VLB ARRAY MEMO No. 603

THE VERY LONG BASELINE ARRAY

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ABSTRACT. The Very Long Baseline Array (VLBA) will be the world's first large-scale dedicated VLBI facility. It is planned as a multipurpose instrument, supporting continuum, spectroscopic, astrometric/geodetic, multi-frequency, bandwidth synthesis, polarization, and pulsar measurements -- with a variety of bandwidths, sampling rates, quantization schemes, and multi-band modes. The Array will consist of ten new 25-m precision antennas, in an optimized geographical configuration. Extremely low-noise receivers will support observations with dual polarization in nine frequency bands from 330 MHz to 43 GHz, including almost all conventional VLBI bands. A wideband, high-density recording system will allow unattended operation at a sustained data rate of 128 Mbit/s for 24 hours, and peak rates up to 512 Mbit/s. The VLBA correlator, planned as a 20-station system to support processing of all observations involving the Array, will be by far the largest ever built for VLBI. The Array will be operated remotely, from a new operations and data-reduction center to be built in Socorro, NM.

INTRODUCTION

The present Symposium is devoted to the impact of VLBI on various scientific disciplines. The Very Long Baseline Array, currently under construction by the National Radio Astronomy Observatory (NRAO), will have a major impact on the conduct of almost every area of research discussed here this week. This paper reviews the capabilities planned for the Array when it is completed early in the 1990's.

The shortcomings of the present ad-hoc VLBI arrays will be apparent to most participants in this meeting. Existing antennas are poorly located for adequate sampling of the aperture plane; many are poorly instrumented over the range of frequencies desired; most cannot be calibrated more than marginally despite heroic efforts; and few perform adequately at high frequencies. Notwithstanding the impressive volume of work in evidence at this symposium, available observing time is insufficient, and proper monitoring of the many structural changes seen with VLBI resolution is all but impossible. The advent of the narrow-track Mark 3A system has shifted the limitation on wideband VLBI observations from tape supply to correlator capacity; current systems cannot cope with the arrays required for imaging with high dynamic range. And despite recent improvements, scheduling remains laborious and must be done well in advance.

In 1982, after seven years of careful study and preliminary design, NRAO proposed the Very Long Baseline Array to alleviate these deficiencies and provide a dedicated national VLBI instrument. A good general description of the VLBA for the non-specialist can be found in the article by Kellermann and Thompson (1985); more detailed technical information is contained in a "VLBA Book" and several series of general and specialized memoranda.

CONFIGURATION

The VLBA configuration has been optimized to provide both high resolution and a large field of view, with the most uniform possible two-dimensional aperture coverage even at low declinations. A degree of condensation, centered on the VLA, extends satisfactory coverage over a broad range of scale sizes. Site selection emphasized high, dry locations, and freedom from RF interference. All sites are on US territory.

The first antenna was recently completed at the Pie Town site, on the Continental Divide west of the VLA; this highest continental site will become operational late this year. Selection of the final site is still underway, with the search concentrated in western Massachusetts, New Hampshire, and Vermont. Table I lists all VLBA sites in the planned order of construction, and shows the current status and planned first operation of each.

Table I. VLBA Configuration and Site Status

Code	Location	N. Latitude	W. Longitude	Elevation	Status	Operational
PT	Pie Town, NM	34° 18′ 03″.61	108° 07′ 07″.24	2371m	Outfitting	87/11
KP	Kitt Peak, AZ	31 57 22.39	111 36 42.26	1916	Erection	88/6
LA	Los Alamos, NM	35 46 30.33	106 14 42.01	1967	Developed	88/9
NL	N. Liberty, IA	41 46 17.03	91 34 26.35	241	Developed	88/12
FD	Fort Davis, TX	30 38 05.63	103 56 39.13	1615	Development	89/5
BR	Brewster, WA	48 07 52.80	119 40 55.34	255	Development	89/9
SC	St. Croix, VI	17°.76	64°.58	15	Acquisition	90/3
OV	Owens Valley, CA	37.23	118.28	1204	Acquisition	90/6
ML	Mauna Loa, HI	19.58	155.49	2735	Acquisition	90/12
NE	"New England"				Selection	91/5

ANTENNA

The VLBA antenna is a new, advanced design developed by the NRAO engineering division. It employs a wheel-and-track azimuth structure for superior pointing in the presence of wind and temperature differentials. A cone-shaped transition section from the elevation structure supports a conventional radial-rib reflector back-up on a ring of 20 equal attachment points; the subreflector support legs are mechanically isolated from the main reflector. These features provide enhanced performance under gravitational deformation. Shaped, high-precision main and subreflector surfaces afford high efficiency at frequencies up to 43 GHz. The fast slew capability will allow rapid sequential observation even of widely separated sources.

The main reflector panels are specified at 0.125 mm RMS surface accuracy, with a total error budget of 0.282 mm (RSS) under the primary "precision operating conditions" of moderate, relatively constant and uniform temperature, low wind, and no precipitation. Operation can continue, with reduced surface accuracy, over a wide range of secondary environmental conditions. The Cassegrain subreflector is specified at 0.15 mm surface accuracy, with a design goal of 0.10 mm. These characteristics will allow satisfactory operation at frequencies as high as 43 GHz, and use at 89 GHz under exceptional conditions.

NRAO has contracted with Radiation Systems, Inc., of Sterling, Virginia, to manufacture the ten VLBA antennas. Three antennas have been fabricated, and a fourth is nearing completion; the fifth and sixth antennas were recently authorized.

RECEIVERS & FEEDS

The Array will support observations in nine frequency bands from 330 MHz to 43 GHz. Details of the frequency ranges, expected total aperture efficiency, and receiver performance, are summarized in Table II. Three "optional" bands, shown in square brackets in the table, are foreseen as possible eventual additions to the VLBA but are not included in the construction project; one such addition would extend the frequency coverage to 89 GHz.

The last two columns in Table II show the planned installation schedule. To facilitate a thorough system evaluation, the frequency bands shown with check marks in column PT will be implemented at the Pie Town station by the end of 1987. These include eight of the nine standard VLBA bands, plus the optional 10.7-GHz band. The 43-GHz band will be deferred to allow further receiver development. All subsequent stations will be instrumented initially only in the 1.5-, 4.8- and 23-GHz bands shown by the asterisk symbol in the "Array" column; other frequencies will be introduced starting in the years shown.

Table II. VLBA Frequency Bands

Band Designation		Frequency Range [GHz]	Aperture Efficiency	Receiver Temp. [K]	System Temp. [K]	Installation PT	Installation Array
330	P	.312 → .342	.50	25	99	✓	'89
610		.580 → .640	.57	31	65	✓	'89
1.5	L	1.35 → 1.75	.57	12	30	✓	*
2.3	S	2.15 → 2.35	.71	15	35	✓	'89
4.8	C	4.6 → 5.1	.72	20	35	✓	*
6.1		[5.9 → 6.4]	.71	20	35		—
8.4	X	8.0 → 8.8	.69	28	49	✓	'88
10.7		[10.2 → 11.2]	.69	36	52	✓	—
15	U	14.4 → 15.4	.68	57	75	✓	'90
23	K	21.7 → 24.1	.66	60	87	✓	*
43	Q	42.3 → 43.5	.51	40	75		'88
89	W	[86? → 92?]	.18	?	?		—

Receivers for the 1.5-GHz and higher-frequency bands generally employ cooled (20K) FET front ends, fed by horns at off-axis Cassegrain foci arranged in a ring. HEMTs (high-electron-mobility transistors) will be substituted as available; the tabulated noise temperatures are for FETs. The 43-GHz receiver will probably use an SIS mixer operating at 3.5K. Weinreb, Norrod, and Pospieszalski (1987) describe the preceding receivers in greater detail. The two lowest-frequency receivers operate at ambient temperature, with a crossed-dipole feed at the prime focus.

Simultaneous observations in orthogonal senses of circular polarization are supported in each individual band. In addition, dichroic optics provide a capability for simultaneous dual-frequency observations in the 2.3- and 8.4-GHz bands. The feed circle is designed to facilitate future dual-frequency band pairing of 4.8 with 15 and 23 GHz, and 15 with 43 and -- eventually -- 89 GHz.

CHANNELIZATION & DIGITIZATION

Each VLBA receiver will produce two independent IFs, in the 500-1000 MHz range. Four such signals -- two from each of any two receivers -- are transmitted to the control building. These inputs can be converted to as many as 16 baseband channels, generated as upper and lower sidebands with respect to 8 independent local oscillators, each tunable in 10 kHz steps. Each such channel can be filtered to bandwidths ranging from 16 MHz down to 62.5 kHz. The filtered signals are sampled at rates ranging from 2 to 32 Msmp/s, allowing oversampling except at the widest bandwidths. Sample quantization is supported at both two and four levels.

The aggregate throughput of these subsystems is thus 256 MHz, 512 Msmp/s, and 1024 Mbit/s. This equipment, developed for NRAO by Haystack Observatory, is designed to allow expansion by a factor of 2 in numbers of baseband converters, channels, and throughput.

RECORDING & PLAYBACK

Central to any VLBI instrument is the data recording and playback technology. The VLBA recording system, currently under development by Haystack Observatory, will represent an extension of the existing Mark 3A system to higher data densities (Webber and Hinteregger 1987), and will incorporate as well numerous technical improvements.

Since the VLBA stations will be controlled remotely, one of the fundamental specifications is the requirement for recording wideband data, without operator intervention, for a 24-hour period. The initial scheme will be capable of sustained recording at 128 Mbit/s for at least 12 hours on a single tape, with a peak rate of 256 Mbit/s. Each station will be equipped with two such recorders, to reach the 24-hour requirement as well as to allow peak data rates of 512 Mbit/s.

Preliminary specifications foresee using the 38-micrometer Mark 3A headstacks, recording up to 16 hour-long passes of 32 data tracks, at 50,000 bits per inch, on 27,000-foot lengths of 0.55-mil tape. Each tape would have a capacity of 7.4 Terabits; further enhancements of data capacity are anticipated by the time the Array is complete.

The recording system will support a flexible, programmable data format. During early VLBA operations, when the first several Array elements are used in conjunction with stations of the existing VLBI networks, and data reduction occurs on existing correlators, one of the standard Mark 3 formats will be written. This cannot support the VLBA's wider bandwidths and four-level sampling capabilities, however. An advanced format, incorporating more robust error-detection, flexible track assignment, and transparent framing, will be substituted when the Array nears completion and the correlator begins routine operation. Since the programmable format requires a commensurately capable decoder/deformatter, it will remain possible to read tapes recorded in Mark 3 format (although this will restrict the observations to relatively narrow aggregate bandwidths).

NRAO recognizes, and indeed urges, the importance of standardization of data recording to future large-scale VLBI ventures. A number of communications have already been received from observatories interested in obtaining VLBA-compatible recording equipment. We expect to be in a position to provide reliable cost and availability information to potential users upon completion of the pre-production phase of our contract with Haystack, currently planned for mid- to late 1988.

CORRELATOR

The VLBA correlator, intended to support processing of all observations involving the Array, will be the first large, wideband VLBI correlator ever built. Its design recognizes that the VLBA will be joined frequently by existing antennas to form a global array. With 20 station inputs, it will be able to accommodate large observations of this type, as well as to support extreme wideband measurements using two recorders simultaneously at each of 10 stations, or simultaneous reduction of two normal 10-station programs. A large, high-resolution system on this scale imposes a new cost/performance logic upon the design. After an extensive study, the spectral-domain or FX correlator algorithm was adopted because of the significant cost efficiencies achievable (especially for a large spectroscopic system), as well as a number of important scientific and technical advantages.

The FX scheme (Chikada, et al. 1984) differs from the conventional lag correlator essentially in the sequence of operations performed to calculate baseline cross-power spectra from the input station samples. Individual station signals are first Fourier transformed; correlation is then replaced by a much more economical pairwise cross-multiplication of the station spectra. Exploiting the efficient FFT algorithm, and organizing as much processing as possible on a station basis, this approach minimizes the number of arithmetic operations required. The reduction is sufficient to realize a significant advantage in basic signal-processing hardware, compared to a lag correlator, despite the greater complexity of the operations involved. The comparison is particularly favorable for many-station and/or high-resolution systems -- for the VLBA the factor is about three.

Further, the weak logarithmic dependence of the FFT's complexity on the number of samples transformed allows the FX correlator to provide superior spectroscopic performance. The preceding cost comparison applies in fact to a lower-performance lag system, which achieves full spectroscopic resolution only for a half-size array. Other advantages inherent in the FX architecture include the feasibility of true station-based fringe rotation, without loss of sensitivity or spurious correlation, and straightforward incorporation of an exact correction for fractional-sample delay error, again with no loss of sensitivity. Finally, the FX algorithm allows a spectrally-dependent de-dispersing gate for pulsar observations, and is easily and inexpensively adaptable to tracking fringes from orbiting VLBI "stations" such as Radioastron and Quasat.

The VLBA FX correlator will provide 160 separate FFT engines, enough to accommodate 8 baseband channels at each of 20 stations. When fewer channels are required (as for typical spectroscopic observations), or if only 10 station inputs are active, these engines are available to support one or more of several multi-processing modes, which serve mainly to obtain higher sensitivity from oversampled data or (for line spectra) to counter the effects of the segmentation inherent in the FX algorithm. Independently of these modes, each FFT engine can operate at resolutions ranging in binary steps from 32 to 1024 spectral points.

The cross-multiplier section imposes virtually no restrictions, but the long-term accumulator and output data rate ceiling limit the maximum available resolution. The correlator will support 1024-point resolution in one channel for a 20-station array, without polarization cross-products. In binary steps, this limit decreases for 2, 4, or 8 channels, or for polarization -- and increases, subject to a limit of 1024 points (512 for polarization), for 14- or 10-station arrays.

Final design of the VLBA correlator is currently in progress. A major element is the gate array which will serve both as a radix-4 FFT stage and as a combined cross-multiplier/accumulator. Correlator construction is expected to begin when funding becomes available at the beginning of 1988, with a 7-station, 2-channel subset system scheduled for completion two years later. Expansion to the final 20-station 8-channel configuration will then take a further two years.

POST-PROCESSING

The output from the correlator will be available to Array users in the standard FITS format. No specialized VLBA software is planned for post-processing (calibration, editing, fringe-fitting, imaging, etc.) of these data, because almost all the functions required are available within the AIPS system used for the VLA, for much of current VLBI work, and for many other applications. Instead, a number of extensions to AIPS are under development to support the few functions specific to VLBA (and other VLBI) observations.

A careful evaluation of the computing capacity required to support Array imaging was included in NRAO's original VLBA proposal, and the construction project will include adequate facilities to ensure that most observations can be processed. Because of the present extremely rapid evolution of computer technology, however, these facilities will neither be specified nor procured until full-time Array operation begins. The use of transportable AIPS software is expected to make available a broad range of potential post-processing hardware.

OPERATIONS

Efficient operation of a distributed instrument such as the VLBA will require that the individual stations be operated remotely from a single center, and all station equipment has been designed to allow unattended operation much of the time. One shift a day is planned, to cover such tasks as changing and shipping tapes, routine maintenance, and module replacement.

Central control will be exercised through polled multidrop communications over dedicated telephone lines. Dial-up lines will be available as a backup, and may be used exclusively during early operation. Much of the traffic over this network will be monitor data reported from the stations to the control center, where it will be logged for later use (including correlator control, calibration, and diagnosis), and analyzed to detect malfunctions. Samples of the received signal will also be transmitted for near-real-time fringe verification. Sufficient buffering will be provided in both directions to allow operation to continue for several hours in the event of a communication outage.

NRAO plans to operate both the VLBA and the existing VLA facility from a new operations center to be built on the campus of the New Mexico Institute of Mining and Technology in Socorro, NM. In addition to array operations, the center will house the VLBA correlator, imaging facilities for both arrays, and VLBA maintenance laboratories, plus other associated scientific, electronics, and computing activities. The building will be funded partially from the VLBA construction project and partially by the State of New Mexico. Bids for the first phase of construction have been solicited; occupancy is scheduled for July 1988.

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