VERY LONG BASELINE ARRAY OBSERVATIONAL STATUS SUMMARY

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1 INTRODUCTION

This document summarizes the current observational capabilities of NRAO's Very Long Baseline Array (VLBA). The VLBA is an array of 10 25-m diameter antennas distributed over United States territory (Napier *et al.* 1994; Napier 1995). It is the first astronomical array dedicated to observing by the method of Very Long Baseline Interferometry (VLBI), pioneered in the 1960s. The VLBA offers (1) in absentia, year-round antenna and correlator operation; (2) antenna locations selected to optimize u-v plane coverage; (3) 9 receivers in the range 90 cm to 7 mm at each antenna; (4) quick computer control of receiver selection (receiver agility) and of frequency selection for a given receiver (frequency agility); and (5) smooth integration of data flow from the acquisition to the processing to the post-processing stages. Systems at 3 mm are also been deployed across the array. VLBA observations conducted in VLBA (Romney 1990) and Mark 3 (Rogers *et al.* 1983) data formats can acquire simultaneous dual circular polarizations from any single receiver or from the 13/4 cm receiver pair. The conference proceedings edited by Zensus, Taylor, & Wrobel (1998) provides a broad overview of the kinds of astronomical research possible with the VLBA. Recommended reading for users new to the VLBA includes a short VLBI overview (Walker 1999b) and a short guide for novice users of the VLBA (Ulvestad 1999b), plus copies of AAS presentations on VLBA cababilites (Ulvestad 1999c) and on using the VLBA (Wrobel 1999).

This document's primary intent is to provide, in concise form, the minimal information needed to formulate technically sound proposals requesting VLBA resources. Its secondary aim is to provide lists of relevant software and documentation, plus a list of key NRAO personnel who can be consulted for further, more detailed information. This document, which is updated approximately annually, is available through the VLBA astronomer page at *http://www.aoc.nrao.edu/vlba/html/vlbahome/observer.html* or through anonymous FTP as a PostScript file with name "obssum.vlba.ps" in directory "pub" on host "ftp.aoc.nrao.edu". If you want a paper copy of this document, then request one from Lori Appel (see Section 26.3). Updates of this document will be announced via the NRAO VLBI e-mail exploder. New subscriptions to this exploder can be made as instructed through the VLBA astronomer page.

The VLBA is operated remotely from the Array Operations Center (AOC) in Socorro, New Mexico, with local assistance at each VLBA antenna site provided by site technicians.

2 ANTENNA SITES

Table 1 gives the surveyed geographic locations of the 10 antennas comprising the VLBA, plus the 2-character codes used to identify the antennas (Napier 1995). The antennas are ordered East through West. The SC location refers to the Puerto Rican Datum of 1949. The MK location refers to the Old Hawaiian Datum of 1866. All other locations refer to the North American Datum of 1927. See Napier (1995) for further site information.

Table 1: **Geographic Locations and Codes**

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

3 ANTENNAS

The main reflector of each VLBA antenna is a 25-m diameter dish which is a shaped figure of revolution with a focal-length-to-diameter ratio of 0.354. A 3.5-m diameter Cassegrain subreflector with a shaped asymmetric figure is used at all frequencies above 1 GHz, while the prime focus is used at lower frequencies. The antenna features a wheel-and-track mount, with an advanced-design reflector support structure. Elevation motion occurs at a rate of 30 degrees per minute between a hardware limit of 2 degrees and a software limit of 90 degrees. This software limit will eventually be lifted, allowing over-the-top elevation motion to 125 degrees. Azimuth motion has a rate of 90 degrees per minute between limits of -90 to 450 degrees. Antennas will be stowed to avoid operation in high winds. Snow or ice accumulation will also be avoided. See Napier (1995) for further antenna information.

4 FREQUENCIES

Table 2 gives the nominal frequency ranges for the 9 receiver/feed combinations available on all 10 VLBA antennas (Thompson 1995). Passband-limiting filters are described by Thompson (1995). Measured frequency ranges are broader than nominal; consult Hronek & Walker (1996) for details. Measured frequency ranges may be especially important for avoiding radio frequency interference (RFI), and for programs involving extragalactic lines, rotation measures (Cotton 1995b; Kemball 1999), and multi-frequency synthesis (Conway & Sault 1995; Sault & Conway 1999). Preliminary performance information is also provided for the available 3-mm systems.

Table 2: **Frequency Ranges and Typical Performance Parameters**

Receivers and Feeds	Nominal Frequency Range [GHz]	Typical Zenith *SEFD* [Jy]	Center Frequency for *SEFD* [GHz]	Typical Zenith Gain [K Jy^{-1}]	Baseline Sensitivity $\Delta S^{128,2\text{m}}$ [mJy]	Image Sensitivity $\Delta I_{\text{m}}^{128,8\text{h}}$ [μJy beam^{-1}]
90 cm	0.312 - 0.342	2227	0.326	0.096	50.7$^{(a)}$	345
50 cm	0.596 - 0.626	2216	0.611	0.088	...	...
21 cm$^{(b)}$	1.35 - 1.75	296	1.438	0.094	4.8	46
18 cm$^{(b)}$	1.35 - 1.75	303	1.658	0.097	4.9	47
13 cm$^{(c)}$	2.15 - 2.35	322	2.275	0.095	5.2	50
13 cm$^{(c,d)}$	2.15 - 2.35	337	2.275	0.091	5.4	52
6 cm	4.6 - 5.1	312	4.999	0.130	5.0	48
4 cm	8.0 - 8.8	307	8.425	0.113	4.9	48
4 cm$^{(d)}$	8.0 - 8.8	407	8.425	0.105	6.6	63
2 cm	12.0 - 15.4	550	15.369	0.112	8.9	85
1 cm	21.7 - 24.1	888	22.236	0.110	14.3	138
7 mm	41.0 - 45.0	1436	43.174	0.079	32.7$^{(a)}$	223
3 mm	80.0 - 90.0	5000$^{(e)}$	86.2	0.025	120.$^{(f)}$	1050$^{(g)}$

Notes: (a) Assumes a fringe-fit interval of 1 minute. (b) Different settings of the same 20 cm receiver. Hronek & Walker (1996) describe additional antenna-specific filters not mentioned by Thompson (1995). (c) New filters at NL and LA restrict frequencies to 2200-2400 MHz. (d) With 13/4 cm dichroic. (e) Range is 3500-8000 Jy. (f) Assumes a fringe-fit interval of 30 seconds and a recording rate of 256 Mbps. (g) Assumes 5 hours of integration with 6 antennas recording at a rate of 256 Mbps.

Also appearing in Table 2 are parameters characterizing the performance of a typical VLBA antenna for the various receiver/feed combinations. Columns [3] and [5] give typical VLBA system equivalent flux densities (*SEFD*s) at zenith and opacity-corrected gains at zenith, respectively. These were obtained from averages of right circularly polarized (RCP) and left circularly polarized (LCP) values from 10 antennas, measured at the frequencies in column [4] by VLBA operations personnel during regular pointing observations.

The typical zenith *SEFD*s can be used to estimate root-mean-square (RMS) noise levels on a baseline between 2 VLBA antennas (ΔS for a single polarization; see Equation 2) and in a VLBA image ($\Delta I_{\rm m}$ for a single polarization; see Equation 3). Characteristic values for $\Delta S^{128,2{\rm m}}$ assuming a fringe-fit interval of $\tau_{\rm ff} = 2$ minutes and for $\Delta I_{\rm m}^{128,8{\rm h}}$ assuming a total integration time on source of $t_{\rm int} = 8$ hours also appear in Table 2. The tabulated baseline sensitivities for 90 cm and 7 mm assume a fringe-fit interval of 1 minute, since 2 minutes is unrealistically long. All the baseline and image sensitivities in the table, except for 3 mm, assume an aggregate recording bit rate equal to the "sustainable" limit of 128 Mbits per second (Mbps) (see Section 5.16). This rate is commonly achieved by recording a total bandwith $\Delta\nu$ of 32 MHz with 2-bit (4-level) sampling (see Section 5.14). No baseline or image sensitivities are given for 50 cm at the sustainable limit, because adequately wide bandwidths cannot be obtained. For 3 mm, it is assumed that twice the sustainable recording rate is used, that the fringe-fit interval is 30 seconds, and that an image is made from 5 hours of integration with 6 antennas; contact Vivek Dhawan (see Section 26.3) for further information.

Opacity-corrected zenith gains are needed for current techniques for amplitude calibration. These zenith gains vary from antenna to antenna, and will be monitored by VLBA operations and communicated to users (see Section 14). The typical values appearing in Table 2 are meant to be illustrative only.

RFI is known to be problematic at VLBA sites at 90, 50, 20, and 13 cm (Thompson 1995; Hronek & Walker 1996). The AOC frequency coordinator, Raul Armendariz (see Section 26.3), can be consulted for details. Thompson (1995) discusses RFI levels harmful to VLBI.

5 VLBA SIGNAL PATH

This section describes the devices in the signal path at a VLBA antenna site. Devices in Sections 5.1-5.6 and 5.8-5.11 are located at the antenna; all others are in the site control building. More information on the VLBA signal path is provided by Napier (1995), Thompson (1995), and Rogers (1995).

5.1 Antenna and Subreflector

These concentrate the radio frequency (RF) radiation. Antenna pointing and subreflector position are controlled by commands from the site computer based on the current observing schedule and/or provided by the array operators or by the site technicians.

5.2 Feed

The feed collects the RF radiation. All feeds and receivers are available at any time, and are selected by subreflector motion controlled by the computer.

5.3 Polarizer

This device converts circular polarizations to linear for subsequent transmission. For receivers above 1 GHz, the polarizer is at cryogenic temperatures.

5.4 Pulse Cal

This system injects calibration tones based on a string of pulses at intervals of 1.0 or 0.2 microseconds. See Section 15.2 for more details.

5.5 Noise Cal

This device injects switched, well calibrated, broadband noise for system temperature measurements. Synchronous detection occurs in the intermediate frequency (IF) distributers (see Section 5.12) and base band converters (see Section 5.13). Switching is done at 80 Hz.

5.6 Receiver

The receiver amplifies the signal. Most VLBA receivers are HFETs at a physical temperature of 15 K, but the 90 cm and 50 cm receivers are GASFETs at room temperature. Each receiver has 2 channels, one for RCP and one for LCP. The 1 cm and 7 mm receivers also perform the first frequency down conversion.

5.7 Maser

The maser is a very stable frequency standard with two output signals, one at 100 MHz and one at 5 MHz. The 100 MHz output is the reference for the front end synthesizers (see Section 5.9) and the pulse cal system (see Sections 5.4 and 15.2). The 5 MHz output is the reference for the base band converters (see Section 5.13), the formatter (see Section 5.15), and the antenna timing.

5.8 Local Oscillator Transmitter and Receiver

The local oscillator (LO) transmitter and receiver multiplies the 100 MHz from the maser to 500 MHz and sends it to the antenna vertex room. A round trip phase measuring scheme monitors the length of the cable used to transmit the signal so that phase corrections can be made for temperature and pointing induced variations.

5.9 Front End Synthesizer

The front end synthesizer generates the reference signals used to convert the receiver output from RF to IF. The lock points are at $(n\times 500) \pm 100$ MHz, where n is an integer. The synthesizer output frequency is between 2.1 and 15.9 GHz. There are 3 such synthesizers, each of which is locked to the maser. One synthesizer is used for most wavelengths, but two are used at 1 cm, at 7 mm, and for the wide band mode at 4 cm described in Section 5.10.

5.10 IF Converter

The IF converter mixes the receiver output signals with the first LO generated by a front end synthesizer. Two signals between 500 and 1000 MHz are output by each IF converter, one for RCP and one for LCP. The same LO signal is used for mixing with both polarizations in most cases. However, the 4 cm IF converter has a special mode that allows both output signals to be connected to the RCP output of the receiver and to use separate LO signals, thereby allowing the use of spanned bandwidths exceeding 500 MHz. Also, the 90 cm and 50 cm signals are combined and transmitted on the same IFs. The 50 cm signals are not frequency converted, while the 90 cm signals are upconverted to 827 MHz before output.

5.11 IF Cables

There are four of these, labeled A, B, C, and D. Each IF converter normally sends its output signals to A and C, or else to B and D, although switching is available for other possibilities if needed. By convention, the RCP signals are sent to A or B while the LCP signals are sent to C or D. Normally only 2 cables will be in use at a time. Certain dual frequency modes, especially 13 cm and 4 cm, can use all four cables.

5.12 IF Distributers

The IF distributers make 8 copies of each IF, one for each base band converter (see Section 5.13). They also can optionally switch in 20 db of attenuation for solar observations. There are two IF distributers, each handling two IFs. Power detectors allow the determination of total and switched power in the full IF bandwidth for system temperature determinations and for power level setting.

5.13 Base Band Converters

The base band converters (BBCs) mix the IF signals to base band and provide the final analog filtering. Each of 8 BBCs generates a reference signal between 500 and 1000 MHz at any multiple of 10 kHz. Each BBC can select as input any of the four IFs. Each BBC provides the upper and lower sidebands as separate outputs, allowing for a total of 16 "BB channels", where one BB channel is one sideband from one BBC. Allowed bandwidths per BBC are 0.0625, 0.125, 0.25, 0.5, 1, 2, 4, 8, and 16 MHz. Thus the 16 possible BB channels can cover an aggregate bandwidth up to 256 MHz. The BBC signals are adjusted in amplitude. With automatic leveling turned on, the power in the signals sent to the samplers is kept nearly constant, which is important for the 2-bit (4-level) sampling mode (see Section 5.14). The BBCs contain synchronous detectors that measure both total power and switched power in each sideband for system temperature determination.

5.14 Samplers

Samplers convert the analog BBC outputs to digital form. There are two samplers, each of which handles signals from 4 BBCs. Either 1-bit (2-level) or 2-bit (4-level) sampling may be selected. A single sample rate applies to all BB channels; rates available are 32, 16, 8, 4, 2, 1, or 0.5 Msamples per second on each channel.

5.15 Formatter

The formatter selects the desired bit streams from the samplers, adds timing and other information, fans the bit streams out (spreads one fast input signal over several tape tracks), establishes the barrel roll scheme used to rotate the bit stream/track mapping with time, and sends the output signals to the tape recorders. As many as 32 bit-streams can be formatted, with a bitstream:track multiplexing scheme of 4:1, 2:1, 1:1, 1:2, or 1:4, which allows for very flexible input signal to output tape track switching. VLBA and Mark 3 data formats are supported. Up to 16 pulse cal tones or state counts can be detected simultaneously. Up to 4 Mbits can be captured and sent to the site computer and on to the AOC for various tests, including real time fringe checks.

5.16 Tape Recorders

These are high speed longitudinal instrumentation tape recorders that use 1 inch wide tape on reels 14 inches in diameter. The headstack contains 36 heads, 32 for data and 4 for system information, cross-track parity, or duplicate data. The headstack can be moved under site computer control transverse to the tape motion. The heads are much narrower than the spacing between heads, so multiple pass recording can be used with 14 passes, or more if not all heads are used in each pass.

As many as 32 data tracks can be written to one tape drive, with a record rate per track of 8, 4, or 2 Mbps. This can result in an aggregate bit rate of as much as 256 Mbps when writing to a single tape drive or 512 Mbps when writing simultaneously to both tape drives. However, operational constraints require that a "sustainable" limit of 128 Mbps (averaged over 24 hours) be imposed on the aggregate bit rate. This can be achieved either by recording continuously at 128 Mbps or by arranging that the duty cycle (ratio of recording time to total allocated time) be less than unity. A thin (17600-foot) VLBA tape lasts 10 h 16 m if recorded continuously at 128 Mbps. The VLBA no longer records (or correlates) thick VLBI tapes.

5.17 Site Computer

A VME site computer running VxWorks controls all site equipment based on commands in the current observing schedule or provided by the array operators or by the site technicians. All systems are set as requested in the current schedule for each new observation.

5.18 Monitor and Control Bus

This carries commands from the site computer to all site hardware and returns data from the site hardware to the computer.

5.19 GPS Receiver

This device acquires time from the Global Positioning System (GPS). GPS time is usually used to monitor the site clock. GPS time is occasionally used to set the site clock if it is disrupted for some reason.

6 RECORDING FORMATS

The VLBA can record data in VLBA and Mark 3 formats. Characteristics of observations recorded in VLBA format are described in Section 5 and elsewhere in this document. Mark 3 observations are limited to that format's 4-MHz maximum BB channel bandwidth and 1-bit sampling, and to the VLBA's 8-BBC complement. Mark 4 (Whitney 1995) systems have largely replaced Mark 3 at most other observatories world-wide. Although the VLBA cannot record Mark 4 format as such, there is a high degree of compatibility between Mark 4 and VLBA formats. Tapes in either VLBA and Mark 4 formats can be played back, for the same observation if necessary, on any VLBA or Mark 4 correlator. Section 18.1 provides further information regarding Mark 4 programs involving the VLBA and/or its correlator. The VLBA cannot record in Mark 2 format, the Japanese K4 format, or the Canadian S2 format, although the Mitaka correlator has a limited translation facility for space VLBI observations.

7 CORRELATOR

The VLBA correlator accommodates the full range of scientific investigations for which the array was designed. The correlator supports wideband continuum, high-resolution spectroscopy, bandwidth synthesis, polarimetric, and gated observations.

The correlator is designed to process all observations involving VLBA stations. With its 20-station capacity and sub-arraying capabilities, it can correlate an extended array combining the VLBA with as many as 10 foreign stations, or an extreme-wideband VLBA observation using both recorders at each of 10 stations, or two 10-station intra-VLBA observations, or virtually any combination of smaller sub-arrays, each in a single processing pass.

Each station input comprises 8 parallel "channels" (as defined in Section 5.13), which operate at a fixed rate of 32 Msamples per second, for either 1- or 2-bit samples. Observations at lower sample rates generally can be processed with a speed-up factor of 2 (for 16 Msamples per second) or 4 (for 8 Msamples per second or less) relative to observe time. Special modes are invoked automatically to enhance sensitivity when fewer than 8 channels are observed, or when correlating narrowband or oversampled data. The correlator accepts input data recorded in VLBA, Mark 3, or Mark 4 longitudinal format. Section 18.1 provides further information concerning Mark 4 recordings destined for the VLBA correlator.

Each input channel can be resolved into 1024, 512, 256, 128, 64, or 32 "spectral points", subject to a limit of 2048 points per baseline across all channels. Adjacent, oppositely polarized channels can be paired to produce all four Stokes parameters; in this case correlator constraints impose a maximum spectral resolution of 128 points per polarization state. The user may also specify a spectral smoothing function, or request an "interpolated" spectrum suitable for inversion to a cross-correlation function if further work is required in that domain.

The correlator forms cross-spectral power measurements on all relevant baselines in a given sub-array, including individual antenna "self-spectra". These can be integrated over any integral multiple of the basic integration cycle, 131.072 milliseconds (2^{17} microsec). Adjacent spectral points may be averaged while integrating to reduce spectral resolution. A time-domain transversal filter is available at the output from the integrator to maximize the fringe-rate window while further reducing the data rate.

Correlator output is written in a "FITS Binary Table" format, and as of about 1999 April 1 includes editing flags plus amplitude, weather, and pulse calibration data logged at VLBA antennas at observe time (Flatters 1998; Ulvestad 1999a). All results are archived on digital-audio-tape (DAT) cassettes. The output data rate is limited to 0.5 Mbytes per second, which must be shared among all simultaneous correlator sub-arrays. Data are copied from the archive for distribution to users on a variety of media, with DAT and Exabyte currently given primary support.

Operation of the correlator is governed primarily by information obtained from the VLBA control system's monitor data or from foreign stations' log files. A few additional items, all of which have been mentioned above, will be specified by the user prior to correlation. Supervision of the correlation process is the responsibility of VLBA operations personnel; user participation during correlation is not expected nor easily arranged, as explained below.

Scheduling of the correlator is currently done on a very short time-scale of days to optimize use of the correlator's resources and the array's stock of tapes. This makes it impractical, in general, to schedule visits by users during correlation of their data. As described in Section 23, however, users are encouraged to visit the AOC after correlation for post-processing analysis.

Consult Benson (1995) and Romney (1995, 1999a), respectively, for more information on the VLBA correlator and on VLBI correlation in general.

8 ANGULAR RESOLUTION

Table 3, generated with the NRAO program SCHED (Walker 2001), gives the maximum lengths rounded to the nearest km (B^{km}_{max}) for each of the VLBA's 45 internal baselines. Both the upper left and lower right portions of the table are filled to make it easier to use. A measure of the corresponding resolution (θ_{HPBW}) in milliarcseconds (mas) is

$$\theta_{HPBW} \sim 2063 \times \frac{\lambda^{cm}}{B^{km}_{max}} \text{ mas}, \quad (1)$$

where λ^{cm} is the receiver wavelength in cm (Wrobel 1995). A uniformly weighted image made from a long *u*-*v* plane track will have a synthesized beam with a slightly narrower minor axis FWHM. At the center frequencies appearing in Table 2 and for the longest VLBA baseline, θ_{HPBW} is 22, 12, 5.0, 4.3, 3.2, 1.4, 0.85, 0.47, and 0.32 mas for receivers named 90, 50, 21, 18, 13, 6, 4, 2, and 1 cm, plus 0.17 mas at 7 mm.

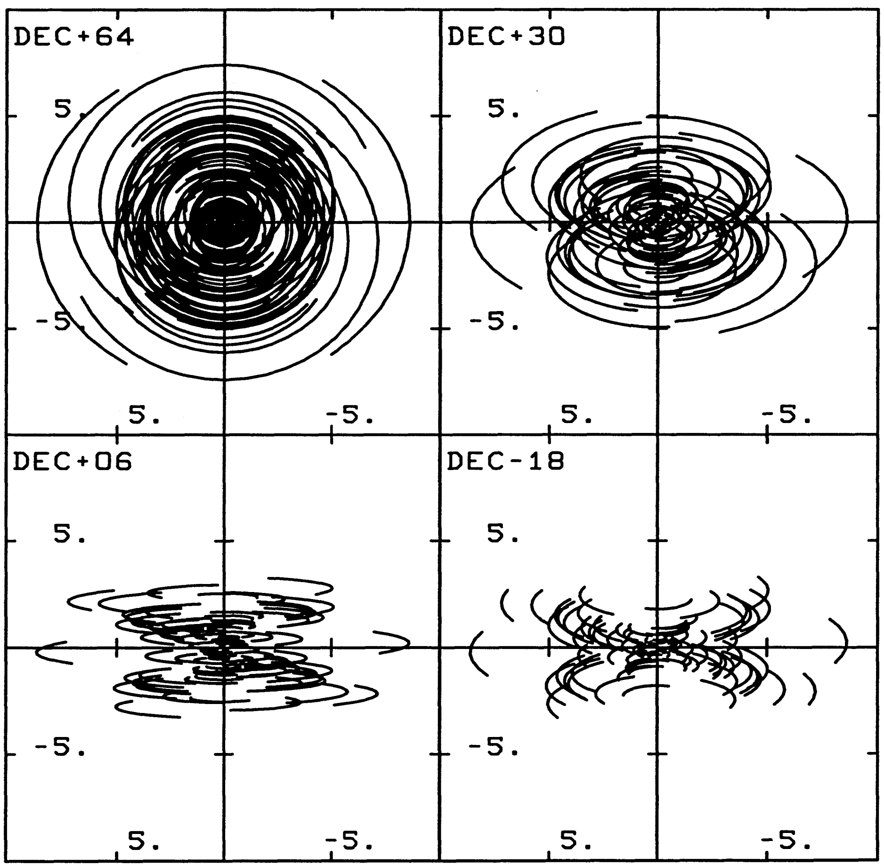
Table 3: **Maximum VLBA Baseline Lengths in km (B^{km}_{max})**

	SC	HN	NL	FD	LA	PT	KP	OV	BR	MK
SC	...	2853	3645	4143	4458	4579	4839	5460	5767	8611
HN	2853	...	1611	3105	3006	3226	3623	3885	3657	7502
NL	3645	1611	...	1654	1432	1663	2075	2328	2300	6156
FD	4143	3105	1654	...	608	564	744	1508	2345	5134
LA	4458	3006	1432	608	...	236	652	1088	1757	4970
PT	4579	3226	1663	564	236	...	417	973	1806	4795
KP	4839	3623	2075	744	652	417	...	845	1913	4466
OV	5460	3885	2328	1508	1088	973	845	...	1214	4015
BR	5767	3657	2300	2345	1757	1806	1913	1214	...	4398
MK	8611	7502	6156	5134	4970	4795	4466	4015	4398	...

9 *u*-*v* PLANE COVERAGE

Plots of the *u*-*v* plane coverage with the VLBA for sources at declinations of $+64, +30, +06$, and -18 degrees are shown in Figure 1 for horizon-to-horizon tracks and in Figure 2 for single "snapshot" tracks of duration $\frac{1}{2}$ hour approximately when the source transits New Mexico. Similar plots can be generated with the NRAO program SCHED (Walker 2001).

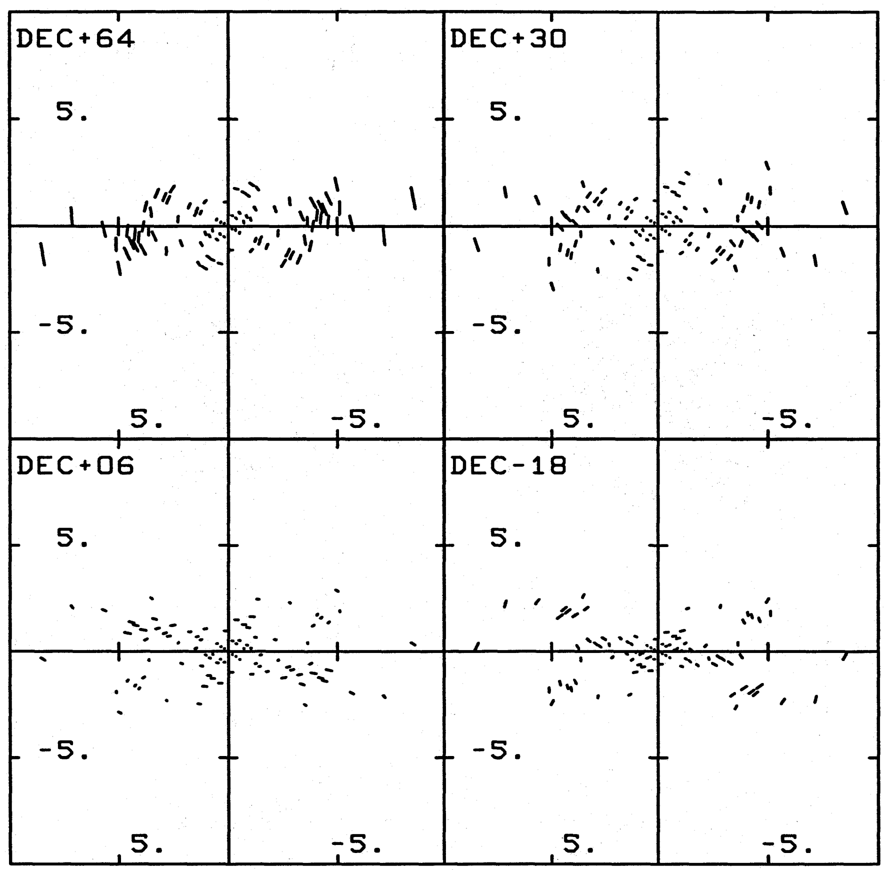
Figure 1: **VLBA u-v plane coverage at four declinations. Horizon-to-horizon tracks for an elevation limit of $10°$. Plotted range is $\pm$ 9000 km.**



10 TIME RESOLUTION

Time resolution is set by the VLBI correlator accumulation time. At the VLBA correlator it is about 2 seconds for most programs, although a mini-

Figure 2: **VLBA *u*-*v* plane coverage at four declinations. Single "snapshot" tracks at New Mexico transit. Plotted range is ± 9000 km.**



mum accumulation time of 131 milliseconds is available for special programs. Pulsar gating is also available on the VLBA correlator (Benson 1998).

11 SPECTRAL RESOLUTION

Spectral resolution is set by the VLBI correlator. With the VLBA correlator each BB channel can be divided into 32, 64, 128, 256, 512, or 1024 spectral points, subject to the limitations specified in Section 7. The spectral resolution is the bandwidth per BB channel divided by the number of spectral points. The VLBA correlator can apply an arbitrary special smoothing, which will affect the statistical independence of these points and thus the effective spectral resolution. Typical continuum programs request averaging to 16 spectral points.

12 BASELINE SENSITIVITY

Adequate baseline sensitivity is necessary for VLBI fringe fitting, discussed in Section 15.3. The following formula can be used in conjunction with the typical zenith $SEFD$s for VLBA antennas given in Table 2 to calculate the RMS thermal noise (ΔS) in the visibility amplitude of a single-polarization baseline between two identical antennas (Walker 1995a; Wrobel & Walker 1999):

$$\Delta S = \frac{1}{\eta_{\mathrm{s}}} \times \frac{SEFD}{\sqrt{2 \times \Delta\nu \times \tau_{\mathrm{ff}}}} \ \mathrm{Jy}. \tag{2}$$

In Equation 2, $\eta_{\mathrm{s}} \leq 1$ accounts for the VLBI system inefficiency (e.g., quantization in the data recording and correlator approximations). Assume $\frac{1}{\eta_{\mathrm{s}}} \sim 2$ for data from a Mark 3 correlator. Although the system inefficiency for the VLBA correlator has not been determined, Kogan (1995) provides the combination of scaling factors and inefficiencies appropriate for VLBA visibility data. $\Delta\nu$ is the bandwidth [Hz]; use the full recorded bandwidth for a continuum target and use a spectral channel for a line target. τ_{ff} is the fringe-fit interval [s], which should be less than or about equal to the coherence time τ_{atm}. Equation 2 holds in the weak source limit and assumes 1-bit (2-level) quantization. About the same noise can be obtained with 2-bit (4-level) quantization and half the bandwidth, which gives the same bit rate. Moran & Dhawan (1995) discuss expected coherence times. The actual coherence time appropriate for a given VLBA program can be estimated using observed fringe amplitude data on an appropriately strong and compact source.

13 IMAGE SENSITIVITY

The following formula can be used in conjunction with the typical zenith $SEFD$s for VLBA antennas given in Table 2 to calculate the RMS thermal noise (ΔI_{m}) expected in a single-polarization image, assuming natural weighting (Wrobel 1995; Wrobel & Walker 1999):

$$\Delta I_{\mathrm{m}} = \frac{1}{\eta_{\mathrm{s}}} \times \frac{SEFD}{\sqrt{N \times (N-1) \times \Delta\nu \times t_{int}}} \ \mathrm{Jy\ beam}^{-1}, \tag{3}$$

where η_s is discussed in Section 12; N is the number of VLBA antennas available; $\Delta\nu$ is the bandwidth [Hz]; and t_{int} is the total integration time on source [s]. Equation 3 also assumes 1-bit (2-level) quantization. If simultaneous dual polarization data are available with the above ΔI_m per polarization, then for an image of Stokes I, Q, U, or V,

$$\Delta I = \Delta Q = \Delta U = \Delta V = \frac{\Delta I_m}{\sqrt{2}}. \quad (4)$$

For a polarized intensity image of $P = \sqrt{Q^2 + U^2}$,

$$\Delta P = 0.655 \times \Delta Q = 0.655 \times \Delta U. \quad (5)$$

It is sometimes useful to express ΔI_m in terms of an RMS brightness temperature in Kelvins (ΔT_b) measured within the synthesized beam. An approximate formula for a single-polarization image is

$$\Delta T_b \sim 320 \times \Delta I_m \times (B_{max}^{km})^2 \text{ K}, \quad (6)$$

where B_{max}^{km} is as in Equation 1.

14 AMPLITUDE CALIBRATION

Traditional calibration of VLBI fringe amplitudes for continuum sources requires knowing the on-source system temperature in Jy (*SEFD*; Moran & Dhawan 1995). System temperatures in degrees K (T_{sys}) are measured "frequently" in each BB channel during observations with VLBA antennas; "frequently" means at least once per observation or once every user-specified interval (default is 2 minutes), whichever is shorter. These T_{sys} values are required by fringe amplitude calibration programs such as `ANTAB/APCAL` in the NRAO Astronomical Image Processing System (AIPS) or `CAL` in the Caltech VLBI Analysis Programs; see Section 21. Such programs can be used to convert from T_{sys} to *SEFD* by dividing by the VLBA antenna zenith gains in K Jy^{-1} provided by VLBA operations, based upon regular monitoring of all receiver and feed combinations. For programs processed on the VLBA correlator after about 1999 April 1, T_{sys} and gain values for VLBA antennas are delivered in TY and GC tables, respectively, in the FITS files archived and distributed by NRAO (Ulvestad 1999a). Single-antenna spectra can be used to do amplitude calibration of spectral line programs (see Section 17).

Post-observing amplitude adjustments might be necessary for an antenna's position dependent gain (the "gain curve") and for the atmospheric opacity above an antenna (Moran & Dhawan 1995). The GC table described above contains gain curves for VLBA antennas. A scheme for doing opacity adjustments is desribed by Leppänen (1993). Such adjustments can be made with AIPS task `APCAL` if weather data are available. For programs processed on the VLBA correlator after about 1999 April 1, VLBA weather data are delivered in a WX table in the FITS files archived and distributed by NRAO (Ulvestad 1999a).

Although experience with VLBA calibration shows that it probably yields fringe amplitudes accurate to 5 percent or less, it is recommended that users observe a few amplitude calibration check sources during their VLBA program. Such sources can be used (1) to assess the relative gains of VLBA antennas plus gain differences among base band channels at each antenna; (2) to test for non-closing amplitude and phase errors; and (3) to check the correlation coefficient adjustments, provided contemporaneous source flux densities are available independent of the VLBA observations. The VLBA gains are measured at the center frequencies appearing Table 2; users observing at other frequencies may be able to improve their amplitude calibration by including brief observations, usually of their amplitude check sources, at the appropriate gain frequencies. Amplitude check sources should be point-like on inner VLBA baselines. Some popular choices in the range 13 cm to 2 cm are J0555+3948=DA 193, J0854+2006=OJ 287, and J1310+3220. Other check sources can be selected from the VLBA Calibrator Survey (see Section 15.6), from major published VLBI surveys available through the VLBA astronomer page at
http://www.aoc.nrao.edu/vlba/html/vlbahome/observer.html :

- Caltech-Jodrell Bank Surveys (Taylor *et al.* 1994; Polatidis *et al.* 1995; Thakkar *et al.* 1995; Henstock *et al.* 1995)
- USNO Radio Reference Frame Survey (Fey, Clegg, & Fomalont 1996; Fey & Charlot 1997)
- VLBA 2 cm Survey (Kellermann *et al.* 1998)
- 6 cm VLBApls Survey (Fomalont *et al.* 2000)

or from compendia summarizing VLBI results (e.g., Valtaoja, Lähteenmäki, & Teräsranta 1992). It might be prudent to avoid sources known to have exhibited extreme scattering events (e.g., Fiedler *et al.* 1994a, b).

15 PHASE CALIBRATION AND IMAGING

15.1 Fringe Finders

VLBI fringe phases are much more difficult to deal with than fringe amplitudes. If the *a priori* correlator model assumed for VLBI correlation is particularly poor, then the fringe phase can wind so rapidly in both time (the fringe rate) and in frequency (the delay) that no fringes will be found within the finite fringe rate and delay windows examined during correlation. Reasons for a poor *a priori* correlator model include source position and antenna location errors, atmospheric (tropospheric and ionospheric) propagation effects, and the behavior of the independent clocks at each antenna. Users observing sources with poorly known positions should plan to refine the positions first on another instrument (see Section 18.1). To allow accurate location of any previously unknown antennas and to allow NRAO staff to conduct periodic monitoring of clock drifts, each user must include at least two "fringe finder" sources which are strong, compact, and have accurately known positions. Consult Markowitz & Wurnig (1998) to select a fringe finder for observations between between 20 cm and 7 mm; your choice will depend on your wavelengths but J0555+3948=DA 193, J0927+3902=4C 39.25, J1642+3948=3C 345, and J2253+1608=3C 454.3 are generally reliable in the range 13 cm to 2 cm. In addition, at 90 and 50 cm we recommend either J1331+3030=3C 286 or J2253+1608=3C 454.3. Fringe-finder positions, used by default by the NRAO program `SCHED` (Walker 2001) and the VLBA correlator, are given in the standard source catalog available as an ancillary file with `SCHED`.

15.2 The Pulse Cal System

VLBA observers using more than 1 BBC will want to sum over the BBCs to reduce noise levels. This should not be done with the raw signals delivered by the BBCs: the independent local oscillators in each BBC introduce an unknown phase offset from one BBC to the next, so such a summation of the raw signals would be incoherent. A so-called "phase cal" or "pulse cal" system (Thompson 1995) is available at VLBA antennas to overcome this problem. This system, in conjuction with the LO cable length measuring system, is also used to measure changes in the delays through the cables and electronics which must be removed for accurate geodetic and astrometric observations. The pulse cal system consists of a pulse generator and a sine-wave detector. The interval between the pulses can be either 0.2 or 1 microsecond. They are injected into the signal path at the receivers and serve to define the delay reference point for astrometry. The weak pulses appear in the spectrum as a "comb" of very narrow, weak spectral lines at intervals of 1 MHz (or, optionally, 5 MHz). The detector measures the phase of one or more of these lines, and their relative offsets can be used to correct the phases of data from different BBCs. The detector is in the correlator for the Mark 3 system and at the antenna in the VLBA. The VLBA pulse cal data are logged as a function of time during observations with VLBA antennas. For programs processed on the VLBA correlator after about 1999 April 1, such pulse cal data are delivered in a PC table in the FITS files archived and distributed by NRAO (Ulvestad 1999a). AIPS software can be used to load and apply the pulse cal data. However, some VLBA observers may still want to use a strong compact source (see Section 15.1) so they can do a "manual" pulse cal if necessary (Diamond 1995). For example, spectral line users will not want the pulse cal "comb" in their spectra, so they should ensure that their observing schedules both disable the pulse cal generators and include observations suitable for a "manual" pulse cal.

15.3 Fringe Fitting

After correlation, the phases on a VLBA target source can still exhibit high residual fringe rates and delays. Before imaging, these residuals should be removed to permit data averaging in time and, for a continuum source, in frequency. The process of finding these residuals is referred to as fringe fitting. Before fringe fitting, it is recommended to edit the data based on the *a priori* edit information provided for VLBA antennas. For programs processed on the VLBA correlator after about 1999 April 1, such editing data are delivered in an FG table in the FITS files archived and distributed by NRAO (Ulvestad 1999a). The old baseline-based fringe search methods have been replaced by more powerful global fringe search techniques (Cotton 1995a; Diamond 1995). Global fringe fitting is simply a generalization of the phase self-calibration technique (see Section 15.5), as during a global fringe fit the difference between model phases and measured phases are minimized by solving for the antenna-based instrumental phase, its time slope (the fringe rate), and its frequency slope (the delay) for each antenna. Global fringe fitting in AIPS is done with programs such as `FRING`. If the VLBA target source is a spectral line source (see Section 17) or is too weak to fringe fit on itself, then residual fringe rates and delays can be found on an adjacent strong continuum source and applied to the VLBA target source.

15.4 Editing

After fringe-fitting and averaging, VLBA visibility amplitudes should be inspected and obviously discrepant points removed (Diamond 1995; Walker 1995b). Usually such editing is done interactively using tasks in AIPS or the Caltech program `DIFMAP` (Shepherd 1997).

15.5 Self-Calibration, Imaging, and Deconvolution

Even after global fringe fitting, averaging, and editing, the phases on a VLBA target source can still vary rapidly with time. Most of these variations are due to inadequate removal of antenna-based atmospheric phases, but some variations can also be caused by an inadequate model of the source structure during fringe fitting. If the VLBA target source is sufficiently strong and if absolute positional information is not needed, then it is possible to reduce these phase fluctuations by looping through cyles of Fourier transform imaging and deconvolution, combined with phase self-calibration in a time interval shorter than that used for the fringe fit (Cornwell 1995; Walker 1995b; Cornwell & Fomalont 1999). Fourier transform imaging is straightforward (Briggs, Schwab, & Sramek 1999), and done with AIPS task `IMAGR` or the Caltech program `DIFMAP` (Shepherd 1997). The resulting VLBI images are deconvolved to rid them of substantial sidelobes arising from relatively sparse sampling of the u-v plane (Cornwell, Braun, & Briggs 1999). Such deconvolution is achieved with AIPS tasks based on the CLEAN or Maximum Entropy methods or with the Caltech program `DIFMAP`.

Phase self-calibration just involves minimizing the difference between observed phases and model phases based on a trial image, by solving for antenna-based instrumental phases (Cornwell 1995; Walker 1995b; Cornwell & Fomalont 1999). After removal of these antenna-based phases, the improved visibilities are used to generate an improved set of model phases, usually based on a new deconvolved trial image. This process is iterated several times until the phase variations are substantially reduced. The method is then generalized to allow estimation and removal of complex instrumental antenna gains, leading to further image improvement. Both phase and complex self-calibration are accomplished with the AIPS task `CALIB` and with program `DIFMAP` in the Caltech VLBI Analysis Programs. Self-calibration should only be done if the VLBA target source is detected with sufficient signal-to-noise in the self-calibration time interval (otherwise, fake sources can be generated!) and if absolute positional information is not needed.

The useful field of view in VLBI images can be limited by finite bandwidth, integration time, and non-coplanar baselines (Wrobel 1995; Cotton 1999b; Bridle & Schwab 1999; Perley 1999b). Measures of image correctness - image fidelity and dynamic range - are discussed by Walker (1995a) and Perley (1999a).

15.6 Phase Referencing

If the VLBA target source is not sufficiently strong for self-calibration or if absolute positional information is needed but geodetic techniques are not used, then VLBA phase referenced observations must be employed (Beasley & Conway 1995). Wrobel *et al.* (2000) recommend strategies for phase referencing with the VLBA, covering the proposal, observation, and correlation stages. A VLBA phase reference source should be observed frequently and be within a few degrees of the VLBA target region, otherwise differential atmospheric (tropospheric and ionospheric) propagation effects will prevent accurate phase transfer. Walker & Chatterjee (1999) have investigated ionospheric corrections using GPS-based models. VLBA users can draw candidate phase calibrators from the source catalog, dated 2000 April 17, in use at the VLBA correlator and distributed with the NRAO program `SCHED` (Walker 2001). Most sources in this catalog are from the Jodrell Bank - VLA Astrometric Survey (JVAS - Patnaik *et al.* 1992; Browne *et al.* 1998; Wilkinson *et al.* 1998), which is being extended to cover the sky north of declination −30 degrees. A VLBA survey of the stronger JVAS sources is in progress, to determine which are compact enough to serve as good VLBA phase reference sources and to obtain improved reference source positions (Peck & Beasley 1998); preliminary results from this VLBA Calibrator Survey are available through the VLBA astronomer page at *http://www.aoc.nrao.edu/vlba/html/vlbahome/observer.html* .

16 POLARIMETRY

In VLBA polarimetric observations, BB channels are assigned in pairs to opposite hands of circular polarization at each frequency. Such observations can be recorded in VLBA or in Mark 3 formats. Typical "impurities" of the antenna feeds are about 3 percent for the center of most VLBA bands and degrade toward the band edges and away from the pointing center in the image plane. Without any polarization calibration, an unpolarized source will appear to be polarized at the 2 percent level. Furthermore, without calibration of the RCP-LCP phase difference, the polarization angle is undetermined. With a modest investment of time spent on calibrators and some increased effort in the calibration process, the instrumental polarization can be reduced to less than 0.5 percent.

To permit calibration of the feed impurities (sometime also called "leakage" or "D-terms"), VLBA users should include observations of a strong (~1 Jy) calibration source, preferably one with little structure. This source should be observed during at least 5 scans covering a wide range (> 100 degrees) of parallactic angle, with each scan lasting about 5 minutes. The electric vector polarization angle (EVPA) of the calibrator will appear to rotate in the sky with parallactic angle while the instrumental contribution stays constant. Some popular calibrator choices are J0555+3948=DA 193 and J1407+2827=OQ 208, although either or both may be inappropriate for a given frequency or an assigned observing time. Fortunately, many calibrators satisfying the above criteria are available.

To set the absolute EVPA on the sky, it is necessary to determine the phase difference between RCP and LCP. For VLBA users at frequencies of 5 GHz and greater, this can be accomplished by observations of one or two of the compact sources that are being monitored with the VLA; see Taylor & Myers (2000) and *http://www.aoc.nrao.edu/~smyers/calibration* . At 1.6 GHz it may be preferable to observe a source with a stable, long-lived jet component with known polarization properties. At frequencies of 5 GHz and below one can use J0521+1638=3C 138 (Cotton *et al.* 1997a), J1331+3030=3C 286 (Cotton *et al.* 1997b), J1829+4844=3C 380 (Taylor 1998), or J1902+3159=3C 395 (Taylor 2000). At frequencies of 8 GHz and above one can also use J1256-0547=3C 279 (Taylor 1998) or J2136+0041=2134+004 (Taylor 2000), although beware that some of these jet components do change on timescales of months to years. It will be necessary to image the EVPA calibrator in Stokes I, Q and U to determine the appropriate correction to apply. Thus it is recommended to obtain 2 to 4 scans, each scan lasting about 4 minutes, over as wide a range in hour angle as is practical.

To permit calibration of the RCP-LCP delays, VLBA users should include a 2-minute observation of a very strong (~10 Jy) calibration source. While 3C 279 is a good choice for this delay calibration, any very strong fringe-finder will suffice.

Post-processing steps include normal amplitude calibration; fringe-fitting; solving for the RCP-LCP delay; self-calibration and Stokes I image formation; instrumental polarization calibration; setting the absolute position angle of electric vectors on the sky; and correction for ionospheric Faraday rotation, if necessary (Cotton 1995b, 1999a; Kemball 1999). All these post-processing steps can currently be done in AIPS, as can the polarization self-calibration technique described by Leppänen, Zensus, & Diamond

(1995).

17 SPECTRAL LINE

Diamond (1995) and Reid (1995, 1999) describe the special problems encountered during data acquisition, correlation, and post-processing of a spectral line program. The spectral line user must know the transition rest frequency, the approximate velocity and velocity width for the line target, and the corresponding observing frequency and bandwidth. The schedule should include observations of a strong continuum source to be used for fringe-finding, "manual" pulse calibration, and bandpass calibration; as well as scans of a continuum source reasonably close to the line target to be used as a fringe-rate and delay calibrator. The pulse cal generators should be disabled.

Post-processing steps include performing Doppler corrections for the Earth's rotation and orbital motion (the correction for rotation is not necessary with observations correlated on the VLBA or any other correlator with antenna based fringe rotators); amplitude calibration using single-antenna spectra; fringe fitting the continuum calibrators and applying the results to the line target; referencing phases to a strong spectral feature in the line source itself; and deciding whether to do fringe rate mapping or normal synthesis imaging and then form a spectral line cube. All these post-processing steps can currently be done in AIPS.

Data reduction techniques for VLBI spectral line polarimetry are discussed by Kemball, Diamond, & Cotton (1995) and Kemball (1999).

18 VLBA/EVN/GLOBAL PROPOSALS

18.1 Preparing a Proposal

After composing the scientific justification and identifying the desired VLBI target source(s), select an appropriate VLBI array. Possibilities include:

1. The VLBA alone (SC, HN, NL, FD, LA, PT, KP, OV, BR, and MK), with the possible inclusion of the VLA. The VLA can be requested in either phased array or single antenna mode. Consult Wrobel & Taylor (2001) for information on VLBI at the VLA. Proposal deadlines are February 1, June 1, and October 1. Observing periods for such programs are identical to those for the VLA and are advertised regularly in the NRAO Newsletter at *http://www.nrao.edu/news/newsletters/* .

Observing time is allocated by the VLA/VLBA Scheduling Committee. Approved VLBA programs are scheduled by the VLBA scheduler Barry Clark (see Section 26.3). Ulvestad (1999b) provides a short guide to using the VLBA, aimed specifically at inexperienced users but also useful to fill in knowledge gaps for more experienced users.

2. The European VLBI Network (EVN). The EVN consists of a VLBI network of antennas in Europe and Asia operated by an international consortium of institutes (Schilizzi 1995). The EVN home page at *http://www.jive.nl/jive/evn* provides access to the "EVN User Guide." That guide includes the "EVN Status Table," giving details of current observing capabilities of all EVN antennas; and the "EVN Call for Proposals," describing how to apply for observing time on the EVN. The EVN handles the proposing, refereeing, and scheduling mechanisms for such programs, which must all be run during a regular VLBI Network session. EVN proposal deadlines are February 1, June 1, and October 1. VLBI Network session dates and wavelengths are announced in the "EVN Call for Proposals" and in the NRAO Newsletter at *http://www.nrao.edu/news/newsletters/* . Observing time is allocated by the EVN Program Committee. Approved EVN programs are scheduled by the EVN scheduler R. Schwartz. Any EVN proposal requesting the VLBA or two or more of the non-EVN VLBA affiliates identified in Item 3 below constitutes a global proposal, and must be submitted to both the VLBA and the EVN.

3. VLBA affiliates in addition to the VLA currently include Effelsberg and the Deep Space Network. A VLBA proposal requesting such affiliates is handled as described in Item 1 above, except that if two or more EVN institutes are requested, then it is a global proposal and must be submitted to both the VLBA and the EVN. A VLBA program involving affiliates other than the VLA might be run outside of a regular VLBI Network session, depending on which affilliates are involved. In particular, about 20 days of time per year, outside of regular VLBI Network sessions, has been reserved for joint VLBI programs involving the VLBA and Effelsberg; submit proposals for such joint time both to the NRAO and to the EVN scheduler.

Once the appropriate VLBI array is selected, run the NRAO `SCHED` program (Walker 2001) to determine the Greenwich Sidereal Time range during which the VLBI target sources are up at the selected antennas. This program can also be used to evaluate the *u-v* plane coverage and synthesized beams provided by the selected antennas (see Section 9).

If the proposal requests use of the VLBA correlator, then the proposed observing strategies must adhere to the guidelines summarized by Romney (1999b). Proposed observing modes, whether in VLBA formats or VLBA-compatible Mark 4 formats, can be be selected from modes tabulated by Romney (1999c). Requirements for source position accuracy at correlation time are discussed by Ulvestad (1999b). An accurate source position service is available through NRAO, but requests to it should be made no later than proposal time for positions needed at correlation time (Walker 1999a).

VLBA proposals may also be supplemented with plans for dissertation research and/or requests for long-term acceptance; for further details, see the NRAO Newsletter dated 1999 October 1 and available through *http://www.nrao.edu/news/newsletters/* . A proposal requesting more than about 300 hours of total time, even over the long term, may trigger a "skeptical review" described at *http://www.cv.nrao.edu/~abridle/lpc/lpc.htm* .

18.2 Submitting a Proposal

Cover sheets for VLBA or Global VLBI proposals are available through *http://www.nrao.edu/administration/directors_office/vlba-gvlbi.shtml* . That link also describes how to submit completed VLBA proposals by e-mail to "propsoc@nrao.edu" or by regular mail to Director, NRAO, 520 Edgemont Road, Charlottesville, Virginia 22903-2475, USA; and how to submit completed EVN proposals by e-mail to "proposevn@HP.mpifr-bonn.mpg.de" or by regular mail R. Schwartz, EVN Scheduler, MPIfR, Auf dem Hügel 69, D-53121 Bonn, GERMANY. VLBA proposals requesting Effelsberg and Global VLBI proposals must be submitted to both the NRAO and the EVN.

Proposals requesting antennas unaffiliated with the VLBA or the EVN must be sent to the directors of those antennas.

19 PREPARATION FOR OBSERVING

Users allocated VLBA observing time will be sent instructions for preparing observing schedules. Most users will be assigned an AOC contact person.

20 DURING OBSERVING

Each VLBA program is run remotely from the AOC by VLBA operations. No observing assistance by a VLBA user is expected, although VLBA operations should be able to reach the observer by telephone during the program. As the program progresses, the array operator monitors the health and state of the antennas and tape recording systems, mainly using a compact yet comprehensive display program. Remote observers can access this display over the Internet by logging in to "jansky.aoc.nrao.edu" as user "vldis". Various logging, calibration, and flagging data are automatically recorded by the monitor and control system running on the station computer at each VLBA site. If necessary, the array operator can request local assistance from a site technician at each VLBA antenna. Recorded tapes are automatically shipped from each VLBA antenna to the correlator specified by the observer.

21 POST-PROCESSING SOFTWARE

21.1 NRAO AIPS

AIPS is a set of programs for the analysis of continuum and line VLBI observations involving one or more BB channel. These programs are available for a wide range of computer operating systems. Section 26.1 gives contact information. Extensive on-line internal documentation can be accessed within AIPS. An entire chapter in the AIPS Cookbook (NRAO staff, 2001) provides useful "how-to" guidance for those reducing VLBI data, including discussion of VLBA calibration transfer, space VLBI, polarimetry, and phase referencing. Ulvestad (2001) provides a step-by-step guide to calibrating many types of VLBA data sets in AIPS, and includes an appendix describing calibration modifications for VLBA+VLA data sets.

21.2 AIPS++

AIPS++ has been publicly released but does not yet offer an end-to-end reduction path for VLBA data. Consult the document "Getting Started in AIPS++" for details on using AIPS++ and an introduction to its capabilties. That document is available from the AIPS++ home page accessed through *http://www.nrao.edu/software* . Section 26.1 gives contact information.

21.3 The Caltech VLBI Analysis Programs

The Caltech VLBI Analysis Programs are a set of programs for the planning and analysis of continuum VLBI observations. These programs are available for VAX/VMS, Sun UNIX, and Convex UNIX. A summary of the major programs can be found in the Bulletin of the American Astronomical Society, volume 23, page 991, 1991. Shepherd (1997) describes the related Caltech program `DIFMAP`. Section 26.1 gives contact information.

22 SPACE VLBI

Some VLBA observing time has been allocated for co-observations with the first dedicated space VLBI mission, VSOP/HALCA. Proposals for co-observations with VSOP are submitted directly to the VSOP mission rather than to the NRAO. For more information on VSOP, see the VSOP home page at *http://www.vsop.isas.ac.jp/* . For a variety of information on the VLBA activities in support of VSOP, see the NRAO Space VLBI Program home page accessed through *http://www.nrao.edu/telescopes* .

VLBA programs using VSOP have some different characteristics from other VLBA programs. First, the observing schedules for the VLBA are prepared by the VSOP Science Operations Group in order to take account of the constraints on the spacecraft observations, and need not be generated by the investigators. Second, the spacecraft frequency reference is provided in series by several of a total of five tracking stations, and the wideband spacecraft data are recorded separately on tapes at each of these tracking stations. This makes the process of correlation, which requires multiple wideband recordings for the spacecraft, as well as multiple clock corrections and the spacecraft ephemeris, considerably more complex. Finally, although the standard VLBA calibration data are available as discussed in Sections 14 and 15, the spacecraft data calibration and fringe-fitting is considerably more complex, owing to (1) the inability to observe fringe-finders for each program; (2) the rapid change in projected baseline length during the spacecraft orbit; and (3) the clock jumps that will occur at each tracking-station hand-off. For further information about processing of VLBA data taken together with an orbiting element, investigators should consult Ulvestad (1999d) or contact one of the "space VLBIers" identified in Section 26.3.

23 VISITING THE AOC

VLBA users are strongly encouraged to make post-processing visits to the AOC. This is especially recommended for users dealing with data processed on the VLBA correlator. The VLBA correlator is scheduled independently of the array: this means that you cannot assume that the correlated data will be available after any given time. Contact one of the

data analysts identified in Section 26.3 to determine if the correlated data are available before arranging a visit. Once the data are available, visitors should contact the AOC reservationist Selfa Lucero (see Section 26.3) at least one week prior to their visit; this timing is needed to optimize the logistics of visitor accommodation, transportation, workstation use, and AOC staff assistance. This contact can be made using the interactive Visitor's Registration Form available through the VLBA astronomer page at *http://www.aoc.nrao.edu/vlba/html/vlbahome/observer.html* or by sending e-mail to "nmreserv@nrao.edu" or by phoning the reservationist. Students visiting for their first VLBA data reduction trip must be accompanied by their faculty advisor. Standard NRAO travel reimbursement policy applies to VLBA data reduction trips; details are posted at
http://www.nrao.edu/administration/directors_office/nonemployee_observing_travel.shtml .

24 DATA ARCHIVE AND DISTRIBUTION

An archive of all output from the VLBA correlator is maintained at the AOC. The user(s) who proposed the observations will retain a proprietary right to the data for a fixed interval of 18 months following the end of correlation of the last observations requested in the original proposal or a direct extension of that proposal. Thereafter, archived data will be available to any user on request.

Data are distributed to users on a variety of media, with DAT and Exabyte currently given primary support. For the initial distribution to the user proposing the observations, this will occur automatically, soon after correlation is complete, provided a medium has been specified. Distributed data will conform to the new FITS binary table standard for interferometry data interchange (Flatters 1998), which is read by AIPS task `FITLD`.

25 PUBLICATION GUIDELINES

Any papers using observational material taken with NRAO instruments (VLBA 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.*

Further information concerning NRAO preprint requirements and page charge policy can be accessed at *http://www.nrao.edu/library/page_charges.shtml* .

Students whose dissertations include observations made with NRAO instruments are expected to donate up to four physical copies of their theses to the NRAO library. Unbound paper copies are acceptable, as the library will arrange for their binding. A single copy as a pdf file on a CD is also acceptable. Please mail all copies of donated theses to: Library, NRAO, 520 Edgemont Road, Charlottesville, Virginia 22903-2475, U.S.A.

26 RESOURCE LISTS

26.1 Software

The following programs or software packages will be of interest to VLBA users, for planning observations and/or for post-processing VLBA data:

1. NRAO `SCHED`: Contact Craig Walker (see Section 26.3) or consult Walker (2001).

2. NRAO AIPS: Contact AIPS Group, NRAO, 520 Edgemont Road, Charlottesville, Virginia 22903-2475, USA; e-mail "aipsmail@nrao.edu"; AIPS home page accessed through *http://www.nrao.edu/software*

3. AIPS++: Contact e-mail "aips2-request@nrao.edu"; AIPS++ home page accessed through *http://www.nrao.edu/software*

4. Caltech VLBI Analysis Programs: Contact T.J. Pearson, Astronomy Department 105-24, Caltech, Pasadena, California 91125, USA; phone +1-818-395-4980; FAX +1-818-568-9352; e-mail "tjp@astro.caltech.edu"; home page at *http://astro.caltech.edu/~tjp/citvlb*

26.2 Documents and Articles

A list of documents and articles referred to in this document follows. Printed copies of documents marked by an asterisk (*) are available from Lori Appel (see Section 26.3). Numerous articles from two books appear; abbreviations for these books and complete references for them are as follows:

VLBI & the VLBA = Very Long Baseline Interferometry and the VLBA, Astronomical Society of the Pacific Conference Series, Volume 82, eds. J.A. Zensus, P.J. Diamond, & P.J. Napier.

Synthesis II = Synthesis Imaing in Radio Astronomy II, Astronomical Society of the Pacific Conference Series, Volume 180, eds. G.B. Taylor, C.L. Carilli, & R.A. Perley.

1. Beasley, A.J., & Conway, J.E. 1995, in *VLBI & the VLBA*, p. 327. *http://www.nrao.edu/library/meetings.shtml*

2. Benson, J.M. 1995, in *VLBI & the VLBA*, p. 117. *http://www.nrao.edu/library/meetings.shtml*

3. Benson, J.M. 1998, Pulsar Gate Observers Guide. *http://www.aoc.nrao.edu/vlba/html/vlbahome/observer.html*

4. Bridle, A.H., & Schwab, F.R. 1999, in *Synthesis II*, p. 371.

5. Briggs, D.S., Schwab, F.R., & Sramek, R.A. 1999, in *Synthesis II*, p. 127.

6. Browne, I.W.A., Patnaik, A.R., Wilkinson, P.N., & Wrobel, J.M. 1998, Monthly Notices of the Royal Astronomical Society, 293, 257.

7. Conway, J.E., & Sault, R.J. 1995, in *VLBI & the VLBA*, p. 309. *http://www.nrao.edu/library/meetings.shtml*

8. Cornwell, T.J. 1995, in *VLBI & the VLBA*, p. 39. *http://www.nrao.edu/library/meetings.shtml*

9. Cornwell, T.J., Braun, R., & Briggs, D.S. 1999, in *Synthesis II*, p. 151.

10. Cornwell, T.J., & Fomalont, E.B. 1999, in *Synthesis II*, p. 187.

11. Cotton, W.D. 1995a, in *VLBI & the VLBA*, p. 189. *http://www.nrao.edu/library/meetings.shtml*

12. Cotton, W.D. 1995b, in *VLBI & the VLBA*, p. 289. *http://www.nrao.edu/library/meetings.shtml*

13. Cotton, W.D. 1999a, in *Synthesis II*, p. 111.

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26.3 Key Personnel

Table 4 gives the primary work locations, telephone extensions, room numbers, and area of responsibilities and/or expertise of key NRAO personnel who are available to assist the VLBA user community. An individual can be contacted through e-mail via their NRAO username constructed from their first initial followed by their last name, with a maximum of 8 letters. Address e-mail enquiries to "username@nrao.edu". In Table 4, "AOC" refers to the Array Operations Center (phone +1-505-835-extension), "VLA" refers to the Very Large Array (phone +1-505-835-extension), and "CV" refers to Charlottesville (+1-804-296-extension).

Table 4: **Resource List of Key Personnel**

Name	Location	Extension	Room	Responsibilites and/or Expertise
Lori Appel	AOC	7310	340	printed user information
Raul Armendariz	AOC	7187	144	frequency coordinator, RFI
Terry Bartelt	VLA	7409	221	VLA lead array operator
John Benson	AOC	7399	366	correlator software, pulsar gating
Chris Carilli	AOC	7306	356	spectral line VLBI
Barry Clark	AOC	7268	308	scheduling, VME systems
Mark Claussen	AOC	7284	268	spectral line VLBI, PT link
Vivek Dhawan	AOC	7378	310	mm VLBI
Steve Durand	AOC	7103	138	formatter, recording/playback
Lisa Foley	AOC	7235	205	data analyst
Ed Fomalont	CV	0232	na	phase-referencing pulsars
Miller Goss	AOC	7300	336	NRAO assistant director for VLA/VLBA
Eric Greisen	AOC	7236	318	AIPS
Robyn Harrison	AOC	7240	269	tape librarian, VLBA webmaster
Ken Hartley	AOC	7239	204	data analyst
Clint Janes	AOC	7430	180	electronics head
Leonid Kogan	AOC	7383	312	AIPS
Selfa Lucero	AOC	7357	218	visitor registration[a]
Dave Medcalf	AOC	7254	275	VLBA array operations supervisor
Amy Mioduszewski	AOC	7263	208	AIPS
Peggy Perley	AOC	7214	282	operations head
Mike Revnell	AOC	7293	284	correlator hardware
Jon Romney	AOC	7360	304	space VLBI
Lew Serna	VLA	7322	105	engineering services head
Meri Stanley	AOC	7238	204	lead data analyst
Greg Taylor	AOC	7237	358	polarimetry, VLBI at VLA
Steve Thompson	AOC	7230	277	VLBA correlator operations supervisor
Jim Ulvestad	AOC	7298	256	scientific services head, AIPS head
Gustaaf van Moorsel	AOC	7396	348	computing head
Craig Walker	AOC	7247	314	SCHED, pointing
Joan Wrobel	AOC	7392	302	VLBI at VLA, scheduling
Jason Wurnig	AOC	7359	204	data analyst

Notes: (a) E-mail "nmreserv@nrao.edu".