Project Close Out Report For: EVLA Construction

Date: May 8, 2013

PREPARED BY	ORGANIZATION	DATE
Chris Langley, Rick Perley, Gene Cole and others	NRAO NM Ops	May 8, 2013

APPROVALS (Name and Signature)	ORGANIZATION	DATE

RELEASED BY (Name and Signature)	ORGANIZATION	DATE

Change Record

VERSION	DATE	REASON

Table of Contents

1 PROJECT CLOSE OUT REPORT PURPOSE 1

2 PROJECT CLOSE OUT REPORT GOALS 1

3 PROJECT CLOSE OUT REPORT SUMMARY 1
- 3.1 Project Background Overview 1
- 3.2 Project Highlights and Best Practices 1
- 3.3 Project Close Out Synopsis 3

4 PROJECT METRICS PERFORMANCE 3
- 4.1 Goals and Objectives 3
- 4.2 Success Criteria Performance 5
- 4.3 Milestone and Deliverables Performance 19
- 4.4 Schedule Performance 20
- 4.5 Budget Performance 22
- 4.6 Metrics Performance Recommendations 22

5 PROJECT CLOSE OUT TASKS 23
- 5.1 Resource Management 23
- 5.2 Issue Management 24
- 5.3 Risk Management 25
- 5.4 Quality Management 25
- 5.5 Communication Management 27
- 5.6 Customer Expectation Management 28
- 5.7 Asset Management 28
- 5.8 Lessons Learned 29
- 5.9 Post-project Tasks 31
- 5.10 Project Close Out Recommendations 31

6 APPENDICES 32
- 6.1 Schedule 33
- 6.2 Budget and WBS 39
- 6.3 Risk Register 47
- 6.4 Remaining EVLA Project Funds Management Plan 49
- 6.5 Lessons Learned 52

Figures

Figure 1: Pointing Results 5
Figure 2: Antenna Slew Settling Time 7
Figure 3: Polarization Results 9
Figure 4: Gain Amplification Vs. Time 11
Figure 5: Antenna Phase Stability (L) and Difference (R) for C-Band 13
Figure 6: Bandpass Stability 14
Figure 7: Power Slope < 1 dB/GHz 15
Figure 8: Maximum Spectral Power Fluctuations < 3 dB 16
Figure 9: Residual Delay Errors < 0.1 ns 16
Figure 10: Typical ESD safe work station 26

Tables

Table 1: Key Performance goals 4
Table 2: On-Axis Efficiency Specifications and Results 8
Table 3: System Temperature Requirements and Results 10
Table 4: Sensitivity Requirements and Results 10

1 PROJECT CLOSE OUT REPORT PURPOSE

This Project Close Out Report is the final document produced by the Expanded Very Large Array (EVLA) construction project and is to be used by senior management to assess the success of the project, identify best practices for future projects, resolve any open issues, and formally close the project.

2 PROJECT CLOSE OUT REPORT GOALS

This Project Close Out Report is created to accomplish the following goals:

- Review and validate the milestones and success of the project.
- Confirm outstanding issues, risks, and recommendations.
- Outline tasks and activities required to close the project.
- Identify project highlights and best practices for future projects.

3 PROJECT CLOSE OUT REPORT SUMMARY

3.1 Project Background Overview

The goal of the Expanded Very Large Array (EVLA) Project is to improve most of the key observational capabilities of the Very Large Array (VLA) by at least an order of magnitude. Originally, the Project was divided into two Phases. The objective of Phase I was to improve the sensitivity, bandwidth, spectral resolution and frequency coverage of the existing 27 element array by the application of modern technologies. Funding was provided for Phase I. The objective of Phase II was to increase the angular resolution of the existing VLA by adding additional array elements around New Mexico. Phase II also included the addition of a condensed array configuration smaller than the existing D configuration and considered, but did not include, the addition of low frequency observing bands to the existing antennas. A proposal for Phase II was submitted to the National Science Foundation (NSF) in April 2004.The proposal was reviewed at the NSF in June 2005. In December 2005, the National Radio Astronomy Observatory (NRAO) was notified that the NSF was not able to support the proposal. This Project Close Out Report describes only the Phase I project.

The principal description of the science requirements, the technical specifications, the design selected to achieve the specifications, the schedule on which tasks were to be accomplished, and the task responsibilities are described in the EVLA Project Book along with the interface requirement specifications where one task interacts with another, either in the design or integration.

3.2 Project Highlights and Best Practices

Project Highlights:

- Leveraged existing VLA antennas and infrastructure to create state of the art array

  The astronomical community received a bargain in the $98M VLA expansion project. This price tag includes $59M in new NSF funds, $20M in contributed effort from NRAO, $17M from the Canadian partner DRAO (WIDAR correlator), and another $2M from Mexico. Building on the existing VLA

site and antenna infrastructure, and using many existing and experienced staff, the EVLA has come in at a fraction of the cost required for a new facility of similar capability.

- VLA technical capabilities increased by at least an order of magnitude in every key observational area, with the exception of angular resolution

  The VLA's historical contributions to the astronomical community are well respected. Notwithstanding this, the instrument had begun to show its age and new technological developments employed by other observatories threatened to make the VLA less relevant heading into the 21st century. The upgrade has enabled the VLA to maintain its leading role in the field of centimeter astronomy.

Best Practices:

- International collaboration between Canada, Mexico, and the United States

  The EVLA construction project was administered by the NRAO under the purview of the NSF and Associated Universities, Incorporated (AUI). Collaborating with NRAO included the Dominion Radio Astrophysical Observatory (DRAO) National Research Council of Canada Herzberg Institute of Astrophysics (NRC-HIA) and the National Autonomous University of Mexico (UNAM). The economic relief realized by sharing the burden between Canada, Mexico, and the United States brings its obvious advantage. In all likelihood, future projects of this magnitude and greater will require international participation in order to become a reality. Also of great advantage is the intellectual exchange which comes with collaborative efforts across borders.

- Regular internal and external reviews

  Project development was greatly assisted by the practice of routine peer design reviews along with preliminary and critical design reviews for the major subsystems. Additionally, external advisory panels were regularly convened to assess progress. The first of these external boards was the EVLA Advisory Panel (EAP). As concerns shifted away from engineering and more towards science, the NRAO Director formed the Science Advisory Group for EVLA (SAGE) and later, the Panel to Advise on Science and EVLA Operations (PASEO). Additional reviews included the biennially held User's and Visitor's Committees. Towards the end of project construction, the NSF EVLA Path to Completion Review and the NRAO Director's Project Review were successfully conducted.

- Quality Assurance program

  Requirements verification, assembly and subsystem acceptance testing, inspection procedures and corrective action, along with consistent documentation standards were observed during development, production, and integration. These practices are carried over into operations.

- Incorporation of project management tools

  Work Breakdown Structure, resource loading, budget and schedule contingencies, risk register, Change Control Board, Earned Value metrics, and a clear reporting structure were all techniques used by management to guide and report on the progress of the project.

- System Requirements verification and acceptance testing

  EVLA Science conceived and conducted a series of rigorous on the sky tests to assure the scientific requirements and engineering specifications were met.

- The EVLA project was completed on time, on budget, and on specification.

3.3 Project Close Out Synopsis

Having met or exceeded nearly all project objectives and deliverables, the EVLA Construction project is now closed.

4 PROJECT METRICS PERFORMANCE

4.1 Goals and Objectives

The VLA was designed and built in the 1970s, utilizing the best technology of that time. Its wide bandwidth (100 MHz/polarization), multiple frequency bands (initially four, expanding to seven over 20 years), digital spectroscopic correlator (providing up to 512 spectral channels), and multiple configurations (providing range of over 50 in spatial resolution), were all unprecedented at the time, and were largely responsible for the continued pre-eminence of the VLA amongst all radio telescopes on earth.

Despite this continued success, there were good reasons to consider an upgrade of the VLA. Primary was that the goals of science evolve over time, as new discoveries are made with the new instruments at many wavebands. Centimeter-wavelength radio astronomy has a major role to play in these emerging fields, but can only do so if the major observational characteristics of its principal instruments improve. Fortunately, emerging new technologies enabled vast improvements in the sensitivity and flexibility of the VLA at a cost which is a small fraction of that for a new facility of comparable capabilities. Utilizing these new technologies, and building upon the established infrastructure in place, we proposed an expansion of the capabilities of the VLA by orders of magnitude in all areas except for spatial resolution.

The technical requirements for the EVLA were based on a comprehensive review of the potential science enabled by utilizing new technologies combined with the established infrastructure. There were four major science themes:

1) The Magnetic Universe: measuring the strength and topology of magnetic fields;

2) The Obscured Universe: enabling unbiased surveys and imaging of dust-shrouded objects that are obscured at other wavebands;

3) The Transient Universe: enabling rapid response to, and imaging of, rapidly evolving transient sources;

4) The Evolving Universe: tracking the formation and evolution of objects in our universe, ranging from stars to spiral galaxies and galactic nuclei.

For all, it was readily demonstrated that the improvements in VLA performance by implementation of modern technologies would result in spectacular new science by the world user community. The EVLA

Project was a comprehensive technical upgrade of the VLA - and a spectacular example of the advantages of a `leveraged investment'. The result of the Project is an efficiently operated `new array', which will provide astronomers a modern, general-purpose radio telescope capable of addressing the key scientific issues of today, and the yet-unforeseen issues of the future.

The primary technical requirements for the EVLA, based on the scientific requirements, and upon the availability of the necessary technology, were:

1) Continuous frequency coverage from 1 to 50 GHz in eight frequency bands, utilizing new or upgraded receivers at the Cassegrain focus;

2) A new wide bandwidth fiber-optical data transmission system, including associated LO and IF electronics, to carry signals with16 GHz total bandwidth from each antenna to the correlator;

3) New electronics to process eight signal channels of up to 2 GHz bandwidth each;

4) A new wide-bandwidth, full polarization correlator providing a minimum of 16348 spectral channels per baseline. The new correlator provides full polarization capability for four polarization pairs of input signals of up to 2 GHz bandwidth each;

5) A new real-time control system for the array, and new monitor and control software for the electronics system

6) New high-level software to provide ease of use of the VLA for its users.

Key performance goals for the upgraded array are given in Table 1.

Band	Center Freq. (GHz)	Frequency Span (GHz)	Maximum IF BW (GHz)	Aperture Efficiency	System Temperature (K)	SEFD (Jy)	1-σ Cont. Sensitivity - 1 hr (μJy)
L	1.5	1 – 2	2 x 1	0.45	26	325	6.3
S	3.0	2 – 4	2 x 2	0.62	29	235	2.9
C	6.0	4 – 8	2 x 4	0.60	31	245	1.9
X	10.0	8 – 12	2 x 4	0.56	34	300	2.3
Ku	15.0	12 – 18	2 x 6	0.54	39	385	1.7
K	22	18 – 26.5	2 x 8	0.51	54	650	3.5
Ka	33	26.5 – 40	2 x 8	0.39	45	760	4.1
Q	45	40 – 50	2 x 8	0.34	66	1220	6.5

Table 1: Key Performance goals

Measured performance is provided in Section 4.2. In some instances, it will be noted that measurements have yet to be taken to corroborate a particular specification. This is due to a lower priority assigned to some exercises, given that end to end performance of telescope operation has proven to be quite exceptional.

In addition to providing the improved scientific and technological capabilities, goals of the EVLA project included fostering international collaboration with our Canadian and Mexican partners, and completing construction on schedule, on budget, and with a minimal loss of observing time. The project succeeded in all of these goals.

4.2 Success Criteria Performance

The top-level goals described in Section 4.1 were translated into specific performance requirements for the Project. These are given in Section 2.2 of the EVLA Project Book. In the following, we present the achieved results, and compare these to the requirements, with explanatory comments when judged needed.

4.2.1 Antenna - Mechanical

4.2.1.1 Pointing

All requirements apply to observing under ideal conditions (low wind, clear skies, at night with antennas in thermal equilibrium with the environment). There are three sub-sections:

a) **Blind Pointing:** Using a recently-determined standard pointing model alone, the rms of the difference between commanded and actual pointing positions is to be less than 6 arcseconds for elevations between 30 and 70 degrees elevation.

Status: Post-fit residuals show this requirement is met for azimuth, but not in elevation. The left-hand panel in Figure 1 below shows the histogram of pointing results taken under ideal nighttime conditions. Azimuth residuals (top left) have an rms of about 6 arcseconds. Elevation residuals (bottom left) are about 8 arcseconds.

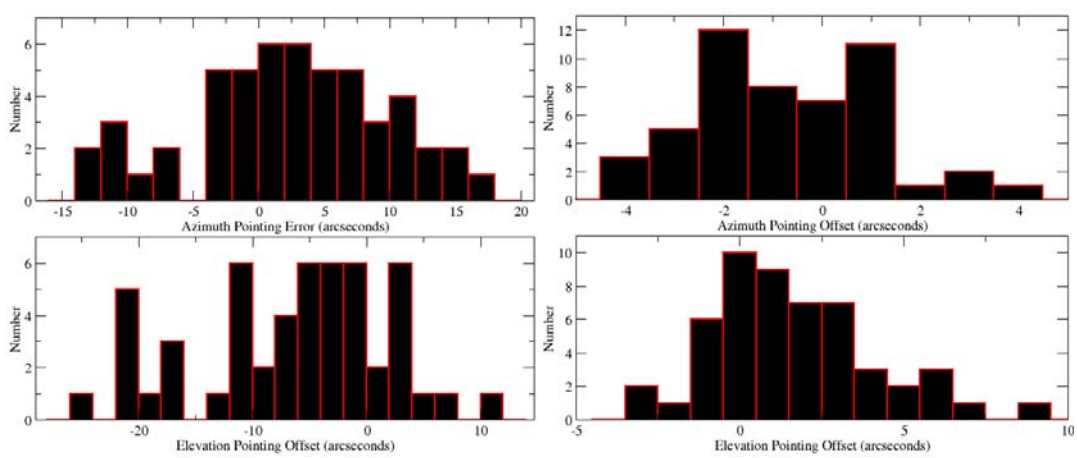

Figure 1: Pointing Results

b) **Referenced Pointing**: Transfer of locally-generated pointing offsets (defined as within 5 degrees in angle, and 15 minutes of time) for declinations between 20 and 70 degrees to be less than 3 arcseconds.

Status: Rms offsets of 3 to 4 arcseconds have been demonstrated for most antennas. The right-hand panel of the figure above shows the residual pointing error, following correction for the raw offsets. The offsets for azimuth (top) and elevation (bottom) are near 2 and 3 arcseconds, respectively.

c) **Super-Sidereal Tracking (OTF Imaging**): Between 20 and 70 degrees elevation, antenna position errors are to be less than 4 arcseconds for drive rates up to 1 deg/min, and less than 8 arcseconds for drive rates between 1 and 2.5 deg/min.

Note: This item has always been regarded as a goal, rather than a requirement, as no budget for the necessary hardware changes was ever identified.

Status: Software tests for this capability have been successfully conducted, but no hardware tests have been conducted.

Comment: As described elsewhere in this document, it is necessary to replace the existing Antenna Control Units (ACUs). This will constitute a major change to our methodologies for determining and achieving accurate pointing. It is expected that the new design will improve our pointing. As the new design will not be implemented until later this year, no results are yet available.

4.2.1.2 Subreflector Positioning

Section 2.2.1.2 of the EVLA Project Book contains a lengthy list of requirements for subreflector focus and rotation accuracy. These requirements were taken from the original VLA requirements, which were themselves based on 23 GHz performance. As good overall performance at 48 GHz (Q-band) has been regularly demonstrated, no effort has been made to determine whether these requirements are met. A significant failure would be readily seen in the Q-band observing.

The same comment regarding the ACU replacement noted above (Sec. 4.2.1.1) applies here.

4.2.1.3 Antenna Slew and Settle Time

The time taken to move and settle between two positions separated by less than 30 arcminutes is to be less than 5 seconds. This requirement is based on enabling survey and holography observing. Figure 2 depicts the voltage amplitude provided by one antenna as it steps through a raster across a strong source. The step size is about 1/3 of the beam width. The step is made every 10 seconds, the integration time is 1 sec, and the dump rate is 1 Hz.

Status: Holography testing shows this requirement is met for elevation motions for all antennas, and in azimuth for most antennas.

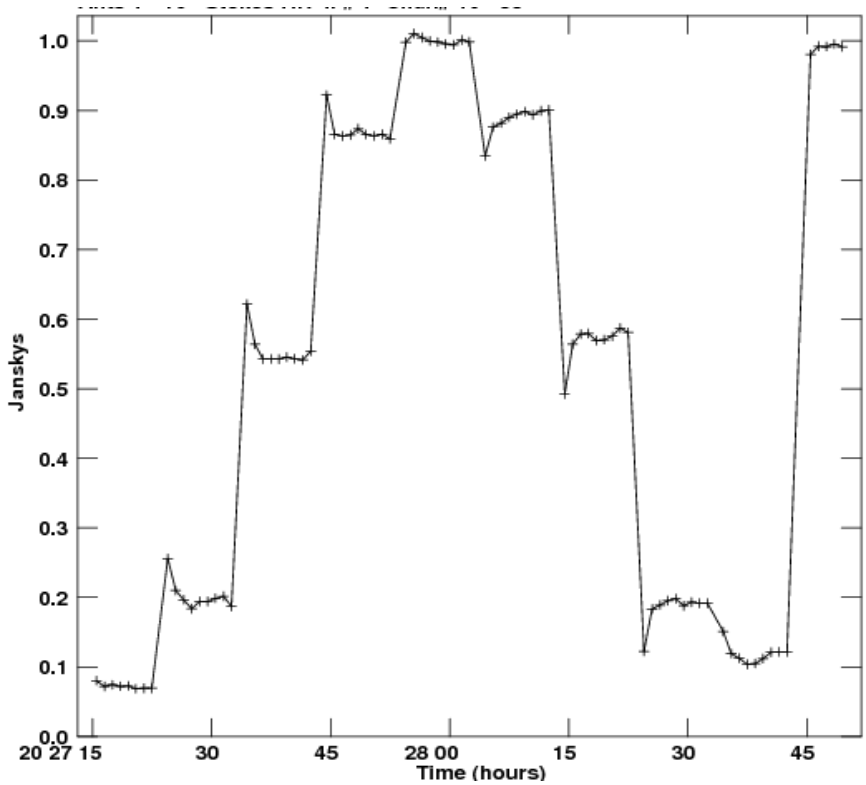

Figure 2: Antenna Slew Settling Time – 1 second integration per plotted point

The same comment regarding the ACU replacement noted above (Sec. 4.2.1.1) applies here.

4.2.1.4 Secondary Focus Feed Positioning

The positioning accuracy for the Cassegrain feeds is to be 10 arcminutes, and adjustable in the field.

Status: All receivers are mounted to permit accurate field alignment. The necessary holographic observations are planned for later this spring.

Comment: The effect of receiver misalignment is to produce a phase gradient across the antenna beam. Holography measurements to date indicate current alignments are sufficient for regular observing.

Antenna – Electrical

4.2.1.5 On-Axis Efficiency

We strive for high on-axis efficiencies across each observing band. The efficiency for each band is to meet the values given in Table 2.

Status: Included in the table are the results from ea24, the only antenna for which detailed measurements have been made.

Band	L	S	C	X	Ku	K	Ka	Q
Freq. Range	1 – 2	2 – 4	4 – 8	8 – 12	12 – 18	18 – 26.5	26.5 – 40	40 -- 50
Required Efficiency	0.45	0.62	0.60	0.56	0.54	0.51	0.39	0.34
Observed Efficiency	0.42– 0.5	0.55	0.58 – 0.65	0.58 – 0.65	0.56 – 0.63	0.48 – 0.56	0.35 – 0.50	0.26 – 0.37

Table 2: On-Axis Efficiency Specifications and Results

The results given in the table are from EVLA Memos 103, 109, 119, 125, 137, 152, and 165, plus unpublished results for S, X, and Ku bands.

Comment: Direct measurements of antenna efficiency and system temperature can only be done with `hot-cold' loads, an extremely labor-intensive activity. We have elected to do this for a single representative antenna. Astronomical measurements provide measures of the ratio 'Efficiency/System Temperature' which when combined with on-board system temperature measurements can provide a reasonable estimate of the antenna efficiencies for the remaining antennas.

4.2.1.6 Main-Beam Efficiency

No requirement was established for this item.

Comment: Main beam efficiency is a function of the aperture taper and antenna optics. The antenna efficiency is also dependent upon these factors – the two parameters are not independent. We decided to utilize the efficiency (which was easier to measure early in the project) as an indicator of antenna performance.

4.2.1.7 Feed Illumination

The feed illumination is to be within 5 cm of the antenna center.

Comment: This requirement is redundant with 4.2.1.4.

4.2.1.8 System Polarization Characteristics

Section 2.2.2.5 of the Requirements is written in terms of antenna polarization ellipse characteristics. Translated into the more familiar 'D' terms, the requirements are:

a) Antenna cross-polarization to be less than 5%.
b) Antenna cross-polarizations to be stable to 0.1% over an 8-hour period.

In addition, there is a requirement that the circular polarization offset (beam squint) remain constant to better than 6" over an 8 hour period.

Status: Polarization measurements have been reported in EVLA Memos 131, 134, 135, 141, and 151, for the L, S, C, X, and K band receivers. For all these, except C-band, the antenna cross-polarization meets project requirements except near the band edges. The C-band polarizers, which do not meet the requirements, are slated to be replaced by a new design expected to provide better than 5% cross-

polarization. Stability at C and K bands is reported as better than 0.1 and 0.2%, respectively. The K-band results were noise-limited, and we have no reason to believe the stability at that band is worse than at C-band.

Specific observations at other bands have not been reported. However, scientific observations for which polarimetry has been done indicate performance at the required values. No measurements of beam squint stability have yet been made. However, this is set by the location of the offset feeds, which are fixed, and in any event affects only Stokes 'V' observations, which are rare.

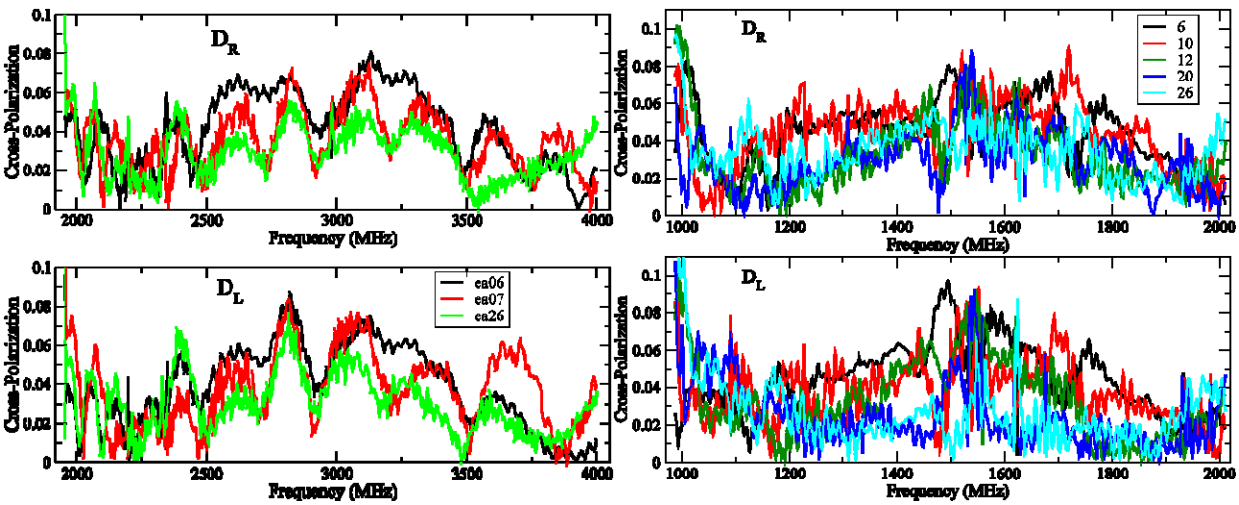

Figure 3: Polarization Results

4.2.1.9 Dichroic Capabilities

Dichroic operations are not part of the Project. The requirement here is only that the system design will not preclude future dichroic operations.

Status: The requirement has been met by arranging the Q, Ka, K and Ku band feeds on one side of the Cassegrain feed ring, and the C and X-band feeds (which would be paired with one of the others in a dichroic system) on the other side. Further, the LO system is designed to be able to operate at two frequencies, each in a different frequency band.

Receivers

4.2.1.10 System Temperature and Sensitivity

The system temperature requirements, and the typical mid-band measured values (except at Q-band, which are for the bottom end), are given in Table 3, in degrees Kelvin. A lower temperature results in a more efficient system. The requirements (and the observations) apply to clear, night-time, winter conditions.

Band	L	S	C	X	Ku	K	Ka	Q
Required	26	26	26	30	37	59	53	74
Observed	28 – 32	25 – 30	25 – 30	25 – 30	22 – 28	30 – 40	40 – 50	55 - 85

Table 3: System Temperature Requirements and Results

The most relevant parameter for observations is the Antenna Sensitivity, parameterized by the SEFD, defined (for a 25-meter antenna) as 5.62*Tsys/Efficiency. Low SEFD values are preferred. The requirements and latest measures are given in Table 4 for typical mid-band observing in good weather, except at Q-band, for which the values are for 41 GHz. Listed values are in Jy, and are the median values from all antennas.

Band	L	S	C	X	Ku	K	Ka	Q
Required	325	235	245	300	385	650	750	1220
Observed	342	246	274	237	212	402	561	1093

Table 4: Sensitivity Requirements and Results

Comment: The observations from which these results were derived were made utilizing the 8-bit samplers. The 3-bit (wideband) samplers cause a loss of about 15% in system sensitivity. As these samplers will only be used at the higher frequency bands (X-band and up), system sensitivity requirements are easily met. The C-band results pertain to the lower half of the band, for which a new 'thermal gap' assembly, to be outfitted in parallel with the new polarizers, is expected to improve sensitivity by ~10%. The upper half of C-band currently meets sensitivity requirements.

4.2.1.11 Linearity of Power Gain Measurement to System Power Variations

There are three requirements listed. Because of a change in operational methods, the requirements listed below are reworded to reflect the modern systems. The basic requirement – to be able to transfer system gain amongst sources with less than 0.5% error, over a range of input powers of a factor of 30 – remains unchanged.

a) Antenna electronics gain changes to remain linear to within 0.5% accuracy over an input power change of up to 15 dB (factor of 30). Any system gain changes of up to 15 dB to be monitored with the same accuracy over that same power range.

   Status: We have not met this requirement yet, by a factor of a few. This issue is being actively pursued at this time.

   Comment: The non-linearity is notable only for observations of the strongest sources. For observations of all 'normal' sources (up to ~ 50 Jy), gain stability and calibration accuracy of 0.5% is assured. Note that this requirement applies to the electronics. It does not apply to accuracy of antenna pointing.

   The following plot (Figure 4) shows the antenna gains over a 25 hour period, utilizing four standard calibrator sources. No trends have been removed. The scatter for each observation is from noise. The typical deviations from unity are less than 1%.

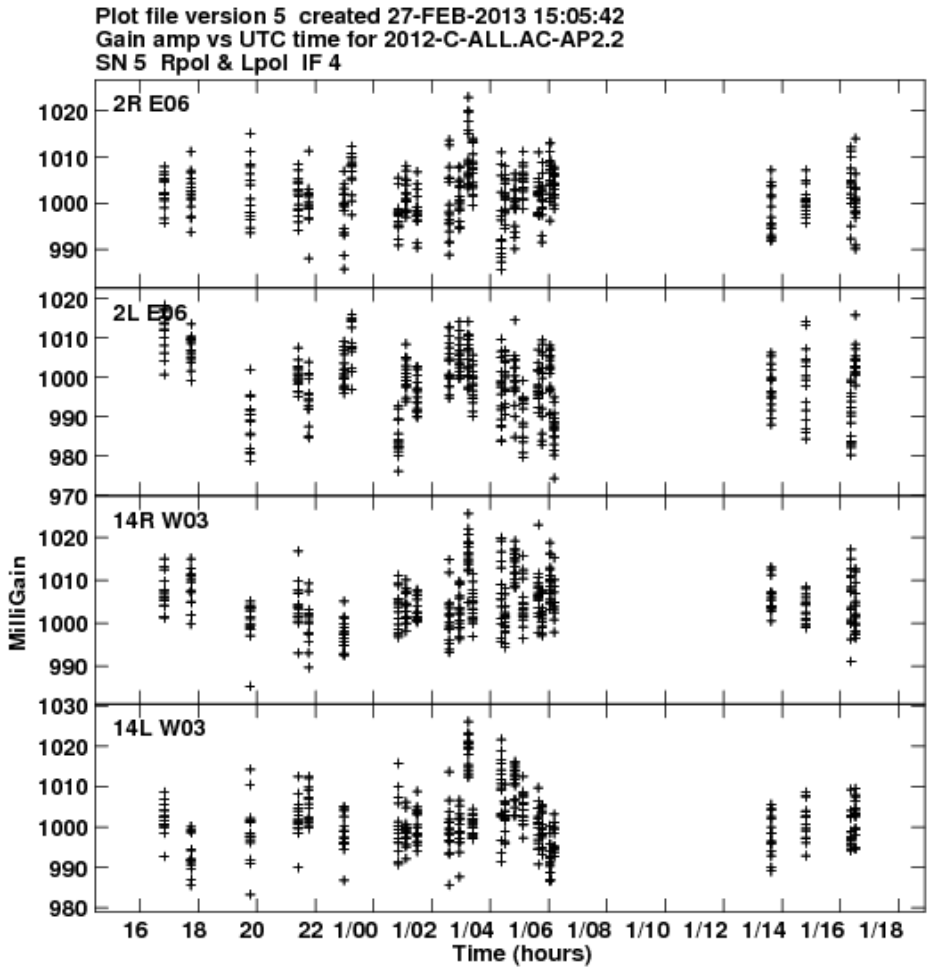

Figure 4: Gain Amplification Vs. Time

b) System gain stability and measurement accuracy to be accurate to 2% for power increments between 15 and 50 dB above cold sky.

Status: No specific measurements have yet been made. This requirement affects only solar observing.

c) Headroom requirements for the front ends, to 1 dB compression from cold sky, are 47, 48, 43, 42, 40, 33, 35, and 27 dB for the L, S, C, S, Ku, K, Ka, and Q bands, respectively. For the IF system, the headroom requirement is 32 dB to 1 dB compression.

Status: The receivers and IF electronics were designed to this level, but no specific test results are available.

Note: The requirements given here correct an error in the EVLA Project Book. The headroom requirements for the receivers were mistakenly written as headroom requirements for the entire electronics chain.

4.2.1.12 Temporal Phase Stability

All requirements presume round-trip phase corrections have been made. The requirements refer to electronics phase stability, and do not include changes due to atmospheric or system geometry errors. Note than a 1 ps time error results in a 17 degree phase error in at 50 GHz.

a) Rms phase jitter within a 1-second interval to be less than 0.5 fs.

b) Phase changes within a 30 minute interval are to be less than 6 ps.

c) Peak-peak fluctuations of the phase about the slope in phase within a 30 minute interval are to be less than 1.4 ps.

d) Any phase change associated with antenna motion is to be less than
   a. 0.7 ps for arbitrary change in pointing direction,
   b. 0.07 ps for antenna pointing changes less than 10 degrees.

e) The R-L phase difference is to be less than 0.5 ps, for all timescales.

Note: Requirements (b), (c), and (d) are all set to meet the limits imposed by the best possible atmospheric conditions

Status:

a) This requirement is to prevent decorrelation loss. The electronics system is designed to meet this requirement. System sensitivities, on sky, meet those expected from antenna performance tests.

b) Tests under good weather in compact configurations show these two requirements are met.

c) Same comment as in b).

d) The best test here is in the determination of baselines, which requires rapid all-sky observations. The result shows that baseline accuracy is not limited by the system stability, but by atmospheric variations.

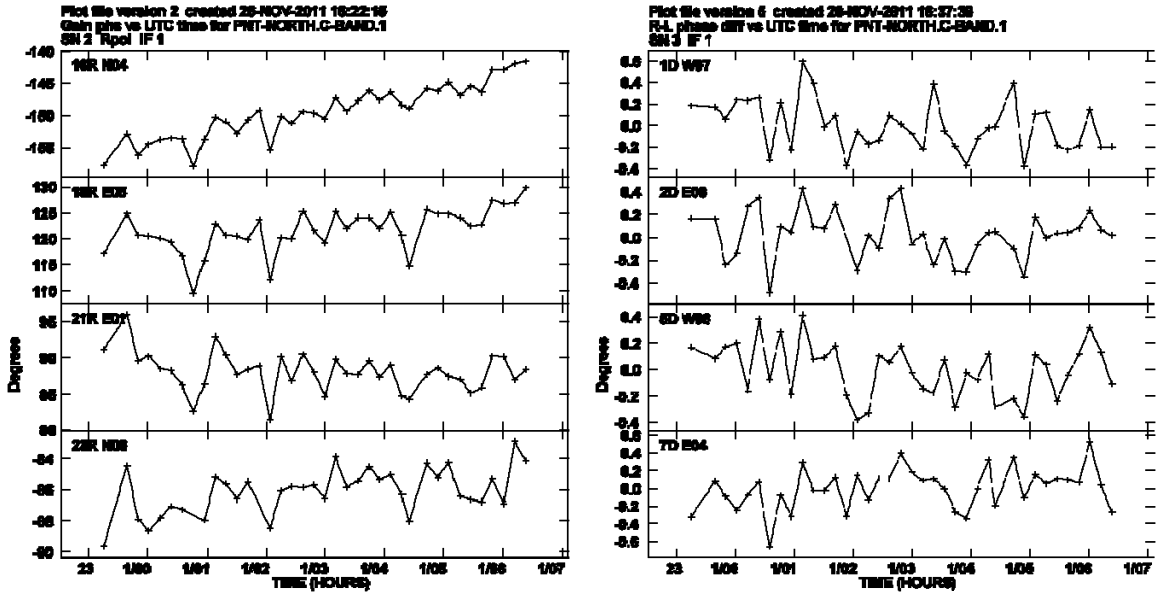

Figure 5: Antenna Phase Stability (L) and Difference (R) for C-Band

The left panel in Figure 5 shows antenna phase stability at C-band over an 8 hour period. Typical fluctuations are 2 degrees, corresponding to 1 ps time – well within requirements. The slope in the top plot is due to a baseline error. The right panel shows the (R-L) phase difference at C-band over an 8-hour period. The typical fluctuation is 0.2 degrees, corresponding to ~0.1 ps – well within requirements.

4.2.1.13 Bandpass Characteristics

The following two requirements refer to differential temporal changes. The requirements assume the gain variations associated with changes in amplifiers or attenuators have been corrected for. Atmospheric effects are not included.

a) Temporal Amplitude Stability: Variations in bandpass shape, in power units, are to be less than 1 part in 10000, on timescales of less than 1 hour, over frequency scales less than the band frequency/1000.

b) Temporal Phase Stability: Phase variations over frequency are to be less than 6 millidegrees, over timescales of less than 1 hour, and over frequency spans less than the band frequency/1000.

Status: The plot below (Figure 6) shows normalized differential bandpass amplitudes (the mean gain and bandpass shape are removed) over a two hour period for antenna 26 at 15 GHz. The fluctuations indicate the bandpass stability. The peak-peak range on these plots is 0.1%. The stability is close to the required level of 0.01%.

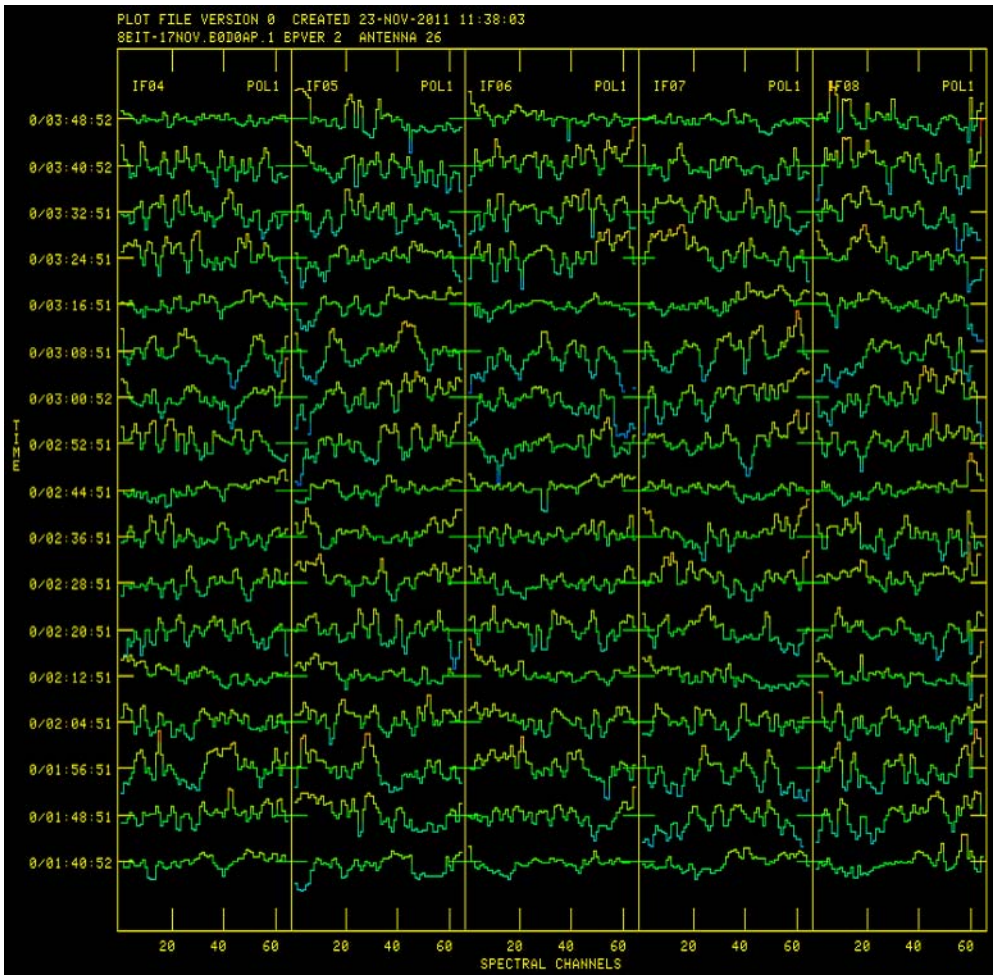

Figure 6: Bandpass Stability

The following requirements refer to the raw slope, in spectral power density or phase, of the bandpass defined by the electronics.

c) The spectral power density slope at the input to the 3-bit samplers is to be less than 1.5 dB/GHz.

d) The spectral power slope of the signals presented to either 3 or 8-bit samplers is to be less than (note: this corrects a typographical error in the EVLA Project Book):
   a. 12 dB/GHz at L-band
   b. 6 db/GHz at S-band
   c. 3 dB/GHz at C or X bands
   d. 1.5 dB/GHz at Ku, K, Ka, or Q bands.

e) Fluctuations ('ripples') is the spectral power density about the slope defined by the inner 1.8 GHz of the 2 GHz input to the 3-bit samplers are to be less than 4 dB, pk-pk.

f) Delay Errors (seen as a phase slope over frequency) are to be less than 2.8 nsec.

Status:

d) Figure 7 shows the raw spectrum covering 1.9 GHz using the 3-bit system at Ku-band. The power slope is less than 1 dB/GHz, well within system specifications.

e) The same plot shows the maximum fluctuations in spectral power are within 3 dB of the mean slope, easily within system specifications.

f) Easily met. The residual delay errors, following system calibration, are limited by atmospheric propagation effects - - much less than 0.1 nsec. Figure 9 shows the delay as a function of time over a 7 hour period.

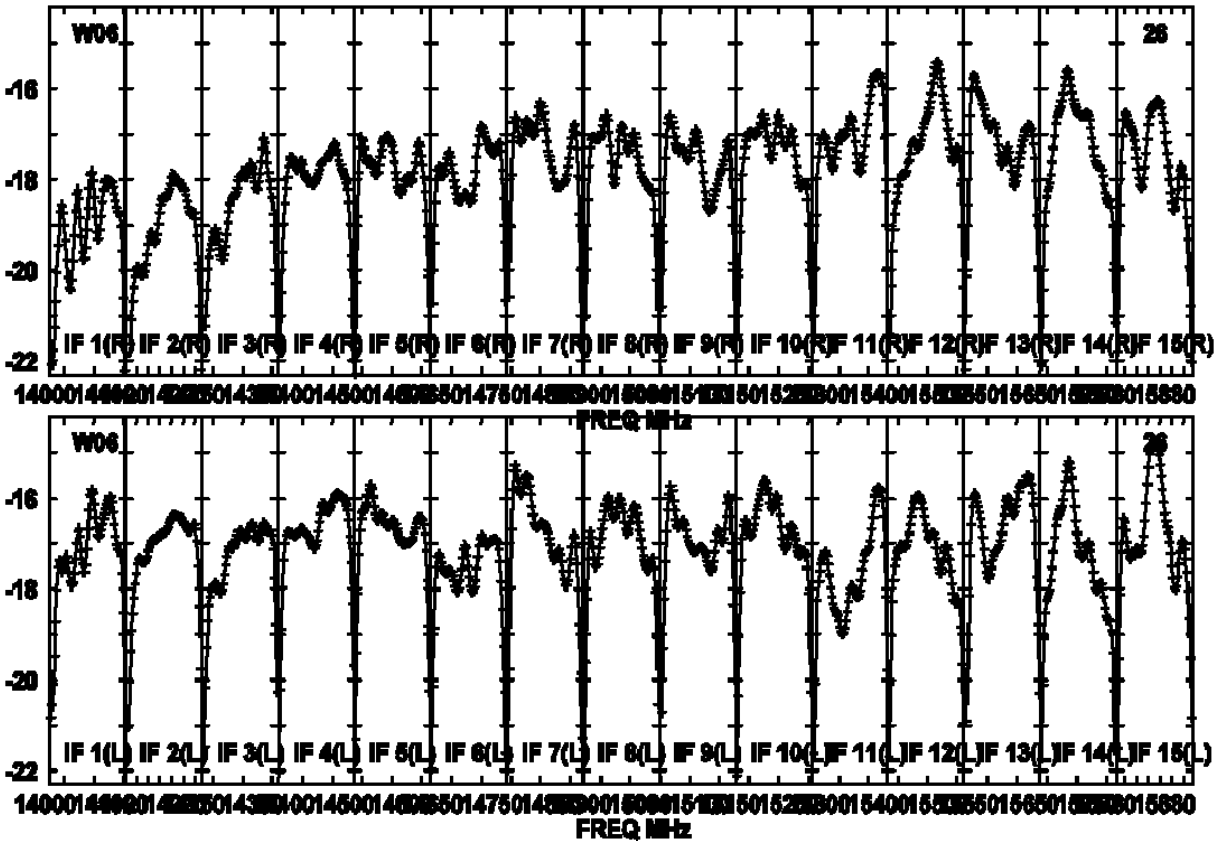

Figure 7: Power Slope < 1 dB/GHz

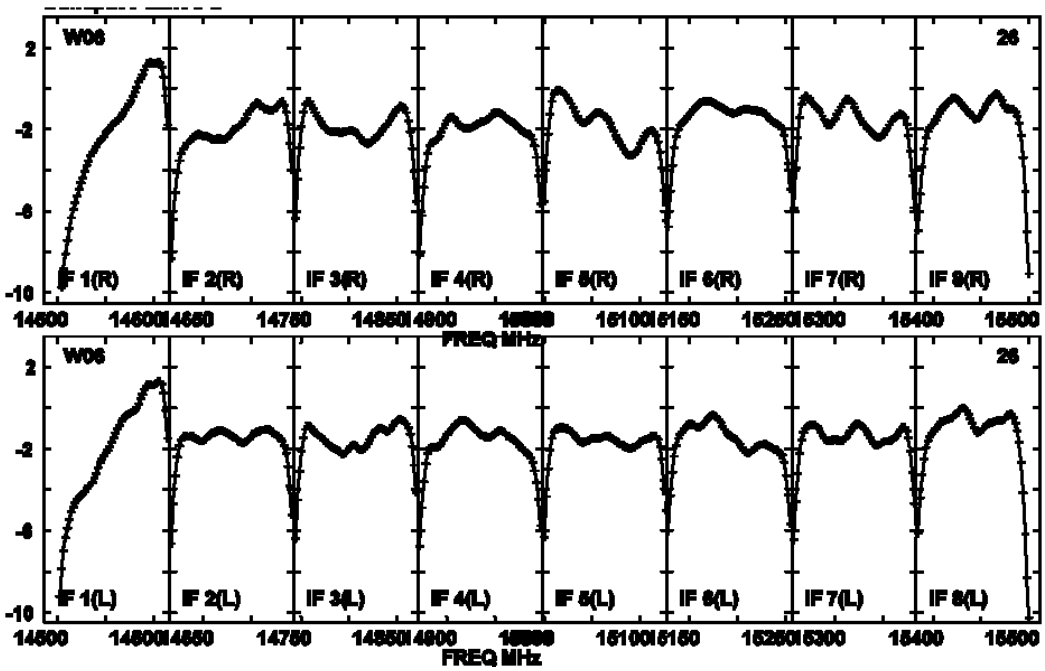

Figure 8: Maximum Spectral Power Fluctuations < 3 dB

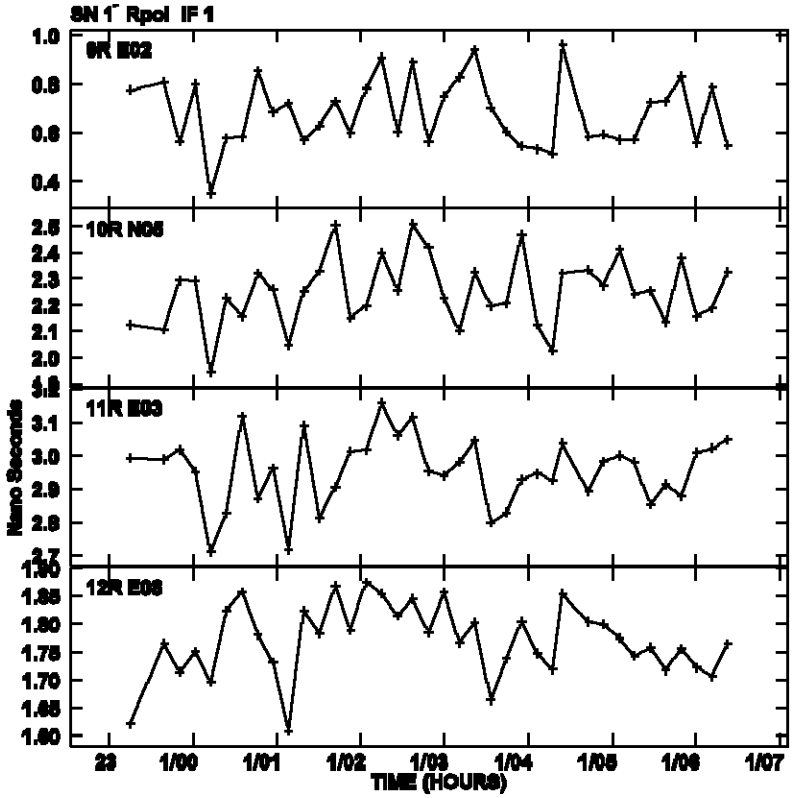

Figure 9: Residual Delay Errors < 0.1 ns

Required: System time must be accurate to 10 nsec.

Comment: Such accuracy is required only for pulsar timing.

User pressure for this capability has been very low, as the pulsar timing community has a strong preference for using single-dishes for this work. Hence, our limited resources have been directed to other areas of correlator development.

Status: The system is designed to enable this capability. No attempt to implement it has been made.

Correlator

The major requirements for the `WIDAR' correlator, as documented in the EVLA Project Book, are given below, with a status report for each.

a) The capability to process at least 27 antenna inputs, and be expandable to at least 48, in anticipation of Phase II of the project.

   Status: Up to 28 antennas are correlated on a regular basis. The ability to correlate up to 32 antennas is currently present. The correlator design would allow up to 48 antenna inputs.

b) Instantaneous bandwidth for each antenna input of up to 16 GHz, nominally organized as four oppositely polarized pairs of signals of 2 GHz each.

   Status: Fully implemented, and utilized on a regular basis.

c) Full polarization capability, with the user specifying which combinations are desired.

   Status: Fully implemented, and utilized on a regular basis.

d) At least 16384 spectral channels per baseline for all input bandwidths.

   Status: Fully implemented, and utilized on a regular basis.

e) The ability to 'target' up to 32 spectral transitions or narrow portions of the input bandwidth simultaneously, with velocity resolution of ~1 km/sec.

   Status: Fully implemented, and utilized on a regular basis.

f) The ability to avoid isolated strong RFI.

   Status: Fully implemented, and utilized on a regular basis.

g) At least 50 dB spectral dynamic range.

   Status: Final results are pending, though 40 dB of spectral dynamic range has been demonstrated.

h) A pulsar binning capability providing at least 2000 bins/baseline, with bin width 0.2 ms or less.

Status: This has not yet been demonstrated, as other correlator capabilities have higher priority. It is expected that the required development will be completed, and the capability demonstrated, within a few months.

i) A flexible subarraying capability, with at least 5 subarrays in cross-correlation modes.

Status: Full capability has been demonstrated in tests. In real science observing, three subarrays have been successfully administered.

j) A minimum data output integration time of no greater than 100 msec, with all spectral channels.

Status: This has been demonstrated by direct correlator observations. However, the data rate produced by this exceeds our current capability to write to the disk archive (external to the correlator). Significant additional resources would be needed to reach this goal. The current minimum integration time achieved is 10 msec, with 256 channels.

k) VLBI-ready, such that recorded data (either by tape or disk) can be correlated with at least the capability of the current VLBA correlator.

Status: This capability is accounted for in the correlator design, but it has not yet been demonstrated, as the VLBA now employs the DifX software correlator.

l) The ability to blank all correlations identified with potential RFI on an antenna input signal.

Status: This capability has not been demonstrated, as the external radio-frequency interference is not so severe to require the need at this time. Implementation of this capability is simply a matter of human resources.

4.2.6 RFI Management Plan

The EVLA Project Book Section 2.4 begins with a general description of the RFI environment and RFI issues, which we do not repeat here. The section concludes with a general description for four foundations – we provide a status report for each.

a) Measurement and Monitoring. We have on staff a full-time engineer, experienced in these matters, for this purpose.

b) Linear and Flexible Design. The receiver suite – including the digital portion – has been designed for maximum linearity. To date, we have no indication that RFI is degrading data quality outside of the correlator subband within which the RFI is found (see Section 4.2.5-g, above).

c) Suppression of man-made signals. This refers to internally generated signals by EVLA electronics and by emissions from other on-site equipment. Detailed testing for internally generated signals has been (and still is) conducted, and design modifications were implemented for those strong enough to affect array performance. There remain a few very weak and very narrow (spectrally) signals which are not expected to affect imaging performance. We will deal with these as staffing levels permit, should there be any indication of degraded performance.

d) Excision of affected data – both through simple flagging and through signal subtraction. The first of these is regularly implemented through new algorithms designed for the purpose. The second of these (which would permit preservation of the underlying astronomical information) is a subject of development world-wide, as strong RFI is a major factor degrading the data from the new generation of low-frequency arrays. No effort in this area has been expended by the NRAO, as the simpler 'flagging' route is sufficient for all users to date, and we have not the required human resources.

4.3 Milestone and Deliverables Performance

The project specified a list of major milestones that was used to measure progress and analyze overall dependencies and project impacts. The milestones were tied to key deliverables that the project had to meet in succession to advance forward. These milestones were used to measure critical path activities that were important to the ongoing success of the project by identifying areas of the project in need of improvement, and to forecast what deliverables would meet their targets so that the project could advance to the next stage. The milestones are listed as "Key Milestones" in Appendix 6.1 C.

The delivery of every major milestone has now been met and all deliverables have been accepted by NM Operations. Inevitably some deliverables were delayed along the way. Successful navigation through the myriad of electronics critical design reviews proved to be more of a challenge than anticipated. This resulted in delaying the start of electronics production and antenna retrofitting by 6 months. The project received an advancement of funding in 2004 which it used to accelerate purchases of large quantities of components. This helped return this portion of the schedule closer to its original baseline of progress.

The Observing in Transition Mode deliverable was two years later than expected due to the project's inability to recruit sufficient numbers of advanced software engineers during the first year of the project.

The delayed delivery of the prototype WIDAR correlator was in part due to finding suppliers that could provide high-speed processor chips that met specifications. The overall delay was 2 years. This delay had a domino effect and propagated through to several milestones that followed. These included the completion of the shielded room which would house the correlator, the start of Shared Risk Observing using the new system, and ultimately, the WIDAR correlator being declared operational.

Despite these schedule slips, all milestones were achieved with a high level of quality and earned customer acceptance by the planned-for end date of the project. No project milestones remain outstanding.

4.4 Schedule Performance

- Project Schedule Overview

The EVLA Project represented the 6th activity within the overall NRAO WBS. The Project was subdivided into the twelve principal Level 2 tasks shown in the Appendix 6.1 A. The detailed WBS task list, down to Level 4, is included in Appendix 6.2 A. Provided in this detailed WBS are the names of the engineers appointed within the Socorro Electronics, Engineering Services, and Computing Divisions that were responsible for the Level 2 tasks. Using Gantt methodology, every Level 4 task was broken down into measurable steps. These detailed schedules had milestones placed where appropriate to integrate the overall master project schedule together. The milestones from the Level 4 schedules were used to generate a Milestone Plan (Appendix 6.1 B) which was then used to track progress. A summary of the Milestone Plan was used as a report document. Periodic schedule updates provided the data used for earned value analyses (EVA) to generate the schedule performance index (SPI). The SPI in turn helped determine the percent ahead or behind schedule within reporting periods. These time metrics were collected, compiled and data validated as part of an ongoing process to review WBS status with the Level 2 engineers.

An example of a Level 4 schedule is shown in Appendix 6.1 D. The Project master schedule including details of all Level 4 schedules are kept in the EVLA Project online archive.

- Project Schedule Control Process

A dedicated scheduler was assigned at the onset of the construction project. This person had the responsibility of keeping track of the engineering activities which took place at the Science Operations Center and VLA in New Mexico, as well as the progress of component deliveries from NRAO's Green Bank (WV) and Central Development Lab (Charlottesville, VA) sites. On a daily basis, the scheduler kept track of all tasks, their dependencies, and the critical paths. Adherence to the project schedule was assisted greatly by key staff attendance at one or more regular meetings, each established with a specific purpose. These will be described later in this report.

Project schedule and budgetary status was routinely conveyed to NRAO upper management by established observatory reporting practices, and to the NSF by way of specified reporting guidelines. External annual or biennial reviews were conducted and progress reports were made available to the Users and Visitors committees, SAGE, and PASEO as part of the project review process.

- Project Schedule Corrective Actions

At the onset of the project the overall schedule baseline for completion was based on the NSF original 9-year funding profile. Shortly after the start of the project the NSF changed the original 9-year funding profile duration to 11 years. As a result the project schedule was modified to match the new profile.

A detailed review of the project schedule was carried out in December 2002 to determine the status of all EVLA WBS elements and their ability to start installation of the prototype system on a VLA antenna for testing in April 2003. It was considered important to start testing the new equipment on an actual antenna at the earliest possible time because it was only in the antenna environment that some problems, such as those caused by Radio Frequency Interference (RFI), would be identified. Some items, principally in the Local Oscillator, Intermediate Frequency, and Monitor & Control subsystems were found to be running late. These items were re-planned by prioritizing and phasing the activities so that essential equipment was available in time to allow for the outfitting of the Test Antenna per schedule.

In the area of Civil Construction, the burial of fiber optics (FO) cable along the array arms finished one full year ahead of schedule. The original intention was to retain some the FTE's used for burying the cable to work on the mechanical outfitting of the antennas when that activity commenced. By completing the task early, antenna outfitting was still a year away without a way to advance its start date. The project managed to keep some of the FO FTE's working in other areas, such as the construction of a cold storage facility. The cold storage building, which was cost shared with NM Operations, was placed under VLA warehouse inventory control and housed volumes of purchased quantities of electronics and mechanical hardware. Although the project lost some staff through attrition, it was able to retain the key individuals necessary to properly staff the antenna outfitting positions.

Early in the project the critical path was in the area of Monitor & Control, a situation that resulted from an inability to recruit software engineers of a sufficient level during the first year of the project. Once this recruitment was completed, the schedule had already suffered and time was required to recover.

During the middle years of the project two critical paths were identified at different times. The first major area of concern involved the completion of software tasks required to integrate the correlator with the EVLA Monitor & Control system. This was remedied when the project hired more software engineers to satisfy the level of work. Crisis averted, the next item warranting major attention involved the Front End subsystem. Design problems with the orthomode transducers (OMT) in some receivers, along with qualified staffing shortages, resulted in the projection of prolonged installation schedules. The new anticipated completion date of receiver installations was pushed out into 2013, which fell after the scheduled end of construction. Some good fortune was realized when the project recruited a particularly bright engineer to solve the design issues. His efforts paid dividends within a shorter period of time than anticipated, and the designs were completed and met specifications without issue. This resulted in a schedule which was brought back into line and the avoidance of completing project hardware after the 2012 due date.

- Project Schedule Integration with Managing Project

Retrofitting an instrument per a specified schedule while at the same time assuring it is available for scientific observations was a unique challenge for project management. A major mission of the EVLA project was to allow for continued VLA science observing throughout the duration of construction. Managing the project with minimal disruption through numerous hardware changes during equipment installations was paramount. It was recognized that any change in upper management personnel could have an adverse effect on VLA observing up-time in an attempt to meet scheduled hardware deliveries.