Scientific Requirements for the Long Wavelength Array

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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.

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 useability 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 instrument 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 on the LWA memo series. Section 5.2 of the current document is devoted to the science that can be done with one full LWA station.

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). 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

4. Scientific Requirements

Based on the key science drivers for the LWA, the science requirements are summarized in Table 2. In Table 3 we review the science requirements for each key science driver. 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. The *required* specification indicates the value that is needed to accomplish the majority of the Key Science for the LWA while the *desired* specification open up additional science through expanded flexibility. We also call out specific examples and/or issues that need to accompany some requirements.

Table 2. Science-Driven Requirements for LWA.

	Required	Desired
Frequency Range	ν_l - ν_u = 20 - 80 MHz	ν_l - ν_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	$\Delta\tau$ = 0.1 ms[c]	$\Delta\tau \lesssim$ = 0.1 ms[c]
Primary Beam Width [@ 80 MHz]	PBW = 2°	PBW $\gtrsim$2°
Largest Angular Scale [@ 80 MHz]	LAS = 1°	LAS = 2°
Baseline Range	200 m - 400 km	100 m - 600 km
Sensitivity[d]	σ = 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$\lesssim$ 74°	Z$\lesssim$ 80°
Number of Beams[g]	Beams=4(core), 3(outer)	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 (core stations) to have $\Delta\nu_{max}$ = 50 MHz for Solar work. This could be accomplished by adding 7 dedicated dark ages tunings (or a total bandwidth of 56 MHz) for these inner stations. Outer stations are only required to have 3 beams, with two or more tunings per beam, and a total bandwidth of at least 8 MHz for each beam.

[c]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. Note that the indicated DR is greater at low frequencies due to the large field of view. These estimates do not take into account likely limitations in DR imposed by calibration and imaging challenges anticipated at the lowest frequencies.

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

[g]Fully independent spatial and frequency beams. The 4'th beam for core stations is the wide bandwidth beam described in tablenote b.

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 $^\circ$	LAS $^\circ$	σ[e] mJy	Σ mJy/bm	DR	Polz	ZaC $^\circ$	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	$\gtrsim 60$	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]	$\lesssim 100$	$\lesssim 2$	0.1[k]	2	1	1[l]		10^4, 10^3	dual	$\lesssim 74$	4[l]
Desired	3-88	$\gtrsim 50$	10	$\lesssim 1$	$\lesssim 0.1$[k]	$\gtrsim 2$	2	$\lesssim 1$[l]		10^5, 10^4	dual	$\lesssim 80$	$\gtrsim 7$[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 Solar 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 2000 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]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.

[m]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 calibration beam + a general observer beam, or the three could be combined for 3D ionospheric tomography work.

4.1. Frequency Range

- 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)
- Ionosphere may permit measurements of bright sources to a few MHz, 10 MHz is optimistic lower bound for astrophysical calibration
- Coordinated campaigns with ionospheric instruments below 20 MHz
- 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.
- Cross-over science with 74 MHz VLA
- In the FM bands above 87.9 MHz there is an increased operating risk due to the strength and density of the radio frequency interference.

Summary: Required $20 - 80$ **MHz, Desired** $3 - 88$ **MHz**

4.2. Instantaneous Bandwidth

- Broader BW increases sensitivity, 8 MHz provides at least 10% bandwidth over the full required frequency range
- 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: $\Delta\nu_{max} \gtrsim 50$ MHz or fast sweep capabilities (10 ms across full RF). Only needed on inner (core) stations.
- Pre-reionization dark ages signal benefits from with bandwidth to search large redshift space for signal. Only needed on inner (core) station.

Summary: Required 8 MHz for 3 beams and 56 MHz for additional fat beam in core stations, Desired $\gtrsim$ 50 MHz

4.3. Minimum Channel Width

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

Summary: Required $\lesssim$ 100 Hz, Desired $\lesssim$ 10 Hz

4.4. Angular Resolution

- Ionospheric wave propagation direction and dissipation: wavelength of disturbances > 50 km
  - while not strictly a resolution requirement this does drive the longest baseline
- 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
- SNR: $\theta \lesssim 5''$ to resolve brightest regions in strong shocks
- 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 $\theta \lesssim 0.5''$

- Normal galaxies: $\theta \lesssim 2''$ to separate compact and diffuse emission
- Scattering: comparable to cm VLBI for interstellar scattering ($\theta_{20cm} \sim 5$ mas) corresponds to $\theta \lesssim [25,1.5]''$ at [20,80] MHz
- Jupiter decametric emission: $\theta \lesssim 1''$ at 40 MHz
- Scattering limits on resolution in Galactic 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

Summary: Required $\lesssim 2''$ at 80 MHz, Desired $\lesssim 1''$ at 80 MHz. λ/D gives us $\theta \sim [7.7,2.1]''$ @ [20,80] MHz for 400 km baseline.

4.5. Minimum Temporal Resolution

- Time-averaging smearing: $\Delta\tau \lesssim 900$ ms for 10% flux reduction at 20 MHz at the primary beam first null on a 400 km baseline
- Solar & Space Weather, CMEs, Flares, IPS, IP Shock: $\Delta\tau \lesssim 10$ msec
- Flare stars: $\Delta\tau \sim$ 20-100 msec bursts, $\Delta\tau \sim 1$ ms for substructure in bursts
- Ionospheric structure including TIDs: $\Delta\tau \sim 1$ msec
- Timing the fastest pulsars: $\Delta\tau \sim 0.1$ ms
  - Needed on inner stations in phased array mode.
- Cosmic-ray airshowers: $\Delta\tau \sim 0.03$ 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

  - Note that this is a special application that needs the raw A/D output at the original sample rate from individual dipoles

- The light travel time across an array of 400 km is 1.33 ms.

Summary: Required 0.1 ms, Desired $\lesssim$ 0.1 ms

4.6. Primary Beam Width

- SNR: PBW $\sim 5°$ at 20 MHz to avoid mosaicking at the lowest frequencies
  - Many SNRs are several degrees in size
- CME: PBW $\gtrsim 2°$ to study full structure
- Transients: PBW $\gtrsim 2°$ to enhance survey speed
- Local supercluster filaments: PBW $\gtrsim 1.5°$
  - Note that for CMEs, transients and local supercluster filaments the PBW requirement is for the full frequency range.
- Survey-speed: increased 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 for fixed collecting area
- Want PBW at least a large as LAS (1° at 80 MHz, see Section 4.7) to allow imaging without mosaicking

Summary: Required 2° at 80 MHz, Desired $\gtrsim$ 2° at 80 MHz. λ/D gives us $\theta_{PBW} \sim$ [8.6,2.1]° @ [20,80] MHz for 100 m diameter stations.

4.7. Largest Angular Scale

- Sun & Solar Wind (e.g. CMEs) : $\theta_{LAS} \gtrsim [5,2]°$ @ [20,80] MHz
  - Important for understanding and predicting space weather as well as Solar astrophysics

  - Need good instantaneous uv coverage

- Local supercluster filament: LAS $\gtrsim 1.5^\circ$
  - Note that this LAS requirement is for the full frequency range.
- SNR: LAS $\sim 1^\circ$ for largest diffuse emission scales within biggest remnants
  - Note that this LAS requirement is for the full frequency range.
- Cosmic density fluctuations in the Dark Ages on scales of $\sim 1^\circ$
- CR Tomography: Map 3D Galactic CR distribution and spectrum using both nearby and distant HII absorption: LAS = 0.5°
  - Note that this LAS requirement is for the full frequency range.

Summary: Required 1° at 80 MHz, Desired 2° at 80 MHz

4.8. Baseline Range

- Driven by angular resolution and largest angular scale:
  - Required LAS=1° @ 80 MHz gives BL_{min}=215 m, desired LAS=2° @ 80 MHz gives BL_{min}=107 m
  - Required angular resolution=2″ @ 80 MHz gives BL_{max}=386 km, desired angular resolution=1″ @ 80 MHz gives BL_{max}=772 km but scattering limits at the lowest frequencies limit the useable baseline to $\sim$ 450 km @ 20 MHz
- Longest baseline is also important for ionospheric studies of wave propagation direction and dissipation, VLA reveals that 35 km is too small
  - TIDs have wavelengths $>$ 50 km

Summary: Required 200 m - 400 km, Desired 100 m - 600 km

4.9. Point Source Sensitivity

- SNR: need 10 mJy sensitivity for compact source removal from diffuse emission
- 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
- Radio Halos/Relics: 1 mJy sensitivity needed for point source removal from diffuse emission
- Surveys: LWA competes with EVLA in short integrations for point source sensitivity 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

Summary: Required 1 mJy, Desired $\lesssim$ 1 mJy

4.10. Surface Brightness Sensitivity

- 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: guidance 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

- Pre-reionization dark ages signals at 1-10 mK
  - Note that this needs a dedicated night-time beam on core stations within 5-10 km; may be shared for daytime Solar studies

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
- SNR: removal of compact source contamination needs DR $\sim 1.7\times10^3$, 3.7×10^2 at 20, 80 MHz
- Radio Lobes and LSS: 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

Summary: Required $10^4, 10^3$ and 20, 80 MHz, Desired $10^5, 10^4$ 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 leverage off polarization information (e.g. V-pol)

Summary: Required dual circular cross polarization isolation of $\gtrsim$ 10 dB, Desired dual circular cross polarization isolation of $\gtrsim$ 20 dB

4.13. Zenith Angle Coverage

- Solar and planetary: reach δ = -23° (Z=57°) for year-round solar monitoring
- 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
- 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
- UHECR: desire to see as much of sky as possible with individual dipoles, Z$\gtrsim$ 60°
- 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

Summary: Required Z $\lesssim$ 74° Desired Z $\lesssim$ 80°

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 at least 50 MHz we need 7 dedicated simultaneous 8 MHz tunings for inner (core) stations
- 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 tunings are required to allow removal of 2π phase ambiguities across frequency space
  - Rapid cycling beam is required to scan & self-calibrate 3C & 4C sources in sky on sufficiently short timescales to track ionospheric changes (Cohen & Paravastu 2008)

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

The requirement is 3 beams for the outer stations and 4 beams for inner, core stations. 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 calibration 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 transient beam or as a maintenance beam.

Summary: Required 3 beams for outer stations with additional 4'th (fat beam with $\Delta\nu = 56$ MHz) for core stations, Desired $\gtrsim$ 7 beams

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
  - Specific science applications that needs good snapshot uv coverage include transients, CME imaging and other fast scale Solar phenomena. As pointed out in § 4.16, detailed simulations are needed to better quantify this.
  - Ionospheric calibration may require sufficient uv coverage to sample many sources on timescales shorter than that of ionospheric changes
- Match or exceed VLA multi-configuration uv coverage
  - Required to image naturally larger fields of view with immovable stations
  - 53 stations doubles multi-configuration VLA coverage (taking into account shared configuration pad locations): $2{\times}N^2_{VLA_A+B+C+D} \sim N^2_{LWA}$

Summary: Required 53 stations, Desired $\gtrsim$ 53 stations

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 Fourier transform imaging
- The desire for symmetric primary and synthesized beams at the celestial equator (§ 4.13) requires elliptical station with a maximum North-South axis of 120 m and an East-West axis of 100 m. In light of possible land acquisition issues, the station elliptical footprint may be constrained to 110m in the North-South direction and 100 m in the East-West direction.
- Extend N-S array geometry to compensate for foreshortening at large zenith angle
- 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.

Summary: 120×100 **m elliptical station elongated North-South**

5. Staged Development Science Program

The LWA will be built through a staged development from the initial stage of one full station to the final stage containing 53 stations. The array will be designed to allow science application at each stage of development. Below we concentrate on the initial stage (LWA-1: considered a full single station plus outlier commissioning dipole(s)) and outline some of the science capabilities accessible to this phase of the instrument as well as the scientific requirements needed to undertake this science. For details of the science see the *Science Commissioning Plan for an LWA-1 Station by Clarke, Kassim & Erickson.*

5.1. LWA-1 Science Drivers

- Acceleration of Relativistic Particles
  - Cas A/Cyg A flux ratios (likely need outlier commissioning dipole(s) to reduce confusion from diffuse Galactic emission
  - Up to 10^{21} ev in Ultra High Energy Cosmic Rays
  - Galactic Halo: 24-hour drift scans at a fixed dec. covering only high galactic latitudes combined with the VLSS catalog to correct for discrete sources.
- 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
  - Galactic background studies, including Ionospheric Riometry
  - Interplanetary scintillation: (see memo # 152) including solar wind studies, e.g. solar wind speed & scintillation index; utilizing background sources to track propagation of disturbances (e.g. CMEs) through the IPM
  - Ionospheric scintillation: use both single and multiple frequency modes, obtain 2D spatial information on structure of ionosphere
- Exploration Science
  - Crab giant pulses over broad bandwidth
  - Transient searches: GCRT J1745-3009 detected at $\gtrsim 3\,\sigma$ detection if $\alpha \lesssim$ -1, GRB counterparts, etc.
  - 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 enhances 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 desirable to access individual dipole signals to undertake interferometry and allow science such as all-sky monitoring (e.g. through use of the transient buffer narrow band, TBN).

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 core 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
- Solar studies: need wide bandwidth (50 MHz) over core stations within 5-10 km
- Pulsars: phased array mode

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,c]	$\Delta\nu_{max} = 8$ MHz[c]
Minimum Channel Width	$\Delta\nu_{min} \lesssim 100$ Hz	$\Delta\nu_{min} \lesssim 100$ Hz
Angular Resolution [@ 80 MHz]	no imaging[d]	$\theta \lesssim 2''$
Minimum Temporal Resolution	$\Delta\tau = 0.1$ ms	$\Delta\tau \lesssim 0.1$ ms
Primary Beam Width [@ 80 MHz]	PBW = 2°	PBW = 2°
Largest Angular Scale[@ 80 MHz]	LAS undefined	LAS = 1°
Baseline Range	no baselines	200 m - 400 km
Sensitivity[e]	no imaging[f]	$\sigma = 1$ mJy
Dynamic Range @ 20, 80 MHz	DR undefined	DR= $10^4, 10^3$
Polarization[g]	dual circular > 10 dB	dual circular > 10 dB
Zenith Angle Coverage	Z$\lesssim$ 74°	Z$\lesssim$ 74°
Number of Beams[h]	Beams=4[i]	Beams= 4
Configuration	single station	2D array
Number of Stations	N= 1	N = 53

[a]Bandwidth requirements per beam.

[b]Need $\Delta\nu_{max} \gtrsim 33$ MHz at individual dipoles for UHECR work.

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

[d]May need outlier dipole for science like Cas A/Cyg A flux ratio where we need long enough baseline to reduce confusion from Galactic diffuse emission.

[e]Point source sensitivity at 80 MHz.

[f]There will be no imaging using the commissioning outlier(s).

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

[h]Fully independent spatial and frequency beams.

[i]In similar fashion to § 4.14 we estimate 4 beams for LWA-1 assuming that it is a core station. We also note that it is a reasonable approach to test all planned capabilities possible with the first station

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.
- Version 2.4: Corrected minor typos.

  - Footnote in Table 3 corrected.
  - Minor revision for consistency with Day in the Life Beam descriptions.

- Version 2.5: Revised to meet PDR changes outlined within approved ECNs.
  - Modified text to accomodate changes from ECN001.
  - Modified text to accomodate chagnes from ECN003.
- Version 2.6: Updated document for minor corrections.
  - Added Summary section for each requirement.
  - Revised Section 5.1 (including Table 5) for LWA1 science.
  - Added science cases for Section 5.1.
- Version 2.7: Updated Temporal Resolution Requirement
  - Revised Table 2 and 5 to reflect a required minimum temporal resolution of 0.1 ms, and desired $\lesssim 0.1$ ms
- Version 2.8: Corrected typos in Table 3 and updated it for compatibility with Table 2.
  - Arranged order of science drivers for clarity in Section 4.
  - Added justification for baseline length
  - Moved all station and array geometry discussion to Section 4.16
  - Clarified in footnote to Table 2 the issue of higher DR for lower frequencies
  - Corrected footnotes in Table 5
  - Noted use of commissioning outlier in Section 5.1

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