VERY LONG BASELINE ARRAY OBSERVATIONAL STATUS SUMMARY

Edited by J. D. Romney & J. S. Ulvestad

September 14, 2009

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 at stations 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) station 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. Secondary aims are to describe a few of the subtleties of data reduction and telescope scheduling, and to list relevant software, documentation, and key NRAO personnel who can be consulted for further, more detailed information. This document, which is updated every 1–2 years, or more often when required by major changes, 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 station provided by site technicians.

2 VLBA FUTURE DEVELOPMENT

A Senior Review commissioned in 2006 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 VLBA Sensitivity Upgrade project to significantly enhance the sensitivity of the VLBA. This project's goal is to achieve a 4 Gigabit per second (Gbps) capability by 2011, for the entire data path downsteam from the IFs – a 32-fold increase over the sustainable data rate of 128 Megabit per second (Mbps) available when the project was initiated, and 16 times the current standard data rate. The 4-Gbps data rate corresponds to an RF bandwidth of 500 MHz per polarization, and will enhance the signal/noise ratio of the typical continuum observation by factors of 4.0–5.6. The latter is equivalent to 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. The first element of this development, described in Section 7, is being brought into routine operation with the current edition of this document. Overviews 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 stations comprising the VLBA, plus the 2-character codes used to identify them (Napier 1995). The stations 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)[2], 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 stations or the NASA Deep Space Network. For details on how to propose for these extra telescopes, see Section 19.1.

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

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

[2]See Item 2. of Section 19.1 for information on future availability of the VLA for VLBI co-observations.

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

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. 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 peak gains, 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-Institut 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 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 stations (ΔS for a single polarization; Equation 3 in Section 10) and in a VLBA image ($\Delta I_{\rm m}$ for a single polarization; Equation 5 in Section 11). Characteristic values for $\Delta S^{256,2{\rm m}}$ assuming a fringe-fit interval of $\tau_{\rm ff} = 2$ minutes and for $\Delta I_{\rm m}^{256,8{\rm h}}$

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 Peak 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 stations recording at a rate of 512 Mbps.

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 the VLBA's current standard aggregate recording bit rate of 256 Mbps (Section 6.16). This rate is commonly achieved by recording a total bandwidth $\Delta\nu$ of 64 MHz (usually 32 MHz per polarization) with 2-bit (4-level) sampling (Section 6.14). 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 a factor of 1.4. For 3 mm, recording at 512 Mbps is assumed, as well as a fringe-fit interval of 30 seconds, and imaging from 4 hours of integration with 7 stations.

Opacity-corrected peak gains are needed for current techniques for amplitude calibration. These vary from antenna to antenna, and are monitored by VLBA operations and communicated to users (Section 13). 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 Peak 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.

6 VLBA SIGNAL PATH

This section describes the devices in the signal path at a VLBA station. Devices in Sections 6.1–6.6 and 6.8–6.11 are located at the antenna; all others are in the control building. More information on the VLBA signal path is provided by Napier (1995), Thompson (1995), and Rogers (1995).

In collaboration with MIT Haystack Observatory, the CASPER Laboratory at UC Berkeley, and the South African KAT project, NRAO currently is developing equipment that will enable sampling, filtering, and recording of data at a rate of 4 Gbps. We expect the new digital backend and recording systems to be implemented in 2010, at which time Sections 6.13 through 6.15 will become obsolete, and substantial changes will appear in Section 6.16.

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 couples free-space electromagnetic waves into waveguides for transmission to the receiver system. 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 extracts orthogonal circularly-polarized signals, which are routed separately to dual receiver channels. For receivers above 1 GHz, the polarizer is at cryogenic temperatures.

6.4 Pulse Cal

This system injects phase calibration tones generated by a series of pulses at intervals of 1.0 or 0.2 microseconds. Monochromatic, phase-stable tones thus are generated at frequency intervals of 1 MHz or 5 MHz. See Section 14.2 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 (Section 6.12) and base band converters (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 (Section 6.9) and the pulse cal system (Sections 6.4 and 14.2). The 5 MHz output is the reference for the baseband converters (Section 6.13), the formatter (Section 6.15), and the station 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 (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 baseband channels, where a channel means 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 baseband 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 (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* *backends are installed on the VLBA in 2010. See the beginning of Section 6 for further information.*

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 baseband 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 backends are installed on the VLBA in 2010. See the beginning of Section 6 for further information.*

6.15 Formatter

The formatter selects the desired bit streams from the samplers, adds time tags, and supports various other functions required to record effectively 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 and state counts also is supported in the formatter. *This subsection will become obsolete when the new digital backends and Mark 5C recorders are installed on the VLBA in 2010. See the beginning of Section 6 for further information.*

6.16 Recorders

The recorders form the VLBA's data transmission system, writing sampled, formatted data on magnetic media which are then shipped to the correlator (Section 7) at the DSOC central facility. The VLBA records on Mark 5A recording systems, which are also used at the VLA, the GBT, and at the correlator. The Mark 5 unit accommodates two removable modules, each comprising eight commercial disk drives. Details on Mark 5 systems may be found at `http://www.haystack.mit.edu/tech/vlbi/mark5/index.html` .

The VLBA's current module complement has a total capacity of 750 Terabytes (TB), about evenly divided between modules based on 250–300 GB disk drives, procured primarily in 2004–05, and those incorporating larger, 500–750 GB drives bought since 2006. The largest modules, with 6-TB capacity each, support continuous recording at 256 Mbps for 52 hours, or

512-Mbps operation for 26 hours. *This subsection will be modified substantially when the new digital backends and Mark 5C recorders are installed on the VLBA in 2010. See the beginning of Section 6 for further information.*

6.17 Site Computer

A VME site computer running VxWorks controls all station 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 station hardware and returns data from the equipment to the computer.

6.19 GPS Receiver

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

7 CORRELATOR

The correlator is situated in the DSOC, at the end of the data path. Its role is to reproduce the signals recorded at the VLBA stations and any others involved in the observation, and to combine them in two-station baseline pairs, to yield the visibility function which is the fundamental measurement produced by the VLBA.

VLBA observations proposed at the 2009 October 1 deadline will be processed using the DiFX software correlator. DiFX was developed at Swinburne University in Melbourne, Australia, (Deller *et al.* 2007) and adapted to the VLBA operational environment by NRAO staff (Brisken 2008). A series of painstaking tests (Romney *et al.* 2009a) carried out prior to its adoption for routine correlation of VLBA observations (Romney *et al.* 2009b) showed excellent agreement between the results delivered by DiFX and by the original VLBA correlator.

In the near future, we also expect to announce opportunities for rapid response "exploratory" proposals (Section 19.2) to use DiFX later in 2009 Trimester 3, and for requesting DiFX correlation of projects already granted observing time but not yet correlated.

Software correlation has become feasible in recent years, and is especially well suited to applications like VLBI with bandwidth-limited data-transmission systems and non-real-time processing. Among its several advantageous aspects are: (1) flexible allocation of processing resources to support correlation of varying numbers of stations, frequency and time resolution, and various special processing modes, with no fundamental fixed limits other than the finite performance of the processing cluster; (2) optimization of resource usage to minimize processing time; (3) integration of control and processing functions; (4) continuously scalable, incremental upgrade paths; and (5) relatively straightforward implementation of special modes and tests. These and other virtues of software correlation are discussed in more detail by Deller *et al.* (2007).

Despite the absence of fixed limits cited in item (1) above, the initial operational use of DiFX occurs in a situation of limited processing capacity and uncertainty as to the scaling of load with various parameters. Thus, NRAO has established temporary guidelines for the extremes of spectral resolution, integration period, and output rate, that will be supported in routine DiFX processing. These are are specified in Sections 7.1, 7.2, and 7.3, below. Exceptions will be considered in all three cases, for proposals including a sufficiently compelling scientific justification.

DiFX processes 2-bit samples with substantially greater efficiency than 1-bit samples over double the bandwidth, basically because only half as many samples must be correlated. Since these two cases have nearly equivalent sensitivity, a specific justification also will be required for proposals requesting the wider-bandwidth, 1-bit mode.

A prime example of item (5) above are the enhanced pulse-synchronous processing modes available in DiFX to support pulsar observations. These capabilities are detailed in Section 16.

Operation of DiFX is governed primarily by an observation description in VEX format. This format is used for both station and correlator control functions in a number of VLBI arrays, and the NRAO `SCHED` software (Walker 2006) has been producing it for many years.

In addition to the Mark 5A recordings from VLBA stations, DiFX can also process input data recorded in Mark 5B format.

Correlator output is written according to the FITS Interferometry Data Interchange Convention (Greisen 2009). In addition to the fundamental visibility function measurements and associated meta-data, the FITS files include amplitude and phase calibration measurements, weather data, and editing flags, that are logged at the VLBA stations (Ulvestad 1999). AIPS (Section 22.1) release 31DEC08 or later is required to handle DiFX data properly.

7.1 Spectral Resolution

DiFX currently supports powers-of-2 numbers of spectral points spanning each individual baseband channel, up to 4096 for routine DiFX processing, and up to 32,768 if required and adequately justified. (The latter limit is the maximum resolution currently supported by AIPS.) Oversampled data (essential for extremely high spectral resolution with the existing VLBA baseband subsystem; see Section 6.14) can be decimated appropriately. Currently, both the number of spectral points, and the oversampling factor, must be the same for all basebands at any given time, although multiple passes with different baseband subsets are possible.

The actual spectral resolution obtained, and statistical independence of the spectral points, depends on subsequent smoothing and other processing. Typical continuum programs request 16 spectral points per baseband, or 32 points for the widest, 16-MHz basebands. These are adequate for imaging near the correlator phase center, but limit the ability to image areas of the main beam away from the phase center (Section 18).

7.2 Integration Period

DiFX accommodates a nearly continuous range of correlator integration periods over the range of practical interest. *Individual* integrations are quantized in multiples of the indivisible internal FFT interval, which is equal to the number of spectral points requested (Section 7.1), divided by the baseband channel bandwidth (Section 6.13). Since the latter are powers-of-2 MHz, the internal FFT interval is always a power-of-2 microseconds.

For most cases, with low to moderate spectral resolution, and/or wideband baseband channels, the FFT intervals are fairly short, and it is straightforward to find an integration period in any desired range that is an optimal integral multiple of the FFT interval, where "optimal" refers to the performance of DiFX. Extreme cases of very high spectral resolution (many spectral points across a narrow baseband channels – resolution of less than about 100 Hz) imply FFT intervals long enough that only limited choices of integral multiples are available.

For flexibility in these situations (although the option exists in all cases), integration periods other than an integral multiple of the FFT interval can be approximated, in a long-term mean, by an appropriate sequence of nearby optimal integral multiples. In this case, output records are time-tagged as if correlated with exactly the requested period.

7.3 Output Rate

Correlation parameters must result in an output rate less than 10 MBytes per second of *observing time* for routine DiFX processing; higher rates may be considered if required and adequately justified. Observers should ensure that their data-analysis facilities can handle the dataset volumes that will result from the correlation parameters they specify.

A rough parameterization for the output rate R, in Byte/s, is given by

$$R = 4 \cdot \frac{N_{\rm stn} \cdot (N_{\rm stn} + 1) \cdot N_{\rm chn} \cdot N_{\rm spc}}{T_{\rm int}} \cdot p, \qquad (1)$$

where $N_{\rm stn}$, $N_{\rm chn}$, and $N_{\rm spc}$ are the numbers of observing stations, baseband channels, and spectral points per channel (Section 7.1), respectively; $T_{\rm int}$ is the correlator integration period (Section 7.2), again referred to observing time; and $p = 1$ for single- or dual-polar (LL&RR) output, $p = 2$ for cross-polar processing (delivering all four Stokes parameters).

Approximate output data rates are also predicted by the `SCHED` software.

8 ANGULAR RESOLUTION

Table 5, generated with the NRAO program `SCHED` (Walker 2006), gives the maximum lengths rounded to the nearest km ($B^{\rm km}_{\rm max}$) 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

$$\theta_{\rm HPBW} \sim 2063 \times \frac{\lambda^{\rm cm}}{B^{\rm km}_{\rm max}} \ \text{ mas}, \qquad (2)$$

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.

9 *u*-*v* PLANE COVERAGE

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

10 BASELINE SENSITIVITY

Adequate baseline sensitivity is necessary for VLBI fringe fitting, discussed in Section 14.3. 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):

$$\Delta S = \frac{1}{\eta_{\rm s}} \times \frac{SEFD}{\sqrt{2 \times \Delta\nu \times \tau_{\rm ff}}} \ \ {\rm Jy}. \qquad (3)$$

In Equation 3, $\eta_{\rm s} \leq 1$ 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 non-identical antennas 1 and 2, Equation 3 is modified to the following:

$$\Delta S = \frac{1}{\eta_\mathrm{s}} \times \frac{\sqrt{(SEFD)_1 (SEFD)_2}}{\sqrt{2 \times \Delta\nu \times \tau_\mathrm{ff}}} \;\; \mathrm{Jy}. \tag{4}$$

The bandwidth in Hz is $\Delta\nu$; for a continuum target, use the baseband channel width or the full recorded bandwidth, depending on fringe-fitting mode, and for a line target, use the baseband channel width divided by the number of spectral points per 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 3 and 4 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.

11 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 (ΔI_m) expected in a single-polarization image, assuming natural weighting (Wrobel 1995; Wrobel & Walker 1999):

$$\Delta I_\mathrm{m} = \frac{1}{\eta_\mathrm{s}} \times \frac{SEFD}{\sqrt{N \times (N-1) \times \Delta\nu \times t_\mathrm{int}}} \;\; \mathrm{Jy\ beam}^{-1}, \tag{5}$$

where η_s is discussed in Section 10; N is the number of VLBA antennas available; $\Delta\nu$ is the bandwidth [Hz]; and t_int is the total integration time on source [s]. 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/EVNcalc` . For example, the RMS noise at 22 GHz for the 10-station 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,

$$\Delta I = \Delta Q = \Delta U = \Delta V = \frac{\Delta I_{\rm m}}{\sqrt{2}}. \qquad (6)$$

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

$$\Delta P = 0.655 \times \Delta Q = 0.655 \times \Delta U. \qquad (7)$$

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

$$\Delta T_{\rm b} \sim 320 \times \Delta I_{\rm m} \times (B^{\rm km}_{\rm max})^2 \ \ {\rm K}, \qquad (8)$$

where $B^{\rm km}_{\rm max}$ is as in Equation 2.

12 CALIBRATION TRANSFER

Data necessary to perform accurate calibration for the VLBA are supplied as part of the correlator output files, and will appear as extension tables within the AIPS (Section 22.1) datasets created by task `FITLD`. 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 stations, 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 stations, 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 stations 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 is quite good at predicting the on-source times for the VLA, GBT, Arecibo, and Effelsberg. In using this file as an input to AIPS task `UVFLG`, it is recommended that all entries for the 10 VLBA stations be deleted. The FG table supplied with the correlator output files includes the actual on-source times for these antennas, obtained directly from VLBA monitor data. For further information on applying calibrations, see Appendix C of the AIPS Cookbook (NRAO staff, 2006) or the relevant AIPS HELP files.

13 AMPLITUDE CALIBRATION

Traditional calibration of VLBI fringe amplitudes for continuum sources requires knowing the on-source system noise in Jy ($SEFD$; Moran & Dhawan 1995). System temperatures in Kelvin ($T_{\rm sys}$) are measured continuously during observations at VLBA stations, with mean values tabulated at least once per source/frequency combination or once every user-specified interval (default 2 minutes), whichever is shorter. These $T_{\rm sys}$ values are used in fringe amplitude calibration by AIPS (Section 22.1) task `APCAL`, which converts $T_{\rm sys}$ to $SEFD$ by dividing by the VLBA antenna gains in K Jy^{-1}, expressed as a peak gain multiplied by a normalized "gain curve". The latter data are based on regular monitoring of all receiver and feed combinations. $T_{\rm sys}$ and gain values for VLBA antennas are delivered in TY and GC tables, respectively (Section 12). Single-station spectra can be used for amplitude calibration of spectral line programs (Section 17).

Additional amplitude adjustments may be necessary to correct for the atmospheric opacity above an antenna, which can be significant at high frequencies (Moran & Dhawan 1995). Leppänen (1993) describes a method for opacity adjustments. AIPS task `APCAL` uses weather data from the WX table (Section 12) to carry out such adjustments.

Further corrections are usually applied to observations taken with 2-bit (4-level) quantization, for the effects of non-optimal setting of the sampler voltage thresholds (Kogan 1995a). These adjustments are usually relatively minor but can induce systematic effects. The system design of the VLBA leads to a 5% to 10% calibration offset of the samplers between even and odd baseband channels; without correction, this may offset the RR and LL correlations in dual polarization observations. Sampling-based calibration adjustments are determined by AIPS task `ACCOR`. The combination of the antenna and sampler calibrations may be found and applied in AIPS using the procedure `VLBACALA`.

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 station; (2) to test for nonclosing 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 stations 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 stations. The recommended technique for this situation is to restrict the gain normalization in self-calibration to a subset of trusted stations (generally some of the VLBA stations), and to high elevations. AIPS task `CALIB` can do both.

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).

14 PHASE CALIBRATION AND IMAGING

14.1 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 station location errors, atmospheric (tropospheric and ionospheric) propagation effects, and the behavior of the independent clocks at each station. Users observing sources with poorly known positions should plan to refine the positions first on another instrument (Section 19.1). 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.

14.2 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 stations to overcome this problem. This system, in conjunction with the LO cable length measuring system, is also used to measure changes in the delays through the cables and electronics which must be removed for accurate geodetic and astrometric observations. The pulse cal system consists of a pulse generator and a sine-wave detector. The interval between the pulses can be either 0.2 or 1 microsecond. They are injected into the signal path at the receivers and serve to define the delay reference point for astrometry. The weak pulses appear in the spectrum as a “comb” of very narrow, weak spectral lines at intervals of 1 MHz (or, optionally, 5 MHz). The detector measures the phase of one or more of these lines, and their relative offsets can be used to correct the phases of data from different BBCs. The VLBA pulse cal data are logged as a function of time and delivered in a PC table (Section 12). AIPS (Section 22.1) 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” phase 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 phase cal. Manual phase calibration also is likely to be necessary for any non-VLBA stations included in an observation, because they may have no tone generators or detectors. In addition, it is necessary at 3 mm, where the VLBA antennas have no pulse calibration tones.

14.3 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 stations. Such editing data are delivered in the FG table (Section 12). 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 (Section 14.5), as during a global fringe fit the difference between model phases and measured phases are minimized by solving for the station-based instrumental phase, its time slope (the fringe rate), and its frequency slope (the delay). Global fringe fitting in AIPS is done with the program `FRING` or associated procedures. If the VLBA target source is a spectral line source (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 (Section 14.6).

14.4 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). VLBA correlator output data also includes a flag (FG) table derived from monitor data output, containing information such as off-source flags for the stations during slews to another source.

14.5 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 station-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 cycles 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 station-based instrumental phases (Cornwell 1995; Walker 1995b; Cornwell & Fomalont 1999). After removal of these instrumental 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 can be accomplished using AIPS task `CALIB` or with the Caltech program `Difmap`. 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 18. Measures of image correctness – image fidelity and dynamic range – are discussed by Walker (1995a) and Perley (1999a).

14.6 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 online 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.

Calibration of atmospheric effects for either imaging or astrometric observations 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 (Section 26.1), 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.

15 POLARIMETRY

In VLBA polarimetric observations, baseband 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.

A viable alternative approach to measuring polarization leakage is to use an unpolarized calibrator source. This can be done with a single scan.

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 above, 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 (~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 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 (Section 22.1), as can the polarization self-calibration technique described by Leppänen, Zensus, & Diamond (1995).

16 PULSAR OBSERVATIONS

Pulsar observing remains an expert mode of the VLBA, requiring additional understanding and effort on the part of the user. Those willing to learn to use them can take advantage of the following enhanced capabilities supporting pulsar observations, available in the DiFX software correlator (Section 7):

1. **Binary Gating:** A simple pulse-phase driven on-off accumulation window can be specified, with "on" and "off" phases. Such gating increases the signal to noise ratio of pulsar observations by a factor of typically 3 to 6, and can also be used to search for off-pulse emission.

2. **Matched-filter Gating:** If the pulse profile at the observation frequency is well understood and the pulse phase is very well predicted by the provided pulse ephemeris, additional signal to noise over binary gating can be attained by appropriately scaling the correlation coefficients as a function of pulse phase. Depending on the pulse shape, additional gains of up to 50% in sensitivity over binary gating can be realized.

3. **Pulsar Binning:** This mode entails generating a separate visibility spectrum for each requested range of pulse phase. There are no explicit limits to the number of pulse phase bins that are supported, however, data rates can become increasingly large. Currently AIPS (Section 22.1) does not support databases with multiple phase bins. Until post-processing support is available, a separate FITS file will be produced for each pulsar phase bin.

In all cases, the user will be responsible for providing a pulsar spin ephemeris. Except for certain applications of mode 3, the ephemeris must be capable of predicting the absolute rotation phase of the pulsar. Pulsar modes incur a minimum correlation-time penalty of about 50%. High output data rates (Section 7.3) may require greater correlator resource allocations. Details of pulsar observing, including practical aspects of using the pulsar modes, and limitations imposed by operations, are documented by Brisken (2009).

17 SPECTRAL LINE OBSERVATIONS

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" phase 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 station-based fringe rotation is applied, as is the case for the VLBA); 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 (Section 22.1).

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

18 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.

Advances in the capacity of computing hardware have made it feasible to correlate and image using relatively short integration periods and/or high spectral resolution, and thus enable imaging over an expanded region surrounding the phase center within a single correlation pass. Either or both of these measures increase the correlator output data rate, as quantified by Equation 1. The following discussion is intended to facilitate estimation of the output rate corresponding to the user's desired field of view, for comparison with the output rate limit specified in Section 7.3.

In the case of short integration periods (Section 7.2), with 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

$$\theta_{5\%,\Delta\nu} \;\approx\; 4.7 \left(\frac{0.5 \text{ MHz}}{\Delta\nu}\right) \text{arcsec}, \tag{9}$$

where $\Delta\nu$ is the width of an individual spectral point in MHz. This parameter is equal to the baseband channel bandwidth divided by $N_{\rm spc}$ in Equation 1 (Section 7.3). Equation 9 assumes a Gaussian bandpass with a circular Gaussian taper.

In the case of narrow spectral channels (Section 7.1), with 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

$$\theta_{5\%,\tau} \;\approx\; 2.8 \left(\frac{8.4 \text{ GHz}}{\nu}\right) \left(\frac{2 \text{ s}}{\tau_{\rm int}}\right) \text{arcsec}, \tag{10}$$

where ν is the observing frequency in GHz and $\tau_{\rm int}$ is the correlator integration time in seconds (denoted by $T_{\rm int}$ in Equation 1).

Equation 10 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 10 generally provides a lower limit to the distance from the phase center at which a 5% loss occurs.

For more details on wide-field imaging techniques, see Garrett *et al.* (1999).

19 VLBA/HSA/EVN/GLOBAL PROPOSALS

19.1 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 (stations 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 these dates fall 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/` . A description of time allocation may be found at `http://www.aoc.nrao.edu/epo/ad/scheduling.shtml` , and referee guidelines at `http://www.nrao.edu/admin/do/refguide/`. Approved

programs are scheduled by the VLBA scheduling officers (Section 26.3), 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 High Sensitivity Array (HSA).** The HSA comprises the VLBA in combination with the VLA[3], the GBT, Effelsberg, and/or Arecibo. Observing time of up to 100 hours per trimester has been reserved for these observations; this opportunity, including the specification of the HSA in the proposal, is described at `http://www.nrao.edu/HSA/` . Stations from this set also may be requested individually, though priority will be given to proposals for the High Sensitivity Array. All deadlines and procedures are the same as for the VLBA alone.

3. **The European VLBI Network (EVN) and Global cm VLBI.** The EVN consists of a VLBI network of stations 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 stations; and the EVN Call for Proposals, describing how to apply for observing time on the EVN. The EVN provides proposal, review, and scheduling mechanisms for such programs, and conducts regular sessions of 2–3 weeks, 3–4 times per year, to carry out these observations. EVN proposal deadlines are February 1, June 1, and October 1, with no allowance made for weekends. EVN session dates, and the wavelengths to be observed, are given in regular Calls for Proposals, and also appear in the NRAO Newsletter at `http://www.nrao.edu/news/newsletters/` . Proposals requesting the EVN in combination with two or more VLBA or non-EVN VLBA affiliates (identified in Item 5 below) are classified as "Global cm VLBI", and must be submitted to both the EVN and the VLBA. Such observations will be carried out during EVN sessions.

4. **The Global 3 mm Array.** This array consists of the VLBA stations outfitted at 3 mm, together with Effelsberg, Pico Veleta, Plateau de Bure, Onsala, and Metsähovi. The European part of the 3 mm Array

[3]The VLA will be unavailable for VLBI observations beginning 2010 January 11, when the original VLA correlator is replaced by the EVLA WIDAR correlator. No date has been established for resumption of VLBI co-observations by the EVLA.

is coordinated by the Max-Planck-Institut für Radioastronomie. For more details, see
`http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm/` .

5. **VLBA affiliates** include the VLA, the GBT, Arecibo, Effelsberg, and the Deep Space Network. A VLBA proposal requesting such affiliates is handled as described in Item 1 above, except for Global cm VLBI proposals, which are defined and handled as described in Item 3. In particular, about 20 days of time per year, outside of regular EVN sessions, has been reserved for joint VLBI programs involving the VLBA and Effelsberg; proposals for such joint time are submitted to both 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 visible at the selected stations. This program can also be used to evaluate the u-v plane coverage and synthesized beams provided by the selected array (Section 9).

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/admin/do/largeprop.shtml` .

19.2 Submitting a Proposal

Several different proposal submission mechanisms are used to propose observations on the various VLBI arrays itemized in Section 19.1.

VLBA proposals, including all the observing opportunities described in Items 1., 2., and 5., are submitted using the NRAO online Proposal Submission Tool at `https://my.nrao.edu/` . Registration, at that same URL, is required to use the Tool.

EVN proposals, defined in Item 3., are submitted using the Northstar online tool at `http://proposal.jive.nl/` .

Global cm VLBI proposals, defined in Items 3. and 5., and those requesting joint VLBA-Effelsberg time as described in Item 5., must be submitted using both of the above-mentioned tools.

Global mm VLBI proposals are submitted as described in the announcement referenced in Item 4.

Proposals requesting stations unaffiliated with the VLBA or the EVN must be sent to the directors of the operating observatories.

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/` .

19.3 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.

20 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.

21 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 status of the antennas and the station data path, 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 station. Recorded media are automatically shipped from each VLBA station to the correlator specified by the observer.

22 POST-PROCESSING SOFTWARE

22.1 AIPS

AIPS, NRAO's Astronomical Image Processing System, is a set of programs for the analysis of continuum and line observations, and is widely used with VLBA and VLBI data. 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 26.1 and 26.3 give contact information. Extensive online 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 utilities, including calibration modifications for VLBA+VLA datasets. A new "frozen" version of AIPS (currently 31DEC08) is produced each year, and a newer version (currently 31DEC09) is updated and made available throughout the calendar year. Observers are encouraged to use a very recent version of AIPS, since only these can properly handle data from the DiFX software correlator, and new capabilities, such as simplified data-reduction procedures and improved astrometric calibration, are implemented frequently.

22.2 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 26.3.

22.3 Difmap

Difmap (Shepherd 1997) provides editing, imaging, self-calibration, and pipelining capabilities in an interactive package. It was developed as part of the Caltech VLBI Analysis Programs and remains widely used, although development has been frozen and continued support is limited primarily to assistance in installation. Section 26.1 gives contact information.

23 VISITING THE DSOC

23.1 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 one cannot assume that the correlated data will be available after any specific time. Contact one of the data analysts identified in Section 26.3 to determine if the correlated data are available before arranging a visit. Once the data are available, visitors should contact the reservationist (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 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/` , via 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; for details, see
`http://www.nrao.edu/admin/do/nonemployee_observing_travel.shtml` .

23.2 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 Natti Gonzales in Room 246 in the DSOC.

24 DATA ARCHIVE AND DISTRIBUTION

All output from the VLBA correlator (both the original, hardware-based system and the new DiFX software correlator) is maintained in the NRAO data archive, and can be accessed via an online facility at `http://archive.cv.nrao.edu` . The user(s) who proposed the observations retains a proprietary right to the data for an interval of 12 months following the end of correlation of the last observations requested in the original proposal, or a direct extension of that proposal. Thereafter, the archived data are available to any person on request. Data can be obtained from the archive either as multiple correlator output files, or as large FITS files with default calibrations attached.

Although the online archive is the preferred distribution path, VLBA data can also be written onto DDS-3 or -4 DAT cassettes and mailed. Initial distribution to the proposing user occurs automatically, soon after correlation is complete.

Distributed data conform to the FITS Interferometry Data Interchange Convention (Greisen 2009), which is read by AIPS (Section 22.1) task `FITLD`.

25 Publication Guidelines

25.1 Acknowledgment to NRAO

Any papers using observational material taken with NRAO instruments (VLBA or otherwise) or papers where a significant portion of the work was done at NRAO, should include the following acknowledgment 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.

25.2 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.

25.3 Page Charge Support

Complete information on the Observatory's policy regarding page charge support is given at `http://www.nrao.edu/library/pagecharges.shtml` . The principal points include:

- When requested, NRAO will pay 100% of the page charges for authors at U.S. scientific or educational institutions whose papers report original observations utilizing any NRAO instrument(s), or original analyses of archival data.
- The paper must include the NRAO acknowledgment footnote (Section 25.1).
- The author must provide the following to the Observatory Librarian (library@nrao.edu): program codes or proposal numbers for the observations being reported; an `astro-ph` link or electronic copy of the paper; requested apportionment of the page charges; and (for non-AAS journals) any required page charge forms.

25.4 Reprints

NRAO does not distribute reprints, nor expects to receive reprints, and will not pay any reprint costs for papers with no NRAO staff author.

26 RESOURCE LISTS

26.1 Software

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

1. **SCHED.** Contact: Craig Walker (Section 26.3) or consult Walker (2006).

2. **AIPS.** Contact: AIPS Group, NRAO, P.O. Box O, 1003 Lopezville Road, Socorro, New Mexico 87801-0387; e-mail "daip@nrao.edu"; AIPS home page: `http://www.aoc.nrao.edu/aips/` .

3. **CASA.** Contact: e-mail "casareq@aoc.nrao.edu"; CASA home page: `http://casa.nrao.edu/` .

4. **Difmap.** Contact: M.C. Shepherd; e-mail "mcs@astro.caltech.edu"; Difmap download site: `ftp://ftp.astro.caltech.edu/pub/difmap/difmap.html` .

26.2 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.cv.nrao.edu/vlbabook/`

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

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http://www.cv.nrao.edu/vlbabook/

4. Benson, J.M. 1998, Pulsar Gate Observers Guide.
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6. Briggs, D.S., Schwab, F.R., & Sramek, R.A. 1999, in *Synthesis II*, p. 127.

7. Brisken, W. 2008, VLBA Sensitivity Upgrade Memo 23.
http://www.vlba.nrao.edu/memos/sensi/

8. Brisken, W. 2009, in preparation.

9. Conway, J.E., & Sault, R.J. 1995, in *VLBI & the VLBA*, p. 309.
http://www.cv.nrao.edu/vlbabook/

10. Cornwell, T.J. 1995, in *VLBI & the VLBA*, p. 39.
http://www.cv.nrao.edu/vlbabook/

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

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

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`http://www.cv.nrao.edu/vlbabook/`

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

68. Walker, C., Romney, J., Brisken, W., & Durand, S. 2007b, VLBA Sensitivity Upgrade Memo # 15.
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26.3 Key Personnel

Table 6 gives the primary work locations, telephone extensions, room numbers, and area of responsibilities and/or expertise of key NRAO personnel who are available to assist the VLBA user community. An individual can be contacted through e-mail via his or her NRAO username constructed from the first initial followed by the 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).[4]

[4]The area code has been changed from "505" to "575" for both the DSOC and the VLA site.

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

Name	Location	Extension	Room	Responsibilities 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	Media librarian
Adam Deller	DSOC	7492	300	DiFX
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
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

Notes: (a) E-mail "schedsoc@nrao.edu" for telescope time allocation issues. (b) E-mail "nmreserv@nrao.edu" for travel reservation issues. (c) E-mail "daip@nrao.edu" for AIPS issues. (d) E-mail "analysts@nrao.edu".

27 Acknowledgments

Over the 16 years since the VLBA dedication in 1993, many individuals have contributed to this document by writing sections, editing previous versions, commenting on draft material, and implementing the capabilities described herein. We thank all these contributors for their efforts. The editors of the present version of this document are responsible for the most recent revisions, and thus are the best contacts for readers who may have questions on the material, or suggestions that would enhance the clarity of this guide.