200 hours at $7/hour	6,400
Labor Overhead at 125%	8,000
<u>Subtotal</u>	$ 43,500
General, Administrative, and Profit at 20%	8,700
<u>Total Excluding Correlator Units</u>	$ 52,200
630 Correlator Units at $127	80,000
<u>Total Cost of 630 Correlator Bank</u>	$132,200
Spare Parts - 2 Correlator Sub-Assemblies (including 32 correlators) and 15 Driver Amplifiers	$ 4,900
72 ALC Loops at $1025	$ 73,800
Total 630 Correlator System, Including Spares and ALC	$210,900
Total 1260 Correlator System, Including Spares and ALC	$343,100
Total 1890 Correlator System, Including Spares and ALC	$475,300
Total 2520 Correlator System, Including Spares and ALC	$607,500

Chapter 19

SYSTEM RELIABILITY AND MAINTENANCE

Chapter 19

SYSTEM RELIABILITY AND MAINTENANCE

A. Reliability

The VLA has a large number of fairly complex elements and there is a legitimate question as to whether component failures will greatly hamper its usefulness. Fortunately, in most cases, the failure of a single component only reduces the data output of the system by a small amount. As an example, if the signal from one antenna is lost, the number of measured Fourier components is reduced from 630 to 595. The brightness temperature map produced under these conditions would have slightly higher sidelobes but would be adequate for most applications.

A simple model of the effect of failures upon system performance will be presented here. This model is too naive to allow component reliability and maintenance requirements to be formulated but it does allow some informative, general conclusions to be made.

Suppose that the reliability, R, of the system is defined as the average fraction of the Fourier components that are correctly measured; i.e., if on the average one antenna output is lost, R = 595/630 = 0.945. The M antenna array is then divided into a sub-system whose failure will destroy all Fourier components, a sub-system of M components where the failure of any one component will destroy (M - 1) Fourier components, and a sub-system consisting of M(M - 1)/2 components where the failure of any one component will destroy one Fourier component. The ratios of mean-time-to-repair and mean-time-between-failures of components in the three sub-systems are then defined as α_0, α_1, and α_2, respectively. The reliability of the system can be easily calculated with the assumption that only one failure occurs at a time to give,

$$R = 1 - \alpha_0 - 2\alpha_1 - \alpha_2 .$$

This result allows the following conclusions to be drawn:

1. The reliability of the system is independent of the number of elements. As the number of elements is increased, the number of failures will increase but the fractional loss in Fourier components per failure will decrease. The reliability of the VLA should be equal to that of the NRAO 3-element interferometer.

2. The requirements upon the reliability of the portions of the system proportional to M^2 are no more stringent than those portions proportional to M^1 or M^0. These portions will fail more often but the loss per failure is less.

3. It is, of course, the ratio of repair time (including time to diagnose fault) to time between failures that is of importance. This emphasizes the requirement for quick fault detection and correction.

4. In general, the requirements do not look too severe; if the α's have values of 1/100, 96% of the Fourier components will be measured. This means that a component which fails once per month must be repaired in 8 hours.

A quantitative study of the reliability of the system could be helpful in minimizing the overall cost per Fourier component by giving guidelines regarding expenses for a monitor system, maintenance manpower, and spare parts. This study will be attempted; the main difficulty will be the lack of valid failure statistics on components.

B. System Monitor

A computer monitor system is briefly described in Chapter 20. This system includes an A/D converter with multiplexer at each antenna, a data communications system, and various output display equipment.

The prime function of the monitor system will be to locate faults down to the level of a replaceable unit. When a fault has been detected, the Fourier coefficients which are affected will be tagged and a message will be typed to the operator indicating the faulty monitor values and a suggested repair procedure.

All control and monitor operations could be handled through the computer but it appears desirable to also be able to control and monitor functions at the equipment location and, to some degree, at the main control room without the use of the computer. Some desirable monitor and control functions, external to the computer, are the following:

1. Antenna control

At each antenna and in the main control room a MANUAL-COMPUTER control switch should be provided. At each antenna simple manual controls, adequate for servicing or stowing, should be provided. In the main control room, 2 independent antenna control consoles should be provided with the ability to control any one or more of the antennas. As a fail-safe precaution, any antenna receiving improper control signals for a short period of time (as detected by check list errors) should remain fixed in position; any antenna receiving erroneous control signals for longer than 10 minutes should go to stow position.

2. Antenna position monitor

Independent of the above control switches, it should be possible to indicate the position of one antenna on each of the 2 control consoles. If it is necessary to indicate the position at the antenna location, a portable test set, capable of indicating antenna position and control signals, should be used.

3. Delay line and lobe-rotator control

Local MANUAL-COMPUTER control switches and controls should be provided.

4. Receiver analysis consoles

Two consoles, each capable of being switched to any receiver, should provide oscilloscope, spectrum analyzer, and chart recorder display of the receiver IF output and meter or chart recorder indication of monitor points or a particular correlator output.

5. Weather instrumentation

Instruments for measuring wind velocity, temperature, barometric pressure, and humidity at appropriate locations should be provided. These variables should have visual indication and should also be fed into the computer.

6. Voice communication and audio monitor

Good quality 2 way phone communication should be provided to each antenna and equipment hut. (Radio communication may cause interference.) An audio monitor unit capable of listening to any one antenna drive package or a mixture of drive packages will be useful.

The cost of the above items has not been included elsewhere. A cost estimate is given in Table 19-1.

Table 19-1

System Monitor Cost (Excluding Computer Cost of Table 20-3)

Item	Cost (Thousands)
Materials, Main Control Room	\$ 50
Materials, Per Antenna	\$ 36
Engineering Labor - 2 Man Years	\$ 25
Technician Labor - 4 Man Years	\$ 28
Drafting Labor - 2 Man Years	\$ 12
Overhead on Labor at 125%	\$ 81
Subtotal	\$232
G&A and Profit at 20%	\$ 46
Total	\$278

C. Test Equipment

The following items of test equipment are required to maintain the system. This equipment is for the repair and alignment of defective units rather than for location of faults; the latter is the function of the monitor system. The total cost of equipment is \$160 thousand.

1. Paramp test set

This will include the paramp pump and equipment to measure the gain, noise temperature, and stability of the paramp. -- \$15,000

2. LO test set

This will include equipment for testing LO launchers, receivers (including lobe rotator), and terminators with simulation of cable loss and phase variations. -- \$25,000

3. IF repeater test set

This will include equipment to measure the gain, phase match, cross-talk, and dispersion equalization of repeaters. -- $10,000

4. Delay system test set

This set will have provisions for simulating computer control signals and accurately measuring delay. -- $15,000

5. Correlator test set

This set will provide noise signals of known correlation for testing of correlators. -- $ 5,000

6. Equipment box oscilloscope

An inexpensive oscilloscope will be provided in each antenna equipment box to facilitate alignment of paramps and testing of the digital-data communication system. -- $25,000

7. Interference measurement sets

This is equipment to monitor the interference level in the RF and IF frequencies used by the array. -- $25,000

8. Portable test equipment

This includes portable oscilloscopes, signal generators, meters, a time-domain reflectometer, phase-angle voltmeters, and counters. -- $40,000

Chapter 20

THE COMPUTER SYSTEM FOR THE VLA

Chapter 20

THE COMPUTER SYSTEM FOR THE VLA

A. The Relation of the Computer to the VLA

Early in the design stage of the VLA, it was realized that an array of several tens of antennas connected to several hundreds of receivers would present problems in control and display far beyond those encountered in any radio astronomy system presently in operation. The most immediate solution to these problems is to have a digital computer perform the detailed functions, receiving from the operator only a generalized description of the task it is to perform. Once one conceives of using a digital computer for control and monitoring of the antennas and receivers, it is very natural to conceive of extending its duties to the manipulation, control, and display of the data of the array as well. Indeed, the computation problems in data manipulation are very quickly seen to be of much greater magnitude than those in monitor and control.

As soon as one decides to use a supersynthesizing array, the decision that a computer should be a very large part of the array is reinforced. To use supersynthesis, data must be remembered during the time that the rotation of the earth is changing the projected configuration of the array. By far the least expensive memory of the desired retention time and precision is digital recording. If a stored program computer is also given access to the information, it can perform various sorting and bookkeeping operations which would be rather difficult to implement in any other fashion.

In the fall of 1965 a subcontract was let to The Defense Electronic Products Division of The Radio Corporation of America to study the computation problems of the VLA and to suggest ways of meeting them. The conditions of the study were somewhat restrictive, in that a block diagram of the system as then conceived was given to RCA for use as a starting point. They were not asked to suggest modifications of this block diagram to reduce or optimize the computer requirements. Their studies led them to propose a "benchmark" system, which would perform the necessary computing tasks for the given block diagram. They then considered most likely ways to modify the computing system, and discussed the costs of achieving the necessary computing power in various ways. These discussions are very valuable, although systems much less costly than the RCA "benchmark" system may be realized by relatively minor changes in the block diagram of the receiver. Since that time the provisional block diagram has been revised to include phase rotators in the local-oscillator lines, and the ability to have up to three correlators per antenna pair.

The RCA study also included consideration of the monitor and control functions of the computer. These, they showed, reduce mainly to the provision of sufficient input-output ability of the computer to supply the individual antennas with information at the required rate. There are many ways of handling information at the desired rate, and computer interfaces of this nature are often constructed for the particular application; however, RCA has described a relatively inexpensive way to handle the necessary data rates, and since it is shown that this is a small part of the total cost of the computing system, further studies of this aspect are properly left to the detailed design of the computer system.

The philosophy that has been evolved for the computer system for the VLA is that in normal operation the operator should have to do as little as possible. The computer must be informed of the position in the sky that it is wished to observe, and the length of time that the observation should continue. The computer will then point the antennas, set the receiver gains, acquire, condense, and record the receiver outputs, monitor many tens of receiver checkpoints, keep a log of the system behavior, and inform the operator if any part of the system is not behaving according to the computer's internal specifications. After the completion of the observation, the computer will sort the observed data points onto the u-v plane, calculate and apply various calibration corrections, combine observations, apply a weighting specified by the observer, perform the Fourier inversion, and output a map of the region of sky under study. This will be done assynchronously with the computations necessary for observations, but at a rate such that these computations will not fall behind. No backlog should be allowed to form.

In case of malfunction of any part of the system, observations would continue, if possible, with the remainder of the system, and the computer would inform the observer of the effect of the malfunction on his data, that he may decide whether it is necessary to repeat all or part of the observation. The computer would assist in abnormal operations to some extent; for instance, in the case of receiver malfunctions it would recite the history of the malfunctioning segment of the receiver and allied checkpoints. Its degree of participation will probably increase with time, as programs are written to cover more and more contingencies.

In the following, the computing needs of the VLA are analyzed in detail. These are divided into three classifications: The data acquisition and reduction, which depends strongly on the receiver block diagram, and will be discussed in an appendix for several possible block diagrams other than the one specified; the monitor and control functions of the computer, which are essentially a problem in digital communication; and the problem of producing and displaying a map of the area of sky in question, which may be attacked asynchronously with the first two functions.

Below, we shall refer to "computing power". This we shall quantitatively define as the number of operations per second necessary to accomplish the given task. If two tasks are to be done by the same computer, we may determine the necessary computing power of the computer simply by adding the computing power of the tasks. This assumes the tasks are independent, so, at the end of the calculation of required computing power we must apply a "safety factor" to allow for the possibility that, because of the nonuniform requirements of the task, the peak demand for computing power may be somewhat greater than the mean. In estimating the necessary computing powers, the inmost loops of the necessary programs have been coded, using a set of commands common to most of the computers in the size range of interest, and the number of operations counted as follows:

Type	Examples	Operations
Generic	COMPLEMENT, JUMP, TEST, STORE (from data channel) INCREMENT INDEX	1
Short Arithmetic	ADD, SUB, LOAD, STORE, AND, OR, COMPARE	2
Long Arithmetic	MULTIPLY	6

The input-out functions of the computer are somewhat harder to specify exactly. One must not only specify a rate of input, but one must also specify whether the inputs tend to come in bursts, and allow for the maximum rate. Input-output is more sensitive to this than computation, because buffers outside of the computer to hold the values waiting to go in are more expensive and less versatile than the core memory inside which can hold the results of calculations until they are needed. Also, a consideration in the price and complexity of the interface is the sheer number of input-output lines. Each correlator will have at least one analog output, which must be read by a digital voltmeter to enter the data into the computer. Several hundred more analog lines will come from the rest of the receiver. If the rates are slow, as many lines as necessary may be added with a tree type relay multiplexer, for a cost of less than $100 per line. However, if the rates are fast, it probably pays to use one of the standard commercial multiplexers, with about two or three hundred input lines, and to multiply the number of digital voltmeters to cover the necessary inputs. This requires greater sophistication of the interface, and a more expensive access mechanism to the computer memory; however, the costs are still small compared with the total computer cost for the array.

B. Correlator Data Processing

In the following discussion, calculations are carried out for an array of 36 elements, with three sets of 630 correlators each. For the most part, the numbers scale in an obvious way for a different number of antennas. The scaling is not carried through the calculations because it will amount to only a few percent, at most, and is comparable to other uncertainties. It is assumed that there are phase rotators in the local-oscillator lines to each antenna, and that these phase rotators can, once started, produce a constant rate of change of phase with no further attention from the computer. It is also assumed that the A/D converter interfaces into the computer in the most convenient fashion, so that the data words require no reformating before processing.

The most convenient way to reduce the high natural fringe frequencies encountered in the array is to rotate the phase of the local-oscillator signal in synchronism with the changing phase of the signal arriving at the antenna, removing the natural phase rate. In addition, an artificial phase rate of n•r may be introduced in the local oscillator signal for antenna n, where r is some convenient rate. The fringe rate from the correlator connecting antenna n with antenna m is then (m-n)r, and ranges from r to (N-1)r, where N is the number of antennas in the array. The superimposed fringes may be either sine waves, or square waves with 90° phase shifts. The square wave would require a perfect integrator in order to avoid losing signal-to-noise ratio on the corners of the output waveform, whereas the sine wave would be more natural if an R-C integrator is to be used.

The lowest fringe rate, r, is dependent on the size of the field of view desired. If we specify the largest possible field of view, 15' at 1" resolution, we find that a cell in the u-v plane is traversed in about 15 seconds. In practice, we shall probably never use such a large ratio of field of view to resolution, because the field of view at 1" resolution is limited by bandwidth effects to about 2'. However, in order to preserve the ability to observe the large field of view with a narrower bandwidth or to time multiplex different polarizations, frequencies, or delay line settings, it is advisable to set r, the slowest fringe frequency, equal to about 0.1 Hz. The highest fringe frequency is then about 4 Hz, and the correlator outputs need to be read at a frequency of about 15 Hz.

A flow diagram of the data reduction loop is given in Fig. 20-1. If the longest fringe period divided by the sampling interval is a prime integer, p, then the p samples of all correlator outputs will fall at phase intervals $\frac{2\pi}{p}k$ all around the circle. The whole 2π phase interval is divided into a moderate number, say, 15, of boxes, and the correlator outputs are accumulated in the proper phase interval, and then at the end of the ten second interval, the resulting 15 numbers are fitted by least squares for the amplitude and phase of the sine wave. The memory requirement is fairly large, 15 words per correlator, or 29,000 total, probably requiring a total memory of 65 K words for this computer. There are algorithms involving much less memory, but which cost nearly a factor of two in computing power. The time required for a data channel to store the input word, and for the computer to find the proper phase interval and add the input to it is about nine operations, as defined above.

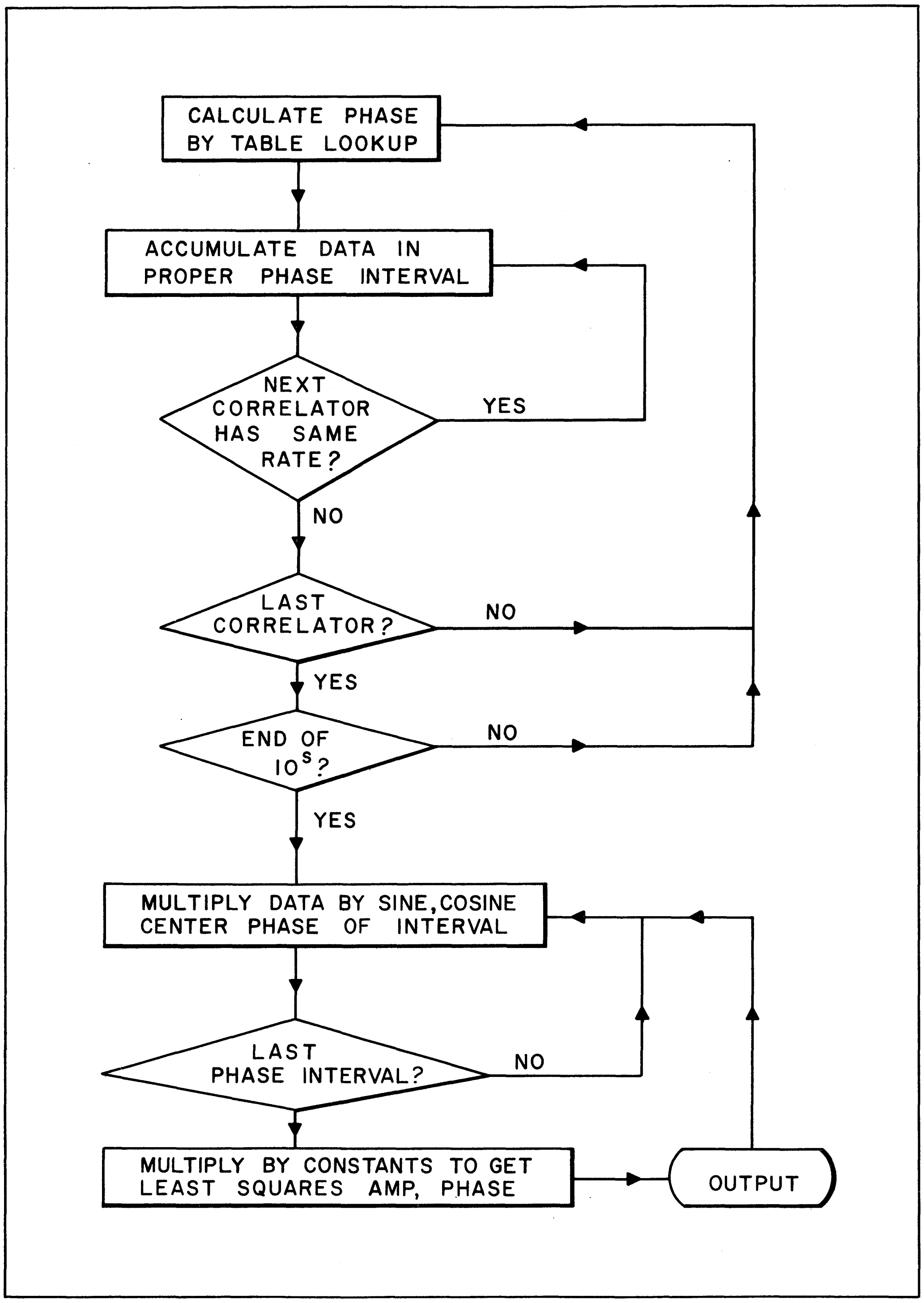


Figure 20 - 1. Flow chart of data reduction program.

The total computing power for these operations is about 2.9×10^5 operations/sec. The fitting of the accumulated data by a sine wave at the end of the 10 second interval requires about 600 operations/correlator, a total computing power of 1.2×10^5. Additional tasks, such as correcting the phases for rapidly varying position terms (e.g., refraction, diurnal aberration) and calculations of (u,v), will probably add an additional 1×10^5 in computing power requirements. The total requirements are thus about 6×10^5 operations/sec. To handle the possible crowding of functions, a machine with a computing power of 10^6, a 1 μs cycle time, is called for. There are several medium sized machines on the market today which have this computing power, among them the IBM 360/44, the RCA 70/55, the CDC 3200, and the SDS SIGMA 7.

The computer may have sufficient spare capacity to perform ancilliary functions at the same time, such as inspecting the output to see if it is reasonable in the light of what is known about the source. It is probably uneconomical to attempt to assign to this computer the job of controlling the array and monitoring the receiver, even if a computer of slightly greater computing power is used, as the load is so heavy that it would take an extremely sophisticated program to handle the requests for time so that data is never lost for want of processor time. The cost of writing such a program and the cost of the lost time on the array while the program is being debugged would probably exceed the cost of a second processor.

C. Monitor and Control Functions of the Computer

The computer must do all of the housekeeping account work for the array, which, although involving long and complicated programs, does not take a measurable fraction of the computing time. In addition to the accounting, there are several jobs which are best accomplished under digital control. These are discussed below.

Firstly, there is the job of antenna pointing. For altitude-azimuth mounts, this involves firstly the coordinate conversion, and possibly, secondly, the closing of the servo loop, to keep the antenna pointed at the source. It is possible that the loop may be closed in a special purpose analog device external to the computer. In order to keep the array elements pointed with sufficient accuracy, the position must be computed and output several times/second. If the servo loop for positioning is closed externally, this might fall to 1/2 per second or lower, depending on the design of the analog device. Most of the time the positioning may be done by simply adding the rate of change of altitude and azimuth to the old values of the coordinates. This need be updated with an exact coordinate conversion only once a minute in the worst case. The main part of the antenna positioning loop is thus the calculation of the individual pointing errors for each antenna, calculating the error signal, and communicating it to the antenna. This is only about 12 operations per axis, or a total computing load of about 5000 operations per second.

Secondly, there is the job of updating the lobe-rotators. If the lobe-rotators are constructed to operate at a constant rate between updatings, the total work load associated with this function is less than 1000 operations/sec. The job of updating the delay lines is very similar in nature. The delay lines must be updated at a given interval in the natural fringes. For a 50 MHz bandwidth, the delay lines should be updated about every four fringes to ensure no loss of gain. The total computing job is about 2×10^4 operations/sec to update 72 delay lines.

Thirdly, there is the job of monitoring the receiver outputs and check points. The most critical of these is the IF level, as this is probably the most convenient point at which to detect burst-type interference. This must be sampled quite frequently -- perhaps 10/second -- to insure the detection of bursts. Even so, the computing load associated with this function is only of the order of 10^4. The other monitor points have an even lower requirement for computing power. Further, they are not time dependent, so that they can be postponed for milliseconds, or in some cases, even seconds, until the computer is free to deal with them. These functions primarily add to the length and complexity of the programs rather than to computing load. There are other necessary, but rarely used, programs which will necessitate the addition of a direct assess storage device to the monitor and control computer for program storage. As an indication, approximately 10,000 commands of program have been written for the NRAO interferometer computer, which will be handling a system of considerably lower complexity, and which has not yet started to grow through use.

Fourthly, the computer must control the various switches in the receiver. This also takes very little computing power. The main effect of these functions is to increase the complexity of the input-output interface rather than to load the computer. The total monitor and control input-output line requirements are summarized in Table 20-1.

A second aspect of monitoring the receiver checkpoints is that the conclusions must be presented to the operator. Three output devices seem to be needed for this function. Quantities always present and changing, but not of interest in the normal operation of the array, are best presented on a character type CRT display; then the quantities of interest may be displayed without generating large amounts of paper which must be examined to find the variable of interest. Alarm conditions, which may require immediate operator attention are probably most conveniently output on a typewriter, since such messages are short and infrequent, but one would like a permanent record of them. A third type of message is the system log, which is likely to be a fairly lengthy document, which will be examined only to determine when changes were made to the system, when a later discovered malfunction first began to appear, and to keep track of the observations made to avoid too much duplication. This document should be output on a line printer or a fast typewriter.

A fairly major portion of the control system is the problem of communicating the necessary information from the central computer to each antenna. The distances are so great that the cost of cable is a major factor, so that a more sophisticated decoding system which makes the entire transmission serial by bit represents a definite saving. RCA has described a bit serial transmission system which would easily handle the data rates given in Table 20-1.

Some block diagrams associated with the communications system are given in Fig. 20-2. The circle labled "comm control" is the heart of the communication system, and consists of serializers and multiplexers for the output data, deserializers for the incoming data, and circuits to generate and analyze the synchronization information. At worst it is as complicated as three high-speed Dataphones; hopefully, it may be somewhat simpler, as various simplifying conditions can be imposed on the

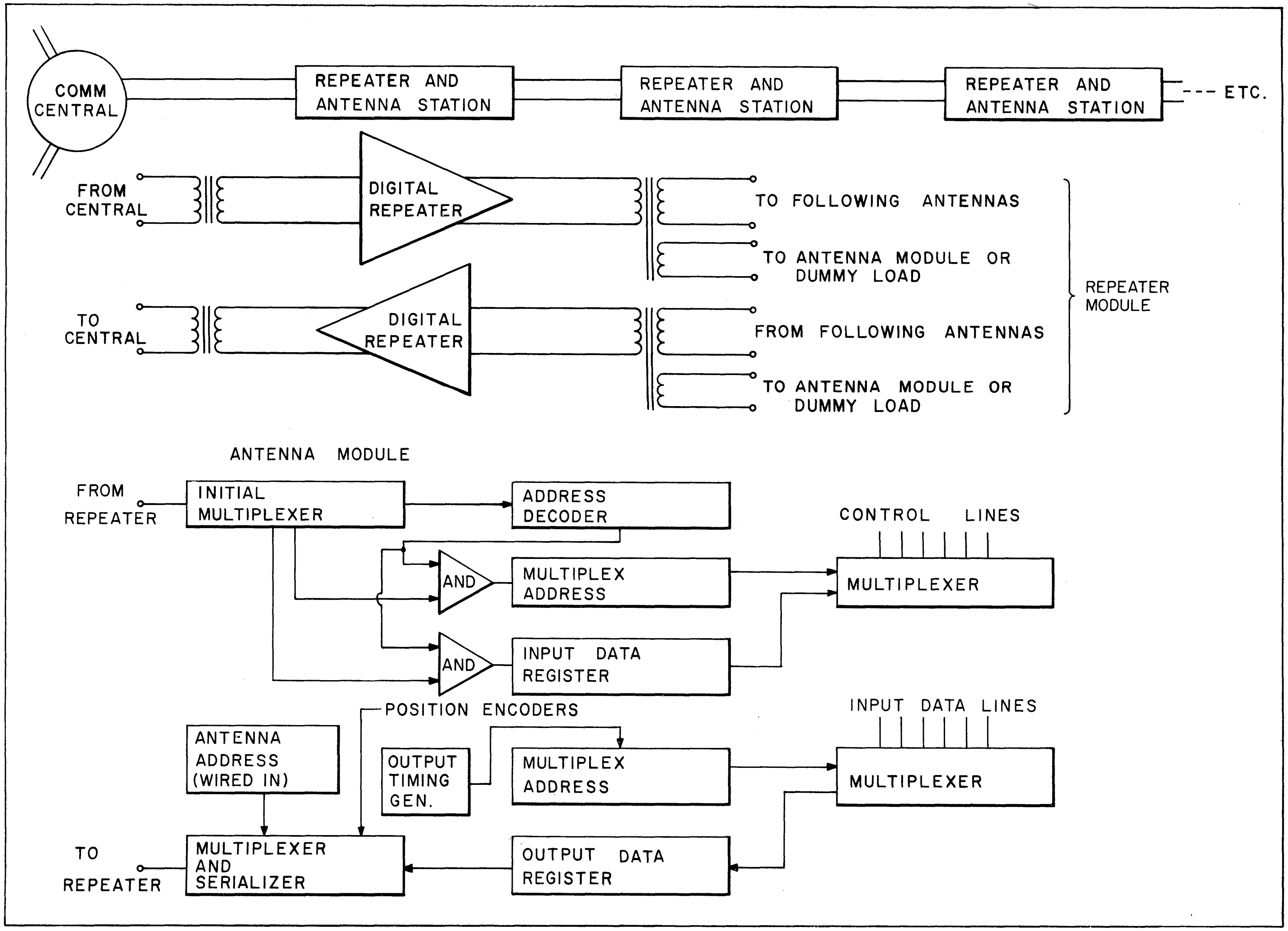


Figure 20 - 2. Digital communication system.

Table 20-1

Computer Input-Output Line Requirements

A. Digital Input Lines

Function	Number of Bits	Rate	Number
Azimuth Angle of Antenna	17	5/sec	36/array
Altitude Angle	17	5/sec	36
Polarization Angle	13	1/min	36
Focus Position	13	1/min	36
Frequency	24	1/min	1
Time and Date	48	1/min	1

Total Digital Input Lines 2500 bits

Total Digital Input Rate 500 words/second

B. Digital Output Lines

Azimuth Motor	not yet	5/sec	36/array
Altitude Motor	decided	5/sec	36
Calibration Signals	4	1/min	36
Polarization Motor	4	1/sec	36
Focus Motor	2	1/sec	36
Delay Line Control	17	5/sec	72
IF Level Control	3	1/min	72
IF ALC Control	1	1/min	72
Correlator Gain Control	1	1/min	3

Total Digital Output Lines ∿ 3000 bits

Total Digital Output Rate 800 words/second

C.

Analog Input Lines, Central Building	Rate	Total Lines
Correlator Output Lines	15/sec	1890/array
IF Monitor	10/sec	72
IF Gain and ALC Monitors	1/min	144
Power Supplies		20
Local-Oscillator System		5
Weather		5

Total Analog Input Lines 250 + correlators

Total Analog Input Rate 750 lines/second + correlators

(Table 20-1, continued)

D.	Analog Input Lines, Each Antenna	
	Paramp Pump Monitor	4 lines
	Crystal Current Monitor	4
	Box Temperature	1
	Weather	2
	Phaselock IF Level	1
	Receiver IF Level	2
	Total analog input lines at each antenna	14

data stream. Depending on the input-output structure of the monitor compute it may be convenient to impose a small data controller computer between the monitor and communications central, in order to achieve proper synchronization without absorbing too much of the input-output ability of the monitor computer.

This system or a simple modification of it would permit communication over the entire array. The most pressing communication need is the transmission of 17 bits of position information for each axis, perhaps as often as five times per second. If we permit up to 20 antennas on each arm, this requires a rate of 20 kilobits/second, assuming alternate words are reserved for nonposition information, and that each transmission includes a six bit address and a parity bit as well as the 17 bits of position information. If it is thought desirable to allow for the possibility of putting all 36 antennas on a single arm, provision could be made for duplicating the cable runs (and operating with two systems on a single arm) on the inner part of each arm. This would be less expensive than constructing a 40 kilobit transmission system. A possible time sequence for the information arriving at the central computer is shown in Fig. 20-3. Each bit time has an assigned meaning, which is checked by examining the occasional check codes in the bit stream. An inflexible system of this sort, with holes left in the timing pattern for future expansion, is probably much easier to implement than a system which tires to lower the bit rates by transmitting each datum only when it is needed.

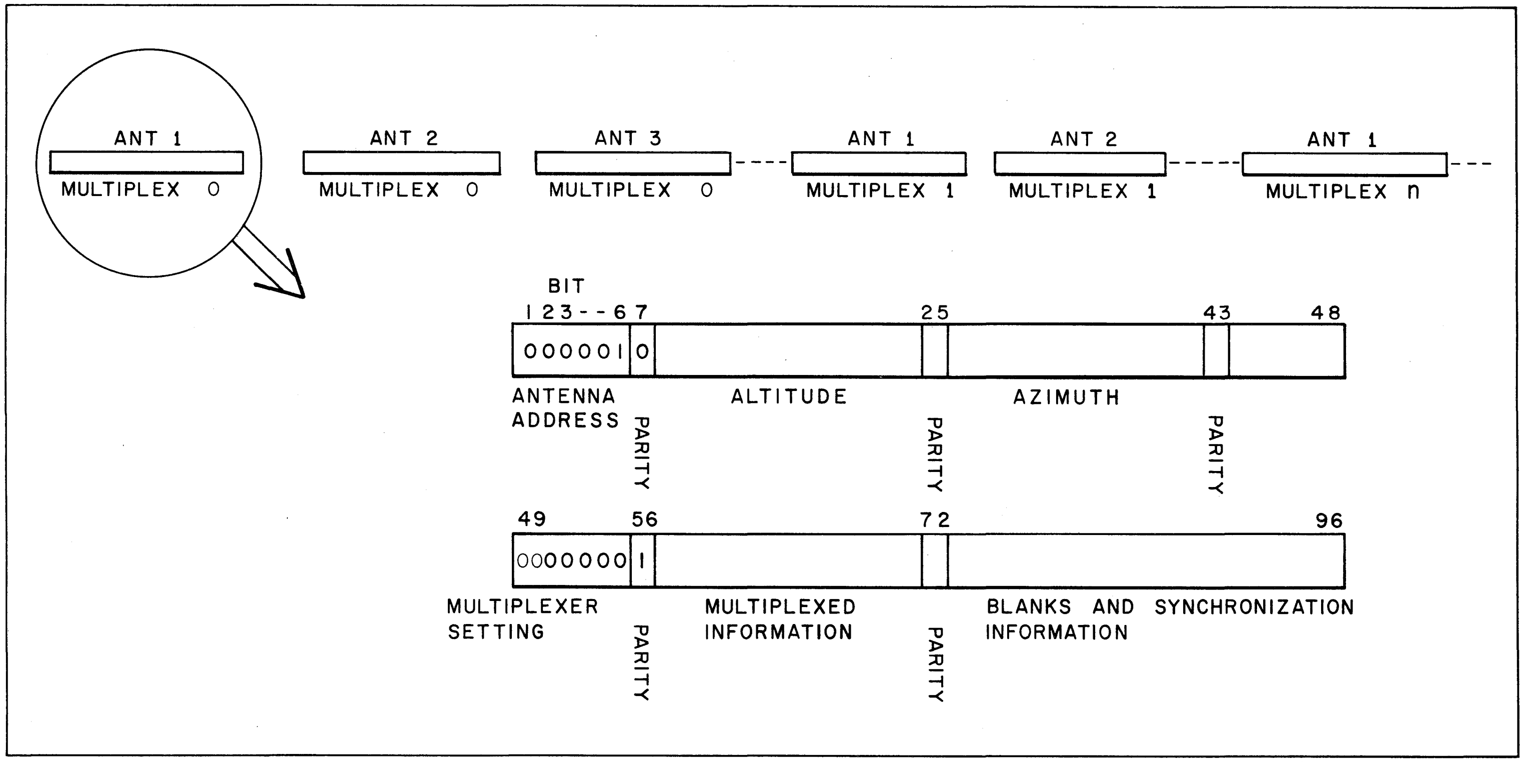


Figure 20 - 3. Digital communication system synchronization.

D. Inversion and Display Function

The third major division of the computer problem is the reduction of the output of the first stage reduction to a map, and producing this output in a form sensible to the observer. This stage of reduction can be subdivided farther.

(1) The output from the first stage reduction is sorted according to time and correlator. In order to make a map, the output must be sorted according to u and v, the resolution components.

(2) The observations must be interpolated to convenient grid points in the u-v plane and suitably combined in order to facilitate the Fourier inversion. At this point, the corrections for gain and phase drifts of the individual correlators are estimated and applied. Weightings are applied.

(3) The obtained brightness spectrum and transfer functions must be Fourier inverted to obtain, respectively, the brightness distribution and the synthesized array pattern.

(4) The map is corrected for the effects of the primary element beam and loss in correlation introduced by the finite bandwidth at points far from the center of the field of view, and is output.

In 600 minutes integration time with 36 antennas, up to 6.8×10^6 data points are produced. This collection of data points can be sorted according to u,v in about 1×10^{10} operations under the assumption that the machine on which this is being done has an efficient TRANSMIT instruction, which, after perhaps two operation times of set up transmits words from one location in memory to another at a rate of two operations per word transmitted. Since we are allowing 30,000 seconds of data in the computation, in order to keep up with real time a computing power of about 3×10^5 is necessary. A block diagram of a sort program is shown in Fig. (20-4). Also, in this operation a great deal of storage is necessary. In order for the sort to run at the speed quoted above, a direct access memory of 12 million words has been assumed. If it is necessary to work to tape units, the time of moving words around from one tape unit to another, although done under data channel control and hence almost entirely overlapped with computation, becomes a large fraction of the

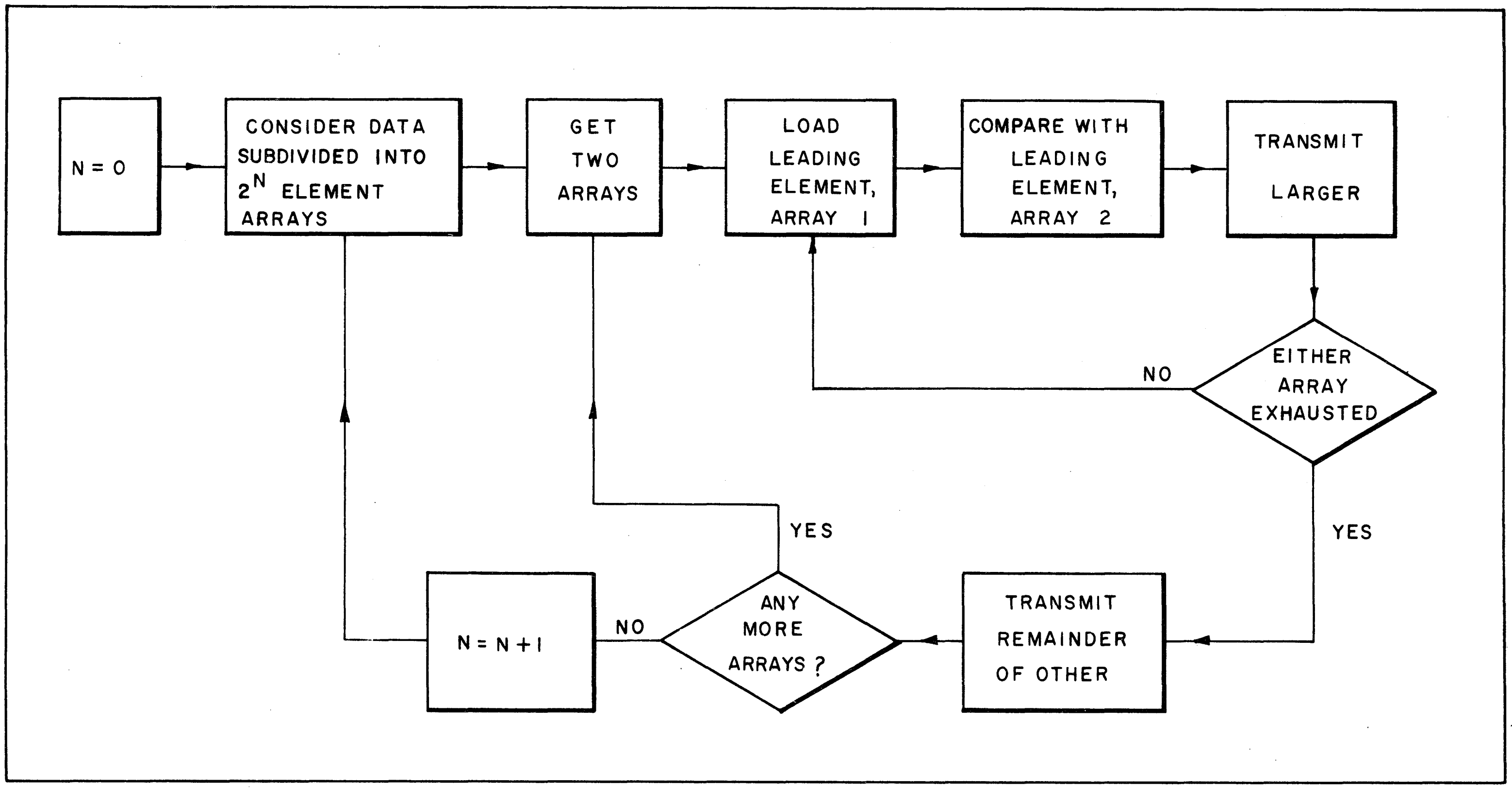


Figure 20 - 4. Sort program block diagram.

eight hours of the observation. The large capacity, direct access memory is to be preferred on the basis of simplicity of programming.

Once the array is successfully sorted by u,v, it takes little effort to isolate the crossings of the tracks and to solve for the gain and phase fluctuations in each correlator, using also the information obtained by observations and calibration sources. This operation should be entirely accomplished in a time of the order of 10^9 operations, depending on the particular circumstances of the observation, the strength and size of the source under observation, the number of calibration observations, etc. Another 3×10^8 operations should suffice to insert the observed values into the appropriate cell in the u-v plane, and to average the various values falling into each cell. Thus the total computation power needed for this calculation is about 3×10^4, a small part of the total computer.

The Fourier inversion of the brightness spectrum to produce a map of the brightness distribution would be accomplished by the method of Cooley and Tukey (Cooley and Tukey, 1965). If we wish to handle a network of measures of the brightness spectrum, 1000 elements on a side (this is a rather extreme case; it is never necessary to have the number of elements on the side of the matrix much exceed twice the inverse of the percentage bandwidth; in our case this number is about 60 for 50 MHz bandwidth, 300 for 10 MHz), the necessary calculations to Fourier invert the data total about 3×10^9 operations, less than the requirement to sort the data. The total computer load required to invert the transform is thus about 10^5.

After this point, a few tens of millions of operations will suffice for applying the last few corrections and outputting the map. The output devices suggested are a density modulated, moving film oscilloscope, which, since rather slow output rates are desired, can be a rather simple device, working from a standard digital to analog converter. This device would give an immediate qualitative picture of the reduction. For quantitative measurements, a more suitable output would be simply a graphical presentation of slices through the real, three dimensional map of the source. In either case, the output map would be recorded on magnetic tape for further computer processing, though it is not immediately anticipated that this special processing should be programmed on the VLA computer system. This is probably more suitably done on a large, general purpose computing machine.

E. Total Computing Requirements

The computer requirements are summarized in Table 20-2. A configuration capable of handling the computing load is presented in Fig. 20-5. The costs of the computer systems are given in Table 20-3. These cost estimates are highly preliminary, and are in all cases based on the estimates for one particular computer; a careful study to find the best component for the application has not yet been made.

Table 20-2

Computing Requirements

On Line Functions	
Data reduction	6×10^5
Lobe-Rotator Control	2×10^4
Antenna Control	5×10^3
Delay Switching	2×10^4
Receiver Checkpoints Monitoring	1×10^4
Logging and Display	1×10^3
Timing Loops	2×10^3
Asynchronous Reduction	
Sort	3×10^5
Gain Calibration	3×10^4
Fourier Inversion	1×10^5
Map Output and Display	6×10^4
Total	1.1×10^6
Safety Factor	$\sim 1 \times 10^6$
	2×10^6

Table 20-3

VLA Computer System Cost
(Cost In Thousands of Dollars)

Data Processor			
Multiplexer, A/D Converter, Interfacing 1 Correlator Bank, 3 Total		126	
Central Processing Unit 65 K Memory		590	
Tape Drives 1600 BPI, 3 Each		126	
Channel-to-Channel Interface with Monitor Computer		12	
			854
Monitor Computer			
CPU 32 K Memory		404	
Tape Units 3•1600 BPI, 2•800 BPI		201	
A/D Converter, Multiplexer		56	
Output Line Multiplexers		216	
Displays			
Line Printers, 2 Each	89		
Card Rd-Punch	35		
2 CRT's with Control	28		
Incremental Plotter	11		
Beam Modulated CRT	9		
		172	
15 M Words Direct Access Storage		237	
			1286
Communications			
Comm. Central (with data buffer)		130	
Repeaters		104	
Wire (5 twisted pair, 2 for digital signals, 1 voice, 1 alarm, 1 spare)		55	
Antenna Receivers		342	
A/D and Multiplexer at Antenna		440	
Packaging		36	

(Table 20-3, continued)

G&A Overhead and Profit, Communications Subsystem	162	
		1269
Programming	150	
		150
		3559

It might be expected that these costs will be reduced enough in selecting the system most fitted to our needs that the reduction will cover the costs of the items omitted in this initial consideration. Also, it is likely that by the time the VLA is to be in operation, the cost and abilities of the central processors will have improved over the present state of the art.

The input-out devices configured for the monitor computer are: (1) two line printers (one for system log, one for data output); (2) one typewriter (for system diagnostic messages); (3) five tape units (three 1600-BPI and two 800-BPI units); (4) two character type CRT's (for display of system parameters); (5) one plotting CRT (for brightness map displays); (6) one incremental plotter (for display of output); (7) card read-punch (for program input and compilation); (8) fifteen million words of direct access storage (for program storage and for data scratch storage). In addition to these standard devices, the computer must be equipped with interfaces for the digital input and output lines listed in Table 20-1, and for the necessary analog to digital converts for the correlators.

There yet remain several cost trade-offs to be investigated in detail, between the computer system and the remainder of the system. However, a great deal of information about these has been accumulated, some of which is presented in the following appendix. However, we can, in summary, say that the computer problems of the VLA can, so far as we can foresee, be solved within the framework of the block diagram of Fig. 20-5, and within a reasonable margin of the cost estimates of Table 20-3.

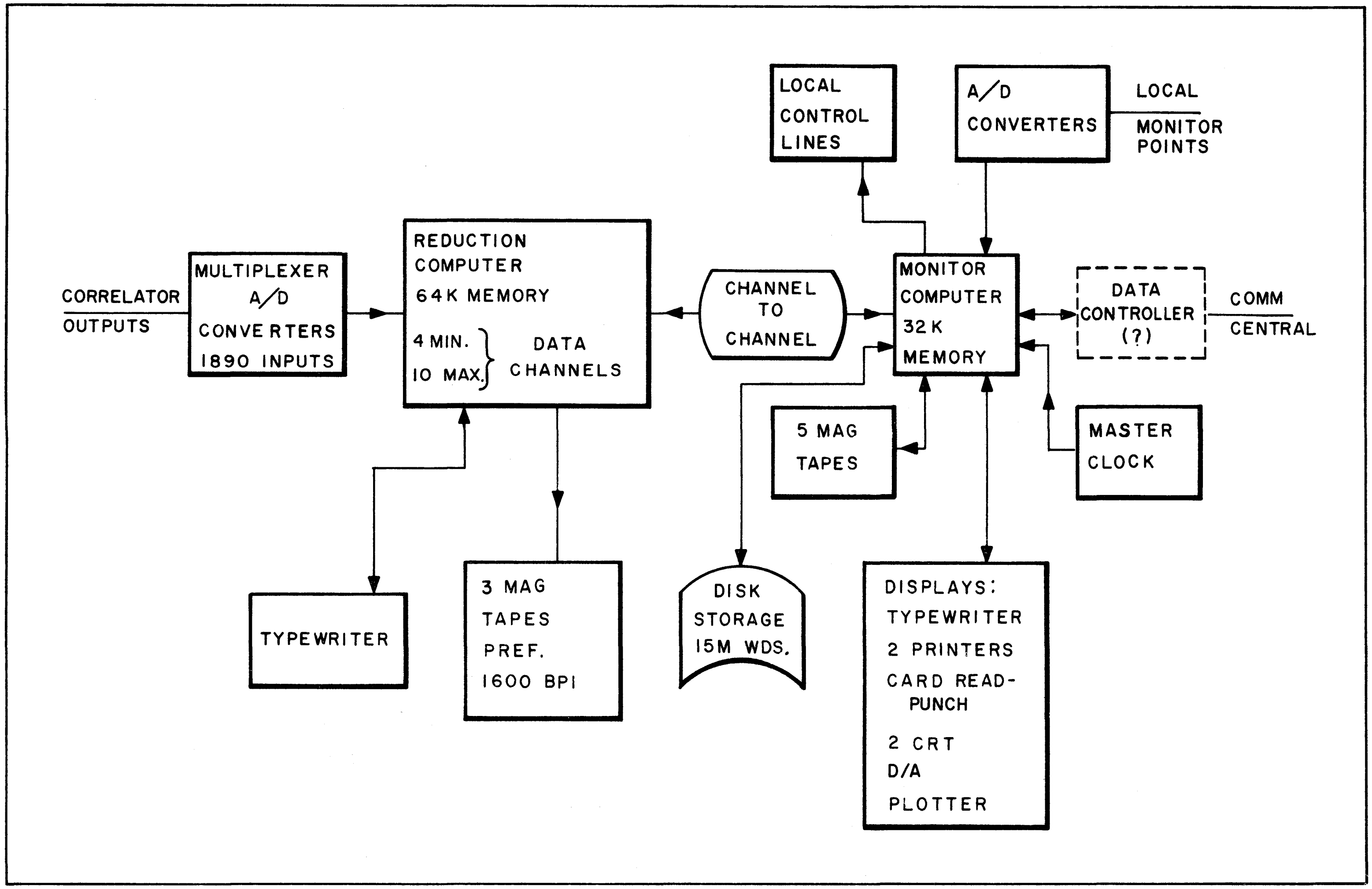


Figure 20 - 5. Possible computer configuration for the VLA.

F. Appendix: Fringe Reduction Computation Loads for Various Block Diagrams

The computational load of the data processing depends strongly on the presence or absence of various signal preconditioners. The preconditioner which makes the most difference is a lobe-rotator in the local-oscillator lines to decrease the natural fringe rates. Below we shall consider the effects on the computational load of three degrees of sophistication of lobe-rotators other than the one considered in Section B. Firstly, we shall calculate the computational load necessary for no lobe-rotators. This, of course, depends on the resolution of the array. For the finest resolution, 1" array beam, this load is very high, so that very great savings are affected in the cost of computers if lobe-rotators are installed. Second, we shall consider the possibility of installing lobe-rotators which approximately remove the effects of the earth's rotation. These would be operated by the central computer which would calculate the approximate phase for each of the three arms of the array, and each lobe rotator would then multiply this phase by the appropriate constant for the antenna it is servicing. This mode of operation makes the minimum demand on the central computer for controlling the lobe-rotators; on the other hand, it places restrictions on the amount by which an arm may differ from a straight line. Thirdly, we shall consider the case in which the signal from the correlators is further processed in an analog fashion, and reduced to DC before it is read into the computer for sorting and storage.

1. Data processing with no lobe-rotators

This straightforward method of processing is based on our experience with the NRAO interferometer. The basis of the method is that a sine wave with an offset is fitted to the data by the method of least squares, and that its amplitude and phase referred to the phase of a fictitious nearby point source are the quantities output. The data processing analysis done for us by RCA was based on this method of data processing. We shall now calculate the computing load for this method of processing.

For a 1" array beam, the greatest fringe rates in the array are about 24 Hz. It becomes significantly difficult to fit a sine wave with much less than three points per cycle, so that the sampling rate of the fastest correlator output should be about 80 Hz. Some saving could be made on this by processing only those correlators which contribute to the formation of the array beam. This is done in the RCA report, where a sampling rate of 60 Hz is used, and the longer baselines would be discarded. A large saving in computing power can be made by fitting this sampling rate to the fringe rate coming from the particular correlator. This may be done by either physically varying the time constant associated with the correlator and changing the sampling frequency directly, or by adding together two or more samples before fitting the sine wave, which requires much less in the way of external hardware, but more computing power. The latter method is assumed in the calculation below.

The first thing the computer does on receiving a new word of data is to decide if it is to be averaged with previous data, or if it is to be entered as an element to be fitted by the sine wave. If it is merely to be accumulated, the program takes the shorter branch, which takes 16 operations (assuming at least three index registers) to handle two, symmetrically placed data points. If the points are entered as elements, in the least squares fit, the program takes the longer branch, which takes about 80 operations (74 if there are five or more index registers, 81 with three index registers, etc.), again to handle two symmetrically placed data points. Averaged over all correlators, the short branch is taken very nearly half of the time, so that the mean number of operations per data point is about 24. Therefore, the necessary computing power is $24 \times 80 \times 630 \times 3 = 3.6 \times 10^6$ operations/second. A factor of the order of two must be applied to this number to allow for bookkeeping overhead, clumping of computation requests, and future inclusion of more sophisticated data reduction procedures. Therefore, the total computing power which should be provided for the VLA, using this method of reduction, is about 7×10^6 operations/second. RCA considered only the case of a single channel system, with only 780 correlators, and proposed providing the still quite large amount of computing power by constructing seven chains of computers, each of which would need a power of less than 0.5 million operations/second. To do this for 1890 correlators would require about 15 chains. There are many small computers in use today which can supply computing powers of 0.5×10^6. RCA suggested that the best buy presently available is the DDP 224, but small computer design is in such a state of flux at present that it is likely that something better will be available by the time the VLA is to be in operation. RCA also suggested that the short branch of the data acquisition loop be implemented in a very small, inexpensive computer (the PDP-8), which would also function as a data channel for the DDP 224, for an additional amount of computing power at very little extra cost. RCA's recommended configuration for the data processing chain is given in Fig. 20-6. The cost of 15 chains of fringe reduction computers is approximately $5.2 million (each chain costs about $350,000, of which about $150,000 is the CPU, $75,000 is the necessary tape units, $40,000 for the Data Controller and A/D converter, and the remaining $85,000 for special purpose interfacing and card readers and printers to be shared among all chains). At this cost it is clear that this system is at a far greater cost disadvantage than the cost of the lobe-rotators.

2. Approximate lobe-rotators

Lobe-rotators in the local-oscillator lines may be used in any of several ways. One method would be to simply use the lobe-rotators to track the instantaneous array beam at a fraction of sidereal rate, thus slowing all fringe rates by a constant amount.

This method of phase rotation is the easiest to implement. The central computer calculates for each arm the phase desired in the first element of the arm. This is then transmitted to all elements in the arm, and elements farther from the center multiply it by a constant to find their phase. The multiplication by a constant would be most easily accomplished by cutting the phase shifts switched in and out to the appropriate length for the station at which the antenna is observing.

Using this system to slow the fringes to a fraction of their natural rate requires no additional equipment at the lobe-rotator for each antenna. The disadvantage of doing this is that the very slow fringe rates for nearly N-S baselines become even slower. The total change in fringe phase from the point where the projected baseline is N-S is given by

$$\Delta\phi = \frac{2\pi D}{\lambda} \cos d \cos \delta \, (1 - \cos \tau) \approx \frac{2\pi D}{\lambda} \cos d \cos \delta \, \frac{\tau^2}{2} \qquad (20\text{-}1)$$

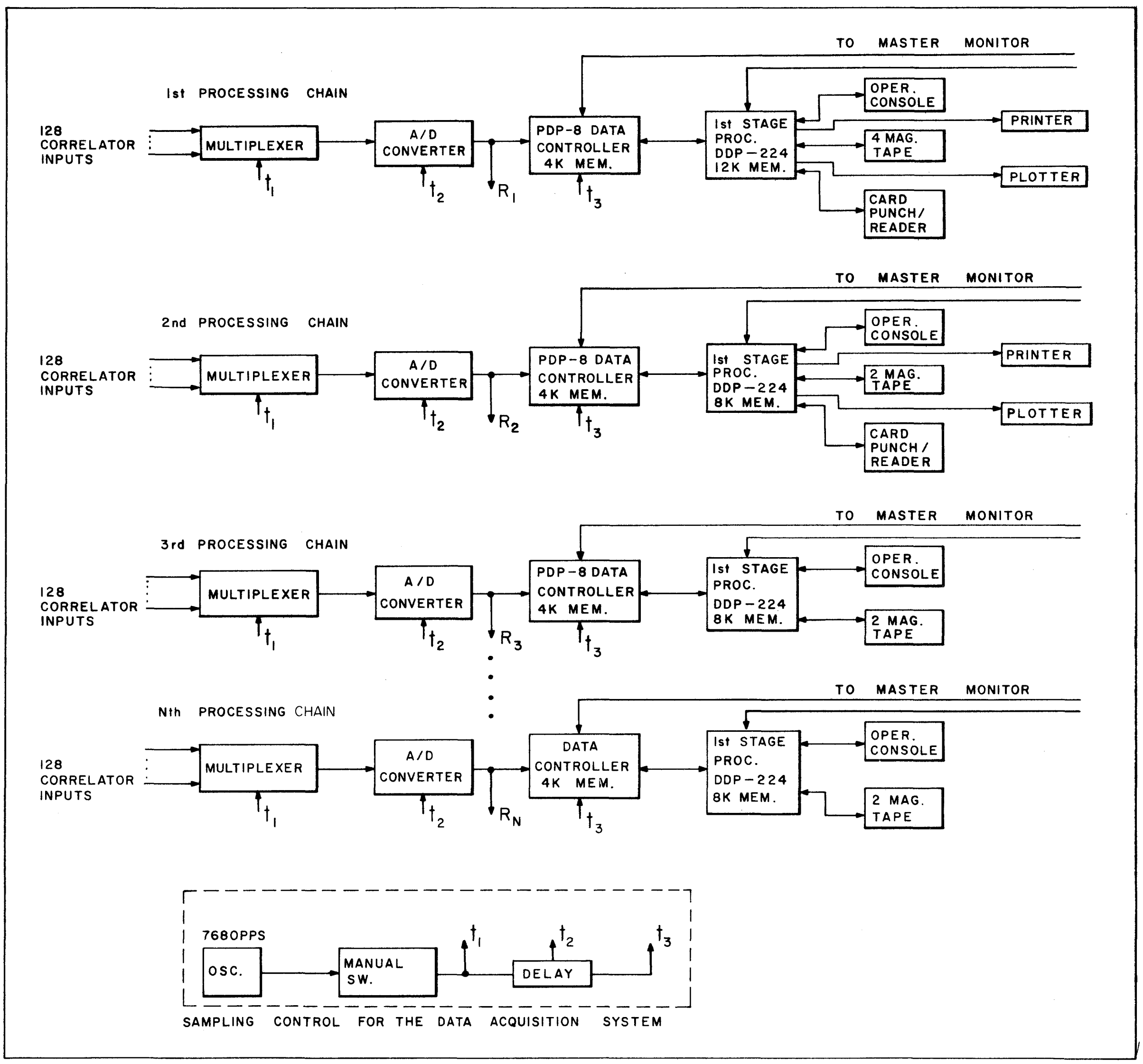


Figure 20 - 6 RCA 'Benchmark' system data processing chain.

If we wish the maximum fringe rate to be a factor k slower than natural fringes of a source at the celestial equator, then all fringe rates are to be reduced by the divisor k cos δ. We cannot divide the u-v plane into cells much smaller than that distance traversed by an interferometer in the course of half a fringe. That is, the maximum cell size is given by

$$\Delta\phi = \pi \; k \; \cos \; \delta \tag{20-2}$$

If one attempts to steer the array beam outside the area given by this cell size, its gain will be reduced and extra side-lobe introduced. Although a moderate extension of the field of view is perhaps possible for special purposes since these effects are relatively small, this limit appears in other manifestations as well, so that much larger fields of view are excluded. Inserting the expressions for $\Delta\phi$ (20-1) and for u (4-20) into (20-2), we find the minimum cell size

$$u_{min} = \frac{D}{\lambda} \; \cos \; d \; \sin \; \tau \approx \sqrt{\frac{k2D}{\lambda} \; \cos \; d} \leq \sqrt{k\frac{2D}{\lambda}} \tag{20-3}$$

and the fineness ratio of the array, the ratio of the extent in the u-v plane divided by the cell size

$$2u_{max}/u_{min} \geq \sqrt{\frac{D}{2k\lambda}} = 104/\sqrt{k} \tag{20-4}$$

for 1" resolution

The computing load is less than the case of no lobe-rotators by the factor k. Thus, with k = 10, we have reduced the computing load to less than a million operations/second, comparable with the system discussed in Section B, but have cut the field of view to about 30 array beam widths, half a minute-of-arc. Thus, in exchange for a slight simplification of the lobe-rotators, the field of view has been seriously cut. The relatively small savings from this do not seem to justify the loss of power of the instrument.

3. Integration in analog

If the analog processing is carried another step beyond that discussed in Section B, the fringes coming from the correlators are multiplied by the appropriate function to reduce them to a single frequency, say 0.1 Hz; the load on the computer is reduced still further. Actually, the outputs must be multiplied by two orthogonal functions to avoid losing a factor of $\sqrt{2}$ in signal-to-noise ratio. For the reduction of a sine wave, the multiplication may be done by selecting through switches the output obtained directly from the correlator, or an inverted output. This results in a loss in signal-to-noise ratio of about four percent. For square wave phase modulation, the direct and inverted outputs may be selected with relays or switches with no loss of signal-to-noise ratio.

In either case the switches may be driven by a standard frequency source with two outputs at each of N-2 frequencies, with no additional computation required.

The necessary computing power for this mode of operation is very small. It essentially involves only the formating and outputting on magnetic tape of the data read in. Even allowing for the handling of a number of small corrections at this point, it is unlikely that the computing power would exceed 2×10^5 operations/second. With this extremely low load of data handling computation, it becomes possible to consider multiprogramming this function on the same computer used for monitor and control and for the Fourier inversion of the brightness spectrum. The cost saving of doing this has not yet been carefully compared with the cost of the analog integrator system. The cost of the computer system using this mode of processing is estimated in Table 20-4.

There are several other variants of the fringe reduction schemes discussed above which will not be considered in detail here, but they differ only slightly from one of those discussed here.

REFERENCES

Cooley, J. W. and Tukey, J. W. 1965, Mathematics of Computation, 19, 297.

Table 20-4

Computer System Costs for Analog Pre-reduction
(Costs in Thousands of Dollars)

Master Computer		
CPU	590	
Multiplexer - A/D	180	
Tape Units	201	
Discrete Input-Output	216	
Displays	172	
Direct Access Storage	237	
		1596
Communications		1269
Programming		150
		3015

Chapter 21

SPECTRAL LINE SYSTEM

Chapter 21

SPECTRAL LINE SYSTEM

A. Introduction

The consideration of spectral-line observations with the VLA is only in a preliminary stage; the several man-years of study which has been applied to the design of the continuum array has only begun for spectral-line operation. The detailed astronomical requirements, the optimization of array configuration, and electronics system design need much study before a detailed design can proceed. At the outset, it appears highly probable that for an additional expenditure of under $5 million, the VLA can be made superior for most spectral observations to a single large telescope costing in excess of $30 million.

The purpose of this chapter will be to state the presently recognized limitations and capabilities of the array for spectral line work, to discuss some of the system design problems, and to describe and estimate the cost of a possible system. The astronomical applications of the spectral-line array are discussed in Chapter 2.

B. Basic Limitations and Capabilities

The brightness temperature uncertainty that can be measured with a filled aperture telescope is independent of the size or beam width of the telescope. This is not true in the unfilled aperture case. For a given amount of total collecting area, the beam area can be multiplied by a fraction, f, if a reduction by this same factor in the brightness temperature uncertainty can be tolerated. This is accomplished by spreading the antennas apart so that only the fraction, f, of the array area is filled.

The fraction, f, is called the filling factor; a value of unity corresponds to the filled aperture case. It is not possible to achieve a unity filling factor for the VLA because the antennas will shadow each other. If a zenith angle coverage of 60° is desired without shadowing, the largest possible filling factor is approximately 0.2.

The trade-off between minimum detectable brightness temperature, $T_{B,min}$ (5 rms deviations) and half-power beam width, β, is expressed qualitatively by the following relation which is obtained from 7-13.

$$T_{B,min} = \frac{15,900°}{\beta^2 \; B^{1/2}}$$

where β is the half-power beam width in seconds-of-arc, B is the half-power bandwidth in kHz, and it is assumed that the integration time is eight hours, the receiver noise is 100°K, the wavelength is 21 cm, and thirty-six 25 meter paraboloids are used.

The maximum beam width which can be obtained is limited by shadowing to approximately 2.5'; this gives $T_{B,min}$ = .07°K for B = 100 kHz. The minimum beam width is limited by the size of the observing site to 2"; this gives $T_{B,min}$ = 400°K for B = 100 kHz.

A second limitation on the spectral-line performance of the array lies in the question of number of frequency channels, K, and number of spatial correlations, C, measured at one time. The number of multipliers required in the electronics system is K•C, and thus this product is limited by economic considerations. The computer cost will also depend on the K•C product. The multiplier cost will be between $100 and $300 each, and thus values of K•C in the neighborhood of 10,000 are feasible. A quantity of 1,890 multipliers are required for continuum polarization mapping; thus if K•C < 1,890 the additional cost of the spectral line system is greatly reduced.

The number of spatial correlations determines the number of beams and side-lobe levels of the array. Because of earth rotation, the number of beams is greater than C by a factor, E, (beams = E•C) which depends on the array configuration, desired side-lobe level, and hours of tracking. For a 1" continuum array, a 2' field-of-view is achieved with C = 630, thus $E \sim 23$.

The maximum field-of-view is limited by the beam width of individual elements to approximately 30' at 21 cm wavelength. For this field-of-view, with C = 630, the beam width is 15", and 13 frequency channels could be allowed if K•C < 10,000. The minimum detectable brightness temperature for this array would be 7°K for 100 kHz bandwidth. A more optimum array for most observations would be one with more frequency channels, greater beam width, and a lower minimum detectable brightness temperature. A major problem in the system design is how to make this trade-off.

C. Frequency Channels for Antenna Beams Trade-Off

The dual-frequency continuum array produces 14,400 beams at two frequencies. For spectral line operation we wish to obtain more frequencies and less beams without reducing the array sensitivity and with a minimum electronics cost. Two methods of accomplishing this are discussed here.

One method is to group a small number of antennas together and add their outputs in phase at IF frequency. The resulting sum is then correlated with other group sums. If four antennas were grouped in this way, only 36 correlators are required. Fifty frequency channels and a few hundred antenna beams could easily be achieved.

The grouping of antennas reduces the maximum field-of-view because the primary pattern of the group is narrow. The antennas should be grouped together as closely as possible without shadowing. If four antennas were grouped 50 m apart, shadowing would not be serious, and the maximum field-of-view would be 15'. At this field-of-view, 1' beams should be possible and low side-lobes (approximately 20 dB maximum) would be expected for eight hours of tracking.

A second method of increasing the number of frequency channels without greatly increasing correlator costs involves the use of a special property of one-bit digital correlators. A correlator consists of a multiplier and an integrator. For one-bit digital correlators the multiplier cost is low (approximately $4 component cost) compared to the integrator cost (approximately $30 component cost). It is thus possible to construct a correlator which combines the output of 10 multipliers in a single integrator at about three times the cost of a single-multiplier, single-integrator correlator (the component cost for combining the multiplier outputs will be approximately $4 per multiplier).

It is possible to use this technique to advantage by arranging the array so that many redundant baselines exist. The redundant baselines reduce the number of beams but increase the array sensitivity in the same manner as grouping of antennas. The redundant pairs of antennas are then multiplied (in separate multipliers), and the multiplier outputs are integrated in one integrator.

As an example of a system utilizing this technique, an array of thirty-six 25 m antennas placed on an equally spaced 100 m grid has been considered.

The array could provide a few hundred 1.5' beams at 21 cm. The filling factor is .05, and a minimum detectable brightness temperature of 0.2°K is achieved with 100 kHz bandwidth and eight hours of integration. The u-v plane coverage of this array has been calculated and 15% holes were found; this is probably too high to give tolerable side-lobe levels. The beam pattern has not been calculated. Sixty correlators, each having between 1 and 30 redundant pair inputs are required for this array. The cost of these correlators has been estimated (in detail) at approximately $2.5 million for 100 frequency channels.

D. Spectral Analysis Method

Two methods of performing spectral analysis require consideration. The first method makes use of a filter-bank at the IF output of each antenna group and utilizes analog correlators (as in the continuum array). The second method is to use one-bit digital delay methods and digital multipliers. The first technique will require different filter banks for each bandwidth that is required; however, use can be made of the 1,890 correlators which are already available for continuum work. The bandwidth can be easily changed with the second method; however, the sensitivity will be reduced by 1.4 (due to one-bit correlation), and the cost will be higher unless many bandwidths are desired. (The cost is higher because the first method can make use of already existing correlators.)

In order to make a quantitative cost comparison, an array consisting of nine groups with four antennas in each group will be considered. Thirty-six correlators are then required, and it will be assumed that 50 frequency channels are desired. A cost of $300 per correlator channel, including assembly and test labor, has been established in the design of an NRAO 400 channel autocorrelation receiver. A cost of $540,000 is then estimated for thirty-six 50 channel correlators.

If this same array is to be processed with the filter method, nine 50 channel filter banks are required for each bandwidth that is desired. Five bandwidths (1 kHz, 3 kHz, 10 kHz, 30 kHz, and 100 kHz) are a reasonable requirement; thus 2,250 filters are required. A filter manufacturer has given a budgetary price of $100 per filter for crystal filters in this bandwidth range. A figure of $50 per filter should be allowed for assembly, test and distribution amplifiers. The total cost is then \$337,000, assuming that the continuum correlators are used.

A digital-analog hybrid correlator system may prove to be optimum. Digital delays and multipliers with analog integrators appears to be an inexpensive combination that needs further investigation.

E. System Cost Estimates

The cost of a system having the specifications given in the following table will be estimated.

Table 21-1

Spectral Line System Specifications

Frequencies of Operation	1330-1420 MHz or 1600-1730 MHz
Beam width at 1420 MHz	10" or 1'
Field-of-View at 1420 MHz	2 1/2' or 15'
Minimum Detectable Brightness (5 times rms fluctuation) at 100 kHz bandwidth	16°K or 0.5°K
Number of Frequency Channels	50
Bandwidths	1 kHz, 3 kHz, 10 kHz, 30 kHz, or 100 kHz
Zenith Angle Coverage	60°
System Noise Temperature	100°K

These specifications can be met with an array of thirty-six 25 m antennas which are grouped into nine clusters of four antennas each. The four antennas are placed at the corners of a 50 m square which has one edge along an arm of the Wye track configuration. The optimum locations of the clusters is not known at present, but it is fairly certain that for a 10" or 1' beam the clusters will be in the inner 4.2 km or 700 m of the array arms. The side-lobe response cannot be predicted until some computer calculations are performed.

The spectral line system can be constructed using the same IF transmission system, LO distribution cables, delay lines, correlators, and computer as the continuum array. The cost additions required for spectral line operation are tabulated in Table 21-2. A discussion of these items is as follows:

Table 21-2

Additional Cost Required for Spectral Line Observations

Item		Unit Cost (Thousands)	Number Required	Total Cost (Thousands)
1330-1430 MHz Front-Ends, Including Feed and Prime-Focus Equipment Box		$ 29	38	$ 1,102
1600-1730 MHz Front-Ends		$ 18.5	38	$ 703
IF Combiners		$ 10	9	$ 90
Filter Banks - 9 Banks, 50 Channels, 5 Bandwidths - 2,250 Filters		$ .150 per filter	2250	$ 337
LO Distribution System for 2.1 km Arms		--	--	$ 500
Observing Station Cluster -				
4 Antenna Foundations	$12,000			
400 ft Track	7,000			
Crossover and Switch	8,500			
Junction Hut	3,000			
Additional Trenching, Power Lines, and Manholes	5,000			
	$35,500	$ 35.5	15	$ 533
Total Cost of 10" - 1' Array for Hydrogen and OH Line Observations				$ 3,265

Front-Ends - Room temperature, 2-stage parametric amplifiers for operation at 1330-1430 MHz and 1600-1730 MHz are priced at $6,000 each, including a solid-state pump source. These prices are budgetary estimates obtained from a paramp manufacturer and are low because of the large quantity involved. The remainder of the items in the front-end are listed and priced in Table 15-1, with the omission of a frequency doubler, pump distributor, and LO distributor. It is assumed that the same prime-focus feed can be used for both frequencies. A temperature controlled equipment box, priced at $5000, including cables and connectors, is included in the 1420 MHz front-end cost.

IF Combiners - This includes the equipment required to add together the IF outputs of four antennas and couple the resultant sum into the continuum IF data transmission system.

Filter Banks - This item was discussed in Section D of this chapter.

LO Distribution System - It is assumed that none of the electronics in the continuum LO distribution system can be utilized. The cost estimate of $500,000 is based upon the pricing shown in Table 14-1, with the consideration that the spectral line LO distribution system must traverse only 1/15 the distance but it must handle a much wider range of frequencies.

Observing Stations - The cost of stations for 15 clusters that are required for 10" or 1' beams are priced.

The total estimated cost of the system is $3,265,000. Three questions which need further consideration are the following:

(1) Does the system have sufficient brightness temperature sensitivity (3.2°K rms) for operation at 10" beam width? Cooled paramps could increase the sensitivity by a factor of three at a cost of $1 million for both frequencies.

(2) Are 50 frequency channels sufficient? It would cost $687,000 (337,000 for filters and $350,000 for correlators) to double this number.

(3) What is the beam pattern and optimum configuration of the array?