A Baseline Design for the Long Wavelength Array Stations

P. S. Ray (NRL), S. Ellingson (VA Tech), R. Fisher (NRAO), N. E. Kassim (NRL),
L. J. Rickard (Independent/UNM), T. Clarke (NRL)

The University of New Mexico

Los Alamos National Laboratory EST.1943

ARL The University of Texas at Austin

Introduction

The Long Wavelength Array (LWA) is intended to be a radio astronomical and ionospheric interferometer consisting of about 50 stations operating in the 20–80 MHz band, with a maximum baseline of up to 400 km. Although various descriptions have been developed for it, they are largely conceptual.

This poster presents a baseline, or "strawman," reference design for an LWA station. The goals of this reference design are two-fold: To focus the engineering and science efforts on a concrete design to guide the development of the optimum system, and to provide the basis for detailed costing of the array. This allows asking concrete questions like, "how does this design enable the science I want to do?" and "what technical and cost issues need to be addressed to turn this design into reality?"

We emphasize that this design is *not* meant to be considered a final design in any way, but rather one realization of a design that largely satisfies the scientific requirements of the LWA.

This is a basic design overview of the hardware at a single LWA station and, as such, it explicitly does not address numerous important aspects of the full LWA project such as site acquisition, correlator design, long-distance data communication, array calibration, software, etc. It does, however, attempt to specify the critical issues on each subsystem, where design and prototyping work should be focused during the development of the actual LWA system design.

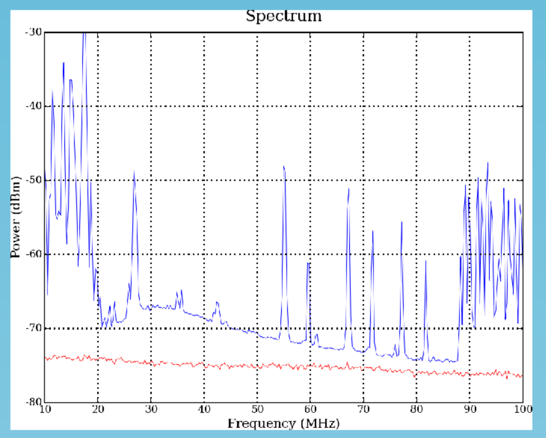
The poster is organized in order of signal path, from antenna through the beam former, where the data is prepared for transmission to the correlator.

Development Plan

Development of the first full LWA station (LWA-1) will begin in earnest in October, 2006, when funding for the first year of development work arrives at the project office at UNM. The goals are to reach PDR for LWA-1 about 6 months after CDR at the end of the first year. Because of limited funding, the initial build of LWA-1 is planned to include all the features of the baseline design described here, except for the beamformer, which will be replaced by a PC-based data acquisition system with a limited bandwidth of only 156 kHz, though all other capabilities will be maintained. In the following year, as the second station (LWA-2) is built, beamformers will be built and installed for both stations, bringing them both up to full capability.

Antenna

Photo of prototype "big blade" antenna. The full assembly of two dipoles and a mounting structure is referred to as a "stand".



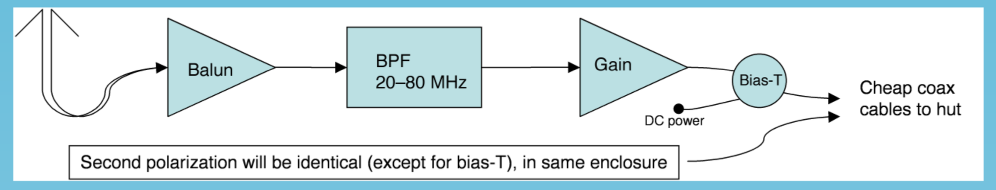
Spectrum from big blade antenna, as measured at the LWDA site. The smooth continuum is the galactic background noise, filtered by the antenna response. The red curve is the same spectrum with the balun inputs terminated with 50 ohm loads, showing that the system is sky noise dominated over the full 20–80 MHz band. The narrow spikes are RFI from HF transmissions, TV channels, and FM radio.

The baseline antenna is the "big blade" antenna, a pair of crossed, linearly-polarized, fat dipoles constructed of aluminum and held at a 45 degree angle by a pyramidal PVC mount. These are scaled-up versions of the "small blade" antennas used for the LWDA (which was only intended to cover the 60–80 MHz range).

The LWA antenna group is currently looking at alternative antenna topologies, as well as optimizations of the big blade design with the intent of selecting a final antenna design for LWA-1. A critical aspect of this research is the improving the manufacturability and reducing the cost of the antenna assembly. Other issues being considered include:

- Should a ground screen be considered? Are the improvements in sensitivity and stability worth the increased cost of installation and maintenance?
- How should the stands be secured to the ground, in a variety of soil conditions that will be encountered at the various sites?
- What is the optimal impedance match to the balun to maximize the sensitivity?
- What are the effects of mutual coupling, and how can they be accommodated?

Front End Electronics

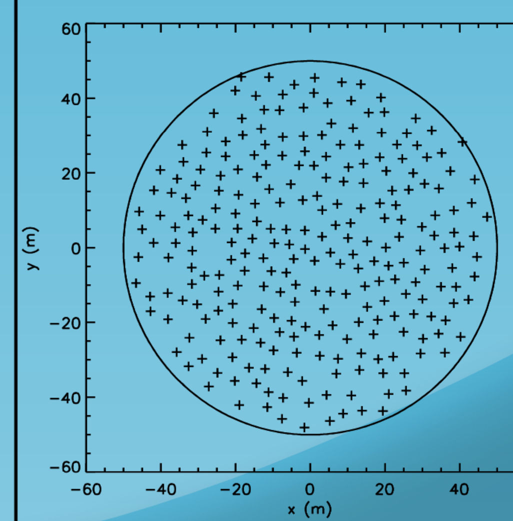


The front end electronics (FEE) consist of the analog balun, filter and gain stages that feed the coax cable connected to the shelter. The strawman FEE is based on the current LWDA balun designed by Brian Hicks using Gali-74 amplifiers (commercial MMIC amplifiers produced by MiniCircuits). This board will be modified and expanded to include a single bandpass filter (20–80 MHz) and a second gain stage. The active balun presents a 50 Ohm input impedance to each arm of the dipole, amplifies the signals with a gain of +24 dB, and converts the balanced signal to unbalanced via a 180° hybrid. This single-ended signal will be fed through an inexpensive bandpass filter (made of discrete components) to suppress the out-of-band RFI signals before going to a second gain stage that will amplify the signal by another +24 dB and match the output impedance of the FEE to the 75 Ohm cable. The filter and additional gain will help reduce the linearity requirements on later stage amplifiers and make sure that the cable loss doesn't contribute significantly to the effective noise temperature of the receiver system, respectively. The FEE will be powered by a bias-T on one of the coax cable inputs and will be in a single, weather tight enclosure.

Some of the critical design issues to address are:

- Investigate the possibility of RFI getting in to the system via the bias-T to see what the constraints on the bias-T design might be, or even if the bias-T scheme should be abandoned for a separate power cable run (which will certainly add cost).
- Look at lowering the cost of the FEE design by using less expensive components
- Work on lowering the effective noise temperature of the balun ($T_{eff}) to a goal of 170 K, which should be achievable with available transistors.}
- Revisit the input impedance to be presented to the dipole. Can a different choice of input impedance improve the mutual coupling or other performance parameters?
- Do lab tests to determine the input impedance dependence of the balun noise temperature for the current design or any potential alternatives
- In addition look at alternative packaging and connector options for cost effectiveness, RFI shielding, and weather proofing qualities.

Station Configuration



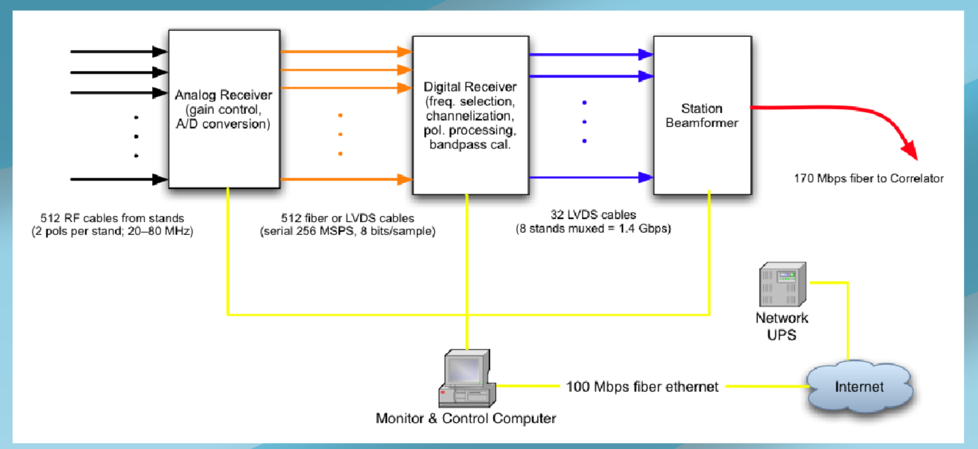
Arrangement of dipoles in an LWA station.

The LWA strawman station configuration is a pseudo-random design created using the CONFI task in AIPS (Kogan 2000), as shown at left. The elements have a natural taper with fewer elements near the station's rim and are positioned to optimize the sidelobe levels for any pointing direction. The optimization is quite robust to errors in the element placement (Polisensky 2005).

The station diameter is set to 100 m to give a 4x smaller field of view and 16x larger collecting area than a VLA dish at 74 MHz while also providing sufficient collecting area at lower frequencies. Extrapolating from VLA experience the number of dipoles needed for successful calibration is estimated to be (Cohen, A. LWA Memo, in preparation):

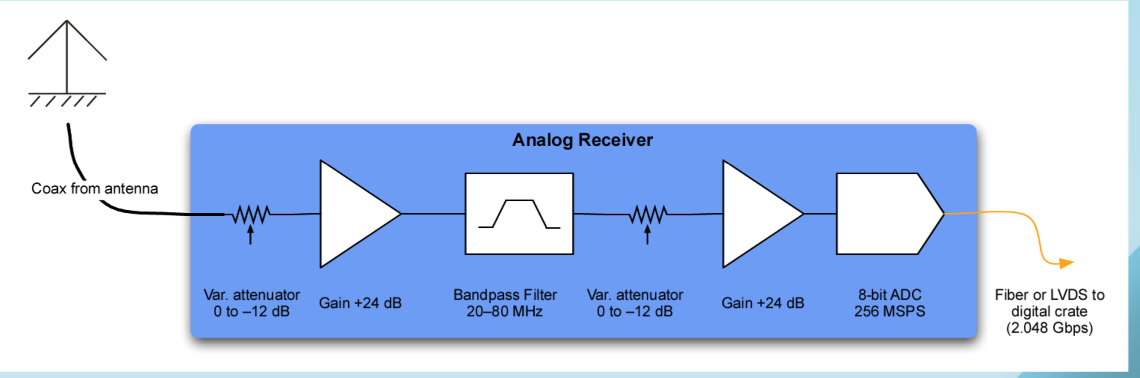
$$N \geq 175 \left(\frac{\lambda}{4}\right)^{-0.1}$$

The number of elements was set to 256 to allow calibration and suppress sidelobe levels while still providing a large number of stations for a fixed number of LWA dipoles. The ``big blade'' design for LWA dipoles is about 2.7m across. In the absence of mutual coupling measurements between the station elements, 4m was chosen as the minimum separation to allow serviceability and tolerance for surveying errors in the element positions.



Overall architecture of the station electronics. The RF signals from each stand are run to an electronics hut that contains the analog receiver, digital receiver, beamformer, monitor & control computer, and connection to the long-distance data communications system to the correlator (located at a central facility near the core of the array).

Analog Receiver



The analog receiver chain amplifies the signals from each antenna, provides variable gain, an anti-aliasing filter, and an analog-to-digital converter (ADC). We envision a single enclosure with multiple compartments to hold something like 8–16 receiver chains. In this design, the analog receiver chains are well separated from the digital processing (which can create a lot of digital noise), as well as being well separated from each other, without driving the cost too high, because the RF enclosure cost is amortized across the number of receiver chains it contains. If possible, a fiber connection would bring the digital output of the ADC to the input of the digital receiver; however, this may be cost prohibitive because of the number of fiber transmitters, connectors, and quantity of fiber cable required.

The ADC itself is a critical component of the design. It must have sufficient number of bits (i.e. quantization dynamic range) to allow quantizing the sky noise with a least the lowest couple of bits, while not allowing the largest RFI signals to cause clipping. In addition, it must have good spurious-free dynamic range (SFDR) performance when quantizing noise in the low-order bits. We feel that a flash ADC architecture is a good choice for this application and the strawman design uses an 8-bit flash ADC running at 256 MSPS. Based on initial measurements at the VLA site, 8 bits should be sufficient, but more would certainly be safer, particularly considering the changing nature of the RFI environment.

The design of the analog system from the balun to the ADC is impossible to evaluate without a gain, noise, intercept (GNI) analysis to determine the effective noise temperature and linearity of the system as a whole. The results of this analysis for the strawman design at two different attenuation settings, and for both the baseline balun and a hypothetical balun with improved noise temperature are presented below.

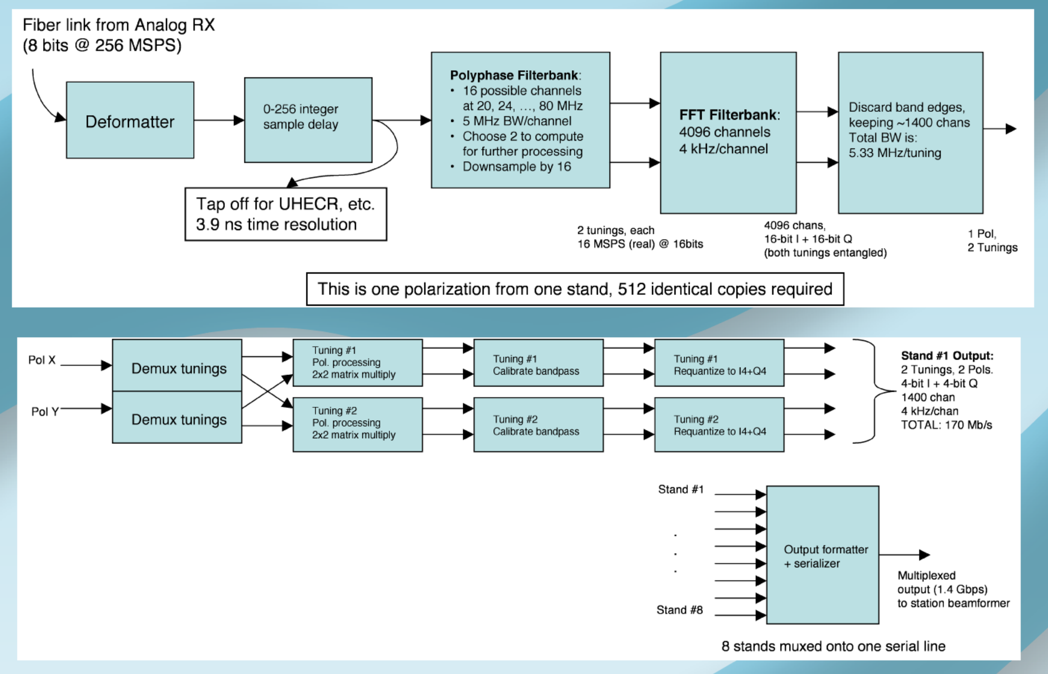
GNI Analysis Inputs
<http://rfcascade.sourceforge.net>

```
defaults rin=50 rout=50
# Hicks' balun + BPF + gain at antenna
balun g=24 iip3=7.5 nf=2.7
bpf1 g=-1.0 nf=1.0
gain2 g=24.0 iip3=6.0 nf=5.0
# Cable (RG-59, 500 ft at 80 MHz)
cable g=-13.0 nf=13.0
# Receiver in hut
# Variable attenuator g=0 to g=-12
# NB: att. noise figure = -gain!
att1 g=-12.0 nf=12.0
gain3 g=24.0 iip3=6.0 nf=5.0
# Antialiasing filter
bpf2 g=-1.0 nf=1.0
# Variable attenuator g=0 to g=-12
att2 g=-12.0 nf=12.0
gain4 g=20.0 iip3=20.0 nf=15.0
```

GNI Analysis Results

ATT1 (dB)	ATT2 (dB)	Gain (dB)	IIP3 (dBm)	$T_{\rm eff}$ (K)
With strawman balun $T_{\rm eff} = 250K$				
0	0	77.0	−37	254
−12	−12	53.0	−18	264
With improved balun $T_{\rm eff} = 170K$				
0	0	77.0	−37	173
−12	−12	53.0	−18	183

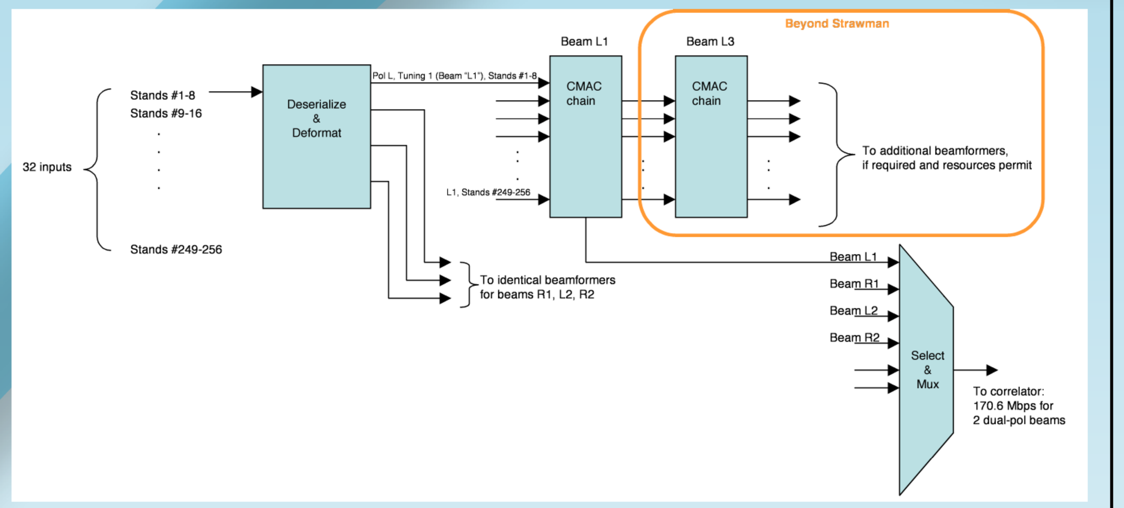
Digital Receiver



All of the digital signal processing between the ADC and the beamformer takes place in the digital receiver, which is block diagramed above. The initial stage of the digital receiver receives the 8-bit/256 MSPS data from the analog receiver and applies an optional 0-256 sample integer sample delay. The main band selection is done by a polyphase filterbank (PFB) that can compute two of 16 possible channels. Any two of these channels (or two copies of the same channel) can be computed by the PFB. Part of the PFB operation is a downsampling in rate by a factor of 16. The two 5 MHz channels coming out of the PFB are then further channelized by a 4096-channel FFT filterbank. These fine channels are each 4 kHz wide. Because the band edges are not usable, we keep only the center ~1400 channels of each FFT, resulting in a total bandwidth of 5.33 MHz per tuning, with two tunings available simultaneously. We believe that these channels are narrow enough to resolve most of the RFI so that only a few percent of the channels will be corrupted and most of the bandwidth will be actually usable for astronomy. They are also narrow enough to allow phase, rather than delay, beamforming and meet the science requirements for all but a small number of specialized applications.

After the fine channelization, the two linear polarizations are combined using a general 2x2 matrix multiply, which can simply convert linear to circular polarizations, or implement a more general polarization calibration if needed. Bandpass calibration and channel blanking are then accomplished in a stage that allows a general complex factor for each channel. A complex factor of 0 can be used for channels that are to be blanked. The amplitudes coming out of this stage should be scaled to be optimal for requantization to 4-bits I + 4-bits Q. Following the requantization, the data from 8 stands are multiplexed and serialized for transmission to the beamformer over a single LVDS cable. The total output rate of the digital receiver is 1.4 Gbps per 8 stands for a total of 44.8 Gbps for the whole station.

Beam Former



The beamformer consists of four identical complex, multiply-accumulate (CMAC) chains that form the four beams coming out of the digital receiver. Phase beamforming is implemented by multiplying each sample by an appropriate complex factor (amplitude and phase), and accumulating the result. For our 4 kHz channel bandwidth, the decorrelation scale size is 75 km. Phase beamforming will thus introduce <0.5° of phase smearing over the 100 m diameter of an LWA station. The beamformer receives 2 polarizations, 2 tunings of 5.33 MHz BW each, with 4 kHz channels from each antenna and produces four beams with the same parameters (a factor of 256 data rate reduction). The time resolution of the data coming out is 256 µs, as set by the length of the FFT in the digital receiver. The output rate to the correlator is 4 beams x 42.6 Mbps/beam = 170.6 Mbps over the long distance fiber (per station).

Comparison with Requirements

Parameter	LWA Spec.	Strawman	LWA-1
Frequency Range	20–80 MHz	20–80 MHz	20–80 MHz
# Stands	256	256	256
Antenna sensitivity	Sky noise dominated	Yes, > +6 dB	Yes, >+6 dB
Bandwidth/beam	4 MHz	5.33 MHz	**156 kHz**
Channel bandwidth	100 Hz	4 kHz	4 kHz
Time resolution	10 ms	TBD (mod 256 µs)	TBD (mod 256 µs)
Polarization	1 circular	2 orthogonal (full in correlator)	2 orthogonal
Sky coverage	$z > 40°$ (3 dB)	$z > 47°$ (40 MHz) $z > 61°$ (60 MHz)	$z > 47°$ (40 MHz) $z > 61°$ (60 MHz)
FOV	[8°, 2°] [20,80] MHz	Yes	Yes
# beams	4 single pol.	2 full pol	2 full pol

This table summarizes the specifications of the strawman station design and compares them with the LWA system specifications based on the science requirements.

Conclusion

We have presented a proof-of-concept baseline design for an LWA station. Work is now beginning to do a detailed cost analysis based on this design, as well as on the many engineering design and analysis tasks that result from such a design exercise. Detailed measurements of the RFI characteristics at the site have begun and will provide important input to the analog receiver detailed design. The 16-element Long Wavelength Development Array (LWDA) installation will be completed by mid-September, 2006 (see poster by J. R. Dickel, et al.), and a great deal will be learned by operating it over the next year.

In addition, a great deal of effort beginning on the many aspects of the LWA project that are beyond the scope of this baseline station design including array calibration, site acquisition, correlator design, long distance data communication, array configuration, etc...

Basic research in radio astronomy at the Naval Research Laboratory is supported by NRL/ONR.