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 (Kellermann & Thompson 1985; Napier *et al.* 1993). It is the first astronomical array dedicated to observing by the method of Very Long Baseline Interferometry (VLBI), pioneered in the 1960s. Unlike existing VLBI networks, 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. VLBA observations conducted in VLBA (Romney 1990) and Mark III (Rogers *et al.* 1983) data formats can acquire simultaneous dual circular polarizations from any single receiver or from the 13/4 cm receiver pair. Also, a comprehensive and user-friendly NRAO schedule preparation program, called `VLBA OBSERVE`, is currently under development. The primary limitation of the VLBA when compared to existing VLBI networks is the small diameter of the VLBA antennas. This limitation was dictated by the combined constraints of array construction cost, the preference for 10 antennas, and the desire that the antennas work efficiently at millimeter wavelengths.

This document's primary intent is to provide in concise form the minimal information needed to formulate technically sound proposals for observing time on VLBA antennas. Its secondary aim is to provide resource lists of relevant software and documentation, plus key NRAO personnel who can be consulted for further, more detailed information. This document will be updated regularly, with updates being paper mailed to everyone on the VLA/VLBA master address list. If you want a paper copy of this document, then request one from Meri Stanley (see Section 26.3); she will also add you to the master list so you will automatically receive printed updates. This document is also available electronically via anonymous-guest FTP as a LaTeX PostScript file with name "obssum.vlba.ps" in directory "pub" on host "zia.aoc.nrao.edu" (146.88.1.4). When this document is updated, abstracts of any major changes will be announced via the NRAO VLBI e-mail exploder and the NRAO Newsletter. Anyone wanting to be added to this exploder should send an appropriate mail message to "vlbi-request@nrao.edu".

Where possible, the symbols used in this document are the same as those in *Synthesis Imaging in Radio Astronomy*, 1989, edited by R.A. Perley, F.R. Schwab, & A.H. Bridle, published as Volume 6 of the Astronomical Society of the Pacific Conference Series. However, the present document introduces some new symbols as well.

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 (Wade 1989), plus the 2 character codes used to identify the antennas. 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.

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 accummulation will also be avoided.

4 FREQUENCIES

Table 2 gives the frequency ranges for the 9 receiver/feed combinations now available on all 10 VLBA antennas. Ranges as measured by Biretta (1991) are given where available; *these correspond to the frequencies at which the zenith system equivalent flux densities (SEFD) in Jy increase by a factor of 1.4*, and although they are based on only a few antennas at each wavelength, the similarity among the antennas suggests that the results apply to the entire VLBA. Frequency ranges based on nominal design specifications, rather than measurements at the antennas, are indicated.

Also appearing in Table 2 are parameters characterizing the performance of a typical VLBA antenna for the various receiver/feed combinations. Columns [3] and [4], respectively, give typical VLBA zenith $SEFD$s and typical VLBA zenith opacity-corrected gains in K Jy^{-1}. These were obtained by averaging right circularly polarized (RCP) and left circularly polarized (LCP) values from 7-10 antennas at 90-1 cm (Walker 1992, plus updates) and from 8 antennas at 7 mm (Dhawan & Zensus 1993). 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; both of these characteristic values assume an aggregate recording bit rate equal to the "sustainable" limit of 128 Mbits per second (Mbps) (see Section 5.16). No $\Delta S^{128,2\rm m}$ or $\Delta I_{\rm m}^{128,8\rm h}$ entries are given for 90 and 50 cm because adequately wide bandwidths cannot be obtained. Entries for 7 mm are also not given, since a

2-minute fringe-fit interval is unrealistically long.

PT has an additional receiver at 3 cm, with zenith $SEFD$s of 715 Jy and 561 Jy for RCP and LCP, respectively; and zenith gains of 0.130 K Jy^{-1} and 0.166 K Jy^{-1} for RCP and LCP, respectively. The frequency range of this receiver is 10.2-11.2 GHz, based on the design specifications.

Opacity-corrected zenith gains are needed for current continuum amplitude calibration techniques. These zenith gains vary from antenna to antenna, and will be monitored by VLBA operations and communicated to users (see Section 21). The typical values appearing in Table 2 are meant to be illustrative only.

As indicated in the footnotes to Table 2, RFI is known to be a problem at all VLBA sites at 90 cm and 50 cm. RFI is also problematic at some sites at some times within the 20 cm and 13 cm regions. The AOC frequency coordinator, Bill Brundage (see Section 26.3), can be consulted for details.

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.

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 AOC 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.

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

Receivers and Feeds	Frequency Range [GHz]	Typical Zenith *SEFD* [Jy]	Typical Zenith Gain [K Jy^{-1}]	$\Delta S^{128,2m}$ [mJy]	$\Delta I_{m}^{128,8h}$ [μJy $beam^{-1}$]
90 cm	0.312 - 0.345[a]	2075	0.107	...	...
50 cm	0.600 - 0.630[b]	2191	0.086	...	...
20 cm	1.30 - 1.70[c]	298	0.100	4.8	46
13 cm	2.13 - 2.35	332	0.092	5.3	51
13 cm[d]	2.13 - 2.35	420	0.076	6.8	65
6 cm	4.50 - 5.14	296	0.129	4.8	46
4 cm	7.88 - 8.93	314	0.116	5.1	49
4 cm[d]	7.88 - 8.93	398	0.110	6.4	62
2 cm	12.0 - 15.4[e]	510	0.111	8.2	79
1 cm	21.1 - 24.6	930	0.092	15	144
7 mm	42.3 - 43.5[e]	1851	0.064	...	...

Notes:
(a) Entire range not usable due to narrrow band radio frequency interference (RFI); see Biretta (1991).
(b) Entire range not usable due to television interference; see Biretta (1991). A filter passing 609-613 MHz is routinely used at all antennas. Although this filter can be removed, its removal is *not* recommended.
(c) UPPER LIMIT: Biretta's upper limit of 1.70 GHz was measured using a bandwidth of 16 MHz, indicating that broad band observations above that frequency will be problematic. The design specification upper limit is 1.75 GHz to accommodate the 1.72 GHz OH line. The 20 cm receiver/feed should permit narrow band (e.g., OH line) work at 1.72 GHz, but the success of such observations will depend upon the RFI environment. LOWER LIMIT: FD and KP have additional filters to limit local radar RFI below 1350 MHz. The local radar RFI at SC is so extreme that SC's IF converter output is filtered to pass only 700 to 1000 MHz; consequently, multi-frequency synthesis observations involving SC require two front end synthesizer settings to span the 20 cm band and so *cannot* be done simultaneously.
(d) With 13/4 cm dichroic.
(e) Design specification.

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 Section 5.4 and Section 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) tranmitter 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 in or out (combines several slow input signals onto one tape track or spreads one fast input signal over several tape tracks), establishes the barrel roll, 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 III data formats are supported. Up to 16 pulse cal tones will be detectable simultaneously, but this is not yet implemented. 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 (if, for example, a head dies). 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 1 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 for 1 tape drive. A doubling of this aggregate bit rate will be possible once each VLBA antenna is equipped with two tape drives and appropriate software is available. 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 at 128 Mbps or by arranging that the duty cycle (ratio of recording time to total allocated time) be less than unity. Rare, particularly meritorious projects may request exemption from the sustainable bit rate limit.

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 AOC operators or by the site technicians. All systems are set as requested in the current schedule for each new observation. The site is very dependent on the site computer. Almost nothing can be set by hand.

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 Mark II System

The Mark II (Clark 1973) formatter accepts data from a sideband of BBC number 1 plus the 5 MHz signal from the maser, keeps time, samples the data, formats it for recording, and sends it at 4 Mbps to modified home video cassette recorders (VCRs). An interface to the site computer allows the formatter status to be checked and the input BBC sideband to be selected. The interface also has a data quality analyzer to allow playback checks of the VHS tapes loaded in the VCRs. A VHS tape can hold 4 hours of data. A Mark II system includes 4 or 5 VCRs, to allow Mark II recording with infrequent tape changes. Mark II system are available at all VLBA antennas except KP, LA, and FD.

5.20 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, Mark III, and Mark II formats. Characteristics of observations recorded in VLBA format are described in Section 5 and elsewhere in this document. Mark III 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.

Single-channel Mark II recording is supported at all VLBA antennas except KP, LA, and FD; simultaneous dual-polarization observations obviously cannot be made in this mode. Mark II recording capability will continue to be supported by the VLBA as long as there is significant user demand.

The VLBA cannot record in the Japanese K4 format or the Canadian S2 format.

7 CORRELATORS

7.1 VLBA

The VLBA correlator accommodates the full range of scientific investigations for which the Array was designed. It supports wideband continuum, high-resolution spectroscopy, bandwidth synthesis, and polarimetric observations, as well as more specialized techniques such as simultaneous multiple frequencies or phase centers, frequency or phase-center switching, and pulsar gating.

The correlator is designed to process all observations involving VLBA stations. With its 20-station capacity and extensive 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 either VLBA or Mark III longitudinal format, but not in Mark II format.

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 the 2048-point limit implies the maximum spectral resolution is 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 includes amplitude and phase calibration data obtained at observe time, and editing flags from both observing stations and the correlator. All results are archived on digital-audio-tape (DAT) cassettes. The output data rate is limited administratively 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 station logs generated from the VLBA array control system's monitor data. A scheme for inserting log information from foreign stations has yet to be determined. A few additional items (all of which have been mentioned above) are specified by the user as part of the observation schedule via the `VLBA OBSERVE` program, although it is possible to modify these inputs prior to correlation if necessary. Supervision of the correlation process will be the responsibility of VLBA operations personnel; user participation during correlation is not expected (nor easily arranged, as explained below).

Scheduling of the correlator is automated, applying rudimentary artificial intelligence techniques 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.

Astronomical testing of the correlator is currently under way. It is expected to become available for selected VLBA projects shortly, and to take over correlation of all intra-VLBA observations during the summer of 1993. The modified transition plan from US VLBI Network operations to the VLBA calls for transfer of correlation responsibilities to be completed at the end of December 1993. *During the transition period, observing projects requiring use of the VLBA correlator will only be scheduled as warranted by the development of correlator capabilities and capacity. Users should realize that such projects may be subject to delay.*

7.2 Mark III

Mark III projects run on VLBA antennas can be processed on existing Mark III correlators, such as the Haystack/MIT correlator operated by Haystack Observatory near Westford, Massachusetts (contact: R.B. Phillips, Haystack Observatory, Off Route 40, Westford, Massachusetts 01886, USA) and the Bonn correlator operated by the Max-Planck-Institut für Radioastronomie (MPIfR) in Bonn, Germany (contact: W. Alef, MPIfR, Auf dem Hügel 69, D-W-5300 Bonn 1, GERMANY; starting 1993 July 1 use MPIfR, Auf dem Hügel 69, D-53121 Bonn, GERMANY). Usage rules for the Bonn correlator appear in Alef, Garrett, & Mantovani (1991; the European VLBI Network [EVN] Handbook hereafter). The EVN Handbook can be obtained through account VLBINFO on ASTBO1. The Internet address is "astbo1.bo.cnr.it" (137.204.51.1). Span access is via ASTBO1::VLBINFO or 38057::VLBINFO.

7.3 Mark II

Mark II projects run on VLBA antennas must be processed on a Mark II correlator. Most such continuum projects are processed on the 16-station Caltech/JPL Mark II correlator operated by Caltech in Pasadena, California. This correlator currently provides in absentia processing as a service to the VLBI community (contact: S.C. Unwin, Astronomy Department 105-24, Caltech, Pasadena, California 91125, USA). However, operation of this Mark II correlator will be phased out by the end of 1993. Proposers of Mark II projects requiring correlation after 1993 must have made prior arrangement for access to correlation facilities.

8 ANGULAR RESOLUTION

Table 3 gives the maximum lengths rounded to the nearest km ($B^{\rm km}_{\rm max}$) 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 ($\theta_{\rm HPBW}$) in milliarcseconds (mas) is

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

where $\lambda^{\rm cm}$ is the receiver wavelength in cm. A uniformly weighted image made from a long u-v plane track will have a synthesized beam with a slightly narrower minor axis FWHM. For the longest VLBA baseline, $\theta_{\rm HPBW}$ ranges from 20 to 0.2 mas as the wavelength runs from 90 cm to 7 mm.

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

	SC	HN	NL	FD	LA	PT	KP	OV	BR	MK
MK	8612	7503	6156	5135	4970	4796	4467	4015	4399	...
BR	5767	3658	2300	2346	1757	1806	1914	1214	...	4399
OV	5461	3886	2328	1508	1088	973	845	...	1214	4015
KP	4840	3623	2076	744	652	417	...	845	1914	4467
PT	4580	3227	1664	565	237	...	417	973	1806	4796
LA	4459	3007	1433	609	...	237	652	1088	1757	4970
FD	4144	3106	1655	...	609	565	744	1508	2346	5135
NL	3645	1611	...	1655	1433	1664	2076	2328	2300	6156
HN	2853	...	1611	3106	3007	3227	3623	3886	3658	7503
SC	...	2853	3645	4144	4459	4580	4840	5461	5767	8612

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° 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 currently be generated by program `PC-SCHED` distributed by Haystack Observatory; Section 26.1 describes how to obtain this program. u-v plots can also be calculated with program `HAZI` distributed with the Caltech VLBI Analysis

Programs. See Section 26.1 for instructions on how to obtain this software. Both `PC-SCHED` and `HAZI` require coordinates for VLBA antennas. This information is improving rapidly, and NRAO staff will attempt to communicate the latest coordinate information to the keepers of `PC-SCHED` and `HAZI`. An NRAO `VLBA OBSERVE` program is currently under development (see Section 20). Among its various project planning tools will be the ability to produce u-v plots.

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

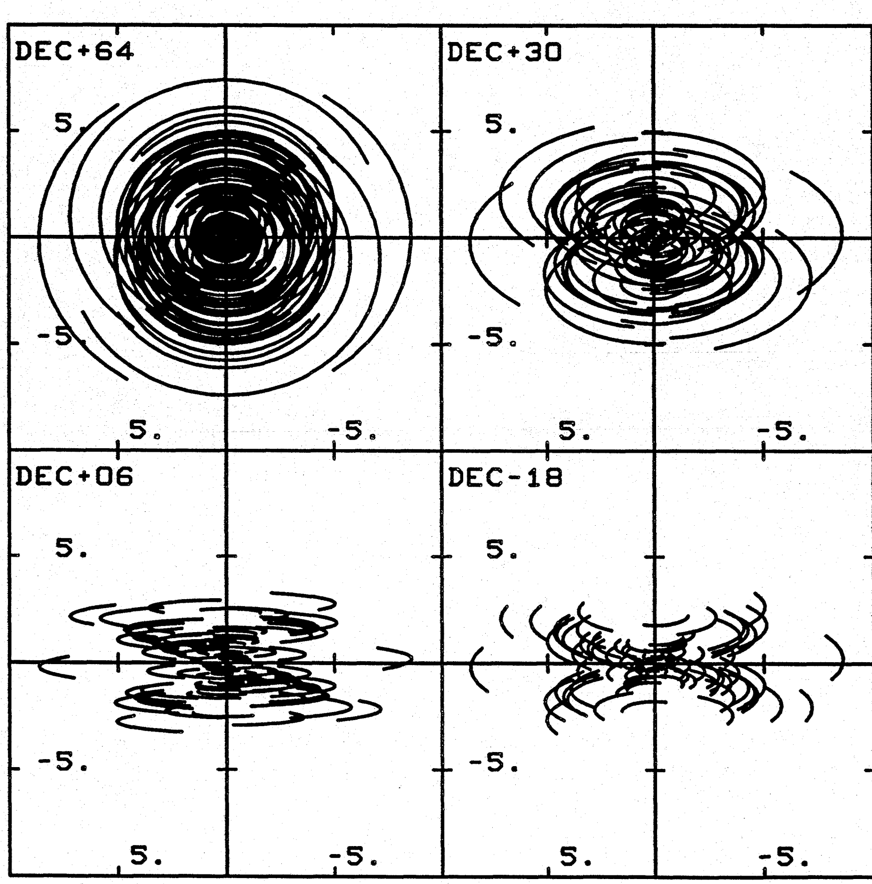
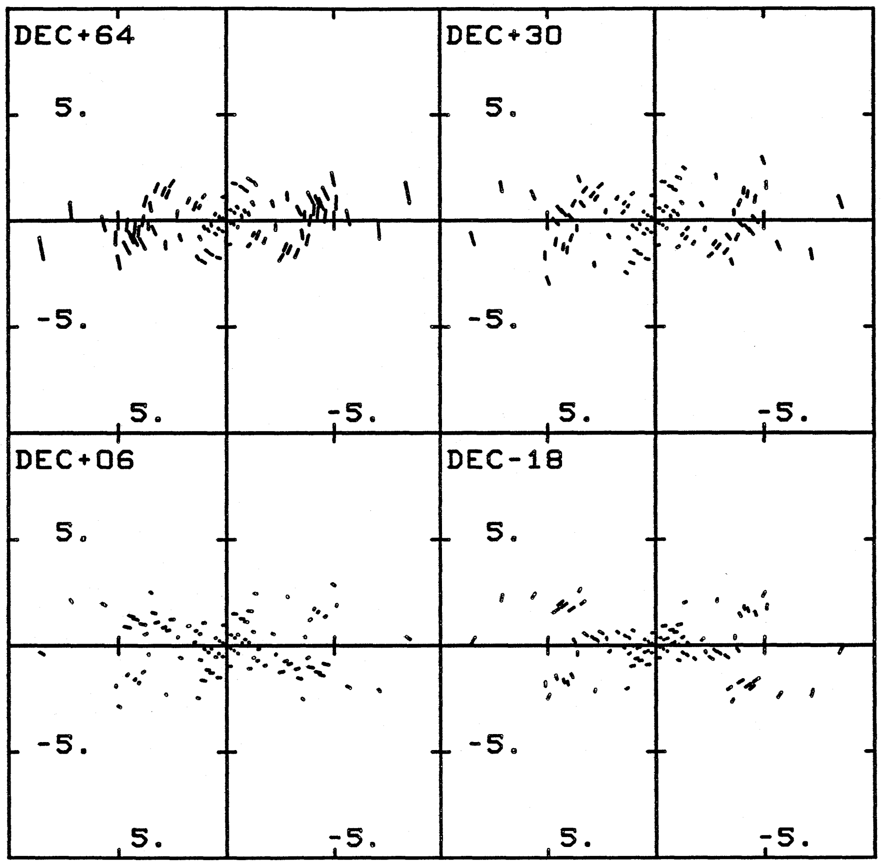


Figure 2: **VLBA u-v plane coverage at four declinations. Single "snapshot" tracks at New Mexico transit. Plotted range is ± 9000 km.**



10 TIME RESOLUTION

Time resolution is set by the VLBI correlator accumulation time. At the VLBA correlator it will be 1 or 2 seconds for most projects, although a minimum accumulation time of 131 milliseconds will be available for special projects. Pulsar gating is planned for the VLBA correlator but an estimate of its implementation date is not currently available.

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 7.1. 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.

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 1989b; Crane & Napier 1989):

$$\Delta S = \frac{1}{\eta_s} \times \frac{SEFD}{\sqrt{2 \times \Delta\nu \times \tau_{\rm ff}}} \ \text{Jy}. \tag{2}$$

In Equation 2, $\eta_s \leq 1$ accounts for the VLBI system inefficiency (e.g., quantization in the data recording and correlator approximations). Assume $\frac{1}{\eta_s} \sim 2$ for Mark II and III data; values are still to be determined for the VLBA. $\Delta\nu$ is the bandwidth [Hz]; use the full recorded bandwidth for a continuum target and use a spectral channel for a line target. $\tau_{\rm ff}$ is the fringe-fit interval [s], which should be less than or about equal to the coherence time $\tau_{\rm atm}$. 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. The following very rough coherence times can be expected (Moran 1989a): $\tau_{\rm atm} \sim$ 1600 s at 1 GHz, 160 s at 10 GHz and 16 s at 100 GHz. The actual coherence time appropriate for a given VLBA project 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 ($\Delta I_{\rm m}$) expected in a *single-polarization* image, assuming natural weighting (Walker 1989b; Crane & Napier 1989):

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

where $\eta_{\rm s}$ is discussed in Section 12; N is the number of VLBA antennas available; $\Delta\nu$ is the bandwidth [Hz]; and $t_{\rm int}$ 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 $\Delta I_{\rm m}$ per polarization, then then for an image of Stokes I, Q, U, or V,

$$\Delta I = \Delta Q = \Delta U = \Delta V = \frac{\Delta I_{\rm m}}{\sqrt{2}}. \tag{4}$$

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

$$\Delta P = 0.655 \times \Delta Q = 0.655 \times \Delta U. \tag{5}$$

It is sometimes useful to express $\Delta I_{\rm m}$ in terms of an RMS brightness temperature in Kelvins ($\Delta T_{\rm b}$) measured within the synthesized beam. An approximate formula for a *single-polarization* image is

$$\Delta T_{\rm b} \sim 320 \times \Delta I_{\rm m} \times (B^{\rm km}_{\rm max})^2 \ \ \text{K}, \tag{6}$$

where $B^{\rm km}_{\rm max}$ is as in Equation 1. The numerical coefficient in Equation 6 differs slightly from that given by Fanti (1989), who assumes a beam area equal to the square of Equation 1; Equation 6 assumes a Gaussian beam area, which is 1.13 times the square of Equation 1.

14 AMPLITUDE CALIBRATION

Traditional calibration of VLBI fringe amplitudes for continuum sources requires knowing the on-source system temperature in Jy ($SEFD$; Cohen *et al.* 1975; Walker 1989a). System temperatures in degrees K ($T_{\rm sys}$) are measured "frequently" in each BB channel during observations with VLBA antennas; "frequent" means at least once per observation or once every 2 minutes, whichever is shortest. These $T_{\rm sys}$ values are currently delivered to VLBA users in machine readable files that can be read by fringe amplitude calibration programs such as `ANCAL` in the NRAO Astronomical Image Processing System (AIPS) or `CAL` in the Caltech VLBI Analysis Programs.

The parameters and file style expected by these programs are documented in their respective help files. Such programs can be used to convert from $T_{\rm sys}$ 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 projects processed on the VLBA correlator, such amplitude calibration data will be delivered directly as tables in the FITS files archived and distributed by NRAO. Single-antenna spectra can be used to do amplitude calibration of spectral line VLBI projects (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. A scheme for doing opacity adjustments is desribed by Leppänen (1993). The VLBA antenna gain curves can be assumed to be flat at most wavelengths. However, at 2 cm, 1 cm, and 7 mm, the gain curves are *not* flat; we are currently in the process of systematically quantifying the gain curves at these wavelengths, and we plan to notify the user community once gain curves are available in tabulated form and/or as polynomial fits.

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 project. Table 4 gives a suggested list of such sources, selected because they are *likely* to be point-like on inner VLBA baselines at wavelengths of 6 cm and 4 cm. Other sources will be added in the future. VLBA observations of sources in Table 4 can be used (1) to assess the relative gains of VLBA antennas; (2) to test for non-closing amplitude and phase errors; and (3) to check the correlation coefficient scaling factor (traditionally called the b-factor), provided simultaneous source flux densities are available independent of the VLBA observations.

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 particulary 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

Table 4: **Suggested Amplitude Check Sources at 6 cm and 4 cm**

IAU Name (B1950)	J2000 Name	Common Name	J2000 R. A. [h m s]	J2000 Decl. [° ′ ″]	Position Ref.
0814+425	J0818+42	...	08 18 16.000011	42 22 45.41232	1
0850+581	J0854+57	...	08 54 41.99648	57 57 29.9234	2
0851+202	J0854+20	OJ287	08 54 48.875237	20 06 30.63898	1
1144+402	J1146+39		11 46 58.298146	39 58 34.30353	1
1308+326	J1310+32	...	13 10 28.664108	32 20 43.78262	1
1404+286	J1407+28	OQ208	14 07 00.394655	28 27 14.68981	1
1502+106	J1504+10	OR103	15 04 24.980092	10 29 39.20026	1
1611+343	J1613+34	DA406	16 13 41.064521	34 12 47.91010	1
1637+574	J1638+57	...	16 38 13.456457	57 20 23.98051	1
1642+690	J1642+68	...	16 42 07.848555	68 56 39.75764	1
1739+522	J1740+52	...	17 40 36.978094	52 11 43.40899	1

Notes:
Ref. 1=Ma *et al.* 1990, RMS accuracy ~ 1 mas
Ref. 2=Patnaik *et al.* 1992, RMS accuracy ~ 12 mas

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 such as the VLA. To allow accurate location of any previously unknown antennas and to allow NRAO staff to conduct periodic monitoring of clock drifts, each user should include at least one, and preferably two, "fringe finder" sources which are strong, compact, and have accurately known positions. The 6 sources listed in Table 5 are commonly used as fringe finders at centimeter wavelengths. (Warning: some of these may be unsuitable at some wavelengths on some VLBA baselines; we are still gaining experience using them.) Their positions, accurate to ~ 1 mas, are from Ma *et al.* (1990).

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

Table 5: **Suggested Fringe Finders at Centimeter Wavelengths**

IAU Name (B1950)	J2000 Name	Common Name	J2000 R. A. [h m s]	J2000 Decl. [° ′ ″]
0316+413	J0319+41	3C84	03 19 48.160533	41 30 42.10341
0552+398	J0555+39	DA193	05 55 30.806004	39 48 49.16340
0923+392	J0927+39	4C39.25	09 27 03.014167	39 02 20.85004
1226+023	J1229+02	3C273	12 29 06.700041	02 03 08.59840
1641+399	J1642+39	3C345	16 42 58.810180	39 48 36.99543
2251+158	J2253+16	3C454.3	22 53 57.748297	16 08 53.56305

the raw signals would be incoherent. A so-called "phase cal" or "pulse cal" system (Rogers *et al.* 1983, Alef 1989a) 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 older generator produces a train of very sharp, weak pulses at 1-microsecond intervals, which are injected into the signal path at the 13 cm and 4 cm receivers and serve to define the delay reference point for astrometry. These older generators are being replaced by improved ones that operate at all wavelengths and create 0.2 or 1 microsecond pulses. 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 in the new system). 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 III system but will be at the antenna in the VLBA. The pulse cal data will be logged as a function of time during observations with VLBA antennas, and included in the calibration information delivered to the user. AIPS software can be use to apply the pulse cal data.

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 (see Section 21) that can be passed easily to task `UVFLG` in AIPS. The old baseline-based fringe search methods have been replaced by more powerful global fringe search techniques (Schwab & Cotton 1983; Alef & Porcas 1986). 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 (Walker 1989a, c). Global fringe fitting in AIPS is done with program `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 (Walker 1989a). Usually such editing is done interactively using task `IBLED` in AIPS or program `IED` in the Caltech VLBI Analysis Programs.

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 because of inadequate removal of antenna-based instrumental phases. 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. Fourier transform imaging is straightforward (Sramek & Schwab 1989), and done with tasks `UVMAP` or `MX` in AIPS or program `INVERT` in the Caltech VLBI Analysis Programs. The resulting VLBI images are deconvolved to rid them of substantial sidelobes arising from relatively sparse sampling of the u-v plane (Cornwell & Braun 1989; Wilkinson 1989b). Such deconvolution is achieved with programs based on the CLEAN or Maximum Entropy methods in AIPS or in the Caltech VLBI Analysis Programs.

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 (Pearson & Readhead 1984; Cornwell & Fomalont 1989; Wilkinson 1989a; Walker 1989c). 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 `AMPHI` 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 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 (Cotton 1989b; Bridle & Schwab 1989; Perley 1989a; Fanti 1989). Measures of image correctness - image fidelity and dynamic range - are discussed in the VLA case by Perley (1989b) and in the VLBI case by Wilkinson (1987).

15.6 Phase Referencing

If the VLBA target source is not sufficiently strong for self-calibration and/or if absolute positional information is needed, then VLBA phase referenced observations must be employed (Alef 1989b; Lestrade 1991). 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 (Moran 1989b) will prevent accurate phase transfer. In the short term, VLBA users can draw candidate phase calibrators from the MERLIN phase calibrator grid of Patnaik *et al.* (1992), which will eventually be extended cover the entire Northern sky. Soon after the VLBA correlator achieves smooth operation, NRAO staff will begin a systematic survey of these MERLIN phase calibrators to determine which ones are compact enough to serve as good VLBA phase reference sources and to obtain improved reference source positions.

16 POLARIMETRY

In VLBA polarimetric observations, BB channels are assigned in pairs to opposite hands of circular polarization at each frequency. Such observation can be recorded in VLBA or Mark III format.

Although straight-forward conceptually, calibration of continuum polarimetery has traditionally been very difficult (Cotton 1989a; Roberts, Brown, & Wardle 1991). Steps that must be followed include normal amplitude calibration; fringe-fitting; self-caibration 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. The polarization calibration path in AIPS is currently being actively developed, tested, and documented (Cotton 1992). It includes powerful global fringe-fitting techniques to locate weak cross-polarized signals (Brown, Roberts, & Wardle 1989).

To permit calibration of the instrumental polarization at centimeter wavelengths, VLBA users should include observations of sources either with simple linearly polarized structure (e.g., 1404+286 = J1407+28 = OQ208, see Table 4) or no linearly polarized emission (e.g., 0316+413 = J0319+41 = 3C84, see Table 5). To set the absolute position angle of electric vectors on the sky, VLBA users will want to observe a source whose linear polarization is known at the epoch of their project. BL Lacertae objects can be used for this purpose (Gabuzda *et al.* 1992), with the caveat that their linearly polarized emission typically varies rapidly in time.

17 SPECTRAL LINE VLBI

Diamond (1989a, b) describes the special problems encountered during data acquisition, correlation, and post-processing of a spectral line VLBI project. The spectral line VLBA 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 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.

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 nearby continuum calibrator 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 (Walker 1981) or normal synthesis imaging and then form a spectral line cube. All these post-processing steps, except for fringe-rate mapping, can currently be done in AIPS.

18 ASTRONOMICAL READINESS

The VLBA is essentially at the end of its construction phase. However, one remaining limitation will be of interest to users: MK will not be fully staffed until the first quarter of 1994. Until MK is fully staffed, observations with it will be done on a best-effort basis. If you plan to submit a proposal for which MK is such a critical antenna that NRAO should make special efforts to have it available, then be sure to justify this in the proposal and note it on the proposal cover sheet.

19 PROPOSALS

19.1 Preparing a Proposal

After composing the scientific justification and identifing 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 as a VLBA affiliate. The VLA can be requested in either phased array or single dish mode; consult Wrobel (1991a, b) for information on VLBI at the VLA. Such a project, even if it includes the VLA, does not have to be run during a regular VLBI Network session. NRAO handles the proposing, refereeing, and scheduling mechanisms for such projects. Proposal deadlines are February 1, June 1, and October 1. Observing periods for such projects are identical to those for the VLA and are advertised regularly in the NRAO Newsletter. Observing time is allocated by the VLA/VLBA Scheduling Committee. Approved VLBA projects are scheduled by the VLBA scheduler Barry Clark (see Section 26.3).

2. The EVN. Prospective proposers can consult the EVN Handbook for updated information on EVN members and the capabilities of EVN

antennas. The EVN handles the proposing, refereeing, and scheduling mechanisms for such projects, 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 routinely announced by EVN mailings and in the NRAO Newsletter. Observing time is allocated by the EVN Program Committee. Approved EVN projects 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 include Arecibo, Effelsberg, the Deep Space Network, Green Bank, Medicina, and Noto. 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 project 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 projects involving the VLBA and Effelsberg; submit proposals for such joint time both to the NRAO and to the MPIfR.

Once the appropriate VLBI array is selected, run Haystack's `PC-SCHED` program or Caltech's `UPTIME` program to determine the Greenwich Sidereal Time range during which the VLBI target source(s) is (are) up at the selected antennas. Haystack's `PC-SCHED` program or Caltech's `HAZI` program can be used to evaluate the u-v plane coverage provided by the selected antennas (see Section 9). The NRAO `VLBA OBSERVE` program, currently under development, will include `UPTIME` and `HAZI`-like functions among its project planning tools; see Section 20.

Those proposing observations in VLBA format should consult files
"std_modes.vlba",
"bas_modes.vlba", and
"setup_names.vlba"
in directory "pub" on host "zia.aoc.nrao.edu" (146.88.1.4) to identify which VLBA setup(s) is (are) desired.

19.2 Submitting a Proposal

All VLBA proposals must be submitted with a VLBI Proposal Cover Sheet, which is available as described in Section 19.3. The cover sheet can be used to request the VLBA and/or VLBA affiliates. If the VLA is requested as an element of the VLBI array, then a separate VLA proposal is not needed. VLBA propoals should be sent to: Director, NRAO, 520 Edgemont Road, Charlottesville, Virginia 22903-2475, USA. All EVN proposals must be submitted with a VLBI Proposal Cover Sheet. EVN propoals should be sent to: R. Schwartz, EVN Scheduler, MPIfR, Auf dem Hügel 69, D-W-5300 Bonn 1, GERMANY (starting 1993 July 1 use MPIfR, Auf dem Hügel 69, D-53121 Bonn, GERMANY). Global VLBI observations require proposals to both the VLBA and EVN, using the addresses given above.

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

19.3 The VLBI Proposal Cover Sheet

A VLBI Proposal Cover Sheet must accompany all VLBA, EVN, and global proposals. Tex and ASCII versions of this cover sheet, authored by Barry Clark (see Section 26.3), can be obtained electronically by using anonymous-guest FTP on host "zia.aoc.nrao.edu" (146.88.1.4) to copy all files from directory /u/ftp/pub/vlbicover. The README file in that directory gives general instructions. Printed cover sheets, for filling in by `typewriter`, are available on request from Meri Stanley (see Section 26.3).

20 PREPARATION FOR OBSERVING

Users allocated VLBA observing time will be sent detailed observing schedule preparation instructions. Currently, the preparation of observing schedules for VLBA, Mark III, and Mark II format observations requires running software on AOC computers, with local assistance provided by the VLA/VLBA data analysts and AOC scientific staff. This arrangement ensures that observing schedules contain proper antenna electronics setup information and are fully compatible with current hardware and control software. Mark II and VLBA format projects are scheduled using program `SCHED` in the Caltech VLBI Analysis Programs. Mark III format projects are usually scheduled with Haytack's `PC-SCHED` program; the so-called DRUDG file output by PC-SCHED is translated at the AOC for use by the Caltech program SCHED, which is then used to create the VLBA observing schedules.

Eventually, an NRAO VLBA OBSERVE program will be widely distributed to the VLBA user community, allowing users to make complete and accurate VLBA observing schedules at their home institutions. VLBA OBSERVE is currently being prototyped by Wes Young (see Section 26.3). The base prototype consists of several parts: (1) antenna database; (2) source catalogs; (3) frequency setups catalog; (4) what's up; (5) schedule maker (VLBA, Mark III); (6) VLBA and VLA antenna control file generator; and (7) SNAP file generator. The base prototype will be available only for SparcStations or their clones running Openwindows or X11R5, and should be ready in 1993. Users will be welcomed to try out the prototype. Announcements of its availability and how to get it using anonymous-guest FTP will be made on the NRAO VLBI e-mail exploder and in the NRAO Newsletter. After some feedback on the prototype, construction of the official release, involving generic X-windows on many different computers, will commence. A VT100-terminal-based version will follow later.

21 DURING OBSERVING

Each VLBA project 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 project. As the project progresses, the VLBA 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 Internet by logging in to "vlbacc.aoc.nrao.edu" (146.88.3.2) 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 VLBA 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.

22 POST-PROCESSING SOFTWARE

22.1 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. See Section 26.1 for instructions on how to obtain this software. Extensive on-line internal documentation can be accessed within AIPS. Chapter 11 in the AIPS Cookbook provides useful "how-to" guidance for those reducing VLBI data. An AIPS Cookbook can be requested from Theresa McBride (see Section 26.3). More extensive documentation addressing VLBI calibration is currently in preparation.

22.2 The Caltech VLBI Analysis Programs

The Caltech VLBI Analysis Programs are a set of programs for the planning and analysis of continuum VLBI observations involving one BB channel. These programs are available for VAX/VMS, Sun UNIX, and Convex UNIX. A summary of the major programs can be found in Bulletin of the American Astronomical Society, volume 23, page 991, 1991. See Section 26.1 for instructions on how to obtain this software, along with its substantial on-line internal documentation.

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. Standard NRAO travel reimbursement policy applies to VLBA data reduction trips to the AOC. Visitors must contact the AOC travel secretary Eileen Latasa (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. Students visiting the AOC for their first VLBI or VLBA post-processing trip must be accompanied by their faculty advisor.

24 DATA ARCHIVE AND DISTRIBUTION

An archive of all output from the VLBA correlator will be maintained at the AOC. The user(s) who proposed the observations will retain a proprietary right to the data for a fixed interval, the length of which has not yet been determined. Thereafter, archived data will be available to any user on request. Indices are planned to facilitate this access to archival data.

Data will be distributed on a medium requested by the user. 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 with the observing schedule.

Distributed data will conform to the new FITS binary table standard for interferometry data interchange (Diamond & Wells 1993), which is read by AIPS task `FITLD`.

25 PUBLICATION GUIDELINES

Any paper using observational material acquired with one or more VLBA antennas should include the following acknowledgement to NRAO and the National Science Foundation:

> The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under co-operative agreement with the National Science Foundation.

Four copies of all preprints including observations with one or more VLBA antennas should be sent to Ellen Bouton, NRAO, 520 Edgemont Road, Charlottesville, Virginia 22903-2475, USA. 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. 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. Although NRAO no longer routinely purchases reprints from major astromonical journals for distribution, NRAO will purchase and distribute reprints if the paper is in a publication less likely to be readily available to other astronomers; and/or the paper is likely to be in great demand. In such cases, send copies of the publisher's reprint order forms to Ellen Bouton.

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. Caltech VLBI Analysis Programs: Contact T.J. Pearson, Astronomy Department 105-24, Caltech, Pasadena, California 91125, USA; phone +1-818-356-4980; FAX +1-818-568-9352; tjp@deimos.caltech.edu.

2. Haystack PC-SCHED: Contact A.E.E. Rogers, Haystack Observatory, Off Route 40, Westford, Massachusetts 01886, USA; phone +1-508-692-4764; FAX +1-617-981-0590; e-mail aeer@wells.haystack.edu.

3. NRAO AIPS: Contact AIPS Group, NRAO, 520 Edgemont Road, Charlottesville, Virginia 22903-2475, USA; aipsmail@nrao.edu.

26.2 Documents and Articles

A list of documents and articles referred to in this document follows. Copies of documents marked by an asterisk (*) are available from Betty Trujillo (see Section 26.3), while those marked by two asterisks (**) are available from Theresa McBride (see Section 26.3). Numerous articles from two books appear; abbreviations for these two books and complete references for them are as follows:

> *Very Long Baseline Interferometry* = Very Long Baseline Interferometry: Techniques and Applications, edited by M. Felli & R.E. Spencer, Kluwer Academic Publishers.
>
> *Synthesis Imaging* = Synthesis Imaging in Radio Astronomy, edited by R.A. Perley, F.R. Schwab, & A.H. Bridle, Astronomical Society of the Pacific Conference Series, volume 6.

1. Alef, W., & Porcas, R.W. 1986, Astronomy & Astrophysics, 168, 365.

2. Alef, W. 1989a, in *Very Long Baseline Interferometry*, p. 97.

3. Alef, W. 1989b, in *Very Long Baseline Interferometry*, p. 261.

4. Alef, W., Garrett, M., & Mantovani, F. 1991, The European VLBI Network Handbook

5. Biretta, J.A. 1991, VLBA Test Memo No. 27. *

6. Bridle, A.H., & Schwab, F.R. 1989, in *Synthesis Imaging*, p. 247.

7. Brown, L.F., Roberts, D.H., & Wardle, J.F.C. 1989, Astronomical Journal, 97, 1522.

8. Clark, B.G. 1973, Proceedings of the I.E.E.E., 61, 1242.

9. Cohen, M.H., *et al.* 1975, Astrophysical Journal, 201, 249.

10. Cornwell, T., & Braun, R. 1989, in *Synthesis Imaging*, p. 167.

11. Cornwell, T., & Fomalont, E.B. 1989, in *Synthesis Imaging*, p. 185.

12. Cotton, W.D. 1989a, in *Very Long Baseline Interferometry*, p. 275.

13. Cotton, W.D. 1989b, in *Synthesis Imaging*, p. 233.

14. Cotton, W.D. 1992, AIPS Memo No. 79. **

15. Crane, P.C., & Napier, P.J. 1989, in *Synthesis Imaging*, p. 139.

16. Dhawan, V., & Zensus, J.A. 1993, VLBA Test Memo No. ???. *

17. Diamond, P. 1989a, in *Very Long Baseline Interferometry*, p. 231.

18. Diamond, P.J. 1989b, in *Synthesis Imaging in Radio Astronomy*, p. 379.

19. Diamond, P.J., & Wells, D.C. 1993, VLBA Correlator Memo No. ???. *

20. Fanti, C. 1989, in *Very Long Baseline Interferometry*, p. 363.

21. Gabuzda, D.C., Cawthorne, T.V., Roberts, D.H., & Wardle, J.F.C. 1992, Astrophysical Journal, 388, 40.

22. Kellermann, K.I., & Thompson, A.R. 1985, Science, 229, 123.

23. Leppänen, K.J. 1993, VLBA Scientific Memo No. 1. *

24. Lestrade, J.-F. 1991, in Radio Interferometry: Theory, Techniques and Applications, IAU Colloquium 131, edited by T.J. Cornwell & R.A. Perley, ASP Conference Series, volume 19, p. 289.

25. Ma, C., Shaffer, D.B., de Vegt, C., Johnston, K.J., & Russell, J.L. 1990, Astronomical Journal, 99, 1284.

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26.3 Key Personnel

Table 6 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 in lower case from their first initial followed by their last name, with a maximum of 8 letters. Address e-mail enquiries to username@nrao.edu via Internet, or to east::"username@nrao.edu" or 6913::"username@nrao.edu" via Span. Users on Bitnet should use the Internet address. In Table 6, "AOC" refers to the Array Operations Center (phone +1-505-835-extension), "VLA" refers to the Very Large Array (phone +1-505-772-extension), and "CV" refers to Charlottesville (+1-804-296-extension).

Table 6: **Resource List of Key Personnel**

Name	Location	Extention	Room	Responsibilites and/or Expertise
Dave Adler	AOC	7272	208	AOC AIPS manager
Durga Bagri	AOC	7216	182	VLBA testing, systems engineer
Tony Beasley	AOC	7243	305	VLBA postdoctoral fellow
Larry Beno	AOC	7212	186	masers, time
John Benson	AOC	7399	366	VLBA correlator
Carl Bignell	AOC	7242	344	VLA/VLBA operations head
Bill Brundage	AOC	7120	188	frequency coordinator, RFI, electronics head
Barry Clark	AOC	7268	308	VLA/VLBA scheduler, on-line systems
Mark Claussen	AOC	7284	268	VLBI at VLA, spectral line
John Conway	AOC	7249	200	Jansky postdoctoral fellow
Tim Cornwell	AOC	7333	362	AOC computing and operations head
Bill Cotton	CV	0319	219	AIPS, linear polarization VLBI
Vivek Dhawan	AOC	7378	310	mm VLBI, RFI
Phil Diamond	AOC	7365	306	AIPS, spectral line VLBI
Chris Flatters	AOC	7208	208	AIPS, orbiting VLBI
Ed Fomalont	CV	0232	305	astrometry
Dale Frail	AOC	7338	373	Jansky postdoctoral fellow
Miller Goss	AOC	7300	334	NRAO assistant director for VLA/VLBA
Bob Greschke	AOC	7214	275	chief VLBA operator
Ken Hartley	AOC	7250	269	VLBA correlator operator
Phillip Hicks	VLA	4319	220	chief VLA operator
Clint Janes	AOC	7256	192	recorder engineer, Mark II support
Eileen Latasa	AOC	7357	218	AOC visitor registration
Theresa McBride	AOC	7000	267	AOC keeper of user documentation
Ruth Milner	AOC	7282	342	AOC computing head
Peter Napier	AOC	7218	218	VLBA construction project head
George Peck	AOC	7136	160	recorder engineer
Susan Prewitt	AOC	7238	204	VLA/VLBA data analyst
Paul Rhodes	AOC	7256	192	VLBA site group head
Terry Romero	AOC	7315	330	AOC scientific services
Jon Romney	AOC	7360	304	VLBA correlator, observing modes, space VLBI
Michael Rupen	AOC	7248	200	Jansky postdoctoral fellow
Meri Stanley	AOC	7300	338	miscellaneous printed VLBA user information
Betty Trujillo	AOC	7231	252	keeper of VLBA memo series
Craig Walker	AOC	7247	314	VLBA pointing, gains, testing, general health
Joan Wrobel	AOC	7392	302	VLBA documentation; VLBI at VLA
Dave Wunker	AOC	7359	204	VLA/VLBA data analyst
Wes Young	AOC	7337	378	`VLBA OBSERVE`
Anton Zensus	AOC	7348	312	mm VLBI, orbiting VLBI