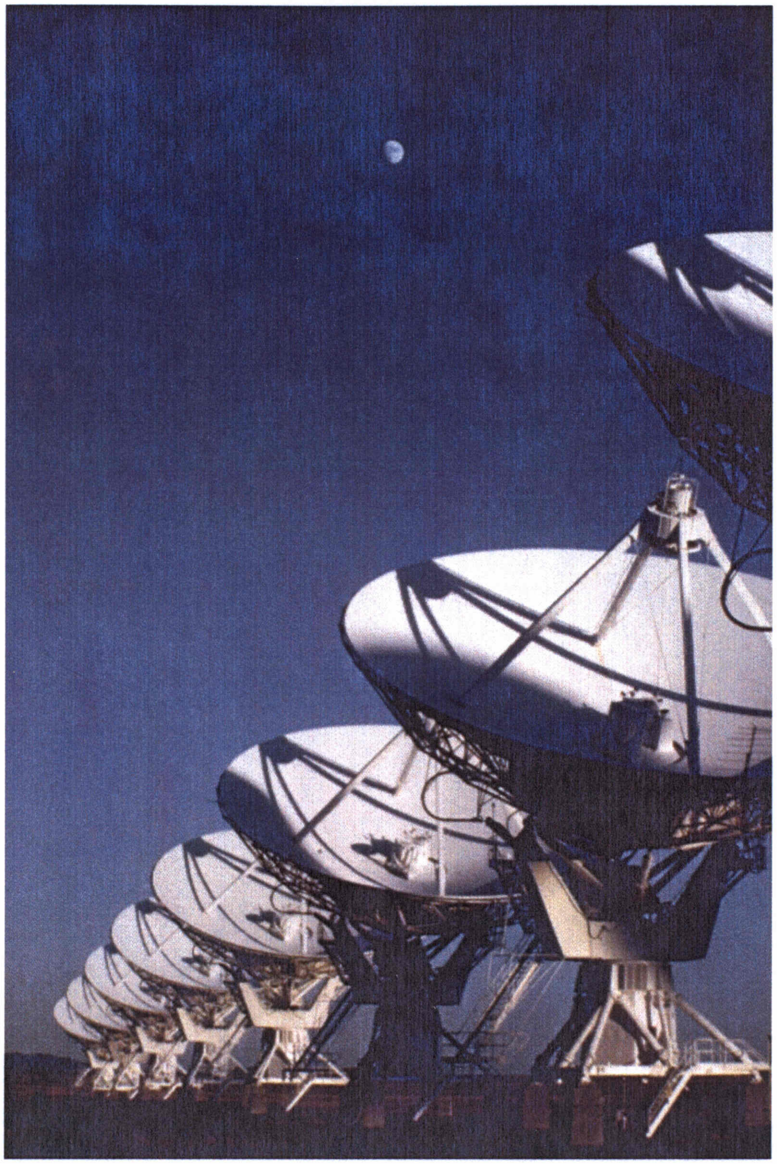
VLA Expansion Project



Response to NSF Request for Additional Information

The Very Large Array Expansion Project

Phase 1 - The Ultrasensitive Array

Response to NSF Request for Additional Information

Submitted by
Associated Universities, Inc.
February 2001

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EVLA Project Information Requested by the NSF

21 February 2001

P. Napier EVLA Project Manager - Designate
R. Perley EVLA Project Scientist

Introduction

In May 2000, the NRAO submitted to the NSF a proposal to fund Phase 1 of the Expanded Very Large Array Project. On December 14 and 15, 2000, an NSF panel met in Socorro to review the proposal. The panel submitted its report to the NSF in January, 2001. Based on the panel's report, the NSF has requested that the NRAO provide further expansion on, and clarification of aspects of the project which were presented verbally to the committee, but which were not in the originally submitted proposal. This document contains this requested information.

We received ten specific requests. These have been included in Appendix 1 with annotations giving the location of the responses in this document, which is organized under three major headings:

1. Management Issues
2. Scientific Issues
3. Technical Issues

We have also taken the opportunity to include material which was of interest to the Site Visit Panel, but which did not appear in the NSF's request for information.

1. Management Issues

1.1 Organizational Responsibilities

The relationship between the EVLA Project and the other operational units and projects at the NRAO is indicated in the planned NRAO organization chart shown in Figure 1. This shows that the EVLA Project, the NRAO Data Management Group, and the ALMA Project, each have their own management structure. The EVLA Project will be managed by a Project Manager reporting to the Assistant Director for Socorro Operations. The manpower resources required to accomplish the EVLA tasks will be supplied by the existing Socorro Divisions with new positions added to these Divisions as necessary using EVLA Project funding. The Socorro Divisions will also continue to provide operations and maintenance support for the VLA and VLBA under the management of the two Socorro Deputy Division Heads.

The EVLA Project organization is shown in more detail in Figure 2. The Socorro Electronics Division, Socorro Engineering Services Division, Socorro Computing Division, Socorro Business Division and Socorro Scientific Staff provide services to the EVLA Project as authorized and managed by the EVLA Project Manager. Certain EVLA software tasks, defined in Section 3.2, will be performed by the NRAO Data Management Group as contracts to the EVLA Project. These contracts will be managed for the

Figure 1. NRAO Organization Chart (Planned)

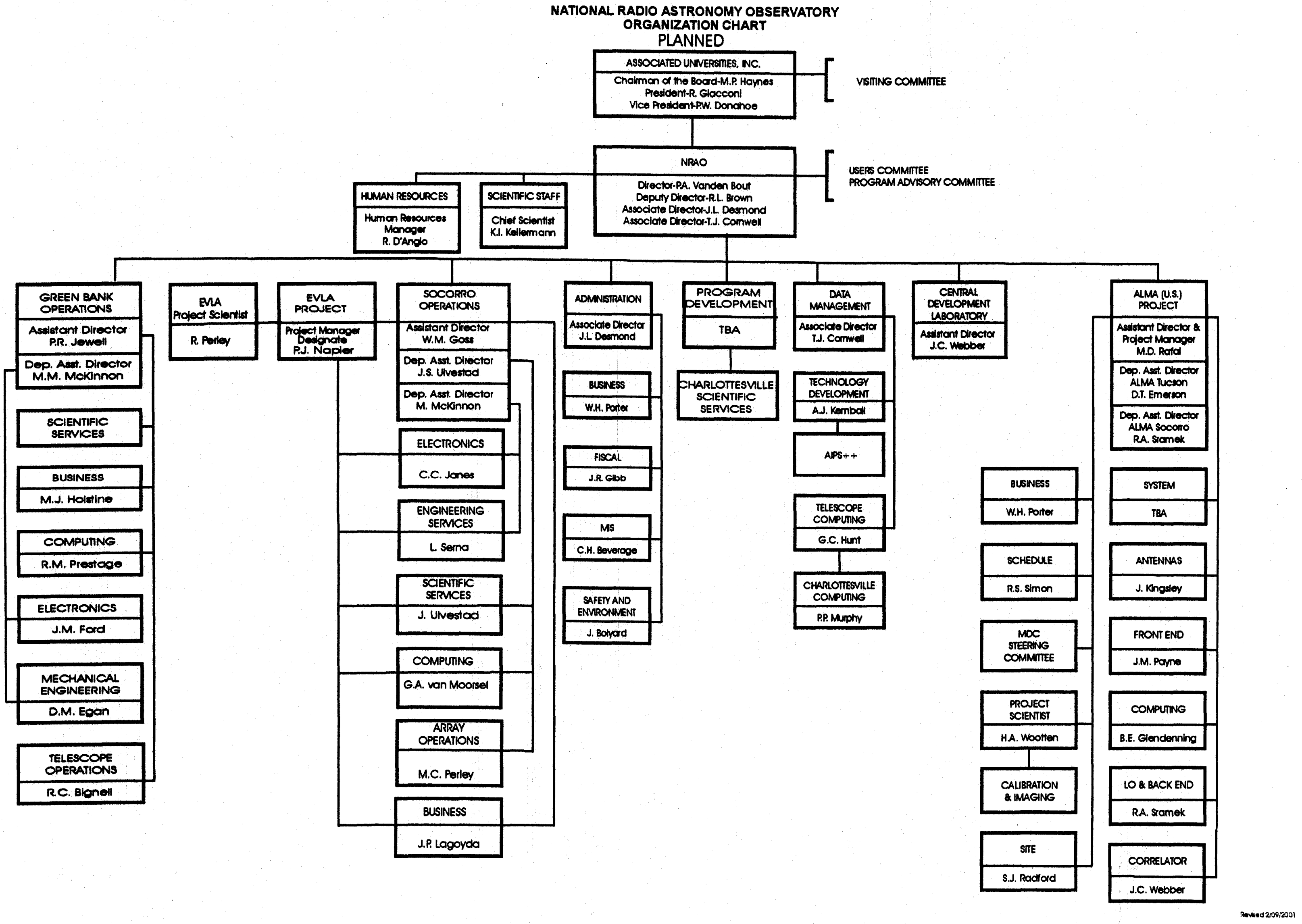
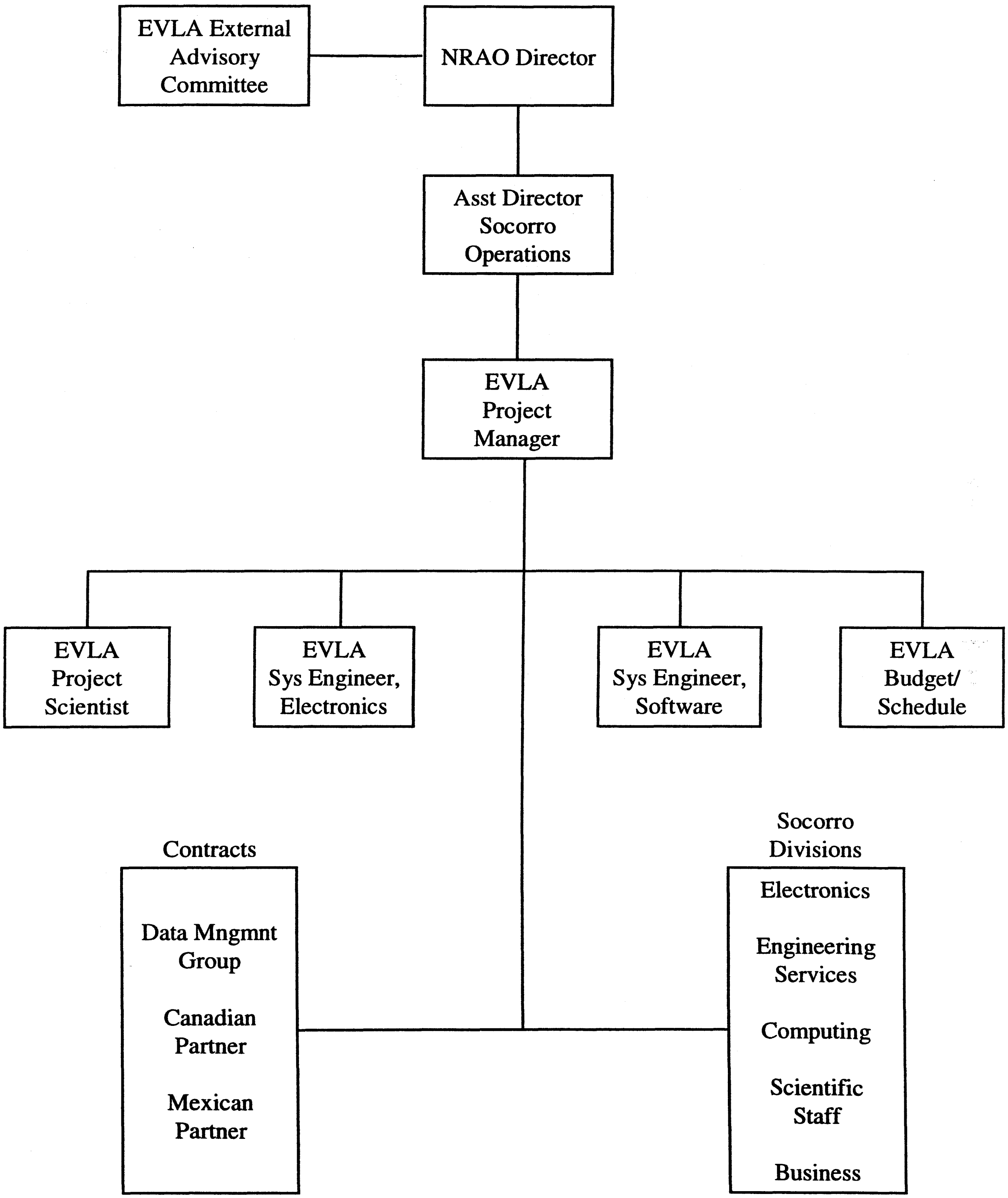


Figure 2. Planned EVLA Management Structure



EVLA by the Socorro Computing Division Head. The activities of the Canadian and Mexican partners will be coordinated by the EVLA Project Manager as contracts to the EVLA project. The responsibilities of the key positions in Figure 2 associated with the EVLA Project are summarized below. The name of the person currently planned to occupy the position is also given. The resumes of these people are included in Appendix 2.

EVLA Project Manager (P. Napier - designate)
Overall responsibility for accomplishing the EVLA Project on budget and on time with all performance requirements achieved. This will be accomplished using the management tools discussed below. An assistant will provide the effort required to implement and update these management tools on a monthly basis.

EVLA Project Scientist (R. Perley)
Responsible for communicating with the scientific community, both inside and outside NRAO, to ensure that the performance requirements for the EVLA match the community's priorities and maximize the scientific capabilities achievable with the available budget.

EVLA Electronics Systems Engineer (J. Jackson)
Responsible for overview of the EVLA electronics system to ensure that the interfaces between all electronic subsystems are correct and that the design will ensure that all performance requirements will be met. Works closely with the EVLA Software Systems Engineer to ensure that all interfaces between hardware and software are correct.

EVLA Software Systems Engineer (TBD)
Responsible for overview of the EVLA software system to ensure that the interfaces between all software subsystems are correct and that the design will ensure that all performance requirements will be met. Works closely with the EVLA Electronics Systems Engineer to ensure that all interfaces between hardware and software are correct.

Socorro Electronics Division Head (C. Janes)
Responsible for the production of the Feed, Receiver, Local Oscillator, Intermediate Frequency and Data Transmission Subsystems required for the EVLA.

Socorro Engineering Services Division Head (L. Serna)
Responsible for all modifications to the VLA antennas required for the EVLA.

Socorro Scientific Staff Head (J. Ulvestad)
Responsible for all scientific studies required to set performance requirements for all hardware and software subsystems, and for all astronomical tests required for system commissioning and specification verification.

Socorro Computing Division Head (G. van Moorsel)
Responsible for ensuring that software and computing hardware required for the EVLA is provided on schedule and budget. Supervises the Manager of the EVLA Control and Monitor Software group. Manages those software packages produced by the NRAO Data Management Division as contracts to the EVLA Project.

Socorro Business Division Head (S. Lagoyda)
Responsible for the preparation of the monthly Project Financial Statement and for all procurement activities required for the EVLA.

Canadian Partner Correlator Project Manager (P. Dewdney)
Responsible for the design and construction of the WIDAR (Wideband Interferometric Digital Architecture) correlator as the contribution of the Canadian Partner to the EVLA Project.

Mexican Partner Project Manager (L. Rodriguez)
Responsible for managing those components that are produced in Mexico as part of the contribution of the Mexican Partner to the EVLA Project, and for sending to the EVLA Project any remaining funds from the Mexican contribution.

NRAO Associate Director for Data Management (T. Cornwell)
Responsible for the coordination of all Data Management software projects within NRAO. Manages the activities of the NRAO Data Management (DM) Group. Responsible for those EVLA software packages provided by the NRAO DM Group under contract from the EVLA Project.

1.2 Project Oversight and Advice

Oversight of the EVLA Project will occur at a number of levels:

AUI Board of Trustees
The Board will receive periodic reports from the Project Manager on the status of the Project. The NRAO Visiting Committee, which reviews the whole of NRAO for the Board, will review the status of the project at the annual Visiting Committee meetings.

NRAO EVLA Advisory Committee
An advisory committee consisting of experienced scientists from outside of the NRAO will advise the NRAO Director on the scientific and technical priorities of the Project. Membership will include representation from the partner countries. This committee will be convened by the Project Scientist and chaired by one of its members and will meet once or twice a year. An important function of this committee will be oversight of the software aspects of the EVLA Project, so committee members will be chosen to provide expertise with astronomical software systems.

NRAO Program Advisory Committee
The NRAO Program Advisory Committee advises the NRAO Director on the status and future planning for all NRAO projects and operational units. The EVLA will be reviewed by this committee at each of its annual meetings.

NRAO Users Committee
The EVLA will be reviewed by the NRAO Users Committee at its annual meeting. This review will be an important mechanism for the astronomical community to provide comment to the Project concerning the EVLA performance requirements and the plan for keeping the VLA in operation during the transition to the full EVLA.

Reports to the NSF
The Project Manager will provide written monthly reports to the NSF giving the technical and financial status of the project.

Internal Advisory Committee
A committee of experienced NRAO scientists and engineers from outside the Project will provide advice to the Project Manager and Project Scientist concerning priorities and decisions. Membership will include the partner organizations. The committee will be convened by the Project Manager and chaired by one of its members

Design Reviews
Preliminary and Critical Design Reviews will be conducted for all hardware and software subsystems under NRAO's Design Review rules which will provide a correct balance of project and external review. The reports of the reviews will be given to the reviewing bodies listed above and it will be the responsibility of the Project Manager to act on the findings of the reviews.

1.3 Management Tools

The management of the EVLA Project will be less complex than the management of the ALMA Project because of the smaller size of the project, because the bulk of the project will be performed primarily by an existing group of co-located people and because of the reduced role of the international partners in the EVLA compared to ALMA. Nevertheless, the EVLA Project will use the same management methodology introduced to NRAO by the ALMA Project. This will include:

- **Work Breakdown Structure**
  - Definitions of Systems and Sub-systems
  - Tasks & Dependencies
  - Schedule
  - Budget
  - Personnel and other Resources
- **Change Control Board**
  - Design and Performance Specifications
  - Interfaces
  - Contingency Allocation - Cost / Schedule
- **Document Control**
  - Project Book (details of work plan)
  - Specification Documents
  - Interface Control Documents
  - Drawings: Approval, Archiving, Revisions
- **Project Monitoring**
  - PDR, CDR
  - Periodic Reporting
  - Milestone Tracking
  - Earned Value & Percent Complete Analysis
- **Weekly Division Head Meeting**
  - A weekly meeting of the managers of the project, at and above the level of Division Head, to review progress, set goals and solve problems on a short term basis.

1.4 Schedule

The current principal milestones for the EVLA Project are:

Milestones	**Date after start of funding**
Top Level System	
Detailed Project Management Plan	0 yr 3 mo
System PDR	0 yr 6 mo
Overall data processing architecture PDR	1 yr 0 mo
System CDR	1 yr 6 mo
Overall data processing architecture CDR	2 yr 6 mo
EVLA Operational	9 yr 0 mo

Feeds and Receivers

Feed Cone PDR	0 yr 6 mo
Rcv Feed PDR	0 yr 6 mo
Feed Cone CDR	1 yr 8 mo
Rcv Feed CDR	1 yr 8 mo
Start Feed Cone Installation	2 yr 3 mo
Start Rcv Installation	3 yr 8 mo
Finish Rcv Installation	8 yr 10 mo

LO/IF/Fiber Optics

LO / IF / FO PDR	0 yr 6 mo
LO / IF / FO CDR	1 yr 6 mo
Start LO/IF/FO Installation	1 yr 11 mo
Finish LO/IF/FO Installation	6 yr 12 mo

Correlator

Correlator PDR	1 yr 6 mo
Correlator CDR	3 yr 0 mo
Start Correlator parts purchase	3 yr 2 mo
Move Correlator to VLA	4 yr 6 mo
Begin Correlator test observing	5 yr 6 mo
Correlator Operational	6 yr 0 mo

Control/Monitor System

Control/Monitor System PDR	0 yr 9 mo
Control/Monitor System CDR	1 yr 8 mo
Control/Monitor System enhanced antenna test	1 yr 8 mo
Control/Monitor System full support of enhanced antennas	2 yr 11 mo
Control/Monitor System ready for WIDAR correlator	4 yr 7 mo
Control/Monitor System, ready for archive	4 yr 11 mo

Observation Proposal Handling Software

Observation Proposal handling PDR	0 yr 8 mo
Observation Proposal handling CDR	1 yr 8 mo
Observation Proposal handling fully deployed	2 yr 6 mo

Observation Preparation and Scheduling Software

Observation Handling tool PDR	0 yr 5mo
Observation Handling tool CDR	2 yr 5mo
Observation Handling tool can generate schedule with pipeline controls	2 yr 11mo

Image Pipeline

Pipeline PDR	0 yr 9mo
Pipeline CDR	1 yr 3mo
Pipeline operates on initial platform from archive	3 yr 0mo
Pipeline operates on new data path	5 yr 6mo

Data Archive

Archive PDR	0 yr 6mo
Archive outsourcing decision	0 yr 9 mo
Initial archive deployed	1 yr 9 mo
Archive EVLA-specific interfaces PDR	2 yr 3 mo
Archive EVLA-specific interfaces CDR	3 yr 3 mo
Archive EVLA-specific interfaces deployed	4 yr 0 mo

Data Post Processing Software

Post-processing PDR	1 yr 0 mo
Post-processing CDR	3 yr 0 mo
Post-processing meets CDR objectives	6 yr 0 mo

1.5 Budget Methodology

The budget for the EVLA Project presented in the Proposal was developed by NRAO personnel using their previous experience with the VLA and VLBA construction projects and the ALMA Design and Development Project. Bottom-up costing was done using a Level 3 WBS in most cases and a Level 4 WBS for systems that are particularly well defined, such as the receivers. A Level 3 WBS means that cost estimating was done at the module level and an example of this is shown in Table 1 which shows the cost estimation for the Local Oscillator System. A Level 4 WBS means that costing was done at the component-within-the-module level. An example of this is shown in Table 2 which shows the cost estimation data for the electronics components for the 22 GHz Receiver. Estimates for parts costs and personnel hours for assembly, test and installation have been included for all subsystems. NRAO's standard rates for the various personnel categories such as scientist, engineer, technical specialist and technician were used to calculate salary costs from the estimates of personnel hours. NRAO's standard personnel benefit rate was used for calculating personnel benefit costs. Contingency was estimated based on the risk level of the individual subsystems, giving an average contingency for the project as a whole of 15%. Contingency will be held at two levels: i) the Project Manager, to be allocated as needed based on Change Board recommendations and, ii) in a reserve held by the Observatory Director against unforeseen major problems, and/or opportunities, as requested by the Project Manager.

Table 1. Example of Level 3 Sub-System Cost Analysis for the EVLA LO System

		Materials & Services			Wages				
WBS		Quant	$/unit ($k)	Cost ($k)	FTE /unit	FTE	$/FTE ($k)	$/unit ($k)	Wages ($k)
6	**Local Oscillator System**								
	H-maser & Rb Frequency Standard	1	300	300					
	LO Ref Generator	1	15	15	0.06	0.1	30	1.8	2
	LO Ref Distributor - Control Bldg	1	5	5	0.06	0.1	30	1.8	2
	Microwave Round-trip Phase Measurement	30	15	450	0.08	2.4	30	2.4	72
	LO Ref Distributor - Antenna	30	5	150	0.04	1.2	30	1.2	36
	Power supply module	30	5	150	0.04	1.2	30	1.2	36
	Engineering Supervisor, testing: module production					5.0	65		325
						4.5	45		203
	Assemble and Test - Bins and racks	60	1.5	90		6.0	65		390
						5.5	30		165
	NR Engineering Design LO (3 x 2yr)	1	50	50		2.0	65		130
						2.0	45		90
						2.0	30		60

			Work-Months						
Local Oscillator System		**FTE**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
Lead Eng, Design Production & Testing	Eng	7.0	12	12.0	12	12	12	12	12
Module production & test, Lead Tech	TS II	6.5	6	12.0	12	12	12	12	12
Module production	Tech	16.5		18.0	36	36	36	36	36
Assemble, sys test bins & racks	Eng	6.0		12.0	12	12	12	12	12
Assemble, sys test bins & racks	Tech	5.5		6.0	12	12	12	12	12
		41.5							

Table 2. Example of Level 4 Cost Estimate Data for EVLA 22 GHz Receiver

	VLA 22 GHz Rcvr Parts List		**Revised 2000-Sep-28**		
	49101.7655.80122				
				Qua	**Cost**
Item	**Component**	**Mfg**	**Model/Drawing #**	**Sys**	**ea**
1	Cooled isolator	PAMTECH	KYG2121-K2	2	$1,900
2	Cal splitter	Krytar	6020265	2	$495
3	WG to SMA adapter	MDL	WR-42 TO SMA	5	$78
4	SMA dewar feedthur	MA-COM	2084-1100-00	3	$37
5	RF Bandpass filter	K&L	13FV10-22250/U8500-O/O	2	$715
6	Post Amp	MITEQ	JS4-18002650-25-8P	2	$1,600
7	Mixer	MITEQ	TB0426LW1	2	$500
8	LO splitter	MAC TECH	PA8207-2H	1	$107
9	IF Filter	K&L	4B380-4750/795-OP/O	2	$185
10	IF isolator	DORADO	31CP51-1	2	$301
11	LO isolator	DITOM	DF2806	1	$165
12	LO amp	MITEQ	JS2-13502150-90-16P	1	$975
13	Cal Atten	NRAO spares		2	$0
14	Noise Diode	NOISE/COM	NC5242	1	$1,710
15	Solar cal amp	MITEQ	JS2-18002650-50-3P	0	$1,145
16	Cal coupler	NRAO	See Dwg lisr	2	
17	WG termation	Microwave Filter Co.	C2T2100	2	$25
18	WR-42 H-plane Bends	AMC	HB4200M1	2	$50
19	WR-42 E-plane Bends	AMC	EB4200M1	1	$50
20	Coax 0.141	Precison Tube	AA50141	8	3/'
21	Coax 0.085	Precison Tube	AA50085	20	5/'
22	SS Coax 0.085	Precison Tube	BS50085	8'	11/'
23	Card Cage	AOC		1	$130
24	Misc			1	$200
25	Misc EPOXY KITS	ARMSTRONG	K50618	1	$17
26	Misc INDIUM SHEETS	METAL SPECIALTIES	6"X12"X0.005" 99.99%PURE	1	$163
27	WR-42 cover flanges	PEM Machine	UG595/U	2	$10
28	WR-42 choke flanges	PEM Machine	UG596A/U	2	$10
29	SMA Connector 0.140	M/A COM	2001-5031-02	10	$10
30	SMA Connector 0.085	M/A COM	2001-5032-02	30	$10
31	½" Brass nipple	AIBUQ VALVE	½" pipe 3" long m2m B-8-HLN-3.0	1	$2
32	Brass fitttings elbow	AIBUQ VALVE	½" pipe 90 deg street-L male to female	1	$2
33	Brass fitttings elbow	AIBUQ VALVE	1/8" 90 deg street elbow MFB2SE	1	$2
34	½" Brass nipple	AIBUQ VALVE	½" pipe 2" long m2m B-8-HLN-2.0	2	$2
35	Valve, manual	AIBUQ VALVE	1/8" pipe swagelock B-2P4T2	1	$5
36	Vacuum flange	Scientific Sales	KSF-0416-1	1	$15
37	Cryo lines	Anamet	2-4',2-7',½" ID	2	$143
38	Modification dog house	AOC/E&S		1	$0
39	Dewar	AOC		1	$700
40	CTI Model 350 Refg	CTI	MODEL 350		
41	Dewar Vacuum Sensor	Teledyne	DV-6R VACUUM TUBES #55-38R		

42	ASCO Vave	G THOMPSON OR SMITH	8030R17VH	1	
43	Pump Vacuum Sensor	Teledyne	DV-6R VACUUM TUBES #55-38R	1	$60
44	50K Sensor	LAKESHORE	DT-471-DI	1	$143
45	15K Sensor	LAKESHORE	DT-471-DI	1	$143
46	Therm Cutout	Elmwood Controls	3450-87-315-L140 96/50	1	$15
47	Heater	Hotwatt	SC252.25	1	$25
48	LNA Bais Conn, u-min "D" feml	ITT Cannon M83513/02-BN	FP12S-1	2	$10
49	Bais Connector	ITT CANNON	KPT01H18-32P	1	$169
50	Bais Connector	ITT CANNON	MS3116F18-32S	1	$20
51	Cryo refig connector female	DEUTSCH	DM9702-3S	2	$104
52	Cryo refig connector male	DEUTSCH	DM9702-3P	2	$104
53	F14 Module	AOC	DCS	1	$2,380
54	F14 Wirewrap	AOC	DCS	1	$400
55	RF Tight box	Compac	S58010-175-1	1	$180
56	RF Tight Gasket	Compac	SRF Gasket	4'	$5

1.6 Procurement Plan

Software and computing hardware subsystems will be provided by software engineers working in either the Socorro Computing Division or the NRAO Data Management Group, or as a contract to an external group or company, as approved by the EVLA Project Manager.

Under the approval of the EVLA Project Manager, mechanical and electronics subsystems will be supplied under contract with an external group or company, or by the Socorro engineering divisions utilizing, to the maximum extent possible, commercial machine shops, printed circuit board fabricators and electronic sub-assembly houses. With the current high demand within the communications industry for RF, fiber optic and high speed digital equipment the rapid procurement of these types of components has been difficult. It is possible that these problems will ease in the future if the US economy continues to slow down, but in any case the key to solving procurement issues of this kind is careful advanced procurement planning. It should be noted that the routine production phase of most of the electronic subsystems for the EVLA does not begin until 1.7 years after commencement of the project, so there is time to make these procurement plans during the early design and development phase of the project. The only electronics subsystems where production components are needed immediately after commencement of the project are the 22 and 45 GHz receivers where it is planned to complete the ongoing production and installation of these receivers. For these receivers reliable component vendors have been used for several years and a supply of components for the next year's worth of receivers are already in-house.

The EVLA and NRAO groups currently planned as being responsible for providing the various EVLA subsystems are identified in Section 3.2.

Under the approval of the EVLA project Manager, all purchasing for the EVLA Project will be performed by the Socorro Business Division, with additional purchasing personnel funded by the Project as needed. The Socorro Business Division is experienced in the procurement of the kinds of materials and services (M/S) needed for the EVLA. The EVLA will cause an approximate 50% increase in the dollar volume of M/S expenditures supported by the Socorro Business Division.

2 Scientific Issues

We were requested to supply an explicit statement of the high-level scientific goals of the EVLA project, including required sensitivity, spectral coverage, bandpass, flux, phase, polarization accuracy, and frequency resolution. We interpret this as a request to justify the stated technical goals of the EVLA project on the basis of projected scientific capability.

The scientific goals of the EVLA project are not based on any specific observations or projects. Rather, the goals are based on an extension of the same philosophy which has proven so effective for the original VLA – to provide astronomers a powerful and flexible instrument for research into all astrophysical phenomena which emit (or reflect) detectable radiation in the radio band. The VLA merged the newly-developed technique of aperture synthesis with (then) modern technologies to provide a ten-fold to one hundred-fold improvement in observational capabilities over existing instruments. The fruits of this design philosophy are evident in the astounding impact the array has had upon science -- as outlined in Chapter 1 of the EVLA Proposal. The EVLA seeks to improve by at least an order of magnitude all key observational capabilities of the VLA through implementation of modern technologies. Improving the capabilities of the existing array, rather than (say) designing and building an entirely new facility is a cost-effective approach to maximizing the science return while minimizing the capital investment because the information-gathering capability of the present array remains largely untapped. This is so because the 1970s technologies used for signal collection, transport, and analysis, being limited to narrow bandwidth, can process only a very small fraction of the information collected by the antennas. As the VLA still utilizes this >20-year-old technology, the array is severely limited in its observational capabilities compared to the potential set by the antennas and array design. Implementation of modern signal processing technologies can completely remove the narrow-bandwidth restrictions imposed on the VLA's designers some 25 years ago, and enable all the information collected by the antennas to be processed for maximum scientific return, without having to design and build a new instrument, or develop a new site and infrastructure.

The scientific impact of the expanded capabilities of the EVLA will be enormous, and has been described in detail in the Appendix to the Proposal. Some especially outstanding examples of the new science to be expected are highlighted in Chapter 4 of the Proposal. These examples were selected to demonstrate the broad reach of the new instrument, but should not be considered as individual science goals. Indeed, we fully expect that the most outstanding new science will be in areas not anticipated by us, just as many of the VLA's outstanding accomplishments were not anticipated by its designers. The technical performance improvements required to enable this new science are summarized in Section 3.1.

We summarize below some examples of experiments which we expect the EVLA to undertake:

A) Observations of phenomena obscured at other wavebands:

Many cosmic phenomena, including star formation and accretion onto massive black holes, occur preferentially behind dense screens of gas and dust which make optical and even infrared observations difficult or impossible. Radio observations, being unaffected by these screens, offer unique information into the content and dynamics of these phenomena. The increased sensitivity, improved frequency access, and vastly superior correlator of the EVLA will enable both sensitive continuum observations and molecular spectroscopy of such regions. Potential experiments include:

- Continuum observations of the spectral energy distribution of young stellar objects (YSOs) will allow separation of the contributions of thermal dust, thermal gas, and relativistic gas. Such a separation is essential for an understanding of the dynamics and evolution of these objects.

- Deep imaging of known protostellar radio jets, connecting the known, inner (younger) radio emission to the outer (older) IR/optical emission, and enabling a complete history of these outflows to be assembled.

- Observations of obscured quasar absorption line systems, permitting high spectral resolution, high sensitivity unbiased spectral line surveys of such regions over a wide range of redshifts. Such studies will measure the evolution of the cosmic baryon density, provide estimates of the microwave background temperature, allow estimates of the abundances of deuterated molecules and molecular oxygen, and even permit estimation of basic physical constants, such as the fine structure constant and the nucleon mass -- all as a function of redshift.

B) Observations of Transient Phenomena:

The radio band is uniquely valuable for finding and tracing the evolution of compact and energetic objects, from solar flares to accreting black holes, to gamma-ray bursts. The EVLA, with its vastly improved sensitivity and spectral reach, will revolutionize studies of this broad class of phenomena. An outstanding example is that given by gamma-ray bursts (GRBs). Currently, the VLA can detect only a few GRBs per year, and of these, perhaps one of two are bright enough to allow detailed monitoring of the long-term evolution of the spectrum. The EVLA will permit detection of many hundreds of GRBs per year (thus allowing analysis of statistical samples) and, perhaps more importantly, a detailed tracking of the afterglows of up to 100 GRBs per year. Only the radio band permits monitoring long-term evolution of GRBs, and the information gained by doing this will directly measure the sizes and expansion rates at early times, and provide hard constraints on source geometry (jets, spheres, etc.) at later times. In addition, radio observations will permit observations of dust-shrouded systems, and imaging of the host galaxies.

C) Observations of Cosmic Magnetic Fields

Radio observations offer unique information into cosmic magnetic fields, through emission processes (such as synchrotron emission, Zeeman splitting), and through Faraday rotation of polarized emission by magneto ionic media. The EVLA, with its dramatically improved sensitivity, spectral coverages and spectral resolution will be by far the best instrument in the world for measurements of magnetic fields throughout the universe. A good example of this class of experiments is the magnetic fields of galaxy clusters. It is known from current observations that galaxy clusters commonly contain magnetized gas--but the details are very poorly understood. With the improved sensitivity of the EVLA, much more sensitive studies of the synchrotron emission and the Faraday rotation of background galaxies whose emission passes through the cluster, as well as that of galaxies embedded within the cluster, should answer questions such as:

i) whether all clusters are magnetized,
ii) at what level are they magnetized and,
iii) what is the spatial topology of the magnetic fields within individual cluster.

Such information is essential to construct theories of the origin and evolution of clusters.

3. Technical Issues

3.1 Technical Goals of the EVLA Project

The technical goals of the project were set by establishing an overall goal of providing the astronomer with all of the astronomical information available at the antennas' feeds, utilizing existing modern technologies. This resulted in the following specific goals:

- **Sensitivity** The goal of 1 microJy rms in 12 hours observing between 2 and 40 GHz is set by consideration of the system temperature, bandwidth, and system efficiency which can be provided by implementing modern technologies. For all of these, we have set ambitious, but realistic, goals which we are confident can be met. For nearly every band, the system temperature goal is dominated by one of ground spillover, galactic emission, or atmospheric thermal emission. The proposed bandwidths include nearly all the frequency span of each band, and the proposed antenna efficiency is the best that the VLA's existing antennas are capable of. In short, once these improvements are in place, the full information collecting ability of the existing antennas and array will be utilized.

- **Spectral Coverage** Our goal is to make available to the astronomer the entire spectral range between 1 and 50 GHz. This can be achieved, with the sensitivity goal listed above, with eight Cassegrain receiver systems. Although our current plan defers frequency coverage below 1 GHz to the 2nd phase of the project, we will review this decision in conjunction with our scientific advisory panels.
- **Bandwidth** Modern technologies enable efficient, cost-effective transport of up to 8 GHz of Intermediate Frequency (IF) bandwidth in each polarization. This is the bandwidth goal of the ALMA project, and its implementation into the EVLA means that nearly all of the available information in any of the eight Cassegrain frequency bands will be instantaneously available to the correlator for processing. The EVLA will utilize the ALMA design for the IF transmission system.
- **Phase** The phase stability design goal of the VLA was 1 degree per GHz. This ensured that the effective phase stability of the array is often dominated by atmospheric instabilities. Since the EVLA LO system will be redesigned, the phase stability will be improved to ensure the instrumental phase instability is smaller than the atmospheric instability at all times. The effect of atmospheric instabilities has been eliminated for stronger target objects through the algorithmic invention known as 'self calibration.' The greatly expanded sensitivity of the EVLA will permit this technique to be applied to much weaker objects -- estimates indicate that all observations in the 1.5 and 3 GHz bands will benefit from this technique, and perhaps even all observations in the 6 GHz band. For higher frequencies, we anticipate improved use of rapid switching methods (as the number of available nearby phase calibrators will vastly increase), and use of water vapor radiometers, which can monitor the phase path through the atmosphere.
- **Flux Density** This is addressed under 'Sensitivity'.
- **Polarization accuracy** The polarization purity of the present feed systems is 2 - 5%. This goal will be maintained for the new full-bandwidth bands, and is expected to be met, except perhaps near the band edges. These polarization errors can be accurately removed, so long as they are constant in time. Experience shows that a corrected (linear) polarization accuracy of 0.1% to 0.5% has been achieved, and this should not change for the expanded systems. This accuracy is sufficient to meet the requirements of the science examples given in the proposal. We would like to do better, and studies of the temporal and spatial variability of the antennas' polarization response will continue.
- **Frequency resolution** The highest frequency resolution required for cold emission or absorption lines is about 500 Hz. A much more demanding frequency specification is based on reflected radar signals from planetary bodies (bistatic radar), for which frequency resolution of about 1 Hz is desirable. The WIDAR correlator design meets these specifications, as well as provides sufficient numbers of channels to allow accurate measurement (and subsequent subtraction) of the surrounding continuum emission. This very high frequency resolution will also enable containment and removal of RFI signals within the observing bands.
- **Bandpass Stability** A key limiting factor which limits the VLA's imaging fidelity is the stability of the analog transmission link between the antennas and the correlator. The EVLA will employ a digital transmission system designed for ALMA which will eliminate bandpass instability.

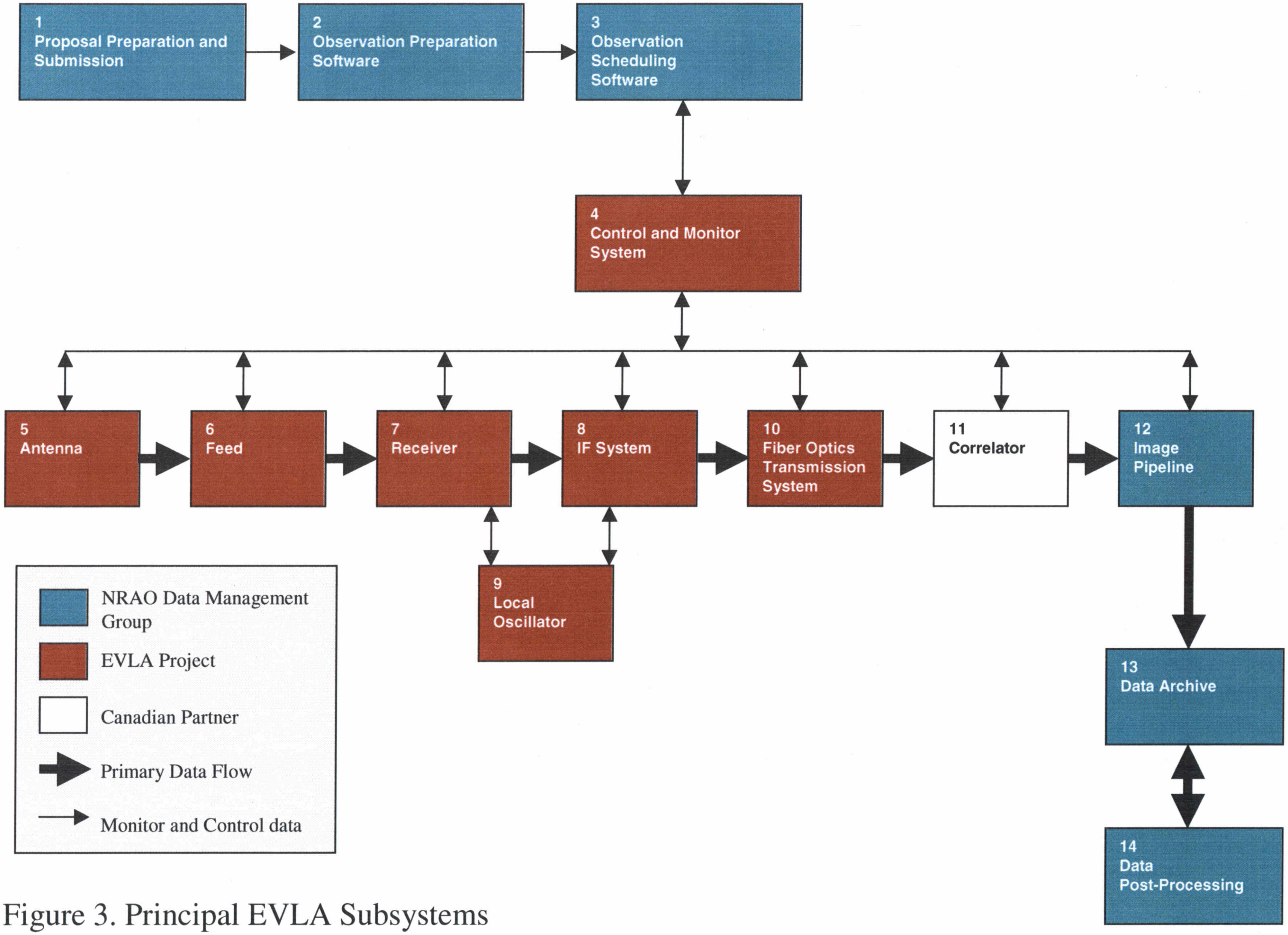


Figure 3. Principal EVLA Subsystems

3.2 EVLA Subsystem Definition

The major EVLA hardware and software subsystems are shown schematically in Figure 3, which also indicates the group responsible for supplying each subsystem. A brief definition of each subsystem, and the plan for supplying each subsystem, is provided below.

3.2.1 Observation Proposal Preparation and Submission

Information submitted by the observer will be maintained and carried through the entire computing system so that, at the completion of an observation, the archive will include proposal cover sheets, telescope schedules, observation status information, the observed data, an automatically generated "reference image", and information entered during subsequent data reduction. Scientific proposals for the EVLA will be handled by a suite of tools that will comprise capabilities for proposal composition, including integration with the observation preparation software so that observers may experiment with various telescope parameters to assist in the refinement of the proposal, electronic proposal submission via the web and electronic mail, and proposal evaluation aids for the review committees. This work has a parallel for other NRAO instruments, so these items will be developed under internal contract by the Data Management Group.

3.2.2 Observation Preparation

EVLA observations will be conducted using goal-oriented observing procedures, interactive graphical user interfaces (GUIs), or detailed observing plans, including the script files that are currently in use at the VLA. The Observing System will provide tools for the preparation of these observation plans. The script will include contextual information needed for the pipeline processing of observations. This work also is important for other NRAO instruments, so these items will be developed under internal contract by the Data Management Group.

3.2.3 Observation Scheduling

Both fixed and dynamic scheduling will be used to allocate time on the EVLA. Fixed scheduling will be used for activities requiring specific observing times. Dynamic scheduling will enable the best use of the remaining array time. A Dynamic Scheduling tool will assist in the scheduling of observations on the telescope, matching observing conditions to observations in an optimal fashion. A dynamic scheduling tool has been developed for the VLBA, and will be adapted for use on the EVLA. The NRAO Data Management Group will be responsible for this development.

3.2.4 Control and Monitor System

The Control and Monitor (C&M) System will accept programs from the observation scheduling system and perform the observations under the control of the EVLA operator and scientific support staff. Interaction with the EVLA will be possible from any remote location with adequate, secure Internet access. The C&M system will provide continuous feedback to the observer, and will enable interactive adjustment of the observing program by the observer. Important milestones in the progress of the observations will be logged and associated with the observed data. The system will be designed and implemented by the Array Support Group (ASG) of the Socorro Computer Division; this will include the acquisition of the appropriate computer equipment.

An expanded description of this critical subsystem follows:

3.2.4.1 Control and Monitor Software

The C&M System will provide a complete and well-integrated tool suite to test, control, monitor, maintain, and calibrate the instrument. It will be available for use by observers, by operations staff, and by scientific, computing, and engineering support personnel. All aspects of the EVLA will be accessible via this tool suite-array and subarray configuration, scan configuration, tools to monitor, operate and maintain the antennas, feeds, receivers, IF system, maser, LO system, signal transmission, the correlator, and ancillary subsystems such as the weather station and radio frequency interference monitor. Measures of data quality from the correlator, and tools to access archived systems data will be provided. Network software (middleware) will mediate the exchange of control and monitor messages among the system components. Choices here are being evaluated.

3.2.4.2 Control and Monitor Hardware

The C&M system will be a distributed computing architecture. It will be possible to control and monitor all hardware from a remote location via an authorized, secure network connection. In the control building, the Array Control computer will issue commands to each Antenna Control computer via an Ethernet fiber-optic network link. In each antenna, an Antenna Control computer will issue commands to its sub-systems via a local field bus. The Array Control computer and the Antenna Control computers will be commercial, off-the-shelf (COTS) equipment - Pentium and/or PowerPC CPUs in CPCI and/or VME crates. The Ethernet connection among these CPUs will run the industry standard TCP/IP protocol. The local field bus within each antenna will either be COTS or a modification of the NRAO-developed Monitor & Control Bus (MCB). The COTS candidates are Controller Area Network (CAN) and Ethernet.

3.2.4.3 Parallel Operation

During construction, it will be essential to operate existing VLA antennas in parallel with the enhanced EVLA antennas. Operationally, the enhanced EVLA antennas will form a separate subarray used to debug the new electronics and the EVLA C&M software; the present VLA computer control system will be used to control existing VLA antennas and the existing correlator, while the enhanced EVLA antennas and correlator will be controlled by the EVLA control system. Control and monitor information must be coordinated between the two systems. To enable this, an enhanced VLA Serial Line Controller to control existing VLA antennas and interface with the EVLA C&M system is currently under development.

3.2.5 Antenna

The only significant changes to the VLA antennas planned for the EVLA (Phase I) are the modification of the feed/receiver mounting structure located in the center of the primary reflector. This structure will be designed and installed by the Socorro Engineering Services Division using EVLA project funding for personnel and equipment. Fabrication of the structures will be by contract to an outside machine shop.

3.2.6 Feeds

The frequency ranges and principal performance requirements for the eight EVLA receiver bands are listed in Table 3 which is taken from Tables 3.1 and 5.1 of the Proposal.

Table 3. Principal performance requirements for the EVLA

Band Center Frequency (GHz)	Frequency Range (GHz)	System Temperature (K)	Total System Efficiency	Maximum IF Bandwidth (GHz)
1.5	1.0-2.0	26	0.50	2x1
3.0	2.0-4.0	29	0.62	2x2
6.0	4.0-8.0	31	0.60	2x4
10	8.0-12.0	34	0.56	2x4
15	12.0-18.0	39	0.54	2x6
22	18.0-26.5	54	0.51	2x8
33	26.5-40.0	45	0.39	2x8
45	40.0-50.0	66*	0.34	2x8

* At low frequency end of the band

To cover the frequency bands listed in Table 3, new corrugated horn feeds will be provided for the 1.5, 3, 6, 10, 15, and 33 GHz bands. Additionally, new feeds for the 22 and 45 GHz bands will be provided for those antennas that have not already had new receivers installed for those two bands. Twelve 22 GHz and three 45 GHz receivers remain to be built and installed. The new feeds will be designed to provide the aperture efficiencies listed in Table 3. These feeds will be designed by the NRAO Central Development Lab (CDL) and fabricated using EVLA Project funds, by the Socorro Electronics Division by contract to an outside machine shop.

3.2.7 Receivers

The existing VLA receivers for the 1.5, 10, 22, and 45 GHz bands will be modified to provide the tuning range and IF bandwidth listed in Table 3. Completely new receivers will be provided for the 3, 6, 15, and 33 GHz bands. The noise temperatures to be achieved are listed in Table 3 for all receivers.

The receivers will be designed, assembled, and tested by the Socorro Electronics Division using EVLA Project funding for personnel and equipment. The cryogenic low-noise amplifiers for all receivers will be built by the CDL. Other electronics components for the receivers will be purchased from outside suppliers and mechanical parts will be fabricated by contract to outside machine shops.

3.2.8 Intermediate Frequency (IF) System

The IF bandwidths to be provided for each band are specified in Table 3. To achieve these bandwidths a new IF system will be provided for every VLA antenna. The outputs for all bands will initially be converted to an 8-12 GHz IF band and then down-converted to a 2-4 GHz band which will be bandpass-sampled by a 4 Gsamp/sec, 3 bits/sample digitizer. It is expected that ALMA designs will be used for the 2-4 GHz IF and digitizer stages. Using EVLA Project funding for personnel and equipment, the Socorro Electronics Division will design the 8-12 GHz stage and will build the entire IF system, using outside contracts for PC board fabrication and assembly where feasible.

3.2.9 Local Oscillator (LO) System

A new LO system will be provided for every VLA antenna to support the new IF system. A fixed first LO selectable in the range 12-58 GHz, in steps of 1 GHz, will be used for the first frequency conversion and an 8-16 GHz synthesizer will be used for the final down-conversion. Local oscillator offset and fringe rotation will be supplied by a Direct Digital Synthesizer (DDS) providing an offset frequency to the 8-16 GHz synthesizer. LO reference signals will be supplied at the antenna on an optical fiber which has a round-trip phase measurement system to allow the line length to be stabilized. It is expected that the designs for the DDS and 8-16 GHz synthesizer will be small modifications to ALMA designs. All other LO design work will be done by the Socorro Electronics Division, which will build the whole LO system using outside contracts for PC board fabrication and assembly where feasible. EVLA Project funds will be used for all personnel and equipment.

3.2.10 Fiber Optics Data Transmission

A fiber optics digital data transmission system will be installed to all VLA antennas. The data from the digitizer will be returned to the Central Electronics Building on twelve 10 Gbps links using commercial OC-192 technology. It is expected that the ALMA design for the digital transmission system will be used. The fiber optic cables will be installed by an outside contractor. The Socorro Electronics Division will build and test all electronic and optical equipment using EVLA Project funds for personnel and equipment.

3.2.11 Correlator

The EVLA correlator will be funded and built by the Canadian Partner. The Hertzberg Institute of Astrophysics will design and construct the correlator using their Wideband Interferometric Digital Architecture (WIDAR) Correlator design. The correlator will process the data from 32 stations with a total bandwidth of 16 GHz per station in 2 GHz baseband slices. At the widest bandwidth the correlator will provide 16,384 spectral channels per baseline. A more complete description of this correlator is given in 3.4.

3.2.12 Image Pipeline

In order to produce images and spectra from observations as soon as they are taken, the correlated data will be passed though an image pipeline. The pipeline will calibrate and image the data using canned procedures. The procedures will contain heuristic methods driven by the goal-oriented descriptions of the observation supplied by the observer. These methods will make use of the status information about all EVLA components to provide a "reference image" from the data. For many observations, this will be sufficient for use by the observer, or at the very least will serve as a starting point for subsequent additional processing by the observer. The pipeline will be implemented using the extensive scripting and synthesis data reduction capabilities of the AIPS++ package. AIPS++ has been developed by an international consortium of observatories led by the NRAO. The most recent release of AIPS++ (version 1.4, released November 2000) contains a complete suite of applications for reduction of radio aperture synthesis data, including editing, calibration, imaging, image enhancement, and displays of image and all intermediate products. The development of pipeline processing is also being developed for other NRAO instruments, so these items will be developed under internal contract by the Data Management group.

3.2.13 Data Archive

The data archive is an integral part of the EVLA data pipeline. As a result of an observation, all of the original correlations with the ancillary data that describe the observations, the conditions during the observation, and the reference image produced by the pipeline will be archived. In the majority of cases, the reference image produced by the pipeline and stored in the archive will constitute a scientific result that does not require further data reduction. Example ancillary data to be archived with visibility data are: observational meta-data (source positions, bandwidths, etc.), proposal cover sheet, observing schedule, operator log, monitor data from all hardware, reference pointing data, derived calibration information, interferometer model accountability data, reference images, and pipeline scripts used to process the data to reference images. After an observation has been stored in the archive, it will be possible to retrieve the data to apply data post-processing tools to the data in the archive to produce additional scientific results. It will be possible to treat the data in the archive as if it were being provided by the telescope in real-time. All data that affect the production of scientific data products are to be archived along with the visibilities. An analysis of EVLA computing needs estimates that typically the average data rate from the EVLA will be from 50 to 100 terabyte per year. Although this is very large by today's standards, we expect that at the end of construction, the cost of such storage will be in the range $50K - $100K per year. It is likely that the data will be stored in a heterogeneous array of computers, rather than on a single, large computer. Approaches to and tools for large (multi-terabyte) distributed databases are currently being evaluated. There will be a system for data distribution to researchers via a portable medium. The archive will be searchable from any authorized location on the Internet. The design and implementation of the archive will be leveraged on other efforts presently in place (*e.g.*, HST, IPAC, Sloan) and in development (the National Virtual Observatory) in the wider astronomical community. If appropriate, the archive subsystem will be out-sourced to an organization that already serves large databases to the community. The archive, which will be located at the NRAO under its control, will enable EVLA results to be used (after the usual proprietary period) in the National Virtual Observatory initiative, thus enhancing the scientific impact of the array. This work is also being developed for other NRAO instruments, so these items will be developed under internal contract by the Data Management group.

3.2.14 Data Post-Processing

Post-processing software will be provided by the AIPS++ package. End-to-end processing of current VLA data is supported by the most recent releases. Some development of new capabilities is needed for radio frequency interference mitigation, but these are well-understood in principle and can be accommodated within the AIPS++ package. These items will be developed under internal contract by the Data Management group.

3.2.14.1 Data Post-Processing Hardware

We have made a detailed analysis of the scope and nature of data processing that will be needed by deployment of the full EVLA. This report is included in this document as Appendix 3. Just as for the VLA, there will be a spectrum of data processing needs. With reasonable predictions for the growth in the computer industry (*e.g.*, Moore's Law continuing to the end of the project), we expect to be able to process the data from the most demanding observations with the EVLA using a moderately parallel cluster within the costs budgeted in the original Proposal. Many of the more typical observations will be entirely processable using a desktop computer. The numerically intensive parts of AIPS++ are able to take advantage of parallel and distributed computing environments in order to support the data processing requirements of the EVLA. A collaboration between NCSA and NRAO has led to AIPS++ parallel codes for the most demanding parts of synthesis data reduction: spectral line imaging, wide-field imaging, and mosaicing.

3.2.15 Network Connectivity

Interaction with the EVLA will be possible from any remote location with adequate, secure Internet access. Remote access will be needed for proposal entry, observation preparation, observation tracking, data quality monitoring, archive query and retrieval. It will be necessary to upgrade the Local Area Network (LAN) at the VLA site and at the Array Operation Center (AOC) to support the predicted increased data flow from the EVLA. We will need to improve the access to the EVLA via higher performance Wide Area Network (WAN) services. We are partners with local universities in New Mexico in a recently funded effort to provide such services to Internet2 (Abilene). The Socorro Computing Division, using EVLA Project funds for personnel and equipment is responsible for the necessary improvements to network connectivity.

3.3 Contingency Plans for Computing Subsystems.

Figure 3 shows that the computing subsystems will play a major role in the EVLA Project. These subsystems will control all aspects of array operation -- both in the real-time data flow, and in all aspects of human interface with the array and its data products. It is thus important to develop contingency plans in the case that any of these subsystems cannot be completed during the project lifetime.

There is only one computing subsystem -- the Control and Monitor System -- which is both critical to the project, and for which there is no suitable existing backup. Thus, in the case that the development of this system is behind schedule, it will receive priority attention for extra resources from project management.

All other computing subsystems will be developed through an internal contract by the new NRAO Data Management Group. Because these computing subsystems are similar to those needed for NRAO's other major instruments, it is expected that this approach will result in a uniform interface between the user and these instruments, and will give significant savings in development costs.

In the case that development of any of these contracted subsystems falls behind schedule, or cannot be completed by the DM Group, project management will:

a) Review the requirements of each affected computing subsystem, and decide which are essential, and which can be deferred or delayed, and
b) Hire the necessary people to develop and deliver the essential portions of each subsystem, using EVLA resources which had been assigned to the DM contracts.

In any event, these subsystems are either not critical to the scientific capability of the EVLA, or have suitable fallbacks which can be employed, as explained below.

For the principal subsystems numbered 1, 2, and 3 in Figure 3, we would likely use an extension of the VLA's present systems of proposal preparation, observation preparation, and observation scheduling. These systems are simple and unsophisticated -- but they are successful and have been in place for nearly 20 years. Most probably they can be extended and improved significantly before deployment. We would also investigate the success of the systems currently being put into use for the GBT, with a view to adapting them for use on the EVLA.

The post-correlation products subsystems (boxes 12, 13, and 14 in Fig. 3) depend on user acceptance of the AIPS++ package. As this package has already demonstrated its capability in filling, editing, calibrating, and imaging VLA data, it is expected that it will be available for use. Nevertheless, if necessary, we will be able to extend existing systems. Specifically,

i) In Data Post-Processing, we could extend and employ existing packages -- e.g., AIPS or MIRIAD. The AIPS package can be modified to accept the EVLA's data products, but is unlikely to be able to handle the processing requirements of the largest proposed projects, or the full pipelined data flow (see Appendix 3). Thus, the major consequence would be an inability for users to process the more challenging data processing-intensive projects until a replacement is developed.
ii) The Data Archive Subsystem would be assigned to a new group based at the AOC, or outsourced to an organization that already serves large databases, as described in Section 3.2.13.
iii) The Image Pipeline depends on the scripting and data reduction capabilities available within AIPS++. Similar scripts could conceivably be written to perform the necessary real-time data reduction in existing analysis packages, although their capability to handle the more challenging data rates may be questionable. In any event, this subsystem is not critical to the project, and could be bypassed, with the data flowing directly from the correlator to the archive.

3.4 Justification of the WIDAR Correlator

The new correlator for the EVLA will be built by the correlator design group of the Herzberg Institute of Astrophysics in Penticton, B.C. This sub-project is contributed under the auspices of the North American Program in Radio Astronomy (NAPRA), which seeks to establish collaborative ventures for the development and construction of instrumentation for the EVLA and other joint radio astronomy programs.

The HIA group's novel design, called WIDAR, has many important performance advantages for the EVLA over traditional designs. Below we list the key advantages, compared to a correlator with the same total bandwidth based, for example, on the existing ALMA design. These advantages are of particular importance for centimeter-wave astronomy.

1. **More spectral channels at all bandwidths**
   The improvement factor over the ALMA design varies with total bandwidth, and is greatest at the maximum bandwidth of 8 GHz/polarization, with 16 times as many channels. This is extremely valuable for spectral line searches and wide-redshift surveys -- a major future use of the EVLA, and to minimize the effect of RFI. More spectral channels at maximum bandwidth also enables wide-field mapping without having to sacrifice sensitivity by "stopping down" the bandwidth.

2. **Sub-Hz spectral resolution**
   Bistatic radar experiments on planetary bodies require ~1 Hz resolution or better with full polarization, plus wideband continuum capability. The WIDAR design provides these capabilities. An ALMA-based correlator would require re-design.

- **Sub-banding Capability**
  The WIDAR design can independently target 128 frequency-selectable, variable-resolution sub-bands. This capability is not possible in an ALMA-like design, and is an enormous advantage for centimeter-wavelength astronomy, where RFI concerns make it likely that certain frequency ranges must be prevented from entering the correlator. It also confers the ability to simultaneously target multiple spectral lines while maintaining enough bandwidth for good continuum sensitivity.

3. **RFI-robustness**
   The WIDAR design has four special characteristics, making it uniquely robust against Radio Frequency Interference (RFI):

   i) Very high spectral dynamic range. Simulations demonstrate up to 55 dB spectral dynamic range, due to a combination of 4-bit digitization and suppression of harmonics and intermodulation products that tend to cause spectral "spreading" of RFI.

   ii) The sub-band's "tuning" capability permits RFI avoidance. If RFI does occur within a sub-band, its effects are limited to that single sub-band.

   iii) Time-variable RFI can render the entire band in an ALMA-like correlator uncalibratable. The WIDAR correlator confines these effects to the sub-band in which it occurs, and even that band's calibration can usually be recovered.

   iv) The very high number of spectral channels means that in most cases, the actual frequency resolution is very high. Even in RFI-crowded environments, most RFI is narrow-band in character. If RFI does occur, its effects are limited to the few channels surrounding the frequency of the RFI, leaving the rest for astronomy.

4. **Digital sub-sample delay capability**
   Most correlator systems require an analog method of correcting for sub-sample delay errors, and are forced to compensate the entire band at once. The WIDAR technique permits delay errors to be compensated for in each sub-band individually. This results in predictable and greatly reduced coherence losses at the band edges.

- **The use of FIR filters to define the sub-band shapes**
  These digital filters give precisely defined, extremely stable bandpasses. This will result in minimal 'closure' errors which cannot be corrected for by standard 'self-calibration' techniques.

- **The design is 'VLBI-ready'**
  The correlator can accept signals from distant stations either in real-time or from tape. Thus, the correlator will enable real-time or tape-based operations for any of its defined subarrays. Some sub-arrays can operate from tape while others are performing real-time correlation.

3.5 Contingency Plans for the EVLA Correlator

One of the questions asked for our contingency plans in case of late delivery or cancellation of the Canadian correlator. The WIDAR design has very attractive and desirable characteristics which make it a superior correlator over other correlator designs for the EVLA. However, Canadian funding for this correlator is not assured, and we must plan our reaction to a potential failure on their part to secure the necessary funding.

It is our conviction that the advantages of this correlator design for centimeter-wavelength astronomy are so significant that we would seek to construct a correlator ourselves, using the WIDAR design. This could be done by one of various routes:

a) Contracting the correlator group at the HIA to build the correlator, using our resources, or
b) Hiring the principal members of that group to build the correlator at the NRAO, or
c) Expanding our own correlator group to design and build the correlator using the WIDAR design. This option is much the least desirable.

All of these scenarios would require us to find additional funding to make up for the loss of Canadian funding. This might be done by looking for additional external partners or by seeking additional resources from NSF by requesting supplemental monies from the NSF. A more likely alternative would be to fund the correlator through savings accrued by 'descoping' technical goals for the EVLA Project. Such descope options could include:

a) Elimination of one or more frequency bands.
b) Reduction in the total available bandwidth.
c) Reduction in computing and operational capabilities.
d) Reduction of the capability of the correlator.

Note that all of these will result in a significant reduction in the scientific productivity of the EVLA.

Another option would be to adopt the ALMA correlator design. This is not a 'free' option -- the ALMA design does not provide the ~1 Hz resolution necessary for planetary radar experiments, is not immediately compatible with VLBI, has considerably lower spectral dynamic range, provides only 1/16 the number of channels at full bandwidth, and must further be modified to enable pulsar observing. Design modification will be necessary to fit that correlator design to the needs of centimeter-wavelength observing. We do not wish to adopt this fall-back solution, and would only do so if it were necessary to abandon any hope of implementing a WIDAR-design correlator.

3.6 Radio Frequency Interference

Radio frequency interference causes problems for all radio astronomy telescopes, especially at frequencies below ~3GHz. This is expected to worsen over time as the radio spectrum usage increases. The protected bands constitute a unique "wilderness" area for radio astronomy that needs vigilance to protect its status. Outside of the protected bands, radio astronomy is possible at various frequencies depending on the exact level and nature of use by other services. Since radio astronomy is entirely passive, this use is allowed and leads to significant science, such as the detection of red-shifted lines. Indeed-full-band usage is necessary to achieve the sensitivity goals of the project.

Both inside and outside the protected bands, RFI may be present and will need mitigation. Radio astronomers have a number of countermeasures that can and must be deployed. Following the signal path, these are:

- Filters in the antenna front-ends can protect against very strong specific fixed interference. In addition the receivers must have sufficient linearity and bandwidth to ensure that saturation of the amplified signal is unlikely.
- The incoming signal must be digitized with sufficient accuracy (3 or 4 bits over a maximum bandwidth) to minimize significant cross-modulation of strong interfering signals into the spectrum of interest.
- The correlator must offer protection against cross-modulation. As noted above, the WIDAR correlator design is particularly effective in dealing with RFI.
- Post-correlation adaptive cancellation techniques pioneered at the ATNF use the consistency of interference between different antennas to identify and remove strong interfering signals. This requires high sampling in both time and frequency so the data must be averaged down after this type of processing, prior to calibration and imaging. We would expect that a specially dedicated parallel machine placed between the correlator and the image pipeline would perform this task.
- Finally, any residual RFI can be detected and removed during the calibration and imaging process. Most of these techniques exploit consistency in Fourier space, time or frequency to identify RFI.

We expect to employ all of these countermeasures in one form or another in the EVLA. The main area needing development is that of post-correlation adaptive cancellation, where research by a number of groups around the world is proceeding. Since this is a research area and the need for such cancellation is evolving, we have not specifically included funding within the EVLA budget. We will monitor progress in the area, and develop a proposal at a later time. What is important at this time is to ensure we do not design out capabilities which may prove useful later.

Appendix 1

Requests for Information from the NSF

We list below the ten requests which were received from the National Science Foundation, plus the location in this document where the responses will be found.

Request #1:

I would like the rationale for your cost. That is -- what was your cost backup? I am sure they were not guesses, but rather well thought out. Determined by asking engineers how many work hours are involved in each task and estimate of materials, salaries, etc. Prices obtained from industry, etc.

The response is given in Section 1.5 -- Budget Methodology.

Request #2:

Explicit statement of the high-level scientific goals for the EVLA project, including required sensitivity, spectral coverage, bandpass, flux, phase, polarization accuracy, and frequency resolution.

A discussion of the high-level scientific goals is given in Section 2 -- Scientific Issues. The specific technical goals, including an explanation of how each was set, are discussed in Section 3.1 -- Technical Goals of the EVLA Project.

Request #3:

Description of the functional technical performance requirements, beginning at the feeds and ending at calibrated science images, and deliverables of the EVLA project as derived from the scientific goals. These two elements are the summary of a 'system requirements review' for EVLA. Writing this information down defines the project deliverables of the EVLA project.

This is shown in Section 3.2 -- EVLA Subsystem Definition.

Request #4:

Explanation of the tasks that "flow down" from the functional technical requirements for the array control (hardware and software) and data processing software and the expected schedule of those tasks and milestone completions in a PERT-style format.

This is included in Section 3.2, where an extra level of detail has been provided in the computing descriptions and Section 1.4, showing the schedule for the principal milestones.

Request #5:

Identification of the key managers for the hardware and software for the top-level EVLA Project and the major sub-projects.

This is provided in Section 1.1 -- Organizational Responsibilities. The requested CVs for the top managers are contained in Appendix 2.

Request #6:

A management plan that assures the coherence of the entire EVLA project and defines the interfaces between the hardware and software sub-projects.

This is provided in Section 1.1 -- Organizational Responsibilities.

Request #7:

Description of the plans for independent community oversight for the EVLA project.

This is shown in Section 1.2 -- Project Oversight and Advice.

Request #8

A plan for conducting project and sub-project PDRs and CDRs by competent, objective judges.

This is given Section 1.2 Project Oversight and Advice and in the Milestones in Section 1.4.

Request # 9

A plan for early procurement of low-risk, long-lead hardware and the early start of routine tasks, especially if these procurements and tasks lie on the schedule critical path.

The plan is described in Section 1.6 -- Procurement Plan.

Request #10

Contingency plans which specifically explain how the impact of late delivery or cancellation of the Canadian correlator would be accommodated.

This is addressed in Section 3.5 -- Contingency Plans for the EVLA Correlator.

Appendix 2

CVs of Key Personnel:

These resumes are provided for information purposes only.

TIMOTHY JAMES CORNWELL
NRAO
PO Box 0
Socorro, NM 87801
Ph 505 835 7333, tcornwel@nrao.edu

Positions Held:

November 1979 – October 1981 Science Research Council Research Fellow
Jodrell Bank, United Kingdom

October 1980: NRAO Post-doctoral Fellowship
June 1983: NRAO Assistant Scientist,
June 1985: September 1988: NRAO Associate Scientist
September 1988: Granted tenure as NRAO Scientist
December 1992 - March 1995: Deputy Assistant Director (NRAO) for Computing and Operations in Socorro.
April 1995 – May 2000: NRAO Assistant Director for AIPS++,
April 1995 – Present: Project Manager for the AIPS++ Project
May 2000 – Present: NRAO Associate Director for Data Management

Education:

Bachelor of Physics, Victoria University of Manchester, United Kingdom, 1976
Ph.D. (Physics), Victoria University of Manchester, United Kingdom, 1980

Membership:

URSI Commission J

Professional Activities:

Scientific organizing committee of NOAO/ESO workshops on "High Resolution Imaging from the Ground", Tucson, Jan. 1987, and "Diffraction Limited Imaging with Very Large Telescopes", Garching, March 1988.
Chairman of Scientific Organizing Committee for IAU Colloquium 131 on “Radio Interferometry - Theory, Techniques and Applications”, Socorro, October 8-12, 1990.
Member of NASA Image Processing Working Group formed to advise NASA on potential of image processing for HST, July - December 1990.
Member of NASA Space Interferometry Science and Engineering Group, April 1991
Member of Scientific Organizing Committee of OSA Topical Meeting on “Signal Synthesis and Recovery”, New Orleans, 1992.
Program Organizing Committee of Astronomical Data Analysis Software and Systems, 1996 – 1998.
Member of NASA Space Interferometry Mission Science Working Group, August 1996
Member of National Virtual Observatory Proposal Team, 2000

Referee for: NSF, M.N.R.A.S., Astron. & Astrophys., Astronomical Journal, Astrophysical Journal, IEEE Trans. Antennas and Propagation, Journal of the Optical Society of America, Experimental Astronomy, Calspace, and others.

Significant publications:

Cornwell, T.J., and Napier, P.J., "The Focal Plane Coherence Function of an Imaging Antenna and Its Use in Measuring and Correcting Aberrations," Radio Science 23, 739-748, 1988

Cornwell, T.J., "The Applications of Closure Phase to Astronomical Imaging," Science, 245, 263-276, 1989.

Cornwell, T.J., and Perley, R.A., "Radio-Interferometric Imaging of Very Large Fields: The Problem of Non-Coplanar Arrays", Astron. & Astrophys. 261, 353, 1992

Cornwell, T.J., Holdaway, M.A., and Uson, J.M.,"Radio-Interferometric Imaging of Very Large Objects: Implications for array design", Astron. & Astrophys. 271, 697-713, 1993

R. Narayan, and Cornwell, T.J., "Imaging with Ultra-resolution in the Presence of Strong Scattering", Astrophys. J., 408, L69-L72, 1993

Students supervised

Daniel Briggs, Ph.D. thesis, New Mexico Tech, "*High Fidelity deconvolution of moderately resolved sources*", April 1995.

Thesis Advisors

Dr. P.N. Wilkinson	NRAL, Jodrell Bank, UK
Dr. R.E. Spencer	NRAL, Jodrell Bank, UK

Feb. 2001

P. E. Dewdney

BASc (1968), University of British Columbia, Engineering Physics
PhD (1978), University of British Columbia, Electrical Engineering

Appointments

Adjunct Professor in the Department of Physics and Astronomy, University of Calgary, Canada

Principal Research Officer at the National Research Council of Canada (NRC), Herzberg Institute of Astrophysics, Dominion Radio Astrophysical Observatory (DRAO), Penticton, B.C., Canada

Research Expertise

Instrumentation: Interferometry, signal processing, radio techniques, electronics, software for astronomical data reduction, calibration of instruments, and design of telescopes.
Astronomy: HII regions, ionization and dissociation processes, observational and modelling studies of the interstellar medium, phase transitions in the interstellar medium, supernova remnants.

Current Projects

A. Instrumentation for radio astronomy

Leads a NRC/university/industry group developing a novel telescope for radio astronomy, the Large Adaptive Reflector.
Directs the development and construction of the ACSIS autocorrelation spectrometer for the James Clerk Maxwell Telescope (JCMT), mm/sub-mm wave radio telescope.
Principal Investigator for Canada in the Space Very Long Baseline Interferometry (SVLBI) program, VSOP, a worldwide collaboration of observatories with the Japanese space agency, ISAS, the Canadian Space Agency (CSA), and NASA.
Directs development work for the future correlator for the Expanded Very Large Array (EVLA).

B. International Activities

Member of an International Science Steering Council (ISSC) for the Square Kilometer Array.

NRC Coordinator for future radio astronomy activities for Canada.

Astronomical Studies (directed at Interstellar Medium studies) effects of very massive stars on their surroundings, various aspects of the behaviour of hydrogen gas as part of the Interstellar Medium, studies of the Faraday Rotation effect, a means of studying magnetic fields, management team for Canadian Galactic Plane Survey (CGPS).

Professional Societies, Councils, and Committees

Member: Scientific Organizing Committee of Division X (radio astronomy) of the International Astronomical Union, 1997 to present --- VSOP International Science Council (governing scientific council for the VSOP Space VLBI Program): 1994 to present --- RadioAstron International Science Council (RadioAstron Space VLBI Program): 1994 to present --- Galactic Plane Survey Management Committee: 1994 to present --- Joint Sub-Committee for Space Astronomy: 1998 – present --- Scientific Organizing Committee for the conference "Radio Astronomy: Visions for the 21st Century", Penticton, B.C., Aug. 1994. --- Steering Committee for the Institute of Space and Terrestrial Sciences. Space Geodynamics Laboratory,

York University, October 1987 - present.
Principal Investigator: Canadian Participation in VSOP VLBI Projects: 1987 - present.
Chairman: RadioAstron International Science Council (RISC): 1992 - 1994.
Member: U.S. National Radio Astronomy Observatory Users Committee: 1990 – 1992
Professional Societies: The Canadian Astronomical Society, the American Astronomical Society, and the International Astronomical Union (IAU).

Training of Highly Qualified Personnel

Co-supervision of both astronomy and electrical engineering students over many years, currently on the PhD committee for an astronomy student at the University of Calgary. Over the years six Master's and PhD level students (formally co-supervised, and a number of others informally).

In the Large Adaptive Reflector (LAR) project, it is part of the job to create opportunities for graduate students. Although not supervising them, the projects are structured to make it possible for students to participate.

Publications

Total number of refereed publications:	52
Number of refereed publications in the last five years:	26

Selected Refereed Journal Publications:

A Low Power 250 MHz 4-bit Correlator Chip for Radio Astronomy. Kwan, B. S. H., Lam, K . W. K., Margala, M., Dewdney, P. E., Carlson, B. R. IEEE Transactions on VLSI Circuits and Systems, in preparation.

Feed-Reflector Design for the Large Adaptive Reflector Antenna. Mousavi, L. Shafai, P. Dewdney, and B. Veidt, IEEE Transactions on Antennas Propagation, Accepted for publication.

The Synthesis Telescope at the Dominion Radio Astrophysical Observatory. T.L. Landecker, P.E. Dewdney, T.A. Burgess, A.D. Gray, L.A. Higgs, A.P. Hoffmann, G.J. Hovey, D.R. Karpa, J.D. Lacey, N. Prowse, C.R. Purton, R.S. Roger, A.G. Willis, W. Wyslousil, D. Routledge, and J.F. Vaneldik

Astronomy and Astrophysics Supplements, **145**, 509-524, 2000

A New View of Cold HI Clouds in the Milky Way. S. J. Gibson, A. R. Taylor, L. A. Higgs, and P. E. Dewdney, Astrophysical Journal, **540**, 851-862, 2000

Efficient Wideband Digital Correlation. B. Carlson and P. Dewdney, Electronics Letters, IEE, **36**, No. 11, p.987, 2000.

First Results of VSOP Imaging of Strong GPS Sources, Lovell, J. E. J., King, E. A., Jauncey, D. L., Tzioumis, A. K., Reynolds, J. E., McCulloch, P. M., Costa, M. E., Preston, R. A., Tingay, S. J., Murphy, D. W., Meier, D. L., Nicolson, G. D., Dewdney, P. E., Cannon, W. H.Advances in Space Research, **26**, Issue 4, pp. 715-718, Springer-Verlag, 2000.

The Canadian S2 VLBI Correlator: A Correlator for Space VLBI and Geodetic Signal Processing, B. Carlson, P. Dewdney, T. Burgess, R. Casorso, W. T. Petrachenko, and W.H. Cannon Publications Astronomical Society of the Pacific, **111**, 1025-1047, 1999.

Radio Polarimetric Imaging of the Interstellar Medium: Magnetic Field and Diffuse Ionized Gas Structure near the W3/W4/W5/HB3 Complex. A.D. Gray, T.L. Landecker, P.E. Dewdney, A.R. Taylor, A.G. Willis, and M. Normandeau Astrophysical Journal, 514, 221-231, 1999.

Free-free Absorption in the Seyfert Nucleus of NGC4151. A. Pedlar, B. Fernandez, N.G. Hamilton, M.P. Redman, and P.E. Dewdney Monthly Notices of the Royal Astronomical Society, **300**, 1071-1076, 1998.

A Large-scale, Interstellar, Faraday Rotation Feature of Unknown Origin Seen Towards the W5 HII Region..

A.D. Gray, T.L. Landecker, P.E. Dewdney, and A.R. Taylor Nature, **363**, 660-662, 1998.

The S2 VLBI System. W.H. Cannon, D. Baer, G. Feil, B. Feir, P. Newby, A. Novikov, P. Dewdney, B. Carlson,W.T. Petrachenko, J. Popelar, P. Mathieu, and R.D. Wietfeldt Vistas in Astronomy, **41**, No. 2, 297-302, 1997.

The Dominion Radio Astrophysical Observatory Galactic Plane Survey Pilot Project: the W3/4/5/HB3 Region. M. Normandeau. A.R. Taylor, and P.E. Dewdney Astrophysical Journal Supplement, **108**, 279-299, 1997.

Aperture Synthesis Polarimetry: Application to the DRAO Synthesis Telescope. R.J. Smegal, T.L. Landecker, J.F. Vaneldik, D. Routledge, and P.E. Dewdney Radio Science, **32**, No. 2, 643-656, 1997.

A Galactic Chimney in the Perseus Arm. M. Normandeau, A.R. Taylor, and P.E. Dewdney Nature, **380**, 687-689, 1996.

Selected Non-Refereed Publications

The EVLA Correlator - Signal Processing for Ultra-Sensitive Astronomy. Dewdney, P. E. & Carlson, B. R., Bulletin of the American Astronomical Soc. Meeting 196, May, 2000.

The Large Adaptive Reflector: A 200-m diameter, wideband, cm-m wave radio telescope, Carlson, B.R., Bauwens, L., Belostotski, L. , Cannon, E. , Chang, Y.-Y. , Xiaohui Deng, X. , Dewdney, P. E., Fitzsimmons, J. T., Halliday, D., Kürschner, K., Gerard Lachapelle, G., Lo, D., Mousavi, P., Nahon, M., Shafai, L., Stiemer, S. F., Taylor, A. R., Veidt, B.G. Proceedings of SPIE Meeting. **4015**, *ed.* H. R. Butcher, Munich, March, 2000.

Steady-state analysis of the multi-tethered aerostat platform for the Large Adaptive Reflector telescope. Fitzsimmons, J.T., Veidt, B.G., Dewdney, P.E. Proceedings of SPIE Meeting, **4015**, *ed.* H. R. Butcher, Munich, March, 2000. (in press)

A New Spectral Line, Multi-beam Correlator System for the James Clerk Maxwell Telescope Hovey. G. J., Burgess, T.A., Casorso, R.V., Dent, W.R.F., Dewdney, P.E., Force, B. , Lightfoot, J.F., Willis, A.G., and Yeung, K. K. Proceedings of SPIE Meeting. **4015**, *ed.* H. R. Butcher, Munich, March, 2000.

The Square Kilometer Array Dewdney, P. Future Large Scale Facilities in Astronomy, 23rd meeting of the IAU, J. D. 9, 23 August 1997, Kyoto, Japan.

James Marshall Jackson

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Socorro, NM 87801
(505) 835-0158
jjackson@sdc.org

Professional Experience

National Radio Astronomy Observatory
Socorro, NM
Project Engineer:

Experience includes:

High Speed Fiber Optic Systems, High Speed Digital Electronics (125MHz-10GHz), Xilinx Field Programmable Gate Arrays (FPGA's), Xilinx Foundation Software, Printed Circuit Layout using OrCad and Protel, Surface Mount Technology, RF electronics, Frequency synthesizers, RFI measurement and suppression, Microchip PIC series Microcontrollers, Controller Area Network (CAN) industrial control bus, LabView 5.1, Have extensive experience with Electronic test and measurement equipment.

Specific duties:
-Design of 10 Gigabit per second digital fiber optic link for Atacama Large Millimeter Array (ALMA) and Enhanced Very Large Array (EVLA) projects.
-Team Leader / Lead Project Engineer on Enhanced VLA project
-Design and layout of several printed circuit boards for lab development use.
-Participation in numerous Engineering Design Meetings for ALMA project

US Department of Defense Menwith Hill Station June 1995 to Jan, 1999
Harrogate, England
Antenna/RF Systems Engineer:

Experience includes:

Feed systems, RF electronics, Frequency translators, RF distribution, Downconverters, Receivers, Servo systems, Tracking controllers, RFI measurement and suppression, Industrial control systems, Radome systems, Timing/Reference Systems, and Environmental sensors. Have extensive experience with RF test and measurement equipment.

Specific duties:
-Design, Installation of new 3-10 meter microwave antenna/radome systems operating from 1-26 GHz
-Upgrade, Rehab and Enhancement of fifteen 2-18 meter microwave antennas/radome systems operating from 1-14 GHz
-Design of a network controlled multi-channel microwave downconverter
-Design of a computer based weather-monitoring system
-Upgrade, Rehab and Enhancement of numerous HF/VHF/UHF antennas
-Site engineer responsible for RFI/EMI issues including coordination with UK government officials

-Task, oversee and evaluate seven-member site contractor antenna crew

National Security Agency Information Security Directorate January 1993 to June 1995
Fort George G. Meade, Maryland

Communications Systems Engineer

Specific Duties:
-Member of NSA team working with the US Navy on the design and testing of a completely new Command Control and Communications architecture for the Navy
-Led a 4 person design team responsible for the construction of a prototype highly versatile cryptographic device for Naval communications
-Participated in Naval exercises testing the feasibility of using wideband SHF communication for ship-ship and ship-shore communications

National Security Agency November 1986 to January 1993
Information Security Directorate
Fort George G. Meade, Maryland

Design Engineer:

Experience includes:
High speed integrated circuit design, Printed circuit board, Computer Aided Design, Digital simulation (Mentor Graphics, ZyCad), Analog Simulation (SPICE, Mentor Graphics), PLD's/FPGA's (Altera, Xilinx), Assembly Language Programming

Specific Duties:
-Developed demonstration model of new cryptographic system for Air Force F22 Advanced Tactical Fighter
-Demonstrated system to Senior Air Force and Contractor Personnel
-Designed and Simulated a High Speed Custom Microprocessor and support IC's
-Prepared designs for transfer to contractors for production
-Designed and built an In-Circuit Emulator/Development system for several in-house microprocessors.

University of Maryland College Park September 1985 to December 1985
Astronomy Department
College Park, Maryland
Technician in Radio Astronomy Lab

Specific Duties:

-Rebuilding and testing of a small VHF Radio Interferometer system
-Maintenance and Repair of Laboratory Equipment

Education

Johns Hopkins University/APL 1989 to 1991

Clarksville, Maryland]
MSEE / Graduated with Honors GPA 4.0/4.0

University of Maryland] 1982 to 1985
College Park, Maryland
BSEE

Florida Institute of Technology 1981 to 1982
Melbourne, Florida

Volunteer Work

[Etscorn Observatory, New Mexico Tech] Mar 1999-Present
[Socorro, NM]
Engineer/Technician

Currently developing a LabView based weather station and control system to allow the use of observatory facilities over the Internet. This has involved design and installation of weather/environmental monitoring equipment and interfacing of the observatory's computers to roof and power control systems. Experience includes: LabView software development, data acquisition cards, PIC microcontrollers, PC board layout, lightning protection, wiring and installation, and Repair of lightning damaged equipment.

Clinton C. Janes

Education:

BSEE, New Mexico State University, Las Cruces, NM, 1966.
Courses at University of Minnesota, University of Arizona, New Mexico Institute of Mining and Technology. Basic and Advanced Management Certificates from University of New Mexico Anderson School, 1996 - 1997.

Experience:

1996 to Present Divison Head at the National Radio Astronomy Observatory (NRAO), Socorro, NM. Lead and manage engineering and technical service support to the Very Large Array (VLA) and Very Long Baseline Array (VLBA) radio astronomy observatories. Since 1999, assigned to manage a receiver build for 22 GHz, 46 GHz, and 86 GHz frequency bands, to plan revisions to all electronics from front end to correlator for an "expanded" VLA, to assist with LO/IF/FO design and development for a two-element millimeter wave interferometer, to measure panel accuracy of the VLBA antennas using microwave holography, and to supervise electronics maintenance for the VLA and VLBA.

1994 to 1996 Group Leader, NRAO, Socorro, NM. Served as electromagnetic compatibility engineer and frequency coordinator for the VLA and VLBA radio astronomy observatories, and leader of the Interference Protection Group. Primarily concerned with the identification and mitigation of radio frequency interference to astronomical observations.

1989 to 1994 Staff Engineer, NRAO, Socorro, NM. Designed instrumentation and performed measurements used to diagnose problems with pointing accuracy of the Very Large Array (VLA) radio telescopes. Also assigned to resolve technical problems during the deployment of instrumentation tape recorders, tape formatters, and 1" wide 16 micron thick magnetic recording tape at the VLA and VLBA radio observatories.

1983 to 1989 Assistant Director for Engineering at the Multiple Mirror Telescope Observatory (MMTO), Tucson, AZ. Brought the telescope and instrumentation from the 80% operational stage to full completion, including routine automatic guiding and phased array use of the six primary mirrors.

1978 to 1983 Design Engineer at Kitt Peak National Observatory (KPNO), Tucson, AZ. Designed computer-controlled systems such as a centralized clock to phase lock time and sidereal tracking at eleven optical telescopes to WWVB, and a "seeing" camera to measure image quality at the 4 Meter Mayall Telescope.

1976 to 1978 Site Engineer at the Cerro Tololo Interamerican Observatory (CTIO), La Serena, Chile. Organized and supervised a group of mechanics, technicians, and engineers to provide operational and maintenance support to a complex of seven optical telescopes. Primary assignment was to uncover and correct reliability problems with the mini-computer systems and observing instruments.

1971 to 1976 Site Engineer at McDonald Observatory, Fort Davis, TX. Designed interfaces and software for DGC Nova minicomputer systems for telescope and instrument control and for data acquisition. With two technicians, provided electronic maintenance support to complex of four optical telescopes.

1969 to 1971 Associate Engineer with Autocon, a subsidiary of Control Data Corporation, St. Paul, MN. Designed motor control supervisory systems for water treatment plants.

1966 to 1969 Active duty in the U. S. Army. Served as a company commander in the 7th Infantry Division during one assignment.

Other Taught electronics courses at Pima Community College, Tucson, AZ; and at New Mexico Tech, Socorro, NM. Prior to graduation from NMSU, planned microwave links for the Mountain Bell Telephone Company, performed engineering economics study for the Humble Oil and Refining

Company, and operated satellite tracking stations for the Physical Science Laboratory of New Mexico State University. Senior Member IEEE. Hold Amateur Radio License, General class.

Awards IEEE Bicentennial Award. NMSU Centennial award.

John Paul Lagoyda

1989 to present:	Business Manager, Socorro Operations
1988 to 1989:	Assoc. Business Mgr., Socorro Operations
1979 to 1988:	Business Officer, Charlottesville, VA,
1977 to 1979:	Admin. Asst., VLA Project, Socorro, NM
1975 to 1977:	Admin. Aide., VLA Project, Socorro, NM
1974 to 1975:	Asst. to Proc. Mgr., VLA Project, Chville, VA
Education:	B.S. McIntire School of Commerce, University of Virginia, '75

Professional Activity: Actively involved in the business aspects of the construction and operation of the Very Large Array & Very Long Baseline Array programs

Peter John Napier - Curriculum Vitae
NRAO
PO Box 0
Socorro, NM 87801
Ph 505 835 7218, pnapier@nrao.edu

Positions Held (since 1980):

Feb, 2000 - Present: ALMA-US Project, Antenna Division Head.

June, 1998 - Feb, 2000: NRAO Project Manager for the Millimeter Array (MMA) Project.

June 1995 -Oct 1995: Acting NRAO Assistant Director, VLA/VLBA Operations.

July 1993 to present: Scientist, NRAO Scientific Staff. Working on instrumental improvements for the VLBA and VLA, design and planning for the MMA.

January 1987 - June 1993: Assistant Director, NRAO; VLBA Project Manager.

1986 Tenure granted by Associated Universities Inc.

July 1985 - Dec. 1986: VLBA Deputy Project Manager

Dec. 1980 - June 1985: VLA Deputy Site Manager in charge of Engineering.Responsible for overseeing the activities of the Technical Divisions (Electronics and Engineering/Services) in the operation, maintenance and further development of VLA antenna and electronics systems. NRAO Project Manager for the NRAO/JPL VLA Voyager Project. Also responsible for VLBA project activities in New Mexico. Also personally designing the RF optics and multi-frequency feed system for the VLBA antenna.

Education:

Bachelor of Electrical Engineering (1st Class Honors)
University of Canterbury, New Zealand, 1968

Ph.D. (Electrical Engineering), University of Canterbury,
New Zealand, 1972.

Membership:

URSI Commission J

Professional Activities:

URSI, US Commission J, Chairman, Jan 2000 to Present
Chairman, Allen Telescope Array (ATA) Technical Advisory Panel, July 2000 to Present.
Chairman, ATA Antenna Optics Preliminary Design Review, April 2000.
Advisory Committee for the Australia Telescope Upgrade Project, CSIRO Australia, August 1997 to present.
Chairman, Joint LSA-MMA antenna study group, August 1997 to Dec 1997.
URSI, US Commission J, Vice Chairman, Jan. 1996 to Jan 2000.
American Geophysical Union, Associate Editor for Radio Science, June 1995 to Jan 2000.
Gemini Project Oversight Committee, AURA, Tuscon Az., Aug. 1993 to Feb 2000.

Review Committee, BIMA Millimeter Array, Berkeley U. and Hat Creek, Ca., 1991.
Arecibo Scientific Advisory Committee, Arecibo, Puerto Rico, 1990 - 1992 (Chairman, 1992).
Scientific and Technical Advisory Group, Smithsonian Astrophysical Observatory Submillimeter Array Project, Boston, 1989 to present.
Review papers for Proceedings IEEE, IEEE Transactions on Antennas and Propagation, Radio Science, ApJ.

Selected Publications:

Weinreb, S., Balister, M., Maas, S., Napier, P. J. "Multi-band Low-Noise Receivers for a Very Large Array," IEEE MTT-25, 243,1977.

Gustincec, J. J., Napier, P. J. "A Hybrid Lens Feed for the VLA," IEEE A/P Symposium Digest, pp. 361-363, 1977.

Napier, P. J., Thompson, A. R., Ekers, R. D. "The Very Large Array: Design and Performance of a Modern Synthesis Radio Telescope," Proc. IEEE, 71, 1295, 1983. (Invited paper.)

Napier, P.J., Bagri, D., Clark, B., Romney, J., Thompson, A., Walker, R., "The Very Long Baseline Array", Proc. IEEE, vol 82, pp 658-672, 1994.

Napier, P.J., "The Primary Antenna Elements", in Synthesis Imaging in Radio Astronomy II, ASP Conf Series, vol 180, G.B Taylor, C.L. Carilli and R.A. Perley editors, pp 37-56, 1999.

Rick Perley
NRAO
PO Box 0
Socorro, NM 87801
Ph 505 835 7312, rperley@nrao.edu

Education

B.Sc.	University of British Columbia 1968
M.Sc.	University of British Columbia 1970
Ph.D.	University of Maryland 1977

Positions Held

Research Associate, NRAO Oct 1977 -- June 1980
Systems Scientist, NRAO July 1980 -- June 1988
Deputy Asst. Director, Socorro Operations July 1989 -- November 1992
Scientist, Continuing Appointment, NRAO July 1988 – July 1997
Scientist, Tenure, NRAO 1997 - present.
EVLA Project Scientist Sept 1995 -- Present.

Professional Activities

Member, AAS
Member, URSI
Member, IAU

Relevent Publications

The Very Large Array Expansion Project, May 2000.

Luis F. Rodríguez

Personal Data:
Place and Date of Birth: Merida, Yucatan, Mexico, 1948 May 29
Office: Instituto de Astronomia
Campus UNAM, Morelia, Mich., 58190 Mexico
Phone: 52-43-222742; Fax: 52-43-222726
e-mail: luisfr@astrosmo.unam.mx

Present Position:
Full Professor (Instituto de Astronomia, UNAM), since 1979
Head of the Morelia Branch of IAUNAM, since 1995

Academic Degrees:
1973 B. S. (Physics) Universidad Nacional Autonoma de Mexico
1978 Ph.D. (Astronomy) Harvard University

Main Areas of Research:
Star Formation, Galactic Superluminals

Selected Awards and Recognitions:
1980 Robert J. Trumpler Award from the Astronomical Society of the Pacific
1984 Henri Chretien Prize from the American Astronomical Society
1985 National Award in Exact Sciences from the Mexican Academy of Sciences
1986 Manuel Noriega Morales Award from the Organization of American States
1988 Guggenheim Fellowship from the Guggenheim Foundation
1993 National Prize of Science
1996 Bruno Rossi Prize from the American Astronomical Society
1997 Physics Award of the Third World Academy of Sciences
2000 Member of El Colegio Nacional

Recent Relevant Publications:

1. A Cluster of Radio Sources near GGD 14," Gomez, Y., Rodríguez, L. F., & Garay, G. 2000, The Astrophysical Journal, 531, 861-867
2. The Nature of the Radio Continuum Sources Embedded in the HH 7-11 Region and Its Surroundings," Rodríguez, L. F.,
   Anglada, G., & Curiel, S. 1999, The Astrophysical Journal Supplement Series, 125, 427-438
3. Sources of Relativistic Jets in the Galaxy," Mirabel, I. F., & Rodríguez, L. F. 1999, Annual Reviews of Astronomy and Astrophysics, 37, 409-443

Lewis Serna
PO Box 1654
Socorro, New Mexico 87801

Education

1975 - 1978 New Mexico Tech Socorro, New Mexico
Petroleum Engineering
Attended New Mexico Tech full time and part time to achieve Engineering Degree. General Studies completed, degree not achieved.

1969 - 1975 United States Navy
Electronic Technician

- 2 years of Advanced Electronic Technical Schools in LF, HF, VHF, UHF, and Crypto communications. Including Loran and Omega navigation systems. Honorable Discharge, Vietnam Veteran.

Numerous training certificates in:
Management Programs, Advanced Power Quality, High Voltage training, HVAC training, Programmable controllers, Occupational & environmental Safety Engineering and Management, Project Management.

Professional experience

1999 - Present National Radio Astronomy Observatory. Socorro, New Mexico
Engineering Services Division Head VLA/VLBA
SUMMARY:

As ES Division Head I am the senior NRAO employee in the ES Division and at the VLA Site. Responsible to the Assistant Director and Deputy Assistant Director for planning, organizing, directing and controlling all activities of the ES Division. In addition I have broad overview responsibilities for the VLA as Site Manager.

DUTIES AND RESPONSIBILITIES:

Responsible for building and road maintenance, HVAC and weed control at the VLA and most VLBA sites. Responsible for water supply, sewerage and waste disposal, vector control, key control, general use equipment, security, fire protection, emergency medical services, safety, hazardous materials program, secretarial support, library, mail delivery, meeting all regulatory requirements, transportation, vehicles, electrical supply and maintenance, coverall repair and washing, housekeeping and custodial support at the VLA site. Responsible for all mechanical, servo, ACU, encoder, drives, and generator maintenance at the VLA and VLBA sites. Responsible for cathodic protection, waveguide manhole, track, transporter and Visitors' Center maintenance at the VLA. Responsible for physical plant maintenance at the Tech Guest House and the AOC as required. Responsible for managing the design, construction, modification and documentation of the parts of the instruments maintained by the ES Division and of all support structures. Operate a machine shop to support NRAO elements and a drafting department to support the VLA and VLBA mechanical design effort. Oversee the ES Division budget, expenditures, Personnel Evaluation Process (PEP), training program, scheduling, inventory, policies and procedures. Recommend salary review for the ES Division. Promote good relations with neighboring land users, with other divisions and with the technical support efforts of other observatories. Represents the division at official functions. Provide technical guidance in a wide variety of areas such as antenna mechanics, painting, electrical and electronic equipment, HVAC, computer hardware and software, automotive mechanics, railroad maintenance, machine shop, drafting, plumbing, carpentry, facilities maintenance and engineering.

1996 - 1999

Deputy Division Head

As Deputy Division Head I assisted the Division Head in planning, organizing, directing and controlling all activities of the ES Division. Acted as Division Head in his absence. Supervised the Electrical, Site & Wye, and Antenna Mechanical Groups.

1976 - 1996

Throughout my career with NRAO I have been a front line supervisor to all maintenance and fabrication shops in the Engineering Services Division at the VLA at one time or another.

- Major accomplishments as Electrical Group Supervisor, in charge of Electricians, HVAC, and Servo personnel included the replacement of all faulty underground high voltage cable, design and supervise the installation of the VLBA SC Site emergency power system, automated VLA Standby Generator controls for remote and automatic operation. Completion of VLA antenna Electrical and HVAC system upgrades. Converted VLA antenna transporter controls programmable logic controls.
- As VLA Servo System Engineer and supervisor, during VLBA construction my responsibilities were to test and coordinate VLBA contractor servo system installations at all VLBA sites. Additionally, I was responsible for the NRAO electrical and servo outfitting of all VLBA Antennas.
- As Machine shop, Drafting and Antenna Mechanic supervisor numerous maintenance, support and retrofitting tasks were accomplished such as Antenna bearing changes, Array reconfigurations, antenna, feed and receiver parts fabrication and assembly.
- Began working for NRAO as an outfitter on the VLA Telescopes in 1976.

VITA—James S. Ulvestad

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Citizenship: USA

NRAO Positions:	2001-	NRAO Deputy Assistant Director for Scientific Services, Operations, & Computing (Socorro)
	2000-	AIPS Group Leader
	1999-	Division Head, Scientific Services (Socorro)
	1999-	Scientist
	1998-2000	Project Scientist/Manager, VLA-Pie Town Link Project
	1996-1998	Associate Scientist

Past Positions:	1992-1996	System Engineer, U.S. Space VLBI Project, Jet Propulsion Laboratory (JPL)
	1991-1994	System Engineer, POINTS Study Team, JPL
	1989-1990	Manager, Astrometric Technology Development, Deep Space Network Advanced Systems Program, JPL
	1988-1989	Technical Group Leader, JPL
	1984-1996	Member of the Technical Staff, JPL
	1981-1984	Postdoctoral Research Associate, NRAO, Charlottesville
	1979-1981	Research Assistant, University of Maryland
	1979-1981	Radio Astronomer, Naval Research Laboratory

Education:	1976-1981	University of Maryland at College Park M.S. in Astronomy, May 1978 Ph. D. in Astronomy, May 1981
	1972-1976	University of California at Los Angeles B.A. in Astronomy (summa cum laude), June 1976

Professional Activities

NASA/JPL Pre-Project Scientist for ARISE: 1997-present
Referee, Coordinated Millimeter VLBI Array: 1997-present
NSF Proposal Review Panels: 1996, 2000 (chair), 2000
NASA New Millennium Science Working Group: 1996-1998

U.S. Project Science Group for Space VLBI: 1993-1997
NRAO Users Committee: 1988-1991 and 1996
Hubble Space Telescope Time Allocation Committee: 1995
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Key Publications

"VLA Imaging of the Nearby Merger NGC 4038/4039: HII Regions and Supernova Remnants in `The Antennae'," Neff, S. G., & **Ulvestad, J. S.** 2000, *Astronomical Journal*, 120, 670-696

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1984 - 1992

employer: Space Telescope European Coordinating Facility (STECF)
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1983 - 1984

Employer: National Radio Astronomy Observatory
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1976 – 1978

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Recent Publications

Morganti, R, Oosterloo, T.A., Tadhunter, C.N., Van Moorsel, G.A., Killeen, N., Wills K.A., *HI absorption in radio galaxies: effect of orientation or interstellar medium?* 2001, MNRAS (accepted)

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Appendix 3

EVLA MEMO 24

COMPUTING FOR EVLA CALIBRATION AND IMAGING

T.J. CORNWELL

Abstract. The EVLA will bring large improvements in all areas of scientific performance. To realize many of these improvements will require processing of the observed data at a level considerably more demanding than that currently required for the VLA. The important questions considered here are (a) whether the computing is feasible? (b) what is the best computing model to use? and (c) how much would the necessary compute power cost when purchased for the EVLA?

In developing answers to these questions we have used two different approaches: first, general scaling arguments based on Moore's law, and, second, detailed scaling arguments based upon the knowledge of the main sources of computing costs in processing various types of observations. We find that these two estimates agree reasonably well, and indicate that the computing load for the EVLA is relatively modest in scale (for 2009).

We also discuss the software development needed for EVLA calibration and imaging. We find that while the current AIPS and AIPS++ packages can support the simpler observational modes of the EVLA, full exploitation of all the capabilities will require some software development, but none beyond that already occurring within the context of AIPS++.

1. IS THE COMPUTING FEASIBLE?

In this section, we use general scaling arguments to investigate the feasibility of the computed required for the EVLA. The feasibility is determined by the playoff between a number of scientific factors and by the way that computing itself evolves between now and the commissioning date. First we consider the scientific factors.

The key scientific factors are:

- Overall data rate and volume
- Typical data quality
- Acceptable turnaround to a scientific result
- Level and type of computing required for a scientific result
- Relative importance of one-off batch processing versus interactive processing.
- The spectrum of scientific observations scheduled on the array
- The necessity to allow growth in computing requirements

We examine all of these factors in turn.

Data rate and volume: After noting that the peak processing rate could potentially be very large, the EVLA scientific specifications (Benson and Owen, EVLA Memo 15, 1999) argue for a compromise of 20-25 MB/s.

Previous studies have shown that between 100 and 10000 floating point operations per floating point value are needed to image radio astronomy data. Thus to keep up with the incoming data, the range

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I thank Brian Glendenning and Athol Kemball for useful discussions.

of peak data processing is 0.5 Gflop - 50 Gflop. The data volume for an 8 hour observation would be roughly 720 GB. A day's observation at this rate would be about 2 TB, equivalent to a few years observing with the current VLA!

Data quality: In the early days of the VLA, data reduction was complicated by the relatively poor data quality which necessitated close inspection and editing of the observations. As the system was debugged, the quality im proved considerably with a concomitant decrease in the level of inspection and editing required. The EVLA will have the same problem, of course, for a few years, but even after that radio frequency interference may limit data quality. In any event, tools for the assessing the quality of large data sets will be important.

Acceptable turnaround: The ratio of observing time to acceptable turn around time magnifies the peak processing rate proportionately. Thus for example, if we wish to reduce an 8 hour observation in minutes, the peak processing rate is magnified by about a factor of 100. This factor is tied to the need for experimentation in the data reduction: if many of the largest experiments must be processed a number of different ways then the acceptable turnaround time will be small. Using the factor of 100, the peak processing rate would be about 5 Tflop.

Peak data rate	25 MB/s
Data for Peak 8-hr observation	700GB
flops per float	100 - 10000
Peak compute rate	5Tflop
Average/Peak computing load	0.1
Average compute rate	0.5T flop
Turnaround for 8-hr peak observation	40 minutes
Average/Peak data volume	0.1
Data for Average 8-hr observation	70GB
Data for Average 1-yr	80TB

Table I: Typical and peak data and computing rates for the EVLA

Level and type of processing: The range in processing required for various scientific experiments varies tremendously. A simple example would be a long detection experiment at greater than arcsecond resolution. This would require straightforward calibration and construction of a dirty image only (assuming no other sources in the field of view). More complicated examples abound, ranging from multi-pointing mosaics to very high dynamic range imaging of an entire primary beam, where time consuming deconvolution and self-calibration would often be necessary.

Batch versus interactive processing: We expect that both batch and interactive processing will be required. Some of the simplest observations are amenable to batch processing, but we know that in the past many of the most spectacular scientific results have relied upon considerable hands on processing by expert users. The EVLA will not change this mixture.

Spectrum of scheduled observations: The peak throughput is set by turnaround but the average is set by the mixture of science scheduled on the array. A reasonable factor here would be 0.1 or less *i.e.* the average project has a tenth or less of the computing requirements of the most difficult projects. We will return to discussion of this factor below.

Growth in computing requirements: Based upon our past experience, we can say with certainty that the level and type of processing will continue to evolve, perhaps roughly as Moore's law. Thus any model must scale.

Thus we have the following interesting conclusions (see Table I).

We know the wonders of Moore's Law [1] but there are related cost scaling laws that also must be considered in answering these questions. We have to know the relative cost of processing, network bandwidth (both local and wide area), disk storage, and software, all of which must be predicted out about 8-9 years to the expected commissioning date of the EVLA. For many of these scaling laws, we have used an excellent comprehensive overview compiled by Jim Gray and Prasant Shenoy of Microsoft Research. A few selected rules of thumb are:

1 Moore's law: Things get 4x better every 3 years
2 You need an extra bit of addressing every 18 months
3 Storage capacities increase 100x per decade
4 Storage device throughput increases 10x per decade
7 Near line Tape: Online Disk: RAM storage cost ratios are approximately 1:3:300
8 In ten years RAM will cost what disk costs today
9 A person can administer $1M of disk storage
14 Gilder's law: Deployed bandwidth triples every year
15 Link bandwidth increases 4x every 3 years

We can now draw some conclusions about the feasibility of EVLA computing, assuming that we deploy a computing solution in 2009:

- 2000 - 2009 is three 3 year cycles, so for Moore's Law scaling (RAM, CPU performance, and network bandwidth), we can expect a factor of 64 improvement over 2000.
- The growth of telescope data rates (from VLA to EVLA) is sub Moore's law, and so on this very basic level, the computing must be feasible.
- Storage capacity growth is roughly Moore's law or better, whereas storage device throughput growth is significantly less. Thus storing the data will not be more of a problem than it is now but minimizing the number of I/Os per flop will become more important.
- Optimum algorithms will change as Moore's law enables simplifications and short cuts (*e.g.* eventually many images will fit into the available fast access memory.
- The current cost of storing a TB in disks is about $50K - $100K, so the cost of storing 100 TB (a year's observing) in 2009 will be roughly the same. 1 One important question is how long Moore's Law will continue. Moore himself has spoken recently (2000) about this topic. He expects the law to hold for about another 10 years.
- Putting the same data onto a tape robot may save a factor of three cost, but that forecast is probably less certain than the others.
- To get 0.5T flop in 2009, we would have to spend an amount that in 2000 would buy 500 Gflop/64 = 8 Gflop, roughly $20K - $100K, depending on how it is done.
- The total deployed bandwidth will be 3^8 times ~ 6000 times greater, which is considerably super Moore's law. Thus moving data will be much cheaper than today, but the transfer time for a typical VLA observation (in seconds) will be roughly as it is now and will therefore be possible in real time.
- All these arguments are based on deployment in 2009. Hence any purchases of computing capabilities prior to 2009 should be as circumscribed as possible.

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[1] One important question is how long Moore's Law will continue. Moore himself has spoken recently (2000) about this topic. He expects the law to hold for about another 10 years.

[2] http://research.microsoft.com/~gray/papers/MS_TR_99_100_Rules_of_Thumb_in_Data_Engineering.pdf

So, in summary, from these rough arguments, we can see that EVLA computing will be feasible in 2009, and that the cost should be in the range of a few times \$100K. This means that the same computing would cost \$5M - \$10M, if deployed today, which is roughly comparable to the cost of the correlator. In this sense, the EVLA will be well balanced.

Finally, in concluding this section, we should note that some of these improvements may be easier to come by than others. We can reply on Moore's law continuing for computers, disk storage, and local area networks. However, this is not necessarily true for wide-area-networks. For example, since the EVLA is physically just as remote as the VLA is (!), the actual provision of high bandwidth network links is highly dependent upon the exact course of development by major band width providers in western New Mexico. Consequently, we will need to continue to be pro-active in pushing our interests in networking within New Mexico.

2. A MORE DETAILED EXAMINATION OF COMPUTING TIME

The above analysis is strongly reliant on the assertion that the number of floating point operations per float has a final range of 100 - 10000. If this assertion is incorrect then the processing required could be correspondingly higher. For this reason, in this section we investigate a number of typical observational scenarios with an eye to determining this number in practice.

To come up with an independent number, we will use a simple model of various imaging algorithms. Most of the time taken in imaging (including deconvolution) lies either in the gridding step or in the Fast Fourier Transform. The other steps such as the minor loop for CLEAN can be tuned to be less than or comparable to these steps. The costs are as follows:

Gridding: To a first approximation, the work involved in gridding is simply proportional to the number of visibility points to be gridded. Some savings could be realized by *e.g.* gridding as MIRIAD does onto a grid that is frequency variable, but we will ignore such optimizations for the moment. De-gridding costs are very close to those of gridding. The total time is therefore given by:

$$T^{grid} = N_{griddings} . N_{mega-vis} . t_{mega-grid}. \quad (1)$$

where $N_{griddings}$ is the number of gridding or de-gridding steps, $N_{mega-vis}$ is the number of millions of visibilities, and $t_{mega-grid}$ is the time taken to grid one million visibilities.

FFT: In theory, the time involved in FFTs is expected to scale as N log(N) but we typically find in practice that it goes roughly linearly in the number of pixels[3]. We therefore have:

$$T^{FFT} = N_{FFTs} . N_{mega-pixel} . t_{mega-FFT} \quad (2)$$

where N_{FFTs} is the number of FFTs required, $N_{mega-pixel}$ is the image size in mega-pixels, and $t_{mega-FFT}$ is the time taken to perform a 1024 by 1024 FFT.

The times for various types of processing can be analyzed in terms of these times.

Single image deconvolution: Typically the work involved per minor cycle of a deconvolution is 2 FFT steps.

This arises because the usual work required is to calculate residuals from an iterate using a double-size zero-padded FFT-based convolution. Adding time for the gridding of the dirty image, PSF, and calculation of residuals at the end, and accounting for the required padding, we have:

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[3] This is presumably because data I/O dominates the transform. AIPS++ recipe number 4 demonstrates this scaling law very nicely.

(3) $$T^{sid} \sim 4.N_{mega-vis}.t_{mega-grid} + 8.N_{cycles}.N_{mega-pixel}.t_{mega-FFT}$$

Multiple image deconvolution: If multiple coupled images on different tangent planes or disjoint images are to be estimated simultaneously, one will have to use FFTs plus gridding and de-gridding at each minor cycle instead of full-size zero-padded FFT-based convolution. This means that multiple image deconvolution is much more gridding/de-gridding intensive than single image deconvolution.

(4) $$T^{mid} \sim (4+2.N_{cycles}.N_{images}).N_{mega-vis}.t_{mega-grid}+2.N_{cycles}.N_{mega-pixel}.t_{mega-FFT}$$

Mosaicing: Only a fraction of the visibilities need to be gridded for each pointing. Also, the FFTs need not be as large as the whole field since the primary beam is limited. Finally, FFT-based convolutions can be used in each minor cycle to avoid repeated gridding and degridding. The time is therefore:

(5) $$T_{mosaic} \sim 4.N_{mega-vis}.\, t_{mega-grid}+8.N_{cycles}.N_{pointings}.N_{pointing-mega-pixel}.\, t_{mega-FFT}$$

where $N_{pointings}$ is the number of pointings and $N_{pointing-mega-pixels}$ is the size of one pointing image. Since on average, the pointings will be critically sampled in two dimensions, the total time can be written:

(6) $$T^{mosaic} \sim 4.N_{mega-vis}\, t_{mega-grid} + 16.N_{cycles}.N_{mega-pixel}.t_{mega-FFT}$$

where $N_{mega-pixel}$ is the size of the total image. This is an asymptotic value for large numbers of pointings where the edge effects are unimportant. In this analysis, the source structure affects the number of cycles. For simple sources, the number of cycles can be 10 - 30, whereas for complicated sources, it can range into the hundreds.

3. SOME EXAMPLES

We are now in a position to estimate the computing times for various EVLA projects. We can use values of $t_{mega-grid}$ and $t_{mega-FFT}$ for typical machines now, and use Moore's law to convert those to 2009 values. For a current 450 MHz Pentium III PC with an Ultra-Wide SCSI disk, $t_{mega-grid} \sim 60$ sec and $t_{mega-FFT} \sim 12$ sec.

We will consider a range of "big" observations, ranging from many pointing mosaics to full sensitivity continuum imaging of the L-band primary beam.

Large RRI mosaic of SGRA West (from Miller Goss): The frequency range would be 28.27 (61 alpha) to 40.63 GHz (54 alpha H) . This allows observation of 8 Hydrogen recombination lines in the range 28.27 to 40.63 GHz *i.e.* the full Ka band. The synthesized beam is 0.4 to 0.6 arc second. There is enough brightness in Sgr A West to image at this resolution. This is a modern version of the Roberts and Goss result at 1.5 to 2 arc sec at H 92 alpha (Ap J suppl, vol 86, page 133 , 1993). The spacings of the recombination lines is about 2 GHz in the middle of the band .

The mosaic must be 8 by 6 pointings with a spacing of 25 arc sec . The primary beam is in the range 60 to 90 arc sec or so. One phase references using Sgr A star at the center of the mosaic. A possible observation lasts for 8 hours or 480 mins, of which about 300 min is observing with the rest bandpass and phase calibration *etc.*.

The resolution of each spectra needs to be about 5 km/s or 0.58 MHz at the center of the band. One needs a velocity range of about plus and minus 300 km/s or about 70 MHz for 128 channels.

HI cube of nearby galaxy (from Rupen, EVLA memo 8): The frequency resolution should be about 6 kHz, and the full bandwidth 7 MHz. The field of view is about 10 arcmin, and the resolution 1.5 arcsec.

Noise-limited image of entire L-band primary beam: All 4 polarizations must be used to reach the theoretical noise level. All sources out to the second sidelobe of the primary beam must be included.

Some commentary at this point is worthwhile. Clearly the range of processing times is huge: the reduction of the entire L-band primary beam takes much longer than any of the other types of processing. The time is driven by the number of images than are needed to represent the non-isoplanatic imaging adequately over the primary beam. In this regime, it may be worth reconsidering the algorithm used for wide field imaging. As Cornwell and Perley (A&A, 261, 353, 1992) note, there are many viable algorithms to choose from, and if the relative cost of various computing resources changes (as it must do over time), the optimum algorithm may well change. Cornwell and Perley demonstrated two algorithms: a faceted transform and a three-dimensional transform. The former wins currently because of the limited memory sizes available. However, if the memory allows the three-dimensional transform to be used then the table shows that the computing time can be cut very substantially. The rules of thumb above tell us that this is likely to be true, so we should assume that the lower number is appropriate.

Another factor to be considered is the important of self-calibration. For the spectral line cases, the incremental cost is relatively small since the self-calibration will often be done on the pseudo-continuum data. For the high dynamic examples, the cost is basically a multiplicative factor between 5 and 10, as the entire imaging must be repeated after each self-calibration. Difference imaging techniques may reduce this number to 3 - 5.

In summary, we see that for the typical (worst) case in our examples, the processing can be done in real time using a parallel processor of 100 (5 * 260) (year 2000) processors. Moore's law from 2000 to 2009 gives a factor of 64, so we would need roughly the equivalent of about 10 (20) (year 2009) processors. Depending on the achieved parallelization speedup (see Appendix A), this could require between 10 (20) and 100 (400) processors. Specifying for the average case, we find that the total hardware cost would be in the range of about $50K - $200K.

4. THE COMPUTING MODEL

We have seen from the arguments above that a moderately parallel computer will be required to reduce data from the most demanding EVLA observations. For many lesser observations, a more standard desktop (but of the year 2009!) will probably suffice, and the networks and local disk space will be available as required to permit observers to process some data at home, if they so desire. By the same argument, many (but not all) projects could be processed only when the data are demanded from the archive. This would allow processing schemes to be continuously updated and improved.

Hence the computing model has the following aspects:

- A moderately parallel machine ($50K - $100K) will be required for the high end projects.
- Standard (2009-issue, probably moderately parallel) workstations will continue to be able to process many projects.
- A central archive costing about $50K - $100K per year will be required
- Data access will be over the Internet, with transmission times for entire data sets being typically a few hours.
- Calibrate-and-image-on-demand is possible for many projects, and perhaps for all.
- Processing capabilities should be available and accessible remotely. NRAO currently has two packages

that can perform many of the necessary algorithms for EVLA processing: AIPS and AIPS++. Over the last twenty years, AIPS has provided the processing required for the VLA. AIPS++ has been designed and developed both for that class of processing, and for the high data volume and pipelined processing necessary for new telescopes such as the EVLA and ALMA.

Observation	**# pol**	**FOV "**	**Cellsize"**	**# pointings**	**# facets**	**# pixels**	**BW (MHz)**	**Freq res (MHz)**	**# vis chan**	**#image chan**	**#I. F. s**	**T obs (hr)**	**T int (sec)**	**# vis / int**
L- band full primary beam(2D)	4	7200	0.3	1	256	24000	500	1.00	500	1	1	12	3	702000
L- band full primary beam (3D)	4	7200	0.3	1	1	24000	500	1.00	500	16	1	12	3	702000
RRI Mosaic of SGRA West	2	200	0.2	64	1	1000	70	0.5468	128	128	8	8	10	718848
HI of nearby galaxy	2	600	0.5	1	1	1200	7	0.006	1166	1024	1	24	10	818532

Observation	**Data rate(MB/ s)**	**Total data (GB)**	**Mpixel**	**Mvis**	**Minor cycles**	**single (d)**	**multiple (d)**	**mosaic (d)**	**Time (d)**	**# processors**	**TB/ year**
L- band full primary beam (2D)	1.87	80.87	576	10108.80	10	28.50	35972.08	40.88	35972.08	71944.16	59.04
L- band full primary beam (3D)	1.87	80.87	9216	10108.80	10	130.48	194.08	232.88	130.48	260.96	59.04
RRI Mosaic of SGRA West	0.58	16.56	128	2070.28	100	19.97	296.85	34.20	34.20	102.59	18.14
HI of nearby galaxy	0.65	56.58	1679.04	7072.12	10	38.30	122.53	56.96	38.30	38.30	20.65

Table II: Quantitative analysis of EVLA computing

Our overall scheme for producing the software required for EVLA data reduction can be summarized in the following table:

	Interactive	Pipelined data reduction
High-end reduction	AIPS++	AIPS++
Low-end reduction	AIPS, AIPS++	AIPS++

Table III: Software strategy for the EVLA

Where we have defined:
low-end reduction: single-field or small mosaic imaging with small data volumes (10's MB up to several GB) on a single CPU.
high-end reduction: multi-field imaging with large data volumes (up to 100GB) using sophisticated visualization, editing, calibration and imaging tools, running on parallel computers.
interactive: the observer is responsible for overseeing and executing the data reduction.
pipelined reduction: automated data reduction driven directly from the observing schedule.

Thus much of the processing of single field observations could be done with the current AIPS and AIPS++ packages, without any addition modifications. We doubt that AIPS will still be in widespread use in 2009, but it is possible. This provides a guaranteed baseline of performance that would accommodate many of the observing modes of the EVLA. As the capabilities of single CPUs improve over time, this guaranteed baseline will include more of the simpler observations of the EVLA but even so not all of the full range of capabilities of the EVLA will be accessible. Going beyond the bottom left corner of this table brings new demands on the software. These we discuss in the next section.

5. SOFTWARE DEVELOPMENT

In this section, we discuss the software development needed to fulfil all the capabilities of the EVLA.

5.1. High data volumes. As described above, the data volumes for the VLA will increase by several orders of magnitude. Fortunately, the cost of data storage will drop to more or less compensate. However, the speed of access will not rise proportionately. This reinforces the importance of I/O in the overall computing cost estimates.

The key software requirements to deal with high data volumes are:

Decoupling logical from physical descriptions: As much as possible, the interfaces for data access should not assume any particular physical storage. Instead the interface should be based on a logical view of the data.

Efficient storage: Spending flops to minimize I/O will be more advantageous. Thus compression of data by a variety of algorithms (*e.g.* Run-Length-Encoding, optimal compression) will be very worthwhile. The optimum algorithm will be different for different data elements in different contexts.

Efficient access tuned to the range of access patterns: For images, one will want to access along all axes, and for visibility data, one will want to access the fundamental data along a number of random parameters: time, baseline, frequency, polarization. Rather than optimizing for just one access pattern, one should optimize for the expected range of access patterns.

In AIPS++, the Table system has been designed from the very beginning to support such requirements. The Table system is now very mature and stable, the bulk of the development having occurred early on in the project.

5.2. More realistic calibration and imaging models. Our understanding of how to best process synthesis telescope data has evolved over the years of operation of various telescopes. We have moved to more and more explicit recognition of various instrumental effects. We now understand the advantages of using encapsulated, modular, parameterized descriptions of various physical effects in the measurements performed by radio telescopes. We also understand the importance of models that can encompass both synthesis and single dish radio telescopes.

In AIPS++, the Measurement Equation framework of classes has been designed from the beginning with such goals in mind. The key elements of this framework are:

- A specific, flexible and complete description of the measurement process for radio telescopes is built into the C++ classes.
- The model of the measurement process may be extended by plugging in C++ classes (Measurement Components) that describe specific calibration effects such as parameterized bandpasses or phase-screens.
- Generic algorithms for calibration and imaging are provided as part of the framework so that calibration and imaging can always be performed for any physical effect that can be described in the framework.
- Well-known algorithms, such as mosaicing, are available automatically from the framework. Extensions to more complex physical effects such as beam squint was relatively easy and automatic.
- Two complementary sky brightness descriptions are available: via images and via discrete components. The combination allows high dynamic range imaging in the presence of extended emission.

The Measurement Equation formalism was prototyped in 1996 (Cornwell and Wieringa, 1997), and since then has been under revision, extension, and testing. A wide range of imaging modalities are now supported. Mosaicing and calibration have been the main focuses of development over the last year. More work is required in optimization, and parallelization, and in the streamlining of actual use of the package for calibration and imaging.

5.3. Algorithmic Flexibility. As illustrated in the discussion of the processing of wide-field images from the VLA, the optimum algorithm is determined partly by the computer hardware on which it is to run. We saw how the advantage shifts from faceted to three-dimensional transforms as the typical fast memory size increases. Another example from the eighties was the tuning of CLEAN algorithms to the availability of the FPS AP-120B array processor. We expect other such shifts to occur continuously. This argues for a very flexible software environment in which substantial algorithms changes can be made with minimal software cost. While this is of course very difficult to ensure in all circumstances, well-engineered interfaces coupled with a high-level language such as C++ help considerably.

The Measurement Equation framework in AIPS++ supports such algorithmic flexibility by decoupling many effects. For example, the Fourier transform (faceted or three-dimensional) is independent of the deconvolution or calibration algorithms.

5.4. General data formats. To accommodate more complex data processing, one must use a more complete and general data format in which all the relevant information is stored. The data format must support the calibration and imaging models used, both for synthesis and single dish radio telescopes. The data format must allow storage of all the information needed for the calibration and imaging models. For example, for mosaicing, the antenna pointing position must be de scribable as a parameterized function of time. Another consideration is that data format must easily accommodate the extraordinary data collecting flexibility of the WIDAR correlator in which the spectral setup may change completely from one scan to another.

The Measurement Set data format in AIPS++ has been through extensive use and testing, as well as one very extensively reviewed round of revision (see AIPS++ Note 229). Thus we can be confident that it supports a wide range of radio astronomical observation modalities, including all those that are likely to occur with the EVLA. The Measurement Set is based on AIPS++ Tables and therefore inherits all the data storage advantages of the Table system.

5.5. Parallelization. The software costs will be driven by the complexity required to achieve these various growths predicted by Moore's Law. Since (non-optical, non-quantum!) CPU speed will presumably saturate at a few to 10's of GHz, parallel processing may be required to fulfil Moore's law in 2009. Hence we may well be required to program on moderately parallel (tens of processors) architectures. Investigation and development of low I/O, moderately parallel algorithms for non-embarrassingly-parallel problems must therefore be budgeted. In addition, the entire question of how best to parallelize I/O must be addressed since this may well be a limiting factor. These considerations apply equally to both desktop and central compute servers since both may well possess parallel architectures.

Relatively little work has been done on parallelizing radio astronomy imaging algorithms. The exceptions are an early use of PVM in multiple field deconvolution by Cornwell (VLA Scientific Memo 164, 1993), and more recently the parallelization project conducted jointly by NCSA and NRAO within the context of AIPS++. The latter project has the goals of (i) providing a common framework for developers to develop parallel algorithms, (ii) parallelizing key imaging algorithms, and (iii) providing the radio astronomical community with access to parallel facilities. An overview of this effort is available in the paper by Roberts. Some recent results on timing are available as AIPS++ Note 232.

The parallelization project funds 4 positions at NCSA and NRAO, and provides AIPS++ with excellent access to NCSA experts and resources. For example, we have recently ported AIPS++ to the UNM Albuquerque High Performance Computing Center RoadRunner cluster. This latter facility is being used to develop and test algorithms such as a parallelized version of the AIPS++ wide-field imaging algorithm.

In this memo so far, we have assumed that the various algorithms simply speed up in proportion to the number of processors available. This can be a valid assumption for the so-called "embarrassingly parallel" algorithms such as spectral line imaging in which the coupling between the processing required for different channels is minimal. However, for more complex algorithms such as multiple image deconvolution, the speed up factor may not be linear with the number of processors but may instead go as some power law, perhaps as bad as the square root. Development and testing is required to find parallelization strategies that yield high speed up factors for the expected number of processors. This of course is a key part of the parallelization project.

The NCSA/NRAO parallelization initiative is focused around the use of the Message Passing Interface (MPI) to coordinate processing on multiple CPUs. An alternate and higher level strategy has been pursued by the correlator group at DRAO in the ACSIS project. ACSIS is a digital auto-correlator being built at the DRAO to handle array heterodyne receivers on the JCMT. It uses a Beowulf cluster to provide the necessary processing for the peak data rate of 10.5 MB/s (about 40% of the EVLA peak data rate). AIPS++ C++ classes and glish are used to implement a distributed object system that processes the data on cluster of loosely coupled Linux based Pentium III computers.

5.6. Pipeline processing. Pipelined processing must be supported in the reduction package. In addition, the necessary contextual information must be passed on from the scheduling software to the pipeline *e.g.* to designate the type of reduction to be applied to particular subsets of the data. This will require either addition of tags to the existing schedule format (easy) or the development of a new scheduling package (considerably harder).

The pipeline itself should support processing of the telescope data using scripts that are tuned to specific situations. For the simpler observational scenarios, these are nothing more than the encapsulation of procedures in the cookbook into executable scripts. For more complex observational scenarios, some scientific investigation and development will be necessary.

The scripting language used in a pipeline must allow variable substitution, functions, complex branching, process handling, and extensive processing of results within the scripting language itself. All of this is possible with the Glish language used within AIPS++.

The actual mechanics of pipelines require the use of meta-information about the observational. Procedures for handling meta-information within AIPS++ are being developed as part of the ongoing pipeline development at NCSA.

5.7. Conclusions. AIPS++ has been designed from the start to allow satisfaction of all of these demands. By comparison, satisfying these demands in AIPS (or another legacy package such as MIRIAD) would mandate new layers on software to be placed on top of the existing code base. Hence our strategy is to base our software efforts around AIPS++, bearing in mind that the current versions of AIPS and AIPS++ provide a baseline of guaranteed capabilities similar to those available with the current VLA.

One potential concern is that AIPS++ has not yet been widely adopted for the processing of synthesis data. Some early adopters have been using the package, as have dedicated bands of testers at various consortium sites. From this experience, we see two major obstacles to wide spread adoption of the package: the sheer complexity of the package, and some remaining inadequacies in the user interface and documentation. Neither of these two obstacles are likely to be permanent, and indeed we have ongoing strategies for addressing both issues. In no case have we found a flaw in the overall design of AIPS++ that would prevent its eventual widespread adoption.

6. SUMMARY

We have investigated the hardware and software needs for calibration and imaging for the EVLA. We have used two different methods to estimate the processing hardware required to support observations with the EVLA. Both give an average CPU rate of ~ 50 - 100 Gflop, and a data rate of ten's of TB per year. Moore's law tells us that this would in principle be sustainable with the equivalent to a personal computer[4].

Allowing a comfortable overhead of an order of magnitude argues for a parallel computer having 10's of nodes, for a cost of $100K - $200K. The general sense of these conclusions agrees with those found (Glendenning, private communication) for ALMA, where the output data rate is similar.

There are some important caveats to this conclusion. First, we note that to achieve these numbers, one may have to re-engineer some of the algorithms to be best suited to the computing hardware then available. The example that we looked at in some detail is wide-field imaging, where simply scaling the currently used multi-facet algorithm overestimates the computing required by about 1.5 orders of magnitude. Such work is ongoing as part of the NCSA/NRAO collaboration on parallelization of AIPS++algorithms. Second, we note that some new algorithms, such as those needed for radio frequency mitigation, will be required. Neither paths of development are particularly difficult but both must be followed.

We note that the throttle of the EVLA is essentially Moore's law: as Moore's law is followed with time (or not), we can contemplate the expansion of the capabilities of the EVLA. Crunching the numbers, we find that the maximum output rate of the WIDAR correlator would then be reached in about 2030!

On the software side, we have described the key requirements for any package that will support EVLA observations. A guaranteed level of processing is available with the existing AIPS and AIPS++packages. However, to fulfill the wide range of observational capabilities of the EVLA will require some continuing development.

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[4] At this point, we feel that Machrone''s Law should be mentioned: the machine you want always costs $5000.

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