Guidelines for LWA Scientific & Technical Requirements

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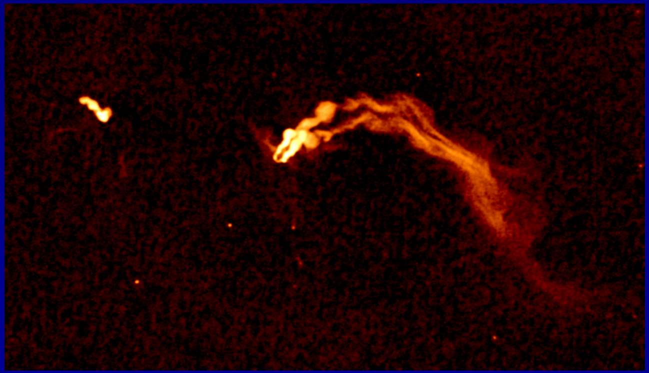
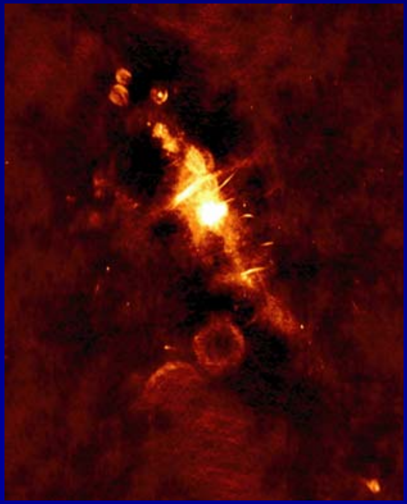




Philosophy

- Step 1
  - Approach 1:
    - » Start with a list of LWA scientific goals
      - Astrophysics, solar & space-science, & ionospheric physics
      - Emphasize a diversity of phenomena and capability for ***exploration science***
    - » Develop a list of instrumental requirements to reach each science goal
  - Approach 2 (emphasized in this presentation):
    - » Start with a list of instrumental specifications
    - » Derive requirements for each based on scientific goals that stretch the capabilities to a maximum
- Step 2
  - Combine results with practical considerations to create a list of top-level technical specifications

Key LWA Science Drivers

- Cosmic Evolution & The High Redshift Universe
  - Large Scale Structure - Dark Matter & Dark Energy
  - 1st super-massive black holes & HI during the EOR & beyond
- Acceleration of Relativistic Particles in:
  - SNRs in normal galaxies at energies up to 10^{15} ev
  - Radio galaxies & clusters at energies up to 10^{19} ev
  - Ultra high energy cosmic rays at energies up to 10^{21} ev and beyond
- Plasma Astrophysics & Space Science
  - Ionospheric waves & turbulence
  - Acceleration, Turbulence, & Propagation in the ISM of Milky Way & normal galaxies
  - Solar, Planetary, & Space Weather Science
- Exploration Science
  - Open the region < 100 MHz to exploration - <u>in the footsteps of the VLA at cm λs</u>
  - Emphasize pioneering capabilities for new frontiers – e.g. the Transient Universe
  - ***Maximizes the opportunity for Discovery Science through flexibility***

SR-1: Frequency Range

- Unexplored frequencies below 100 MHz for which the ionosphere has traditionally limited resolution and sensitivity
- Unique physical processes which can be studied only at low frequency:
  - spectral turnovers
  - scattering
  - steep-spectrum emission
  - thermal absorption – distance indicator
- Coherent processes: Jupiter “turn on” at 40 MHz
- Solar radar, Cosmic-Ray tomography, CR air-showers - below 60 MHz
- Continuum Spectra – emission, absorption, & scattering
  - $\geq$ 2 octaves allows accurate spectra within LWA band

Required: $20 \leq \nu \leq 80$ MHz (2 octaves)
Desirable: $1 \leq \nu \leq 111$ MHz (t_{FF}-80MHz = 2*t_{FF}-111MHz)

TS-1: Frequency Range

- Practical Considerations:
  - Economics: need to use a single dipole element
    - » $\Delta\nu_{max}$ for active antenna with 6 db sky-dominated T_{sys} is ~4X
  - Due to the FM bands, a practical upper limit is 88 MHz: 4X gives 20-80 MHz
  - No reason to go to higher frequencies where other instruments (eg. GMRT) are more sensitive
  - Practical lower limit tied to feasibility of ionospheric calibration & DR limits due to global RFI reflection
  - Ionosphere might permit measurements of bright sources to a few MHz, 10 MHz is an optimistic lower bound

Required: 20 MHz ≤ ν ≤ 80 MHz
Desirable: 10 MHz ≤ ν ≤ 88 MHz

SR-2A: Highest Angular Resolution

- Radio galaxies:
  - θ_{median}~10” to image 1’ sources with ≥ 28 beams
  - Jets: $\theta_{res} \leq 2$” at 80 MHz to sample γ=50-200 e^- population responsible for IC X-ray emission at 0.2-8 keV
  - Knots: $\theta_{res} \leq 0.5$” at 80 MHz
- Normal galaxies - $\theta_{res} \leq 2$” at 80 MHz
- Scattering:
  - compete with cm VLBI for ISS (θ_{20cm}~5 mas): ≤ [25,1.5]” at [20,80] MHz
- Exploration: ≥ 20 dB improvement over past low frequency arrays

Required: $\theta \leq$ [6,1.5]”at [20,80] MHz
Desirable: $\theta \leq$ [2,0.5]”at [20,80] MHz

TS-2A: Longest Baselines (B_{max})

- Practical Considerations: Confusion
  - Sufficient resolution to avoid classical confusion in short to moderate integrations
  - Assume A_e=1E6 m^2 at 20 MHz, $\Delta\nu$=4 MHz, array effic.= 50%
    - » 100 km: CC is [4,0.2] mJy at [20,80] MHz, requires [0.25,23] hrs
    - » 400 km: CC is [0.5,0.025] mJy at [20,80] MHz, requires [16,1470] hrs.
    - » 600 km: CC is [0.3,0.015] mJy at [20,80]MHz, requires [44,4100] hrs.
  - Sufficient resolution to mitigate strong source sidelobe confusion
- Practical upper limit: run out of calibrators of sufficient brightness
- Sharing of infrastructure: 400 km LWA fits with New Mexico Array
- Scattering limits on resolution: [7,0.4]" at [20,80] MHz
- Longer than existing and previous interferometers by 2-3X

Required: B_{max}≥ 400 km, or ≤[8,2]" at [20,80] MHz

Desirable: B_{max} ≥ 600 km, or ≤[7,1.4]" at [20,80] MHz

Ref: 400 km ~ [2.7E4,1.1E5]λ at [20,80] MHz; $B_{max\text{-}VLA}$~1.8E5 λ at 20 cm

SR-2B: Largest Angular Scale

- Cosmic Ray Tomography (HII regions): $\theta_{LAS} \geq [40,10]'$ at [20,80] MHz
- Largest nonthermal sources
  - Cen A ~ 10°
  - SNRs, Cygnus Loop & HB21 ~ 5°
  - Galactic Center structures ~4°
- Clusters and Large Scale Structure
  - Typical cluster ~ 2 Mpc = [2.5,0.3]º at z = [0.01,0.1]
  - Supercluster/filaments visible at redshifts comparable to the Coma Cluster (z~0.025) with sizes ~ 7° across
- Sun & Solar Wind (e.g. CMEs) : $\theta_{LAS} \geq [5,2]^{o}$ at [20,80] MHz

Requires: θ_{LAS} ***≥ [8,2]° at [20,80 MHz]***
Desirable: θ_{LAS} ***≥ [16,4]° at [20,80 MHz]***

TS-2B: Shortest Baselines (B_{min})

- Configuration studies required to quantify radial density profile of collecting area to realize naïve λ/D-based estimates
  - » Need simulations to demonstrate realistic capability of recovering extended structure in both snapshot & synthesis imaging
  - » Need to determine radial density profile consistent with assumptions about needs to avoid classical confusion in short to medium integrations
- Can stations be closer than theoretical 100 m minimum (ie overlapping stations)?
- Shadowing constraints?

Required: $B_{min} \leq 100$ m {LAS≥[8,2]° at [20,80] MHz}

Desirable: overlapping $B_{min} \leq 50$ m {≤[16,4]° at [20,80] MHz}

Ref: 100 m ~ [7,27]λ at [20,80] MHz; $B_{min\text{-}VLA}$~175 λ at 20 cm

SR-3: Thermal Noise Sensitivity

[sensitivities for $\Delta\nu$ = 4 MHz, Δt = 1 hr]

- Ability to image weak and extended sources at mJy to sub-mJy/bm sensitivity
  - Steep-spectrum sources such as cluster relics and halos
  - Extra-solar planets
  - HII region tomography for determining the 3D distribution of the cosmic ray electron gas
- Detection of non-thermal sources should be competitive with other large facilities – at least for surveys
  - » eg. EVLA: σ_{20cm} = 6 μ Jy (stokes I, 1 hr)
  - » With $A_e \sim$ 1 E6 m^2 (20 MHz) the LWA competes for $\alpha \leq$ [-1.2,-1.5] at [20,80] MHz – much better for surveys because of large FoV
- Exploration: realize ≥ 20 db improvement over past arrays

Required:* σ *= [1.0,0.5] mJy at [20, 80] MHz *[A_e = 1 E6 m^2 at 20 MHz]*
Desirable:* $\sigma \leq$ *[0.5*,0.1] mJy at [20,80] MHz *[A_e = 4 E6 m^2 at 20 MHz]*
**Classical Confusion at 400 km*

TS-3A: Collecting Area

- A_e = 1E6 m^2 provides ≥ 20 dB sensitivity improvement over existing and past low frequency arrays
- # of Dipoles
  - Ω_{FWHP} ~ 3 steradians at [20,80] MHz
  - $A_{e\text{-dipole}} \sim \lambda^2/\Omega \sim$ [75,4.7] m^2 at [20,80] MHz (subtle function of ν)
  - A_e ~1 E6 m^2 at 20 MHz requires ~ 13,500 dipoles

Required: A_e= 1 E6 m^2 at 20 MHz
Desirable: A_e= 4 E6 m^2 at 20 MHz

TS-3B: Dynamic Range (DR)

- Scientifically flows from many requirements, most notably sensitivity
- DR should allow thermal noise limited imaging beyond short integrations and ideally to classical confusion limits
- Thermal noise is not the main limitation
  - » Sidelobe & main beam confusion
  - » RFI
  - » Calibration errors (e.g. poor phase calibration related to ionosphere)
- Simulations needed to verify calibration & imaging performance
- DR to accommodate powerful solar bursts – requires special consideration

Required: DR ≥ [1 x10^3,2x10^3] at [20,80] MHz

1 hr thermal noise in presence of 1 Jy source

Desirable: DR ≥ [2x10^3,8x10^3] mJy at [20,80] MHz

20 MHz limit assumes 400 km classical confusion limit in presence of 1 Jy source.

SR-4: Instantaneous Bandwidth

- Continuum studies
  - Broader bandwidth increases sensitivity but introduces errors in flux density related to the spectral index of each source
  - For SI work it is desirable to have a few % flux accuracy or better
    - » $\Delta\nu/\nu$ = 10%: for α = [-0.7,-3], ΔS = [3,16]%
    - » errors may be mitigated in some cases by spectral modeling of data
- Broad-band phenomena (handle as special requirements, or address with multiple beams)
  - CR air-showers: $\Delta\nu > 32$ MHz at dipoles
  - Coherent emission from GRBs
  - Tracking drifts of solar bursts: $\Delta\nu \geq 32$ MHz

Required: Tunable with $\Delta\nu_{max}$= 4 MHz: $\Delta\nu/\nu \leq$ [20,5]% at [20,80] MHz
Desirable: Tunable with $\Delta\nu_{max}$= 8 MHz: $\Delta\nu/\nu \leq$ [40,10]% at [20,80] MHz

SR-5: Spectral Resolution

- Radio Recombination Lines from the cold ISM – require $\Delta\nu \leq 500$ Hz
- HI absorption requirements: $\Delta v \sim$ few km/s, or $\Delta\nu \leq 1$ kHz at 100 MHz
- Must prevent bandwidth smearing in widefield imaging:
  - 10% reduction in 1.25 kHz channel at 20 MHz and primary beam first null for 400 km baselines
- Radar: Solar: ≤ 100 Hz; Planetary: ≤ 10 Hz
  - Consider as special requirement?

Required: $\Delta\nu \leq 100$ Hz
Desirable: $\Delta\nu \leq 10$ Hz

SR-6: Temporal Resolution

- Wide-field Imaging; prevent time averaged smearing
  - $\Delta\tau \leq 0.9$ sec for 10% flux reduction at 20 MHz, primary beam first null and 400 km baseline
- Time variable phenomena such as:
  - Flare stars: $\Delta\tau \sim$ 50-100 msec
  - Solar & Space Weather , CMEs, Flares, IPS, IP Shock: $\Delta\tau \leq$ 100 msec
    - » Consistent with low frequency FASR specs
  - Pulsars: $\Delta\tau \sim$ 100 μs
- Cosmic-ray airshowers: $\Delta\tau \sim$ 50 nsec at the dipoles – special application
- Ionospheric structure including TIDs: $\Delta\tau \sim$ 10 msec

Requires: $\Delta\tau \leq$ 10 msec
Desirable: $\Delta\tau \leq$ 100 μsec
(need special provision for dipole based sampling at $\Delta\tau \leq$ 50 nsec)

TS-4 ,5& 6: Bandwidth, Spectral & Temporal Resolution

- Instantaneous Bandwidth
  - Must be able to achieve twice Nyquist sampling rate
- Spectral Resolution
  - RFI excision requires $\Delta\nu \leq 1$ kHz
- Temporal Resolution
  - Calibration – need to sample data on timescales fast compared to ionospheric changes: ≤ 1 second
- Correlator design is directly impacted: instrument bit-rate must support maximum desired timescales and spectral resolution requirements in combination with bandwidth, polarization, sampling rate, etc.

Required: $\Delta\nu_{max} = 4$ MHz, $\Delta\nu \leq 100$ Hz, $\Delta\tau = 10$ msec
Desirable: $\Delta\nu_{max} = 8$ MHz, $\Delta\nu \leq 10$ Hz, $\Delta\tau \leq 100$ μsec

SR-7 & TS-7: Polarization Studies

- Scientific Goals
  - Polarization studies of pulsars, solar and interplanetary magnetic phenomena, Jupiter, and polarized Galactic and extragalactic sources are all possible
  - A second polarization provides increased sensitivity
  - 2 circular polarizations are required to mitigate against differential absorption of circularly polarized coherent sources
- Technical Requirement
  - Circular polarization must be presented to the correlator because of Faraday rotation in the ionosphere
  - Polarization purity – realizing ≥ 10 db over much of the sky will be challenging – hope to achieve ≥20 dB after calibration

Required: 1 circular polarization, isolation ≥ 10 dB
Desirable: full polarization (2 linears or 2 circular) ≥ 20 dB

SR-8: Sky Coverage

- Desire the widest possible sky coverage to maximize visible objects
- Declination coverage
  - Galactic center studies require good imaging to at least $\delta = -30°$
  - Ideally would extend into the 4th quadrant, and include imaging of bright, isolated objects at low declinations
    - Clark Lake imaging of eg. Fornax A, Puppis A

Requires: Good imaging to $\delta \leq -30°$

Desirable: Bright objects to $\delta \leq -40°$

TS-8: Zenith Angle Coverage

- Zenith Angle Coverage
  - Ω_{HPBW} of our active antennas is ~ 100° (z > 40° gives δ > -16°)
  - As demonstrated at Clark Lake and the 74 MHz VLA, observations to z >15° (δ > -40°) will be possible in good ionospheric weather and at reduced sensitivity
- Extend array geometry in the north-south direction to compensate for forshortening at low zenith

Requires: Good dipole performance to z > 40°
Desirable: Restricted dipole performance to z > 15°

SR-9 & TS-9: Field of View

- Science requirements:
  - Would like a FoV as least as large as the LAS we hope to image, to avoid mosaicking
  - Survey-speed will be maximized by larger FoV
  - Sky monitoring efficiency is also increased
  - A larger FoV improves the chances of finding rare and/or transient sources in each observation
- Technical Considerations
  - λ/D gives us $\theta_{FoV} \sim [8,2]°$ at [20,80] MHz for 100 m stations

Requires: FoV ≥ [8,2]° at [20,80] MHz
Desirable: FoV ≥ [16,4]° at [20,80] MHz

SR-10: Multiple Beams

- Useful to have at least 2 full sensitivity beams
  - "solar beam"
  - "student/outreach beam"
  - "maintenance beam"
  - "survey beam"
  - "transient beam"
- Use of multiple beams enhances the survey speed of the instrument
- Multiple beams can be used to increase the instantaneous observed bandwidth for spectral studies

Requires: 2 dual pol. beams (equiv. to 4 single pol. beams)

Desirable: ≥ 4 single pol. beams

TS-10: Multi-beaming

- Can be used to multiply instantaneous bandwidth
- Phase Calibration
  - 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

Required: 4 single pol. beams
Desirable: ≥4 single pol. beams

TS-11: uv coverage

- Flows from many scientific requirements
  - Need sufficient uv coverage to suppress main-beam and side-lobe confusion in order to obtain good dynamic range
  - Need to achieve good balance between angular resolution and demanding surface brightness sensitivity requirements
  - Snapshot capability requires good instantaneous uv coverage
  - Simulations required to derive the optimal array configuration
    - » Ionospheric calibration may put priority on aperture plane coverage over uv coverage
    - » Need to sufficiently sample ionospheric pierce points required for Fourier (or other) characterization of ionospheric waves across FoV
  - Immovable stations is key challenge to achieving good uv coverage

Required: Approach VLA multi-configuration uv coverage

Desirable: Exceed VLA multi-configuration uv coverage

The Perfect Array?
Guidance for Number & Size of Stations,

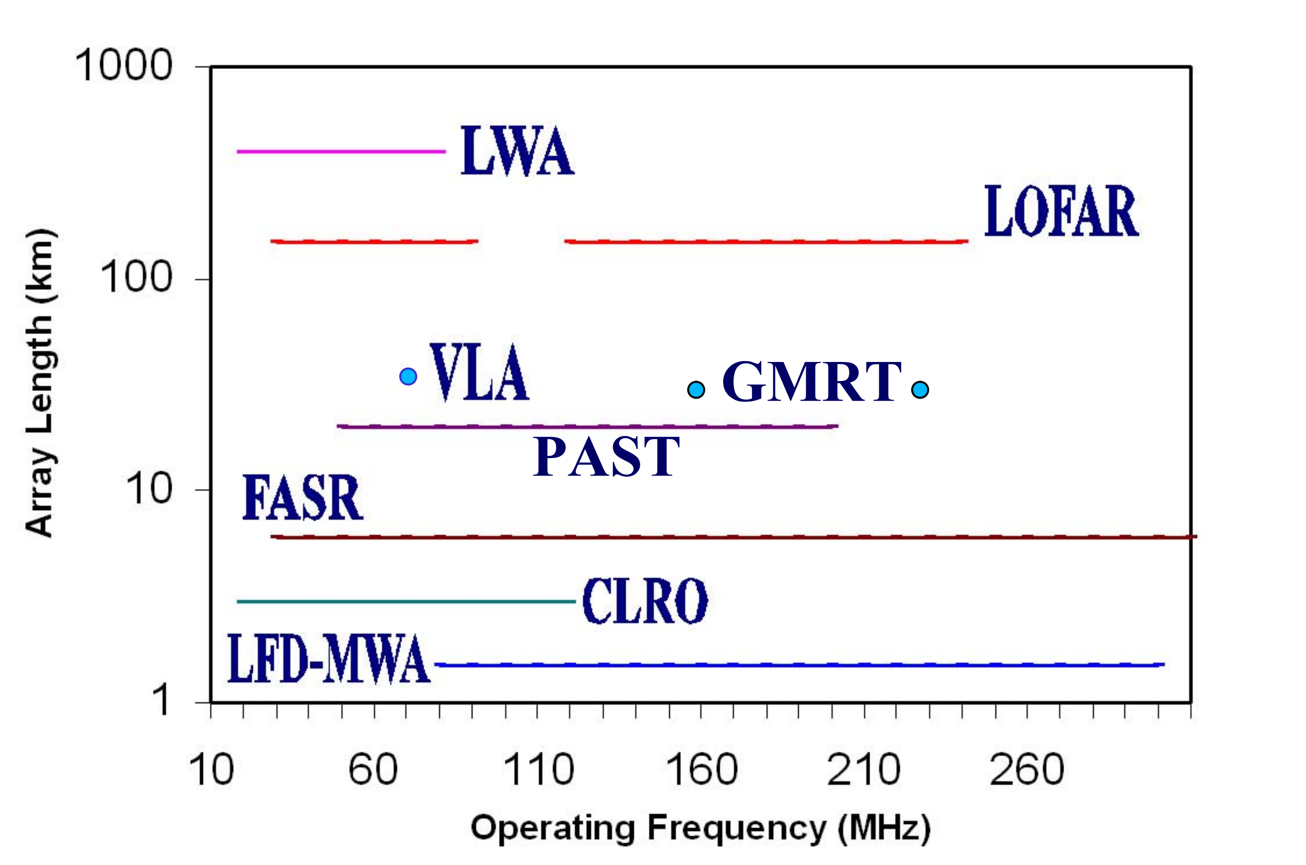
- Station Diameter (D_S)
  - VLA : D_S = 25 m too small at 74 MHz (6.2 λ), OK at 300 MHz (27 λ)
  - The equivalent at 80 MHz is D_S = 100m or 4X smaller FoV (16X in area)
- # of Dipoles per station (N_{DS})
  - Minimize station sidelobes, & preserve collecting area across 20-80 MHz
    - » N_{DS} = 250-350 allows a natural taper to minimize primary beam sidelobes
  - Estimate needed for calibration: $N_{DS} \geq 234 (\lambda_m/4)^{0.1}$
    - » Based on VLA experience (self-cal and VLSS)
- ***For N_{DS} = 256 dipoles, and A_e = 1 E6 m^2: # of stations N_s = 53***
- ***uv coverage: N_S= 53 matches multi-configuration VLA: $4N_{VLA}^2 \sim N_{LWA}^2$!!***

Required: D_S= 100m, N_{DS}= 256, N_S = 53

Desirable: D_S > 100m, N_{DS}> 256, N_S > 53

Simulations needed to verify calibration & imaging performance

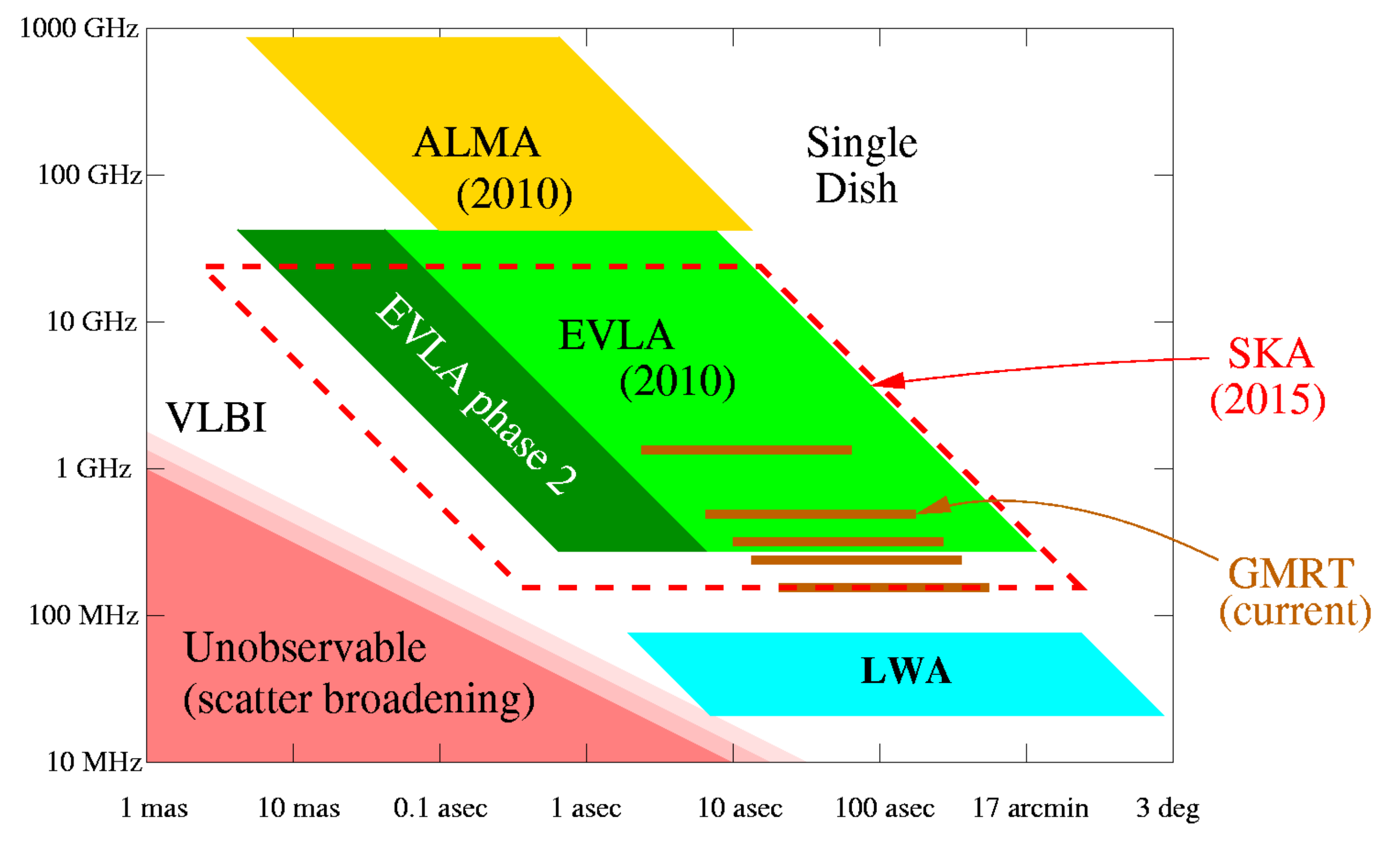
LWA Discovery Space:
in frequency & baseline



Going to the lowest frequency & longest baselines makes the LWA unique even when compared to other low frequency instruments.

LWA Discovery Space

in frequency, resolution, & surface brightness



Technical Specifications: Summary

	Required	Desirable
Frequency Range:	20 MHz to 80 MHz	10 MHz to 88 MHz
Angular resolution:	$\theta \leq [8,2]''$	$\theta \leq [7,1.4]''$
LAS at [20,80] MHz	$\geq [8,2]^\circ$	$\geq [16,4]^\circ$
Baseline range:	100 m to 400 km	50 m to 600 km
Sensitivity [20,80 MHz]:	$\sigma \leq [1.0,0.5]$	$\sigma \leq [0.5,0.1]$
Collecting Area (m^2)	$A_e = 1 \times 10^6$	$A_e = 4 \times 10^6$
Dynamic range:	$DR \geq [1 \times 10^3, 2 \times 10^3]$	$DR \geq [2 \times 10^3, 8 \times 10^3]$
$\Delta\nu_{max}$ (per beam)	$\Delta\nu \geq 4$ MHz	$\Delta\nu \geq 8$ MHz
$\Delta\nu_{min}$	$\Delta\nu \leq 100$ Hz	$\Delta\nu \leq 10$ Hz
Temporal Res	$\Delta\tau = 10$ msec	$\Delta\tau \leq 0.1$ msec
Polarization:	1 circular	Full
Sky Coverage:	$z \geq 40^\circ$	$z \geq 15^\circ$
FoV [20,80] MHz	$[8,2]^\circ$	$\leq [16,4]^\circ$
# of beams:	4 single pol.	$\geq$ 4 single pol.
Configuration:	2D array, N = 53 stations	2D array, N≥53
Philosophy:	User-oriented, open facility; proposals solicited from entire community	
Mechanical lifetime	≥15 years for potentially long lifetime	

Backup Slides

Discovery Space – what is left?

√
- New wavelengths - just about finished
  - *The region below 100 MHz is the last poorly explored one*

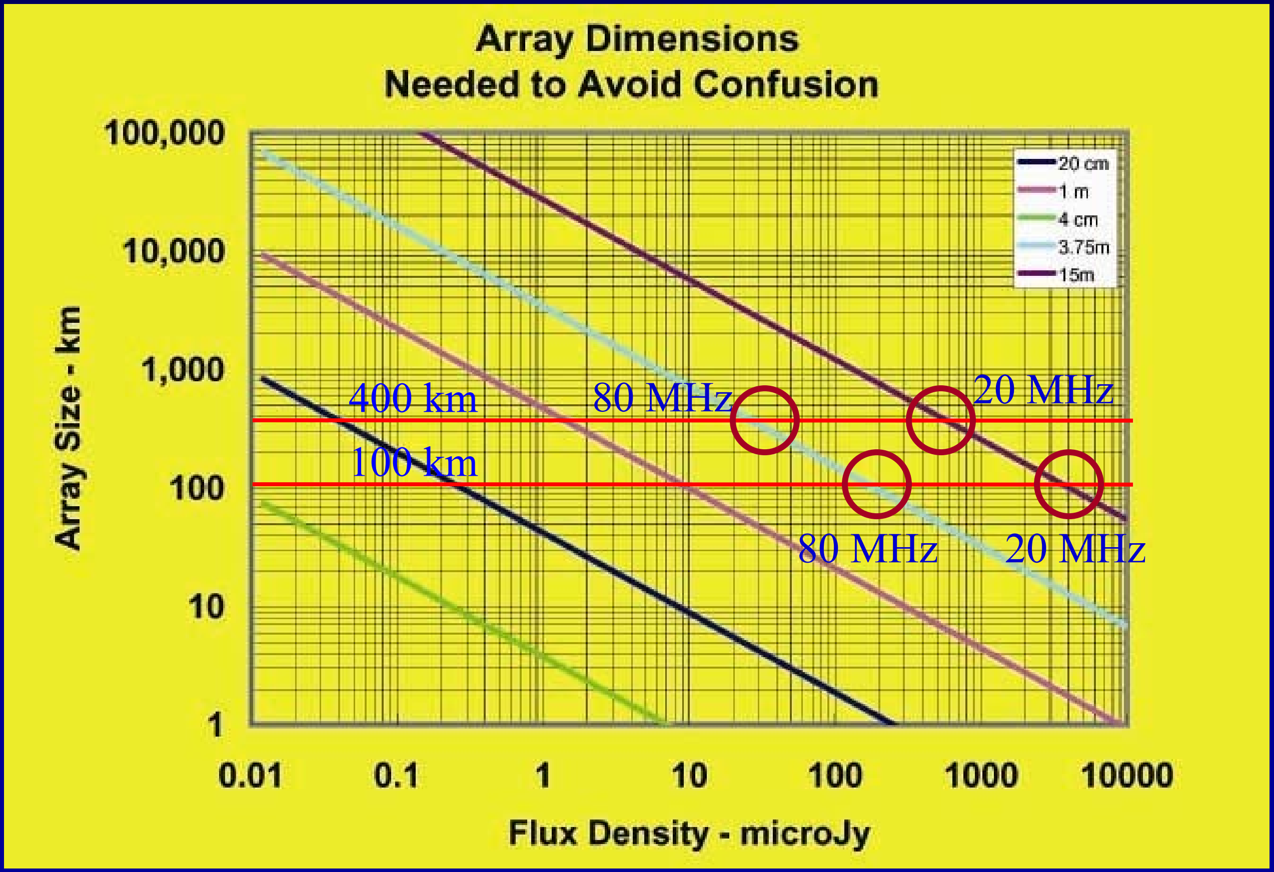
√
- Angular resolution & sensitivity
  - *The LWA will increase both the angular resolution and sensitivity by more than two orders of magnitude compared to Clark Lake*
    - » *Like going from Einstein to Chandra (while skipping ROSAT & ASCA)*

√
- Volume of space sampled
  - *An area where low frequency instruments, with their intrinsically large fields of view, will naturally thrive*

√
- New observing paradigms: multi-beaming
  - *Another natural capability of an electronic low frequency array*

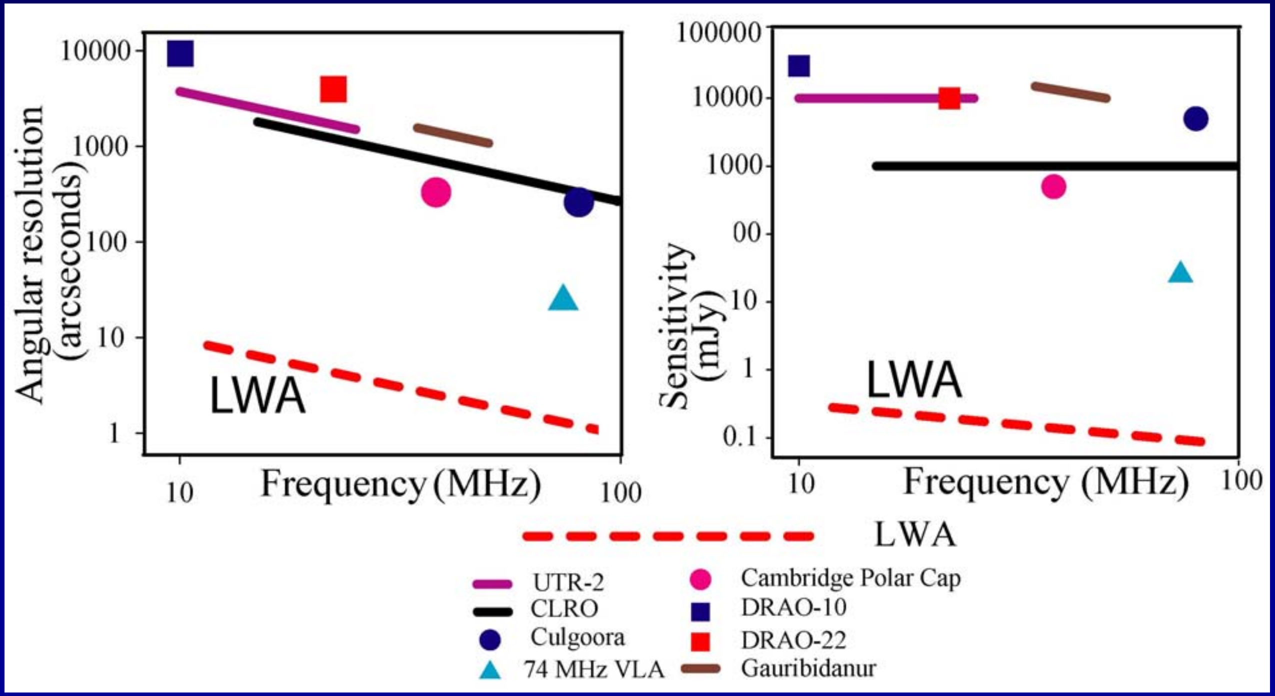
The LWA efficiently exploits the last remaining areas of astrophysical discovery space

LWA Classical Confusion Space



(slide courtesy KIK – consistent with Cohen LWA specific confusion calculations)

LWA Discovery Space:
in resolution & sensitivity



	LWA	*LOFAR (low)*
B_{max}:	400 km	150 km
Dipoles:	~13500	~7700
ν (MHz):	~20-80	~30-90
Sky Cov:	δ ≥ - 40	δ ≥ - 20