

VERY LARGE ARRAY OBSERVATIONAL STATUS SUMMARY

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1 INTRODUCTION

This document summarizes the current instrumental status of the Very Large Array. It is intended as a ready reference for those contemplating use of the VLA for their astronomical research. The information contained herein is in summary form – those requiring greater detail should consult one of the VLA’s staff members, listed in Section 7, or refer to the manuals and documentation listed in Section 6. Most of the information contained herein, and much more, is on the Web, and can be accessed through the NRAO home page, at URL <http://www.nrao.edu>. A companion document for the VLBA is also available from the same address.

The Very Large Array is a large and complex modern instrument. It cannot be treated as a “black box”, and some familiarity with the principles and practices of its operation is necessary before efficient use can be made of it. Although the NRAO strives to make use of the VLA as simple as possible, users must be aware that proper selection of observing mode and calibration technique is often crucial to the success of an observing program. Inexperienced and first-time users are especially encouraged to enlist the assistance of an experienced colleague or NRAO staff member for advice on, or direct participation in, an observing program. Refer to Section 4.11 for details. The VLA is an extremely flexible instrument, and we are always interested in imaginative and innovative ways of using it.

2 AN OVERVIEW OF THE VLA

The VLA is a 27-element array which will produce images of the radio sky at a wide range of frequencies and resolutions. The basic data produced by the array are the visibilities, or measures of the spatial coherence function, formed by correlation of signals from the array’s elements. The most common mode of operation uses these data, suitably calibrated, to form images of the radio sky as a function of sky position and frequency. Another mode of observing (commonly called *phased array*) allows operation of the array as a single element through summation of the individual antenna signals. This mode is commonly used for VLBI observing and for observations of rapidly varying objects.

The VLA can vary its resolution over a range exceeding a factor of ~ 50 through movement of its component antennas. There are four basic arrangements, called configurations, whose scales vary by the ratios 1 : 3.2 : 10 : 32 from smallest to largest. These configurations are denoted D, C, B, and A respectively. In addition, there are 3 “hybrid” configurations labelled BnA, CnB, and DnC, in which the North arm antennas are deployed in the next larger configuration than the SE and SW arm antennas. These hybrid configurations are especially well suited for observations of sources south of $\delta = -15^\circ$ or north of $\delta = +75^\circ$. Beginning in 1998, the standard ‘C’ configuration will be replaced by a slightly modified one, formerly known as ‘CS’, in which one antenna from the middle of the north arm (probably from N10) will be placed at N1 (at the center of the array) to give better short-spacing baseline coverage.

The array completes one cycle through all four configurations in approximately a 16 month period. The configuration schedule for 1998 through 1999, and the approximate long-term schedule to 2001, are outlined in Tables 1 and 2. Updates to these tables are published in the NRAO and AAS Newsletters, and are available through the NRAO home page (www.nrao.edu). Refer to Section 4.1 for information on proposal deadlines, and on how to submit an observing proposal.

Table 1: VLA Configurations for 1998 - 1999

DATES	CONFIG	Proposal Deadline
30 Oct 1998 - 16 Nov 1998	CnB	01 Jun 1998
20 Nov 1998 - 01 Feb 1999	C	01 Jun 1998
12 Feb 1999 - 01 Mar 1999	DnC	01 Oct 1998
05 Mar 1999 - 01 Jun 1999	D	01 Oct 1998
19 Jun 1999 - 27 Sep 1999	A	01 Feb 1999
08 Oct 1999 - 25 Oct 1999	BnA	01 Jun 1999
29 Oct 1999 - ?? Jan 2000	B	01 Jun 1999

Table 2: Approximate Long Term VLA Configuration Schedule

	T1	T2	T3
1998	A	B	C
1999	D	A	B
2000	C	D	A
2001	B	C	D
2002	A	B	C

Observing projects on the VLA vary in duration from as short as 1/2 hour to as long as several days. Most observing runs have only one, or perhaps a few, target sources. However, since the VLA is a two-dimensional array, images can be made with data durations of less than one minute. This mode, commonly called *snapshot* mode, is well suited to surveys of relatively strong, isolated objects. See Section 3.16 for details.

The VLA can be broken into as many as five sub-arrays, each of which can observe a different object at a different band. This is especially useful for multi-band flux density monitoring observations, and for observing compact objects for which the VLA's full imaging capability and sensitivity are not required. However, important restrictions apply when multiple sub-arrays are used – refer to Section 3.8 for these restrictions.

All antennas are permanently outfitted with receivers for six wavelength bands centered near λ 90, 20, 6, 3.6, 2.0 and 1.3cm. These bands are commonly referred to as P, L, C, X, U, and K bands, respectively. One observing band is partially outfitted – thirteen antennas are equipped with 0.7cm receivers (Q-band). The NSF has recently announced that funds will be provided to complete the outfitting of the array at this important band. It is expected that all antennas will be outfitted with Q-band receivers by 2002.

The '4-band' system (better known as the 74 MHz system) is now available on all antennas, but is not permanently installed. The long dipoles needed to efficiently illuminate the antennas have been shown to reduce the gain and increase the system temperature at all other bands by small but significant amounts. Tests of other feed systems are ongoing. Mounting of the temporary dipoles for observations at this band in the near future will depend on proposal pressure.

The array can tune to two different frequencies from the same wavelength band provided the frequency difference does not exceed approximately 450 MHz. Right-hand circular

(RCP) and left-hand circular (LCP) polarizations are received by both frequencies. Each of these four data streams is called an *IF*. These four data streams are known in VLA-ese as IFs 'A', 'B', 'C', and 'D'. IFs A and B receive RCP, IFs C and D receive LCP. IFs A and C are always at the same frequency, as are IFs B and D. (But the (A,C) frequency is usually different than the (B,D) frequency). Observations at more widely separated frequencies can only be made within the same run by time switching between the frequencies. This operation takes less than 30 seconds. The array can also simultaneously observe one frequency within L band and one within P band (known as LP band), or one within 4-band and one within P band (known as 4P band). These are the only currently *supported* modes in which frequencies within two different bands can be observed simultaneously (others are possible but not supported).

Observations at seven different bandwidths (given by $50/2^n$ MHz, with $n = 0, 1, \dots, 6$) are possible¹. A 200 kHz bandpass is also available in spectral line mode. Continuum mode users wishing to use the 200 kHz bandpass should consult VLA staff first. Different bandwidths can be used for each of the two separate frequencies. Wider bandwidths provide better sensitivity, but also increase the chromatic aberration. Refer to Section 3.4.2 for details.

A scheme in which the VLA can provide a 70 MHz bandwidth in continuum mode only has recently been successfully tested. Full implementation of this capability requires significant changes to hardware and software that will not be completed until at least 2000.

The VLA correlator has two basic modes, Continuum and Spectral Line. In Continuum mode, the correlator provides the four correlations (RR, RL, LR, LL) needed for full polarimetric imaging at both frequencies. This mode is particularly well suited to high sensitivity, narrow field-of-view projects. The Spectral Line mode is a spectrum-measuring mode principally intended for observing spectral lines. There are many options allowed in this mode. Besides its use for all spectral line projects, certain continuum projects which require extremely high dynamic range and/or large field-of-view without undue loss of sensitivity will benefit from use of this mode. This mode is also used to great advantage when RFI (Radio Frequency Interference) is expected within the bandpass. The Spectral Line modes are further described in Section 3.14.

3 PERFORMANCE OF THE VLA

This section contains details of the VLA's resolution, sensitivity, tuning range, dynamic range, pointing accuracy, and modes of operation. Detailed discussions of most of the observing limitations are found elsewhere. In particular, see Reference 1, listed in Section 6.

3.1 Resolution

The VLA's resolution is set by the configuration and frequency of observation. It is important to be aware that a synthesis array is "blind" to structures on angular scales both smaller and larger than the range of fringe spacings given by the antenna distribution. For the former limitation, the VLA acts like any single antenna – structures smaller than the diffraction limit are broadened to the resolution of the antenna. The latter limitation is

¹The VLA's maximum bandwidth is commonly referred to as 50 MHz per IF, but the actual effective bandwidth is closer to 43 MHz, due to bandpass roll-off.

unique to interferometers – it means that structures on angular scales significantly larger than the fringe spacing formed by the shortest baseline are simply unseen. No subsequent processing can fully recover this missing information, which can only be obtained by observing in a smaller array configuration, using the mosaicing method, or with an instrument (such as a large single antenna) which provides this information.

Table 3 summarizes the relevant information. This table shows the maximum and minimum antenna separations, the approximate synthesized beam size (full width at half-power), and the scale at which severe attenuation of large scale structure occurs.

A project is currently under way to double the longest baseline available in the 'A'-configuration by establishing a real-time fiber optic link between the VLA and the VLBA antenna at Pie Town. It is anticipated that this link will be operational for observations in late 2000. Contact Jim Ulvestad for details.

3.2 Sensitivity

Table 4 shows the VLA sensitivities expected for natural weighting. The values listed are the expected r.m.s. fluctuations due to thermal noise on an image made with natural weighting, calculated using the standard formulae with the system temperatures and efficiencies listed. These values are realized in practice except at P-band and 4-band where the sensitivities are limited by confusing sidelobes from objects outside the image, and in imaging very bright objects where the residual image noise is due to baseline dependent errors (“closure errors”).

In general, the expected r.m.s. noise in mJy/beam on an output image, for natural weighting, can be calculated with the following formula:

$$\Delta I_m = \frac{K}{\sqrt{N(N-1)(N_{IF}T_{\text{int}}\Delta\nu_M)}} \text{ mJy/beam} \quad (1)$$

where N is the number of antennas, T_{int} is the total on-source integration time in hours, $\Delta\nu_M$ is the effective continuum bandwidth or spectral-line channelwidth in MHz, N_{IF} is the number of IFs (from 1 to 4) or spectral line channels (from 1 to 512) which will be combined in the output image², and K is a system constant, equal to 55, 8.0, 7.8, 6.6, 27, 47 and 32 for P, L, C, X, U, K³, and Q bands respectively. This constant K can also be expressed in terms of system temperature and efficiency as:

$$K = \frac{0.12T_{\text{sys}}}{\eta_a} \quad (2)$$

where T_{sys} is the system temperature, and η_a is the antenna efficiency, as listed in Table 4. (A correlator efficiency of 0.78 has already been incorporated into this expression). For the more commonly used uniform weighting employing the robust weight scheme (available in the AIPS task IMAGR), the sensitivity will be a factor of about 1.2 worse than the listed values.

²For most continuum observations, N_{IF} will be either 4 (all IFs), or 2 (one IF pair), and $\Delta\nu_M$ will be the IF bandwidth. Thus, $N_{IF} = 2$ for Stokes' Q, U and (true) I images at a single frequency. For spectral line work, $\Delta\nu_M$ is the spectral resolution (channel width) in MHz.

³The NRAO has begun a project to replace the K-band receivers with a much improved model. The expected K-factor will drop to 20, and tuning between 18 and 26 GHz will be enabled. This retrofit should be completed by 2002.

Table 3: Configuration Properties

Configuration	A	B	C	D
B_{\max} (km)	36.4	11.4	3.4	1.03
B_{\min} (km)	0.68	0.21	0.055	0.035
Synthesized Beamwidth θ_{HPBW} (arcsec)				
400 cm	24.0	80.0	260.0	850.0
90 cm	6.0	17.0	56.0	200.0
20 cm	1.4	3.9	12.5	44.0
6 cm	0.4	1.2	3.9	14.0
3.6 cm	0.24	0.7	2.3	8.4
2 cm	0.14	0.4	1.2	3.9
1.3 cm	0.08	0.3	0.9	2.8
0.7 cm	0.05	0.15	0.47	1.5
Largest Angular Scale θ_{LAS} (arcsec)				
400 cm	800.0	2200.0	20000.0	20000.0
90 cm	170.0	540.0	4200.0	4200.0
20 cm	38.0	120.0	900.0	900.0
6 cm	10.0	36.0	300.0	300.0
3.6 cm	7.0	20.0	180.0	180.0
2 cm	4.0	12.0	90.0	90.0
1.3 cm	2.0	7.0	60.0	60.0
0.7 cm	1.3	4.3	43.0	43.0

These estimates of the synthesized beamwidth are for a uniformly weighted, untapered map produced from full synthesis observations of a source which passes near the zenith.

Notes:

1. B_{\max} is the maximum antenna separation, B_{\min} is the minimum antenna separation, θ_{HPBW} is the synthesized beam width (FWHM), and θ_{LAS} is the largest scale structure "visible" to the array.
2. The listed resolutions are appropriate for sources with declinations between -15 and 75 degrees. For sources outside this range, the extended north arm hybrid configurations (BnA, CnB, DnC) should be used, and will provide resolutions similar to the smaller configuration of the hybrid, except for declinations south of -30. No double-extended north arm hybrid configuration (e.g., CnA, or DnB) is provided.
3. The approximate resolution for a naturally weighted map is about 1.5 times these numbers. The values for snapshots are about 1.3 times the listed values.
4. The largest angular scale structure is that which can be reasonably well imaged in full synthesis observations. For single snapshot observations these numbers should be divided by two.
5. The 0.7-cm antennas will be distributed in a manner intended to give the listed resolution performance.
6. The standard 'C' configuration has been replaced by a slightly modified one, formerly known as 'CS', wherein an antenna from the middle of the north arm has been moved to the central pad 'N1'. This will result in improved imaging to extended objects, but will degrade snapshot performance. Although the minimum spacing will be the same as in 'D' configuration, the surface brightness sensitivity to extended structure will be considerably inferior to that of the 'D' configuration (but considerably better than standard 'C' configuration).

It is important to note that these listed sensitivities are calculated from data taken in optimum conditions. For many bands, the system temperature and gain are significant functions of elevation and weather conditions (see next section).

A useful alternate form of the sensitivity equation is

$$\Delta I_m = \frac{42.4K}{\sqrt{N_{\text{pts}} N_{\text{IF}} \Delta t_{\text{int}} \Delta \nu_{\text{M}}}} \text{ mJy/beam} \quad (3)$$

Table 4: VLA Sensitivity

Frequency (GHz)	Band Name		System Temperature ¹ (K)	Antenna Efficiency ² (%)	RMS (10 min) Sensitivity (mJy/beam)
	approximate wavelength	letter code			
0.073 - 0.0745	400 cm	4	1000-10000	20	150 ⁽³⁾
0.3 - 0.34	90 cm	P	150-180	40	1.4 ⁽³⁾
1.3 - 1.70	20 cm	L	35	55	0.056
4.5 - 5.0	6 cm	C	45	69	0.054
8.1 - 8.8	3.6 cm	X	35	63	0.045
14.6 - 15.3	2 cm	U	120	58	0.17
22.0 - 24.0	1.3 cm	K	150 - 180	40	0.31 ⁽⁴⁾
40.0 - 50.0	0.7 cm	Q	100 - 140	35	0.60 ⁽⁵⁾

Frequency (GHz)	RMS Sensitivity in 12 hours (mJy/beam)	Untapered Brightness Sensitivity ⁽⁶⁾ (D-config) (mKelvins)	Antenna Primary Beam Size (FWHP) θ_{PB}	Peak Confusing Source in Beam (Jy)	Total Confusing Flux in Primary Beam (Jy)
0.073 - 0.0745	15 ⁽³⁾	300	700'	20	350
0.3 - 0.34	0.17 ⁽³⁾	52.0	150'	1.8	15
1.34 - 1.73	0.0066	1.9	30'	0.11	0.35
4.5 - 5.0	0.0064	1.9	9'	0.002	0.02
8.0 - 8.5	0.0053	1.5	5.4'	0.001	—
14.4 - 15.4	0.020	6.0	3'	0.0001	—
22.0 - 24.0	0.036 ⁽⁴⁾	10.0	2'	0.00001	—
40.0 - 50.0	0.070 ⁽⁵⁾	20.0	1'	—	—

All sensitivity calculations assume 44 MHz bandwidth per IF, (except for P-band and 4-band, where 3.125 MHz and 0.78 MHz are used), 27 antennas, two IF pairs (four IFs), natural weighting, and an elevation of 45 degrees. Performance will degrade for large zenith angles at high frequencies and for sources close to the galactic plane at low frequencies.

Footnotes:

(1) Temperature ranges listed at P, K, and Q bands include sky temperature variations due to the galactic plane (P-band) or atmosphere (K and Q bands).

(2) This is the system efficiency without the correlator factor (about 0.78). Efficiencies at U, K, and Q bands at low elevations (< 30 degrees) are considerably decreased due to gravitational distortions of the antenna figure.

(3) Values listed assume observations near the galactic poles, and '3-D' imaging. Snapshot observations will not usually reach this level, as the confusion problem is insoluble with only snapshot u,v coverage. Full-beam A-configuration deconvolution at 74 MHz remains computer-limited. Moore's law should enable full deconvolution within a few years.

(4) Listed sensitivity is for El = 45 and very dry atmosphere at 22 GHz. A wet atmosphere can increase zenith opacity from 5 to 15 percent, and increase the sky temperature from 10 to 40 K. The K-band receivers will be replaced with newer models capable of tuning between 18 and 27 GHz with nearly 3 times the sensitivity. This retrofit is expected to be completed in 2002.

(5) Listed sensitivity is for El = 45 and dry atmosphere at 43 GHz with 13 antennas. A wet atmosphere can increase zenith opacity from 6 to 8 percent, and increase the zenith sky temperature from 15 to 24 K. Atmospheric attenuation and temperature increase dramatically with increasing frequency - sky temperatures exceeding 55 K and zenith opacity of 25 percent are expected at 49 GHz. All 28 antennas will be outfitted with receivers by 2002.

(6) Values listed assume a uniform object which just fills the synthesized beam in D-configuration. Realistic objects will always have a higher brightness temperature limit - roughly increasing in proportion to the number of synthesized beams across the source.

where N_{pts} is the number of visibility points (which is listed in the AIPS header), and Δt_{int} is the integration time per visibility in seconds. N_{FF} and Δt_N , and K are defined as above.

The limiting brightness temperature achievable by an array is a complicated function of the source distribution and array configuration. However, for the simplified case of an object approximately the size of the synthesized beam, the following relation between brightness temperature and flux density can be applied:

$$T_b = F \cdot S \quad (4)$$

where T_b is the brightness temperature (Kelvins) corresponding to S mJy per beam, and F is a constant depending only upon array configuration: $F = 300, 30, 3, 0.3$ for A, B, C, and D configurations, respectively. The limiting brightness can be obtained by substituting the rms noise, ΔI_m , for S . A more detailed description of the relation between flux density and surface brightness is given in Chapter 7 of Reference 1 in Section 6.

The sensitivity varies across each observing band. Table 5 gives the frequency ranges for each band at which the sensitivity degrades by 10% and by a factor of two. Also included are the maximum ranges over which the VLA receivers remain operative. At these extreme ends, the system sensitivity is typically 10 to 100 times worse than at band center. Furthermore, not all antennas will operate at these frequencies. Consult a VLA staff scientist if you wish to observe near these band edges.

Table 5: Sensitivity ranges of VLA bands

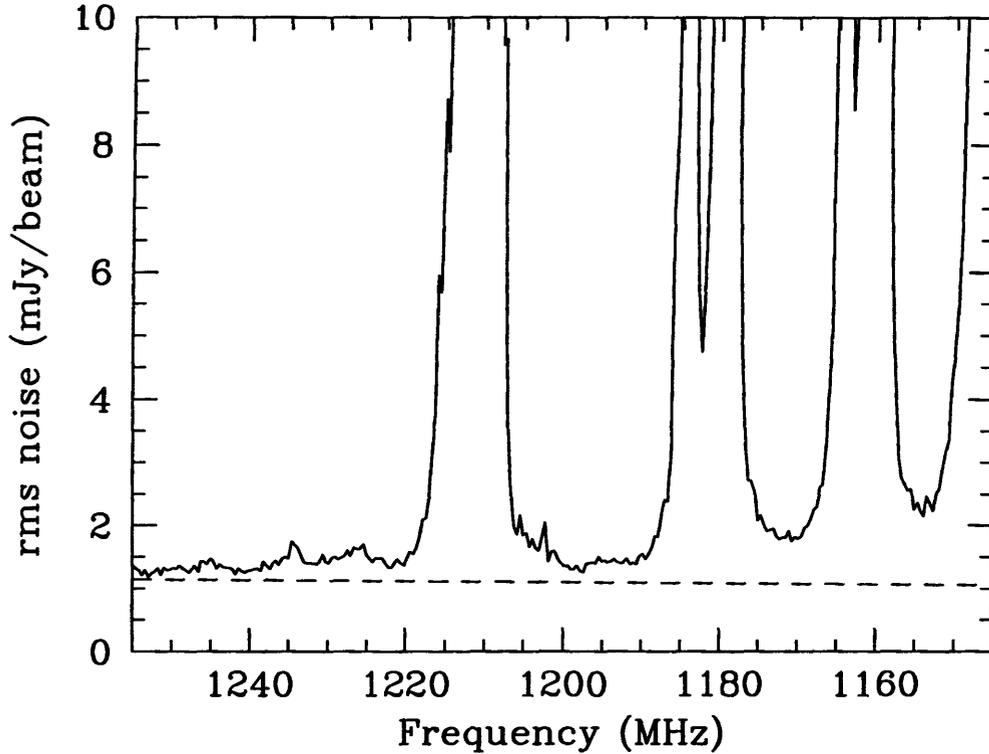
Band	0.9 x Nominal	0.5 x Nominal	Extreme Range
90 cm	305 - 335 MHz	298 - 345 MHz	295 - 350 MHz
20 cm	1240 - 1700 MHz	1170 - 1740 MHz	1150 - 1750 MHz
6 cm	4500 - 5000 MHz	4250 - 5100 MHz	4200 - 5100 MHz
3.6 cm	8080 - 8750 MHz	7550 - 9050 MHz	6800 - 9600 MHz
2 cm	14650 - 15325 MHz	14250 - 15700 MHz	13500 - 16300 MHz
1.3 cm	22000 - 24000 MHz	21700 - 24500 MHz	20800 - 25800 MHz
0.7 cm	40500 - 44500 MHz	39000 - 47500 MHz	38000 - 51000 MHz

In view of the importance of frequencies at the lower edge of the 20-cm band for studies of red-shifted HI, some special words are appropriate to describe the performance of the VLA at frequencies below 1250 MHz. The roll-off of this band at the low frequency edge is very gentle, and useful observations at 1155 MHz and lower have been made. However, not all frequencies can be tuned, as tests have shown there are four 10 MHz wide 'notches', centered at 1212, 1182, 1162 and 1150 MHz, within which the array can take no useful data. These notches exist in both RR and LL correlations. A plot of the relative sensitivity between 1150 and 1250 MHz is shown in Figure 3.2.

The sensitivity at the low frequency bands (90cm and 400cm) is difficult to parameterize. There are two important effects which limit the sensitivity.

1. The diffuse galactic background contributes an important fraction of the total system temperature – especially at 400cm, where it is the only important contributor. This means that the sensitivity will vary by nearly a factor of ten between locations on the galactic plane and locations near the galactic poles.
2. The primary beam at both bands is very broad, and the sidelobe levels comparatively high, resulting in significant sensitivity to objects far from the target object. Because

Figure 1: **The Sensitivity of the VLA Between 1150 and 1250 MHz** This plot shows the relative sensitivity of the VLA at the lower end of the 20cm band. The dashed line represents the sensitivity at the center of the band, so it can be seen that serious degradation in sensitivity is not notable until below 1190 MHz. The four 'notches' are instrumental in origin.



of the difficulty in imaging very large fields of view (due to the non-coplanar baseline effect, see Section 3.4.4 and the non-isoplanicity over large angles), the sidelobes of undeconvolved objects in non-imaged areas (essentially the entire 2π steradians visible to the antennas!) will appear in the map of the target source. Use of the AIPS program **IMAGR** will permit removal of the major background objects, and should result in a sensitivity not worse than a factor of two higher than that expected on the basis of the system temperature.

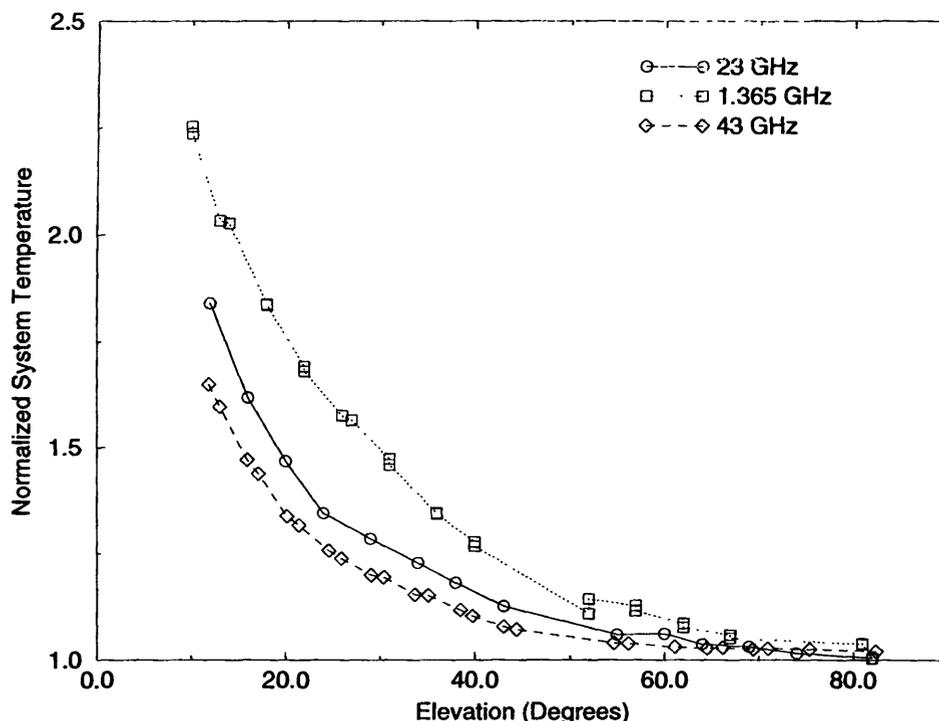
3.3 Elevation Effects

The VLA's antenna performance changes with elevation. These changes are significant at L, U, K, and Q bands, and must be corrected for in high-precision imaging.

The loss of performance is due to two different effects:

1. The sky and ground temperature contributions to the total system temperature increase with decreasing elevation. This effect is very strong at L, K, and Q bands, as shown in Figure 1, and is relatively unimportant at the other bands. The source of the excess noise at L-band is the ground itself ('spillover'), probably due to the microwave lens feed structure. At K and Q bands, the extra noise comes directly from atmospheric emission, primarily from water vapor at K-band, and from water

Figure 2: Variation of System Temperature with Elevation at L, K, and Q Bands
 The data have been normalized by the system temperature at the zenith – approximately 90K at 43 GHz, 170K at 23 GHz, and 35K at 1365 MHz. The observations were taken in good weather conditions.



vapor and the broad wings of the strong 63 GHz O₂ transitions at Q-band.

In general, the zenith atmospheric opacity to microwave radiation is very low – typically less than 0.01 at L and C and X bands, 0.02 at U band, 0.05 to 0.2 at K band, and 0.05 to 0.1 at the lower half of Q band, and rising to 0.3 by 49 GHz. The opacity at Q and K bands displays strong variations with time of day and season, being best at night, and in the winter.

Observers should remember that clouds, especially clouds with large water droplets (read, thunderstorms!), can add appreciable noise to the system temperature. Significant increases in system temperature can, in the worst conditions, be seen at wavelengths as long as 6cm.

2. The antenna figure degrades at low elevations, leading to diminished forward gain at the shorter wavelengths. In general, the forward power gain of the antennas can be well fitted by a simple parabola of form: $G(E) = G_0 - G_2(E - E_m)^2$, where E is the elevation, and E_m is the elevation of maximum forward gain. The average coefficients G_0 , G_2 , and E_m are given in Table 6. The gain-elevation effect is negligible at frequencies below 8 GHz.

These power coefficients are not directly useful for correcting the effects of antenna gain loss, which require the individual antenna (inverse) voltage correction factors expressed as the coefficients of a polynomial fit to the voltage gain as a function of zenith distance. That

Table 6: Average Power Gain Coefficients for the VLA antennas

Band	G_0	G_2	E_m
Q	1.00	3.0×10^{-4}	50
K	1.00	1.5×10^{-4}	58
U	1.00	3.6×10^{-5}	46
X	1.00	0.7×10^{-5}	50

is, the AIPS suite of programs can implement gain corrections of the form

$$V_c = G_0 + G_1 Z + G_2 Z^2 + \dots,$$

where V_c is the voltage gain correction of an antenna-IF, and the G_i are the coefficients of a polynomial series. The preferred method for determining these is through direct measurement of the relative system gain using the AIPS task ELINT on data from a strong calibrator which has been observed over a wide range of elevation. If you are unable to determine these coefficients directly from your own data, an approximate correction can be obtained using the amplitude coefficients given below in Table 7. These are applied using the AIPS task CLCOR.

Table 7: Average Inverse Voltage Gain Coefficients for the VLA antennas

Band	G_0	G_1	G_2
Q	1.00	-1.29×10^{-2}	1.59×10^{-4}
K	1.00	-0.41×10^{-2}	0.69×10^{-4}
U	1.00	-0.17×10^{-2}	0.19×10^{-4}
X	1.00	-0.23×10^{-3}	0.33×10^{-5}

These coefficients are averages over all the antennas, and are appropriate for an atmosphere of zero opacity. Considerable differences exist between antennas, particularly for antennas #1 and #2. Contact Rick Perley if you wish to obtain coefficients for individual antennas.

When using these coefficients, one must first correct for the opacity (typically measured using the TIPPER procedure), via the AIPS program CLCOR, then apply the gain coefficients in a subsequent run of CLCOR. The TIPPER procedure is an observing mode on the VLA's Modcomps which entails a simple measurement of the sky brightness as a function of elevation. The on-line software uses these data to derive the atmospheric zenith opacity and system temperature. This observing mode is known to the OBSERVE program. Contact Bryan Butler or Rick Perley for advice on these techniques.

3.4 Field of View

At least four different effects will limit the field of view. These are: primary beam; chromatic aberration; time-averaging; and non-coplanar baselines. We discuss each briefly:

3.4.1 Primary Beam

The ultimate factor limiting the field-of-view is the diffraction-limited response of the individual antennas. An approximate formula for the full width at half power in arcminutes is: $\theta_{PB} = 45/\nu_{\text{GHz}}$. Objects larger than approximately half this angle cannot be directly observed by the array. However, a technique known as “mosaicing”, in which many different pointings are taken, can be used to construct images of larger fields. Refer to Reference 1 for details.

3.4.2 Chromatic Aberration (Bandwidth Smearing)

The principles upon which synthesis imaging are based are strictly valid only for monochromatic radiation. When radiation from a finite bandwidth is accepted, aberrations in the image will result. These take the form of radial smearing which worsens with increased distance from the delay-tracking center. The peak response to a point source simultaneously declines in a way that keeps the integrated flux constant. The net effect is a radial degradation in the resolution and sensitivity of the array.

These effects can be parameterized by the product of the fractional bandwidth ($\Delta\nu/\nu_0$) with the source offset in synthesized beamwidths ($\theta/\theta_{\text{HPBW}}$). Table 8 shows the decrease in peak response and the increase in apparent radial width as a function of this parameter.

Table 8: **Bandwidth smearing.** The reduction in peak response and increase in width of an object due to bandwidth smearing (chromatic aberration). $\Delta\nu/\nu_0$ is the fractional bandwidth; $\theta_0/\theta_{\text{HPBW}}$ is the source offset from the phase tracking center in units of the synthesized beam.

$\frac{\Delta\nu}{\nu_0} \frac{\theta_0}{\theta_{\text{HPBW}}}$	Peak	Width
0.0	1.00	1.00
0.50	0.95	1.05
0.75	0.90	1.11
1.0	0.80	1.25
2.0	0.50	2.00

3.4.3 Time-Averaging Loss

The sampled coherence function (visibility) for objects not located at the phase-tracking center is slowly time-variable due to the changing array geometry, so that averaging the samples in time will cause a loss of amplitude. Unlike the bandwidth loss effect described above, the losses due to time averaging cannot be simply parameterized. The only simple case exists for observations at $\delta = 90^\circ$, where the effects are identical to the bandwidth effect except they operate in the azimuthal, rather than the radial, direction. The functional dependence is the same in this case with $\Delta\nu/\nu_0$ replaced with $\omega_e \Delta t_{\text{int}}$, where ω_e is the Earth’s angular rotation rate, and Δt_{int} is the averaging interval.

For other declinations, the effects are more complicated and approximate methods of analysis must be employed. Chapter 13 of Reference 1 considers the average reduction in image amplitude due to finite time averaging. The results are summarized in Table 9, showing the time averaging in seconds which results in 1%, 5% and 10% loss in the

amplitude of a point source located at the half-power point of the primary beam. These results can be extended to objects at other distances from the phase tracking center by noting that the loss in amplitude scales with $(\theta\Delta t_{int})^2$, where θ is the distance from the phase center and Δt_{int} is the averaging time.

Table 9: **Time averaging smearing** The averaging time (in seconds) resulting in the listed amplitude losses for a point source at the antenna half power point

Configuration	Amplitude loss		
	1.0%	5.0%	10.0%
A	2.1	4.8	6.7
B	6.8	15.0	21.0
C	21.0	48.0	67.0
D	68.0	150.0	210.0

3.4.4 Non-Coplanar Baselines

The procedures by which nearly all images are made in Fourier synthesis imaging are based on the assumption that all the coherence measurements are made in a plane. This is strictly true for E-W interferometers, but is false for the VLA, with the single exception of snapshots. Analysis of the problem shows that the errors associated with the assumption of a planar array increase quadratically with angle from the phase-tracking center. Serious errors result if the product of the angular offset in radians times the angular offset in synthesized beams exceeds unity. The effects are especially severe at $\lambda 90$ cm, where standard two-dimensional imaging can only be done for D-configuration data. This effect is noticeable at $\lambda 20$ cm in certain instances, but can be safely ignored at shorter wavelengths.

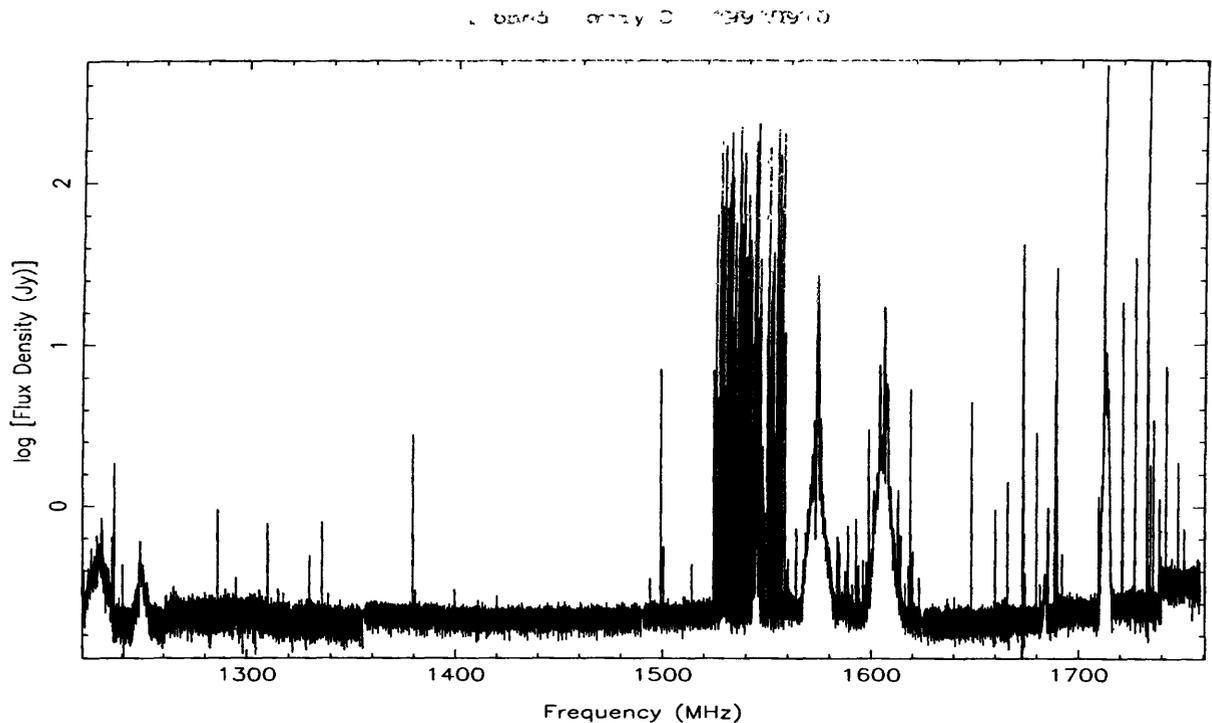
The solution to the problem of imaging wide-field data taken with non-coplanar arrays is well known, and has been implemented in the AIPS program **IMAGR**. This program can now correctly image up to 64 subfields, sufficient to handle observations in the B, C, and D configurations. We expect that as computer performance continues to improve, full imaging of even A configuration data will soon be practical.

3.5 Time Resolution

The minimum integration time at which all data can be written to tape is a function of the total number of channels of data produced by the correlator. This minimum time varies from 1 2/3 seconds for the continuum mode to 20 seconds for 512 channel spectral line modes. Note that in order to ensure the complete removal of correlator offsets, averaging times should be an integer multiple of the Walsh function period of 3 1/3 seconds.

Averaging times less than those listed above can be selected, but only at the cost of removing antennas from the array. For the spectral line modes, the approximate relation is that the minimum integration time in seconds equals the total number of baselines plus antennas ($= N(N + 1)/2$) multiplied by the total number of correlated channels (less than or equal to 512) divided by 10,000. A convenient table can be found on the web by going to the NRAO home page, and following the link to the VLA. In continuum mode, integration times as short as 0.4 seconds are available, but are appropriate only for solar observing. Contact Ken Sowinski for details on their use.

Figure 3: Typical L-band interference spectrum with 6 kHz resolution



Users must keep in mind the large data rate of the VLA when planning their observing. The array's maximum data rate of more than 3 GByte per day can easily overwhelm some data reduction facilities. This rate can be reduced to manageable levels by increasing the averaging time and/or decreasing the number of spectral channels. Consult your VLA friend for advice.

The maximum recommended integration time for any VLA observing is 60 seconds. The maximum allowable integration time in the spectral line modes is 90 seconds. There is no formal limit in the continuum modes.

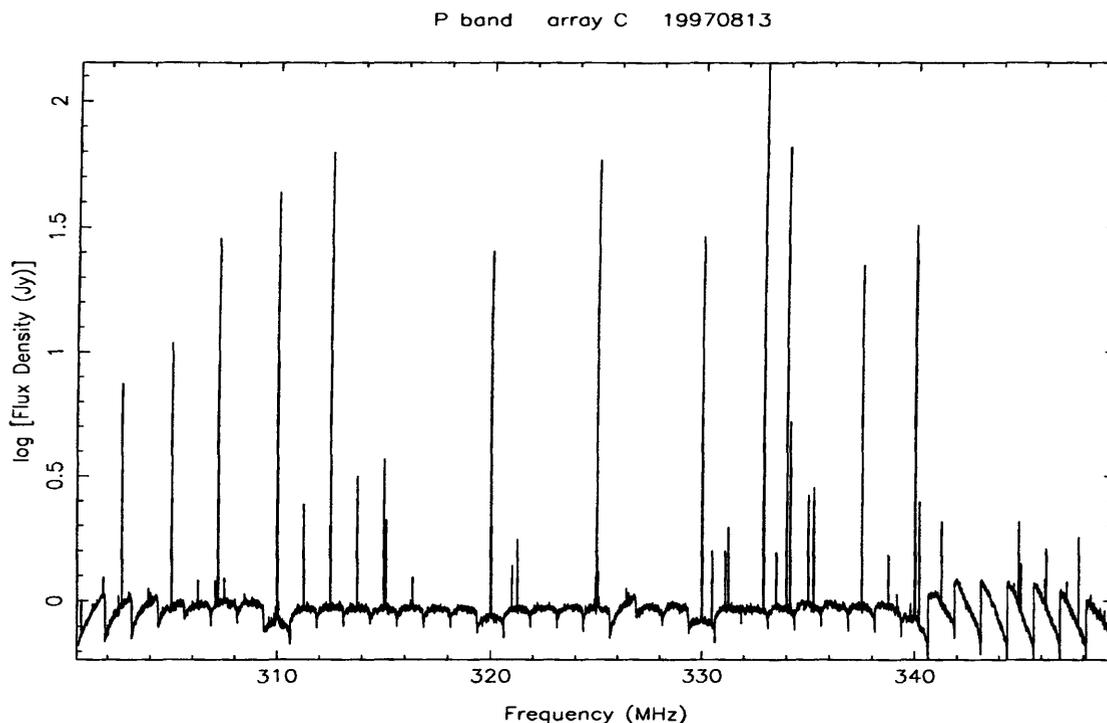
See Section 3.19 for a description of the High Time Resolution Processor and correlator gating for pulsar observations.

3.6 Radio-Frequency Interference

The bands within the tuning range of the VLA which are allocated exclusively to radio astronomy are 1400 – 1427 MHz, 1660 – 1670 MHz, 4990 – 5000 MHz, 15.35 – 15.4 GHz, 22.2 – 22.5 GHz and 23.6 – 24.0 GHz. No external interference should occur within these bands. Experience shows that RFI is a serious problem only within the 20 and 90 cm bands. At 20 cm, interference is most serious to the D configuration, as the fringe rates in other configurations are often sufficient to reduce interference to tolerable levels.

RFI at the VLA is an increasing problem to astronomical observations. To monitor this increase, and to provide a rough guide to the severity of this interference, the RFI spectrum at all bands from P through X is measured approximately once monthly, using the VLA correlator system. Plots of typical spectra in the L and P bands are shown in Figures 3 and 4.

Figure 4: Typical P-band interference spectrum



Downloadable plots of all RFI observations from 1993 onwards are available on the Web. For general information about the RFI environment, contact the head of the IPG (Interference Protection Group), Dan Mertely, at dmertely@nrao.edu, or at the telephone number listed in Table 16.

Table 10 is a convenient summary of eight such observations taken during the 1993/1994 D-configuration. This table lists the “line” frequency, the average equivalent flux density (in mJy) in 50 MHz, and the peak flux density, also reduced to 50 MHz equivalent bandwidth. A significant difference between these columns indicates that the RFI is intermittent. These equivalent flux densities are approximate, and should be used only to give a rough approximation to the severity and likelihood of a problem.

Between 1220 and 1250 MHz, very strong and very broad RFI is always present (apparently due to GLONASS satellite transmissions). It may be possible to observe in selected, narrow bandwidths in this region. Between 1435 and 1530 MHz, aeronautical telemetry from White Sands Missile Range will occasionally interfere with observing. These transmissions are very occasional, and unpredictable. They are worst in the spring, during the WSMR wargames exercises.

Note that the listed RFI signal strengths are appropriate for the ‘D’-configuration. These signal strengths are considerably reduced in the larger configurations – an average attenuation of perhaps a factor of 100 will be obtained in the ‘A’-configuration due to fringe phase winding.

In late 1998, the Iridium constellation of Low Earth Orbit (LEO) satellites will be activated. This system of 72 satellites is the first of what will probably be many such constellations offering direct personal communications around the world. The effect of

Table 10: VLA RFI Between 1260 and 1740 MHz

Frequency	Avg. Flux	Pk. Flux	Source	Comments
1277 MHz	12 mJy	20 mJy	Aerostat Radar	Sometimes absent
1286	2	5	Farmington Radar	Other weak lines nearby
1300	2	5	Internal RFI	
1310	100	100	ABQ Radar	
1316	???	???	ABQ Radar	Weaker, often absent
1330	45	80	ABQ Radar	Sometimes absent
1381	3	100	GPS L3 IONDS	On < 3% of the time
1400	60	60	Internal RFI	
1429-1435	15	130	Military	Four separate lines
1444,1453	5	> 100	Hi altitude balloons	NASA/NSBF
1500	2	5	Internal RFI	
1515	15	> 100	High Altitude Baloons	
1525	6	> 100	High Altitude Baloons	
1530-1544	> 130	> 200	INMARSAT	Many 'lines'
1557-1567	10	20	GPS Sidelobe?	Wide spectrum
1570-1580	> 500	> 500	GPS-L2	Wide spectrum
1600	120	120	Internal RFI	
1602-1616	> 500	> 500	GLONASS	Many separate 'lines'
1620	80	300	?	
1621-1627	>500	>500	IRIDIUM!	See text
1650	13	25	Internal RFI	
1678-1698	50	100	Radiosondes, satellite	> 6 variable 'lines'.
1710	10	10	?	
1714	> 500	> 500	Forest Service	
1725	10	10	" "	
1730	25	25	" "	
1735	> 100	> 100	Forest Service	

Iridium on radio astronomy will be great, as the utilized frequencies lie within the band 1616 and 1627 MHz. Although the spillover of Iridium transmission into the adjacent bands meets agreed limits, the VLA's filtering and system linearity will not permit observing of any frequency for which Iridium's transmissions lie within the band defined by the front-end (FE) filters. Unfortunately, this precludes observations of the 1612 MHz OH lines without significant system redesign. Discussions of these necessary changes are now underway.

In general, it may be possible to observe in spectral regions containing strong RFI provided: (1) That the RFI is not so strong as to cause serious gain compression in the amplifiers, and (2) That the RFI is kept out of the correlator through use of a narrow back-end filter. This latter requirement is particularly important for spectral line correlator modes, although use of Hanning smoothing is very helpful in reducing the Gibbs' ringing. Gain compression in the front-end amplifiers can often be prevented by using a narrower (12.5 or 25 MHz) front-end filter, rather than the default 50 MHz filter. Note that use of these FE filters greatly restricts the range of tunable frequencies. The scheduling program OBSERVE is aware of these restrictions, and should be used when contemplating use of the

narrow front-end filters.

Observers can use Table 10 to assist in deciding which center frequencies and bandwidths are most likely to result in good data. There are very few good combinations for 50 and 25 MHz bandwidths. These are summarized in Table 11, which shows the “statistically” best frequencies to use at L-band with the listed bandwidths. Note that the VLA LO system restricts the selection of frequencies at both 50MHz and 25MHz bandwidths. The restrictions are particularly severe at a bandwidth of 50 MHz – the only frequencies (in MHz) which can be observed with that bandwidth are those ending in 15, 35, 65, or 85. (For example, between 1400 and 1500 MHz, the only permitted frequencies are 1415, 1435, 1465 and 1485 MHz). With the 25 MHz frontend bandwidth filters, regions 5 MHz wide centered on 1250, 1300, 1350, . . . , cannot be tuned. And when using the 12 MHz frontend bandwidth filters, 8 MHz wide regions centered at 1225, 1275, 1325, 1375, . . . , and 18 MHz wide regions centered at 1250, 1300, 1350, 1400, . . . , cannot be tuned.

Table 11: Recommended Center Frequency/Bandwidth Combinations for L-Band

BW	Class A No RFI Expected	Class B Weak/Occas'l RFI	Class C “Tolerable” RFI
50 MHz	none	1365,1435,1465,1485	1335,1385,1415
25MHz	1343 – 1347 1353 – 1387 1413 – 1417 1663 – 1665	1290 – 1297 1453 – 1470 1503 – 1517	Use Table 10

The ubiquity of L-band interference makes it difficult for users wishing high sensitivity to find significant bandwidths free of RFI. As a result of monitoring the RFI, we have established a number of standard bands which are more likely to be free of significant RFI. These are shown below in Table 12.

Table 12: OBSERVE names of L-band “Standard frequencies”. Note that ‘L2’ was employed for the NVSS and FIRST surveys.

OBSERVE Name	AC		BD	
	Center Frequency	Bandwidth	Center Frequency	Bandwidth
LL	1465.1	50	1385.1	50
L1	1365.1	50	1435.1	50
L2	1515.9	25	1365.1	25
L3	1515.9	25	1435.1	25

At P-band, the RFI situation can be particularly difficult. Interference is relatively infrequent in the evenings and on weekends, but during the day, very strong interference – sufficient to saturate the receivers – is common. The best advice is to arrange observing to fall outside of regular working hours. Very sensitive spectral line observations at P-band require special measures at the VLA site to turn off known sources of RFI. To implement these measures, contact Dan Mertely (see Table 16). The situation at 4-band is generally better, as nearly all of the RFI is generated by the antennas themselves, and can be removed in processing provided the spectral line correlator is employed.

In the 327 MHz and 75 MHz bands, use of the spectral line correlator modes is strongly recommended for all observations. Use of these modes will allow diagnosis and removal of internal and external interference. The only observing mode at low frequencies which should be done in continuum are observations in the two-frequency systems, 4P and LP, when full polarization information is required.

Another important form of RFI consists of signals which are generated by each antenna. These signals are picked up by nearby antennas, or by the generating antenna's feed, and produce correlated signals in the visibility data. This form of RFI is especially important in the 90 cm and 500 cm bands when in the C and D configurations. They appear at all multiples of 5 and 12.5 MHz - frequencies divisible by these numbers must be avoided. (It is this spectrum of RFI which limits our P-band bandwidth to 3.125 MHz.) Another family of RFI occurs at multiples of 100 kHz - these are much weaker and can be ignored for continuum work at 90 cm, but are important on many baselines at the 400 cm band. Another 'family' to avoid are multiple of 600 MHz.

For L, C, K, and Q bands, observers should avoid using an L6 setting of 3760 or 3790 MHz, due to an internal birdie produced by those LO settings. For X and U bands, avoid using 3840 and 3810 MHz. The OBSERVE program is aware of these restrictions, so users should not inadvertently fall victim to this problem.

3.7 Antenna Pointing

The pointing parameters of the antennas are measured monthly under calm nighttime conditions. The antenna model, using these parameters, suffices under good weather to allow blind pointing to an accuracy of about 10 arcsec rms. The pointing accuracy in daytime is a little worse, due to the effects of solar heating of the antenna structures.

Moderate winds have a very strong effect on both pointing and antenna figure. The advertised maximum wind speed for precision operations is 15 mph (7 m/s), and careful observations have demonstrated this to be the practical maximum wind speed for useful observing at K and Q bands. Observations at these bands in winds significantly in excess of this limit are not advisable, and users should consider moving to a lower frequency. Wind speeds near the stow limit (45 mph) will have a similar negative effect at X and U bands.

To achieve better pointing, we have added a capability for repeated calibration and correction of the local pointing error during astronomical observations. In this observing mode, known as 'referenced pointing', a nearby calibrator is observed in interferometer pointing mode every hour or so. The local pointing corrections thus measured can then be applied to subsequent target observations. Tests show that this mode reduces rms pointing errors to typically 2 - 3 arcseconds if the reference source is within about ten degrees (in azimuth and elevation) of the target source, and the source elevation is less than 70 degrees. The OBSERVE program is aware of this observing mode.

Use of referenced pointing is highly recommended for all K- and Q-band observations, and for X- and U-band observations of objects whose total extent is a significant fraction of the antenna primary beam. It is usually recommended that the referenced pointing measurement be made at X-band, regardless of what band your target observing is at, since X-band is the most sensitive, and the closest calibrator is likely to be rather weak. Proximity of the reference calibrator to the source position is of paramount importance. The calibrator should have at least 300 mJy flux density and be unresolved on all baselines to ensure an accurate solution.

Measuring the pointing offsets at K-band for subsequent K-band observing is usually

successful, but should not be attempted on objects of less than 1 Jy flux density. However, attempting to measure these offsets at Q-band directly is generally not recommended, since the blind pointing error is often larger than the Q-band half-power half-width – which will cause the referenced pointing to fail.

Secondary referenced pointing (*i.e.*, using X-band referenced pointing to permit subsequent Q-band or K-band determination of the residual pointing errors), is recommended only for high precision observations at Q and K bands when observing extended objects which fill the antenna primary beam. For general observing of small objects, simple referenced pointing using the offsets determined at X-band is nearly always sufficient to keep all antennas pointing to within 5 arcseconds.

Consult with Rick Perley or Ken Sowiński for more information about these modes. There is considerable information on the use of this pointing mode on NRAO's website.

3.8 Subarrays

The VLA can simultaneously process five different observing programs. However, the subarrays are not all fully independent. If use of this capacity is contemplated, the following limitations must be understood and followed:

1. Each subarray uses a different observing file. (Strictly speaking, this is not a requirement, but is sensible.) The VLA operator must be told which file is to control which subarray, and which antennas are to be in each subarray. Antenna 'shuffling', in which antennas are reassigned from one subarray to another after observing has begun, is **strongly discouraged**.
2. Only one integration time for the entire array can be defined. Unless told otherwise, this time is that assigned for subarray #1. All other requested integration times (which are given on the //DS card in the `observe` file) are ignored.
3. All subarrays must be in continuum mode, or all must be in spectral line mode. Any spectral line/continuum mix will result in **no data** at all. This is true for both standard observing and for a pointing determination.
4. If an IF (*i.e.* A, B, C, or D) is used in more than one subarray, it must have the same bandwidth in each. (This restriction applies only to spectral line observations).
5. There are only two sets of Fluke synthesizers (the final LOs in the frequency conversion system) – hence, only two subarrays can have completely independent frequency selection. If using two subarrays, notify the operator about your requirements for synthesizer setting – this selection is not made within the observing file. For three or more subarrays, a decision will have to be made on which subarrays will be 'slaved'. This will constrain the frequencies used for bandwidths other than 50 MHz.

Note that tipping scans (used to measure the atmospheric opacity) can be done at any time by any number of subarrays. If any of the above restrictions confuse you, (and we are sympathetic if they do), consult your VLA contact, or talk to Ken Sowiński.

Single-antenna (or multiple-antenna) VLBI programs cause special problems. Such programs use one of the Fluke sets, leaving only one for the remaining four subarrays – these must then share that single Fluke set, or use the same values assigned to the VLBI run. Generally, VLBI Fluke settings are compatible with continuum observing. Fortunately, the

correlator restrictions listed above (points 3 and 4) do NOT apply to the single-antenna VLBI subarrays.

3.9 Positional Accuracy

The accuracy with which an object's position can be determined is limited by the atmospheric phase stability, the closeness of a suitable (astrometric) calibrator, and the calibrator-source cycle time. Under good conditions, in A-configuration, accuracies of about 0.05 arcseconds can be obtained. Under more normal conditions, accuracies of perhaps 0.1 arcseconds can be expected. Under extraordinary conditions (probably attained only a few times per year on calm winter nights in A-configuration when using rapid phase switching on a nearby astrometric calibrator – see Section 3.12.1), accuracies of 1 milliarcsecond have been attained.

If highly accurate positions are desired, only 'A' code (astrometric) calibrators from the VLA Calibrator List should be used. The positions of these sources are taken from lists published by the USNO.

3.10 Imaging Performance

Imaging performance can be limited in many different ways. Some of the most common are:

Image Fidelity: With conventional point-source calibration methods, and even under the best observing conditions, the achieved dynamic range will rarely exceed a few hundred. The limiting factor is the atmospheric phase stability. If the target source contains more than 50 mJy in compact structures (depending somewhat on band), self-calibration can be counted on in improving the images. Dynamic ranges in the thousands can be achieved using these techniques. At this level, the limitations are generally due to errors in the calculation of the correlation coefficient ('closure' errors). Recent (1998) software changes in the VLA's calculation of these coefficients have dramatically reduced the level of these errors for continuum observing, particularly for the narrower bandwidths where these errors were larger.

If the target source is bright enough for dynamic ranges exceeding 10,000 (based on peak/rms thermal noise) to be conceivable, use of one of the spectral line correlator modes should be considered, since the correlator errors which limit the dynamic range are greatly reduced. However, due to inherent limitations in correlator capacity, this will necessarily require a reduction in bandwidth by a factor of at least 4. If the target source is only slightly resolved, use of the continuum mode with phased array observing will reduce the 'closure' errors without loss of bandwidth.

Invisible structures: An interferometric array acts as a spatial filter, so that for any given configuration, structures on a scale larger than the fringe spacing of the shortest baseline will be completely absent. Diagnostics of this effect include dark bowls around extended objects, and large-scale stripes in the image. Table 3 gives the largest scale visible to each configuration/band combination.

Poorly sampled Fourier plane: Unmeasured Fourier components are assigned values by the deconvolution algorithm. While this often works well, sometimes it fails noticeably. The symptoms depend upon the actual deconvolution algorithm used. For the CLEAN

algorithm, the tell-tale sign is a fine mottling on the scale of the synthesized beam, which sometimes even organizes itself into coherent stripes. Further details are to be found in Reference 1.

Sidelobes from confusing sources: At 90 and 20 cm, large numbers of background sources are located throughout the primary antenna beam. Sidelobes from these objects will lower the image quality of the target source. Although bandwidth and time-averaging will tend to reduce the effects of these sources, the very best images will require careful imaging of all significant background sources. The AIPS task **IMAGR** is well suited to this task at $\lambda 20$ cm. The problem at $\lambda 90$ cm is much worse, and is greatly complicated by the non-coplanar nature of the array, as described in Section 3.4.4. Table 3 gives the highest flux density expected of these background sources, and the total background flux density.

Sidelobes from strong sources: Another image-degrading effect is that due to strong nearby sources. Again, the 20 and 90 cm bands are especially affected. The active Sun will be visible to any D configuration daytime spectral line observation at these bands. Even with 50 MHz bandwidth in continuum mode, the active Sun can ruin the short spacings of observations within about 20 degrees of the Sun. The quiet Sun poses a lesser threat, so the general rule is to go ahead and observe, even if the target source is close to the Sun. At 90 cm, observations within approximately 10 degrees of Cygnus A, Cassiopeia A, Taurus A, and Virgo A will be greatly degraded.

3.11 Calibration and the Flux Density Scale

The VLA Calibrator List contains information on 1065 sources sufficiently unresolved and bright to permit their use as calibrators. Copies of the list are distributed throughout the AOC. The list is also available within the **OBSERVE** program and is on the Web (at URL <http://www.nrao.edu/~gtaylor/calib.html>). Also available from this URL is the history since Dec. 1996 of the flux densities of the calibrators.

Accurate flux densities are obtained by observing one of 3C286, 3C147, 3C48 or 3C138 during the observing run. Not all of these are suitable for every observing band and configuration – consult the VLA’s Calibrator Manual for advice. These sources are slowly variable, so we attempt to monitor and update their flux densities when the VLA is in its D-configuration. The VLA’s flux density scale is based on the Baars *et al.* values for 3C295 at all bands except K-band (23 GHz) and Q-band (43 GHz). For these bands, the scale is set by the flux densities of the planets. The planetary nebula NGC7027 is used to link these two scales.

Table 13 shows the flux densities of these sources in February 1998 at our standard bands. Polynomial coefficients have been determined which permit accurate interpolation of the flux density at any VLA frequency. These coefficients are updated approximately every other year, and are implemented into the AIPS task **SETJY**, starting with the July 1996 release.

For most observing projects, the effects of atmospheric extinction will automatically be accounted for by regular calibration when using a nearby point source whose flux density has been determined by an observation of a flux density standard taken at a similar elevation. However, at high frequencies (most notably K-band and Q-band), both the antenna gain and the atmospheric absorption may be strong enough to make ‘simple’ flux density

Table 13: Flux densities of Standard Calibrators for February 1998

Source/Frequency	322	1475	4885	8435	14965	22485	43340
3C48 = J0137+331	42.7	15.46	5.42	3.20	1.75	1.16	0.70
3C138 = J0521+166	19.9	8.09	3.77	2.49	1.54	1.10	0.72
3C147 = J0542+498	53.6	21.31	8.04	4.92	2.87	2.01	1.34
3C286 = J1331+305	26.2	14.41	7.48	5.23	3.42	2.52	1.64
3C295 = J1411+522	60.9	21.36	6.53	3.42	1.62	1.03	0.41
NGC7027	<0.2	1.53	5.49	6.05	5.73	5.50	5.15

The errors in these values are set by the error in the assumed flux densities of 3C295 (assumed to be that given by Baars *et al.* below 15 GHz), and the error in the spectral index of NGC7027 (assumed to be -0.1 above 15 GHz). The errors in the measured ratios are much less than 1%, except at Q-band, where they may be as high as 5%.

bootstrapping unreliable. The AIPS task ELINT is now available to permit actual measurement of an elevation gain curve using your own observations, and subsequent adjustment of the derived gains to remove these elevation-dependent effects. The current calibration methodology does not require knowledge of the atmospheric extinction (since the true flux densities of the standard calibrators are believed known). However, if knowledge of the actual extinction is desired, a simple antenna tipping procedure is available (and is known to the OBSERVE program) which will provide both the vertical extinction and the total system temperature. For advice on these procedures, contact Bryan Butler or Rick Perley.

3.12 Phase Calibration

Adequate phase calibration is a complicated function of source-calibrator separation, frequency, array scale, and weather. And, since what defines adequate for some experiments is completely inadequate for others, it is impossible to define any simple guidelines to ensure adequate phase calibration in general. However, some general statements remain valid most of the time. These are given below.

- Tropospheric effects dominate at wavelengths shorter than 20cm, ionospheric effects dominate at wavelengths longer than 20cm.
- Atmospheric (troposphere and ionosphere) effects are nearly always unimportant in the C and D configurations at L and P bands, and in the D configuration at X and C bands. Hence, for these cases, calibration need only be done to track instrumental changes – once hourly is generally sufficient.
- If your target object has sufficient flux density to permit self-calibration, there is no need to calibrate more than once hourly.
- The smaller the source-calibrator angular separation, the better. In deciding between a nearby 'S' calibrator, and a more distant 'P' calibrator, the former is usually the better choice.
- At high frequencies, and longer configurations, rapid switching between the source and nearby calibrator is often helpful. See the following section.

3.12.1 Rapid Phase Calibration and the Site Testing Interferometer (STiFR)

For some objects, and under suitable weather conditions, the phase calibration can be considerably improved by rapidly switching between the source and calibrator. A new observing technique, denoted ‘fast switching’, has been developed to more conveniently permit the user to implement this methodology. Source-Cal observing cycles as short as 40 seconds can now be used – such a short cycle is impossible with standard observing techniques.

This method is not for everyone! Considerable integration time is lost with very short cycle times, so it is important to balance this certain loss against a realistic estimate of the possible gain. Experience has shown that cycle times of 100 to 150 seconds have been effective for source-calibrator separations of less than 10 degrees. The fast switching technique ‘stops’ tropospheric phase variations at an effective baseline length of $\sim v_a t/2$ where v_a is the atmospheric wind velocity aloft (typically 10 to 15 m/sec), and t is the total switching time. This technique has been demonstrated to result in images of faint sources with diffraction-limited spatial resolution on the longest VLA baselines. Under average weather conditions, and using a 120 second cycle time, the residual phase at 43 GHz should be reduced to ≤ 30 degrees. Further details can be found in VLA Scientific Memos # 169 and 173. These memos, and other useful information, can also be obtained through the NRAO Web page (<http://www.nrao.edu/>). Click on ‘VLA’, then on ‘Special Topics/Observing Modes’, then on ‘7mm’.

The fast switching system has been implemented in the current version of the `OBSERVE` program. Note that the technique will not work in bad weather (such as rain showers, or when there are well-developed convection cells – most notably, thunderstorms). Contact Chris Carilli for details and advice.

The NRAO site testing interferometer (STiFR) is now operational at the VLA, and software has been installed for real time monitoring of the phase stability through the web. This can be accessed through the NRAO home page (www.nrao.edu) by following the link to the Phase Monitor located on the VLA page. The STiFR continuously measures the tropospheric contribution to the interferometric phase using an interferometer comprised of two 1.5 meter antennas separated by 300 meters, observing an 11.3 GHz beacon from a geostationary satellite. The STiFR data can be used to estimate the required calibration cycle times when using fast switching phase calibration, and in the worst case, to indicate to the observer that high frequency observing may not be possible with current weather conditions. Contact Chris Carilli for further details.

3.13 Polarization

The continuum correlator mode provides full polarimetric information for both observing frequencies. The polarimetric spectral line modes (PA and PB) are also available for observations of linearly polarized spectral lines, or for observations of continuum objects where large field-of-view or high dynamic range is necessary. Spectral line modes ‘2AC’, ‘2BD’, and ‘4’ provide only circular polarization information.

For each observation requiring polarization information, the instrumental polarization should be determined through observations of a bright calibrator source spread over a range in parallactic angle. In nearly all cases, the phase calibrator chosen can double as a polarization calibrator. The minimum condition that will enable accurate polarization calibration is four observations of a bright source spanning at least 90 degrees in parallactic

angle. The accuracy of polarization calibration is generally better than 0.5% for objects small compared to the antenna beamsize. At least one observation of 3C286 or 3C138 is required to fix the absolute position angle of polarized emission. 3C48 can also be used to fix the position angle at wavelengths of 6cm or shorter.

High sensitivity linear polarization imaging may be limited by time dependent instrumental polarization, which can add low levels of spurious polarization near features seen in total intensity and can scatter flux throughout the polarization image, potentially limiting the dynamic range. The instrumental polarization averaged among all baselines can vary by 0.3% on timescales of minutes to hours, limiting the believable fractional polarization to about 0.1%.

Wide field linear polarization imaging will be limited by the instrumental polarization beam. For a snapshot observation, the spurious linear polarization (after the standard polarization correction for the on-axis polarization response is applied) is $< 1\%$ at angles less than $\lambda/4D$ radians (D is the antenna diameter), is 1 - 3% at $\lambda/2D$, and increases sharply beyond this, reaching 10% at $3\lambda/4D$. Since the instrumental polarization response is directed radially and rotates with parallactic angle, the spurious polarization will tend to average down for long integrations. However, if the object being observed is very bright, and has a low degree of linear polarization, errors in the polarization calibration will cause flux to be scattered across the polarization image, limiting the polarization dynamic range.

Ionospheric Faraday rotation is always present at 20 and 90 cm. The typical daily maximum rotation measure under quiet solar conditions is 1 or 2 radians/m², so the ionospherically-induced rotation of the plane of polarization at these bands is not excessive - 5 degrees at 20cm, and perhaps 90 degrees at 90cm. However, under active conditions, this rotation can be many times larger, such that accurate polarimetry is impossible at 20cm.

The approximate correction scheme available within the AIPS task FARAD cannot be recommended - it employs an overly-simple uniform ionospheric model and requires TEC (Total Electron Content) data in a format which has not been available for the last five years. A promising new method employing GPS satellites and a more sophisticated model is being developed, and should be generally available by early 1999. Test programs running under AIPS and data from local GPS receivers are available for observers. Contact Rick Perley or Chris Flatters for advice.

Circular polarization measurements are limited by the beam squint - the RCP and LCP primary beams are separated by 6 percent of the beamwidth along the axis perpendicular to the azimuth of the secondary focus feed position. Since circular polarization is determined from the difference between RCP and LCP signals, there results an appreciable error in all measurements of circular polarization off the pointing axis. The effect is large - the apparent circular polarization is $\sim 10\%$ at $\lambda/4D$, and $\sim 20\%$ at $\lambda/2D$. This false circular polarization is antisymmetric with respect to the center of the antenna beam, so 12-hour observations should partially cancel out the effect - however, even so, the residual apparent circular polarization is probably only accurate to a few percent.

3.14 Spectral Line Modes

The VLA correlator is very flexible, and can provide data in many ways. The various spectral line modes currently available are shown in Tables 14 and 15 and described below.

Most spectral line modes are distinguished by a code comprising a number followed by

Table 14: Available bandwidths and number of spectral line channels in normal mode

BW Code	Bandwidth MHz	Single IF Mode ⁽¹⁾		Two IF Mode ⁽²⁾		Four IF Mode ⁽³⁾	
		No. Channels ⁽⁴⁾	Freq. Separ. kHz	No. Channels ⁽⁴⁾ per IF	Freq. Separ. kHz	No. Channels ⁽⁴⁾ per IF	Freq. Separ. kHz
0	50	16	3125	8	6250	4	12500
1	25	32	781.25	16	1562.5	8	3125
2	12.5	64	195.313	32	390.625	16	781.25
3	6.25	128	48.828	64	97.656	32	195.313
4	3.125	256	12.207	128	24.414	64	48.828
5	1.5625	512	3.052	256	6.104	128	12.207
6	0.78125	512	1.526	256	3.052	128	6.104
8	0.1953125	256	0.763	128	1.526	64	3.052
9	0.1953125	512	0.381	256	0.763	128	1.526

Notes:

(1) Observing Modes 1A, 1B, 1C, 1D.

(2) Observing Modes 2AB, 2AC, 2AD, 2BC, 2BD, 2CD.

(3) Observing Modes 4, PA, PB. It is possible to use the output from one, two or four IFs in such a way as to obtain different combinations of number of spectral line channels and channel separation. The minimum and maximum number of channels is 4 and 512 respectively.

(4) These are the numbers of spectral line channels produced in the array processor. Any number of spectral line channels that is a power of 2, that is less than or equal to the number in the table and that is greater than or equal to 2 may be selected using the data selection options available within the OBSERVE program.

Table 15: Available Bandwidths and Number of Spectral Line Channels in Hanning Smoothing Mode

BW Code	Bandwidth MHz	Single IF Mode ⁽¹⁾		Two IF Mode ⁽²⁾		Four IF Mode ⁽³⁾	
		No. Channels ⁽⁴⁾	Freq. Separ. kHz	No. Channels ⁽⁴⁾ per IF	Freq. Separ. kHz	No. Channels ⁽⁴⁾ per IF	Freq. Separ. kHz
0	50	8	6250	4	12500	2	25000
1	25	16	1562.5	8	3125	4	6250
2	12.5	32	390.625	16	781.25	8	1562.5
3	6.25	64	97.656	32	195.313	16	390.625
4	3.125	128	24.414	64	48.828	32	97.656
5	1.5625	256	6.104	128	12.207	64	24.414
6	0.78125	256	3.052	128	6.104	64	12.207
8	0.1953125	128	1.526	64	3.052	32	6.104
9	0.1953125	256	0.763	128	1.526	64	3.052

Notes:

(1) Observing Modes 1A, 1B, 1C, 1D.

(2) Observing Modes 2AB, 2AC, 2AD, 2BC, 2BD, 2CD.

(3) Observing Modes 4, PA, PB.

(4) These are the numbers of spectral line channels produced in the array processor. Any number of spectral line channels that is a power of 2, that is less than or equal to the number in the table, and that is greater than or equal to 2 may be selected using the data selection parameters available in the OBSERVE program.

zero, one, or two letters. The number refers to the number of spectra being produced; the letters describe which IF channels are involved. Recall that each VLA antenna returns four signals: these are the RCP and LCP for each of two separately tuned frequencies. These signals are referred to as *IFs*, and are named A, B, C, and D. The first two represent RCP,

and latter two LCP. IFs A and C are at one frequency (and cannot be different); B and D are at another (and also must be the same). In normal usage, the AC pair and the BD pair are at different frequencies within the same band. The spectral line modes can subdivide these IFs into four to 512 units, evenly spaced in frequency across the bandwidth of the input IF. These narrower units are referred to as *spectral line channels*. In addition to these interferometric spectra, autocorrelation spectra for all antennas are produced.

The single-IF modes provided by the spectral line correlator are known as 1A, 1B, 1C, and 1D. In these modes, only one spectrum is produced. These modes give the highest spectral resolution at any given bandwidth. The dual-IF modes are denoted 2AB, 2AC, 2AD, 2BC, 2BD and 2CD, and provide spectral information for the two IFs named (*e.g.* mode 2AC provides AA and CC correlations). Linear polarization measurements are not possible with these modes, but circular polarization can be determined using the 2AC and 2BD modes. The four-IF modes are known as 4, PA and PB. The first of these provides spectra for all four IFs. Circular, but no linear polarization measurements are possible in this mode. The other two modes provide full polarimetric information – PA provides this for the A and C IFs (that is, it performs the correlations AA, AC, CA, and CC, providing a spectrum for each), PB for the B and D IFs. Note that for these polarimetric modes, the descriptor 4 is omitted. The characteristics of all of these modes are summarized in Tables 14 and 15.

It is also possible to use multiple, independent subarrays in spectral line mode.

Correlator modes 2AB, 2AD, 2BC and 4 allow the IFs to use different bandwidths as well as to be tuned to different frequencies within the same band (*e.g.*, mode 2AB will permit the AA correlations to be at a different frequency and bandwidth than the BB correlation). There are other restrictions. See Section 3.8, and the Spectral Line Users' Guide (listed in Chapter 6) for details.

Of central interest to observers is the stability of the spectra. Spectral line dynamic range is commonly defined as the ratio of the continuum brightness to the minimum detectable line brightness in an image. This ratio is limited by instrumental effects which must be calibrated out. The spectral dynamic range depends on bandwidth in a poorly understood way. Applying the on-line autocorrelation bandpass correction only should result in about 50:1 dynamic range and is strongly discouraged. Values exceeding 10,000:1 at C and X-bands can be achieved but it requires careful data editing and bandpass calibration. A more typical limit is around 1,000:1. L-band spectral dynamic ranges of 1000:1 can be achieved by observing a suitable bandpass calibrator. Consult with Michael Rupen for more details.

Consult "A Guide for VLA Spectral Line Observers" for more information. This document is available for downloading from the NRAO website – follow the link to 'VLA', then to 'Documentation'.

3.15 VLBI Observations

The VLA often participates in VLBI observations with the VLBA, and in Global Network sessions which occur four times per year. The VLA supports VLBI observations in either single-antenna or phased-array modes. Data can be recorded in VLBA or Mark III/IV formats. Each type of recording makes use of the VLA's VLBA data acquisition system. A comprehensive document entitled "VLBI at the VLA" is available on the Web – point your browser to the NRAO Home Page (<http://www.nrao.edu/>), select 'VLA', then 'Documentation'.

VLBI at the VLA is overseen by Greg Taylor and Joan Wrobel. Either can be consulted

for general information regarding matters such as observing in VLBA or Mark III/IV formats; phased-array or single-dish observations; or calibration of the VLA for VLBI. However, each VLBI project involving the VLA, whether run during or outside of a Network session, will be assigned an AOC contact by Barry Clark. Queries from an observer concerning specific information about a specific project should be directed to the AOC contact assigned to the project. If the project's principal investigator is an AOC employee, then that person will be assumed to be the AOC contact.

See Section 4.12 for information on absentee observing.

3.16 Snapshots

The two-dimensional geometry of the VLA allows a snapshot mode whereby short observations can be used to image relatively bright unconfused sources. This mode is ideal for survey work where the sensitivity requirements are modest. Due to confusion by background sources, use of snapshots is not recommended at $\lambda 90$ cm or $\lambda 400$ cm.

Single snapshots with good phase stability should give dynamic ranges of a few hundred. Note that because the snapshot synthesized beam contains high sidelobes, the effects of background confusing sources are much worse than for full syntheses, especially at 20 cm in the D configuration for which a single snapshot will give a limiting noise of about 0.2 mJy/beam. This level can be reduced by taking multiple snapshots separated by at least one hour. Use of the AIPS program `IMAGR` is necessary to remove the effects of background sources. Note that the all-sky surveys undertaken by the VLA should make future snapshot observations at L-band unnecessary, except perhaps for variable sources, or for observations in the A-configuration. Information on the all-sky surveys (including the images and the source lists) can be obtained via the Web from the NRAO home page: URL <http://www.nrao.edu/>.

3.17 Shadowing and Cross-Talk

Observations at low elevation in the C and D configurations will commonly be affected by shadowing. It is strongly recommended that all data from a shadowed antenna be discarded. This will automatically be done within the AIPS task `FILLM` when using the default inputs. Note that `FILLM` is ignorant of antennas in other subarrays, or antennas which are out of the array, so flagging of antennas shadowed by antennas in other subarrays will not occur.

Cross-talk is an effect in which signals from one antenna are picked up by an adjacent antenna, causing an erroneous correlation. At $\lambda 20$ cm, this effect is important principally in the D configuration. At $\lambda 90$ cm, C and even B configurations can also be affected. And at $\lambda 400$ cm, all configurations show strong cross-talk on many baselines. Careful editing is necessary to identify and remove this form of interference. For the 90 and 400 cm bands, use of the spectral line modes is strongly recommended to allow detection and removal of these contaminating signals.

3.18 Combining Configurations and Mosaicing

Any single VLA configuration will allow accurate imaging up to a scale approximately 30 times the synthesized beam. Objects larger than this will require multiple configuration observations. Observers only need ensure that the frequencies used are similar for each configuration. It is not necessary that they be identical, but differences greater than 50 MHz could cause errors due to spectral index gradients. The different configurations may

employ different bandwidths - indeed, this is often required to prevent bandwidth smearing (chromatic aberration). Objects larger than the primary antenna pattern may be mapped through the technique of interferometric mosaicing. Time-variable structures (such as the nuclei of radio galaxies and quasars) cause special, but manageable, problems. Consult with Tim Cornwell for details and advice.

3.19 Pulsar Observing, Gated Correlator, and the High Time Resolution Processor

The VLA's correlator supports gated observations (*i.e.*, the correlator is on only when the pulsar's pulse is on) to enhance the SNR for pulsar observing. Note, however, that the software changes implemented for support of full complex correlation and the upcoming 70 MHz continuum bandwidth have temporarily disabled gated correlator observations when in the continuum mode. Observers wishing to use this feature when observing in the continuum mode must contact Ken Sowinski to ensure that an older version of the Modcomp operating software is running.

The High Time Resolution Processor (HTRP) is a 14-channel polarimeter designed for observations of short timescale phenomena such as pulsars and flare stars. The HTRP has been used successfully in pulsar polarimetry, pulsar searches, and pulsar timing. The HTRP directs two, oppositely polarized input signals from the VLA analog sum ports through a 14-channel filter bank. The bandwidth of each input channel can be set to 0.125, 0.25, 0.5, 1.0, 2.0, or 4.0 MHz. The HTRP provides full polarimetry, producing a total of 56 detected outputs.

The integration times for each output can be individually set to between 25 and 5000 microseconds, and the detector outputs can be individually offset by $\pm 5V$. The maximum aggregate sample rate is about 200 kilo-samples per second, so the minimum sampling interval for each channel is about 5 microseconds multiplied by the number of sampled channels. The HTRP is controlled by an IBM compatible PC, and the sampled data are written to the PC hard disk or Exabyte tape. Current versions of monitor and control software and data acquisition software are adequate for general use. Observers interested in using the HTRP should plan on investing some time in developing their own data analysis software. The Princeton MkIII Timing System, although not supported by the NRAO, is available for general use. It accepts 32 outputs from the HTRP detectors for time-stamped synchronous signal averaging at aggregate sampling rates up to about 2.5 MHz. For further information regarding the HTRP, contact Dale Frail or Tim Hankins.

The HTRP is a complicated, special purpose instrument, requiring special hardware and software settings. Observers using the HTRP are therefore advised to come to the telescope at least one full day, and preferably two, in advance of their observing runs.

3.20 Observing High Flux Density Sources – Special Corrections

The VLA correlator is a digital device, which causes a small but noticeable error in the calculation of the correlation coefficient when this coefficient is high. A recent change to the AIPS program FILLM now enables an approximate correction of this error when observations are taken in the continuum mode. Users may wish to apply this correction (commonly known as the 'Van Vleck' correction) when observing relatively unresolved objects with flux densities exceeding about one hundred Jy (depending on band). Unfortunately, no correction for this effect for data taken in the spectral line modes is yet available.

4 USING THE VLA

4.1 Obtaining Observing Time on the VLA

Observing time on the VLA is available to all researchers, regardless of nationality or location of institution. There are no quotas or reserved blocks of time. The allocation of observing time on the VLA is based upon the submission of a VLA Observing Application Form obtainable at any NRAO office, or via anonymous ftp as described below. The form consists of a cover sheet whereon the proposer must summarize all technical details of the observations, and an appended, self-contained, scientific justification of the project not to exceed 1000 words in length. Proposals may be sent either by regular mail, or by electronic mail if in Adobe Postscript format.

If submitted by regular mail, send the complete observing request (cover sheet plus appended justification) to:

Paul A. Vanden Bout
Director, NRAO
Edgemont Road
Charlottesville, VA 22903-2475.

Please allow suitable time for delivery – a week from the U.S., two weeks from outside the U.S. If using UPS, Fedex, or other private delivery service, it is suggested you allow an extra two days over the vendor’s promised delivery date.

These forms can be obtained in a TeX version via anonymous ftp from the ftp server ftp.cv.nrao.edu (192.33.115.50). Login as “anonymous”, and use your e-mail address as the password. In the subdirectory ‘proposal’ are found a number of files: the files ‘instructions’ contains a detailed up-to-date set of instructions. The file ‘covervla.ps’ contains a postscript version of the VLA application form, which you may copy, print, and submit through the regular mail.

For electronic submission, copy the files ‘covervla.tex’, and ‘nraologo.ps’ to your computer. Edit the former file, inserting the details of your proposal, then run your TeX compiler. E-mail the finished postscript version to: propsoc@nrao.edu. This e-mailed postscript file must be printable on our systems – if it cannot be printed, it won’t be accepted. We will acknowledge the successful printing of received proposals, and will work with proposers to modify those files which are received but did not print successfully, if the file is received at least 5 days before the actual deadline. If your default paper size is not US standard, take care to override your default in your submission.

Submissions by FAX are no longer accepted.

The VLA is scheduled on a term basis, with each term lasting 4 months. The proposal deadline for a particular configuration is 5PM, Eastern time on the 1st of February, June, or October which precedes the beginning of that configuration by three months or more. (If the first of the month falls on a Saturday or Sunday, the deadline is advanced to the next Monday). Table 1 details the deadlines through 2000. It is not necessary to submit a proposal in the preceding term, since all proposals will be refereed immediately following the deadline of submission, regardless of the configuration requested. Early submissions – more than one deadline in advance of the relevant configuration deadline – will benefit from referee feedback and the opportunity for revision and additional review if warranted.

All proposals are externally refereed by several experts in relevant subdisciplines (e.g. solar system, stellar, galactic, extragalactic, etc.). The referees’ comments and rating are advisory to the internal VLA scheduling committee, and the comments of both groups are

passed on to the proposers soon after each meeting of the committee (3 times yearly) and prior to the next proposal submission deadline.

A special refereeing process has been established for proposals requesting an unusually large amount of time - approximately 300 hours for the VLA. Details of this process will be found on the web.

Scheduling the telescope is a non-exact science, and because of competition even highly rated proposals are not guaranteed to receive observing time. This is particularly true for programs that concentrate on objects in the LST ranges occupied by popular targets such as the galactic center or the Virgo cluster.

4.2 Target-of-Opportunity Observations

The NRAO provides a means by which observations can be scheduled on the VLA on quite short notice. Observations of order one hour, for the current configuration, can often be fitted into the established schedule in the interstices between allocated projects. To obtain such an observation, send a request to Barry Clark (bclark@nrao.edu), giving the object name, position, and a brief justification of why an observation on short notice is required. The requestor must be prepared to provide an observe file on short notice. Note that the data resulting from this must be reduced by the requestor following the usual procedures.

4.3 Data Analysts and General Assistance

General assistance of all kinds is available through the Data Analysts. They can be considered to be advocates for all VLA users, and should be consulted first when you encounter any problem. Note that they are not available to perform remote data calibration. The e-mail address for all the analysts is: analysts@nrao.edu. Contact the head of this group, Meri Stanley (505 835 7238), when you have questions or requests.

4.4 Observing File Preparation

To use the VLA an observing file must be prepared and submitted to the VLA Operators. This file may be generated by the NRAO-supplied program **OBSERVE**, which is available to all users and can run on a wide variety of machines. We recommend that all users obtain a copy of this program, and periodically check that they have the latest version. The latest version is 4.0.3, dated 23 December, 1997.

At this time, **OBSERVE** is available for Sun and IBM RS6000 workstations and PCs under LINUX. Coming soon will a version for SGI. Tentative plans remain for a version for Dec Alpha workstations.

OBSERVE can be obtained by one of these routes - listed in order of preference:

1. For users with Internet access; for SUN and IBM versions, use anonymous ftp from directory pub/observe on ftp.aoc.nrao.edu (or 146.88.1.103).
2. Telephone Gayle Rhodes and specify the machine type (SUN, IBM, PC/LINUX) and medium (disc, floppy, Exabyte, or DAT), which she will then mail to you.

A considerable training effort is required to become fully conversant with **OBSERVE**. For help, call the Data Analysts head, Meri Stanley, or through E-mail (analysts@nrao.edu).

After your file is prepared, E-mail it to the operators at observe@nrao.edu. Include the program name in the subject line. The operators always acknowledge receipt of the

observing file by e-mail. If you do not receive a timely response, call the operators at 505 835 7180. Please complete these operations at least two working days before your observing.

4.5 The Observations and Remote Observing

Observers need not be present at the VLA to obtain VLA data. However, we encourage VLA users to come to Socorro when observing. There is no better way to interact with the data, and to calibrate and image data quickly. And coming to Socorro is the best way to benefit from discussions with staff members.

We recommend that observers who are coming to and who intend to set up their observing files in Socorro arrive two days before their scheduled observations to allow sufficient time to interact with key staff members. See Section 4.9 for information on coming to and staying in Socorro.

For those who choose to process their data at home, the data analysts will, upon request, mail you a tape (Exabyte or DAT) containing your uncalibrated data in its original Modcomp format. The AIPS task FILLM is used to load these data to disk. For short observations requiring fast turnaround, the data analysts will load your data in FITS format onto a local machine, from where you may transfer the data through ftp to your home computer. Contact the Data Analysts for this service.

4.6 Travel Support for Visiting the AOC and VLA

The NRAO will subsidize travel expenses incurred by a visiting observer to Socorro. Individuals eligible for reimbursement are those employed by a U.S. academic or research institution who do not receive their salary from any U.S. government agency including NSF, NASA, DOE, etc. Individuals affiliated with foreign institutions are not eligible. The subsidy applies only to travel originating from within the U.S. (including Puerto Rico and the U.S. territories), and covers air fare only.

For each observing program scheduled on an NRAO telescope, reimbursement may be requested for one of the scientific investigators to travel to the NRAO to observe, and for one of the investigators to come to reduce data. Allowance will be made for two observers on a single proposal when one of these is a student coming to the NRAO for the first time, and the other is his or her research advisor.

The reimbursement is the actual cost of economy air fare in excess of \$150 for air fare up to \$300, and is \$150 plus 75% of the airfare in excess of \$300 for air fares over \$300, and will be made only to the traveller's institution.

To claim this reimbursement, obtain an expense voucher from Betty Trujillo in the Assistant Director's office (Rm 338).

4.7 Real-Time Observing

A Sun Sparc 20 workstation, connected to the on-line computers by an Ethernet link, is now in place at the VLA site. A special version of the AIPS task FILLM will fill VLA data into this workstation's disks. Each scan is available for editing, calibration, and imaging within a few seconds of the end of that scan. Data can also be written to a local Exabyte tape. All regular AIPS tasks are available on this workstation.

The real-time data pipeline has now been extended to the AOC. Any workstation at the AOC can now receive VLA data as it is produced by the Modcomps. However, this capacity is not available beyond the AOC, as tests have given inconsistent results.

4.8 Computing at the AOC

A primary goal of the computing environment at the AOC is to allow every user full access to a workstation during his/her visit. There are 14 public workstations available at the AOC for full-time data reduction by visitors. Of these, two are Sparc 20s, 5 are Sparc Ultra 1s, 6 are Sparc Ultra 2s, and two are SGI machines designated exclusively for space VLBI use.

For hardcopy, we have a number of laser printers, including a color Postscript laser printer which can reproduce on both paper and transparencies. Our Solitaire film recorder has been decommissioned, but exposures of images on the Charlottesville Solitaire can be done from the AOC.

Visitors may reserve time on these workstations when they make their travel arrangements with the Reservationist, Selfa Lucero (see Section 4.9). The reservationist's e-mail is: nmreserv@nrao.edu. Meri Stanley schedules all public computers.

If you require UNIX assistance while at the AOC, please e-mail 'nmhelpdesk', dial 7213, or go to room 267.

For a fuller description of computing facilities at the AOC, access the NRAO home page with your favorite Web browser (URL <http://www.nrao.edu/>), and press the 'Socorro' link.

4.9 Reservations for VLA and/or AOC

Advance contact with the Reservationist (Selfa Lucero - nmreserv@nrao.edu) at least 1 week prior to your visit to the NRAO/NM is required, and 2 weeks' notice is preferred, in order to optimize the logistics of room occupancy, transportation, computer load, and staff assistance. You may now book your visit to the AOC through the WWW. From the NRAO Home Page, press the 'Socorro' link, then the 'Visitor's Registration Form' link.

First time visiting students will be allowed to come to the NRAO/NM for observations or data reduction only if they are accompanied by their faculty advisor, or if they have a collaborating NRAO staff member.

4.10 Staying in Socorro

Visitors to Socorro can now take advantage of the NRAO Guest House. This facility contains 8 single, 4 double, and 2 two-bedroom apartments, plus a lounge/kitchen, terminal facility, and full laundry facilities. The Guest House is located on the NMIMT campus, a short walk from the AOC. Reservations are made through the Reservationist, Selfa Lucero (nmreserv@nrao.edu.)

4.11 Help for Visitors to the VLA and AOC

We encourage observers to come to Socorro to calibrate and image their data. This is the best way to ensure the quickest turnaround and best results from their observing. While in Socorro, each observer will interact with members of the AOC staff in accordance with his/her level of experience and the complexity of the observing program. If requested on the original VLA application form, the visiting observer will be guided through the steps of data calibration and imaging by a prearranged staff friend or scientific collaborator. Data Analysts and the computer operations staff are also available for consultation on AIPS procedures and systems questions.

4.12 VLBI Remote Observing

The VLA supports absentee VLBI observations, whether conducted during, or outside of, a Global Network session. Queries from an absentee observer concerning a specific project should be directed to the AOC contact assigned to that project (see Section 3.15). VLA schedule file preparation assistance is provided by the Data Analysts (see Section 4.3). Absentee observers must provide the Data Analysts with all necessary scheduling information. For a Network project, this information is due at least two weeks before the start of the appropriate Network session. For a non-Network project, this information is due by the schedule file due date assigned by Barry Clark.

Although VLA Operations fully supports absentee VLBI observing, visits by observers are welcomed and are especially encouraged if the observations are in any way atypical. Included in this category are VLBI spectral line projects regardless of recording format, and any phased-array VLBI projects for which radio frequency interference is expected.

For more information, consult "VLBI at the VLA".

4.13 VLAPLAN

VLAPLAN and VLAUVPL are MS-DOS PC-based tools to help continuum and line observers design VLA proposals and observing strategies.

VLAPLAN does basic calculations needed when designing an observation to produce a given image quality and sensitivity within the restrictions imposed by the VLA hardware. VLAPLAN is a spreadsheet that lets you adjust imaging parameters interactively while seeing their consequences for VLA configuration selection, bandwidth, total integration time and other critical parameters. The program warns of conflicts between the imaging parameters and the VLA's hardware capabilities, and suggests strategies for removing such conflicts. It also plots context-sensitive graphs of the bandwidth and time-average smearing effects, primary beam correction and Gaussian source visibilities. For L Band observing, it warns of conflicts with persistent RFI signals.

VLAPLAN has menu-based documentation to guide your choice of parameters and to help you learn its capabilities. It consolidates numerous graphs and algorithms that are useful when designing observations but which originate from many different documents. These documents include the lecture "Synthesis Observing Strategies" from the NRAO Summer Schools on Synthesis Imaging, VLA Scientific and Test Memoranda, the NRAO Newsletter, the VLA Observational Status Report and the Introduction to the NRAO VLA (the "Green Book").

Starting with Version 2.0 (May 1994), VLAPLAN is available as a stand-alone MS-DOS executable that does not require a separate spreadsheet program as a host. It is still available as a worksheet template that can be run under Lotus 1-2-3, Borland Quattro, or any other spreadsheet program that reads Lotus .WK1 format and macros. The stand-alone and worksheet forms of VLAPLAN use the same menus to lead you through the basic calculations and to document the required input parameters. VLAPLAN can therefore be used without much prior experience of spreadsheets.

VLAPLAN recommends the most compact configuration for your observing based only on the observing frequency and the largest angular size and declination of your source. To do this quickly, it uses a table of the shortest projected baselines in snapshots on the meridian. VLAUVPL is an ancillary program to help you choose configurations and sampling for longer observations. It plots u,v tracks for the innermost and outermost antennas, and

other graphs that help you refine your choice of configuration when working off-meridian. It is also available both as a stand-alone program and as a worksheet template.

Both programs and their documentation can be obtained by anonymous-ftp from the /pub/vlaplan directory on ftp.aoc.nrao.edu. Paper documentation is available as VLA Computer Memorandum No. 187, which can be obtained by contacting Gayle Rhodes.

4.14 On-Line Information about the NRAO and the VLA

NRAO-wide information is available on the World Wide Web through your favorite Web browser at URL: <http://www.nrao.edu/>. VLA- and AOC-specific information are available from the Home Page. We strongly recommend usage of this on-line service, which is regularly updated by Michael Rupen.

5 MISCELLANEOUS

5.1 VLA Archive Data

An INGRES-based archive system has been developed which provides a complete accounting of all VLA observations. This archive is accessible from the NRAO Home Page. As of 1 Oct., 1998, all past observations which are recoverable are listed in this database.

The program and data lists are available by anonymous ftp to ftp.aoc.nrao.edu in the pub/vlasors subdirectory. It is also available on-line in the VLA information system (see Section 4.14).

Archive data taken prior to 1988 cannot be read by the AIPS task FILLM. A general-purpose program has been developed to reformat all old data. To obtain reformatted tapes of archive data, contact the Data Analysts.

The NRAO has just completed a major project of converting all of the old VLA data to the current, modern data format, and archiving it on high density Exabyte tapes. A comprehensive catalog of all VLA data taken since 1976 is now available. A program to access this catalog is available on the WWW, and is found on the NRAO Home Page, in the column entitled 'Astronomical Tools' (or, go directly to URL <http://www.nrao.edu/doc/vladb/VLADB.html>).

NRAO has the following policy on the extent to which an observing team has exclusive use of the raw data obtained as part of their VLA observations:

Eighteen months after the end of a VLA observation the raw (uncalibrated visibility) data will be made available to other users on request. Miller Goss or Barry Clark must first be notified. The end of an observation is defined to be after the last VLA configuration requested, either in the original proposal or in a direct extension of the proposal. VLA correlator data taken for VLBI observations are immediately available to all.

5.2 Publication Guidelines

5.2.1 Acknowledgement to NRAO

Any papers using observational material taken with NRAO instruments (VLA or otherwise) or papers where a significant portion of the work was done at NRAO, should include the following acknowledgement to NRAO and NSF:

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

5.2.2 Preprints

NRAO requests that you submit four copies of all papers which include observations taken with any NRAO instrument or have NRAO author(s) to Ellen Bouton in the Charlottesville Library. NRAO authors may request that their papers be included in the official NRAO preprint series. Multiple author papers will not be included in the series if they are being distributed by another institution. All preprints for distribution should have a title page that conforms to the window format of the NRAO red preprint covers. Note that preprints will be distributed ONLY when the NRAO author so requests; inclusion in the series is not automatic. This action will also cause the paper to be included in NRAO's publication lists.

We encourage everyone whose papers have an NRAO staff author or include original results from any NRAO telescope(s) to consider adding the electronic full text of their preprints to the NRAO WWW preprint page. For further information, contact the Librarian in Charlottesville (library@nrao.edu) or read the instructions to authors on the WWW page (http://www.cv.nrao.edu/library/intro/author_inst.html).

5.2.3 Reprints

NRAO no longer distributes reprints, but will purchase the minimum number of reprints for NRAO staff members. The NRAO does not want reprints, and will not pay for any reprint costs for papers with no NRAO staff author.

5.2.4 Page Charge Support

The following URL contains complete information on the observatory's policy regarding page charge support: http://www.cv.nrao.edu/library/intro/page_charges.html. The following is a summary:

- When requested, NRAO will pay the larger of the following:
 - 50% of the page charges reporting original results made with NRAO instrument(s) when at least one author is at a U.S. scientific or educational institution.
 - 100% of the page charges prorated by the fraction of authors who are NRAO staff members.
- Page charge support is provided for publication of color plates.
- To receive page charge support, authors must comply with all of the following requirements:
 - Include the NRAO footnote in the text: “The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.”
 - Send four copies of the paper prior to publication to Ellen Bouton in Charlottesville.

- Notify Ellen Bouton in Charlottesville of the proposed date of publication and apportionment of page charges so that the necessary purchase orders may be initiated. Convenient ways to do this are to send her copies of the completed page charge form, or send her an e-mail message (library@nrao.edu), or call her by telephone at (804)-296-0254.

When filling out page charge forms, use the following information:

- Contact person for NRAO is Ellen Bouton, 804-296-0254.
- Billing address for both page charges and reprints is NRAO Fiscal Division at the Charlottesville address: 520 Edgemont Road, Charlottesville, VA 22903-2475.
- Shipping address for reprints should be the NRAO author.
- On ApJ and AJ forms, cite the purchase order number as “NRAO blanket PO”. For all other publications, contact Ellen Bouton for a purchase order number.

6 DOCUMENTATION

Documentation for VLA data reduction, image making, observing preparation, etc., can be found in various manuals. Some manuals are available on-line via the World Wide Web (see Section 4.14). Those manuals marked by an asterisk (*) can be mailed out upon request, or are available for downloading from the NRAO WWW site. Direct your requests for mailed hardcopy to Gayle Rhodes. Many other documents of interest to the VLA user, not listed here, are available from our website.

1. **PROCEEDINGS FROM THE 1988 SYNTHESIS IMAGING WORKSHOP:** Synthesis theory, technical information and observing strategies can be found in: “Synthesis Imaging in Radio Astronomy”. This collection of lectures given in Socorro in June 1988 has been published by the Astronomical Society of the Pacific as Volume 6 of their Conference Series. This book has recently been reprinted.
2. **PROCEEDINGS FROM THE 1998 SYNTHESIS IMAGING WORKSHOP:** The lectures from the most recent summer school are now being assembled into a separate volume, which will be published by the Astronomical Society of the Pacific during 1999.
3. **INTRODUCTION TO THE NRAO VERY LARGE ARRAY (Green Book):** This manual has general introductory information on the VLA. Topics include theory of interferometry, hardware descriptions, observing preparation, data reduction, image making and display. Major sections of this 1983 manual are now out of date, but it nevertheless remains the best source of information on much of the VLA. Copies of this are found at the VLA and in the AOC, but no new copies are available. Much of this document is available for downloading through the NRAO’s website.
4. ***A SHORT GUIDE FOR VLA SPECTRAL LINE OBSERVERS:** This is an important document for those wishing to carry out spectral-line observations with the VLA. The revised, 1995 version now available.

5. *AIPS COOKBOOK: The "Cookbook" description for calibration and imaging under the AIPS system can be found near all public workstations in the AOC. The latest version has expanded descriptions of data calibration imaging, cleaning, self-calibration, spectral line reduction, and VLBI reductions. The AIPS COOKBOOK is now produced in a ring binder format for greater ease of updating.
6. *GOING AIPS: This is a two-volume programmers manual for those wishing to write programs under AIPS. It is now somewhat out of date.
7. *VLA CALIBRATOR MANUAL: This manual contains the list of VLA Calibrators in both 1950 and J2000 epoch and a discussion of gain and phase calibration, and polarization calibration.
8. *VLBI AT THE VLA. Everything you ever wanted to know about VLBI at the VLA.
9. *The Very Large Array: Design and Performance of a Modern Synthesis Radio Telescope, Napier, Thompson, and Ekers, Proc. of IEEE, 71, 295, 1983.
10. *OBSERVE, A GUIDE FOR SPECTRAL LINE OBSERVERS. A tutorial manual for observers, with special emphasis on spectral line applications.
11. THE VLA 7MM SYSTEM (1994) D.O.S. Wood, VLA Test memo 189. A comprehensive overview of the new Q-band system.

7 KEY PERSONNEL

The following list gives the telephone extensions and AOC room numbers of personnel who are available to assist VLA users. In most cases the individuals have responsibilities or special knowledge in certain areas as noted in the right hand column.

You may also contact any of these people through E-mail. The NRAO has adopted a uniform standard for E-mail addresses: first initial followed by last name, with a maximum of eight letters. Thus, Joseph H. User would be reached at `juser@nrao.edu`. The VLA control room number is: 505 835 7180. The AOC's front-desk number is: 505 835 7000.

Table 16: List of Key VLA Personnel

You may e-mail any of the following individuals by addressing your message to 'first initial last name'@nrao.edu. Thus, you may contact Chris Carilli at: 'ccarilli@nrao.edu'. The name is truncated to eight characters. The listed four-digit numbers are sufficient for calls made from within the AOC. If you are calling from outside, the 4-digit numbers must be preceded with: 505-835.

Name	Phone	Room	Notes
K.R. Anantharamaiah	7365	332	Spectral line (Nov '97 - Dec '98)
Lori Appel	7310	340	Scheduling secretary
Durga Bagri	7216	182	Technical advice, 327 MHz observing
Tim Bastian	7259	318	Solar Observing
Larry Beno	7212	186	Head of Electronics
Bryan Butler	7261	344	13 and 7 mm observing, planets
Chris Carilli	7306	356	Q-band support, Calibration
Barry Clark	7268	308	Scheduling
Mark Claussen	7284	268	VLBI, Spectral Line
Tim Cornwell	7333	376	Imaging, aips++
Ketan Desai	7450	208	AIPS support
Phil Diamond	7365	306	VLBI, AIPS, Operations (leaving Jan. '99)
Chris Flatters	7209	208	AIPS, HALCA
Dale Frail	7338	360	Pulsars, HTRP Support, Lunch talk coordinator
Miller Goss	7300	336	VLA/VLBA Director
Tim Hankins	7326	278	Pulsar Observing, HTRP
Phil Hicks	7319	VLA 220	VLA Chief Operator
Bob Hjellming	7273	326	Stellar Observing
Athol Kembball	7330	216	aips++, VLBI, polarimetry
Selfa Lucero	7357	218	NRAO Reservationist
Leonid Kogan	7383	312	AIPS support
George Martin	7287	373	Real-time Observing, UNIX support
Dan Mertely	7187	145	RFI control
Peter Napier	7218	250	Technical advice
Frazer Owen	7304	320	Polarimetry, High dynamic range
Rick Perley	7312	362	Calibration, Imaging, Polarimetry, Low-freq.
Gayle Rhodes	7245	252	Documentation, VLA Archive
Terry Romero	7315	330	Visitor Support
Michael Rupen	7248	206	Spectral Line, Colloquium coordinator
Ken Sowinski	7299	375	On-Line Systems
Dick Sramek	7394	328	Electronics Problems
Meri Stanley	7238	204	Head analyst, User support
Greg Taylor	7237	358	Calibration, Imaging, VLBI, RFI
Jim Ulvestad	7298	256	VLBI, HALCA, PT Link project
Gustaaf van Moorsel	7396	348	Spectral Line, Head of Computing
Dave Westpfahl	7225	373	Spectral Line Observing
Joan Wrobel	7392	302	VLBI, VLA/VLBA Head of Operations
Wes Young	7337	378	OBSERVE