Low-frequency Interferometry

Lincoln Greenhill

Thirteenth Synthesis Imaging Workshop

2012 May 29– June 5

Science

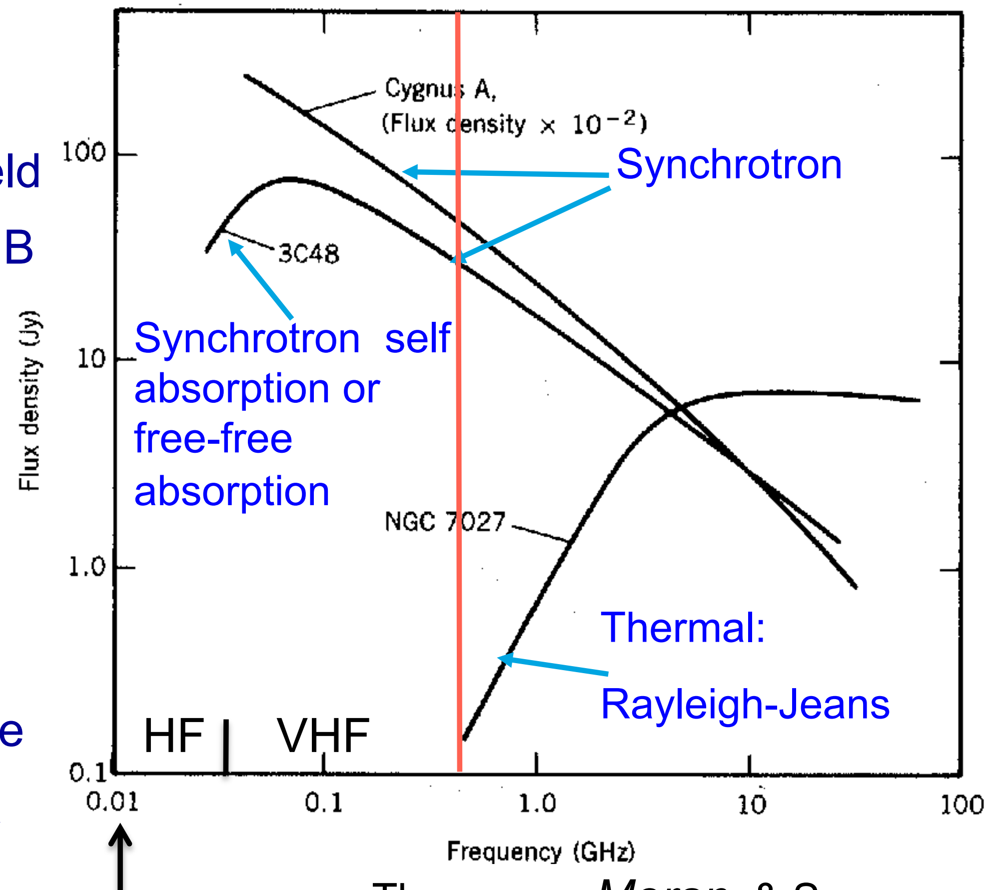
- Key science drivers at low frequencies:
  - Dark Ages (spin decoupling)
  - Epoch of Reionization (highly redshifted 21 cm lines)
  - Early Structure Formation (high z RG)
  - Large Scale Structure evolution (diffuse emission)
  - Evolution of Dark Matter & Dark Energy (Clusters)
  - Wide Field (up to all-sky) mapping
  - Large Surveys
  - Transient Searches (including extrasolar planets) *(Hallinan talk)*
  - Galaxy Evolution (distant starburst galaxies)
  - Interstellar Medium (CR, HII regions, SNR, pulsars)
  - Solar Burst Studies
  - Ionospheric Studies
  - Ultra High Energy Cosmic Ray Airshowers
  - Serendipity (exploration of the unknown)

The Low Frequency Sky

Mainly two emission processes

- synchrotron emission
  - prominent @ meter λ (≪1 GHz)
  - relativistic e^- spiraling around B field
  - function of e^- energy, density, and B
  - emission is polarized
  - coherent or incoherent
- Bremsstrahlung (thermal free-free)
  - prominent @ cm λ (≫1 GHz)
  - acceleration of e^- by ions
  - function of density and temperature
  - possibly seen in absorption if thick
- also radio recombination lines

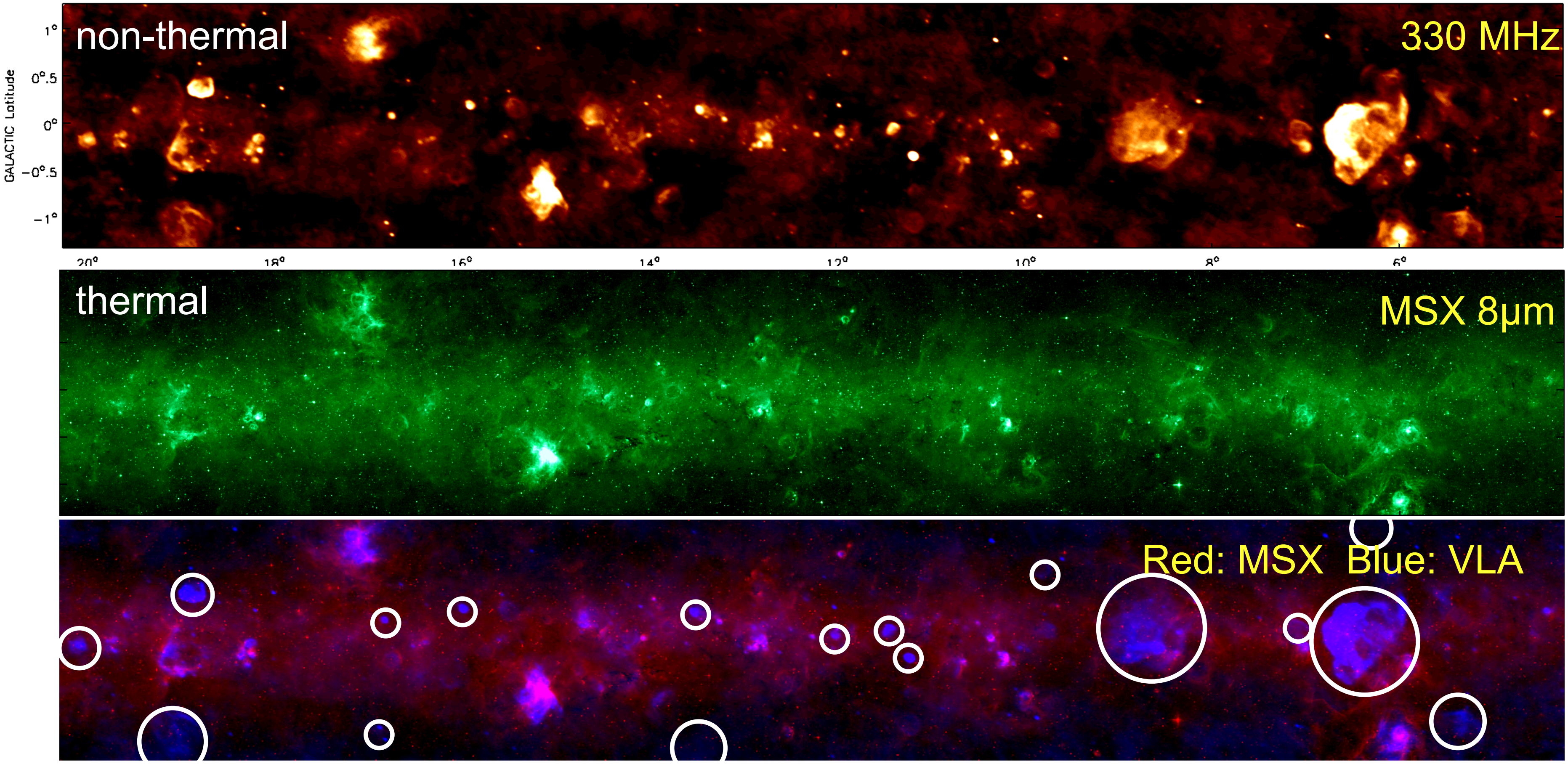
a story of two skies



ionospheric cutoff

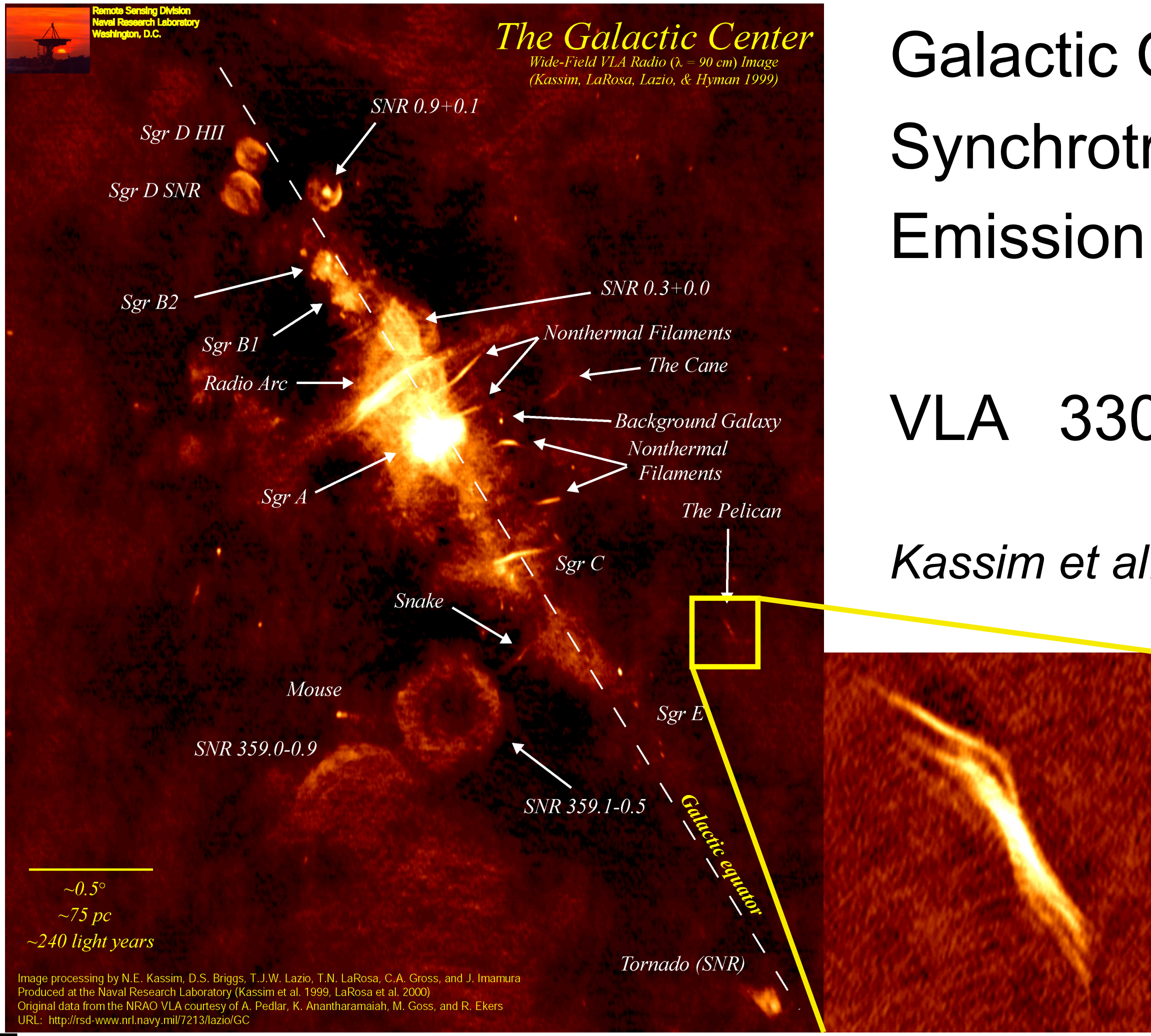
Thompson, *Moran*, & Swenson

The Low Frequency Sky



Brogan et al. 2006

The Low Frequency Sky

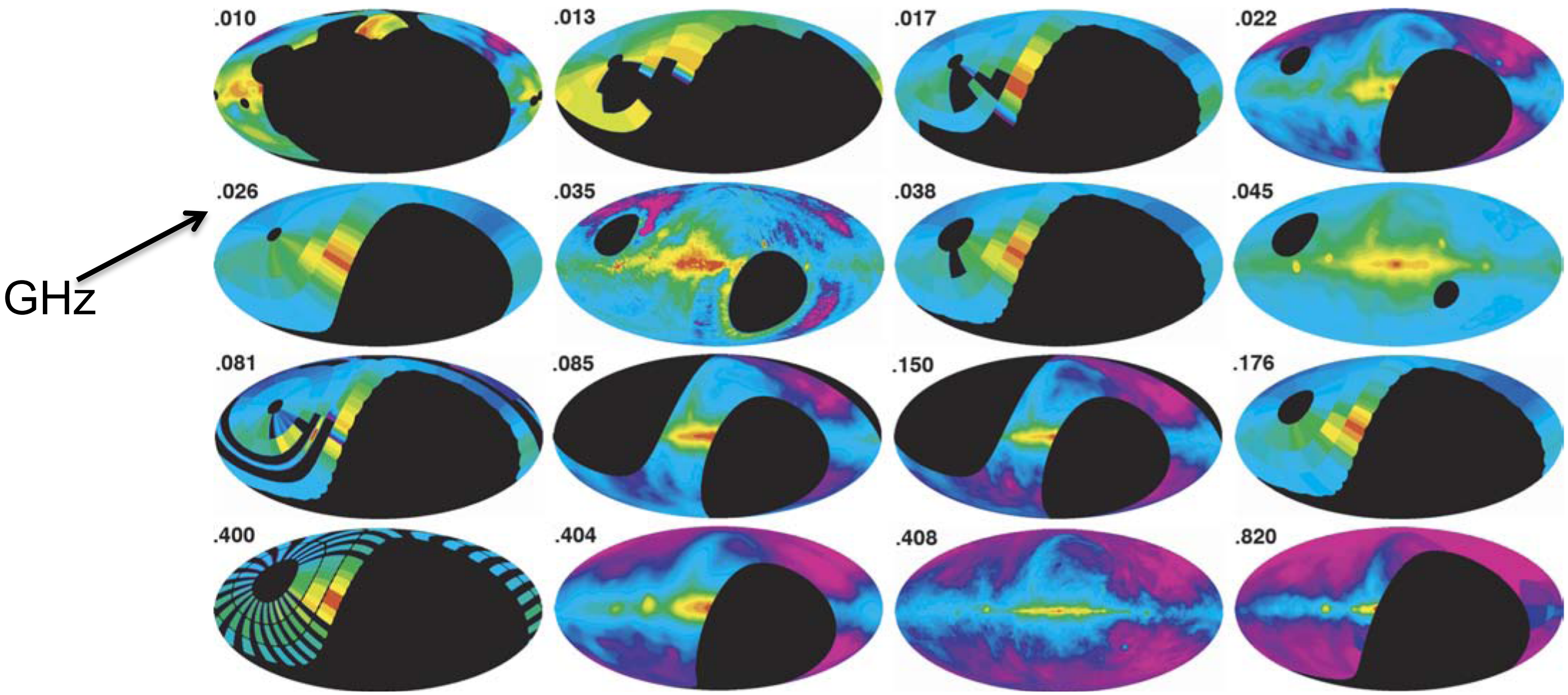


Galactic Center Synchrotron Emission

VLA 330 MHz

Kassim et al. 1999

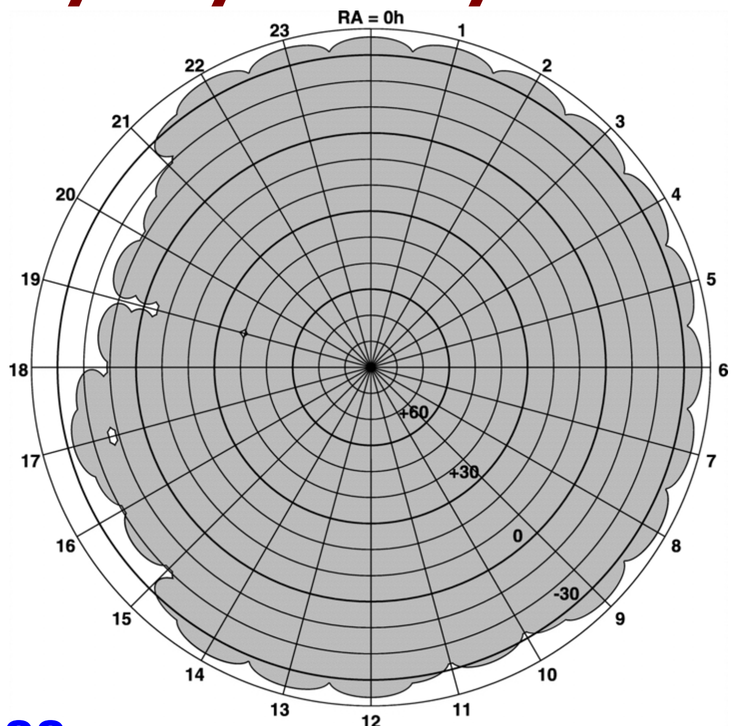
Resources: All sky surveys



Costa et al. 2008

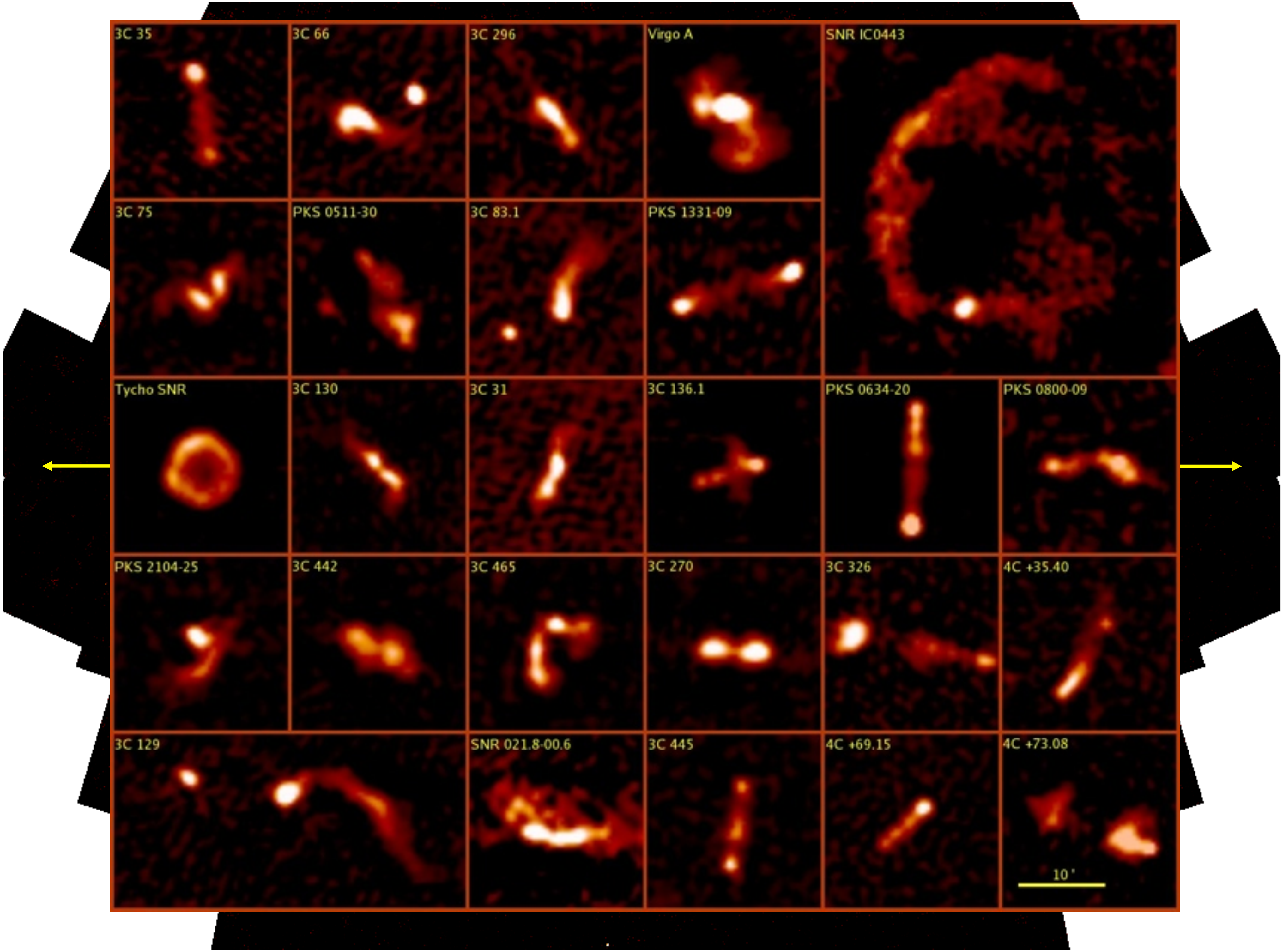
- Understanding of the low frequency sky is limited
  - an observational frontier
  - a few surveys sensitive to O(1°)-scale emission
  - two all sky surveys sensitive to compact emission
    - 74 & 150 MHz

Resources: VLA Low Frequency Sky Survey



Cohen et al. (2007)

- survey parameters: ν = 74 MHz, δ > -30°,
  Θ = 80″ resolution,
  RMS~100 mJy/beam
- N ~ 70,000 sources in ~ 95% of sky > -30°
  Statistical sample of mundane & rare populations
  ➟ fast pulsars, distant radio galaxies, cluster radio halos and relics
- calibration grid for low-frequency instruments
- data online at NED & http://lwa.nrl.navy.mil/VLSS
- successor ELVA low-frequency system in development
  - 10x bandwidth @ 74 MHz
  - leverages increased correlator capability

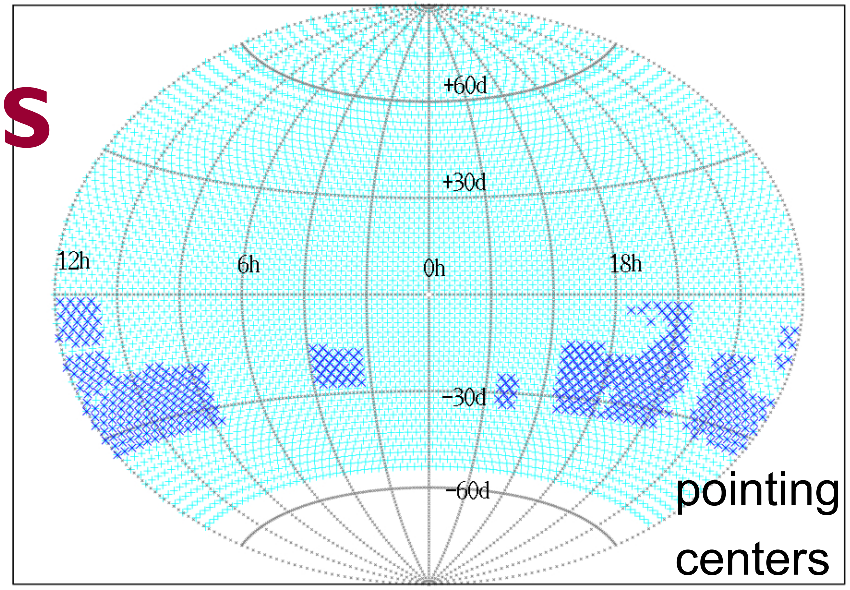

3C 35
3C 66
3C 296
Virgo A
SNR IC0443
3C 75
PKS 0511-30
3C 83.1
PKS 1331-09
Tycho SNR
3C 130
3C 31
3C 136.1
PKS 0634-20
PKS 0800-09
PKS 2104-25
3C 442
3C 465
3C 270
3C 326
4C +35.40
3C 129
SNR 021.8-00.6
3C 445
4C +69.15
4C +73.08
10'

Resources: GMRT/TGSS

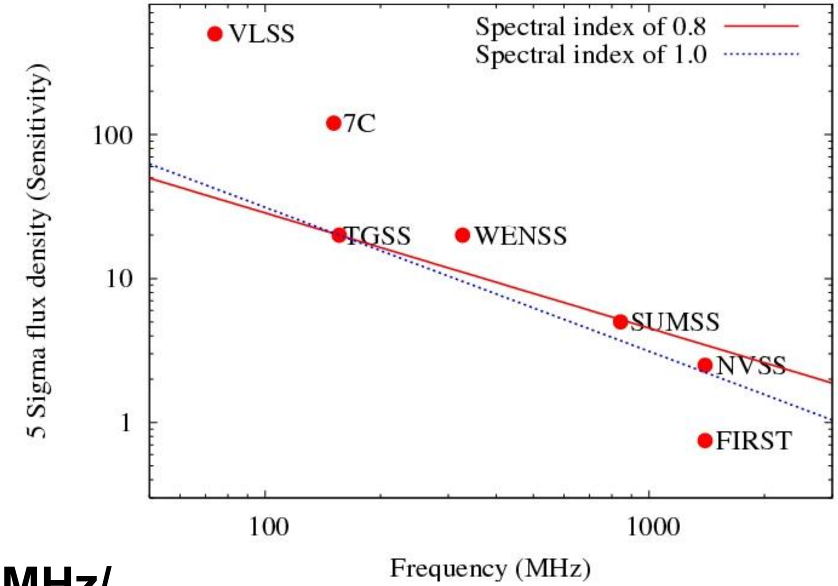
- in progress (DR4 online April 2012)
- survey parameters:
  ν= 150 MHz, $\delta \gtrsim$ -55°
  θ = 20″, σ ~ 10 mJy/beam

- N ~ 10^6 sources anticipated
  statistical samples of populations...

- enhances low-freq. calibration grid



pointing centers

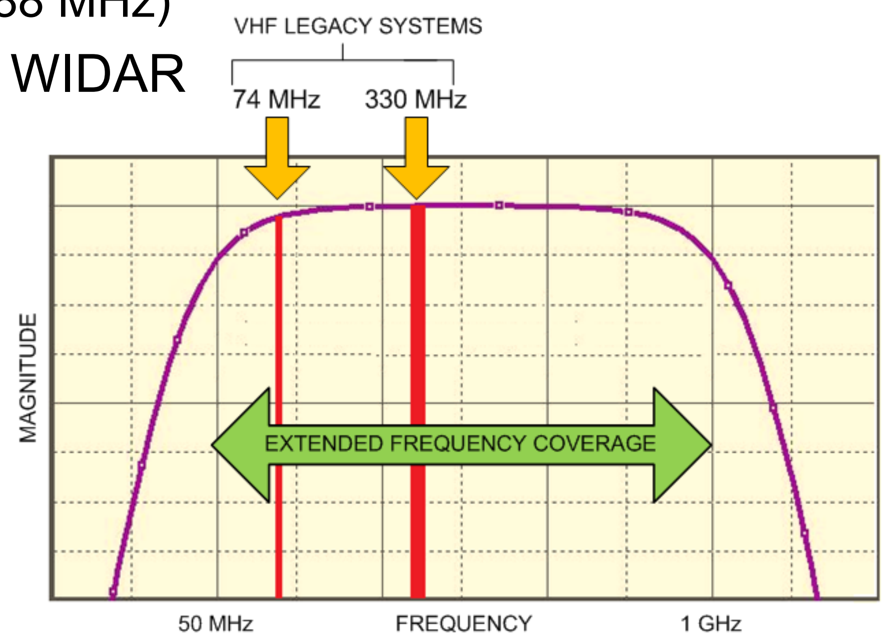


- data online at **http://tgss.ncra.tifr.res.in/150MHz/**

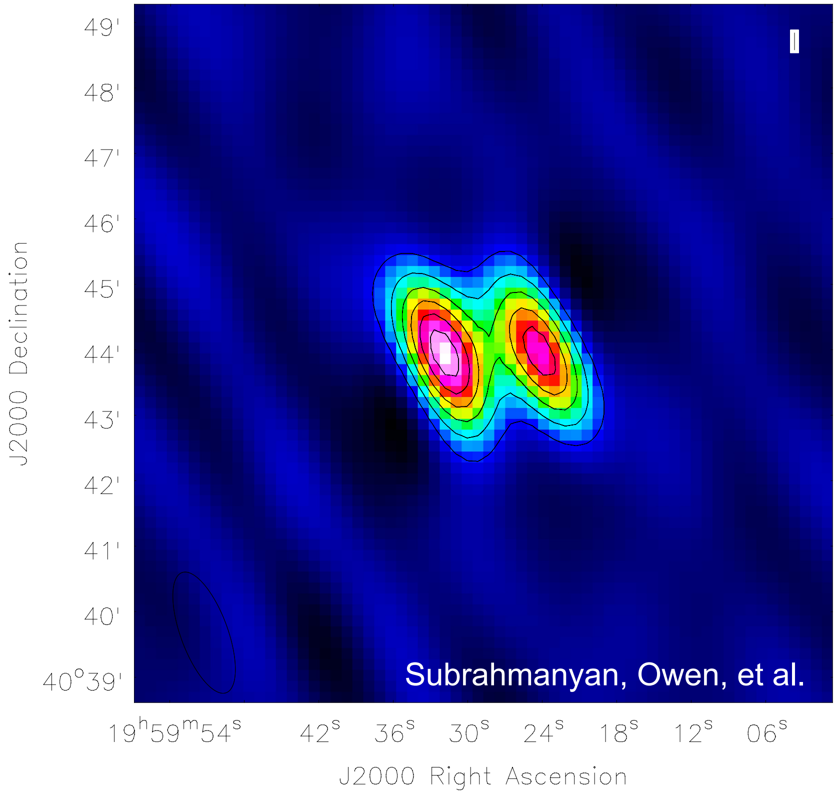
Sirothia et al.

Sucessor EVLA Low-Band System

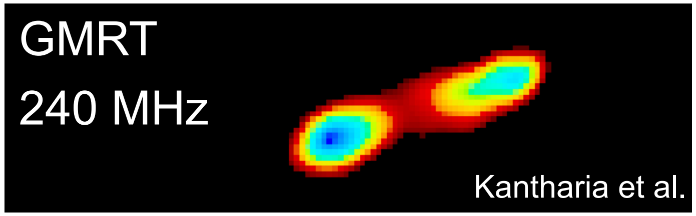
- receivers (in development) and single broadband feed (in study)
- P-band: BW increased, 40 ➟ 240 MHz (230 to 470 MHz)
  - demonstrated
- 4-band: BW Increase, 1.5 ➟ 16 MHz (66 to 82 MHz)
  - Limited on low end by present EVLA IF system
  - Limited on high end by the FM band (88 MHz)
- more flexible RFI rejection enabled by WIDAR
- Improved algorithms for large FOV



Early Results EVLA @ P-band



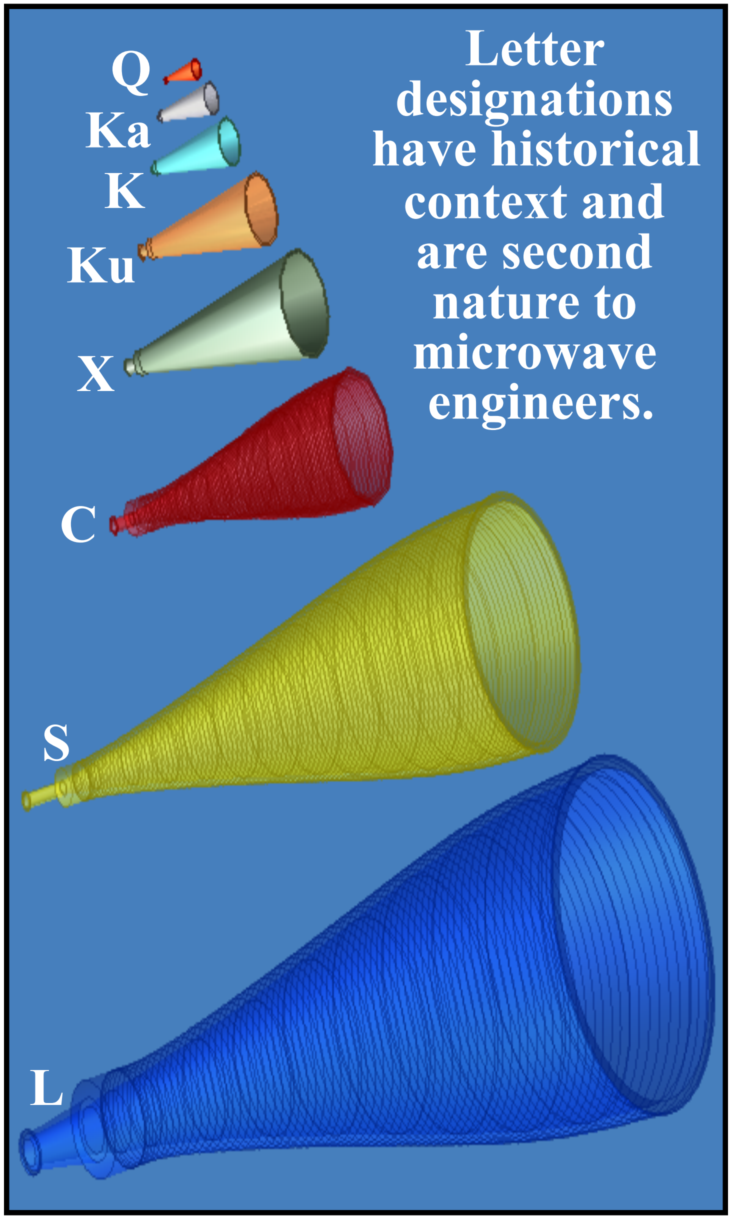
- Cyg A
- 12 May 01
- 270-480 MHz (New Capability!)
- 4 antennas; 10^m
- CASA learning curve: 3 weeks

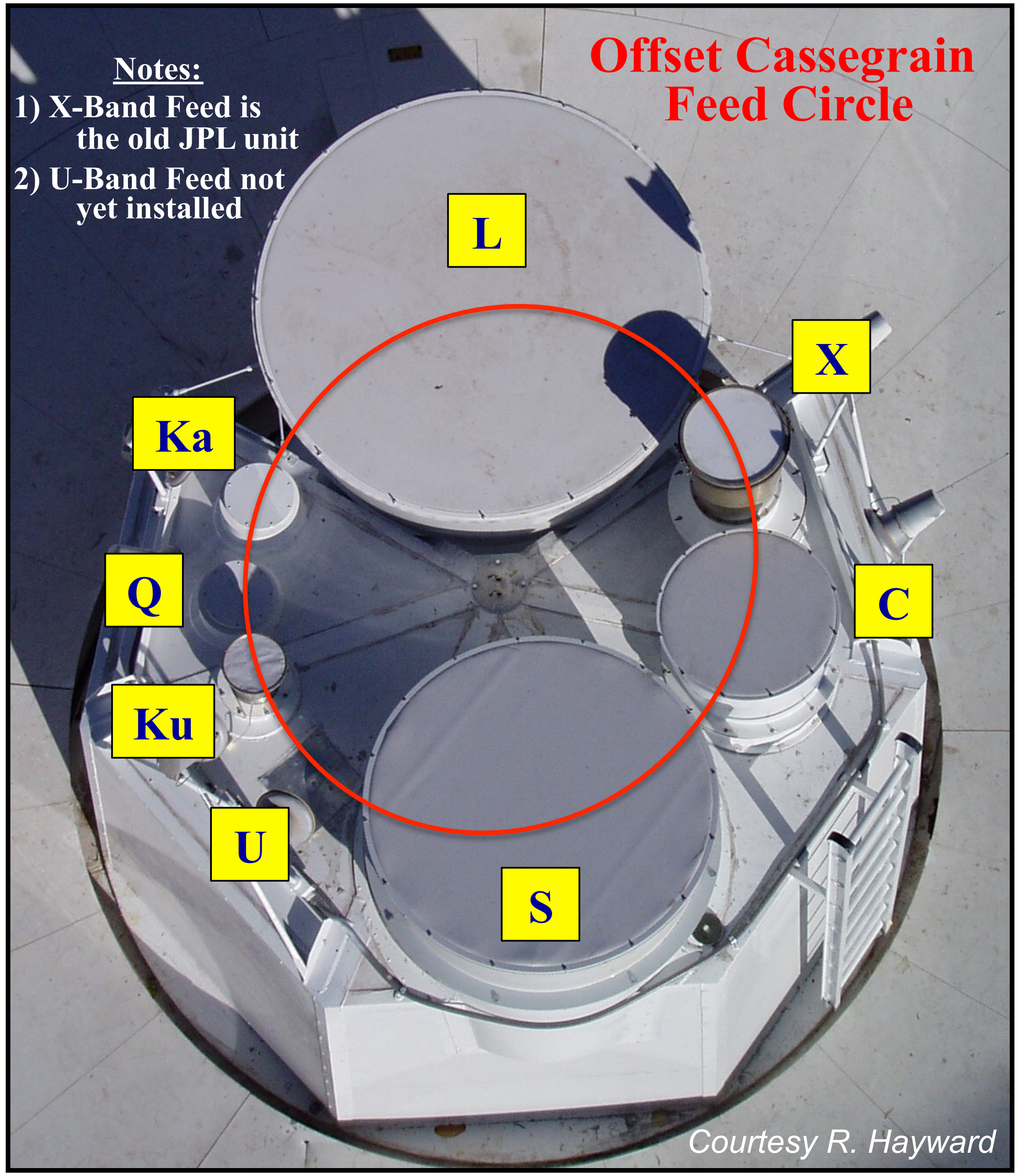


Low Frequency Receptors

- feeds *(Hayward talk)*
  - horns at high/mid frequency
    - impractical below ~ 1 GHz: size > λ ➟ massive, awkward
  - bare dipoles at low frequency
    - basic model: λ/2 resonant (narrow-band) antenna
    - 'electrically short' dipoles are effective
    - diversity of space-saving configurations
    - BUT broadband designs involve many trade-offs
      - messy circuit elements (variable impedance, ugly gain patterns,…)
- two common configurations
  - dipole + dish: large collecting area per dipole ($$$)
  - dipole + ground screen: small area, $A_e \sim G\lambda^2/4\pi$ ($)
    - motivates 'large-N' arrays or beam forming ⇐ *crazy-new architectures*

JVLA Feeds





Jim Ruff's Web Pages - http://www.aoc.nrao.edu/~jruff/A1Vertex.jpg

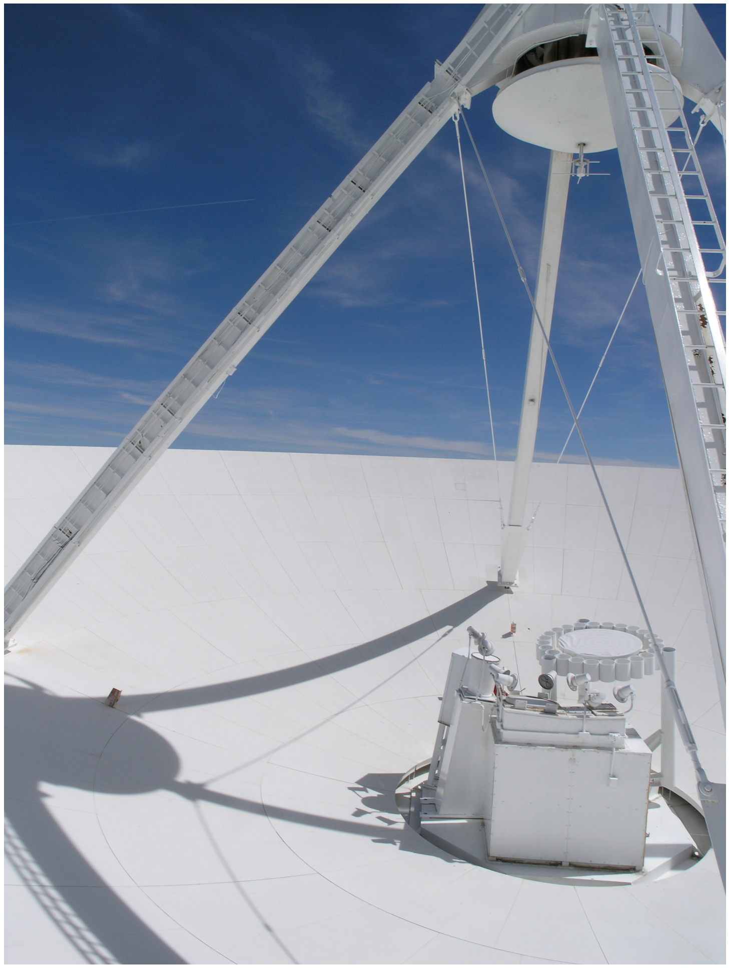
Low Frequency Receptors

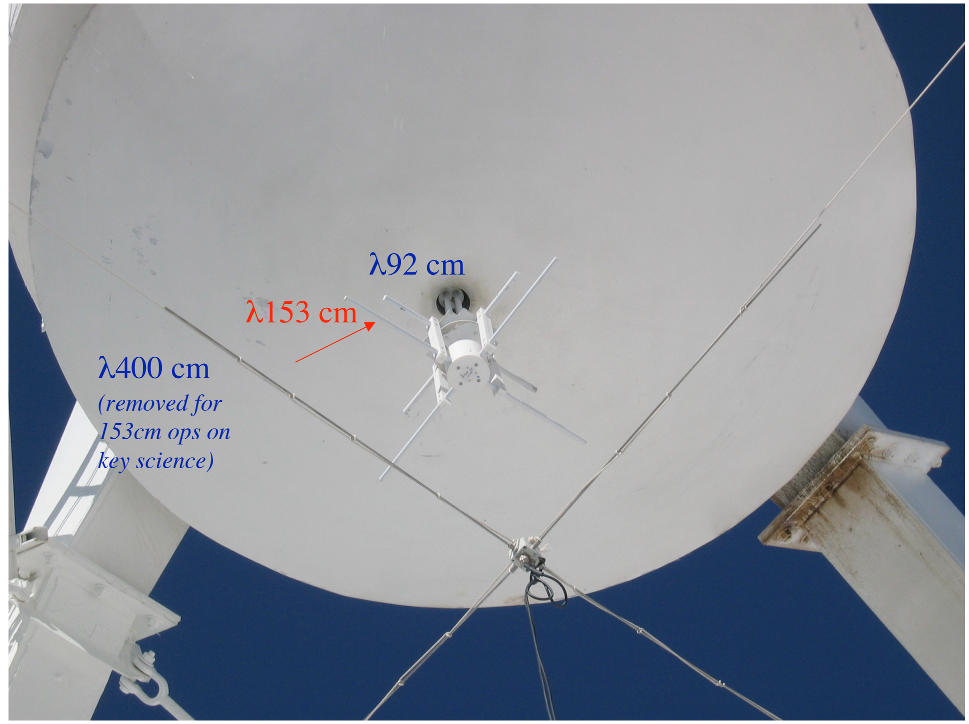
150 MHz feed: folded dipole

GMRT

30-80 MHz feed: folded dipole

Low Frequency Receptors





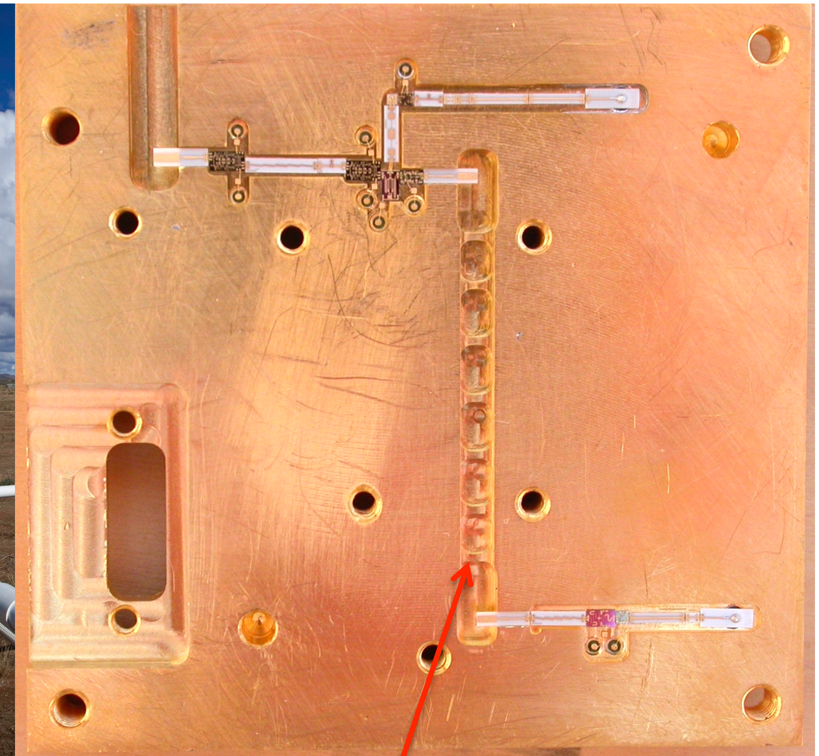
74, 190, 330 MHz dipoles
sub-reflector acts as
ground screen

VLA

(c.2005)

Low Frequency Receptors

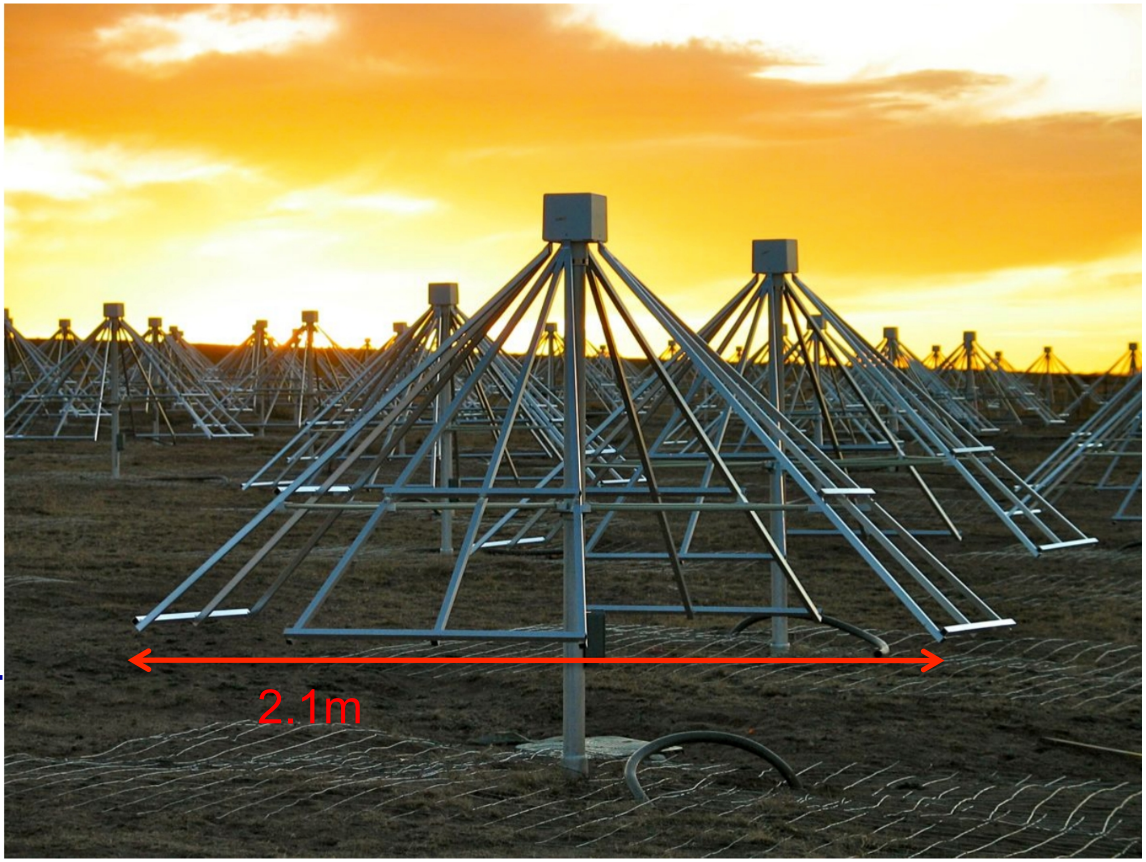
- bare dipoles
- PAPER
  - Precision Array to Probe the Epoch of Reionization
  - 100-200 MHz dipoles
  - ground screen crib increases A_e (~8 m^2)
  - drift scan operation
  - smooth, stable gain pattern
  - eor.berkeley.edu/



structural details affect characteristics

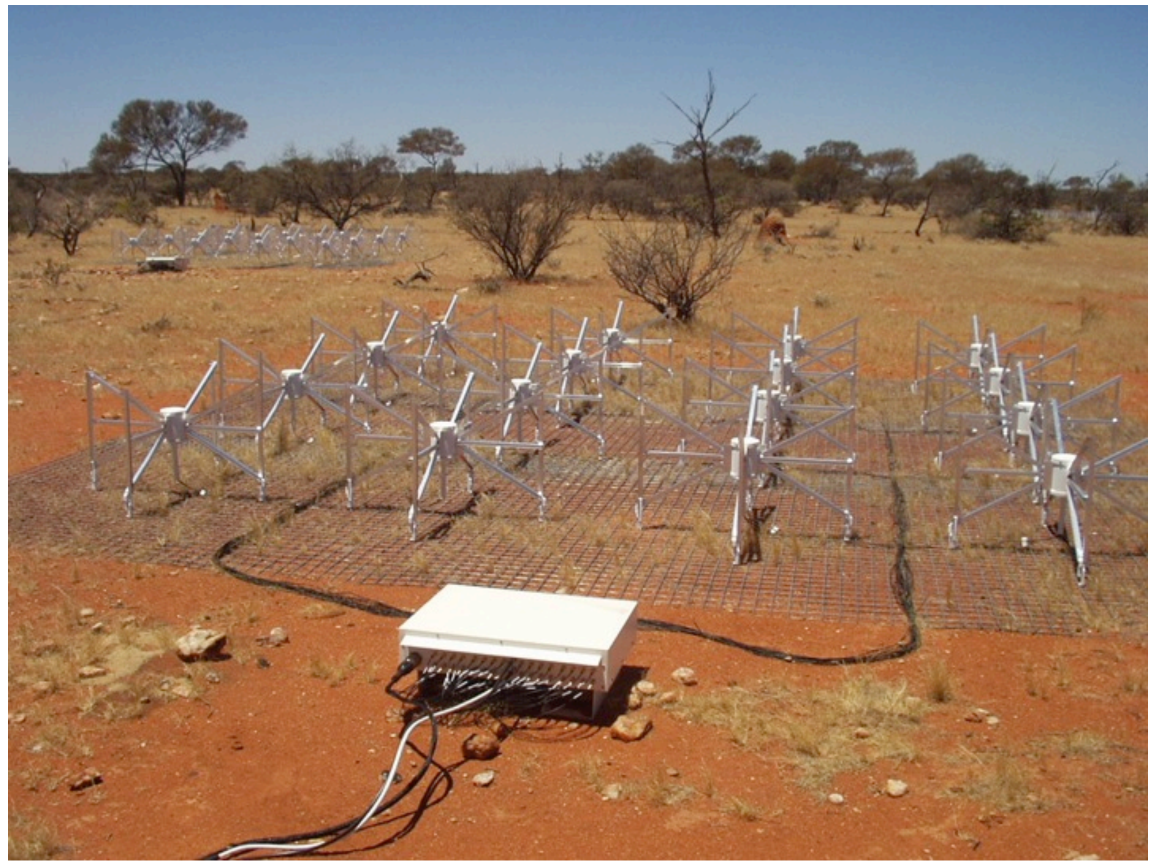
Low Frequency Receptors

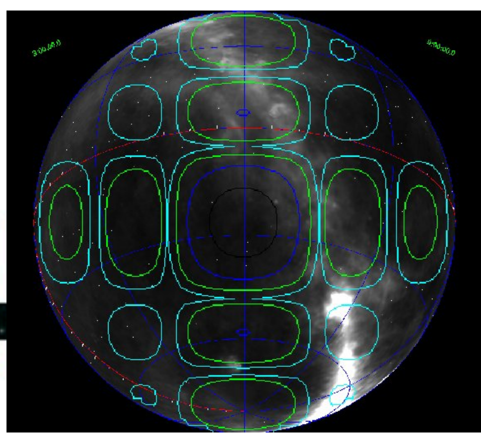
- bare dipoles
- LWA
  - Long Wavelength Array
  - 10-88 MHz dipoles
  - dipole size ∝ λ
  - A_e~7 m^2
  - drift scan
  - close packing (0.5-1.4λ)
    - mutual coupling perturbs gain patterns…
  - open access facility adjacent to VLA

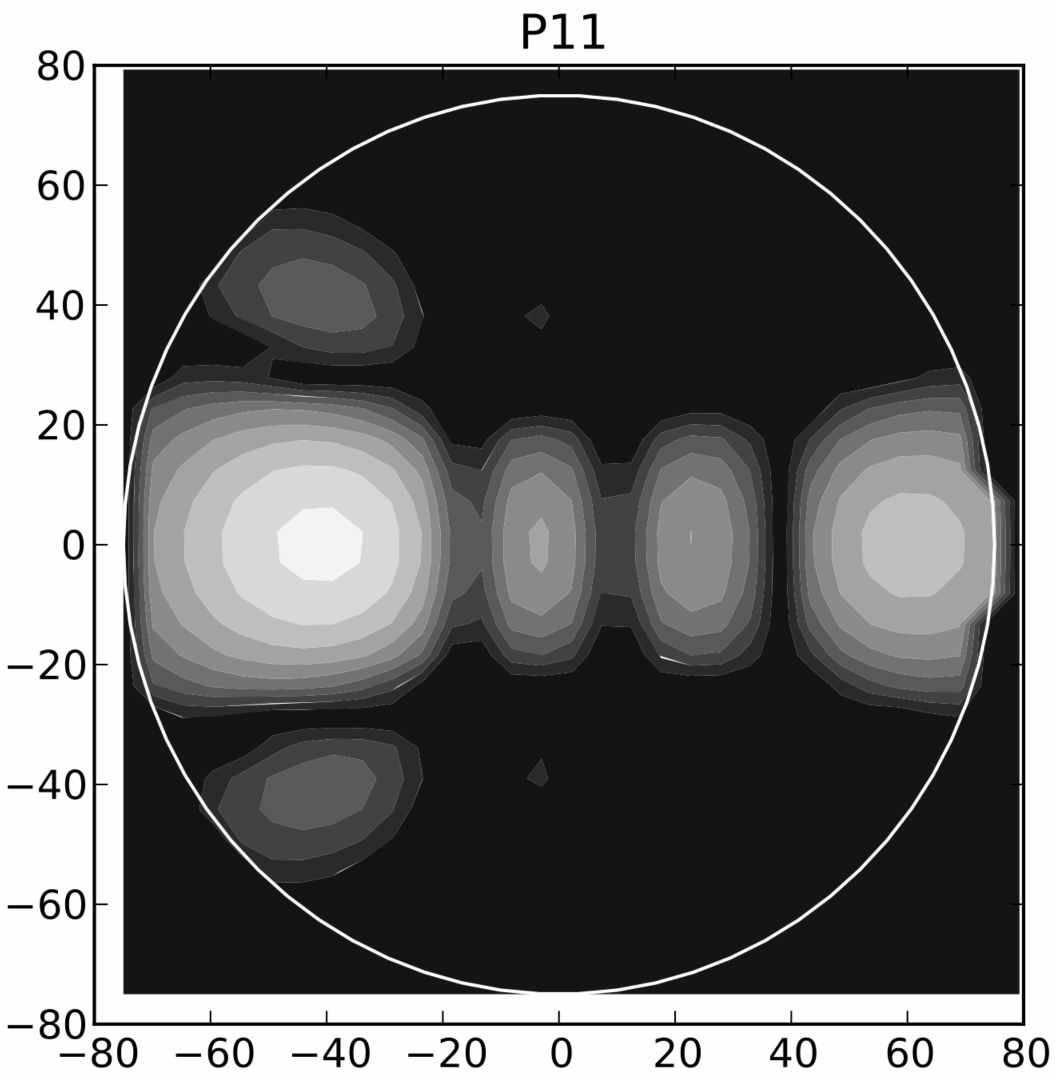


Low Frequency Receptors

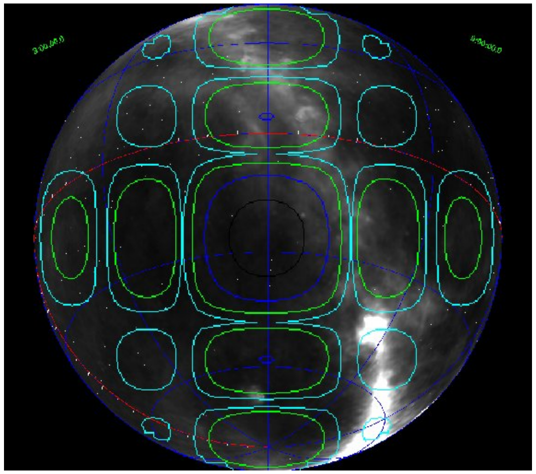
- bare dipoles (phased)
- MWA
  - Murchison Wide-field Array
  - 80-300 MHz dipoles
  - bowtie geometry
  - tiling increases A_e (~20 m^2)
  - tracking via crude phasing
  - complicated beam pattern
  - multiplies costs
  - mwatelescope.org







- discrete tracking
- complex sidelobes
- rotate on the sky
- beam former electronics determine stability/ repeatability

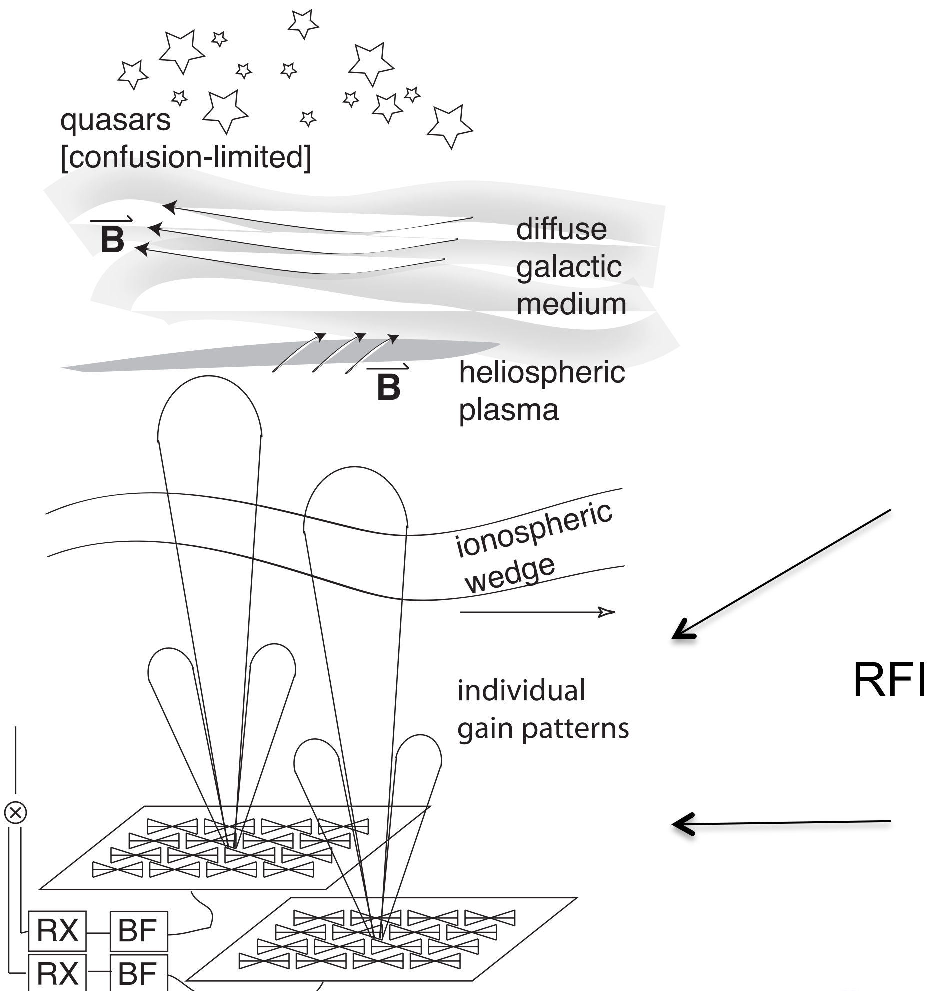


Mixed Blessings

- **dipole + dish**
  - the good
    - sensitive
    - continuous, accurate tracking
    - stable receptor gain pattern
    - effective for small N
    - moderate computation
    - moderate algorithm development
    - narrow FOV
  - the bad
    - expensive
    - snapshots deliver limited DNR
    - narrow FOV
- **bare dipoles**
  - the good
    - inexpensive
    - wide FOV
    - steerable when arrayed
  - the bad
    - inexpensive
    - wide FOV
    - steerable when arrayed
  - the ugly
    - require very large N
    - computationally demanding
    - difficult algorithmic challenges

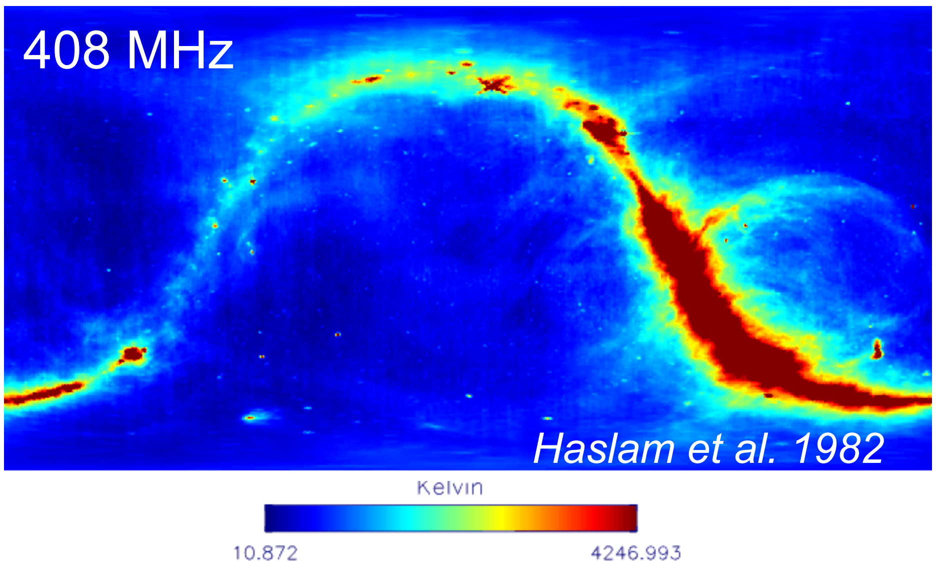
Low Frequency Challenges

- Sky brightness
- Source confusion
- Ionospheric distortion
- Radio Frequency Interference (RFI)
- Wide fields of view (FOV)
- Variable dipole response (for fixed dipole arrays)


quasars
[confusion-limited]
B
diffuse
galactic
medium
heliospheric
plasma
B
ionospheric
wedge
individual
gain patterns
RFI
RX
BF
RX
BF

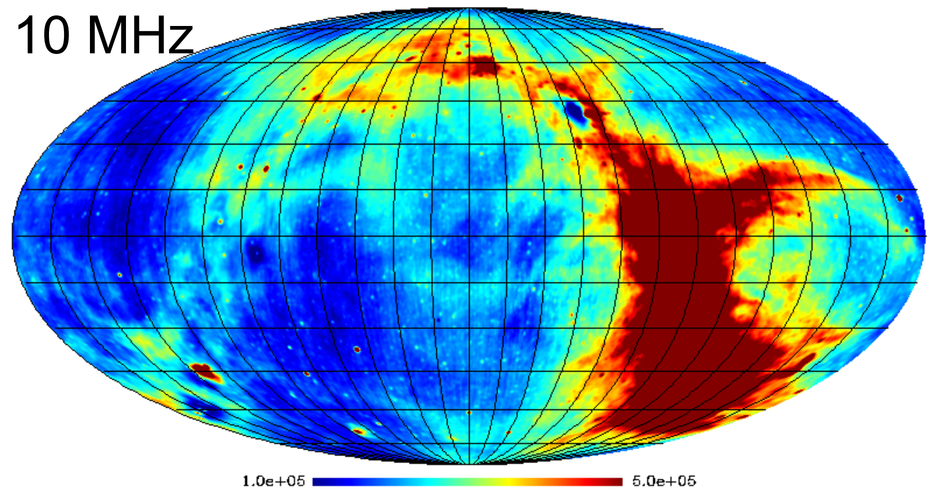
Sky brightness

$$T_{sys}(K) = 131000 \left(\frac{\nu}{15\ MHz} \right)^{-2.55}$$



Peak: 4200 K

10 MHz



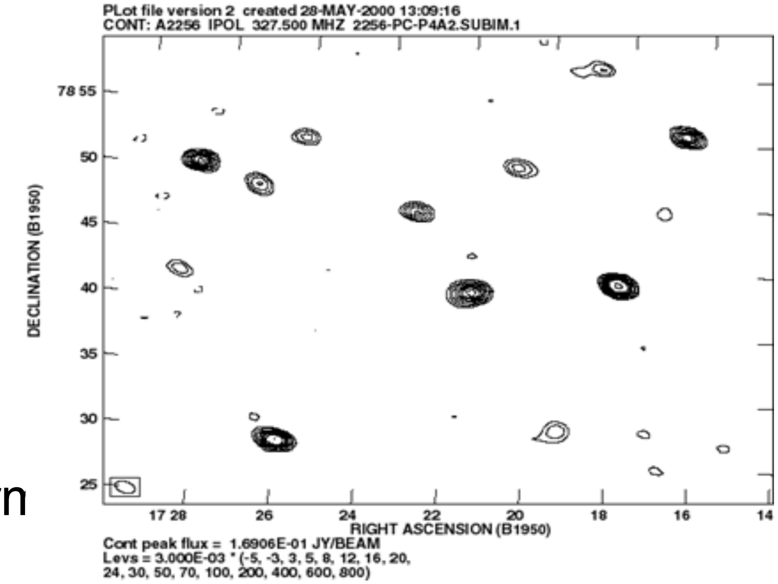
Peak: 500,000 K

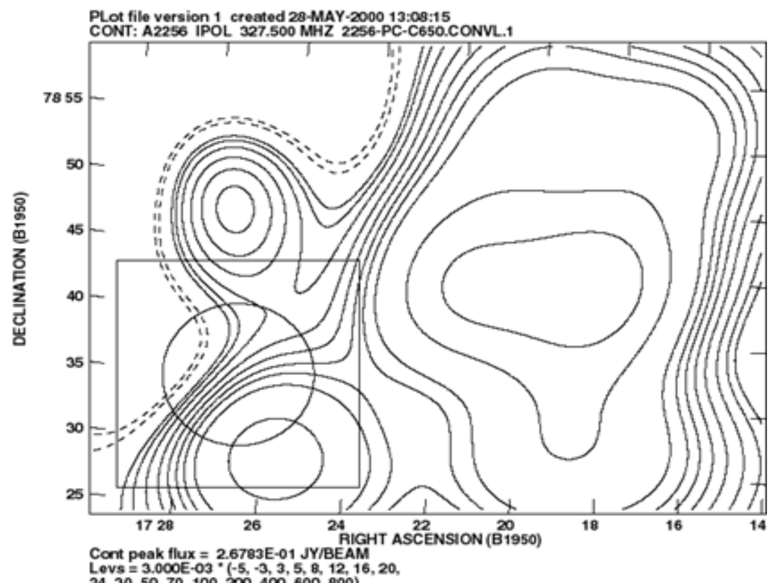
adapted from Costa et al. 2008
courtesy G. Bernardi

Confusion

- source counts rise to lower F_ν
- for any angular resolution θ
  - there is a confusion limit
  - individual weak sources blend
  - the resulting sky noise may exceed thern
  - such cases are “confusion limited”
- $F_\nu \sim 3$ mJy $(\theta/2')(150\ \mathrm{MHz}\ /\ \mathrm{nu})^{0.7}$

  (Bernardi et al. 2010)





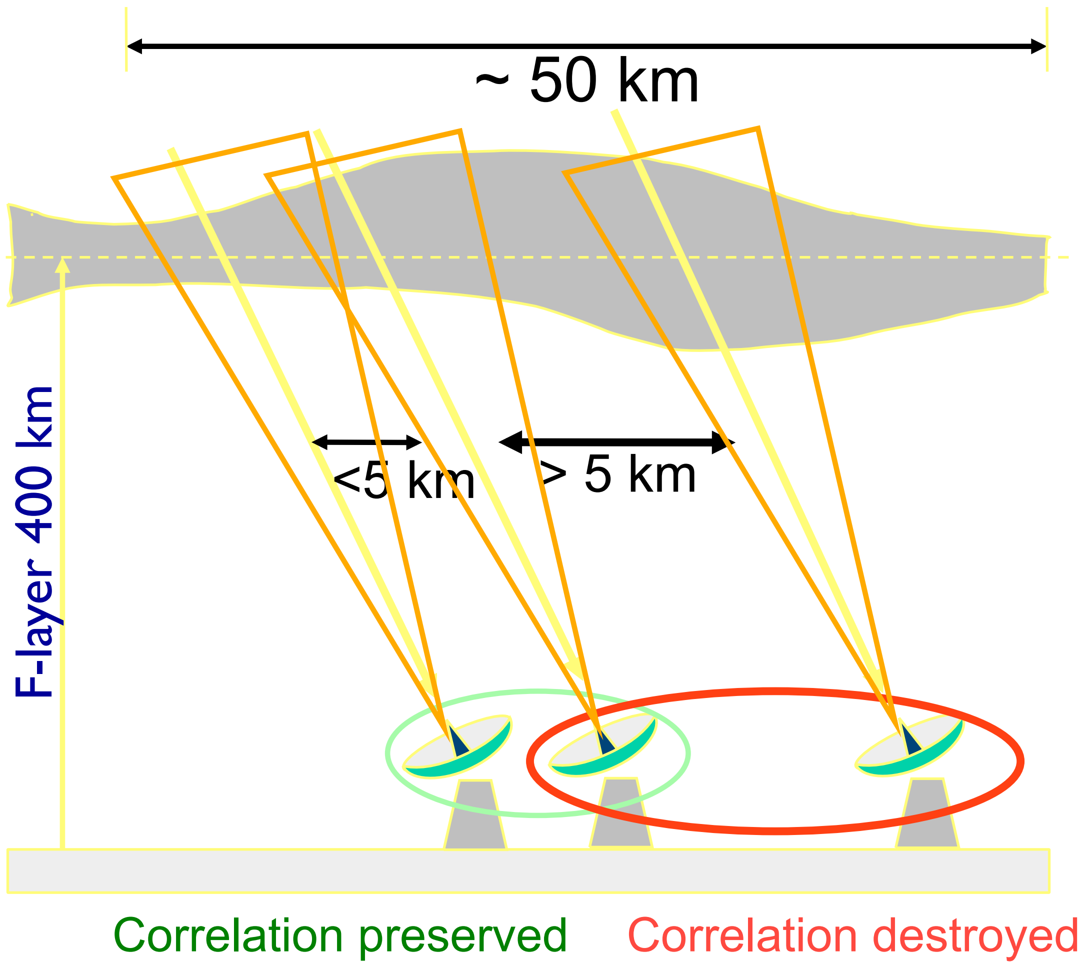
θ ~ 1’, rms ~ 3 mJy/beam

θ ~ 10’, rms ~ 30 mJy/beam

Low Frequency Challenges

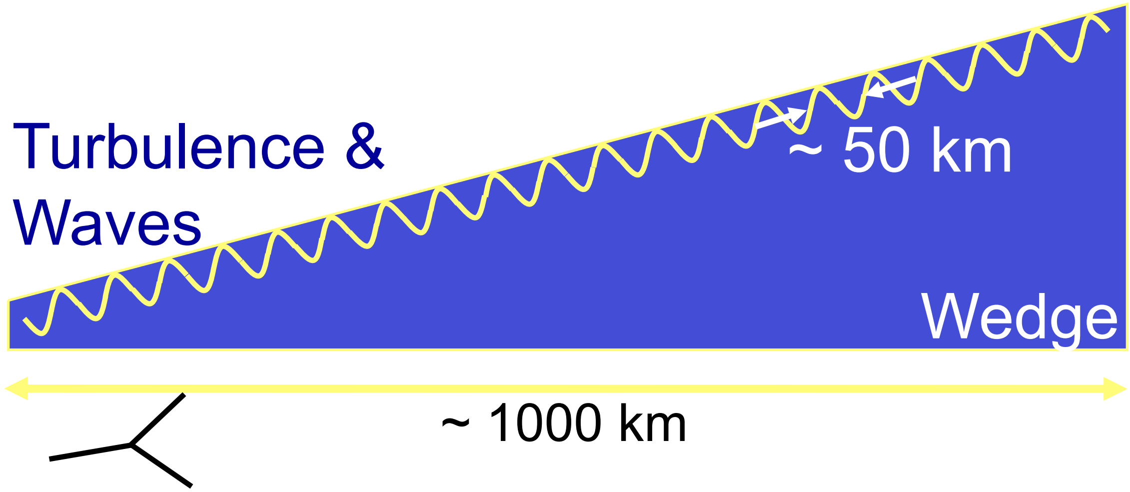
- Sky brightness
- Source confusion
- Ionospheric distortion
- Radio Frequency Interference (RFI)
- Wide fields of view (FOV)
- Variable dipole response (for fixed dipole arrays)

Ionosphere



- Waves in the ionosphere introduce rapid phase variations (~1°/s on 35 km BL)
- Phase coherence is preserved on BL < 5km (gradient)
- BL > 5 km have limited coherence times
- Without proper algorithms this limits the capabilities of low frequency instruments

Ionosphere



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

$\Delta L \propto \lambda^2 * TEC$
$\Delta\phi \sim \Delta L/\lambda \sim \lambda * TEC$

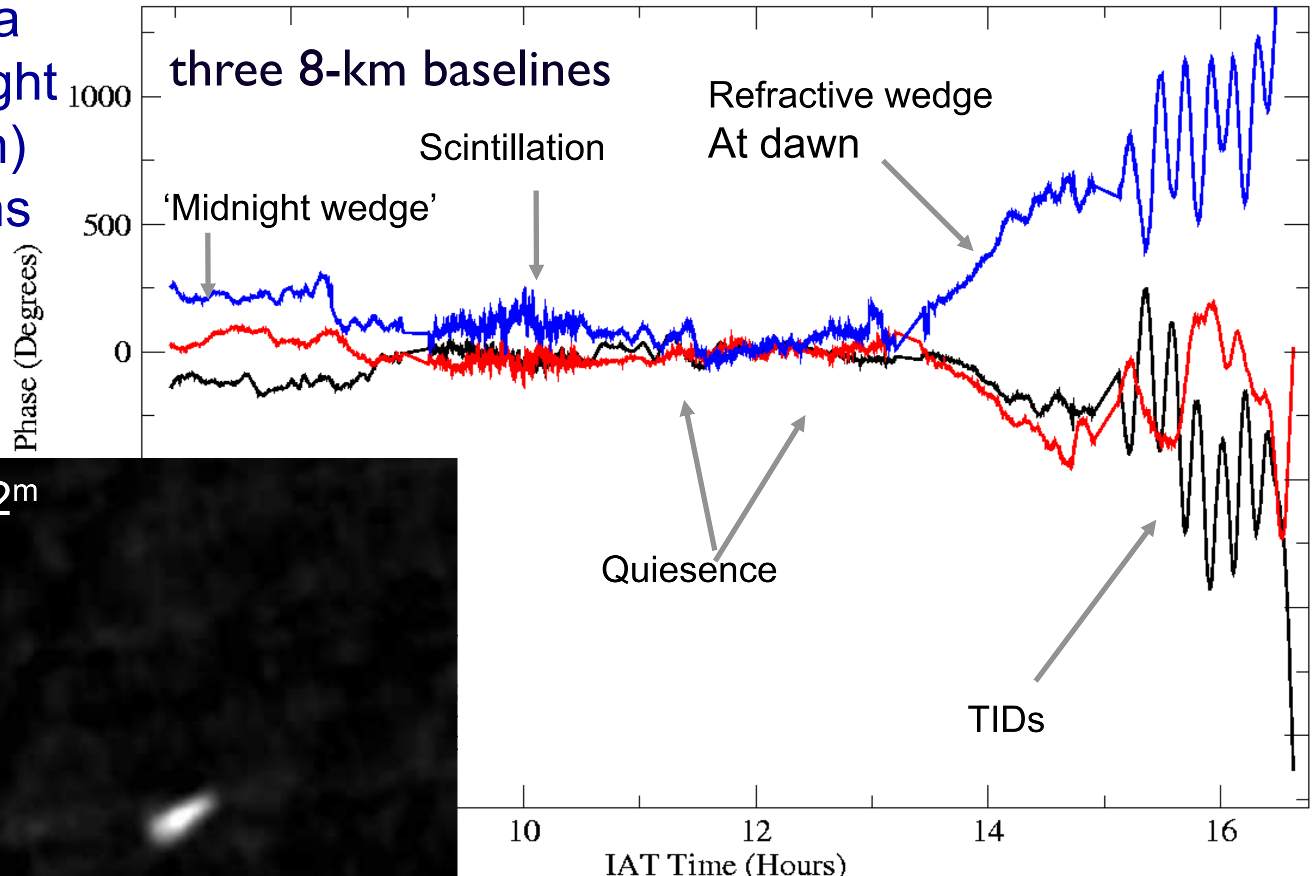
Waves: <1% fluctuations superimposed

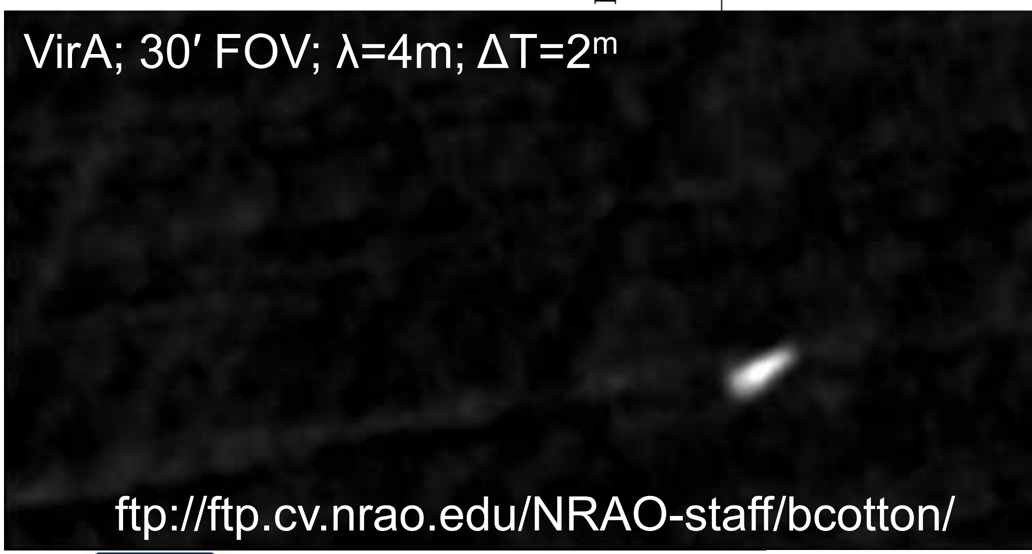
wedge – refraction, absorption (< 30 MHz), Faraday rotation
wave and turbulence – rapid phase winding, differential refraction, source distortion…

- wedge introduces thousands of turns of phase at 74 MHz per LOS
- interferometers sense differences among antennas and across FOV's
  - primarily culprits: waves and turbulence

Antenna Phase as a Function of Time

- a range of phenomena observed over 12^h @ night
- daytime (but not dawn) can have good conditions

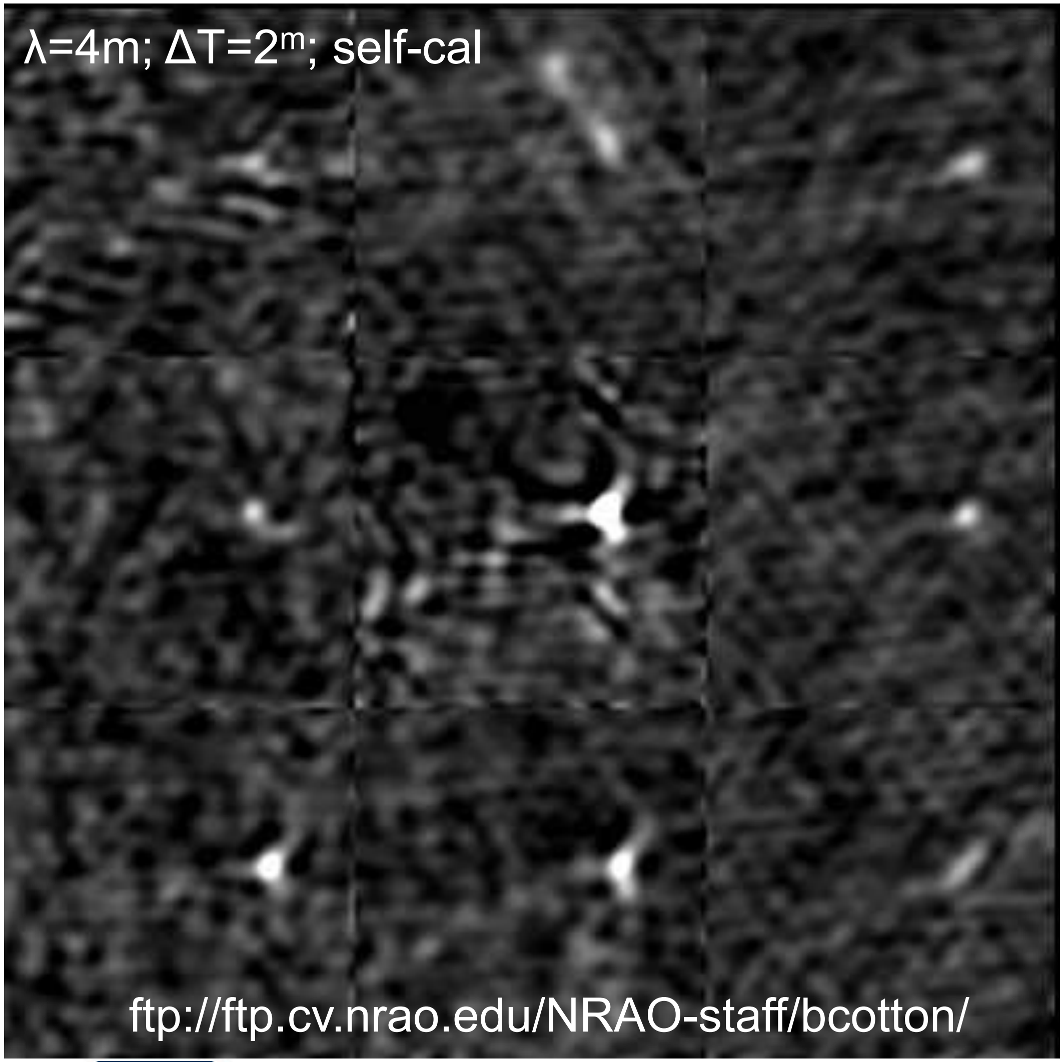




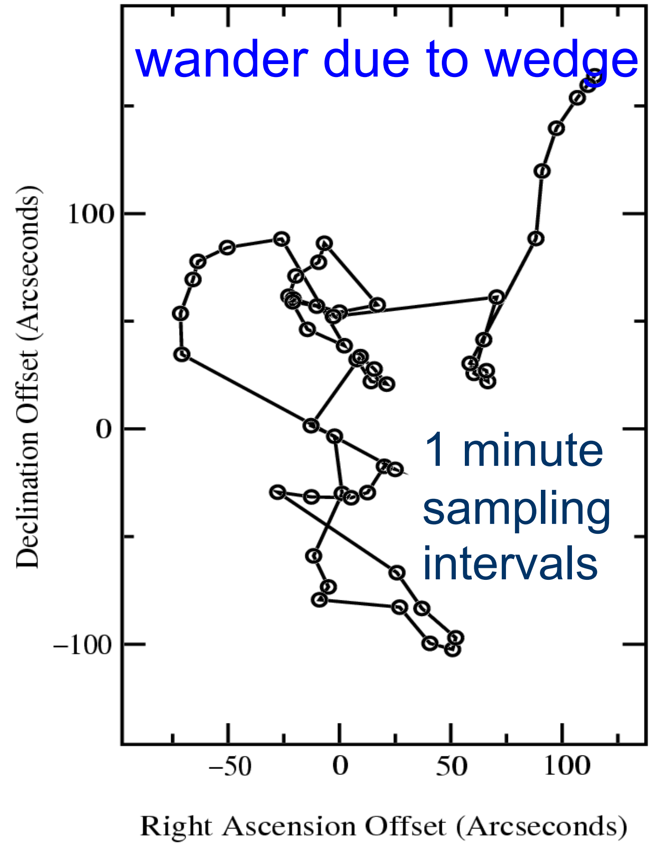
Perley et al.

NRAO New Mexico Tech SCIENCE · ENGINEERING · RESEARCH · UNIVERSITY The University of New Mexico New Mexico CONSORTIUM

Ionospheric Refraction & Distortion

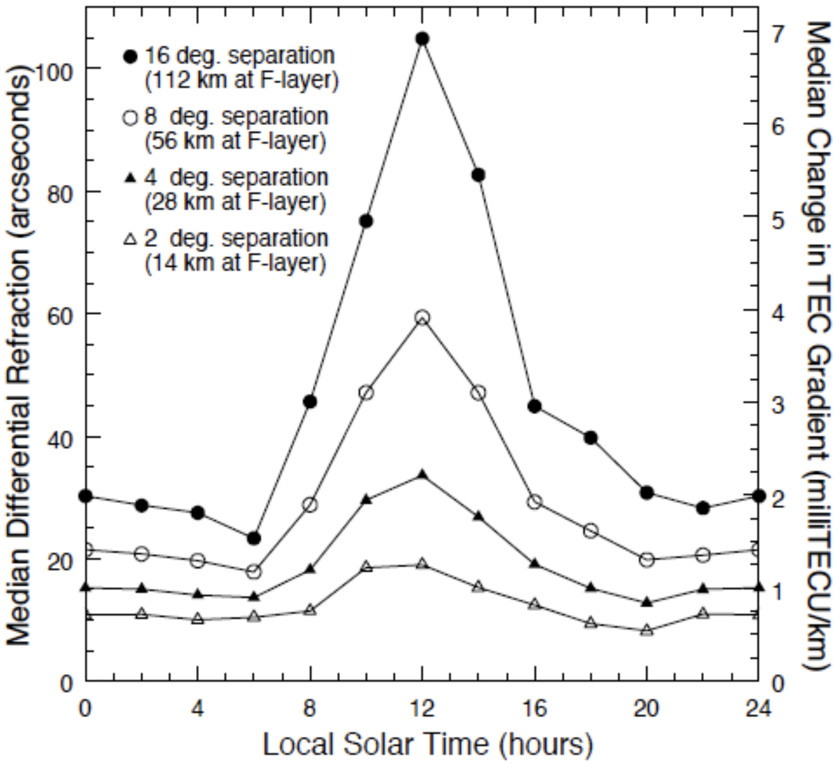


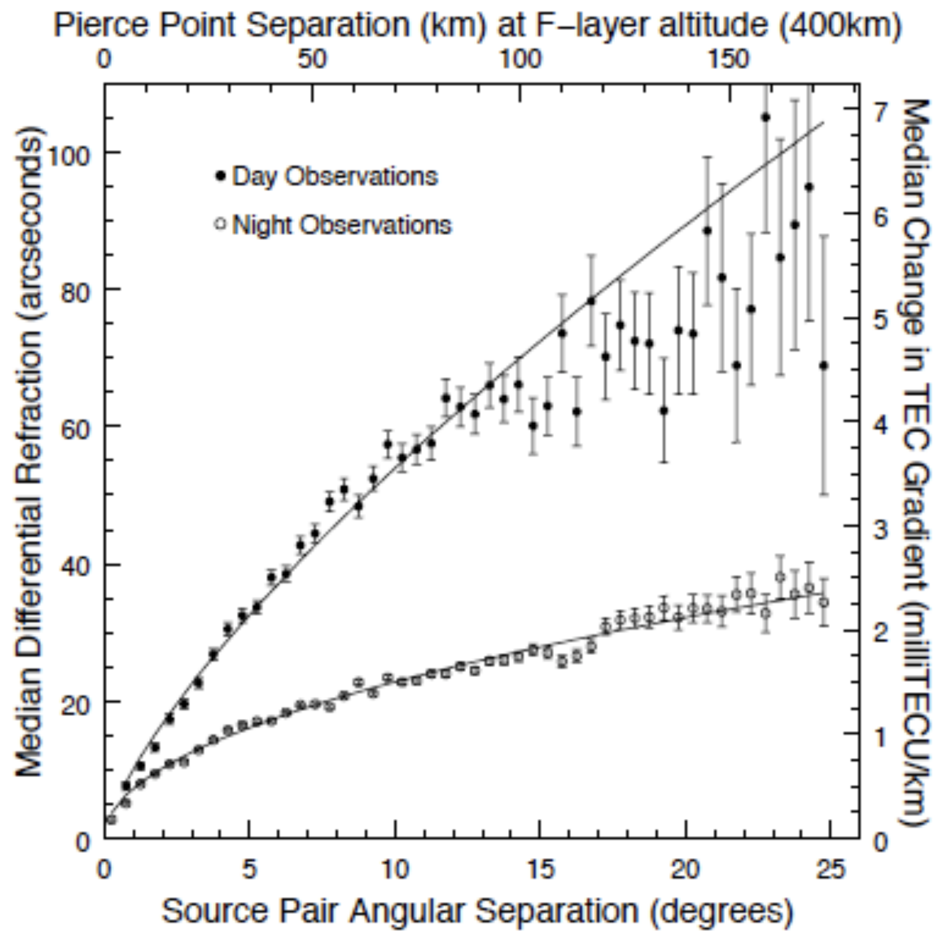
(NRL group; Kassim)



- common mode & differential refrac'n
- variability over 1 min or less
- length scales @ altitude < 10km

Ionospheric Differential Refraction

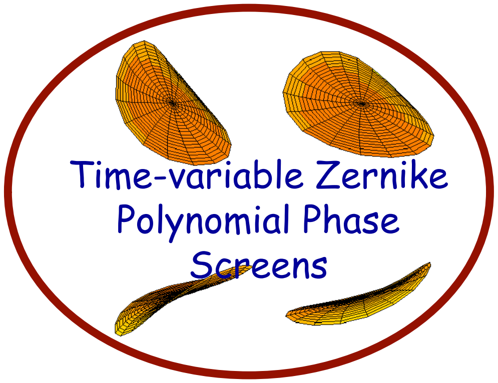




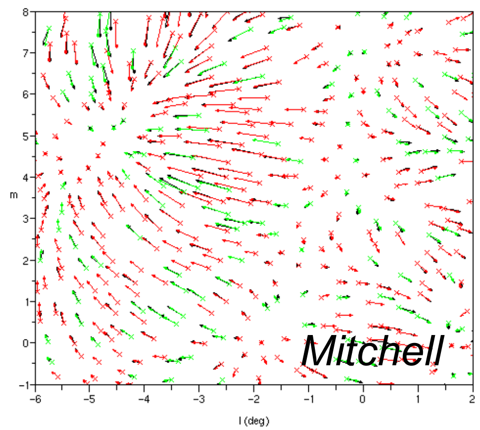
Cohen et al (2009)

Correcting for the Ionosphere

Intema; Cotton



- frontier in research
- assumptions
  - 2D sheet
    - refractive model (Intema et al. 2009; Cotton: Lane et al. 2012)
  - 3D sheet
    - tomography for a power spectrum in n_e (Koopmans 2010) TBD
- corrections may be applied in
  - l, m grid
    - rubber sheet; Mitchell et al. 2008
  - visibility model calc. during deconvolution
    - Intema et al. 2009
  - u,v plane, in combination w/ direction-dependent gridding
    - CASA plan - U. Rao, S. Bhatnagar, p.c.



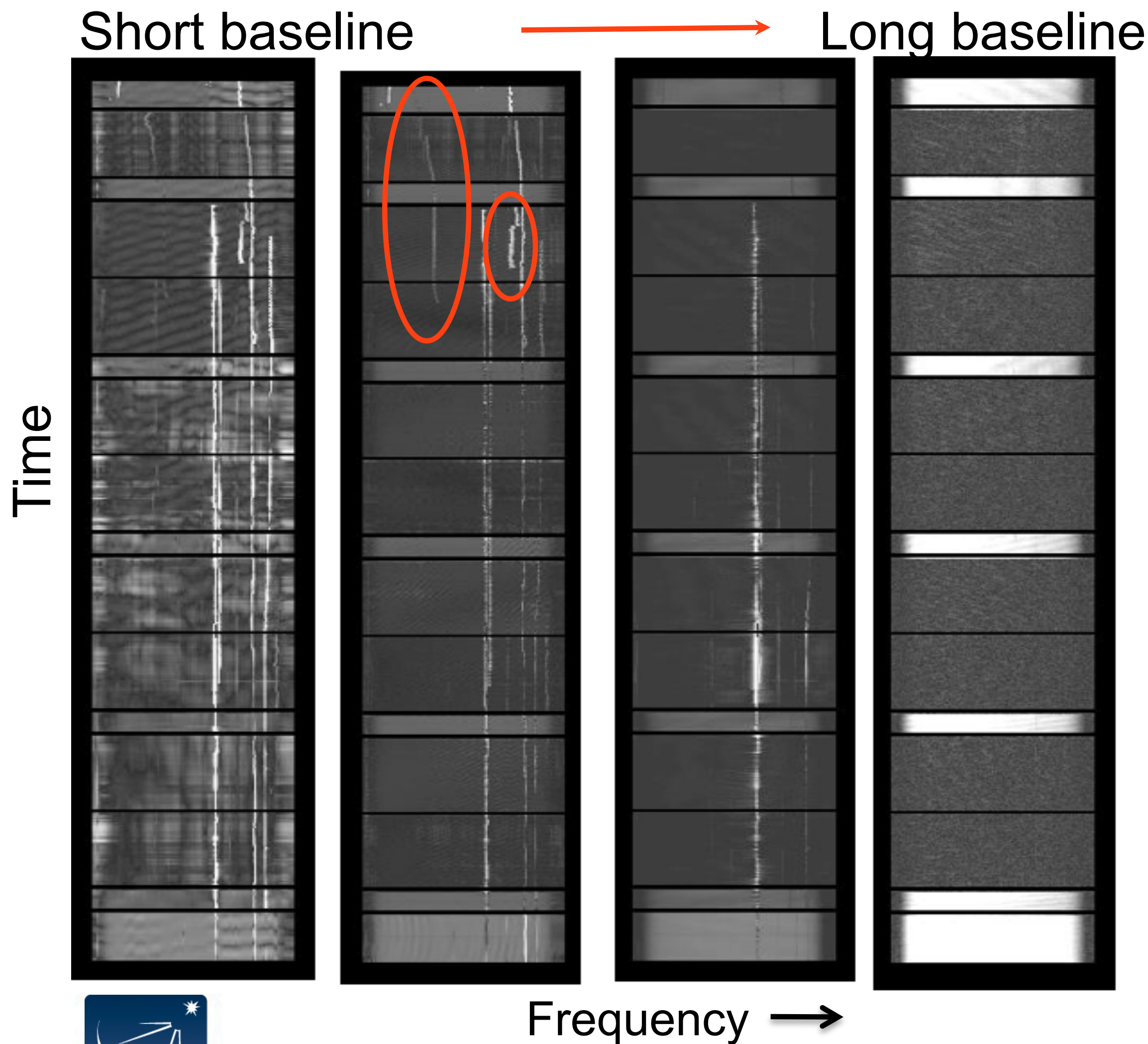
Low Frequency Challenges

- Sky brightness
- Source confusion
- Ionospheric distortion
- Radio Frequency Interference (RFI)
- Wide fields of view (FOV)
- Variable dipole response (for fixed dipole arrays)

Radio Frequency Interference

- natural & man-generated RFI at low frequencies is pervasive
  - power lines
  - broadcast, communications, & radar
  - digital hardware
  - keeping sites clean requires care / easily spoiled
- at GMRT & LWA: power line noise has been a problem
- at VLA: many signatures between 74 and 330 MHz
  - narrowband, wideband, time varying, ‘wandering’
  - can be wideband (affecting C & D configurations)
  - solar effects – unpredictable
    - quiet sun is a benign 2000 Jy disk at 74 MHz
    - solar bursts can be 10^9 Jy and lead to geomagnetic storms
- mitigation is done first in a processing path
  - usually requires high spectral resolution and short time averaging

RFI Examples



- RFI is worst on short baselines
- Several 'types': narrow band, wandering, wideband, ...
- Wideband interference can degrade automated routines

Spectral Kurtosis

- Kurtosis estimator:

$$V_k^2 = \frac{MNd+1}{M-1}\left(M\frac{S_2}{S_1^2}-1\right)$$

- Comparison:

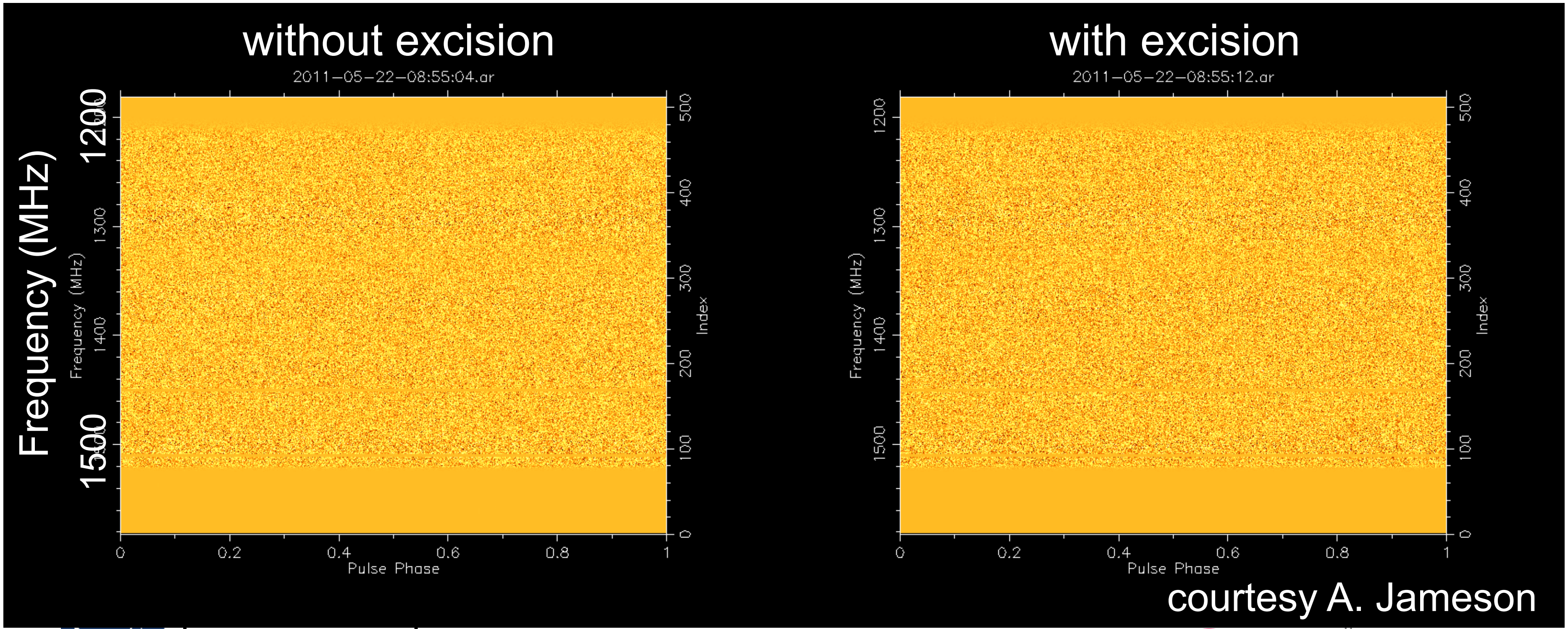
$$\mathrm{Var}(V_k^2) \approx 4N^2/M$$

(Nita et. al. 2010b)

- Kurtosis characterizes Gaussian nature of noise
  - e.g., power in a spectral channel
- Estimate V_k^2 for each spectral channel
  - M: no. of time samples
  - N: sample pre-averaging before accumulation (N=1)
  - S_1: accumulated power spectral density ~ Σx^2
  - S_2: accumulated square of power spectral density ~ Σx^4
  - d = 1

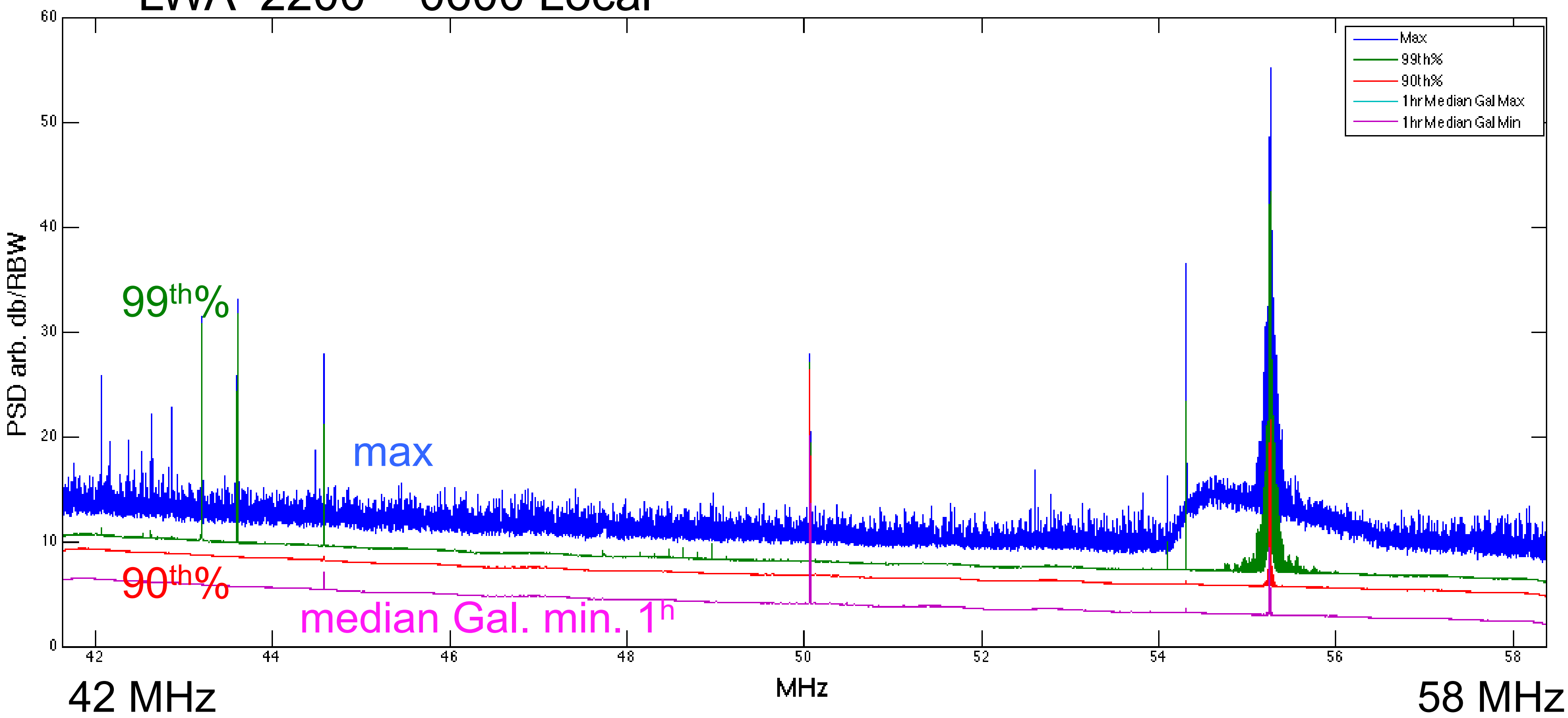
Excision via Spectral Kurtosis Analysis

- Parkes CASPSR time-series data intended for pulsar detection
- movies with and without excision based on real-time kurtosis calculation
- evaluate V_k^2 every 256 τ-samples, across 512 ν-channels
- flag for $V_k^2 > 3 \times \mathrm{var}(V_k^2)$



Excision via Spectral Kurtosis Analysis

- Analysis of spectral kurtosis ➟ time occupancy estimate
- LWA 2200 – 0600 Local

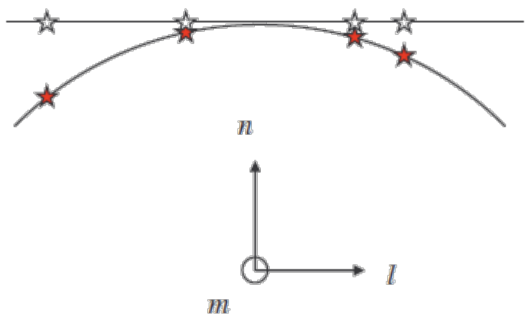


LWA / Obenberger & Dowell

Low Frequency Challenges

- Sky brightness
- Source confusion
- Ionospheric distortion
- Radio Frequency Interference (RFI)
- Wide fields of view (FOV)
- Variable dipole response (for fixed dipole arrays)

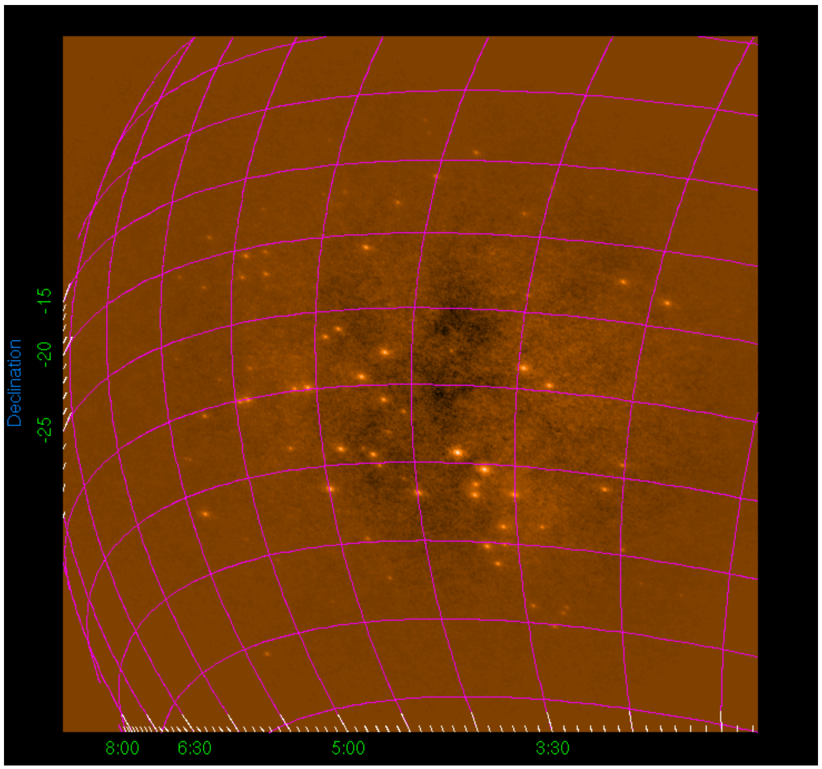
Wide FOV



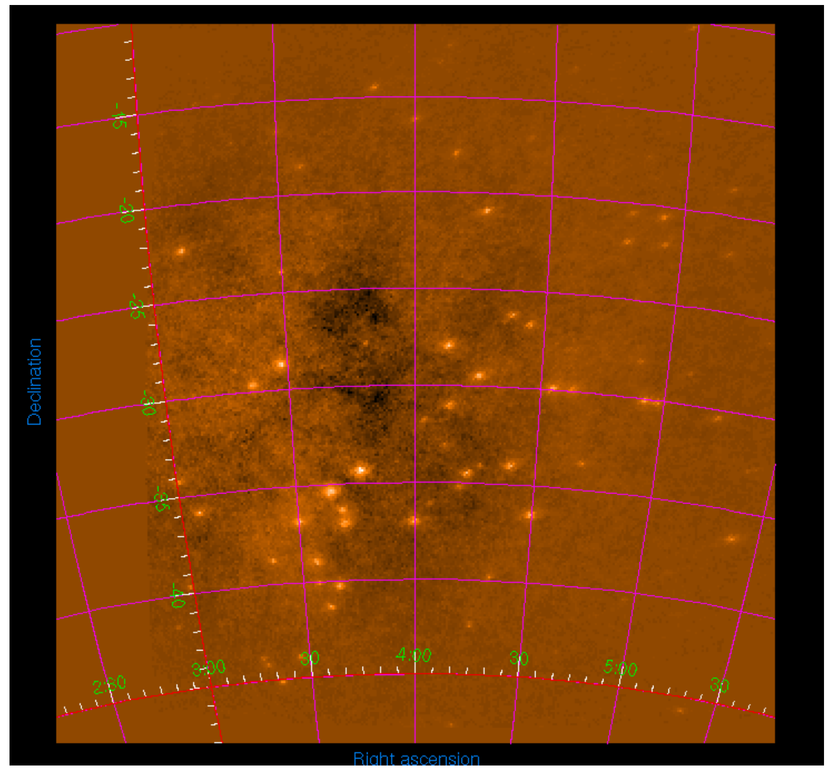
- dipoles: PAPER: 60°; MWA: 20°; LWA/LEDA: 130°
- dishes: VLA: 11° (74 MHz); GMRT: 3° (150 MHz)
- requires advanced techniques if non-coplanar
  - faceting (well understood)
  - w-correction + various (uv) deconvolution schemes *(Bhatnagar talk)*
  - potentially computationally expensive
- can use warped snapshot imaging if coplanar (Ord et al. 2010)
  - enables geometric correction alone
  - effective in combination with peeling for large-N_{ant}

Wide FOV

(l,m) grid from FFT
$\Delta HA = \pm 3.5^h$ FOV = 45°



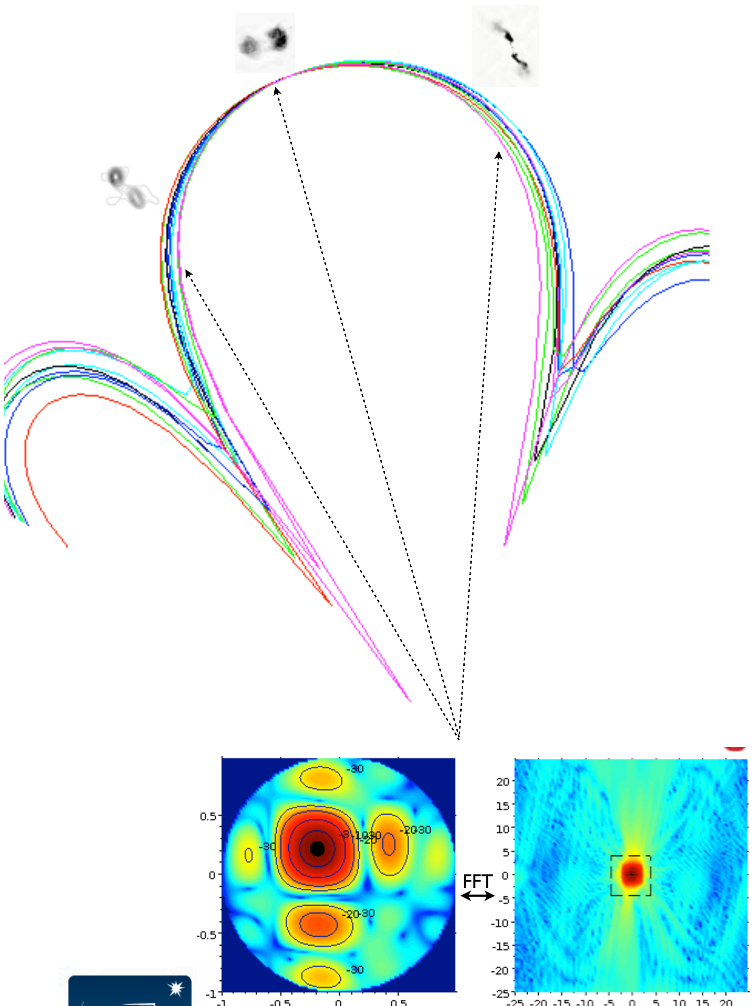
re-sample to a fixed coordinate frame



Demonstration for a fixed dipole array

courtesy D. Mitchell

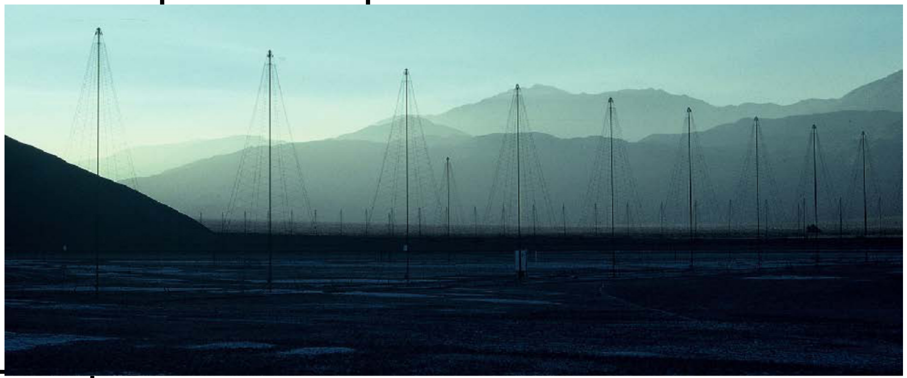
Gain Patterns



- cutting edge
  - A-projection in CASA (Bhatnagar, Rao)
  - cuWARP package (Mitchell et al. 2012)
    - MWA, LEDA
- dipole arrays may admit variation in gain pattern, receptor to receptor
  - downside of low cost
  - downside of beam forming
    - e.g., MWA, LOFAR
  - mutual coupling
    - e.g., LWA (Ellingson et al. 2012)
- <u>cannot</u> repair via image-plane correction
- <u>can</u> repair during gridding *(u,v)*
  - convolve each visibility w/ a FT kernel representing the gain pattern
  - different FT pair for each visibility! ($$)

Summary

- low-frequency interferometry is wild
  - challenges everywhere: sky brightness, confusion, ionospheric variability, RFI, FOV approaching 2 rad, and fundamental instrument calibration
  - new algorithms & implementations are providing solutions
- dish arrays: deep high resolution sky surveys
  - active programs expand capability
- dipole arrays: past 1st light – pursuing cosmology to exoplanets
  - breaking all the rules of the game
    - "…may I please have a high frequency, narrow band dataset on an isolated unpolarized pt source?"



Summary

➢This is our motivation:
- Dark Ages (spin decoupling)
- Epoch of Reionization (highly redshifted 21 cm lines)
- Early Structure Formation (high z RG)
- Large Scale Structure evolution (diffuse emission)
- Evolution of Dark Matter & Dark Energy (Clusters)
- Wide Field (up to all-sky) mapping
- Large Surveys
- Transient Searches (including extrasolar planets) *(Hallinan talk)*
- Galaxy Evolution (distant starburst galaxies)
- Interstellar Medium (CR, HII regions, SNR, pulsars)
- Solar Burst Studies
- Ionospheric Studies
- Ultra High Energy Cosmic Ray Airshowers
- Serendipity (exploration of the unknown)

-end-