THE LARGE SYNTHESIS RADIO TELESCOPES OF THE NATIONAL RADIO ASTRONOMY OBSERVATORY

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ABSTRACT

Large radio telescope arrays such as the Very Large Array and Very Long Baseline Array challenge the state-of-the-art of microwave technology in many areas. Examples include the design of optimized sparse arrays and the design and economic construction of high performance, frequency flexible antennas, reliable low noise receivers and highly phase stable local oscillator systems.

INTRODUCTION

Forefront research in the field of radioastronomy requires radio imaging of astronomical objects using a wide range of angular resolutions. For example, studies of the nearest galaxies and nebulae require a telescope capable of imaging a field of several degrees with resolutions of a few arc seconds whilst investigations of the nuclei of the most distant radio galaxies and quasars require fields of less than an arc second with resolutions of a thousandth of an arc second or less. Resolutions over this range require telescopes with apertures from about 10^4 to more than 10^8 wavelengths. At centimeter wavelengths apertures of such large extent are achieved with arrays using the technique of earth rotation synthesis (1),(2),(3). In a synthesis radio telescope the two-dimensional spatial coherence function of the electromagnetic field radiated by an astronomical object is measured by cross-correlating the signals received by a number of antennas. This spatial coherence function is known to astronomers as the visibility function. Each pair of antennas in an array forms an interferometer which samples the visibility function on a baseline which varies in both length and orientation as earth rotation moves the antennas with respect to the observed astronomical object. With enough antennas it is possible to completely sample the visibility function. An image, formally the two-dimensional brightness distribution, of the astronomical object is then obtained as the Fourier transform of the measured visibility function. Two state-of-the-art synthesis arrays, the Very Large Array (VLA) and the Very Long Baseline Array (VLBA) are operated by the National Radio Astronomy Observatory from its Array Operations Center (AOC) in Socorro, New Mexico. In this paper we will describe some of the microwave technology used in these instruments.

THE VERY LARGE ARRAY

The VLA has been in operation since 1981. Since it has been described in some detail previously (1),(2),(4),(5), here we will give a brief overview of the instrument and discuss some of the recent improvements in its microwave instrumentation. The VLA is a Y shaped array of twenty-seven 25m diameter antennas located on the Plains of San Augustine 80 km West of Socorro. The antennas can be moved on rail mounted transporters into any one of four different array sizes in which the arms of the Y are 600 m, 1.8 km, 4.6 km or 21 km long. The antennas use an off-axis shaped Cassegrain geometry which allows several feeds and receivers to be permanently located on the antenna in a circle around the primary reflector axis (5). Frequency changing is simply accomplished by rotating the subreflector to position the secondary focus on the desired feed. The antennas were originally equipped with feeds and receivers for observations at frequencies of 1.5 GHz, 5 Ghz, 15 GHz and 22 GHz. The principal enhancement to the instrument since completion of construction has been improvements in the sensitivity of these receiving systems and the addition of feeds and receivers for three new observing bands. The original low noise receivers (5) used cooled parametric devices for the two lower frequency bands and cooled Schottky diode mixers for the two higher frequency bands. The recent advent of cryogenically cooled HEMT amplifier receivers (6) has dramatically improved the performance, reliability and cost of radio astronomy receivers for centimeter wavelength arrays and all of the original VLA low noise devices have now been replaced with HEMTs. Table 1 shows the performance of all current receivers. The three new receivers added to the antennas allow observations at 75 MHz, 327 MHz and 8.4 GHz. The prime-focus feed for the 75 MHz receiver is simple thin wire crossed half-wave dipoles stretched between the legs of the quadruped subreflector support structure. The dipoles are located below the subreflector which functions as a partial ground plane. Aperture efficiency is low because of the simplicity of the feed, which does not compromise performance of the secondary focus receivers, and because of the small size of the primary reflector. The receivers use commercial uncooled bi-polar transistor amplifiers. They have been installed on eight antennas, enough to test the feasibility of synthesis imaging through the ionosphere which is highly unstable at this low frequency.

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Frequency Band(GHz)	T_{sys} (°K)	Aperture Efficiency
.075	2100	0.20
.308-.343	150	0.40
1.34-1.73	35	0.51
4.5-5.0	60	0.65
8.0-8.4	40	0.63
14.4-15.4	120	0.52
22.0-24.0	160	0.43

Table 1. VLA receiver sensitivity. T_{sys} is the total system temperature including the noise from the sky. The aperture efficiency is the total efficiency of the 25m aperture.

The 327 MHz prime-focus feed is crossed half wavelength dipoles permanently located at the center of the subreflector which functions as a ground plane. When 327 MHz operation is required the subreflector is moved away from the primary reflector, using an automated mechanism, to locate the feed phase center sufficiently close to the prime focus. The 8.4 GHz feed is located with the other Cassegrain feeds at the secondary focus. The feed is a corrugated horn and the receiver is a cryogenically cooled HEMT receiver (6) identical to the VLBA receivers described below.

Communication between the antennas and the central control building is provided by buried 60 mm diameter, helix lined, circular waveguide operating in the low-loss TE_{01} mode (1). The waveguide is used to bring back received signals of 200 MHz total bandwidth from each antenna to the central correlator, as well as providing phase stable LO and monitor and control data for each antenna. Planning is underway to replace the waveguide with fiber optics and build a new correlator so that the usable bandwidth can be increased to 1 GHz for each antenna. Also, testing is beginning with a goal of increasing the highest reception frequency for the antennas to 49 GHz.

THE VERY LONG BASELINE ARRAY

The VLBA (7), currently scheduled for completion at the end of 1992, consists of ten 25m diameter antennas located so as to provide the largest possible array extent on reasonably accessible US territory. The exact locations of the antenna sites were chosen, using extensive computer simulation, so as to provide the most complete sampling possible of the visibility function with a ten element array. An additional constraint was that a few antennas would be located close to the VLA so that they could be used to increase the resolution of the VLA and the VLA could be used to provide additional short antenna spacings with the VLBA. Details of the antenna location optimization process can be found in (8). The array chosen, which has an extent of 8000 km, has antennas located at Mt. Mauna Kea (Ha), Owens Valley (Ca), Brewster (Wa), Kitt Peak (Az), Pie Town (NM), Los Alamos (NM), Fort Davis (Tx), North Liberty (Ia), Hancock (NH) and St. Croix (VI). The array is shown in Figure 1.

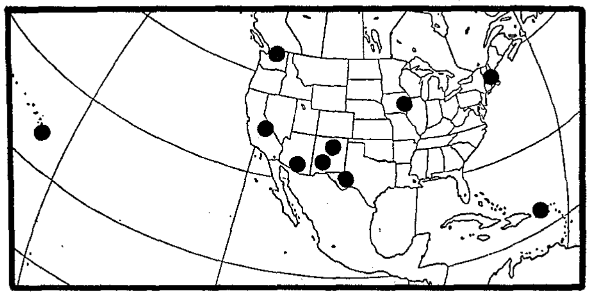

Figure 1. Locations of the VLBA Antennas

The extent to which this array samples the visibility function over it's 8000 km aperture is shown in Figure 2 for astronomical objects at various declinations. In antenna engineering terms, Figure 2 shows the synthesized aperture autocorrelation function of the VLBA telescope for each declination. Clearly, for lower declinations, the visibility function of the source is poorly sampled. Astronomers have developed effective computer image processing techniques to reduce the effect of this undersampling on image quality (1-3).

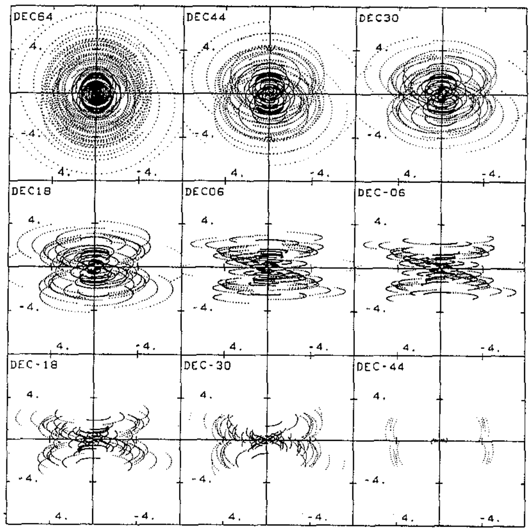

Figure 2. Visibility sampling function for the VLBA array for nine different declinations. (baseline units 10^3 km).

The VLBA antennas are elevation over azimuth reflectors with wheel-and- track azimuth drives. Some of their principal performance parameters are as follows:

Diameter	25m
F/D	.35
Elevation coverage	0° to 125°
Azimuth coverage	-270° to +270°
Elevation slew	30°/min
Azimuth slew	90°/min
Pointing, 6 m/s wind	8 arc. sec. rms.
Pointing, full sun	14 arc. sec. rms.
Survival wind speed	50 m/s
Main reflector accuracy	.28 mm rms
Subreflector accuracy	.15 mm rms

Some of the principal dimensions of the antenna are shown in Figure 3.

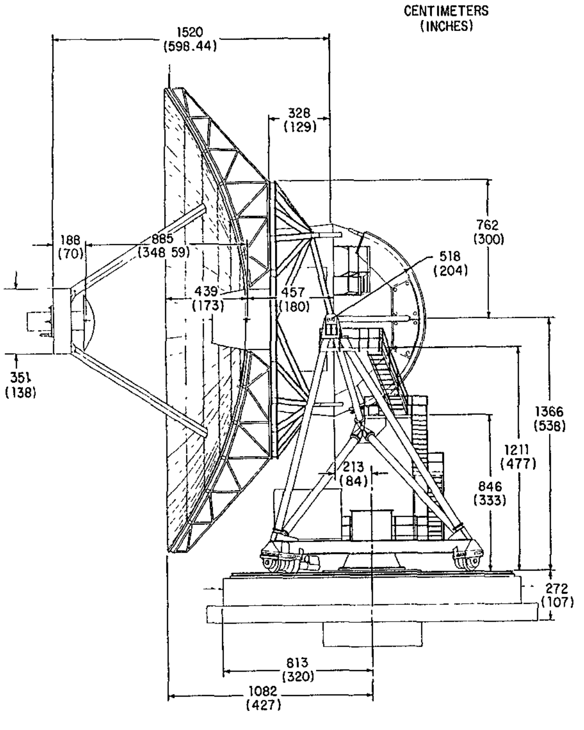

Figure 3. VLBA Antenna Dimensions

The antennas are equipped with feeds and receivers for observations in nine frequency bands as shown in Table 2. The antenna geometry is an off-axis shaped Cassegrain similar to the VLA geometry described above. The 327/610 MHz feed is a dual frequency crossed dipole permanently mounted in the center of the subreflector. It is moved to its operating position at the prime focus by moving the subreflector, on an automated mechanism, 66 cm away from the primary reflector. All other feeds are corrugated horns located at the secondary focus. Frequency changes simply require automated rotation of the subreflector, as for the VLA. For geodetic and astrometric observations it is necessary to observe simultaneously at both 2.3 GHz and 8.4 GHz to correct for ionospheric phase fluctuations. This is achieved using a flat plate dichroic reflector that is permanently located over the 2.3 GHz feed and an ellipsoidal reflector that is automatically deployed over the 8.4 GHz feed. These reflectors transfer the phase center of the 8.4 GHz feed on to the 2.3 GHz phase center so that both feeds have the same pointing on the sky.

Frequency Band (Ghz)	T_{sys} (°K)	Aperture Efficiency
.312-.342	160	40
.580-.640	120	40
1.35-1.75	32	57
2.15-2.35	34	58
4.6-5.1	40	72
8.0-8.8	35	70
8.0-8.8 DF	41	66
12.1-15.4	80	69
21.7-24.1	90	62
41-45	127	51

Table 2. Sensitivities of VLBA receivers. Definitions are as in Table 1. The DF entry for 8 GHz is with the dual frequency optics in operating position. The entries for 327/610 MHz, 14 GHz and 43 GHz are predictions not test results.

The ten VLBA sites are designed to operate unattended most of the time, with typically only two technicians based at each site. Control and monitor of the antennas and electronics are performed remotely from Socorro using the Internet communications network. It is therefore essential that the receivers and electronics be as simple and reliable as possible whilst maintaining high performance. Cryogenically cooled HEMT amplifiers (6) have proven ideal for this purpose and they are used for all of the receivers above 1 GHz. An additional advantage of HEMT receivers at some of the VLBA sites is that they can withstand relatively high levels of RFI without gain compression. Each of these receivers is cooled by a small, closed cycle helium refrigerator capable of 1 or 3 watts cooling at the HEMT amplifier operating temperature of 15 °K. All receivers are dual circularly polarized. To provide circular polarization the 1.5 GHz receiver uses a room temperature quarter-wave phase shifter followed by a cooled quad-ridged orthomode junction, the 43 GHz receiver uses a cooled waveguide phase-shifter and orthomode junction and all the other cooled receivers use cooled sloping-septum polarizers. The prime-focus 327/610 MHz receiver uses ambient temperature FET amplifiers.

Stable time and local oscillator signals sufficiently coherent to allow correlation between antennas is provided by a hydrogen maser frequency standard located in a temperature stabilized control building at each site. The maser has an Allan variances at 1 sec of 1 X 10^{-13} and at 100 sec of 7 X 10^{-15} . The primary reference signal derived from the maser is 500 MHz and this is sent to the antenna where it is multiplied to provide the local oscillator needed to down convert received signals to an IF in the 500 MHz to 1000 MHz range. The 500 MHz reference is also returned from the antenna to the control building to allow corrections to be made for length changes in the cables between the building and the antenna. To maintain the highest possible phase stability through the electronics chain at each site a low level phase reference signal, derived from the primary 500 MHz in the antenna, is injected into the input to each receiver and its phase is measured after the received signal has been digitized (9). Even when instrumental phase errors can be made negligible, phase errors due to the ionosphere at low observing frequencies or the troposphere at high frequencies will usually prevent image formation unless additional corrections are made. Computer data processing techniques such as "fringe fitting" and "self calibration" have proven effective in removing phase errors from the measured visibility data (1-3).

Return of the wide bandwidth received signals from each site to the AOC in real time by fiber optics, microwave or satellite communication links would be prohibitively expensive. Instead, the astronomical data is recorded on a custom made, high bandwidth tape recorder. The recorder is capable of recording at 128 Mbit/sec, the normal reception data rate for the VLBA, for 12 hours on a single 14 in diameter reel of 1 in. wide magnetic tape (10). Tapes will be returned daily to the AOC for correlation on the 20 station processor.

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