LWA1 Technical and Observational Information

April 10, 2012

Edited by Y. Pihlström, UNM

Contents

1 Overview

The LWA1 is the first LWA station to be completed in April 2011, and is located near the VLA site. LWA1 is a 256 element array, operating as a single-station telescope at frequencies between 10-88 MHz. One additional dipole antenna is placed at a distance of 300 m from the main array. Shared risk operations of the full LWA1 are ongoing alongside with commissioning activities.

This document intends to provide information about the basic functionality of the instrument for observing purposes. This document is under constant revision, and will be updated regularly. The most recent version will be found on the LWA Astronomer web pages http://www.phys.unm.edu/ lwa/astro.html.

1.1 Summary of Specifications

Table 1.1 summarizes the observational capabilities of the LWA1 station.

Specification	Details	Comments
Frequency coverage ν	10-88 MHz	
Number of antennas	257	
Number of beams	4	
Number of tunings	2 per beam	Independently tunable
Number of polarizations, N_{pol}	2 per beam per tuning	
Bandwidth per beam and polarization, B	19.6 MHz	∼16 MHz usable bw due to bandedges
Number of channels, N_{ch}	32	
Minimum channel width, $\Delta\nu$	7.8125 kHz	
Transient mode Narrow, TBN	1-100 kHz bandwidth	Continuous observing all dipoles
Transient mode Wide, TBW	78 MHz bandwidth	Short bursts of obserbing
Declination range	$-30°$ to $+90°$	
Main beam FWHM	$2.2° \frac{74MHz}{\nu} sec^2 Z$	Z is zenith angle
SEFD zenith angle $Z = [0°, 65°])$	[3, 17] kJy	Frequency independent
Thermal noise (at zenith)[a]	1 Jy	For 1s integration, $B = 16$ MHz, $N_{pol} = 2$ and $\nu = 74$ MHz
Confusion noise (zenith)[b]	25 Jy/beam	for a 2° beam at 74 MHz

[a]The thermal noise, as well as the confusion noise, will increase at angles away from zenith.
[b]The confusion limit will be reached in about 1 msec using 8 MHz bandwidth. Longer integrations can be achieved for narrower bandwidths.

2 Signal Path

2.1 Station Architecture

The LWA1 station consists of 256 dipole antennas spread over a 100 m diameter area. The minimum distance between each antenna is 5 m, and the position of each antenna is pseudo-random. The geometry is determined by minimizing the station side lobes. One additional dipole antenna is located on a 300 m baseline, initially for calibration purposes.

The path for a signal through the system is illustrated in Figure 1. The signal enters the antenna where a first gain stage is located (Sect. 2.3) and is then transferred to an analog processor for a second gain stage and filtering options (Sect. 2.4). The signal then enters the digital processor, where it is digitized (Sect. 2.5) and distributed in parallel to the transient buffers (Sect. 2.8) and to the beamformers where an electronical delay is entered into the signal path to correct for pathlength differences (Sect. 2.6). The digital receiver then furthers the signal by determining the tuning frequencies and bandwidths (Sect. 2.7), and eventually the signal is recorded. The following subsections of this document contains more details of each step in this signal path, see also [Craig (2009)].

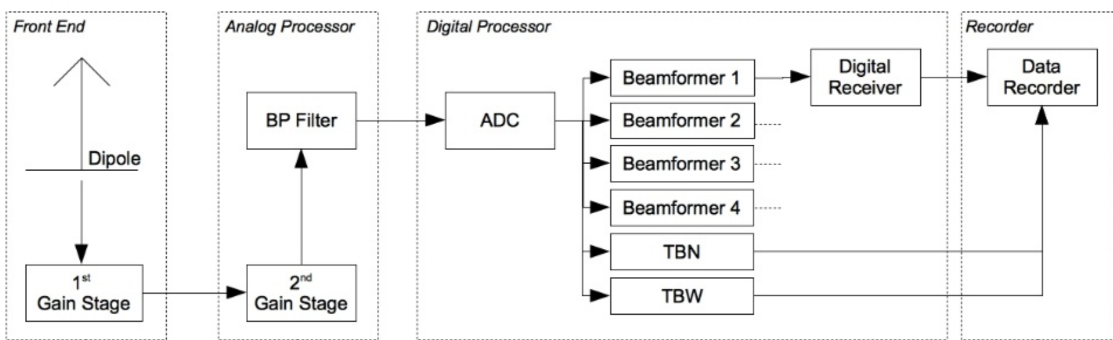

Figure 1: Overview of the LWA1 signal path.

2.2 Antennas

A single antenna element is a orthogonally and linearly polarized 'tied-fork' dipole (Fig. 2), with the arms drooping downward at about 45° [Craig (2009)]. They are placed on top of a ground screen to stabilize the antenna impedance and improve the collecting area.

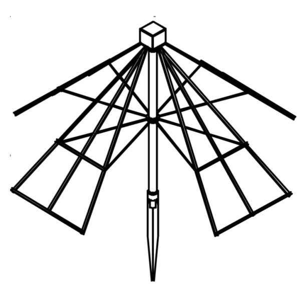

Figure 2: Sketch of an LWA1 tied fork dipole antenna.

2.3 First Gain Stage

The first gain stage is placed at the antenna, consisting of an active balun providing about 36 dB gain.

2.4 Analog Processor

The analog processor provides a second gain step of about 68 dB gain, of which 60 dB can be adjustable in 2 dB steps. The adjustment level will depend on the signal strength and will be determined at a system level rather than by the user.

To allow some flexibility in the rejection of strong RFI signals, the analog receiver provides three filter configurations (Fig. 3; [Craig (2008)], [Craig (2009)]) that can be set by the user:

a. Full bandwidth: 10-80 MHz

b. Reduced bandwidth: 28-54 MHz

c. Split bandwidth: 10-80 MHz with 30 dB of gain control over the low-frequency part of the passband.

The full bandwidth option implies a passband between 10-88 MHz, while the reduced bandwidth option suppresses signals outside the 28-54 MHz frequency range (both options with a response within 3 dB across the given frequency range).

The split bandwidth filter option is introduced to allow a stronger suppression in the low frequency part of the band, especially below 28 MHz where the RFI signal power is highly variable in time. Below 28 MHz, the attenuation is adjustable in steps of 2 dB up to 30 dB maximum. If the gain of this part of the band needs to be adjusted during observations, it should be noted that the gain changes may require the station array to be recalibrated.

2.5 Digital Processor

After the first stages of gain the signal enters the digital processor, where it is first direct sampled with 12 bits at 196 Msps. This sampling rate has been chosen for an alias-free digitization of the whole 10-88 MHz frequency range.

After digitization, the signal is distributed to 5 parallel processors. There are 4 beamformers (Sect. 2.6), and one transient buffer (Sect. 2.8).

2.6 Beamformer

The beamformer is a part of the digital processor system, and is responsible for adding delays to each dipole signal to form beams in the desired pointing direction. The delays are automatically calculated dependent on the pointing position specified, and are not directly accessible to observers. The bandwidth of the sampled signal at this stage is the full digitized bandwidth. Four different beams can be formed that can be run separately and simultaneously, effectively giving 4 telescopes.

2.7 Digital Receiver

Following the beamformer, the digital receiver processes the data to the desired tunings. The signal from each beam can be tuned to two different center frequencies ν_1 and ν_2 between 10-88 MHz. The center frequency settings are on a grid with spacings of 0.046 Hz.

Each tuning will have an associated passband of width B_1 and B_2 that do not need to be the same. B_1 and B_2 can be set to values between 0.250 MHz to 19.6 MHz (see Table 2.7). The actual usable bandwidth is somewhat smaller due to the band edges, and a conservative number is 0.8. Observations

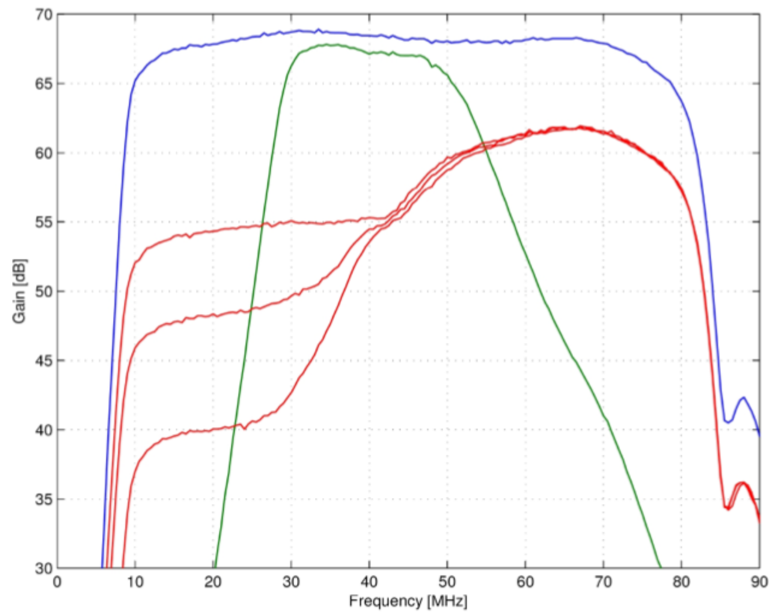

Figure 3: The response of the analog receiver across the passband for each of the three configurations: Full (blue), reduced (green) and split (red). The three red lines correspond to to different attenuator settings of 6, 12 and 20 dB respectively.

have shown that observing with a 19.6 MHz bandwidth gives an effective bandwidth of approximately 16 MHz.

Currently, the default output is the raw time series data. There are two options for the user to get spectral data, via either a software or a hardware spectrometer. Using the software option, you can use LSL to set an FFT of any length (with the potential of up to tens of thousands of channels). The time resolution for the FFTs will be limited by the length of the window. For example, a 1024 point FFT will have a spectral resolution of 19.1 kHz (assuming 19.6 MHz bandwidth observed), and the maximum time resolution will be 1024 times 51.2 ns or 5.22μs. The post processing software part of LSL can control spectral resolution and process to the Stokes parameters. The cost of this is that the software is slower and of course another step in the data reduction process. The second option is to use the hardware spectrometer (which still is under development). The spectrometer gives 32 channels, so if using the spectrometer together with the smallest bandwidth of 0.250 MHz the minimum channel width that can be achieved is 7.8125 kHz. The spectrometer averages 6144 spectra, which at 19.6 MHz will give a read out every 10 ms. This will successively increase as the bandwidth is decreased.

As an example, an observer could point a beam to a source, and define 2 individual frequencies. With a 9.8 MHz bandwidth, about 7.8 MHz would be achieved per frequency and polarization. In total, a bandwidth of 16 MHz could thus be covered. A second beam could be pointed to a different source, or tuned to a different set of frequencies.

Filter number	Bandwidth MHz	Usable bandwidth[a] MHz	Spectrometer $\Delta\nu^b$ kHz	Spectrometer Δt^c ms
1	0.25	0.20	7.8125	784
2	0.50	0.40	15.625	392
3	1.0	0.80	31.25	196
4	2.0	1.60	62.5	98
5	4.0	3.20	125.0	49
6	9.8	7.84	306.25	20
7	19.6	15.68	612.5	10

[a]Edges of the band have to be discarded, usable quoted bandwidth assumes a ratio of sample rate to bandwidth of 0.8
[b]If the 32 channel spectrometer is specified
[c]The spectrometer reads out averages of 6144 spectra at a time

Table 1: The available LWA1 DRX filter bandwidths and estimated actual observed bandwidths.

2.8 Transient Buffer

Parallel to the processing of the beamformer and digital receiver, the signal from each dipole is also fed into the transient buffer system after digitization. The transient buffers record the raw digitized signal directly for each polarization and antenna.

2.8.1 Transient Buffer Wideband

The Transient Buffer Wideband (TBW) records the full bandwidth output from the digitizer for as long as possible, which currently have two options available. Per trigger you can observe either 12×10^6 12-bit samples with a capture of 61.2 ms (giving $\Delta\nu$=16 Hz) or 36×10^6 4-bit samples with a capture time of 183.7 ms (giving $\Delta\nu$=5 Hz). There is approximatly 60 s between each trigger, resulting in $\sim 0.1\%$ duty cycle.

Science uses of TBW includes long duration total power transients, solar observations and riometry.

2.8.2 Transient Buffer Narrowband

A Transient Buffer Narrowband (TBN) will be available, which will collect data continuously. The TBN records data without any beamforming applied, and records all data streams, both polarizations, for each individual dipole. User settings for this buffer are the frequency (10-88 MHz) and sample rate of (1-100 ksps, see Table 2.8.2).

Science uses of TBN includes all-sky transient searches, and perhaps recombination lines.

Filter number	Sample rate (ksps)	Effective bandwidth (kHz)
1	1	0.67
2	3.125	2.09
3	6.25	4.19
4	12.5	8.38
5	25	26.75
6	50	33.5
7	100	67

Table 2: The available LWA1 TBN filter bandwidths

2.9 Data Recorder

For LWA1, the data recorder consists of a LAN and a network connector. The four beams processed through the digital receiver are being recorded on one station computer each, and a fifth station computer records the output from the TBN/TBW.

The storage unit is a RAID array, consisting of 5 streaming-tuned hard disk drives. For more information and how to assemble a data recorder storage unit see [Wolfe, Ellingson & Patterson (2009)].

3 Backends

The only backends currently planned for LWA1 are the digital receiver Sect. 2.7 and the All-sky Imaging Backend Sect. 3.1. Other backends are anticipated and the project is open to proposals.

3.1 All-sky Imaging Backend (ASI)

The correlation of the data from the dipoles will occur through a software FX correlator, consisting of an IBM computing cluster. The data will come from the TBN and all baselines from the 256 dipoles can be processed.

Note: The ASI is under development during the first year of LWA1 operations and exists under the name of 'PASI', Prototype All-Sky Imaging. PASI receives the TBN data stream of continuous 100 ksps data from all dipoles at 75 MHz. It splits the data into eight channels for imaging, and the firts and the last channel are discarded. PASI images most of the sky ($\sim 1.5\pi$ sr) many times per minute at a 100% duty cycle.

PASI data is available for users, and can be requested together with a justification of the science. In addition, if other frequencies and/or integration times are desirable, a proposal can be submitted.

4 Observing modes

A couple of standard observing modes are available for the LWA1, basically limited by the backends available.

4.1 Interferometric modes

The basic interferometric mode is used when the data is passed through the digital receiver with individual tunings of each beam. In this mode the following observing modes are available:

- DRX Tracking RA/DEC
- DRX Tracking Jupiter (UNTESTED AT THIS STAGE, USE RA/DEC)
- DRX Tracking Solar (UNTESTED AT THIS STAGE, USE RA/DEC)
- DRX Stepped (NOT AVAILABLE AT THIS STAGE)
- TBW
- TBN

4.2 Transient mode

The transient mode is suitable for all-sky imaging and monitoring, and for diagnostics of the system. The ASI backend available in 2012 will be the PASI (Sect. 3.1).

5 Sensitivity

The theoretical sensitivity that can be reached using the LWA1 can be estimated (Sect. 5.1). However, with a single station the instrument is severely limited by confusion noise (Sect. 5.2).

5.1 Theoretical Noise

The theoretical rms noise is derived using the effective collecting area A_e of the station, the system temperature T_{sys}, number of polarizations N_{pol}, the bandwidth $\Delta\nu$ and the integration time Δt:

$$\Delta S = \frac{2kT_{sys}}{A_e\sqrt{2N_{pol}\Delta\nu\Delta t}} \ \ \mathrm{Wm^{-2}Hz^{-1}sr^{-1}} \tag{1}$$

or

$$\Delta S = \frac{SEFD}{\sqrt{2N_{pol}\Delta\nu\Delta t}} \ \ \mathrm{Jy/beam} \tag{2}$$

where $SEFD$ is known as the System Equivalent Flux Density:

$$SEFD = \frac{2kT_{sys}}{A_e}10^{26} \ \ \mathrm{Jy} \tag{3}$$

A_e is estimated from the collecting area of an LWA dipole, A_{dip} times 256 for the number of dipoles in the array. A_{dip} depends on the zenith angle, and can be expressed as:

$$A_e = G(\lambda)\frac{\lambda^2}{4\pi}\cos\theta^{1.6} \tag{4}$$

where λ is the wavelength, θ is the zenith angle and $G(\lambda)$ is the antenna zenith gain ranging from 8.5 dB at 20 MHz to 5.9 dB at 88 MHz [Ellingson et al. (2009)].

The system temperature is a combination of external noise (cosmic, atmospheric and earth-generated noise) and internal noise (noise generated in the active parts of the antenna, and in the receiver). Except for night time atmospheric noise at the lowest frequencies around $10-20\,$MHz, and excluding man made interference signals, the system temperature between $10-88\,$MHz is dominated by the Galactic background radio emission, and can be approximated by a power law:

$$T_{sys} \approx 50\lambda^{2.56}\mathrm{K} \tag{5}$$

Table 5.1 gives the LWA1 theoretical noise in steps of 10 MHz, assuming dual polarizations, a bandwidth of 4 MHz, a 10 min integration time and a zenith pointing direction.

5.2 Confusion Limit

The rms fluctuations are affected by unmodeled sources in the field of view as well as sources passing through the sidelobes. These effects are large at low frequencies, and will limit the sensitivity of the LWA1.

The confusion noise limit σ_c at 74 MHz using a 2° beam and resolution θ is given by [Cohen (2004)]:

$$\sigma_c = \left(\frac{\theta}{1''}\right)^{1.54} 29 \ \ \mu\mathrm{Jy/beam} \tag{6}$$

Frequency (MHz)	A_e[a] (m^2)	T_{sys} (K)	SEFD (Jy)	ΔS (mJy)
15	2.56×10^4	1.07×10^5	11540	118
25	9200	2.89×10^4	8670	88
35	4700	1.21×10^4	7180	73
45	2840	6420	6240	64
55	1900	3840	5570	57
65	1360	2500	5080	52
75	1020	1740	4680	48
85	800	1260	4370	45

[a] A_e calculated in the zenith direction, assuming a zenith gain $G = 6$ dB.

Table 3: LWA1 theoretical noise estimates using dual polarizations, a bandwidth of 4 MHz, a 10 min integration time and a zenith pointing direction.

6 Estimating Data Volume

To estimate your data volume, you can use the following formulas:

6.1 DRX data rate

DRX datarate per beam:

$$BW_{MHz} \times N_{pol} \times N_{tunings} \times 0.9611 \text{MB/s/beam}$$

where BW_{MHz} is the DRX bandwidth in MHz, N_{pol} is the number of polarizations (2 by default), and $N_{tunings}$ is the number of tunings per beam (usually 2). Thus observing with two tunings and using filter code 7 (19.6 MHz), two polarizations for an hour will give a data set of 264.9 GB.

6.2 TBN datarate

TBN datarate:

$$BW_{kHz} \times N_{pol} \times N_{stands} \times 1.952 \times 10^{-3} \text{MB/s}$$

where BW_{kHz} is the TBN bandwidth in kHz, N_{pol} is the number of polarizations (2 by default), and N_{stands} is the number of stand used (usually 256). Thus observing with two tunings and using filter code 7 (100 kHz) and two polarizations for an hour will give a data set of 351.4 GB.

7 Observing with the LWA1

The first set of shared-risk observations and commissioning observations are under way. A call for proposals for the general community will be made during Spring 2012.

7.1 Proposing

An invitation for observing with the LWA1 late 2012 will be issued during Spring 2012. For this call, the LWA1 will be operated under a shared risk agreement.

Proposal information will be available on the LWA web pages http://www.phys.unm.edu/∼lwa.

7.2 Observing schedule file

The user will be responsible for producing an observing schedule file, with the LWA1 Session Definition GUI. This is a python-based GUI, which requires the LWA Software Library (LSL) to be installed. Information on how to download these software can be found at the following pages:

LSL: http://fornax.phys.unm.edu/lwa/trac/wiki/
Session Schedules: http://fornax.phys.unm.edu/lwa/trac/wiki/SessionGUI

7.3 Data reduction

The LWA Software Library (LSL) can be used for working with LWA1 data. LSL consists of python routines and demo scripts that:

- describe the setup of the station
- read in the three main data formats
- export time series and spectral data to FITS files
- estimate uv-plane coverage
- simulate visibility data sets
- displays integrated TBW/TBN spectra
- read in TBW/TBN data and save the data to FITS files
- obtain stand positions and cable lengths
- plot the station beam for a zenith snapshot

With the LSL FITS writer, you can thus transfer you data to another program of your choice. For more details, and information about how to download and install LSL, please consult the LSL web page: http://fornax.phys.unm.edu/lwa/trac/wiki.

7.4 Publication Policy

The LWA Project has been and will be a collaborative effort. In order to recognize the contributions of the entire collaboration involved in construction to the project in an equitable fashion we adopt the following publication policy: All peer-reviewed papers and edited books making use of commissioning data from the LWA1 Radio Observatory shall have ”opt-in” authorship. What this means in practice is that the first author for a publication should submit a draft to a member of the LWA1 Radio Observatory Publication Board and then wait a minimum of two weeks time before submission during which the

LWA1 Director disseminates a copy of the abstract plus instructions for responding to all relevant individuals and institutions. For a full policy description please read the LWA1 Publication Policy document http://www.phys.unm.edu/~lwa/pub_policy_jan30.pdf.

All publications (making use of commissioning data or otherwise) should include the following line in the acknowledgements: "Construction of the LWA has been supported by the Office of Naval Research under Contract N00014-07-C-0147. Support for operations and continuing development of the LWA1 is provided by the National Science Foundation under grant 1139974 of the University Radio Observatory program."

As of this date all telescope modes are considered to be producing commissioning data. Data supplied to Users in response to specific proposals will have a proprietary period of 1 year from the date of observation.

8 Contact Information

If you have questions about observing with the LWA1, please send an email to lwa@unm.edu, or contact one of our support staff in the list below.

Clarke, Tracy	System Scientist	tracy.clarke@nrl.navy.mil	202-404-4297
Craig, Joe	Systems Engineer	jcraig@unm.edu	505-246-6004
Pihlström, Ylva	LWA User Support	ylva@unm.edu	505-277-4492
Taylor, Greg	LWA Scientific Director	gbtaylor@unm.edu	505-277-5238

References

[Cohen (2004)] Cohen, A., 2004, LWA Memo 17

[Craig (2009)] Craig. J., 2009, LWA Station Architecture, LWA Memo 161

[Craig (2008)] Craig. J., 2008, LWA Engineering Memo ASP0003

[Ellingson (2008)] Ellingson, S., 2008, LWA Memo 121

[Ellingson et al. (2009)] Ellingson, S., Clarke, T.E., Cohen, A.,Craig, J, Kassim, N.E., Pihlström, Y.M., Rickard, L.J., & Taylor, G.B., 2009, Proc IEEE, vol. 97, No. 8, pp. 1421-1430

[Wolfe, Ellingson & Patterson (2009)] Wolfe, C., Ellingson, S., & Patterson, C., LWA Engineering Memo MCS0019