Low Frequency (LF) Interferometry

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(see http://rsd-www.nrl.navy.mil/7213/lazio/tutorial)

with contributions from:
NRL: Cohen, Lane, & Lazio
NRAO: Brogan, Clarke, Cotton, Greisen, & Perley
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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

"LF"≤ 330 MHz

Focus on 74 and 330 MHz VLA

- 330 MHz "P band" VLA - 1990
  - 6" resolution, 2.5° FOV
- 74 MHz VLA – "4 Band" - 1998
  - 20" resolution, 11° 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')
  - GMRT: 330, 235, 160, 50? (25 km)

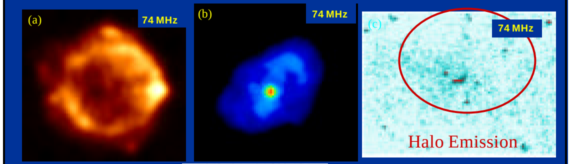
Science Overview

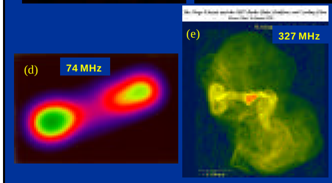
- LF: favors studies of nonthermal sources which are brighter
  - Intrinsic link to shock physics, high energy phenomena
    - MeV, GeV particles
- LF: Unique insights into interaction of thermal & nonthermal sources, self-absorption processes
- LF: Large field of view, high surface brightness sensitivity
  - 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
    - Traces electron spectrum: $N(E) = KE^{-\gamma}$ ➔ $S \alpha \nu^{\alpha}$, $\alpha \sim (1-\gamma)/2$
    - Acceleration in Galactic & EG sources, spectral aging in radio galaxies & clusters
- Coherent emission – important at LF
  - λ^6 dependence makes it very efficient at LFs
  - 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: $\tau \sim 1.643 \times 10^5 n^{-2.1}$ EM $T_e^{-1.35}$ – constrains HII region ρ & T
  - Constrains radial geometry of overlapping thermal & nonthermal sources
  - Absorption "Holes" Powerful tracers of Cosmic Rays
- Recombination lines
  - Meter wavelengths – stimulated emission from low density ionized gas
  - Decameter wavelengths – from lower density gas in the cold ISM

Nonthermal Emission at 74 & 330 MHz

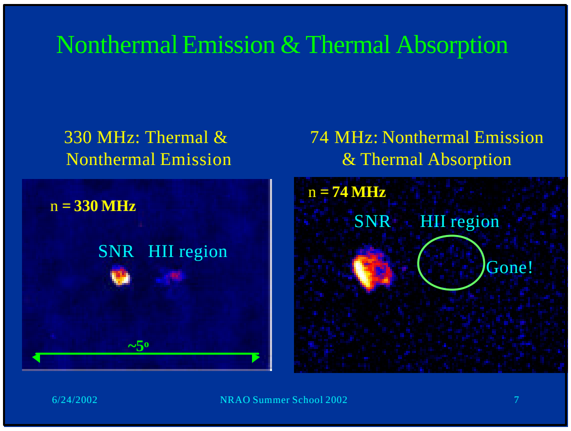




(a,b) shock physics of supernova remnants (a: Cas A, Kassim *et al*. 1995; b: Crab Nebula, Bietenholz *et al*. 1997)

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

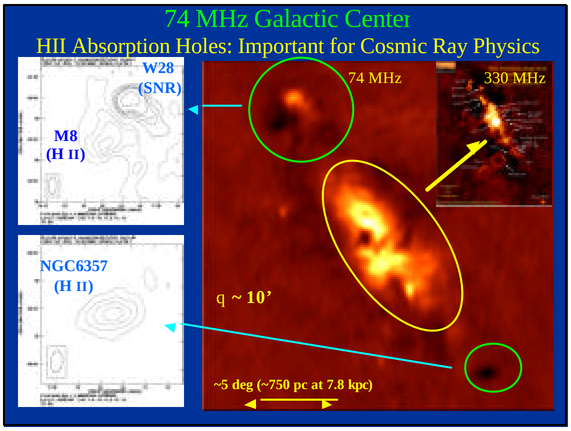
(d,e) radio galaxies & halos (Kassim et al. 1996; Owen et al. 2000)



Nonthermal Emission & Thermal Absorption

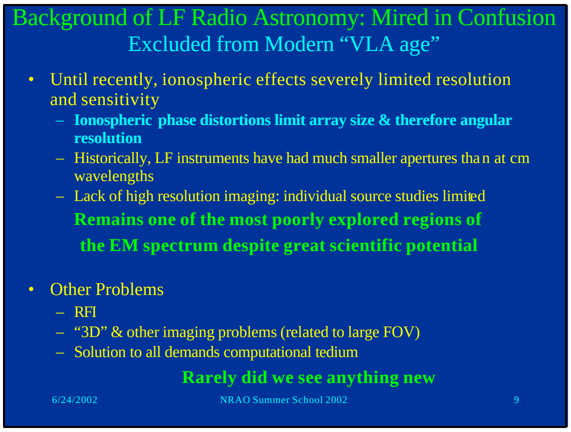
330 MHz: Thermal & Nonthermal Emission

74 MHz: Nonthermal Emission & Thermal Absorption



74 MHz Galactic Center

HII Absorption Holes: Important for Cosmic Ray Physics



Background of LF Radio Astronomy: Mired in Confusion

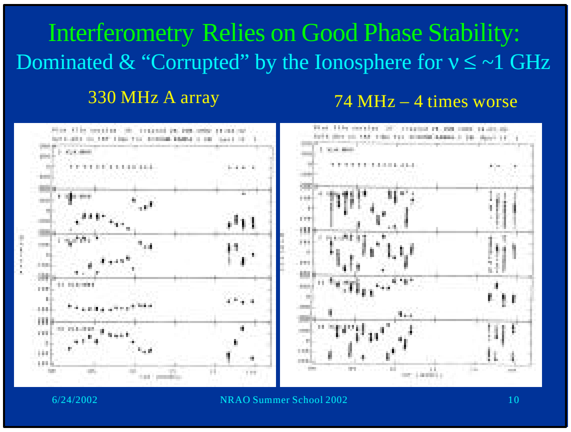
Excluded from Modern "VLA age"

- 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

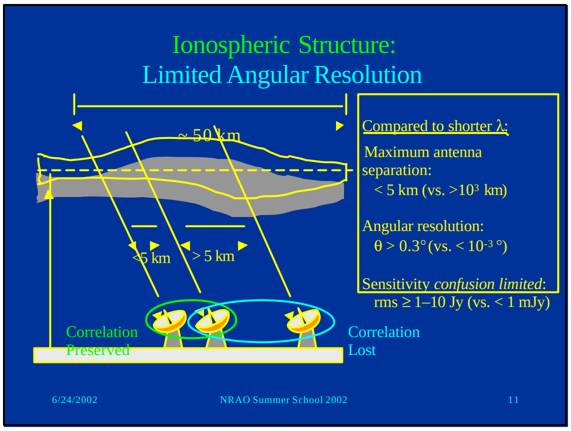


Interferometry Relies on Good Phase Stability:

Dominated & "Corrupted" by the Ionosphere for ν ≤ ~1 GHz

330 MHz A array

74 MHz – 4 times worse



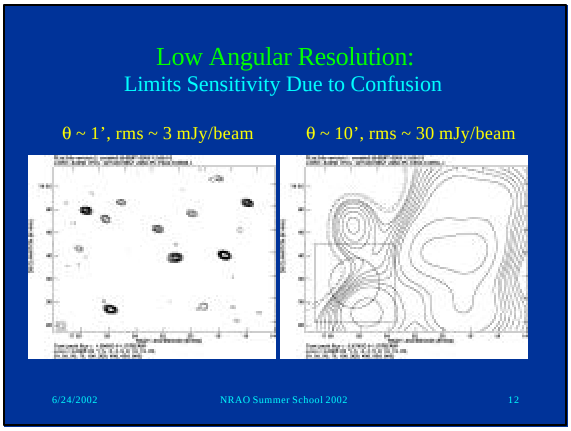
Ionospheric Structure: Limited Angular Resolution

Compared to shorter λ:

Maximum antenna separation:
< 5 km (vs. >10^3 km)

Angular resolution:
θ > 0.3° (vs. < 10^{-3} °)

Sensitivity *confusion limited*:
rms ≥ 1–10 Jy (vs. < 1 mJy)

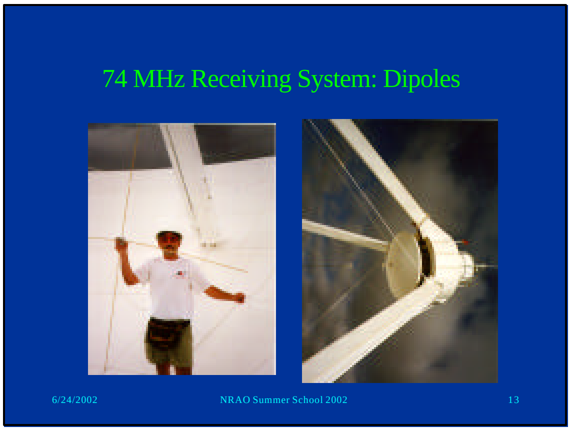


Low Angular Resolution:

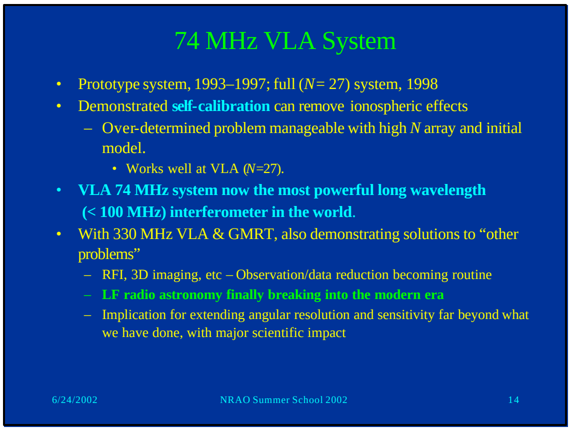
Limits Sensitivity Due to Confusion

θ ~ 1', rms ~ 3 mJy/beam

θ ~ 10', rms ~ 30 mJy/beam

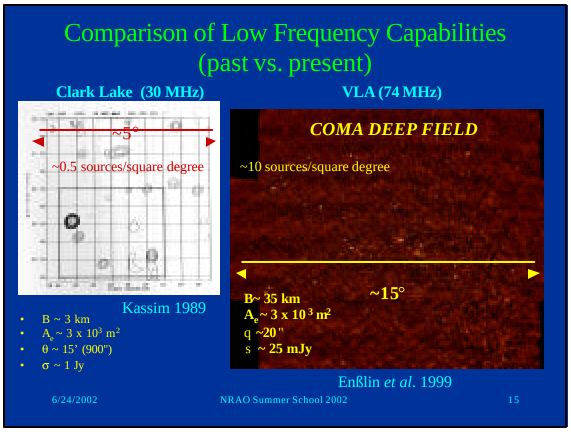


74 MHz Receiving System: Dipoles



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 era**
  - Implication for extending angular resolution and sensitivity far beyond what we have done, with major scientific impact



Comparison of Low Frequency Capabilities (past vs. present)

Clark Lake (30 MHz)

Kassim 1989

- B ~ 3 km
- A_e ~ 3 x 10^3 m^2
- θ ~ 15’ (900")
- σ ~ 1 Jy

VLA (74 MHz)

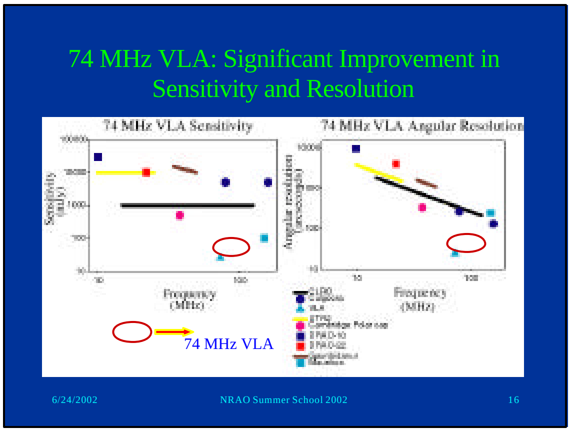
COMA DEEP FIELD

~10 sources/square degree

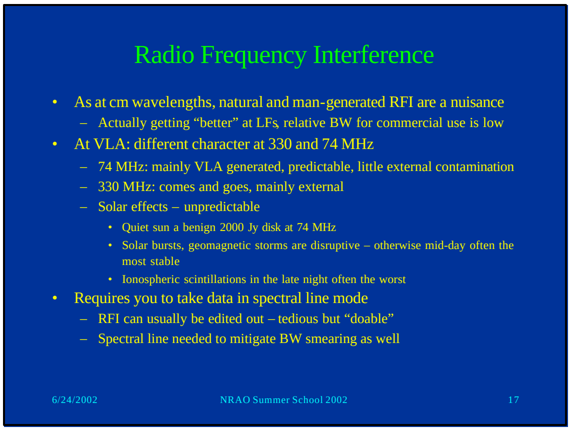
~15°

B~ 35 km
A_e ~ 3 x 10^3 m^2
q **~20"**
s **~ 25 mJy**

Enßlin *et al*. 1999

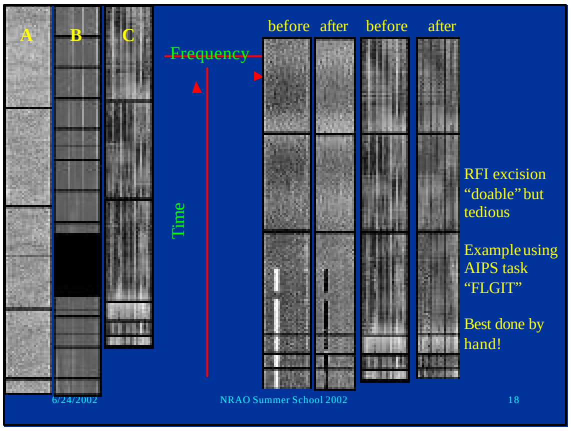


74 MHz VLA: Significant Improvement in Sensitivity and Resolution



Radio Frequency Interference

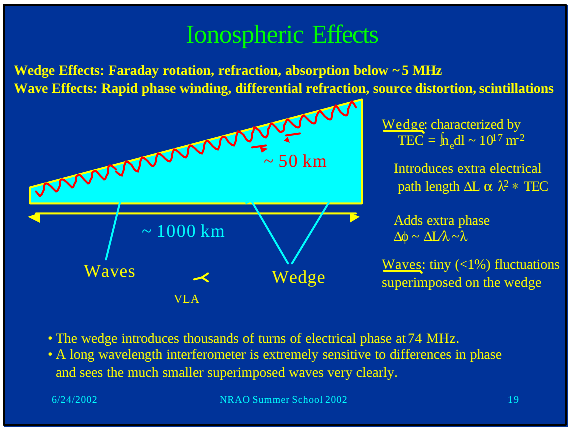
- As at cm wavelengths, natural and man-generated RFI are a nuisance
  - Actually getting “better” at LFs, relative BW for commercial use is low
- At VLA: different character at 330 and 74 MHz
  - 74 MHz: mainly VLA generated, predictable, little external contamination
  - 330 MHz: comes and goes, mainly 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



RFI excision “doable” but tedious

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

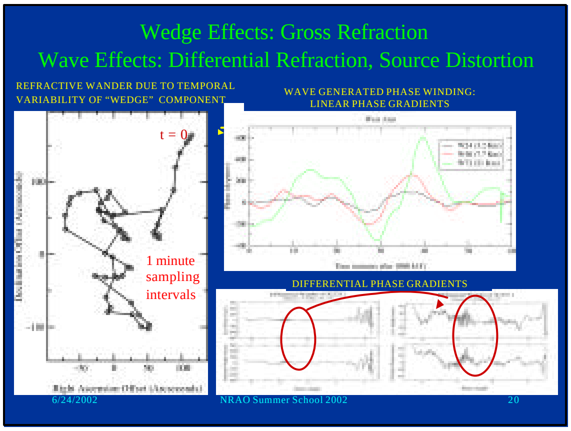
Wedge: characterized by TEC = $\int n_e dl \sim 10^{17}$ m^{-2}

Introduces extra electrical path length $\Delta L \; \alpha \; \lambda^2 * \mathrm{TEC}$

Adds extra phase $\Delta\phi \sim \Delta L/\lambda \sim \lambda$

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

- The wedge introduces thousands of turns of electrical phase at 74 MHz.
- A long wavelength interferometer is extremely sensitive to differences in phase and sees the much smaller superimposed waves very clearly.



Wedge Effects: Gross Refraction
Wave Effects: Differential Refraction, Source Distortion

REFRACTIVE WANDER DUE TO TEMPORAL VARIABILITY OF "WEDGE" COMPONENT

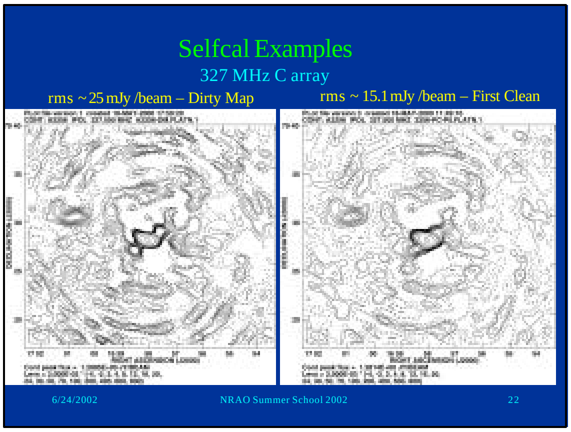
WAVE GENERATED PHASE WINDING:
LINEAR PHASE GRADIENTS

DIFFERENTIAL PHASE GRADIENTS

Self-calibration

(Useful only if the "Infinite Isoplanatic Patch" Assumption Holds)

- Selfcal models the ionosphere as a time-variable antenna based phase: j_i**(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 bad because 20-30 Jy 3C sources every 8 degrees
  - Need only 3 Jy at 330 MHz - usually satisfied but not always

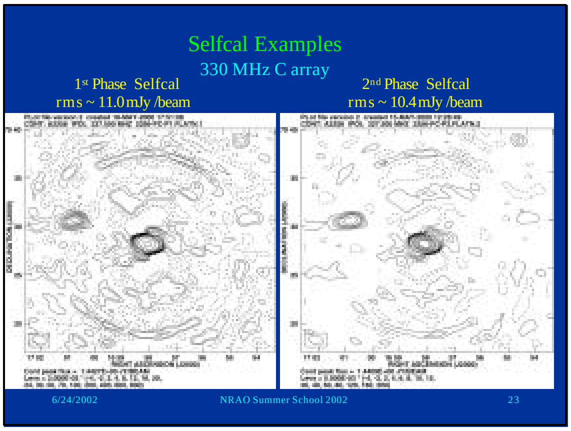


Selfcal Examples

327 MHz C array

rms ~ 25 mJy /beam – Dirty Map

rms ~ 15.1 mJy /beam – First Clean

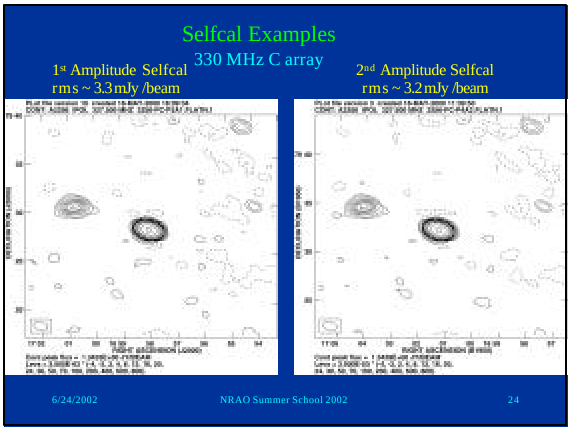


Selfcal Examples

330 MHz C array

1st Phase Selfcal
rms ~ 11.0 mJy /beam

2nd Phase Selfcal
rms ~ 10.4 mJy /beam

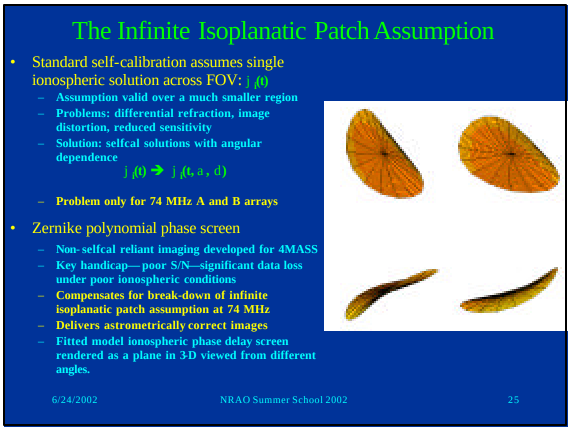


Selfcal Examples

330 MHz C array

1st Amplitude Selfcal
rms ~ 3.3 mJy /beam

2nd Amplitude Selfcal
rms ~ 3.2 mJy /beam

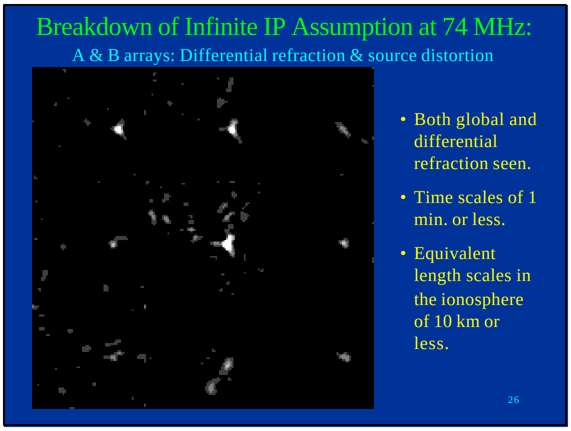


The Infinite Isoplanatic Patch Assumption

- Standard self-calibration assumes single ionospheric solution across FOV: $j_i(t)$
  - **Assumption valid over a much smaller region**
  - **Problems: differential refraction, image distortion, reduced sensitivity**
  - **Solution: selfcal solutions with angular dependence**

$$j_i(t) \rightarrow j_i(t, a, d)$$

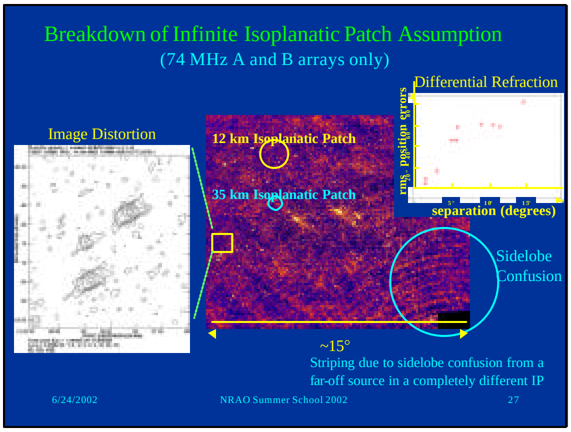
  - **Problem only for 74 MHz A and B arrays**
- Zernike polynomial phase screen
  - **Non-selfcal reliant imaging developed for 4MASS**
  - **Key handicap—poor S/N—significant data loss under poor ionospheric conditions**
  - **Compensates for break-down of infinite isoplanatic patch assumption at 74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



Breakdown of Infinite IP Assumption at 74 MHz:

A & B arrays: Differential refraction & source distortion

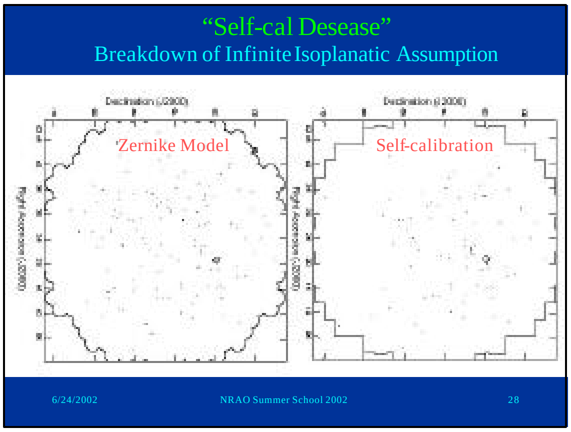
- Both global and differential refraction seen.
- Time scales of 1 min. or less.
- Equivalent length scales in the ionosphere of 10 km or less.



Breakdown of Infinite Isoplanatic Patch Assumption

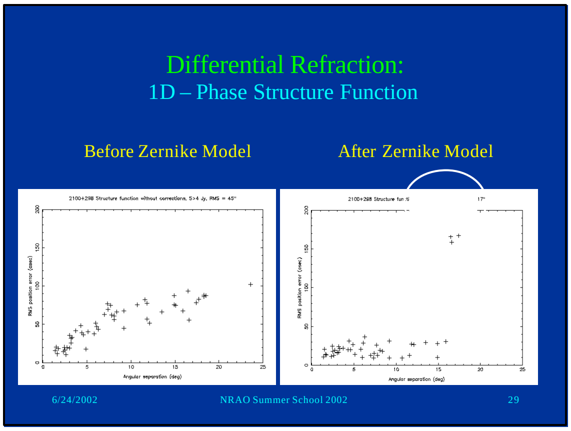
(74 MHz A and B arrays only)

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



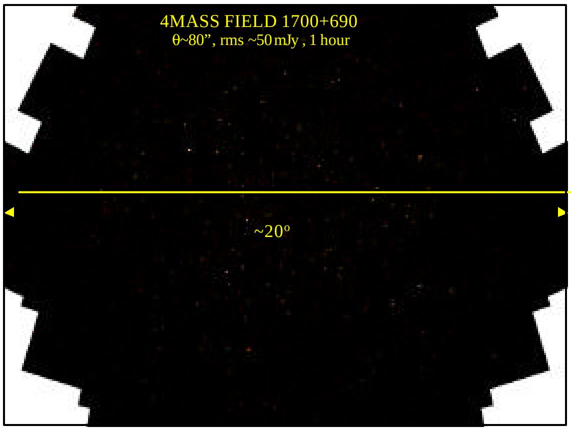
“Self-cal Desease”

Breakdown of Infinite Isoplanatic Assumption



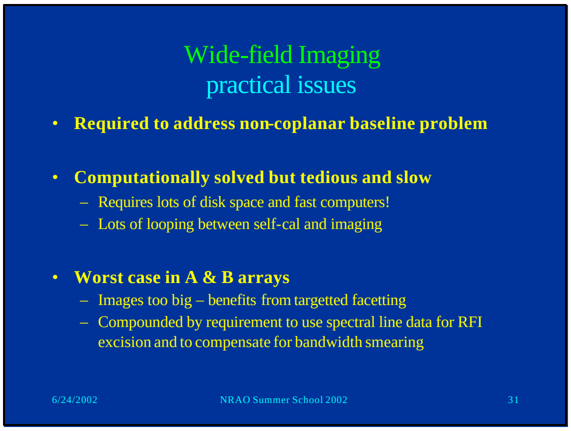
Differential Refraction:

1D – Phase Structure Function



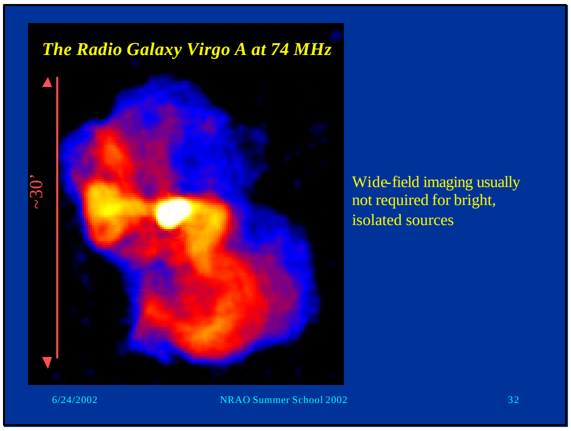
4MASS FIELD 1700+690

θ~80”, rms ~50 mJy , 1 hour



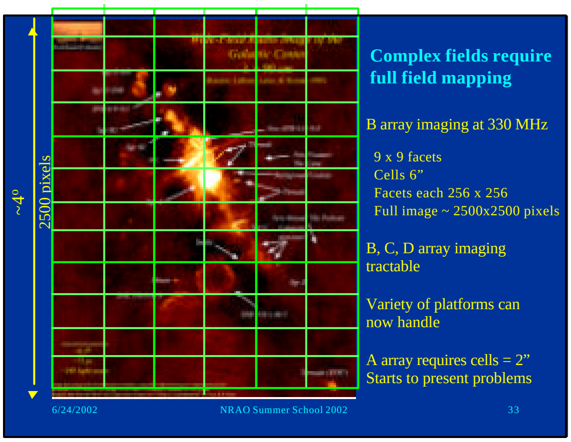
Wide-field Imaging
practical issues

- **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 targetted facetting
  - Compounded by requirement to use spectral line data for RFI excision and to compensate for bandwidth smearing



The Radio Galaxy Virgo A at 74 MHz

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



Complex fields require full field mapping

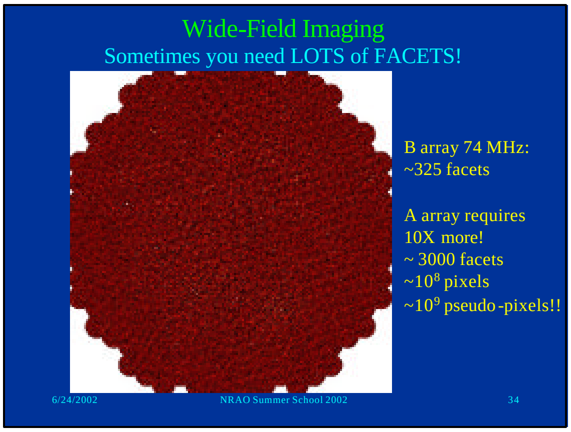
B array imaging at 330 MHz

9 x 9 facets
Cells 6”
Facets each 256 x 256
Full image ~ 2500x2500 pixels

B, C, D array imaging tractable

Variety of platforms can now handle

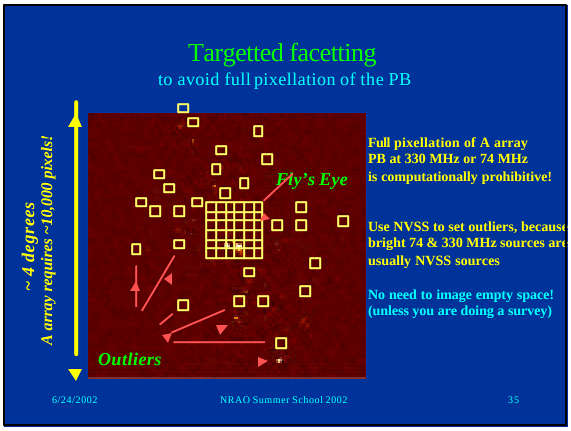
A array requires cells = 2”
Starts to present problems



Wide-Field Imaging
Sometimes you need LOTS of FACETS!

B array 74 MHz:
~325 facets

A array requires
10X more!
~ 3000 facets
~10^8 pixels
~10^9 pseudo-pixels!!

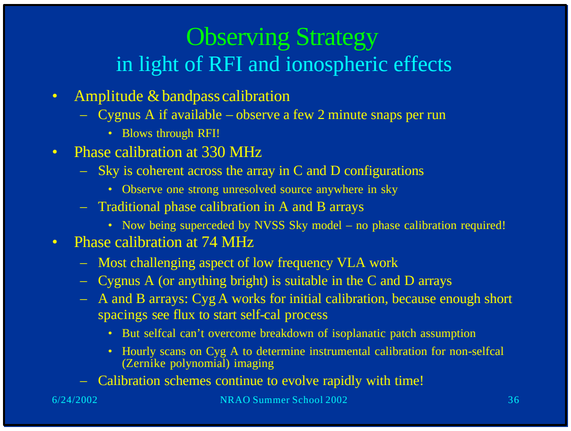


Targetted facetting
to avoid full pixellation of the PB

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)



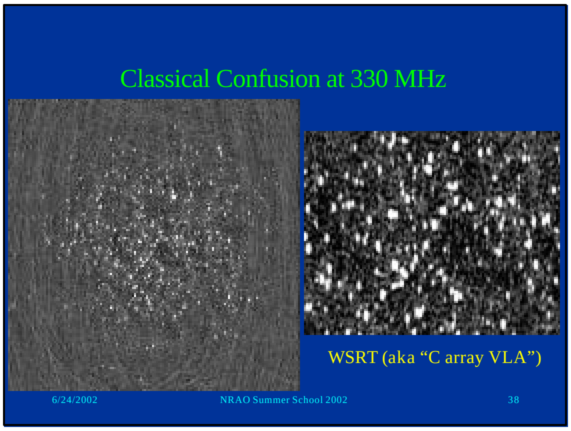
Observing Strategy
in light of RFI and ionospheric effects

- Amplitude & bandpass calibration
  - Cygnus A if 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 superceded 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 see flux to start self-cal process
    - But selfcal can’t overcome breakdown of isoplanatic patch assumption
    - Hourly scans on Cyg A to determine instrumental calibration for non-selfcal (Zernike polynomial) imaging
  - Calibration schemes continue to evolve rapidly with time!

Noise: Confusion & Thermal

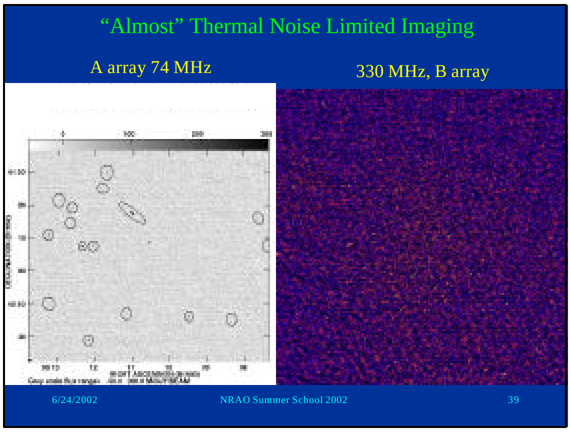
relative levels at 74/330 MHz

- 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
    - Compounded 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 good uv 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
    - Good number 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



Classical Confusion at 330 MHz

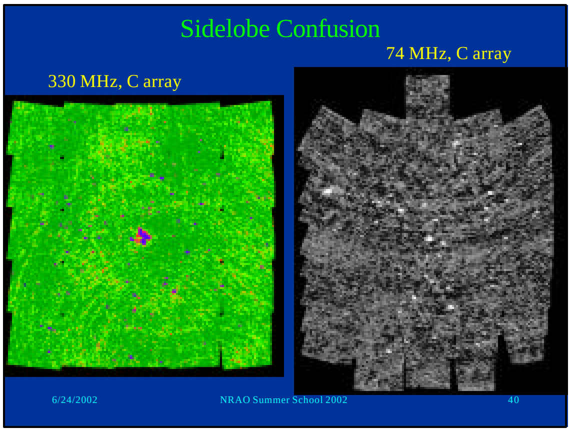
WSRT (aka “C array VLA”)



“Almost” Thermal Noise Limited Imaging

A array 74 MHz

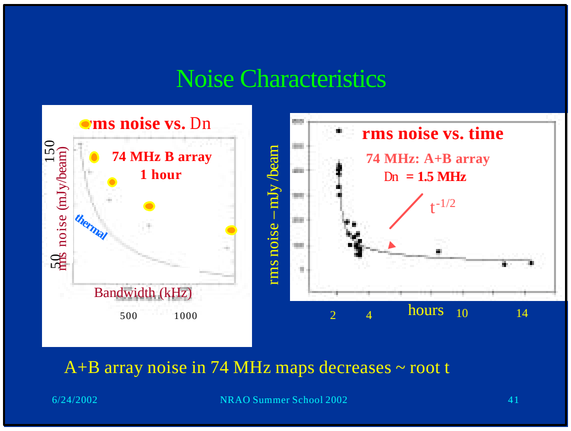
330 MHz, B array



Sidelobe Confusion

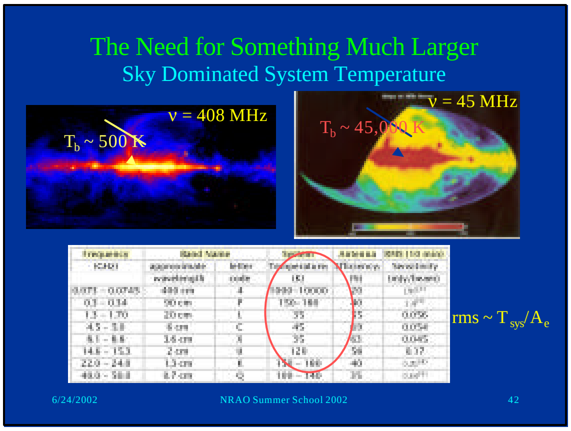
74 MHz, C array

330 MHz, C array



Noise Characteristics

A+B array noise in 74 MHz maps decreases ~ root t



The Need for Something Much Larger

Sky Dominated System Temperature

Frequency (GHz)	Band Name approximate wavelength	letter code	System Temperature (K)	Antenna Efficiency (%)	RMS (10 min) Sensitivity (mJy/beam)
0.073 – 0.0745	400 cm	4	1000 – 10000	20	[illegible]
0.3 – 0.34	90 cm	P	150 – 180	40	[illegible]
1.3 – 1.70	20 cm	L	35	55	0.056
4.5 – 5.0	6 cm	C	45	65	0.058
8.1 – 8.8	3.6 cm	X	35	63	0.045
14.6 – 15.3	2 cm	U	120	58	0.17
22.0 – 24.0	1.3 cm	K	150 – 180	40	[illegible]
40.0 – 50.0	0.7 cm	Q	100 – 140	35	[illegible]

rms ~ T_{sys}/A_e

LOFAR Concept

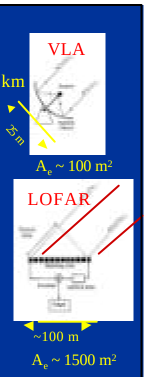
(LOFAR = Low Frequency Array)

(http://lofar.nrl.navy.mil & http://www.lofar.org)

- 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: $\Delta\nu \sim 10$–240 MHz
  - Low frequency limit: ionospheric absorption, scintillation
  - High frequency limit: λ^2 collecting area, better to use dishes above this
- "Stations" (dishes) are 160 m in size, comprised of 256 receptors
  - Good primary beam definition, low sidelobe levels
- **Large aperture**: baselines ≤ 500 km (no limit on baseline length)
  - Good angular resolution, low confusion
- **Large collecting area** : $\geq 10^6$ m^2
  - 2–3 orders of magnitude improvement in resolution & sensitivity
  - 8"@15 MHz, 0.8"@150 MHz; < 1 mJy@15 MHz, < 300 μJy@ 150 MHz
- Multiple beams: new approach to astronomical observing

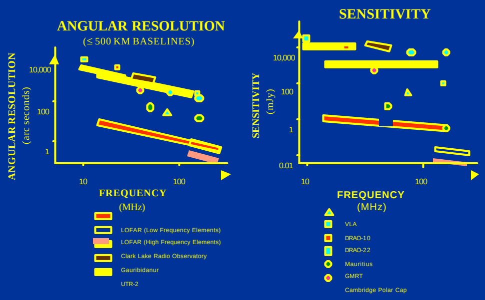
LOFAR Stations

200 Dipoles per "Station", 100 Total Stations over 500 km



Opening A New Window On The Universe

(http://lofar.nrl.navy.mil & http://www.lofar.org)



Summary

(see http://rsd-www.nrl.navy.mil/7213/lazio/tutorial)

- 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 limitation: poor relative sensitivity & resolution as compared to cm wavelength systems
    - Scientifically 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