Low Frequency (LF) Interferometry

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Outline
- Definition
- Science Overview
- Background of LF Imaging
- Challenges faced at the VLA
  - Radio Frequency Interference: RFI
  - Ionospheric Effects
- Self-calibration: LF Examples
- Non-selfcal approaches to LF imaging
- Wide-field Imaging: LF Examples
- Confusion & Thermal Noise: LF Examples
- Future: the need for something much larger - LOFAR
- Summary

Outline

- LF ≤ 330 MHz
  - Focus on 74 and 330 MHz VLA
    - 330 MHz "P band" VLA - 1990
      - 6" resolution, 2.5° FOV
    - 74 MHz VLA - "A Band" - 1998
      - 20" resolution, 13° FOV
        - 1st sub-arcminute resolution LF imaging system - major advance
        - 1st system to overcome the "ionospheric barrier"
    - Comparable systems:
      - 330 MHz WSRT (3 km - C-array VLA - 1')

Science Overview

- LF: favors studies of nonthermal sources which are brighter
  - Intrinsic link to shock physics, high energy phenomena
    - MeV, GeV particles
- LF: Unique insights into interaction of thermal & nonthermal sources, self-absorption processes
- LF: Large field of view, high surface brightness sensitivity
  - Often an advantage

Nonthermal & Thermal Emission & Absorption

- LF selects steep spectrum, often rare and most interesting objects
  - "High Redshift Universe" - Most distant galaxies, Re-ionization Epoch signature
- PSRs discovered at 80 MHz, clues for 1st msec PSR from LF observations
- Incoherent synchrotron emission
  - Smoothly varying continuum spectrum - LF maps permit accurate spectral studies
  - Tracton electron spectrum: N(E) ~ KE^(1-δ) , δ ~ α
    - Acceleration to Γ ~ 10^4 - 5, spectral aging in radio galaxies & clusters
- Coherent emission: important at LF
  - P dependence makes it very efficent at LPs
  - PSRs, Jupiter bursts, solar and stellar bursts, extra-solar planets - what else?
- Thermal sources can be optically thin or thick emitters at 330 MHz, optically thick absorbers at 74 MHz
  - Key equation: T = (a T^4 + b T^λ) / (c + d T^λ)
    - Constrains radial geometry of overlapping thermal & nonthermal sources
- Absorption "Holes" Powerful tracers of Cosmic Rays
- Recombination lines
  - Meters wavelengths - stimulated emission from low density ionized gas
  - Decameter wavelengths - from lower density gas in the cold ISM

Nonthermal Emission at 74 & 330 MHz

(a) (b) (c) (d) (e)
- (a) shock physics of supernova remnants (e.g. Cas A, Kassim et al. 1995)
- (b) emission from relics & clusters of galaxies (Ensslin et al. 1999)
- (c) radio galaxies & halos (Kassim et al. 1998; Owen et al. 2000)
Nonthermal Emission & Thermal Absorption

330 MHz: Thermal & Nonthermal Emission
74 MHz: Nonthermal Emission & Thermal Absorption

SNR HII region
\[ v = 330 \text{ MHz} \]

SNR HII region
\[ v = 74 \text{ MHz} \]

Gone!

Background of LF Radio Astronomy: Mired in Confusion
Excluded from Modern “VLA age”

- Until recently, ionospheric effects severely limited resolution and sensitivity
  - Ionospheric phase distortions limit array size & therefore angular resolution
  - Historically, LF instruments have had much smaller apertures than at cm wavelengths
  - Lack of high resolution imaging: individual source studies limited
  - Remains one of the most poorly explored regions of the EM spectrum despite great scientific potential

- Other Problems
  - RFI
  - 3D & other imaging problems (related to large FOV)
  - Solution to all demands computational tedium

Rarely did we see anything new

Interferometry Relies on Good Phase Stability:
Dominated & “Corrupted” by the Ionosphere for \( \nu \leq 1 \text{ GHz} \)

330 MHz A array
74 MHz – 4 times worse

Ionospheric Structure:
Limited Angular Resolution

Correlation
Preserved

Correlation
Lost

\[ \lambda \text{ ~ 50 km} \]

\[ \lambda \text{ ~ 5 km} \]

\[ \theta > 0.3^\circ (\text{vs. } < 10^{-3}^\circ) \]

Sensitivity confusion limited: \( \text{rms} \geq 1-10 \text{ Jy} \) (vs. < 1 mJy)

Low Angular Resolution:
Limits Sensitivity Due to Confusion

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

\[ \theta \sim 10^\circ, \text{ rms } \sim 30 \text{ mJy/beam} \]
74 MHz Receiving System: Dipoles

74 MHz VLA System
- Prototype system, 1993–1997; full (N=27) system, 1998
- Demonstrated self-calibration can remove ionospheric effects
  - Over-determined problem manageable with high N array and initial model.
  - Works well at VLA (N=27).
- VLA 74 MHz system now the most powerful long wavelength (<100 MHz) interferometer in the world.
- With 330 MHz VLA & GMRT, also demonstrating solutions to "other problems"
  - RFI, 3D imaging, etc – Observation/data reduction becoming routine
- LF radio astronomy finally breaking into the modern age
  - Implications for extending angular resolution and sensitivity far beyond what we have done; with major scientific impact

74 MHz VLA: Significant Improvement in Sensitivity and Resolution

Comparison of Low Frequency Capabilities (past vs. present)
Clark Lake (30 MHz)
- B ~ 35 km
- A_e ~ 3 x 10^{33} m^2
- θ ~ 15'
- σ ~ 1 Jy

Enßlin et al. 1999

VLA (74 MHz)
- B ~ 5 km
- A_e ~ 5 x 10^{33} m^2
- θ ~ 8'
- σ ~ 1 Jy

Kassim 1989

Radio Frequency Interference
- As at cm wavelengths, natural and man-generated RFI are a nuisance
  - Actually getting "better" at LF's relative BW for commercial use is low
- At VLA: different character at 330 and 74 MHz
  - 74 MHz: mainly VLA generated, predictable, little external contamination
  - 330 MHz: comes and goes, mainly external
- Solar effects – unpredictable
  - Quiet sun a benign 2000 Jy disk at 74 MHz
  - Solar bursts, geomagnetic storms are disruptive – otherwise mid-day often the most stable
- Ionospheric scintillations in the late night often the worst
- Requires you to take data in spectral line mode
  - RFI can usually be edited out – tedious but "doable"
  - Spectral line needed to mitigate BW smearing as well

Radio Frequency Interference

Example using AIPS task "FLGIT"
Best done by hand!
Ionospheric Effects

Wedge Effects: Faraday rotation, refraction, absorption below ~5 MHz
Wave Effects: Rapid phase winding, differential refraction, source distortion, scintillations

Wedge: characterized by
\[ \Delta \phi \sim 10^4 \text{ rad} \]

Introduces extra electrical path length \( \Delta L \sim 10^4 \times \text{TEC} \)

Adds extra phase
\[ \Delta \phi = \Delta L / \lambda \approx \lambda \]

Waves: tiny (<1%) fluctuations superimposed on the wedge

\[ \text{Wedge} \]

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Self-calibration

(Useful only if the “Infinite Isoplanatic Patch” Assumption Holds)

- Self-cal models the ionosphere as a time-variable antenna based phase \( \phi(t) \)
- Approach involves looping between self-calibration & imaging
  - Model continuously improves, S/N for self-cal gets better and better
- Initial model generally enough for initial self-calibration convergence - works because
  - 1) the VLA has lots of antennas
  - 2) short spacings do not “see” the ionosphere
  - 3) there is plenty of flux in the primary beam.
- 330 MHz sky - ~ one 1 Jy source in every FOV, 12 Jy of confusing sources
- 74 MHz sky - ~ one 20 Jy source in every FOV, 100 Jy confusing sources
- 4) latest/best approach - use a priori NVSS (VLA 20 cm sky survey) based sky model
  - Freezes out time variable refraction
  - Ties positions to NVSS

Practical requirements
- Need ≥ 30 Jy at 74 MHz - not hard because 20-30 Jy 3C sources every 8 degrees
- Need only ≥ 3 Jy at 330 MHz - usually satisfied but not always

Self-cal Examples

327 MHz C array
1st Phase Selfcal
\[ \text{rms} \sim 25 \text{ mJy/beam} \]
2nd Phase Selfcal
\[ \text{rms} \sim 15.1 \text{ mJy/beam} \]

330 MHz C array
1st Amplitude Selfcal
\[ \text{rms} \sim 11.0 \text{ mJy/beam} \]
2nd Amplitude Selfcal
\[ \text{rms} \sim 10.4 \text{ mJy/beam} \]
### The Infinite Isoplanatic Patch Assumption

- **Standard self-calibration assumes single ionospheric solution across FOV:**
  - Assumption valid over a much smaller region
  - Problems: differential refraction, image distortion, reduced sensitivity
  - Solution: self-cal solutions with angular dependence
  - Problem only for 74 MHz A and B arrays

- **Zernike polynomial phase screen**
  - Non-self-cal reliant imaging developed for 4MASS
  - Key handicap—poor S/N, significant data loss under poor ionospheric conditions
  - Compensates for breakdown of infinite isoplanatic patch assumption at 74 MHz
  - Delivers astrometrically correct images
  - Fitted model ionospheric phase delay screen rendered as a plane in 3D viewed from different angles.

### Breakdown of Infinite IP Assumption at 74 MHz: A & B arrays: Differential refraction & source distortion

- Both global and differential refraction seen.
- Time scales of 1 min. or less.
- Equivalent length scales in the ionosphere of 10 km or less.

### Breakdown of Infinite Isoplanatic Patch Assumption

(74 MHz A and B arrays only)

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

### Differential Refraction: 1D – Phase Structure Function

- Before Zernike Model
- After Zernike Model

### "Self-cal Desease"

Breakdown of Infinite Isoplanatic Assumption

- Zernike Model
- Self-calibration

### 4MASS FIELD 1700+690

- 0-80', rms ~50 mJy, 1 hour
- ~20°
Wide-field Imaging
practical issues

- Required to address non-coplanar baseline problem
- Computationally solved but tedious and slow
  - Requires lots of disk space and fast computers!
  - Lots of looping between self-cal and imaging
- Worst case in A & B arrays
  - Images too big – benefits from targeted faceting
  - Compounded by requirement to use spectral line data for RFI excision and to compensate for bandwidth smearing

Wide-field imaging usually not required for bright, isolated sources

The Radio Galaxy Virgo A at 74 MHz

Wide-field imaging not required for bright, isolated sources

Complex fields require full field mapping

B array imaging at 330 MHz

- 9 x 9 facets
- Cells = 6\(^\circ\)
- Facets near 256 x 256
- Full image ~ 2500x2500 pixels

B, C, D array imaging tractable

Variety of platforms can now handle

A array requires cells = 2\(^\circ\)

Starts to present problems

Targeted faceting to avoid full pixellation of the PB

Full pixellation of A array PB at 330 MHz or 74 MHz is computationally prohibitive!

Use NVSS to set outliers, because bright 74 & 330 MHz sources are usually NVSS sources

No need to image empty space! (unless you are doing a survey)

Observing Strategy
in light of RFI and ionospheric effects

- Amplitude & bandpass calibration
  - Cygnus A is available—observe a few 2 minute snaps per run
  - Blows through RFI!
- Phase calibration at 330 MHz
  - Sky is coherent across the array in C and D configurations
  - Observe one strong unresolved source anywhere in sky
  - Traditional phase calibration in A and B arrays
  - Now being replaced by NVSS Sky model—no phase calibration required!
- Phase calibration at 74 MHz
  - Most challenging aspect of low frequency VLA work
  - Cygnus A (or anything bright) is suitable in the C and D arrays
  - A and B arrays: Cyg A works for initial calibration, because enough short spacings are thin to start self-cal process
  - But self-cal can't overcome breakdown of isoplanatic patch assumption
  - Hourly scans on Cyg A are de-facto instrumental calibration for non-self-cal (Zernike polynomial) imaging
  - Calibration schemes continue to evolve rapidly with time!
Noise: Confusion & Thermal relative levels at 74/330 MHz

- Classical confusion – ≤ ~50 synthesized beams per source within FOV
  - only more angular resolution can help!
- Side-lobe confusion
  - Failure to de-convolve response to real sources outside the main field of view
    - Componented by calibration and other errors
- A and B arrays
  - Sidelobe confusion limited for short integrations at both frequencies
  - Thermal noise limited at 330 MHz with possum/coverage in plausible integration times
    - Good number for long synthesis ~ 1 mJy – record ~0.2 mJy
  - Sidelobe confusion and thermal noise comparable at 74 MHz with long uv tracks
    - Noise goes down with time
      - Sidelobe for long synthesis is 50 mJy – record ~25 mJy
  - C and D arrays
    - Generally sidelobe confusion limited at both frequencies
      - Possible to approach classical confusion at 330 MHz with good uv coverage
- Confusion limits: 330 MHz: C: 0.1-0.2 mJy/beam, D: 2-3 mJy/beam
- Confusion limits: 74 MHz: C: 100-200 mJy/beam, D: ~500 mJy/beam

Noise Characteristics

- rms noise vs. Δν
  - 74 MHz B array
    - 1 hour
- rms noise vs. time
  - 74 MHz: A+B array
    - Δν = 1.5 MHz

The Need for Something Much Larger

Sky Dominated System Temperature

\[ T_b \approx \frac{T_{sys}}{A_e} \]

Classical Confusion at 330 MHz

WSRT (aka "C array VLA")

Sidelobe Confusion

A array 74 MHz

"Almost" Thermal Noise Limited Imaging

330 MHz, B array

330 MHz, C array

74 MHz, C array

The Need for Something Much Larger

Sky Dominated System Temperature

\[ T_b \approx \frac{T_{sys}}{A_e} \]
LOFAR Concept
(LOFAR = Low Frequency Array)

- Inspired by 74 MHz VLA, which demonstrates major breakthrough in sensitivity and angular resolution.
- Reflects impact of self-calibration, ability to emerge from confusion.
- Fully electronic, broad-band antenna array.
- Basic element is an active dipole receptor: \( \Delta \nu \approx 10^{-240} \text{MHz} \)
- Low frequency limit: ionospheric absorption, scintillation.
- High frequency limit: \( \lambda^2 \) collecting area, better to use dishes above this.
- “Stations” (dishes) are 160 m in size, comprised of 256 elements.
- Good primary beam definition, low side-lobe levels.
- Large-aperture baselines \( \leq 500 \text{km} \) (no limit on baseline length).
- Good angular resolution, low confusion.
- Large collecting area: \( \geq 10^6 \text{m}^2 \).
- 2–3 orders of magnitude improvement in resolution & sensitivity.
- 8″@15 MHz, 0.8″@150 MHz, \(< 1 \text{mJy}@15 \text{MHz, < 300 } \mu \text{Jy}@150 \text{MHz} \).
- Multiple beams: new approach to astronomical observing.

LOFAR Stations
200 Dipoles per “Station”, 100 Total Stations over 500 km

Opening A New Window On The Universe

- Emerging Renaissance in Low Frequency Radio Astronomy
  - Ability to increase imaging power by 2-3x orders of magnitude.
  - Many other previous limitations can now be overcome.
  - Enabled by self-calibration & other new imaging techniques & big computers.
- 74 MHz VLA
  - Major advance in imaging power over previous LF systems.
  - Significant limitations: poor relative sensitivity & resolution as compared to cm wavelength systems.
  - Scientically powerful if you use your imagination, ask the right questions, and have courage.
  - Key challenges:
    - RFI excision, phase calibration for full-field mapping in A and B arrays when infinite isoplanatic patch assumption breaks down.
    - Computational tedium, bad ionospheric weather.
- 330 MHz VLA
  - Mature, versatile system for many unique and important applications.
  - Key challenges:
    - RFI excision, computational tedium.
- LF interferometry is unique and largely untapped – now entering unexplored region with hope of new discoveries.
  - LOFAR – a much more powerful instrument coming by the end of the decade.