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A Strawman Design for the Long Wavelength Array Stations

Paul S. Ray[1] (NRL), S. Ellingson (VA Tech), R. Fisher (NRAO), N. E. Kassim (NRL), L. J. Rickard (Independent), T. Clarke (Interferometrics/NRL)

ABSTRACT

This document presents a "strawman" design for the Long Wavelength Array (LWA) stations.

1. Introduction

The Long Wavelength Array (LWA) is intended to be a radio astronomical and ionospheric interferometer operating in the 20–80 MHz band. Although various descriptions have been developed for it, they are largely conceptual. Recently, working groups have been formulated, with members drawn from various institutions, and the choice of working groups is similar to what might be envisaged for sub-systems of the array. To unify the work of these disparate groups, it helps to have a common concept of the full instrument design that is concrete and provides a reference with which to compare alternatives.

This document presents such a "strawman" reference design. The goals of this reference design are two-fold: To focus the engineering and science efforts in the design and 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 issues need to be addressed to turn this design into reality?" We hope it proves useful and we encourage discussion, criticism, contributions via the LWA discussion group hosted at http://groups.yahoo.com/group/long_wavelength_array.

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 and, as such, it explicitly does not address several important aspects of the full LWA project such as site acquisition, legal issues, test & evaluation plan, etc. It also does not explain the scientific requirements that the design is attempting to meet, because those are detailed elsewhere. 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 document is organized in order of signal path, from antenna through data archive and analysis.

[1]Paul.Ray@nrl.navy.mil

2. Antenna

The strawman antenna is the "big blade" design mounted on a pyramidal PVC structure as shown in Figure 1. Each PVC pyramid with two linearly-polarized dipoles attached will be referred to as a "stand". The impedance, beam patterns, and sky noise dominance of the big blade antenna is shown in Figures 2–4.

Fig. 1.— Strawman big blade antenna on a PVC pyramidal mount.

The big blade antenna design appears to be usable for the LWA, however there is little margin, particularly at the top and bottom ends of the band. That is, the expected performance is very close to the minimum acceptable level. Thus, small improvements have the potential to make large effects in the sensitivity (e.g. integration time required) and beam pattern. In addition, a key issue is making them inexpensive to produce and install as well as durable enough for 10 year or more lifetimes in the New Mexico environment.

Some of the important research aspects to get closer to a final design include:

- Should a ground screen be included, and if so, what dimensions are required? Here the cost to install and maintain a ground screen must be weighed against the potential performance improvements.
- How will the stands be secured to the ground, in a variety of soil conditions that will be encountered at the various sites?

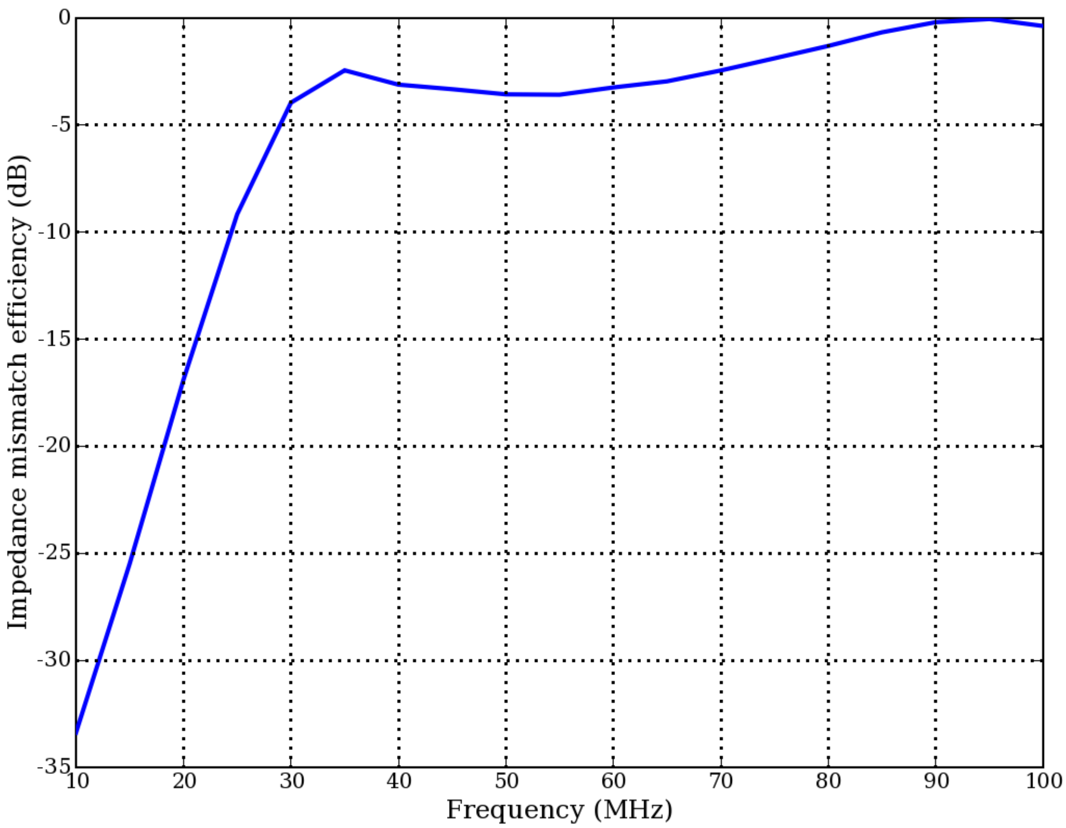

Fig. 2.— Dipole impedance mismatch efficiency as a function of frequency for the big blade antenna. The antenna impedance, Z_a was calculated using CST Microwave Studio assuming a perfect electrical conductor (PEC) ground. The balun impedance ($Z_{\rm pre}$) is assumed to be 50 Ω per arm, and the reflection coefficient (Γ) is thus $\Gamma = \frac{Z_{\rm pre}-Z_a}{Z_{\rm pre}+Z_a}$. The "impedance mismatch efficiency", $10\log_{10}(1-|\Gamma|^2)$ (in dB), is the fraction of power captured by the antenna that is accepted by the balun.

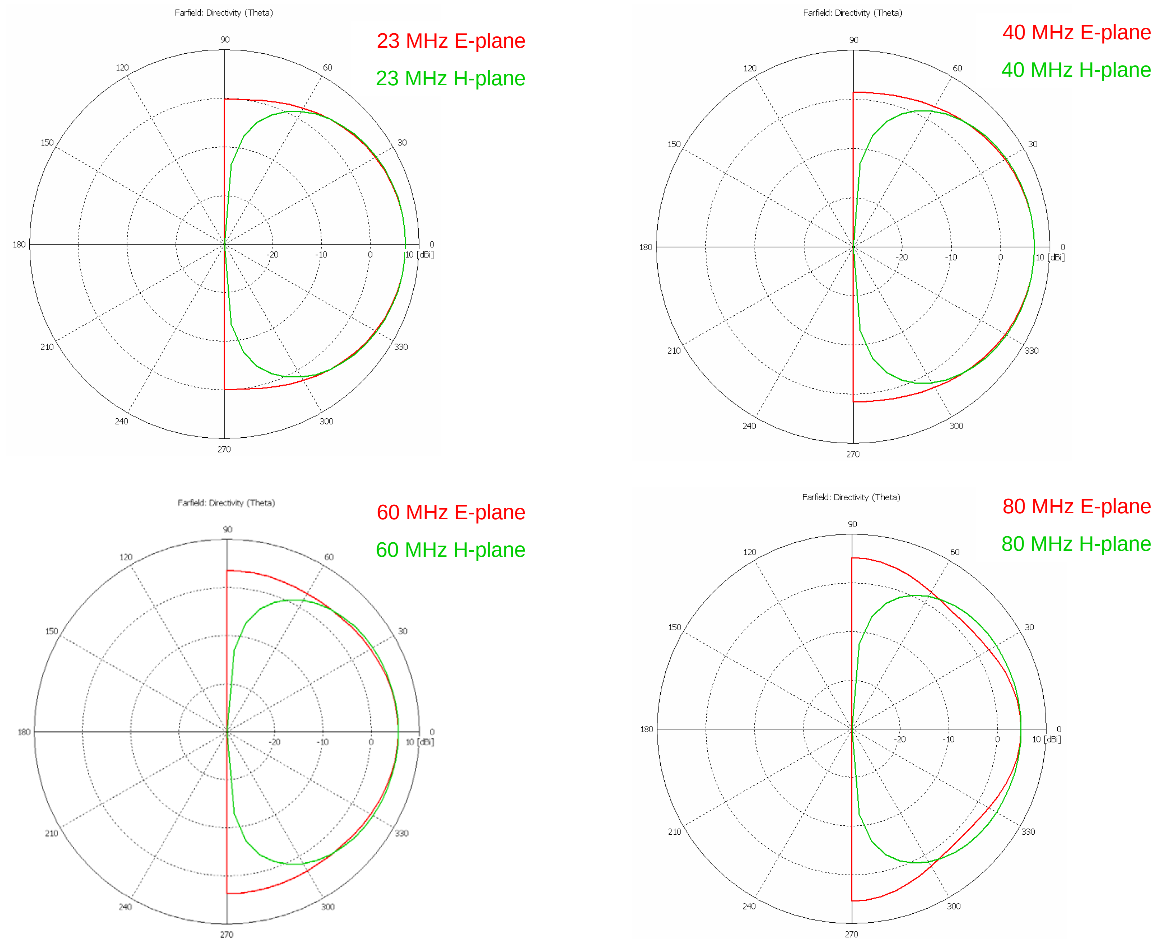

Fig. 3.— Simulated beam patterns (i.e. far-field directivity in dB) as a function of angle for the large blade antenna in both the E- and H-planes, for four different frequencies. Calculated using CST Microwave Studio assuming a perfect electrical conductor (PEC) ground.

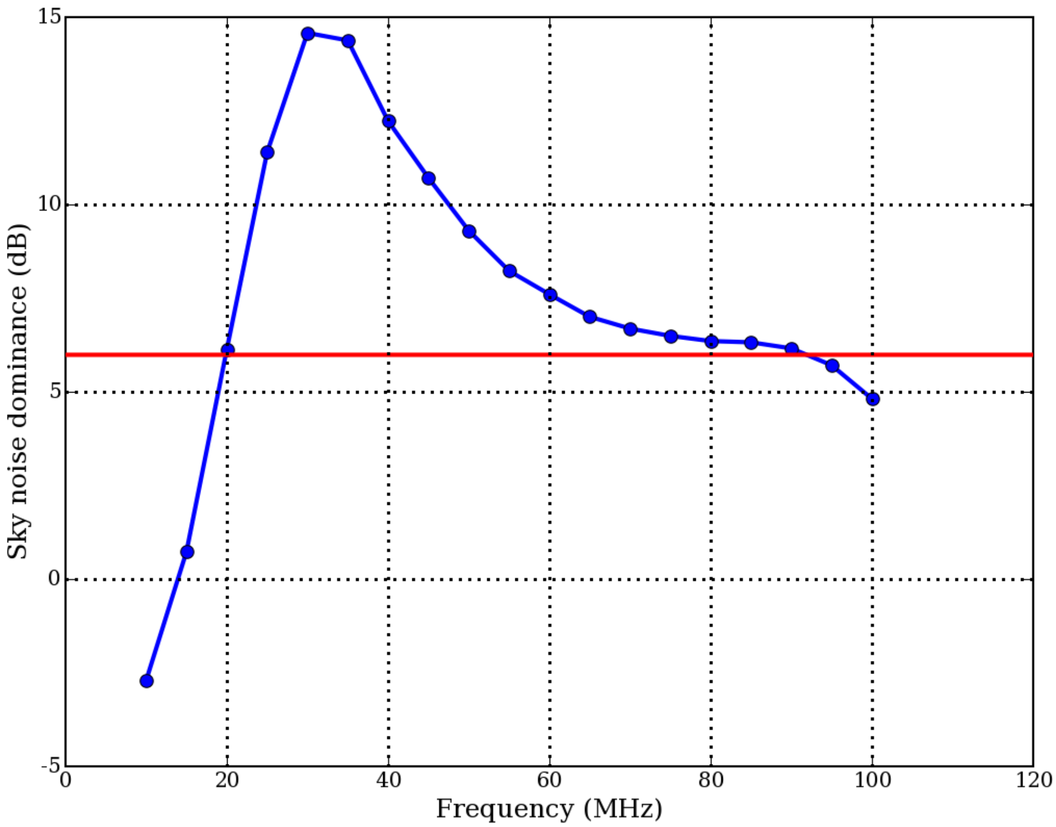

Fig. 4.— Simulated sky noise dominance (in dB; assuming a 250 K balun effective noise temperature and 100 Ω input impedance) as a function of frequency for the big blade antenna. The red line shows the LWA requirement of +6 dB. Values were computed using the impedance calculation from CST Microwave Studio assuming a perfect electrical conductor (PEC) ground, combined with Galactic noise model from Cane (1979).

- 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? Both simulations and measurements should be started as soon as practical. The measurements should include S-parameter measurements on antennas in the field, repeated as additional antennas are placed nearby. These results can give feedback to the simulation work. Does increasing the balun impedance significantly help? Are there other techniques that should be considered (e.g. phase switching schemes)?

- A prototype stand should be fabricated and put at the LWDA site as soon as possible to see how it withstands the environment. What is the best design and materials choice to maximize the durability?

- Accurate ($\sim 5\%$) measurements of the antenna pattern and sky noise dominance should be performed. This requires moving beyond the simple spectrum analyzer-based measurements to a real digital receiver system.

3. RFI Issues

Radio Frequency Interference (RFI) is important enough to the operation of the LWA that it must be considered at all stages of design and testing. This includes both the response of the system to external RFI and the production of self-generated RFI that could affect the system itself or other radio instruments that may be in close proximity to an LWA station (e.g. VLA/EVLA/FASR/VLBA).

Self-generated RFI must be minimized by both careful design and shielding.

External RFI must be well understood and characterized because it is a critical input to many aspects of the design, including the linearity of the analog balun and amplifiers, the quantization dynamic range of the analog-to-digital converters, the number of bits required in the DSP processing, the spectral resolution required in the digital receiver, the data rate required across the long distance fiber, and the design of post-corrlation RFI rejection algorithms.

The first step in dealing with the RFI environment is understanding it. Substantial and continuing effort should be dedicated to understanding the local RFI environment. This includes both keeping track of licensed transmitters (e.g. via the FCC database of TV transmitters at http://www.fcc.gov/fcc-bin/audio/tvq.html) and regular RFI monitoring measurements at all potential LWA station locations. This monitoring should cover at least the range 10 MHz to 200 MHz so that it covers the full observing band, as well as the signals in the second Nyquist zone that can alias in to the band pass (which determines the required stop band specifications for the anti-alias filter). This can not be done "once and for all" because the RFI environment is constantly changing. The roll out of digital television services, the possible deployment of broadband over power lines (BPL), and the sale of spectral space to new users will all cause the situation to be highly dynamic.

Suggested actions:

- Test candidate ADC designs in the actual RFI environment to measure their performance at real signal and RFI levels.
- Perform a time-domain Monte Carlo simulation of intermodulation products produced in candidate analog receiver/front-end electronics chains. This involves folding real measured RFI levels through a mathematical model of the nonlinearities to see what fraction of the spectrum is affected by spurious signals.
- Perform frequent, calibrated RFI measurements at candidate LWA sites across the state.

Note that poorly shielded coax cable from the antenna to the receiver can easily pick up RFI emissions. Burying it can greatly reduce this effect.

4. Station Configuration

The LWA strawman station configuration is a pseudo-random design created using the CONFI task in AIPS (Kogan 2000), as shown in Figure 5. 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 strawman station is evaluated by performance metrics defined below and plotted in Figures 6 and 7.

The station diameter is set to 100 m to give a 4× smaller field of view and 16× 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 when hung at a 45° angle. In the absence of mutual coupling measurements between the station elements, 4m was chosen as the minimum seperation to allow servicability and tolerance for surveying errors in the element positions.

Beam Size & Ellipticity The main beam is only circularly symmetric at zenith, therefore the beam size metric is defined as:

$$\text{Beam Size} = (B_{\text{major}} \times B_{\text{minor}})^{1/2}$$

where $B_{\rm major}$ and $B_{\rm minor}$ are the largest and smallest angular extents of the beam. The ellipticity metric measures the distortion from circular symmetry:

$$\text{Ellipticity} = \frac{B_{\rm minor}}{B_{\rm major}}$$

Beam Efficiency The beam efficiency metric gives an indication of the amount of power in the main beam versus the amount spread around in sidelobes.

$$\text{Beam Efficiency} = \frac{\int_{\rm MainBeam} P(l,m)\, d\Omega}{\int_{4\pi} P(l,m)\, d\Omega}$$

Peak Sidelobe A metric to keep track of the strongest power level outside the first null of the main beam.

Max Effective Area A measure of how effective the station is at absorbing radiation from the region of sky the station is pointed.

$$A_{\rm eff} = \frac{\lambda^2}{\int_{4\pi} P(l,m)\, d\Omega}$$

Aperture Efficiency The aperture efficiency is defined as the ratio of the effective area to the physical area of the station:

$$\text{Aperture Efficiency} = \frac{A_{\rm effective}}{A_{\rm physical}}$$

For a circular station, the aperture efficiency is:

$$\text{Aperture Efficiency} = \frac{\lambda^2}{\pi R_{\rm station}^2} \frac{1}{\int_{4\pi} P(l,m)\, d\Omega}$$

5. Front End Electronics

The front end electronics (FEE) consists 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 simple bandpass filter (20–80 MHz) and a second gain stage (see Figure 8). The active balun presents a 50 Ω 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

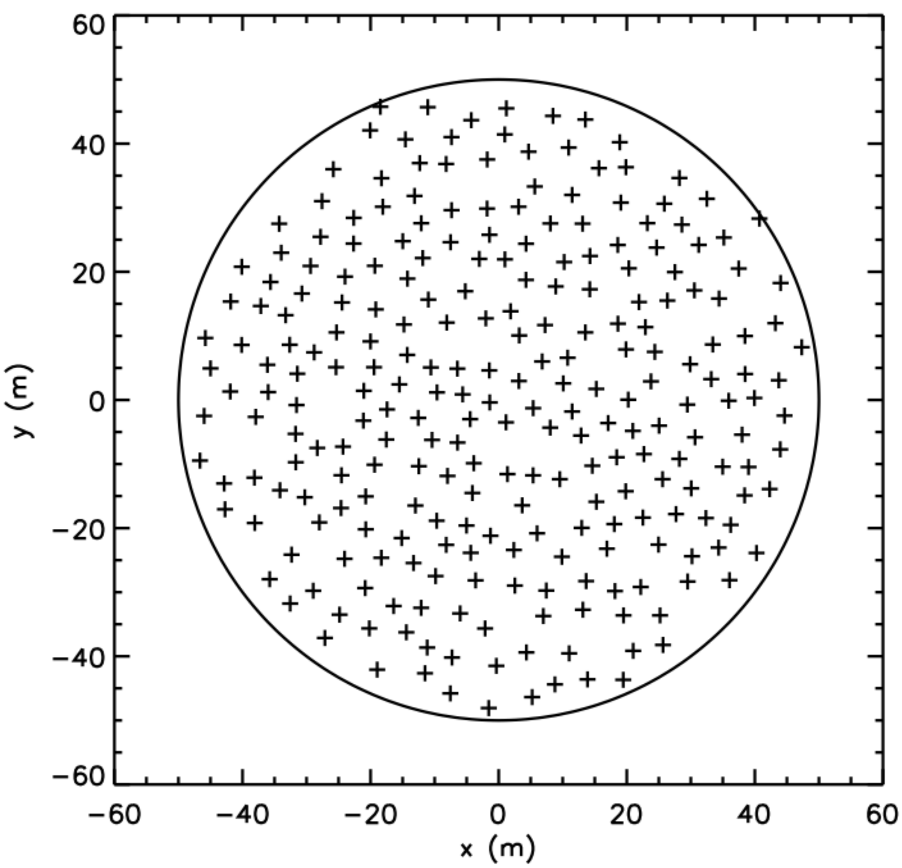

Fig. 5.— Configuration of elements within each station.

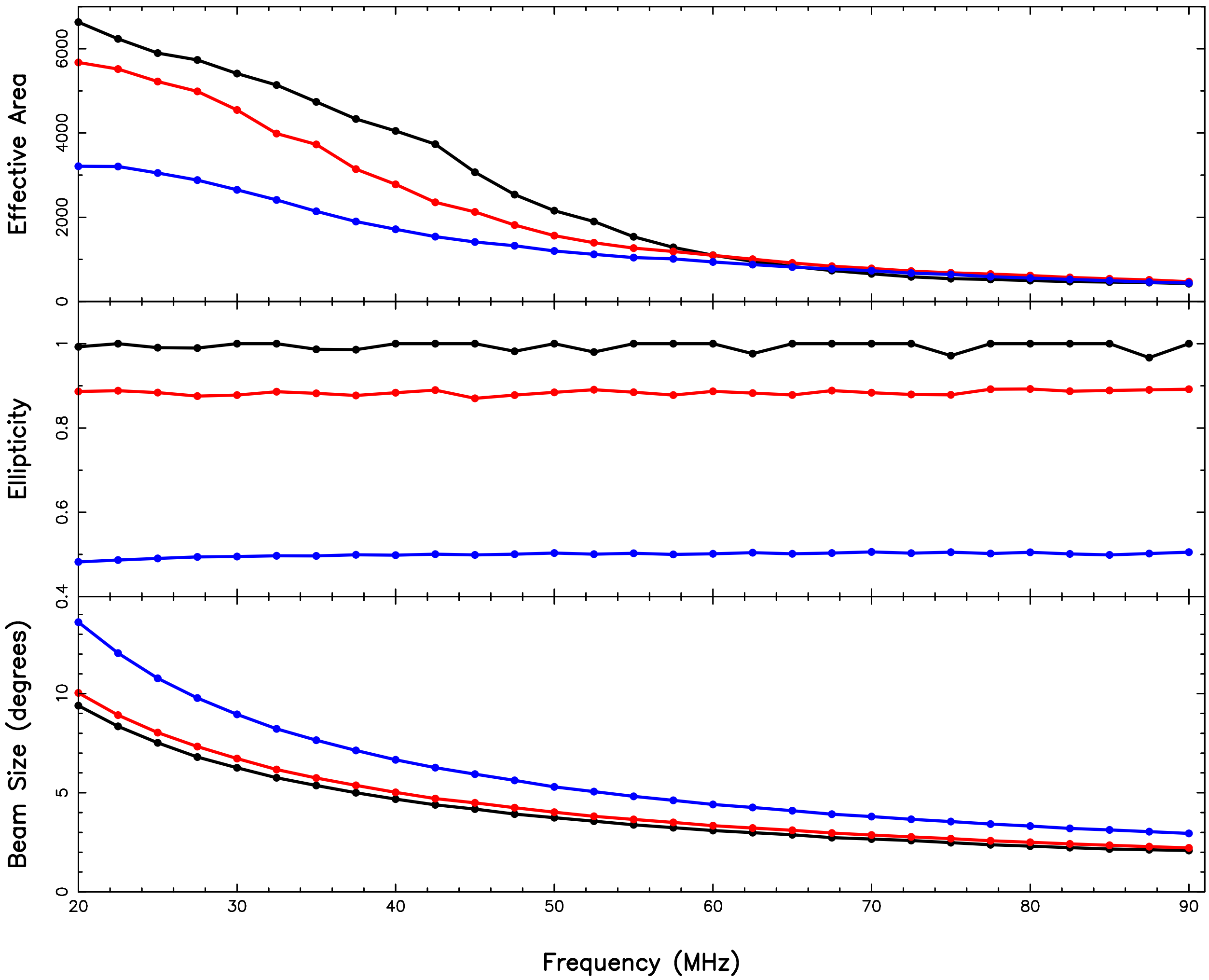

Fig. 6.— Strawman station effective area, beam ellipticity, and beam size as a function of frequency for three different zenith angles (black = 0°, red = 30°, blue=60°). Element patterns have not been included in these metric calculations.

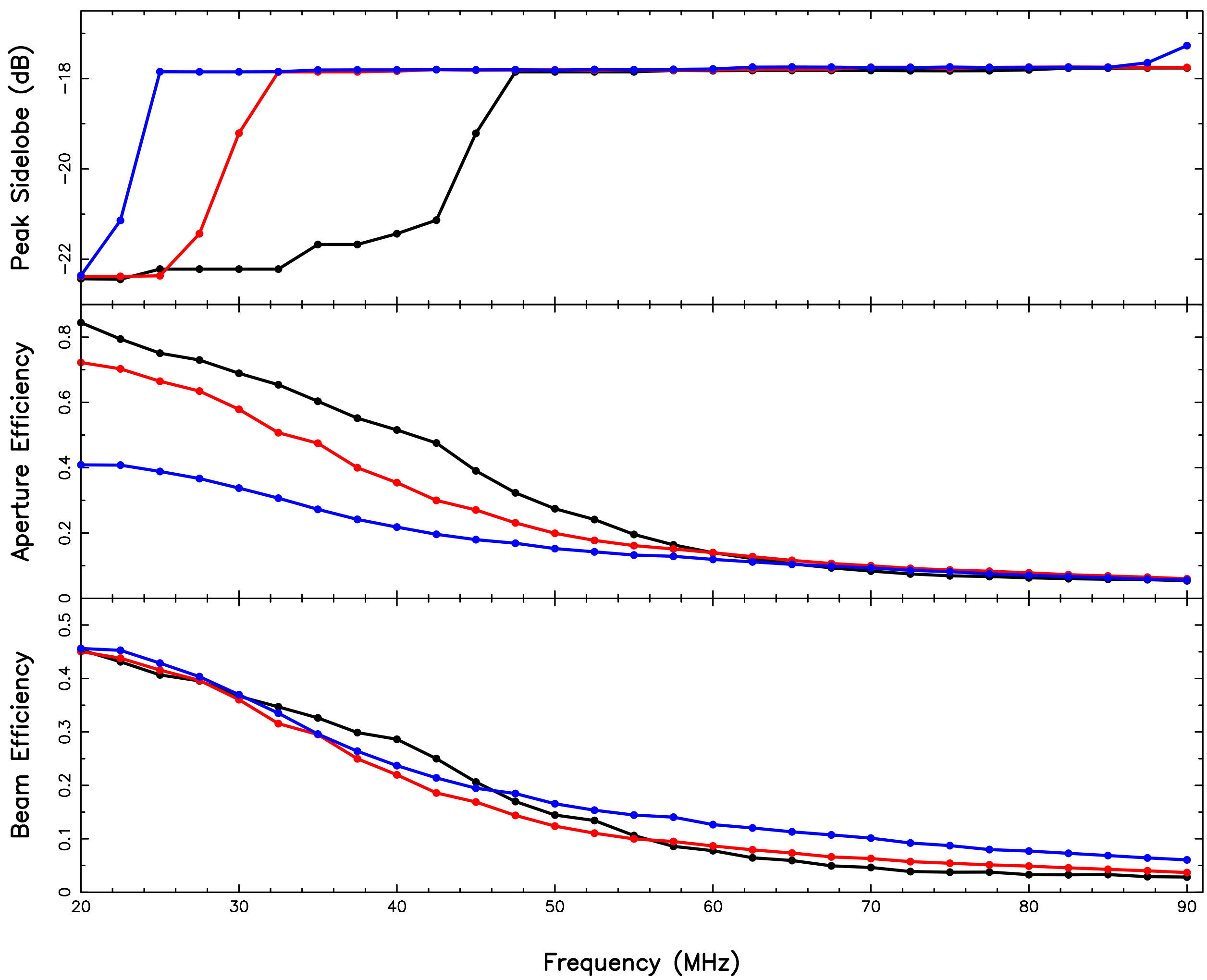

Fig. 7.— Strawman station peak sidelobe level, aperture efficiency, and beam efficiency as a function of frequency for three different zenith angles (black = 0°, red = 30°, blue=60°). Element patterns have not been included in these metric calculations.

output impedance of the FEE to the 75 Ω 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 and such.
- Work on lowering the effective noise temperature of the balun ($T_{\rm eff}$) 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.

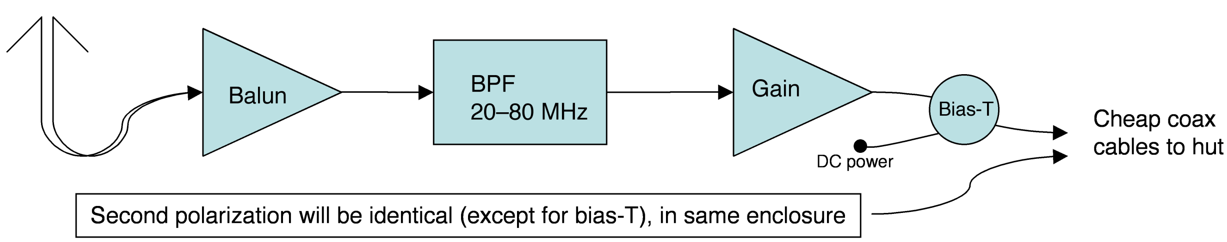

Fig. 8.— Front end electronics block diagram.

6. Station Electronics

The station electronics encompass all of the hardware in the equipment hut. A basic block diagram is shown in Figure 9. The station electronics takes the RF signals from all of the antennas and processes them into a small number of "beams" which are sent over a long-distance fiber-optic link to the central processing facility that houses the correlator. The operation of the station is controlled by a Monitor & Control computer that communicates via a modest speed internet connection. The following subsections describe each component of the station processing in more detail.

6.1. 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, as described in §3.

The key issues to consider are:

- Can we get 10-bit flash ADCs, or some other architecture which will get more bits without compromising the SFDR performance when used in our application.
- The linearity of the whole analog chain is dominated by the linearity of the final amplification stage. Some analysis is required to specify the minimum IP3 required for this stage (e.g. see §3).
- Candidate ADCs for the real design must be tested with real input, in the field. The data sheet SFDRs don't reflect the needs of the LWA accurately, since they are typically measured with a 95% full scale sine wave, which is nothing like our typical signal level or character.
- Particularly since the design will be cost constrained and may be operating at close to the minimum acceptable levels of nonlinearity and dynamic range, we should consider building a small number of "gold-plated" analog chains using expensive COTS parts that have specifications that greatly exceed our needs. These analog receivers will make great test devices to help with instrument validation and for comparison with candidate designs.

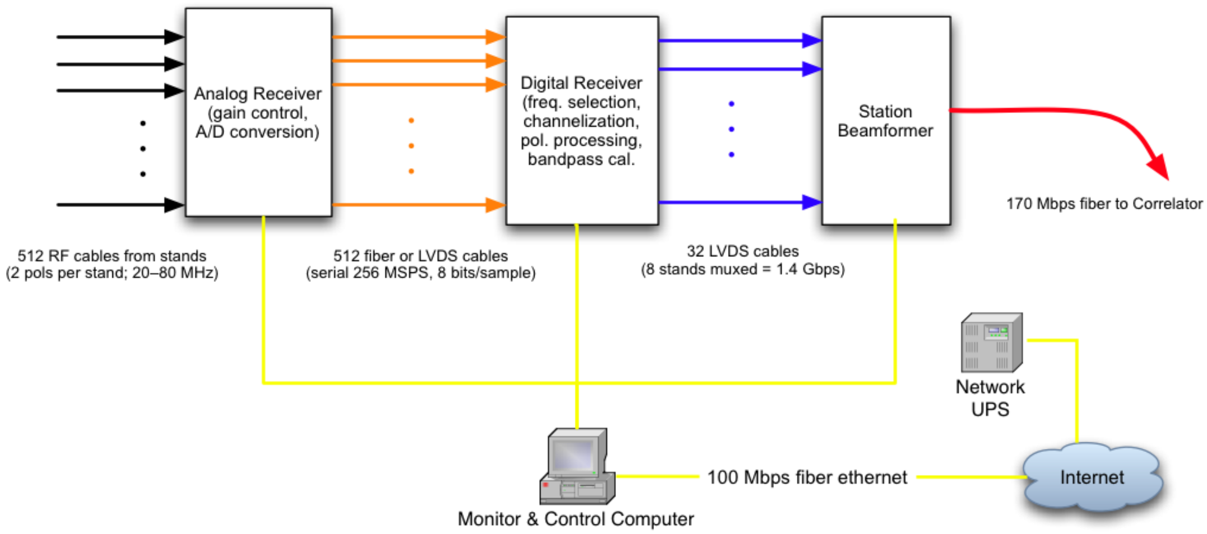

Fig. 9.— Block diagram of station electronics.

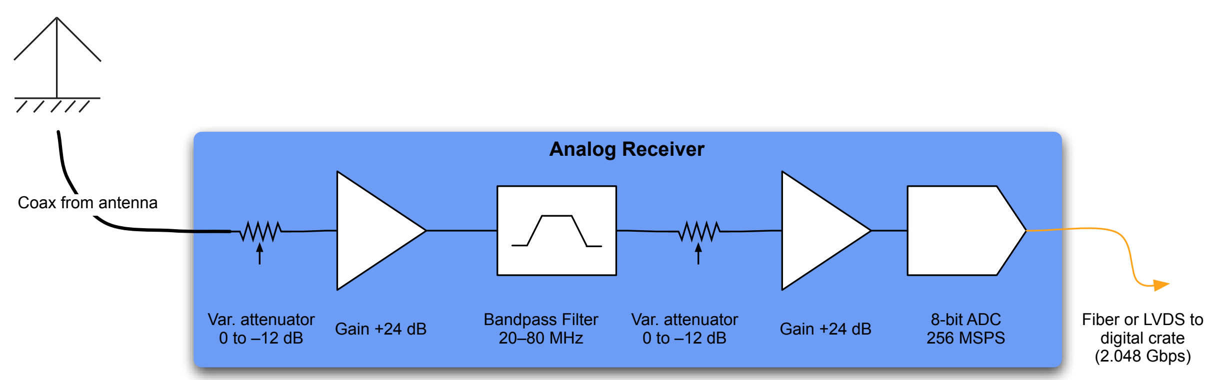

Fig. 10.— Analog receiver block diagram. This shows a single analog chain (one polarization from one stand) out of the 512 needed for a full station.

6.1.1. GNI Analysis

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 (Razavi 1998). We have done this for the strawman design using the free `cascade` program available at http://rfcascade.sourceforge.net. `cascade` allows the user to enter a file containing lines that specify each component in the analog chain, with one component per line. Each component can have a name, a gain (`g` in dB), an input IP3 (`iip3` in dBm), and a noise figure (`nf` in dB). It then analyzes the performance of the full chain. Note that when putting in a lossy element such as an attenuator or a cable, the noise figure should be set equal to the attenuation (i.e. the negative of the gain). Also, note that effective temperature of an amplifier is related to the noise figure according to

$$T_{\rm eff} = 290{\rm K} \times (10^{\rm NF/10} - 1) \tag{1}$$

The input to `cascade` for the strawman consists of this file:

```
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 (cheapo 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
```

The results are specified in Table 1.

6.2. Digital Receiver

All of the digital signal processing between the ADC and the beamformer takes place in the digital receiver, which is block diagramed in Figures 11 & 12.

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. This is easy to implement in the FPGA and does not consume many resources, so it is included in the design should it be found to be useful, however the strawman beamformer uses phases, rather than delays, on the narrow band channels so this stage is not strictly necessary.

Because there are several potential applications for the LWA stations that require the raw data stream from all elements (such as radio pulses from ultra-high-energy cosmic rays (UHECRs) or a wide-field correlator), we propose to provide a tap off the digital receiver at this point to accommodate such applications. This way, these specialized applications don't need to drive the design of the main LWA electronics, but can be added as resources and interest permit.

The main band selection is done by a polyphase filterbank (PFB) that can compute two of 16 possible channels. The center frequencies are fixed at integer multiples of 4 MHz and each channel is 5 MHz wide. 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. Note that no numerically-controlled oscillator (NCO) or CORDIC tuner is required in this design, which saves FPGA resources (and also limits the center frequencies to the 4 MHz grid).

The two 5 MHz channels coming out of the PFB are then further channelized by a 4096-channel FFT filterbank (or alternatively a PFB, of which the FFT is a low-performance special case). These fine channels are each 4 kHz wide. Because the band edges are not usable, we keep only the center $\sim$ 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. In principle, these applications that require higher resolutions ($\sim$ 100 Hz) could be enabled by a special firmware version that could be uploaded for special situations. This would have to fit in the same FPGA resources, of course, so compromises on time resolution or total bandwidth would probably be required in those modes.

After the fine channelization, the two linear polarizations are combined using a general 2×2 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.

The key research items are:

- Is it ok to requantize to 4-bit I + 4-bits Q before beamforming?
- How should the bookkeeping issues be handled (blanked channels, applied gains, etc.)?
- Is 4 kHz resolution really fine enough to resolve out the RFI sufficiently? Test in the field soon!
- Is there a real requirement for larger instantaneous bandwidths than the $\sim$ 10 MHz provided by this design?
- Does the FFT need a window function applied?
- For the fine channelization stage is the baseline FFT the best choice or would a polyphase filterbank be preferable?
- What FPGA components are required to fit this design (and how much do they cost)? This can only really be ascertained by actually synthesizing the design and fitting it to real parts. This should be done soon as well.

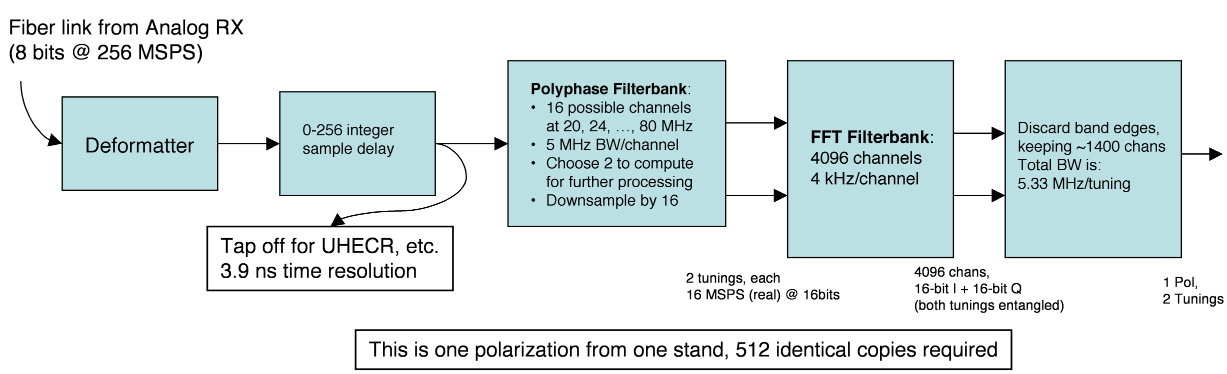

Fig. 11.— Digital receiver block diagram, first section.

6.3. Beamformer

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

Table 1. 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

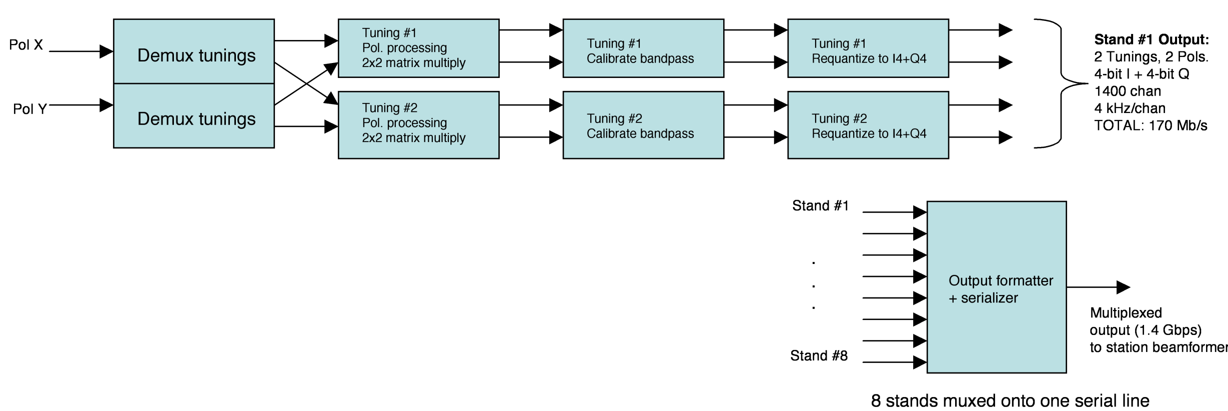

Fig. 12.— Digital receiver block diagram, second section.

the result. For our 4 kHz channel bandwidth, the decorrelation scale size is $c/\Delta\nu = 75$km. Phase beamforming will thus introduce $< 0.5^\circ$ 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 $\times$ 42.6 Mbps/beam = 170.6 Mbps over the long distance fiber (per station).

The issues that need attention are:

- Additional beams (from the same pair of tunings) can be added in a straightforward manner as shown in the orange block in Figure 13. The primary costs are additional FPGA resources, higher fiber bandwidth, and increased correlator resources required.
- Adding more beams to cover more frequency space than the 10 MHz maximum in the strawman design would require a different digital receiver architecture, that will certainly increase cost and complexity. This needs more study if there is a compelling requirement for larger instantaneous bandwidth.

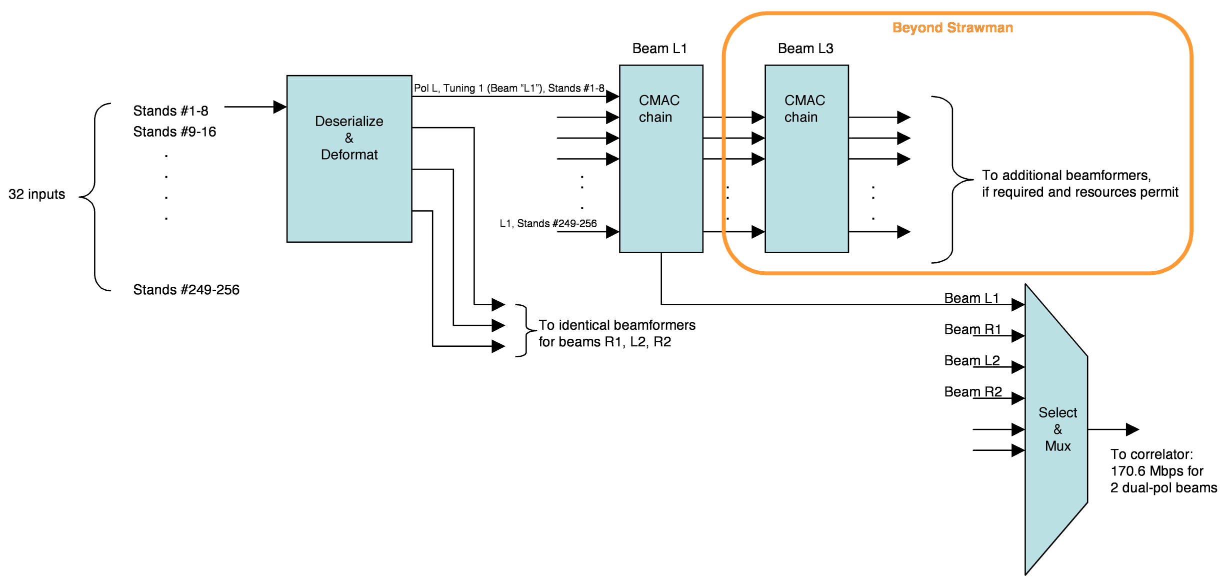

Fig. 13.— Beamformer block diagram.

7. Long Distance Data Communications

The implementation and cost of the long distance data communications (which will almost certainly be over fiber) needs much more study and no strawman design is ready at this point. Here we just make some observations and recommendations:

- Burying cable has been quoted at $35k/mile, so leasing dark fiber from phone companies is an attractive option. In this case we must provide our own electronics, which could contain only the functionality required and no fancy extras.

- With wavelength domain multiplexing, the signals from multiple stations can be sent over a single fiber.

- The LWA fiber connections probably need only to be 1-way since M&C information can be sent over an ethernet connection (since the bandwidth and latency requirements are not so stringent as for the streaming data). However, if wavelength-domain multiplexing is used, some wavelengths could be devoted to bidirectional communication.

- The Fibre Channel solutions being explored for the GBT might be of interest, but the Fibre Channel protocol has a lot of overhead and unnecessary stuff that we don't need.

- For the early station deployments, it is possible that stations will be built before the fiber connections are ready. For this, a recorded data ("VLBI") mode may be useful. Since the data can be time stamped at the stations using the GPS-disciplined clock, they can be recorded to a disk storage array and transported to the correlator for non-realtime correlation.

8. Correlator

The correlator plan for the LWA is complicated because of the multiple stages of operation and requirements to correlate with the VLA. It clearly requires significantly more study. For the purposes of the strawman design, we propose a correlator based on the BEE2 boards being developed at Berkeley, similar to what is being designed for the PAPER array and the ATA correlator (Chang et al. 2005). This will be an FX correlator, but the 'F' is already done by the digital receiver, so significantly less computation is required by the correlator than for those other projects.

The strawman time/frequency standard for the stations will be a GPS-disciplined Rubidium standard (such as Timing Solutions TSC 4410A). These cost about $7k/station.

Some of the many issues to investigate are:

- How hard would it be for us to write our own software FX correlator, for use when there are just a few (1–3) LWA stations?

- How do we digitize a VLA dish data stream for correlation with LWA stations?

- A survey of commercial data recorders should be done to find options appropriate for non-realtime analysis with a software correlator.

9. Comparison with LWA Requirements

Table 2 compares the specifcations of the strawman design presented here with those in the LWA specifications document.

10. Development Plan for LWA-1 & LWA-2

Within the LWA project, there is both a strong management desire and very good engineering reasons to proceed quickly with building a first full station, called LWA-1. This is the successor to the 16 element LWDA station, and will be built in the same location.

We considered what might be feasible to be ready to start building about 1 year after the start of LWA project funding. The goal was to retain as much of the LWA functionality as possible so that real world experience would be gained on actual candidate LWA designs. However, it is likely that the full strawman station would not be ready to build in a short enough time.

Our suggested strawman for the LWA-1 station is to build the station just as suggested in the above strawman, including the 256 antennas, front end electronics, analog receiver, and digital receiver. However, instead of the full beamformer, we suggest building a data aggregation board that selects only 156 kHz of bandwidth (out of the 5 MHz total per beam) that combines 32 inputs of 8 stands each into 5 data streams of ~ 50 MB/s, which can be recorded to a PC-based disk array. Both beams and both polarizations can be recorded this way, and the 156 kHz was chosen simply as the maximum bandwidth that can be easily recorded in this way. Other than the bandwidth per beam, the characteristics of LWA-1 are the same as the LWA strawman in Table 2. In addition, the data aggregation boards will be very useful test fixtures for future stations as they are built.

For this simplified station we do not need to build the beamformer, the fiber optic transmission system, or the correlator. Using this station design, we will be able to:

- Implement the beamformer in software on the data recorder PCs, and test beamforming algorithms and performance (including nulling schemes if desired)
- Do full sky imaging/transient searches (which is actually *not* possible with the full LWA).
- Correlate the station beams (using a software correlator) with an outlier dipole, presumably a well characterized, frequency tunable, EMI measurement dipole.
- Map the dipole and station beam patterns to high accuracy.
- Investigate mutual coupling effects.
- Correlate with the VLA (using the reduced bandwidth of 156 kHz).
- Carefully characterize the RFI susceptibility and self-generated RFI properties of the system.

- Expose many unanticipated problems in turning a design into a real operating system, by getting early experience with real LWA hardware designs.

During the deployment and testing of the LWA-1 station, the LWA-2 station will be in development. We anticipate that it would include the full beamformer and include many improvements and lessons learned from LWA-1. Other design improvements that were not ready for LWA-1 could also be included such as improved balun designs, new antenna designs or mounting hardware, etc.

11. Strawman Cost Analysis

An important next step in utilizing the strawman design is to do some cost analysis and see if it is affordable under the current budgetary requirements. This will force some discipline on the engineering designs and may require some difficult decisions by the science requirements group.

12. Additional Work

This document, the product of a relatively short meeting involving only a few people, is intended to encourage a wider, cross-system analysis of the technical realization of the LWA project, given what we know at this early stage. The "strawman station" concept, by definition a work in progress, provides a first potentially realizable vision of a complete LWA station. By posing the question "Why can't this work?", it is hoped that debate within the relevant Working Groups (and beyond) will address the strengths and shortfalls of the approaches proposed, indicate how improvements or replacements could better meet the needs of the LWA, and define the required tests and development work.

An initial pass at an LWA station strawman design was also a necessary step in working out a viable path towards a fast-track LWA-1 station. LWA-1 needs to demonstrate "facts on the ground" progress reflective of a healthy, functioning project soon after the onset of real funding. Equally important, it has to be a forward-looking, rather than diversionary exercise, which will enhance our experience base and efficiently illuminate a pathway to a yet improved LWA-2, and so on.

What was stated at the onset but bears repeating here is that this document, with its relatively narrow focus on station design, is only one piece of a comprehensive system-engineering based description of the full LWA instrument not yet in hand. We have commented on aspects of a few of those additional areas, such as long range data communication and correlator considerations, in our document. However, the number of areas that need careful study are many and a, certainly incomplete, list includes:

- Array Configuration
- Long Distance Data Communications

- Correlator
- Monitor & Control System and Software
- Post-Correlation Processing
  - Ionospheric Calibration & Wide-field Imaging
  - Data Handling & Archiving
  - Detailed Cost Analysis

In closing, we suggest that the results of the system-engineering based exercise reflected in this document for a single LWA station recommend it as a model for other small, focused groups to convene and generate similar strawman solutions for other necessary components of the system design. It is often the case that, by restricting to a small group, it is possible to sustain the kind of focus needed to do significant creative work in a short time span (in this case, just a day and a half). We suggest that such a model might be used as a means of convening small, parallel focus groups at the start of the July LWA planning meeting, with the aim of developing proposed strawman solutions to as many of the areas listed above as is possible based on the expertise base present.

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Table 2. Comparison with LWA 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