Novice's Guide to Using the VLBA
Version 3.0
VLBA Scientific Memo No. 27

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Abstract

The VLBA is a system of 10 identical telescopes, separated by distances ranging from 200 km to 8600 km, that can be used to observe and image a variety of compact radio sources having brightness temperatures higher than $\sim 10^6$ K. The telescopes are capable of observing in 10 frequency bands ranging from 300 MHz to 86 GHz. This document is a guide to using the VLBA, aimed specifically at inexperienced users, but also useful to fill in knowledge gaps for more experienced observers. It is intended to address the $> 90\%$ of all observations that might be classified as "standard" and relatively simple to make.

1 Why use the VLBA?

A wide range of scientific programs can be carried out by the VLBA, ranging from observations of nearby stars to imaging of the most distant quasars. Programs range from classic observations of jets in active galactic nuclei, to position measurements of gamma-ray bursters, and movies of supernovae and extended stellar atmospheres. The VLBA is an integrated telescope, similar to the VLA, thus surmounting many of the problems (e.g., reliability and calibration) of past VLBI networks using arrays of disparate telescopes operated by many different organizations. This enables a much wider variety of science to be done; in particular, phase referencing for weak source detection, and polarimetry, are routine. Accessible scales range from ~ 0.1 mas at 86 GHz (compared to 40 mas for the VLA at 43 GHz) to more than an arcsecond at 300 MHz, and a peak brightness temperature greater than about 10^6 K is needed for source detection.

To learn more about the general capabilities of the VLBA, see the "Astronomer" link at the VLBA web site: *http://www.nrao.edu/vlba/html/VLBA.html*. The annually updated VLBA Observational Status Summary (hereafter **OSS**) available here provides a wealth of details for all VLBA users, including references to even more detailed technical material. A good source of detailed information on all aspects of VLBI and use of the VLBA can be found in the proceedings of the 1993 NRAO summer school, which has been published as

ASP Conference Series Volume 82, "Very Long Baseline Interferometry and the VLBA." A number of useful tips also are in the VLBA Scientific Memo series, available from the VLBA web site.

2 Pathway from Proposal to Final Product

The pathway from proposal to final product is similar to the VLA, and to telescopes operating in most wavebands. For completeness, we list the basic steps below, as well as the organization or individual who has the responsibility of carrying out the steps. Each step is then described in more detail in succeeding sections. (Note that "PI" stands for the Principal Investigator and his/her science team.)

1. Proposal – PI (assistance from documentation)
2. Refereeing – Outside referees and NRAO
3. Observing Allocation – NRAO
4. Schedule Preparation – PI (NRAO service available for some users)
5. Observations – VLBA operations
6. Correlation, Data Validation and Distribution – VLBA operations
7. Calibration – PI (Data pipeline available)
8. Imaging and Analysis – PI (NRAO advice/assistance available)
9. Scientific Results and Publications – PI

3 What Kinds of Observations are Easy?

The simplest VLBA observations are those of strong continuum sources at centimeter wavelengths; these are even easier than VLA observations of similar sources, since a-priori amplitude calibration is used, and the source serves as its own phase calibrator. Observations of weak sources are readily accomplished using the technique of phase referencing, exactly analogous to the standard observing technique at the VLA. Details are described in VLBA Scientific Memo No. 24, "Strategies for Phase Referencing with the VLBA," available on the VLBA web site. Phase referencing is now done for more than 40% of all VLBA observations. Continuum polarimetry is slightly more complex, and requires a more specialized observing schedule (described in the **OSS**), but can be done routinely with moderate care. Observations at the extreme frequency bands of the VLBA, 0.3, 0.6, 1.4, 43, and 86 GHz (and to a lesser extent, 22 GHz), are somewhat more difficult because of ionospheric and tropospheric effects. Finally, the most difficult observations are those of spectral lines (e.g., HI absorption, water masers), simply because of the need to compute the frequency and to image spectral-line cubes. In fact, the VLBA and its correlator are inherently spectral-line instruments, and all users are delivered spectral-line data, but data for continuum sources eventually will be averaged in frequency to produce continuum data sets. Table 1 summarizes the major VLBA observing types and an estimated degree of difficulty for each.

Table 1. Types of VLBA observations (from easiest to hardest)

Type	Difficulty	Comments
Strong continuum source: 1.4–15 GHz	Easiest	simple schedule
Weak continuum source: 1.4–15 GHz	Very easy	phase referencing, like VLA
Multi-source continuum: 1.4–15 GHz	Very easy	more complex schedule, like VLA
Continuum: 22, 43 GHz	Easy	more complex calibration
Continuum: 0.3, 0.6 GHz	Moderate	may use in-beam phase referencing
Polarimetry: 1.4–15 GHz	Moderate	more bookkeeping complexity
Polarimetry: 0.3, 0.6, 22, 43 GHz	Moderate	complex schedule and calibration
Spectral-line	Moderate	more complex analysis; large data sets
Continuum: 86 GHz	Difficult	new systems; troposphere and pointing
Spectropolarimetry	Difficult	combines polarimetry and spectral line

4 How to Propose

VLBA proposal deadlines are February 1, June 1, and October 1 of each year. A proposal consists of a 2-page cover sheet and a scientific justification containing 1000 words or fewer, plus any accompanying figures. Instructions and a standard LaTeX template are available at *http://www.nrao.edu/administration/directors_office*. The preferred submission method is to send the postscript file of the proposal by e-mail to *propsoc@nrao.edu*; paper submissions also are accepted. Various types of "Rapid Response" science can be proposed as well, some outside the normal deadlines. See *http://www.vla.nrao.edu/astro/prop/rapid* for further details.

Before writing a proposal, the proposer must develop the scientific rationale for the program, develop a source list, decide on the observing band(s) to be used, and estimate the expected source strengths and their detectability. For spectral-line sources, the proposer also must decide on the desired velocity resolution, and convert that to a spectral resolution.

The most confusing entries on the cover sheet are items 9, 11, and 13 through 18. Some reasonable defaults are discussed below:

- **(9) Recording format:** It is now permitted to check a single box for the VLBA continuum defaults. For spectral lines, choices of modes will depend on the desired velocity resolution. Some generally good choices for line observations are to use 2-bit samples, choose the number of BBC channels and their widths based on the expected frequency coverage of the lines, leaving some continuum on either side available for calibration, and use Nyquist sampling (two samples per hertz of bandwidth) except in the case of oversampling on very narrow bandwidths. For example, if one is observing two lines that are separated by 16 MHz and are each 4 MHz wide, one might use 4 BB channels (two at each polarization) of 16 MSamples/sec (corresponding to 8 MHz bandwidth each) with 2-bit sampling. Then, the baseband frequencies would be adjusted to center the lines in the two right/left polarization pairs.

- **(11) Telescope request:** Most observations request only the VLBA. However, for observations that need considerably more sensitivity, it also is possible to request larger U.S. telescopes, specifically the phased VLA, the Green Bank Telescope, and Arecibo. Some observations may request the Effelsberg 100-m telescope as well. For observations that need more short spacings, a single VLA antenna may be requested. Finally, for programs that require more sensitivity, more short baselines, or transatlantic baselines, proposers also may ask for antennas from the European VLBI Network (EVN). All proposals that request telescopes in addition to the 10 VLBA antennas must include a specific rationale for those telescopes in the scientific justification.

- **(13) Observation type:** This is usually interferometry. If the source is weaker than 50–100 mJy at centimeter wavelengths, phase referencing must be used and also should be checked.

- **(14) Dynamic scheduling:** This refers to scheduling that takes best advantage of required weather and telescope conditions to optimize all the science done on the VLBA. Proposals are not suitable for dynamic scheduling if they require coordination with external observatories (including the VLA and GBT) and/or specific (rather than approximate) intervals between multiple epochs.

- **(15) Polarization:** Dual Circular Polarization is usually best for spectral-line observations, to increase the signal-to-noise in a limited bandwidth.

- **(16) Tape usage:** The recording time and total time need not be entered unless they are substantially different. The maximum sustainable data rate for the VLBA is currently 128 Mbit s^{-1}, and may be exceeded only for proposals with very strong scientific justifications. However, it often is possible (for example) to observe at 256 Mbit s^{-1} with the recording time set to half the total time allocation. This can be particularly useful at high frequencies, because it may enable a shorter phase-referencing cycle and better atmospheric calibration.

- **(17) Assistance required:** Proposers are welcome to ask for extensive help in order to make sure that they get the details right. For VLBA-only data, users may request data calibration by NRAO. Continuum observations between 1.4 and 15 GHz are calibrated routinely by NRAO using a data pipeline in AIPS, though many observers prefer to calibrate their data themselves.

- **(18) Processor:** For VLBA-only observations, this is almost certainly the Socorro correlator. Other correlators might be used for global observations, 86-GHz (3-mm) observations, and/or some specialized astrometric observations. All the "special processing" options may be left blank if standard continuum observations are desired. For line observations, the averaging time and number of spectral channels per baseband channel should be determined based on the spectral resolution desired, and the field of view to be imaged. There are limitations on the number of spectral channels (due to finite number of FFT processors) and on the product of baselines and spectral channels divided by integration time (due to the upper limit on the correlator output rate). See "Correlator Capabilities" on the VLBA web site for details.

5 Refereeing and Observing Allocation

The refereeing and time-allocation process is summarized here; more details may be found at *http://www.aoc.nrao.edu/epo/ad/scheduling.shtml*. An e-mail acknowledgment is sent within a few days of a proposal's receipt, and the proposal is assigned a code such as BXnnn, where "B" designates the VLBA, "X" is the first letter of the proposer's last name, and "nnn" is a sequential number for investigators whose last names begin with "X" (e.g., BU012 is the 12th VLBA proposal received from proposers whose last names start with "U"). This code is used to identify a program throughout the observing process.

Each proposal is reviewed by several (external) referees who specialize in the particular scientific area of the proposal. NRAO compiles their reports and calculates grades, which are strongly advisory to a scheduling committee. That committee also incorporates knowledge about the technical capabilities of the VLBA, then uses the oversubscription of large additional telescopes and of the VLBA as a function of sidereal time to determine the final time allocation. Proposers receive e-mail notification of the results from this committee about three months after the proposal deadline.

If a proposal is accepted, the contact author receives e-mail notification of the specific time allocation and the deadline for schedule submission, and (for difficult observations) may be assigned an NRAO contact person in Socorro. For a dynamically scheduled proposal, a specific date will not be assigned, but a particular range of sidereal times will be specified.

6 Schedule Preparation

VLBA schedules are prepared using the SCHED software, which has an extensive on-line help file and template input files. Most users start with a template input (or "key-in") file, then modify it as needed. See *http://www.aoc.nrao.edu/~cwalker/sched/sched/sched.html* for details. SCHED also has the facility for planning an observation by computing the times at which sources are up at different stations, and can plot the (u,v) coverage for a particular draft schedule; these capabilities may be useful in writing the proposal, as well as in scheduling.

Preparation of schedule files is nominally the responsibility of the PI, but NRAO also offers assistance in schedule preparation if necessary. See Section 9 for contact information.

6.1 Source Positions

The most accurate possible source positions are needed for generating the proper correlator models for data processing. NRAO maintains a list of milliarcsecond positions for strong sources that appear in astrometric VLBI or connected-element interferometer catalogs. (See Section 6.5 for information about phase-referencing sources.) For other sources, positions generally are taken from the schedule file, so it is essential that the schedule file have the most accurate possible source positions. A limiting rule of thumb is that the source position error, σ_θ, must be

$$\frac{\sigma_\theta}{\text{arcsec}} < 0.5\left(\frac{22\ \text{GHz}}{\nu}\right) . \tag{1}$$

If possible, it is desired that positions be better than this by a factor of at least 3–5, to provide the best results. The correlator model is very detailed, and used to best advantage when source positions are as accurate as possible.

6.2 Setup Files

Setup files control most parameters of data acquisition, such as observing band and channelization. Most observations use one of the standard files produced by NRAO; see the SCHED user manual. File names typically describe the nature of the setup; for example, v2cm-128-4-2.set is the standard file for a 2-cm observation recording 128 Mbit/s in 4 channels (2 RCP and 2 LCP), with digitization of 2 bits per sample. The file v2cm-128-4-2-L.set is a similar setup file, except that all 4 channels are LCP. The standard files set up the default VLBA frequencies; observers who wish to use non-standard setups (frequencies or otherwise) should consult the SCHED documentation or NRAO staff. Default frequencies are given in Table 2.

6.3 Clock and Fringe Calibration

The user must determine the relative delays and rates of change of the delay between the stations during the data reduction. The largest delay errors are due to clock offsets between

Table 2. Default VLBA Observing Frequencies in SCHED		
Band	Center Frequency	
90 cm	330.49 MHz	
50 cm	610.98 MHz	
21 cm	1465.49 MHz	for 128 MHz total bandwidth
21 cm	1435.49 MHz	for 64 MHz total bandwidth
21 cm	1416.49 MHz	for narrow-band HI observations
18 cm	1658.49 MHz	most 18cm observing, including with phased VLA
18 cm	1653.99 MHz	32 MHz bandwidth with Jodrell, but not phased VLA
13 cm	2295.49 MHz	
6 cm	4990.49 MHz	
4 cm	8415.49 MHz	
2 cm	15285.49 MHz	
1 cm	22235.49 MHz	
7 mm	43135.49 MHz	
3 mm	$\cdots$	default not yet established; $\sim$ 86 GHz
sx	2295.49 & 8415.49 MHz	dual-frequency, usually used for astrometry

the stations (typically kept under 100 nsec for the VLBA, but with final calibration of better than a nanosecond required). Other offsets may be attributable to causes such as atmospheric propagation or incorrect source positions. The bulk of the delay errors can be removed either by the use of pulse-calibration tones injected at the front ends, or by observations of appropriate strong sources in the schedule. Pulse calibration is generally used for continuum observations, but strong artificial line sources are unacceptable for spectral-line experiments. In the latter case, occasional (every few hours) observations of strong continuum sources are required for the calibration.

After the initial delay calibration, more specific calibration of the delays and possibly delay rates in a particular direction may be called for. In particular, weaker sources require phase referencing for this fringe calibration. Phase referencing is very similar to the phase calibration done at the VLA, and is described in detail in Chapter 17 of "Very Long Baseline Interferometry and the VLBA" and in VLBA Scientific Memo No. 24, referenced previously.

6.4 Amplitude Calibration

Standard antenna gain files are maintained, and system temperatures are measured every 1–2 minutes during an observation. Therefore, there is no need to schedule a standard flux calibrator as is done for VLA observations by including 3C 48 or 3C 286. (There are no constant-flux, unresolved sources on VLBI baselines!) However, an amplitude-check source should be observed several times to check for consistency among the antennas. In addition, gains are measured regularly only for standard frequencies in each band. If a frequency far from the standards is employed, an amplitude-check source should be observed at both standard and non-standard frequencies in order to correct for any variation as a function of frequency. See the **OSS** for more details.

6.5 Phase Referencing

Phase referencing permits imaging of sources that are too weak to give detectable fringes in a coherent integration time. Many details of this process are given in VLBA Scientific Memo No. 24. Typically, sources weaker than ~ 50 mJy at centimeter wavelengths, and 100–200 mJy at 22 and 43 GHz, require phase referencing; to date, there has been no successful (out-of-beam) phase-referencing at 0.3, 0.6, or 86 GHz, due to the extreme problems with the ionosphere and troposphere. When using phase-referencing, a VLA-like sequence of calibrator–source–calibrator is recommended. The calibrator should be within $\sim 3^\circ$–5° of the program source, dominated by a point source, and have a compact flux of at least ~ 150 mJy. Smaller source/calibrator separations are desirable, and may be essential at 1.4, 22, and 43 GHz. Users should consult the VLBA Calibrator Survey, available on the VLBA web page, to find the best calibrator for each source. Cycle times can be estimated from equations (17-9) and (17-10) of the article by Beasley and Conway, on page 337 of ASP Conf. Series 82. Tabulated and plotted estimates based on those equations, as a function of source elevation and weather, also are in VLBA Scientific Memo No. 20. The time estimates in Scientific Memo No. 20 only take the troposphere into account; modifications to account for the ionosphere may be found in VLBA Scientific Memos No. 18 and 22.

6.6 Cross-Polarization Observations

Data reduction of dual-polarization observations depends critically on the observational strategy. The basic strategy is to observe a strong source (typically the program source or a phase-reference source) over a wide range of parallactic angles to solve for the polarization leakage ("D" terms). In addition, observations of a point source of known polarization position angle (PA) are needed to calibrate the absolute polarization PA. NRAO is carrying out a VLA flux/polarization monitoring program that can be used to calibrate the polarization position angles. For more information, see the "Polarimetry" section of the **OSS** and VLBA Scientific Memo No. 26.

6.7 Readback Gaps

Recording gaps (i.e., tape stoppage) of at least two minutes should be scheduled at least once per two hours of observing, so that the recording quality can be checked at the telescopes.

6.8 Dynamic Scheduling

At present, more than half of all VLBA observations are done dynamically, with time allocation made approximately 1–2 days in advance, depending on weather forecasts and telescope availability. For dynamic schedules, observers must generate a schedule input file starting at a particular sidereal time. The proposer submits only this SCHED input file (often called a "key" file). NRAO staff will create the final schedule files once the exact time allocation is established shortly before the observation.

6.9 Schedule Submission

For observations at fixed times, the control files (**.crd* output from SCHED) are placed in a subdirectory to the *vlbiobs* account on *aspen.aoc.nrao.edu.* The password for this account is available from the data analysts by fax or phone; they can be contacted by phone at 505-835-7238, by fax at 505-835-7027, or by e-mail to *analysts@aoc.nrao.edu*). For example, files for the observation bm157c carried out in October 2001 are located in the directory /home/aspen6/astronomy/oct01/bm157c/.[1] After file deposition, e-mail notification must be sent to *vlbiobs@aoc.nrao.edu.*

For dynamically scheduled observations, the input file for SCHED, incorporating any non-standard setup files, is e-mailed to *vlbiobs@aoc.nrao.edu*, then placed in a subdirectory of /home/aspen6/astronomy/dynamic/ by the NRAO data analysts. Comments at the start of this file must be used to specify required conditions for the observation (e.g., weather and antenna availability). A required template for the comments may be found at *http://www.aoc.nrao.edu/vlba/html/VOBS/astronomy/dynamic/dynamic.memo.* The user-specified requirements depend on the scientific goals, but the more flexible the specified conditions are, the greater the likelihood that an observation with a medium or low priority will be carried out expeditiously (or at all!).

After the schedule is submitted, the correlation parameters in the schedule (e.g., source positions and number of spectral channels) are assumed to be correct, and are used in the data correlation. Therefore, it is important that the correlation parameters are checked carefully when the schedule is submitted. Correlation with incorrect parameters may result in the failure of the observation.

7 Observations

The observer doesn't have to do anything; NRAO staff will perform all the tasks necessary to run the VLBA. A real-time display of the array activities can be accessed by clicking on "VLDIS" from *http://www.nrao.edu/vlba/html/VLBA.html.*

[1] Note that the directory /home/aspen6/astronomy now maps automatically to the much longer directory name /home/archive/e2e/archive/operations/VLBA/observe.

8 Correlation, Data Validation, and Distribution

NRAO staff will perform the data processing on the VLBA correlator, confirm the quality of the correlator output, and distribute the data to the observer. Correlation and data-distribution parameters are derived from the original schedule file (see Section 6.9). The default data distribution media are either DDS3 (DAT) or Exabyte tapes. Multiple FITS-format files are included, corresponding to the multiple correlator job scripts that were used to process the data. Users should be aware that the proprietary period of data ownership for VLBA observations has been changed in early 2004; it now is 12 months from the time the correlated data are released, instead of the previous proprietary period of 18 months.

9 Calibration

NRAO supplies a pipeline data calibration for all continuum observations between 1.4 and 15 GHz. This includes amplitude, delay, delay-rate, and phase calibration. Users who would like to request additional assistance should specify it in their proposal or else contact Greg Taylor at *gtaylor@nrao.edu* at least 3 weeks before the time of the observation.

Tables that can be used to perform much of the calibration of VLBA data are extracted from VLBA monitor data and appended to the correlator output FITS files. There is no longer any need for observers to prepare input files for various types of calibration, unless telescopes in addition to the VLBA and VLA are used. The supplied tables are as follows:

- **TY table:** system temperatures measured every 1–2 minutes
- **GC table:** a-priori VLBA telescope gains
- **PC table:** extracted pulse-calibration amplitudes and phases
- **FG table:** flagging information from individual telescopes
- **WX table:** weather information from stations

For more information about application of these tables, see VLBA Operations Memo No. 34, available on the VLBA web site. For detailed instructions on all aspects of calibration, see Appendix C of the AIPS Cookbook,"A Step-by-Step Recipe for VLBA Data Calibration in AIPS," available at *http://www.aoc.nrao.edu/aips/cook.html*.

10 Final Imaging and Analysis

Final imaging and analysis of the scientific data generally is the responsibility of the observer, although considerable assistance is available from NRAO. NRAO also will provide an imaging service for novice users from U.S. institutions, though it is generally desirable for the user to visit NRAO to take advantage of this service.

Within AIPS, task IMAGR is typically used for imaging, with CALIB used for self-calibaocration cycles. See the AIPS Cookbook (*http://www.aoc.nrao.edu/aips/cook.html*) for details. The DIFMAP package, developed at Caltech, also can be used for data editing, self-calibration, and imaging. See *ftp://ftp.astro.caltech.edu/pub/difmap/difmap.html* for further information on DIFMAP.

11 Staff Collaboration

Some users may be interested in being provided with an NRAO staff collaborator, who would work with the user on all aspects of an observation, from schedule preparation to imaging and data analysis. This can be arranged on an individual basis for users based at U.S. institutions. Proposers should bear in mind the fact that NRAO staff will not do all the VLBA work for them, but will work collaboratively to help teach them VLBI techniques while working on the scientific program. The VLBA web site gives a list of research interests of the scientific staff in NRAO-Socorro, and potential proposers are welcome to contact these individuals directly about possible proposal ideas, or contact Greg Taylor (*gtaylor@nrao.edu*), who will identify a potential contact or collaborator.

12 Financial Support for Data Reduction

Financial support is available for observers affiliated with U.S. institutions who wish to visit NRAO to reduce their VLBA data. Details about the financial support are available from the NRAO Director's office, at *http://www.nrao.edu/administration/directors_office/*.

13 Scientific Results and Publications

Timely preparation of scientific papers based on VLBA observations is the responsibility of the investigators. NRAO will provide assistance with page charges for observations which are based wholly, or in part, on VLBA observations; this financial assistance is available only for investigators based at U.S. institutions. For more information, see *http://www.nrao.edu/library/page_charges.shtml*.

14 Graduate Students

NRAO has a pre-doctoral fellowship program that permits students to spend 2 years at an NRAO site working on their dissertation using data from the VLBA (or other NRAO telescopes). In addition, NRAO's summer-student program has a number of slots for graduate students. Students in both programs are paid stipends during their tenure at

NRAO. Information about these and other NRAO student programs can be found at *http://www.nrao.edu/students/*.

15 Summary

We hope this document provides a useful introduction to the end-to-end process of observing with the VLBA. A number of NRAO staff members have contributed information to this document, but the author accepts full responsibility for any errors. Corrections, comments, and suggestions should be sent to the author at *julvesta@nrao.edu*.