Scientific Requirements for the Long Wavelength Array

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Version 2.3

2007-November-19

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1. Introduction

The Long Wavelength Array (LWA) is designed as a user-oriented facility with capabilities across a wide area of Ionospheric and Space Science as well as Astrophysics. The design and development of the LWA is driven by the scientific requirements which are outlined within this document.

This document outlines the LWA scientific requirements based on a review of the low frequency key science drivers. The document outlines the top-level scientific requirements together with some technical specifications that impact the science case. Future modifications of the science requirements may be necessary following science-engineering trade-offs and/or cost and time limitations. An obvious requirement is that the instrument be useful for science. To address use issues, top level calibration and operations requirements should also be considered in a separate document. The intent is for the technical requirements to flow down from the top level science requirements in this document so that changes and short falls in the project design can be traced to a specific requirement and the impact on science can then be assessed. Details of the science behind the specifications are given in other documents (upcoming LWA Key Science Summary memo). Section 5.2 of the current document is devoted to the science that can be done with one full LWA station plus two partial outrigger stations.

2. Acronyms and Symbols

In this section we provide brief descriptions of the acronyms, definitions and symbols used throughout this document. These are all summarized in Table 1.

Table 1. Acronyms and Symbols.

Notation	Description
δ	Declination
e^{-}	Electron
γ	Lorentz Factor
λ	Wavelength
ν_l (ν_u)	Lower (Upper) End of Frequency Range
σ	Point Source Sensitivity
Σ	Surface Brightness Sensitivity
mJy/bm	MilliJansky per Beam
BL_{min} (BL_{max})	Minimum (Maximum) Baseline Length
BW	Bandwidth
CMB	Cosmic Microwave Background
CME	Coronal Mass Ejection
CR	Cosmic Ray
D	Station Diameter
DR	Imaging Dynamic Range
EVLA	Expanded Very Large Array
GC	Galactic Center
HizRG	High Redshift Radio Galaxies
HI	21 cm Hyperfine Line of Neutral Hydrogen
IP	Interplanetary
IPS	Interplanetary Scintillation
ISM	Interstellar Medium
LAS	Largest Angular Scale
LSS	Large Scale Structure
LWA	Long Wavelength Array
mas	milli-arcsecond
PBW	Primary Beam Width
Polz	Polarization
RFI	Radio Frequency Interference
RRL	Radio Recombination Line
SNR	Supernova Remnant
TID	Traveling Ionospheric Disturbance
UHECR	Ultra High Energy Cosmic Ray
VLA	Very Large Array
VLSS	VLA Low-Frequency Sky Survey
Z	Zenith Angle
ZaC	Zenith Angle Coverage

3. LWA Key Science Drivers

The science for the Long Wavelength Array is separated into four key science drivers each of which addresses fundamental astrophysics or space-science issues which are uniquely probed by study at low radio frequencies. Details of the key science drivers are found elsewhere (Falke & Gorham 2001; Kassim 2003; Lazio & Farrell 2004; Kassim et al. 2005; Cohen et al. 2007, LWA pending Key Science Specification memo[3]). The key science drivers are:

1. Cosmic Evolution and the High Redshift Universe
    - 1.1 Dark Ages
    - 1.2 First Supermassive Black Holes
    - 1.3 Large Scale Structure - Dark Matter and Dark Energy
2. Acceleration of Relativistic Particles
    - 2.1 Up to 10^{15} eV in SNRs in Normal galaxies
    - 2.2 Up to 10^{19} eV in Radio Galaxies and Clusters of Galaxies
    - 2.3 Up to 10^{21} eV in Ultra High Energy Cosmic Rays
3. Plasma Astrophysics and Space Science
    - 3.1 Ionospheric Waves and Turbulence
    - 3.2 Solar, Planetary, and Space Weather Science
    - 3.3 Acceleration, Turbulence, and Propagation in the ISM of the Milky Way and Normal Galaxies
4. Exploration Science
    - 4.1 Emphasize Pioneering Capabilities for Survey and Discovery Space
    - 4.2 Transients and Extra-Solar Planets

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[3] to be submitted as an LWA memo

4. Scientific Requirements

Based on the key science drivers for the LWA as outlined in the LWA Key Science Specifications Document (to be submitted as an LWA memo), the science requirements are summarized in Table 2. In Table 3 we review the science requirements for each key science driver. This table is taken directly from the Key Science Specifications Document and should be updated to track changes to that document. Entries in Table 3 with no numeric value indicate that there is no known associated science driver for that entry. Below we only outline bullets under science requirements for the science cases that push the limits of that requirement. We also call out specific examples and/or issues that need to accompany some requirements.

Table 2. Science-Driven Requirements.

	Required	Desired
Frequency Range	ν_l - $\nu_u = 20$ - 80 MHz	ν_l - $\nu_u = 3$ - 88 MHz
Instantaneous Bandwidth[a]	$\Delta\nu_{max} = 8$ MHz[b]	$\Delta\nu_{max} \gtrsim 50$ MHz
Minimum Channel Width	$\Delta\nu_{min} \lesssim 100$ Hz	$\Delta\nu_{min} = 10$ Hz
Angular Resolution [@ 80 MHz]	$\theta \lesssim 2''$	$\theta \lesssim 1''$
Minimum Temporal Resolution	$\Delta\tau = 10$ ms[c]	$\Delta\tau = 1$ ms[c]
Primary Beam Width [@ 80 MHz]	PBW = 2°	PBW $\gtrsim 2^\circ$
Largest Angular Scale [@ 80 MHz]	LAS = 1°	LAS = 2°
Baseline Range	200 m - 400 km	100 m - 600 km
Sensitivity[d]	$\sigma = 1$ mJy	$\sigma \lesssim 1$ mJy
Dynamic Range @ 20, 80 MHz[e]	DR = 10^4, 10^3	DR = 10^5, 10^4
Polarization[f]	dual circular $\gtrsim 10$ dB	dual circular $\gtrsim 20$ dB
Zenith Angle Coverage	Z$\lesssim 60^\circ$	Z$\lesssim 74^\circ$
Number of Beams[g]	Beams=4	Beams$\gtrsim 7$
Configuration	2D array	2D array
Number of Stations	N=53	N$\gtrsim 53$
Operation model is a user-oriented, open facility that solicits proposals from the entire scientific community		

[a] Bandwidth requirement per beam.

[b] Require stations in inner 5-10 km to have $\Delta\nu_{max} = 50$ MHz for dark ages work. This could be accomplished by adding 7 dedicated dark ages beams for these inner stations.

[c] Temporal resolution required to track fast pulsars using phased-array mode is 0.1 ms. Require sampling at dipole level in a station of 3×10^{-5} ms for UHECR work.

[d] Thermal point source sensitivity in 1 hour, with dual polarization and 8 MHz bandwidth at 80 MHz.

[e] This requirement refers to imaging dynamic range.

[f] This requirement refers to the cross-polarization isolation.

[g] Fully independent spatial and frequency beams.

Table 3. Key Science Specification Document Summary Table.[a]

KSD[b]	ν_l - ν_u MHz	$\Delta\nu_{max}$ MHz	$\Delta\nu_{min}$[c] Hz	θ @ 80 MHz arcsec	$\Delta\tau$[d] ms	PBW °	LAS °	σ[e] mJy	Σ mJy/bm	DR	Polz	ZaC °	Beams
1.1	7-88	$\gtrsim$ 50[e]	⋯	⋯	⋯	1	1	⋯	1-10 mK (1 yr)	TBD	dual	⋯	1[g]
1.2	50-80	⋯	⋯	$\lesssim$ 5	⋯	⋯	⋯	9.2,5	⋯	902,740	⋯	⋯ [h]	⋯
1.3	20-80	⋯	⋯	$\lesssim$ 5	⋯	$\gtrsim$ 1.5	$\gtrsim$ 1.5	2.6,1	252,60 [θ=1′]	16700, 3700	⋯	⋯	⋯
2.1	20-80	⋯	⋯	$\lesssim$ 5	⋯	$\gtrsim$ 5 [@ 20 MHz]	$\gtrsim$ 1	26,10	1 [θ=20″]	1670, 370	⋯	$\lesssim$ 74	⋯
2.2	20-80	⋯	⋯	$\lesssim$ 2	⋯	⋯	⋯	2.6,1	2 [θ=6″]	16700, 3700	⋯	⋯	⋯
2.3	$\lesssim$ 60	$\gtrsim$ 33	⋯	⋯	3×10^{-5}	⋯	⋯	⋯	⋯	⋯	⋯	$\gtrsim$ 60[i]	⋯
3.1	9-80	⋯	⋯	⋯	1	⋯	⋯	⋯	⋯	10^4	dual	TBD	$\gtrsim$ 3
3.2	20-80	$\lesssim$ 60	10	1 [@ 40 MHz]	$\lesssim$ 10	$\gtrsim$ 2	$\gtrsim$ 2	⋯	500 mJy/arcmin^2	$\gtrsim$ 4000[j]	dual	$\lesssim$ 57	$\gtrsim$ 1
3.3	$\lesssim$ 10-88	⋯	$\lesssim$ 100	1.5	⋯	⋯	0.5	⋯	1 [θ=10″ @ 30 MHz]	20700 cont	dual	$\lesssim$ 74	⋯
4.1	3-80	Full RF	⋯	2	⋯	$\gtrsim$ 2	⋯	$\lesssim$ 1	⋯	$\gtrsim$ 3700	dual	⋯	$\gtrsim$ 1
4.2	3-80	⋯	TBD	⋯	$\lesssim$ 0.1[k]	$\gtrsim$ 2	⋯	$\lesssim$ 1	⋯	$\gtrsim$ 3700	dual	$\lesssim$ 74	$\gtrsim$ 1
Required	20-80	8[f]	$\lesssim$ 100	$\lesssim$ 2	10[k]	2	1	1[l]		10^4, 10^3	dual	$\lesssim$ 60	4[l]
Desired	3-88	$\gtrsim$ 50	10	$\lesssim$ 1	1[k]	$\gtrsim$ 2	2	$\lesssim$ 1[l]		10^5, 10^4	dual	$\lesssim$ 74	$\gtrsim$ 7[m]

[a] Ranges of angular resolution, sensitivity, and dynamic range correspond to ν_l - ν_u unless otherwise specified. If only one number is given it applies to 80 MHz.

[b] Number refers to key science driver (KSD) category in Section 3.

[c] A minimum channel width of 1 kHz is necessary for RFI excision. Bandwidth smearing of $\lesssim$ 10% at the first null on 400 km baselines requires channel width less than 1.25 kHz.

[d] Time-averaging smearing of $\lesssim$ 10% at the first null on 400 km baseline for a 100 m station at 20 MHz requires temporal resolution be shorter than 0.9 s.

[e] Sensitivity is at 80 MHz except where two values are shown when the lower frequency cutoff is above 20 MHz. Numbers in latter case are for ν_l, 80 MHz.

[f] Bandwidth requirement of $\gtrsim$ 50 MHz on baselines within 5-10 km for dark ages work.

[g] Shared beam day/night with Solar/Dark Ages.

[h] Studies of high redshift radio galaxies down to a zenith angle of 74° provides opportunity for full Keck/Gemini followup.

[i] Note that this is a dipole-based measurement.

[j] Requirement is a lower limt as it assumes 200 Jy quiescent disk for Sun at 80 MHz. CME are often associated with a powerful Solar burst which may be orders of magnitude brighter than the quiescent sun. DR requirement must be met on short enough timescale to track CME.

[k] Temporal resolution of 0.1 ms is needed to track the fastest pulsars. This exceeds the communication speed across full array and is only required for inner stations in phased-array mode. Require sampling at dipole level in a station of 3×10^{-5} ms for UHECR work.

[l] Sensitivity in 1 hour, dual polarization, and 8 MHz bandwidth.

[l] The total required number of beams could be arrived at with various metrics for scientific output. The required number of 4 was arrived at assuming that there is a long terms dedicated Solar/DA beam plus three additional beams. Those three beams could be broken up to be a survey beam + a transient beam + a general observer beam, or the three could be combined for 3D ionospheric tomography work.

4.1. Frequency Range

- Coherent emission processes (e.g. Jupiter "turn on" below 40 MHz)
- Efficient RRL studies below 40 MHz
    - Integration time for RRL studies goes as (filling factor)$^{-2}$ making it more efficient to observe with a completely filled aperture. The pseudo-random array design of the LWA approaches 100% filling factor at frequencies $\lesssim$ 40 MHz.
- Coordinated campaigns with ionospheric instruments below 20 MHz
- HI studies of cosmic density fluctuations in the Dark Ages
    - $15 \lesssim z \lesssim 200$ neutral gas decoupled from CMB ($88 \gtrsim \nu \gtrsim 7$ MHz)
- Cross-over science with 74 MHz VLA
- Ionosphere may permit measurements of bright sources to a few MHz, 10 MHz is optimistic lower bound for astrophysical calibration
- In the FM bands above 87.9 MHz there is an increased risk due to the strength and density of the radio frequency interference.

4.2. Instantaneous Bandwidth

- Broader BW increases sensitivity
- UHECR air-showers: need $\Delta\nu_{max} > 33$ MHz at individual dipoles
    - Note special requirement: UHECR air-shower studies require a receiver at each dipole within a station. This may be provided for one or more stations by targeted funding through collaborative agreements with special interest groups.
- Tracking drifts of solar bursts: $\Delta\nu_{max} \gtrsim 60$ MHz or fast sweep capabilities (10 ms across full RF)
- Pre-reionization dark ages signal need $\Delta\nu_{max} \gtrsim 50$ MHz for detection in $\lesssim 1$ year
    - Note that this bandwidth is only needed for stations in inner 5-10 km

4.3. Minimum Channel Width

- RRL from the cold ISM (e.g. 1.5 km/s at 20 MHz requires $\Delta\nu_{min} \lesssim 100$ Hz)
- HI absorption requirements: channels $\sim$ few km/s corresponds to $\Delta\nu_{min} \sim 200$ Hz at 20 MHz
- Solar radar: $\Delta\nu_{min} \lesssim 100$ Hz
- Planetary radar: $\Delta\nu_{min} \lesssim 10$ Hz
- RFI excision requires $\Delta\nu_{min} \lesssim 1$ kHz
- Bandwidth smearing: $\Delta\nu_{min} \lesssim 1.25$ kHz for 10% reduction in flux at first null on 400 km baseline

4.4. Angular Resolution

- Radio galaxies: $\theta \sim 10''$ to image $1'$ sources with 28 independent resolution elements
- High redshift radio galaxies: angular extent of $\sim 5''$
- Large scale structure: $5''$ to separate compact radio galaxies from diffuse emission
- Radio jets and hotspots: $\theta \sim 2''$ at 80 MHz to sample γ=50-200 e- population responsible for inverse Compton emission
  - Note that study of knots in radio jets would need $\theta \lesssim 0.5''$
- SNR: $\theta \lesssim 5''$ to resolve brightest regions in strong shocks
- Normal galaxies: $\theta \lesssim 2''$ to separate compact and diffuse emission
- Jupiter decametric emission: $\theta \lesssim 1''$ at 40 MHz
- Scattering: competing with cm VLBI for interstellar scattering ($\theta_{20cm} \sim 5$ mas) corresponds to $\theta \lesssim [25,1.5]''$ at [20,80] MHz
- Ionospheric wave propagation direction and dissipation: wavelength of disturbances $>$ 50 km
  - while not strictly a resolution requirement this does drive the longest baseline

- Scattering limits on resolution in plane: [7,0.4]$''$ at [20,80] MHz corresponds to maximum baselines of [450,2000] km
- Avoid classical confusion in short to moderate integrations: see Table 4

4.5. Minimum Temporal Resolution

- Flare stars: $\Delta\tau \sim$ 20-100 msec bursts, $\Delta\tau \sim 1$ ms for substructure in bursts
- Solar & Space Weather, CMEs, Flares, IPS, IP Shock: $\Delta\tau \lesssim 10$ msec
- Timing the fastest pulsars: $\Delta\tau \sim 100\ \mu$s
  - Needed on inner stations in phased array mode.
- Cosmic-ray airshowers: $\Delta\tau \sim 30$ nsec
  - Note that this is a special application that needs the raw A/D output at the original sample rate from individual dipoles
- Ionospheric structure including TIDs: $\Delta\tau \sim 1$ msec
- Calibration: sample calibrators on timescales fast compared to ionospheric changes ($\Delta\tau \lesssim 1$ sec)
- Time-averaging smearing: $\Delta\tau \lesssim 0.9$ sec for 10% flux reduction at 20 MHz at the primary beam first null on a 400 km baseline
- The light travel time across an array of 400 km is 1.33 ms.

Table 4. Classical Confusion

	20 MHz	80 MHz
100 km	4.0 mJy, 0.18 hr	0.2 mJy, 16 hr
400 km	0.5 mJy, 11 hr	0.025 mJy, 1040 hr
600 km	0.3 mJy, 31 hr	0.015 mJy, 2900 hr

4.6. Primary Beam Width

- Local supercluster filaments: PBW $\gtrsim$ 1.5° at 20 MHz
- SNR: PBW $\sim$ 5° at 20 MHz to avoid mosaicking at the lowest frequencies
  - Many SNRs are several degrees in size
- CME: PWB $\gtrsim$ 2° to study full structure
  - Note that this PBW requirement is for the full frequency range.
- Transients: PBW $\gtrsim$ 2° to enhance survey speed
  - Note that this PBW requirement is for the full frequency range.
- Survey-speed: maximized by larger primary beam width
  - survey speed=PBW*$(A_e/T_{sys})^2\Delta\nu_{max}$, moving from a 2° to a 4° primary beam width is a factor of 2 increase in survey speed
- Want PBW at least a large as LAS to allow imaging without mosaicking
- λ/D gives us $\theta_{PBW} \sim [8.6,2.1]^\circ$ @ [20,80] MHz for 100 m diameter stations

4.7. Largest Angular Scale

- Local supercluster filament: LWA $\gtrsim$ 1.5°
  - Note that this LAS requirement is for the full frequency range.
- SNR: LAS $\sim$ 1° for largest diffuse emission scales within biggest remnants
  - Note that this LAS requirement is for the full frequency range.
- Map Galactic CR distribution with distant HII regions: LAS = 0.5°
  - Note that this LAS requirement is for the full frequency range.
- Sun & Solar Wind (e.g. CMEs) : $\theta_{LAS} \gtrsim [5,2]^\circ$ @ [20,80] MHz
  - Important for understanding and predicting space weather as well as astrophysics of the Sun
  - Need good instantaneous uv coverage
- Cosmic density fluctuations in the Dark Ages on scales of $\sim$ 1°

4.8. Baseline Range

- Driven by angular resolution and largest angular scale:
  - LAS=1° @ 80 MHz gives BL_{min}=215 m
  - Angular resolution=2″ @ 80 MHz gives BL_{max}=386 km
- Longest baseline also driven by ionospheric studies of wave propagation direction and dissipation, VLA reveals that 35 km is too small
  - TIDs have wavelengths $>$ 50 km

4.9. Point Source Sensitivity

- HizRG: 5 mJy sensitivity at 80 MHz allows studies $>$ 10 times deeper than current work, assuming α=-1.3, this translates to 9.2 mJy at 50 MHz
- LSS: 1 mJy sensitivity needed for point source removal from diffuse emission
- SNR: need 10 mJy sensitivity for compact source removal from diffuse emission
- Radio Halos/Relics: 1 mJy sensitivity needed for point source removal from diffuse emission
- Surveys: LWA competes with EVLA in short integrations for $\alpha \lesssim$ [-1.2,-1.5] @ [20,80] MHz and has a much larger primary beam width
  - push to sub-mJy to extend low frequency studies 2-3 orders of magnitude deeper than previous work (i.e. VLSS)
- Extrasolar Planets: push to sub-mJy based on model predictions for currently known systems where range of predicted fluxes is 0.1-1000 mJy in LWA frequency range

4.10. Surface Brightness Sensitivity

- Pre-reionization dark ages signals at 1-10 mK
  - Note that this needs a dedicated beam with τ= 1 yr and $\Delta\nu_{max}$=50 MHz but only on inner stations within 5-10 km, may be shared for Solar studies

- LSS: need 60 mJy/beam at 1′ resolution @ 80 MHz, 252 mJy/beam at 1′ resolution at 20 MHz
- SNR: need surface brightness sensitivity of 1 mJy/beam at 20″ resolution at 80 MHz for deep searches to detect new Galactic SNRs
- Radio Lobes: based on 3C129 lobe surface brightness at 330 MHz this needs 2 mJy/bm at 6″ resolution at 80 MHz
- Radio Halos/Relics: based on observations and models in the literature this needs 1 mJy/beam at 10″ resolution at 80 MHz
- CME: based on CME observations at Nancay this needs 500 mJy/square arcminute at 80 MHz
- HII region tomography of the Galactic CR population needs 1 mJy in 10″ beam at 30 MHz

4.11. Dynamic Range

Taking 1000 random fields from the VLSS (74 MHz) catalogue at 80″ resolution the median peak emission is 4.3 Jy. Assuming a typical extragalactic spectral index of α = -0.7 ($S_\nu \propto \nu^\alpha$) this translates to a median peak of 3.7 Jy/bm in a 2.2° beam at 80 MHz. A similar study for 50, 30, and 20 MHz yields peaks of 8.3, 20.7, and 43.4 Jy/bm in a 3.5, 5.8, and 8.8° beam respectively. At higher resolution the field peak may be lower but for lack of better information below we assume the VLSS median peak applies to arcsecond resolution.

- HizRG: the point source sensitivity for a $>20\sigma$ detection needs DR$\sim 10^3$, 7×10^2 at 20, 80 MHz
- LSS: removal of compact source contamination needs DR $\sim 1.7\times10^4$, 3.7×10^3 at 20, 80 MHz
- SNR: removal of compact source contamination needs DR $\sim 1.7\times10^3$, 3.7×10^2 at 20, 80 MHz
- Radio Lobes: removal of compact source contamination needs DR $\sim 1.7\times10^4$, 3.7×10^3 at 20, 80 MHz
- CME: need to reach DR $\gtrsim 10^3$ on timescales fast enough to track CME.

  - CME DR calculated assuming a quiescent sun at 2000 Jy. The DR needed may be orders of magnitude larger since CMEs are often associated with powerful Solar bursts.

- ISM: removal of compact source contamination needs DR $\sim 2\times10^4$ at 30 MHz

- Sub-mJy sensitivity for survey and extra-solar planets will need to push the DR an order of magnitude further down to DR $\sim 1.7\times10^5$, 3.7×10^4 at 20, 80 MHz

4.12. Polarization

- Dark ages: need dual polarization to improve sensitivity and excise RFI in very long integrations

- Jupiter: decametric bursts have preferred circular polarization, need polarization purity of at least 10 dB

- Ionosphere: dual polarization for Faraday rotation studies

- RRL: second polarization provides confirmation of recombination line detection and improved sensitivity

- Circularly polarized coherent sources: need two circular polarizations to distinguish differential absorption

- Correlator: Circular polarization must be presented to the correlator because of ionospheric Faraday rotation on baselines $\gtrsim$ 1 km

- RFI: excision techniques may be able to leverage off polarization information (e.g. V-pol)

4.13. Zenith Angle Coverage

- Galactic center: good imaging to at least δ= -30° (Z=64°)
  - Actually need good imaging to 10° lower, Z$\lesssim$74°, also allows study of bright transients in Galactic center regions and probe into the 4th Galactic quadrant

- UHECR: desire to see as much of sky as possible with individual dipoles, Z$\gtrsim$ 60°

- Solar and planetary: reach δ = -23° (Z=57°) for year-round solar monitoring

- Bright, isolated objects at low declinations: imaging capabilities extending to Fornax A (δ=-37°, Z=71°), Puppis A (δ=-43°, Z=77°), and Centaurus A (δ=-43°, Z=77°)
- Ω_{HPBW} of our active antennas is ∼100° (Z = 50° gives δ = -16°)
- Clark Lake and the 74 MHz VLA demonstrated that observations to Z $\lesssim$ 75° ($\delta \gtrsim$ -40°) will be possible in good ionospheric weather at reduced sensitivity
- Need to target two anomalies of interest to the ionospheric community:
  - the 'winter' anomaly in the northern hemisphere (centered around 30 degrees latitude but extending to pole)
  - the 'equatorial' anomaly within 20 degrees of the magnetic equator
- Extend N-S array geometry to compensate for foreshortening at large zenith angle
  - Note than an elliptical station may also be desired to provide a circular beam at the celestial equator. The extended array and station geometry allow roughly uniform resolution and field of view over as much of the sky as possible. This is particularly desirable for deep integrations and surveys.

4.14. Number of Beams

Note that one beam is considered to contain two independent circular polarizations. Each beam referred to is capable of independent frequency tuning, bandwidth, spectral resolution, temporal resolution and spatial pointing.

- 3D dynamic imaging of the ionosphere will need at least 3 dedicated beams
- Dual science day/night beam for solar/dark ages needs 1 dedicated beam
- Survey efficiency requires at least 1 dedicated beam
  - Multiple beams enhance the survey speed of the instrument
- Rapid response to transient triggers requires at least 1 dedicated beam
- Multiple simultaneous frequency beams can be used to increase the instantaneous bandwidth
  - To track solar burst across 32 MHz we need 4 dedicated simultaneous 8 MHz beams

  - For dark ages we would need 7 dedicated 8 MHz beams from inner stations within 5-10 km

- Multiple simultaneous spatial beams increase the instrument output
  - Possible additional beams include: student/outreach beam, maintenance beam, calibration beam

- Dedicated calibration beam
  - Opens option to bootstrap calibration from our highest frequencies where [phase distortions, sensitivity] are at a [minimum, maximum] to lower frequencies
  - More than 2 beams are required to allow removal of 2π phase ambiguities across frequency space
  - Multiple beams may be required to scan & self-calibrate 3C & 4C sources in sky on sufficiently short timescales

- Time-multiplexing may be able to relax the constraint on the number of dedicated beams

The requirement is 4 beams with $\gtrsim 7$ desired beams. The total number of required beams could be arrived at with various metrics for scientific output. The required number of 4 was arrived at assuming that there is a long term dedicated Solar/DA beam plus three additional beams. Those three beams could be broken up to be a survey beam + a transient beam + a general observer beam, or the three could be combined for 3D ionospheric tomography work. One of more of the beams could be used at times for a calibration beam or as a maintenance beam.

4.15. Snapshot *uv* Coverage

- Need sufficient uv coverage to suppress main-beam and side-lobe confusion in order to obtain good dynamic range for snapshot observations

- Snapshot: requires good instantaneous uv coverage
  - The Key Science Summary memo calls out specific science that needs good snapshot uv coverage (e.g. transients, CME imaging and other fast scale Solar phenomena). As pointed out in § 4.16, detailed simulations are needed to quantify this.

  - Ionospheric calibration may require sufficient uv coverage to sample many sources on timescales shorter than that of ionospheric changes

- Approach VLA multi-configuration uv coverage
  - 53 stations matches multi-configuration VLA coverage: $4 \times N_{VLA}^2 \sim N_{LWA}^2$

4.16. Collecting Area Profile

The science requirements in the previous sections can in principle be met by the specifications outlined in Table 2. In practice, the interferometer response to emission is dependent on the collecting area profile and integration time. For the LWA, exact station locations are dependent on terrain and land availability. Below we outline several areas where simulations combining science requirements and viable station locations are needed to ensure optimization of the LWA station configuration.

- Need to quantify radial density profile of collecting area through configuration studies
  - Need simulations to demonstrate realistic capability of recovering extended structure in both snapshot & synthesis imaging
  - Need to determine radial density profile consistent with needs to avoid classical confusion in short to medium integrations
  - Need to determine impact on ionospheric sampling of configurations optimized for transform imaging
- The desire for symmetric primary and synthesized beams at the celestial equator (§ 4.13) requires elliptical station and array geometries with North-South to East-West axis ratio of ~ 1.2.

5. Staged Development Science Program

The LWA will be built through a staged development from the initial stage of one full station + 2 sub-stations to the final stage containing 52 stations. The array will be designed to allow science application at each stage of development. Below we concentrate on the initial stage (called LWA-1+) and outline the science capabilities accessible to this phase of the instrument as well as the scientific requirements needed to undertake this science.

5.1. LWA-1+ Science Drivers

- Acceleration of Relativistic Particles
    - Up to 10^{21} ev in Ultra High Energy Cosmic Rays
- Plasma Astrophysics and Space Science
    - Solar bursts: study fast (50 ms) narrow-band (<10 kHz) structures
    - RRL: detect in [5,25] hrs @ [$\lesssim$ 40,74] MHz, $\Delta\nu_{min}$=0.1 kHz (1-2 km/s @ 25 MHz)
    - Jupiter decametric bursts: fine temporal and spectral structure seen by Voyager
    - ISM tomography: single pulse studies
- Exploration Science
    - Bright transients: GCRT J1745-3009 detected at $\gtrsim 5\ \sigma$ detection if $\alpha \lesssim -1$
    - Nearby pulsar spectra: ability to detect 68 bright, low DM pulsars

In addition to the science, the initial stage of LWA development will be important for:

- Significant engineering and commissioning experience (risk assessment)
- Insight into realistic constraints on array efficiency and limitations for deep integrations
- Combination with 74 MHz VLA expands science of both instruments

5.2. Science Requirements Comparison: LWA-1+ & LWA

We show in Table 5 how the requirements for initial LWA-1+ phase compare to the requirements for the full LWA. We note that at the very earliest stage of a single station it will likely be necessary to access individual dipole signals to undertake interferometry and allow science such as all-sky monitoring.

Table 5. Science-driven requirements.

	LWA-1+	LWA
Frequency Range	20 - 80 MHz	20 - 80 MHz
Instantaneous Bandwidth[a]	$\Delta\nu_{max} \gtrsim 8$ MHz[b]	$\Delta\nu_{max} = 8$ MHz[c]
Minimum Channel Width	$\Delta\nu_{min} \lesssim 100$ Hz	$\Delta\nu_{min} \lesssim 100$ Hz
Angular Resolution [@ 80 MHz]	$\theta \lesssim 16''$	$\theta \lesssim 2''$
Minimum Temporal Resolution	$\Delta\tau = 10$ ms[d]	$\Delta\tau = 10$ ms[d]
Primary Beam Width [@ 80 MHz]	PBW = 2°	PBW = 2°
Largest Angular Scale[@ 80 MHz]	LAS undefined	LAS = 1°
Baseline Range	20 km - 50 km	200 m - 400 km
Sensitivity[e]	$\sigma = 25$ mJy	$\sigma = 1$ mJy
Dynamic Range @ 20, 80 MHz	DR undefined	DR= $10^4, 10^3$
Polarization[f]	dual circular > 10 dB	dual circular > 10 dB
Zenith Angle Coverage	Z$\lesssim$ 60°	Z$\lesssim$ 60°
Number of Beams[g]	Beams=3[h]	Beams= 4
Configuration	2D array	2D array
Number of Stations	N= 1 full + 2 small	N = 53

[a] Bandwidth requirements per beam.

[b] Need $\Delta\nu_{max} \gtrsim 33$ MHz at individual dipoles for UHECR work. LWA-1+ will not have sufficient collecting area for dark ages science.

[c] Stations in inner 5-10 km need $\Delta\nu_{max} = 50$ MHz for dark ages work.

[d] Temporal resolution needed to track fast pulsars using phased-array mode is 0.1 ms.

[e] Point source sensitivity at 80 MHz.

[f] This requirement refers to the cross-polarization isolation.

[g] Fully independent spatial and frequency beams.

[h] In similar fashion to § 4.14 we estimate 3 beams for LWA-1+ assuming that there is a dedicated transient beam, a general observer beam and a shared day/night beam where day is solar and night is used for surveys, deep integrations etc. The three beams could be combined for 3D ionospheric tomography work.

6. Observing Modes

In additional to standard operating modes of tracking astronomical sources, the LWA should be sufficiently flexible to allow access to a wide range of modes necessary for using the full potential of the instrument. There are several examples of expanded capabilities that are only required for stations within a compact central region of $\sim 5 - 10$ km. Other operational modes are needed over a more extended area. Below we list several instrumental modes but note that this list is not yet complete.

- Transients: all-sky monitoring limited to the stations in the inner 5 km would allow a resolution of 2.5 $'$ and thus a position accuracy of better than an arcminute
- UHECR: need individual dipole signals at the station, particle detectors required through upgrade
- Dark Ages: need wide bandwidth (50 MHz) over stations within 5-10 km to detect the expected signal in 1 year
- Pulsars: phased array mode

7. Version History

The history for development of this document is:

- Version 1.0: LWA memo #10 (Kassim 2003)
  - LWA concept and key science drivers outlined.
- Version 1.1: LWA memo #49 (Kassim et al. 2005)
  - Science requirements of key science drivers outlined.
- Version 1.2: LWA memo #70 (Kassim et al. 2006)
  - Science requirements for LWA-1+ outlined.
- Version 1.3: LWA memo #80 (Cohen et al. 2007)
  - Early science target list for LWA Phase II developed based on VLSS results.
- Version 1.4: LWA Kickoff and Pre-SRR meeting presentation (Clarke 2007)

  - Updated version of science requirements based on key science drivers.
- Version 2.0: Draft Document prepared for Scientific Requirements Review
  - Document re-formatted in latex and numbers firmed up.
- Version 2.1: Revised Scientific Requirements Review Document
  - Document revised, expanded and corrected based on comments from Ellingson, Munton, and Rickard.
- Version 2.2: Revised Scientific Requirements Review Document
  - Updated table footnotes to clarify temporal resolution requirements. Moved notes from § 4.7 to new § 4.16.
- Version 2.3: Revised Scientific Requirements Review Document
  - Updated table footnotes to clarify PBW requirement, added notes to § 4.6 and § 4.7 to clarify frequency range for PBW and LAS requirements, and added note to § 4.16 about symmetric beams.

8. Acknowledgements

Compilation of this document involved the effort of many people. In particular thanks go to: Namir Kassim, Wendy Lane, Joe Lazio, Aaron Cohen, Henrique Schmitt, Frazer Owen, Crystal Brogan, Clint Janes, Tracey Delaney, Brian Butler, and Imke de Pater.

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This preprint was prepared with the AAS LaTeX macros v5.0.