Long Wavelength Array
Station Architecture

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LWA Station Architecture
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Contents

1 Introduction **4**
- 1.1 Purposes . . . 4
- 1.2 Terminology and Acronyms . . . 4
- 1.3 Specifications . . . 4
- 1.4 Subsystems & Nomenclature . . . 4

2 Array Subsystem (ARR) **10**
- 2.1 Antenna (ANT) . . . 10
- 2.2 Array Geometry . . . 10
- 2.3 Ground Screen (GND) . . . 11

3 Analog (RF) Signal Path **13**
- 3.1 Introduction . . . 13
- 3.2 Front End Electronics (FEE) . . . 13
- 3.3 RF & Power Distribution (RPD) . . . 13
- 3.4 Analog Receiver (ARX) . . . 14
- 3.5 Analog Array Processing (AAP) . . . 14

4 Digital Signal Path **16**
- 4.1 Digitizer (DIG) . . . 16
- 4.2 DP1 Daisy Chain . . . 16
- 4.3 Beamforming Unit (BFU) . . . 16
- 4.4 Digital Receiver (DRX) . . . 17
- 4.5 Additional DRXs and Custom Backends . . . 18
- 4.6 Transient Buffer Systems . . . 18
  - 4.6.1 Transient Buffer – Wideband (TBW) . . . 19
  - 4.6.2 Transient Buffer – Narrowband (TBN) . . . 19

5 Timebase & Clock Distribution (TCD) **20**

6 Monitoring & Control System (MCS) **21**

7 Data Aggregation & Communication (DAC) **22**

8 Interface Specifications **23**

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9 Higher-Level Signal Processing Functions **24**
9.1 Array Calibration 24
9.2 Dual Beamforming in Support of Ionospheric Calibration 24
9.3 RFI Mitigation 25

10 Issues to Address in Future Versions of this Document **26**

11 Acknowledgments **27**

12 Document History **28**

List of Figures

1 Station architecture: antennas through analog receivers. 7
2 Station architecture: digital processing through external communications. The number of BFUs, TBWs, TBNs, and DRXs shown here may or may not represent the actual number used, and even at the time of construction and operation may not rigidly fixed; see the associated sections of this document for additional discussion. The DP1 daisy chain is explicitly shown, whereas the DP2 daisy chain(s) are not. . . 8
3 Station monitoring & control architecture. Interface to RPD is not necessary unless AAP is implemented there; see Section 3.3. 9
4 Artist's concept of a station array based on preliminary design concepts. 11
5 Two LWA candidate antennas. 12
6 Candidate pseudorandom array geometry. *Courtesy A. Cohen, NRL.* 12

List of Tables

1 Subsystem hierarchy and nomenclature. 5
2 A simplified subset of specifications for an LWA Station. Any contradiction with science or technical requirements documents should be resolved in favor of those documents. 6
3 Subsystems arranged in order of "primary" (i.e., BFU to DRX to DAC) signal flow, assuming AAP is not implemented. Transient buffer paths are not considered primary, but would be identical with the substitution of the appropriate transient buffer for the BFU+DRX. 6
4 Half-power beamwidth of a station beam. 12
5 Characteristics of a candidate LWA analog signal path (FEE, RPD+SEP, ARX). The cascade receiver temperatures (i.e., not including Galactic noise) are 134 K, 140 K, and 604 K respectively. 15

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 [18, 24]. This document 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. This document replaces LWA Memo 35 [21], which previously served similar purposes.

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.

It should be emphasized that the architecture described in this document in some cases *might not* consistently meet the specifications shown in Table 2. Achieving convergence between specifications (scientific and technical) and architecture will be an important activity over the next few months of the LWA project.

1.4 Subsystems & Nomenclature

The station architecture is summarized in Figures 1–3. Table 1 identifies the hierarchy of subsystems within an LWA station. Subsystems ARR, ASP, DP1, DP2, 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 DP2'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 DP1 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, DP1-MCS, and Station MCS respectively.

Section	Nomenclature	Subsystem	Remarks
2	**ARR**	**Array**	Geometry: Sec. 2.2.
2	STD	Stand	ANT + FEE
2.1	ANT	Antenna	
3.2	FEE	Front End Electronics	a.k.a. *active balun*
3.3	RPD	RF & Power Distribution	a.k.a. cable system
2.3	GND	Ground Screen	
	ASP	**Analog Signal Processing**	
3.4	ARX	Analog Receiver	
3.5	AAP	Analog Array Processing	
	PCD	Power Conditioning & Distribution	
	MCS	Monitoring & Control System	
	EMD	Electromechanical Design	
	DP1	**Digital Processing 1**	
4.1	DIG	Digitizer	ADC + Post-processing
4.3	BFU	Beamforming Unit	
4.6.1	TBW	Transient Buffer – Wideband	
4.6.2	TBN	Transient Buffer – Narrowband	
	PCD	Power Conditioning & Distribution	
	MCS	Monitoring & Control System	
	EMD	Electromechanical Design	
	DP2	**Digital Processing 2**	
4.4	DRX	Digital Receiver	
4.5		Additional back ends	
	PCD	Power Conditioning & Distribution	
	MCS	Monitoring & Control System	
	EMD	Electromechanical Design	
5	**TCD**	**Timebase & Clock Distribution**	
6	**MCS**	**Monitoring & Control System**	*Station* MCS
7	**DAC**	**Data Aggregation & Communication**	
	SHL	**Shelter**	
	SEP	Signal Entry Panel	connections to ARR
	PCD	Power Conditioning & Distribution	
	ECS	Environmental Control System	

Table 1: Subsystem hierarchy and nomenclature.

Specification	Name	Value	Remarks
Domain			
Max integration time	τ_{max}	8 h	
Min Frequency	ν_{min}	10 MHz	
Max Frequency	ν_{max}	88 MHz	
Sky Coverage	Ψ	$z \leq 74^\circ$	z is zenith angle
Other			
Number of Stands	N_a	256	Memo 94 [4].
Beam Size	ψ	8° (20 MHz/ν)	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	(expandable) Each with 2 orthogonal pol's
Instantaneous Bandwidth	B	8 MHz	via DRX or TBN, adjustable downward
		78 MHz	via TBW or DP2 data recorder
Finest Spectral Resolution	$\Delta\nu$	100 Hz	via DRX or TBN, adjustable upward
Finest Temporal Resolution	Δt	1 ms	via DRX or TBN, adjustable upward
		13 ns	via TBW or DP2 data recorder ($= 1/B$)
Power consumption		25–36 kW	estimated

Table 2: A simplified subset of specifications for an LWA Station. Any contradiction with science or technical requirements documents should be resolved in favor of those documents.

Section	Nomenclature	Subsystem	Remarks
2.1	ANT	Antenna	See also Sec. 2.2–2.3
3.2	FEE	Front End Electronics	a.k.a. *active balun*
3.3	RPD	RF & Power Distribution	a.k.a. cable system
	SEP	Shelter Entry Panel	
3.4	ARX	Analog Receiver	
4.1	DIG	Digitizer	
4.3	BFU	Beamforming Unit	
4.4	DRX	Digital Receiver	
7	DAC	Data Aggregation & Communication	

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

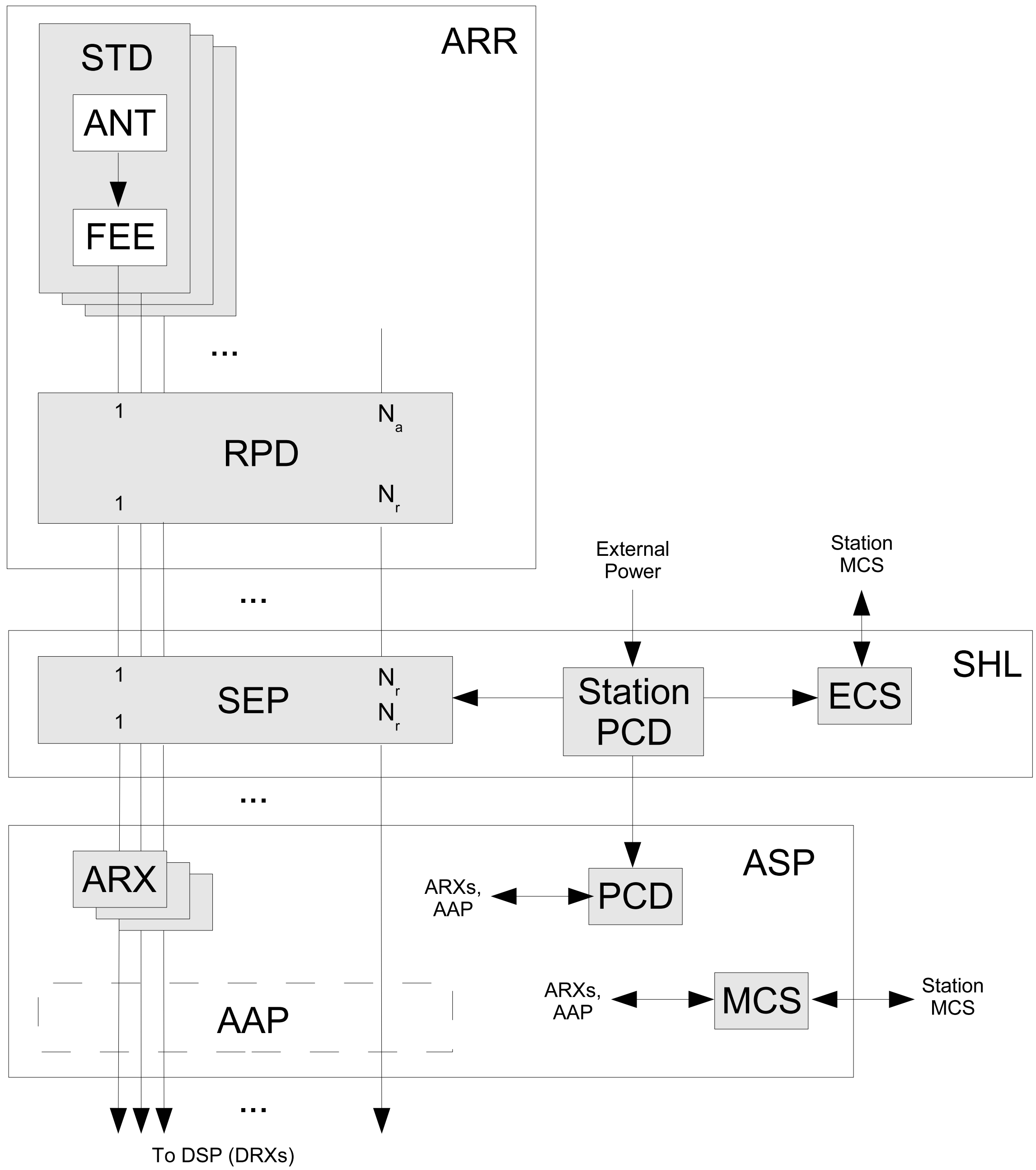

Figure 1: Station architecture: antennas through analog receivers.

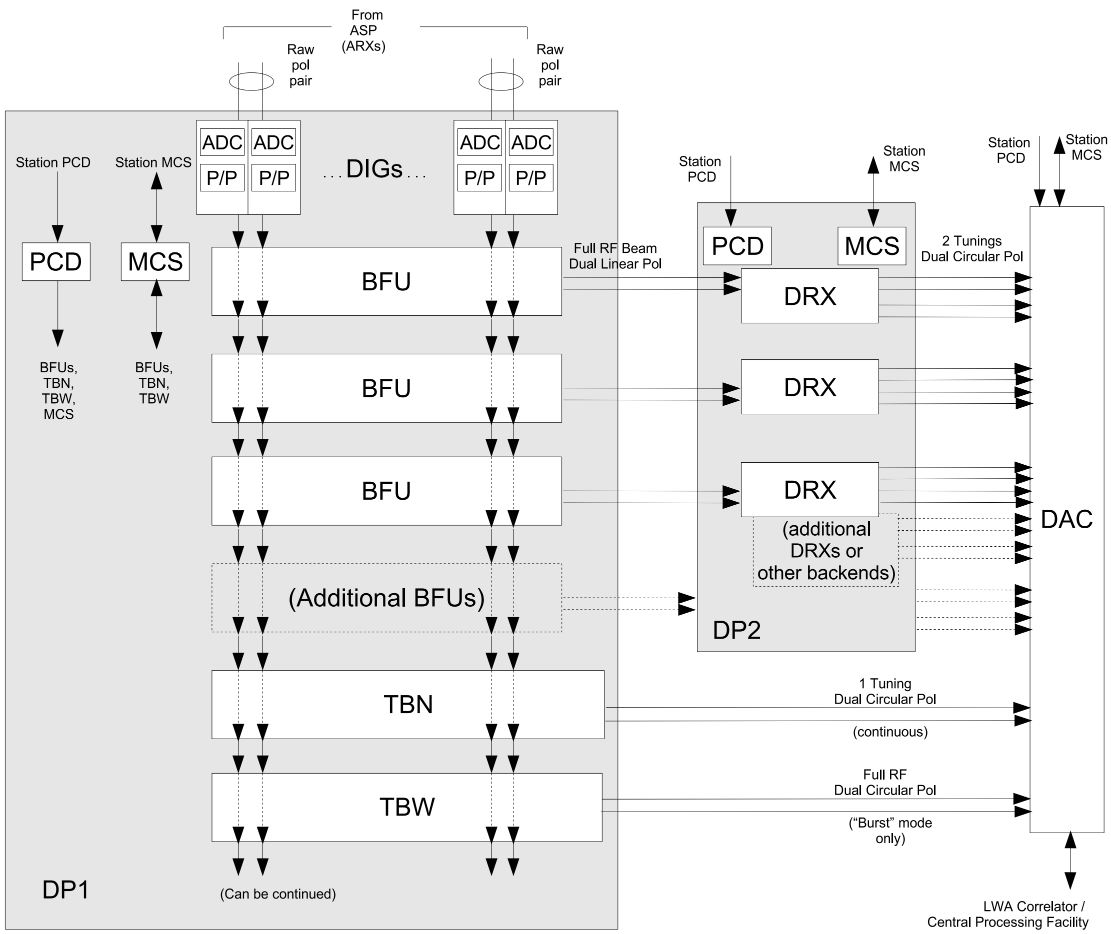

Figure 2: Station architecture: digital processing through external communications. The number of BFUs, TBWs, TBNs, and DRXs shown here may or may not represent the actual number used, and even at the time of construction and operation may not rigidly fixed; see the associated sections of this document for additional discussion. The DP1 daisy chain is explicitly shown, whereas the DP2 daisy chain(s) are not.

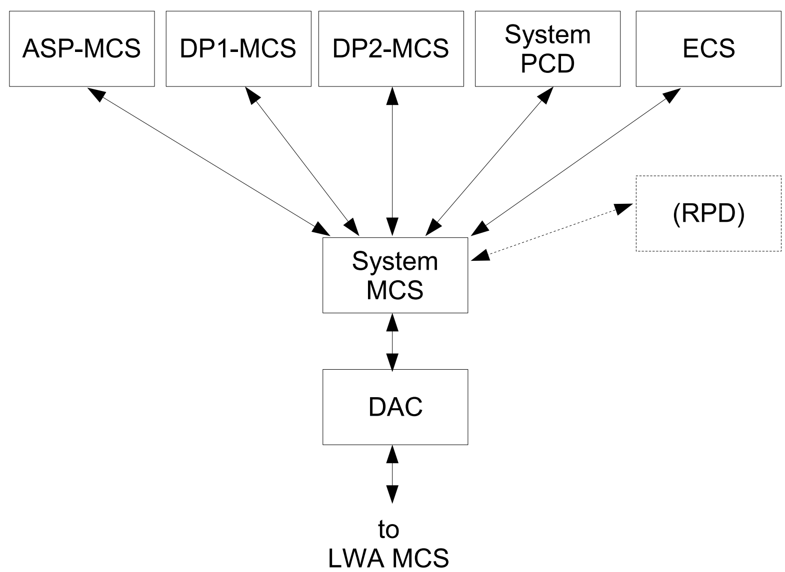

Figure 3: Station monitoring & control architecture. Interface to RPD is not necessary unless AAP is implemented there; see Section 3.3.

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 4. 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. Currently it is assumed that these will be linearly polarized and resonant somewhere within the tuning range. The relevant theory is summarized in LWA Memo 22 [2]. The arms of the dipole will likely be angled downward at approximately 45° to form an inverted-vee shape, as this is known to broaden the antenna pattern. Candidate antenna designs currently include:

- "Big blades," as shown in Figure 5(a), described in LWA Memos 32 [12], and 35 [21].
- The "fork" design, as shown in Figure 5(b), described in LWA Memo 88 [19].
- Thin dipoles, described in LWA Memo 22 [2].

It is worth noting that the "big blades" and "fork" designs are inherently broadband with respect to impedance bandwidth, whereas the impedance bandwidth of the thin dipole is significantly less. It should also be noted that the "thin dipole" approach is currently favored in this frequency range by the LOFAR project, and may turn out to be compelling for LWA especially if the "compact array" option (See Section 2.2) is pursued.

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.

It is frequently useful to have a simple method to estimate the effective collecting area of a single antenna. Such a method is described in Section 2.2 of LWA Memo 94 [4].

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.

The determination of $N_a = 256$ is based on an estimate from LWA Memo 94 [4] of what is required for interferometer-scale image calibratibility using "full-field" techniques.

The smallest dimension of the station array D is constrained by maximum beam size (HPBW). This is suggested to be 8° (20 MHz/ν) in LWA Memo 70 [16], 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 [4]:

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

and is summarized in Table 4. It is likely that this notional circular outline will be abandoned in favor of an elliptic outline extended in the north-south direction, so as to yield a better beam shape for Galactic Center observing.

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

Figure 4: Artist's concept of a station array based on preliminary design concepts.

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 currently preferred. A candidate pseudorandom geometry is shown in Figure 6. This geometry was obtained by minimizing sidelobes while enforcing a minimum 4 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 [17].

It should be emphasized that considerable uncertainty remains as to whether the sparse, pseudorandom array of 256 stands described above is the best choice overall. 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, it is unlikely that this revised strategy would be implemented in the first station (LWA-1) but might be considered for subsequent stations.

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 [20, 22, 25]. A ground screen is also effective in stabilizing the antenna impedance with respect to changes in soil moisture [20].

A consideration for the ground screen is whether it is *per-stand*, i.e., consisting of small, disconnected ground screens for each stand; or *per-station*, i.e., consisting of a single continuous ground screen for the entire station. The results indicated in [3] are determined on a per-station basis, and the per-stand benefit is harder to analyze for an entire station when mutual coupling is properly taken into account.

(a) Big Blade (b) Fork

Figure 5: Two LWA candidate antennas.

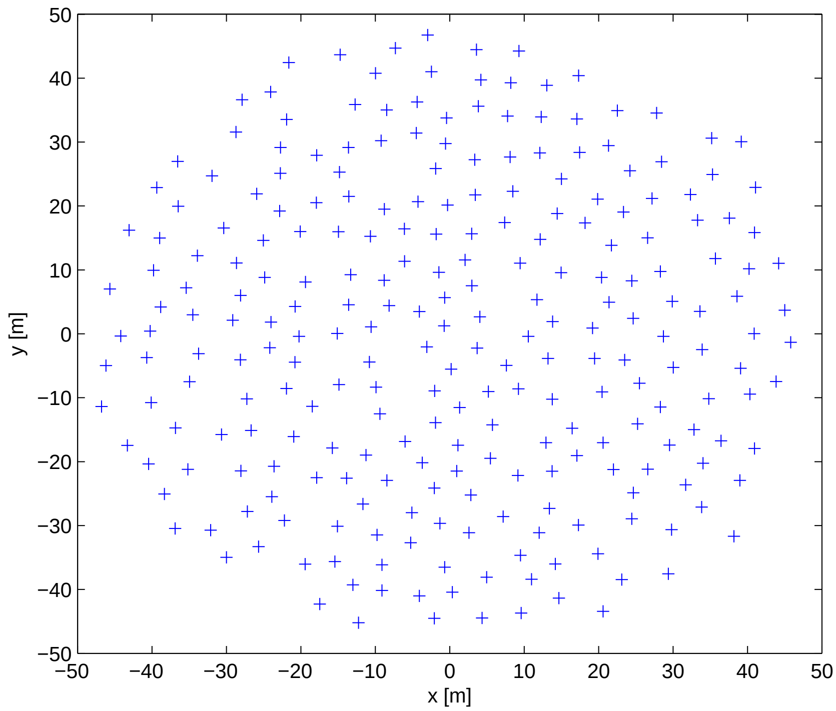

Figure 6: Candidate pseudorandom array geometry. *Courtesy A. Cohen, NRL.*

ν	$\psi(z = 0°)$	$\psi(z = 74°)$
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: Half-power beamwidth of a station beam.

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 $[\nu_{min}, \nu_{max}]$.

3.1 Introduction

Based on successful experiences with Long Wavelength Development Array (LWDA) and Eight-meter-wavelength Transient Array (ETA), 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. Techniques for the analysis and design of direct sampling receivers for this frequency range are presented in a masters thesis by Taylor [23]. In Section 6.4 of his thesis, Taylor uses these techniques to develop a prototype design for the LWA analog signal path. He determines that the LWA digitizer requires at least 5 bits, but selects 8 bits since suitable 8-bit A/Ds are commonly available and the additional bits provide headroom which is useful in dealing with RFI. Assuming 10 dB margin between external (nominally, Galactic) noise and quantization noise, and 10 dB minimum headroom to accommodate RFI (based on RFI studies available at the time), he determines that the analog signal path nominally has 68 dB of gain, and requires a minimum of 46 dB gain.

The digitizer described in Section 4 uses 10-12 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. It should be emphasized that significant refinements are possible, both in the analysis (e.g., updating using more recent RFI data) and design (moving existing subsystem designs closer to a mutually optimum design).

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 candidate (but incomplete) FEE has been developed by NRL, and is described in LWA Memo 88 [19]. It is included in Table 5 and its gain, noise temperature, and input third-order intercept point (IIP_3) can be regarded as interim specifications.

An open question for the FEE is the method of delivering power (for example, separate DC power terminals vs. bias-tee); see LWA Memo 86 [15] for a discussion. Another open question is output impedance (i.e., 50Ω or 75Ω); this impacts jointly the RPD (cable) system. Yet another issue is whether the input impedance should be increased from the value of 100Ω differential for the Memo 88 unit to some higher value, taking into account the observation that higher impedances (in the 200Ω to 400Ω range) typically yield better Galactic noise dominance and, as a result, increased effective bandwidth [2].

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. In the event that FEEs are powered by separate power lines, the power lines shall be considered part of the RPD. The RF characteristics shown in Table 5 are easily achieved using inexpensive coaxial cable. Open questions for the RPD are the associated open questions for the FEE, namely (1) whether bias-tees are to be used to move power over signal cables, and (2) impedance (50Ω vs. 75Ω).

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 $2N_a$. However, it is possible that N_a turns out to be so large that analog beamforming on a subarray basis is required to reduce the number of RF feeds to be digitized (see Section 3.5 for additional discussion). One possible location for analog beamforming is in the RPD (the other is in the ASP, following ARXs). This is one reason why N_r might be less than $2N_a$.

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. An exploratory ARX design has been developed by VT and is described in LWA Memos 82 [13] and 89 [14]. Its characteristics are summarized in context in Table 5.

An open question for the ARX is the extent to which gain control is necessary or desirable. Any gain control implemented should operate slowly; in fact, it should be essentially fixed upon installation and never changed unless absolutely necessary. At sites with very low RFI, gain control is probably irrelevant. However, in the presence of strong RFI, gain control could be essential. Gain control might also be used to equalize uneven losses in the RPD should they occur and (for whatever reason) lead to objectionably large differences. However, gain control entails additional cost and complexity. In the Memo 82 prototype, slow gain control over a 24 dB range is available using a 3-bit digital step attenuator. 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 be noted that gain changes might require recalibration of the station array.

A possible feature of the ARX is a user-reconfigurable bandpass. For example, it may be desirable to narrow the analog bandwidth to exclude strong RFI (for example, the FM broadcast band near the upper band edge) or to selectively notch selected broadcast TV channels.

3.5 Analog Array Processing (AAP)

Currently, AAP is a "placeholder" system. It is defined here to identify the possibility that analog beamforming might be required. For example, if the number of stands N_a increases much beyond 256, it may turn out that the station becomes cost-dominated by the DP1 subsystem sufficiently that it becomes compelling to do analog beamforming on a subarray basis in order to reduce the amount/cost of DSP hardware required. Also, it should be emphasized that in the case that analog beamforming is implemented, it might alternatively be moved forward into the RPD and physically collocated amongst the stands.

Subsystem	Assumed to consist of...	G [dB]	F [dB]	IIP_3 [dBm]
FEE	Memo 88 Active Balun [19]	+32	1.5	−6
RPD+SEP	500 ft inexpensive coaxial cable	−13	13.0	∞
ARX	Memo 82 ARX [13] with Memo 89 mod [14]			
	Maximum gain	+55	6.0	−16
	Set to achieve +68 dB cascade gain	+48	7.4	−10
	Minimum gain	+30	21.2	+7
	CASCADE: Maximum gain	+73	1.7	−35
	CASCADE: Set to achieve +68 dB cascade gain	+68	1.7	−29
	CASCADE: Minimum gain	+49	4.9	−13

Table 5: Characteristics of a candidate LWA analog signal path (FEE, RPD+SEP, ARX). The cascade receiver temperatures (i.e., not including Galactic noise) are 134 K, 140 K, and 604 K respectively.

4 Digital Signal Path

The digital signal path includes portions of the DP1, DP2, and DAC level-1 subsystems. Within the DP1 subsystem, ARX output is digitized by DIG subsystems and placed on a "daisy chain" for distribution to BFUs, TBW(s), TBN(s), and other future (as yet unspecified) level-2 subsystems. Each subsystem on the DP1 daisy chain accepts the data stream, internally fans out the data stream so as to generate an identical copy for its internal use, and transparently outputs the input data for use of the subsystems which follow in the daisy chain.

BFU outputs are conveyed to the DP2 subsystem, nominally to DRX level-2 subsystems. A DP2 daisy chain, analogous to the DP1 daisy chain, may be sourced by the DRX so as to allow multiple DP2 level-2 subsystems to access the same BFU output.

DAC is described in Section 7.

4.1 Digitizer (DIG)

A preliminary design for the DIG is documented in LWA Memo 101 [6]. DIG consists of an ADC followed by a post-processor. The ADC directly samples ARX output with nominally 10-12 bits at 196 MSPS. This allows alias-free digitization of the frequency range 10–88 MHz. Candidate ADCs currently include the Maxim MAX1215N, Analog Devices AD9211, and Analog Devices AD9230 [5].

The DIG post-processor is an FPGA which accepts the output from the ADC and includes:

- An independent variable-length (in integer sample increments) delay line. This can be used to equalize propagation delays associated with possibly unequal cable lengths, which has some convenience value especially in diagnostics.
- A quadrature conversion to complex baseband (zero center frequency, I/Q format).
- Filtering and decimation by 2, resulting in 24 bits (12 "I" + 12 "Q") per sample at 98 MSPS. The number of bits per sample is primarily determined by dynamic range required to accommodate RFI and might be reduced, either by design (i.e., fixed) or adaptively.
- Output in DP1 daisy chain format (See Section 4.2). (Note that Memo 101 (dated Sep 11, 2007) describing DIG predates the preliminary DP1 daisy chain specification; the latter takes precedence.)

4.2 DP1 Daisy Chain

A preliminary design for the DP1 daisy chain is documented in [7] (primarily electrical / data format information) and LWA Memo 108 [10] (primarily mechanical information). In this scheme, the full-bandwidth output from DIG is conveyed using 4 LVDS lanes. Each lane runs at 686 Mb/s for a total "per antenna" data rate of 2.352 Gb/s. This rate includes 4 in-band signaling bits per sample. Signaling bits are used to convey data format, flag invalid data, and facilitate synchronization between sample streams.

This architecture has the benefit of facilitating scalability while minimizing the number of external connections; however, it also relies on each subsystem in the daisy chain to convey data transparently and without degradation.

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, followed by a configurable finite impulse response (FIR) filter for each antenna, 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 Memos 107 [9] and 108 [10]. 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 BFU may need to include 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.[1] To understand what this entails, consider first that the desired correction can be achieved *at a single frequency* by means of a 2×2 matrix multiply with the raw linear polarizations as input and the desired ("purified") linear polarizations as output [8]. Thus, the same processing can be achieved over a specified bandwidth by replacing each of the four coefficients in the 2×2 matrix with a filter. The current design concept [10] assumes that polarization calibration can be accomplished with a single-frequency correction, but it has not been confirmed that this will be sufficient.

Ideally the BFU outputs calibrated orthogonal circular polarizations from the uncalibrated input linear polarizations.

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 9.2) and nullforming for RFI mitigation.

An open question is the output format of the BFU; i.e., the format in which data is conveyed from BFU to DRX. One possibility is that this format is identical to the input format, i.e., the DP1 daisy chain format.

4.4 Digital Receiver (DRX)

DRXs reside in the DP2 subsystem. Each BFU has an associated DRX, to which it is directly attached, and perhaps has access to multiple DRXs using the mechanism described in Section 4.5. Since there are nominally 4 BFUs per station, there is likely to be at least 4 DRXs per station. However given the daisy-chaining feature it is possible that many more DRXs will be desired and installed.

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 DAC.

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 mul-

[1] 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.

tiple operating modes that trade decreased $\Delta\nu$ for decreased B. For example, the mode achieving minimum $\Delta\nu = 100$ Hz might have $B = 409.6$ kHz, and a mode achieving $B = 8.192$ MHz might have $\Delta\nu = 2$ 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 may be convenient to fix the number of spectral channels to be a constant.

A design issue concerns whether the tuning function of the DRX is best implemented using FPGAs (as in LWDA and ETA), or using digital downconverter (DDC) chips, as in MIT/Haystack's Deuterium Array or Ohio State's Argus array. A description of a candidate DDC for LWA is given in Memo 61 [1].

4.5 Additional DRXs and Custom Backends

The capability exists within the DP2 subsystem to connect multiple sub-subsystems to a single BFU output. This is accomplished using a daisy chain architecture analogous to that which exists in DP1. This shall be referred to as a "DP2 daisy chain," and it should be noted that there may be multiple DP2 daisy chains; specifically, up to 1 per BFU.

For example, a DRX connected to a BFU could serve as the source of a DP2 daisy chain by transparently relaying the BFU output to a second DRX, or to an alternative backend. The secondary device can use the DP2 daisy chain in turn transparently relay the same BFU output to additional devices. This has several uses. One possible use is that the entire 78 MHz bandwidth output from a BFU could be processed to fine time-frequency resolution using a daisy chain consisting of (78 MHz)/(8 MHz) $\approx$ 10 DRXs – although of course the DAC and subsequent data communications would need to have sufficient capacity to accommodate all 8 DRX outputs. Alternatively, a custom backend could be attached to the DRX input daisy chain, with the ability to process the BFU output in parallel. Types of backends envisioned in this case 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.
- Direct-to-disk recording of the full bandwidth of a BFU output (has both scientific and system development/diagnostic uses).

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.

4.6 Transient Buffer Systems

The station includes transient buffer systems. Transient buffers serve as alternative, parallel backends to the BFU+DRX combinations. A transient buffer accepts all $2N_r$ of the outputs from the DP1 daisy chain (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.

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

4.6.1 Transient Buffer – Wideband (TBW)

Once triggered, a TBW simply captures the full-bandwidth output of the DP1 daisy chain for as long as possible. A reasonable length will be determined during the design process, with the goal that the buffer not "significantly" increase the cost or risk of the station design. A rough lower bound on useful capture length is on the order of 100 μs for spectral resolution of about 6 kHz. Of course, much longer record length and finer spectral resolution would be of great interest.

Some preliminary design concepts for the TBW exist and are described in LWA Memo 109 [11]. One scheme implements the TBW as a firmware-only modification to a BFU, resulting in a maximum capture length of 41 μs. Another scheme described in Memo 109 increases this to 85.6 ms albeit with considerable increase in cost and design risk.

Once triggered, the TBW would acquire until full, and then stop. Data would be read out asynchronously after acquisition.

4.6.2 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 TBN output is treated similarly to that of a BFU+DRX chain. The center frequency would be user-selectable. The reduced bandwidth will be determined as part of the design process; however a reasonable lower bound might be on the order of 100 kHz, resulting in a sample rate reduction 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 196 MHz clock to DIG subsystems as a sample clock, and (3) synthesize and distribute synchronous and coherent clocks as needed for other subsystems.

The station timebase will be a GPS-disciplined time standard capable of producing (1) a 1-pulse-per-second (1PPS) reference signal, (2) a 10 MHz reference signal, and (3) a data port providing absolute date & time information. There are no special accuracy requirements for a single station; however the interface between the timebase and these three signals 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 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. It is not explicitly necessary for the signal to be "fanned out" to DIG subsystems; alternatively, the signal could be distributed using a single cable from which signal power is extracted using directional couplers; and hybrid schemes are possible. 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 computer which controls the station, and provides status information in return. Various subsystems including the ASP, DP1, and DP2 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.

The station MCS architecture is shown in Figure 3. 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.

7 Data Aggregation & Communication (DAC)

The DAC subsystem provides the interface between the station's DP1, DP2, 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 above description has not specified details about how data are represented (e.g., number of bits, real or complex), sample rates, or formats (e.g., serial vs. parallel, multiplexed vs. packetized, and so on). This is deliberate so as not to preclude flexibility in the design process. However, it may be useful to see some elaboration on this with respect to impact on aggregate data rate. The data rate at the output of the DAC, including all beams but excluding the transient buffer and MCS communications, is:

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

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. For $a = 1.5$, $b = 8$ (e.g., for 4 bits "I" + 4 bits "Q"), $B = 8$ MHz, $N_b = 3$, $N_t = 2$, 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 DP1, DP2, and DAC subsystems.

Furthermore, note Table 2 indicates that $\Delta\tau < 1$ ms need not be supported, which makes possible further reductions for $\Delta\nu > 1$ kHz. For example, for $\Delta\nu = 10$ kHz we have $1/\Delta\nu = 100$ μs but are only required to offer $\Delta\tau = 1$ ms, yielding an order of magnitude reduction in r_S.

The DAC includes separate output to facilitate local recording of output directly to disk. For example, this would allow continued operation of the station should data path to the LWA central processing facility be interrupted, or not yet implemented. There are also many uses for this with respect to development and diagnostics. Ideally, this output would be flexible so as to facilitate the recording of just a single BFU-DRX output, or other subsets of outputs in various combinations.

8 Interface Specifications

The following is a list of interfaces which require explicit definitions (likely to appear in the form of separate interface control documents (ICDs)):

1. *Interface between STD and RPD.* This interface involves several issues including cable types, method of power transfer, and coordination of mechanical interfaces.

2. *Interface between RPD and SEP.* Similar issues as above.

3. *Interface between SEP and ASP.* Involves distribution of RF signals from the SEP to the ARXs.

4. *Interface between ASP and DP1.* This is the problem of how to get signals from ARXs to DIGs.

5. *DP1 Daisy Chain Interface Specification.* This is the electromechanical interface specification which applies between BFUs, transient buffers, and additional future equipment in the DP1's digitized antenna output daisy chain architecture. Careful attention to detail in this specification will help ensure the ability to independently develop the interconnected subsystems and also promote the easy future expansion of the system. A preliminary version is available: [7].

6. *BFU Output Specification.* Input to DRX; might be elegant to make this simply a subset (single polarization-pair version) of the DP1 Daisy Chain Interface Specification.

7. *DAC Sky-side Data Specification.* The input specification for data (as opposed to monitor & control traffic) from DRXs, transient buffers, and other backends in the daisy chain should be standardized in a way to easily facilitate development, bench diagnostics, and to accommodate alternative backends possibly developed by others.

8. *DAC Ground-side Interface Specification.* This is essentially the problem of how to move data and MCS traffic between the station and the larger LWA system.

9. *Inter-MCS Specification.* The interfaces between MCS subsystems should be standardized to facilitate communications in a simple, open way. For example, one possibility would be to use TCP/IP over ethernet as a foundation for this interface. Standardization through the application layer is desirable.

10. *Station PCD Sky-side Interface Specification.* This should describe how subsystems interface to the station PCD in order to obtain power.

11. *Station PCD Ground-side Interface Specification.* This should describe how the shelter obtains power from external source(s).

There are of course many other interfaces; however these are likely to be 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.

9 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.

9.1 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.

9.2 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[2] 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

[2] 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.

9.3 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.

10 Issues to Address in Future Versions of this Document

1. Elaboration of RFI mitigation strategy; in particular, actions/capabilities desired from the various subsystems in this respect.
2. Station RF stage-cascade analysis should consider IP_2 as well as IP_3.
3. Provide estimate of sensitivity per station beam.
4. Add list of acronyms and list of variables.

11 Acknowledgments

Many people have offered suggestions and corrections in the development of this document. These include 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 9.2.

12 Document History

- 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 [7].
  - 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 $\leq$ 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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