# 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. 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.

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, which will be updated regularly, is available via either anonymous FTP as a PostScript file with name "obssum.vlba.ps" in directory "pub" on host "ftp.aoc.nrao.edu" (146.88.1.103), or from the VLBA home page via a WWW browser like Mosaic or Netscape (see Section 25.3). If you want a paper copy of this document, then request one from Lori Appel (see Section 25.4). Updates of this document 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". If you want to subscribe to the NRAO Newsletter, contact Joanne Nance in Charlottesville (jnance@nrao.edu, telephone +1-804-296-0323).

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 an-

tenna 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 projects involving extragalactic lines, rotation measures (Cotton 1995b), and multi-frequency synthesis (Conway & Sault 1995).

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

*(handwritten marginal notes: $\theta_{HPBW}$ (mas))*

| Receivers and Feeds | Nominal Frequency Range [GHz] | Typical Zenith $SEFD$ [Jy] | Typical Zenith Gain [K Jy$^{-1}$] | $\Delta S^{128,2m}$ [mJy] | $\Delta I_m^{128,8h}$ [$\mu$Jy beam$^{-1}$] | $\theta_{HPBW}$ (mas) |
|---|---|---|---|---|---|---|
| 90 cm | 0.312 - 0.342 | 2184 | 0.096 | ... | ... | 22 |
| 50 cm | 0.596 - 0.626 | 2205 | 0.086 | ... | ... | 11 |
| 20 cm$^{(a)}$ | 1.35 - 1.75 | 304 | 0.095 | 4.9 | 47 | 4.3 |
| 13 cm | 2.15 - 2.35 | 315 | 0.091 | 5.1 | 49 | 3.1 |
| 13 cm$^{(b)}$ | 2.15 - 2.35 | 391 | 0.07, | 6.3 | 61 | |
| 6 cm | 4.6 - 5.1 | 289 | 0.132 | 4.7 | 45 | 1.4 |
| 4 cm | 8.0 - 8.8 | 299 | 0.117 | 4.8 | 46 | 0.86 |
| 4 cm$^{(b)}$ | 8.0 - 8.8 | 390 | 0.111 | 6.3 | 60 | |
| 2 cm | 12.0 - 15.4 | 513 | 0.111 | 8.3 | 80 | 0.48 |
| 1 cm | 21.7 - 24.1 | 937 | 0.105 | 15.1 | 145 | 0.31 |
| 7 mm | 41.0 - 45.0 | 1402 | 0.084 | ... | ... | 0.17 |

*(additional handwritten marginal values beside table: 18, 3.1, 1.3)*

Notes: (a) Hronek & Walker (1996) describe additional antenna-specific filters not mentioned by Thompson (1995).
(b) With 13/4 cm dichroic.

Also appearing in Table 2 are parameters characterizing the performance of a typical VLBA antenna for the various receiver/feed combina-

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tions. Columns [3] and [4] 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 9 or 10 antennas, as measured by VLBA operations 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 ($\Delta S$ for a *single polarization*; see Equation 2) and in a VLBA image ($\Delta I_\mathrm{m}$ for a *single polarization*; see Equation 3). Characteristic values for $\Delta S^{128,2\mathrm{m}}$ assuming a fringe-fit interval of $\tau_\mathrm{ff} = 2$ minutes and for $\Delta I_\mathrm{m}^{128,8\mathrm{h}}$ assuming a total integration time on source of $t_\mathrm{int} = 8$ 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 $\Delta S^{128,2\mathrm{m}}$ or $\Delta I_\mathrm{m}^{128,8\mathrm{h}}$ entries are given for 90 cm 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.

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 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, Clint Janes (see Section 25.4), 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 GAS-FETs 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 1C 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 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 bit-stream: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 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 (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 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. *The VLBA has recently done a recording density upgrade, meaning that a thin (17600-foot) VLBA tape now lasts 10 h 16 m if recorded continuously at 128 Mbps.* 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 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 III 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. The VLBA cannot record in Mark II format, the Japanese K4 format, or the Canadian S2 format.

# 7 CORRELATOR

The VLBA correlator accommodates the full range of scientific investigations for which the array was designed. Ultimately, the correlator will support 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. Current correlator restrictions are summarized in "Guidelines for VLBA Observations" by Jon Romney (see Section 25.4); that document is available from the VLBA home page (see Section 25.3).

The correlator is designed to process all observations involving VLBA stations. With its 20-station capacity and new 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.

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 will eventually include amplitude and pulse 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. Ultimately, the output data rate will be 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 in the form either of station logs generated from the VLBA control system's monitor data or log information from foreign stations. 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.

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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 22, however, users are encouraged to visit the AOC after correlation for post-processing analysis.

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

# 8   ANGULAR RESOLUTION

Table 3, generated by Tony Beasley, gives the maximum lengths rounded to the nearest km ($B_{max}^{km}$) 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 ($\theta_{HPBW}$) in milliarcseconds (mas) is

$$\theta_{HPBW} \sim 2063 \times \frac{\lambda^{cm}}{B_{max}^{km}} \quad \text{mas,} \tag{1}$$

where $\lambda^{cm}$ 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. For the longest VLBA baseline, $\theta_{HPBW}$ 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 ($B_{max}^{km}$)**

|    | 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 $-18$ 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 1996) or the Haystack program PC-SCHED (see Section 25.1).

# 10  TIME RESOLUTION

Time resolution is set by the VLBI correlator accumulation time. At the VLBA correlator it is about 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 the implementation date is not yet known.

# 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.

# 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 ($\Delta S$) in the visibility amplitude of a *single-polarization* baseline between two identical antennas (Walker 1995a):

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

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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.**
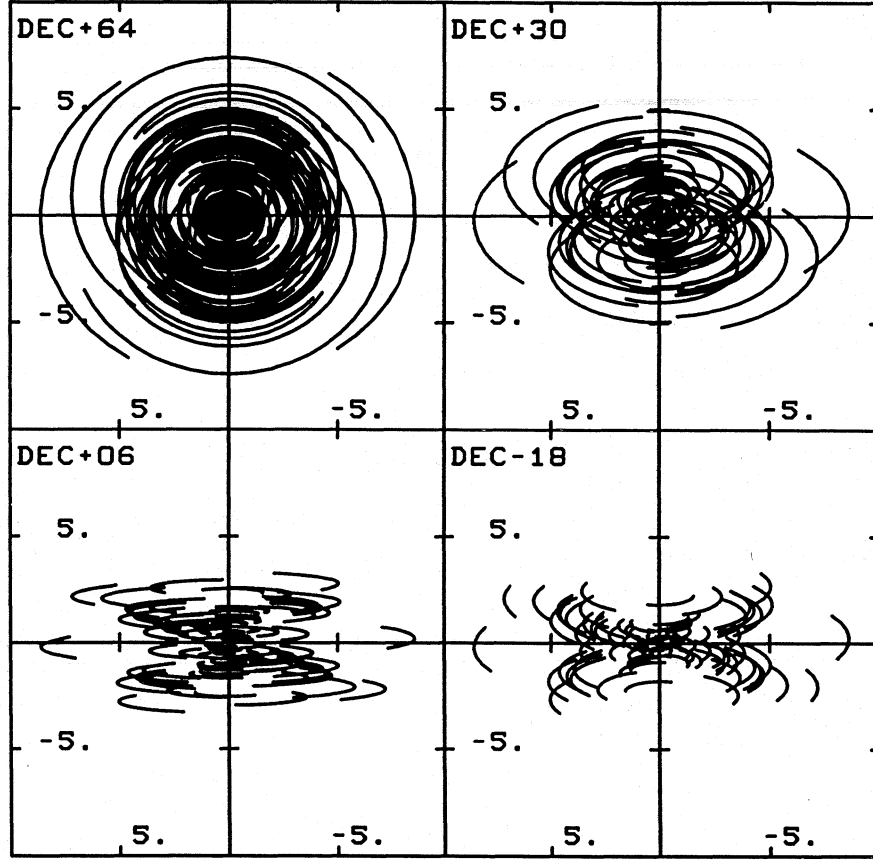


In Equation 2, $\eta_s \leq 1$ accounts for the VLBI system inefficiency (e.g., quantization in the data recording and correlator approximations). Assume $\frac{1}{\eta_s} \sim 2$ for data from a Mark III correlator; values are soon to be determined for the VLBA correlator. $\Delta\nu$ is the bandwidth [Hz]; use the full recorded bandwidth for a continuum target and use a spectral channel for a line target. $\tau_{ff}$ is the fringe-fit interval [s], which should be less than or about equal to the coherence time $\tau_{atm}$. Equation 2 holds in the weak source limit and

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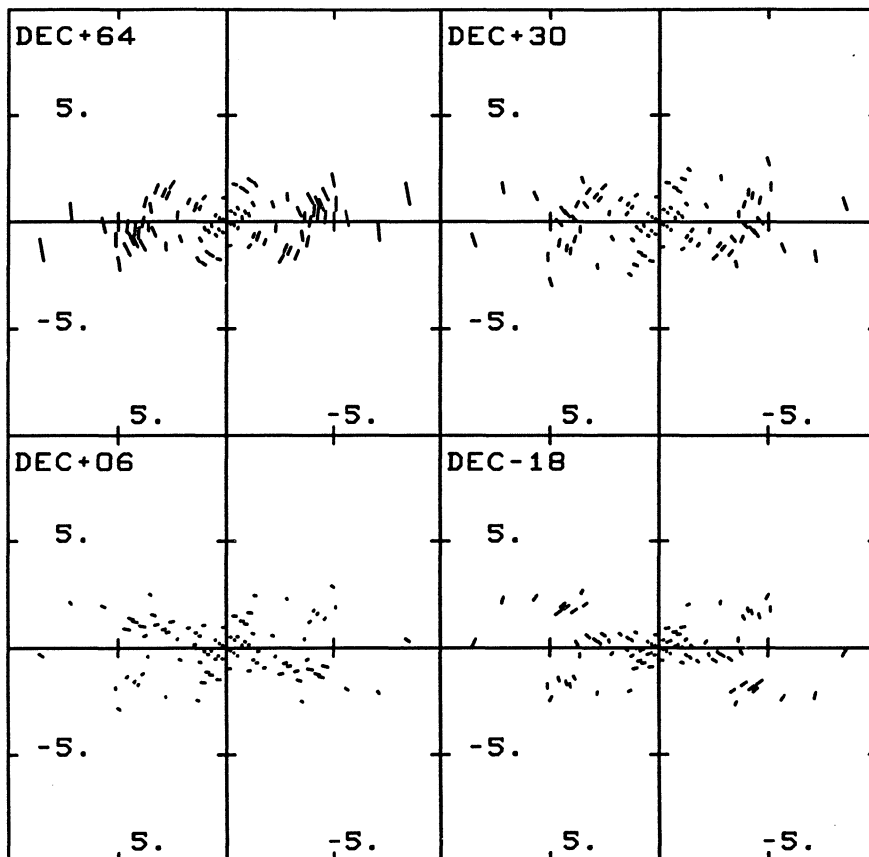


assumes 1-bit (2-level) quantization. About the same noise can be obtained with 2-bit (4-level) quantization and half the bandwidth, which gives the same bit rate. Moran & Dhawan (1995) discuss expected coherence times. The actual coherence time appropriate for a given VLBA project can be estimated using 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 ($\Delta I_\mathrm{m}$) expected in a *single-polarization* image, assuming natural weighting (Wrobel 1995):

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

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

$$\Delta I = \Delta Q = \Delta U = \Delta V = \frac{\Delta I_\mathrm{m}}{\sqrt{2}}. \qquad (4)$$

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

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

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

$$\Delta T_\mathrm{b} \sim 320 \times \Delta I_\mathrm{m} \times (B_\mathrm{max}^\mathrm{km})^2 \quad \text{K}, \qquad (6)$$

where $B_\mathrm{max}^\mathrm{km}$ 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 ($T_\mathrm{sys}$) 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 $T_\mathrm{sys}$ values are currently delivered to VLBA users in machine readable files that can be read by fringe amplitude calibration programs such as **ANCAL** or **ANTAB** in the NRAO Astronomical Image

Processing System (AIPS) or CAL in the Caltech VLBI Analysis Programs; see Section 21. The parameters and file style expected by these programs are documented in their respective help files. Such programs can be used to convert from $T_{sys}$ 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. Anonymous FTP can be used to access these VLBA zenith gains; consult file "vlba_gains.key" in directory "pub" on host "ftp.aoc.nrao.edu" (146.88.1.103). For projects processed on the VLBA correlator, such amplitude calibration data will eventually 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 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 (Moran & Dhawan 1995). File "vlba_gains.key", 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.

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, and other wavelengths, will be added in the future. In the meantime users may want to consult major published VLBI surveys (e.g., Taylor *et al.* 1994; Polatidis *et al.* 1995; Thakkar *et al.* 1995; Henstock *et al.* 1995; plus references therein), or 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., Fielder *et al.* 1994a, b). VLBA observations of the sources in Table 4, or other suitably selected sources, 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. Positions for the sources in Table 4, used by default by the NRAO program SCHED (Walker 1996) and the VLBA correlator, are given in the standard source catalog available as an ancillary file with SCHED. The source names in Table 4 are as they appear in the standard source catalog.

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

```
J0818+4222=0814+425=J0818+42
J0854+5757=0850+581=J0854+57
J0854+2006=0851+202=J0854+20=OJ287
J1146+3958=1144+402=J1146+39
J1310+3220=1308+326=J1310+32
J1407+2827=1404+286=J1407+28=OQ208
J1504+1029=1502+106=J1504+10
J1613+3412=1611+343=J1613+34
J1638+5720=1637+574=J1638+57
J1642+6856=1642+690=J1642+68
J1740+5211=1739+522=J1740+52
```

# 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 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 sources listed in Table 5 can be used as fringe finders between 20 cm and 7 cm, except as noted. In addition, at 90 and 50 cm we recommend either

J1331+3030=1328+307=3C286=J1331+30 or
J2253+1608=2251+158=3C454.3=J2253+16.

Fringe-finder positions, used by default by the NRAO program SCHED (Walker

1996) and the VLBA correlator, are given in the standard source catalog available as an ancillary file with SCHED. Fringe-finder names are as they appear in the standard source catalog.

Table 5: **Suggested Fringe Finders at 20 cm to 7 mm**

| |
|---|
| J0319+4130=0316+413=3C84=J0319+41 (avoid at 7 mm) |
| J0555+3948=0552+398=DA193=J0555+39 (avoid at 20 cm & 7 mm) |
| J0927+3902=0923+392=4C39.25=J0927+39 |
| J1229+0203=1226+023=3C273=3C273B=J1229+02 |
| J1642+3948=1641+399=3C345=J1642+39 |
| J2253+1608=2251+158=3C454.3=J2253+16 |

## 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 III 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, and included in the calibration information delivered to the user in tabular form. Although AIPS software can be used to load and apply the pulse cal data, this path is still new; VLBA users may still want to observe a strong compact source (see Section 15.1) so they can do a "manual" pulse

cal if necessary (Diamond 1995).

## 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 20) 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 (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 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 (Diamond 1995; Walker 1995b). Usually such editing is done interactively using task IBLED in AIPS or program DIFMAP (Shepherd, Pearson, & Toyle 1994) 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

(Cornwell 1995; Walker 1995b). Fourier transform imaging is straightforward, and done with tasks `UVMAP`, `MX`, or `IMAGR` in AIPS or program `DIFMAP` 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. Such deconvolution is achieved with programs based on the CLEAN or Maximum Entropy methods in AIPS or `DIFMAP` 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 1995). 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 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). Measures of VLBI image correctness - image fidelity and dynamic range - are discussed by Wilkinson (1987) and Walker (1995a).

## 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 (Beasley & Conway 1995). 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. In the short term, VLBA users can draw candidate phase calibrators from the MERLIN phase calibrator grid of Patnaik *et al.* (1992) and Browne *et al.* (1996), which will eventually be extended to cover the sky north of declination −30 degrees. Tony Beasley (see Section 25.4) is leading a systematic VLBA 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 1993, 1995b). Steps that must be followed include normal amplitude calibration; fringe-fitting; 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. The polarization calibration path in AIPS is currently being actively developed, tested, and documented. This path includes powerful global fringe-fitting techniques to locate weak cross-polarized signals. A polarization self-calibration technique is described by Leppänen, Zensus, & Diamond 1995).

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., J1407+2827, see Table 4) or no linearly polarized emission (e.g., J0319+4130, 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 (Cotton 1993; Gabuzda *et al.* 1994), with the caveat that their linearly polarized emission typically varies rapidly in time.

# 17   SPECTRAL LINE

Diamond (1995) and Reid (1995) describe the special problems encountered during data acquisition, correlation, and post-processing of a spectral line project. 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 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 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).

# 18   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 & Claussen (1996) for information on VLBI at the VLA. 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 25.4).

2. The European VLBI Network (EVN). Prospective proposers can consult Schilizzi (1995) and Alef & Mantovani (1995; the EVN Handbook hereafter) for information on EVN members and the capabilities of EVN antennas. The EVN Handbook can be obtained through account VLBINFO on ASTBO1; the Internet address is "astbo1.bo.cnr.it" (192.167.165.1). 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 the NRAO SCHED program (or the related Caltech UPTIME program available with SCHED) (Walker 1996), or the Haystack PC-SCHED program (see Section 25.1) to determine the Greenwich Sidereal Time range during which the VLBI target source(s) is (are) up at the selected antennas. These programs can also be used to evaluate the $u$-$v$ plane coverage provided by the selected antennas (see Section 9).

Those proposing observations in VLBA format should consult files "std_modes.vlba" and "OK_modes.vlba" in directory "pub" on host "ftp.aoc.nrao.edu" (146.88.1.103) to identify which VLBA setup(s) is (are) desired. These files are also available from the VLBA home page (see Section 25.3).

If the proposal requests use of the VLBA correlator, then the proposed observing strategies must adhere to the "Guidelines for VLBA Observations" summarized by Jon Romney (see Section 25.4) and available from the VLBA home page (see Section 25.3).

## 18.2 Submitting a Proposal

All VLBA proposals must be submitted with a VLBI Proposal Cover Sheet, which is available as described in Section 18.3. 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-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.

### 18.3   The VLBI Proposal Cover Sheet

A VLBI Proposal Cover Sheet must accompany all VLBA, EVN, and global proposals. Tex or PostScript versions authored by Barry Clark are available via anonymous FTP on host "ftp.cv.nrao.edu" in directory "proposal". If you want to print a PostScript cover sheet at your home institution that will be filled in *after* printing, then get file covervlbi.ps. If you want to print a PostScript cover sheet at your home institution that will be filled in *before* printing, then get files covervlbi.tex, nraologo.ps, and evnlogo.ps. Printed cover sheets can be requested from Joanne Nance (jnance@nrao.edu, telephone +1-804-296-0323).

## 19   PREPARATION FOR OBSERVING

Users allocated VLBA observing time will be sent detailed observing schedule preparation instructions. Currently, the preparation of schedule files for observations in VLBA and Mark III formats is best handled by running software on AOC computers, with local assistance provided by the VLA/VLBA data analysts and AOC scientific staff. This arrangement ensures that observing schedule files (1) contain proper antenna electronics setup information, (2) are fully compatible with antenna hardware and control software, and (3) make use of the latest schedule preparation software.

Projects in VLBA formats are scheduled using the NRAO program SCHED, which is which is available for use both at the AOC and elsewhere (Walker 1996). Most projects in Mark III formats are scheduled with the Haytack program PC-SCHED; Section 25.1 gives contact information. The so-called DRUDG file output by PC-SCHED is translated at the AOC for use by program SCHED, which is then used to create the VLBA observing schedule files.

# 20  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 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" (146.88.2.2) 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 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 25.1 gives contact information. Extensive on-line internal documentation can be accessed within AIPS. An entire chapter in the AIPS Cookbook (NRAO staff, 1996) provides useful "how-to" guidance for those reducing VLBI data.

## 21.2  The Caltech VLBI Analysis Programs

The Caltech VLBI Analysis Programs are a set of programs for the planning and analysis of continuum VLBI observations. 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, Pearson, & Taylor (1994) describe the important program DIFMAP, which can now handle multi-channel data in FITS format. Section 25.1 gives contact information.

## 22 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. *Please contact the operations staff to determine if the correlated data are available before arranging a visit.*

Standard NRAO travel reimbursement policy applies to VLBA data reduction trips to the AOC. Visitors must contact the AOC reservationist Eileen Latasa (see Section 25.4) 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.

## 23 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 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. 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. Distributed data will conform to the new FITS binary table standard for interferometry data interchange (Diamond *et al.* 1996), which is read by AIPS task FITLD.

## 24 PUBLICATION GUIDELINES

### 24.1 Acknowledgement to NRAO

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.*

## 24.2 Preprints

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

## 24.3 Reprints

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

## 24.4 Page Charge Support

The following summarizes NRAO's policy:

- When requested, NRAO will pay the larger of the following:

  - 50% of the page charges reporting original results made with NRAO instrument(s) when at least one author is at a U.S. scientific or educational institution.
  - 100% of the page charges prorated by the fraction of authors who are NRAO staff members.

- Page charge support is provided for publication of color plates.

- To receive page charge support, authors must comply with all of the following requirements:

- Include the NRAO footnote in the text; see Section 24.1.
- Send four copies of the paper prior to publication to Ellen Bouton in Charlottesville.
- Notify Ellen Bouton in Charlottesville of the proposed date of publication and apportionment of page charges so that the necessary purchase orders may be initiated. Convenient ways to do this are to send her copies of the completed page charge form, or send her an e-mail message (library@nrao.edu), or call her by telephone at +1-804-296-0254.

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

- Contact person for NRAO is Ellen Bouton, +1-804-296-0254.

- Billing address for both page charges and reprints is NRAO Fiscal Division at the Charlottesville address.

- Shipping address for reprints should be the NRAO author.

- On ApJ and AJ forms, cite the purchase order number as "NRAO blanket PO". For all other publications, call Ellen Bouton for a purchase order number.

## 25  RESOURCE LISTS

### 25.1  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: Consult Walker (1996).

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.

4. 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.

## 25.2 Documents and Articles

A list of documents and articles referred to in this document follows. The symbol *www* indicates that the item is available on the WWW from the NRAO home page (see Section 25.3). Printed copies of documents marked by an asterisk (*) are available from Selfa Lucero (see Section 25.4), while those marked by two asterisks (**) are available from Theresa McBride (see Section 25.4). Numerous articles from one book appear; an abbreviation for this book and a complete reference for it are as follows:

> *VLBI & the VLBA* = Very Long Baseline Interferometry and the VLBA, edited by J.A. Zensus, P.J. Diamond, & P.J. Napier, Astronomical Society of the Pacific Conference Series, volume 82.

1. Alef, W., & Mantovani, F. 1995, The EVN Handbook.

2. Beasley, A.J., & Conway, J.E. 1995, in *VLBI & the VLBA*, p. 327. *www*

3. Benson, J.M. 1995, in *VLBI & the VLBA*, p. 117. *www*

4. Browne, I.W.A., Patnaik, A.R., Wilkinson, P.N., & Wrobel, J.M. 1996, Monthly Notices of the Royal Astronomical Society, soon to be submitted.

5. Conway, J.E., & Sault, R.J. 1995, in *VLBI & the VLBA*, p. 309. *www*

6. Cornwell, T.J. 1995, in *VLBI & the VLBA*, p. 39. *www*

7. Cotton, W.D. 1993, Astronomical Journal, 106, 1241.

8. Cotton, W.D. 1995a, in *VLBI & the VLBA*, p. 189. *www*

9. Cotton, W.D. 1995b, in *VLBI & the VLBA*, p. 289. *www*

10. Diamond, P.J. 1995, in *VLBI & the VLBA*, p. 227. *www*

11. Diamond, P.J., Benson, J., Cotton, W.D., Romney, J., Wells, D.C., and Hunt, G.C. 1996, VLBA Correlator Memo (in prep). *

12. Fiedler, R., Dennison, B., Johnston, K.J., Waltman, E.B., & Simon, R.S. 1994a, Astrophysical Journal, 430, 581.

13. Fiedler, R., Pauls, T., Johnston, K.J., & Dennison, B. 1994b, Astrophysical Journal, 430, 595.

14. Gabuzda, D.C., Mullan, C.M., Cawthorne, T.V., Wardle, J.F.C., & Roberts, D.H. 1994, Astrophysical Journal, 435, 140.

15. Henstock, D.R., Browne, I.W.A., Wilkinson, P.N., Taylor, G.B., Vermeulen, R.C., Pearson, T.J., & Readhead, A.C.S. 1995, Astrophysical Journal Supplement Series, 100, 1.

16. Hronek, A., & Walker, R.C. 1996, VLBA Test Memo No. 51. *

17. Kemball, A.J., Diamond, P.J., & Cotton, W.D. 1995, Astronomy & Astrophysics Supplement Series, 110, 383.

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

19. Leppänen, K.J., Zensus, J.A., & Diamond, P.J. 1995, Astronomical Journal, 110, 2479.

20. Moran, J.M., & Dhawan, V. *VLBI & the VLBA*, p. 161. *www*

21. Napier, P.J., Bagri, D.S., Clark, B.G., Rogers, A.E.E., Romney, J.D., Thompson, A.R., & Walker, R.C. 1994, Proc. IEEE, 82, 658. *

22. Napier, P.J. 1995, in *VLBI & the VLBA*, p. 59. *www*

23. NRAO staff, 1996, AIPS Cookbook. *www* **

24. Patnaik, A.R., Browne, I.W.A., Wilkinson, P.N., & Wrobel, J.M. 1992, Monthly Notices of the Royal Astronomical Society, 254, 655.

25. Pearson, T.J., & Readhead, A.C.S. 1984, Annual Reviews of Astronomy & Astrophysics, 22, 97.

26. Polatidis, A.G., Wilkinson, P.N., Xu, W., Readhead, A.C.S., Pearson, T.J., Taylor, G.B., & Vermeulen, R.C. 1995, Astrophysical Journal Supplement Series, 98, 1.

27. Reid, M.J. 1995, in *VLBI & the VLBA*, p. 209. *www*

28. Rogers, A.E.E. 1995, in *VLBI & the VLBA*, p. 93. *www*

29. Rogers, A.E.E., *et al.* 1983, Science, 219, 51.

30. Romney, J.D. 1990, VLBA Specification A56000N003. *

31. Romney, J.D. 1995, in *VLBI & the VLBA*, p. 17. *www*

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## 25.3   WWW and VLAIS

There are two sources of on-line information about the VLBA. First, NRAO-wide information is available via the WWW using a browser like Mosaic or Netscape. Use the URL http://www.nrao.edu/ to point to the NRAO home page, which offers easy selection of the VLBA home page. Second, there is a simple ASCII information system, vlais, on the Zia computer system at the AOC. Access to this system is by Internet address 146.88.1.4 or through the NRAO Socorro terminal switch (+1-505-835-7010). At the login message for Zia type "vlais"; contact Lori Appel (see Section 25.4) for the password.

A menu will list the major categories available. Choose VLBA to get to the VLBA specific information.

## 25.4 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 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. 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 | Extension | Room | Responsibilites and/or Expertise |
|---|---|---|---|---|
| Dave Adler | AOC | 7272 | 208 | AIPS manager |
| Lori Appel | AOC | 7310 | 340 | printed user information |
| Durga Bagri | AOC | 7216 | 182 | testing, systems engineer |
| Tony Beasley | AOC | 7243 | 305 | VLBA phase calibrators |
| Larry Beno | AOC | 7212 | 186 | masers, time, LO, IF, BBCs |
| John Benson | AOC | 7399 | 366 | correlator software |
| Steve Blachman | AOC | 7327 | 368 | correlator & on-line software |
| Chuck Broadwell | AOC | 7257 | 269 | correlator hardware |
| Scott Broadwell | AOC | 7359 | 204 | VLA/VLBA data analyst |
| Chris Carilli | AOC | 7306 | 356 | high frequency VLBI |
| Barry Clark | AOC | 7268 | 308 | VLA/VLBA scheduler, on-line systems |
| Mark Claussen | AOC | 7284 | 268 | space VLBI, VLBI at the VLA |
| Bill Cotton | CV | 0319 | 219 | polarimetry |
| Vivek Dhawan | AOC | 7378 | 310 | mm VLBI, RFI |
| Phil Diamond | AOC | 7365 | 332 | FITLD, computing & operations head |
| Chris Flatters | AOC | 7209 | 208 | space VLBI, AIPS |
| Ed Fomalont | CV | 0232 | 305 | astrometry |
| Dale Frail | AOC | 7338 | 360 | pulsars, scattering |
| Miller Goss | AOC | 7300 | 336 | NRAO assistant director for VLA/VLBA |
| Kevin Healy | AOC | 7239 | 204 | VLA/VLBA data analyst |
| Phillip Hicks | VLA | 4319 | 220 | chief VLA operator |
| Clint Janes | AOC | 7193 | 145 | frequency coordinator, RFI |
| Athol Kemball | AOC | 7330 | 266 | AIPS, VLBI spectropolarimetry |
| Leonid Kogan | AOC | 7383 | 312 | AIPS, correlator theory |
| Eileen Latasa | AOC | 7357 | 218 | visitor registration |
| Craig Lewis | AOC | 7235 | 205 | VLA/VLBA data analyst |
| Paul Lilie | AOC | 7128 | 184 | receivers |
| Selfa Lucero | AOC | 7000 | 214 | VLBA memo series |
| Theresa McBride | AOC | 7245 | 267 | printed user documentation |
| George Peck | AOC | 7136 | 144 | formatter, recording/playback |
| Peggy Perley | AOC | 7214 | 275 | chief VLBA operator |
| Jon Romney | AOC | 7360 | 304 | correlator, space VLBI |
| Alan Roy | AOC | 7372 | 300 | postdoctoral fellow |
| Michael Rupen | AOC | 7248 | 206 | radio supernovae |
| Richard Simon | CV | 0381 | 317 | low frequency VLBI |
| Meri Stanley | AOC | 7238 | 204 | VLA/VLBA data analyst |
| Greg Taylor | AOC | 7237 | 358 | HI abs. VLBI, VLA phase calibrators |
| Maggie Tongue | AOC | 7235 | 205 | VLA/VLBA data analyst |
| Huib van Langevelde | AOC | 7297 | 276 | JIVE, spectral line VLBI |
| Craig Walker | AOC | 7247 | 314 | SCHED, testing |
| Joan Wrobel | AOC | 7392 | 302 | documentation, VLBI at VLA |