VERY LONG BASELINE ARRAY OBSERVATIONAL STATUS SUMMARY

Edited by J. S. Ulvestad

August 4, 2008

WARNING WARNING WARNING

This is an archival version of the VLBA Observational Status Summary (OSS).

It is maintained on the NRAO website primarily to support scientific research based on archival VLBA observations.

It does not present a current description of the VLBA instrument, and should not be used in proposing or planning future VLBA observations. For these purposes, consult the current VLBA OSS, at https://science.nrao.edu/facilities/vlba/docs/manuals/oss .

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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) 10 receivers in the range 90 cm to 3 mm at each antenna (two antennas not equipped at 3 mm); (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 can acquire simultaneous dual circular polarizations from any single receiver or from receiver pairs at 13/4 cm or 90/50 cm. The conference proceedings edited by Zensus, Taylor, & Wrobel (1998), as well as the VLBA 10th anniversary proceedings (Romney & Reid 2005) provide broad overviews of the kinds of astronomical research possible with the VLBA. Recommended reading for users new to the VLBA includes a short VLBI overview (Walker 1999b) and a short guide for novice users of the VLBA (Ulvestad 2004).

This document's primary intent is to provide, in concise form, the minimal information needed to formulate technically sound proposals requesting VLBA resources. Its secondary aims are to provide information about a few of the subtleties of data reduction and telescope scheduling, lists of relevant software and documentation, plus a list of key NRAO personnel who can be consulted for further, more detailed information. In particular, note that Sections 17 and 18 contain a number of hints and directions about data calibration and imaging. This document, which is updated every 1–2 years, is available through the VLBA astronomer page at `http://www.vlba.nrao.edu/astro/` .

The VLBA is operated remotely from the Pete V. Domenici Science Operations Center (DSOC, formerly known as the AOC) in Socorro, New Mexico, with local assistance at each VLBA antenna site provided by site technicians.

2 VLBA FUTURE DEVELOPMENT

The recent Senior Review commissioned by the National Science Foundation's Division of Astronomical Sciences lauded the VLBA as a unique facility, but recommended that outside funding assistance be obtained for operations by 2011, or else that the VLBA be closed. NRAO is confident of its ability to attract this funding, and has embarked on a program to significantly enhance the sensitivity of the VLBA by substantially increasing the data rate supplied from the telescopes to the correlator. The goal of this increase is to achieve a 4 Gigabit per second (4 Gbps) capability by 2011, a 32-fold increase over the present sustainable data rate of 128 Megabit per second (128 Mbps). This will increase the standard observing bandwidth from 16–32 MHz per polarization to 500 MHz per polarization (a factor of 5 above the current VLA) and will enhance the signal/noise ratio of the typical continuum observation by a factor of $\sqrt{32} = 5.6$, the equivalent of nearly two optical magnitudes. New technologies for digital backends, data transmission and recording, and data correlation make this an achievable goal for a fairly modest investment over the next several years. In the nearer term, an upgrade of the 1 cm receivers at the VLBA recently has been completed, with financial assistance from the Max Planck Institut für Radioastronomie; see Section 5. Overall descriptions of the VLBA sensitivity upgrade are given by Romney (2007) and Walker et al. (2007b).

3 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. All locations are based on the WGS84 ellipsoid used by the GPS system[1], with Earth radius $a = 6378.137$ km and flattening $1/f = 298.257223563$. See Napier (1995) for further site information.

Several other radio telescopes often participate in VLBI observing in conjunction with the VLBA. These include the Very Large Array (VLA), either with up to 27 antennas added in phase (Y27) or with a single antenna (Y1); the Green Bank Telescope (GBT); Arecibo; Effelsberg; the European VLBI Network (EVN); plus (occasionally) various geodetic antennas or the NASA Deep Space Network. For details on how to propose for these extra

[1]Note that the reference system has been changed relative to early versions of this document.

Table 1: **Geographic Locations and Codes**

Location	North Latitude [° ′ ″]	West Longitude [° ′ ″]	Elevation [m]	Code
Saint Croix, VI	17:45:23.68	64:35:01.07	16	SC
Hancock, NH	42:56:00.99	71:59:11.69	296	HN
North Liberty, IA	41:46:17.13	91:34:26.88	222	NL
Fort Davis, TX	30:38:06.11	103:56:41.34	1606	FD
Los Alamos, NM	35:46:30.45	106:14:44.15	1962	LA
Pie Town, NM	34:18:03.61	108:07:09.06	2365	PT
Kitt Peak, AZ	31:57:22.70	111:36:44.72	1902	KP
Owens Valley, CA	37:13:53.95	118:16:37.37	1196	OV
Brewster, WA	48:07:52.42	119:40:59.80	250	BR
Mauna Kea, HI	19:48:04.97	155:27:19.81	3763	MK

telescopes, see Section 21.1.

A total of up to 100 hours per four-month trimester has been reserved for a High Sensitivity Array (HSA) composed of the VLBA, Y27, GBT, Arecibo, and Effelsberg; the HSA is described at `http://www.nrao.edu/HSA/` . In this context, users should be aware that Arecibo only operates at frequencies up to 10 GHz, and can view sources only within about 19.7° of its zenith; see `http://www.naic.edu` for further information about Arecibo's properties. The VLA and GBT are NRAO facilities, while Arecibo is operated by the National Astronomy and Ionosphere Center, and Effelsberg is operated by Germany's Max Planck Institut für Radioastronomie (MPIfR). Table 2 lists the locations of the HSA telescopes.

Table 2: **Locations of Other HSA Telescopes**

Location	North Latitude [° ′ ″]	West Longitude [° ′ ″]	Elevation [m]	Code
Arecibo, PR	18:20:36.60	66:45:11.10	497	AR
Green Bank, WV	38:25:59.24	79:50:23.41	807	GB
VLA, NM	34:04:43.75	107:37:05.91	2115	Y27
Effelsberg, Germany	50:31:30	−6:53:00.3	319	EB

4 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° per minute between a hardware limit of 2° and a software limit of 90°. Azimuth motion has a rate of 90° per minute between limits of −90° to 450°. Antennas are stowed to avoid operation in high winds, or in case of substantial snow or ice accumulation. In 2007, the St. Croix antenna was taken out of service for three months to repair severe corrosion caused by its location very close to the ocean. See Napier (1995) for further antenna information.

5 PERFORMANCE PARAMETERS

Table 3 gives the nominal frequency ranges for the receiver/feed combinations available on all or most 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 and `http://www.vlba.nrao.edu/cgi-bin/wbd_dir.pl` for updates on the antenna performance as a function of frequency across the VLBA bands. Measured frequency ranges may be especially important for avoiding radio frequency interference (RFI), and for programs involving extragalactic lines, rotation measures (Cotton 1995b; Kemball 1999), and multi-frequency synthesis (Conway & Sault 1995; Sault & Conway 1999).

Also appearing in Table 3 are parameters characterizing the performance of a typical VLBA antenna for the various receiver/feed combinations. Columns [3] and [5] give typical VLBA system equivalent flux densities ($SEFD$s) at zenith and opacity-corrected gains at zenith, respectively. These were obtained from averages of right circularly polarized (RCP) and left circularly polarized (LCP) values from 10 antennas, measured at the frequencies in column [4] by VLBA operations personnel during regular pointing observations. In 2007, Germany's Max Planck Insitut für Radioastronomie funded a program to enhance the 1 cm sensitivity of the VLBA by installing modern low noise amplifiers to replace the original VLBA hardware. This program, implemented by NRAO, was completed in early 2008

Table 3: **Frequency Ranges and Typical Performance Parameters**

Receivers and Feeds	Nominal Frequency Range [GHz]	Typical Zenith $SEFD$ [Jy]	Center Frequency for $SEFD$ [GHz]	Typical Zenith Gain [K Jy^{-1}]	Baseline Sensitivity $\Delta S^{256,2\mathrm{m}}$ [mJy]	Image Sensitivity $\Delta I_{\mathrm{m}}^{256,8\mathrm{h}}$ [μJy beam^{-1}]
90 cm	0.312 - 0.342	2227	0.326	0.097	51.1 (a)	350
50 cm	0.596 - 0.626	2216	0.611	0.088	101.1 (b)	700 (b)
21 cm (c)	1.35 - 1.75	296	1.438	0.096	3.3	32
18 cm (c)	1.35 - 1.75	303	1.658	0.100	3.7	36
13 cm (d)	2.15 - 2.35	322	2.275	0.093	3.6	35
13 cm (d,e)	2.15 - 2.35	337	2.275	0.090	3.8	37
6 cm	4.6 - 5.1	312	4.999	0.130	3.5	34
4 cm	8.0 - 8.8	307	8.425	0.113	3.6	35
4 cm (e)	8.0 - 8.8	407	8.425	0.106	4.7	46
2 cm	12.0 - 15.4	550	15.369	0.104	6.2	60
1 cm (f)	21.7 - 24.1	502	22.236	0.107	5.9	57
1 cm (f)	21.7 - 24.1	441	23.799	0.107	5.1	50
7 mm	41.0 - 45.0	1436	43.174	0.078	22.2 (a,g)	151
3 mm (h)	80.0 - 90.0	4000	86.2	0.025	57. (i)	850 (j)

Notes: (a) Assumes a fringe-fit interval of 1 minute. (b) Assumes a fringe-fit interval of 1 minute and a data rate of 32 Mbps. (c) Different settings of the same 20 cm receiver. Hronek & Walker (1996) describe additional antenna-specific filters not mentioned by Thompson (1995). (d) Filters at NL, LA, and OV restrict frequencies to 2200-2400 MHz. (e) With 13/4 cm dichroic. (f) Different settings of the same 1 cm receiver. Continuum performance is better at 23.8 GHz, away from the water line. (g) Performance may be worse on some baselines due to poor subreflector or primary reflector shapes or poor atmospheric conditions (almost universal at SC). (h) "Average" 3 mm antennas are assumed; see Table 4 for more details. (i) Assumes a fringe-fit interval of 30 seconds and a recording rate of 512 Mbps. (j) Assumes 4 hours of integration with 7 antennas recording at a rate of 512 Mbps.

and achieved its goal of reducing the zenith $SEFD$s by more than 30%. See Walker et al. (2007a, 2008) for more details.

The typical zenith $SEFD$s can be used to estimate root-mean-square (RMS) noise levels on a baseline between 2 VLBA antennas (ΔS for a single polarization; see Equation 6) and in a VLBA image (ΔI_{m} for a single polarization; see Equation 8). Characteristic values for $\Delta S^{256,2\mathrm{m}}$ assuming a fringe-fit interval of $\tau_{\mathrm{ff}} = 2$ minutes and for $\Delta I_{\mathrm{m}}^{256,8\mathrm{h}}$ assuming a total integration time on source of $t_{\mathrm{int}} = 8$ hours also appear in Table 3. The tabulated baseline sensitivities for 90 cm, 50 cm, and 7 mm assume a fringe-fit interval of 1 minute, since 2 minutes is unrealistically long. All the baseline and image sensitivities in the table, except for 50 cm and 3 mm, assume an aggregate recording bit rate equal to the typical value of 256 Mbps (see Section 6.16). This rate is commonly achieved by recording a total bandwith $\Delta\nu$ of 64 MHz (usually 32 MHz per polarization) with 2-bit (4-level) sampling (see Section 6.14). Although the original sustainable observing rate of the VLBA was 128 Mbps, advances in recording capabilities enabled the average data recording rate to reach 230 Mbps in 2007. Thus, beginning at the October 2008 proposal deadline, the default VLBA data rate for continuum observations probably will be increased from 128 Mbps to 256 Mbps. Recording at 512 Mbps is possible when required for scientific reasons and justified carefully in the observing proposal; for continuum sources, this may reduce system noise by factors of 1.4 or 2, respectively.[2] For 3 mm, it is assumed that twice the sustainable recording rate is used, that the fringe-fit interval is 30 seconds, and that an image is made from 4 hours of integration with 7 antennas.

Opacity-corrected zenith gains are needed for current techniques for amplitude calibration. These zenith gains vary from antenna to antenna, and are monitored by VLBA operations and communicated to users (see Section 17). The typical values appearing in Table 3 are meant to be illustrative only.

The 3 mm band is beyond the design specification for the VLBA subreflectors, and challenging for both the panel-setting accuracy of the primary reflectors and the pointing of the antennas. In addition, performance is highly dependent on weather conditions. Poor performance is the primary reason why neither HN nor SC is outfitted at 3 mm. Table 4 gives the approximate current performance at 86 GHz for each antenna, as well as the rms noise in 30 seconds (at 512 Mbps) on a baseline to LA, one of the more sensitive 3 mm antennas at present.

Table 4: **Typical Performance Parameters at 86.2 GHz**

Antenna	Nominal Frequency Range [GHz]	Typical Zenith $SEFD$ [Jy]	Typical Zenith Gain [K Jy^{-1}]	Typical Zenith T_{sys} [K]	Baseline (a) Sensitivity $\Delta S^{512,30s}$ [mJy]
BR	80.0 - 90.0	3500	0.039	135	55.
NL	80.0 - 96.0	4900	0.055	270	65.
FD	80.0 - 96.0	3600	0.034	120	55.
LA	80.0 - 90.0	3100	0.051	160	···
PT	80.0 - 96.0	4100	0.024	100	55.
KP	80.0 - 96.0	4600	0.025	110	60.
OV	80.0 - 96.0	5800	0.020	100	65.
MK	80.0 - 96.0	4100	0.023	100	55.

Note: (a) Baseline to LA is assumed.

[2] For the HSA, the default recording rate is 256 Mbps, and 512 Mbps often is employed.

6 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). In collaboration with the South African KAT group, MIT Haystack Observatory, and the CASPER group at UC Berkeley, NRAO currently is developing a digital back end that will enable data to be delivered to recording systems at a rate of 4 Gbps. We expect the new back end systems to be implemented in 2009. At that time, subsections 6.13 through 6.15 will become obsolete.

6.1 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.

6.2 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. The shaped subreflector illuminates all feeds above 1 GHz; these feeds are located on a ring at the Cassegrain focus, and changes from one feed to another (hence changes in observing band) take only a few seconds. In addition, a permanently installed dichroic enables simultaneous 2.3/8.4 GHz observations. The 330 and 610 MHz feeds are crossed dipoles mounted on the subreflector near prime focus. Therefore, it is possible to make simultaneous 330/610 MHz observations.

6.3 Polarizer

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

6.4 Pulse Cal

This system injects calibration tones based on a string of pulses at intervals of 1.0 or 0.2 microseconds. Pulses thus are generated at frequency intervals of 1 MHz or 5 MHz. See Section 18.2 for more details.

6.5 Noise Cal

This device injects switched, well calibrated, broadband noise for system temperature measurements. Synchronous detection occurs in the intermediate frequency (IF) distributors (see Section 6.12) and base band converters (see Section 6.13). Switching is done at 80 Hz.

6.6 Receiver

The receiver amplifies the signal. Most VLBA receivers are HFETs (Heterostructure Field Effect Transistors) at a physical temperature of 15 K, but the 90 cm and 50 cm receivers are GaAsFETs (Gallium Arsenide FETs) at room temperature. Each receiver has 2 channels, one for RCP and one for LCP. The 1 cm, 7 mm, and 3 mm receivers also perform the first frequency down conversion.

6.7 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 6.9) and the pulse cal system (see Sections 6.4 and 18.2). The 5 MHz output is the reference for the base band converters (see Section 6.13), the formatter (see Section 6.15), and the antenna timing.

6.8 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.

6.9 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, 3 mm, and for the wide band mode at 4 cm described in Section 6.10.

6.10 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.

6.11 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.

6.12 IF Distributors

The IF distributors make 8 copies of each IF, one for each base band converter (see Section 6.13). They also can optionally switch in 20 db of attenuation for solar observations. There are two IF distributors, 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.

6.13 Base Band Converters

The base band converters (BBCs) mix the IF signals to base band and provide the final analog filtering. Each of 8 BBCs generates a reference signal between 500 and 1000 MHz at any multiple of 10 kHz. Each BBC can select as input any of the four IFs. Each BBC provides the upper and lower sidebands as separate outputs, allowing for a total of 16 "BB channels", where one BB channel is one sideband from one BBC. Allowed bandwidths per BBC are 0.0625, 0.125, 0.25, 0.5, 1, 2, 4, 8, and 16 MHz. Thus the 16 possible BB channels can cover an aggregate bandwidth up to 256 MHz. The BBC signals are adjusted in amplitude. With automatic leveling turned on, the power in the signals sent to the samplers is kept nearly constant, which is important for the 2-bit (4-level) sampling mode (see Section 6.14). The BBCs contain synchronous detectors that measure both total power and switched power in each sideband for system temperature determination. *This subsection will become obsolete when the new digital back ends are installed on the VLBA in 2009.*

6.14 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, or 2 Msamples per second on each channel; for spectral-line observations at channel widths smaller than 0.5 MHz, oversampling is required. *This subsection will become obsolete when the new digital back ends are installed on the VLBA in 2009.*

6.15 Formatter

The formatter selects the desired bit streams from the samplers, adds time tags, and supports various other functions required to record efficiently on the VLBA's original tape-based data acquisition system. Although no longer required for disk-based recording, these functions are still used in the transitional Mark 5A system mentioned in Section 6.16. Auxiliary detection of up to 16 pulse-calibration tones are state counts also is supported in the formatter. *This subsection will become obsolete when the new digital back ends are installed on the VLBA in 2009.*

6.16 Recorders

The VLBA records on Mark 5A recording systems, also in use at the VLA and the GBT. Each unit records on two removable modules, sequentially in most cases, but in parallel at the 512-Mbps data rate that is the highest currently supported. Each module comprises eight commercial disk drives. The current VLBA complement of modules is based primarily on 250 or 300

Gbyte disks, for a total of 2–2.4 Terabytes of recording capacity.[3] Presently, a few modules with eight 500–750-Gbyte disks (4–6 Terabyte total capacity) are available. Thus, a single module lasts for approximately 17–52 hours if recorded continuously at 256 Mbps, or commensurately shorter periods for recording at 512 Mbps.[4] More details on Mark 5 systems may be found at `http://web.haystack.mit.edu/mark5/Mark5.htm` .

As part of the VLBA sensitivity upgrade, we have a goal to convert the VLBA to Mark 5C recording systems, capable of recording data at 4 Gbps, by 2010. See VLBA Sensitivity Upgrade Memo No. 12 (MIT-Haystack and NRAO 2008) for more details about the Mark 5C system.

6.17 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.

6.18 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.

6.19 GPS Receiver

This device acquires time from the Global Positioning System (GPS). GPS time is usually used to monitor the site clock, providing critical information for data correlation. GPS time is occasionally used to set the site clock if it is disrupted for some reason. Five of the stations have co-located geodetic GPS receivers that are part of the International Global Navigation Satellite Systems network.

7 RECORDING FORMATS

The VLBA records data on Mark 5A disk-based systems in VLBA format. Although the VLBA cannot record Mark 4 format as such, there is a high degree of compatibility between Mark 4 and VLBA formats. In general,

[3]By comparison, the old system with dual tape drives had a total capacity of 1.2 Terabytes.

[4]For example, most 3 mm continuum observations record at 512 Mbps.

disks in either VLBA or Mark 4 formats can be played back, for the same observation if necessary, on any VLBA or Mark 4 correlator.

As part of the VLBA sensitivity upgrade, we have a goal to convert the VLBA to Mark 5C recording systems by 2010. The data then will be "format-free" data recorded as standard disk files, though there will be a compatibility mode possible to record in formats useful for earlier versions of Mark 5 hardware correlators.

8 CORRELATOR

As part of the VLBA sensitivity upgrade, NRAO currently is integrating the DiFX software correlator into the operational environment of the VLBA, and performing tests to validate its results by comparison with those of the original VLBA correlator. The DiFX system was developed at Swinburne University in Melbourne, Australia (Deller et al. 2007). We anticipate that DiFX will become the operational VLBA correlator in 2009. At that time, the present section will become obsolete.

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

The correlator is designed to process all observations involving VLBA stations. With its 20-station capacity and sub-arraying capabilities, it is designed to correlate an extended array combining the VLBA with as many as 10 other stations. At present, the VLBA correlator has available 17 data inputs from Mark 5A recorders, so the rare observations requiring correlation of more than 17 stations including the VLBA require multiple correlator passes.[5]

Each station input comprises 8 parallel "channels" (as defined in Section 6.13), which operate at a fixed rate of 32 Msamples per second, for either 1- or 2-bit samples. Observations at lower sample rates generally can be processed with a speed-up factor of 2 (for 16 Msamples per second) or 4 (for 8 Msamples per second or less) relative to observe time. Special modes are invoked automatically to enhance sensitivity when fewer than 8 channels are observed, or when correlating narrowband or oversampled data. The correlator accepts input data recorded in VLBA or Mark 4 longitudinal

[5] In view of the extra operational resources needed for multiple correlator passes, strong scientific justification must be made for any observation that requires correlation of more than 17 observing stations.

format, or on Mark 5A disk modules, and plays these data back on tape or disk drives similar to the station recorders (see Section 6.16).

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. The correlator cannot process maximally (16-fold) oversampled data at the highest spectral resolution, which effectively prohibits 1024-channel resolution at the narrowest bandwidth of 62.5 kHz. 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 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 (see Sections 12 and 13).

Correlator output is written in a "FITS Binary Table" format, and includes editing flags plus amplitude, weather, and pulse calibration data logged at VLBA antennas at observe time (Flatters 1998; Ulvestad 1999). All results are archived on digital-audio-tape (DAT) cassettes. The output data rate is limited to 1.0 Mbytes per second (MB/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. Observations since approximately 1998 (or earlier, depending on when you read this document!) can be retrieved directly from the NRAO archive at `http://archive.nrao.edu`.

Operation of the correlator is governed primarily by information obtained from the VLBA control system's monitor data or from foreign stations' log files. A few additional items, all of which have been mentioned above, will be specified by the user prior to correlation. Supervision of the correlation process is the responsibility of VLBA operations personnel, and requires no participation by the observers. As described in Section 25, however, users are encouraged to visit the DSOC after correlation for post-processing analysis.

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

9 ANGULAR RESOLUTION

Table 5, generated with the NRAO program `SCHED` (Walker 2006), gives the maximum lengths rounded to the nearest km ($B_{\rm max}^{\rm km}$) for each of the VLBA's 45 internal baselines as well as the baselines to other HSA telescopes. Both the upper left and lower right portions of the table are filled to make it easier to use. A measure of the corresponding resolution ($\theta_{\rm HPBW}$) in milliarcseconds (mas) is

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

where $\lambda^{\rm cm}$ is the receiver wavelength in cm (Wrobel 1995). A uniformly weighted image made from a long *u*-*v* plane track will have a synthesized beam with a slightly narrower minor axis FWHM. At the center frequencies appearing in Table 3 and for the longest VLBA baseline, $\theta_{\rm HPBW}$ is 22, 12, 5.0, 4.3, 3.2, 1.4, 0.85, 0.47, and 0.32 mas for receivers named 90, 50, 21, 18, 13, 6, 4, 2, and 1 cm, plus 0.17 mas at 7 mm. The longest VLBA-only baseline at 3 mm is currently the one between MK and NL, which is about 30% shorter than the longest baseline at other wavelengths.

Table 5: **Maximum VLBI Baseline Lengths in km ($B_{\rm max}^{\rm km}$)**

	SC	HN	NL	FD	LA	PT	KP	OV	BR	MK	EB	AR	GB	Y27
SC	...	2853	3645	4143	4458	4579	4839	5460	5767	8611	6822	238	2708	4532
HN	2853	...	1611	3105	3006	3226	3623	3885	3657	7502	5602	2748	829	3198
NL	3645	1611	...	1654	1432	1663	2075	2328	2300	6156	6734	3461	1064	1640
FD	4143	3105	1654	...	608	564	744	1508	2345	5134	8084	3922	2354	515
LA	4458	3006	1432	608	...	236	652	1088	1757	4970	7831	4246	2344	226
PT	4579	3226	1663	564	236	...	417	973	1806	4795	8014	4365	2551	52
KP	4839	3623	2075	744	652	417	...	845	1913	4466	8321	4623	2939	441
OV	5460	3885	2328	1508	1088	973	845	...	1214	4015	8203	5255	3323	1025
BR	5767	3657	2300	2345	1757	1806	1913	1214	...	4398	7441	5585	3326	1849
MK	8611	7502	6156	5134	4970	4795	4466	4015	4398	...	10328	8434	7028	4835
EB	6822	5602	6734	8084	7831	8014	8321	8203	7441	10328	...	6911	6335	8008
AR	238	2748	3461	3922	4246	4365	4623	5255	5585	8434	6911	...	2545	4317
GB	2708	829	1064	2354	2344	2551	2939	3323	3326	7028	6335	2545	...	2516
Y27	4532	3198	1640	515	226	52	441	1025	1849	4835	8008	4317	2516	...

Note: See Tables 1 and 2 for exact coordinates.

10 *u*-*v* PLANE COVERAGE

Customized plots of the *u*-*v* plane coverage with the VLBA and/or other VLBI antennas can be generated with the NRAO program `SCHED` (Walker 2006).

11 TIME RESOLUTION

Time resolution is set by the VLBI correlator accumulation time. At the VLBA correlator it is about 2 seconds for most programs, although a minimum accumulation time of 131 milliseconds is available. The combination of time and spectral resolution for an observation must result in a correlator output rate of less than 1.0 Megabyte per second (MB/s). Approximate output rates are predicted by the `SCHED` software (Walker 2006), or see Section 13 for a rough parameterization. Pulsar gating also is available on the VLBA correlator (Benson 1998). *The limits on time resolution will become far more flexible when the DiFX correlator becomes operational in 2009.*

12 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 8. The spectral resolution is the bandwidth per BB channel divided by the number of spectral points. The VLBA correlator can apply an arbitrary special smoothing, which will affect the statistical independence of these points and thus the effective spectral resolution. Typical continuum programs request averaging to 16 spectral points, although this limits the ability to image parts of the field away from the correlator phase center (see Section 13). *The limits on spectral resolution will be eliminated when the DiFX correlator becomes operational in 2009.*

13 WIDE-FIELD IMAGING

The field of view that may be imaged by the VLBA is limited by smearing due to averaging over time and frequency at positions away from the correlator phase center, where the fringes are "stopped" (see Bridle & Schwab 1999, upon which this section is based). The maximum field of view is relatively independent of observing frequency in the case limited by bandwidth smearing (chromatic aberration), but depends on observing frequency for time-average smearing. As computing hardware has become more capable, it now is feasible to reduce the averaging in time and in frequency, subject to the maximum correlator output rate of 1.0 MB/s, in order to enable imaging all or part of a wider field of view. Care must be taken to reduce the averaging time and/or spectral channel width in the data output by the correlator, and then to retain these smaller averaging values in subsequent data processing.

A standard set of correlator parameters for VLBA observations of a continuum source would have 16 spectral points per 8 MHz BB channel, and time averaging over 1.97 s. (Correlator averaging times are integer multiples of the fundamental time step of 131.072 milliseconds; see Section 8.) In the limit of short time averaging so that there is no time-averaging loss, the approximate distance from the phase center for a 5% loss in peak amplitude due to bandwidth smearing is given by

$$\theta_{5\%,\Delta\nu} \;\approx\; 4.7 \left(\frac{0.5 \text{ MHz}}{\Delta\nu}\right) \text{arcsec}, \tag{2}$$

where $\Delta\nu$ is the width of an individual spectral point in MHz. Equation 2 assumes a Gaussian bandpass with a circular Gaussian taper. In the limit of narrow spectral channels, so that there is no bandwidth smearing loss, the approximate distance from the phase center for a 5% loss in peak amplitude due to time-average smearing is given by

$$\theta_{5\%,\tau} \;\approx\; 2.8 \left(\frac{8.4 \text{ GHz}}{\nu}\right) \left(\frac{1.97 \text{ s}}{\tau_{\text{acc}}}\right) \text{arcsec}, \tag{3}$$

where ν is the sky frequency in GHz and τ_{acc} is the correlator accumulation time in seconds. Equation 3 assumes circular coverage in the u-v plane with a Gaussian taper, for a source at the celestial pole. Away from the celestial pole, the allowed field of view is somewhat larger, and also depends on direction relative to the phase center, so Equation 3 generally provides a lower limit to the distance from the phase center at which a 5% loss occurs.

For a fixed bit rate in a continuum observation, bandwidth smearing is reduced by using 2-bit sampling rather than 1-bit sampling; this provides approximately the same sensitivity (see Section 14 below) with 1/2 the total bandwidth, or 1/2 the spectral point width for the same correlator output rate. For a 10-station VLBA observation with two 8-MHz BB channels at each of two polarizations, and correlation of all four polarization pairs (RR, RL, LR, and LL), the limiting correlator output rate of 1.0 MB/s is approached (for example) with an accumulation time of 0.26 s and 32 spectral points in each of the 8-MHz BB channels. A rough scaling law for the data output rate from the VLBA correlator in this case is

$$\text{Rate} \;\approx\; 0.87 \left(\frac{N}{10}\right)^2 \left(\frac{0.26 \text{ s}}{\tau_{\text{acc}}}\right) \left(\frac{N_{\text{sp}}}{32}\right) \text{MB/s} \; . \tag{4}$$

If one were to correlate only the parallel hands, RR and LL, Equation 4 would be modified to

$$\text{Rate} \approx 0.43 \left(\frac{N}{10}\right)^2 \left(\frac{0.26\ \text{s}}{\tau_{\text{acc}}}\right) \left(\frac{N_{\text{sp}}}{32}\right) \text{MB/s}. \tag{5}$$

In the two equations above, N is the number of antennas available and N_{sp} is the number of spectral points output by the correlator for each BB channel. For more details on wide-field imaging techniques, see Garrett *et al.* (1999).

14 BASELINE SENSITIVITY

Adequate baseline sensitivity is necessary for VLBI fringe fitting, discussed in Section 18.3. Typical baseline sensitivities are listed in Table 3. Alternatively, the following formula can be used in conjunction with the typical zenith $SEFD$s for VLBA antennas given in Table 3 to calculate the RMS thermal noise (ΔS) in the visibility amplitude of a single-polarization baseline between two identical antennas (Walker 1995a; Wrobel & Walker 1999):

$$\Delta S = \frac{1}{\eta_{\text{s}}} \times \frac{SEFD}{\sqrt{2 \times \Delta\nu \times \tau_{\text{ff}}}} \ \text{Jy}. \tag{6}$$

In Equation 6, $\eta_{\text{s}} \leq 1$ accounts for the VLBI system inefficiency (e.g., quantization in the data recording and correlator approximations). Kogan (1995b) provides the combination of scaling factors and inefficiencies appropriate for VLBA visibility data. For the VLBA correlator $\eta_{\text{s}} \approx 0.5$ for 1-bit sampling and $\eta_{\text{s}} \approx 0.7$ for 2-bit sampling. For non-identical antennas 1 and 2, Equation 6 is modified to the following:

$$\Delta S = \frac{1}{\eta_{\text{s}}} \times \frac{\sqrt{(SEFD)_1 (SEFD)_2}}{\sqrt{2 \times \Delta\nu \times \tau_{\text{ff}}}} \ \text{Jy}. \tag{7}$$

The bandwidth in Hz is $\Delta\nu$; for a continuum target, use the BB channel width or the full recorded bandwidth, depending on fringe-fitting mode, and for a line target, use the BB channel width divided by the number of spectral points per BB channel. τ_{ff} is the fringe-fit interval in seconds, which should be less than or about equal to the coherence time τ_{coh}. Equations 6 and 7 hold in the weak source limit. About the same noise can be obtained with either 1-bit (2-level) or 2-bit (4-level) quantization at a constant overall bit rate; cutting the bandwidth in half to go from 1-bit to 2-bit sampling is approximately compensated by a change in η_{s} that is very nearly equal to $\sqrt{2}$. Moran & Dhawan (1995) discuss expected coherence times. The actual coherence time appropriate for a given VLBA program can be estimated using observed fringe amplitude data on an appropriately strong and compact source.

15 IMAGE SENSITIVITY

Typical image sensitivities for the VLBA are listed in Table 3. Alternatively, the following formula may be used in conjunction with the typical zenith $SEFD$s for VLBA antennas given in Table 3 (or a different $SEFD$ for lower elevations or poor weather) to calculate the RMS thermal noise ($\Delta I_{\rm m}$) expected in a single-polarization image, assuming natural weighting (Wrobel 1995; Wrobel & Walker 1999):

$$\Delta I_{\rm m} = \frac{1}{\eta_{\rm s}} \times \frac{SEFD}{\sqrt{N \times (N-1) \times \Delta\nu \times t_{\rm int}}} \ \ {\rm Jy\ beam}^{-1}, \tag{8}$$

where $\eta_{\rm s}$ is discussed in Section 14; N is the number of VLBA antennas available; $\Delta\nu$ is the bandwidth [Hz]; and $t_{\rm int}$ is the total integration time on source [s]. The expression for image noise becomes rather more complicated for a set of non-identical antennas such as the HSA, and may depend quite strongly on the data weighting that is chosen in imaging. The best strategy in this case is to estimate image sensitivity using the EVN sensitivity calculator at `http://www.evlbi.org/cgi-bin/EVN/calc` . As an example, note that the rms noise at 22 GHz for the 10 antenna VLBA in a 1-hr integration is reduced by a factor between 4 and 5 by adding the GBT and the phased VLA.

If simultaneous dual polarization data are available with the above value of $\Delta I_{\rm m}$ per polarization, then for an image of Stokes I, Q, U, or V,

$$\Delta I = \Delta Q = \Delta U = \Delta V = \frac{\Delta I_{\rm m}}{\sqrt{2}}. \tag{9}$$

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

$$\Delta P = 0.655 \times \Delta Q = 0.655 \times \Delta U. \tag{10}$$

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

$$\Delta T_{\rm b} \sim 320 \times \Delta I_{\rm m} \times (B^{\rm km}_{\rm max})^2 \ \ {\rm K}, \tag{11}$$

where $B^{\rm km}_{\rm max}$ is as in Equation 1.

16 CALIBRATION TRANSFER

Data necessary to perform accurate calibration for the VLBA are supplied as part of the correlator output files, and will appear within the Astronomical Image Processing System (AIPS) as extension tables attached to the FITS files. These tables include GC (gain), TY (system temperature), and WX (weather) tables for amplitude calibration, PC (pulse-cal) tables for system phase calibration, and FG (flag) tables for editing. For non-VLBA antennas, some or all of these tables may be missing, since relevant monitor data are not available at the time of correlation. For example, for the HSA, GC and TY information are available for most antennas, except that calibration of the phased VLA requires additional information about the flux density of at least one source. Flag (FG) tables for non-VLBA antennas are absent or only partially complete, lacking information about antenna off-source times. In such cases, the "flag" input file that is output by the `SCHED` software may be very useful for flagging data when antennas are not on source; this file appears to be quite good at predicting the on-source times for the GBT, Arecibo, and Effelsberg, but presently underestimates by about 10 seconds the time it takes for Y27 to change source.[6] For further information in applying calibrations, see Appendix C of the AIPS Cookbook (NRAO staff, 2006) or the relevant AIPS HELP files.

17 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 ($T_{\rm sys}$) are measured "frequently" in each BB channel during observations with VLBA antennas; "frequently" means at least once per source/frequency combination or once every user-specified interval (default is 2 minutes), whichever is shorter. These $T_{\rm sys}$ values are required by fringe amplitude calibration programs such as `ANTAB/APCAL` in AIPS or `CAL` in the Caltech VLBI Analysis Programs; see Section 24. Such programs can be used to convert from $T_{\rm sys}$ to $SEFD$ by dividing by the VLBA antenna zenith gains in K $\rm Jy^{-1}$ provided by VLBA operations, based upon regular monitoring of all receiver and feed combina-

[6]For observers who wish to use the text file produced by `SCHED` as an input text file in the AIPS task `UVFLG`, it is recommended that all entries for the 10 VLBA antennas be deleted. More accurate flagging information (e.g., actual on-source times) for these antennas is provided in the VLBA monitor data used to construct the FG table that is supplied with the correlator output files.

tions. $T_{\rm sys}$ and gain values for VLBA antennas are delivered in TY and GC tables, respectively (see Section 16). Single-antenna spectra can be used to do amplitude calibration of spectral line programs (see Section 20).

An additional loss of sensitivity may occur for data taken with 2-bit (4-level) quantization, due to non-optimal setting of the voltage thresholds for the samplers (see Kogan 1995a). This usually is a relatively minor, but important, adjustment to the amplitude calibration. In the VLBA, for instance, the system design leads to a systematic (5% to 10%) calibration offset of the samplers between even and odd BB channels; for dual polarization observations, this may lead to a systematic offset between RR and LL correlations that must be accounted for in the calibration. The combination of the antenna and sampler calibrations may be found and applied in AIPS using the procedure `VLBACALA`.

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, particularly at high frequencies (Moran & Dhawan 1995). The GC table described above contains gain curves for VLBA antennas. A scheme for doing opacity adjustments is desribed by Leppänen (1993). Such adjustments can be made with AIPS task `APCAL` if weather data are available in a WX table (see Section 16).

Although experience with VLBA calibration shows that it probably yields fringe amplitudes accurate to 5% or less at the standard frequencies in the 1–10 GHz range, it is recommended that users observe a few amplitude calibration check sources during their VLBA program. Such sources can be used (1) to assess the relative gains of VLBA antennas plus gain differences among base band channels at each antenna; (2) to test for non-closing amplitude and phase errors; and (3) to check the correlation coefficient adjustments, provided contemporaneous source flux densities are available independent of the VLBA observations. These calibrations are particularly important if non-VLBA antennas are included in an observation, since their *a priori* gains and/or measured system temperatures may be much less accurate than for the well-monitored VLBA antennas. The VLBA gains are measured at the center frequencies appearing in Table 3; users observing at other frequencies may be able to improve their amplitude calibration by including brief observations, usually of their amplitude check sources, at the appropriate frequencies. Amplitude check sources should be point-like on inner VLBA baselines. Some popular choices in the range 13 cm to 2 cm are J0555+3948=DA 193, J0854+2006=OJ 287, and J1310+3220. Other check sources may be selected from the VLBI surveys available through `http://www.vlba.nrao.edu/astro/obsprep/sourcelist/` . It might be prudent to avoid sources known to have exhibited extreme scattering events (e.g., Fiedler *et al.* 1994a, b).

18 PHASE CALIBRATION AND IMAGING

18.1 Fringe Finders

VLBI fringe phases are much more difficult to deal with than fringe amplitudes. If the *a priori* correlator model assumed for VLBI correlation is particularly poor, then the fringe phase can wind so rapidly in both time (the fringe rate) and in frequency (the delay) that no fringes will be found within the finite fringe rate and delay windows examined during correlation. Reasons for a poor *a priori* correlator model include source position and antenna location errors, atmospheric (tropospheric and ionospheric) propagation effects, and the behavior of the independent clocks at each antenna. Users observing sources with poorly known positions should plan to refine the positions first on another instrument (see Section 21.1). To allow accurate location of any previously unknown antennas and to allow NRAO staff to conduct periodic monitoring of clock drifts, each user must include at least two "fringe finder" sources which are strong, compact, and have accurately known positions. Typically, a fringe finder should be observed for 5 minutes every 1–3 hours. Consult Markowitz & Wurnig (1998) to select a fringe finder for observations between between 20 cm and 7 mm; your choice will depend on your wavelengths but J0555+3948=DA 193, J0927+3902=4C 39.25, J1642+3948=3C 345, and J2253+1608=3C 454.3 are generally reliable in the range 13 cm to 2 cm. In addition, at 90 and 50 cm we recommend either J1331+3030=3C 286 or J2253+1608=3C 454.3. Fringe-finder positions, used by default by the program `SCHED` (Walker 2006) and the VLBA correlator, are given in the standard source catalog available as an ancillary file with `SCHED`.

18.2 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, located at the VLBA antennas, 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 VLBA pulse cal data are logged as a function of time and delivered in a PC table (see Section 16). AIPS software can be used to load and apply these data. However, some VLBA observers may still want to use a strong compact source to do a "manual" pulse cal if necessary (Diamond 1995). For example, spectral line users will not want the pulse cal "comb" in their spectra, so they should ensure that their observing schedules both disable the pulse cal generators and include observations suitable for a "manual" pulse cal. Manual pulse calibration also is likely to be necessary for any non-VLBA antennas included in an observation, because they may have no tone generators, or else may not have detectors located at the antenna. In addition, it is necessary at 3 mm, where the VLBA antennas have no pulse calibration tones.

18.3 Fringe Fitting

After correlation and application of the pulse calibration, the phases on a VLBA target source still can 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. Such editing data are delivered in the FG table (see Section 16). 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 18.5), 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 the program `FRING` or associated procedures. If the VLBA target source is a spectral line source (see Section 20) 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 (see Section 18.6).

18.4 Editing

After fringe-fitting and averaging, VLBA visibility amplitudes should be inspected and obviously discrepant points removed (Diamond 1995; Walker 1995b). Usually such editing is done interactively using tasks in AIPS or the Caltech program `DIFMAP` (Shepherd 1997). Note that VLBA correlator output data also will include a flag (FG) table derived from monitor data output, containing information such as off-source flags for the antennas during slews to another source.

18.5 Self-Calibration, Imaging, and Deconvolution

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

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

The useful field of view in VLBI images can be limited by finite bandwidth, integration time, and non-coplanar baselines (Wrobel 1995; Cotton 1999b; Bridle & Schwab 1999; Perley 1999b); the first two of these effects have been discussed in some detail in Section 13. Measures of image correctness - image fidelity and dynamic range - are discussed by Walker (1995a) and Perley (1999a).

18.6 Phase Referencing

If the VLBA target source is not sufficiently strong for self-calibration or if absolute positional information is needed but geodetic techniques are not used, then VLBA phase referenced observations must be employed (Beasley & Conway 1995). Currently, more than half of all VLBA observations employ phase referencing. Wrobel *et al.* (2000) recommend strategies for phase referencing with the VLBA, covering the proposal, observation, and correlation stages. A VLBA phase reference source should be observed frequently and be within a few degrees of the VLBA target region, otherwise differential atmospheric (tropospheric and ionospheric) propagation effects will prevent accurate phase transfer. VLBA users can draw candidate phase calibrators from the source catalog in use at the VLBA correlator, distributed with the NRAO program SCHED (Walker 2006); easy searching for the nearest calibrators is available on-line through the VLBA Calibrator Survey (Beasley et al. 2002) at http://www.vlba.nrao.edu/astro/calib/ . Most of these candidate phase calibrators now have positional uncertainties below 1 mas, as announced in the NRAO Newsletter dated 2001 October.

Calibration of atmospheric effects for either imaging or astrometric experiments can be improved by the use of multiple phase calibrators that enable multi-parameter solutions for phase effects in the atmosphere. See AIPS Memos 110 (task DELZN, Mioduszewski 2004) and 111 (task ATMCA, Fomalont & Kogan 2005), available from the AIPS web page (see Section 28.1), for further information.

Walker & Chatterjee (1999) have investigated ionospheric corrections. Such corrections can even be of significant benefit for frequencies as high as 5 GHz or 8 GHz (Ulvestad & Schmitt 2001). These corrections may be made with the AIPS task TECOR, as described in AIPS Cookbook Appendix C (NRAO 2006), or the procedure VLBATECR. In addition, it is strongly recommended that the most accurate Earth-Orientation values be applied to the calibration, since correlation may have taken place before final values were available; this may be done with AIPS task CLCOR or more easily with the AIPS procedure VLBAEOPS.

The rapid motion of VLBA antennas often can lead to very short time intervals for the slew between target source and phase reference source. Some data may be associated with the wrong source, leading to visibility points of very low amplitude at the beginnings of scans. Application of the AIPS program QUACK using the 'TAIL' option will fix this problem.

19 POLARIMETRY

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

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

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

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

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

20 SPECTRAL LINE OBSERVING TECHNIQUES

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

Post-processing steps include performing Doppler corrections for the

Earth's rotation and orbital motion (the correction for rotation is not necessary for observations when all antennas have antenna-based fringe rotators, as is the case for the VLBA antennas); amplitude calibration using single-antenna spectra; fringe fitting the continuum calibrators and applying the results to the line target; referencing phases to a strong spectral feature in the line source itself; and deciding whether to do fringe rate mapping or normal synthesis imaging and then form a spectral line cube. All these post-processing steps can currently be done in AIPS.

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

21 VLBA/HSA/EVN/GLOBAL PROPOSALS

21.1 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). Proposal deadlines are February 1, June 1, and October 1. (Deadlines are delayed until the following Monday if one of these dates falls on Saturday or Sunday.) Observing periods for such programs are identical to those for the VLA and are advertised in the NRAO Newsletter at `http://www.nrao.edu/news/newsletters/` . Time allocation is described at `http://www.aoc.nrao.edu/epo/ad/scheduling.shtml` and referee guidelines may be found at `http://www.nrao.edu/administration/directors_office/refguide`. Approved VLBA programs are scheduled by the VLBA schedulers (see Section 28.3), who may be contacted at schedsoc@nrao.edu. Ulvestad (2004) provides a short guide to using the VLBA, aimed specifically at inexperienced users but also useful to fill in knowledge gaps for more experienced users.

2. The VLBA (SC, HN, NL, FD, LA, PT, KP, OV, BR, and MK), with the additional inclusion of the VLA, the GBT, Effelsberg, and/or Arecibo. Observing time of up to 100 hours per trimester has been reserved for a "High Sensitivity Array" consisting of the VLBA, VLA, GBT, Effelsberg, and (when possible) Arecibo; this opportunity, including the specification of the High Sensitivity Array on the proposal cover sheet, is described at `http://www.nrao.edu/HSA/` . Antennas

from this set also may be requested individually, though priority will be given to proposals for the High Sensitivity Array. In addition, the VLA can be requested in either phased array or single antenna mode (Wrobel & Taylor 2002); the single VLA antenna generally is most useful if one needs short baselines to sample properly extended structure in the target source. All deadlines and procedures are the same as for the VLBA alone.

3. The European VLBI Network (EVN). The EVN consists of a VLBI network of antennas operated by an international consortium of institutes (Schilizzi 1995). The EVN home page at `http://www.evlbi.org` provides access to the "EVN User Guide." That guide includes the "EVN Status Table," giving details of current observing capabilities of all EVN antennas; and the "EVN Call for Proposals," describing how to apply for observing time on the EVN. The EVN handles the proposing, refereeing, and scheduling mechanisms for such programs, which must all be run during a regular VLBI Network session. EVN proposal deadlines are February 1, June 1, and October 1, with no allowance made for weekends. VLBI Network session dates and wavelengths are given in the "EVN Call for Proposals" and in the NRAO Newsletter at `http://www.nrao.edu/news/newsletters/` . Observing time is allocated by the EVN Program Committee. Approved EVN programs are scheduled by the EVN scheduler. Any EVN proposal requesting the VLBA or two or more of the non-EVN VLBA affiliates identified in Item 5 below constitutes a global proposal, and must be submitted to both the VLBA and the EVN.

4. The Global 3 mm Array. This array consists of the VLBA antennas outfitted at 3 mm, together with Effelsberg, Pico Veleta, Plateau de Bure, Onsala, and Metsähovi. Procedures are similar to those for the EVN, although the European part of the 3 mm Array is operated by the Max Planck Institut für Radioastronomie. For more details, see `http://www.mpifr-bonn.mpg.de/index_e.html` .

5. VLBA affiliates in addition to the VLA, the GBT, and Arecibo currently include Effelsberg and the Deep Space Network. A VLBA proposal requesting such affiliates is handled as described in Item 1 above, except that if two or more EVN institutes are requested, then it is a global proposal and must be submitted to both the VLBA and the EVN. A VLBA program involving affiliates other than the VLA might be run outside of a regular VLBI Network session, depending on which

affilliates are involved. In particular, about 20 days of time per year, outside of regular VLBI Network sessions, has been reserved for joint VLBI programs involving the VLBA and Effelsberg; submit proposals for such joint time both to the NRAO and to the EVN scheduler.

Once the appropriate VLBI array is selected, run the NRAO `SCHED` program (Walker 2006) to determine the Greenwich Sidereal Time range during which the VLBI target sources are up at the selected antennas. This program can also be used to evaluate the u-v plane coverage and synthesized beams provided by the selected antennas (see Section 10).

Requirements for source position accuracy at correlation time are discussed by Ulvestad (2004). An accurate source position service is available through NRAO, but requests to it should be made no later than proposal time for positions needed at correlation time (Walker 1999a).

Proposals requesting more than 200 hours of total time on the VLBA, the HSA, or various combinations of NRAO telescopes in VLBI and non-VLBI modes, are covered under the NRAO Large Proposal Policy described at
`http://www.nrao.edu/administration/directors_office/largeprop.shtml` .

21.2 Submitting a Proposal

Until now, VLBA proposals have been submitted via e-mail, using a LaTeX format cover sheet that is available at http://www.nrao.edu/administration/directors_office/vlba-gvlbi.shtml . That link also describes how to submit completed VLBA proposals by e-mail to "propsoc@nrao.edu" or by regular mail to Director, NRAO, 520 Edgemont Road, Charlottesville, Virginia 22903-2475, USA. The NRAO on-line Proposal Submission Tool at
`http://wwww.vla.nrao.edu/astro/prop/pst/` has been used for several years for the GBT and VLA, and is now being expanded to include the VLBA as well. It is likely that this on-line tool will be required for all VLBA proposals beginning with the October 2008 deadline; an official decision on this change awaits the results of the tests of the new VLBA tool at the June 2008 deadline.

All EVN and global VLBI proposals must be submitted using the Northstar on-line tool that is available at `http://proposal.jive.nl/` .

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

Some VLBA proposals may fall under the category of Rapid Response Science. This includes proposals for Known Transient Phenomena, Exploratory Time, or Targets of Opportunity. All must make use of the standard proposal formats, and proposals for Known Transient Phenomena must adhere to the normal proposal deadlines. Further details about Rapid Response Science are at `http://www.vla.nrao.edu/astro/prop/rapid/` .

21.3 Student Support and Dissertations

VLBA proposals also may be supplemented with plans for dissertation research and/or requests for long-term acceptance; for further details, see the NRAO Newsletter dated 1999 October and available through `http://www.nrao.edu/news/newsletters/` . The student support program initiated for the GBT several years ago now has been expanded to include the VLBA and HSA; see `http://wiki.gb.nrao.edu/bin/view/Observing/NRAOStudentSupportProgram` for details.

22 PREPARATION FOR OBSERVING

Users allocated VLBA observing time, either on fixed dates or for the dynamic scheduling queue, will be sent instructions for preparing observing schedules. Approximately 65% of all VLBA observations are scheduled dynamically, based on array and weather conditions predicted 1–2 days in advance. Most users will be assigned a DSOC contact person.

23 DURING OBSERVING

Each VLBA program is run remotely from the DSOC by VLBA operations. No observing assistance by a VLBA user is expected, although VLBA operations should be able to reach the observer by telephone during the program. As the program progresses, the array operator monitors the health and state of the antennas and tape recording systems, mainly using a compact yet comprehensive display program. 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 media are automatically shipped from each VLBA antenna to the correlator specified by the observer.

24 POST-PROCESSING SOFTWARE

24.1 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, including various flavors of Linux and the Mac-OS/X operating system. Sections 28.1 and 28.3 give contact information. Extensive on-line internal documentation can be accessed within AIPS. An entire chapter in the AIPS Cookbook (NRAO staff, 2007) provides useful "how-to" guidance for those reducing VLBI data, including discussion of VLBA calibration transfer, space VLBI, polarimetry, and phase referencing. Appendix C of the AIPS Cookbook provides a step-by-step guide to calibrating many types of VLBA data sets in AIPS, employing simple VLBA utilites, including calibration modifications for VLBA+VLA data sets. A new "frozen" version of AIPS (currently 31DEC06) is produced each year, and a newer version (currently 31DEC07) is updated and made available throughout the calendar year. Observers are encouraged to use a very recent version of AIPS, since new capabilities such as improved astrometric calibration and simpler data-reduction procedures are implemented frequently.

24.2 CASA

CASA (Common Astronomy Software Applications) is a new software tool that embodies an improved implementation and user interface for the software tools that have been under development for AIPS++ at NRAO and elsewhere. CASA is primarily focused on ALMA and EVLA, and does not yet offer an end-to-end reduction path for VLBA data. However, CASA does contain imaging and calibration tools that may be of use for VLBI data. For more information, see `http://casa.nrao.edu` or contact staff listed in Section 28.3.

24.3 The Caltech VLBI Analysis Programs

The Caltech VLBI Analysis Programs are a set of programs for the planning and analysis of continuum VLBI observations. These programs are available for VAX/VMS, Sun UNIX, and Linux. A summary of the major programs can be found in the Bulletin of the American Astronomical Society, volume 23, page 991, 1991. Shepherd (1997) describes the related Caltech program `DIFMAP`. Section 28.1 gives contact information.

25 VISITING THE DSOC

25.1 General Information

VLBA users are strongly encouraged to make post-processing visits to the DSOC. 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 specific time. Contact one of the data analysts identified in Section 28.3 to determine if the correlated data are available before arranging a visit. Once the data are available, visitors should contact the reservationist at nmreserv@nrao.edu (see Section 28.3) at least one week prior to their visit; this timing is needed to optimize the logistics of visitor accommodation, transportation, workstation use, and DSOC staff assistance. This contact can be made using the interactive Visitor's Registration Form available through the VLBA astronomer page at `http://www.vlba.nrao.edu/astro/visitors/`, by sending e-mail to "nmreserv@nrao.edu" or by phoning the reservationist. Students visiting for their first VLBA data reduction trip must be accompanied by their faculty advisor. Standard NRAO travel reimbursement policy applies to VLBA data reduction trips; see `http://www.nrao.edu/administration/directors_office/nonemployee_observing_travel.shtml` for details.

25.2 Travel Support for Visiting the DSOC

For each observing program scheduled on an NRAO telescope, reimbursement may be requested for one of the investigators from a U.S. institution to travel to the NRAO to observe, and for one U.S.-based investigator to travel to the NRAO to reduce data. Reimbursement may be requested for a second U.S.-based investigator to either observe or reduce data provided the second investigator is a student, graduate or undergraduate. In addition, the NRAO will, in some cases, provide travel support to the Observatory for research on archival data. The reimbursement will be for the actual cost of economy airfare, up to a limit of $1000, originating from within the U.S. including its territories and Puerto Rico. Costs of lodging in NRAO facilities can be waived for students on advance request and with the approval of the relevant site director. No reimbursement will be made for ground transportation or meals.

To qualify, the U.S. investigator must not be employed at a Federally Funded Research and Development Center (FFRDC) or its sponsoring agency. The NSF maintains a master government list of some FFRDCs at `http://www.nsf.gov/statistics/nsf06316/` .

To claim this reimbursement, obtain an expense voucher from Terry Romero in Room 330 in the DSOC.

26 DATA ARCHIVE AND DISTRIBUTION

An archive of all output from the VLBA correlator is maintained at the DSOC. The user(s) who proposed the observations will retain a proprietary right to the data for a fixed interval of 12 months (changed from 18 months in early 2004) 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. A new on-line data archive has been developed, and data beginning from 1998 currently are on line. The most recent data are available either as multiple correlator output files or as large FITS files, sometimes with default calibrations attached. See `http://archive.nrao.edu` for further information.

Data are distributed to users on a variety of media, with DDS3 and Exabyte currently given primary support. Distribution also is possible via ftp. For the initial distribution to the user proposing the observations, this will occur automatically, soon after correlation is complete, provided a medium has been specified. Distributed data will conform to the new FITS binary table standard for interferometry data interchange (Flatters 1998), which is read by AIPS task `FITLD`.

27 Publication Guidelines

27.1 Acknowledgement to NRAO

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

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

27.2 Dissertations

Students whose dissertations include observations made with NRAO instruments are expected to provide copies of, or links to, their theses for inclusion and maintenance at the NRAO library. These will be catalogued and made available via the NRAO library catalogue. If a paper copy (unbound is acceptable), it may be submitted to the DSOC Librarian who will send it to Charlottesville for cataloguing.

27.3 Preprints

NRAO requests that you submit the `astro-ph` link or an electronic copy of any accepted papers that include observations taken with any NRAO instrument or have NRAO author(s) to the Observatory Librarian. For further information, contact the Librarian in Charlottesville (library@nrao.edu) or see the web page at `http://www.nrao.edu/library/preprints.shtml` .

27.4 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.

27.5 Page Charge Support

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

- When requested, NRAO will pay the larger of the following:
  - 100% of the page charge share for authors at a U.S. scientific or educational institute reporting original results made with NRAO instrument(s). See the VLA web pages for more details.
  - 100% of the page charge share for 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 27.1).

– Send the `astro-ph` link or an electronic copy of the paper upon acceptance or posting on `astro-ph` to the Observatory Librarian (library@nrao.edu), with the request for page charge support. The Librarian will respond with the amount covered (based on the NRAO page charge policy) and will request the page charge form, with manuscript information completed, via fax (434-296-0278) or e-mail (library@nrao.edu). For questions, contact the Observatory Librarian at 434-296-0254.

28 RESOURCE LISTS

28.1 Software

The following programs or software packages will be of interest to VLBA users, for planning observations and/or for post-processing VLBA data. NRAO software can be accessed through `http://www.nrao.edu/astrores` under the heading "NRAO Software Resources."

1. `SCHED`: Contact Craig Walker (see Section 28.3) or consult Walker (2006).
2. AIPS: Contact AIPS Group, NRAO, P.O. Box O, 1003 Lopezville Road, Socorro, New Mexico 87801-0387, USA; e-mail "daip@nrao.edu"; AIPS home page access is at `http://www.aoc.nrao.edu/aips/` .
3. CASA: Contact e-mail "casareq@aoc.nrao.edu"; CASA home page accessed through `http://casa.nrao.edu/` .
4. Caltech VLBI Analysis Programs: Contact T.J. Pearson, Astronomy Department 105-24, Caltech, Pasadena, California 91125, USA; phone +1-818-395-4980; FAX +1-818-568-9352; e-mail "tjp@astro.caltech.edu"; home page at `http://astro.caltech.edu/~tjp/citvlb` .

28.2 Documents and Articles

A list of documents and articles referred to in this document follows. Numerous articles from two books appear; abbreviations for these books and complete references for them are as follows:

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

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

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

2. Beasley, A.J., Gordon, D., Peck, A.B., Petrov, L., MacMillan, D.S., Fomalont, E.B., & Ma, C. 2002, Astrophysical Journal Supplement, 141, 13

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

4. Benson, J.M. 1998, Pulsar Gate Observers Guide. `http://www.vlba.nrao.edu/astro/obsprep/`

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

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

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

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

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

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

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

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`http://www.nrao.edu/meetings/proceedings.shtml`

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

21. Flatters, C. 1998, AIPS Memo No. 102.
`http://www.aoc.nrao.edu/aips/aipsdoc.html`

22. Fomalont, E., & Kogan, L. 2005, AIPS Memo No. 111.
`http://www.aoc.nrao.edu/aips/`

23. Garrett, M. A., Porcas, R. W., Pedlar, A., Muxlow, T. W. B., & Garrington, S. T. 1999, New Astronomy Reviews, 43, 519.

24. Hronek, A., & Walker, R.C. 1996, VLBA Test Memo No. 51.
`http://www.vlba.nrao.edu/memos/`

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`http://www.vlba.nrao.edu/memos/`

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31. Markowitz, A., & Wurnig, J. 1998, VLBA Test Memo No. 60.
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32. Mioduszewski, A. 2004, AIPS Memo No. 110.
http://www.aoc.nrao.edu/aips/

33. MIT-Haystack Observatory & NRAO, VLBA Sensitivity Upgrade Memo No. 12.
http://www.vlba.nrao.edu/memos/sensi/

34. Moran, J.M., & Dhawan, V. *VLBI & the VLBA*, p. 161.
http://www.nrao.edu/meetings/proceedings.shtml

35. Napier, P.J. 1995, in *VLBI & the VLBA*, p. 59.
http://www.nrao.edu/meetings/proceedings.shtml

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63. Walker, C., Durand, S., Kutz, C., & Hayward, R. 2007a, VLBA Sensitivity Upgrade Memo No. 10.
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`http://www.vlba.nrao.edu/memos/sensi/`

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`http://www.nrao.edu/meetings/past.shtml`

28.3 Key Personnel

Table 6 gives the primary work locations, telephone extensions, room numbers, and area of responsibilities and/or expertise of key NRAO personnel who are available to assist the VLBA user community. An individual can be contacted through e-mail via their NRAO username constructed from their first initial followed by their last name, with a maximum of 8 letters. Address e-mail inquiries to "username@nrao.edu," except where notes to the table give a group e-mail account that should be used in appropriate circumstances. In Table 6, "DSOC" refers to the Pete V. Domenici Science Operations Center (phone +1-575-835-extension) and "VLA" refers to the Very Large Array (phone +1-575-835-extension).[7]

[7] Note that the area code has changed from "505" to "575" for both the DSOC and the VLA site. Late in 2008, the old "505" area code will cease working for reaching both locations.

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

Name	Location	Extension	Room	Responsibilites and/or Expertise
Lori Appel	DSOC	7310	336	Scheduling administrator
John Benson	DSOC	7399	366	Correlator software, data archive
Walter Brisken	DSOC	7133	301	Pulsars, Mark 5 systems, DiFX
Bryan Butler	DSOC	7261	344	Head of EVLA Computing
Claire Chandler	DSOC	7365	328	Deputy Assistant Director, Science
Barry Clark (a)	DSOC	7268	308	Scheduling officer, VME systems
Mark Claussen	DSOC	7284	268	Spectral line VLBI
Juan Cordova	DSOC	7240	269	Tape librarian
Vivek Dhawan	DSOC	7378	310	Millimeter VLBI
Bob Dickman	DSOC	7300	336	VLA/VLBA Assistant Director
Steven Durand	DSOC	7103	178	Head of Electronics, 4 Gbps
Ed Fomalont	CV	434-296-0232	CV	Astrometric VLBI
Natti Gonzales (b)	DSOC	7357	246	NRAO reservationist
Miller Goss	DSOC	7267	332	Spectral line VLBI
Eric Greisen (c)	DSOC	7236	318	AIPS head
Leonid Kogan (c)	DSOC	7383	312	AIPS, astrometric software
Dan Mertely	DSOC	7128	184	RFI monitoring and mitigation
Amy Mioduszewski (c)	DSOC	7263	367	AIPS, HSA, VLBI at VLA
George Moellenbrock	DSOC	7406	373	VLBI in CASA
Peggy Perley	DSOC	7214	282	Deputy Assistant Director, Operations
James Robnett	DSOC	7226	258	Head of Computing Infrastructure
Terry Romero	DSOC	7315	330	Visitor and meeting support
Jon Romney	DSOC	7360	304	Correlator, Mark 5, 4 Gbps
Michael Rupen	DSOC	7248	206	Transient-source VLBI
Lorant Sjouwerman	DSOC	7332	367	AIPS pipelines, archive imaging
Meri Stanley (d)	DSOC	7238	204	Lead data analyst
Jim Ulvestad	···	505-270-2325	···	Principal Scientist; VLBA partnerships
VLA Operator	VLA	7180	VLA	On-duty VLA Operator
VLBA Operator	DSOC	7251	269	On-duty VLBA Operator
Craig Walker	DSOC	7247	314	`SCHED`, pointing, 4 Gbps
Joan Wrobel (a)	DSOC	7392	340	Scheduling officer, VLBI at VLA

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29 Acknowledgments

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