The VLA Expansion Project
Technical Goals

February 15, 1999

1 Overview of the VLA Expansion Project

The NRAO is preparing a comprehensive plan to modernize and expand the Very Large Array. The project will build on the existing instrument to produce a refitted array with typically an order of magnitude improvement in sensitivity, frequency accessibility, resolution, spectral capability, and imaging performance.

The project plan retains the antennas, array plan, and infrastructure, and replaces most other components with new electronics based on modern technologies. The end product will be a radio telescope with enormously improved scientific capability, whose operational costs will be increased only minimally.

The project consists of a number of major components:

- Construction of a modern correlator, a new fiber-optic, wideband transmission system, and implementation of a new on-line computer and monitor/control system.
- New or retrofitted receivers and feeds that will provide complete frequency coverage between 1 and 50 GHz,
- An A+ configuration that will increase tenfold the resolution of the VLA, fill the "VLA-VLBA gap", and which can be used as a standalone array that will combine the resolution of MERLIN with the sensitivity of the VLA.
- Low frequency receiver systems to provide frequency coverage between 50 MHz and 1.2 GHz, and a super-compact "E" configuration to fill the resolution gap between the GBT and the "D"-configuration.

Each of these major components is summarized in the following sections.

2 Components of the VLA Expansion Project

2.1 A New Correlator and Wideband Signal Transmission System

The VLA correlator is 20 years old, and limits virtually every scientific project on the VLA. A new correlator, based on the evolving MMA design, would revolutionize the scientific capabilities of the VLA. A more detailed description of the proposed correlator is given in Section 3.4.

In this first, and most urgent, category, are three important items:

- A **new correlator,** able to support at least 40 antennas with full polarization, with up to 8 GHz in each polarization and up to 8,192 spectral channels per baseline per polarization product, and the ability to independently and simultaneously process up to 8 different frequencies from one or two frequency bands. Up to 32,768 channels will be produced.
- A **fiber-optic data transmission system** to transmit broad-band signals and monitor data, replacing the original waveguide.
- A **new on-line computing system, monitor/control system**, and associated software, to enable a much improved user and operator interface with the array, and to permit more flexible observing modes and other new capabilities.

2.2 Full Frequency Coverage from 1 to 50 GHz

The second major component of the VLA Expansion Project will allow observing with outstanding sensitivity over the entire frequency range of 1 to 50 GHz. To obtain the full benefit of this capability, the correlator and IF transmission system described above are necessary. These top two components, when taken together, define what has been called "The Ultra-Sensitive Array". Over most of this frequency range, sensitivity better than 1 microJy in 12 hours will be obtained.

Included are:

- **Improved sensitivity and coverage in L-band.** This frequency band is arguably our most critical. The VLA's current performance in this band is significantly degraded by scattering of ground radiation by the microwave lens, and the performance at the low end of this band is limited by a polarizer designed over 20 years ago. A new horn and polarizer will be installed which will reduce the ground pickup and permit high sensitivity performance from ~ 1.2 GHz to 2 GHz.
- **C-band and U-band Retrofit.** The sensitivity and tuning range of the existing C and U bands are very poor. New receivers and feeds covering the ranges 4 – 8 and 12 – 18 GHz would be installed.
- **New observing capabilities at 2 – 4 and 27 – 40 GHz.** The current VLA cannot observe in these bands – both of which offer exciting science potential.

- **Improvement for X, K, and Q bands.** Funding for the completion of the installation of Q-band (40 – 50 GHz), and the retrofit of K-band (18 – 27 GHz), is already secured. These components of the expansion will be completed in 2002. The current X-band system's tuning range will be extended to cover 8 – 12 GHz.
- **Improved antenna performance** by adjusting panels for higher efficiency, developing techniques to permit better pointing, and employing new feeds with improved performance. This will complete an ongoing effort which has already proven spectacularly successful.
- **RFI Tolerance and Excision.** The wide bandwidths and frequency tuning range will greatly increase our exposure to radio frequency interference (RFI), especially from elevated sources such as balloons, aircraft, and satellites. The new receivers and transmission system will be designed with particular attention to the extra demands imposed by these signals. And, design of flexible digitial filters to automatically remove strong RFI before the correlator will begin.

2.3 Extending the Array – The A+ Configuration

The VLA's maximum baseline of 35 km limits its resolution, while the VLBA's minimum effective baseline of about 300 km limits its sensitivity to extended structures. This "VLA-VLBA" gap will be filled by the addition of:

- **New antennas** to provide now-unavailable baselines between those in the VLA and in the VLBA. To maintain VLA-like imaging fidelity, about eight new stations will be required, to be distributed throughout New Mexico at distances up to about 300 km from the VLA.
- **Fiber-optic links** between the VLA and the inner VLBA antennas, and between the VLA and the proposed new antennas, to provide for real-time data correlation of the existing VLA antennas, the proposed new antennas, and the existing nearby VLBA antennas with the upgraded correlator.

Note that the antennas comprising the VLA, the VLBA, and the new proposed antennas could be combined into many different independently operating arrays, using the new correlator. For example, the existing VLA could be operated as one array, the eight most distant VLBA antennas as another (using the existing VLBA correlator), and the ten antennas at intermediate distance (eight new and two VLBA) with one or more VLA antennas as an entirely independent array with outstanding imaging fidelity and sensitivity.

These new proposed antennas will cause an increase in operational costs. However, these antennas would not require remote VLBA data recording systems, as all signals will be sent in real time by optical fiber links to the AOC for either real-time correlation (VLA mode), or tape recording (VLBA mode). Thus, only weekly maintenance of these new sites will be required. This can be provided from the AOC, as all proposed antennas are within three hours' drive.

2.4 Further Enhancements for the VLA

So sound is the basic design of the VLA that numerous other enhancements and improvements are possible. This last major component of the VLA Expansion Project contains items which may overlap capabilities being developed elsewhere, or are of less broad appeal to the astronomical community. As such, further study will be required to establish their role and priority. Prominent among these are:

- **New prime focus receivers:** rebuild the focus-rotation mount so that the subreflector can be removed, and add wide-band low-frequency feeds at the prime focus to provide complete frequency coverage from approximately 50 MHz to 1.2 GHz.
- **New antenna stations** for a "super-compact" **E** configuration with maximum baseline of about 250 meters. This will allow fast mosaicing of large fields with much better fidelity and surface brightness sensitivity than can be achieved now with the "D"-configuration.

3 Design Performance of the Expanded VLA

Here we give the expected performance of the Expanded VLA after implementation of all the components described in the preceding section.

3.1 Continuum Observations – Basic Assumptions

Table 1 gives the expected performance for the 27-antenna basic VLA. The listed sensitivity assumes a 12-hour on-source integration. Tables 2 through 4 give the configuration-dependent characteristics in more detail.

Resolution: Defined for the frequency at the center of the band, assuming a robustness that gives 20% degradation relative to uniform weighting. For a given image, the resolution can be improved by up to 20% relative to the quoted value, at the expense of a similar loss of sensitivity. No tapering in the (u,v) plane is assumed; tapering would give poorer resolution, but will improve the brightness temperature sensitivity roughly as the square of the resolution loss.

Sensitivity: Listed are the $1-\sigma$ values for the parameters listed in Table 1. Quoted bandwidth is the sum of both orthogonal polarizations. A robustness parameter giving a degradation of 20% relative to natural weighting is assumed. In a given image, the sensitivity can thus be 20% better than the quoted value, at the expense of a similar loss of resolution. The brightness temperature sensitivity is computed for a source whose size is equal to the quoted resolution. For an extended object, the temperature sensitivity will rise roughly as the number of resolution elements across the object. For an object smaller than the resolution, the temperature sensitivity will rise as $(\theta_{\mathrm{res}}/\theta_{\mathrm{obj}})^2$. The efficiency η is a general efficiency factor that includes both aperture efficiency and correlator losses. A two-bit, four-level correlator has been assumed.

Configurations: Tables 2, 3, and 4 show the range of resolution and surface brightness senstivity for the A, C, and E configurations, respectively. Observation of a source at declination $+30^\circ$ is assumed. In the E configuration, the 12-hr sensitivity has been adjusted for a loss of 1/3 of the visibilities due to shadowing, while the 2-minute snapshot has been assumed to take place at an hour angle when no shadowing occurs. An E configuration with a maximum baseline of 250 meters has been assumed. Note that the brightness-temperature sensitivity units change from K to mK for Tables 3 and 4.

Frequency Bands: UHF frequency bands listed are for illustration only – no decision on their definition has been made. A single, or a pair, of wideband feeds is an attractive possibility. The listed frequency ranges of the other bands is relatively firm.

Table 1: **Frequency Coverage and Sensitivity**

Band	Frequency (GHz)	Freq. Range (GHz)	$\Delta\nu$ (GHz)	$T_{\rm sys}$ (K)	η	Sensitivity μJy/beam
UHF1	0.25	0.20–0.30	0.10	135	0.45	38
UHF2	0.37	0.30–0.45	0.10	70	0.50	18
UHF3	0.57	0.45–0.70	0.20	46	0.50	8.4
UHF4	0.90	0.70–1.10	0.50	28	0.50	3.6
L	1.5	1.10–2.00	1.0	26	0.50	1.9
S	3.0	2.00–4.00	3.0	29	0.62	1.1
C	6.0	4.00–8.00	6.0	31	0.60	0.82
X	10.0	8.00–12.00	6.0	34	0.56	0.95
U	15	12.00–18.00	8.0	39	0.54	0.98
K	22	18.00–26.50	12.0	54	0.51	1.2
K_a	33	26.50–40.00	16.0	45	0.39	1.1
Q	45	40.00–50.00	10.0	66	0.34	2.4

Table 2: **Standard A Configuration - Continuum Properties.** For the **B**-configuration, multiply the resolution by 3.2, and divide the brightness sensitivity by 10

Frequency (GHz)	Resolution (arcsec)	Point Source rms (μJy/beam)		T_b rms (K)	
Dual pol.		2 min	12 hr	2 min	12 hr
0.25	9.6	720	38	215	11.4
0.37	6.4	340	18	100	5.4
0.57	4.2	160	8.4	48	2.5
0.90	2.7	68	3.6	20	1.1
1.5	1.6	36	1.9	11	0.57
3.0	0.80	21	1.1	6.3	0.33
6.0	0.40	16	0.82	4.8	0.25
10	0.25	18	0.95	5.4	0.30
15	0.17	19	0.98	5.7	0.30
22	0.12	23	1.2	6.9	0.36
33	0.08	21	1.1	6.3	0.33
45	0.06	46	2.4	14	0.72

Table 3: **Standard C Configuration - Continuum Properties.** For the **D**-configuration, multiply the resolution by 3.2, and divide the brightness sensitivity by 10.

Frequency (GHz)	Resolution (arcsec)	Point Source rms (μJy/beam)		T_b rms (mK)	
Dual pol.		2 min	12 hr	2 min	12 hr
0.25	90	720	38	2200	115
0.37	57	340	18	1000	54
0.57	39	150	8.4	480	25
0.90	24	68	3.6	200	11
1.5	14	36	1.9	110	5.7
3.0	7.2	21	1.1	62	3.3
6.0	3.6	16	0.82	48	2.5
10.0	2.2	18	0.95	55	2.9
15	1.5	19	0.98	60	3.0
22	1.1	23	1.2	70	3.6
33	0.75	21	1.1	63	3.3
45	0.60	46	2.4	140	7.2

Table 4: **Optimum E Configuration - Continuum Properties**

Frequency (GHz)	Resolution (arcsec)	Point Source rms (μJy/beam)		T_b rms (mK)	
Dual pol.		2 min	12 hr	2 min	12 hr
0.25	840	720	47	36	2.0
0.37	480	340	22	17	0.92
0.57	290	160	10	8.2	0.43
0.90	190	68	4.4	3.4	0.19
1.5	120	36	2.3	1.9	0.10
3.0	60	21	1.3	1.1	0.056
6.0	29	16	1.0	0.81	0.042
10.0	19	18	1.2	0.94	0.049
15	12	19	1.2	1.0	0.051
22	9.6	23	1.5	1.2	0.061
33	7.0	21	1.3	1.1	0.056
45	5.0	46	2.9	2.4	0.12

3.2 Spectral Line Observations – Basic Assumptions

All assumptions are the same as for continuum observations. In addition, the spectral lines are assumed to have widths of 1 km s^{-1}, so that the relevant bandwidth becomes $\Delta\nu_{\rm line} \approx 2\nu_0/(3\times10^5)$, where ν_0 is the center of the observing band, and the factor of 2 is based on the assumption that both polarizations are observed. The rms noise is thus increased relative to the continuum noise by $\sqrt{\Delta\nu_{\rm cont}/\Delta\nu_{\rm line}}$. In the tables, note the change in units relative to the continuum tables: from μJy/beam to mJy/beam for the point-source sensitivity, and from GHz to KHz for the bandwidth. Values are given only for A, C, and E configurations; estimates for B and D configurations can be derived using simple scaling laws.

Table 5: **Standard A Configuration - Spectral Line (1 km s^{-1}) Properties.** For the **B**-configuration, multiply the resolution by 3.2, and divide the brightness sensitivities by 10.

Frequency (GHz)	$\Delta\nu$ (kHz)	Resolution (arcsec)	Point Source rms (mJy/beam)		T_b rms (K)	
	Dual pol.		2 min	12 hr	2 min	12 hr
0.20–0.30	1.7	9.6	170	9.1	52,000	2700
0.30–0.45	2.5	6.4	70	3.7	21,000	1110
0.45–0.70	3.8	4.2	36	1.9	11,000	570
0.70–1.10	6.0	2.7	17	0.9	5,000	270
1.10–2.00	10	1.6	11	0.58	3,300	170
2.00–4.00	20	0.80	7.6	0.40	2,300	120
4.00–8.00	40	0.40	5.7	0.30	1,700	90
8.00–12.00	67	0.25	5.1	0.28	1,500	84
12.00–18.00	100	0.17	5.1	0.27	1,500	81
18.00–26.50	148	0.12	6.1	0.32	1,800	96
26.50–40.00	222	0.08	5.3	0.28	1,600	84
40.00–50.00	300	0.06	7.6	0.40	2,300	120

Table 6: **Standard C Configuration - Spectral Line (1 km s^{-1}) Properties.** For the **D**-configuration, multiply the resolution by 3.2, and divide the brightness sensitivities by 10.

Frequency (GHz)	$\Delta\nu$ (kHz)	Resolution (arcsec)	Point Source rms (mJy/beam)		T_b rms (K)	
	Dual pol.		2 min	12 hr	2 min	12 hr
0.20–0.30	1.7	100	170	9.1	510	27
0.30–0.45	2.5	64	70	3.7	210	11
0.45–0.70	3.8	42	36	1.9	110	5.7
0.70–1.10	6.0	27	17	0.9	50	2.7
1.10–2.00	10	16	11	0.58	32	1.7
2.00–4.00	20	8.0	7.6	0.40	23	1.2
4.00–8.00	40	4.0	5.7	0.30	17	0.90
8.00–12.00	67	2.5	5.1	0.28	15	0.84
12.00–18.00	100	1.7	5.1	0.27	15	0.81
18.00–26.50	148	1.2	6.1	0.32	18	0.96
26.50–40.00	222	0.80	5.3	0.28	16	0.84
40.00–50.00	300	0.60	7.6	0.40	23	1.2

Table 7: **Optimum E Configuration - Spectral Line (1 km s^{-1}) Properties**

Frequency (GHz)	$\Delta\nu$ (kHz)	Resolution (arcsec)	Point Source rms (mJy/beam)		T_b rms (K)	
	Dual pol.		2 min	12 hr	2 min	12 hr
0.20–0.30	1.7	840	170	11	7.7	0.50
0.30–0.45	2.5	480	70	4.6	3.2	0.21
0.45–0.70	3.8	290	36	2.4	1.6	0.11
0.70–1.10	6.0	190	17	1.1	0.76	0.050
1.10–2.00	10	120	11	0.71	0.50	0.032
2.00–4.00	20	60	7.6	0.50	0.34	0.023
4.00–8.00	40	29	5.7	0.37	0.26	0.027
8.00–12.00	67	19	5.1	0.34	0.23	0.015
12.00–18.00	100	12	5.1	0.34	0.23	0.015
18.00–26.50	148	9.6	6.1	0.40	0.27	0.018
26.50–40.00	222	7.0	5.3	0.35	0.24	0.016
40.00–50.00	300	5.0	7.6	0.50	0.34	0.023

3.3 The A+ Configuration – Design Performance

The A+ configuration can assume a number of forms. Tables 8 and 9 show the point-source and brightness sensitivity for a 37-antenna array consisting of the existing 27 VLA antennas, two existing VLBA antennas (PT and LA), plus eight new antennas distributed in two rings, two on an inner ring and six on an outer ring. The best sensitivity is achieved with natural weighting, while the best resolution is achieved with uniform weighting. The strong (and unavoidable) central concentration of antennas results in a wide variation in resolution and imaging performance as a function of the u-v weighting. The best overall imaging capability is achieved by weighting the data with a robustness of ~ -1. Using natural weighting will lower the resolution by a factor of three, and increase the sensitivity by about 50% (and thus increase the surface brightness sensitivity by a factor of about 15!). It also greatly degrades the imaging performance. Increasing the 'robustness' parameter from -1.0 to $+0.5$ will reduce the resolution by a factor of 1.7, and improve the sensitivity by about 25%, thus giving about four times the surface brightness sensitivity. This combination will maintain good imaging characteristics.

Table 8: **A+ Configuration (37 antennas) - Continuum Properties**

Frequency (GHz)	$\Delta\nu$ (GHz)	Resolution (marc)	Point Source rms (μJy/beam)		T_b rms (K)	
	Dual pol.		2 min	12 hr	2 min	12 hr
0.20–0.30	0.10	800	660	36	22,000	1190
0.30–0.45	0.10	500	320	17	11,000	550
0.45–0.70	0.20	340	150	8.1	4,900	270
0.70–1.10	0.50	220	65	3.3	2,100	110
1.10–2.00	1.0	125	33	1.8	1,000	60
2.00–4.00	3.0	64	20	1.1	660	36
4.00–8.00	6.0	32	15	.75	500	25
8.00–12.00	6.0	20	17	.90	560	30
12.00–18.00	8.0	13	18	.90	600	30
18.00–26.50	12.0	9	22	1.1	725	36
26.50–40.00	16.0	6	20	1.0	660	33
40.00–50.00	10.0	4	43	2.3	1420	76

Table 9: **A+ Configuration (37 antennas) - Spectral Line (1 km s^{-1}) Properties**

Frequency (GHz)	$\Delta\nu$ (kHz)	Resolution (marc)	Point Source rms (mJy/beam)		T_b rms (K)	
	Dual pol.		2 min	12 hr	2 min	12 hr
0.20–0.30	1.7	800	160	8.8	5.3×10^6	2.9×10^5
0.30– 0.45	2.5	500	64	3.2	2.1×10^6	1.1×10^5
0.45– 0.70	3.8	340	35	1.9	1.6×10^6	62,000
0.70– 1.10	6.0	220	19	0.94	6.0×10^5	31,000
1.10– 2.00	10	125	10	0.56	3.4×10^5	19,000
2.00– 4.00	20	64	7.7	0.43	2.5×10^5	14,500
4.00– 8.00	40	32	5.8	0.29	1.9×10^5	9,600
8.00– 12.00	67	20	5.1	0.27	1.7×10^5	8,900
12.00–18.00	100	13	5.0	0.25	1.6×10^5	8,300
18.00–26.50	148	9	6.3	0.31	2.1×10^5	10,000
26.50–40.00	222	6	5.4	0.27	1.8×10^5	8,900
40.00–50.00	300	4	7.7	0.41	2.5×10^5	13,500

Two other forms of the A+ configuration are of practical interest. The proposed eight-antenna, two-ring arrangement will give outstanding imaging characteristics when used as a stand-alone array, or as an array with one or more VLA antennas added. For the case of an eleven-element array (ten antennas in two rings, plus a single VLA antenna), the sensitivity will be worsened by a factor of 2.7, and the resolution will be improved by 40% compared to the entries in Tables 10 and 11, thus lowering the brightness sensitivity by a factor of five from the tabled entries. For the case of a 14-element array, comprising the ten antennas in two rings, plus four VLA antennas (one at the center, and one each at the ends of the arms of the A-configuration), the sensitivity would be worsened by a factor of 2.2, and the resolution improved by about 35%, leading to a decrease in surface brightness sensitivity by a factor of about 4. For both of these arrangements, the resolution and sensitivity can be traded off by about 15% by adjusting the weighting.

3.4 The New Correlator

The following description of the Expanded VLA's correlator is based on the MMA correlator concept. This correlator is envisioned to have four pairs of independent inputs, each of maximum 2 GHz bandwidth. These input pairs could be connected to individual input signals in several ways, some of which are listed below:

1. Connect four input signal polarization pairs to the four correlator pairs, achieving the performance characteristics listed in Table 10 for each of the four input pairs. These input pairs need not have the same bandwidth or center frequency.
2. Connect one input signal pair to two correlator input pairs. The number of output channels for this input signal pair would be doubled over the values listed in Table 10, up to a maximum value of 16,384 channels, while the frequency resolution would be improved by a factor of two. The other two correlator input pairs could be used in a similar fashion for a single input signal pair, or could be used for two separate input pairs.
3. Connect all four correlator input pairs to a single signal input pair. The number of channels would be increased by a factor of four over the values listed in Table 10, up to a maximum of 32,768 channels. The frequency resolution would be improved by a factor of four over the values listed in the table.

Table 10: **Bandwidths and number of spectral line channels for a single baseband pair**(1)

	Single polarization product(2)		Two polarization products(3)		Four polarization products(4)	
Bandwidth	No.	Freq.	No.	Freq.	No.	Freq.
MHz	Channels(5)	Separ. kHz	Channels(5)	Separ. kHz	Channels(5)	Separ. kHz
2000	256	7812.5	128	15625	64	31250
1000	512	1953.1	256	3906	128	7812.5
500	1024	488.28	512	976.56	256	1953.1
250	2048	122.07	1024	244.14	512	488.28
125	4096	30.52	2048	61.04	1024	122.07
62.5	8192	7.629	4096	15.259	2048	30.518
31.25	8192	3.815	4096	7.629	2048	15.259
15.625	8192	1.907	4096	3.815	2048	7.629
7.813	8192	0.954	4096	1.907	2048	3.815
3.906	8192	0.477	4096	0.954	2048	1.907
1.953	8192	0.238	4096	0.477	2048	0.954
0.977	8192	0.119	4096	0.238	2048	0.477

Notes: (1) There are four baseband pairs possible. (2) Single polarization product, *e.g.,* RR or LL. (3) Two polarization products, RR and LL. (4) Full (four) polarization products: RR, LL, RL, and LR. (5) Channel count and channel separation are those *before* smoothing.

4 Budget and Timescale for the VLA Expansion

The estimated total budget for the major components of the VLA Expansion Project is given in the following table. In this table, “M&S” means Materials and Services, and covers the cost of material purchases, “FTE” is the total number of man-years needed to complete the project component. Salaries include benefits.

Table 11: **VLA Expansion Project Costs**

Component	M&S M$	Salaries M$	Total M$	FTE Man-Years
Correlator	7.2	1.8	9.0	37
Wideband Data Transmission	7.4	4.3	11.7	112
On-Line Computing	1.7	2.9	4.6	36
Subtotal, Comp. 1	16.3	9.0	25.3	185
Eight Cassegrain Systems	8.4	5.2	13.6	88
Ant. Feed Cone	0.9	1.2	2.1	29
Subtotal, Comp. 2	9.3	6.4	15.7	117
Prime Focus System	4.6	2.5	7.1	43
E-Configuration	4.8	0.1	4.9	2
Subtotal, Comp. 3	9.4	2.6	12.0	45
Misc. Hardware	0.9	0.0	0.9	0
Management	0.8	1.6	2.4	24
Subtotal, Misc. and Mngmt.	1.7	1.6	3.3	24
Total	36.7	19.6	56.3	371
Contingency (20%)	7.3	3.9	11.2	
Grand Total	44.0	23.5	67.5	371

A detailed budget is not yet available for the A+ configuration. The total cost can be estimated by taking the cost of a fully-equipped 25-meter antenna as $6.25 million, and addding in a rough estimate of 700 miles of fiber lines as $13M. Thus, for eight new antennas, and adding 20% contingency, the total cost is roughly $75M.

Operational costs for the three components of the project listed in the table are not expected to rise over current levels, as aging hardware will be replaced with modern, more reliable components. Operational costs for the A+ configuration will rise, but not at a rate set by current op