Future Ideas for Low Frequencies at the VLA
(and in New Mexico)

Namir Kassim
Naval Research Laboratory
Background & Objectives

- Success of 74 MHz VLA demonstrates that modest investment of resources can result in significant progress in low frequency astronomy.
- In light of recently awarded funding from NRL to pursue basic research in radio astronomy we are considering a modest program to gradually expand the performance of the VLA at low frequencies by utilizing mainly existing NRAO infrastructure in NM.
  - This will also help develop and exercise new technology as part of NRL’s responsibilities to the LOFAR project.
- Philosophy – institute technical improvements:
  - without adversely impacting VLA/VLBA operations.
  - so that they efficiently translate into concrete scientific enhancements of the instrument and can be readily realized by a growing user community.
Background of Low Frequency Radio Astronomy: Mired in the Dark Ages

- Radio astronomy began at low frequencies: $\nu \sim 20 \text{ MHz}$
- Until recently, ionospheric effects severely limited angular resolution & sensitivity
- Remains one of the most poorly explored regions of the EM spectrum despite great scientific potential

![Diagram of correlation change based on distance]

- Correlation preserved for distances less than 5 km
- Correlation changed for distances greater than 5 km

$\sim 50 \text{ km}$
Low Angular Resolution: Limits Sensitivity Due to Confusion

\[ \theta \sim 1', \text{ rms } \sim 3 \text{ mJy/beam} \]

\[ \theta \sim 10', \text{ rms } \sim 30 \text{ mJy/beam} \]
74 MHz VLA SYSTEM

• 74 MHz VLA imaging system implemented 1993–1997

• Demonstrated **self-calibration** can remove ionospheric effects
  – Over-determined problem manageable with high N array & initial model
    • Works well at VLA (N=27)
    • Originally motivated by recognition that *phase transfer* from higher frequencies can increase coherence times and S/N – rarely required

• VLA 74 MHz system is now the most powerful long wavelength interferometer in the world.
THE 74 MHz NRL-NRAO VLA SYSTEM
Phase Transfer: Enhancing S/N for Self-cal

- Ionospheric waves introduce rapid phase variations
  - ~ 1°/sec for A–array (35 km) VLA.
- Disrupt phase measurements and limit coherence times
- Self-calibration can remove them to the level needed for normal synthesis observations.

(Kassim et al. 1993)
74 MHz VLA: Significant Improvement in Sensitivity and Resolution
Comparison of Low Frequency Capabilities (past vs. present)

Clark Lake (30 MHz)

- B ~ 3 km
- $A_e \sim 3 \times 10^3 \text{ m}^2$
- $\theta \sim 15'$ (900’’)
- $\sigma \sim 1 \text{ Jy}$

Kassim 1989

VLA (74 MHz)

- B ~ 35 km
- $A_e \sim 3 \times 10^3 \text{ m}^2$
- $\theta \sim 20''$
- $\sigma \sim 25 \text{ mJy}$

Enßlin et al. 1999

COMA DEEP FIELD

~5°

~0.5 sources/square degree

~15°

~10 sources/square degree
4MASS FIELD 1700+690

$\theta \sim 80''$, rms $\sim 50$ mJy
Results from VLA 74 MHz System

(a,b) internal absorption in supernova remnants (a: Cas A - Kassim et al. 1995; b: Crab Nebula - Bietenholz et al. 1997)

(c) emission from relics & clusters of galaxies (Enßlin et al. 1999, Kassim et al. 1999, 2000)

(d,e) radio galaxies & halos (Kassim et al. 1993, Owen et al. 1999, 2000)
A new halo-relic system in the Abell 754 cluster of galaxies recently discovered with the 74 MHz VLA

Color: ROSAT X-ray image
Contours: 74 MHz VLA image

SNRs: Extrinsic ISM Absorption
(images courtesy C. Lacey)

Free-Free Absorption Towards W49B SNR

- First example of spatially resolved free-free absorption towards a Galactic SNR (Lacey et al. 2001)

Lacey, Kassim, & Duric 1999
Investigating SNRs and the ISM
(images courtesy C. Brogan)

G349.7+0.2 at 327 MHz
G349.7+0.2 at 74 MHz
VLA 74 MHz: Galactic Center
Absorption Holes => Synchrotron Emissivity Vectors

74 MHz Galactic Center: Preliminary D-array Image – (θ~10’)
(courtesy Mike Nord – UNM-NRL PhD Thesis Project)

Typical 30 MHz absorption “hole” flux for 10’ HII region:
~ 0.5 mJy (outer Galaxy)
~ 3 mJy (inner Galaxy)
(There are at least 1000 Galactic HII regions of this scale.)
Possible Near Term Activities

• Some room for improvement with current VLA system
  – New calibration/imaging algorithms being explored for use with current VLA system and in anticipation of LOFAR
    • New strategies being explored with NRAO on the 4MASS project
      – 4MASS – initial LOFAR calibration grid

• However, the main limitations of the present 74 MHz VLA are sensitivity and angular resolution

• Possible modest near term programs to address these:
  – Increase the available bandwidth at 74 MHz
  – Outfit PT at 74 MHz and implement 74/330 MHz PT link tests
  – Plan for a few inner VLBA 74 MHz campaigns
    • To constrain the practical limits of low frequency interferometry in anticipation of LOFAR and to do unique science
Possible Longer Term Activities

• The VLA was not designed to provide good sensitivity at these wavelengths: $\varepsilon \sim 15\%$, sidelobes $\sim 20\text{dB}$, $\text{Tsys}/Ae$ too high
  – It would be far better to use an array of broad-band antennas, electronically phased to act as a single dish

• We are designing a stand-alone low frequency (10-90 MHz) “station” consisting of several hundred antenna elements (for LOFAR)

• We would like to build two stations as prototypes for the low frequency part of LOFAR and use them to enhance the capabilities of the present VLA 74 MHz system
  – Station I – VLA center; Station II – VLA outlier (eg. A+ site)
    • Command & control systems compatible with present & future (EVLA) control systems
  – Two stations will allow us to explore LOFAR beam-forming at frequencies other than 74 MHz
SKY NOISE DOMINATED SYSTEM TEMPERATURE

\[ T_b \sim 500 \text{ K} \quad \nu = 408 \text{ MHz} \]

\[ T_b \sim 45,000 \text{ K} \quad \nu = 45 \text{ MHz} \]

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Band Name</th>
<th>System Temperature (K)</th>
<th>Antenna Efficiency (%)</th>
<th>RMS (10 min) (mJy/beam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.073 – 0.0745</td>
<td>400 cm</td>
<td>1000 – 10000</td>
<td>20</td>
<td>150(3)</td>
</tr>
<tr>
<td>0.3 – 0.34</td>
<td>90 cm</td>
<td>150 – 180</td>
<td>40</td>
<td>1.4(4)</td>
</tr>
<tr>
<td>1.3 – 1.70</td>
<td>20 cm</td>
<td>35</td>
<td>55</td>
<td>0.056</td>
</tr>
<tr>
<td>4.5 – 5.0</td>
<td>6 cm</td>
<td>45</td>
<td>69</td>
<td>0.054</td>
</tr>
<tr>
<td>8.1 – 8.8</td>
<td>3.6 cm</td>
<td>35</td>
<td>63</td>
<td>0.045</td>
</tr>
<tr>
<td>14.6 – 15.3</td>
<td>2 cm</td>
<td>120</td>
<td>58</td>
<td>0.17</td>
</tr>
<tr>
<td>22.0 – 24.0</td>
<td>1.3 cm</td>
<td>150 – 180</td>
<td>40</td>
<td>0.31(4)</td>
</tr>
<tr>
<td>40.0 – 50.0</td>
<td>0.7 cm</td>
<td>100 – 140</td>
<td>35</td>
<td>0.60(5)</td>
</tr>
</tbody>
</table>

rms \sim \frac{T_{sys}}{A_e}
Impact of Central Station:
Relaxing the finite Isoplanatic Patch assumption

• Current self-calibration assumes single ionospheric solution across full field of view (FOV)
  – Assumption valid over a much smaller region than the full FOV
  – Problems: differential refraction, image distortion, reduced sensitivity
  – Solution: selfcal solutions with angular dependence

\[ \phi_1(t) \rightarrow \phi_1(t, \alpha, \delta) \]

• Zernike polynomial phase screen correction now available prior to self-calibration
  – Non-selfcal reliant imaging code developed for 4MASS by Cotton
  – Key handicap – poor S/N – significant data loss except under very good ionospheric conditions
Breakdown of Finite Isoplanatic Patch Assumption

Image Distortion

Differential Refraction

Striping due to sidelobe confusion from a far-off source in a completely different IP

~15°

12 km Isoplanatic Patch

35 km Isoplanatic Patch

Sidelobe Confusion
Phase Delay Screen Modeling
1D – phase structure function

Before Zernike Model

After Zernike Model

(Cyg A > 20° away)
Phase Delay Screen Model
(Zernike polynomial models – courtesy B. Cotton, J. Condon)

Fitted model ionospheric phase
Delay screen rendered as a plane in 3-D viewed from different angles.
Impact of Central Station

• Will significantly increase the power and sophistication of 74 MHz VLA calibration
  – At least 10X the sensitivity of a VLA dish will aid calibration much as a large dish helps when initially calibrating VLBI data
    • Should greatly improve efficiency of VLAFM
    • Allow us to “map out” the larger FOV of the 25 m dish and aid in determining antenna based phases with an angular dependence
      – ~100 m diameter - sufficient room in central sector
      – Better calibration ➔ Better DR, image fidelity & sensitivity
• Useful for exploring proposed LOFAR calibration schemes which rely on a large “virtual core” of antenna elements
Outlier Station Objective
Extending resolution and uv coverage

$$\delta = +20^\circ$$

VLA+PT  VLA+PT+Dusty  VLA+PT+Dusty+Bernardo
Benefits of Higher Angular Resolution

Resolution of the hotspots at 74 MHz will easily differentiate between competing models for spectral turnover.
Antenna Design

• Conventional approach: Log-Periodic Array
  – Advantages: well studied – good frequency & sky coverage
  – Disadvantages: large

• New-technology approach: “Active” Dipoles
  – Advantages: small
  – Disadvantages: impedance matching, sensitivity, sky coverage, ground plane, strong inter-element coupling
    • exploring feasibility in consultation with Erickson & Fisher
    • NRL testing underway

Electrically short dipole
Requires Ground Screen
Station Design

- Consists of ~256-1000 broad-band wire antenna elements
- Phased array will deliver one signal which looks like the signal from a single VLA antenna (EVLA compatible)
  - Plug & play philosophy for VLA integration
  - Will serve as prototypes for LOFAR lower frequency antennas
High Sensitivity Station
Prototype for LOFAR Low Frequency Antennas

Analogous to one VLA antenna but with >10X the sensitivity

~100 meter diameter

@74MHz:

VLA antenna ~ 125 m²
LWA Station ≥ 1500 m²

(fractal element distribution shown here is not necessarily our favorite)
Future Prospects

- The proposed near-term plans provide a significant increase in capabilities of an existing VLA system.
- They also make it possible to prototype a future standalone, broad-band capability at the VLA.
  - Permits eventual realization VLA SM146: “A proposal for a large, LF array located at the VLA” – Perley & Erickson, 1984
    - Partly implemented as 74 MHz system - after “phase transfer” insured self-cal convergence.
- Everything we now know scientifically & technically ensures that SM146 would work beautifully and be a powerful instrument for both Galactic & EG work.
SM146 Concept
(VLA Scientific Memorandum #146)

• Perley & Erickson concept
  – Standalone stations along VLA arms
    • VLA arm easement enough room for 100 m stations
    • Logistical issues remain – how will the cows like them?
  – Might proceed with EVLA-I

• Augmented SM146
  – Addition of A+ capability
  – Might proceed with EVLA-II
SM146 CAPABILITY

**SM146 Angular Resolution**

(≤500 km baselines)

**SM146 Sensitivity**

(1 square km @15 MHz, 8 hrs, Δv~3 MHz)

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**Graphs showing angular resolution and sensitivity as a function of frequency for various observatories:**

- **CLRO**
- **Culgoora**
- **VLA**
- **UTR2**
- **Cambridge Polar cap**
- **DRAO-10**
- **DRAO-22**
- **Gauribidanur**
- **Mauritius**
- **GMRT**
Advantages of New Technology Electronic Arrays: Speed, Flexibility, Multibeamming

Multiple, independent beams $\Rightarrow$ speed and flexibility
$\Rightarrow$ multiple, simultaneous science programs
Relationship to LOFAR

- LOFAR is much more complex than SM146
  - It has a substantial technology development element as well as purely scientific goals
    - Larger Freq. Range (LOFAR: 10-240 MHz; SM146: 10-90 MHz)
    - Much larger bandwidth (larger than EVLA)
    - Many more stations (>100)
    - Complex configuration (log spiral)
    - MUCH more software, etc …
- SM146 and LOFAR: parallel, mutually beneficial
  - SM146 development clearly meshes with LOFAR technical developments for low frequencies (< 100 MHz)
  - Might SM146 develop into the low frequency portion of LOFAR?
    - LOFAR site is not yet determined; there are other good candidates
    - Anything is possible
- Independent of LOFAR – VLA based SM146 makes sense
KEY LOFAR SCIENCE DRIVERS

• High Redshift Universe
  – unbiased sky surveys, select highest z galaxies
  – trace galactic & intergalactic B fields, infalling shocks around clusters
  – Epoch of Reionization: search for global signature, detect and map spatial structure

• Cosmic Ray Electrons and Galactic Nonthermal Emission
  – map 3D distribution, test expected origin and acceleration in SNRs

• Bursting and Transient Universe
  – broad-band, all-sky monitoring for variable/transient sources (GRBs, etc …)
  – search for coherent emission sources; e.g. from stars, quasars, & extra-solar planets

• Solar-Terrestrial Relationships
  – study fine-scale ionospheric structures
  – image Earth-directed CMEs (as radar receiver)

• LOFAR science plan was recommended by the NAS Astronomy Survey Committee in the new Decade Report.

• LOFAR Consortium (growing) – NRL-MIT/HO-ASTRON-UT
  – Science advisory board forming with growing US University membership
Summary

- We are considering a modest, incremental program for enhancing the scientific and technical performance of an existing VLA system
  - Some of these have synergetic overlap with planned EVLA activities – e.g. development of a common A+ outlier site
  - Some of these satisfy NRL’s responsibilities for developing new technology for LOFAR – e.g. low frequency antennas/stations
- If it were possible to start down this road, our philosophy would be to
  - realize these enhancements in a manner that translates to immediate scientific benefits to the low frequency user community
  - implement them with minimum impact on VLA/VLBA operations
- These plans also lay the ground work for a broad-band standalone system as described in NRAO SM146
  - It could possibly proceed in parallel with EVLA I & II