# VERY LONG BASELINE ARRAY OBSERVATIONAL STATUS SUMMARY

J.M. Wrobel and J.D. Romney
National Radio Astronomy Observatory
Socorro, New Mexico 87801, USA
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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 1991). 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 90cm to 7mm at each antenna; (4) quick computer control of receiver selection (receiver agility) and of frequency selection for a given receiver (frequency agility); (5) smooth integration of data flow from the acquisition to the processing to the post-processing stages; and (6) simultaneous observations in dual circular polarizations. Also, a comprehensive and user-friendly NRAO schedule preparation program, called VLBA Observe, will be available in the near future. 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 plain ASCII 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 under file name 'obssum.vlba' 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'.

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 two site technicians.

## 2. ANTENNA SITES

Table 2.1 gives the geographic locations of the 10 antennas comprising the VLBA, plus the 2 character codes used to identify the antennas. The antennas are ordered East through West.

Table 2.1. Geographic Locations and Codes

| Location | North Latitude [d ' "] | West Longitude [d ' "] | Elevation [m] | Code |
|---|---|---|---|---|
| Saint Croix, VI | 17 45 30.57 | 64 35 02.61 | 16 | SC |
| Hancock, NH | 42 56 00.96 | 71 59 11.60 | 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 f/D=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/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/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 4.1 gives the frequency ranges for the 9 receiver/feed combinations that will soon be 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 4.1 are typical VLBA zenith SEFD and typical VLBA zenith opacity-corrected gains in K/Jy. These were obtained by averaging right circularly polarized (RCP) and left circularly polarized (LCP) values from 3 to 8 antennas (Walker 1992). The typical zenith SEFDs can be used to estimate root-mean-square (rms) noise levels on a baseline between 2 VLBA antennas (see section 12) and in a VLBA image (see section 13). Opacity-corrected zenith gains are needed for current continuum amplitude calibration techniques; antenna-dependent gains will be monitored by VLBA operations and communicated to users (see section 14). The typical values appearing in Table 4.1 are meant to be illustrative only.

Table 4.1. Frequency Ranges, SEFDs and Gains

| Receiver and Feeds | Frequency Range [GHz] | Typical Zenith SEFD [Jy] | Typical Zenith Gain [K/Jy] |
|---|---|---|---|
| 90cm | 0.312- 0.345*1* | 2610 | 0.065 |
| 50cm | 0.600- 0.630*2* | 3510 | 0.061 |
| 20cm | 1.30 - 1.70 *3* | 334 | 0.091 |
| 13cm | 2.13 - 2.35 | 479 | 0.087 |
| 13cm*4* | 2.13 - 2.35 | 572 | 0.073 |
| 6cm | 4.50 - 5.14 | 338 | 0.116 |
| 4cm | 7.88 - 8.93 | 348 | 0.107 |
| 4cm*4* | 7.88 - 8.93 | 431 | 0.098 |
| 2cm | 12.0 -15.4 *5* | 598 | 0.117 |
| 1cm | 21.1 -24.6 | 1154 | 0.091 |
| 7mm | 42.3 -43.5 *5* | ... | ... |

Notes:
*1* Entire range not usable due to narrrow band interference. See Biretta (1991).
*2* Entire range not usable due to narrrow band interference. A filter passing 609-613 MHz must be used at some antennas. See Biretta (1991).
*3* 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 20cm 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 interference environment.
*4* With 13/4cm dichroic.
*5* Design specification.

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

## 5. VLBA SIGNAL PATH

This section descibes 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 detection. For most receivers the polarizer is at cryogenic temperatures.

### 5.4. Phase 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 (section 5.12) and base band converters (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 90cm and 50cm receivers are GASFETs at room temperature. Each receiver has 2 channels, one for RCP and one for LCP. The 1.3cm and 7mm 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 (section 5.9) and the phase cal system (sections 5.4 and 15.2). The 5 MHz output is the reference for the base band converters (section 5.13), the formatter (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 X 500) +/- 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 1.3cm, at 7mm and for the wide band mode at 4cm 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 4cm 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 90cm and 50cm signals are combined and transmitted on the same IFs. The 50cm signals are not frequency converted, while the 90cm 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 13cm and 4cm, 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 'IF channels', where one IF 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 IF 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 IF channels; rates available are 32, 16, 8, 4, 2, 1 or 0.5 Msamples/s 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 (Romney 1990) and Mark III (Rogers et al. 1983) data formats are supported. Up to 16 phase 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 Mbits/s. This can result in an aggregate bit rate of as much as 256 Mbit/s 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 Mbits/s (averaged over 24 hours) be imposed on the aggregate bit rate. This can be achieved either by recording at 128 Mbits/s 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 Mbits/s 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. Four or 5 VCRs are present at each of 7 VLBA sites (see Table 18.1) to allow Mark II recording with infrequent tape changes.

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 Mark II, Mark III and VLBA formats. Table 6.1 characterizes each format scheme by the number of BBCs used, the bandwidth range per BBC available (BW), the maximum number of antennas available and whether or not simultaneous dual circular polarization data can be acquired. Table 18.1 identifies which antennas can currently make Mark II recordings. The VLBA has participated in many Mark II and Mark III format observing projects. The latter have primarily been in Mode B, although projects with limited forms of Mode A and Mode C have also been undertaken. Special dual circular polarization Mark III modes have also been used. The VLBA cannot record in the Japanese K4 format or the Canadian S2 format.

Table 6.1. Current Recording Formats

| Format | BBCs | BBC BW [MHz] | Maximum No. of Antennas | Simultaneous RCP and LCP |
|---|---|---|---|---|
| Mark II | 1 | 0.0625 - 2 | 7 | no |
| Mark III | 8 | 0.0625 - 4 | 10 | yes |
| VLBA | 8 | 0.0625 -16 | 10 | yes |

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/s, 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/s) or 4 (for 8 Msamples/s 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 the 2048-point limit implies a maximum spectral resolution of 512 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 Mbyte/s, 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.

Final debugging and checkout of the correlator is currently under way. It is expected to become available for selected VLBA programs at the end of 1992, and to take over correlation of all intra-VLBA observations by the end of March 1993. The transition plan from US VLBI Network operations to the VLBA calls for transfer of correlation responsibilities to be completed at the end of June 1993. ** During the transition period, observing programs 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 programs 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 fuer Radioastronomie in Bonn, Germany (contact: W. Alef, MPIfR, Auf dem Huegel 69, D-W-5300 Bonn 1, 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).

## 8. ANGULAR RESOLUTION

Table 8.1 gives the maximum lengths rounded to the nearest km (LKM) for each of the VLBA's 45 internal baselines. A measure of the corresponding resolution in milliarcseconds (mas) (RMAS) is

RMAS ~ 2063 mas * LAMBDACM / LKM, (1)

where LAMBDACM 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, RMAS ranges from 20 to 0.2 mas as the wavelength runs from 90cm to 7mm.

Table 8.1. Maximum VLBA Baseline Lengths in km (LKM)

| \ | 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 | ... | ... |
| OV | 5461 | 3886 | 2328 | 1508 | 1088 | 973 | 845 | ... | ... | ... |
| KP | 4840 | 3623 | 2076 | 744 | 652 | 417 | ... | ... | ... | ... |
| PT | 4580 | 3227 | 1664 | 565 | 237 | ... | ... | ... | ... | ... |
| LA | 4459 | 3007 | 1433 | 609 | ... | ... | ... | ... | ... | ... |
| FD | 4144 | 3106 | 1655 | ... | ... | ... | ... | ... | ... | ... |
| NL | 3645 | 1611 | ... | ... | ... | ... | ... | ... | ... | ... |
| HN | 2853 | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| SC | ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |

## 9. U-V PLANE COVERAGE

The ASCII nature of this document does not permit the inclusion of U-V plane coverage plots for the VLBA or for VLBI arrays containing one or more VLBA antenna. Such 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.

## 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 IF 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 IF 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. The following formula can be used in conjunction with the typical zenith SEFDs for VLBA antennas given in Table 4.1 to calculate the rms noise (RMSBL) of the visibility amplitude (Walker 1989b; Crane & Napier 1989):

RMSBL = (1/C) * SEFD / SQRT(2Bt) [Jy]. (2)

In equation (2), C <=1 accounts for losses in quantization in the data recording and approximations in the correlator systems (assume C~0.5 for Mark II and III data, still to be determined for the VLBA); B is the bandwidth [Hz]; and t is the data integration time [s], which should be less than about twice the coherence time. 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): 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 SEFDs for VLBA antennas given in Table 4.1 to calculate the rms noise (RMSIM) expected in single polarization image, assuming natural weighting (Walker 1989b; Crane & Napier 1989):

RMSIM = (1/C) * SEFD / SQRT(N(N-1)BT) [Jy], (3)

where C <=1 is discussed in section 12; N is the number of VLBA antennas available; B is the bandwidth [Hz]; and T is the total time on source [s]. Equation (3) also assumes 1 bit (2 level) quantization. If dual polarization RCP and LCP data are available, then for an image of Stokes I, Q, U, or V,

RMSI = RMSQ = RMSU = RMSV = RMSIM / SQRT(2). (4)

For a polarized intensity image of P = SQRT (Q**2 + U**2),

RMSP = 0.655*RMSQ = 0.655*RMSU. (5)

It is sometimes useful to express RMSIM in terms of an rms brightness temperature in Kelvins (RMSTBK) measured within the synthesized beam. An approximate formula is

RMSTBK = 320 * RMSIM * LKM**2, (6)

where LKM 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 (TK) are measured 'frequently' in each IF channel during observations with VLBA antennas; 'frequent' means at least once per observation or once every 2 minutes, whichever is shortest. These TK 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 TK to SEFD by dividing by the VLBA antenna zenith gains in degrees/Jy 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).

At wavelengths of 1.3cm or longer it is not necessary to correct for the position dependent gain of a VLBA antenna, as the so-called 'gain curve' is known to be flat. However, at short cm wavelengths users will want to make corrections for apparent gain reductions arising from atmospheric opacity. These can vary on short time scales and by large factors. Such corrections may be determined empirically, since the observed TK values for a VLBA antenna will be increased above the nominal receiver temperature by an atmospheric contribution (see equation 13.49 of Thompson, Moran & Swenson 1986). Such corrections can be made with AIPS task CLCOR.

Although experience with VLBA calibration shows that it probably yields fringe amplitudes accurate to 5 percent or less, it is recommended that users observe one or more amplitude calibration check sources during their VLBA project. Table 14.1 gives a suggested list of such sources, selected because they are LIKELY to be point-like on inner VLBA baselines at wavelengths of 6cm and 4cm. (Analysis of 4cm Mark II VLBA data on them is currently in progress. VLBA format test observations at all VLBA wavelengths are planned.) Other sources will be added in the future. VLBA observations of one or more sources in Table 14.1 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.

Table 14.1. Suggested Amplitude Check Sources at 6cm and 4cm

| Names | | | | | |
|---|---|---|---|---|---|
| IAU (B1950) | J2000 | Common | J2000 Right Ascension [h m s] | J2000 Declination [d ' "] | Position Ref. |
| 0804+499 | J0808+49 | ... | 08 08 39.666666 | 49 50 36.52788 | 1 |
| 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 |

Ref. 1=Ma et al. 1990, rms accuracy ~ 1 mas
2=Patnaik et al. 1992, rms accuracy ~ 12 mas

# 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 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 15.1 are commonly used as fringe finders at cm 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).

Table 15.1. Suggested Fringe Finders at cm Wavelengths

| Names | | | | |
|---|---|---|---|---|
| IAU (B1950) | J2000 | Common | J2000 Right Ascension [h m s] | J2000 Declination [d ' "] |
| 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 |

## 15.2. The Phase 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' system (Rogers et al. 1983, Alef 1989a) is currently available at some VLBA antennas to overcome this problem at 13cm and 4cm; see Table 18.1. 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 phase 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 receiver 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 phase 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 phase 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 program 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 programs 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 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, IF 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 cm wavelengths, VLBA users should include observations of sources either with simple linearly polarized structure (e.g., 1404+286/OQ208, see Table 14.1) or no linearly polarized emission (e.g., 0316+413/3C84, see Table 15.1). 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 rapidly approaching the end of its construction phase. Table 18.1 summarizes the current readiness of the VLBA antennas for astronomical observing. The entries under the antenna code headings have the following meaning: 'A' - item is currently available; month/year or quarter number/year - date when item is likely to be installed at the antenna; 'NP' - not planned; '...' - no date information available at this time. If a past date is given then the item is available but is not yet checked out.

Table 18.1. VLBA Astronomical Readiness as of 1992 September 4

| Property | PT | KP | LA | FD | NL | OV | BR | HN | SC | MK |
|---|---|---|---|---|---|---|---|---|---|---|
| | Antenna (Construction Order) | | | | | | | | | |
| Pointing | A | A | A | A | A | A | A | A | A | 04/93 |
| Mark II | A | A | A | A | A | A | A | NP | NP | NP |
| 1st VLBA recorder | A | A | A | A | A | A | A | A | A | 01/93 |
| 2nd VLBA recorder | A | A | A | 09/92 | 09/92 | 09/92 | 10/92 | 10/92 | 12/92 | 01/93 |
| 8 BBCs | A | A | A | A | A | A | A | A | A | A |
| Phase cal | A | A | A | A | ... | A | ... | ... | ... | ... |
| Receivers and feeds | | | | | | | | | | |
| 90cm (0.33 GHz) | A | A | A | A | A | A | A | A | A | Q4/92 |
| 50cm (0.61 GHz) | A | A | A | A | A | A | A | A | A | Q4/92 |
| 20cm (1.5 GHz) | A | A | A | A | A | A | A | A | A | Q4/92 |
| 13cm (2.3 GHz) | A | A | A | A | A | A | A | A | A | Q4/92 |
| 6cm (4.8 GHz) | A | A | A | A | A | A | A | A | A | Q4/92 |
| 4cm (8.4 GHz) | A | A | A | A | A | A | A | A | A | Q4/92 |
| 3cm (10.7 GHz) | A | NP | NP | NP | NP | NP | NP | NP | NP | NP |
| 2cm (15 GHz) | A | A | A | 10/92 | A | A | 10/92 | A | 10/92 | Q4/92 |
| 1cm (23 GHz) | A | A | A | A | A | A | A | A | A | Q4/92 |
| 7mm (43 GHz) | A | A | A | A | A | A | A | A | Q3/92 | Q4/92 |
| 13/4cm dichroic | A | A | A | A | A | A | A | A | A | Q4/92 |
| Network observing | A | A | A | A | A | A | A | 09/92 | 09/92 | 04/93 |

## 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:

Case 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. Such a project, even if it includes the VLA, does not have to be run during a VLBI network session. Prospective proposers can consult section 18 for astronomical readiness information for the VLBA. Similar information for the VLA is given by Wrobel (1991a, b). NRAO handles the proposing, refereeing and scheduling mechanisms for such projects. Proposal deadlines and 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).

Case 2: The EVN, whose members are Effelsberg, Jodrell Bank, Medicina, Metsaehovi, Nancay, Noto, Onsala, Pushino, Shanghai, Simeiz, Torun, Wettzell and Westerbork. Prospective proposers can consult the EVN Handbook for updated information on the capabilities of EVN antennas. The EVN handles the proposing, refereeing and scheduling mechanisms for such projects, which must all be run during a VLBI network session. EVN proposal deadlines and VLBI network session dates and wavelengths are regularly 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 VLBA affiliates (see case 3) constitutes a global proposal, and must be submitted to both the VLBA and the EVN.

Case 3: VLBA affiliates in addition to the VLA include Arecibo, Effelsberg, the Deep Space Network, Green Bank, Haystack, Medicina and Noto. A VLBA proposal requesting such affiliates is handled as in case 1, except that if two or more EVN antennas 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 VLBI network session, depending on which affilliates are involved.

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.

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,
Max-Planck-Institut fuer Radioastronomie,
Auf dem Huegel 69, D-W-5300 Bonn 1, 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 VLBA, EVN and global proposals. Tex or ASCII versions of this cover sheet, authored by Barry Clark, are available electronically via anonymous-guest FTP on host 'zia.aoc.nrao.edu' (146.88.1.4) in 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 Mark II, Mark III and VLBA 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 antenna 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 1992 October. Users will be welcomed to try out the prototype. Announcements of its availability and how to get it using anonymous ftp will be made on the NRAO VLBI e-mail exploder and the NRAO Newsletter. After some feedback on the prototype, construction of the official release, involving generic X-windows on many different computers, will commence in the beginning of 1993. 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. 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 IF 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 multi-IF 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 IF 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 1992), 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 OF SOFTWARE, DOCUMENTS AND KEY PERSONNEL

### 26.1. Software

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.

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.

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

### 26.2. Documents

Numerous articles from two books occur in the list below. 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.

The document list follows. Copies of documents marked ** are available from Betty Trujillo (see section 26.3).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Diamond, P.J., & Wells, D.C. 1992, VLBA Correlator Memo No. ???. **

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

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

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

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.

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

Moran, J.M. 1989a, in Very Long Baseline Interferometry, p. 27.

Moran, J.M. 1989b, in Very Long Baseline Interferometry, p. 47.

Napier, P.J. 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. 390.

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

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

Perley, R.A. 1989a, in Synthesis Imaging, p. 259.

Perley, R.A. 1989b, in Synthesis Imaging, p. 287.

Roberts, D.H., Brown, L.F., & Wardle, J.F.C. 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. 281.

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

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

Schwab, F.R., & Cotton, W.D. 1983, Astronomical Journal, 88, 688.

Sramek, R.A., & Schwab, F.R. 1989, in Synthesis Imaging, p. 117.

Thompson, A.R., Moran, J.M., & Swenson, G.W., Jr. 1986, Interferometry and Synthesis in Radio Astronomy, John Wiley and Sons, Inc.

Walker, R.C. 1981, Astronomical Journal, 86, 1323.

Walker, R.C. 1989a, in Very Long Baseline Interferometry, p. 141.

Walker, R.C. 1989b, in Very Long Baseline Interferometry, p. 163.

Walker, R.C. 1989c, in Synthesis Imaging, p. 355.

Walker, R.C. 1992, VLBA Test Memo No. 33. **

Wilkinson, P.N. 1987, in Superluminal Radio Sources, edited by J.A. Zensus & T.J. Pearson, Cambridge University Press, p. 211.

Wilkinson, P.N. 1989a, in Very Long Baseline Interferometry, p. 69.

Wilkinson, P.N. 1989b, in Very Long Baseline Interferometry, p. 183.

Wrobel, J.M. 1991a, 'VLBI at the VLA. I. A Short Guide for Absentee Observers'.

Wrobel, J.M. 1991b, 'VLBI at the VLA. II. The Long Guide'.

26.3. Key Personnel

Table 26.3.1 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.

Table 26.3.1. Resource List of Key Personnel

| Name | *1* Location | *1* 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 | 200 | VLBA postdoctoral fellow |
| Larry Beno | AOC | 7212 | 186 | masers, time |
| John Benson | AOC | 7399 | 366 | VLBA correlator |
| Carl Bignell | AOC | 7242 | 305 | 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 |
| 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 |
| Bill Junor | AOC | 7210 | 276 | VLBA testing |
| 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 |
| Peggy Perley | AOC | 7239 | 204 | VLA/VLBA data analyst |
| Rick Perley | AOC | 7312 | 332 | AOC computing and operations head |
| 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 |
| Cam Wade | AOC | 7232 | 256 | VLBA pointing |
| Craig Walker | AOC | 7247 | 314 | VLBA pointing, gains, testing, general health |
| Joan Wrobel | AOC | 7392 | 302 | VLBI at VLA, VLBA user contact |
| 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 |

Note: *1* AOC=Array Operations Center +1-505-835-extension
VLA=Very Large Array +1-505-772-extension
CV =Charlottesville +1-804-296-extension

(end document)