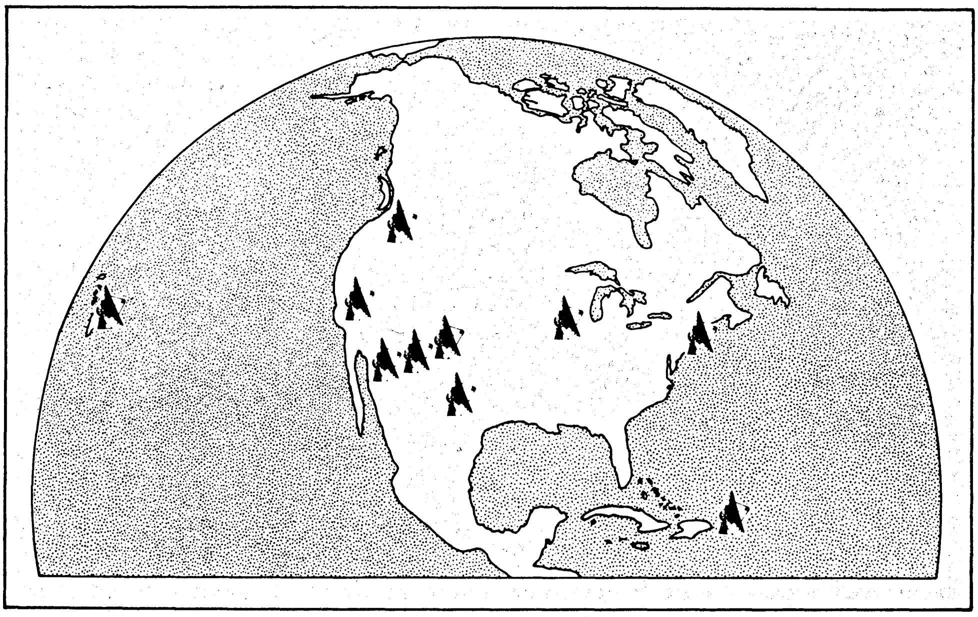
Very Long Baseline Array Project

SECTION 1

CONFIGURATION

R. C. Walker



NATIONAL RADIO ASTRONOMY OBSERVATORY
Edgemont Road · Charlottesville, Virginia 22901

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

SECTION 1

CONFIGURATION

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1.1 Design Goals

The configuration of the VLBA is the result of an extensive search for an optimal distribution of telescopes that would meet the goals and constraints defined in the original program plan. Those constraints are briefly:

1.1.1 Performance goals

1.1.1.1 Highest possible resolution. The longest possible baseline within U.S. territory is about 8000 km using Hawaii.

1.1.1.2 Large field of view. The shortest baseline in the array should be no longer than 200 km and that baseline should be placed near the VLA so even shorter baselines could be obtained to elements of the VLA.

1.1.1.3 2-Dimensional configuration. The array should be able to make maps of low declination sources.

1.1.1.4 Image quality. The VLBA should provide high dynamic range images over a wide range of source scale sizes. Uniform coverage is desired for the high dynamic range while an emphasis on short baselines is desired for coverage of a wide range of scale sizes.

1.1.2 Practical Constraints

1.1.2.1 Low cost. The smallest possible number of antennas should be used consistent with the performance goals. Also as many sites as possible should be at facilities where local support can be obtained.

1.1.2.2 Proximity to the VLA. The short baselines should be near the VLA in order to take most effective advantage of that instrument for additional, short baselines and for a wide range of very sensitive baselines. This constraint has become especially important now that the value of eventually adding telescopes near the VLA to fill the hole in the coverage between the VLA and the VLBA has been clearly recognized.

1.1.2.3 Dry Sites. The VLBA is expected to operate at 22 and 43 GHz so it is important to use as many high, dry sites as possible to minimize problems caused by water vapor. Such sites are most commonly found in the Southwest.

1.1.2.4 Ease of Access. Each antenna should be near a major transportation center.

1.1.2.5 U.S. Territory. The initial VLBA sites are restricted to U.S. territory in order to minimize the administrative and logistical difficulties and the expense of operations.

The minimum number of antennas required to cover the range of spacings from 200 to 8000 km, with the limitation on north-south coverage given by the U.S. territory constraint,is 10. With fewer than 10, large holes in the coverage of the transform (u-v) plane appear or the minimum spacing must be larger than 200 km. Also, with fewer than 10 antennas, the fraction of the total information contained in the calibration independent closure parameters, upon which VLBI depends for its mapping capabilities, drops rapidly.

1.2 The Configuration

The configuration that has been chosen is shown in Figure 1.1. The sites are discussed individually below. The coverages of the transform plane for the array, for maximum scales of 8000, 4000, 2000, 1000, 500, and 200 km are shown in Figure 1.2. The plots on the 1000, 500 and 200 km maximum scales include baselines that would be provided if 4 elements of the VLA were used with the VLBA. It is expected that the VLA will be equipped with the record units necessary for combined experiments and that the resulting science will justify the frequent use of VLA antennas.

The sites of the antennas of the VLBA are listed below. The latitudes and longitudes listed are those used in the configuration study and may differ slightly from those of the final selected sites.

1. HAWAII (19.80, 155.50): A high altitude site will be needed to avoid the high atmospheric water vapor levels that occur in tropical, maritime regions such as Hawaii. The best sites are probably on Mauna Kea between the mid level facilities and the summit, although alternate sites on Mauna Loa and Haleakala are being investigated. All sites appear to have problems due to interference, politics, and/or weather. Water vapor measurements have been made and confirm that a high site is needed, although the minimum altitude is still not clear. The water vapor fluctuations appear to be significantly lower than in Puerto Rico, even at sea level. The favored site is at about 12,000 feet on Mauna Kea. It is expected that the political process of obtaining permission to build may be very difficult, especially if a site on Mauna Kea is chosen.

2. PUERTO RICO or VIRGIN ISLANDS (18.34, 66.75): (Listed as Arecibo on the Figures) The u-v coverage provided by a station in the West Indies is very attractive although the high water vapor content of the atmosphere in the area is a concern. Unlike Hawaii, neither Puerto Rico nor any of the Virgin Islands has high altitude sites. VLBI experiments at 6 cm using Arecibo and a rubidium vapor frequency standard give coherence times of 1 - 3 minutes (probably limited by the frequency standard) which suggests that useful observations can be made at frequencies at least as high as 10 GHz. Measurements have been made at various sites in Puerto Rico using a water vapor radiometer to try to predict the performance of an Array telescope at 22 and 43 GHz. The results show that observations should be possible and that a site on the South Coast may be best.

A specific location in a wildlife refuge on the South Coast or Puerto Rico was identified in 1984. However the Voice of America has informed NRAO that it intends to build about 10 Megawatts worth of transmitters about a mile away. As a result of concerns about Puerto Rico, the island of St. Croix in the Virgin Islands was investigated in mid 1985 and found to offer considerable advantages in access and local conditions. St Croix is now the favored site, with a possible specific location on a marine research laboratory operated by Fairleigh Dickinson University.

The quality of the u-v coverage is sufficiently good that Puerto Rico or the Virgin Islands will be used even though observations at the highest frequencies will sometimes require special calibration techniques such as simultaneous observations at lower frequencies to remove the atmosphere. Note that the uv coverage of the array degrades gracefully if this site is lost for an observation - some resolution is lost and the beam becomes somewhat elongated, but no big holes at the shorter spacings are opened up.

3. NEW ENGLAND (42.43, 71.49): (Listed as HSTK) This site was originally supposed to be at the existing radio astronomy facilities of the Haystack Observatory in Massachusetts where there is very good local support. However the severe interference environment at that site has caused its rejection. A possible alternative is the Five College Radio Observatory in central Massachusetts. The u-v coverage would be similar to that provided by Haystack and the proximity to a mm telescope would facilitate possible millimeter wavelength VLBI experiments (Note that the OVRO and Kitt Peak sites are also at existing mm facilities). Other sites within about an hour's drive of Haystack are also being investigated. Such sites could use support from Haystack.

4. WASHINGTON (48.90, 119.75): (Listed as OROVILE) This site is very near the Canadian border in central Washington State. This is the only site in the configuration that is not near known local support. There is considerable freedom to move the site around in central Washington so logistical factors can determine which specific site is chosen. Note that this site is very near Penticton. There is a Comsat station near Brewster that will be closed in late 1986 or early 1987. We may be able to take advantage of facilities and/or personel that will become available.

5. OVRO (37.05, 118.28): The Owens Valley Radio Observatory in California is an existing VLBI site with good local support. There is some support for the concept of choosing a site far enough from OVRO to provide interesting baselines to the 130' antenna. Possibilities are near Owens Lake or in California's central valley. More work is needed on these options.

6. IOWA (41.58, 91.57): The North Liberty Radio Observatory is an existing facility with local support. The obvious, although probably not serious, hole in the coverage at Dec 64 at a little over 2000 km can be filled by moving this site to Illinois with some corresponding, but more subtle, degradation of performance in other parts of the u-v plane. There is considerable freedom in the choice of the location of this site so local factors can be considered seriously.

7. FORT DAVIS (30.47, 103.95): (Listed as FDVSNEW) The Fort Davis, Texas, site could be at the existing radio observatory (George R. Agassiz Station - Harvard) that is active

in VLBI or at the University of Texas facilities at McDonald Observatory. GRAS is the likely choice.

8. KITT PEAK (31.96, 111.60): Kitt Peak, Arizona, is an existing NRAO site with good local support. A specific area near the picnic ground on the mountain has been selected. There is some concern that wind may be a problem but an evaluation of wind measurements and of the effects of wind on the antennas led to the tentative decision to favor the logistical advantages of being on the existing facility over an undeveloped, low elevation site.

9. LOS ALAMOS (35.81, 106.27): (Listed as LASL2) A site on the southern border of the Los Alamos Scientific Laboratory property has been chosen for this antenna. This is the second closest antenna to the VLA and it is hoped that eventually it will be linked to the VLA so that it can be used as a VLA outrigger. However the link will be sufficiently difficult that it will not be part of the original construction. The site should be easy to maintain from headquarters in Socorro.

10. PIE TOWN (34.33, 108.14): This site is west of the VLA on Rt. 60. Access from the VLA is good and power and phones are nearby. The site is the closest to the VLA and will be equipped with a link to the VLA so that it can be used as a VLA outrigger and so that the VLBA recordings can be made at the VLA, reducing the need for staff at the site. Maintanence from the VLA or from the VLBA headquarters will be relatively easy.

1.3 Possible Extensions

The 10 stations described above make a very powerful instrument that meets the specifications given at the beginning of the VLBA project. Recent impressive results from MERLIN in Britain and experience gained on current large VLB Network and VLA experiments have increased the awareness of the importance of a wide range of spacings. An attractive eventual goal would be an interferometer that covers the full range of baseline lengths possible on the surface of the Earth, allowing us to construct a "matched u-v filter" to the needs of any mapping experiment. The combination of the VLBA described above and the VLA comes close to providing this capability. However, there is a range of spacings between 35 km and about 200 km that is poorly covered. It has been found that 3 or 4 additional stations in New Mexico are needed to fill this gap. The 10 station VLBA has been partially optimized (with very little sacrifice of capability as a 10 station array) as part of a 13 station array that fills the gap. A superior, but more expensive, 14 station array that shares 12 sites with the 13 station array has also been identified and would be favored if sufficient funds were available. In any such array, as many of the VLBA stations as possible would be operated remotely from the VLA by microwave link. Data from these stations could be correlated in real time with the VLA and/or recorded on tape for later processing with the rest of the VLBA. The additional sites of the 13 station configuration are:

1. DUSTY (33.62, 107.65): This site is south of the VLA. It is easily reached by dirt road from the VLA or by paved road from the Rio Grande Valley.

2. BERNARDO (34.35, 106.90): This site is near Bernardo, New Mexico, between Socorro and Albuquerque along Interstate 25.

3. ROSWELL (33.40, 104.55): Roswell, New Mexico is east and a bit south of the VLA. There is some freedom in finding a specific site.

The 14 station option uses sites in Holbrook, Arizona and Vaughn, New Mexico, instead of the Roswell site.

The u-v coverage provided by the 13 station array plus 4 elements of the VLA on scales of 500 km and 200 km are shown in Figure 1.3. The 3 stations listed above are an extremely attractive addition that should be made at a future date. It must be emphasized that the scientific capability they provide greatly extends that originally specified for the VLBA and is not necessary for the VLBA to be a valuable and capable instrument. The 14 station option fills the large percentage hole at about 200 km that is slightly offset from the east-west direction.

One constraint placed on the configuration of the VLBA has been that all antennas be on United States territory. That constraint limits the coverage of north-south spacings at the low declinations to approximately that obtained by the final configuration. Another addition that might be made to the VLBA at some future date is an antenna in northern South America (for example, in Equador). The improved performance that such an antenna would provide for observations of sources at low declinations is very attractive. The uv coverage of the VLBA plus a station in Quito Equador is shown in Figure 1.4. This addition would be independent of the 3 antenna addition for filling the hole between the VLA and the VLBA.

1.4 Configuration Selection Criteria

1.4.1 Meeting the Constraints

The configuration given above was derived using a combination of educated guesses and a systematic exploration of large numbers of possibilities using numerical quality measures. The large number of constraints, desired characteristics, and degrees of freedom in the problem made identification of a straight-forward method of finding arrays difficult, if not impossible. The procedure used involved exploring the coverage provided by many general classes of configurations using plots of the u-v coverage such as those in Figure 1.2 and then measuring the relative performance of large numbers of variations within each of the promising classes. In this usage, a class of configurations is a group of configurations with sufficiently similar distributions of antennas that there is an identifiable, one-to-one correspondence between each element of one array and some element in each of the other arrays in the class. For example, all members of the class to which the final array belongs have a Northeast site, a Midwest site, a Northwest site, a California site, a Southern Texas site etc.

With the experience gained during the configuration search, it is clear why an array of the adopted class was chosen. Each of the sites is important for some special aspect of the coverage. Hawaii, along with the east coast and Puerto Rico provide the longest baselines possible in the U.S. Puerto Rico to New England provides the longest possible north-south baselines available without using Alaska. Alaska is so far north that it cannot see sources at the southern declinations where the north-south baseline is most important. Intermediate length eastwest baselines require stations near the east and west coasts. At least two such baselines are needed to avoid holes near zero declination. With New England already specified and the water vapor conditions so poor in the Southeast, the obvious way to get those baselines is with a site in Washington and one in California. Intermediate length north-south baselines are best obtained using a site in southern Texas but that station should not be too near the Gulf Coast where the water vapor content is high. The shortest baseline should be across the VLA as discussed earlier so two sites should be in New Mexico, within less than 200 km of the VLA. One of those two sites might as well be close enough to the VLA to constitute one of the VLA outriggers that have been discussed for many years. With the concentration of telescopes in the Southwest, there is a large hole between the Hawaii-New England baselines and the Hawaii-New Mexico baselines that must be filled with a Midwest site. One more site is needed to complete the coverage of short to intermediate length baselines. It should go somewhere in the Southwest although it is not tightly constrained from first principles.

In the end, the array was optimized to be a good 10 station array that is a subset of a good 13 station array that fills the gap between the VLA and the VLBA. To fill the gap, two additional sites close to the VLA plus one about 200 km away are needed. The three `VLA outrigger´ antennas (one of which is among the original 10) should be about 50-70 km from the VLA in three different directions.

1.4.2 Quality Measures

Once a general class of configurations was identified by the criteria outlined above, numerical quality measures were used to search for the actual location of antenna sites. Such factors as ease of access, existing facilities, climate etc. were considered in choosing the sites to examine. A strong bias was given to sites with existing radio astronomy activity. In general, at least half of the sites can be picked on grounds other than coverage, as long as they are in the general regions specified by the requirements of the class. The rest of the sites can be adjusted to give performance almost indistinguishable from that of an array for which all sites were chosen purely for the coverage. This allows considerable freedom to use existing facilities.

Several quality measures were explored and used to varying degrees:

1.4.2.1 Dynamic Range. Pseudo data is generated using the coverage that would be provided by the configuration under study if it were observing some model source. A clean map is made using that data and is compared with the original model. The dynamic range is the ratio of the peak on the map to the maximum difference between the map and the model. This method tests the mapping capability of the array but is somewhat sensitive to the model used and to the mapping methods used. (ref: CIT and NRAO Design Studies, Linfield, VLBA Memo No. 49)

1.4.2.2 Distance between Grid Points and Sampled Points. This quality measure is based on measuring the distance from each point on a uniform grid in the u-v plane to the nearest point sampled by the array. An inverse radial weighting is applied to the points to emphasize the coverage on short spacings and the analysis is performed for a wide range of declinations. The method tests the uniformity of the coverage but is sensitive to edge effects and to the choice of the grid. (Ref: Mutel and Gaume, VLBA Memo 84)

1.4.2.3 Match of Density of Points to Desired Density. This method is an analog of a statistical test known as the Cramervon Mises test. The test measures the discrepancy between the cumulative distribution function of the sampled points in the u-v plane and the desired distribution function. As with all tests, it is sensitive to the choice of the desired distribution function. (Ref: Schwab, VLBA Memo 100)

1.4.2.4 Number of Sampled cells in a Polar, Logarithmic Grid. This method counts the number of sampled cells in a polar grid in which each cell has a radial width of some fixed percentage of the u-v distance. The count is made for several declinations, each representative of an equal fraction of the total sky, and summed (weighted so that all declinations are equally important) to produce an overall measure. It relies on the concept that, since all configurations give about the same total number of samples, an array with big holes will have more redundancy elsewhere and will receive a lower rating. The polar, logarithmic grid was chosen because an array that gives uniform coverage on such a grid will give mapping capability that is independent of scale size within the limits imposed by the maximum and minimum baselines of the array. For 10 element arrays with a minimum spacing of 200 km, the number of sampled cells in a second, smaller grid with even radial spacings were counted and added (weighted) to the total quality figure. The second grid was needed to avoid problems in the inner regions where the cells in the main grid are small. The results from the method are sensitive to the choice of the sizes of the grid cells and to edge effects. (Ref: Walker, VLBA Memo No. 144)

The last of the above tests was the one most heavily used toward the end of the configuration search. It was originally designed as a first pass test to narrow down the field of good arrays and was coded to run nearly 100 times faster on the computer than the other methods. However the results were sufficiently good that the other tests were not used for the final selection. The program was coded so that many members of a given class of arrays could be tested easily. The user would specify several possible sites for each region required by the class and the program would test all possible combinations. The number of sites so tested was large but was still severely limited by the fact that many thousands of combinations are possible with only a few test sites in each region.

All of the quality measures generally agreed on the ranking of tested arrays and those rankings agreed with the impressions derived from examination of u-v plots (the method trusted most by the workers in the field). The final configuration is not necessarily the absolute best according to any given quality measure but it is among the top few for which measured differences are as much a result of details of the measuring methods as of real differences in coverage. It has the distinct advantage that it uses a large number of sites with good local support.

1.5 Remaining Tasks

The work on the configuration is nearly complete. The important job that needs to be done is to identify the exact sites to be used within the small regions specified for each of the stations. For several of the sites, the task should be easy since the new telescope will presumably be built somewhere on the grounds of an existing facility. For other sites, such as Hawaii, New England, and Washington, much work needs to be done to identify a good plot of land. This work must be complete in time for site testing to be done and administrative details (eg.environmental impact statements etc.) to be completed before construction begins. The detailed time schedules will be dealt with in the sections of this report on the sites. If no site can be found near the position of some element of configuration presented here, the configuration search may need to be resumed to find alternatives, or at least to check that a relatively large move can be tolerated.

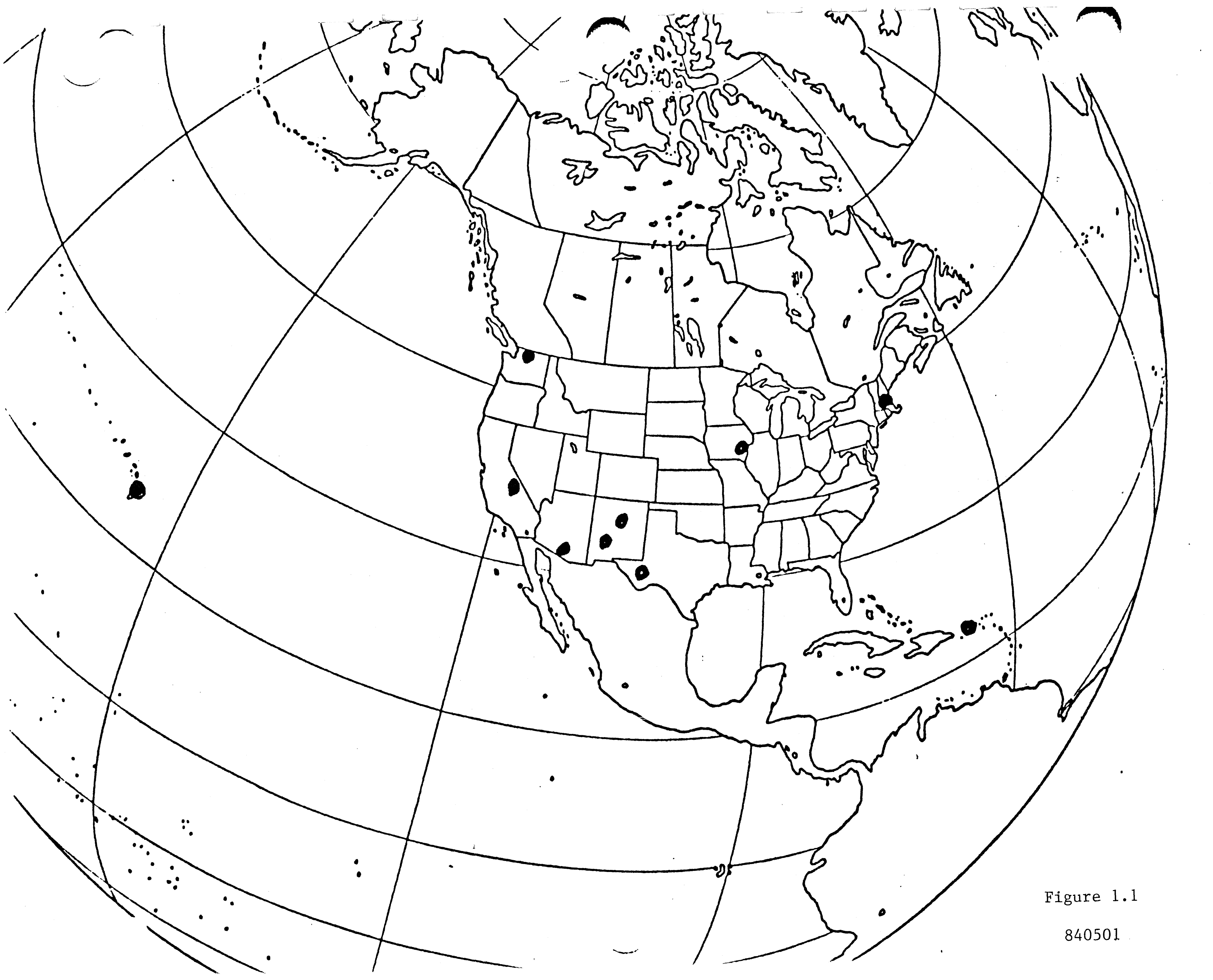

Figure 1.1

840501

HAWAII	19.80	155.50
ARECIBO	18.34	66.75
HSTK	42.43	71.49
OROVILE	48.90	119.75
OVRO	37.05	118.28
IOWA	41.58	91.57
FDVSNEW	30.47	103.95
KITT	31.96	111.60
LASL2	35.81	106.27
PIETOWN	34.33	108.14

Scale in km
(kilometers x 10^3)

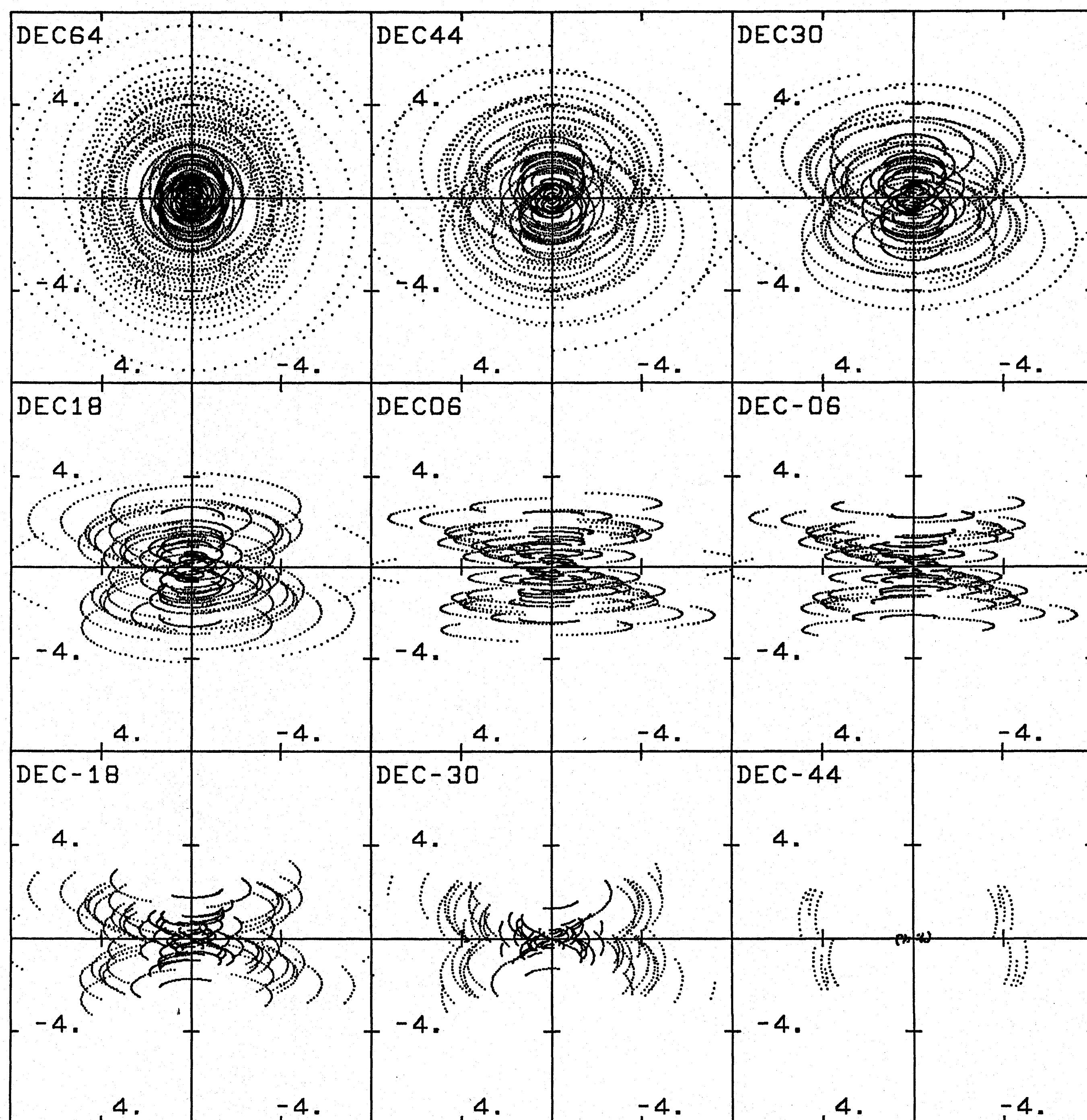

Figure 1.2a
8000 km

HAWAII	19.80	155.50
ARECIBO	18.34	66.75
HSTK	42.43	71.49
OROVILE	48.90	119.75
OVRO	37.05	118.28
IOWA	41.58	91.57
FDVSNEW	30.47	103.95
KITT	31.96	111.60
LASL2	35.81	106.27
PIETOWN	34.33	108.14

Scale in km
(kilometers x 10^3)

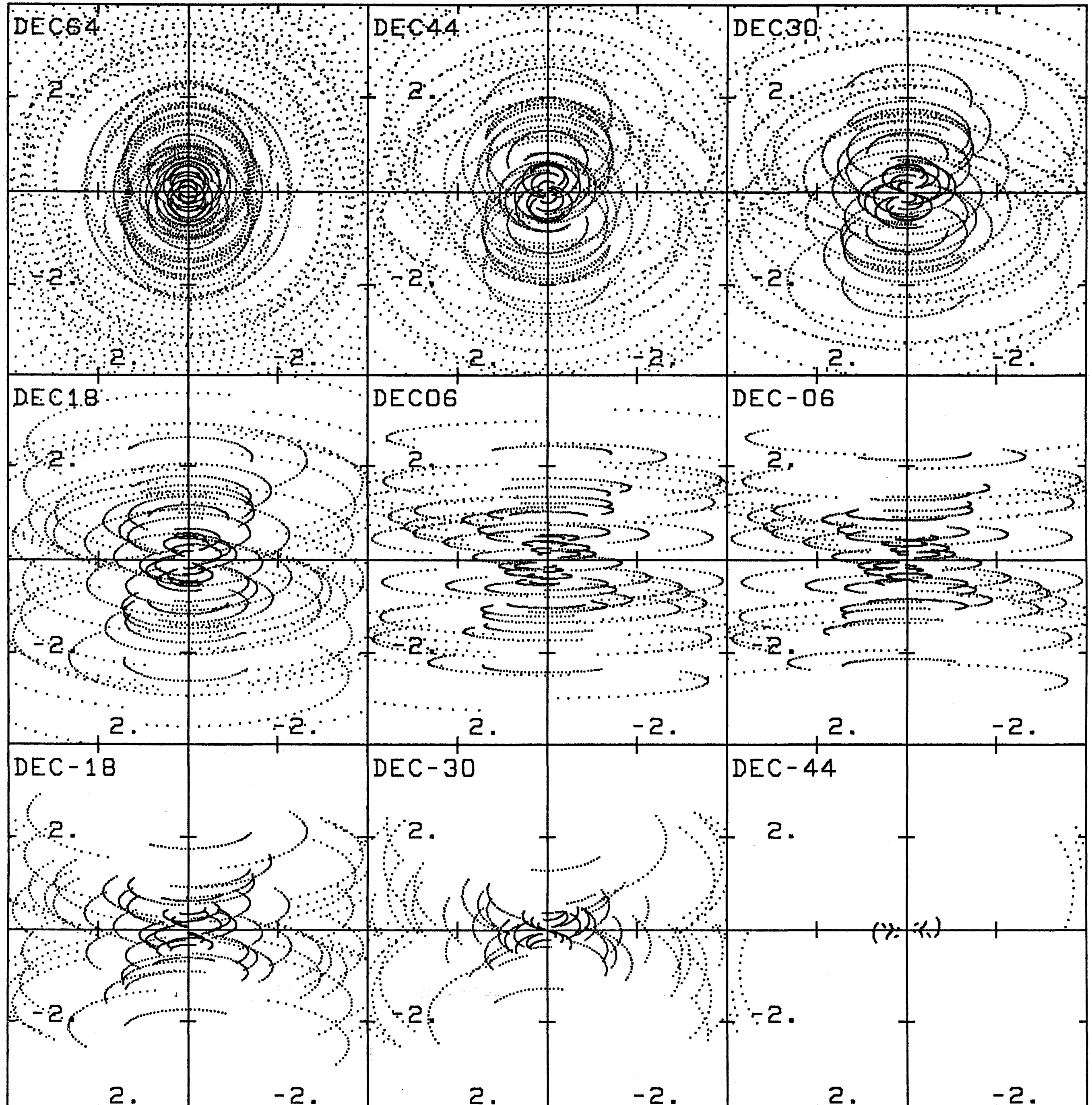

Figure 1.2b
4000 km

840501

HAWAII	19.80	155.50
ARECIBO	18.34	66.75
HSTK	42.43	71.49
OROVILE	48.90	119.75
OVRO	37.05	118.28
IOWA	41.58	91.57
FDVSNEW	30.47	103.95
KITT	31.96	111.60
LASL2	35.81	106.27
PIETOWN	34.33	108.14

Scale in km
(kilometers x 10^2)

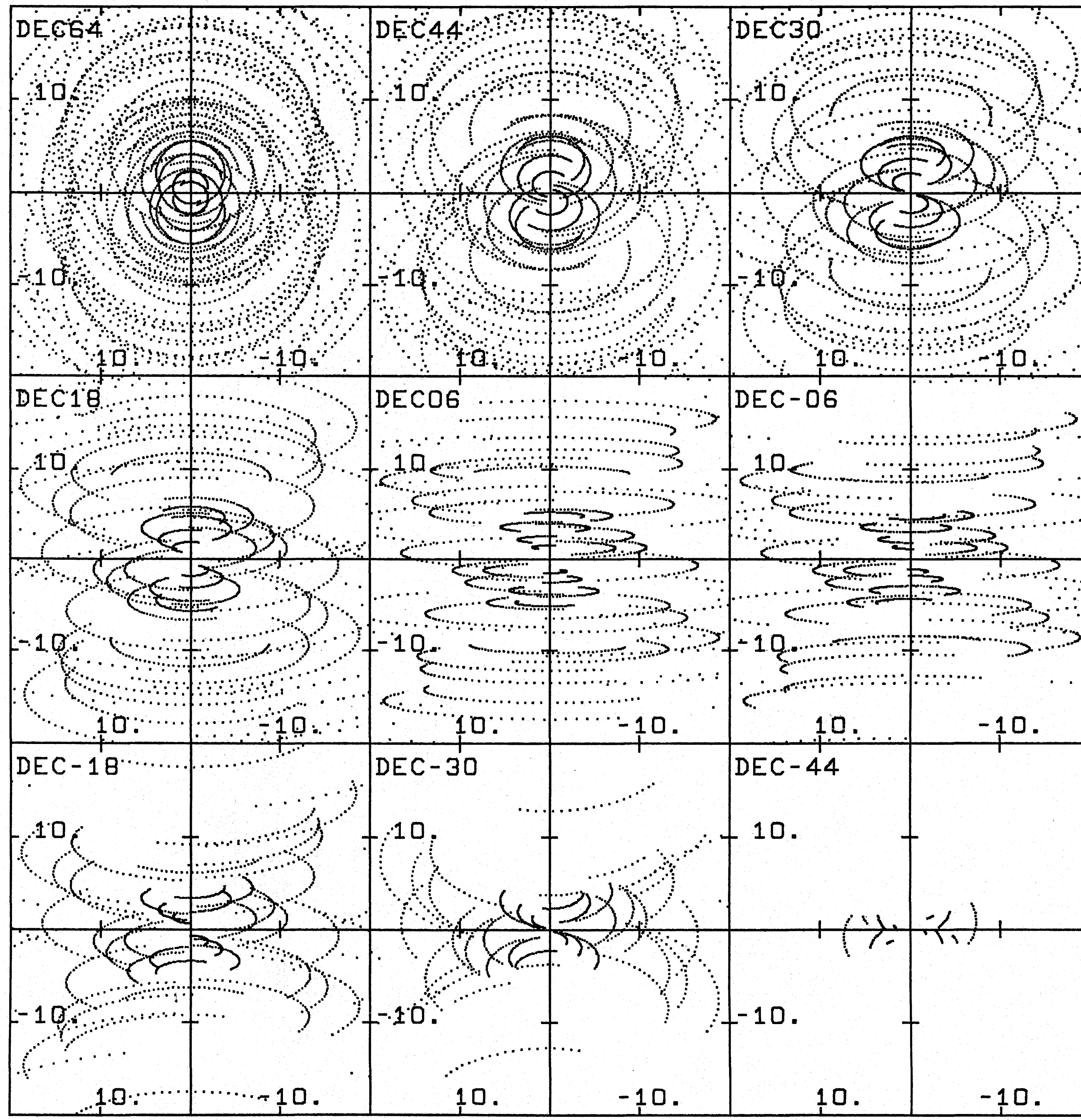

Figure 1.2c
2000 km

HAWAII	19.80	155.50
ARECIBO	18.34	66.75
HSTK	42.43	71.49
OROVILE	48.90	119.75
OVRO	37.05	118.28
IOWA	41.58	91.57
FDVSNEW	30.47	103.95
KITT	31.96	111.60
LASL2	35.81	106.27
PIETOWN	34.33	108.14
AN9	34.24	107.63
AW9	33.97	107.81
AE9	34.00	107.41
AW3	34.06	107.64

Scale in km
(kilometers x 10^2)

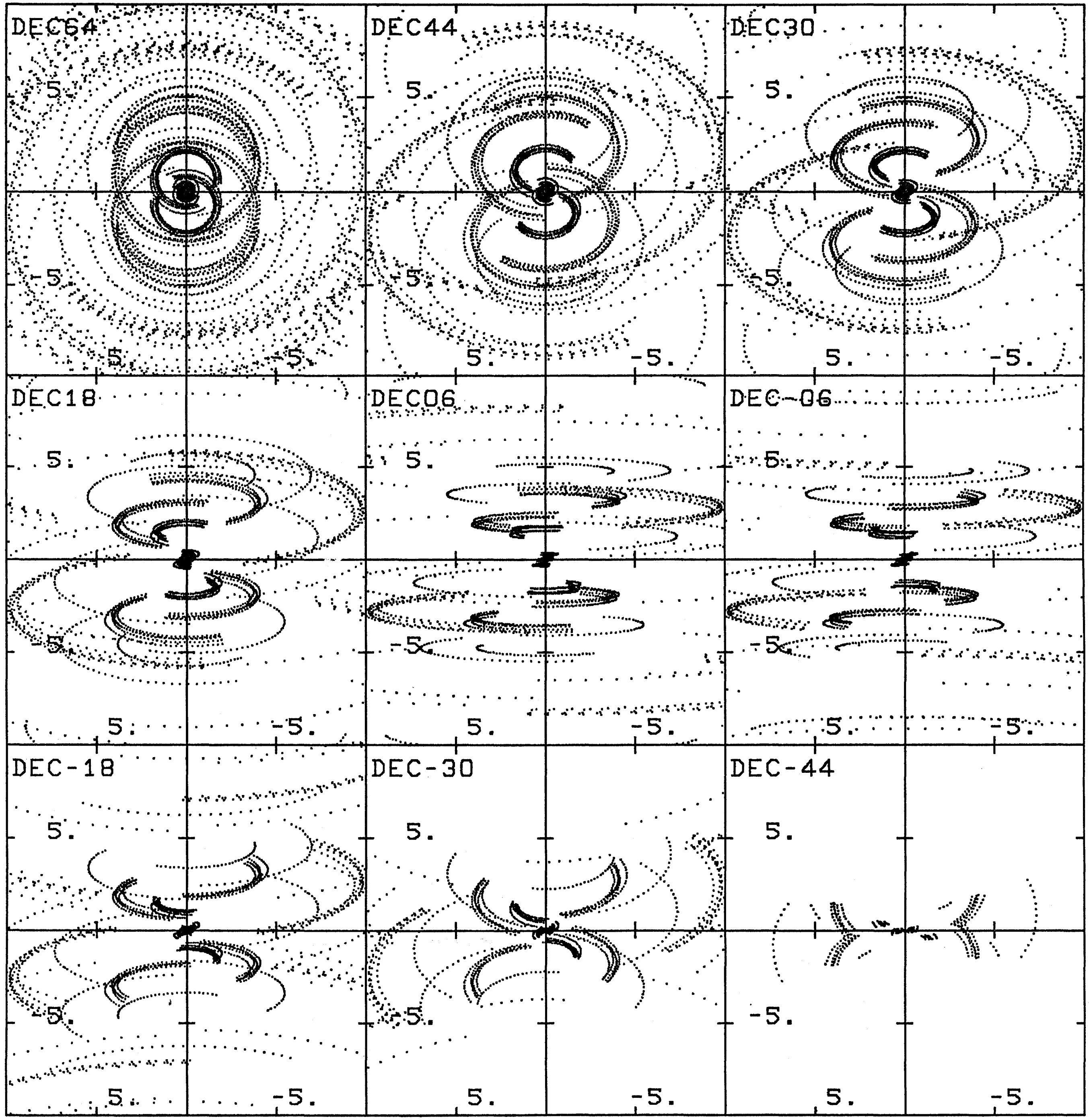

Figure 1.2d
1000 km

840501

HAWAII	19.80	155.50
ARECIBO	18.34	66.75
HSTK	42.43	71.49
OROVILE	48.90	119.75
OVRO	37.05	118.28
IOWA	41.58	91.57
FDVSNEW	30.47	103.95
KITT	31.96	111.60
LASL2	35.81	106.27
PIETOWN	34.33	108.14
AN9	34.24	107.63
AW9	33.97	107.81
AE9	34.00	107.41
AW3	34.06	107.64

Scale in km
(kilometers x 10^2)

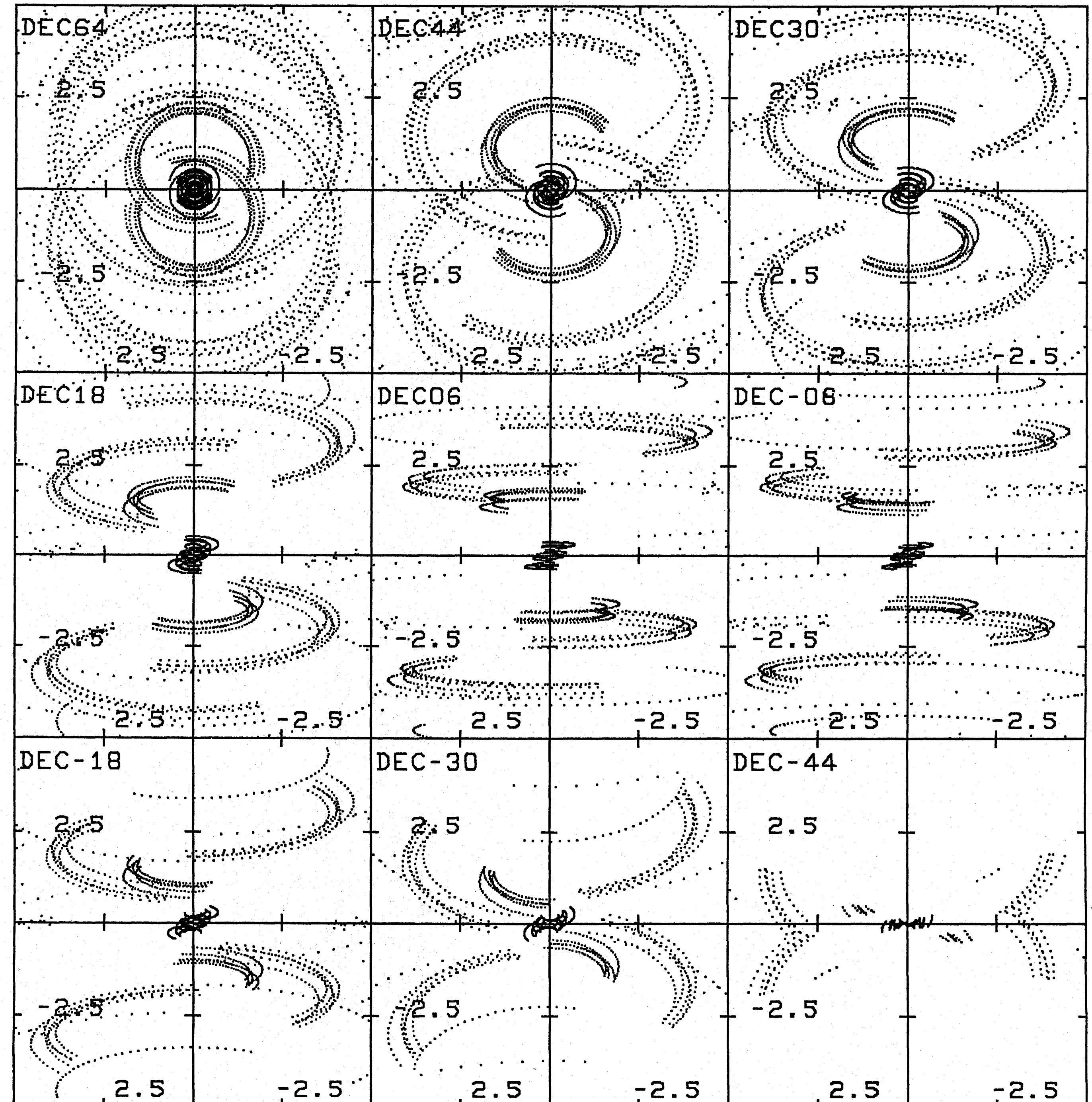

Figure 1.2e
500 km

HAWAII	19.80	155.50
ARECIBO	18.34	66.75
HSTK	42.43	71.49
OROVILE	48.90	119.75
OVRO	37.05	118.28
IOWA	41.58	91.57
FDVSNEW	30.47	103.95
KITT	31.96	111.60
LASL2	35.81	106.27
PIETOWN	34.33	108.14
AN9	34.24	107.63
AW9	33.97	107.81
AE9	34.00	107.41
AW3	34.06	107.64

Scale in km
(kilometers x 10^1)

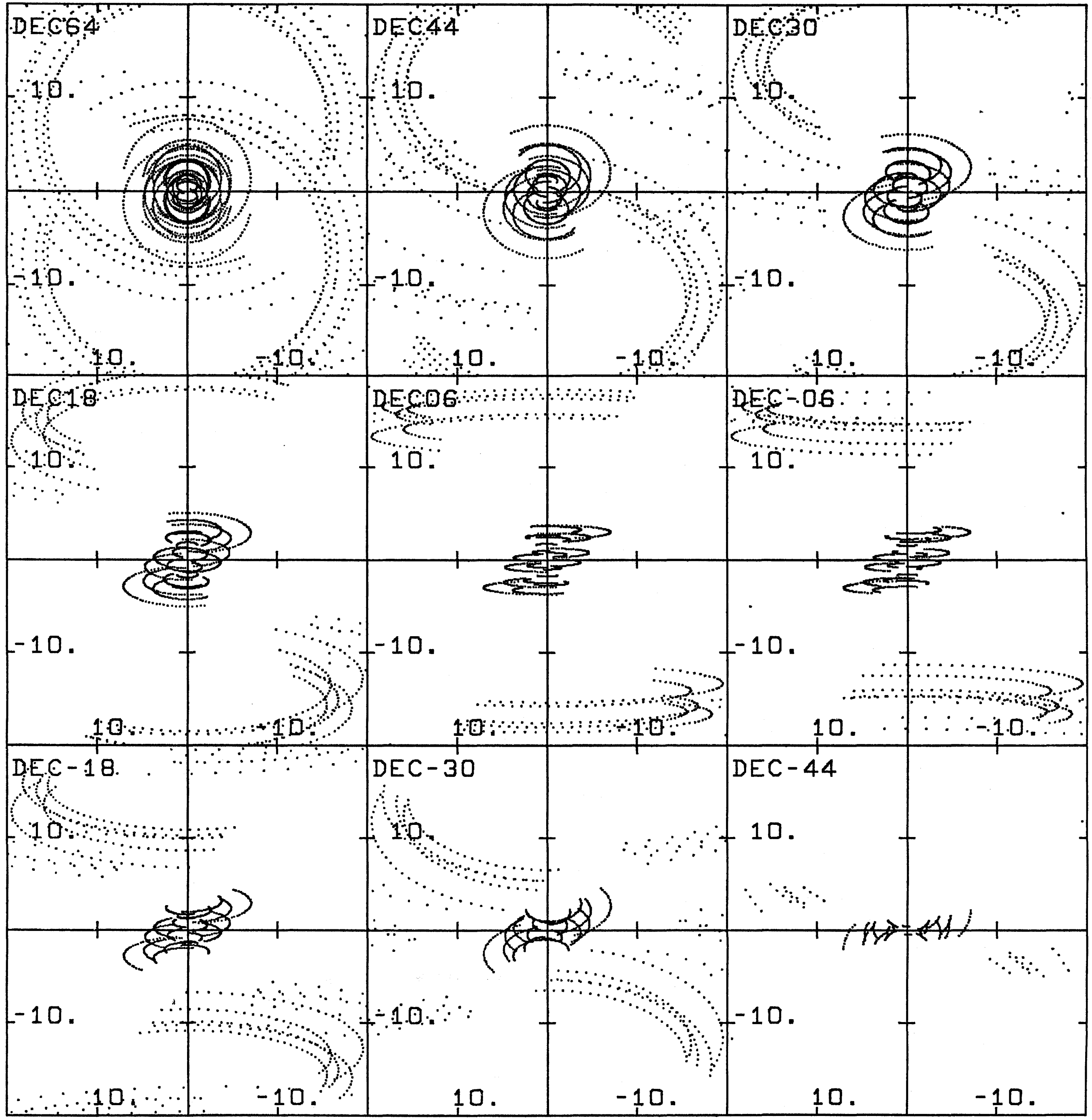

Figure 1.2f
200 km

840501

HAWAII	19.80	155.50
ARECIBO	18.34	66.75
HSTK	42.43	71.49
OROVILE	48.90	119.75
OVRO	37.05	118.28
IOWA	41.58	91.57
FDVSNEW	30.47	103.95
KITT	31.96	111.60
LASL2	35.81	106.27
PIETOWN	34.33	108.14
BERNARDO	34.35	106.90
DUSTY	33.62	107.65
ROSWELL	33.40	104.55
AN9	34.24	107.63
AW9	33.97	107.81
AE9	34.00	107.41
AW3	34.06	107.64

Scale in km
(kilometers x 10^2)

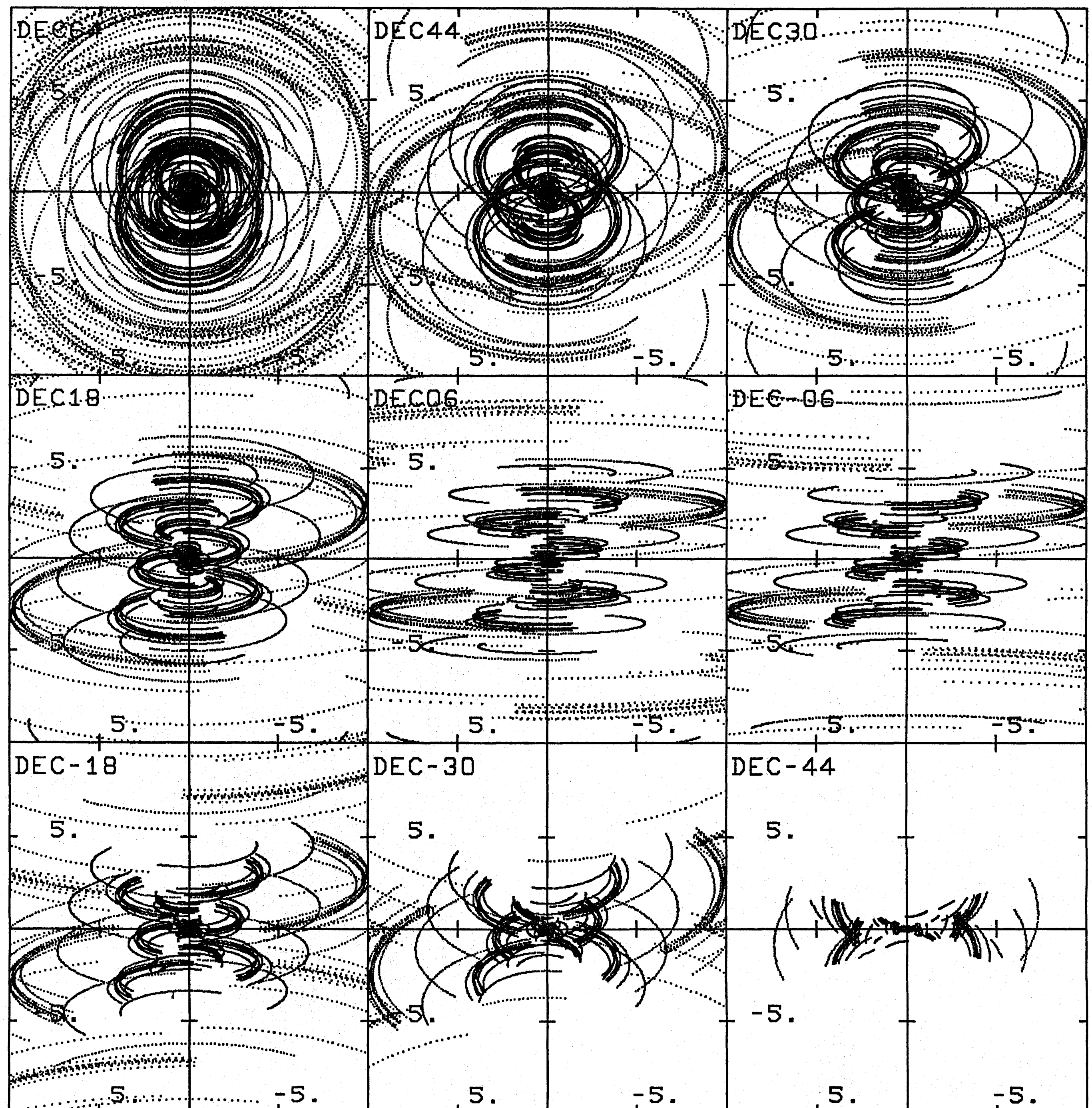

Figure 1.3a
1000 km

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ARECIBO	18.34	66.75
HSTK	42.43	71.49
OROVILE	48.90	119.75
OVRO	37.05	118.28
IOWA	41.58	91.57
FDVSNEW	30.47	103.95
KITT	31.96	111.60
LASL2	35.81	106.27
PIETOWN	34.33	108.14
BERNARDO	34.35	106.90
DUSTY	33.62	107.65
ROSWELL	33.40	104.55
AN9	34.24	107.63
AW9	33.97	107.81
AE9	34.00	107.41
AW3	34.06	107.64

Scale in km
(kilometers x 10^2)

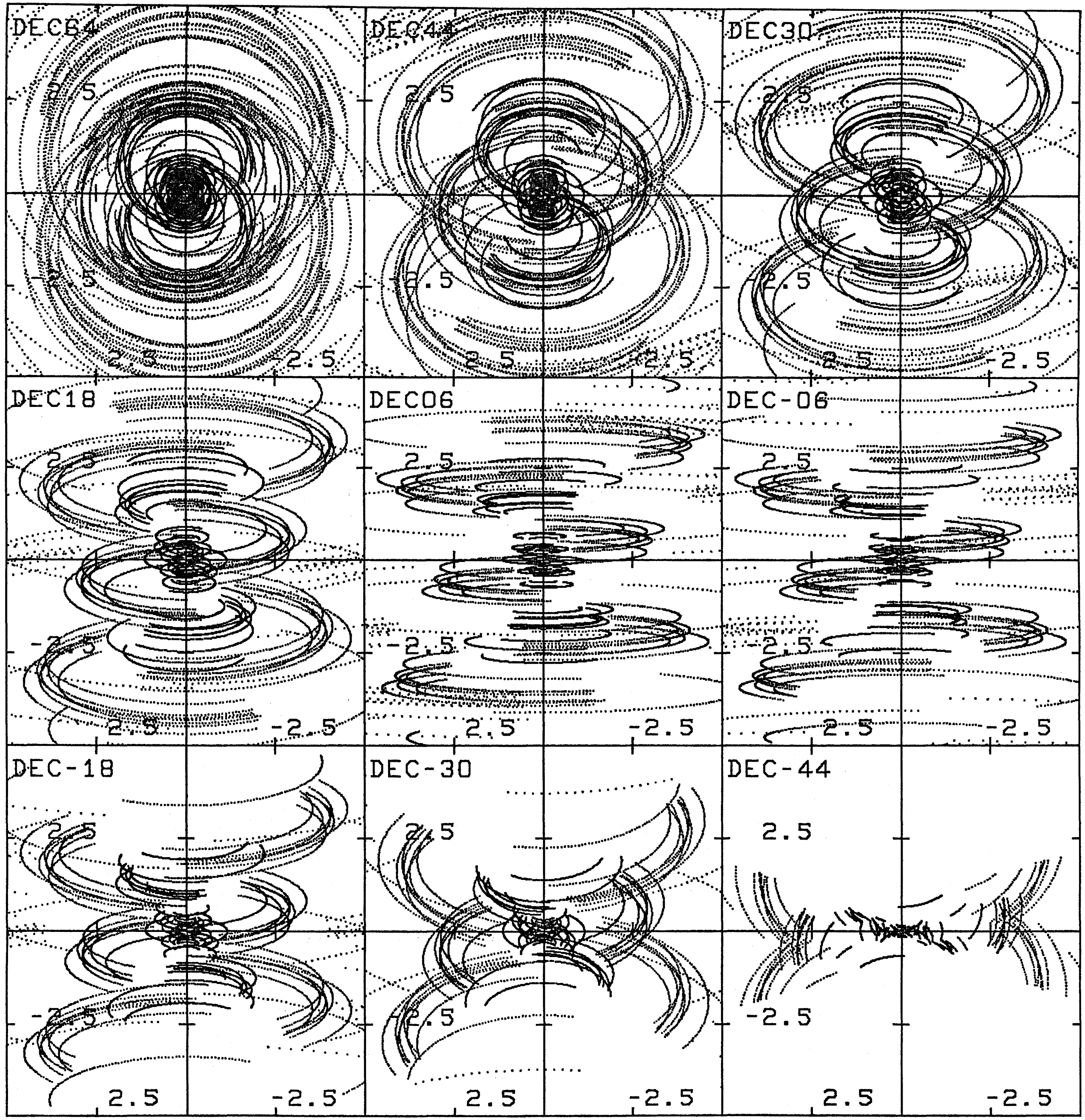

Figure 1.3b
500 km

840501

HAWAII	19.80	155.50
ARECIBO	18.34	66.75
HSTK	42.43	71.49
OROVILE	48.90	119.75
OVRO	37.05	118.28
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LASL2	35.81	106.27
PIETOWN	34.33	108.14
BERNARDO	34.35	106.90
DUSTY	33.62	107.65
ROSWELL	33.40	104.55
AN9	34.24	107.63
AW9	33.97	107.81
AE9	34.00	107.41
AW3	34.06	107.64

Scale in km
(kilometers x 10^1)

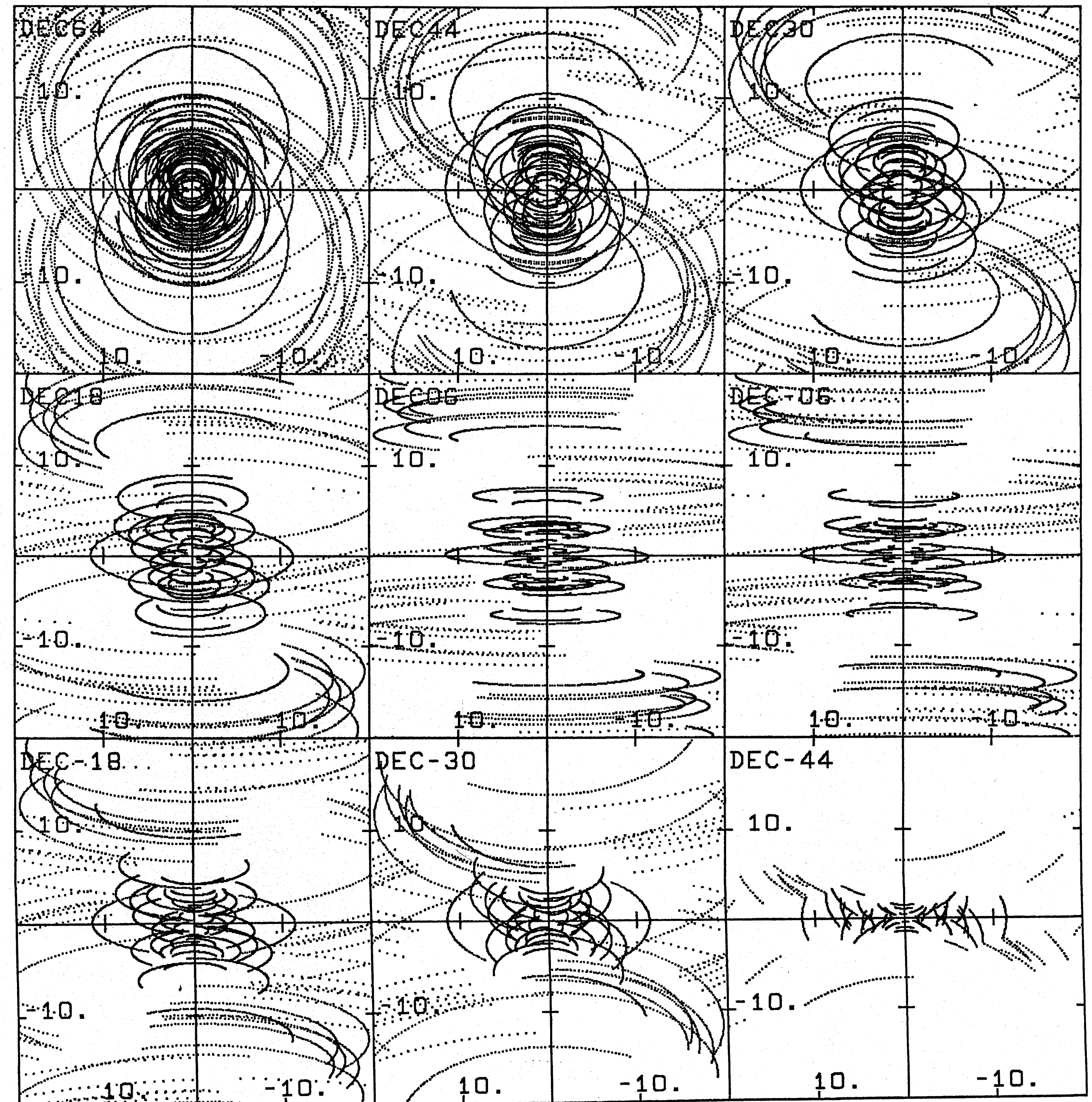


Figure 1.3c
200 km

HAWAII	19.80	155.50
ARECIBO	18.34	66.75
HSTK	42.43	71.49
OROVILE	48.90	119.75
OVRO	37.05	118.28
IOWA	41.58	91.57
FDVSNEW	30.47	103.95
KITT	31.96	111.60
LASL2	35.81	106.27
PIETOWN	34.33	108.14
QUITO	-0.20	77.00

Scale in km
(kilometers x 10^3)

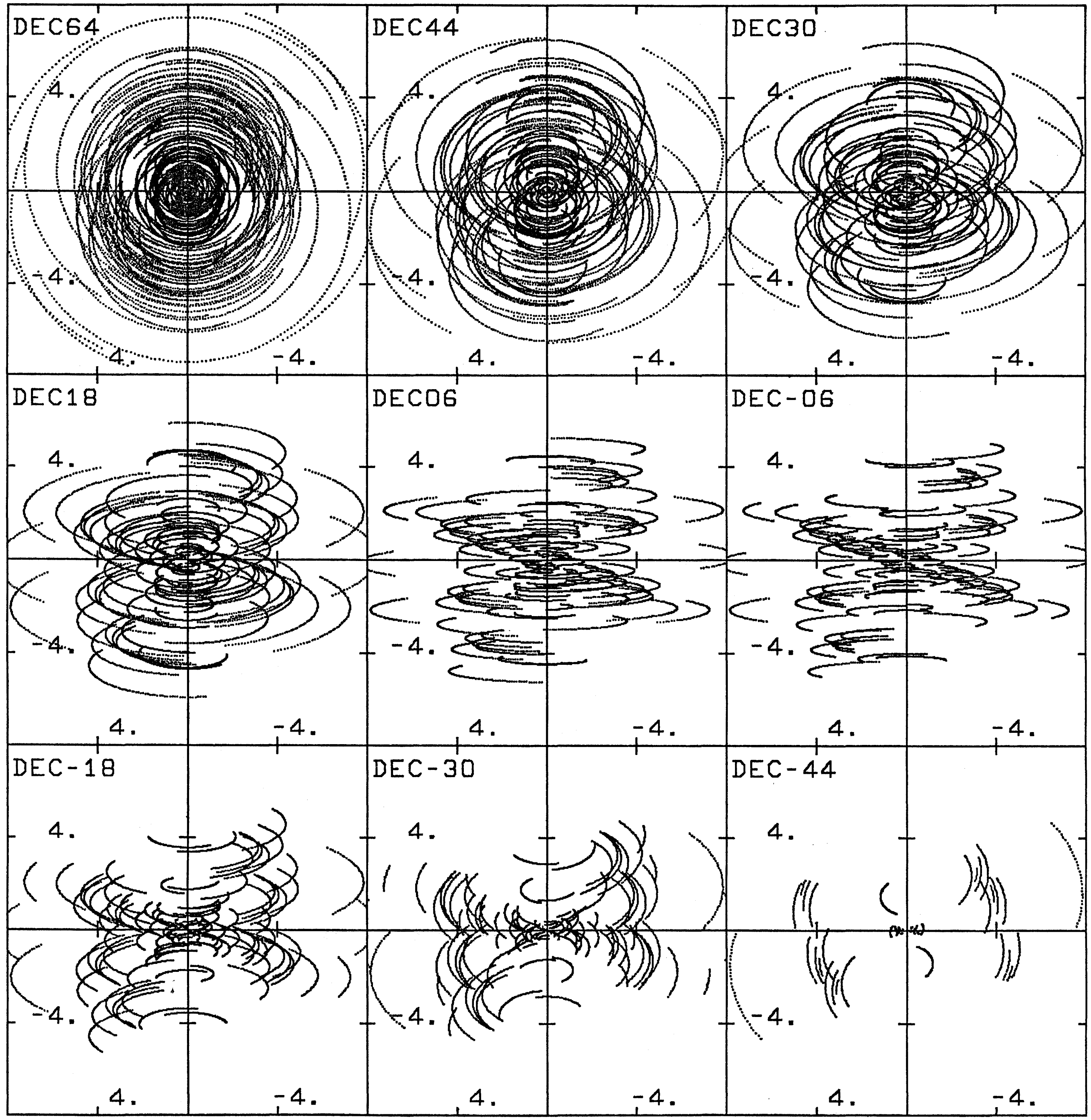


Figure 1.4
VLBA and QUITO

Section 1 - Updates

850726 Bring site info up to date. Mention 4 station possibility in New Mexico. R. C. Walker

850107 Add reference to frequency of previous Arecibo VLBI expts. R. C. Walker

841126 Update: Add station coordinates, update status of sites, R. C. Walker

841115 Put in section numbers. Carolyn (this entry by RCW)

840306 Updates of station names to appear on figures. Switch to Dusty from Winston. R. C. Walker

840228 Initial version brought up to date. R. C. Walker

840207 Initial version; not edited, not necessarily up to date.

SECTION 2

ANTENNA STATIONS AND ARRAY OPERATION CENTER

B. Peery

2.1 SPECIFICATIONS

2.1.1 Number of Stations

The VLB Array will consist of ten antennas at separate locations and an Operation Center strategically located to serve all ten antennas and to interface with other existing radio astronomy facilities that might support or occasionally function in conjunction with the VLBA. The number of antennas needed to achieve the scientific goals of the instrument was determined in an extensive study of configurations of the array, as described in the chapter on configurations and in Volume I, dated May 1982.

2.1.2 General Location

All ten antennas and the operation center will be located inside United States territory. Eight antennas and the operation center will be located on the continent with the other two located on islands. The spacings and general locations were determined by optimizing the UV coverage while giving consideration to utilizing existing radio telescope installations and to local weather conditions. These decisions are explained in the configuration section of this volume. The antennas will be located in the states of Arizona, California, Hawaii, Iowa, Massachusetts, New Mexico (two sites), Texas, Washington and the Commonwealth of Puerto Rico. Exact locations, on the ground, will be determined by checking for conformity with the criteria set forth below. The operation center will be located at Socorro, New Mexico. There will be a single service facility to provide maintenance and service support for the entire array which is the VLA near Socorro, New Mexico.

2.1.2.1 Specific Antenna Locations in Proposed Order of Developing

Pie Town, New Mexico
Kitt Peak, Arizona
Los Alamos, New Mexico
Oroville, Washington
Fort Davis, Texas
St. Croix, Virgin Islands

North Liberty, Iowa
Owens Valley, California
Hawaii
Westford, Massachusetts

2.1.3 Requirements of a Typical Station

The following general requirements will help establish the exact location within the tolerances allowed by the configuration study. Areas, dimensions, arrangements, relative locations on the ground and in the building will be refined or changed to meet local requirements, conditions and equipment sizes as the design and program develops.

2.1.3.1 Land Area: Each antenna station will require a fence enclosed land area of approximately 225 ft x 250 ft or 1.25 to 1.75 acres.

2.1.3.2 Control Building: Each antenna station will require a control building.

2.1.3.2.1 Function: The building will house the antenna control equipment, electronic equipment, a micro computer for operating the antenna, facilities for controlling and monitoring the antenna, radiometers, and recording system, magnetic tape storage space, hydrogen maser clock system, mechanical equipment (building environmental system and electrical power system), sanitary facilities, spare parts and components storage area, and a space for repair facilities. Only minor repairs and preventative maintenance will be performed at the individual stations. Components will be replaced and the defective ones shipped to the service facility or supplier for repair.

2.1.3.2.2 Area: A building approximately 49 ft x 24 ft inside or 1176 sq ft subdivided into six rooms would provide the space to perform the operations outlined above. A conceptual floor plan showing a general arrangement is included (Fig. 2.1). The dimensions will be refined to conform to good design by the A/E.

2.1.3.2.3 Conceptual Specifications: The antenna control building will be an energy efficient, masonry, single story building on grade with minimum windows and doors. Security doors and windows will be provided to protect against vandalism. The building will be equipped with an environmental control system to maintain 25 deg C +_ 1 deg C continuously with 40% +_ 10% relative humidity. Special temperature control will be provided for some equipment. The building will be equipped wiht hot and cold water and a toilet. The exterior walls, ceiling and some interior walls will contain a grounded metal screen grid to serve as an electromagnetic shield against radio frequency interference (RFI). RF filters and shielding will be provided in electrical, telephone and antenna services as required. "Computer Room Flooring" will be installed in the equipment room and control room. A loading dock will be provided at the shipping and receiving entrance. Special isolated foundations will be provided for the masers. The building will be designed and constructed to meet all applicable building and safety codes. Automatic burglar and fire will be provided as required for the specific location. Automatic fire protection will be considered.

2.1.3.3 Access

2.1.3.3.1 From a distance: The antenna station will be reasonably near a transportation center where daily flights are available for the rapid transporting of tapes, parts and personnel between the STATION and the operation center and the service facility.

2.1.3.3.2 Locally: The exact location will be chosen to be near a residential or similar non-industrial area close to a public highway of such quality and status that the station will be accessible 24 hours a day year round.

2.1.3.4 Weather: The operation of the antenna and the quality of the data obtained are materially affected by temperature, temperature changes, rain, snow, cloud cover, wind and precipitable water vapor. The exact location will be chosen where these factors are minimal.

2.1.3.5 Utilities: The station will require commercial electric power, water, sewer and telephone services. Equipment to provide clean power or instant power will be installed, as required. The estimated power demand is 100 to 125 kW at 120/208 volts, 3 phase, 4 wire for a typical station. Fig. 2.5 gives the estimated electrical loads and their proposed sources of supply. It is estimated three telephone lines of digital transmission grade will be required to each station. If public sewer and water systems are not accessible, a septic system and will be installed. An approach road from the highway, and a parking area will be provided. The approach road and parking area will be thoroughly compacted gravel with a light coat of asphalt topping as a wearing surface. Storm and surface drainage will be controlled by grading of the site and roadway. An auxiliary generator for emergency use during commercial power outages, estimated to be 75 kVA, an equipment storage building and snow removal equipment will be provided each station as required. An elevator for antenna maintenance and other required maintenance equipment will be provided each station.

2.1.3.6 RFI Protection: Radio frequency electromagnetic interference must be minimal. To meet these requirements, the exact location will be chosen to be as far as possible, within the tolerances allowed, from radio and TV transmitter antennas, industrial installations, busy roadways, electrical distribution lines, electrical generators, electrical substations, microwave equipment and radio navigation aids. Where potential sources of interference exist, the exact location will be chosen, so far as possible, to have distance, forest, wooded areas, hills or other forms of natural shielding between the antenna and the potential source of interference. Filters for and shielding of utility and antenna services will be installed as required.

2.1.3.7 Terrain: The actual location of the antenna will be chosen so as to have reasonably level ground with stable soil conditions at such an elevation that the horizon to the south, east and west of the antenna will generally not project higher than a 5 degree angle above the horizontal plane passing through the elevation axis of the antenna. Segments of the horizon (in azimuth) below 5 degrees will be considered, where practical, in locating the antenna.

2.1.3.8 Seismic History: The exact location will be chosen in an area as far as possible from any geological faults and having a history of minimal seismic activity. The soil conditions in the area must be stable and well drained and not subject to slides or major condition changes due to moisture content.

2.1.4 Conceptual Station Plan: A typical conceptual station plan is included (Fig. 2.2). The exact location of the building, relative to the antenna, will be approximately 100 feet from the center of the antenna and on an azimuth that will cause minimum obstruction of the horizon from the antenna.

2.1.5 Location of the Operation Center

The operation center will be located in Socorro, New Mexico. Warehouses, shops, repair and maintenance facilities to serve as the service facility for the new Array will be those at the VLA installation in New Mexico.

2.1.6 Requirements of the Operation Center

2.1.6.1 Function: The operation center will provide housing and facilities to operate and monitor the ten remote antennas, to receive from and ship to remote stations, parts, tapes, etc., to play back and analyze the data tapes received from the remote stations, and to combine the data from all remote antennas to produce the end results, maps, image plots, etc. It will have space for scientific staff offices, electronics engineers offices, laboratories and shops for developing new electronic equipment, tape storage and control, computer programming and software development, visiting scientist offices, and administration and management of the complete operation.

2.1.6.2 Area: A three-story building approximately 180 ft x 40 ft or 21,000 sq ft subdivided into offices, laboratories, work areas, computer space, control room and shops will provide the space to perform the functions outlined above. A conceptual floor plan showing a general arrangement is included (Fig. 2.3). The size, number and arrangement of spaces will be refined to match the equipment installed and to meet known functional requirements as they develop and the overall program develops. The final floor plan will be limited to the area indicated but will be arranged for expansion to double (or more) the size shown. The location chosen for the building will be for the building actually built plus an equal amount or more for future expansion. The building plan will be adapted to the location chosen. Conceptual studies will be made for: (a) a combined VLBA and VLA operation, estimated to require 53,291 sq. ft. of usable area, (b) optimum VLBA stand alone operations, estimated to require 33,313 sq. ft. of usable space and (c) VLBA stand alone operations, maximum that can be constructed with the funds available, estimated to be 20,000 to 25,000 sq. ft. of usable space. All studies will include possible future increases to the combined operation and move.

2.1.6.3 Conceptual Specifications: The operation center building will be an energy efficient, masonry, three-story building on grade. The building will be equipped with an environmental control system to maintain 25 deg C +_ 1 deg C continuously with 40% +_ 10% humidity in areas requiring humidity control. The building will be equipped with toilet facilities including a limited number of showers to meet the requirements for the number of people occupying the building. Hot and cold water distribution systems will be provided throughout the building. The required stairways and exits will be installed to meet applicable fire codes. Automatic fire protection and alarms will be provided. A loading dock will be provided at the shipping and receiving entrance. The building will be designed and constructed to meet all applicable safety and building codes including facilities and access for the handicapped. The architecture will be such as to conform to that existing where the control center is finally located. The design will be such as to provide for a major expansion in the future.

2.1.6.4 Access: The operation center is located near a major transportation center (Albuquerque, N.M.) where frequent flights are available for the rapid movement of tapes, parts, equipment and personnel to any of the remote stations. Local access will be available 24 hours a day year round.

2.1.6.5 Utilities: The operation center will require commercial electric power, water, sewer and telephone services. The estimated power demand is 300 kVA. A minimum of 15 telephone lines of digital transmission grade will be needed. Water, sewer, storm drains, driveways, walks, parking security and landscaping will be incorporated into and be an extension of the existing system in the area. The land area required will be that on which the building rests plus an equal amount for future expansion. A 50 kVA auxiliary generator for emergency use during a commercial power failure will be provided.

2.2 DESCRIPTION

(This subsection not yet written.)

2.3 COST ESTIMATES

2.3.1 Typical station:

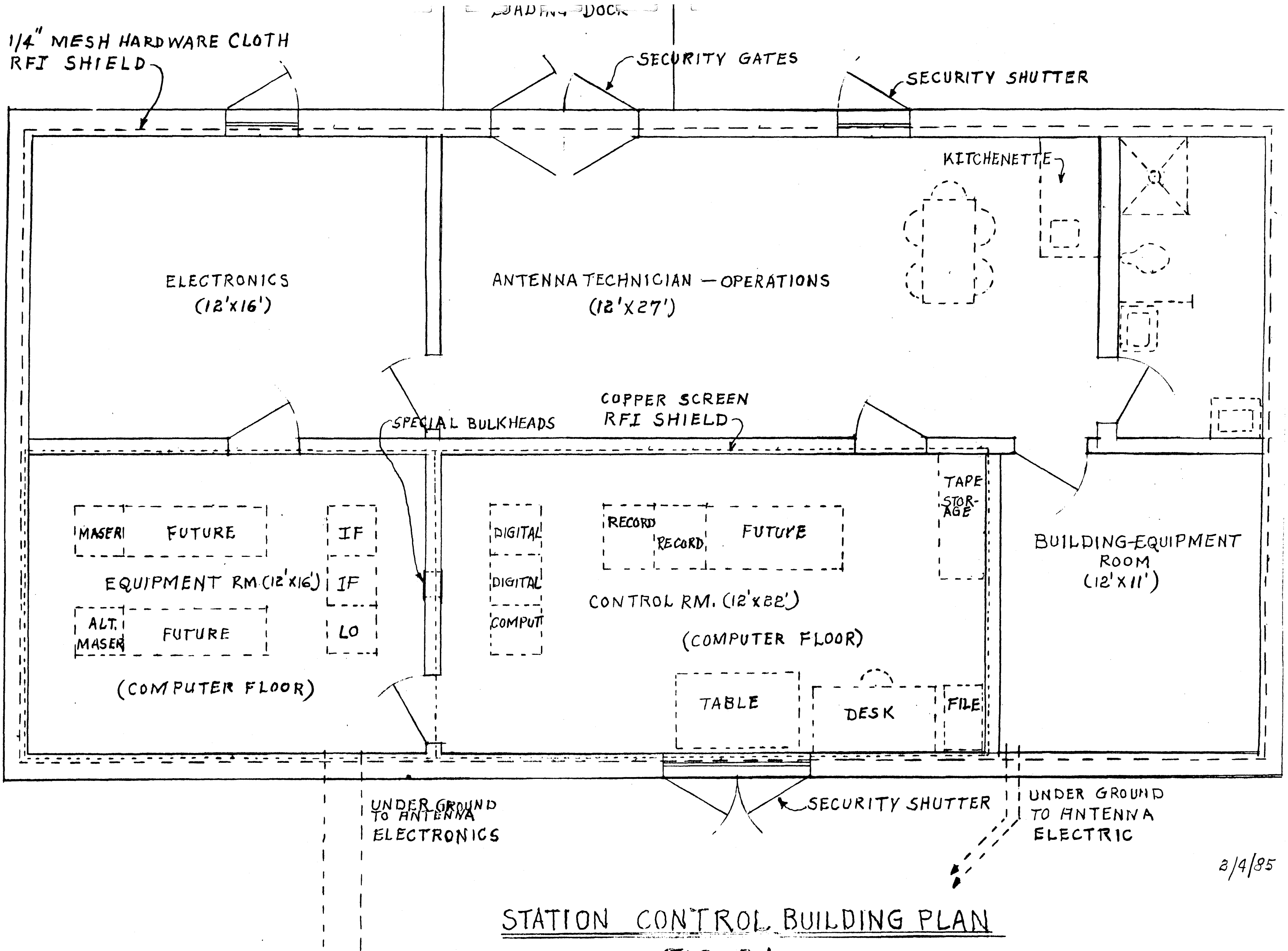
	1985 Dollars
Land	10,000.00
Survey and Soils Test	15,000.00
A/E Design Fee	20,000.00
Site Work	80,000.00
Antenna Foundations	100,000.00
Building	190,000.00
Standby Power	50,000.00
Station Outfitting	53,000.00
Misc. (utilities)	25,000.00
Total for 1 typical station	543, 000.00

2.3.2 Operation Center:

Survey and Soils Test	10,000.00
A/E Design Fee	155,000.00
Site Work	15,000.00
Building	2,500,000.00
Standby Power	60,000.00
Station Outfitting	95,000.00
Misc. (utilities,etc.)	10,000.00
Total for Operation Center	2,845,000.00

2.3.3 These estimates do not include a contingency fee (15%) or management fee (10%).

2.3.4 A suggested Design and Construction Schedule is included (Fig. 2.4).



STATION CONTROL BUILDING PLAN

FIG. 2.1

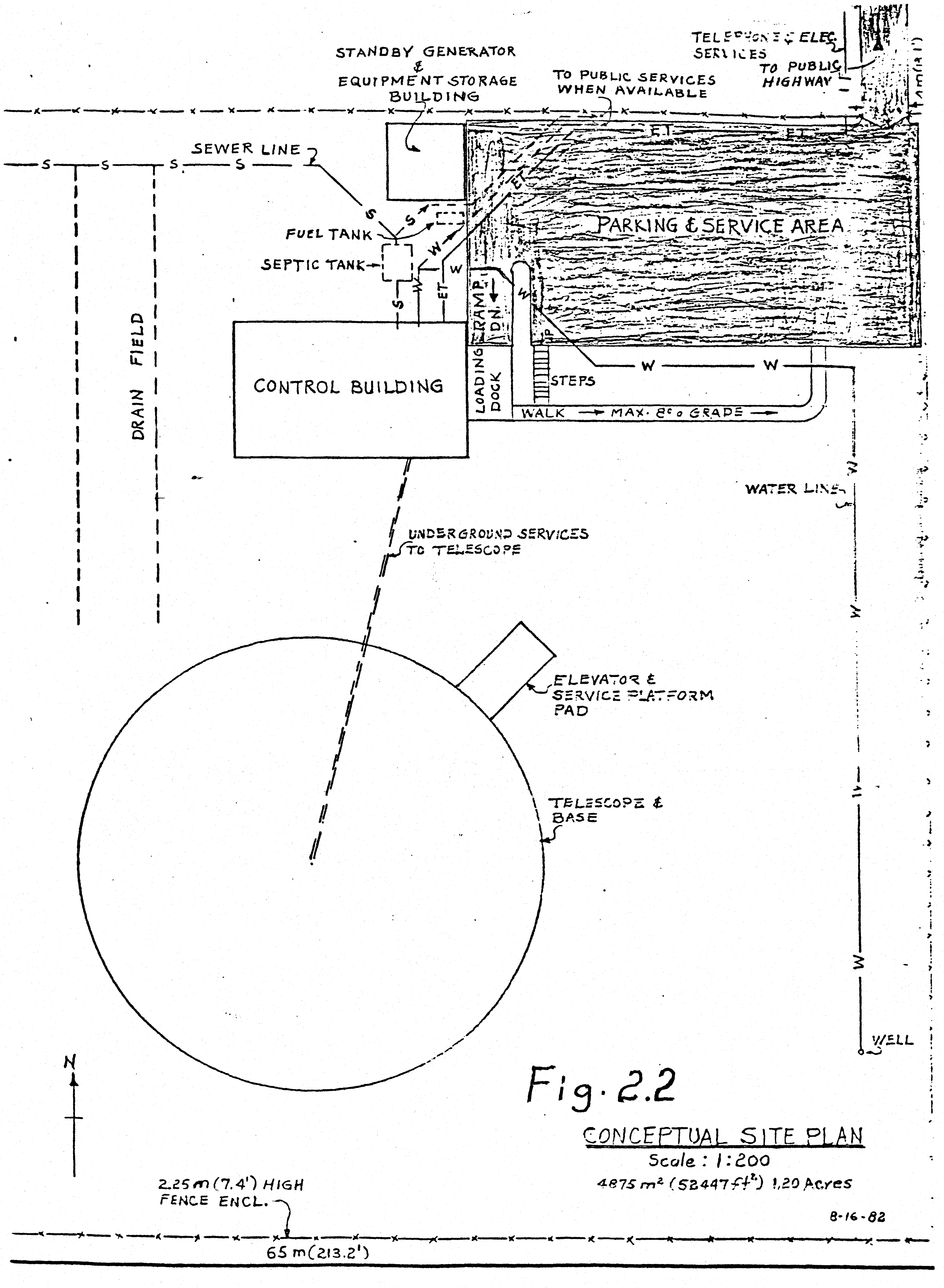


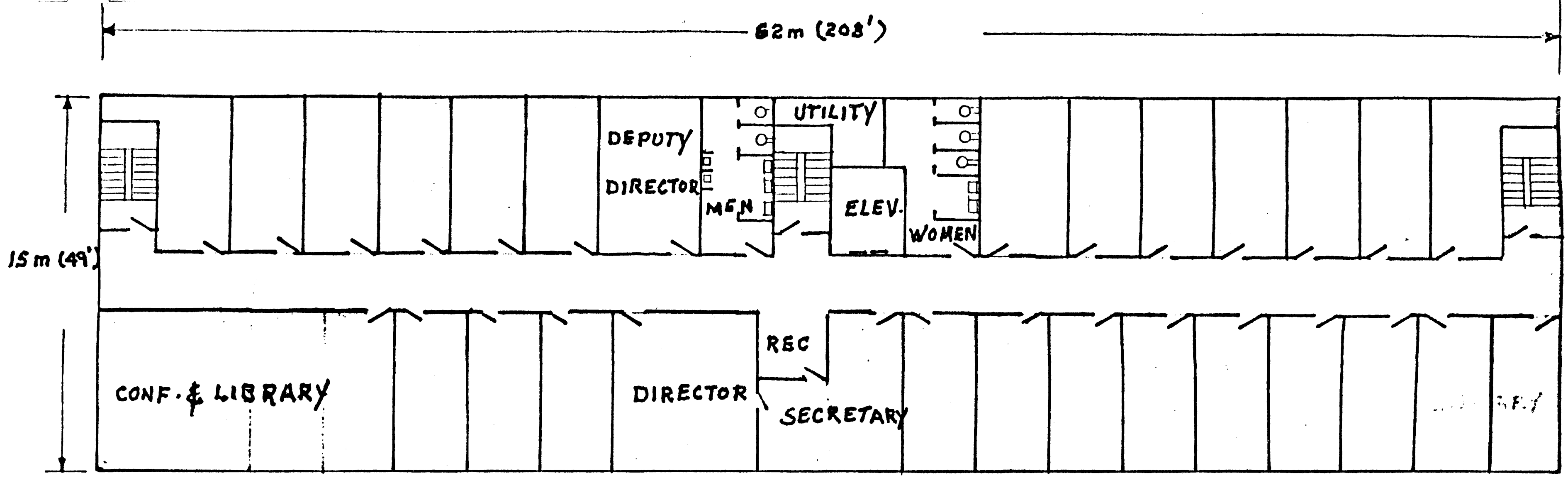
Fig. 2.2

CONCEPTUAL SITE PLAN

Scale: 1:200

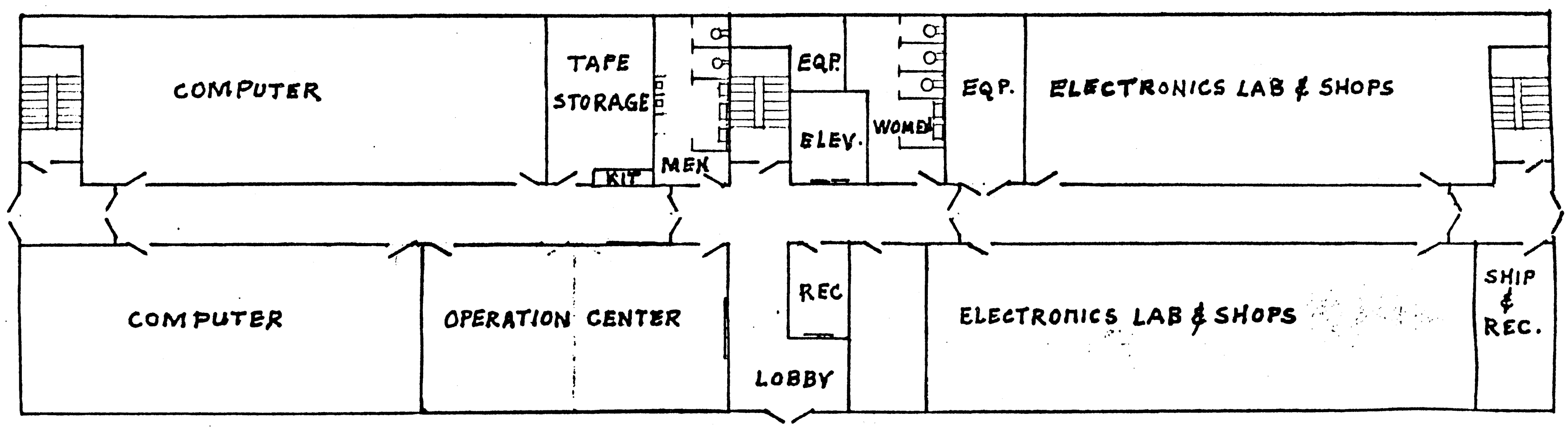
4875 m² (52447 ft²) 1.20 Acres

8-16-82



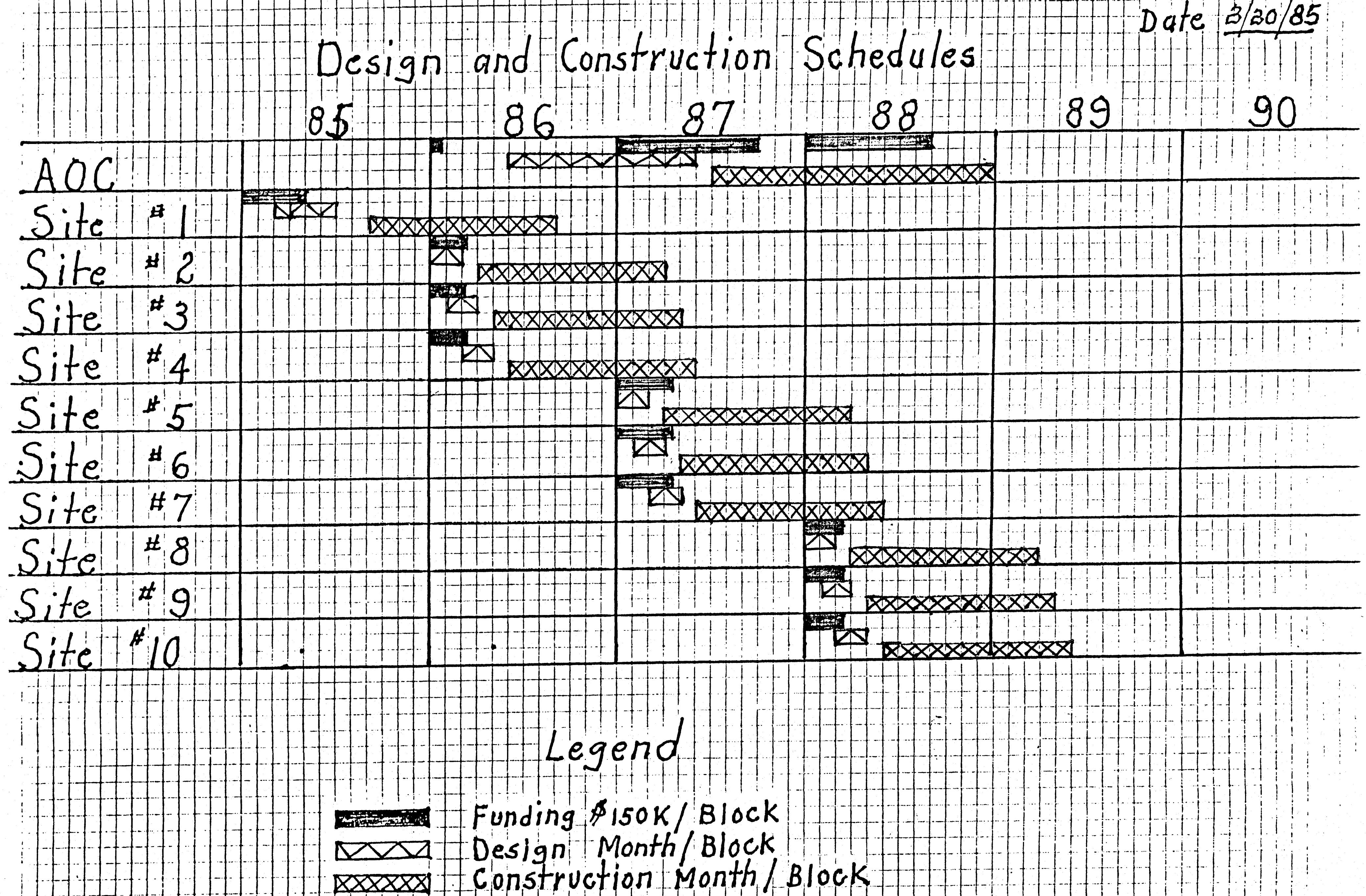
2ND. FLOOR

OPERATIONS CENTER



1ST FLOOR

Fig. 2.3



Date 3/20/85
Design and Construction Schedules
85
86
87
88
89
90
AOC
Site #1
Site #2
Site #3
Site #4
Site #5
Site #6
Site #7
Site #8
Site #9
Site #10
Legend
Funding $150K/ Block
Design Month/ Block
Construction Month/ Block

Fig. 2.4

2/20/85

Station Electrical Loads - KW
120/208 V-3 Φ 4 Wire

Area	Equipment	Commercial	Comm.& Gen.	UPS.
Antenna	Elev. Drive		30.0	
	Az. Drive	30.0		
	Heater	.5		
	Lights	1.0		
	Brakes		1.0	
	Controls		1.0	
	Air Cond.	15.0		
	Front Ends		2.3	
	Cryogenics (3)		15.0	
	Electronics - Racks	4.0		
	Misc.	1.0		
Building	Masers (2)		6.0	6.0
	Cryogenics	5.0		
	Control Unit		.3	.3
	Computer-Etc.		1.8	1.8
	Record-Electronics (2)		1.0	1.0
	Recorders (2)		1.5	1.5
	L.O. (2)			
	Digital (2)			
Build System	Lights.	3.0		
	Power (Rec.)	6.0		
	A/C & Heat.	12.0		
	Water Heater	10.0		
	Misc.	5.0		

Fig. 2.5

Section 2 - Updates

850722 Corrected schedule - Paragraph 2.1.2.1; Revised estimates - Paragraphs 2.3.1, 2.3.2

850220 Revised: Paragraphs 2.1.2.1; 2.1.3.2.2; 2.1.3.2.3; 2.1.3.5; 2.1.3; 2.1.6.2; and 2.1.6.5; Replaced Fig 2.1 with a new plan; Replaced Fig. 2.4 with latest schedule and added Fig. 2.5 "Schedule of Estimated Electrical Loads".

841201 General Edit

840424 Added paragraph 2.1.2.1; corrected text for location of operation center and service center; revised construction schedule (Fig. 2.4).

840420 Corrected formats, paragraph numbering, subsection titles, figure numbers. LRD.

840321 Edited and numbered paragraphs, Updated estimate & design and construction schedule.

840314 Figure numbers added; Cost estimates revised.

840207 Initial version; not edited, not necessarily up to date.

SECTION 3

THE ANTENNA ELEMENTS

W. G. Horne

03.1 SPECIFICATIONS (Note: When reading the text of this Section 3.1 and reference is made to a Section (Example 03.2.1) insert the numeral 1 following the 03 to find the correct section of this document (Ex. Sect. 03.1.2.1).

03.1.1 Introduction

03.1.1.1 General Statement of Work

The work described herein shall consist of the furnishing of labor, materials, services, drawings, data, detailed specifications, test documents, and other items required for the detailed design, manufacture, assembly on site, alignment, and testing of antennas for the VLBA telescope system.

03.1.1.2 Objectives of the Program

The objectives of the effort under this subcontract are the following:

The design of an antenna that meets the operating parameters and requirements set forth in this specification.

The design for an antenna that is optimized for production of a quantity of ten (10) antennas, taking advantage of economies that may be realized by maximum duplication and standardization of parts, use of tooling to minimize labor, and simplification of assembly effort. Since assembly of the antennas will be at ten widely separated sites geographically, antennas shall be designed for manufacture and shipping in such modules as will minimize shipping and assembly costs to the extent possible.

A design that takes into consideration ease of maintenance and the reliability of components to minimize maintenance.

The fabrication of antennas using the techniques specified in the design effort.

03.1.2 Design

03.1.2.1 Applicable Documents

The followiing documents may be used as a guide in preparation of the design. The development of the required additional configuration and detailed design drawings and specifications supplementing and extending these documents are a part of the effort required in the design stage. In the event of a conflict between this specification and any of the documents listed, this specification shall govern:

VLBA Antenna Memo No. 4 - Drive System Analysis

VLBA Antenna Memo No. 5 - Structural Data

Antenna Configuration Drawings D52502T001 Sheets 1 through 5.

Electronic Industries Association RS-222 - Structural Standards for Steel Transmitting Antennas and Supporting Steel Towers.

National Fire Protection Association - National Electrical Code - Latest Edition.

Bureau of Standards RP-1 (Federal Property Fire Protection.

American Institute of Steel Construction - Manual of Steel Construction - Latest Edition.

MIL.STD.461A - Electromagnetic Interference.

The first three items listed above are for use in describing a configuration and design that AUI has developed to describe a wheel and track antenna well fitted to perform the observations required and analyzed to assure an antenna which will meet the performance requirements set forth later in this specification. The antenna shall be of wheel and track design and shall meet the mechanical and operating parameters and conditions as set forth in section 03.2.2. Subcontractor is not required to adopt this configuration and design, but if the Subcontractor chooses to adopt another configuration and design, it must meet the operating parameters set forth in this specification as fully as the design described in the NRAO documents. Once under contract, if the Subcontractor elects to use the NRAO design, it will be the Subcontractor's responsibility to confirm and validate the NRAO design during the design stage of the subcontract, and to develop the detailed design, drawings, and component specifications necessary to accomplish a finished antenna design which meets the performance requirements set forth in this document.

03.1.2.2 Design and Performance Parameters

The antenna system for which this antenna is designed consists of ten (10) antennas with 25-meter (approximately 82 feet) diameter reflectors located at ten (10) sites, widely separated geographically. Design parameters are therefore set forth for climatic conditions which may not exist at each station.

The antenna shall be an elevation over azimuth configuration, with a 25-meter diameter solid surface, which is approximately a paraboloid of revolution, as the main reflector. The observing systems to be used shall be both Cassegrain and prime focus. The Cassegrain observing system shall be considered the normal mode of operation. The feed for prime focus operation will be permmanently mounted in the center of the subreflector and will be used by moving the subreflector away from the main reflector to position the prime focus feed close to the prime focus. A clear opening of approximately 1.8 m (6 feet) in diameter will be required at the apex of the feed legs symmetrical about the reflector axis.

The antenna concept and design developed by NRAO and described in Section 03.2.1 above is one in which the gravity, thermal, and wind performance of the antenna structure is believed to be compatible with 86 GHz operation. It is NRAO's intent to preserve this structural performance capability so that a later upgrading of the antenna surface to operation at 86 GHz is not restricted by the structural capability of the antenna.

03.1.2.2.1 Mechanical Parameters

Diameter: 25 meters (82.02 feet)

Focal Length: 8.85 meters (29.035 feet)

f/D: 0.354

Sky Coverage: Elevation +0 deg to 125 deg; Azimuth + 270deg

Presently Planned Operational Frequencies: Cassegrain: 43 GHz, 22 GHz, 15 GHz, 10.7 GHz, 8.46 GHz, 6.1 GHz, 5.0 GHz, 2.3 GHz, 1.4-1.7 GHz.

Prime Focus: 611 MHz, 325 MHz.

Surface Accuracy: See Section 03.3.1 below.

Reflector Surface: The reflector surface shall be a surface of revolution which approximates a parabola but which is shaped to increase gain. The maximum deviation of any point on the shaped surface will not exceed 30 mm (1.2 inch) from the basic parabola; coordinates will be furnished later by AUI. Panels shall be individually adjustable doubly curved, solid surface aluminum panels. The panels must withstand either a 20 lb/ft^2 uniform load or a concentrated "shoe" load of 250 lbs over designated step areas without suffering permanent deformation.

A circular area of approximately 3 m (11 ft.) in diameter in the center of the reflector will not be covered with reflector panels.

Panel gap: Spacing between panels shall be 2 mm (0.080 inches) + .75 mm (0.030 inches).

Axis Alignment: Azimuth axis tilt to plane perpendicular to gravity: maximum error of 15 arcseconds.

Total azimuth axis runout: 10 arcseconds maximum error.

Azimuth axis nonrepeatability: 4 arcseconds maximum.

Orthogonality elevation to azimuth: 15 arcseconds maximum error.

Offset of elevation axis from azimuth axis to a maximum tolerance of 0.25 cm (0.1 inches).

Orthogonality of collimation axis to elevation axis: 15 arcseconds maximum error.

Subreflector axis to collimation axis: the structure of the apex of the feed legs must locate the center of the opening coincident within 0.25 cm (0.1 inches) and the axis of the opening parallel within 30 arcseconds of the collimation axis of the reflector.

Counterbalancing: Shall be sufficient, at 0 deg elevation, to overbalance the antenna in the direction of the zenith by a minimum of 15,000 lb. ft. of net torque, with all instrumentation and the subreflector in place, but no wind, snow or ice loading.

Drive Requirement: Azimuth and elevation drives shall have a capability of driving the antenna at a velocity of 90 deg/minute in azimuth and 30 deg/minute in elevation, with the reflector in any attitude under the specified operating conditions. Azimuth and elevation drives shall drive the antenna at sidereal tracking rates with an accuracy as specified in paragraph 03.2.2.3. and 03.2.2.4. below.

Under the conditions described as Precision (Primary) and Normal (Secondary) operating conditions below, acceleration to full speed shall be accomplished in less than 2 seconds.

03.1.2.2.2 General Operating Parameters and Conditions

The antenna will be exposed to the elements at various sites and under various climatic conditions, with one site perhaps as high as 14,000 ft. above sea level, and the remaining sites no higher than 7,000 ft. above mean sea level. The antennas are to be designed for a life expectancy of 20 years. No damage to the operating components of the antennas must occur due to airborne sand or dust or accumlation of frozen or liquid water.

03.1.2.2.3 Precision (Primary) Operating Conditions

The antenna shall meet the required precision pointing and surface accuracies under the following conditions:

Temperature range: -18 deg C (0 deg F) to +32 deg C (90 deg F).

Rate of change of ambient air temperature is no greater than 2 deg C/hour.

No parts of the telescope structure differ in temperature more than 3.5 deg C (6.3 deg F).

The wind at 12 m above the foundation is no greater than 6 m/sec (13.4 mph), with gusts of +1 m/sec (2.2 mph) super imposed. Wind from any direction with the reflector in any attitude.

No snow or ice load.

3.1.2.2.4 Normal (Secondary) Operating Conditions

The antennas must continue to operate under "normal" operating conditions but it is understood that the pointing, tracking and surface accuracies set forth under precision operation may not be achieved.

Normal operation must be possible under the following conditions:

Ambient air temperature: -30 deg C (-22 deg F) to +40 deg C (104 deg F).

Relative humidity: 0 to 99%

Rain rate: up to 5 cm/hour (2 in/hour)

Ice and snow load: None

Wind velocity measured at 12 m above the foundation) up to 18 m/sec (40 mph), with gusts of +2.5 m/sec (5.6 mph) superimposed. Wind may be from any direction; reflector in any position. A special condition is to be provided which will allow the antenna to operate in winds to 25 m/sec (56 mph), but for which the acceleration time to full speed may be 4 seconds and maximum speed may be allowed to fall to 60 deg/min in azimuth for the worst case of wind direction and antenna attitude.

Requirements to be met in moving to stow and in the stowed position:

Slew to stow: The antenna shall be capable of being slewed to the stow position in elevation in winds of 27 m/sec (60 mph) with all exposed surfaces of the structure coated with 1 cm (0.4 inch) radial thickness of ice. The slew rate may then fall to 10 deg/minute.

Slew to dump snow: The antenna shall be capable of dumping snow by slewing at 30 deg/min to any position 5 deg above the horizon, with a wind of 11 m/sec (25 mph) from any direction and with an original snow load in the reflector of 4 lb/ft^2. No damage or overload shalla occur to either structure, drives or brakes.

Survival: The antenna is to be designed to survive in the zenith position in winds of 50 m/sec (110 mph) with 1 cm (0.4 inch) of radial ice on all exposed surfaces. The antenna shall also be designed to survive in the zenith position with a surface load of 20 lb/ft^2 of snow. When loaded under these conditions, design stresses of materials shall not be exceeded and no permanent deformation shall occur. For survival wind loads (110 mph), combined with one cm of radial ice on all exposed surfaces, NRAO will allow the design stress increase set forth in the AISC specifications to be applied. Stow brakes shall be provided capable of holding the antenna in the zenith position when subjected to the design survival loading.

03.1.3 The Antenna Performance

03.1.3.1 Surface Accuracy

With the installation of the selected 0.125 mm (0.005 inch) RMS panels, the installed RSS surface accuracy shall not exceed the total RSS surface accuracy as specified in the error budget below under the precision operating conditions specified in 03.2.2.3. It is further required that, under precision operating conditions, the distortions of the antenna structure caused by wind, gravity and temperature effects be consistent with satisfactory antenna performance at 86 GHz as set forth in Sections 03.2.1, 03.2.2 and 03.5.2.2.(Part C of the following surface accuracy error budget will ensure compliance with this requirement).

Surface Errors, Precision Operating Conditions
(All table entries are RMS values).

A.	Surface Panels:		
	Manufacturing	0.125 mm	(0.005 inch)
	Gravity	0.075 mm	(0.003 inch)
	Temperature	0.050 mm	(0.002 inch)
	Wind	0.040 mm	(0.0016 inch)
	Subtotal RSS	0.160 mm	(0.0063 inch)
B.	Measuring and Setting: 1)		
	Subtotal RSS	0.125 mm	(0.005 inch)
C.	Reflector Structure:		
	Gravity 2)	0.140 mm	(0.0055 inch)
	Temperature 3)	0.125 mm	(0.005 inch)
	Wind	0.055 mm	(0.0022 inch)
	Subtotal RSS	0.196 mm	(0.0077 inch
	Total Surface RSS	0.282 mm	(0.0111 inch)

Notes:

1) The setting and measurement errors of the assembled surface shall contribute no more to the error budget of the reflector than the panel manufacturing error (0.125 mm (0.005 inch)).

2) At any elevation angle over the range 0 to 90 deg with the surface set at 50 deg. elevation.

3) For temperature differences of 3.5 deg. C within the reflector structure.

The panel-setting RSS of the antenna surface may be calculated relative to a reference design surface that may be allowed to translate along the collimation axis and rotate about an axis parallel to the elevation axis as elevation angle changes. However, at no elevation angle shall such surface deviate from its "set" position at the surface setting elevation angle of 50 deg by more than 1.5 mm (0.06 in.) peak.

The term RSS where used in this document shall mean the "Root Sum Square" of the various error contributions from different types of contributor sources of error. Where the term RMS is used with respect to the manufacturing accuracy of the surface panels it shall mean the "Root Mean Square" of the departures from the design surface. The RMS value of measurements depends to some extent on the formulae used and shall be as defined in the proposal. In measuring the manufacturing accuracy of each panel a grid of points shall be chosen such that each measured point represents approximately 650 cm^2 (100 inch^2) of surface area.

03.1.3.2 Pointing and Tracking Errors

The pointing error is defined as the difference between the commanded position of the antenna and the position of the main beam of the reflector. Tracking error is a part of the pointing error and includes the effects of the servo update rate and axis velocity as determined by axis position. The repeatable pointing error is due to gravity deformation, axis alignment error, inductosyn offset, bearing runout, bearing alignment, and similar errors. The nonrepeatable pointing error is due to wind forces and gusts, acceleration forces, effects of temperature differences and temperature changes, inductosyn resolution, inductosyn error, data converter errors, servo and drive errors, position update rate, bearing nonrepeatability and random errors. The repeatable pointing error for this antenna shall not exceed 3 arcminutes. Of this pointing error budget the gravity deformation of the main reflector and feed legs shall not contribute more than 1 arcminute. In addition the translation of the vertex of the secondary reflector from the best fit collimation axis shall not exceed 2.5 mm (0.1 inch) nor shall the rotation of the apex exceed 4 arcminutes in the plane of the elevation motion, or 1 arcminute rotation about the collimation axis.

The non-repeatable pointing errors are of two types with different statistical behavior: (1) Random pointing errors with a time constant less than one minute and (2) random pointing errors with time constants longer than about one minute and up to several hours.

The first type, which averages out in observations lasting several minutes or more, shall not exceed 8 arcseconds RSS with the antenna in any position and operating at specified tracking rates. In some cases, such as pointing errors caused by wind on the reflector alidade and tower, only the peak error or "worst case" can be identified. In such cases, one half of the "worst case" error values should be used in the RSS error calculations.

The second type, which usually is caused by thermal effects, shall not exceed a peak of 14 arcseconds. Passive measures, such as antenna paint, sun shields and/or thermal insulation, aimed at reducing the temperature effects on the antenna structure, should be investigated during the design. The antenna design shall assure that temperature differentials which place the antenna outside the precision operating condition do not occur more than 5% of the time.

03.1.3.3 Slewing Motion

Slewing motion is defined as the rapid movement of the antenna about either axis simultaneously or independently. The antenna shall be capable of driving at the rate of 30 deg/min of time about the elevation axis and 90 deg/min about the azimuth axis in winds to 18 m/sec (40 mph) with the reflector in any attitude. It shall be possible to slew either axis independently while the other axis is stationary or moving at the tracking rate, or to slew both axes simultaneously. The antenna shall be capable of accelerations of 0.25 deg/sec^2 about the elevation axis and 0.75 deg/sec^2 about the azimuth axis except for the special conditions set forth in 03.2.2.4 above.

03.1.3.4 Tracking Motion

The antenna shall be capable of tracking a stellar source at the azimuth and elevation rates which correspond to the sidereal rate for the source position and maintaining the pointing accuracy as set forth in 03.2.2 above under precision operating conditions with a command update rate of 20 times/sec. The cone of avoidance near the zenith when in the tracking mode shall have a half-angle less than 2.5 deg.

03.1.4 General Requirments

03.1.4.1 Feed Legs and Apex

The feed leg supports shall be designed to support simultaneously and asymmetric subreflector of 3.2 m (10.5 ft) diameter and adjusting mechanism, weighing approximately 1300 lbs, and a prime focus feed of approximately 300 lbs. The feed legs shall also be designed to support a cable weight of 4 lb/ft on each leg. The apex structure shall be designed so that a clearance as shown on Drawing D52502T001 Sheet 1 exists between the bottom of the apex structure and the focal point of the main reflector. Its configuration shall be such that a clear opening of approximately 1.8 m (6 ft) diameter exists on the center line of symmetry for the location and attachment of the adjustment mechanism. The feed legs and apex, including a 3.2 m (10.5 ft) asymmetric subreflector, shall not cause RF blockage in excess of 6.5% of the total 25 meter aperture area.

03.1.4.2 Vertex Equipment Room and Feed Mounts

An approximately circular room with a minimum of 18.6 m^2 (200 ft^2) area, having a height of 2.3 m (7.5 ft) for mounting of feeds and equipment, shall be provided. The floor of this room shall be parallel to the ground with the antenna pointed at zenith and shall be a minimum of 8 ft. below the vertex of the antenna. This room shall be provided with the following features:

Mounting provisions for up to seven 0.6 m x 0.6 m x 2.1m (2 ft. x 2 ft. x 7 ft.) ceiling mounted racks, with a total weight of 2000 lbs.

An access door for access by personnel and for means of installing racks by use of a permanent hoist.

Thermal insulation, air conditioning, and duct heating to provide 18 + deg C control of temperature measured at a central point in the vertex room with all equipment racks (see this Section, above) in place, an equipment heat input of up to 2 kW, and under "normal" operating conditions as describedin 03.2.2.4. This control shall be accomplished with a temperature change no greater than 3 deg. C between supply and return air. A proportional control modulated heating and cooling system is recommended. No specific modulated heating and cooling system is recommended. No specific humidity conditions are required.

The roof of the vertex equipment room shall contain a mounting ring for the mounting of a removable feed cone. Dimensions of this ring shall be determined in the design stage, but is anticipated that it will be approximately 3 m (10 ft) in diameter.

The weight of removable feed cone and the feed horns supported therein is estimated at 4400 points, with the center of gravity located approximately 33 inches above the interface of the feed cone with the projection of the vertex room.

The vertex room shall be electrically shielded in order to prevent the leakage of radio frequence interference out of the room. The room will be constructed to have an outside metal wall that is electrically continuous. All incoming power lines will be filtered and RFI gaskets will be provided around the vertex room door and around the interface between the vertex room and the feed cone. Manufacturer's data for any filters and gasket materials used must demonstrate at least 60 dB suppression or shielding over the frequence range 1 MHz to 44 GHz.

03.1.5 Statement of the Design Work

The objective of the design work shall be a design of an antenna which will meet the Design and Performance Parameters as set forth above. The design shall be for a wheel and track type antenna which will be used as primarily a Cassegrain antenna but which at lower frequencies will be used at prime focus. The antenna structure will be a fully steerable elevation over azimuth configuration supporting a 25 meter (approximately 82 feet) diameter reflector. It is anticipated that the main structure will be of steel with surface panels of aluminum.

The areas of design for which the antenna subcontractor will be responsible include the following:

Antenna Strucuture

- Reflector Assembly
  - Primary reflector surface
  - Reflector back-up structure
  - Feed leg structure
  - Apex structure
  - Vertex equipment cabin
  - Elevation wheel
  - Reflector counterweight system
- Azimuth Structure
  - Tower structure
  - Elevation bearing & supports

Elevation drive system (including motors, gears, operating and stow brakes, gear reducers and servo system).

Elevation and azimuth data system

Azimuth drive system (including motors, gears, operating and stow brakes and gear reducers and servo system)

Azimuth Base structure (including alignment features)

Azimuth rail and attachment

Equipment room at base of tower

Pintle bearing and support

Cable loop system

Foundation (Reinforced Concrete - Typical type)

Interfaces

Foundation interface

Power cable interface

Secondary reflector mechanism interface

Servo/AUI control and data system interface

Maintenance and Repair Features

Procurement, Assembly and Alignment Plans

03.1.5.1 Design Analysis

A three-dimensional analysis of the reflector, back-up structure, pedestal and tower shall be conducted under varying conditions of pointing directions, wind force, and thermal gradients. A computer analysis shall be conducted using standard accepted programs to determine structural deflections, coordinates of the best fit paraboloid and the RMS deviation of the surface from this paraboloid. The computer analysis shall also determine the repeatable and nonrepeatable pointing errors contributed by the various elements of the antenna for use in assuring that the error budget has been met. Results of these analysis shall be submitted to AUI along with the design drawings of the antenna structure as they are submitted for approval. Analysis of the dynamics of the antenna shall be conducted to determine the significant frequencies and the transfer functions applicable to the drive system and wind disturbance characteristics of the servo system. The total error analysis shall be made considering all factors which degrade the surface accuracy and the pointing and tracking capabilities of the antenna system. This analysis shall include: consideration of the error contributions of the antenna structure as developed in the structural analysis (under wind, thermal and gravity loads); the pointing and tracking error of the servo and drive system under required rates and wind conditions; antenna structural and mechanical alignment; the position indicating and data readout system errors and other system components contributing to pointing errors.

03.1.5.2 Design Requirements

The antenna shall perform as required in Section 03.3. under any combination of operational and environmental conditions as specified herein.

03.1.5.2.1 Mechanical Motion

Elevation 0 deg to +125 deg
Azimuth + 270 deg

03.1.5.2.2 Operational Wavelength

In the NRAO design calculations for this antenna it will be noted that the gravity performance of the reflector backup structure, the stiffness of the tower, the resolution and accuracy of the position indicating system and the accuracy of the servo system are consistent with requirements for observing at 0.35 cm wavelength (86 GHz). It is AUI's goal to be able to achieve efficient 86 GHz operation at some later date by performing such improvements as installing more accurate panels, improved panel setting and azimuth track adjustment.

The subcontractor's final design shall maintain this objective.

03.1.6 Structural and Mechanical Features

03.1.6.1 Reflector Assembly

Surface - The reflecting surface shall be a surface of revolution comprised of approximately 200 individually adjustable, doubly curved, solid surface aluminum panels. The reflecting surface of the antenna shall be a shaped surface which approximates a paraboloid, but deviates to a minor extent in order to secure a higher gain. The exact shape of this surface will be specified to the Subcontractor during the design phase, but it is anticipated that the peak deviation from a parabola will not exceed 3 cm (1.2 inch). The spacing between panels shall be nominally 2.0 mm (0.08 inch) with a tolerance of +0.75 mm (+0.03 inch). Flush panel surfaces are preferred. Projecting rivets, are acceptable provided the sum of the areas of all rivet heads on each panel surface is less than one-half of one percent of the panel surface area. An error budget shall be prepared during the design stage showing distribution and projected levels of each error contribution.

Panels shall be designed to withstand either a 20 lb/ft^2 uniform load or a concentrated load of 250 lb over a 6 inch square area located at specified step areas without exceeding the allowable design stresses for the material.

Reflector Back-up Structure - The reflector back-up structure shall provide the rigidity required to achieve the specified reflector tolerance and shall be designed so as to achieve the highest practical stiffness to weight ratio.

The reflector back-up structure shall be designed to support at the vertex of the reflector a removable feed cone assembly of approximately 3 m (10 ft) diameter (furnished by AUI, shown on Dwg. D52502T001 Sheet 1) and a fixed equipment room (Paragraph 03.4.2). It shall attach rigidly to the reflector support structure and shall support the feed cone assembly. Access shall be provided from inside the vertex room up into the feed cone assembly. Access shall be provided from the back of the reflector to the equipment room.

Panel Supports - Each surface panel shall be supported on four points by means which allow adjustment to the required surface accuracy. The panel supports shall be designed to allow a 250 lb man to walk on the panel without causing permanent deformation.

Feed Systems Design - The antenna feed system and Cassegrain reflector are not a part of this specification. The parameters and interface information for the antenna feed and Cassegrain subreflector will be specified to the succcessful antenna Subcontractor during the design phase.

03.1.6.2 Azimuth Structure

Structure - The azimuth structure shall be designed to provide the stiffness and strength required to meet the operating and survival requirements and to provide the range of motion specified. Components of the azimuth structure shall be designed to facilitate field assembly to the required tolerances. Field assembly shall be by use of high strength bolting (the preferred method) or by welding. Flanged connections for tubular members

The VLBA Options List

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The VLBA Options List was originally intended to facilitate selection among numerous possible cost-saving or performance-enhancing variations on Array specifications. As the VLBA project has developed from design to construction, most original options have either been incorporated into the Array, or rejected (implicitly or explicitly) and omitted from further planning. The Options List has thus evolved into a "wish list" of desirable upgrades to the basic VLBA currently foreseen in the construction plan.

In general, the nominal specifications from which the options depart are those presented in the current chapters of the "VLBA Project Book". I have attempted to include all options seriously considered at at the date of compilation, although this necessarily involves an exercise of judgement. Not included in the List are choices of a strictly technical nature which have a negligible impact on *both* cost and performance.

The options are grouped into major areas generally paralleling the group structure of the VLBA project with some exceptions to allow a more unified presentation. Each option is given a mnemonic name, briefly described, and its effect on Array performance outlined. The cost is estimated as precisely as possible, generally for the entire 10-station VLBA unless indicated as cost per station. Development costs are mentioned (but not estimated) *only* for those options where they may be substantial.

ANTENNAS

$\Longrightarrow$ 86-GHz Operation (see also 86-GHz Receiver)

Description: Improve pointing performance by grinding azimuth track and/or implementing circulating-coolant system.

Effect: Satisfactory pointing for 86-GHz operation.

Cost: To be determined from operating experience; probably less than 120 k$.

Receivers & Feeds

6.1-GHz Receivers

Description: Add 6.1-GHz receivers (sharing 4.8-GHz feeds) at some stations.
Effect: Observations of 6.035-GHz OH line possible.
Cost: 19 k$ *per station*, plus development cost.

10.7-GHz Receivers

Description: Add 10.7-GHz receivers *and feeds* at some stations. (One such system already installed at Pie Town site.)
Effect: Additional X-band capability beyond planned 8.4 GHz (for continuity of ongoing observing programs, and compatibility with global array).
Cost: 20 k$ *per station.*

12.2-GHz Receivers (Uncooled)

Description: Add uncooled 12.2-GHz receivers *and feeds* at some stations. (Would have to replace 10.7-GHz.)
Effect: Observations of 12.2-GHz methanol maser line possible.
Cost: 13 k$ *per station*, plus development cost.

12.2-GHz Receivers (Cooled)

Description: Add cooled 12.2-GHz receivers *and feeds* at some stations. (Would have to replace 10.7-GHz.)
Effect: High-sensitivity observations of 12.2-GHz methanol line.
Cost: 20 k$ *per station*, plus development cost.

⟹ 86-GHz Receivers (see also 86-GHz Operation)

Description: Add 86-GHz receivers *and feeds* at some stations.
Effect: Observations at 86 GHz possible.
Cost: 50 k$ *per station*, plus development cost.

Additional Dual-Frequency Pair(s)

Description: Implement additional dichroic reflector systems for, *e.g.*, 4.8/23, 10.7/43, or 15/43-GHz pairs.
Effect: Improved atmospheric/ionospheric calibration, and extended coherence times at high frequencies.
Cost: ~80 k$ *per pair.*

Remote Dual-Frequency Operation

Description: Equip dichroic reflectors for remotely commanded operation.
Effect: Improved sensitivity for single-band observations, and unimpeded observation using neighboring feeds.
Cost: ~100 k$ *per pair* equipment cost, plus development cost.

Auxiliary Station Electronics

Fewer Water-Vapor Radiometers

Description: Delete 22/31-GHz radiometers for measuring atmospheric water vapor content at some stations.

Effect: Restricted calibration of atmospheric phase fluctuations for astrometric/ geodetic observations, and mapping at high frequencies.

Saving: 100–200 k$ *per station.*

Dual-Frequency GPS Systems

Description: Replace standard satellite timing receivers with advanced, dual-frequency systems at some stations.

Effect: Enhanced calibration of ionospheric propagation effects.

Cost: 40 k$ *additional, per station.*

Baseband Electronics, Record & Playback Systems

⟹ 32 Channels

Description: Double station complement of baseband converters (to 16) and sampler modules (to 4).

Effect: More channels (32) and tunable LO's (16) available for specialized observations; bandwidth per channel limited by standard peak recordable data rate (512 Mbit/s — 4 times sustainable rate).

Cost: 570 k$.

128 Tracks

Description: Double station complement of formatter data-path modules (to 4) and recorder headstacks (to 4 — 2 per recorder).

Effect: Higher peak recordable data rate (1024 Mb/s — 8 times sustainable rate) for high-sensitivity, short-coherence-time observations; matches capacity of standard baseband converter complement.

Cost: 320 k$.

Extended Array

These options represent extensions of the 10-station VLBA project to VLBA project to cover more uniformly the range of baselines available on the surface of the Earth and approach a "matched u-v filter" appropriate to any angular scale. The extensions provide facilities to integrate the VLA and VLBA apertures into a fully-capable joint instrument, and to broaden the aperture coverage more generally using additional stations.

Additional Acq./Rec. System(s)

Description: Provide complete or partial acquisition/recording systems for fixed sites (*e.g.*, the VLA, Green Bank, ...) or as portable units.

Effect: Enhancement of the Array (in particular to include elements with large collecting areas or high-frequency performance).

Cost: 230 k$ *per station* for *single* DAR/REC system, including control computer.

Pie Town VLA Station

Description: Implement wideband digital data link from Pie Town site to the VLA; provide VLA electronics at Pie Town, and upgrade VLA correlator delay *etc.*

Effect: Pie Town usable as VLA "outrigger".

Cost: ~1 M$.

Additional Southwest VLBA Stations

Description: Build additional fully-equipped stations at three or four sites close to the VLA: Dusty, Bernardo, and Roswell, NM; or Dusty, Bernardo, Vaughn, NM, and Holbrook, AZ.

Effect: VLBA aperture extended inwards from 200 km towards 35 km outer envelope of VLA aperture.

Cost: ~5.6 M$ *per station.*

South American VLBA Station

Description: Build an additional fully-equipped station in northern South America, probably in Ecuador.

Effect: Improved north-south aperture at equatorial and southern declinations.

Cost: ~7 M$.

shall be gasketed to provide a water-tight seal. Flanges shall have a center hole at least four (4) inches in diameter to provide for fluid flow. Adjustment provisions shall be provided for alignment of bearings, gear racks, gear reducers, azimuth drives and azimuth wheel assemblies. The antennas shall so designed and assembled that the azimuth and elevation axis are orthogonal within the tolerances specified in Section 03.2.2.1. The axis of symmetry of the reflectiing surface shall intersect the elevation axis within a tolerance of 0.25 cm (0.1 inch) and shall be orthogonal to the elevation axis within the tolerance specified in Section 03.2.2.1. The azimuth structure shall be a space frame with an equipment room located near the base. The base shall be rectangular in shape and shall interface with the azimuth rail and foundation at 4 points (the corners of the base rectangle). These 4 points consist of the wheel assembly, 2 of which shall be driven. An additional foundation interface shall exist at the center of the azimuth where the antenna is supported on the pintle bearing.

A joint use equipment room shall be located on the base of the azimuth structure, shall provide approximately 16.7 m^2 (180 ft^2) of area with a height of 2.4 m (8 ft), and shall be temperature controlled at 18.3 deg C +5 deg. C (65 deg F +9 deg F) with a 5 kW interior heat input. A door and access provisions shall be included. This room shall provide adequate space for drive controls and cabinets, electrical circuit breaker cabinet, and a cabinet or rack for the antenna control unit and data converter.

Drive Equipment - Electrical drives using DC servo motors are the preferred drive system for each axis. The drive systems shall be supplied in pairs and torque biasing shall be provided so that paired gear trains oppose each other during operational function so as to minimize backlash. Motors selected shall have a base speed not to exceed 2500 rpm. The drive motors shall be able to withstand the following current load conditions:

100% rated	continuous
150% rated	2 minutes out of every 20 minutes
200% rated	instantaneous, 0.5 seconds, repeated once every minute

Consideration shall be given to the use of identical drive motors on both elevation and azimuth axes. The NRAO analyses indicate that dual 15 hp DC drive motors are required for the azimuth axis and that while these are somewhat oversized for the elevation axis, commonality will simplify spare parts stocking.

The reducer ratio from motor to antenna axis shall be sized to deliver the torque required and to meet the speed requirement.

The azimuth drive configuration shall be such that the motor-reducer assembly does not carry antenna weight and may be decoupled and removed without removing the associated wheel from the alidade.

The NRAO analysis indicates that a common gear reducer can be used on both elevation and azimuth axes. The NRAO analysis used Philadelphia Gear Co. 10 HP 4 reducers similar to existing gear boxes on the VLA antenna elevation axis but with the reduction ratio changed from 541 to 1 to 400 to 1.

Brakes - Brakes that actuate with the power off shall be provided on each axis. Brakes on each axis shall have the capacity of three times rated motor torque. Brakes must have the capacity to hold the antenna in any position in winds to 27 m/s (60 mph) and to hold the antenna in the stow position in winds to 50 m/s(110 mph). Brakes may be provided in either of two configurations:

1. Operating brakes mounted on the motors and braking through the gear train plus stow brakes which act on the main section gear; or

2. Brakes which serve both as operating and stow brakes which operate through the gear train.

Remotely controlled stow locking devices, such as stow pins, shall not be used as an operating feature.

A manually operated stow pin shall be provided for the elevation axis for use in maintenance, and stow clamping devices shall be provided to lock the alidade in position when required.

Bearing and Gears - All main axis bearings and power train gearing shall be conservatively designed with a minimum 20 year expected life period. Running friction and breakaway friction for the drive system shall be held to levels which satisfy the non-repeatable pointing error budget.

Cable Wraps - Access shall be provided at the azimuth axis in the form of a cable wrap which will accommodate a minimum of 20 cables of 3.8 cm (1.5 inch) in diameter with connectors of 7.5 cm (3 inch) outside diameter. Arrangement shall be such that cables are neither stressed by twisting or damaged by pulling over edges of fixed structure. Cables may pass the elevation axis by means of a cable loop.

Lubrication - Provisionshall be made in the design for proper lubrication of all components. Gear boxes, gear trains, couplings, bearings, motors and similar equipment provided by the Subcontractor shall have easily accessible lubrication fittings, drain fittings and be provided with vents where advisable. The design Subcontractor shall prepare a list of recommended lubricants and lubrication schedule. Lubricants shall be adequate to meet he performance and environmental requirements specified herein. The use of different types of lubricants shall be held to a minimum. Equipment shall not require lubrication more frequently than once every six months.

Lighting and Grounding - Adequate outside lighting shall be provided and installed on the structure for operation, safety and maintenance. All lighting shall be incandescent type.

The antenna requires safety and equipment grounds. A station ground will be provided by NRAO for the antenna structure. The Subcontractor shall ground the antenna structure, and its equipment, in accordance with National Electrical Code Specifications to this station ground. All elevation and azimuth bearings shall have a by-pass grounding connection as shall the wheel bearings at the azimuth wheel assemblies.

03.1.6.3 Additional Requirements

All operating components of the antennas, such as motors, bearings, drive units, brakes, gear boxes, switches, breakers, etc., shall to the extent possible be of standard design, and of proven operating life.

Access stairways, ladders, walkways and platforms shall be provided to afford access for service and maintenance to bearings, motors and drives, all equipment and equipment rooms. The access features shall be designed according to best antenna practice, shall meet the requirements of the Occupational Safety and Health Act and shall have sufficient strength to support at least a concentrated load of 400 lbs at any point. No ladders shall be used for access to the vertex equipment room.

An electric hoist of 1/2-ton capacity shall be provided to permit lifting of equipment to the platform adjacent to the access door of the vertex room when the antenna is in zenith position.

Safety devices shall be provided for protection of the antenna in the event of servo or mechanical failure. An auxiliary control shall be provided foruse of maintenance personnel who may be servicing the antenna. This shall provide at least rate loop driving of the antenna in both azimuth and elevation from a control such as a potentiometer located at the antenna. This auxiliary control shall also provide control of the brake mechanism.

Limit switches shall be provided for each axis of the antenna. Limit switches, cables, connectors used on telescope drives, brakes, motors, gear boxes, interlocks, etc., are to be weather-tight.

All machinery shall be covered or protected in such a way that working personnel are not subject to hazards.

Smoke detectors are required in both the base room and vertex room and shall be interlocked to remove all electrical power from the antenna. Either smoke detector shall energize a local alarm and have a contact or solid state switching for use by AUI. Emergency power for the smoke detectors and local alarm shall utilize "Gel-cells" with a reserve of 6 hours minimum.

Lightning rods shall be provided at the apex and the top edge of the main reflector.

Cable trays, for use by the Subcontractor and AUI shall be provided in the base room, from the base room to the vertex room and elevation cable loop, and to the apex.

03.1.7 Foundations

The Subcontractor shall provide the design of a typical foundation based upon subsurface information furnished by AUI during the design stage. Final design and detailing of all foundations and construction of these foundations will not be the responsibility of the Antenna Subcontractor but the Subcontractor must assure that the design of the typical foundation provides the stiffness and the pointing accuracy required by the error budget for the antenna. The Antenna Subcontractor shall be responsible for designing and specifying all azimuth rail attachment hardware, rail adjustment features and rail connection details and shall furnish all azimuth rail hardware except anchor bolts imbedded in the foundation concrete. The Antenna Subcontractor shall be responsible for designing and specifying all azimuth rail attachment hardware, rail adjustment features and rail connection details and shall furnish all azimuth rail hardware except anchor bolts imbedded in the foundation concrete. The Antenna Subcontractor shall be responsible for installing the azimuth rail and hardware and adjusting the rail surface to the accuracy required by the error budget.

03.1.8 Servo and Controls

03.1.8.1 Servo System

The servo system shall provide the necessary control for drives as well as monitor the angular position of the antenna in both aximuth and elevation. The major subsystems of the servo system are (1) the drive units, (2) the control units, and (3) the position indicator system. The Antenna Subcontractor will be responsible for the design, furnishing, fabricating and installation of these systems. The servo control units The servo control units interface with the drive units ofthe drive motors, brakes, clutches, limit switches and of the electrical circuit breaker cabinet. Cabling from these facilities to the servo control units shall be supplied and installed by the Antenna Subcontractor. The interface connection between the servo control units and the position indicator system shall be furnished by the Antenna Subcontractor.

03.1.8.1.1 Areas of Design

The areas of design for which the Subcontractor will be responsible include the following:

Azimuth and Elevation Drive System
Power Amplifiers
Current Loop
Velocity Loop
Position Loop
Interlocks
Monitoring

Azimuth and Elevation Control System
Mode Switching
Monitoring
Servo Loops
Auto Stowing
Local Control
Local Readouts
Interface with the AUI Monitor and Control System

03.1.8.1.2 Total Tracking Error

The total tracking error (including the effects of friction, noise, dynamic lag at peak rates, wind gusts) shall be consistent with the following telescope performance while maintaining the stability specified above during performance in the precision operating condition:

Non-repeatable pointing error shall not exceed 8 arcseconds RSS as defined in section 03.3.2. The above accuracies shall be maintained at the azimuth and elevation velocities and accelerations required when tracking a source at the sidereal rate at any position of the source outside of the cone of avoidance. An acceleration rate shall be provided under this tracking mode which allows the antenna to reach the required velocity in less than one second of time. Angular errors refer to space angle errors.

03.1.8.2 Wiring and Cables

The subcontractor shall design, furnish and install all cables required for interconnection and interface with the equipment furnished under this contract including:

Drive Motors
Tachometers
Position System Data Converter
Synchros
Limit Switches
Stow Pin Switches
Other as required

Prime power connection between the motor amplifiers and the circuit breaker shall be wire and conduit.

03.1.8.3 Servo Control System

The Control System shall have the following modes of operation: (1) a non-operating mode in which the antenna brakes are applied and power is removed from the drive system, and (2) operating modes which shall coverall occasions in which brakes are released and power is applied to the drive and control system.

03.1.8.3.1 Non-Operating Modes

Pre-standby Mode
This mode shall be entered at all times when conditions exist such that all motors are inoperable and all brakes are engaged dueto a fault within the system or an "emergency stop" engaged.

Standby Mode
This mode shall be entered when all faults and emergency stops allow the system to be ready for operation by either the local operator or the array operator (computer mode).

Local Mode/Computer Mode

This mode shall be determined by an alternate action switch located on the front panel of the Antenna Control Unit (ACU). A contact closure indicating local mode shall be available on an external connector for use by others.

03.1.8.3.2 Operating Modes

Manual Mode

This mode shall be entered only when the Local/Computer switch is in "Local". It shall allow operation of both axes simultaneously or independently, and the rate of each axis shall be variable from zeroto maximum. In this mode it shall be possible to operate either axis on one motor.

Computer Mode

This mode shall be entered only when the Local/Computer switch is in "Computer". It shall be possible to operate either axis with the other axis in "Standby". Commanded axis position received shall be subtracted from the actual position of the encoders to provide slewing or tracking rates or position of the antenna axis. This mode shall allow operation of either axis with one motor if the wind is less than 30 mph or auto stow is engaged.

Auto Stow Mode

The elevation axis shall automatically be driven to the stow position of 88 deg to 92 deg (adjustable) if any of the following conditions exist:

Loss of updated commands for greater than 10 minutes.
Winds in excess of 55 MPH.
Ambient temperature less than -20 deg F.
Both azimuth drives are inoperable.
One axis drive is inoperable and wind is greater than 30 mph.
If commanded by the computer.
Encoder power supply interlock fault.

This mode shall cause the azimuth axis to revert to "Standby" and the elevation axis shall revert to "Standby" within 10 seconds after reaching the stow position.

03.1.8.3.3 Emergency Stop

An emergency off condition shall completely remove power from the antenna drive control, allow the brakes to set and be initiated by controls on the antenna structure or by command by the control console.

The subcontractor shall supply, wire and install emergency switches that can be padlocked in the emergency stop position. Emergency Stop conditon shall completely remove power from the antenna drive control, allow the brakes to set and be initiated by switches on the antenna structure. These switches are to be located:

Vertex Room
Pedestal Room
Azimuth Rotating Stairway
Elevation Drive Platform
Each Azimuth Drive Motor

03.1.8.3.4 Position Loop

The position loop for each axis shall utilize System Type 2 loop only if the axis position error is less than 1 arcminute and both drives are operational. Other methods of inhibiting limit cycles may be suggested.

03.1.8.4 Control System Monitor

03.1.8.4.1 Local Monitor

The Antenna Control Unit shall monitor the following as a minimum:

Binary encoder position (LEDs)*
Binary commanded position (LEDs)*
Motor status (each) (LED)
Field status (each) (LED)
Motor over Temperature (each) (LED)
Emergency Stop (LED)
Stow Pins (LED)
Limit Switch Status (each) (LED)
Computer Mode Status (LED)
Each Motor Current (Analog)
Axis synchro position readouts
Each Tachometer (Pin Jacks)
Velocity commands, analog (Pin Jacks)
Position error, analog (Pin Jacks)
Circuit Breakers (each) (LED)

* LSB = 0.62 arcseconds and 22 bits includes the synthetic 360 deg (azimuth) bit.

03.1.8.4.2 Computer Monitor

The Antenna Control Unit shall transmit the following data in digital form as shown.

Actual Azimuth Position (22 bits)*
Commanded Azimuth Position (22 bits)
Actual Elevation Position (21 bits)*
Commanded Elevation Position (21 bits)
Motor Fault Status (each)
Emergency Stop
Limit Switch Status (each)
Computer Mode Status
Each Motor Current (Analog lines)
Velocity Command for each axis (Analog lines)
Auto Stow Status (Each type)
Stow Pin Status
Circuit Breaker Status (each)
All Control and Signal Power Supply Voltages (Analog lines)
Other error and fault status required and Spares

* See note above. 360 deg bit to be generated from the Azimuth 2:1 synchro output appropriately combined with the azimuth encoder output.

03.1.8.5 Computer Command System

The Antenna Control Unit must be capable of receiving the commands necessary to execute the proper modes and axis position commands necessary to track at the required tracking and slew rates. A typical list of commands is as follows:

Azimuth and Elevation mode (Computer, Standby, Stow, etc.)
Azimuth Commanded Position (22 bits)
Elevation Commanded Position (21 bits)
Motor Disable (each)
Spare Mode Commands (8 bits)

Other Commands

TTL logic level signals will be supplied by AUI to command:

Wind Auto Stow
Low Temperature Auto Stow
> 30 mph Wind (Single motor operation)
3 Spares

These logic signals shall be connected through opto-isolators in the Antenna Control Unit or by other approved isolation methods.

Signal sense should be zero current to indicate that the condition is true.

03.1.8.6 Computer Command and Monitor Interface

A monitor and control interface card will be supplied by AUI and installed by the Subcontractor. This care supplies to the servo system a 16 bit bidirectional digital bus and 8 lines of analog monitoring capability. The card will be approximately 6 1/2 x 4 inch and will require connection to the servo system 5 V and + 15 V power, and a four wire connection to a connector on the rear of the Antenna Control Unit (ACU).

Since the position commands, echo position commands, and actual positions are longer than 16 bits, they must be transmitted by two bus cycles. In order to ensure the compatibility of the high order and low order positions of the commands, AUI can provide an odd/even indication in each half of the command and comparision of the commanded and actual positions for axis position will be compared only when the bits are identical. Other schemes suggested by the subcontractor may be acceptable if approved by AUI. The exact format and electrical specifications of these signals must be approved by AUI before manufacture. Timing and connector specifications of the AUI supplied board will be provided to the Subcontractor upon request. Azimuth and Elevation commands will normally be provided at a 20 Hz rate. The system must include circuitry to detect missing commands and stow the antenna if no commands are received for longer than 10 minutes.

03.1.8.7 Limit Switch Interface

Limit switches shall have redundancy provided for each antenna limit and shall be arranged such that there are no common components, electrical or mechanical. A failure in the first limit system shall not render the second limit inoperative.

The servo system shall utilize the limit switch signals as follows:

03.1.8.7.1 Each Axis 1st Limit

Inhibit the velocity loop from driving further into the limit but allow opposite direction when the appropriate override is allowed in "Manual", "Computer" or "Auto Stow" mode. The override is to be automatic when in "Computer" or "Auto Stow" mode, and the override shall be automatically cancelled when the axis is out of 1st limit. A velocity signal to drive further into the limit should cause brake release inhibit.

03.1.8.7.2 Each Axis 2nd Limit

Inhibit the current loop from driving further into the limit but allow opposite direction when a local override is utilized in "Manual Mode" only. This override is not to be readily accessible. The 2nd limit switch for each direction of each axis shall be wired in series with one of the axis brakes.

03.1.8.8 Prime Power - Servo

The drive system prime power shall be 120/208 V + 10 %, 3 phase, 4 wire, 60 Hz connected to a 3 phase circuit breaker located in the pedestal room.

The Antenna Control Unit shall be connected to 120 V, 1 phase 60 Hz and have varistor surge protection. The encoder prime power shall be connected to the same source and have varistor surge protection. This prime power shall be connected to a disconnecting device (supplied under this contract) that will allow resetting all servo and encoder power supplies, motor faults and other faults. The disconnecting device will be actuated by an AUI remote 28 V DC signal.

03.1.8.9 D.C. Power Supplies

All ACU and encoder power supplies shall be interlocked to cause the "Computer" mode to revert to Standby in the event of an ACU power supply failure or to go to "Auto Stow" mode in the event of an encoder power supply failure.

03.1.8.10 RFI & EMI

The control circuits, D.C. drive motors amplifiers, and switching devices shall be designed and constructed in accordance with Mil-Std-461A, paragraphs 4.2.1.2., 4.2.1.4., and 4.2.1.5. concerning radiated and conducted electromagnetic energy. In particular, all motor leads, power and control should be filtered. All relay contacts and actuators should be properly bypassed, shielded and/or filtered. All amplifiers and oscillators should be mounted in shielded enclosures that will provide effective shielding of radio frequency energy. Silicon-controlled rectifier switching devices shall not be used unless they are designed so as not to cause radio frequency interference in the frequency range 1 MHz to 86 GHz in receivers mounted on the antenna. No gaseous discharge devices, except noise sources for test, shall be employed. Means shall be employed to reduce static electricity and the consequent R.F. noise generated in any rotating machinery. The motor leads may be shielded instead of filtered, provided the shielding provides suppression at least equal to that achieved with the filters. The frequency range of interest extends from 10 MHz to 44 GHz. No verification measurements by the contractor will be required. All wires and cables within the vertex room shall have RFI suppression.

03.1.8.11 Azimuth and Elevation Position Angles

The azimuth and elevation position angles shall be measured by position indicating devices directly coupled to the axes and shall use coarse and fine resolvers converted to azimuth (including an overlap bit) and elevation binary words by appropriate electronic equipment located in the pedestal equipment room. The position encoding system shall be a system making the measurement directly in binaryform. The system provided shall provide 21 bits using an inductosyn for the fine transducer. The RMS error of the position indicating system, including couplings and electronics, shall not exceed 2 arcseconds.

Position indicating devices shall be accessible for servicing, shall be easily installed, shall be capable of later realigment, shall have provisions for mechanical indexing and shall be environmentally protected.

A separate synchro transmitter with accuracy of 0.5 deg shall be installed on each axis separate from the position angle transducers. These synchros will be used by the subcontractor for a local readout and the "auto-stow" feature. The elevation axis to synchro ratio shall be a 1:1 and the azimuth axis synchro ratio shall be 2:1.

03.1.8.12 Electrical

03.1.8.12.1 Junction Boxes

Junction boxes shall be provided to accommodate all electrical connections to be supplied by the Subcontractor. Separation in junction boxes shall be provided for power and signal wiring; junction boxes shall meet National Electrical Code specification, for NEMA Type IV.

03.1.8.12.2 Power

The Subcontractor shall supply a 50 kVA electric service entrance inside the pedestal equipment room for connection to the outside power source. The Subcontractor shall be responsible for all his antenna electrical wiring from this point. In addition he shall furnish for the later use of AUI, one 100 A 120/208 V, 3 phase, 4 wire disconnect switch or breaker.

The antenna Subcontractor shall supply a two bus system from a junction box (supplied by AUI) in the pintle bearing pit to two circuit breaker panels located in the lower equipment room (base room). One bus is the "critical bus" for servo, encoding system, cryogenic compressors, and a sub-panel in the vertex room. The other bus is the "non-critical bus" for lighting, air conditioning, a sub-panel in the vertex room, electronics and miscellaneous. Size and type of circuit breakers are to be determined later. Fuses shall not be used for equipment protection unless specifically authorized by AUI. Both buses shall have single phase and reverse phase protection interlocked with the smoke detectors specified in 03.6 3.

03.1.9 Materials and Fabrication

03.1.9.1 General

Material shall be in agreement with the general requirements as set down in these specifications. It shall be the responsibility of the Subcontractor to prepare specific material specifications for the various components of the antennas. These specifications may be either on the drawings or in a separate document and shall be subject to AUI review and approval. Fabrication shall be in accordance with the best shop practice and shall be fabricated to proper size and tolerance as shown on the approved drawings. The approval cycle shall normally be 30 days.

03.1.9.2 Materials

The rail base structure, azimuth pedestal and reflector back-up structure is to be of carbon or low alloy steel using the most economical shapes available from both a weight and fabrication cost standpoint. The type of steel selected for the antenna structure shall be such that the low temperature embrittlement characteristics shall be acceptable to AUI. The nil-ductility transition temperature of the selected material shall not exceed -50 deg F. Nil-ductility transition temperature is defined as a temperature below which a specimen will exhibit cleavage fracture with very little or no evidence of notch ductility. It is the intent of these specifications to secure a metal which at the lowest operating temperature will not be brittle enough for flaws or defects in joints or welds to be subject to brittle propogation. A guide to meeting this requirement would be that the Charpy V-notch value of the metal chosen should be a minimum of 15foot-poinds at a temperature of -37.2 deg C (-35 deg F).

All components which are designed for welded connections shall be of a weldable grade material. Bull gears and pinions shall be of a material having a minimum hardness of 255 BHN and may be surface hardened.

03.1.9.3 Manufacture

All structural components shall be manufactured to proper size and tolerance and in the manner shown on the approved drawings. Methods of manufacture shall be of the best shop practice. Mis-manufactured members shall be discarded and not repaired unless prior approval is obtained from AUI. Shop connections may be either welding or bolting (as stated on the design drawings), but components to be field assembled shall be high strength bolted. All holes shall be drilled or sub-punched and reamed according to good practice so that connection clearances may be held to a minimum. Manufacture and assembly of all components will be such that uniform dimensions of the components and sub-assemblies of the antenna may be maintained and maximum commonality of both components and antennas amy be obtained.

03.1.9.4 Protective Coatings and Finishes

The reflector surface of the antenna shall receive a protective coating which will provide diffuse reflection of the solar rays. During the design (Phase I) effort, the Subcontractor may attempt to satisfy the above diffuse reflection requirement through and adaptation of their dry powder coating process. The Subcontractor shall demonstrate to NRAO's satisfaction that any adaptation is as effective as the process set forth in National Radio Astronomy Observatory Process Specification, entitled "Application of Diffuse Reflection Coating for Solid Faced Antenna Reflectors", attached hereto as Appendix D. Otherwise, the methods of Appendix D shall be employed.

To limit the effect of solar heating and associated differential expansion of structural members and to protect the structure against atmospheric corrosion, the antenna structure, with the exception of the reflecting surface, shall be painted with a while solar reflecting paint. Material, preparation, application and quality control testing shall be as set forth in National Radio Astronomy Observatory Process Specification, entitled "Exterior Protective Coating for all Exposed Metallic Surfaces other than Reflector Surfaces", attached hereto as Appendix-E

Appendix E, Section IIA, Surface Preparation, is hereby modified to include sand blasting as an approved method of surface preparation. Sand blasting shall be to the condition of "Commerical Near-White" of the specifications of the Steel Structure Painting Council.

Appendix E, Seciton IIB, Primer, is modified to permit the application of the specified primer by spray painting when the surface is prepared by sand blasting to the "Near-White" condition, and the primer is applied within 48 hours of the completion of sand blasting.

The antenna to be provided for the Puerto Rico location shall have a prime coat differing from that specified in "Exterior Protective Coating for all Exposed Metallic Surfaces other than Reflector Surfaces," Appendix E. This prime coat shall be a zinc-enriched primer "Plasite 1000" as manufactured by Wisconsin Protective Coating Co., or ZRC Compound as manufactured by ZRC Chemical Products Co. applied according to manufacturer´s instructions.

03.1.10 Reserved

03.1.11 Drawings, Specifications and Other Data

03.1.11.1 Design and Manufacturing Drawings

Design and manufacturing drawings shall be completed to the point at which shop and supplier detailing is all that is required for a complete description of the antenna.

Drawings shall be produced on standard size drawing forms whose size and format have been approved by AUI, shall conform to good commercial practice, and shall use symbols, conventions and notations endorsed by manufacturing and standards associations. At the start of the design phase, the Subcontractor shall submit a copy of his drafting standards to AUI forits review and approval.

Two print copies of all design and manufacturing drawings shall be submitted to AUI for its review and approval at the time of completion of the drawings.

One reproducible and five print copies shall be furnished to AUI after approval of drawings.

One reproducible of all drawings generated by the Subcontractor or any subsidiary will be supplied as part of this contract. Lower tier vendors will furnish sufficient drawings so that their equipment can be operated and maintained by NRAO. Specfically, sufficient information will be furnished so that assembly, disassembly, repair, and alignment can be performed to the extent covered by the O & M manuals.

03.1.11.2 Manufacturing and Procurement Specifications

Five copies of all manufacturing and procurement specifications, referenced on any drawing or prepared and procurement of purchase items, are to be submitted for AUI approval.

03.1.11.3 Shop Drawings

Detail drawings of all fabricated components and assemblies and any working drawing or sketches which the Subcontractor, or its subcontractors, may require to detail or illustrate any part of the work, supplementing the information in design or manufacturing drawings and specifications shall be furnished by the Subcontractor at no additional cost to AUI.

Such detail and/or working drawings shall be consistent with the purpose and intent of the design drawings and specifications and shall be subject to the approval of AUI.

Detail drawings and sketches prepared by the Subcontractor and for all purchased manufactured components shall be submitted to AUI for approval. One reproducible and five copies of all such drawings and sketches shall be submitted to AUI not later than four weeks prior to manufacture.

03.1.11.4 Design Calculations and Data

Three copies of all design calculations, design data, studies or other information prepared or utilized by the Subcontractor in the performance of the work shall be delivered to AUI.

One copy of all computer programs* and calculation runs and print-outs shall be furnished AUI for review. Magnetic tapes will be provided on all structural input data.

*(where computer program is not owned by the Subcontractor input and output data will be provided along with identification of the computer program.)

One copy of all purchase orders issued for this contract shall be delivered to AUI immediatelyupon issuance.

03.1.11.5 Assembly and Alignment Plans

The Subcontractor shall, at the completion of detailed design, prepare and submit to AUI for its approval the following items:

(a) An assembly plan which shall specify each step in the assembly, equipment proposed, assembly area, and facilities to be used, and schedule for completion of the work.

(b) An alignment plan which shall demonstrate to AUI the methods to be used to assure that the alignment tolerances specified in the document and specified in the antenna Subcontractor's design effort shall be accomplished. Performance parameters and error budgets set forth in specifications shall be satisfied.

(c) Estimates of manpower requirements for each phase of assembly and alignment.

03.1.11.6 Testing and Acceptance Plans

The Subcontractor shall prepare a test plan acceptable to AUI that will qualify the mechancial, electrical and servo system performance in accordance withthis specification after assembly and alignment are completed. Four copies of the test plan shall be submitted to AUI for its approval prior to commencement of acceptance testing of any antenna. Approval of a test plan shall not preclude AUI from requiring additional testing and shall not be deemed to be a waiver of the requirement to demonstrate the performance of the antenna in accordance with any or all performance specifications.

AUI shall provide for this testing program a digital command input to Subcontractor's equipment connection at the equipment room of the antenna.

During this testing program, the Subcontractor shall demonstrate to AUI that the performance specifications set forth in this specification have been met.

03.1.11.7 Quality Assurance Plan and Inspection Procedures

The Subcontractor shall prepare and submit to AUI for review and approval, prior to the start of procurement and manufacturing, four copies each of a Quality Assurance Plan and Inspection Procedures to be utilized during the course of the work.

Quality assurance tests will be performed on materials, components and assemblies as specified in the Quality Assurance Plan.

AUI will be notified of such tests and may witness such tests.

All quality assurance test results recorded by either the Subcontractor or its subconstractors shall be signed and submitted to AUI in an approved documented form.

AUI may perform such inspections or tests as it considers necessary, on any component, or assembly, during or after fabrication at the site of fabrication or assembly.

Copies of results of test normally performed by suppliers, such as certification of steel, bearings, etc., shall be supplied to AUI, in duplicate.

03.1.11.8 Spare Parts

Within sixty (60) days of approval of detailed design, the Subcontractor shall submit a recommended spare parts list to be based on the number of antennas supplied. Six copies of the list shall be furnished AUI. Each item listed shall be detailed as to identity, part number, drawing reference, manufacturer, model number, etc.

AUI shall have the right by Change Order to its subcontract to order such spare parts as it has selected and/or such parts, whether so selected or not, which were originally manufactured by the Subcontractor. The Subcontractor agrees to negotiate in good faith to arrive at a firm fixed price for such spare parts.

The Subcontractor shall maintain a capability to furnish to AUI the agreed spare parts for a period of ten years from the acceptance of the final antenna.

AUI may purchase such spare parts from any supplier or have such parts manufactured by others as it appears in its best interest so to do without limitation or liability to the Subcontractor and/or its lower tier subcontractor(s).

03.1.11.9 Operation and Maintenance Manuals

The antenna Subcontractor shall deliver at start of assembly of the first antenna four (4) copies of an Operation and Maintenance Manual. This Operation and Maintenance Manual shall contain the following information:

(a) Manufacturer's drawings, exploded view assembly drawings, parts lists and recommended lubrication procedures for all purchased mechancial components. Manufacturer's drawings, parts lists, specifications, wiring diagrams and testing procedures for all purchased electrical or electronic components. A lubrication schedule showing lubrication points, types of lubrication and recommended lubricant, frequency of lubrication.

(b) A maintenance section which describes method of removal of mechanical components, methods and control to be used in reassembly and realignment and components which might reasonably be expected to be replaced because of wear characteristics. Assembly and subassembly drawings which include mechanical setting dimensions such as bearing preloads, gear runouts, gear backlash settings, torque bias settings, drive train alignment requirements and weight of components.

(c) An operations section which describes the function of the various mechanical and electrical components of the antenna. A narrative section shall be provided which describes the various controls and modes of operation which shall include illustrations of the control circuitry.

03.2 Description

Chapter IV-A of VLBA report dated May 1982 contains a discussion of the requirements of reflector size and the relative merit of different sizes possible. The considerations of cost and accuracy presented in that discussion are still relevant and the further development of the antenna element presented in this report has been based on the reflector diameter of 25 meters as proposed in that report. An effort has been made in the continuing design of the antenna element to develop an antenna structure which would allow a later addition of an operating frequency of 86 GHz even though, due to cost considerations, certain of the antenna features cannot be provided which would permit operation at the 86 GHz frequency. A larger reflector diameter than 25 meter size would not allow this feature to be incorporated in the design.

03.2.1.2 Observing Frequencies

The antenna system proposed for this project will operate at the following frequencies:

325 MHz	(92 cm)
611 MHz	(49 cm)
1.4/1.7 GHz	(21.4/17.6 cm)
2.3 GHz	(13.0 cm)
5 GHz	(6 cm)
8.4 GHz	(3.57 cm)
10.7 GHz	(2.8 cm)
15 GHz	(2 cm)
22 GHz	(1.3 cm)
43 GHz	(0.7 cm)

Since the highest observing frequency (43 GHz) determines the required surface manufacturing and installation accuracies and also the allowable gravity deformation of the reflector structure initial target designs were based on this frequency. As stated in previous reports and proposals this frequency requires and RMS surface accuracy of 0.45 mm (/16, and nonrepeatable pointing errors of 8 arcseconds RMS. During the just completed review and development study a further design goal of possible later addition 86 GHz as an operating frequency was presented as a desirable feature which if possible, should be provided for in the antenna structural design.

03.2.1.3 Sky Cover Required

Sites for VLBA element location presently being considered vary from a latitude of 18.3 deg to 48.9 deg and a longitude of 66.7 deg to 156.2 deg. The presently proposed antennas will provide 540 deg (+270 deg) of azimuth rotation; elevation motion will be from 0 deg above horizon to 35 deg beyond the vertical. This amount of azimuth travel will permit continuous tracking from horizon to horizon, will permit rapid calibration by traveling the minimum angular distance in azimuth and will permit in certain cases calibration by plunging the antenna in elevation over zenith.

03.2.1.4 Observational Configuration

Antennas are proposed to operate at prime focus for 325 MHz and 611 MHz and in a Cassegrain configuration for the remaining configurations. The primary reflector will be a shaped surface to increase efficiency.

Two approaches to basic antenna structural configuration were considered from the start of design studies (a) a yoke and alidade antenna similar to the VLA antennas and (b) a wheel and track antenna similar to the numerous existing communications antennas or the proposed 25 meter millimeter wave antenna. As will be discussed in Section 3.3 of the antenna report the most recent cycle of design studies has concentrated on a wheel and track configuration. One feature common to either configuration is the provision of a vertex room of approximately 200 sq. ft. area.

03.2.1.5 Weather Limitations on Operational Availability

The antenna elements of the VLBA will be exposed to a wide range of environmental conditions due to their locations which range from tropical (Puerto Rico and Hawaii) to northern United States (North Central Washington and New England). Disregarding the subject of water vapor in the air and cloud cover which are evaluated in another chapter of this report the weather environment impacts the antenna design and operational availability in the following manner.

03.2.1.5.1 Snow - The antenna specifications provide a strength requirement in the zenith position such that 20 lbs/ft2 of snow (approx. 3 ft.) could be supported without damage to panels of structure. The antenna may be moved to dump snow with a load of 4 lb/ft without overloading panels, structure or drive. No provisions has been made for snow or ice removal by melting as such systems are quite expensive. When conditions are such that snow accumulations occur which are greater than approximately 6 inches but which will not release from the panel surface the antennas affected will be left inoperative in the zenith position. Site selection should be such that these conditions are held to a minimum.

03.2.1.5.2 Ice - Antenna is capable of being driven with coating of 1 cm thickness of ice and winds of 60 MPH (26.8 m/sec) operational efficiency however will be limited to only the lower frequency due to beam displacement. Site selection should consider frequency of ice storm occurrence. Antenna is designed to survive in the stowed position with 1 cm radial ice on all exposed surfaces and with winds of 110 MPH.

03.2.1.5.3 Hail - Hail storms because of their very localized occurrence are difficult to predict. There are however certain areas of the United States which are subject to small, localized very damaging hail storms in the general area. An antenna subjected to one of these hail storms could suffer considerable damage to its reflecting surface. A study of weather records is being made by the configuration and site group to determine if desirable sites from a configuration standpoint are located in the higher risk areas.

03.2.1.5.4 Wind - These antennas will be designed for precision performance in winds to 6 meters/sec (13.4 MPH), for "normal" operation in winds to 18 meters/sec (40 MPH) with reduced precision. Since a desire has been expressed by the scientific and coordinating committees for the possible continuation in service of the antennas at somewhat higher wind speeds a special condition will be provided for which will permit operation in winds to 24 meters/sec (54 MPH) but in which winds we will permit the acceleration rate of the antenna to full speed to be a maximum of 4 secs of time and the maximum speed of the antenna to fall to 60 deg/min in azimuth for the most adverse wind direction and antenna attitude. While these requirments establish the antenna operational parameters they do not establish the operational availability. Site selection will determine the wind environment that antennas will be subjected to and hence the operational availability of the different frequencies. It has been suggested that a requirement that winds not exceed 15 MPH more than 35% of the time, not exceed 25 MPH more than 20% of the time, and not exceed 45 MPH more than 15% of the time would be a reasonable basis for site selection.

03.2.1.5.5 Temperature - Temperature effects on the antenna must be considered from 2 quite different aspects. The most important aspect (and the most difficult to compensate for) affects the surface accuracy and pointing accuracy of the antenna. Because of sun elevation, wind velocity and antenna attitude temperature differences occur across the antenna structure which can cause reflector distortion or deflection of the main beam of the antenna. We have specified that the precision pointing requirement shall be met when temperature differentials are not greater than 3.5 deg C(6.3 deg F) across the structure. Since this statement only sets up the conditIons under which the antenna shall meet the precision pointing requirements we have required that the design assure that temperature differentials do not occur more than 5% of the time which places the antenna outside the precision operating condition. Section 03.1.3.2 of the specifications sets forth the measures to be taken to accomplish this requirement.

The second aspect of temperature effects to be considered involves the impact of either high or low temperatures on the structural strength, mechanical tolerances and clearances, drive and gear box performance, bearing lubrication and performance of electronic controls, data handling and receivers. All of these effects are subject to control provisions in the final design stage. The specifications Section 03.1.2.2.3,set forth the temperature ranges in which the antenna will be in either the precision or secondary operating condition and which establish the design parameters for the antenna. It is not anticipated that any of the seclected sites will be exposed to lower temperatures that the -30 deg C (-22 deg F) for appreciable periods of time such that any appreciable structural or mechanical special measures (other than possible gear box heating for the Central Washington antenna) will be required. The high temperature range +40 deg C (104 deg F) has been set forth to establish a reasonable range for air conditioning and heating design.

03.2.2 Antenna Configuration Studies

03.2.2.1 Standard Yoke and Alidade Antenna

In the preparation of the initial VLBA proposal studies (dated Feb. 1981 and May 1982) the VLA antenna was used as a baseline for design comparisons and for cost estimating purposes since extensive knowledge of both that telescope's performance and costs existed. This antenna is a quite good antenna of its type and as it existed came quite close to meeting the reflector and pointing requirements for the VLBA antennas. To meet requirements of the VLBA it was merely necessary to estimate additional costs for improving certain features of the VLA antenna to the requirements of the VLBA. Basically these consisted of improving the panel manufacturing accuracy, the panel setting accuracy, and the pointing performance of the pedestal and yoke and alidade sections.

03.2.2.1.1 Reflector Performance

For 43 GHz performance and using the standard lambda/16 surface accuracy requirements the required surface RSS accuracy is 0.438 mm or 0.017 inches. This can be broken into an error budget as follows:

	Inches
Reflector distortion due to gravity (90 deg wrt* 50 deg)	- 0.010 RMS
Panel manufacturing accuracy	- 0.008 RMS
Panel setting accuracy	- 0.008 RMS
Wind (13.8 MPH)	- 0.006 RMS
Thermal (Refl.)	- 0.004 RMS
RSS =	0.0167 inches

* with respect to

This budget encompasses the major controlling error items (a few minor items are ignored). A comparison with the error budget actually accomplished for the VLA reflector (design target RSS accuracy of 0.032 inches) would be:

Achieved VLA Error Budget

Reflector distortion due to gravity (90 deg wrt 50 deg)	0.0129 in. RMS
Panel manufacturing accuracy	0.0133 in. RMS
Panel setting accuracy	0.0106 in. RMS
Wind (15 MPH)	0.007 in. RMS
Thermal (Refl.)	0.005 in. RMS
RSS =	0.023 inches

As can be seen from examining the above 2 tables the VLA reflector and panels almost meet the required surface accuracy and with minor improvements in reflector gravity performance and panel setting but with improved panel manufacturing accuracy the reflector performance of a VLA type yoke and alidade antenna could be satisfactory for operation at 43 GHz. In the limited time and with the limited number of personnel available in the recent review cycle further design development of the yoke and alidade reflector has not been done.

03.2.2.1.2 Pointing Error Budget

In arriving at a pointing error budget the required non-repeatable pointing error is not as easily agreed upon. Factors varying between B/10 and B/5 are generally used where B is the half-power beamwidth. At 43 GHz this would require a non-repeatable pointing error of between 7 arcseconds and 14 arcseconds depending on the selected criteria. The difficulty of defining the required non-repeatable pointing error is compounded when we try to define whether this is RMS, RSS or peak error or define how the errors are computed. It has been practice to calculate a pointing error by taking an RMS of each type of contributions and taking an RSS of the various different contributors to arrive at the final pointing error. In place of the RMS (where that would require very extensive calculations as in the case of wind induced pointing errors) we have specified that a peak error be calculated and that one half of that peak value be used in establishing the values to be used in the RSS table. In the case of temperature effects however this procedure of taking an RSS of the RMS of individual contributions gives a distorted picture of the true pointing error as the temperature effects on the reflector, yoke and alidade and pedestal may be directly additive. The specifications (section 3.2.4.2) have been written to provide for control of thermal distortions in a specific sense in that under precision operating conditions non-repeatable pointing errors due to thermal differentials should not exceed 7 arcseconds. All other non-repeatable pointing errors when summed in the RSS pointing error budget should not exceed 8 arcseconds.

With specific reference to the pointing performance of a yoke and alidade type antenna for VLBA and remembering that a complete pointing analysis for an upgraded VLA type antenna has not been performed an error budget for the yoke and alidade antenna under the precision operating conditions would be:

Servo System - RMS	2.50 arcseconds
Data System - RMS	2.12 arcseconds
Reflector - Wind (1/2 Peak)	0.75 arcseconds
Yoke - Wind (1/2 Peak)	5.20 arcseconds
Az. Brg. RMS	0.65 arcseconds
Pedestal - Wind (1/2 Peak)	3.25 arcseconds
Fndn. wind (1/2 Peak)	1.50 arcseconds
RSS	7.18 arcseconds

The thermal pointing error budget for the precision pointing conditions would be:

Reflector - 1/2 Peak	0.60 arcseconds
Yoke - 1/2 Peak	5.1 arcseconds
Pedestal - 1/2 Peak	1.6 arcseconds
Error	7.3 arcseconds

Note that this thermal error is not an RMS or RSS value as in general the thermal errors will occur on each component of the antenna simultaneously and will be directly additive. The above thermal budget also assumes extensive passive thermal control of both the Yoke Section and the Pedestal Section of the antenna.

03.2.2.1.3 Relative Manufacturing and Assembly Costs

The yoke and alidade type of antenna is slightly heavier in weight than a wheel and track antenna of the same general accuracy because of the heavy plate of the yoke and alidade and the heavy members used in fabricating the pedestal. The drives, trucks and rails of the wheel and track antenna are somewhat more expensive than an azimuth bearing and gear but because of the machining required for the azimuth bearing for an accurate antenna the azimuth motion system costs are approximately equal.

03.2.2.2 Wheel and Track Antenna

As stated in 3.2.2.1 previously, because of current familiarity, the "baseline" costs estimates and performance estimates used a "yoke and alidade" type antenna. The recent effort in the antenna area has concentrated on a "wheel and track" type antenna because of superior pointing characteristics and somewhat cheaper costs. Two wheel and track configurations have been considered; the first would use a reflector very similar to the existing VLA reflector while the second would use an advanced design reflector and elevation wheel structure to obtain clearly superior gravity performance which would open the possibility of higher frequency operation. Figures 3.1 through 3.5 show views of this improved performance antenna. The azimuth structure would be the same for either of the two types of wheel and track antennas.

03.2.2.3 Reflector Performance

In general there are two types of elevation structures for a 25 meter telescope:

(A) An integrated reflector/elevation wheel design in which the reflector is an integral part of the elevation support structure. This design is quite compact, weighs less than the second type and is consequently somewhat cheaper. The surface deflections for the compact type however show two stiff quadrants over the elevation bearings and two soft quadrants 90 degrees from the elevation axis which are further distorted by reactions from the drive forces. The surface RMS errors due to change in gravity direction are larger for this type of design than for a design in which the support reaction forces are more evenly distributed to the reflector.

The VLA design is one of the best of the integrated reflector-elevation structure designs in that the heavy star-shaped plate girder in the reflector structure at the elevation bearing and elevation wheel girder radius plus the system of ring trusses does smooth out the gravity distortions of the surface caused by the supports and drive and counterweight reactions. For a wheel and track antenna the VLA type reflector as proposed for the yoke and alidade antenna would quite adequately reach the performance required as shown in Section 3.3.1.1.

(B) The second type of elevation structure is one in which the reflector structure is supported on a number of equally spaced points provided by a transition structure between the reflector structure and the elevation wheel/counterweight structure. The support stiffnesses are thus equalized to give an improved gravity RMS at the surface. The various homology antenna designs are good examples of this type of antenna. One feature of this type of antenna is that the surface is pushed further away from the elevation axis and the elevation weight is consequently heavier.

The proposed advanced design is of this second type. The reflector structure is a conventional radial rib design with circular trusses, and is supported at 20 equally spaced points by the transition structure. The basic geometry of the transition structure is a box-cone structure. The elevation axle and the single elevation gear forming the cone are connected to the base of the box section.

A comparison of this advanced design reflector and the VLA reflector is tabulated as follows:

	Proposed Design	VLA
Surface RMS (Gravity)	(90^o wrt 60^o) 0.123mm(.0048in)	(90^o wrt 50^o)0.33mm(.013in)
	(0^o wrt 60^o) 0.147mm(.0057in)	(90^o wrt 50^o)0.300mm(.0118in)
Elev. Struc. Wt.	324,500 lb.	256,150 lb.

03.2.2.4 Pointing Error Budget

The pointing error budget for the wheel and track antenna will be quite similar to the error budget set forth in Section 3.3.1.2 for the yoke and alidade antenna with a contribution from the rail and wheel non-repeatability replacing the azimuth bearing contribution at the yoke and alidade. It is however in meeting the requirements of the pointing error budget that the wheel and track antenna clearly demonstrates its superiority to the yoke and alidade antenna. Due to its wide base and space frame design up to the elevation bearing level (as opposed to the more narrow base, the small diameter azimuth bearing and the beam action of the yoke arms of the yoke and alidade antenna) the wheel and track antenna is much more resistant to rotation and translation of the elevation bearing platform with respect to the base which is the main source of pointing error due to wind forces.

An extensive analysis of the base structure below the elevation bearings for the wheel and track antennas has not been performed for the VLBA but the same base structure would be used for either type of reflector chosen (with minor configuration changes).

03.2.2.5 Manufacturing and Assembly Costs

Of the two types of wheel and track antennas under consideration the advanced reflector design will be appreciably the heavier. A comparision of approximate weights of the three types of antennas considered would be:

	Yoke % Alidade	Conventional Wh. & Tr.	Adv. Des. Wh. & Tr.
Surface Panels	12,800	12,800	12,800
Feed Legs,Solor.	6,200	6,200	6,200
Reflector	58,700	58,700	50,700
Elev. Wheel	42,300	36,200	132,600
Ctwt.	116,000	116,000	96,600
Yoke & Alidade	64,000	-	-
Tower	55,000	96,000	96,000
Drives, Platforms Etc.	22,000	16,000	16,000
Misc. (Equip, Cables)	21,000	15,000	15,000
Azimuth Trucks	-	16,000	16,000

Pintle Bearing	-	8,000	8,000
Vertex R.M. Feeds	19,400	19,400	incl.
Totals	418,200	400,000	449,900

Material and fabrication costs for the yoke and alidade antenna would be marginally higher than for the conventional wheel and track because of the slightly higher weight and because of the machining required for the azimuth bearing to achieve the required accuracy. The advanced design wheel and track material and fabrication costs will be higher than the other two due to the higher weight. Assembly costs of the advanced design wheel and track will be slightly higher than for the other two designs because of the increased weight and greater height of the antenna.

03.2.3 Cost Estimates and Comparisons

VLBA Proposal dated May 1982 Chapter VII contains the estimate for ten VLA type yoke and alidade antennas. As stated in that write-up and previously in this report that design was used as a baseline to prepare the May 1982 proposal in the full knowledge that a wheel and track type antenna could more easily meet the pointing and performance requirements and could possibly be less expensive. The estimate of cost for that system given in 1982 dollars in that document is briefly summarized (based on delivery of 5 antennas in 1983 and 5 antennas in 1984) as follows:

Antennas, Engineering, Tooling	$16,856k
AUI Supplied Antenna Components (10x63k)	630k
	$17,486k

A. Wheel and Track Antenna - Concept I

An estimate for a wheel and track antenna using a VLA reflector (upgraded) has been prepared and is as follows:

A.	Antenna Engineering Costs (Contr)		$ 660k
	Servo Design		65k
	Focusing Feed Mount Design		25k
			$ 750k
B.	Three Antennas Delivered in 1985		$ 4,257k
	Antenna and Panel Tooling		110k
			$ 4,367k
C.	Four Antennas Delivered in 1986		$ 5,677k
D.	Three Antennas Delivered in 1987		$ 4,367k
		TOTAL	$15,161k

To the above must be added the cost of the feed support ring and the feed support tower at the vertex of the antenna which estimated at $30k x 10 = $300k.

It should be noted that this estimate is in terms of 1983 dollars and no escalation has been added for delivery in later years. It should also be noted that this estimate is based on an optimum commitment schedule; that is that commitment is made in the antenna contract for all ten antennas. If commitment is made in this manner considerable economics can be accomplished by the antenna manufacturer in procurement of the more costly materials and equipment (such as structural material, gear reducers, gears, azimuth rail and antenna drives) even though fabrication, delivery and antenna assembly is spread over three years.

B. Wheel and Track Antenna - Concept II

An estimate for a wheel and track using an advance design reflector has been prepared since one of the suggestions made by the VLBA scientific committee was that consideration be given to the possible operation at 86 GHz sometime in the future. As explained in Section 3.1.2 and 3.3.2 a standard reflector has difficulty reaching the gravity deformation performance required for 86 GHz frequency so an advanced design reflector was developed. It should be emphasized however that the estimate prepared here does not represent an antenna which could operate at 86 GHz in that we have only provided for the reflector back-up structure performance and have not provided a position system, surface panels of the required accuracy or for the required accuracy at the azimuth rail system. The surface panels for 86 GHz in particular are beyond the present budget limitations in that manufacture to the required accuracy would require a different and far more expensive manufacturing process than those proposed for the 43 GHz presently contemplated. As stated in Section 3.3.1.1 the panel manufacturing accuracy required for 43 GHz operation is 0.0008 inches RMS which two sources have assured us is achievable but which is about the limit of a "standard" manufactured panel. The estimated manufacturing costs of such panels is $31.00 per square foot making the panel costs per antenna approximately $179,000. We do not have good estimates from manufacturers for panels required for 86 GHz operation but since a more exotic method of manufacturing would be required have estimated (based on panel costs for the 12 meter antenna) that costs may run around $160.00 per square foot making the panel costs reach $900,000.00 per antenna.

With this understanding then the estimate for the advanced design wheel and track antenna is as follows:

A.	Antenna Engineering Costs (Contr)	800k
	Servo Design	65k
	Focusing Feed Mount Design	25k
		890k
B.	Three Antennas Delivered in 1985	4514.7k
	Tooling	167.0k
	AUI Supplied Equipment	222.0k
		4903.7k
C.	Four Antennas Delivered in 1986	6019.5k
	AUI Supplied Equipment	296.0k
		6315.5k
D.	Three Antennas Delivered in 1987	4514.7k
	AUI Supplied Equipment	222.0k
		$4736.7k
	TOTALS	$16,846k

It should be noted that this estimate is in terms of 1983 dollars and no provision for escalation has been added for delivery in later years. It should be also noted that this estimate is based on an optimum commitment schedule, that is that commitment is made initially in the antenna contract for all ten antennas. If commitment is made in this manner considerable economics can be accomplished by the antenna manufacturer in procurement of the more costly materials and equipment (such as structural material,gear reducers, gears, bearings, azimuth rail and antenna drives) even though fabrication, delivery and antennas assembly is spread over several years.

03.2.4 Recommendations on Configuration and Design

On the basis of the performance forecasts set forth in Section 3.3 and the cost estimates set forth in Section 3.4 it is recommended that a wheel and track antenna design be chosen in preference to a yoke and alidade design for two reasons.

A. The wheel and track antennas because of its wider base and better configuration is better suited mechanically to achieve the pointing precision in the expected wind and temperature regime than the yoke and alidade design.

B. The wheel and track antenna from the estimate would appear to be somewhat cheaper in price.

As to a choice between the two wheel and track designs studied a clear choice is not so evident; there is no question that the first wheel and track design is appreciably cheaper than the second concept and will quite adequately meet the requirements of the proposed 43 GHz. If the possibility of later conversion to 86 GHz operation as suggested by the scientific committee is however a viable consideration the reflector design for concept I does not offer the gravity performance that would be desired. Analysis to see if a reduced area of the surface would support satisfactory performance has not been done and is one area which should be pursued prior to final engineering design. As far as non-repeatable pointing performance is concerned the two designs will yeild essentially equal performance. As stated in Section 3.4 however the concept and estimate presented herein merely provides a structural capability to operate at 86 GHz. Surface panel accuracy and some mechancial features to perform at 86 GHz frequency have not been provided for.

It is recommended that scientific appraisal of the value of 86 GHz operation be made in the light of the approximate $1.7 million additional cost which would be required now and the later cost of approximately $700k per antenna for the surface panels required plus costs of removing old panels and installing and aligning new ones. In the meantime an analysis of the performance of limited areas of the concept I antenna should be prepared for scientific evaluation.

Update 840423 WGH

Since the Sept. 15, 1983 publication of Chapter 3 - Antennas of the VLBA report additional design development, antenna specification preparation and project planning have modified the results presented in that report. The results of the additional effort are summarized as follows:

(A) Design Development

A decision has been made to adopt the configuration described in the Sept. 15 report as the advanced design reflector with the wheel and track base. This decision has been made with the following two goals in mind.

(1) The advanced design reflector combined with a well designed base and tower of wheel and track configuration provides a telescope structure whose gravity, wind and thermal performance makes it possible at some future date to convert to 86 GHz operation. This upgrading to 86 GHz operation would require the replacement of the antenna surface panels with higher accuracy panels, a more accurate panel alignment and upgrading of some of the antenna subsystems.

(2) If conversion to 86 GHz operation is never made however, superior 43 GHz performance will be achieved due to the better pointing and surface distortion characteristics of the advanced design antenna.

Non-repeatable pointing error due to wind at 7 m/sec (15.66 MPH) has been calculated for the advanced design antenna as follows:

Pitch Angle	Refl. RMS	Refl. P.E.	Tower P.E.
0 degrees	20 micrometers	0.33 arc.sec.	5.57 arc.sec.
60 degrees	57 micrometers	1.47 arc.sec.	3.06 arc.sec.
90 degrees	14 micrometers	2.18 arc.sec.	3.51 arc.sec.
120 degrees	19 micrometers	2.49 arc.sec.	4.93 arc.sec.
180 degrees	9 micrometers	0.52 arc.sec.	6.55 arc.sec.

(B) Antenna Specifications

Complete antenna specifications expanding and modifying those specifications set forth in Section 3.2 have been prepared and issued as RFP-VLBA-01. For an up-to-date version of the specifications RFP-VLBA-01 should be consulted.

(C) Project Planning

At the time of preparation of Chapter III of the VLBA report it was anticipated that antenna procurement could be scheduled on a basis which would provide for the optimum procurement of antennas which would result in the lowest possible cost for the antenna materials and components. The procurement schedule has been stretched out since then to accomodate a more level funding schedule which essentially adds one year to the completion schedule and resulted in adjustments to the estimated antenna costs.

Update 841204 WGH

Since the April 23, 1984 update of the Antenna Section proposals have been received on July 5 from 3 vendors for design, manufacture and erection of the antennas. These proposals have been evaluated, negotiations with the vendors have been held, specifications have been agreed upon with the chosen vendors, a best and final price secured, a successful vendor chosen, a final contract arrived at end the final contract submitted to NSF for their approval. The antenna specifications contained in the contract with the successful vendor are included as Section 3.1 of this document.

Budget and funding constraints, vendor pricing, scientific committee preference, overall project, scheduling (both fiscal and construction) and contract negotiation have modified both construction planning and antenna performance from that previously set forth in this description of the antenna elements. A general description of the major modifications follows.

A. Schedule

Due to the projected funding schedule, the construction schedule has evolved into a procurement schedule of 1, 3, 3, 3 antennas with the following dates:

Antenna No.	Fabr. Start	Antenna Accept.
1	July 1, 1985	Dec. 1, 1986
2 - Kitt Peak	Jan. 31, 1986	Apr. 1, 1987
3 - Owens Val.		July 1, 1987
4 - Oroville		Oct. 1, 1987
5 - Los Alamos	Jan. 31, 1987	Jan. 15, 1988
6 - Puerto Rico		May 15, 1988
7 - North Liberty		Aug. 15, 1988
8 - Fort Davis	Jan. 31, 1988	Nov. 15, 1988
9 - Hawaii		Mar. 15, 1989
10 - Westford		July 15, 1989

B. Antenna Frequency

The original RFP set forth the requirement that the antenna be basically designed for a highest operating frequency of 43 GHz but with the added requirement that gravity deformation of the reflector support structure, wind and thermal performance of the telescope structure be satisfactory for performance at 86 GHz. This was specified in this manner because we did not believe we could secure panels manufactured to the surface accuracy necessary for 86 GHz within the budgeted funds. Vendors were asked during the proposal stage to propose an option for panels manufactured to better accuracy than that required for 43 GHz. The final proposals from the two vendors contained this feature. We were able to contract for panels manufactured to an accuracy of 0.005 in (0.127mm) with panel setting to the corresponding accuracy within the budget. The surface accuracy budget for the antenna now is:

Surface Errors - Precision Operating Condition

(I) Surface Panels:	
Manufacturing RMS	0.005 inch (0.125 mm)
Gravity RMS	0.003 inch (0.075 mm)
Temperature RMS	0.002 inch (0.050 mm)
Wind RMS	0.0015 inch (0.040 mm)
Subtotal RSS	0.0063 inch (0.160 mm)
(II) Measuring & Setting: RSS	0.005 inch (0.125 mm)
(III) Reflector Structure:	
Gravity RMS 90^o Wrt 50^o	0.0055 inch (0.140 mm)
Wind RMS (peak)	0.0022 inch (0.055 mm)
Temperature (delta = 3.5 C deg)	0.005 inch (0.125 mm)
Subtotal RSS	0.0077 inch (0.196 mm)
Total Surface RSS	0.011 inch (0.282 mm)

This surface compares quite favorably with the standard lambda/16 requirement of 0.018 inch (0.45 mm) for the 43 GHz frequency.

The 86 GHz frequency could be used satisfactorily under conditions of low wind velocity and low temperature differentials (primarily night time) in which the surface error would be:

Surface Error Budget - Benign Conditions

(I)	Surface Panels:	
	Manufacturing RMS	0.005 inch (0.125 mm)
	Gravity RMS	0.0015 inch (0.038 mm)
	Temperature RMS	0.000 inch (- - - -)
	Wind RMS	0.001 inch (0.025 mm)
	RSS Subtotal	0.0053 inch (0.133 mm)
(II)	Measuring and Setting RSS	0.005 inch (0.125 mm)
(III)	Reflector Structure	
	Gravity RMS (90^o wrt 50^o	0.0055 inch (0.140 mm)
	Wind RMS (6 MPH)	0.001 inch (0.025 mm)
	Thermal	0.001 inch (0.025 mm)
		0.0057 inch (0.144 mm)
	RSS Total	0.0092 inch (0.234 mm)

It should be recognized that this RSS is calculated using the worst case gravity deformation (ie deformation from 50 deg elevation to 90 deg elevation) and for operation near the panel setting angle performance will be improved.

(C) Antenna Pointing Performance

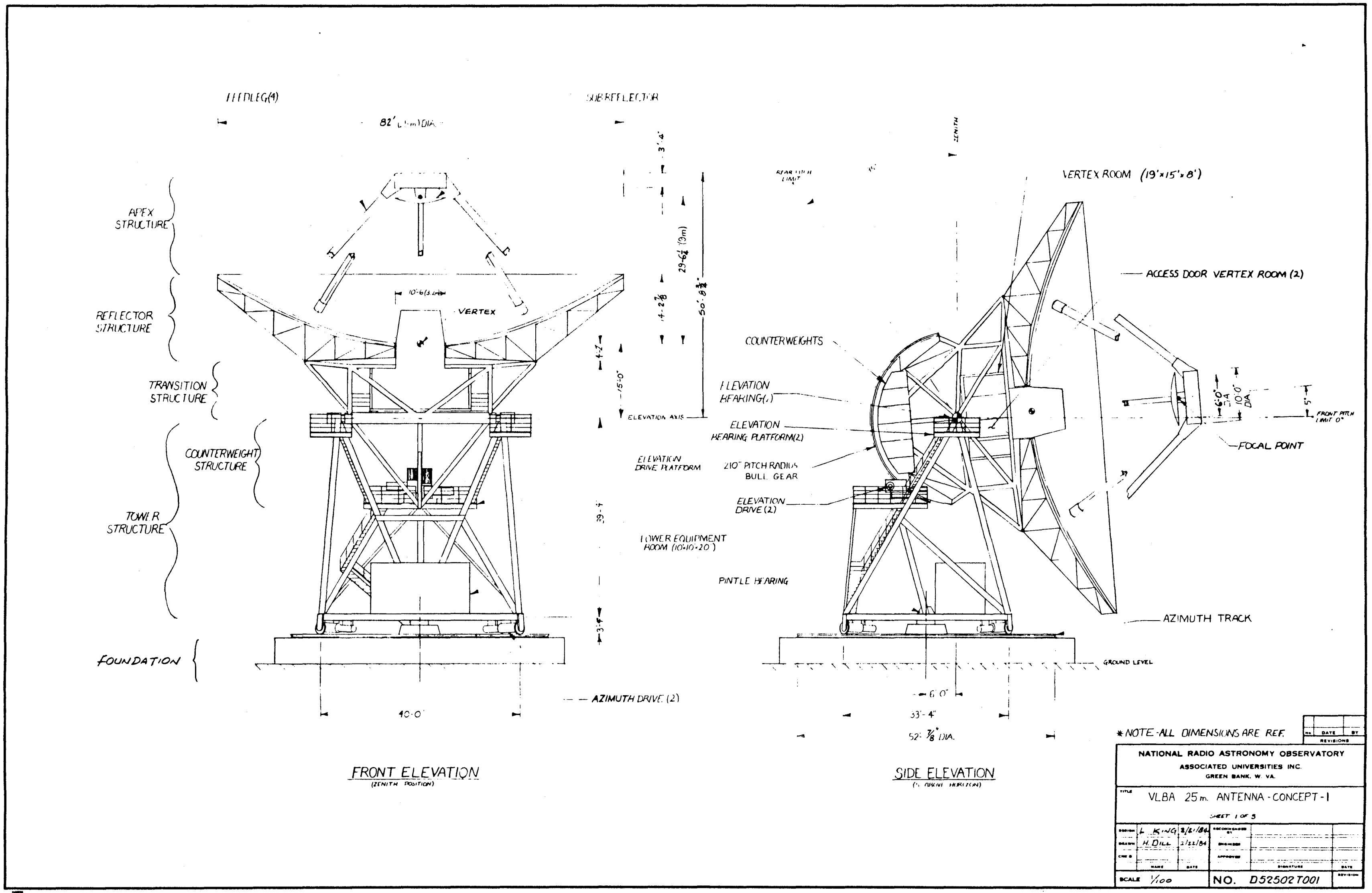
Contract antenna pointing performance remains basically as shown in Section 3.2.2.1.2 of this document as modified by Section A of the April 23, 1984 update. Two changes have however been made which will improve slightly the pointing performance of the antenna. First a 22 bit inductosyn has been agreed on in place of a 21 bit and second the track accuracy has been tightened.

While final design is yet to be accomplished it is anticipated that the thermal pointing performance will be achieved by proper insulation and thermal reflecting paint. The contract does provide however for watertight flanges and gaskets such that an active circulating system for thermal pointing control of the azimuth tower can be provided later if desired.

850806 Update, WGH

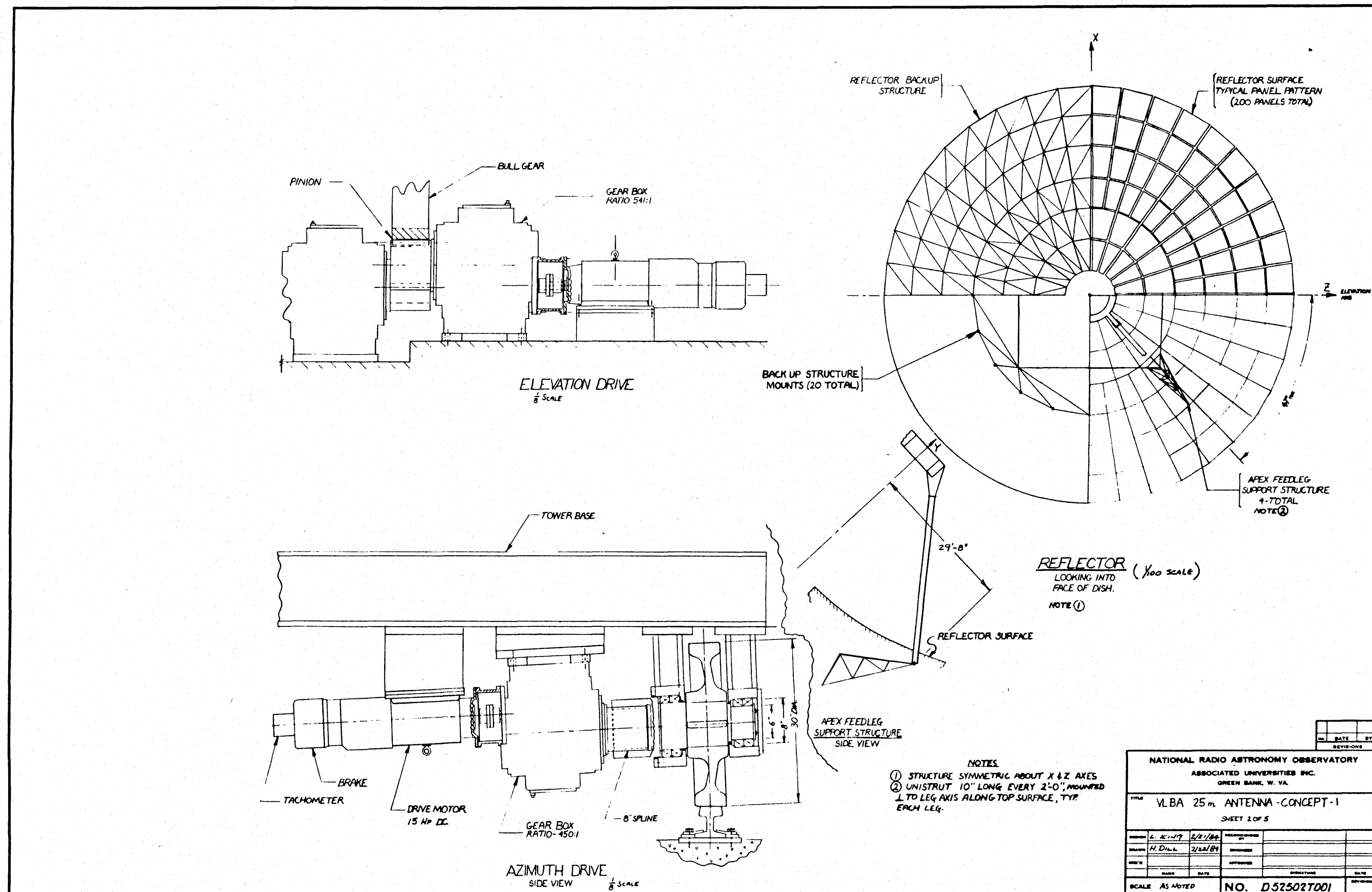
Since the Dec. 4, 1984 update discussion within the AUI scientific and coordinating groups indicated a preference for a different order of installation of antennas from that set forth in the antenna contract. This revised order of installation was negotiated with the antenna subcontractor and on June 26, 1985 Change Order No. 1 to VLBA-100 was issued changing the order of antenna installation to the following:

Antenna No.	Installation Start	Antenna Accept
1 - Pie Town, NM	July 1, 1986	Dec. 1, 1986
2 - Kitt Peak, AZ	Nov. 1, 1986	Apr. 1, 1987
3 - Los Alamos, NM	Mar. 1, 1987	July 1, 1987
4 - Oroville, WA	June 1, 1987	Oct. 1, 1987
5 - Fort Davis, TX	Oct. 1, 1987	Jan. 15, 1988
6 - Puerto Rico	Feb. 1, 1988	May 15, 1988
7 - North Liberty, IO	May 1, 1988	Aug. 15, 1988
8 - Owens Valley, CA	Aug. 1, 1988	Nov. 15, 1988
9 - Hawaii	Dec. 1, 1988	Mar. 15, 1989
10- Westford, MA	Apr. 1, 1989	July 15, 1989



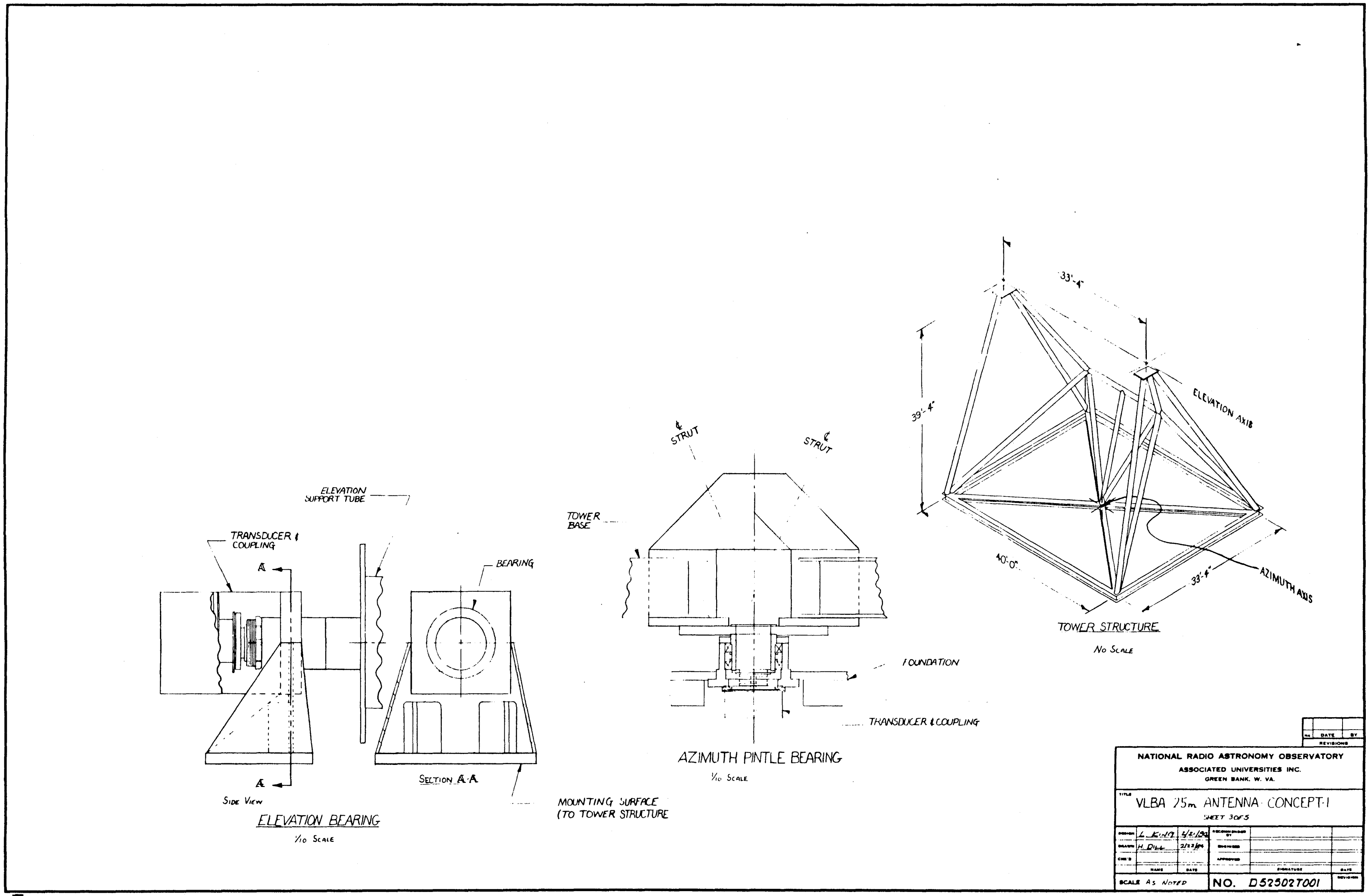
APEX STRUCTURE
REFLECTOR STRUCTURE
TRANSITION STRUCTURE
COUNTERWEIGHT STRUCTURE
TOWER STRUCTURE
FOUNDATION
VERTEX
ELEVATION AXIS
ELEVATION DRIVE PLATFORM
LOWER EQUIPMENT ROOM (10·10·20)
PINTLE BEARING
AZIMUTH DRIVE (2)
40·0"
FRONT ELEVATION
(ZENITH POSITION)
VERTEX ROOM (19'×15'×8')
ACCESS DOOR VERTEX ROOM (2)
COUNTERWEIGHTS
ELEVATION BEARING PLATFORM(2)
210" PITCH RADIUS BULL GEAR
ELEVATION DRIVE (2)
FOCAL POINT
AZIMUTH TRACK
GROUND LEVEL
33'-4"
52'-7/8" DIA.
SIDE ELEVATION
*NOTE-ALL DIMENSIONS ARE REF.
NATIONAL RADIO ASTRONOMY OBSERVATORY
ASSOCIATED UNIVERSITIES INC.
GREEN BANK, W. VA.
VLBA 25m. ANTENNA - CONCEPT - I
SHEET 1 OF 5
L. KING 3/6/84
H. DILL 3/22/84
SCALE 1/100
NO. D52502T001

Figure 3.1



REFLECTOR BACKUP STRUCTURE
REFLECTOR SURFACE TYPICAL PANEL PATTERN (200 PANELS TOTAL)
X
Z
ELEVATION AXIS
BACK UP STRUCTURE MOUNTS (20 TOTAL)
APEX FEEDLEG SUPPORT STRUCTURE 4-TOTAL NOTE 2
REFLECTOR (1/100 SCALE)
LOOKING INTO FACE OF DISH.
NOTE 1
PINION
BULL GEAR
GEAR BOX RATIO 541:1
ELEVATION DRIVE
1/8 SCALE
TOWER BASE
Y
29'-8"
REFLECTOR SURFACE
APEX FEEDLEG SUPPORT STRUCTURE SIDE VIEW
30" DIA
8"
6"
BRAKE
TACHOMETER
DRIVE MOTOR 15 HP DC
GEAR BOX RATIO-450:1
8" SPLINE
AZIMUTH DRIVE
SIDE VIEW
1/8 SCALE
NOTES
1 STRUCTURE SYMMETRIC ABOUT X & Z AXES
2 UNISTRUT 10" LONG EVERY 2'-0", MOUNTED ⊥ TO LEG AXIS ALONG TOP SURFACE, TYP. EACH LEG.
REVISIONS
DATE
BY
NATIONAL RADIO ASTRONOMY OBSERVATORY
ASSOCIATED UNIVERSITIES INC.
GREEN BANK, W. VA.
VLBA 25m ANTENNA-CONCEPT-1
SHEET 2 OF 5
L. King 2/21/84
H. Dill 2/22/84
SCALE AS NOTED
NO. D52502T001

Figure 3.2



TRANSDUCER & COUPLING
ELEVATION SUPPORT TUBE
BEARING
A
A
SIDE VIEW
SECTION A-A
ELEVATION BEARING
1/10 SCALE
MOUNTING SURFACE (TO TOWER STRUCTURE
TOWER BASE
STRUT
STRUT
FOUNDATION
TRANSDUCER & COUPLING
AZIMUTH PINTLE BEARING
1/10 SCALE
33'-4"
39'-4"
40'-0"
33'-4"
ELEVATION AXIS
AZIMUTH AXIS
TOWER STRUCTURE
NO SCALE
NATIONAL RADIO ASTRONOMY OBSERVATORY
ASSOCIATED UNIVERSITIES INC.
GREEN BANK, W. VA.
VLBA 25m ANTENNA CONCEPT-I
SHEET 3 OF 5
SCALE AS NOTED
NO. D525027001

Figure 3.3

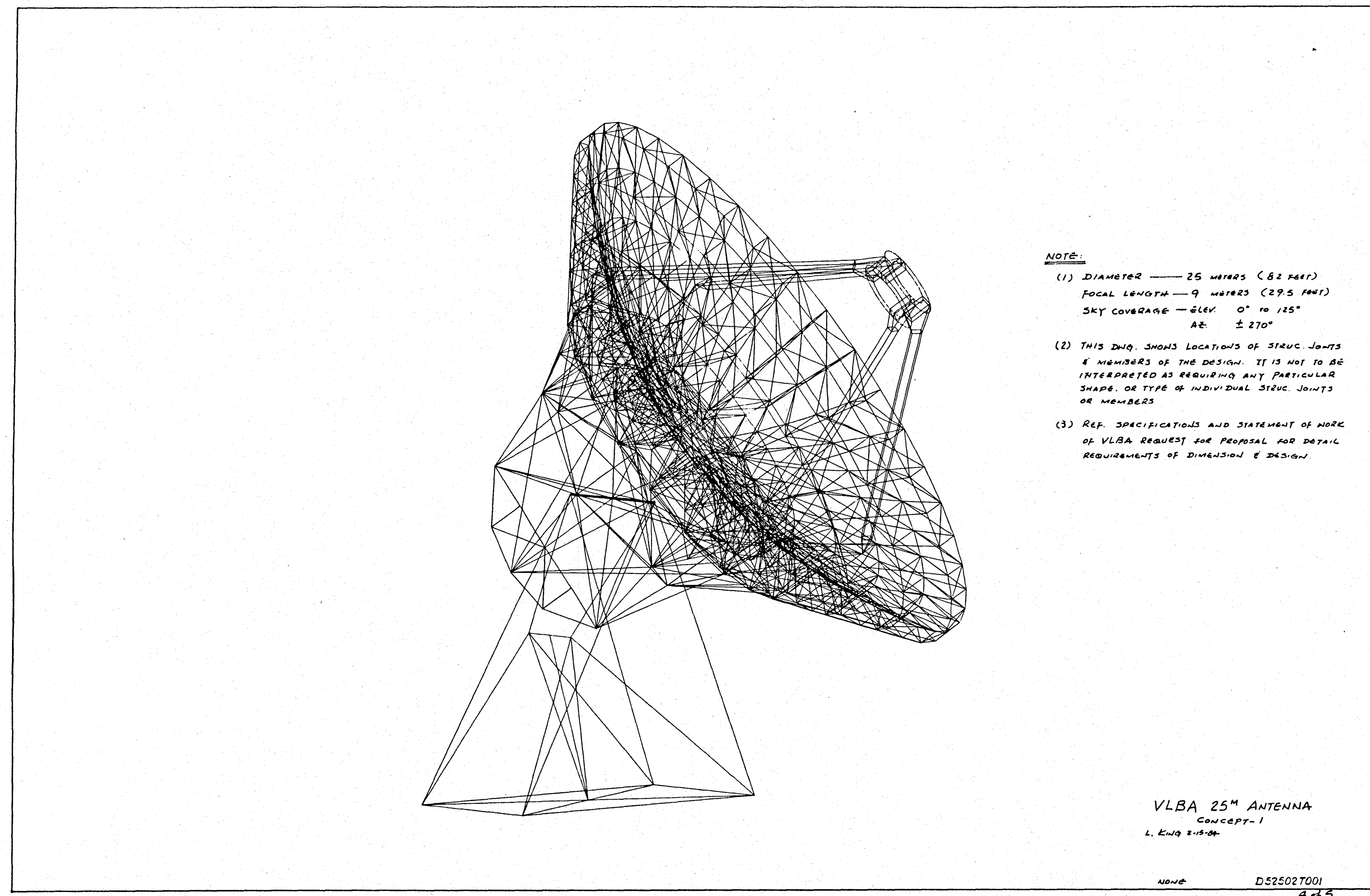

NOTE:
(1) DIAMETER —— 25 METERS (82 FEET)
FOCAL LENGTH — 9 METERS (29.5 FEET)
SKY COVERAGE — ELEV. 0° TO 125°
AZ. ± 270°
(2) THIS DWG. SHOWS LOCATIONS OF STRUC. JOINTS & MEMBERS OF THE DESIGN. IT IS NOT TO BE INTERPRETED AS REQUIRING ANY PARTICULAR SHAPE, OR TYPE OF INDIVIDUAL STRUC. JOINTS OR MEMBERS
(3) REF. SPECIFICATIONS AND STATEMENT OF WORK OF VLBA REQUEST FOR PROPOSAL FOR DETAIL REQUIREMENTS OF DIMENSION & DESIGN.
VLBA 25M ANTENNA
CONCEPT-1
L. KING 2-15-84
NONE
D52502T001
4 of 5

Figure 3.4

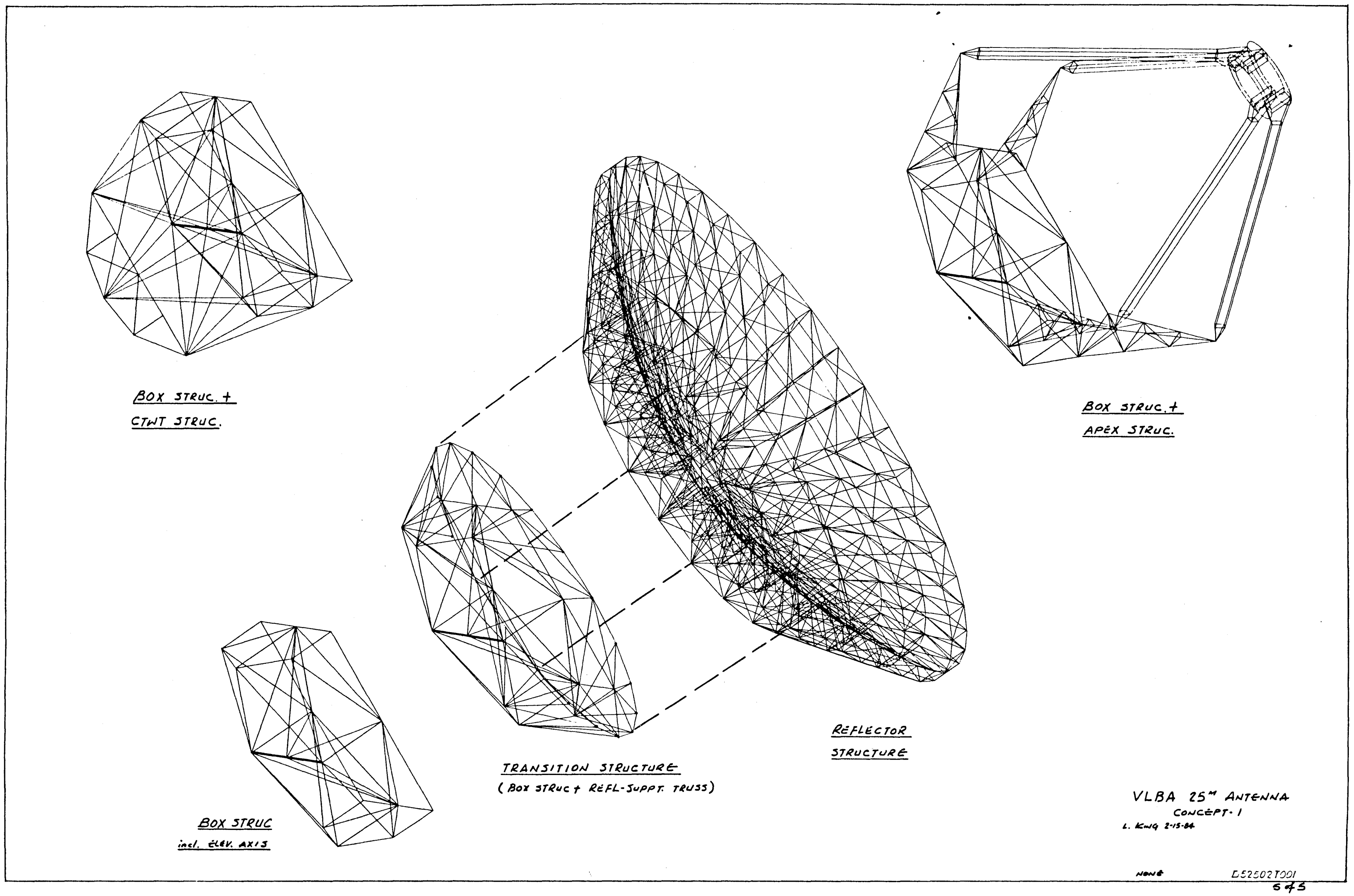

BOX STRUC. +
CTWT STRUC.
BOX STRUC. +
APEX STRUC.
TRANSITION STRUCTURE
(BOX STRUC + REFL-SUPPT. TRUSS)
REFLECTOR
STRUCTURE
BOX STRUC
incl. ELEV. AXIS
VLBA 25m ANTENNA
CONCEPT-1
L. King 2-15-84
NONE
D52502T001
545

Figure 3.5

Section 3 - Updates

850806	Update Audit: Revised Antenna Installation Order. WGH
841204	Revised Specifications added as Sect. 3.1, Sect. 3.2 (Specifications) of original chapter deleted. Sect. 3.1, Sec. 3.3, Sect. 3.4 and Sect. 3.5 renumbered to conform to VLBA Memo 317 (I hope). Update of narrative description added. WGH
840423	Narrative update describing design development and configuration selection. WGH
840207	Initial Version. WGH

SECTION 4

CONTROL AND MONITORING

B. G. Clark

4.1 SPECIFICATIONS

Monitor and Control Bus: 55001N001

Standard Interface: 55001N002

4.2 DESCRIPTION

4.2.1 Concept

The overall concept of the Control and Monitor System includes a central control computer linked by telephone lines to a small computer at each VLBA station, which in turn communicates digitally with all of the observing equipment at that station. Commands to the equipment are obviously needed to set it into the state required for a particular observation. Monitor information serves several purposes:

- verifying that the equipment is in the desired state and is functioning correctly;

- measuring parameters which must be known during correlation of the data tapes, such as receiver gains and phase calibrator line lengths;

- allowing detailed diagnosis of failures from the control center, where the most expert technical personnel will be located, thus minimizing travel requirements and downtime; and

- compiling an historical record (log) of the equipment state, in order to allow post-facto flagging of data, analysis of failures (especially intermittent ones), and studies of equipment performance.

Particularly because of the last two requirements, designers of antenna-based equipment will be encouraged to provide signals to the monitor system well beyond those needed to verify normal operation. It turns out that this will not result in very high data rates.

As an additional overall check on performance, small amounts of received signal data will be transmitted to the control center via the telephone link for crosscorrelation in near real-time.

The hierarchy of decision making between the central computer and the small computer located in each antenna has not yet been decided. On the one hand, if the station computer is limited to simple, repetitive tasks then its hardware and software should be more reliable and easy to maintain. On the other hand, the ability to perform sophisticated tasks during periods of communication outages may then be limited; also, we do not want to foreclose the possibility of later implementing control schemes which would tax the communication system, although none are envisioned at this time.

A major consideration in the system design is reliability. NRAO's experience with data transmission via telephone links suggests that such links cannot be relied upon for real-time control, but we lack detailed statistics of the expected outages. In order to minimize the effect of loss of communication, we propose to utilize leased lines for normal operation, with dial-up lines also available at each station as a backup. In addition, control information will be sent well in advance, with sufficient buffering at the station to allow a ride-through of several hours without communication (this could be expanded to 24 hours or more if necessary). Monitor information will be similarly buffered.

The strongest efforts will be made to make the user interfaces as uniform as possible, not only for the interfaces of operators, scientists, and engineers but also for all systems of the VLBA that a single person might have to deal with. There is a special concern that the control languages for the real-time array functions and for the correlator control functions be as similar as possible.

4.2.2. Central Control and Monitoring of the Array

In normal operation, the Array will be controlled from a previously prepared schedule and will require no direct intervention from an operator; the array operator's main responsibility will be to ensure that the correct schedules are operational and to monitor the performance. However, the array operator will be able to send commands directly to individual antennas or the whole array at any time.

Although from one point of view, the system will appear as an array, from another, the antennas will simply be working according to a schedule sent to them by the array control computer, and each antenna will require no knowledge of what any other antenna is doing. Therefore, the array operator can control the division of the array into subarrays in a very simple manner, just by controlling the communication of the schedule sent to the stations. Subarraying in the correlator is a much less simple matter, and careful records must be kept in the logs, so that correlation between a given pair is done only when it is sensible to do so.

The following tasks will run in a computer system at the array control center.

SENDER/RECEIVERS. These programs match the programs which run at the station computers and accomplish the transmission of data. Depending on which particular program, they would be initiated on a regular cycle or by the operator.

MONITOR DATABASE FILLER. This program would put monitor data sent from the various stations into a conveniently accessible disk data base for access by the array maintenance engineers.

MONITOR DATABASE PRUNER. Because of the lack of the capability of putting a chart recorder on a monitor point directly that we have, and use, at the VLA, I would make a very much denser monitor data base for the VLBA, an order of magnitude more voluminous. This dense database would be kept only for a couple of days. A roughly VLA style monitor database would then be made by pruning the original down to a manageable size.

ARRAY LOG WRITER. Additional data, other than the monitor information, will be inserted in the database, for the use of the correlator control programs and other purposes. This data would include all of the control schedule sent to the stations.

STATION COMPUTER INITIALIZER. Unless the station computer runs from ROM this would include the down-line load. It would also send such stuff as date, time, location, tables of equipment present, etc.

ARRAY CONTROL. By appropriately controlling the distribution of control schedules, the operator at the array control computer can assign antennas to subarrays or run antennas standalone for pointing calibration.

MONITOR DATA PLOTTER/LISTER. Equivalent to the VLA programs Monplt and Monlst. Probably should be available over the link to the stations, though in a real pinch, accessability over a dialup might be acceptable. These programs would have access to any material stored in the array database.

REAL TIME FRINGE CHECK. Receives data from the fringe check buffers from the array and does the correlation. On a VAX 750 this program would probably require several seconds per baseline and per lag. This is much less than the data transmission time, and poses no real problem, unless we lose a station and have to go hunting for it over many tens of lags, or unless we decide we want to do this on such weak sources that all baselines must be processed and global fringe fitting done. The output of this program would be stored in the array database.

OBSERVATION PLANNING AID/OBSERVATION REQUEST GENERATOR. The VLA program OBSERV could serve as a basis for a program to aid with the VLBA scheduling. It is clear that additional auxiliary functions will be needed, such as display of rise/set times at various stations, (u,v) tracks, etc.

TAPE INVENTORY. This program will keep track of all movements of tapes between the remote stations and the processors, and maintain statistics on tape usage and tape quality.

MAINTENANCE RECORDS. A database must be kept of maintenance done in order to find the weak links in the system that need further design work. In such a far-flung system as the VLBA, it may well be profitable also to automate the spare parts inventory, so that a needed spare part can be located quickly or automatic reminders to ship spare parts may be generated.

4.2.3 Functions of undecided residence

The following programs might be written to run in the station computer or in the array control computer.

DEVICE CONTROL PROGRAMS. These are the equivalent of the VLA Modcomp DMT overlays. They could run in either the station computer or in the array control computer, so long as a terminal can access them from the other computer using the dedicated computer link. Having the programs run in the array control computer and accessed by a separate, dial up, modem appears unacceptable.

DATA FLAGGER. This would automatically set two flags - antenna off source (including subreflector not set), and LO chain malfunction - based on the monitor data. These bits will eventually become part of the array database, and inform that correlator computer systems that the associated data are invalid.

MONITOR DATA CHECKER. This program will notice out-of-range monitor points and call them to the attention of the array operator. At the VLA, this program and the above are combined into a single package. The advantages of this have been less than expected, and do not, for instance, constitute a constraint that the programs must run in the same computer.

4.2.4 Programs for the station computer

The following programs would run in the station control computer.

THE ANTENNA DRIVER. This program will send az-el to the antenna controller at a 20Hz rate. The VLA uses a linear extrapolation for ten seconds, with the full spherical triangle solved only every 10 seconds. It would seem more likely that the spherical triangle would be solved at the full 20Hz rate for the VLBA antenna. This eliminates one level of tasking and the concomitant handshaking. The price is about ten or fifteen percent of the CPU, either for a CPU with floating point hardware, done in Fortran, or for a CPU without floating hardware, done in assembler scaled binary fixed point.

THE NEW SOURCE EXECUTOR. This program would be responsible for switching between two observation control blocks, mentioned above. The program would primarily make sure that all of the receiver switches are thrown to the correct position.

NEW SOURCE ORGANIZER. In order to permit more observation requests to reside in the in-core buffer of requests received from the array control computer, the latter would be sent in some rather condensed form, and expanded to make an observation control block. There is a lot to be said for sending the observation requests as text, rather than binary. It makes it possible to examine them from anywhere in the system in a rather easy fashion, and, if care is taken, to constructively interfere with them. Even if the control block is sent verbatim, a program to mark it active, and possibly to do some precomputations for next use, is needed.

MONITOR DATA INHALER. This program would maintain the core image of monitor data, as mentioned above.

MONITOR DATA LOGGER. This program would sample the monitor data core image at appropriate intervals and store it into a buffer, with appropriate identifying information, still in the station computer.

TAPE SYSTEM CONTROLLER. This program would do the bookkeeping about how much tape is available, when to switch tapes with minimum disruption, and generally supplies any information that the tape subsystem needs.

DATA SENDER/RECEIVERS. These include Observation request receiver, monitor log sender, possibly a fast monitor data sender (if the device control programs mentioned above reside in the array control computer), a fringe check data sender, and a real-time remote debugger. It does not appear necessary for the station computer to initiate communications, but to simply respond to the polling of the array control computer.

4.2.5 Hardware

The exact sizing of the hardware of the systems depends on decisions yet to be made about where various programs are to be run. The material below is thus highly preliminary, but should give an idea about the order of size of the systems we are contemplating.

The array control computer will be a DEC VAX computer running the VMS operating system. The particular model of VAX depends on which of the above tasks actually run in the array control computer, and on the degree of support of database type operations for monitor data, schedules, and logs is decided upon. The machines under consideration are the VAX 11/750 and the VAX 11/785. It is currently believed that a VAX 11/750 is adequate. A fairly large memory, perhaps three megabytes, will be needed. The main peripherals will include two 1600/6250 bpi tape drives, perhaps 512 Mbytes of disk memory, a line printer, and a number of console printers and CRT terminals. A card reader may be necessary but it is hoped other media will serve as the main observing program transport. A multiplexor system will be provided, both to communicate with the array stations and to provide remote user dial in. Hardcopy graphics are needed on this system, either by means of a printer-plotter as the line printer or by a separate device.

It is necessary to have some sort of backup for the array control computer. It may well be possible to have this by arranging to use one of the post-processing computers as a backup, if the software and communications systems are compatible. If not, it might be necessary to have redundant devices to provide the required backup.

4.2.6 Communication

The achievement of the communications necessary for the VLBA has been carefully considered by A. Shalloway, with a report presented in VLBA memorandum 299. One of the more constrictive requirements derived from this study is given by the fact that it is cost effective (with a payout period of roughly five years) to purchase our own satelite equipment, rather than leasing lines from the telephone company. In order to preserve this option, it is highly desirable that the discipline on the links be a polled multidrop, preferably SLDC/HLDC. It is not yet clear whether this should be implemented in the station computers or in a separate communication processor feeding the station computer. Proprietary network bridges between OSI network interfaces at the station and array control center are also being considered, as are the use of statistical multiplexors and multiple ports of dedicated use on the computers.

Because the purchase of satelite equipment is a large capital investment, we wish to preserve this as an option, but not to excercise the option yet. The first stations will be implemented by reserved telephone lines, but with multidrop polling disciplines rather than through the use of statistical multiplexors.

In addition to the reliability of our equipment, the reliability of the telephone links is of great concern. We propose to have a dial-up line available at each station as a backup. It should be noted, however, that most of the stations are at remote sites. Experience at similar locations has shown that a loss of communication often involves all lines to the site. Although existing statistics are controversial, occasional outages are assumed a reality.

4.2.7 Control and Monitoring At Each Station

It is expected that all equipment at each station will be connected to a common digital bus, over which control and monitor signals will be sent in a simple serial format. The system must have sufficient capacity not only to handle normal operation, but also to support remote diagnosis of faults when they occur. Sufficient monitor information must be routinely collected to establish the quality of the astronomical data and to enable timely repairs to be made; but much more detailed information must be available on demand for troubleshooting.

It turns out that the data rates required for routine control and monitoring are extremely modest, both within the station and between the station and the control center. This is because very little equipment needs to be commanded more often than once per source change (normally several minutes), and because quality control requires status checking no more often than once per integrating period (normally 2 sec or more). Within the station, the highest data rate is required for commands to the antenna servo, whose azimuth and elevation must be updated about twenty times per second. To reduce the data rate on the communication link, we require that the conversion from RA-DEC to AZ-EL coordinates be done at each station, so only the former need be sent.

The communication between the station computer and all station equipment is by means of a fast serial communication bus. The bus protocol and electrical properties are specified in specification 55.001N001. The bus protocol specifies two fifteen bit address spaces, one for commands and one for monitor data. The addresses to which a given interface responds will be determined by that interface. No assumption is made that there is a one-to-one relationship between "interfaces" and "devices"; a given "device" may be monitored or controlled by more than one interface, or a given interface may control more than one device.

Most of the equipment will be able to interface to the bus through a "standard interface," which is a microprocessor based device occupying a PC board approximately 4" by 6" in size. The standard interface will provide analog to digital conversion, some analog multiplexing, address decoding, and error checking. Devices for which the standard dataset is not appropriate can contain special interfaces. This scheme provides an address space about ten times larger than appears necessary for initial operation of the telescope. Its speed is about twenty times more than will be needed initially. There is thus plenty of room for future growth.

The station controller will be a microcomputer from the Motorola 68000 family, equipped with very few peripherals, chiefly the monitor/control bus of the antenna hardware, and the modem connecting it to the central computer. In normal operation, it will have only straight-forward, repetitive jobs to perform. However, some of these may be of such complexity to perform that we see the necessity of a higher level language than assembly for the programming of this computer. The residence of the programs has not been decided. It may be that the standard programs are downloaded by the central computer at startup, with a backup of being able to load them from local disk, or the other way around. On the other hand, it may make things substancially more reliable to have programs in local ROM memory. It may even be profitable to split residence, having a kernal program in ROM, and others, changed more frequently, on disk. It is probable that things can be arranged so that a hard disk is not required, that only a floppy disk drive is required at the station, and that even this is not required for normal station operation.

Each antenna station will operate unattended most of the time, and some stations will have no regular personnel. Therefore, extensive support of local work independent of the array control computer is not required. Nevertheless, during installation, checkout, and maintenance work all facilities available at the AOC are likely to be needed sometime. This may be done through the use of terminal access to the central array control computer, by directly using the station control computer, or by the use of a portable microcomputer attached to the station control computer. All of these options will work. The best solution is the subject of current study.

A duplicate station controller will be maintained at the operations center to facilitate software development.

4.2.8 Programming

The monitor/control programing effort will be centered in Socorro. Programs will, when possible, be written in the C language. Maximum efforts will be expended to make the programming compatible with the VLA on-line system, the Greenbank telescope control systems, and the VLBA correlator control system.

4.2.9 Manpower

The software development for the control and monitor system is estimated to require 16 man years. Most likely we will be able to purchase commercial software, such as data base systems for some of the utility programs. The costs of such software will be deducted from the cost of 16 man years of programming.

Hardware development, installation, and testing (consisting mainly of interfaces to the station equipment) is expected to require an average of one electronics engineer and two electronics technicians for the duration of the project, or 15 man years total.

Section 4 - Updates

850524 Changes to reflect decisions made ofer the last year: Monitor and control bus specification finalized (refered by number only), Standard interface spec finalized, choice of VAX-VMS for the array control computer, choice of the 68000 familiy for the station computer, decision (still tentative) to use a unified database structure, choice of C as the principal programming language. BGC.

840430 Corrected section numbering; added subsection 4.1; made Bus Spec into Appendix A. LRD.

840306 Major revison of Volume 3. Insertion of material from Memo number 278. Insertion of station bus specification from Memo 302. Change of bus spec response times from 100 microseconds to 500 microsec.

840227 Project Book Section 4: Monitor and Control (initial version)

SECTION 5

FEEDS, SUBREFLECTOR, RELATED OPTICS.

P.J.Napier

5.1 Specifications.

Items (a) through (c) below are essential requirements.

(a) An optics and feed system is required which will provide outputs for each of the following nine frequency bands: 0.31-0.34 GHz, 0.58-0.64 GHz, 1.35-1.75 GHz, 2.15-2.35 GHz, 4.60-5.10 GHz, 8.00-8.80 GHz, 14.4-15.4 GHz, 22.2-24.6 GHz, 42.3-43.5 GHz.

(b) All feeds will provide dual circularly polarized outputs with less than -30db cross coupling between orthogonal polarizations in the on-axis direction.

(c) A dual-band capability is required for the 2 GHz and 8 GHz bands so that both bands can be used at the same time with coincident beams in the sky.

Requirements (d) through (g) below are considered to be highly desirable and must be satisfied to the extent possible within the constraints imposed by budget and space limitations.

(d) Frequency changes from one band to another should be performed under computer control without requiring technicians to visit the antenna.

(e) The feeds should be optimized to provide the maximum possible on-axis G/T performance from the antenna and low-noise receiving systems.

(f) Space should be provided so that 2 feeds ,in addition to those listed in (a) above, can be located on the feed circle. These locations would be used for 5.90-6.40 GHz, 10.2-11.2 GHz ,86 GHz or other feeds in the future.One of the spare locations will be close to the elevation axis on the feed circle.

(g) Feeds should be positioned so that dual-band operation (as in (c) above) can be provided for the frequency pairs 5/22 GHz and 10/43 GHz at some time in the future. If possible, at lest one of the 3 dual frequency feed pairs will be arranged so that dual frequency operation can be initiated without any manual intervention on the antenna.

5.2 Description

The requirement to provide a large number of feeds covering a wide range of frequencies led to the selection of an offset Cassegrain geometry of the type used on the VLA for the antenna optics. Because of the limited space at the secondary focus, the two lowest frequency bands will be placed at the primary focus. The subreflector focussing mechanism will retract the subreflector to expose the prime focus of the main reflector. The prime focus feeds will be mounted on or beside the subreflector. The main and sub reflectors are shaped for high efficiency. The geometry is optimized so that the areas blocked by the subreflector and feed system are approximately the same. The subreflector is asymmetric so that the secondary focal point lies off of the main reflector axis and is above the main reflector vertex. When the subreflector is rotated around the main reflector axis the secondary focus describes a circle about the main reflector axis. This circle is called the feed circle and the phase centers of all feeds lie on it. Locations for the up to nine secondary focus feeds will be provided around the feed circle at the top of the feed support cone. All Cassegrain feeds will have their phase centers close to their apertures and be as short as possible. The cryogenically cooled receivers will be attached directly to the feed outputs at varying heights above and below the main reflector vertex. The important dimensions of the Cassegrain geometry are:

Primary reflector diameter = 2500 cm
F/D of best fit parabola for main reflector = 0.354
Distance from main vertex to subreflector vertex = 819 cm
Best fit prime focus behind subreflector vertex = 66 cm
Maximum radius of asymmetric subreflector = 175 cm
Depth of subreflector at maximum radius = 56 cm
Radius of feed circle = 85 cm
Radius of top of feed cone = 135 cm
Radius of bottom of feed cone = 175 cm
Plane of feed circle above main vertex = 209 cm
Angle subtended by subref. from sec. focus = +-13.3 deg
Angle between main reflector axis and feed axis = 7.9 deg
Feed pattern taper at edge of subreflector = -14 db

5.3 Component Design

5.3.1 Main Reflector Profile

The shaped main reflector is designed to give uniform aperture illumination out to 90 percent of the radius. The illumination over the outer 10 percent of radius rolls off to give a taper of -15 db at the edge of the aperture. This roll off is very important in reducing subreflector spillover to the ground and therefore maximizing G/T in the 1.5 GHz and 2.3 GHz bands. In the frequency range 1.5 to 5 GHz the reduced edge illumination results in G/T improvements of 20 to 30% compared to full uniform illumination. At 43 and 86 GHz, where spillover noise is less important, the reduced edge illumination causes a 6% loss in G/T.

The maximum deviations of the shaped profile above and below the best fit parabola are 1.7 cm and 1.8 cm respectively occurring at radii of 909 cm and 1250cm respectively. The deviation of the shaped surface from a parabola results in a gain loss of 0.95 when the prime focus is used at a frequency of 0.6 GHz.

5.3.2 Asymmetric Subreflector

The asymmetric subreflector is designed to give uniform phase in the aperture of the main reflector, even though the feed is offset. Frequency changes for Cassegrain feeds are accomplished by rotating the subreflector about the main reflector axis so that the secondary focal point lies on the phase center of the desired feed. Requirements for the computer controllable movement of the subreflector are:

Subref rotation about main refl axis = +-180 deg. minimum
Subreflector focus towards main reflector = 4 cm minimum
Subreflector focus away from main reflector = 66 cm minimum

Requirements for the positional stability of the subreflector to provide adequate gain and pointing performance at 85 GHz are:

Lateral offset between subref vertex and main axis = 3 mm max
Angle between subref axis and main axis = 4 arc.min. maximum
Stability of rotation about main refl axis= 2 arc.min. max

The asymmetric subreflector, which is not a surface of revolution, is currently planned and budgeted to be a metal coated fiberglass reflector of the type used at the VLA. This type of construction will provide a surface accuracy of approximately .008 in rms which will cause significant gain loss at 86 GHz. To do justice to the improved accuracy of the main reflector, the subreflector should be .004 in rms.The cost of a subreflector of this accuracy will be determined to see if it can be provided from budget contingency.

A circular area 25 cm in diameter in the middle of the subreflector is in the shadow of the feed cone and is available for mounting a .6 GHz feed.

5.3.3 0.31-0.34 GHz Feed

Three options exist for this feed. A simple prime focus feed, such as crossed-dipoles in a cavity, could be placed off-axis at the edge of the subreflector. In this position the beam would be approximately four beamwidths off-axis resulting in significant gain loss. An aperture efficiency of between 30 and 40 percent could be obtained. If this option is chosen, because the antenna has an elevation over azimuth mount, it is important that the off-axis feed be as close as possible to the vertical plane orthogonal to the elevation axis and containing the main reflector axis so as to avoid increasing the cone of avoidance near the zenith. The advantage of the off-axis location is that the feed would have minimal impact on G/T at the secondary focus and could be left permanently in position. A second possibility is to mount a simple wire antenna feed, such as crossed-dipoles or pairs of orthogonal dipoles on the subreflector. Here the problems are interference with the performance of the 0.6 GHz feed and the Cassegrain feeds. Experience at the VLA shows that any significant structure on the subreflector rapidly degrades Cassegrain performance so it may be necessary to manually dismount the feed, contravening requirement 5.1(d) above. The third possibility would be to swing a feed in and out of position beneath the subreflector using a moving mechanism located on a quadrupod leg. Experience at the VLA will help in selecting the best system. Circular polarization will be formed using a quadrature hybrid coupler in front of the low noise amplifiers.

The feed currently chosen for prototyping is a crossed dipole permanently mounted in the middle of the subreflector. The dipoles will have a tuned circuit half way along so that they will support 0.6 GHz operation as well.

5.3.4 0.58-0.64 GHz Feed

This feed should be small enough so that it can be permanently mounted in the shadow area in the middle of the subreflector. A coaxial cavity feed or crossed-dipole feed are possibilities currently being investigated. A quadrature hybrid in front of the amplifiers will be used to form circular polarization.

The feed currently being prototyped places a 0.6 GHz tuned open circit half way along the 0.3 GHz dipoles in the middle of the subreflector. Thus, the coaxial output from a dipole will provide both 0.3 GHz and 0.6 GHz signals. A frequency diplexer will be needed at the receiver input.

5.3.5 1.35-1.75 GHz Feed

This feed will be a compact corrugated horn in which the horn is bell shaped, rather than the usual simple conical shape, to produce higher modes in the horn aperture. Compact horns are 10 to 20 percent smaller than conventional corrugated horns. Because of its large size it is essential that a low cost fabrication technique be developed for the major portion of the horn. Fabrication techniques to be investigated include metal coated fiber glass or foam and sheet metal fabrication. Circular polarization over the large bandwidth will be obtained by using a VLA style room temperature dielectric-in-waveguide quarter wave plate in front of the Greenbank style quad-ridged orthomode junction.

5.3.6 2.15-2.35 GHz Feed

This feed will be a compact corrugated horn as described in 5.3.6 above and will use a cryogenically cooled sloping septum polarizer to generate circular polarization. A resonant grid dichroic plate will be placed above the feed to provide a dual band capability with the 8 GHz feed. This plate reflects the 8 GHz signal over to the 8 GHz feed but allows the 2 GHz signal to pass through with low loss.

5.3.7 4.6-5.1 GHz, 5.9-6.4 GHz, 8.0-8.8 GHz, 10.2-11.2, 14.4-15.4 GHz and 22.2-24.6 GHz Feeds

All these feeds will be conventional corrugated horns using cryogenically cooled sloping septum circular polarizers. The 8 GHz feed will have an elliptical reflector above it as part of the 2/8 GHz dual frequency system.

The 4.6-5.1 GHz horn will have sufficiently good performance at 6.1 GHz that it can be used for that frequency, if desired, with only a few percent loss in gain.

5.3.8 42.3-43.5 GHz, 86 GHz Feeds.

These feeds will be conventional corrugated horns. Circular polarization will be formed either using a cooled quarter-wave phase shift waveguide polarizer or quarter-wave phase shift vanes over the feed aperture.The feeds should be placed close to the elevation axis on the feed circle so that subreflector rotation can be used to correct for the effect of quadrupod gravitational deformation. The feeds should be designed for a little less than 14 dB taper at the edge of the subreflector to correct for the effect of the aperture edge illumination roll-off that is needed at lower frequencies.

The principal dimensions of the feeds are given in the following table.

Frequency (GHz)	Feed Input ID (cm)	Feed Aperture Outside Diameter (cm)	Feed Length To Recvr (cm)
0.31-0.34		48	50
0.58-0.64		24	50
1.35-1.75	16.33	140	360
2.15-2.35	9.75	90	256
4.6-5.1	4.490	41	119
5.9-6.4	3.578	32	94
8.0-8.9	2.602	24	71
10.2-11.2	2.045	19	56
14.4-15.4	1.487	14	41
22.2-24.6	0.931	9	27
42.3-43.5	0.526	5	16
86	0.263	3	8

5.4 Performance Estimates

The VLBA offset shaped Cassegrain geometry was designed by first generating a prototype symmetrical shaped geometry. The main reflector of this prototype is retained and the subreflector is discarded. The asymmetrical subreflector is then generated such that uniform phase in the aperture of the main reflector is obtained when the secondary focus is offset to the desired location. Estimates of the performance of the VLBA feed system have been made by analyzing the prototype symmetrical geometry using the geometrical theory of diffraction. The program to generate the prototype geometry and to perform the analysis was provided by G. James of the CSIRO Division of Radiophysics. The table below gives estimates of aperture efficiency. Esurf is the reflector surface efficiency assuming that the main reflector surface rms is 0.011 in rms (the spec for precision operating conditions) and the subreflector rms is improved to 0.004 in. Eillum is the combined effects of aperture taper and subreflector diffraction. Espil is feed spillover efficiency. Eblock is aperture blockage efficiency. Ephase is aperture phase efficiency, including the shaping of the main reflector for the prime focus feeds. Emisc represents miscellaneous losses due to VSWR, resistive and other losses. Etotal is total aperture efficiency.

Freq (GHz)	Esurf	Eillum	Espil	Eblock	Ephase	Emisc	Etotal
0.32	1.00	.80	.80	.86	.96	.95	.50
0.61	1.00	.80	.80	.86	.93	.95	.49
1.5	1.00	.96	.90	.86	.95	.95	.67
2.3	1.00	.96	.92	.86	.98	.95	.71
4.9	1.00	.97	.93	.86	.99	.95	.73
6.1	.99	.97	.93	.86	.99	.95	.72
8.4	.99	.97	.93	.86	.99	.95	.72
10.7	.98	.97	.93	.86	.99	.95	.71
14.9	.96	.97	.93	.86	.99	.95	.70
22	.92	.97	.93	.86	.99	.95	.67
43	.75	.97	.93	.86	.99	.95	.55
86	.32	.97	.93	.86	.99	.95	.23

To indicate the range of efficiencies that result from variations in the main reflector surface rms due to gravity and environment, or due to a more or less accurate subreflector, four cases are examined in the table below. A main reflector rms of 0.011 in (the spec for precision operating conditions) and 0.007 in (no gravity, thermal or wind; ie panels and setting only) is considered. Subreflectors of 0.004 in and 0.008 in rms are considered.

Main rms (in)	Sub rms (in)	Total Effic 43 GHz	Total Effic 86 GHz
0.007	0.004	0.64	0.42
0.007	0.008	0.58	0.28
0.011	0.004	0.55	0.23
0.011	0.008	0.50	0.16

Estimates of the noise contributions of the feed and antenna system are shown in the table below. Tloss is the noise contribution due to resistive losses in the feeds and on the reflector surfaces; for the 2.3 GHz and 8.4 GHz feeds an additional loss due to the dichroic reflector system is included. Tspill is the effect of subreflector diffraction or feed spillover to the ground. Tscatter is ground radiation entering the feed due to scattering off of the quadrupod or other structure on the antenna. Tsky is the total sky brightness due to zenith tropospheric emission, galactic emission in a direction well away from the galactic plane and the 3 degree microwave background. Ttotal is the sum of these four effects and is the total noise entering the receiver input when the antenna is pointed at the zenith with no source in the beam. All contributions are in degrees kelvin.

Freq (GHz)	Tloss	Tspill	Tscatter	Tsky	Ttotal
.32	6	15	3	50	74
.61	6	15	3	10	34
1.5	4	3	5	6	18
2.3	7	2	5	6	20
4.9	2	2	5	6	15
6.1	2	1	5	6	14
8.4	8	1	5	7	21
10.7	3	1	5	7	16
14.9	3	1	5	9	18
22	5	1	5	16	27
43	6	1	5	23	35
86	7	1	5	56	69

The off-set geometry will result in the left and right hand circularly polarized beams from the Cassegrain feeds being separated in the sky by approximately 0.05 beamwidths.

Section 5 - Updates

850726 In section 5.4 modified aperture efficiency estimates to reflect improved antenna surface rms from .013in to .011in.

850304 Added requirement for at least one permanent dual frequency feed pair in Sect 5.1(g).

841204 Sect.5.1(f) spec change; Sect.5.3.2 subreflector accuracy discussion added; Sect.5.33-5.34 0.3 and 0.6 GHz feeds combined; Sect.5.37 comment on 5 GHz feed added; Sect.5.4 effects of more accurate main and sub reflectors added.

840426 Minor corrections to aperture efficiency and horn dimension tables.

840422 Major update. Complete rewrite of all sections to conform to current design.

840218 Initial version based on Volume 3; not necessarily up to date.

SECTION 6

ELECTRONIC RECEIVING SYSTEM

A. R. Thompson and M. Balister

6.1 System Definition

This section is concerned with the receiving system from the feeds in the antenna vertex room to the inputs of the baseband system located in the equipment room of the antenna building. It includes the low-noise front ends, the frequency converters, the local oscillator system, the 500-1000 MHz IF amplifiers, and the cables that transmit the IF signals from the antenna to the antenna building. Also included are the system for monitoring the length of the local oscillator cable, and the monitor and control interfaces of the receiving electronics. Other items that fall within this section include the water vapor radiometers, and the radio link between the Pie Town antenna and the VLA site. Most of the items listed above are shown in the Station Block Diagram: see drawing No. D58001K001.

6.2 Front Ends

Table 6.1 lists the twelve frequency bands that have been considered for the VLBA. Two of these (5.9-6.4 GHz and 10.2-11.2 GHz) are considered to be optional, and are listed with other options in section 6.10. For a discussion of the frequency bands see VLBA Electronics Memo No. 15. The types of amplifiers, receiver noise temperatures, antenna temperatures and system temperatures are given in Table 6.1.

TABLE 6.1. Front-End Characteristics

Frequency Band	Frequency Coverage	Amplifier Type	Physical Temp	Receiver Temp	Antenna Temp
330 MHz	312-342 MHz	GASFET	360K	30K	60K
610 MHz	580-640 MHz	GASFET	360K	32K	30K
1.5 GHz	1.35-1.75 GHz	GASFET	15K	12K	20K
2.3 GHz	2.15-2.35 GHz	GASFET	15K	16K	20K
4.8 GHz	4.6-5.1 GHz	GASFET	15K	20K	20K
6.0 GHz	5.9-6.4 GHz	GASFET	15K	20K	20K

8.4 GHz	8.0-8.8 GHz	GASFET	15K	27K	20K
8.4 GHz	8.0-8.8 GHz	HEMT	15K	11K	20K
10.7 GHz	10.2-11.2 GHz	GASFET	15K	29K	20K
15 GHz	14.4-15.4 GHz	GASFET	15K	45K	22K
23 GHz	21.7-24.1 GHz	HEMT	15K	40K	32K
43 GHz	42.3-43.5 GHz	SIS Mixer	3.5K	40K	37K

The antenna temperatures are approximate and correspond to high angles of elevation and good atmospheric conditions. For all bands except 43 GHz the front ends will use FET amplifiers. Those for 330 and 610 MHz will operate at a stabilized temperature of approximately 360 K, and those for other bands at 15 K. The superconductor-insulator-superconductor (SIS) mixer for 43 GHz will operate at 3.5 K and be followed by an FET amplifier cooled to 15 K. For 4.8 GHz and higher bands, high electron mobility transistors (HEMTs) will be used where possible, as availability allows. In the original proposal masers were considered for the 23 and 43 GHz bands, but later rejected on consideration of the maintenance problems of the cryogenics involved. For a further discussion see VLBA Electronics Memo No. 32.

6.3 Cryogenics

The amplifiers of the 15 K front ends will be cooled by closed-cycle helium refrigerator systems. The polarizers, which produce outputs corresponding to signals of opposite circular polarization from the feeds, are also cooled to minimize the noise associated with resistive losses. For 4.8 GHz and higher bands, the polarizer will be cooled to 15 K, which is the second-stage temperature of the refrigerator. For 1.5 and 2.3 GHz the polarizer is large and would load the second stage too heavily, so it will be cooled to the first-stage temperature of 60 K. For 2.3 GHz and higher bands the CTI model 22 refrigerator will be used. For 1.5 GHz the larger CTI model 350 refrigerator will be used: see VLBA Electronics Memo No. 33. Table 6.2 gives some details of these refrigerators, and for comparison includes the model 1020 which is used on the VLA but is not included in plans for the VLBA. There will be two CTI model 1020 compressors (plus one spare) at each antenna. One such compressor will nominally drive five model 22 refrigerators, or three model 22 and one model 350 refrigerators (or one model 1020 and two model 22 refrigerators).

TABLE 6.2. C.T.I. Refrigerators

Model No.	22	350	1020
Load 60K			35W
Load 15K	1W	2-3W	10W
He (cu ft per min)	9	17	28
Cycles per min	200	72	72
Weight (lbs)	15	22	30
Length of Cooling Section (inches)	7.1	11.2	13.2
Approximate Cost	$3.5k	$6k	$7.2k

6.3 Local Oscillator

6.3.1 Hydrogen Masers

A preliminary specification for the hydrogen maser frequency standard is given in VLBA Memo No. 382. This specification is very similar to that of the Oscilloquartz maser currently in use at the VLA site. The short term stability requirement states that the integrated effect in the range 1 Hz to 1 MHz shall correspond to no more than 0.60 ps rms at 100 MHz. This value is based upon a requirement of 90% correlation at 86 GHz. The long term stability is specified in terms of a curve of Allan variance for which the value at 1 s is 7×10^{-14}.

6.3.2 LO System Modules

The distribution and synthesis of local oscillator signals requires three principal units which are briefly described as follows.

(a) LO Transmitter Module

This unit takes the maser output signals at 100 MHz and 5 MHz and generates signals at 500 MHz and various subharmonics of 5 MHz (e.g. 10 kHz) that are required for timing. The 100 MHz and 500 MHz signals are combined and transmitted by coaxial cable to the antenna vertex room. A signal with a small frequency offset from 500 MHz is generated in a modulated reflector in the vertex room and returned back down the cable. In the LO Transmitter Module the returned signal is used to monitor the electrical length of the cable, and this information goes to the computer and is eventually used to correct the visibility phases at the correlator.

(b) LO Receiver Module

This module is at the vertex-room end of the local oscillator cable, and in it the 100 and 500 MHz signals are separated and made available to the frequency synthesizer units. This module also contains the modulated reflector for round-trip phase measurement of the cable length.

(c) 2-16 GHz Synthesizer Module

This unit takes the reference signals at 100 and 500 MHz and generates signals at (N X 500 $\pm$ 100) MHz, where N is an integer in the range 4 to 32. Three of these units will be required at each antenna (or two of them plus a fixed-tuned 9.4 GHz oscillator).

6.4 The IF System

In the frequency bands up to and including 15 GHz the signals are converted to a first IF band which extends from 500 MHz to 1000 MHz. The frequency conversion is by means of the signals from the 2-16 GHz Synthesizer Modules described under section 6.3.2. For the 23 and 43 GHz band a higher first IF will be used to improve the image rejection. The frequency conversion to 500-1000 MHz will be performed in a frequency converter module of which there will be one for each band. The two IF signals from the two polarizations will be amplified within the converter module, and the power levels at the outputs monitored by a detector. The output signals go to an IF Switching Panel in which the signal bands required for a particular observation are selected and transmitted by cable to the equipment room of the station building. Recommended power levels at various points in the signal path are given in VLBA Electronics Memo No. 30. The total gain (RF plus IF) at the antenna for each band is in the range 60 $\pm$ 10 dB to produce a level of -42 dBm at the cable output.

For the 610 MHz frequency band the received signals lie within the required IF band, but because of the high levels of television signals in nearby bands at many of the sites, a double-conversion filtering system will be included. Signals in the band 608-614 MHz will be converted to 8-13 MHz using local oscillator frequencies of 500 MHz and 100 MHz. The signals will then pass through a filter with a bandwidth of 4 MHz at the -3dB level and 7.2 MHz at -50 dB, and will then be reconverted to the original input band. At other bands special filtering may be required to reduce particular interfering signals, and in most cases it should be possible to insert such filters in the 500-1000 MHz IF band. The concern here is with signals that would be rejected by the baseband filters, but would be strong enough to cause gain compression in the 500-1000 MHz IF amplifiers. Levels of signals that can be tolerated within the receiving bands are discussed in VLBA Memo No. 81.

6.5 Monitor and Control Interfaces

There will be a separate control module for each front end, with interface to the monitor and control bus. A Switch Control Module containing an interface and a series of switch drivers will be used with the switching panel that makes the local oscillator and IF interconnections required for any particular observation. The 2-16 GHz Synthesizer Modules will each contain an interface with the monitor and control bus to receive tuning commands.

6.6 VLBA Water Vapor Radiometers

The largest phase errors in the visibility data produced by the VLBA in the higher frequency bands will be those caused by fluctuations in the amount of water vapor along the line of site to each antenna. The size of these phase errors can be reduced by measuring the amount of water vapor above each antenna using water vapor radiometers and applying a phase correction based on these measurements. A WVR consists of a pair of accurate microwave radiometers which measure the brightness temperature of the sky at frequencies of approximately 21.7 GHz and 30.7 GHz. It is proposed to leave the construction of these radiometers until late in the program so that the project can benefit from the development efforts that are currently underway at the VLA, JPL and other laboratories.

6.7 Radio Link for VLA Area Antennas

It has been proposed that the antenna at Pie Town should be linked by microwave systems to the VLA site to allow real time correlation with the VLA ad tape recording at the VLA site. To accommodate the signal bandwidth of 200 MHz required for maximum sensitivity in real time correlation with the VLA, the links would have to be in the 18 GHz or 25 GHz regions of the spectrum. Some preliminary considerations of the link requirements have been given in VLBA Memos No. 213, 240 and 246, and VLBA Electronics Memo No. 1. The radio link could also include transmission of LO reference freqencies from the hydrogen maser at the VLA site, and thus eliminate the need for a maser at the Pie Town site. The radio link was included in the VLBA proposal as an option for one maser, on the assumption that the link cost would not exceed that of a maser.

6.8 Construction Plan

Construction of the receiving electronics will be spread between the Green Bank, Charlottesville and VLA electronics groups as best fits the available manpower. A preliminary construction plan is given in VLBA Electronics Memo No. 18, but this will be modified to match the eventual funding plan. The principal aims in planning the construction are to have a local oscillator system and about five front ends ready for installation as each antenna is completed. Other front ends, water vapor radiometers and optional items will be constructed and installed in the later years of the construction program. For planning purposes receiving bands are divided into five groups as follows:

A	1.5, 4.8 and 15 GHz
B	330 and 610 MHz
C	2.3 and 8.4 GHz
D	23 and 43 GHz
E	6.0 and 10.7 GHz

Installation will generally follow the order A to E, early bands being chosen because of their astronomical importance (group A) or low cost (group B) and later ones because of longer development required (group D) or lesser importance (group E).

6.9 Cost Estimate

A preliminary cost estimate is given in Table 6.3. This will be revised as more precise figures become available.

TABLE 6.3. VLBA Receiver Front-End Cost Estimate, 1983 k$

Frequency	Amplifier Design				Subsystem Design				Fabrication Installation				Total Labor			
	E	T	S	D	E	T	S	D	E	T	S	D	E	T	S	D
.312-.342	0	0	0	1	4	3	2	2	6	10	5	0	10	13	7	3
.580-.640	3	4	1	1	4	3	2	2	6	10	5	0	13	17	8	3
1.35-1.75	0	0	0	1	6	4	3	3	6	10	6	0	12	16	9	4
2.15-2.35	6	4	2	1	6	4	2	2	6	12	5	0	18	20	9	3
4.6-5.1	3	2	1	1	6	4	2	2	6	12	5	0	15	16	8	3
8.0-8.8	6	3	1	1	6	4	2	1	6	10	5	0	18	17	8	2
10.2-11.2	3	3	1	1	6	4	2	1	6	10	5	0	15	17	8	2
14.4-15.4	0	0	0	1	6	4	2	1	4	10	5	0	10	14	7	2
23/43	18	16	5	6	8	7	3	3	67	97	7	3	93	120	15	12
System					12	12	0	3	6	6	6	2	18	6	6	5
Total	39	32	11	14	64	37	20	20	119	187	54	5	222	256	89	39

Frequency	Labor Cost	Total Materials	Total Cost
.312-.342	87	67 (13)	154
.580-.640	110	67 (13)	177
1.35-1.75	108	191 (15)	299
2.15-2.35	137	182 (25)	319
4.6-5.1	115	182 (25)	297
8.0-8.8	126	182 (25)	308
10.2-11.2	115	182 (25)	297
14.4-15.4	87	182 (25)	269
23/43	667	1133 (228)	1800
System	104	605	709
Total	1656	2973	4629

Notes: E, T, S, and D are engineering, technician, shop and drafting man-months. Engineering labor is costed at a 1983 labor rate of $45k/man-year; other labor is costed at a labor rate of $26k/man-year. Both rates include benefits.

Design labor has been separated into amplifier design, and subsystem which includes dewar, transition, final L.O., mixer, calibration, and monitor circuits. A total 96k$ per antenna for cryogenics costs has been split into refrigerator costs included in the cost for each frequency and a common system cost for compressors and helium lines. All cryogenic costs have been listed as materials but may be exchanged for labor costs if a decision is made in favor of internal fabrication of compressors and 4K modification of cooling heads. A provisional cost estimate of $50k per antenna has been made for the water vapor radiometers.

6.10 Optional Items

The items listed below with their estimated costs are regarded as optional since decisions upon which of them are to be procured will be made as the project progresses. These decisions will depend upon the funding which is found to be available as more accurate cost estimates are developed for other parts of the electronics, and upon further analysis of the scientific usefulness of the various options.

	1985 dollars
1. Improved-Accuracy Subreflectors (will improve aperture efficiency at 80 GHz in good observing conditions)	$50k x 10 = $500k
2. Water Vapor Radiometers	$50k per antenna
3. 10.7 GHz Feeds and Front Ends	$(4k + 20k) x 10 = $240k
4. 6 GHz Front Ends (share 4.8 GHz feeds)	$20k x 10 = $200k
5. 100 ns Timing System (Navstar Receivers)	$25k x 10 = $250k
6. Pie Town Radio Link to VLA Site (or spare H maser)	$300k (approximate estimate only)

Of the above items, only the water vapor radiometers and receiving systems for one of the two frequency bands (6 and 10.7 GHz) were included in the original VLBA budget. A spare maser is required and is available from the spares item in the budget. It is considered an option since the radio link would release a maser to be used as a spare. For a more detailed list of options see Section 13.

Section 6 - Updates

850826 Allan variance spec. plus minor changes.

850221 Complete rewrite except for section 6.9.

840424 System noise changed to match TA from Section 5.

840420 Minor changes plus update of construction plan.

840322 Added summary Table 6.1 and block diagram 6.2 plus statement about 23 GHz paramp.

840218 Initial version based on Vol 3; not necessarily up to date.

SECTION 7

LOCAL OSCILLATORS

L. R. D'Addario

7.1 SPECIFICATIONS

For the exact tuning range on each band, see VLBA Memo No. 295.

Detailed specifications for each component of the LO system have not yet been determined. Power levels, phase stability, interfaces, monitoring, and other details need to be specified.

7.2 DESCRIPTION

The frequency conversion scheme has been considerably revised from that described in Volume I of the VLBA proposal. Here we describe the present plan, which is depicted in Figures 7.2.1 and 7.2.2.

In the vertex room of the antenna, the received signal in each band is converted to an IF of 500 to 1000 MHz. For all but the 1.3 cm and 0.7 cm bands, this is done in a single mixing. For those bands where the input bandwidth exceeds 500 MHz (namely 3.6 cm, 3 cm, and 2 cm), the band is covered by two L.O. tuning frequencies, one above and one below the signal band; this allows good image rejection provided that the bandwidth does not much exceed 1000 MHz. To cover the bandwidth of the 3.6 cm front end (8.0 to 8.8 GHz) requires two L.O. frequencies on each side of the band.

Because of the availability of wide-range, YIG tuned oscillators in the microwave region, it is feasible to design a single synthesizer to provide the required first L.O. signals for all bands through 2 cm. To accommodate dual-band operation, two such synthesizers are needed. A switching arrangement which allows each synthesizer to connect to any receiver is considered unnecessarily complicated and expensive, but the arrangement shown in Figure 7.2.2 allows most of the interesting dual-band setups to be implemented. A transfer switch is provided to swap the roles of the synthesizers, allowing single-band operation to continue on any band even if one synthesizer fails.

At 3.6 cm, it is considered necessary to be able to observe both ends of the band simultaneously. To accomplish this, we provide two mixers for each polarization, with one driven by a fixed-frequency oscillator at 9.4 GHz (so that it converts the upper portion of the band), while the other mixer remains driven by the synthesizer (which can be set to convert the lower portion of the band). We also provide switching so that any two mixer outputs may be connected to the two I.F. channels. The 9.4 GHz oscillator is also needed for the 1.3 cm band (see below); its use here leaves the second synthesizer available for dual-band operation.

The two highest frequency bands require an additional frequency conversion in order to maintain image rejection. At 1.3 cm, the first LO will be provided y the 2-16 GHz synthesizer, and the second LO will be the 9.4 GHz PLO. At 0.7 cm, the planned SIS mixer will require a first IF at 1.3 to 1.8 GHz, which requires a special PLO at 41.2 to 41.7 GHz; the 2-16 GHz GHz synthesizer then provides the second LO at 2.3 GHz.

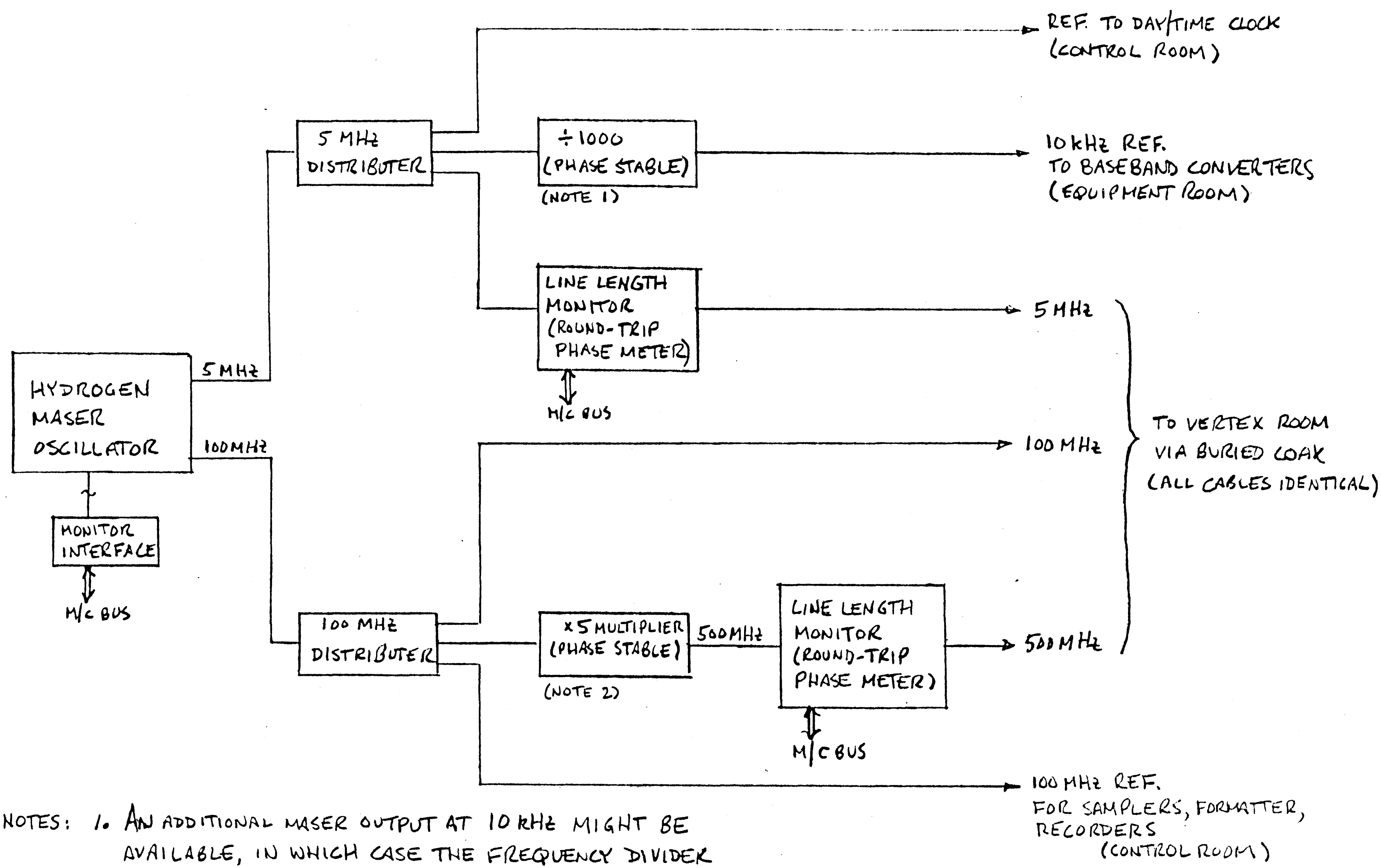
As of August 1985, it is uncertain whether the 2-16 GHz synthesizer can be made to operate reliably at all multiples of 100 MHz (except harmonics of 500 MHz), as originally planned. Instead, operation may be restricted to 500N+_100 MHz, for $4 <= N <= 32$. It turns out that this affects only two bands: 20 cm and 0.7 cm (the latter because it uses an L-band first IF). At 20 cm, the input band will not be coverable in a single tuning; separate synthesizer tunings will give accessible frequencies of 1.1 to 1.6 GHz and 1.4 to 1.9 GHz, respectively. In each case, one end will be outside the specified front end range, and the other end will be at the edge of the IF band. At 0.7 cm, a slight shift in the optimization of the IF amplifier toward higher frequencies will probably avoid any tuning problems, but this must be decided before certain major components of that receiver are ordered.

Four 500 MHz bandwidth IF signals are selected by switches from the 26 possible outputs of the front-ends, and these four signals are transmitted by cable to an equipment room in the station control building. To avoid excessive complexity in the switches, a full 26-by-4 matrix is not implemented; nevertheless, every front-end output can be connected to either of two IF channels, so no band is lost in the event of a single-channel failure.

At the equipment room, the IF signals are converted to baseband in image-rejecting mixers, with the L.O. tunable over the 500 to 100 MHz range in .01 MHz steps. A distribution and switching arrangement allows an IF to be connected to any baseband converter. The baseband signals are quantized and sampled in the digitizing process. The sampling clock generator is thus the final L.O.

(These operations are part of the Digitization System, covered in Section 8 of the Project Book.)

All L.O. signals are ultimately derived from the hydrogen maser frequency standard. Most of them must be tunable, with coarse tuning (about 100 MHz steps) in the vertex room and fine tuning (10 kHz) in the equipment room. The hydrogen maser provides two standard frequencies: 100 MHz and 5 MHz (see Figure 7.2.1). Although we could transmit only the 100 MHz reference to the vertex room, this would require generation of many undesired harmonics of 100 MHz near the sensitive receivers, and would require a high order of frequency multiplication in a poorly controlled environment. Also, in order to compensate for transmission line length variations, the line length must be monitored, and this can be done more precisely at a higher frequency. Therefore, the maser output is multiplied to 500 MHz in the equipment room and this frequency is transmitted to the vertex room. The 10 kHz reference for the baseband converters is derived by dividing down the 5 MHz from the maser.



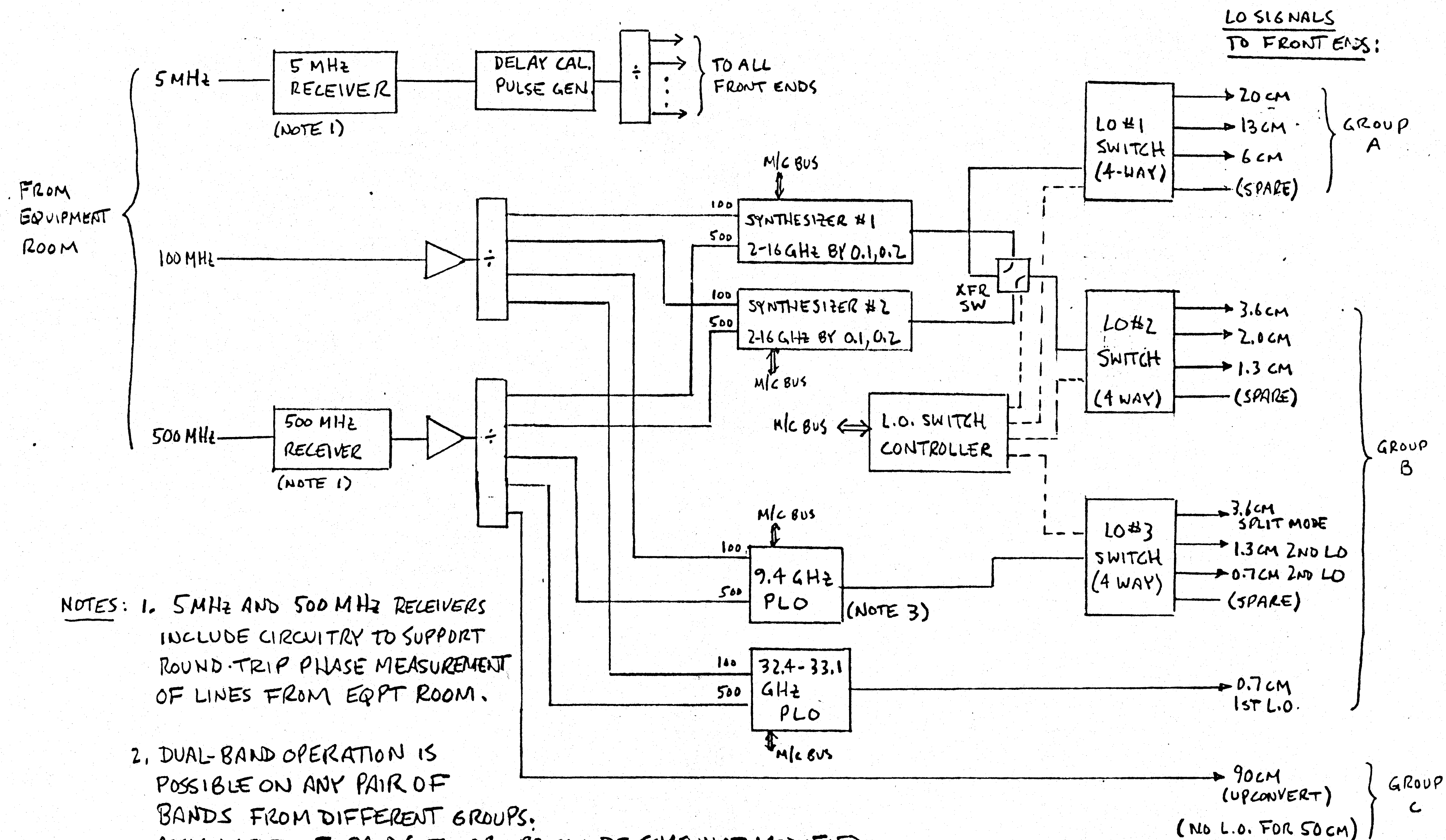
NOTES:
1. AN ADDITIONAL MASER OUTPUT AT 10 kHz MIGHT BE AVAILABLE, IN WHICH CASE THE FREQUENCY DIVIDER COULD BE ELIMINATED.

2. AN ADDITIONAL MASER OUTPUT CONTAINING A 100 MHz COMB MIGHT BE AVAILABLE, IN WHICH CASE THE x5 MULTIPLIER COULD BE REPLACED BY A 500 MHz FILTER.

FIGURE 7.2.1, sheet 1 of 1.

VLBA LOCAL OSCILLATOR SYSTEM:
EQUIPMENT ROOM PORTION,
BLOCK DIAGRAM

831216 LRD



NOTES: 1. 5 MHz AND 500 MHz RECEIVERS INCLUDE CIRCUITRY TO SUPPORT ROUND-TRIP PHASE MEASUREMENT OF LINES FROM EQPT ROOM.

2. DUAL-BAND OPERATION IS POSSIBLE ON ANY PAIR OF BANDS FROM DIFFERENT GROUPS. ASSIGNMENT OF BANDS TO GROUPS CAN BE SOMEWHAT MODIFIED IF NECESSARY.

3. IN CASE ADDITIONAL FLEXIBILITY IS NEEDED IN THE FUTURE, THE 9.4 GHz PLO CAN BE REPLACED BY A THIRD SYNTHESIZER.

VLBA LOCAL OSCILLATOR SYSTEM:
VERTEX ROOM PORTION
BLOCK DIAGRAM

[redacted]16 [redacted]

FIGURE 7.2.2, sheet 1 of 1

Section 7 - Updates

850809 Revised to indicate effects of possible 200 MHz min spacing of 2-16 GHz synthesizer frequencies. Revised 0.7 cm LO freq to reflect probable 1.5 GHz first IF. Figures not yet revised to agree with text.

841130 Contents reviewed; no changes required.

840412 Revised 3.6 cm receiver description so that both IFs can be on same polarization but with different LOs. Brief section on specifications added.

840207 Project Book Section 7: Local Oscillators (initial version)

SECTION 8

DIGITIZER

A. E. E. Rogers

----Contents ----

8.1 SPECIFICATION

GENERAL
INTERFACES
I.F. INPUT FROM RECEIVERS
FREQUENCY AND TIME
COMMUNICATIONS
OUTPUT TO RECORDER
I.F. DISTRIBUTORS
BASEBAND CONVERTERS
FORMATTER
DECODER/DATA BUFFER

8.2 DESCRIPTION

8.1.1 GENERAL

Number of I.F. inputs:	4
I.F. frequency range :	500 - 1000 MHz
Number of baseband channels:	32 (16 upper and lower sideband pairs)
Baseband L.O. coverage:	500-1000 MHz in 10 KHz steps
Baseband bandwidths:	8,4,2,1,0.5,0.25,0.125,0.0625,ext MHz
Sample clock rates:	16,8,4,2,1,0.5,0.25,0.125 MHz
Sample Quantization:	(-W=00, -1=01, +1=10, +W=11) or 2-level coded in 1 bit (sign)
Data format:	modified MK III with non-data replacement
Flexibility:	1) Each baseband converter can connect to any of the 4 I.F.s

	2) Baseband converters are independent and can have different L.O. frequencies and bandwidths
	3) Any formatted output can be assigned to any digitizer output (within the restrictions given below)
Restrictions:	1) All channels must be sampled at the same rate
	2) Maximum digitization throughput(in 2 units - see sect 8.1.5) 2x32x8=512 Mbits/s
	3) All outputs must be used in same formatter mode (see section on formatter)

8.1.2 INTERFACES

8.1.2.1 I.F. INPUT FROM RECEIVERS

Signals:	4 I.F.s in the range 500 - 1000 MHz
Levels:	-40 dBm nominal in 500 MHz bandwidth
Cables:	RG-9 or equivalent
Connectors:	Type N (male on cable ends from receivers)

8.1.2.2 FREQUENCY AND TIME

FREQ:	
Signals:	5 MHz at +13 dBm (nominal)
Cable:	RG-9 or RG-142 or equiv
Connector:	Type N or SMA
TIME:	
Signal:	20 Hz square wave -0.5 to +0.5 volt plus 1 pps to allow for the possibility of manually synchronizing the formatter
Cable:	RG-142 or equiv
Connector:	SMA or BNC

8.1.2.3 COMMUNICATIONS

via MONITOR/CONTROL bus see sect 4

8.1.2.4 OUTPUT TO RECORDER

Signals: 2 independently buffered sets of
32 balanced ECL signals from formatter in each rack
(32 balanced ECL from each of 2 formatters to each of 2 recorders)

8.1.3 I.F. DISTRIBUTORS

Input frequency range:	500-1000 MHz
Gain:	0 dB at 750 MHz
Input atten range:	0,-15 +/-1 dB, -30 +/-1.5 dB, infinity
Max phase change with gain:	<0.6 deg peak to peak

Square law linearity:	< 1% from 5% to full scale
Isolation between outputs:	> 20 dB
Noise temperature:	< 100,000 deg K

8.1.4 BASEBAND CONVERTERS

Input range:	492-1008 MHz
Gain through conv(2 MHz BW):	64 +- 1 dB maximum gain
Level control max atten:	30 dB
Level control phase shift:	< 0.5 deg over full range of atten
Gain for other bandwidths:	-3 dB/ octave increase in bandwidth
Image rejection:	>26 dB over video range 10 kHz to 8 MHz
Output power:	0 +-0.5 dBm
L.O. range:	500-1000 MHz in 10 KHz steps
Energy in 10 KHz sidebands:	< -40 dBc
L.O. phase noise:	< 2 deg. rms
L.O. leakage into video	< -50 dB
Gain compression:	< 0.05 dB (1%)
SNR(noise from converter):	> 25 dB
Noise temperature:	< 100,000 deg K when combined with IFD
Dynamic range:	> 30 dB
Temperature coeff of phase:	< 1 deg/ deg C/ GHz
L.O. settling time:	< 1 sec
L.O. repeatability:	< 0.1 deg upon return to same frequency
L.O. leakage into input:	< -60 dBm
Temperature coeff. of gain:	< 0.1 dB/ deg C
Temperature coeff. of differential phase:	< 0.1 deg/ deg C
Temperature coeff. of baseband delay:	< 0.1 ns/ deg C at 8 MHz BW
4-way input switch isolation:	> 60 dB
Bandpass response:	1) >10 dB down at bandedge x 1.08 2) <0.5 dB ripple across lower 80% 3) <1 dB between units across upper 20% 4) <5 deg phase ripple between units across lower 80% of band 5) <10 deg between units across upper 20% 6) <0.1 deg/deg C temperature coefficient of phase over 80% of band 7) <0.1 dB/deg C temperature coefficient of amplitude over 80% of band (The above should ensure that closure errors are < 0.1 degrees)
Bandwidths:	8,4,2,1,0.5,0.25,0.125,0.0625 MHz and external filter
Data processing:	1) Total power integration and synchronous detection with periods of an integral number of 20 Hz half-cycles or 25 msec 2) Auto-leveling of output power

Monitor and control:

FUNCTION	#bits	control	monitor
IF input select	2	Y	Y
L.O. frequency	12	Y	Y
L.O. unlock	1	N	Y
USB bandwidth	4	Y	Y
LSB bandwidth	4	Y	Y
USB gain	12	Y	Y
LSB gain	12	Y	Y
USB TPI for last ref period	16	N	Y
LSB TPI for last ref period	16	N	Y
USB TPI(sig-ref)	16	N	Y
LSB TPI(sig-ref)	16	N	Y
#cycles to be averaged	16	Y	Y
USB auto-level on/off	1	Y	Y
LSB auto-level on/off	1	Y	Y
serial number	16	N	Y

8.1.5 FORMATTER

Number of video inputs:	16 (8 USB plus 8 LSB) in each of 2 identical formatters (one per rack)
Number of formatter outputs:	32 (64 for both units)
Sample rates:	16,8,4,2 MHz
Output format:	Serial data format with time code, auxillary data, CRC error detection, (if needed to meet playback error rate specs), sync word, parity and programmable data block and frame length.
Video input level:	0+-0.5 dBm
Input impedance:	50 ohms unbalanced
Threshold equivalent DC offset and hysteresis:	< 5 mv
Threshold level:	200 mv (for magnitude) 0 mv (for sign)
Sampling epoch accuracy:	< 2 ns (between channels)
sampling jitter and drift:	< 0.2 ns
Sampling modes:	2-level (1 bit) and 4-level (2 bits) (4-level coding -w=00,-1=01,+1=10,+w=11 with MSB (sign) bit and LSB bit on separate tracks)
Formatter modes:	1X (output rate/track = sample rate) 2X (output rate/track = sample rate/2) 4X (output rate/track = sample rate/4) Notes: In 1X mode adjacent time samples are on the same track

In 2X mode odd and even samples are on separate tracks
In 4X mode there is a 4-way split i.e. 1st. sample to trk w, 2nd. to trk x, 3rd. to trk y, 4th. to trk z

tracks/video signal:

SAMPLING	FORMATTER MODE 1X	2X	4X
2-LEVEL	1	2	4
4-LEVEL	2	4	8

Track switch: 32x32 switch to allow an arbitrary reassignment of data samples to recorder tracks - This assignment can be changed dynamically every frame

Output

Signals: 2 independently buffered sets of
32 balanced ECL signals from formatter in each rack
(32 balanced ECL from each of 2 formatters to each of 2 recorders)
Data Quality Analyser/Data Buffer (submodule of Formatter)
Data Memory: 4 Mbits

8.2 DESCRIPTION

The data acquisition system will use conventional VLBI techniques with fixed-phase sampling and no fringe rotation - other than that which might be provided by offsetting the local oscillators in fixed steps. The system is modular with multiple baseband converters for multiple polarizations, frequency bands, bandwidth synthesis and pulsar dispersion. Sampling can be either 2 or 4-level. 4-level being provided to provide higher SNR for spectral line observations and to achieve the same SNR in continuum with a narrower bandwidth (for interference avoidance).

Section 8 - Updates

840301 Section 8 - Digitizer (initial version)

840420 Section 8 - Digitizer (version #2)

841127 Section 8 - Digitizer (version #3)

850218 Section 8 - Digitizer (version #4)

850805 Section 8 - Digitizer (version #5)

SECTION 9

RECORDERS AND PLAYBACK

A. E. E. Rogers

----Contents ----

9.1 SPECIFICATION

GENERAL
INTERFACES
FORMATTERS TO RECORDERS
RECORDERS TO PROCESSOR
RECORDER

9.2 DESCRIPTION

9.1.1 GENERAL

Longitudinal recording will be used in which a narrow track headstack is physically moved between passes of the tape

Average recording rate:	100 Mb/s for 24 hours unattended
High data rate (HDR):	200 Mb/s or greater

For each channel and for an averaging time of 1 minute (real time)

Fraction of bits out of sync but flagged valid:	<10**-5
Fraction of incorrect bits flagged valid(excluding bits out of sync):	<3 x 10**-4
Fraction of bits flagged invalid:	<10**-2

If the above specs are met for the prescribed averaging time
of 1 minute then there can be no loss of data (dropout) longer
than 600 msec.
(In no circumstances even when performance degrades should data which
fail to meet error specs 1 (fraction of bits out of sync but flagged valid)
or 2 (fraction of incorrect bits flagged valid) be passed to the correlator)
*** see spec. A54001N001

Weight of tape/day/station	< 50 lbs at average rate
Redundancy:	The system will continue to ensure that observations can continue without maintenance in the event of single failures, provided unrecorded tape is available on at least one working transport
Phase switching:	The DPS should be able to unscramble any phase swithing that might be applied in the LO system. This unscrambling can be accomplished by reversing the sign of the data being fed to the correlator using a deterministic algorithm.

9.1.2 INTERFACES

9.1.2.1 FORMATTERS TO RECORDERS see sect. 8.1.2.4

9.1.2.2 RECORDERS TO PROCESSOR

DPS/CORRELATOR INTERFACE

TIMING INTERFACE (Correlator to DPS):

1-s tick and a "bit clock". Signals provided on differential ECL lines. Rise time of the 1-s tick signal shall be sufficient to resolve a single "bit clock" cycle. Each "bit-clock" transition will advance all DPS channel outputs by one bit.

SIGNAL INTERFACE (DPS to Correlator):

The signals provided by the DPS at this interface are:

16 output channels, where each channel contains sign, magnitude, and validity data as separate signals. These signals are clocked out by the "bit clock" at 16M samples/s with repeated samples for data being reproduced at lower rates. A constant delay offset (which is specified to within

one sample interval) can be applied to all DPS output channels. This delay which is common to all DPS output channels can be used to augment the delay offset capabilities of the processor.

A clock synchronous with data and a 1-s tick , to allow unambiguous reclocking of the data.

All signals shall be differential ECL with a maximum data rate of 25 Mbits/sec on each signal line. Line drivers will be capable of driving cables of up to fifty feet long.

CHANNEL SWITCHING:

Each of the 16 DPS output channels can be independently connected to any recorded baseband channel (to be set-up by control interface).

DPS CONTROL INTERFACE

Each DPS microcomputer will communicate with the Correlator Control Computer (CCC) via the VLBA Monitor and Control Bus proposed for the VLBA antenna systems.

DPS ADDRESSING

There may be 24 or more DPS units to be controlled. Either of two addressing modes can be used: a global mode, in which all recorders are commanded identically with a single command, and an individual mode with only one unit responding. The address specification for DPS units should allow for at least 64 separate units. (Perhaps with address 0 being used for Global commands.)

TIME SYNCHRONIZATION

To implement synchronization each DPS maintains a data-time command clock which is initialized by the correlator control computer and 1-s tick, and incremented by the 16-MHz clock. The DPS slaves the reproduced tape-time to match this command clock. Data are flagged invalid when this synchronization fails.

COMMANDS

Commands not requiring an immediate response can be either global or individual. The general functions that will be required are as follows:

1. SET PLAYBACK CONFIGURATION: accept assignments of recorded tracks to interface channels, playback rate (if the optional slow speed is implemented)and a fixed time offset to be applied to the commanded tape-time.

2. SET RECORDING MODE: accept recorded data rate, track fanout, and number of bits/sample. These additional data are needed for correct routing of the reproduced signals by the DPS.

3. ALIGN: accept start time and tape footage/pass, and tape serial number (for verification). The DPS positions the tape sufficiently before the specified point to allow for speedup and synchronization.

4. SYNCHRONIZE: set all DPS tape-time command clocks to the desired scan start time (which generally precedes all the ALIGN start times), and begin counting at the next 1-s tick. Each DPS is then responsible for starting its tape as necessary to achieve synchronization when the ALIGN tape-time occurs.

5. POSITION: positions tape at high speed to an arbitrary footage

6. STOP: stop all command clocks and tape transports.

7. UNLOAD: rewind and unload tape.

8. RELOAD: restore tape transport to ready state.

9. STATUS: report DPS status to the CCC. These requests from the CCC occur periodically during normal operation to monitor performance. Reported data include recorder status (online, ready, etc.), parity and CRCC error rates,tape serial #, and other housekeeping and self-check results.

10. DIAGNOSTICS: We anticipate that some DPS diagnostic functions will be exercised by special commands through the control interface.

9.1.3 RECORDERS

Nominal record speeds: 60,120,240 inches/sec
Playback speed: 240 inches/sec

Section 9 - Updates

840420 Section 9 - Recorders and playback system (initial version)

841127 Section 9 - Recorders and playback system (version #2)

850218 Section 9 - Recorders and playback system (version #3)

850806 Section 9 - Recorders and playback system (version #4)

SECTION 10

CORRELATOR

M. S. Ewing

------------------ INDEX ------------------------------

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10.1 SPECIFICATIONS

10.1.1 Major modes

Table 2-1 emphasizes the modes available for spectroscopy, without polarization processing. In most cases, "quarter" mode will be adequate for continuum work.

Tables 2-2 to 2-5 give further details of the correlator operating modes. They show polarized (P) vs. non-polarized (NP) modes, the number of correlator input channels (CICs), the number of separate IF bands, and the RF bandwidth of an observing mode. The delay coverage (in lags) and the corresponding frequency resolution are also indicated. Variants tagged with a letter (1a, 2b, etc.) show modes that support higher frequency resolution at the cost of reduced bandwidth. Bandwidth may also be traded to process multiple phase centers; these modes are primed (2a′, etc.).

In polarized (P) modes, baseband channels will be recorded in L, R pairs. The correlator forms all four cross-correlation products: L x L, L x R, R x L, R x R. Since each baseband takes two channels, the maximum available observing bandwidth is half that available in NP modes; and since four correlator products must be evaluated for every cross-correlation lag, the number of independent frequency channels is divided by four.

In "alternate full mode," the correlator is set up as it would be for a 20-station run, but only 10 stations are played back. This mode delivers double the number of channels per station and therefore double the processing bandwidth. In some cases, 2 or 4 DPS units per station are required.

Note that quantization (1-bit/2-level or 2-bit/4-level) is selectable for any of the modes described. Thus for example, mode 2 could correspond to a recording rate of 256 Mb/s (1-bit quantization) or 512 Mb/s (2-bit).

Higher recording rates can require more than one tape transport per station. Such operating modes are not in the basic VLBA specifications, but will be supported by the correlator. For example, a 512 Mb/s rate takes two tape transports and 64 "tracks," according to recording system plans. Mode 8 with 1024 Mb/s for 2-bit sampling takes 4 transports and 128 tracks.

Tables 2-2 to 2-5 do not show the various additional modes that are produced by changing the data shift clock rate (see section 2.10) or the tape speedup factor (see section 2.3). Slower data shift clock rates provide higher frequency resolution while decreasing the total bandwidth. Tape speedup is used to increase correlator throughput when the maximum recording rates are not required.

10.1.2 Number of on-line data playback systems (DPS)

24. This is the maximum number which can be supported by the correlator input switching; not more than 20 units can play back at once. The number of DPS units provided may be smaller, but several units should be allocated as "buffers" to permit efficient tape changing and "hot spares" in case of hardware failure. Note that the limit of 24 DPS units implies that some of the modes listed in section2.1 (e.g., mode 8) cannot be supported for the full number of stations.

10.1.3 Speedup factor

1, 2, or 4. Data recording speed may be lower than the constant playback speed. Correlator phase and delay tracking and the effective fringe rate window will be degraded. These effects are due to the correlator updates and readouts running at constant intervals at correlation time.

10.1.4 Geometric array tracking

```
   Delay range:
        Static:         arbitrary via DPS offset
        Dynamic:        RAM buffer, at least 21 ms
   Delay rate range:    -25 to +25 sample/s
   Delay tracking error:     < 1/2 sample
   Fringe rate range:  -128 to +128 kHz
   Phase tracking error:     < 0.05deg x (speedup factor)^2
        for D/lambda = 1.4 x 10^9   (e.g., D= 10,000 km, lambda=7 mm)
```

Speedup factor may degrade phase tracking, since phase tracking updates will occur at fixed correlator intervals.

10.1.5 Maximum number of correlator input channels per DPS

16. The total numbers of CICs available is 320. Modes that require 32 CICs per station will use two or more DPS units per station.

10.1.6 Channel input clock rate

16 Msample/s, nominal.

10.1.7 Sample quantization

1 bit (2 levels) or 2 bit (4 levels). Input channels always carry 2-bit data samples, but one bit may be ignored if 1-bit operation is desired. The correlator input data will be coded as sign and magnitude.

10.1.8 Data validity flag

1 bit/sample. The validity bit permits correlation of a sample if true

and inhibits correlation if false. The bit is generated in the DPS; it may change state on any sample.

10.1.9 Correlator multiplier clock rate

16 Msample/s, nominal.

10.1.10 Correlator data shift clock rate

16 Msample/s, 8 Msample/s, ..., 0.125 Msample/s. Running the shift clock at less than the sample rate allows the spanned delay range to be increased, and therefore the frequency resolution, at the cost of discarding some fraction of the samples. This may be useful when the IFs are oversampled (sampled at greater than the Nyquist rate), i.e., when narrow bandwidths are observed. An implementation option for the correlator VLSI chip is to provide extra delay stages between multipliers, so that all samples may be correlated in some oversampling modes. (SNR gains are small for 4-level sampling, however.)

10.1.11 Phase calibration

Number of detectors per station:	4
Tone offset within channel:	0.01-7.99 MHz
LO resolution:	10 kHz
LO quantization:	256 levels
Hardware integration interval:	1 s

Phase calibrator detection occurs before delay correction. Invalid data are blanked. Each detector can be switched among four data channels and among any number of tones within each channel. Detector switching can occur on any 1-s integration boundary. Integration beyond 1 s occurs in software. (It has not yet been decided whether phase calibrator detection in the correlator is required. This specification indicates how it would be implemented if it is decided to do so.)

10.1.12 Simultaneous correlation of unrelated experiments

2 experiments. If two independent experiments involve a total of 10 or fewer antennas (including possible duplicated antennas), they may be processed together in "full" mode. If the total is 11-14, they may be processed in "half" mode; 15-20, in "quarter" mode. The two experiments must be of compatible types. High-resolution spectroscopy cannot generally be processed in parallel with wideband continuum, for example. In some cases, four simultaneous experiments might usefully be correlated; this capability is considered an implementation option.

10.1.13 Correlator maximum integration time

10 seconds (maximum).

10.1.14 Correlator minimum integration time (maximum dump rate)

2 Hz (full correlator) up to 8 Hz (some correlator subset). The maximum dump rate is determined by the need to handle a range of fringe rates, due either to a wide field of view or unknown a priori rates. Higher dump rates may be achieved by reducing other requirements, e.g., the number of lags to be read out.

10.1.15 Pulsar time gating

Periods:	0.1 ms to 10 s
Precision:	<1 us
Windows per period:	1-3
Window widths:	0.1%-50% of period, non-overlapping
Parameter update period:	30 s or greater
No. of gate generators:	16 (i.e., 1 per channel)

Pulsar gates will be generated channel-by-channel. Channel windows may be offset to allow for dispersion, etc. Gating off is equivalent to setting data "invalid."

10.1.16 Post-correlation processing

Correlation normalization.
Van Vleck correction.
Fractional bit-shift correction.
Accumulation with selectable filter characteristics
(boxcar or more efficient sample rate reduction).
FFT (lag to frequency).
LSR correction (if required).
Phase calibration correction (if required).

10.1.17 Calibration source processing

The control computer will reduce short calibrator runs and fit fringes sufficiently well to monitor clock and LO offsets and apply corrections to station parameters for subsequent scans.

10.1.18 Maximum supported archive output rate

0.5 Mbyte/s, sustained.

10.1.19 Archive data format

FITS, or some variant which is better suited to real-time, high-speed output. Standard 9-track magnetic tape, 6250 bits/inch.

10.2 DESCRIPTION

10.2.1 INTRODUCTION AND OVERVIEW

10.2.1.1 Introduction

This report is divided into five sections and two appendices. This first section describes the place of the correlator in the VLBA project, emphasizing the interfaces between the correlator and the other parts of the project, and describes the general organization of the correlator. Section 2 lists the specifications that the correlator design is required to meet. Section 3 describes the external interfaces, Section 4 describes the design of the major internal blocks, and Section 5 discusses operational considerations. Appendix A is a glossary of acronyms and technical terms used in the report, and Appendix B lists the contents of the primary product of the correlator, the archive tapes.

10.2.1.2 The place of the correlator in the VLBA

Figure 1-1 presents the highest level description of the environment of the VLBA correlator. The antennas and recording systems generate data tapes which are read by the Data Playback Systems and presented to the correlator (interface 1). The correlator system must also control and monitor the data playback process (interface 2). A correlator operator, who will likely also be an Array operator (on other shifts), is responsible for controlling and monitoring the whole correlator (interface 3).

A second data path from the antennas is available through the VLBA Database (interface 4). This database collects scheduling and logging data from the Array Operations Control computer, which in turn gathers information from the stations over communications lines. The correlator uses this information to set up correlator runs and to make some calibrations of the results. The correlator will also add its own logging results, and perhaps its own calibration results, to the database.

The primary correlator output is the archive tape (interface 5). The archive tape contains all the visibility measurements as well as the logging and calibration data necessary for post-processing. A secondary output is the distribution tape (interface 6), which is created from the archive tape by an offline program. The distribution tape is a reformatted version of the archive, sorted by user or by experiment. This tape is available for export to a user's home institution or for use in the VLBA post-processing system.

10.2.1.3 General organization

Figure 1-2 shows the correlator at a greater level of detail. Data from the Data Playback Systems (DPSs) are received by a Station Electronics (SE) subsystem. The SE contains a crossbar switch which allows any DPS unit to be used for any VLBA station. Furthermore, the output of any DPS unit can be sent to multiple correlator inputs, and channels from different DPS units can be grouped together to be sent to a single 16-channel correlator station input.

Other components of the SE subsystem perform phase and delay model calculations, delay tracking, and phase-calibration tone detection. M68000-series microprocessors are used for calculation and I/O functions. Phase information, calculated on a "per-station" basis, is sent along with the delay-corrected data to the Correlator Electronics (CE) subsystem. In the CE, each correlator processing a particular channel and baseline accepts phase and fractional-bit delay information from two stations, differences the information, and applies appropriate corrections.

The CE subsystem is divided principally into 16 20-station correlators, each handling one of the 16 correlator channels. Some interconnections between correlators facilitate polarization processing and high-resolution spectral-line processing. The 20-station correlators also have modes allowing high-resolution processing of 14- and 10-station data.

Correlation products in the CE subsystem are formed and accumulated for a time in counters on a custom VLSI gate-array correlator chip, and are then dumped into an adder/RAM system. Following a further accumulation, the data are passed through a time-decimation filter which allows efficient sampling of wide fringe-rate windows. The filter is implemented in specialized digital signal processors.

The accumulated and filtered correlator output data are passed to a Transform and Output Processor (TOP) where the data are converted from the delay-lag domain to the frequency domain by a fast Fourier transform. The transformed data are formatted, merged with housekeeping information from the correlator control computer, and written on archive tapes. The TOP consists of an Aptec DPS-2400, a Floating Point Systems FPS-5000 array processor (AP), and a magnetic-tape output system. The DPS-2400 provides a large multi-ported RAM with independently controlled I/O to the CE subsystem, the AP, and the tape drives; its high speed bus permits efficient use of the AP and concurrent I/O transfers.

Software is provided to sort the archive tape into user-specific distribution tapes. This software can run in any VAX-level computing environment. We envisage a small dedicated VAX system to generate these tapes, but this hardware is not in our current budget plan.

The Correlator Control Computer (CCC) is a VAX-series processor. It assembles database information into correlator control commands and passes these to the SE subsystem where geometric models are computed. The CCC also communicates with the operator and the DPS units to ensure that the correct tapes are playing, and acts as host to the microprocessors in the other subsystems.

10.2.3. EXTERNAL INTERFACES

10.2.3.1 DPS data interface

The Data Playback System (DPS) has two interfaces to the correlator: the control interface (see section 3.2) and the data interface. These interfaces must, of course, be coordinated with the DPS development effort at Haystack. We present here our current views of the requirements on the control interface, subject to further discussion with the Haystack group.

The data interface transfers data from the DPS to the Station Electronics (SE). The transfer rate is always 16 Msample/s with the DPS repeating samples if necessary. The DPS is responsible for deskewing and reclocking recorded data according to the 16-MHz system clock which will be supplied by the correlator.

1. Signals from DPS to SE: sign, magnitude and validity from each of 16 channels at 16 Mb/s.

2. Signals from SE to DPS: 16-MHz clock and 1-s tick (1 pps).

3. Electrical specifications: differential ECL for all signals.

4. Connector specifications: four connectors, one for group of four baseband channels. The connectors will be used with twisted-pair ribbon cable.

5. Data switching. The DPS will allow arbitrary assignment of recorded baseband channels to correlator input channels (CICs). In addition, the DPS must be able to present the data from one recorded channel to more than one CIC: the high-frequency-resolution correlator modes require each recorded channel to be passed to 2, 4, 8, or 16 CICs.

10.2.3.2 DPS control interface

Each DPS microcomputer will communicate with the Correlator Control Computer via a slow-to-medium rate I/O bus. The Monitor and Control Bus proposed for the VLBA antenna systems would be adequate for this purpose, although industry standard buses including RS-422 would also be acceptable. The choice of physical link and protocol has not yet been made.

10.2.3.2.1 DPS addressing

There may be 24 or more DPS units to be controlled. We suggest two addressing methods: a global "datagram" method, in which all recorders are commanded identically with a single command, and a specific method, with only one unit responding. The address specification for DPS units should allow for at least 64 separate units.

10.2.3.2.2 Time synchronization

To implement synchronization, each DPS maintains a data-time command clock which is initialized by the correlator control computer and incremented on the fundamental 16-MHz clock tick; the DPS slaves the reproduced tape-time to match this command clock. Data are flagged invalid when this synchronization fails.

10.2.3.2.3 Commands

Detailed definitions of commands for the DPS control interface have not yet been developed. We discuss the general functions that will be required, and indicate those cases where global addressing is appropriate. As very little of the communication on this interface requires high-resolution synchronization, these commands will not be time-tagged, except where so noted.

1. set playback configuration: accept assignments of recorded to interface channels, playback rate (if the optional slow speed is implemented), and a fixed time offset to be applied to the commanded tape-time.

2. set recording mode: accept recorded data rate, track fanout, and number of bits/sample. These additional data are needed for correct routing of the reproduced signals by the DPS.

3. align: accept start time and tape footage/pass, and tape serial number (for verification). The DPS positions the tape sufficiently before the specified point to allow for speedup and synchronization.

4. synchronize (global): set all DPS tape-time command clocks to the desired scan start time (which generally precedes all the align start times), and begin counting at a given 1-s tick. Each DPS is then responsible for starting its tape as necessary to achieve synchronization when the align tape-time occurs. This is the only command requiring precise timing; it may be broadcast by the "datagram" method and refer to the next 1-s tick, or may require a time tag referencing a particular future tick.

5. stop (global): stop all command clocks and tape transports.

6. unload: rewind and unload tape.

7. reload: restore tape transport to ready state.

8. status: report DPS status to the CCC. These requests from the CCC occur periodically during normal operation to monitor performance. Reported data include recorder status (online, ready, etc.), parity and CRCC error rates, and other housekeeping and self-check results.

9. diagnostics. We anticipate that some DPS diagnostic functions will be exercised by special commands through the control interface.

10.2.3.3 Operator interface

The operator interface is the interface between the VLBA Correlator System and the human operators, engineers, and technicians who have to control and monitor its operations. It is defined by a group of computer programs that reside in the Correlator Control Computer, and it accepts commands from the operators, generates status messages and graphical displays, and issues instructions to the operators when human intervention is needed (e.g., to load or unload tapes). In normal operation, the correlator operator interface closely resembles the array control operator interface, allowing operators to move from one control task to the other with minimum confusion.

10.2.3.4 VLBA database

A general-purpose database system is an essential element of the VLBA. In a project with the scope of the VLBA, such a system is needed to provide a coherent structure for, optimum access to, and security of, the Array's basic operating data. While the VLBA database is as yet only vaguely defined, and indeed perhaps still controversial, we assume here that such an entity exists and describe in this section the correlator's interface with it.

The predominant data flow through the interface is from the database to the correlator system, both for internal control within the correlator and for further transmission to the archive. However, the interface is fundamentally bidirectional, and the correlator is responsible for creating or updating certain vital database entries.

Since we have decided to use VAX/VMS systems for array and correlator control, the database system can be assumed to operate in such an environment and to communicate with the Correlator Control Computer via DECnet.

For present purposes it suffices to regard the database as a single logical entity containing a number of logically distinct data structures, with access routines callable from the correlator control software. The following enumeration of VLBA database elements is strictly the correlator's view of the system, and is neither complete nor indicative of its internal logical structure.

Array program history. An open-ended chronological record of the Array's activity at a program-name level, including both observation and correlation. Each entry points to an associated observation history or archive entry.

Observation histories. Each is the primary record of all Array operations connected with a particular program, maintained from the time of observation until correlation is complete, and then retained in the archive with the associated data. This is the major interface between the VLBA database and the correlator, with data flowing in an obvious direction for each of three substructures: (a) Global parameters, including frequencies, polarizations, and other acquisition-system parameters, and names and positions of stations and sources, time and polar motion data, etc., as used in processing; (b) Observing log, detailing chronologically the sources observed, tape numbers, and numerous instrumental variables; (c) Processing log, recording the progress of correlation of the data and its disposition.

Station catalog. A relatively static list giving the current best values for all station coordinates, also related items such as axis offsets. Data are extracted from this catalog only to create an observation history; all further references are to the history. Each entry also points to an associated station history.

Station histories. Long-term chronological record of station-based measurements, including among others: (a) Clock log, a compilation of clock and LO offsets derived from observations of calibration sources; (b) Calibration file, extracted from monitor data and passed to archive for amplitude and phase calibration, perhaps also including meteorological data; (c) Validity file, also extracted from monitor data and probably supplemented by the correlator before being passed to the archive, detailing intervals when recorded data is invalid.

Source catalog. A relatively static list giving the current best values for coordinates of all known sources. Data are extracted from this catalog only to create an observation history; all further references are to the history.

Time catalog. A dynamic chronological FIFO list relating IAT to GST, including polar motion variables. Continuously updated as necessary to reflect current best values, but should probably be restricted to values originating from a single agency. Data are extracted from this catalog only to create an observation history; all further references are to the history.

Geodynamic catalog. A relatively static list of all constants of geodynamic origin used in refined calculations of the interferometer geometry. Includes as a minimum precession and nutation constants. Data are extracted from this catalog only to create an observation history; all further references are to the history.

Tape catalog. A dynamic tabulation of information pertaining to all magnetic tapes known to the system, including current location, status of recorded data, and history of use and data quality, updated as appropriate during correlation.

10.2.3.5 Archive tape

The contents of the archive are described in Appendix B. The archive tapes are written one at a time and stream continuously. There may be two different experiments being correlated and archived simultaneously, on the same tape.

As far as possible, the archive tape format will conform to FITS standards, but deviations from these standards may be required to efficiently accommodate the very high data rates. A read/write error detection/correction encoding scheme will be used to protect the archive data set.

The archive tapes are 9-track, 2400-foot, 6250-bpi magnetic tapes. (It is possible that by the time the correlator is operational, there will be economical alternatives, e.g., optical disks; but at present magnetic tape is the only acceptable medium.)

10.2.3.6 Distribution tape

The fundamental product of the VLBA correlator is the archive. It is not envisaged that archive tapes will ever leave the Array Operations Center; instead, "distribution tapes" will be generated from the archive tapes when required. There are several reasons for this:

1. The archive tapes are valuable, and if lost, cannot be reproduced except by repeating the observations. Additional copies of the distribution tapes can be generated on demand.

2. The data will be recorded on the archive tapes in the order in which they are generated by the correlator, which may not be the most convenient for post-processing. The distribution tapes will contain standard FITS files.

3. A single archive tape may contain interleaved data from several separate experiments belonging to different investigators. The distribution tapes will each contain data from only one experiment.

The correlator design will include software which can be used for generating distribution tapes. It will be possible to run the software on any VAX computer with suitable peripherals; at least three 6250-bpi tape drives will be required. It would be convenient if this computer had a link to the VLBA database, to enable it to determine which archive tapes contain the desired data, and in order to keep records of distribution-tape generation.

Although the organization of the distribution tapes will be different from that of the archive tapes, their contents will be logically equivalent. The distribution tapes will be written in FITS format and will rigorously conform to all FITS standards. They will be be 9-track, 2400-foot, 6250-bpi magnetic tapes.

10.2.4 MAJOR SYSTEM BLOCKS

10.2.4.1 Control computer

The Correlator Control Computer (CCC) is responsible for coordinating all the activities of the correlator. It supports the external interfaces to the operator and to the VLBA database, and it serves as host for the microprocessors in the SE, CE, TOP, and PWG subsystems. It is also responsible for the analysis of clock calibration observations.

10.2.4.1.1 Tasks

The major tasks of the control computer are:

Correlator scheduling. Referring to the Array observing history in the VLBA database and to guidelines specified by the operations manager, the control computer organizes the overall schedule to optimize throughput and tape turnaround. This is a semi-automatic process, requiring occasional prompting and confirmation by the operator.

Scan initialization. A scan is a continuous period during which model parameters, station assignments, and other correlator control parameters are constant for some subarray; the minimum scan duration is 10 s (in the extreme case of "model switching"). The control computer initiates a new scan by transmitting the required parameters to the DPS via the external interface (section 3.2) and to the other subsystems (SE, CE, TOP, and PWG) via internal interfaces. During the execution of a scan, the control computer monitors the activity of all these subsystems, notifying the operator of abnormal events and taking corrective action if appropriate.

Processing history logging. Upon termination of a scan, the processing history in the VLBA database is updated to show the location of the correlated data and a summary of recording quality and hardware performance.

Calibration. This represents a major system block in its own right, and appears here primarily to localize this function in the control computer. Calibration processing itself is discussed in section 4.7. The results of this calibration are recorded in the VLBA database, and applied in subsequent correlator scans. This task will dominate the CCC's requirements for processing speed, memory, and mass storage.

Diagnostics. Several of the major system blocks incorporate diagnostic features, described in the appropriate sections. The control computer is responsible for exercising these features and monitoring the results.

Software support. All microprocessor programs for distributed processing in the subsystems will reside in the control computer. This software will be downloaded whenever the correlator system is initialized.

10.2.4.1.2 Hardware

For compatibility with other areas of the VLBA and with existing software, and for convenience in software development, the control computer will be a member of the DEC VAX family, running the VMS operating system. The majority of the computational and I/O loads associated with model calculations, correlator readout, data processing, and data formatting will occur in secondary processors under the guidance of the control computer. As a result the control computer requires only modest computing power, and need not support a critical real-time oriented environment. We estimate that a VAX-11/750 processor will be suitable. A possible configuration is shown in Figure 4-1.

Required peripherals will include video terminals for the operators, the operations manager and a data analyst, and at least one hardcopy printer for logging purposes. The standard operator interface programs will be able to run on any VMS-compatible terminal (e.g., VT200 series or any similar terminal supported by the VMS screen management software), but in order to use the full capability of the interface, a bit-mapped graphics terminal or display will be required. At least eight I/O ports will be available on the control computer for the support of terminals and displays. The preferred connection method is through a terminal concentrator connected to the control computer by an ethernet network. A tape drive will be required for maintenance and backup purposes. (It may be possible to configure the TOP subsystem so that its tape drives can be used as peripherals of the CCC when they are not required for writing the archive tapes.)

10.2.4.2 Station electronics

The Station Electronics (SE) subsystem contains the correlator functions that are performed on a per-station basis. These include input switching, delay correction, phase calibration, and model calculation. Figure 1-2 shows the general environment of the SE subsystem. It is divided into four quadrants, with each quadrant responsible for four correlator channels.

The input Crossbar Switch allows the Correlator Control Computer to select the source of each of the 320 Correlator Input Channels (CICs). Each CIC may come from the corresponding output channel of any of up to 24 DPS units. The crossbar switches only in the "station" sense, that is, it is not possible to cross-connect channel n and channel m if n <> m. Some switching in the "channel" sense is provided in each DPS (see section 3.1). Some further switching is available in the correlator input (section 4.3).

The crossbar switch does not cross channels, but it does switch channels independently. Thus channel 1 may come from recorder A, but channel 2 may come from recorder B. This capability allows great flexibility in scheduling correlation runs, fringe checks, etc.

Following the crossbar, four channels of each of 20 stations' data are passed into the delay/phase section (cf. Figure 4-2). The 3-bit streams in each channel are delayed in a RAM buffer according to the interferometer geometry. Station phase and fractional bits of delay are encoded onto a fourth wire and transmitted along with the data samples to the Correlator Electronics (section 4.3).

Before delay correction, any one of the four input channels may be selected for the phase calibration tone detector. The detector is driven by a tone generator, capable of generating any fixed tone within the IF band on 10 kHz intervals (0.01-8.99 MHz).

A Station Model Processor (SMP) computes delay and phase for each of the channels (actually for four channels of 20 stations). It controls the delay RAM and phase adder/encoders, whose outputs are passed on the P line to the correlators. The SMP also sets up the crossbar switch, controls the calibration tone detector, and reads out the tone-detector counters. The SMP is connected to the control computer (CCC) by a medium-rate (~1 Mb/s) bus. This bus is used for I/O during operation and also for program down-line loading. The SMP is a 68000-family processor in a VME bus system. It resembles the Correlator Output Processor (COP) in the correlator subsystem (described below, section4.4).

10.2.4.3 Correlator arrays

The correlator is divided into 16 Elementary Correlator Arrays (ECAs), each of which contains 220 Elementary Correlators (ECs).

10.2.4.3.1 Philosophy

An ECA consists of the usual triangular array of Elementary Correlators (ECs) for N input stations, i.e., N(N-1)/2 ECs. (As will be seen below, the ECA should contain the diagonal (autocorrelator) elements making a total of N(N+1)/2 ECs.) We fix the maximum number of stations that can be processed at 20, implying 190 baselines, and 210 ECs. (Actually, 220 = 4 x 10(10+1)/2 ECs are required to fully support 10 stations.) Each EC contains its own lobe rotator.

Each ECA has two input vectors comprising 20 data streams of width four bits (sign, magnitude, validity, and phase/delay). There are up to 16 input vectors corresponding to the 16 correlator input channels (CICs) provided by the 20 Data Playback Systems (DPS). Sixteen ECAs are sufficient to support the VLBA task. ECAs may be grouped into four quadrants; only within a quadrant is the effect of polarization (P) modes evident. As we shall see later, some signals will have to be distributed in common to more than one quadrant, but, in the main, quadrants are isolated from each other.

In this section we discuss the connections needed within a quadrant, the connections between quadrants, and the required station switching. We show how "consolidation" of ECs within an ECA will allow high-resolution modes with 10 or 14 input stations to be processed.

10.2.4.3.2 Connections

An ECA will be represented by the symbol in Figure 4-3. Remember that an ECA is a complete 20-station correlator (with 16 lags per baseline) including a lobe rotator for each baseline. Each "input" is a 20-dimensional vector corresponding to a one-channel slice of all the input stations.

To process NP data in a maximum bandwidth (maximum sensitivity) mode, the ECAs are connected as shown in Figure 4-4(a). In this mode, four independent 8-MHz channels are correlated, with a delay coverage of 16 samples, giving 8 frequency channels.

To process P data, four ECAs are connected as show in Figure 4-4(b). In this mode two CICs, labelled R and L, carry the two orthogonal polarizations from one 8-MHz frequency band. The delay coverage is also 16 samples, yielding a frequency resolution of 8 channels.

Greater frequency resolution is available by using the capability of the DPS to deliver the same baseband channel to more than one CIC. Different delay offsets are then applied to these streams in the SE. Two such configurations are possible within a single quadrant as demonstrated in Figure 4-5. The connection in Figure 4-5(a) will give double resolution for each of two frequency channels, while Figure 4-5(b) shows how to obtain four times the resolution for one 8-MHz channel. With some simple connections between quadrants, 8 or 16 times resolution increase may be obtained; internally, the quadrant is connected as shown in Figure 4-5(c).

10.2.4.3.3 Consolidation: 14- and 10-station modes

Further increases in resolution are available by "consolidating" ECs within each ECA and reducing the number of stations correlated per tape pass. The simplest consolidation, from the standpoint of input switching, is to combine four ECs to correlate 10 stations, achieving a factor of four increase in delay coverage and frequency resolution. (Note that the 10-station "full" mode can only be supported if the ECAs contain the diagonal elements of the triangular array, i.e., $N(N+1)/2$ ECs are required per ECA. This is a relatively small increase (N) in the number ECs compared with the off-diagonal ECs; furthermore, the extra ECs are conveniently used to obtain the autocorrelation function.) The full mode consolidation is shown in Figure 4-6 for the simplified case N=4.

The same ECs may be rearranged in a "half" mode (3 stations) according to Figure 4-7. Unfortunately, the array of ECs must be rearranged considerably to accommodate the "half" case, especially when N is large. The irregular interconnections are not especially difficult since they are all within each ECA, and span a distance not exceeding a few feet.

10.2.4.4 Data accumulation, filtering, and readout

The 16 Elementary Correlator Arrays (ECAs) are grouped in fours to form quadrants, each controlled by one Correlator Output Processor (COP). The 220 Elementary Correlators (ECs) within an ECA are grouped (somewhat arbitrarily) into 11 groups of 20 ECs each for the purposes of readout, accumulation, and filtering. Each of these groups (Figures 4-8, 4-9) contains, in addition to the 20 ECs which are part of the VLSI: a hardware accumulator consisting of a 20-bit adder, 2K by 20-bit RAM, address counter, interface registers, and a state machine controller; and a digital signal processor (DSP) unit consisting of one TMS 32010 processor, 64K 16-bit words of data RAM with control logic, 2K by 16 bits of program RAM (downloadable from the COP bus), address counter, and logic for interfacing to the COP.

10.2.4.4.1 Hardware accumulator

The VLSI accumulator registers will be read out sequentially, all of them being read every 250 us. The sums will be stored in the accumulator RAM up to a period of 125 ms, at which time they are read by the DSP. Read-out is accomplished transparently by dividing the accumulator RAM into halves and allowing the DSP to access the half not currently being used by the accumulator. The bank selection is reversed every DSP read-out period.

There will be a path around the accumulator by which the DSP will load setup information into and obtain diagnostic information from the VLSI.

10.2.4.4.2 Digital Signal Processor

The DSP will extend the accumulation period up to 262 s, and will perform a sample rate reduction by factors of 2 or 4 on the 8-Hz samples if requested. The data are normalized by the DSP after accumulation and before sample rate reduction.

The sample rate reduction is accomplished using a half-band FIR filter, which is cascaded with itself to produce successive factors of two. The algorithm requires seven multiplies and seven additions per real or imaginary output sample per stage. For an input sample rate of 8 Hz and an output sample rate of 2 Hz, the amplitude response of the filter (in residual fringe frequency) is flat to within +/- 0.5% up to 0.6 Hz, rolls of by 10% at 0.8 Hz, and drops by 99% at 1.4 Hz. The phase response of the filter is flat to 0.001deg to 0.8 Hz.

10.2.4.4.3 Correlator Output Processor

The COP is an M68000-based VME-bus computer with 512 kbyte of RAM, DMA controller, one high-speed port for interface to the TOP, and one low-speed port for interface to the Correlator Control Computer. There are four COPs in the correlator.

The output data from the DSP is moved to the COP memory via DMA. In the case where 8-Hz visibility samples are to be passed directly to the COP from all DSPs, the maximum input rate on the COP bus will be 900 kbyte/s. This data rate can be supported if only one-fourth of the correlator is used. In the full-bandwidth maximum dump rate case, each DSP outputs 0.5-s samples to the COP, whose input rate will then be 112 kbyte/s.

The COP will be able to transmit configuration commands to its DSPs, request status information, and download their programs.

The correlator control computer will communicate with the COP through a separate lower-bandwidth interface to download software, transmit configuration information, and receive status information.

10.2.4.5 Fringe rotator and vernier delay control

The fringe-rotator and vernier-delay system is a logical system block comprising three distributed physical components. A model-computation subsystem generates the model delay and phase for each input channel (CIC). The integral part of the delay is sent to the appropriate SE module for delay control; the fractional delay and the phase are transmitted serially to the appropriate correlator array element along a distribution path which represents the second component of the system. The third component resides in the EC: it differences the fractional delays and phases received from the two input streams, and controls the vernier delay bits and fringe rotator. This section describes each of these components in further detail.

10.2.4.5.1 Model-computation subsystem

The first stage of model computation is carried out in the four SMP processors (one per quadrant), which receive the necessary top-level model parameters, station and channel assignments, and other control parameters from the Correlator Control Computer when each scan is initialized. In addition to the SMPs, the model-computation subsystem includes hardware fringe-phase generators (FPGs) which perform a high-speed linear interpolation.

The model-computation algorithm has not yet been established definitively, but will be similar to the following, which is based on that employed in the Block-II correlator. The fringe phase is precomputed, to high (64-bit floating-point) accuracy, for four equally-spaced time points spanning about 30 s. A cubic spline interpolation is derived passing through these points, and expressed as a third-order polynomial with scaled 32-bit fixed-point constants. This polynomial is evaluated by a cascade addition every 4 ms, and the updated zeroth- and first-order terms are transmitted to the appropriate FPG. Finally, the FPG provides new values, correct to 4 bits, at 0.5-us intervals. This entire process is performed separately for each of the correlator's 320 CICs.

The delay computation is similar, with the following differences. The required accuracy and update rate are much lower, so that a complete third-order calculation every millisecond will suffice, with no need for external hardware interpolation. There will be far fewer delay results required, since in general the station delay will be the same on all or at least many channels from a single DPS; to support two or more different sources (or even telescopes) on a "station" input should require no more than 40 such calculations. The integral part of the delay, in bit-clock units, is available for the appropriate CIC delay line; the leading two bits of the fractional delay are distributed with the phase.

10.2.4.5.2 Distribution path

The 0.5-us outputs from the FPGs, and the less frequently updated fractional delay, are assembled into a fourth data stream from the SE to the CE, parallel to the streams of sample data and validity bits.

10.2.4.5.3 Differencing section

The phase and fractional delay received serially from the station electronics by each elementary correlator are buffered in the EC and differenced at the 0.5-us phase-update interval. The phase and fractional-delay differences drive the fringe rotator and the vernier delay.

10.2.4.6 Data processing, formatting, and output

The transform and output processor (TOP) receives the visibility data stream from the correlator electronics, performs three operations on the data stream, formats the data, and generates the archive. The three operations correct the data for station-based Doppler offsets in frequency (phase ramps across the delay functions), transform the data from delay lags into frequency channels, and apply corrections for fractional bit shift errors (phase ramps across frequency channels). The output of the TOP will consist of separate cross-correlation and auto-correlation spectra for each baseband channel. The output data rate will be one half of the input data rate because the empty sidebands are discarded.

Since none of the operations performed in the TOP involve averaging in time or frequency, we effectively archive the raw correlator data. Given the model information used in the TOP, the operations are reversible, and the raw data could be recovered in the post-processing software.

The transform processor tasks are fairly simple and straightforward. They consist of calculating and loading phase ramps into vectors, multiplying delay functions and frequency spectra by these vectors, and doing FFTs. The operations will be nearly the same for all of the different observing and correlating modes. The high data rate through the TOP (1 Mbyte/s) necessitates fast hardware: enough computing power is needed to handle 100 1024-point complex FFTs per second and to perform two complex multiplies on each word (500,000 multiplies per second).

10.2.4.6.1 Hardware

We have investigated two choices for the transform processor hardware:

1. A system based on the Aptec Computer Systems, Inc., Dimensional Processing System (DPS-2400). The DPS-2400 provides a high speed data bus, a large mass memory and intelligent ports to Unibus devices. The transform processing would be supported in one or more FPS-5000 series array processors connected to the DPS-2400 internal bus.

1. An array of four M68020 processors each supporting one of four Sky Warrior array processors. This system would connect via the VME bus and run under VersaDOS.

We have provisionally chosen the Aptec-FPS system for the transform processor. The technology of such systems is evolving rapidly, however, and we shall continue to evaluate alternative systems. The Aptec-FPS system will consist of the following elements (Figure 4-10):

Aptec DPS-2400. The Aptec DPS-2400 serves as a central node that connects many Unibus devices to a high speed bus and a large mass memory. It interfaces to the Correlator Control Computer via the VAX Unibus. The DPS-2400 consists of three basic elements: (a) a Data Interchange Bus (DIB)--24 Mbyte/s, 32 bits wide--that allows high speed data transfers between the Aptec peripherals and the mass memory; (b) up to 27 Mbyte of Mass Memory with an access speed of 11.75 Mbyte/s per 1-Mbyte board; (c) several Data Interchange Adapters (DIAs) to connect Unibus devices to the DIB and mass memory. The DIAs contain 2901 bit-slice processors and can be programmed in DIA-Staple and microcode.

FPS 5000-series array processor. Using the execution times in the FPS 120B Programmer's Manual, we estimate that at the peak correlator data rates, about one second of execution time is required per second of data. In order to handle the required transform rates, the array processor will need additional arithmetic coprocessors and I/O processors. Using a single AP from the FPS 5200 or FPS 5300 series will be less expensive than using two FPS 5105s.

Archive writer. The correlator archive will be written on 6250-bpi, 125-ips magnetic tape drives connected to the Aptec by a Unibus and a DIA. At least two drives will be required so that the correlator need not wait while tapes are rewound.

10.2.4.6.2 The data path through the Transform Processor

The correlated data stream from the correlator electronics appears on one or more VME buses. The data enter the transform processor through VME-to-Unibus adapters and a dedicated DIA port. The data are transferred into the Aptec mass memory and held for one correlator dump cycle and then sent into the FPS-5000 common system memory in sorted order. The sort is accomplished by retrieving the data from mass memory in a specified sequence. The transform processor tasks will run to completion on an entire correlator dump cycle's worth of data. The system common memory in the array processor will be large enough to hold one correlator dump. The I/O through the AP DIA (from and to the Data Interchange Bus) will occur only once in each direction. The data stream returning from the AP will be buffered in mass memory prior to output on the archive tape.

10.2.4.6.3 Algorithms

The three TOP tasks are (in order of execution):

Station Doppler shift corrections. The Correlator Control Computer will calculate Doppler frequency shifts for each station at the current record time. These Doppler shifts will be sub-divided into a term for the diurnal earth rotation, and a term consisting of the sum of the earth's orbital motion and a source LSR velocity. The diurnal earth rotation corrections will be applied to all types of observations (continuum and spectral line). For spectral line observations, corrections for the earth's orbital motion and source LSR velocity corrections will be applied. The correlator control computer will calculate the appropriate phase shift per delay lag for each station. The array processor algorithm will load phase ramps into the AP memory. The Doppler correction is applied by complex multiplying the station A phase ramp with the AB baseline. Recall that the correlator lobe rotator removes the station B - station A difference in the diurnal Doppler shift. As part of the post-processing calibration, bandpass amplitude responses will be removed by subtracting off-source scans. Doppler shifting before bandpass removal, as we are doing here, is the reverse of the normal sequence. Although the off- and on-source frequency scales will be misaligned in the post-processing environment, off-source bandpasses can be shifted into alignment by Fourier interpolation.

FFT. The data are transformed from the delay lag domain to the spectral frequency domain by an FFT algorithm; individual baseband channels are transformed separately. (The "wide-band" transforms required for astrometry and geodesy are done in post-processing, not online in the TOP.) After the transform, the empty sideband channels are discarded, reducing the aggregate data rate by a factor of two.

Fractional bit-shift correction. The fractional bit-shift correction involves multiplying the cross correlation spectrum of each baseband channel by a phase ramp. The phase ramps for each baseband and each baseline are calculated by the Correlator Control Computer using the fractional bit-shift error algorithm currently in use on the Haystack Mark-III correlator. The array processor loads the phase ramps into AP memory and performs the complex multiplies.

10.2.4.7 Calibration

The correlator has two roles in the calibration of the VLBA: (a) it makes online estimates of clock errors from calibration source observations, and (b) it ensures that the archive tapes contain all the relevant calibration data from the VLBA database.

10.2.4.7.1 Clock calibration observations

The VLBA will probably make two or more clock calibration observations of 5-10 minutes each per day, using, say, 10-20 stations, 4 baseband channels, 4 spectral channels per baseband channel, and online averaging to 10 s. These observations must be analysed in the correlator quickly enough for the results to be applied to subsequent observations, with a delay of no more than, say, 1 hour. The calibrator fringe-fitting will be done in the correlator control computer, using algorithms adapted from the AIPS task VBFIT. The resulting estimates of the station-dependent clock and clock-rate offsets will be stored in the VLBA database.

The clock calibration observations must be of sufficient accuracy to hold the program source fringes to within +/- 5 ns of the center of the zero delay lag channel and to within +/- 5 mHz of zero residual fringe rate. A suitable clock calibration source must have 100 mJy of nearly unresolved flux density. Source structure must not extend beyond 0.01 arcsec from a central core-like feature. A 100-mJy unresolved source will allow 3sigma delay and rate measurements to 5 ns and 5 mHz at the least sensitive VLBA observing bands.

10.2.4.7.2 Calibrations based on information in the VLBA database

Some of the information that the astronomer needs for proper calibration of his data will be stored in the VLBA database at the time of observation or correlation; this includes the system noise temperature and phase-calibration measurements. The correlator will write this information on the archive tape along with the visibility data.

10.2.4.8 VLSI

In "full" mode, the VLBA correlator is required to handle up to 16 data streams from up to 10 stations (55 baselines, including autocorrelation), with 1024 complex lags per baseline per channel. Therefore, the total number of multipliers and accumulators needed is 112,640. The most economical method of providing this amount of hardware is to design a special-purpose VLSI circuit or chip (Figure 4-11).

10.2.4.8.1 Choice of Technology

The choice of technology for the VLSI circuit is driven by data rate (16 Msample/s), the projected costs (both silicon and manpower) and the desire for a high probability of producing a successful chip on the first attempt. After careful consideration, we have chosen 2-um CMOS gate array technology for the VLBA correlator chip.

10.2.4.8.2 Functions

Signal selection. To allow the many modes in which the correlator is required to operate, two 1-of-4 signal selectors will be present at the input to the chip. (Each "signal" consists of sign, magnitude, validity and phase/delay.)

Vernier delay. Because the geometrical delay offset is being done on a station basis, it is necessary to incorporate a "vernier" delay of -1, 0 or +1 bits to keep the delay error to +/- 0.5 bit.

Lags. The system is being designed assuming that 8 complex lags will be present on each chip. It may be possible to squeeze 16 complex lags on the largest available gate array. In this case, the package count (7040 plus spares) will be reduced by a factor of two and the silicon cost lowered somewhat. The design assumes that the increase in SNR that can be achieved by oversampling will cause a corresponding decrease in resolution. If space allows, an on chip remedy will be considered. The lags are arranged in a symmetric (bi-directional) configuration so that zero delay remains in the center of the lag range when more chips are concatenated.

Multipliers. The multipliers must be capable of 2x2 or 4x4-level multiplication. For economic reasons, we have chosen to design incomplete multipliers with 4:1 level weights (Figure 4-12). This decision results in a small loss of SNR.

Fringe rotation. Three-level fringe rotation will be provided on chip. In the present design, the same phase will be applied to all lags (rotation after multiplication).

Prescalers. A 6-bit prescaler will be provided. The prescaler may be reset to zero, if desired. This length of prescaler can cause an increase of system temperature of ~ 1% after an integration of 125 ms due to prescaler roundoff of +/- 0.5 bit. If extra room is available on chip, then a change of some prescaler bits to read-out accumulator bits will be considered.

Accumulators. The accumulators are 8 bits long which, together with the prescaler, implies a maximum dump time of 256 us. This rapid dump rate is extended by an external hardware adder and RAM accumulator to 125 ms (or more). The 8 bits are registered so that accumulation can continue while the previous accumulation is being read out. Both the prescalers and accumulators are ripple-up counters and therefore take some time to ripple through before the registers can be loaded, resulting in the loss of a few samples each dump time.

Normalization. The design of the multipliers is such that both valid and invalid data produce a DC offset in the prescaler-accumulator chain. This feature allows separate validity for each lag (necessary for the DPS) while preserving a common DC offset for all lags. To remove the DC offset a sample counter is provided on chip. In addition, it is necessary to count the number of valid samples for the cosine and sine channels separately. The 8-lag chip will have two normalizing counters with programmable inputs so that all three counts will be available for a 16-lag pair.

Phase generators. The per-station phase and fractional delay bits will be transmitted serially by the SE along with the data. The phase generator will compare the values from each of the two stations and perform the necessary vernier delay and phase functions. The update period is 0.5 us and hence a small SNR loss (~ 2%) will occur at the highest fringe frequencies (~ 250 kHz).

Test circuitry. VLSI companies recommend that a sufficient number of internal signals be testable in order that (a) an automated hardware tester can determine that a chip works to specification before one pays for it and (b) a faulty design can be diagnosed before committing to another (expensive) design cycle. In this design, a number of signals can be selected to be put on the I/O bus, 16 at a time.

10.2.4.8.4 Package

The chip will be packaged in an 84-pin plastic leaded chip carrier. This package is widely available, inexpensive and makes efficient use of board space.

10.2.4.8.5 Operation

Data interface. The chip accepts data at 16 Msample/s. Two data selectors select the data streams to be correlated. The selected data streams are also passed out of the chip in such a way that any number of chips can be concatenated.

Control Interface. The chip is configured to look like a microprocessor peripheral with a data bus, address lines, chip select and read/write lines. The setup of the chip and the reading out of the results are done through this interface. In addition, a number of pins are assigned hardware functions such as reset, clock, blanking, result register load, phase register load, etc. The multiplier-prescaler-accumulator section always runs at 16 Msample/s (except when blanked). The delay line can be shifted at a slower rate to remove unnecessary samples from oversampled data and hence preserve maximum spectral resolution.

10.2.4.9 Pulsar window generator

The Pulsar Window Generator (PWG) is used to generate timing windows for the purpose of increasing the SNR of pulsar observations. It can also be used with multi-pass processing to obtain separate correlation coefficients for different parts of the pulse profile. The PWG consists of 16 identical units (one for each channel) controlled by a 68000-family processor on the VME bus. This processor also provides the communications channel to the Correlator Control Computer. The interface to the control computer is relatively slow speed, all high-speed activity being assigned to the 68000 and the window generating hardware. The signals generated by the PWG are routed via 16 coaxial cables to the 16 ECAs where they are used to invalidate all data outside the windows. The specifications for the PWG are listed in section 2.15.

10.2.5 OPERATIONS

10.2.5.1 Normal operation

In normal operation, the correlator will be controlled by a previously created script or command file. The correlator session controlled by the script may, but need not, correspond to a single observed experiment; it will probably be more convenient to schedule the Correlator in, say, 12 or 24 hour sessions, independently of the observing schedule.

A possible mode of operation is the following: each day the operator will decide what data are to be correlated during the next 24 hours. He will then run a script preparation program. This program will search the VLBA database for the relevant information and prepare the necessary script(s). It will search the tape database to ensure that all the required tapes are in the AOC ready for processing, and issue appropriate warnings if they are not. The generated script will be a readable text file that the operator can review; if necessary, he will be able to make corrections with an editor (e.g., to supply information missing from the database), although this is strongly discouraged. The script will indicate at what times during the session operator intervention will be required for loading input and output tapes.

The operator will then issue a command to start execution of the script; operation will then proceed automatically without operator intervention except as needed for tape changes. The control system will issue requests for the next tape to be loaded as soon as a drive is free, rather than waiting until the tape is actually needed. It should be possible for the operator to place the tape on any convenient DPS unit; control software will recognize the tape and configure the crossbar accordingly. The goal is that the correlator should never have to wait for the operator, and that the operator should always have plenty of time to respond to a request.

During the processing of one session, the operator will be able to prepare a script for the next session and queue it for execution, so that correlation can proceed continuously from one session to the next without stopping. The only occasion that it will be necessary to halt correlation is when changing from one major mode to another (e.g., quarter mode to full mode, full mode to half mode).

When two independent experiments are to be processed simultaneously, i.e., when some DPS units are to be synchronized at one time and some at another, two scripts will be executed in parallel. Note that both experiments must use the correlator in the same mode (full, half, or quarter). When all the DPS units are synchronized at the same time only one script is needed; this applies, for example, to cases where the changeover from one experiment to the next occurs at different times on different antennas; but again, only one correlator mode can be used at once.

10.2.5.2 Testing and diagnostics

Each hardware module in the correlator will have built-in diagnostic features. Each module will alert the operator through front-panel indicators and through the control computer when it detects a malfunction. Some modules will have special diagnostic capability that can be invoked through the control computer by operators or engineers. Complete testing of the data path through the correlator can be achieved by passing the same data through the correlator along two different channels, and comparing the results. In experiments which do not require the full power of the correlator, it will be possible to use such data paths for continuous verification of correlator performance.

10.2.5.3 Control software

Operators, engineers, and technicians will be able to control and monitor the operations of the correlator and through the operator interface. This interface will be defined by a group of computer programs that will reside in the Correlator Control Computer, and that will accept commands from the operators, generate status messages and graphical displays, and issue instructions to the operators when human intervention is needed (e.g., to load or unload tapes). The following are some of the major features of the control software.

Multiprocessing. The control system consists of many independent computers, communicating with one another according to a variety of protocols. The interface conceals this complexity from the operator, so that he is unaware which of the computers is actually executing his command or returning the value of a requested parameter.

Multiple operators. More than one operator can talk to the computer system at once. Clearly this requires protocols to ensure that the operators cannot attempt to execute conflicting commands; but there will be many occasions when more than one operator will want to be able to communicate with the system. For example, an engineer may want to monitor the behavior of some part of the system while the operator is processing an experiment, or conceivably a scientist may want to monitor the progress of his experiment from a remote dial-up terminal. On occasion two operators may be needed, e.g., one to load the video tapes while another changes the output archive tapes, or one each to control two experiments being processed simultaneously but asynchronously.

A powerful, programmable, command interpreter. The computer system is controlled by a number of predefined (built-in) basic commands, which provide complete access to all the hardware. To simplify operations, additional commands may be defined as macros or procedures that superficially are indistinguishable from the basic commands (i.e., they share the same syntax), but are actually interpreted as a series of basic commands. These procedures can include conditional commands that test the values of user-defined or hardware-generated parameters, loops, and other structured programming devices. Series of commands can also be stored in disk files and executed sequentially with a RUN command. Such a complicated command interpreter may seem superfluous, but with modern compiler technology it is not difficult to create, and it provides sufficient flexibility for an operator or engineer to control the hardware in ways which may be difficult to foresee before the system is completed.

A simplified interface to the command interpreter. In normal operation, only a small number of the basic and user-defined commands will be needed. This interface will look to the operator similar to that used for array control: see VLB Array Memo No. 431. This interface will probably only be used for routine operation, not for debugging and maintenance.

User-definable display screens. Continually updated display screens are a necessary feature of a real-time control system. They allow an operator or engineer to monitor the current and historical values of hardware and software parameters. As it is difficult to anticipate precisely what displays will be most useful in operation, the control system will allow the user to define his own screen layouts. The defined displays may then be called up as required and displayed at specified locations on specified devices. Commonly used screen layouts can be compiled for greater efficiency. At least three sorts of displays will be available: text displays, which show the current numerical values of one or more parameters, along with appropriate legends; bar-graph displays, which show current parameter values in a graphical form rather than a numerical one; and time-series (chart recorder) displays, which show the immediate past history of one or more parameters.

Modularity. The interfaces between the various components of the operator interface will be fully defined and designed to minimize the work required, say, to substitute a different command interpreter, or to adopt new graphical display technology.

10.2.5.4 Correlator utilization

At this stage in the project, it is difficult to estimate how much time the correlator will be required to spend in each mode. A preliminary estimate has been made by Craig Walker (VLB Array Memo No. 365). Table 5-1 divides the observing programs into four classes, according to correlator dump rate.

Case (a) is for routine continuum observations, with an average of 14 stations, 8 baseband channels, and 4 spectral channels per baseband channel. Cases (b), (c), and (d) all use all of the available correlator lags. The aggregate dump rate to the archive is 3.25 Gbyte/day, or 1185 Gbyte/year. This will require 6600 6250-bpi, 2400-ft magnetic tapes per year for archival storage.

10.2.A. GLOSSARY

Correlator Control Computer (CCC). See section 4.1.

Correlator Electronics (CE). See sections 4.3, 4.4. The CE subsystem correlates the data streams from the Station Electronics and accumulates and averages the results. The CE is divided into 16 Elementary Correlator Arrays.

Correlator Input Channel (CIC). See sections 2.1, 2.5, 2.6. Each CIC can accept one 16-Msample/s data stream from one baseband output of one Data Playback System. The correlator contains 320 CICs.

Correlator Output Processor (COP). See section 4.4. There are 4 COPs in the system, one controlling each quadrant of the Correlator Electronics. The COPs receive their instructions from the Correlator Control Computer.

Data Playback System (DPS). See sections 3.1, 3.2. Each DPS plays back the recordings made at one antenna and formats the resulting data streams for input to the correlator via the Correlator Input Channels. The DPSs are not part of the correlator but operate under the control of the Correlator Control Computer. The correlator can control up to 24 DPSs. [DPS is also an abbreviation for the Dimensional Processing System suggested as a component of the TOP: see section 4.6.]

Digital Signal Processor (DSP). See section 4.4. The DSP is an element in each Elementary Correlator Array responsible for data accumulation and sample rate reduction.

Elementary Correlator (EC). See sections 4.3, 4.4. Each EC correlates one pair of 16-Msample/s data streams at 16 separate delay lags. The complete correlator contains 3520 ECs.

Elementary Correlator Array (ECA). See sections 4.3, 4.4. The correlator is divided channel by channel into 16 ECAs. Each ECA contains 220 Elementary Correlators.

Fringe Phase Generator (FPG). See section 4.4. The FPG is a subcomponent of the SE. The complete correlator contains 320 FPGs.

Non-Polarized Mode (NP). See section 2.1. In NP mode, one CIC from a single DPS is correlated with the corresponding CICs from the other DPSs, forming one correlation product for each baseline. cf. P mode.

Polarized Mode (P). See section 2.1. In P mode, the CICs from each DPS are grouped in pairs carrying two orthogonal polarizations (L and R) of one baseband channel. Each member of a pair is correlated with both members of the corresponding pair from the other DPSs, forming four correlation products (L x L, L x R, R x L, R x R) for each baseline. cf. NP mode.

Pulsar Window Generator (PWG). See section 4.9. The PWG generates timing windows for selecting a part of the duty-cycle of a pulsar.

Station Electronics (SE). See section 4.2. The SE subsystem receives data from the Data Playback Systems via the Correlator Input Channels. It contains a cross-bar switch that allows any DPS to be used for any VLBA station, and it performs phase and delay model calculations, delay tracking, and detection of calibration tones.

Station Model Processor (SMP). See section 4.2. There are 4 SMPs in the system, one controlling each quadrant of the Station Electronics. The SMPs receive their instructions from the Correlator Control Computer.

Transform and Output Processor (TOP). See section 4.6. The TOP Fourier-transforms the correlated data from the lag domain to the frequency domain, applies station Doppler shift corrections and fractional bit-shift corrections when required, and generates the output archive tapes.

10.2.B ARCHIVE CONTENTS

10.2.B.1 Introduction

This appendix lists the logical contents of the archive tapes. The archived data are grouped into five divisions based on the rates at which the information changes. Epochal times will be kept in TAI (international atomic time) modified Julian date (MJD). Time intervals will be kept in seconds.

10.2.B.2 Observing run information

This is information that remains the same over an entire observing run. An observing run is defined as a refereed observing project that is scheduled under one project identifier.

OBS NAME: Observing run title, e.g., B343V.

PI ID: Principal investigators, by name.

START TIME: Observing run start time, modified Julian date.

STOP TIME: Observing run stop time, modified Julian date.

REFERENCE TIME: Epoch chosen as a reference time for the relative times in the data records.

NSTNS: Number of stations.

STATIONS: List of names of all stations in run.

STATION IDS: List of station identification numbers.

STNPOS: Geocentric coordinates of the stations in the STATIONS list.

AXISOFFS: The axis offsets for the antennas in the STATIONS list.

AXISTYPE: The telescope mount types for the antennas in the STATIONS list.

TAI-UTC: Difference between International Atomic Time and UTC. One entry per day over the length of the observing run.

UT1-UTC: UT1-UTC time difference. One entry per day.

GAST-GMST: Equation of the equinoxes. One entry per day.

GMST: Greenwich Sidereal time at 0 hr UT. One entry per day.

POLAR: Polar motion offsets in x and y.

MODULES: Name, version number, and version date of each software module in the correlator control computer and satellite processors.

10.2.B.3 Observing scan information

An observing scan is considered to be a contiguous time interval during which none of the experimental parameters change. Changes in the array configuration would be allowed within scan boundaries.

SCAN ID: Scan identification code.

OBS NAME: Observing run title.

START SCAN: Scan start time relative to run reference time.

STOP SCAN: Scan end time relative to run reference time.

SOURCE: Source name.

QUAL: Source name qualifier.

CALCODE: Calibration source code.

RAEPO: Right ascension at epoch.

DECEPO: Declination at epoch.

EPOCH: Reference epoch, i.e., J2000.0.

SRCMOV: N derivatives of RA and Dec for moving sources.

FLUXES: Flux densities at N observing frequencies.

PSR PERIOD: Pulsar period.

PSR RATES: N derivatives of pulsar period.

PSR PHASE: Pulse longitude at PSR EPOCH.

PSR EPOCH: Fiducial time of pulsar model.

STN IDS: Station numbers of stations in the sub-array used in this scan.

NBASE: Number of baseband channels.

OBS FREQ: Sky frequencies (sum of LOs) of each of N baseband channels.

BANDWIDTH: Observing bandwidths of each of N baseband channels.

POLARIZ: Polarization descriptor of each of N baseband channels.

NXCCHANS: Number of cross-correlation spectral channels for each of N baseband channels.

XC AVG: Integration time for cross-correlation data.

XC FREQ: Sky frequency of the spectral channel at the low frequency edge of the baseband, for N basebands.

NACCHANS: Number of auto-correlation spectral channels for each of N baseband channels.

AC AVG: Integration time for auto-correlation data.

AC FREQ: Sky frequency of the spectral channel at the low frequency edge of the baseband, for N basebands.

REST FREQ: Spectral line rest frequency for each of N basebands.

VELOCITY: Velocity at the low frequency edge of the baseband, for N baseband channels.

FRAME: Velocity reference frame descriptor.

FILTERS: Digital filter type used in correlator.

FP FLAGS: Flags that indicate which correlator processing options were used.

10.2.B.4 Gain table information

Station-based information that changes as fast as once per minute should be stored in an archive gain table. The gain table will contain some information derived from the VLBA database.

TIME: Time of center of interval, TAI seconds from run reference time.

TIME INTRVL: Time interval of gain table entry.

STN ID: Station identification number.

BASEBAND ID: Baseband channel identification number.

T SYSTEM: System temperatures for each baseband channel.

T SYS RMS: rms in the T SYSTEM samples for each baseband channel.

DLY OFFSET: Group delay residuals used to correct correlator model (from online source fringe fit solutions). One for each baseband channel.

LO OFFSET: Delay rate residuals used to correct correlator model. One for each baseband channel.

CAL PHASE: Phases for each baseband channel from phase calibration tone detectors.

CAL PHS RMS: rms in the CAL PHASE averages per baseband.

GROUP DLY: Center earth group delay for each station calculated by the correlator model software at wavefront arrival at TIME.

PHASE DLY: Phase delay modulo 2pi, for each baseband channel.

DERIV1, DERIV2, DERIV3, DERIV4: Derivatives of GROUP DLY for each station.

10.2.B.5 The visibility records

The visibility data records are listed below. Separate records will be required for each baseband channel. One visibility weight is included per record.

TIME: Wavefront arrival time at station A, TAI seconds from run reference time.

STN IDS: Identification numbers of stations A and B.

U, V, W: Baseline components (u,v,w).

GROUP DLY: Group delay from correlator model.

PHASE DLY: Phase delay from correlator model, modulo 2pi.

DLY RATE: Phase delay rate from correlator model.

WEIGHT: Visibility weight.

XC REAL, XC IMAG: Normalized correlation coefficient for N spectral channels, in M baseband channels.

10.2.B.6 The autocorrelation spectra

The autocorrelation spectra will be kept separate from the visibility records. The autocorrelation records will have been averaged to between 1 s and 60 s.

TIME: Wavefront arrival time at station A, TAI seconds from run reference epoch.

STN ID: Station identification number.

BASEBAND ID: Baseband identification number.

WEIGHT: Weight.

AC DATA: Normalized autocorrelation spectra, N spectral channels.

10.2.B.7 Maintaining model accountability

The archive format must preserve enough information about the online correlator models to allow retrieval of the exact model totals for any UTC in the post-processing analysis. There are at least three ways to do this and all three are included in the above list.

1. Keep an accurate and reliable description of the various versions of the software modules used in the correlator. It is easy to keep version numbers and dates in the observing run header. All of the versions of all software modules will have to be stored (for life) in a library.

2. Have the correlator calculate total model group delays and derivatives for the times of the gain table entries, every UTC minute or so. Four derivatives will extrapolate a total delay to an error of less than 10^-14 s over 2 minutes (0.3deg phase at 86 GHz).

3. Carry the correlator model totals in the visibility records. Recalculate model totals using an offline model algorithm that is within about 0.1 m of the online correlator model. Calculate the differences between the offline model totals and the visibility record totals. By linear interpolation, use these deltas to estimate the delta at the desired UTC. Calculate the offline model totals at the new UTC, and add the interpolated deltas. These model totals are within 10^-14 s of the delay model totals that would have been calculated by the correlator model (interpolated over 4 minutes).

TABLE 2–1. MAJOR CORRELATOR MODES

Mode	Maximum number of stations	Maximum number of baselines	Frequency channels per baseline	Lags per baseline
FULL	10	45	512	1024
HALF	14	91	256	512
QUARTER	20	190	128	256

TABLE 2–2. QUARTER MODE (20 STATIONS)

Mode	Polarization	No. of CICs	No. of IFs	Bandwidth (MHz)	Lags per baseline	Resolution (kHz)	Phase centers	Comment
1	P	8	4	32	64	1000	1	
1*a*	P	4	2	16	64	500	1	High resolution
1*b*	P	2	1	8	64	250	1	
1*a*′	P	4	2	16	32	1000	2	Mult. phase ctr
1*b*′	P	2	1	8	16	1000	4	
2	NP	16	16	128	256	1000	1	(Geodetic/MkIII)
2*a*	NP	8	8	64	256	500	1	High resolution
2*b*	NP	4	4	32	256	250	1	
2*c*	NP	2	2	16	256	125	1	
2*d*	NP	1	1	8	256	62.5	1	
2*a*′	NP	8	8	64	128	1000	2	Mult. phase ctr
2*b*′	NP	4	4	32	64	1000	4	
2*c*′	NP	2	2	16	32	1000	8	
2*d*′	NP	1	1	8	16	1000	16	

TABLE 2–3. HALF MODE (14 STATIONS)

Mode	Polarization	No. of CICs	No. of IFs	Bandwidth (MHz)	Lags per baseline	Resolution (kHz)	Phase centers	Comment
3	P	8	4	32	128	500	1	
3*a*	P	4	2	16	128	250	1	High resolution
3*b*	P	2	1	8	128	125	1	
3*a*′	P	4	2	16	64	500	2	Mult. phase ctr
3*b*′	P	2	1	8	32	500	4	
4	NP	16	16	128	512	500	1	
4*a*	NP	8	8	64	512	250	1	High resolution
4*b*	NP	4	4	32	512	125	1	
4*c*	NP	2	2	16	512	62.5	1	
4*d*	NP	1	1	8	512	31.25	1	
4*a*′	NP	8	8	64	256	500	2	Mult. phase ctr
4*b*′	NP	4	4	32	128	500	4	
4*c*′	NP	2	2	16	64	500	8	
4*d*′	NP	1	1	8	32	500	16	

TABLE 2–4. FULL MODE (10 STATIONS)

Mode	Polarization	No. of CICs	No. of IFs	Bandwidth (MHz)	Lags per baseline	Resolution (kHz)	Phase centers	Comment
5	P	8	4	32	256	250	1	
5a	P	4	2	16	256	125	1	High resolution
5b	P	2	1	8	256	62.5	1	
5a′	P	4	2	16	128	250	2	Mult. phase ctr
5b′	P	2	1	8	64	250	4	
6	NP	16	16	128	1024	250	1	
6a	NP	8	8	64	1024	125	1	High resolution
6b	NP	4	4	32	1024	62.5	1	
6c	NP	2	2	16	1024	31.25	1	
6d	NP	1	1	8	1024	15.625	1	
6a′	NP	8	8	64	512	250	2	Mult. phase ctr
6b′	NP	4	4	32	256	250	4	
6c′	NP	2	2	16	128	250	8	
6d′	NP	1	1	8	64	250	16	

TABLE 2–5. ALTERNATE FULL MODE (10 STATIONS)

Mode	Polarization	No. of CICs	No. of IFs	Bandwidth (MHz)	Lags per baseline	Resolution (kHz)	Phase centers	Comment
7	P	16	8	64	128	1000	1	
7a	P	8	4	32	128	500	1	High resolution
7b	P	4	2	16	128	250	1	
7a′	P	8	4	32	64	1000	2	Mult. phase ctr
7b′	P	4	2	16	32	1000	4	
8	NP	32	32	256	512	1000	1	(2 or 4 DPS units)
8a	NP	16	16	128	512	500	1	High resolution
8b	NP	8	8	64	512	250	1	
8c	NP	4	4	32	512	125	1	
8d	NP	2	2	16	512	62.5	1	
8a′	NP	16	16	128	256	1000	2	Mult. phase ctr
8b′	NP	8	8	64	128	1000	4	
8c′	NP	4	4	32	64	1000	8	
8d′	NP	2	2	16	32	1000	16	

TABLE 5–1. OBSERVING MODES AND ARCHIVE DATA RATES

	Dump rate (Hz)	Fraction of observing time (%)	Data rate (kbyte/s)	Data rate (Gbyte/hr)	Tape consumption (tapes/hr)
Class (a)	0.2	80	4.6	0.02	0.13
Class (b)	0.5	10	100	0.36	2.4
Class (c)	1.0	8	200	0.72	4.8
Class (d)	2.0	2	400	1.44	9.6

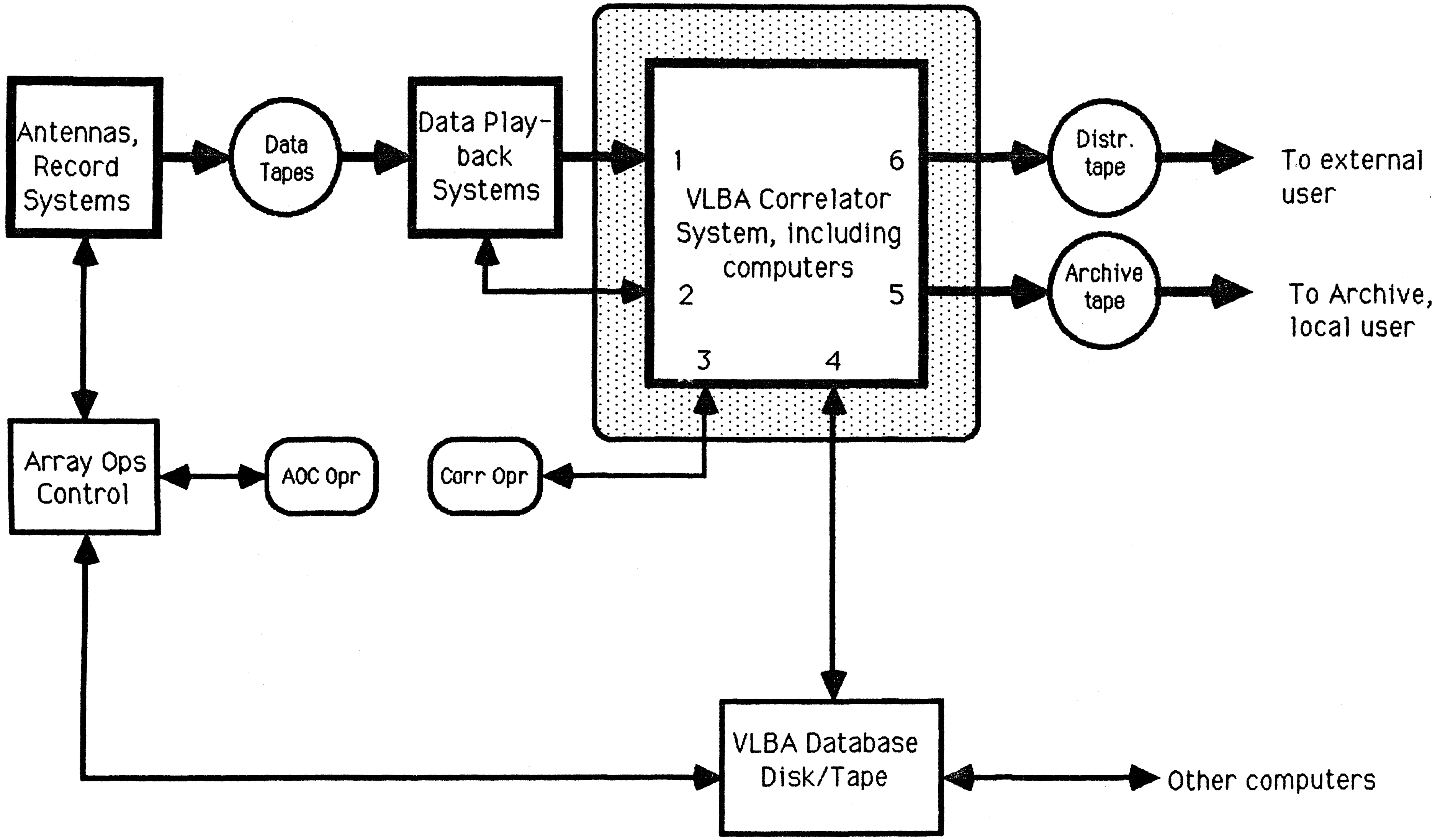


Fig. 1-1
VLBA Functional Block Diagram with Correlator Interfaces

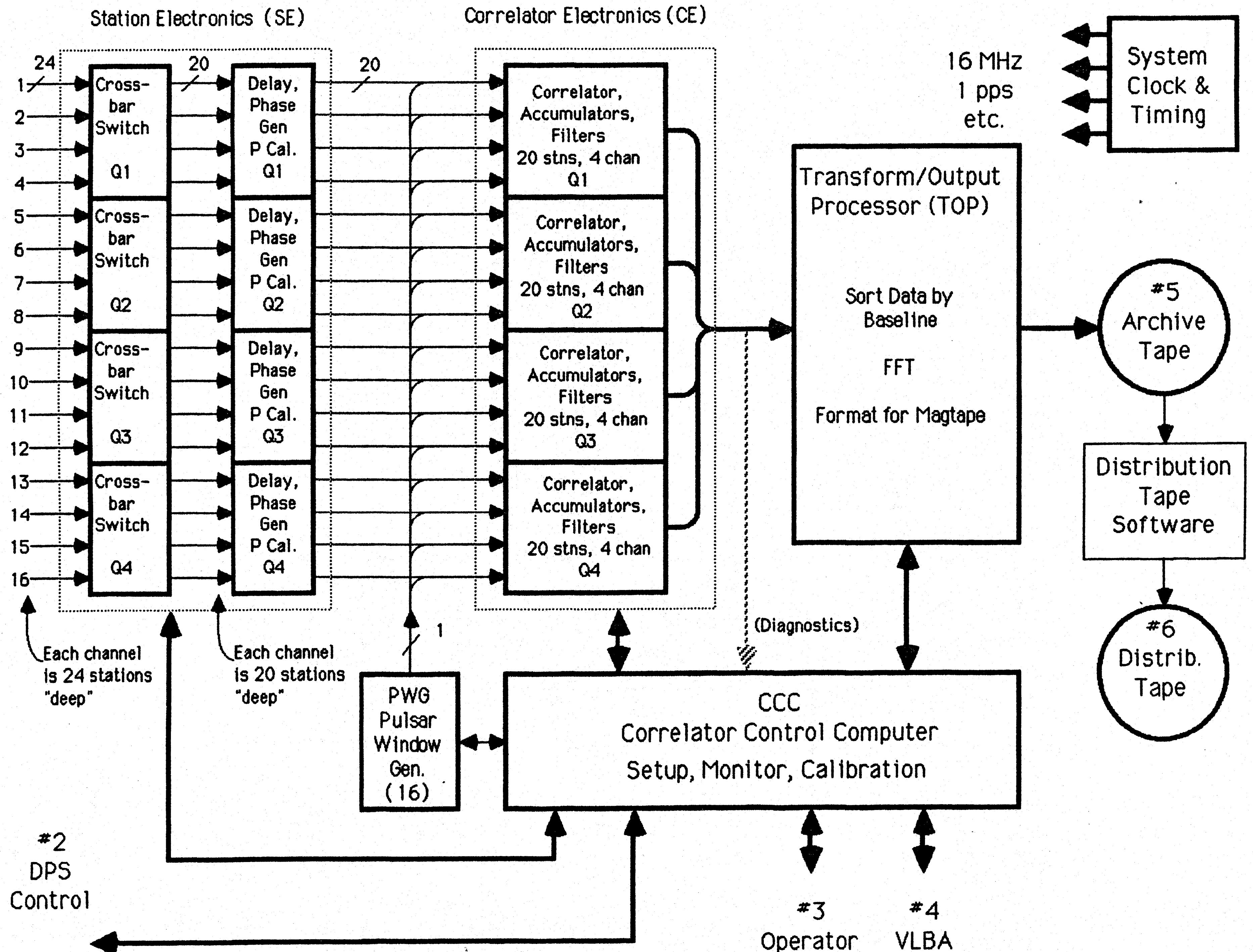
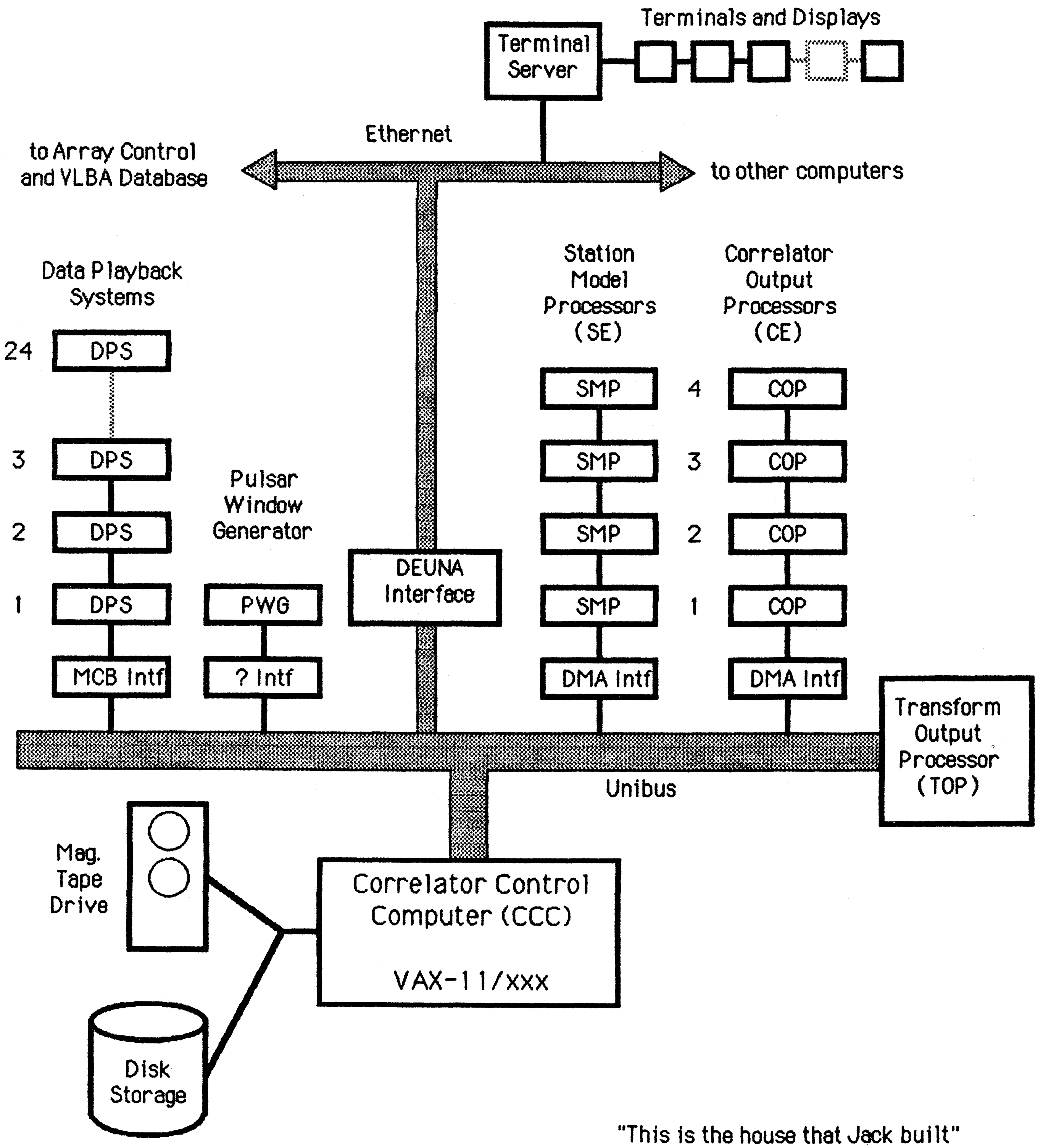


Fig. 1-2
VLBA Correlator Functional Block Diagram



"This is the house that Jack built"

Fig 4-1. Correlator Control Computer

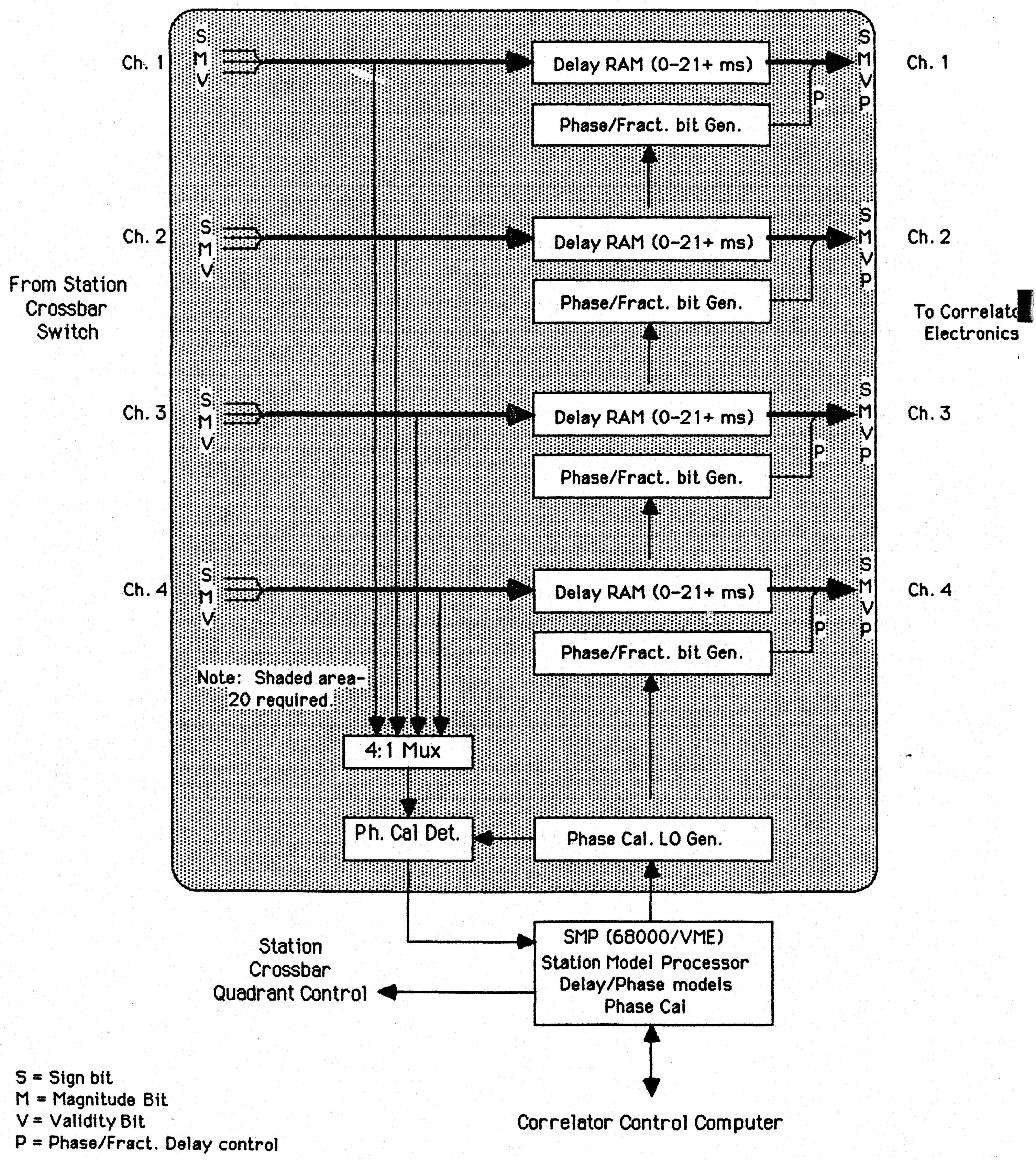


Fig. 4-2. Station Electronics Subsystem, 1 Quadrant

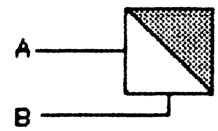


Fig. 4-3. Elementary Correlator Array (ECA)

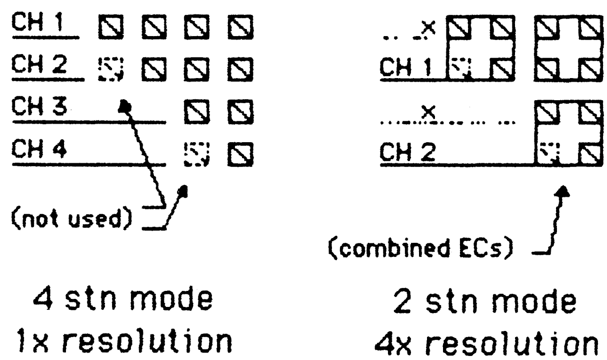


Fig. 4-6. 4:1 EC Consolidation

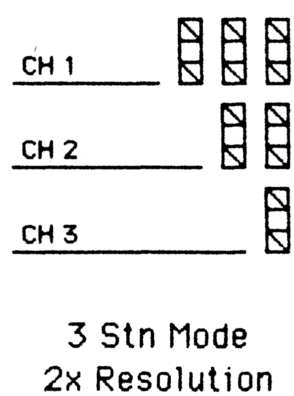


Fig. 4-7. 2:1 EC Consolidation

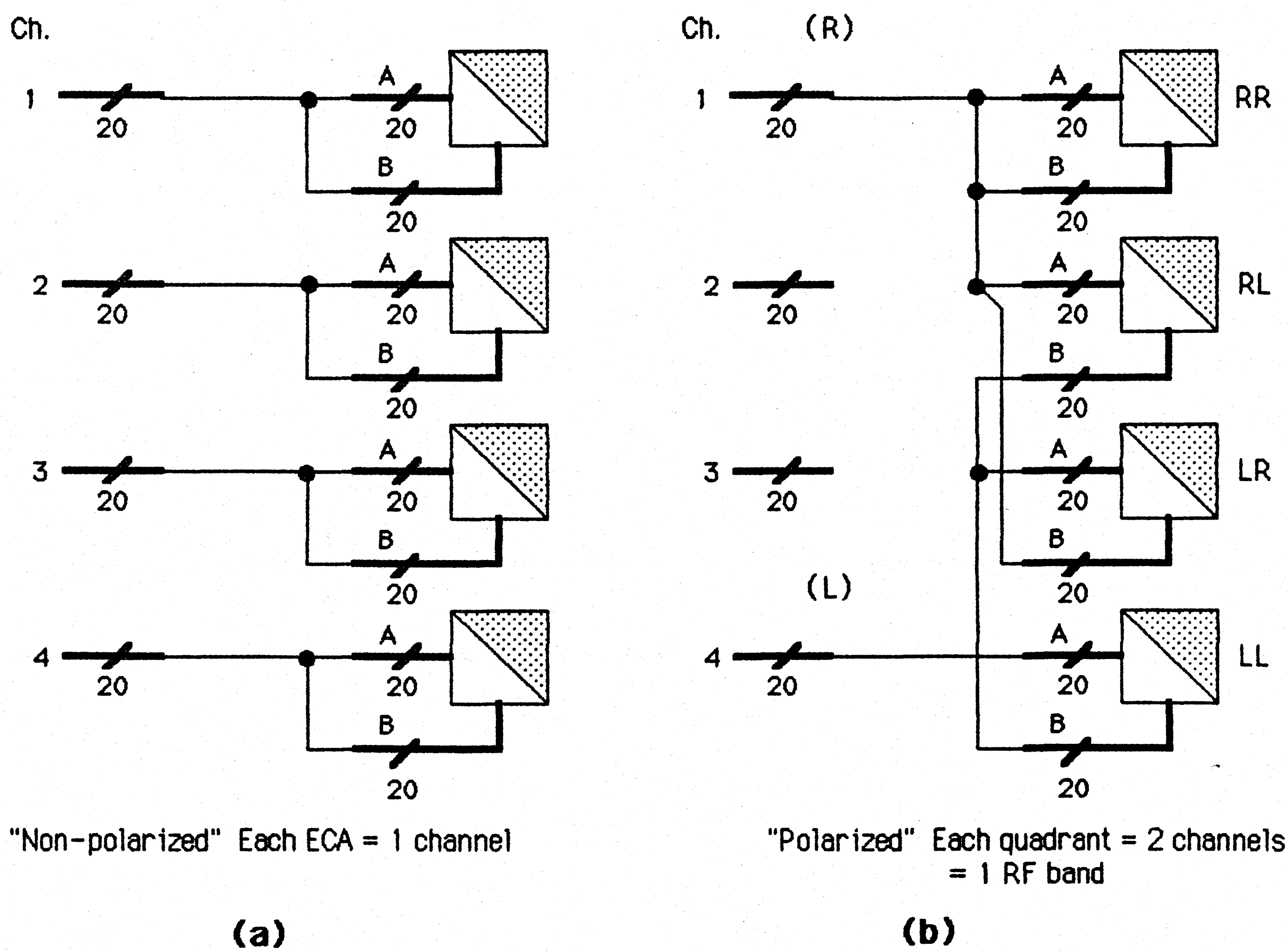


Fig. 4-4. Correlator Input Connections
Polarized vs Non-polarized

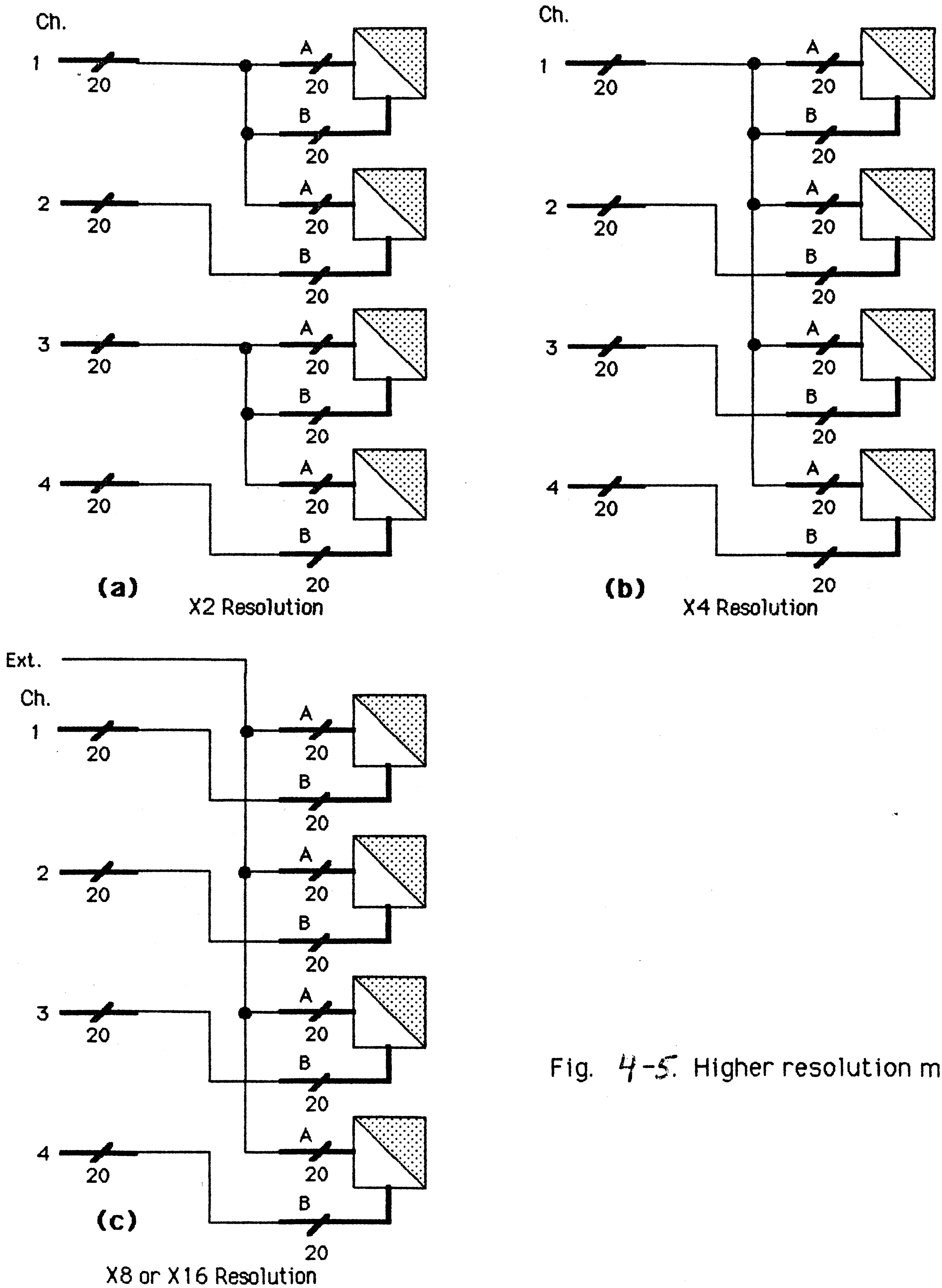


Fig. 4-5. Higher resolution modes

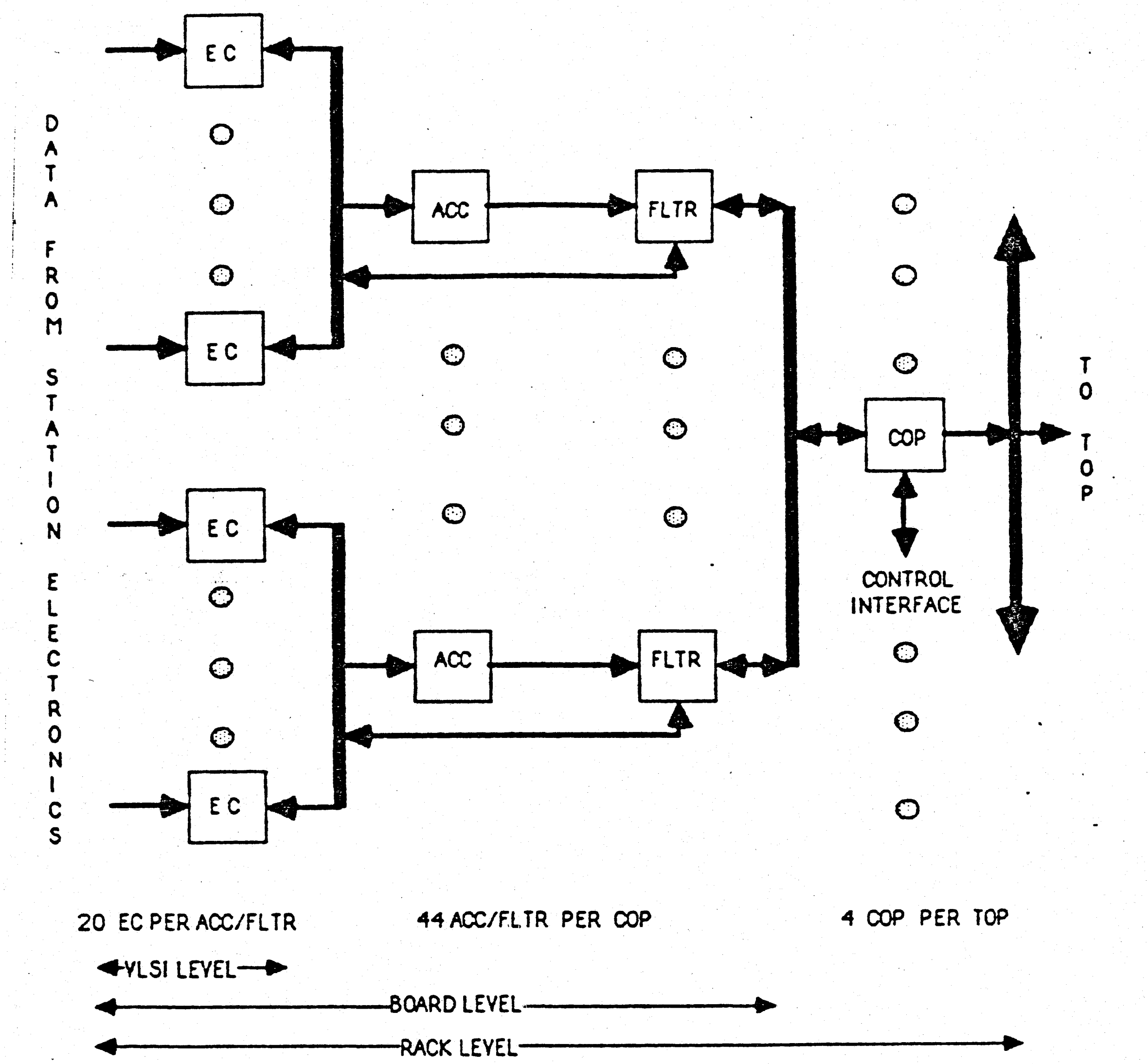


FIG. 4-8. CORRELATOR ELECTRONICS (ONE QUADRANT)

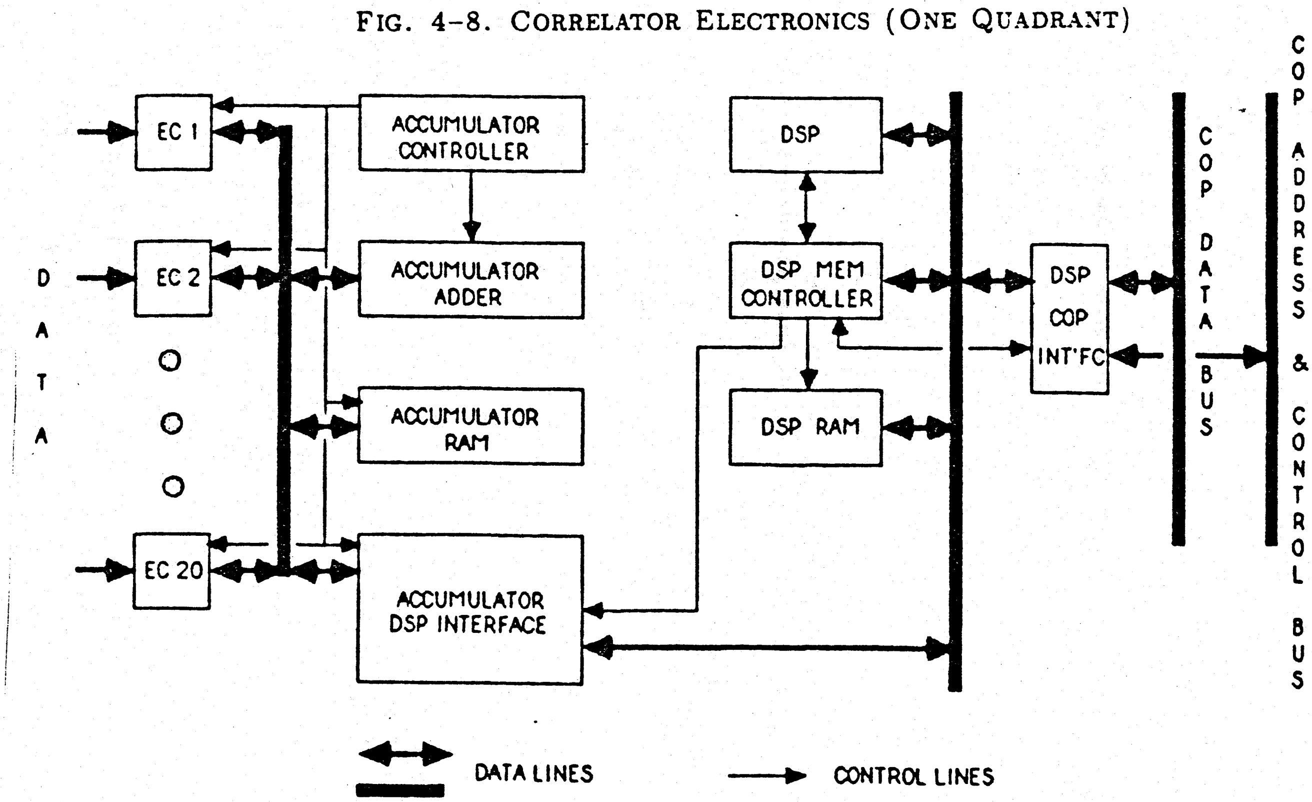
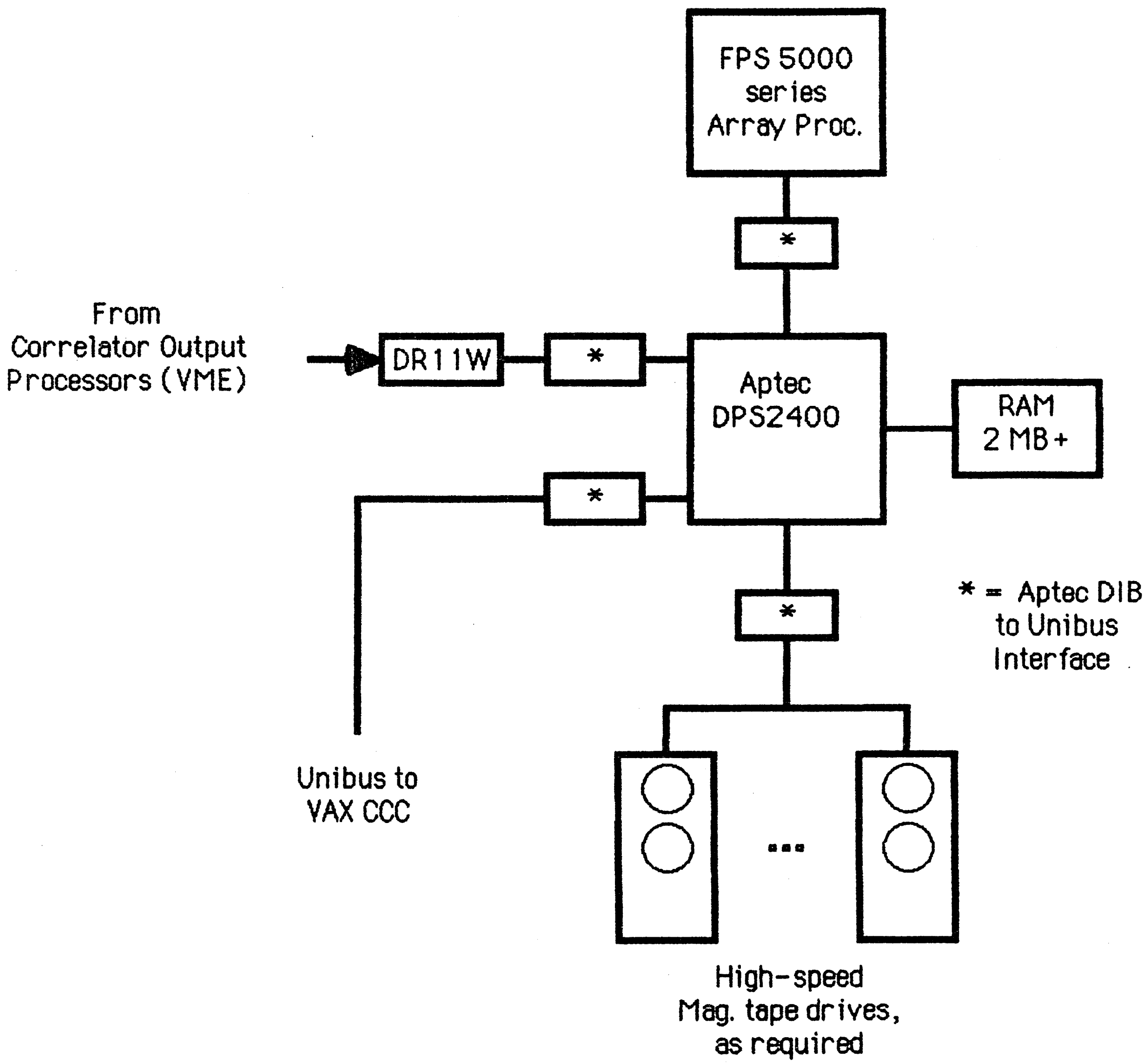
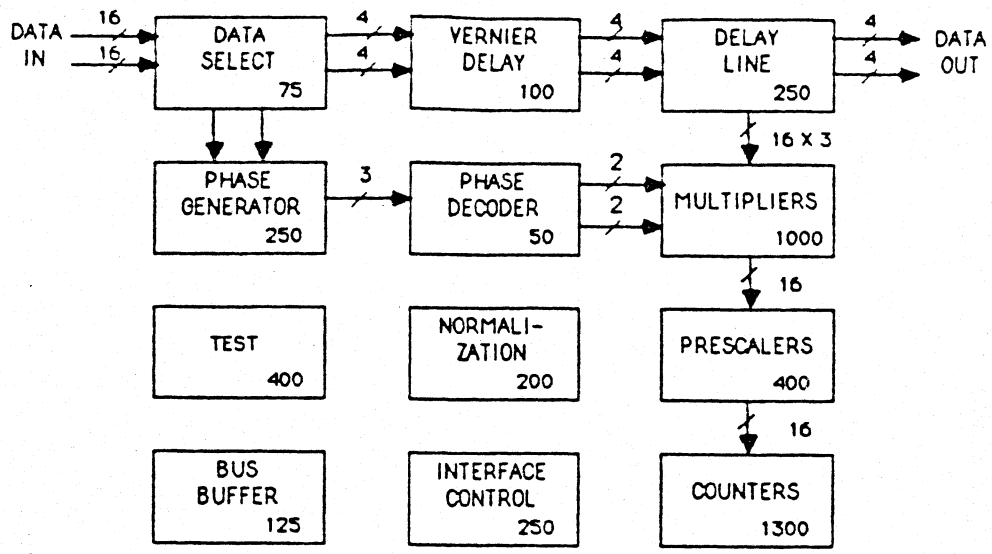


FIG. 4-9. CORRELATOR ELECTRONICS: ACCUMULATOR AND DIGITAL SIGNAL PROCESSOR



APTEC / TOP System

Fig 4-10



TOTAL GATES	4400
PERCENTAGE USE	72 %
TARGET USEAGE	< 80 %

FIG. 4-11. CORRELATOR VLSI CHIP
THE NUMBER SHOWN IN EACH BLOCK IS THE NUMBER OF GATES REQUIRED

INPUT A

INPUT B			S M V	S M V	S M V	S M V	S M V
			1 1 1	1 0 1	0 0 1	0 1 1	X X 0
			+4	+1	-1	-4	0
S M V	1 1 1	+4	+4	+1	-1	-4	0
S M V	1 0 1	+1	+1	0	0	-1	0
S M V	0 0 1	-1	-1	0	0	+1	0
S M V	0 1 1	-4	-4	-1	+1	+4	0
S M V	X X 0	0	0	0	0	0	0

S, M and V are the sign, magnitude and validity of the input data streams. X means "don't care".

FIG. 4-12. CORRELATOR MULTIPLIER TABLE

Section 10 - Updates

850611 Major revision reflecting Correlator Architecture Report, April, 1985 (correlator memo VC041).

841214 Revise sampling spec, etc., improve format

841129 Major revision

SECTION 11

POST PROCESSING

W. D. Cotton

11.1 Specifications

11.2 Description

11.2.1 General

The processing path, as the data progresses from the correlator through the mapping stage, is divided into two parts, synchronous processing (on-line) and post-processing (off-line). Historically synchronous processing has referred to processing which operates on raw correlator output. This is further refined here.

Synchronous processing is defined as those programs which are run automatically on the raw correlator output in dedicated computers that are directly linked to the correlator. The "standard VLBA correlator output" that is archived and supplied to the astronomer will be the output of the synchronous processor system.

Post-processing is defined as those programs which operate on the data thereafter. These are run by the astronomer on demand. Post-processing includes all further processing including analysis. No attempt is made to differentiate between the post-processing that is done for the original map set (if appropriate) and that done at the observers home institution.

11.2.2 Correlator Interface And Synchronous Processing

There is a certain set of operations that must be performed on almost all VLBA visibility records and need only be done once. These tasks will be done in several dedicated computer systems that synchronously accept the raw correlator output. This synchronous processing system consists of three separate hardware/software sub-systems : the fringe processors, the calibration computer and the archive writer. The fringe processors are planned to be "board-level" computers using M68020 cpu's with fast floating point hardware. They will connect directly to the outputs of the cross-correlation modules (CCM's) and auto-correlation modules (ACM's). The fringe processor computers will provide the 10 to 20 Mflop capacity required for transforming and calibrating the correlator output at high dump rates. The calibration processing system consists of software in the correlator control computer and possibly in an additional small VAX computer. The calibration processor calculates the slowly varying corrections that are passed in a gain table. The archive writer organizes and writes the archive data set.

The hardware for the fringe processor is described in the correlator section (Section 10) because it is intimately connected with the correlator. The budget allotments for the fringe processor and calibration software are also in the correlator chapter.

In order to present a unified overview of the data flow from the correlator into the post-processing system, the tasks performed by the synchronous processor system are described here. The fringe processor cards will receive the raw correlator output. They will calculate normalized correlation coefficients, slew out station based doppler shifts in the observing frequencies, make corrections for discrete delay tracking, transform cross-correlation functions into cross-correlation spectra and remove previously measured delay and delay rate offsets.

The calibration processor organizes tables of visibility corrections that are based on calibration source observations, measured system temperatures, standard gain curves and higher order interferometer model terms. The calibration processor passes the appropriate correction factors to the fringe processors. Rapidly variable calibration parameters will be applied to the data but slowly varying parameters will be kept in a calibration table and not applied directly to the data. Data from the station monitor log files are used by the calibration processor to create tables of bad data flags. The visibility data records are then flagged either in the fringe processor cpu's or in the archive writer.

The archive writer will create the output archive data set in uv FITS like format; the internal structure of the records will be FITS but the structure of the file may be different and all will be protected by an error correction code. Besides the visibility data, the archive data base will include gain tables containing the system temperatures and antenna gains applied in the calibration computer, and correlator model values at the times of the gain table entries. To maintain accountability, the correlator model delays, delay rates and phases will be carried along in each visibility record. An alternate possibility is that the parameters of the interferometric model will be kept in tha calibration/gain table with sufficient derivatives that the model values can be determined with "sufficient" accuracy for an arbitrary time. Thus each archive visibility record (residual values) can be rapidly converted to interferometric observables.

11.2.3 Post-Processing

11.2.3.1 Architectural Overview And Philosophy

The various types of observations to be made on the VLBA should use the same software to the greatest extent possible. Specifically, the data format should be flexible enough to handle continuum, spectral line, and astrometric / geodetic data. This insures that, for example, source maps can be made from astrometric data or that astrometric source positions can be found from mapping data (within the limitations imposed by observing style).

Much of the science that can be done with the VLBA will concern changes in the source and/or baseline parameters over long periods of time. Therefore the data archive system must preserve all of the information needed to reconstruct any amplitude, phase, and delay modifications made to the data and must preserve all information needed for full geodetic and astrometric analysis of the data. Such a reconstruction should not require reference to the original software since that software will probably change with time. To satisfy this requirment, the total interferometer model values with suffucuent derivatives will be kept in the gain table to compute with sufficient accuracy the model at an arbitrary time. Any calibration of the data which modifies this model will modify the values and the derivatives in the gain table.

11.2.3.2 Hardware

11.2.3.2.1 Current Hardware Thinking

The proposed hardware configuration is shown in Figure 11.1. The hardware of a sort that would be used in post-processing involves a technology which is undergoing extremely rapid evolution. Component selection changes on a time scale of as little as six months; some components become uneconomical to operate after a lifetime of only 5 to 7 years. Because of this rapid technological evolution, significant effort was not put toward optimizing the detailed hardware configuration. Nor was effort spent cross comparing various manufacturers´ products. Developement of the post-processing software may proceed using existing computer hardware at NRAO (VAX 11/780's). The VLBA post-processing computer hardware need not be purchased until late in the project schedule.

The configuration shown is based on a VAX 11/780 and is conceptually very close to that developed for the original proposal in May 1982. It is felt that the four VAX system still represents an attractive possible system. Some detailed changes have been made, however. The number of displays has been increased based on AIPS experience. The disk subsystem has been upgraded and the intercomputer interfacing improved taking advantage of more recent technology. More work needs to be done to compare the present concept to alternative approaches.

11.2.3.2.2 Size Of Problem And Comparison To VLA

The computing capability now (Aug. 1985) available for the VLA seriously limits the science that can be done with that instrument. This is the conclusion of studies that have led to a proposal that NRAO acquire a supercomputer for the reduction of VLA data. The problems that drive the need for the supercomputer are those for which it is desirable to image the entire field of view of the primary antenna beams at high resolution. The size of the images needed is very large. Many of the experiments that need the large images are spectral line observations where there are many images to make.

A study of the computing needs of the VLBA has also been done, although the needs of an instrument that will not be on line for several years cannot be known as well as those of an instrument already in operation. The conclusions are that, for most observations, the wide fields that drive the large VLA needs are not needed for VLBI. The brightness temperature sensitivity of the VLBA is very much worse (because of the resolution) than for the VLA so typically only very compact sources can be observed. Also, delay and fringe rate offsets insure that confusing sources in the primary beams will not affect data from the program source in most cases. Therefore the image sizes are driven by the source structure only and should generally be manageable with the super-minicomputers currently in use for VLA data reduction.

There are some extreme cases for the VLBA however. The worst that is forseen would be an effort to image the water masers in an extended source such as Orion by brute force methods. Maps with over 40,000 pixels on a side, for each of 512 channels might be desired. These extreme cases are so bad that they could not be done even if several supercomputers were available. Therefore more clever techniques such as making low resolution images, or fringe rate maps, of the whole field, followed by small images of the region of each maser cluster, must be used in any case. If such techniques are used, and if the extreme case experiments are a small fraction of the total (few percent, at the most) then these observations can be reduced on the super-minicomputers.

The conclusion of the study of the computing needs of the VLBA is that a computing power about equivalent to that now available in the AIPS systems at NRAO, on which most VLA data reduction is now performed, is about what is needed for the VLBA. These systems are the equivalent of four VAX 11/780's, each with FBS 120B array processor, and IIS television display.

This conclusion only applies to the VLBA used as a stand alone instrument or used with other VLBI stations. When the VLBA stations near the VLA are used as outriggers to the VLA, they make the problems for the VLA worse. They increase the resolution without either reducing the brightness sensitivity or providing delay and rate discrimination sufficient to overcome the need to image wide fields. Therefore, for many experiments, the size of the images needed, in pixels, will be even larger than for the VLA alone. This will further increase the already very large computing needs of the VLA. The current budget of the VLBA does not support the additional needs of the VLA caused by the nearby VLBA stations.

11.2.3.3 Software

11.2.3.3.1 Decision To Use Common Software For Processing VLBA And VLA Data.

The techniques used and the software needed for all kinds of interferometry are sufficiently similar that there is no need for specific software packages for every instrument. In particular, the software needed for the VLBA will be so similar to that needed for the VLA that the VLA software package, which represents many man-years of work, should be used. Until the late 1970's, the techniques used for linked interferometers and for VLBI were very different, largely because the linked interferometers were able to measure the visibility phase while VLBI was not able to obtain any phase information. Since then, the VLA has been operating at high frequencies on baselines that are sufficiently long that the phase measurements are poor. Techniques have been developed to use closure phases and "self-calibrated" amplitudes. As a result, the techniques used for both kinds of instruments are now very similar.

11.2.3.3.2 Need For Transportability.

Much of the software developed in support of the VLBA will be run at various university facilities as well as at NRAO processing centers. This both allows the user to make late changes to the displays and analysis and relieves NRAO facilities of some of the computing burden generated by the observations. Software involved in observation preparation and post-processing may be very common at these other facilities. This is certainly the case in VLA support software, where the main post-processing package is run at more than 25 institutions. As such it is important that the software be as transportable as possible.

The widespread use of the VAX11/780 in the VLBI community eases the transportability problem somewhat by reducing the number of hardware environments which need be considered. However, it is not clear what the mix of hardware might be ten years from now. As such, machine independence should be a consideration.

11.2.3.3.3 Use Of AIPS For All Software Involving User Interactions.

The primary data analysis system for the VLA is now the AIPS (Astronomical Image Processing System) package. This package already has most of the functions needed for processing astronomical data from the VLBA and is routinely used for VLBI data reduction. There are a few functions that are still needed (e.g., editing and calibration) for complete VLBA data reduction but those should be available sometime during 1986. This package should be used for the VLBA. If there are capabilities that are missing, they should be added.

Using AIPS makes a large body of data analysis and display capabilities available that would require a tremendous effort to duplicate in a VLBA specific package. To avoid requiring users to learn two systems, AIPS should contain all user routines used on the VLBA data after correlation, including all editing and calibration routines that are now outside of AIPS for the VLA.

An advantage of the AIPS system as it is now coded is that it is designed to be easy to move from one type of computer to another. This allows users that have a reasonably powerful computer at their home institution to take their data home and analyze it at their leisure.

It is not yet clear where the geometric (geodetic and astrometric) analysis will be made. The capability should be provided within the standard package but the Geodetic community may also want to be able to use their own software. The VLBA software should be able to provide an output data set that contains all of the necessary data to extract geodetic information. This means that all alterations made to the data by the processor and reduction software should be undone or at least documented to the extent that they can be undone easily.

11.2.3.3.4 AIPS

Most of the astronomical data obtained with the VLBA will be processed through the AIPS system or its successor so it is desirable to have a post-correlation database compatible with that used in AIPS.

Distribution Tape format. The uv-FITS format will be used whenever data is written to tape whether correlator output, archive or processed data. In the case of the archive tape, an error correcting code will be wrapped around the files. The uv-FITS format is sufficiently compact and flexible that it should be a rather efficient means of storing data.

Database structure. AIPS data files are structures very much like FITS files on tape. There are two basic types of data sets: 1) regularly spaced arrays (i.e., images) and 2) irregularly spaced arrays (i.e., uv data). Additional types may be added if necessary. Since VLBA data will be predominantly of the second type, most of the following comments will be directed towards this type of dataset. There are three distinguishable parts of the AIPS database structure: the catalog header, the main data file and extension files.

- Catalog. The catalog header contains information about a database such as source name, observing date, the amount of data, details of the structure of the main data file and the existence of and number of any extension files. The catalog header record currently has a fixed structure which, although more general than those of previous data reduction systems, is the least flexible portion of the AIPS database.

- Main data files. The form of the uv data files in AIPS is a sequence of logical records containing a regular, rectangular array of data (e.g., correlator lags, spectral channels, time, etc.) and a number of `random´ parameters describing the array (u, v, w, time, baseline, etc.). The number and order of the random parameters is given in the catalog header. At the present time there is no limit on the number of random parameters but there is space in the catalog header for the labels for only the first seven. The data array in each record is also described in the catalog header which gives the number of axes, the axis type, the dimension of each axis, the axis value increment, a reference pixel (needs be neither integer nor in the bounds of the array given) and the axis value at the reference pixel. The format of the current catalog header allows up to seven dimensions. The current convention is to have RA, Dec, Stokes type and Frequency as an axis even if that axis is degenerate. This allows a convenient way to specify position, frequency, etc. This structure requires that there be a uniform spacing along each axis which may present problems for the VLBA (e.g., when observations are made in the bandwidth synthesis mode). This limitation can be circumvented by use of channel number instead of frequency.

- Extension files. Extension files are used to store information not contained in the catalog header or the main data file. An example of an extension file is the History file which is carried along with all AIPS data files. This file contains ASCII records describing all processing which has been done on the data in the file. Other current extension files are the antenna files, calibration and editing files. Extension files contain a header record containing general information; for instance Antenna file headers carry time information like the Greenwich Sidereal Time at IAT midnight for the reference date. Extension file entries consist of fixed length logical records which may be complex data structures. VLBA data bases will use extension files to store antenna logs, correlator logs, calibration tables, correlator models, etc.

Database access. AIPS programs generally access the main data files sequentially which allows reading large blocks of data at a time and overlapping I/O and computation by means of double buffering. In order to increase I/O speed, DMA transfer requests are sent directly to system utilities rather than using FORTRAN I/O. This allows programs to directly access the I/O buffer removing one core-to-core copy of the data. The I/O routines are quite fast and are probably comparable in speed with mapping virtual memory onto the data base. The AIPS I/O routines have been designed to maximize speed and flexibility at the cost of increasing the complexity of their use.

I/O to extension files is generally sequential but the routines which handle the I/O are capable of random access and mixed reads and writes. This increased flexibility comes at a cost of reduced speed. However, since the extension files are generally much smaller than the main data file the reduced I/O speed is usually not serious.

11.2.3.3.5 Calibration And Editing Software

Since the calibration and editing of data for the VLBA and VLA are so similar and the DEC-10 software currently used for the VLA needs to be replaced, there is a joint VLBA/VLA calibration and editing project. This software is to be written as AIPS tasks and the design of this system is currently under discussion. A procedure has been established to formally specify the data structures and functions needed for this software.

The basic proposed scheme is to keep the data in the raw form in multi-source files in time order. This data would never be modified but gain and flagging tables would contain the information necessary to flag and calibrate the raw data. The gain table will contain information which varies on fairly short time scales (seconds to minutes). Calibration information which is much more slowly varing, such as bandpass calibration, will be kept in separate files.

Flagging information will be kept in a file which contains a list of flagging criteria. There may be several sets of these files to be used in selecting data.

In order to perform an editing or calibration function, a task will call a subroutine UVGET (and CALCOP) which will select data by given criteria and optionally apply calibration and/or user flagging information. Calibration and/or editing information is send to interface routines which will update the gain table and other tables as appropriate. Thus access to the data base will be thru a set of interface routines.

For many purposes, a subset of the data may be selected and converted to a more traditional AIPS uv or image file for extended processing. An example of this is when a calibrator source needs to have several iterations of self-calibration in order to derive a proper model of the source. In this case, the calibration information derived in this process would be used to update the gain table.

The AIPS task FILLR which reads VLA Modcomp/archive tapes will create a multi-source, indexed file with 1 or 2 IFs as observed by the VLA. As yet, the only operational software to operate on this form of data is a task to sort tables (TASRT) and PRTTA which will print the contents of tables. FITTP is being modified to write arbitrary extention tables, hence the ones used in the calibration and editing software. UVLOD should read such files automatically.

11.2.3.4 Special Considerations For Astrometry And Geodesy

Correlator. The primary correlator outputs of interest for astrometry and geodesy are the group delay (from bandwidth synthesis), the phase, and the phase delay rate. It is felt that the values of these quantities should be given as totals, not as residuals from the correlator model. If total values are kept, there is no need ever to remember the details of the correlator model. If residuals and/or geocentric values are being kept, the correlator model should be carried along for all further stages of reduction, to very high accuracy. We will be able to carry along the delays and phases used during correlation in the calibration/gain table. Thus the VLBA data sets would be similar to the current Mk III data sets in that observables can be recovered essentially as fast as data sets can be read in.

Calibration data include weather measurements (temperature, pressure, and humidity or dew point), water vapor radiometer measurements (reduced off-line), perhaps with algorithms that are the in the correlator. Provisions for deriving dual-frequency ionospheric corrections must be available. This procedure requires knowledge of all the frequencies used for bandwidth synthesis in order to determine the effective frequency at each band. Source image information may be used to correct the measured delays.

In the first stage of analysis, a model for station position and earth orientation (tides, precession, nutation, polar motion, etc.), source positions, the Solar System barycenter, general relativity, antenna geometry, etc is used to calculate a priori values of group delay, delay rate and phase. Changes to the model are found by a least-squares procedure that compares a priori's with the observables. During the analysis stage, the investigator should be able to turn on or off the various parameters to be solved for. It should be possible to analyze single, short experiments as well as large ensembles of data from several observing sessions. It should be possible to classify some parameters as "global" (having the same value for many experiments), such as source and station positions; and some as "arc" (having values that change from experiment to experiment, or even within an experiment) such as clock or atmospheric parameters.

11.2.4 Miscellaneous Computing Support

The VLBA like other similar instrumentation will require ongoing support and continued development. This work will utilize computer resources over and above those required for the normal data processing operations. Similarly, astronomers located at the center will also require additional facilities.

It is important that these auxiliary aspects and the normal data processing operations do not interfere with each other. If common resources are used for both data processing and development this implies liberal overall capacity. This is the approach that has been taken here. It may not be best, however, because the necessary data processing load is very inelastic and difficult to predict. The question of separating the operational and development facilities is perhaps best faced after we have some early operational experience.

11.3 Manpower Requirements

We estimate that 10 man-years of programming effort are required to upgrade the AIPS software for VLBA data analysis. A fairly large effort has already gone into writing new AIPS tasks for VLBI and many VLBI experiments are now being reduced through AIPS. Ten man-years over and above the current level of VLBI programming effort in AIPS will allow creating the special calibration and editting programs for VLBA data. The greatest uncertainty in the manpower estimate concerns the special software required to support astrometry and geodesy. We may choose to integrate an existing non-NRAO, non-AIPS geodetic software package into AIPS. The 10 year manpower estimate excludes creating an entirely new and duplicate geodetic software system.

11.4 Cost Estimates

Post-processing requirements are outlined in terms of the DEC VAX-11/780 system. This system should however only be taken as a possible system. This hardware need not be purchased prior to 1987. It is hoped that advances in computer technology over this period will improve the performance/cost ratio. Post-processing software will depend largely on procedures already developed for the VLA and existing specialized VLBI software. Cost estimates are given below:

Quantity	Description	Unit Price ($)	Total Price ($)
4	VAX 11/780 (SVAXECA-CA)	245k	980k
	4 Mbyte memory		
	0.5 Gbyte disc storage (non-removable)		
	1 Tape drive (6250/1600)		
	Operating system		
4	3.2 Gbyte disc expansion (non-removable)		500k
	1.4 Gbyte expansion	50k	
	1.8 Gbyte additional system	75k	
4	0.8 Gbyte disc expansion (removable)		280k
	0.8 Gbyte additional system	70k	
1	Mass store (high density tape similar to VCR under devel. at NRAO)	40k	40k
2	Additional tape drives	25k	50k
4	Array processors	75k	300k
3	Image display subsystems	60k	180k
1	Video disc (fast image refresh disk system under devel. at NRAO)	20k	20k
2	Printers	30k	60k
25	CRT terminals		40k
	20 text terminals	20k	
	5 graphics terminals	20k	
	Computer interconnection		150k
	Local Area Network	40k	
	CI Interconnect	110k	
	Miscellaneous	50k	50k
Total Hardware			2,650k
Software Development (10 man-years)			450k
Total Hardware & Software			3,100k

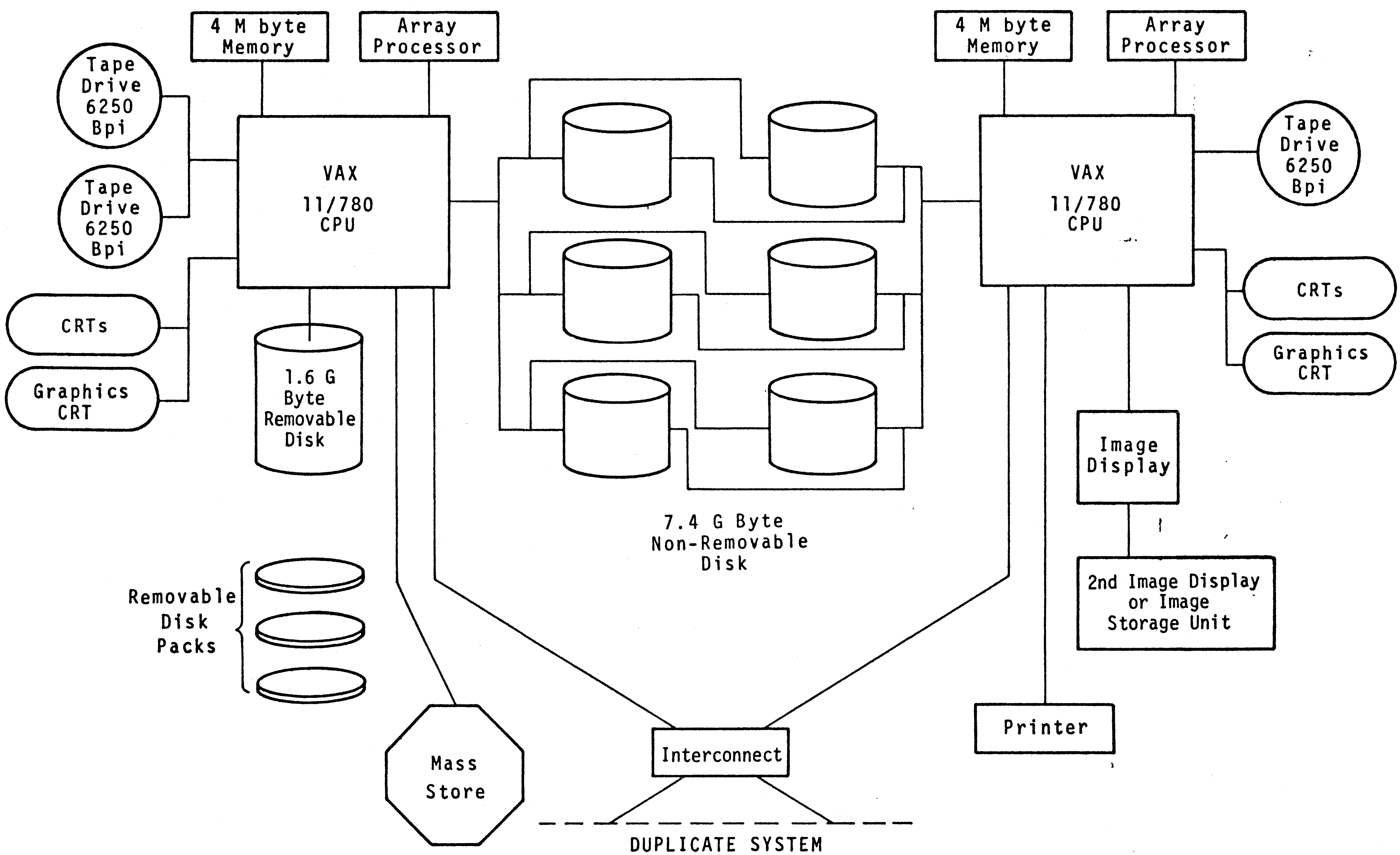


Figure 11.1

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Section 11 - Updates

850812 General update. Most revisions reflect current thinking about calibration procedures and geometric accountability. Cotton.

841129 General update. Sections dealing with the comparison between the post processing computing needs for the VLA and VLBA and dealing with the post correlation, pre archive operations on the data have been rewritten. The calibration and editting project is described. Numerous other minor textual changes. Remove Table 11.1, Figure 11.1. Cotton, Benson, Walker.

840423 General update. No significant changes of content. Burns and Cotton
The biggest changes were in the subsection numbering.

840421 General update. No significant changes of content. Walker
The biggest changes were in the VLA/VLBA comparison.

840216 Initial version based on Volume 3; not necessarily up to date.

SECTION 12

VLBA OPERATIONS

C. Bignell

The current estimates of the operational needs are summarized in the following tables. These tables cover the following subjects:

I. Manpower requirements.
II. Work load of antenna site personnel.
III. AOC building space requirements.
IV. AOC office space requirements.
V. One plan to reduce AOC space.
VI. Estimated operating costs.

Table I (a)

Distribution of Personnel / Combined

Division	Position	VLA Personnel at Site	VLA Personnel in Socorro	VLBA Personnel at Site	VLBA Personnel at Socorro
Electronic	Head	0	1	0	0
	System Technician	0	0	0	1
	Cryogenic Grp Ldr	1	0	0	0
	Cryogenic Tech	2	0	3	0
	Low Noise Rcv Grp Ldr	0	1	0	0
	Low Noise Rcvr Engr	0	1	0	1
	Low Noise Rcvr Tech	2	4	0	2
	IF/LO Grp Ldr	0	1	0	0
	IF/LO Engr	0	0	0	2
	IF/LO Tech	1	3	0	2
	Digital Grp Ldr	0	1	0	0
	Digital Engr	0	0	0	1
	Digital Tech	1	2	0	2
	Correlator Engr	0	1	0	1
	Correlator Tech	1	0	0	2
	Recorder Engr	0	0	0	1
	Recorder Tech	0	0	0	3
	Field Grp Ldr	0	0	0	1
	Field Tech(at sites)	0	0	0	20
	Waveguide Grp Ldr	1	0	0	0
	Waveguide Tech	1	0	0	0
	Draftsman	0	1	0	1
	Total	10	16	3	40

E&S/Antennas	Head	1	0	0	0
	Vehicle Mechanic	1	0	0	0
	Site Electrician	1	0	0	0
	Aircondition,Plumbng	1	0	0	0
	Carpenter	1	0	0	0
	Antenna Mechanic	8	0	2	0
	Antenna Servo Tech	4	0	2	0
	Engineer/Supervisors	3	0	0	0
	Machinist	2	0	1	0
	Draftsman	1	0	2	0
	Labourer	3	0	0	0
	Total	26	0	7	0
Array	Head		1		
	Chief Array Oper.		1		1
	Array Oper.	4	5		5
	Main. Coord.		1		
	Chief Corr. Oper.				1
	Corr. Oper.				5
	Data Analysts		1.5		2
	Total		9.5	0	14
Business	Head		1		
	Sr. Adm. Ass.		1		
	Admin. Aide-personnel		1		
	Secr. Pool	2	1		2
	Recep./Oper.		1		
	Libr./Ship Clerk				1
	Guard/Janitor	3.5			
	Janitor				1
	Warehouse/Bus	1			
	Receiving		1		
	Leadman/Shuttle Dr.		1		
	Shuttle Driver		1		
	Sr. Buyer		1		
	Buyer		1		1
	Purch. Secr.		1.8		0.7
	Head Cook	1			
	Cook/Housekeeper	1			
	Accountant		2		
	Bookeeper		1		
	Fiscal Clerks		2		
	Total	8.5	16.8	0	5.7

Computer	Head		1		
	Ass. Div. Hd/Op. Man.		1		1
	Systems Programmers		1		1
	Senior Programmers		4		2
	Programmers		3		2
	Engineer		1		
	Technician		2		2.5
	Prog. Libr/Comp. Oper.		3		2
	Total		16	0	10.5
Scientific Services/ Management	Director		1		
	Deputy Director		1		1
	Scientists		5		3
	Systems Scientists		5		4
	Post Docs		2		2
	Resident Cust./Sup.	1			
	Secretaries		1		
	Total		15	0	10
Grand total		44.5	73.3	10	80.2

Table I (b)

Stand Alone/Combined Personnel

Division	Position	VLA Pers. Stand Alone	VLBA Pers. Stand Alone	Total Personnel VLA and VLBA Stand Alone	Total Personnel VLA/VLBA Combined	Diff
Electronic	Head	1	1	2	1	-1
	System Technician		1	1	1	0
				0		
	Cryogenic Grp Ldr	1	1	2	1	-1
	Cryogenic Tech	2	3	5	5	0
				0		
	Low Noise Rcv Grp Ldr	1		1	1	0
	Low Noise Rcvr Engr	1	1	2	2	0
	Low Noise Rcvr Tech	6	2	8	8	0
				0		
	IF/LO Grp Ldr	1		1	1	0
	IF/LO Engr	1	1	2	2	0
	IF/LO Tech	4	2	6	6	0
				0		
	Digital Grp Ldr	1		1	1	0
	Digital Engr		1	1	1	0
	Digital Tech	3	2	5	5	0
	Correlator Engr	1	1	2	2	0
	Correlator Tech	1	2	3	3	0
	Recorder Engr		1	1	1	0
	Recorder Tech		4	4	3	-1
				0		
	Field Grp Ldr		1	1	1	0
	Field Tech(at sites)		20	20	20	0
				0		
	Waveguide Grp Ldr			0	1	1
	Waveguide Tech			0	1	1
				0		
	Draftsman	2		2	2	0
	Total	26	44	70	69	-1

E&S/Antennas	Head	1	1	2	1	-1
	Vehicle Mechanic	1		1	1	0
	Site Electrician	1		1	1	0
	Aircondition,Plumbng	1		1	1	0
	Carpenter	1		1	1	0
	Antenna Mechanic	8	3	11	10	-1
	Antenna Servo Tech	4	2	6	6	0
	Engineer/Supervisors	3		3	3	0
	Machinist	2	2	4	3	-1
	Draftsman	2	1	3	3	0
	Labourer	3		3	3	0
	Total	27	9	36	33	-3
Array	Head	1		1	1	0
	Chief Array Oper.	1	1	2	2	0
	Array Oper.	7	5	12	14	2
	Main. Coord.	1		1	1	0
	Chief Corr. Oper.		1	1	1	0
	Corr. Oper.		5	5	5	0
	Data Analysts	1.5	2	3.5 0	3.5	0
	Total	11.5	14	25.5 0	27.5	2
Business	Head	1	1	2	1	-1
	Sr. Adm. Ass.			0	1	1
	Admin. Aide-personnel	2		2	1	-1
	Secr. Pool	1	3	4	5	1
	Recep./Oper.	2		2	1	-1
	Libr./Ship Clerk		1	1	1	0
	Guard/Janitor	3.5		3.5	3.5	0
	Janitor	1	1	2	1	-1
	Warehouse/Bus	1		1	1	0
	Receiving	1		1	1	0
	Leadman/Shuttle Dr.	1		1	1	0
	Shuttle Driver			0	1	1
	Sr. Buyer	1	1	2	1	-1
	Buyer	2		2	2	0
	Purch. Secr.	0.8	1	1.8	2.5	0.7
	Head Cook	1		1	1	0
	Cook/Housekeeper	3.8		3.8	1	-2.
	Accountant	2		2	2	0
	Bookeeper	1	1	2	1	-1
	Fiscal Clerks	2	2	4	2	-2
	Total	27.1	11	38.1	31	-7.

Computer	Head	1	1	2	1	-1
	Ass. Div. Hd/Op. Man.	1	1	2	2	0
	Systems Programmers	1	1	2	2	0
	Senior Programmers	4	2	6	6	0
	Programmers	3	4	7	5	-2
	Engineer	1		1	1	0
	Technician	2	2.5	4.5	4.5	0
	Prog. Libr/Comp. Oper.	3	2	5	5	0
	Total	16	13.5	29.5	26.5	-3 *
Scientific Services/ Management	Director	1	1	2	1	-1
	Deputy Director	1	1	2	2	0
	Scientists	5	5	10	8	-2
	Systems Scientists	5	5	10	9	-1
	Post Docs	2	2	4	4	0
	Resident Cust./Sup.			0	1	1
	Secretaries	1	1	2	1	-1
	Total	15	15	30	26	-4
Grand total		122.6	106.5	229.1	213	-16

30-Jan-85

SPECIAL REQUIREMENTS FOR THE VLBA OPERATIONS CENTER

(A) Each room will have terminal or Ether-Net outlets installed in addition to telephone jacks.

(B) The building will have moveable walls so that the interior can be redesigned when the VLBA needs change with time. Also a modern approach to office grouping within large rooms should be considered.

(C) The array control room will have a special arrangement with respect to the computer rooms such that access to necessary tape drives is made easy. The same will hold true for the correlator control room.

(D) The appropriate rooms will be screened in a Faraday cage.

(E) The air conditioning, heating and humidity requirements will be controlled closely for the computers and special hardware.

(F) There should be an easy access cable trough system installed.

(G) The tape storage areas should have temperature, humidity and clean air controls.

(H) Special safety requirements.

(I) The building should be designed such that it can be expanded easily to accommodate (a) the combined VLA/VLBA operations and (b) possible inclusion of the mm array operations in the future.

8-May-84

Table II

WORK LOAD OF ANTENNA SITE TECHNICIANS

Equipment/Area	Work Description	Rate	Hours Per Year	Days Per Year
Antennas	Monthly inspection	4 hrs/mo	48	6.0
	Quarterly maintenance	16 hrs/3mo	64	8.0
	Semi-yearly maintenance	38 hrs/6mo	76	9.5
	Yearly inspection	58 hrs/yr	58	7.3
	Servo main./semi-annual	12 hrs/6mo	24	3.0
	Unscheduled repair/repl.	92 hrs/yr	92	11.5
Electronics	Prev. maintenance	4 hrs/wk	208	26.0
	Module replacement	16 hrs/wk	832	104.0
	Systems tests	18 hrs/mo	216	27.0
Computers	Preventative main.	2 hrs/wk	104	13.0
	Repairs, diagnostics	8 hrs/mo	96	12.0
Supervisory	Schedule,procure part time assistance	16 hrs/mo	192	24.0
	Keep track of module, tape and other shipments	3 hrs/wk	156	19.5
Tape Handling	Unpack/pack tapes and record inform.	1.5 hrs/day	540	67.5
Busisness	Travel for module, other equip. deliv. (tapes?)	14 hr/wk	728	91.0
	Janitorial duties	2.5 hrs/wk	130	16.3
Total			3564	445.5

Final manpower requirements: 1.9 employees. 29-Jan-85

Table III (a)

VLBA OPERATIONS BUILDING SPACE REQUIREMENTS

Division	Purpose	Unit Area (sq. ft.)	VLBA Stand Alone #	VLBA Stand Alone Area(sq ft)	VLA #	VLA Area(sq ft
Scientific Services	Library /study area	750	1.0	750	1.0	750
	Secretary Office	150	1.0	150	1.0	150
	Receptionist Area	250	1.0	250	1.0	250
	Directors Office	300	1.0	300	1.0	300
	Deputy Dir. Off.	200	1.0	200	1.0	200
	Scientific Offices	150	16.0	2400	21.0	3150
	Visitors Offices	75	7.0	525	15.0	1125
	Auditorium	750	1.0	750	1.0	750
	Journal/Coffee area	250	1.0	250	1.0	250
	Visitor's kitchen	100	1.0	100	1.0	100
	Conference room	200	1.0	200	1.0	200
	Canteen	100	1.0	100	1.0	100
	Measur. Eng./Prt Rm	300		0	1.0	300
Array Operations	Array Control Room	600	1.0	600	1.0	600
	Correl. Control Rm	200	1.0	200		0
	Tape Staging Area	500	1.0	500		0
	Offices(C.O.+DA+Oprs	150	5.0	750	2.0	300
		75			6.0	450
Tape Storage	Storage for 60 days at AOC	750	1.0	750		0
Computer	Offices	150	5.0	750	7.0	1050
		75	8.0	600	6.0	450
	Comp. rm(not P.Proc)	300	1.0	300	8.0	2400
	Correlator Room					
	Racks(+con. comp)	20	46.0	920		0
	Expan rack space	20	15.0	300		0
	Comp. rm (4 Vaxes)	300	4.0	1200	2.0	600
	AIPs terminal rooms	150	2.0	300	2.0	300
	Gen. tape archiving	500	1.0	500	2.0	1000
	Maintenance lab	400	1.0	400	1.0	400
	Comm equip/supp.	150	2.0	300	1.0	150
	Special AC room	300	1.0	300	1.0	300

Business	Offices	150	2.0	300	6.0	900
		100	8.0	800	9.0	900
		50	1.0	50	1.0	50
	Files	100	6.0	600	7.0	700
	Warehouse, Equip. rm	500	3.0	1500	2.0	1000
	Mach. (copiers, etc)	200	1.0	200	1.0	200
Electronics and Field	Front End Lab	864	1.0	864	1.0	864
	Cryogenics Lab	960	1.0	960		0
	Local Osc. & IF Lab	648	1.0	648	1.5	972
	Digital Lab	432	1.0	432	2.0	864
	Recorder Lab	432	1.0	432		0
	Maser Lab	324	1.0	324		0
	Test System Lab	162	1.0	162	1.5	243
	Diagnos. & Mon. Area	288	1.0	288	1.0	288
	Rec. Keep/File Area	144	1.0	144	1.0	144
	Offices	150	12.0	1800	8.0	1200
	Ship. and Rec. Area	192	1.0	192		0
	Stock Area	288	1.0	288		0
	Broken Modules Area	50	1.0	50	1.0	50
	Repaired Mod. Area	50	1.0	50	1.0	50
	Drafting area	360	1.0	360	1.0	360
	Screened room	130		0	1.0	130
Antennas	Drafting Area	50	1.0	50		0
	Office	150	1.0	150		0
	Antenna Servo/Elect	648	1.0	648		0
	Antenna Mechanical	864	1.0	864		0
	Machine Shop	960	1.0	960		0
Overhead (hallways, washrooms, etc)				5552		4908
				-------		-------
Total				33313		29448

30-Jan-85

Table III (b)

VLBA OPERATIONS BUILDING SPACE REQUIREMENTS

Division	Purpose	Unit Area (sq. ft.)	VLBA Savings by combined #	oper(sq ft)	Total Space for combined oper(sq ft)
Scientific Services	Library /study area	750		0	1500
	Secretary Office	150	1.0	150	150
	Receptionist Area	250	1.0	250	250
	Directors Office	300	1.0	300	300
	Deputy Dir. Off.	200		0	400
	Scientific Offices	150	3.0	450	5100
	Visitors Offices	75		0	1650
	Auditorium	750		0	1500
	Journal/Coffee area	250		0	500
	Visitor´s kitchen	100		0	200
	Conference room	200		0	400
	Canteen	100		0	200
	Measur. Eng./Prt Rm	300		0	300
Array Operations	Array Control Room	600		0	1200
	Correl. Control Rm	200		0	200
	Tape Staging Area	500		0	500
	Offices(C.O.+DA+Oprs	150		0	1050
		75		0	450
Tape Storage	Storage for 60 days at AOC	750		0	750
Computer	Offices	150	4.0	600	1200
		75		0	1050
	Comp. rm(not P.Proc)	300		0	2700
	Correlator Room				
	Racks(+con. comp)	20		0	920
	Expan rack space	20		0	300
	Comp. rm (4 Vaxes)	300		0	1800
	AIPs terminal rooms	150		0	600
	Gen. tape archiving	500		0	1500
	Maintenance lab	400	0.5	200	600
	Comm equip/supp.	150		0	450
	Special AC room	300		0	600

Business	Offices	150	2.0	300	900
		100	3.0	300	1400
		50		0	100
	Files	100	6.0	600	700
	Warehouse, Equip. rm	500	1.5	750	1750
	Mach. (copiers, etc)	200	1.0	200	200
Electronics and Field	Front End Lab	864		0	1728
	Cryogenics Lab	960	1.0	960	0
	Local Osc. & IF Lab	648		0	1620
	Digital Lab	432		0	1296
	Recorder Lab	432		0	432
	Maser Lab	324		0	324
	Test System Lab	162		0	405
	Diagnos. & Mon. Area	288		0	576
	Rec. Keep/File Area	144		0	288
	Offices	150		0	3000
	Ship. and Rec. Area	192		0	192
	Stock Area	288		0	288
	Broken Modules Area	50		0	100
	Repaired Mod. Area	50		0	100
	Drafting area	360	1.0	360	360
	Screened room	130		0	130
Antennas	Drafting Area	50		0	50
	Office	150		0	150
	Antenna Servo/Elect	648	1.0	648	0
	Antenna Mechanical	864	1.0	864	0
	Machine Shop	960	1.0	960	0
Overhead (hallways, washrooms, etc)				1578	8882
Total				9470	53291

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Table IV

Office Space Requirements for Stand Alone AOC

Division	Classification	#Pers.	#Off.	Off. Size (sq. ft.)	Tot. Area (sq. ft.)
Scientific Serv.	Director	1	1	300	300
	Dep. Director	1	1	200	200
	Secretary (+file stor.)	1	1	200	200
	Receptionist	1	1	250	250
	Scientific	12	16	150	2400
	Visitors		4	150	600
Array Operations	Supervisors	2	2	150	300
	Data Analyst,Operators	12	3	150	450
Computer	Supervisors	2	2	150	300
	Senior Programmers	3	3	150	450
	Junior Programmers	4	2	150	300
	Prog. Libr./Comp. Oper.	2	1	150	150
	Technicians	3	1	150	150
Business	Supervisors	2	2	150	300
	Secretaries,Clerks(+files)	6	6	200	1200
	Shipping Clerk	1	1	50	50
Electronics	Supervisors, Engineers	8	8	150	1200
	Technicians	16	4	150	600
Antennas	Supervisor	1	1	150	150
Total		78	60		9550

30-Jan-85

Table V

VLAB Array Operations Center Size

One problem which we are currently faced with is an incompatibility between what is currently our best guess of the size of AOC required for full time operations and the construction money available to build the AOC. The estimated building size for the stand alone operation is about 33,000 square feet and available funds suggest that a building of only about 20,000 to 25,000 suare feet can be afforded.

In the extreme case that no more monies can be put into the construction of the AOC than is currently available a decision will have to be made on what must be cut from the present plans. The following is a first pass at what might be cut and is based principally on the assumption that any resources which NMIMT or the VLA have and could be used as a substitute will be and that feature would be eliminated from the AOC.

Proposed List of Items to Eliminate

Item	Savings (sq. ft.)
Auditorium	750
Library/study area	750
Visitor's kitchen	200
Canteen	100
Conference room	200
Warehouse/equip. room	1500
Reduce offices by 5	750
Drafting area	210 *
Cryogenics Lab.	205 *
Antenna servo/electric	324 *
Antenna mechanical	432 *
Machine shop	480 *
	====
Subtotal	5901
Overhead (20 percent)	1180
	====
Total	7081

*These areas were cut in half since moving them to the VLA site would require adding additional space to an already space limited environment.

The AOC building space would be reduced from about 33,000 to about 26,000 sq. ft. Some of the above choices may not be the most appropriate and there may be others which could be reduced. If the need is to reduce the area still further this could be done somewhat arbitraily by reducing the overall office space. Another facter in this decision is some uncertainty (and/or controversy) over what is needed in some of the equipment and other areas. It may be possible to reduce such areas as the operation rooms, tape storage ares, etc over what is currently envissioned. As the details of the construction plans in the different areas mature a more accurate estimate of building space will be possible.

Table VI

STANDALONE VLBA OPERATING COSTS (1986$)

Category	Costs ($1000)	NOTE
Personnel (wages and benefits)	3175	1
Travel		
Service	172	2
Other (Sci.,etc)	87	3
Communications		
To antennas (10)	236	4
Other (reg. tele., etc)	169	5
Power		
At antennas (10)	275	6
At operations center	225	7
M & S		
Antennas	39	8
Electronics	112	9
Computer	500	10
Plant	79	11
Other (administrative)	213	12
Shipping	251	13 *
New Equipment	500	14
Total	6033	*

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* These numbers should be increased for the first and second 2 year operating periods by $43K and $21K respectively. See note 13 for details.

Note: Since these estimates were originally made (about (9 months ago) there has been at least one significant developement which would affect the budget. The power rates are expected to increase by more than 25 percent in NM over the next year or two

NOTES for Table VI

1. The number of personnel to operate the VLBA as a stand alone array is estimated at 105.5. This assumes that the core of the AIP group is not paid directly out of VLBA funds. However three of the five Systems Scientists will contribute programming effort to the AIPS system. The operating cost for wages and benefits includes costs for only 97.5 personnel. The Deputy Director is assumed to be one of the existing Division Heads and the 5 Scientists and 2 Post Doctoral Fellows will be paid from other parts of the NRAO operating budget.

2. Travel for antenna maintenance is based on assuming a need for at least 12 trips per antenna per year by an average of 1.5 people per trip.

3. General travel is based on VLA experience and scaled directly to the number of employees.

4. Digital communications estimates were taken from the volume I, which seem to be in the correct range.

5. Regular telephone communications estimates are based directly on the VLA costs scaled by the number of employees.

6. Power requirements at the antennas are based on assuming each site will require about 40KW and using a rate of $.079 per KWH.

7. Power requirements for the operations center are based on the following consumptions: correlator 30-60KW, 6 computers (20KW each) 120KW, and operating experience of the VLA Control Building. A total consumption of 807 KW for a 39,000 sq. ft. building and a rate of $.079 per KWH was used.

8. Antenna M&S is based directly on VLA costs scaled by the number of antennas.

9. Electronics M&S is based on VLA experience.

10. Computer M&S consists of the following contributions: contract maintenance for 6 computers (4 Post Processing, 1 Array control and 1 correlator control) $230K, non-contract maintenance $45K, Tape recorder head replacement $45K, Tape transport replacement $22K, Tape inventory replacement $45K and general M&S $112K. It should be noted that the initial tape supply of some 25,000 has not been allowed for in the operating costs. This will amount to between $250K and $500K cost. The tape replacement allocation could be used in the first year or so to help purchase these, however the bulk will have to found from construction or elsewhere.

11. Plant maintenance is based directly on VLA experience allowing for the fact that the VLBA has no rail system to maintain. The estimate for the plant maintenance is very uncertain and it may depend upon whether NRAO owns or rents/leases the AOC. If rented the rental fee should be include in this estimate (it currently does not).

12. Other M&S includes all the necessary administrative supplies ($213K) and is based on VLA experience.

13. The shipping costs are based on assuming: (a) a 50lb package being shipped each way between each site and the AOC for 300 days/yr, (b) shipment is by UPS for continental US and Blue Label overseas to give a total of $208K, (c) regular freight, postage and data for $64K and (d) shipping costs for modules which is expected to be $85K and $64K in the first and second 2 year periods of operation respectively and $43K in subsequent years.

14. The new equipment estimate was taken directly from volume.

January 18, 1985

Section 12 - Updates

850118 Initial version.

SECTION 13

OPTIONS LIST

J. D. Romney

The VLBA Options List enumerates proposed cost-saving and/or performance-enhancing variations on the current Array specifications. It includes both extensions ("positive options") of, and reductions ("negative options") in the basic specifications. The List is intended to facilitate a coherent, coordinated, and timely selection among the options under the constraint of a fixed budget for construction of the VLBA. It will be reissued aperiodically, as existing options are decided or new options added.

In general, the nominal specifications from which the options depart are those presented in the current chapters of the "VLBA Book". I have attempted to include all options seriously considered at the date of compilation, although this necessarily involves an exercise of judgement. Not included in the List are choices of a strictly technical nature which have a negligible impact on both cost and performance.

The options are grouped into major areas generally paralleling the group structure of the VLBA project with some exceptions to allow a more unified presentation. A special final section is devoted to options which extend the scope of the Array beyond the current 10-station project. References are given for each group (and occasionally under particular options) to documents outlining the nominal specifications and, where possible, the options. These should be consulted for more complete information, as the Options List is deliberately terse.

Each option is given a mnemonic name for reference, and briefly described. Its effect on the Array's performance is outlined and any dependencies on associated options mentioned. The estimated cost or saving, always expressed for the 10-station VLBA, is given where available; those few cases where provisional allocations have already been budgeted are noted. Finally, a decision point -- the latest time at which the option must be selected or rejected to avoid an adverse impact on another, critical project area -- is established if possible.

SITES

Reference(s) --
VLBA Book, Section 2.

No RFI Shielding --
Description: Delete RFI shielding from equipment and control rooms.
Effect: Possible interference from local digital signals.
Saving: 755 k$.
Decision Point: ASAP; required for first site contract.

No Backup Generator --
Description: Delete generator, fuel system, and building; increase UPS capacity.
Effect: Operation shutdown during failure of commercial power; critical equipment stays up only until UPS batteries discharge.
Saving: 300 k$.
Decision Point: ASAP; required for first site contract.

No Backup Power --
Description: Delete generator, fuel system, and building, and also UPS.
Effect: Complete shutdown during failure of commercial power; possible difficulty restarting.
Saving: 500 k$.
Decision Point: ASAP; required for first site contract.

No Fire Suppression --
Description: Delete Halon fire suppression system.
Effect: Increased damage in event of fire.
Saving: 110 k$.
Decision Point: ASAP; required for first site contract.

Smaller Building --
Description: Reduce size of building.
Effect: Depends on details.
Saving: 1.5 k$/sq.ft. of building design (current design: 1176 sq.ft.).
Decision Point: ASAP; required for first site contract.

ANTENNAS (including SUBREFLECTORS)

Reference(s) --
VLBA Book, Sections 3 & 5.

High-surface-accuracy Subreflector --
Description: Improve specified subreflector surface accuracy from current 0.008 to 0.004 inches rms; may require different fabrication technique.
Effect: Increased total aperture efficiency at 43/86 GHz (from .50/.16 to .55/.23).

Cost: 550 k$ (net); already budgeted.
Decision Point: ASAP, pending receipt of price quotes.

86-GHz Operation --
Description: Improve pointing performance by grinding azimuth track and/or implementing circulating-coolant system.
Effect: Satisfactory pointing for 86-GHz operation. [Dependencies: high-surface-accuracy subreflector; 86-GHz receivers.]
Cost: To be determined from operating experience; probably less than 120 k$.
Decision Point: Late.

RECEIVERS & FEEDS

Reference(s) --
VLBA Book, Sections 5 & 6 (especially 6.10).

10.7-GHz Receiver --
Description: Provide 9 additional 10.7-GHz receivers and feeds; include feed in feed circle. (One such receiver already under construction.)
Effect: Additional X-band capability beyond planned 8.4 GHz (for continuity of ongoing observing programs, and compatibility with global array).
Cost: 270 k$.
Decision Point: ASAP; required input for feed-circle design and dual-frequency pairing;

6-GHz Receiver --
Description: Add 6-GHz receivers (sharing 4.8-GHz feeds).
Effect: Observation of 6.035-GHz OH line possible (reference: VLBA Memo 306).
Cost: 200 k$.
Decision Point: Late.

No 2.3-GHz Receiver --
Description: Delete 2.3-GHz receivers and 2.3/8.3-GHz dichroic reflector systems.
Effect: Reduced frequency commonality with the DSN and other antennas used in geodetic/astrometric programs; no dual-frequency observations with 8.3 GHz.
Saving: 600 k$.
Decision Point: Before beginning of design and construction (planned 1986).

86-GHz Receiver --
Description: Add 86-GHz receivers and feeds.
Effect: Observations at 86 GHz possible. [Dependencies: high-surface-accuracy subreflector; 86-GHz antenna operation.]
Cost: 600 k$.
Decision Point: Late.

4.8/22-GHz Dual-Frequency Pair --
Description: Implement additional dichroic reflector systems.
Effect: Dual-frequency observations possible.
Cost: ~80 k$.
Decision Point: Late.

10.7/43-GHz or 15/43-GHz Dual-Frequency Pair --
Description: Implement additional dichroic reflector systems.
Effect: Dual-frequency observations possible.
Cost: ~80 k$.
Decision Point: Late.

Remote Dual-Frequency Operation --
Description: Equip dichroic reflectors for remotely commanded operation.
Effect: Improved sensitivity for single-band observations, and unimpeded observation using neighboring feeds.
Cost: ~100 k$ per pair equipment cost, plus design cost.
Decision Point: Late.

Solar Cal --
Description: Add high-level noise signals at one antenna (see also VLBA Electronics Memo 30).
Effect: More accurate calibration of solar observations.
Cost: 1.4 k$ per frequency.
Decision Point: Late.

AUXILIARY STATION ELECTRONICS

Reference(s) --
VLBA Book, Section 6.

Water-Vapor Radiometer --
Description: Design and build 22/31-GHz radiometers to measure atmospheric water vapor content.
Effect: Improved calibration of atmospheric phase fluctuations for observations at high frequencies.
Cost: 500 k$.
Decision Point: Late; hope for development progress elsewhere.

Absolute Time --
Description: Acquire receiver for satellite timing signals at one station.
Effect: Absolute timing linked to UTC; essential for geodetic/astrometric observations.
Cost: 25 k$.
Decision Point: Late.

Time Reference --
    Description: Acquire receivers for satellite timing signals at all stations.
    Effect: Convenient comparison of station clocks to UTC.
    Cost: 250 k$.
    Decision Point: Late.

BASEBAND ELECTRONICS, RECORD & PLAYBACK SYSTEMS

Reference(s) --
    VLBA Book, Sections 8 & 9.
    VLBA Acquisition Memo 42.

4 Recorders --
    Description: Increase number of recorders to 4 per station.
    Effect: Doubled maximum record rate (1024 Mb/s), continuously sustainable.
    Cost: 920 k$.
    Decision Point: Late (assuming design allows for later retrofit).

64 Tracks --
    Description: Increase number of tracks to 64 per recorder.
    Effect: Doubled maximum record rate (1024 Mb/s), non-sustainable.
    Cost: 580 k$.
    Decision Point: Late (assuming design allows for later retrofit).

16-MHz Channels --
    Description: Implement 16-MHz channel bandwidth in baseband converters; upgrade formatter for 32-Mb operation.
    Effect: Doubled maximum recorded bandwidth (512 MHz); possibly poorer stability in 16-MHz mode. [Dependency: 32-Mb correlator channel.]
    Cost: To be determined.
    Decision Point: Before final design of acquisition/recording system.

Half-Speed Playback --
    Description: Implement data playback at half as well as full tape speed, using same reproduce heads (but different equalizers).
    Effect: Correlation at half real-time speed possible (supporting wider field of view); some degradation of playback SNR at half speed.
    Cost: 48 k$.
    Decision Point: Late (design will allow later retrofit).

Eighth-Speed Playback --
    Description: Implement high-speed (480 ips) recording and low-speed (60 ips) playback using special-purpose heads in each case.
    Effect: Correlation at one-eighth real-time speed possible (supporting much wider field of view); technically questionable.
    Cost: 634 k$.
    Decision Point: Late (design will allow later retrofit).

Station Phase-Cal Detectors --
Description: Transfer phase-cal detection from correlator to stations.
Effect: No significant effect on performance. [Dependency: no correlator phase-cal detectors.]
Cost: To be determined; probably minimal net cost.
Decision Point: Before final design of acquisition/recording system.

Mark 2 Terminal --
Description: Build or borrow Mark 2 VLBI formatters and recorders for first several VLBA stations during "transition period".
Effect: Continued and improved scientific activity during Array construction.
Cost: 6 k$ per station; none if equipment can be borrowed.
Decision Point: Before completion of first VLBA antenna.

Reduced Formatter ("Option 1") --
Description: Combine formatting of all 32 baseband channels, onto at most 32 tracks, in one unit.
Effect: Halved maximum record rate (256 Mb/s); increased vulnerability to formatter failure.
Saving: 176 k$.
Decision Point: Before final design of acquisition/recording system.

Single Sideband Converter ("Option 2") --
Description: Eliminate LSB baseband channels.
Effect: Halved maximum number of channels (16) and recorded bandwidth (128 MHz); degraded de-dispersion of pulsar observations.
Saving: 98 k$.
Decision Point: Late (assuming design allows for later retrofit).

16 Tracks ("Option 3") --
Description: Reduce number of tracks to 16 per recorder and playback unit.
Effect: Halved maximum record rate (256 Mb/s), requiring high-speed recording on two tape transports, and correlation without speedup.
Saving: 284 k$.
Decision Point: Late (assuming design allows for later retrofit).

8 Baseband Converters --
Description: Reduce number of baseband converters to 8.
Effect: Halved maximum number of channels (16) and recorded bandwidth (128 MHz); degraded bandwidth synthesis observations.
Saving: 200 k$.
Decision Point: Late (assuming design allows for later retrofit).

CORRELATOR

Reference(s) --
VLBA Book, Section 10.
VLBA Memo 375.
VLBA Correlator Memos 41 & 47.

Accelerated Correlator Dump --
Description: Upgrade internal data paths to accommodate accumulator dump rates up to 10 Hz (while maintaining aggregrate data rate limit of 0.5 Mbyte/sec).
Effect: Expanded field of view or higher time resolution, using subset of stations, channels, or lags.
Cost: To be determined.
Decision Point: Before final design of correlator electronics.

32 Channels ("Option +1") --
Description: Increase number of channels to 32.
Effect: Doubled maximum correlator bandwidth (256 MHz) or frequency resolution (2048 lags).
Cost: 1700 k$.
Decision Point: Late.

Computer Expansion ("Option +2") --
Description: Add output tape or disk drives, upgrade CPU.
Effect: Increased computing capacity for more rapid data output and greater calibration capability.
Cost: Depends on specific choices; range 50-250 k$.
Decision Point: Late.

12/17/24 Stations ("Option +3") --
Description: Expand design to 12/17/24 stations in full/half/qtr modes.
Effect: Single-pass processing of enhanced array (VLBA plus 2 other stations at full spectral resolution, VLBA plus 12 stations in continuum).
Cost: 650 k$.
Decision Point: Before final design of station and correlator electronics.

High-Speed Archive Dump ("Option +4") --
Description: Design and build buffer and high-density tape system to record RAM accumulator output.
Effect: Archiving (and reprocessing during slack correlator time) with minimal restriction of field of view.
Cost: 300-400 k$ (very uncertain).
Decision Point: Before final design of accumulator, digital filter, and TOP.

32-Mb Correlator Channel ("Option +5") --
Description: Exploit 2 um CMOS VLSI to run at 32 Mb/s clock rate.
Effect: Correlation of 16-MHz baseband channels [dependency]; doubled maximum correlator bandwidth (256 MHz); technically questionable.
Cost: ~150 k$.
Decision Point: ALAP, but before final design of station and correlator electronics.

Oversampling at Full Resolution ("Option +6") --
Description: Add extra delay stages to correlator VLSI chip.
Effect: Correlation of oversampled bits (with some sensitivity enhancement in narrowband spectral observations) with full spectral resolution.
Cost: ~150 k$.
Decision Point: Before final VLSI design.

32-Lag EC ("Option +7") --
Description: Expand elementary correlator to 32 complex lags.
Effect: Doubled frequency resolution for spectroscopy.
Cost: 1100 k$.
Decision Point: Before final design of correlator electronics; possibly before final VLSI design.

1-to-1 Phase-Cal Detectors ("Option +8") --
Description: Provide 1 phase-cal detector per channel (instead of 1 per 4 channels).
Effect: Higher sensitivity to phase-cal signals; simpler or more flexible switching among detectors.
Cost: 75 k$.
Decision Point: Before final design of station electronics.

No Digital Filter ("Option -1") --
Description: Delete sample-rate-reduction module.
Effect: Narrower field of view (by factor of 2 or 4) for fixed output data rate.
Saving: 325 k$.
Decision Point: Late (module designed for later retrofit).

No Correlator Phase-Cal Detectors ("Option -2") --
Description: Transfer phase-cal detection to stations.
Effect: No significant effect on performance. [Dependency: station phase-cal detectors.]
Saving: To be determined; probably minimal net saving.
Decision Point: Before final design of station electronics.

8 Channels ("Option -3") --
Description: Reduce number of channels to 8.
Effect: Halved maximum correlator bandwidth (64 MHz) or frequency resolution (512 lags).
Saving: 900 k$.
Decision Point: Before construction of station and correlator electronics.

4 Channels ("Option -3") --
Description: Reduce number of channels to 4.
Effect: Halved maximum correlator bandwidth (32 MHz) or frequency resolution (256 lags).
Saving: 1300 k$.
Decision Point: Before construction of station and correlator electronics.

5/7/10 Stations ("Option -4") --
Description: Reduce design to 5/7/10 stations in full/half/qtr modes.
Effect: Single-pass processing of entire VLBA only with quarter resolution.
Saving: 1000 k$.
Decision Point: Before final design of station and correlator electronics.

POST-PROCESSING

Reference(s) --
VLBA Book, Section 11.

Expanded Post-Processing Capacity --
Description: Expand post-processing hardware configuration from 4 to 5 fully-equipped VAX 11/780's (or modern equivalent); partial steps also possible.
Effect: Increased throughput for post-processing.
Cost: 600 k$.
Decision Point: Late.

Reduced Post-Processing Capacity --
Description: Reduce post-processing hardware configuration from 4 to 3 fully-equipped VAX 11/780's (or modern equivalent); partial steps also possible.
Effect: Decreased throughput for post-processing.
Saving: 600 k$.
Decision Point: Late.

CONTROL & MONITOR

Reference(s) --
VLBA Book, Section 4.
VLBA Memo 299.

Satellite Communications Link --
Description: Replace leased telephone lines with satellite link.
Effect: Increased reliability of communications; reduced operating cost.
Cost: 1200 k$ (equipment costs only).
Decision Point: Late.

OPERATIONS

Reference(s) --
VLBA Book, Section 12.

Expanded Operations Center --
Description: Expand AOC floor area to 40000 sq.ft. (from 33000 sq.ft.)
Effect: Expansion of VLBA/VLA operations possible.
Cost: 525 k$ (@ 75 $/sq.ft.)
Decision Point: Before AOC construction contract.

Reduced Operations Center --
Description: Reduce AOC floor area to 26000 sq.ft. (from 33000 sq.ft.)
Effect: Dependence on NMIMT or VLA for deleted resources.
Saving: 525 k$ (@ 75 $/sq.ft.)
Decision Point: Before AOC construction contract.

EXTENDED ARRAY

Reference(s) --
VLBA Book, Sections 1.3 & 6.7.
VLBA Memos 213, 240, & 246.
VLBA Electronics Memo 1.
VLBA Acquisition Memo 42.

These options represent extensions of the 10-station VLBA project to cover more uniformly the range of baselines available on the surface of the Earth and approach a "matched u-v filter" appropriate to any mapping observation. The extensions provide facilities to integrate the VLA and VLBA apertures into a fully-capable joint instrument, and to broaden the aperture coverage more generally by providing or facilitating the incorporation of additional stations. While this extended array is not formally part of the VLBA project, the following options are included in the Options List to remind designers of the Array that we may have to implement and support such additional facilities in the future.

Pie Town VLA Station --
Description: Implement digital data and phase-stable LO links between Pie Town site and the VLA; provide VLA electronics at Pie Town, and upgrade VLA correlator delay etc.
Effect: Pie Town usable as VLA "outrigger".
Cost: ~500 k$ for links (including design costs); VLA equipment cost to be determined.

Additional Acq./Rec. System(s) --
Description: Provide complete or partial acquisition/recording systems for fixed sites (e.g., the VLA, Green Bank, ...) or as portable units.
Effect: Enhancement of the Array (in particular to include elements with large collecting areas or high-frequency performance).
Cost: 195 k$ per station.

Additional Southwest VLBA Stations --
Description: Build additional fully-equipped stations at the following sites in the vicinity of the VLA: Dusty, NM; Bernardo, NM; and Roswell, NM.
Effect: VLBA aperture extended inwards from 200 km towards 35 km outer envelope of VLA aperture.
Cost: ~4.5 M$ per station.

South American VLBA Station --
Description: Build an additional fully-equipped station in northern South America, probably in Ecuador.
Effect: Improved north-south aperture at equatorial and southern declinations.
Cost: ~4.5 M$.

Section 13 - Updates

850812 Initial incorporation of Options List into VLBA Book. Text identical to printed version issued as VLBA Memo 473 on same date.