Long Wavelength Array
Station Architecture

Version 2.0

Prepared By:		
Names(s) and Signature(s)	**Organization**	**Date**
Joe Craig	UNM – LWA Project	2009-02-26
Approved By:		
Name and Signature	**Organization**	**Date**
Joe Craig	UNM	2009-02-26
Lee J Rickard	UNM	2009-02-26

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Joe Craig*

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*University of New Mexico, 1009 Bradbury, Albuquerque, NM 87131 USA. E-mail: `joecraig@unm.edu`

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1 Introduction

1.1 Purposes

This document describes the architecture of a Long Wavelength Array (LWA) station. For an introduction to and overview of the LWA, refer to [20, 8]. This document (along with [8]) is intended to provide a detailed introduction to LWA station design and specification issues, as well as to provide a framework for developing subsystem and interface specifications. With regard to the latter, this document defines subsystems, interfaces, and concise identifying nomenclature.

1.2 Terminology and Acronyms

The LWA is an array of stations which collectively operate as an interferometer. Each station has an array of antennas which are used to form beams. Thus, the use of the word "array" in LWA discussions can sometimes be ambiguous. In this document, the word "array" always refers to the antennas that are part of the station and which are used to form station beams, unless explicitly indicated otherwise.

In this document, LWA subsystems are typically identified by a 3-letter acronym, as shown in Table 1. Additional terms and symbols are introduced in Table 2.

1.3 Specifications

A summary of specifications for an LWA station appears in Table 2.

Note that Table 2 identifies certain specifications as "domain specifications". These are specifications which define the parameter spaces over which all other specifications apply. Any contradiction with science or technical requirements documents should be resolved in favor of those documents.

The Data Aggregation and Communication (DAC) subsystem will not be implemented in the first station (LWA-1) as described in section 7. Data recording functionality for LWA-1 is described in section 6.1 (MCS-DR) and the DAC will be limited to a Local-Area Network (LAN) and internet connection only.

1.4 Subsystems & Nomenclature

The station architecture is summarized in Figures 1–4. Table 1 identifies the hierarchy of subsystems within an LWA station. Subsystems ARR, ASP, DP, TCD, MCS, DAC, and SHL are referred to as "level-1" subsystems, for which there is one per station and which, taken together, comprise the entire station. Subordinate subsystems such as the DP's DRX are referred to as "level-2" subsystems. Each level-1 subsystem may include multiple (in fact, variable) numbers of level-2 subsystems. As an aid in understanding, Table 3 identifies those subsystems which lie directly in the "primary" signal flow, in the expected order.

Note that the same nomenclature is sometimes used for multiple sub-subsystems playing similar roles in different subsystems. For example, both the ASP and the DP have an MCS, and also there is a "master" MCS for the station. When the possibility for ambiguity arises, the subsystems should be referred to as ASP-MCS, DP-MCS, and Station MCS respectively.

Section	Nomenclature	Subsystem	Remarks
2	**ARR**	**Array**	Geometry: Sec. 2.2.
2	STD	Stand	
2.1	ANT	Antenna	
3.2	FEE	Front End Electronics	a.k.a. *active balun*
2.3	GND	Ground Screen	
3.3	RPD	RF & Power Distribution	a.k.a. cable system
	ASP	**Analog Signal Processing**	
3.4	ARX	Analog Receiver	
	PCD	Power Conditioning & Distribution	includes FEE Power
	MCS	Monitoring & Control System	
	EMD	Electromechanical Design	
	DP	**Digital Processor**	
	DP1	Digital Processing 1	
4.1	DIG	Digitizer	ADC
4.3	BFU	Beamforming Unit	
4.5.1	TBW	Transient Buffer – Wideband	
4.5.2	TBN	Transient Buffer – Narrowband	
	DP2	Digital Processing 2	
4.4	DRX	Digital Receiver	
	MCS	Monitoring & Control System	
	PCD	Power Conditioning & Distribution	
	EMD	Electromechanical Design	
6	**MCS**	**Monitoring & Control System**	*Station* MCS
6.1	DR	Data Recorders	for LWA-1 only
	PCD	Power Conditioning & Distribution	
	EMD	Electromechanical Design	
5	**TCD**	**Timebase & Clock Distribution**	a.k.a. GPS Timing
7	**DAC**	**Data Aggregation & Communication**	not implemented in LWA-1
9	**SHL**	**Shelter**	
	SEP	Signal Entry Panel	connections to ARR
9.1	PCD	Power Conditioning & Distribution	a.k.a Shelter PCD
	ECS	Environmental Control System	
	MCS	Monitoring & Control System	
8	**ABE**	Alternative back ends	

Table 1: Subsystem hierarchy and nomenclature.

Specification	Name	Value	Remarks
Domain			
Max integration time	τ_{max}	8 h	where, $\frac{\Delta T}{T_{sys}} = \frac{1}{\sqrt{\Delta\nu \cdot \tau}}$ may no longer be valid
Min Frequency	ν_{min}	10 MHz	
Max Frequency	ν_{max}	88 MHz	RF beamforming over the range ν_{min} to ν_{max}
Sky Coverage	Ψ	$z \leq 74°$	z is zenith angle
Other			
Number of Stands	N_a	256	Memo 94 [7].
Beam Size	ψ	$8° \ (20 \text{ MHz}/\nu)$	Between half-power points
Number of tunings	N_t	2	Per beam (i.e., per BFU, via one DRX)
Number of beams	N_b	4	Each with 2 orthogonal pol's
Polarization		dual circular $\geq$ 10 dB	cross-polarization isolation
Instantaneous Bandwidth	B	8 MHz	via DRX, adjustable downward
		78 MHz	via TBW
Finest Spectral Resolution	$\Delta\nu$	100 Hz	via DRX or TBN, adjustable upward
Finest Temporal Resolution	Δt	0.1 ms	via DRX or TBN, adjustable upward
		13 ns	via TBW $(= 1/B)$
Power consumption		30 kW	estimated maximum

Table 2: A simplified subset of specifications for an LWA Station.

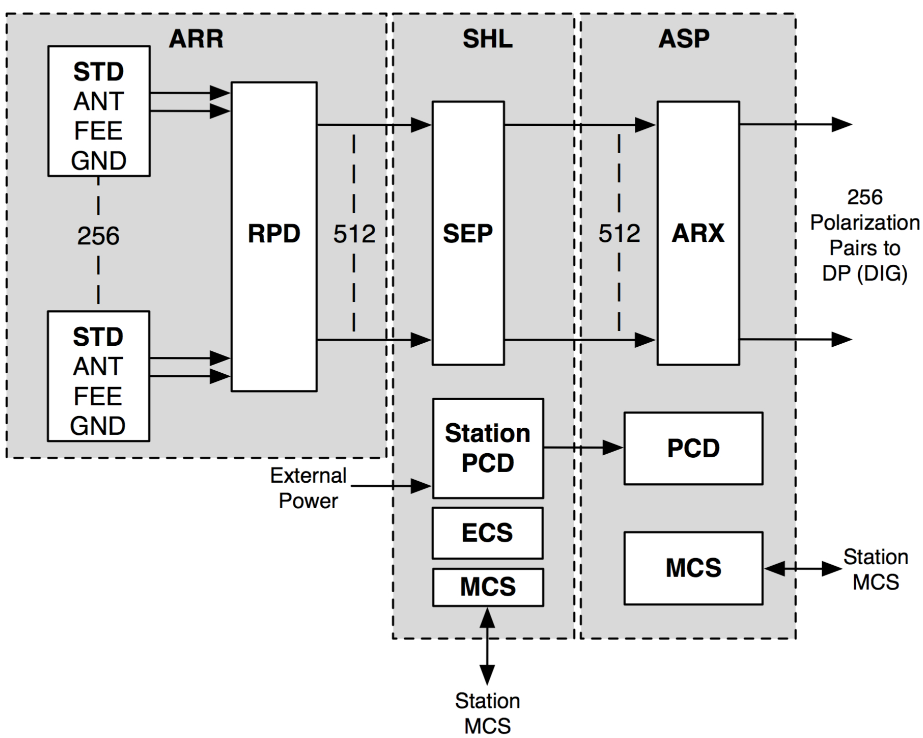


Figure 1: Station architecture: antennas through analog receivers.

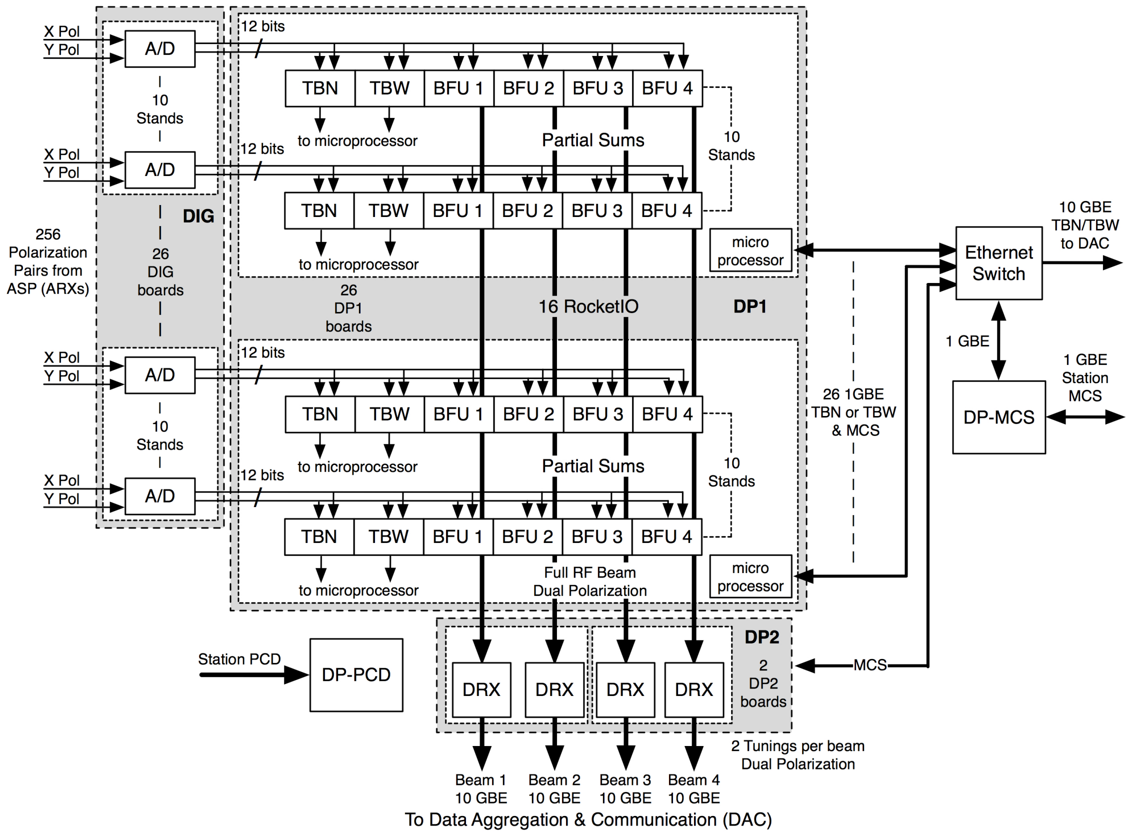


Figure 2: Station architecture: digital processor. "GBE" is Gigabit Ethernet.

Section	Nomenclature	Subsystem	Remarks
2.1	ANT	Antenna	See also Sec. 2.2–2.3
	Analog Signal Path		
3.2	FEE	Front End Electronics	a.k.a. *active balun*
3.3	RPD	RF & Power Distribution	a.k.a. cable system
9	SEP	Shelter Entry Panel	
3.4	ARX	Analog Receiver	
	Digital Signal Path		
4.1	DIG	Digitizer	
4.3	BFU	Beamforming Unit	
4.4	DRX	Digital Receiver	
7	DAC	Data Aggregation & Communication	not implemented in LWA-1
6.1	MCS-DR	Data Recorders	for LWA-1 only

Table 3: Subsystems arranged in order of "primary" (i.e., BFU to DRX to MCS-DR) signal flow. Transient buffer paths are not considered primary, but would be identical with the substitution of the appropriate transient buffer for the BFU+DRX.

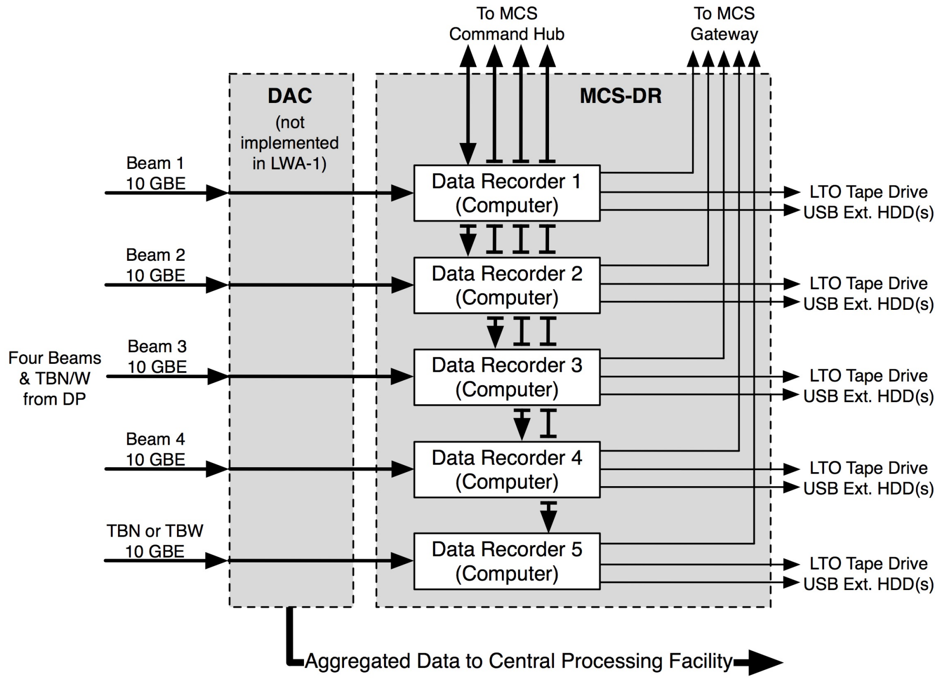


Figure 3: DAC and MCS Data Recorders. For LWA-1, the MCS-DR will be implemented. For subsequent stations, the DAC will be implemented.

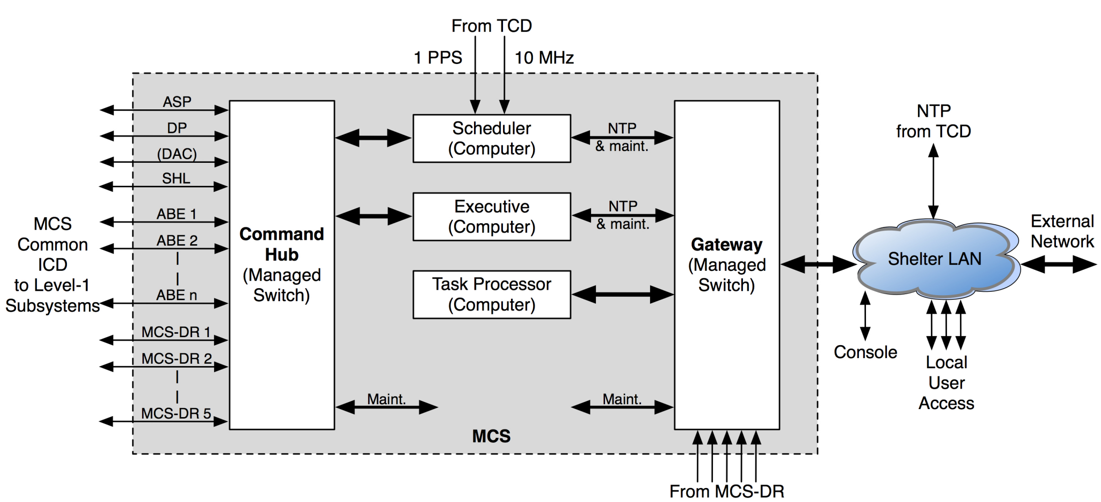


Figure 4: Station monitoring & control architecture.

2 Array Subsystem (ARR)

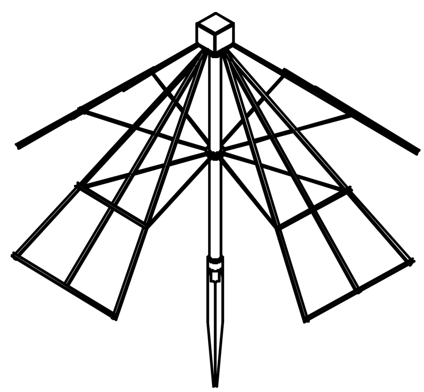
The array subsystem includes antennas, ground screen, and electronics collocated with antennas. An artist's concept of a station array based on preliminary design concepts is shown in Figure 5 (a). A single dual-polarization antenna unit and associated FEE are tightly integrated and are therefore collectively identified as a "stand" subsystem (STD).

2.1 Antenna (ANT)

The ANT subsystem is a pair of orthogonally-polarized dipole-like antennas. These elements are linearly polarized and resonant around 30 MHz. The relevant theory is summarized in LWA Memo 22 [2]. The arms of the dipole are angled downward at approximately 45° to form an inverted-vee shape, as this is known to broaden the antenna pattern. A survey of antenna dipole designs [37] concluded that the "tied-fork" design performs adequately and is cost-effective for manufacturing. It is worth noting that the "tied-fork" design is inherently broadband with respect to the impedance bandwidth, whereas the impedance bandwidth of a thin dipole [2] is significantly less. The preliminary "Central Mast Tied-Fork" antenna design, illustrated in Figure 5 (b), is provided in [41].

It is important to note that the output of the ANT subsystem is a balanced signal from each of the two polarizations. The balun used to convert this signal to single-ended form is part of the FEE subsystem.

(a) Artist's concept of a station array.



(b) Central Mast Tied-Fork Antenna.

Figure 5: LWA Station and Antenna

2.2 Array Geometry

Array geometry is an attribute of the ARR subsystem. There are two primary issues: (1) number of stands, N_a; and (2) arrangement of stands to form the station array.

From an image calibratibility viewpoint, arguments can be made for N_a as small as 50 and as large as 2500 [8], although $N_a > 176$ has been suggested in [1] for zenith pointing at 74 MHz only. At lower pointing elevations, the required N_a for full-field calibration increases drastically to well over 1000 stands per station. Since the system cost scales roughly linearly with N_a, it is desired to keep N_a as small as possible while also providing an adequate effective collecting area, A_e, to meet the full LWA interferometer sensitivity requirements, $\sigma = 1$ mJy in [18]. We find that for $N_a = 256$ (arbitrarily chosen to be a power of 2), yields $\sigma \sim 1$ mJy over 20-80 MHz [1].

The smallest dimension of the station array D_{minor} is constrained by maximum beam size (HPBW). This is required to be 8° (20 MHz/ν) in LWA Memo 117 [18], and leads to $D \geq 100$ m. $D = 100$ m is currently chosen to minimize spacings between stands in order to best avoid aliasing (grating lobes). The half-power beamwidth associated with this geometry is given approximately by [7]:

$$\psi(z) \sim 1.02 \left(\frac{\lambda}{D}\right) \sec z \ . \tag{1}$$

and is summarized in Table 4.

ν	$\psi(z=0^\circ)$	$\psi(z=74^\circ)$
10 MHz	17.5°	63.6°
20 MHz	8.8°	31.8°
38 MHz	4.6°	16.7°
74 MHz	2.4°	8.6°
80 MHz	2.2°	7.9°
88 MHz	2.0°	7.2°

Table 4: Major axis half-power beamwidth of a station beam.

Any distribution of 256 stands within the area indicated above results in spacings which undersample the aperture by a factor of ~ 3 at the highest frequencies. To prevent aliasing of the main lobe and mitigate large sidelobes, it is required to either dramatically increase N_a, or to use a pseudorandom distribution of stands. Because the cost of the station scales approximately as N_a, the pseudorandom geometry is preferred. A pseudorandom (elliptical) geometry is shown in Figure 6. This geometry was obtained by minimizing sidelobes while enforcing a minimum 5 m spacing between stands. However, mutual coupling was not taken into account, and it is currently uncertain as to whether this geometry is actually optimum in this sense. Some jointly optimum choice of antenna design and spacing might exist [19].

Issues such as mutual coupling and calibratibility may lead us to abandon this approach in favor of an array with similar D but consisting of a greater number of closely-spaced antennas – perhaps more similar in concept to the current state-of-the-art in modern broadband military phased arrays. For programmatic reasons, this revised strategy will not be implemented in the first station (LWA-1) but might be considered for subsequent stations.

[1] Assuming number of stations is 53, integration time is 1 hour, number of polarizations is 2, and the bandwidth is 8 MHz.

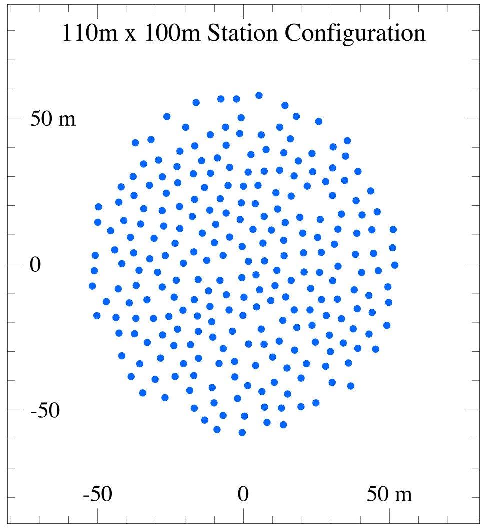


Figure 6: Pseudorandom elliptical array geometry [35].

An elliptical outline (120 m x 100 m) extended in the north-south direction has been chosen, so as to yield a more circular field of view over as much of the sky as possible [6].

2.3 Ground Screen (GND)

Analysis suggests that a conducting ground screen results in significant improvement in the collecting area of the station array [3] and that even a small very sparse wire grid can be effective as a ground screen [22, 31, 34]. A ground screen is also effective in stabilizing the antenna impedance with respect to changes in soil moisture [22].

The ground screen for LWA1 will be installed on a *per-stand* basis, i.e., consisting of small (roughly 3 m x 3 m) disconnected ground screens for each stand. The collecting area results indicated in [3] are determined on a *per-station* ground screen basis, and the per-stand benefit is harder to analyze for an entire station when mutual coupling is properly taken into account, but is assumed to yield similar results.

3 Analog (RF) Signal Path

As indicated in Table 3, the analog signal path consists of the front end electronics (FEE), RF & power distribution (RPD), shelter entry panel (SEP), and analog receiver (ARX) subsystems. In this path, the signal output from the antenna is transported to the shelter, amplified, and filtered to approximately the frequency range of interest [ν_{min}, ν_{max}] from Table 2.

3.1 Introduction

Based on successful experiences with Long Wavelength Development Array (LWDA) and Eight-meter-wavelength Transient Array (ETA) [13], LWA will use a *direct sampling* receiver architecture, such that the analog signal path involves only gain and filtering, and the sky signal is sampled without frequency conversion. This LWA receiver scheme has been demonstrated in [10] and [11].

LWA Memo 121 [4] uses RFI data obtained at the LWA-1 site to derive requirements for the analog signal path's gain and linearity. The dynamic range of the ADC chosen for the LWA is about 50 dB. RFI must fit in this range to prevent clipping of the ADC, and at the same time, the sky signal must sit comfortably above the quantization noise floor of the ADC. Since strong in-band RFI exists in the range of 13-23 MHz, it is advantangeous to not only provide gain control over the entire LWA bandwidth, but also to provide some gain control (attenuation) over the 13-23 MHz portion of the analog signal. The ARX described in section 3.4 provides multiple filter configurations and gain control to ensure that the analog signal fits comfortably in the dynamic range of the ADC, even in the presence of strong RFI.

Although a 10 bit digitizer may be sufficient as shown in LWA Memo 121 [4], the digitizer described in Section 4 uses 12 bits for digitization. This is to provide additional headroom in severe RFI environments. In more benign RFI environments, the additional bits might provide an opportunity to reduce the minimum gain required from the analog signal path.

A summary of the RF chain characteristics is shown in Table 5. Subsequent sections define the subsystems and give some additional details.

3.2 Front End Electronics (FEE)

The front end electronics are collocated with the antenna as part of the STD subsystem, and includes the balun (see Section 2.1) and sufficient low-noise gain to establish the Galactic noise-dominance of the system temperature. As the next component in the signal path is a long cable, this must be done with sufficiently high gain to overcome cable attenuation. A prototype FEE has been developed by NRL, and is described in [42]. It is included in Table 5 and its gain, noise temperature, and input third-order intercept point (IIP_3) can be regarded as specifications.

3.3 RF & Power Distribution (RPD)

The RPD is essentially the system of coaxial cables used to move the signal from the output of the FEEs to the SEP, but also includes any additional hardware or infrastructure used to route the cables, such as lightning protection, trenching, conduit, and junction boxes.

The cables are 50 Ω impedance and also carry the DC power out to the antennas. The FEEs are powered over bias-tees located in the ARX. The RF characteristics shown in Table 5 are easily achieved using inexpensive coaxial cable.

Note that the RPD has N_a inputs (stands) and N_r outputs, corresponding to analog receiver inputs. Since each stand has 2 polarizations and therefore requires 2 receivers, N_r is nominally $2N_a$.

3.4 Analog Receiver (ARX)

ARXs are subsystems which are part of the ASP subsystem, and provide the additional gain and selectivity required for input to the digitizer.

A prototype ARX design (aka Brassboard ARX) has been developed by UNM and is described in [44], [45], [46]. Its characteristics are summarized in context in Table 5. The Brassboard ARX provides 68 dB of gain, with 60 dB of gain control in 2 dB steps (via digital step attenuators), a reconfigurable filter bank with three filter configurations (summarized below), and an integrated bias-tee for powering the FEEs.

Brassboard ARX Filter Configurations:

- Full Bandwidth: 10 MHz to 80 MHz
- Reduced Bandwidth: 28 MHz to 54 MHz
- Split Bandwidth: 10 MHz to 80 MHz, 30 dB of gain control over the low-frequency portion of the passband.

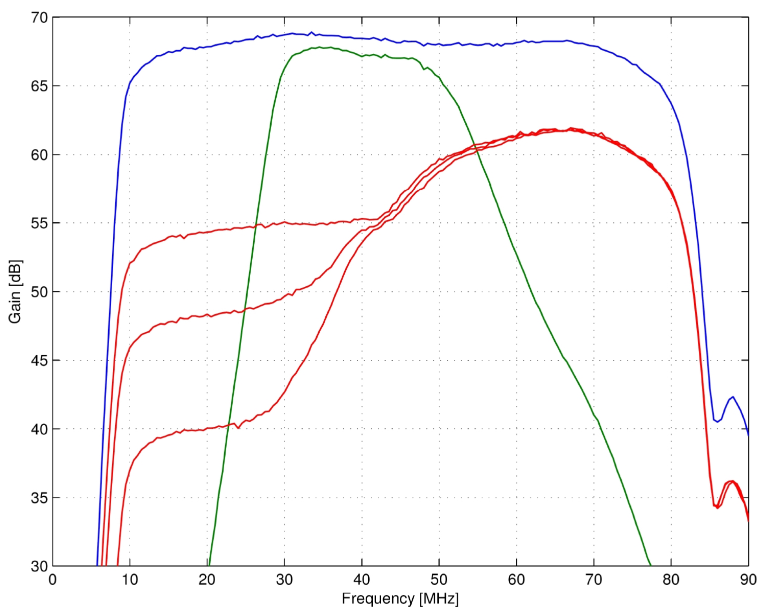


Figure 7: Magnitude response of the ARX in full-gain configurations for each of the 3 filter settings. Split Bandwidth attenuator settings (red) at 6 dB, 12 dB, & 20 dB down.

It should be noted that the Split Bandwidth configuration may be used to attenuate the 10 MHz to 30 MHz RFI which is extremely time variable. If for any reason gain must be changed during an observation, it should be coordinated to occur between integration periods, with the data flagged in some way to indicate this. It should also be noted that gain changes might require recalibration of the station array.

Subsystem	Assumed to consist of...	G [dB]	F [dB]	IIP_3 [dBm]
FEE	FEE v1.6 [43], [21]	+36	2.7	-1.8
RPD+SEP	500 ft inexpensive coaxial cable at 38 MHz [44]	-15	15.0	∞
ARX	Brassboard ARX [45]			
	Maximum gain	+68	3	-37
	Set to achieve +68 dB cascade gain	+47	3.5	-17
	Minimum gain	+8	16	+10
	CASCADE: Maximum gain	+88	2.8	-57
	CASCADE: Set to achieve +68 dB cascade gain	+68	2.8	-37
	CASCADE: Minimum gain	+28	3.5	-11

Table 5: Characteristics of the LWA analog signal path (FEE, RPD+SEP, ARX). The cascade receiver temperatures (i.e., not including Galactic noise) are 250 K, 250 K, and 360 K respectively.

4 Digital Signal Path

The digital signal path includes portions of the DP, MCS-DR, and DAC subsystems. Within the DP subsystem, ARX output is digitized by DIG subsystems and distributed to BFUs, TBW(s), and TBN(s). BFU outputs are conveyed to the DP2 subsystem, nominally to DRX level-2 subsystems, and then to DAC (or in LWA-1, MCS Data Recorders). Eventually the data may go to a central processing facility, through the DAC subsystem. MCS Data Recorders are described in Section 6.1. DAC is described in Section 7. A detailed preliminary design of the DP subsystem is provided in LWA Memo 154 [48].

4.1 Digitizer (DIG)

The preliminary design for the DIG is documented in LWA Memo 154 [48]. DIG consists of an ADC, which directly samples ARX output with 12 bits at 196 MSPS. This allows alias-free digitization of the frequency range 10–88 MHz. The ADC selected is the Analog Devices AD9230, described in LWA Memo 98 [12]. This digitizer has been field tested in [9], [10], and [11], with the analog signal path described in section 3.

Twenty ADCs (digitizers for 10 stands) exist on each DIG board, which is constructed as a "rear transition module" and plugs into a connector at the back of the corresponding DP1 board. The digitizer sample clock runs at 196 MHz, and samples are processed at this rate throughout DP1. Thirteen DIG/DP1 board pairs are installed in each of two 13U high ATCA chassis [48].

4.2 DP1 Subsystem

A preliminary design for the DP1 subsystem is documented in [48]. After digitization, the samples are distributed to 6 parallel processes: 4 beamformers (BFU), the wideband transient buffer (TBW), and the narrowband transient buffer (TBN). The four dual-polarization beams are passed between DP1 board via 16 RocketIO lines. The partial sums are carried from each DP1 board to the next with a 20 bit word at an aggregate data rate of 31.36 Gbps for the four beams.

4.3 Beamforming Unit (BFU)

BFUs are part of the the DP1 subsystem. Each BFU forms a beam in the desired pointing direction, with bandwidth equal to the full digitized bandwidth. The method of beamforming consists of first applying integer-sample-period delays using a first-in first-out (FIFO) buffer (a.k.a. coarse delay), followed by a configurable finite impulse response (FIR) filter for each antenna (a.k.a. fine delay), followed by a matrix multiply for polarization adjustments, and then summing the results across antennas to form the beam. In its simplest form, this can be interpreted as a delay-and-sum beamformer, where the FIR filter is used to implement an approximately frequency-independent, continuously-variable delay. Details are provided in LWA Memo 154 [48].

The FIR filter coefficients for each antenna can be further manipulated to introduce (for example) additional phase and magnitude variations which are useful for beam pattern control including spatial and space-frequency nulling. The FIR filter also provides (to some extent) the ability to correct for dispersion characteristics in the analog signals due to cable and antenna dispersion characteristics.

The partial sums for combining the processed stand signals into beams are daisy-chained through the DP1 boards, with each board adding the signals from 10 stands. A beam submodule exists for each stand and is illustrated in Figure 8.

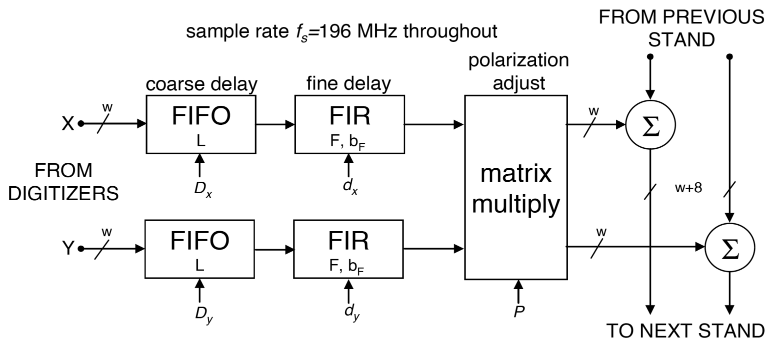


Figure 8: Beam Submodule. Each incoming sample is $w = 12$ bits wide, and the partial sums are $w + 8 = 20$ bits wide. D_x, D_y, d_x, and d_y are control numbers; P is a 2x2 coefficient matrix; and L, F, b_f are filter design parameters.

The BFU includes a "polarization processing" stage. The concern is that the raw linear polarizations from each antenna in a pseudorandom geometry will be affected by mutual coupling in such a way that the desired polarization purity can be achieved only by accounting for the coupling prior to beamforming.[2]

LWA Memo 149 [5] shows that polarization differences are significant, but that main lobe gain and pattern are not affected much when polarization correction is ignored. Note, this analysis says nothing about sielobes, which could be very much affected. The preliminary design for polarization processing [48] assumes that polarization calibration can be accomplished at a single-frequency with a 2×2 matrix, but it has not been confirmed that this will be sufficient.

It should be noted that that the BFU must generate beams with the desired shape, in addition to having the correct pointing and polarizations. The desired shape may vary depending various factors; two of these factors include LWA interferometer calibration considerations (including, for example, the issue discussed in Section 12.2) and nullforming for RFI mitigation.

4.4 Digital Receiver (DRX)

DRXs reside in the DP2 subsystem. Each BFU has an associated DRX, to which it is directly attached. Each DRX provides 2 tunings of the corresponding beam. A single tuning of the DRX is illustrated in Figure 9.

Each DRX consists in part of two parallel paths, corresponding to 2 simultaneous "tunings" ν_1 and ν_2. In each path, a single spectral swath of width B is selected from the digital passband, divided into smaller contiguous channels of width $\Delta\nu$, and sample rates are adjusted appropriately. The center frequency of each of the two tunings is fully independent and possibly the same; however the choice of center frequencies might be quantized to a grid (e.g., to accommodate a polyphase filter bank type implementation). The bandwidth B and channel width $\Delta\nu$ is ideally also fully independent and potentially different between tunings. Each of the four parallel outputs (= 2 tunings $\times$ 2 polarizations) of the DRX is routed to the MCS Data Recorders.

[2]This in contrast to dish arrays such as the ATA, in which the antennas are not significantly electromagnetically coupled and therefore there is no difficulty in obtaining the desired polarizations after beamforming using the raw linear polarizations. This is also in contrast to previous large arrays of small tightly-coupled but regularly-spaced antennas, for which the coupling affects all antennas in approximately the same way.

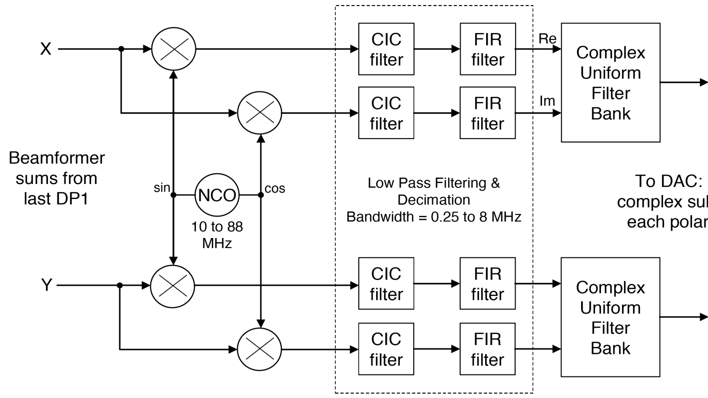


Figure 9: Single Tuning of the DRX.

While the DRX will achieve both the maximum B and minimum $\Delta\nu$ defined in Table 2, it is not necessary for both conditions to be achieved simultaneously. Instead, the DRX will provide multiple operating modes that trade decreased $\Delta\nu$ for decreased B. For example, the mode achieving minimum $\Delta\nu = 100$ Hz will have $B = 409.6$ kHz, and a mode achieving $B = 8$ MHz will have $\Delta\nu \sim 2$ kHz. This is because candidate DRX architectures make it most straightforward to offer modes for which $B/\Delta\nu$ is constrained to be a constant. In particular, it is convenient to fix the number of spectral channels to be a constant.

4.5 Transient Buffer Systems

The station includes transient buffer systems. Transient buffers serve as alternative, parallel back-ends to the BFU+DRX combinations. A transient buffer accepts all $2N_r$ of the outputs from the DIG (i.e., both polarizations for all available RF inputs) and coherently records the data stream in a form suitable for later recovery and analysis. Transient buffers serve multiple purposes:

1. They provide an internal diagnostic mechanism, allowing access to coherent data from all inputs simultaneously. This facilitates monitoring and troubleshooting of the signal path separate from the BFU+DRX paths, which is convenient as the association with individual RF inputs is lost as a consequence of beamforming. This also simplifies the process of observing the digitized output of antennas locally (i.e., at the station), especially if BFUs are not available or are otherwise committed. Placing this capability in a separate subsystem as opposed to inside the BFUs serves to streamline the design of the BFUs.

2. Access to data obtained by the transient buffers have tremendous value in the study and analysis of the station itself, which is an important objective for LWA-1 in particular. For example, this capability facilitates investigation of mutual coupling effects and beamformer design.

3. Access to data obtained by transient buffers can be used for all-sky imaging/monitoring, which has both diagnostic and scientific value.

4. Transient buffers offer a form of triggered transient science; now, in the scientific sense of the words. For example, this could facilitate acquisition of data in response to a trigger from the Gamma ray bursts Coordinates Network (GCN). The utility of this mode depends greatly on the capabilities (especially recording time) offered by the transient buffer.

It should be emphasized that the primary motivation for including transient buffers is (1) and (2) above. The remaining purposes are considered to be valuable, but not in the sense that they should be allowed to influence the specifications. Because of the large amount of bandwidth required to pass all the Transient Buffer data from DP to DAC (or MCS-DR); either TBN or TBW will be selectable, but not both at the same time.

Two types of transient buffer are presently defined: "transient buffer – wideband" (TBW) and "transient buffer – narrowband" (TBN). These are explained below.

4.5.1 Transient Buffer – Wideband (TBW)

Once triggered, a TBW simply captures the full-bandwidth output of the DIG for as long as possible. The design is implemented in a DRAM device for a total of 32 MB of RAM for each RF signal. This provides 57 Msec if the full 12b-wide samples are recorded, or proportionally longer if fewer bits of each sample are recorded. The spectal resolution can be better than 100 Hz in this case.

Once triggered, the TBW acquires until full, and then stops. Data is read out asynchronously after acquisition.

4.5.2 Transient Buffer – Narrowband (TBN)

A TBN differs from a TBW in that the digitized antenna data undergoes a bandwidth reduction prior to acquisition, enabling the TBN to run continuously. In this scheme, the DIG outputs are digitally downconverted, low-pass filtered, and decimated to reduce the Nyquist frequency. The center frequency is user-selectable between 10-88 MHz and the reduced bandwidth can be configured from 1 kHz to 100 kHz. Using 100 kHz bandwidth, the sample rate reduction is on the order of 500 such that the aggregated (multiplexed) bandwidth-reduced array output assumes a sample rate on the order of 50 MSPS; i.e., comparable to that of a single antenna after the original digitization.

5 Timebase & Clock Distribution (TCD)

The timebase & clock distribution (TCD) subsystem has three essential functions: (1) provide accurate time information (especially for the station MCS), (2) synthesize and distribute a 1PPS (pulse per second) and 10 MHz clock to the DP for synthesizing the 196 MHz sample clock, and (3) synthesize and distribute synchronous and coherent clocks as needed for other subsystems, currently only MCS.

The station timebase will be a GPS-disciplined time standard capable of producing (1) a 1PPS reference signal, (2) a 10 MHz reference signal, and (3) a data port providing absolute date & time information. For consistency of internal timing within a station, it is important that the two reference signals be accurately synchronized with each other. Although the accuracy of the chosen GPS receiver ($\pm$50 nsec of UTC) should be sufficient for LWA interferometry, the interface between the timebase and reference signal distribution should be amenable to a subsequent upgrade when required to support long-baseline interferometry.

The 196 MHz digitizer clock will be synthesized at a single location in the digital processor as a sinusoid which is phase-locked to the 10 MHz reference signal. This signal will be passively divided as necessary for distribution to DIG subsystems. Differences in sample clock phase will be perceived by the system as indistinguishable from excess delay (e.g., differences in cable length) and calibrated accordingly.

6 Monitoring & Control System (MCS)

The station MCS is essentially the set of computers which control the station, and provides status information in return. Various subsystems including the ASP, and DP also have MCSs, which are embedded computers subordinate to the station MCS. The subsystem MCSs are implemented to facilitate modularity in the station design and to facilitate independent development of subsystems. A more complete definition is provided in [51].

The station MCS architecture [49] is shown in Figure 4 and summarized below. "DAC" is not currently implemented in LWA-1, (see section 7. "ABE" (see section 8) is not currently defined, but taken into account to facilitate future expansion. "Maint." refers to (1) access ports to allow connection of laptop-type computers for development, integration, and troubleshooting activities, and (2) data paths available for the same purpose.

- The *Scheduler* is a computer whose primary fucntion is to issue commands and receive status from other LWA subsystems. The command and status communications are through the *Command Hub*, using the "MCS Common ICD [50]" augmented by the corresponding subsystem ICD. The Scheduler handles tasks that are extremely time-sensitive and that must be coordinated on timescales down to milliseconds.
- The *Executive* is the computer which exercises top-level control over MCS as well as the station. It is responsible for interpreting observation requests and, from these, generating the data which becomes the content of command messages issued by the Scheduler. This includes numerically-intensive operations such as computation of FIR filter coefficients. The Executive manages tasks that are moderately time-sensitive and that must be coordinated on timescales down to seconds.
- The *Task Processor* is a computer which exists primarily to host applications which are not "time critical" and therefore can be "offloaded" to reduce the processing burden of the Executive. The Task Processor is the primary interface with users, managing command line and GUI interactions. The Task Processor is also responsible for the scheduling and interpretation of internal diagnostics (both automatic or user-directed), and manages MCS-DR. In general, the Task Processor handles tasks that do not need to be manged at resolutions of seconds or less.

Note that the shelter LAN and physical access for local users (Figure 4) are not part of MCS. Although this will be provided for LWA-1, these systems will eventually be subsumed into the DAC subsystem.

In addition to the interfaces shown, each MCS subsystem has its own "maintenance" interface (USB, Ethernet LAN, or something of that nature) to facilitate direct connection of a computer for development and diagnostic purposes.

6.1 Data Recorders

MCS-DR consists of 5 identical computers as shown in Figure 3. Four of these computers receive data streams from DP corresponding to the output of each of the four station beams. The fifth computer receives the DP output data streams corresponding to TBW/TBN outputs. All computers contain internal arrays of very large hard drives, to which data can be streamed at the rate received from DP. Refer to [49], and [50] for additional details on the MCS data recorders.

7 Data Aggregation & Communication (DAC)

The DAC subsystem provides the interface between the station's DP and MCS subsystems and the outside world. One function is to consolidate output from the DRXs, TBN(s), TBW(s), and any other backends for transmission to a remote location; ultimately, to the LWA correlator or central processing facility. A second function is to provide the bidirectional communication path between the station MCS and the distant LWA über-MCS.

The DAC subsystem for LWA-1 consists of a LAN and an external network connection. In LWA-1, the outputs from DRX's, TBN(s), and TBW(s) are routed directly to the MCS-DR (section 6.1). As subsequent stations emerge, the full functionality of the DAC will be required, but has no immediate need since the central processing facility does not exist.

However, it may be useful to provide some elaboration on how sample rates, number of bits, etc. impact the aggregate data rate of the DAC for an LWA station. The data rate at the output of the DAC, including all beams but excluding the transient buffer and MCS communications, is:

$$r_S = abBN_bN_pN_t\frac{1}{\Delta\nu\Delta\tau} \tag{2}$$

where a is the oversampling factor with respect to Nyquist (i.e., at least 1; conservatively 1.5), b is the number of bits used to represent a sample in the $\Delta\nu$-wide spectral channels, and $\Delta\tau$ is integration time, N_p is number of polarization, N_b is number of beams, and N_t is number of tunings per beam. For $a = 1.5$, $b = 8$ (e.g., for 4 bits "I" + 4 bits "Q"), $B = 4$ MHz, $N_b = 3$, $N_p = 2$ $N_t = 2$, and $\Delta\tau = 1/\Delta\nu$ (i.e., no integration) we find $r_S = 576$ Mb/s. This value can of course be reduced by reducing b or increasing $\Delta\tau$, and it should be noted that there may be various constraints and limitations imposed by the implementation of the DP and DAC subsystems.

The number of beams and tunings, designated by N_b and N_t respectively, correspond to the LWA requirements for backhaul from the outer stations. In this case, the bandwidth is 4 MHz per tuning or 8 MHz per beam. Thus for the outer stations, the bandwidth requirement remains 576 Mbps. For the inner stations, the bandwidth increases to 1.92 Gbps. These are lower limits imposed by an extra beam of 56 MHz bandwidth; assuming 4 bits of I data and 4 bits of Q data and an oversampling factor of 1.5 to 1.

8 Alternative Backends

The capability exists within the station to connect multiple sub-subsystems to the DP beam and TBW/TBN outputs. Types of backends envisioned include:

- Pulsar survey/monitoring backends.
- Generalized (e.g., single-event) transient detectors.
- Custom spectrometers; e.g., perhaps with optimized RFI mitigation capabilities.
- RFI monitoring/survey systems.

It is envisioned that these backends could be developed separately from the “main effort” of the LWA project, facilitated by open interface control documents (ICDs) developed within the scope of the project and made available to interested parties.

9 Shelter (SHL)

The SHL system includes the shelter itself, the shelter entry panel (SEP), station-level power condition and distribution (PCD) system, and the environmental control system (ECS) [39]. A conceptual design is illustrated in 10 and detailed in the shelter package, [40].

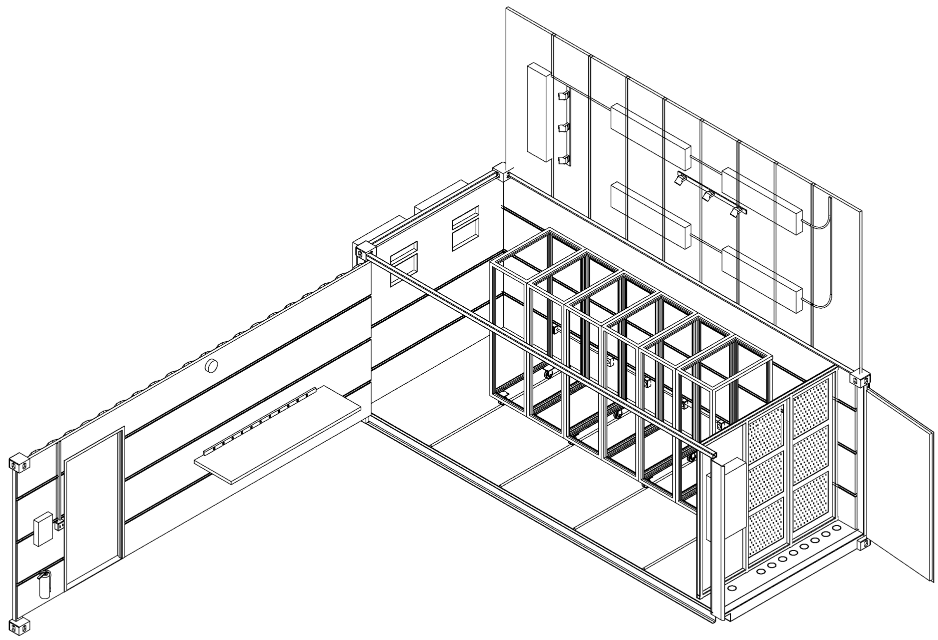


Figure 10: Design drawing of SHL.

The SHL is a modified ISO shipping container, of size $8' \times 9.5' \times 20'$. This is similar to equipment shelters used in the Telecommunications industry. The SEP is built into the side wall and houses all signal entry cables. These connections are sealed with a door. Floor space for up to 6 full size electronics equipments racks, and the ability to move racks for maintainance and installation is provided. The HVAC system is capable of cooling up to 15 kW of electornics via two separate HVAC units. The personel entry door is an RFI tight door which will also be sealed by an exterior door to prolong the lifetime of the (expensive) RFI door.

Since the LWA electronics generate significant RF signals, there must be sufficient shielding of the antennas and receivers from the other station electronics. 100 dB minimum shielding (electronics to antennas) will be provided by RFI tight racks and the shelter.

9.1 SHL Power Conditioning & Distribution (SHL-PCD)

The SHL is also responsible for providing power to all subsystems. The shelter is directly connected to 240/1010 VAC site power, filters and conditions this power and distributes it in AC form to Level-1 subsystems. It is estimated that the electronics will consume 10-15 kW of power and the HVAC units could consume up to 15 kW. The station will be capable of monitor and control of the SHL-PCD and SHL-ECS subsystems.

10 Site & Infrastructure for LWA-1 (SIT)

LWA-1 construction will begin in the summer of 2009 at the LWDA (aka VL) site [47]. The CAD drawing of the site layout with antenna placements, conduit (see section 3.3), shelter location, and fenced area is shown in Figure 11.

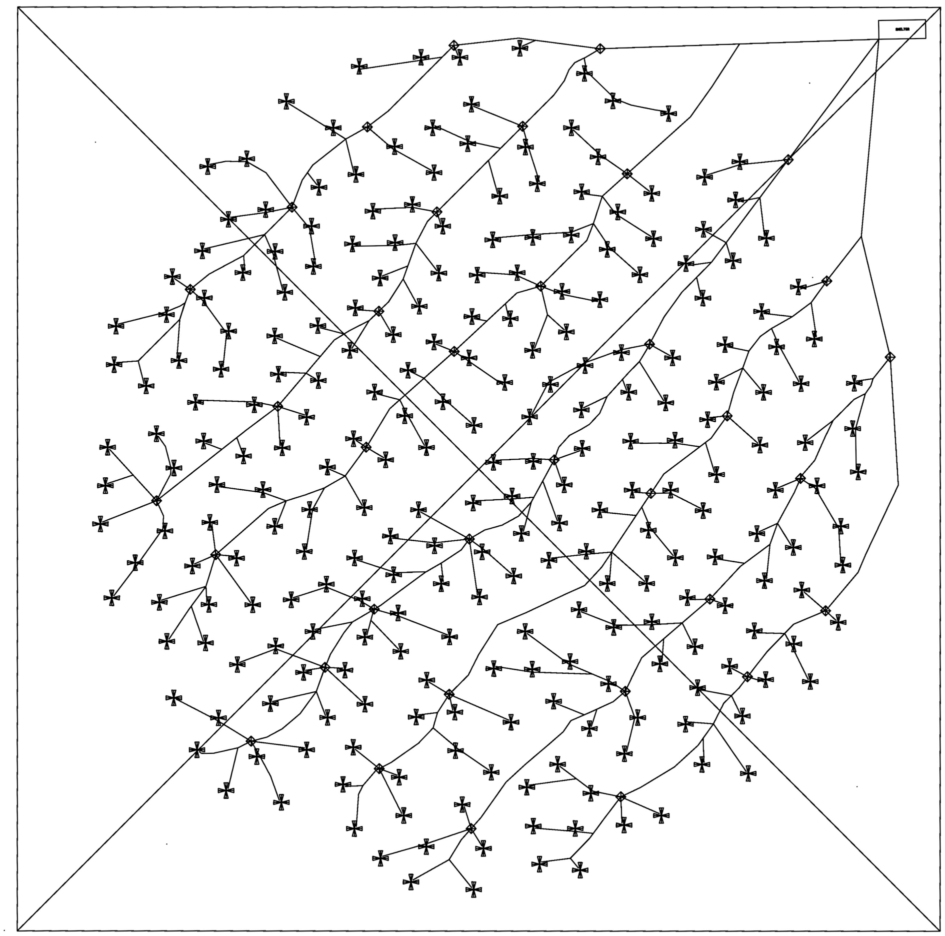


Figure 11: CAD drawing of the site layout.

In addition to the 256 stands inside the station area, a small area, 300 meters to the east, is fenced off to allow for interferometer measurements during commissioning. Trenching and cable for multiple dipoles has already been completed for this area.

11 Interface Specifications

The following is a list of interfaces which require explicit definitions (appearing in the form of separate interface control documents (ICDs). Level-1 subsystems which require monitor/control interfaces are specified as "Common" ICDs (defined in [50]) and electromechanical interfaces are provided as traditional To/From interface documents.

1. Electromechanical Interfaces

   - *Interface between STD and RPD.* This interface involves several issues including cable types, method of power transfer, and coordination of mechanical interfaces [24].
   - *Interface between RPD and SEP.* Similar issues as above [25].
   - *Interface between SEP and ASP.* Involves distribution of RF signals from the SEP to the ARXs [26].

2. Common ICDs. These ICD are common among subsystems which require monitor and control interfaces. The MCS Common ICD [50] is used as the top-level interface document and other subsystems (such as ASP and DP) provide their individual common ICD which references the MCS Common ICD.

   - *MCS Common ICD.* [50] specifies the top-level monitor/control prototcol to all Level-1 subsystems.
   - *ASP Common ICD.* [27] specifies the monitor/control points of the ASP.
   - *DP Common ICD.* [28] specifies the monitor/control points of DP and electromechanical connections from ASP and to DAC.
   - *PCD Common ICD.* [29] specifies the monitor/control points of shelter PCD and electromechanical connections from the site power, through the PCD distribution, to all Level-1 subsystems.
   - *TCD Common ICD.* [30] specifies the monitor/control points of TCD and electromechanical connections from the GPS antenna to Level-1 subsystems requiring timing signals.

There are of course many other interfaces; however these are engineered internally, i.e., anticipating the situation that a single organization will be responsible for both sides of the interface as well as for the larger subsystem.

12 Higher-Level Signal Processing Functions

Previous sections have provided a description of hardware, firmware, and software at the station's lowest levels of functionality. This section addresses some necessary functions which require coordination between multiple subsystems and interfaces into higher-level functionality. These functions include array calibration, beamforming, and RFI mitigation.

12.1 Array Calibration

Formally, *array calibration* is the process of identifying the *array manifold*; that is, the response of the station antenna array to a plane wave arriving from the locus of possible directions corresponding to the entire sky, possibly right down the horizon. In this case, the array manifold at any given frequency is a set of $2N_a$ complex-valued antenna outputs, which is itself a function of direction of arrival and polarization. The manifold is required if blind "go to" beam pointing is desired. Without the manifold, the station is limited to "phasing up" on a strong source, such as Cas A, and then making assumptions about how the beamforming solution changes as the beam is steered away from the calibration source. Alternatively, an approximate manifold can be constructed using a reduced set of measurements (for example, from beacons or other strong sources) combined with various assumptions. For example, if one assumes mutual coupling is not significant, then the array manifold can be determined relatively easily by assuming the antennas have identical pattern, polarization, and impedance characteristics, and assuming the array geometry is known with sufficient precision. Under these conditions, the manifold can be validated and refined using a small number of external measurements; e.g., the response due to a beacon signal placed at a known location.

However, the antennas in the LWA station array will be strongly coupled, and the coupling will be "disorderly" due to the pseudorandom spacings. Thus, many more independent measurements of known signals may be required; conceivably as many as $2N_a$ known sources scattered over the antenna's field of view could be required to achieve the necessary "basis set" of independent measurements. It is conceivable that astronomical sources could be used for some of these; however there are only a handful that are strong enough to be detected with high signal-to-noise ratio in short integration times using the station array.

Since the station will be strongly sky noise-limited, it is possible that this problem can be overcome by comparing correlations between antennas (visibilities) to a sky brightness temperature model. In this approach, the array manifold is identified as that which minimizes the difference between a sky brightness temperature map derived from visibilities using the array manifold, and the known true map.

Additional work is required to determine a viable array calibration strategy. It is possible that a combination of beacons and sky model-based calibration will be employed.

12.2 Dual Beamforming in Support of Ionospheric Calibration

Beamforming generally is discussed in Section 4.3. An additional consideration is the variability of the beam and its sidelobes as a function of pointing and frequency. This variability has potential to create serious problems when attempting to perform calibration to remove the refractive effects of the ionosphere for aperture synthesis imaging. A possible countermeasure[3] is to simultaneously form 2 beams: one beam for maximum directivity, and the second beam formed in the same direction, but after a magnitude taper is applied to the antennas in the station aperture in order to broaden the beam and suppress sidelobes. The second beam should be easier to manage from an imaging calibration point-of-view, and can be used to bootstrap a solution for the more directive but less-well-behaved primary beam. Although the architecture described in this document supports this

[3]Suggested by W. Cotton and F. Owen, both of NRAO.

approach without modification, it does obviously reduce the number of BFUs available for other uses.

12.3 RFI Mitigation

Radio frequency interference (RFI) is a pervasive and potentially limiting problem for low frequency radio astronomy. Two classes of RFI are of concern: "Self-RFI", which is generated by the system itself; and external RFI, which is originates from off-site and cannot be controlled.

Self RFI will be managed in the design process by ensuring that subsystems meet criteria derived from existing protocols established for LWA and operation at the VLA site.

External RFI, as well as self-RFI which is not completely suppressed through the above process, involves additional considerations. A variety of countermeasures will be considered. In the ARX, these include slow gain control (to control the noise figure vs. linearity tradeoff) and possible reconfigurable bandpass/bandstop filters. In the DIG, this may include the ability to modify the response of digital filters suppress RFI, or pulse blanking to remove strong, bursty interference. In the BFU, this may include spatial or space-frequency nulling. In the DRX or other spectrometer-related devices, this may include time-frequency blanking. Other devices may use additional specialized or application-specific methods, and the specific mix of techniques employed will depend on the observing mode and RFI present.

13 Acknowledgments

Thanks to Steve Ellingson for providing version 1.0 of this document. Many people have offered suggestions and corrections in the development of this document. These include J. Lazio (NRL), T. Clarke (NRL), A. Cohen (NRL), C. Janes (UNM), P. Ray (NRL), and J. York (ARL). W. Cotton and F. Owen (both of NRAO) suggested the dual beam procedure in Section 12.2.

14 Document History

- Version 1.5 (Febuary 24, 2009)
  - updated remarks of Table 2
  - polarization isolation $\geq$ 10 dB
  - D_{min} used for table 4
  - added ARX magnitude figure
- Version 1.4 (Febuary 22, 2009)
  - addressed several comments from S. Ellingson
- Version 1.3 (Febuary 14, 2009)
  - Update Digital Processor Figure
  - Updated MCS andData Recorders Figures
  - Updated Digital Processing sections
  - Updated TCD, MCS, DAC, ICD sections
- Version 1.2 (February 10, 2009)
  - Updated Architecture Figures
  - Updated Nomenclature Table
  - Changed antenna section to indicate single design
- Version 1.1 (January 27, 2009)
  - J. Craig added as author
  - Updated from all current Engineering Notices (DAC section)
  - Array Geometry section modified to reflect latest elliptical station footprint
  - Updated antenna figures and text on candidate antennas
  - Updated FEE section
  - Updated Table 5
  - Updated RPD section
  - Updated ARX section
- This is Version 1.0. (Submitted for SRR.)
  - Number of BFUs increased from 3 to 4 per most recent draft of the technical requirements document.
  - Added Section 1.2 (“Terminology and Acronyms”).
  - Replaced θ with z for zenith angle for consistency in all sections.
  - Replaced term “element” with term “antenna” for consistency in all sections.
  - Added references to design information recently available from LWA Memos 106–109.

- Various minor modifications to text, including accommodation of comments by T. Clarke and A. Cohen.

- Version 0.6 (October 9, 2007).
  - Introduced digitizer (DIG) subsystem, which includes the analog-to-digital converter and subsequent post-processing. Settles "open question" from previous versions concerning location of digitizer.
  - Elaboration on DP1 daisy chain via reference to preliminary ICD [15].
  - Introduced timebase & clock distribution (TCD) subsystem.
  - Added new section "Higher-Level Signal Processing Functions" addressing array calibration, making beamforming "ionospheric calibration friendly," and RFI mitigation (superficially).
  - Added power consumption figure to specification table.
  - Incorporated changes to DRX section per emails between J. York and S. Ellingson, Sep. 26-30, 2007.
  - Introduced "level-1" vs. "level-2" distinction in attempt to clarify hierarchy of subsystems.

- Version 0.5 (August 28, 2007).
  - The "DSP" subsystem in Ver. 0.4 has been split into two separate subsystems, DP1 and DP2. DP1 contains the BFUs, transient buffers, and other backends directly in the daisy chain. DP2 contains the DRXs and is also able to accommodate additional devices such as pulsar backends, custom spectrometers, RFI analyzers, and data recorders which would also be monitoring BFU outputs via a daisy chain arrangement.
  - Edited Table 2 to make explicit separate time resolutions and bandwidths possible using TBW or DP2 data recording, in contrast to the "primary" (BFU to DRX to DAC) path.
  - Added "open question" language addressing possibility of making station footprint elliptical as opposed to circular for better beam shape when observing the Galactic Center.
  - Added text describing a "direct to disk" capability for the DAC.

- Version 0.4 (August 9, 2007).
  - Major revision to station digital architecture (Full RF beamforming first, followed by DRXs operating on beam outputs); associated figures and text modified accordingly. As a consequence, "BFS" and "TBS" subsystems deprecated, "BFU", "TBN", and "TBW" added.
  - Changed "A_e/T_{sys}" specification to N_a (number of stands) specification and added Memo 94 as a reference.
  - Added station power estimate as a "to do".
  - Dropped "DRAFT" designation on title page (redundant given version number ≤ 1.0).
  - Recommended "simple method for estimation of the collecting area of a single antenna" in Section 2.1 is dropped in favor of a reference to Section 2.2 of LWA Memo 94.

- Version 0.3 (July 5, 2007): Incorporates comments of C. Janes (email dtd. July 2, 2007) and removes questionable estimates of station effective aperture and beam sensitivity.

- Version 0.2 (June 27, 2007): Preliminary draft for comment distributed to L. Rickard, G. Taylor, N. Kassim, and C. Janes.

- Version 0.1 (June 4, 2007): Incomplete preliminary draft for comment distributed to L. Rickard.

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