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CHAPTER 4

The VLBA Design

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Abstract The Very Long Baseline Array (VLBA) is a highly flexible radio telescope designed for research in high resolution astronomy and geodesy. It is intended to make the technique of Very Long Baseline Interferometry (VLBI) available to observers who are not experts in radio interferometry. The top-level design goals for the Very Long Baseline Array are discussed and details of the design and performance of the antennas are presented.

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4.1 Introduction

By the middle of the 1970's the radioastronomical technique of Very Long Baseline Interferometry (VLBI) had matured to such a level that observing sessions with arrays of antennas, provided by various observatories around the world, were being routinely scheduled. Although much exciting science was produced by these observations, the use of such ad hoc arrays suffered from several limitations. The amount of observing time was limited, the locations of the antennas were not optimum, there was inadequate frequency overlap between the antennas and data calibration was complicated because the array elements were not identical. VLBI was still a sufficiently difficult technique that it could only be used effectively by skilled radio interferometrists. In this setting, discussions began on the need for a dedicated VLBI array which could remove many of these limitations.

The first formal study of a dedicated VLBI array in the US was produced by NRAO in 1977 (Kellermann 1977). Further studies by Caltech (Cohen 1980) and NRAO (NRAO 1981) led to the VLBA being ranked by the Astronomy Survey "Field Committee" (Field 1982) as the highest priority new ground-based astronomical instrument for the 1980's. A formal proposal was submitted to the NSF in 1982 (NRAO 1982) for construction of the VLBA at a cost of $51 M ($1982) over a period of 4.7 years. Funds for design of the instrument were approved in March, 1984 and first construction monies were approved in March, 1985. Due to NSF budget constraints, the construction duration was stretched out and the last construction monies were approved in March 1992 for a total expenditure of $84M ($1989 approx.). The tenth antenna (Mauna Kea) became operational in May 1993.

In this lecture I will discuss the overall design goals for the VLBA and briefly mention the major design features used to meet these requirements. Details of the design and performance of the sites and the antennas and their feed systems are given in section 4.3 on page 66. Details of the design of other parts of the VLBA are given in later lectures in this book. Refer to the *VLBA Project Book* (NRAO 1988) for a detailed reference of the design specification of the array, and to the extensive series of *VLBA Memoranda*.

4.2 VLBA Design Goals

Eight major design goals for the VLBA can be identified:

4.2.1 Imaging with High Resolution and High Dynamic Range

The need for high resolution required that the largest baseline in the array be as long as possible. The decision was made, primarily for logistical reasons, to locate the array completely on easily accessible US territory. The array chosen is shown in figure 4.1 on the next page and the locations of the antennas are listed in table 4.1 on the facing page. The most eastern antenna is located on St. Croix in the US Virgin Islands and the most western is on Mt. Mauna Kea on Hawaii. Locations further west and south could have been found on other islands in the Pacific Ocean but it was decided that access to these was too difficult. No antenna was located in Alaska because of the limited view of southern sources available from this northern latitude.

Table 4.1: Locations of the VLBA antennas

Code	Location	N Latitude (d m s)	W Longitude (d m s)	Elevation (m)
SC	St. Croix VI	17 45 30.57	64 35 02.61	16
HN	Hancock NH	42 56 00.96	71 59 11.69	309
NL	N. Liberty IA	41 46 17.03	91 34 26.35	241
FD	Fort Davis TX	30 38 05.63	103 56 39.13	1615
LA	Los Alamos NM	35 46 30.33	106 14 42.01	1967
PT	Pie Town NM	34 18 03.61	108 07 07.24	2371
KP	Kitt Peak AZ	31 57 22.39	111 36 42.26	1916
OV	Owens Valley CA	37 13 54.19	118 16 33.98	1207
BR	Brewster WA	48 07 52.80	119 40 55.34	255
MK	Mauna Kea HI	19 48 15.85	155 27 28.95	3720

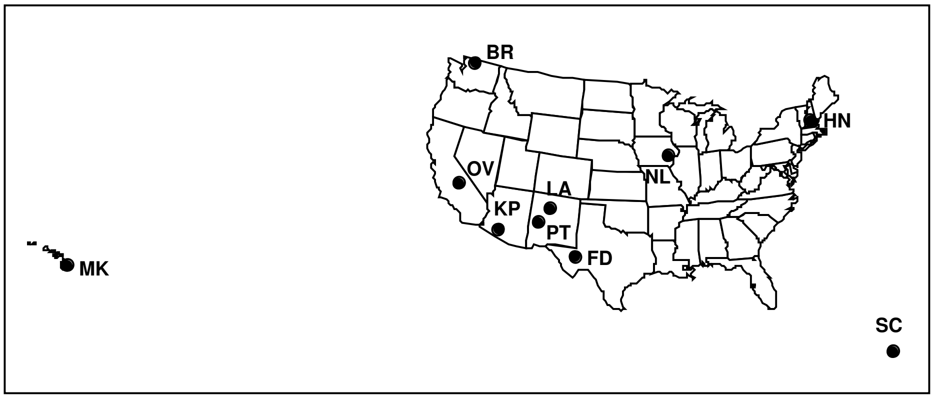

Figure 4.1: VLBA array configuration

The requirement for high quality images requires good sampling of the (u, v) plane. The number of elements in the array, ten, was chosen as a compromise between the need for many baselines on the one hand and the cost of construction and operation on the other. The locations of the eight elements between the east and west ends of the array were optimized to give the best possible filling of the (u, v) plane. Examples of the (u, v) coverage provided by the VLBA are shown by Walker (fig. 8.1 on page 143).

High dynamic range imaging also requires well calibrated visibility data and several design features of the VLBA address this need. The antennas are identical to ease the problem of obtaining sufficiently accurate models for pointing, focus, gain, phase and spillover noise, all as functions of azimuth and elevation, compared to this determination for ten dissimilar antennas. Calibration of visibility amplitudes is accomplished by a calibrated switched noise signal which is injected into the input of the low noise receivers to provide a continuous measurement of system temperature. This measurement, together with a knowledge of the way spillover noise varies with elevation angle, also allows corrections to be made for the absorption of the atmosphere. Two calibration systems aid in removing phase errors caused by phase changes in the electronics equipment at an antenna site. One system measures changes in the length of the cable used to carry the local oscillator reference signal from the hydrogen maser to the antenna vertex room. The other system measures changes in signal path length from the receiver input all the way through to the point at which the received signal is digitized. To prevent large timing errors at a site, the time indicated by the station clock locked to the hydrogen maser is continuously compared with the time provided by a GPS (Global Positioning System) satellite receiver. Finally, to allow data quality to be improved using the techniques of self-calibration, all parts of the electronics system have been designed to minimize closure errors.

4.2.2 High Sensitivity

High sensitivity observations require large antenna collecting area, low system temperature, wide bandwidth and long integration time. Construction budget constraints limited the antenna diameter to 25 m but the antennas use a shaped Cassegrain geometry to provide high aperture efficiency. To minimize system temperature all receivers except for the two UHF prime focus receivers are cryogenically cooled. The wide-bandwidth tape recorders are capable of continuous operation at 128 Mb/s with one tape change per day. One recorder running at double speed can record 256 Mb/s and two recorders running at double speed can record 512 Mb/s, with correspondingly more frequent tape changes. The phase calibration systems mentioned in section 4.2.1 on page 60 will help to extend integration time. Additionally, the antennas have high slew rates so that they can rapidly switch between sources and extend integration time using phase referencing techniques (see chapter 17).

4.2.3 Spectral Coverage From 300 MHz To 45 GHz

The VLBA can observe over the frequency range from 300 MHz to 45 GHz, with a future upgrade capability to 86 GHz. The antennas are equipped with feeds and receivers for the nine frequency bands shown in table 4.2 on the next page. The receiving system has been designed for good frequency flexibility so that any one of the nine bands can be selected in less than 20 seconds. Most of the bands have usable bandwidths greater than 10% allowing the techniques of multi-frequency synthesis to be used (chapter 16). The major antenna components have been designed to provide useful performance at 86 GHz and a location for a feed and receiver for this frequency has been provided.

Table 4.2: Antenna and receiver performance at different frequency bands

Band Name (cm)	Nominal Band (GHz)	Tunable^a Band (GHz)	Ant Eff^b (K)	T$^c_{ant}$ (K)	T$_{rx}$ (K)	System Temp (K)	Exp $\frac{T_{sys}}{A}$ (Jy)	Meas^d $\frac{T_{sys}}{A}$
90	.312–.342	.305–.350	0.50	74	95	169	1900	1930
50	.595–.625	.590–.630	0.49	34	133	167	1915	1950
20	1.35–1.75	1.2–1.85	0.63	18	9	27	246	300
13	2.15–2.35	2.0–2.8	0.70	20	8	28	225	330
6	4.6–5.1	4.4–5.2	0.72	15	12	27	211	275
4	8.0–8.8	7.8–9.1	0.71	16	18	34	270	290
4	8.0–8.8^e	7.8–9.1	0.66	21	18	39	332	380
2	12.1–15.4	11.8–15.7	0.69	18	32	50	407	400
1.3	21.7–24.1	21.1–25.1	0.66	27	50	77	655	800
0.7	41–45	40–46	0.51	35	55	90	990	1100

Notes: [a] System usable over this frequency range with a reduction in sensitivity by a factor of about 2. [b] Predicted antenna efficiency is a product of the following six effects: (1) primary surface accuracy of 0.28 mm rms, and subreflector surface accuracy of 0.15 mm rms, (2) aperture taper and subreflector diffraction, (3) spillover, (4) blockage, (5) aperture phase efficiency including shaping of the main reflector with the prime focus feed and the effect of the subreflector misalignment due to the quadrupod deformation, and (6) miscellaneous losses such as VSWR effects, resistive and other losses. [c] Predicted T$_{ant}$ is the total antenna temperature due to: (1) resistive losses in the feed and the reflector surfaces; for the 2.3 GHz feed additional losses due to the dichroic reflector are included, (2) subreflector diffraction and feed spillover to the ground, (3) ground radiation entering the feed due to scattering from the quadrupod or other antenna structures, and (4) sky brightness due to zenith tropospheric emission, Galactic background radiation away from the Galactic plane, and the 3^o K microwave background. [d] T$_{sys}$ is the total system temperature measured at the zenith. A is the effective collecting area of the antenna. T$_{sys}/A$, expressed as a flux density equivalent to the system temperature, is known as the *system equivalent flux density* (SEFD) and is measured in Janskys: 1 Jansky (Jy) = 10^{-26} W m^{-2} Hz^{-1}. The value given is typical of the measured performance in the nominal band on several of the more sensitive antennas and is the performance which it is expected will be achieved on all antennas after a period of receiver and optics optimization. For observation planning purposes use the values for Typical Zenith SEFD given in table 8.1 on page 140. [e] Dual frequency operation with ellipsoid deployed.

4.2.4 Spectral Line Imaging Capability

The baseband filter system (see chapter 5) and the correlator (see chapter 7) have been designed with sufficient spectral resolution and spectral dynamic range to allow observations of celestial masers.

4.2.5 Support of Research in Geodesy and Astrometry

Geodetic and astrometric observations involve the precise measurement of phase and delay and place a number of special requirements on the design of the instrument. Simultaneous observations in two widely-separated frequency bands are needed so that corrections can be made for variations in delay due to the ionosphere. This capability is provided for the 2.3 and 8.4 GHz bands using a dichroic reflector system located over the 2.3 and 8.4 GHz feeds. Instrumental path lengths are carefully controlled by stabilizing the temperature of all electronic equipment, by using high phase stability cables in critical locations and by using a specially designed cable wrap which minimizes phase changes when the antenna rotates. Finally, the active phase calibration systems mentioned in section 4.2.1 aid in removing instrumental delay and phase errors.

4.2.6 User-Friendly and Reliable Operation

In order to make the techniques of VLBI available to observers who are not specialists in radio interferometry it is essential that the VLBA produce reliable correlated data that can be further processed using standardized procedures that do not require expert knowledge. This requirement has affected much of the VLBA design and determines many of the array operating procedures. The array is centrally monitored and controlled by a single operator located in the Array Operations Center (AOC) in Socorro, New Mexico. Each of the ten sites is connected in real time to the array control computer, located in the AOC, via the Internet communication network. In the event of a temporary loss of the Internet a site continues to observe under the control of its local site computer and a backup communication path is established on a direct-dial telephone line. Approximately 1000 monitor points at each site are continuously and automatically checked to determine if the equipment is functioning correctly. In addition, as a weekly preventive maintenance measure the pointing and sensitivity of the nine receiving systems on each antenna are checked, as is the correct locking of all phaselock loops in the various synthesizers and baseband converter modules. A capability is provided to capture and return to the array control computer, using the monitor and control communication network, up to 4 Mb of data. This allows fringes on strong sources to be obtained to check the coherence of sites in almost real time. Another important aspect of the user friendliness of the VLBA is the design of the software interface between the users and the instrument. Observing schedules for the VLBA will be prepared using the OBSERVE program which is designed to minimize the amount of knowledge needed concerning the detailed workings of the VLBA. Post processing of correlated data will be performed primarily with the AIPS reduction software (see chapter 12).

4.2.7 Full-Time Operation with Low Down Time

One of the major limitations of VLBI experiments with earlier ad hoc arrays has been the limited amount of observing time available. The VLBA will operate full time except for three days per year (Thanksgiving, Christmas and New Year). This will make it easier to perform experiments requiring frequent observations of time-variable sources or to respond to targets of opportunity such as supernovae. The major aspects of the VLBA which make full time operation possible are the correlator, tape supply, and operating manpower requirements. The correlator (see chapter 7) can process two 10-station experiments in one-half the time taken to record the tapes and therefore is readily able to support full time operation. The supply of tape will allow full time operation provided that tapes can be processed and returned to the antennas for re-use within approximately 45 days of recording. Operating manpower requirements have been minimized by automating the antenna sites so that they can operate unattended for most of the time. Each site has only two local employees except for the Mauna Kea site which, because of its more difficult access, has three employees. The use of two tape recorders at each site and thin recording tape (see chapter 6) allows full time operation at a data rate of 128 Mb/s with only one visit per day by the technicians to the site for tape changing.

4.2.8 Compatibility with Other VLBI Antennas

For many experiments it will be desirable to enhance the performance of the VLBA by adding to it non-VLBA antennas either to improve (u, v) plane coverage or to increase sensitivity. Several design decisions in the areas of array layout, choice of recorder, baseband channelization and receiver frequency were made to make it as easy as possible to observe with existing VLBI antennas.

In selecting the locations for the VLBA sites the locations of the antennas in the southwest of the US were chosen so that the VLA could be used effectively to provide improved short-baseline coverage. The (u, v) coverage on the longer baselines was kept to the minimum needed for reasonably good imaging with the stand-alone VLBA, with the expectation that it can be improved when needed by adding antennas in Europe (see Craig Walker's figure 8.2 on page 144).

The VLBA formatter, deformatter, tape recorder and tape playback drive are able to write and read tapes in the widely used Mark IIIA format (Hinteregger 1982). Additionally, the correlator can process data written in Mark IIIA format (chapter 7) so it is straightforward to observe in collaboration with antennas equipped with Mark IIIA data acquisition equipment. The maximum data rate available with the VLBA recorder system is 512 Mb/s (2 recorders, 2 times normal tape speed). This data rate can be provided by only four baseband converter (BBC) modules: 4×16 MHz (max bandwidth) $\times 2$ (upper and lower sidebands) $\times 2$ (Nyquist sampling) $\times 2$ (bits per sample). To provide more compatibility with Mark IIIA data acquisition systems, which use 14 BBCs, the number of VLBA BBCs was increased to eight. Although some Mark IIIA astronomical and geodetic observing modes cannot be fully supported, the compatibility is sufficient for most purposes. The actual baseband bandwidths supported by the BBCs were chosen to be the same as the Mark IIIA bandwidths, rather than the bandwidths supported on the VLA.

In general the RF bands available in the receivers were chosen to include the standard observing frequencies used by existing VLBI arrays. The only previously used band not available on the VLBA is 10.7 GHz which has been replaced by the 8.4 GHz band. The frequencies for the 2.3/8.4 GHz dual-frequency capability were chosen to match those used for geodetic observations.

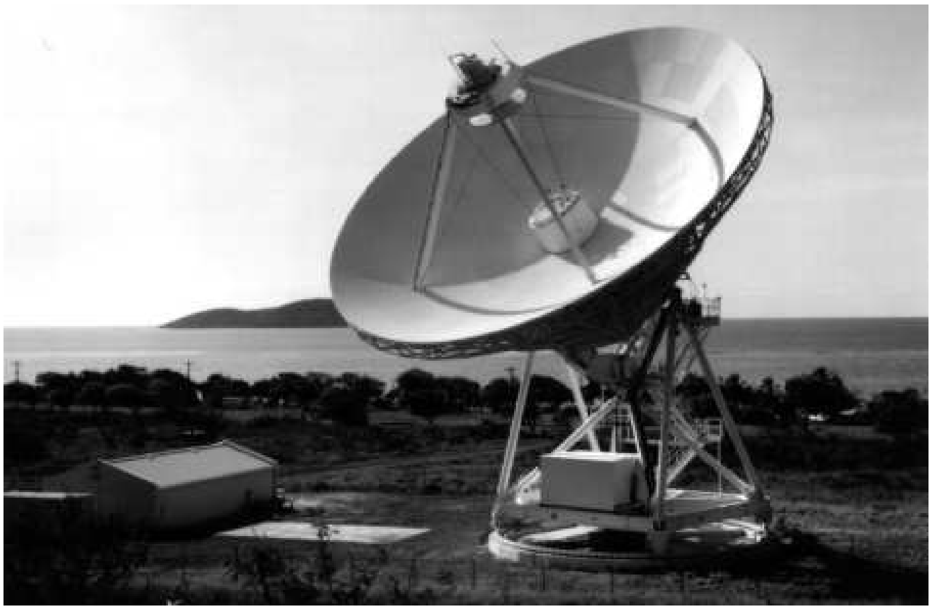

Figure 4.2: VLBA site and antenna on St. Croix

One significant Mark IIIA incompatibility which remains on the VLBA is the detection system which extracts the phase calibration tones used to monitor path length changes from the receiver input to the signal digitizer. In Mark IIIA systems the tones are extracted in the correlator in parallel with the astronomical processing. This capability is not provided on the VLBA correlator because the tones are extracted at the antenna by the formatter. Extraction of phase calibration tones for non-VLBA antennas in the VLBA correlator requires that processing of the astronomical data be halted.

4.3 Antennas, Optics, and Feeds

4.3.1 VLBA Sites

A typical VLBA site is shown in figure 4.2. A site consists of a fenced enclosure of area 45 m by 67 m. The primary elements on the site are the antenna and its foundation, a 120 m^2 control building, an emergency electricity generator and a weather station. The control building comprises five rooms: an equipment room containing the hydrogen maser frequency standard, an IF and LO rack and a baseband conversion and formatter rack; a computer room containing the site control computer, communications equipment, the two VLBA tape recorders and Mark II recording equipment; an auxiliary room containing an uninterruptable power supply and technician work space; a mechanical room containing HVAC

Figure 4.3: Overall dimensions of a VLBA antenna, dimensions in cm.

equipment; a bathroom and shower. The building has RFI shielding in the walls and is temperature controlled. Temperature stabilities of $\pm 2^o$C are typically held in the maser room. To allow unattended operation several emergency systems are in place in the building: all electrical power is automatically switched off in the event of smoke detection; an automated message system calls the local site technicians in the event of fire, loss of power or HVAC problems. The emergency generator is used to automatically stow the antenna and keep the cryogenics and hydrogen maser operating in the event of loss of commercial power. The weather station is equipped to provide continuous monitoring of ambient temperature, dew point, precipitation, barometric pressure, wind velocity, and wind direction.

4.3.2 Antennas

The VLBA antennas, built by Radiation Systems Inc., use elevation over azimuth mounting with a wheel and track azimuth drive. Overall dimensions are shown in figure 4.3 and principal performance parameters are given in table 4.3 on the following page.

The reflector back-up structure is a conventional radial-rib and circular-beam design supporting 200 surface panels each no larger than 1.8 m by 2.1 m. Each panel has four supports and is made of a doubly curved aluminum skin riveted to

Table 4.3: VLBA antenna specification

Diameter	25 m
Focal ratio	0.35
Elevation range	$+2^o$ to $+125^o$
Azimuth range	$-270^o to + 270^o$
Elevation slew rate	30^o min^{-1}
Azimuth slew rate	90^o min^{-1}
Time to accelerate to full speed	2 s
Pointing accuracy, 7 m s^{-1} wind	8 arcsec rms
Pointing accuracy, $3.5^o C$ temperature gradient	14 arcsec rms
Elevation natural frequency	2.6 Hz
Azimuth natural frequency	2.2 Hz
Reflector panel accuracy including gravity	0.160 mm rms
Surface measuring and setting accuracy (panels set at 50 °elev.)	0.125 mm rms
Reflector structure accuracy (wind, thermal and gravity)	0.196 mm rms
Total primary reflector surface accuracy	0.282 mm rss
Total subreflector surface accuracy	0.150 mm rms
Survival wind at stow (zenith)	50 m s^{-1}

"Z" stiffeners. To reduce gravitational deformations the back-up structure sits on 20 equal-rigidity supports provided by a cone-shaped structure which interfaces to the counterweight and elevation bullgear. The cone-shaped structure also provides supporting trusses for the four sub-reflector support legs (quadrupod). The structure between the azimuth platform and the elevation axis is thermally insulated to improve the pointing accuracy by reducing temperature gradients caused by solar heating. Since the antenna is operated unattended most of the time, several emergency systems are provided to protect the antenna. Seven conditions cause the antenna to automatically stow: winds greater than 22 m s^{-1} as indicated by anemometers mounted on the edge of the reflector; winds greater than 13 m s^{-1} if either axis is operating with only one of its two motors; ambient temperature below -20^oC; an encoder fault; loss of azimuth drive; loss of the link to the site computer for more than ten minutes; loss of commercial power. Both axis have three levels of limit switches. All power is switched off in the event of smoke detection in the pedestal or vertex rooms.

4.3.3 Feed System

To provide the frequency flexibility required for the VLBA, the antenna uses an offset Cassegrain geometry similar to that used on the VLA (Weinreb et al. 1977). In this geometry, shown in figure 4.4 on the next page, the subreflector is tilted so that the secondary focal point lies 85 cm off of the axis of the symmetrical primary reflector. Nine Cassegrain feeds are arranged in a circle,

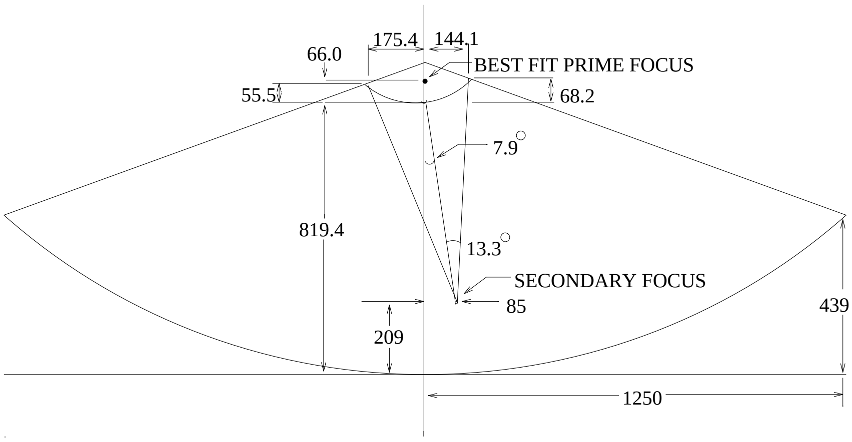

Figure 4.4: VLBA offset Cassegrain geometry, dimensions in cm.

with radius 85 cm, around the axis of the primary and any one of the feeds can be quickly (5 to 20 s) selected by rotating the subreflector around this axis. The frequency ranges supported by the feeds are given in table 4.2 on page 63 and the arrangement of the feeds on the feed circle is shown in figure 4.5 on the next page. The feeds for the highest frequency bands, 43 GHz and 86 GHz, are located close to the elevation axis on the feed circle. This allows gain lost by gravity-induced movement of the subreflector to be recovered by a correction to the subreflector rotation angle.

In addition to the Cassegrain feeds, a UHF dual-frequency crossed-dipole feed for 327 MHz and 610 MHz is permanently mounted in the middle of the subreflector which acts as a ground plane for the dipoles. A tuned circuit half way along each dipole section provides a short circuit at 327 MHz and an open circuit at 610 MHz so that the dipole is effectively a half wavelength long at both frequencies. The automated mechanism which focuses and rotates the subreflector has sufficient focus travel (70 cm) to move the subreflector vertex to the prime focus when operation at 327 MHz and 610 MHz is required. A diplexer is used for each dipole to separate the outputs for the two bands.

The primary and secondary reflectors are shaped for high efficiency. The shaping was generated using the computer programs described by James (1980) and transforms a feed pattern with a -14 db subreflector edge taper into an aperture illumination which is uniform out to 95% of the aperture radius and then rolls off to -15 db at the edge. The offset geometry was designed by first generating an azimuthally symmetric shaped geometry with an on-axis secondary focus. The symmetric shaped primary was kept and the symmetric secondary was replaced with an asymmetric shaped secondary reflector which produces equal path lengths from the primary aperture to the off-axis secondary focus. The resulting aperture field distribution has uniform phase and small (< 1 db)

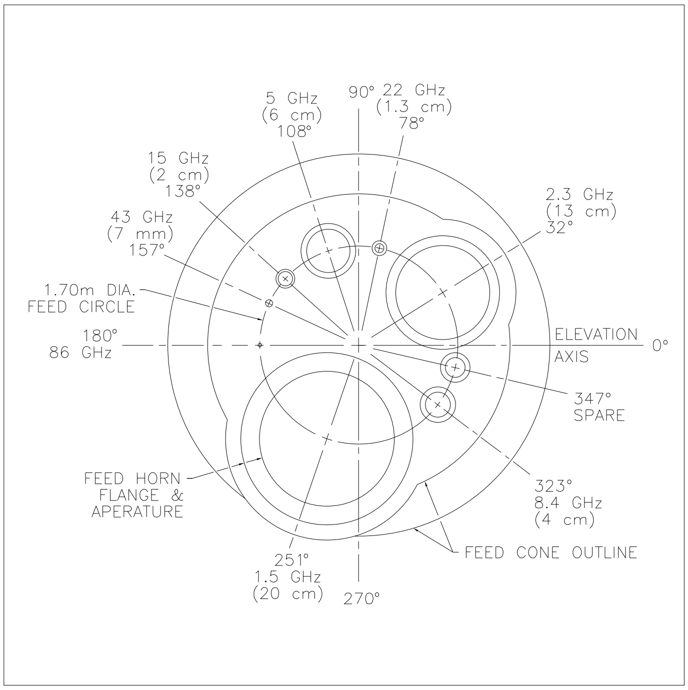

Figure 4.5: Arrangement of feeds around the feed circle

asymmetries in amplitude. Deviation of the symmetric shaped primary reflector from a parabola causes a 5% gain loss for prime-focus operation at 610 MHz. All the secondary focus feeds for bands above 2.0 GHz are conventional conical corrugated horns providing -14 dB taper at the 13.3^o half angle subtended by the edge of the subreflector. Because of its necessarily large size, the feed for the 1.5 GHz band uses a compact corrugated horn of the type developed for the Australia Telescope (James 1992). A novel low-cost, light-weight fabrication technique is used in which the corrugations are formed from sheet metal "washers" and "bands" held together with an external epoxy/fiberglass skin. All feeds are sensitive to left and right circularly polarization. The devices used to form circular polarization are incorporated into the receiver packages (see chapter 5). The polarization performance is typically better than 0.5 db axial ratio across the band, except for those receivers having nominal bands wider than 10%, for which the axial ratio rises to 1 db at the band edges. The offset geometry gives rise to an undesirable, but tolerable, beam separation of 0.05 beamwidths between the two circularly polarized beams for all feeds located at the secondary focus.

The geodetic and astrometric requirements for simultaneous observations with the 2.3 GHz and 8.4 GHz bands is satisfied using quasi-optical reflectors de-

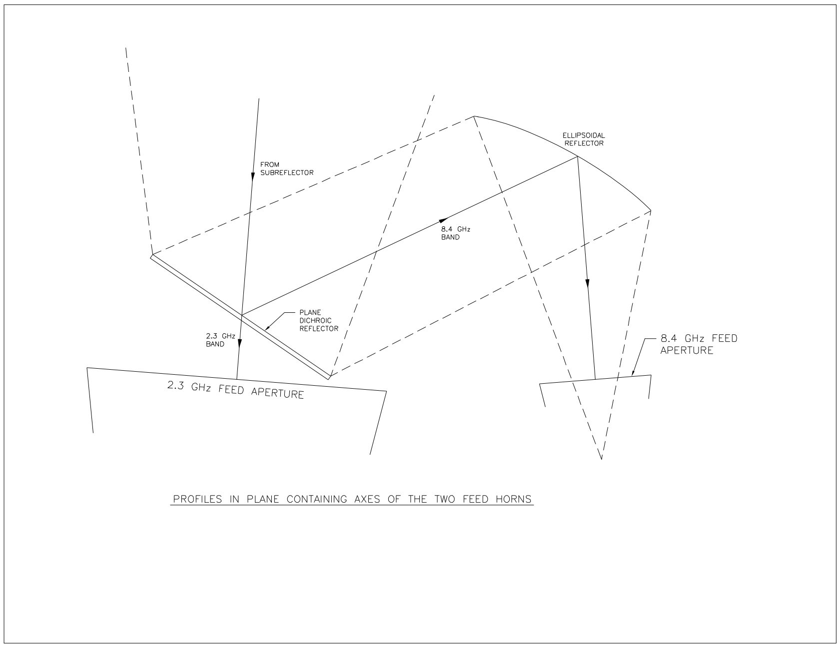

Figure 4.6: Dual-frequency 2.3/8.4 GHz reflector system

ployed over the feeds for these two bands, as shown in figure 4.6. A flat dichroic reflector, which is transmissive at 2.3 GHz and reflective at 8.4 GHz, is permanently mounted over the 2.3 GHz feed. When the subreflector is pointed towards the 2.3 GHz feed the 2.3 GHz signal passes through the dichroic reflector to the feed. The 8.4 GHz signal is reflected by the dichroic to an ellipsoidal reflector, located above the 8.4 GHz feed, which refocuses the signal down into the 8.4 GHz feed. The ratio of gain over system temperature (G/T) in both bands is reduced by approximately −1 db by this dual-frequency reflector system. The additional optics asymmetry introduced by the ellipsoidal reflector causes a beam separation of 0.11 beamwidths between the two circularly polarized beams at 8.4 GHz. When dual-frequency operation is not needed the 8.4 GHz ellipsoid can be moved out of position using an automated mechanism. The locations of the feeds on the feed circle are chosen so that, in the future, simultaneous observations with other frequency pairs would be possible using similar quasi-optical reflector systems. Possible future frequency pairs include 4.8/23 GHz, 4.8/14 GHz and 14/43 GHz.

The predicted and measured antenna performance is shown in table 4.2 on page 63. Performance at 2.3 GHz and 8.4 GHz in dual frequency mode is worse than predicted because losses in the dual frequency reflector system are higher than expected. In other bands the causes for differences between expected and measured sensitivities are under investigation to identify sources of increased system temperature and decreased aperture efficiency. In particular the antenna gain loss at 43 GHz at low and high elevation angles (see figure 9.3 on page 169) is larger than expected. This effect is presumably due to gravitational deformation of the antenna and/or subreflector support. Tests of the antenna at Pie Town, NM, have been made at 86 GHz and gave a measured total aperture efficiency of 0.18, indicating that useful performance at this frequency can be obtained in the future (Walker and Bagri 1989).

4.4 Conclusion

The major design features of the VLBA include high image resolution and dynamic range, high sensitivity, good spectral coverage from 300 MHz to 45 GHz, spectral line imaging capability, support of geodetic observations, full time operation, user friendliness and compatibility with other VLBI instruments. These features should ensure that the VLBA is capable of performing observations for a wide range of astronomical problems and that it will be suitable for use by astronomers who are not necessarily experts in radio interferometry.

The antennas and their feed systems provide high sensitivity and excellent frequency flexibility and have been designed for unattended operation.

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