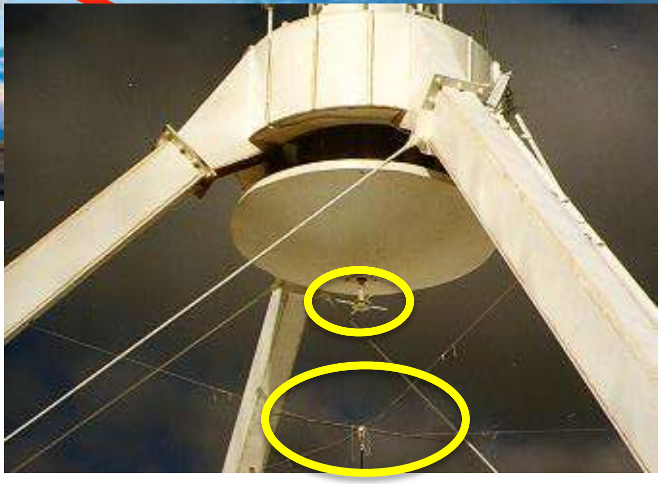
Low Frequency Interferometry

Tracy Clarke (Naval Research Laboratory)



Fourteenth Synthesis Imaging Workshop

2014 May 13-20

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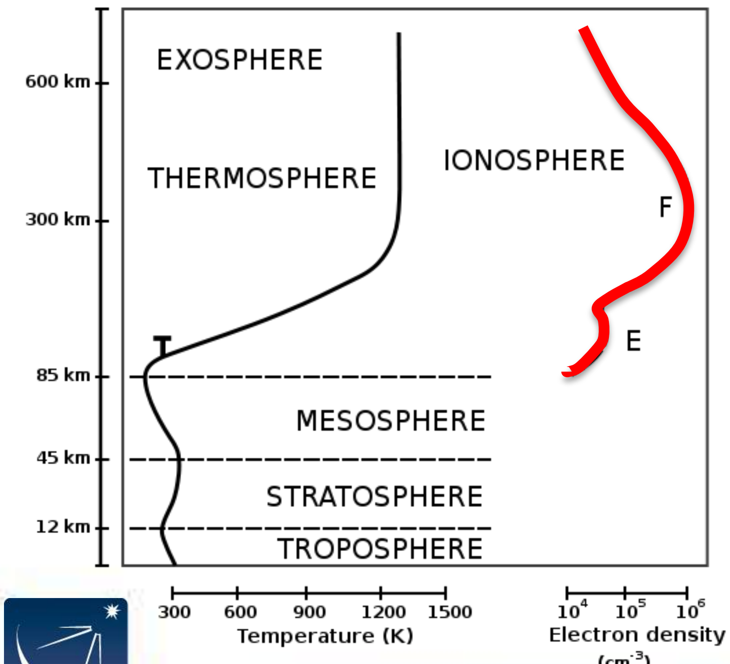
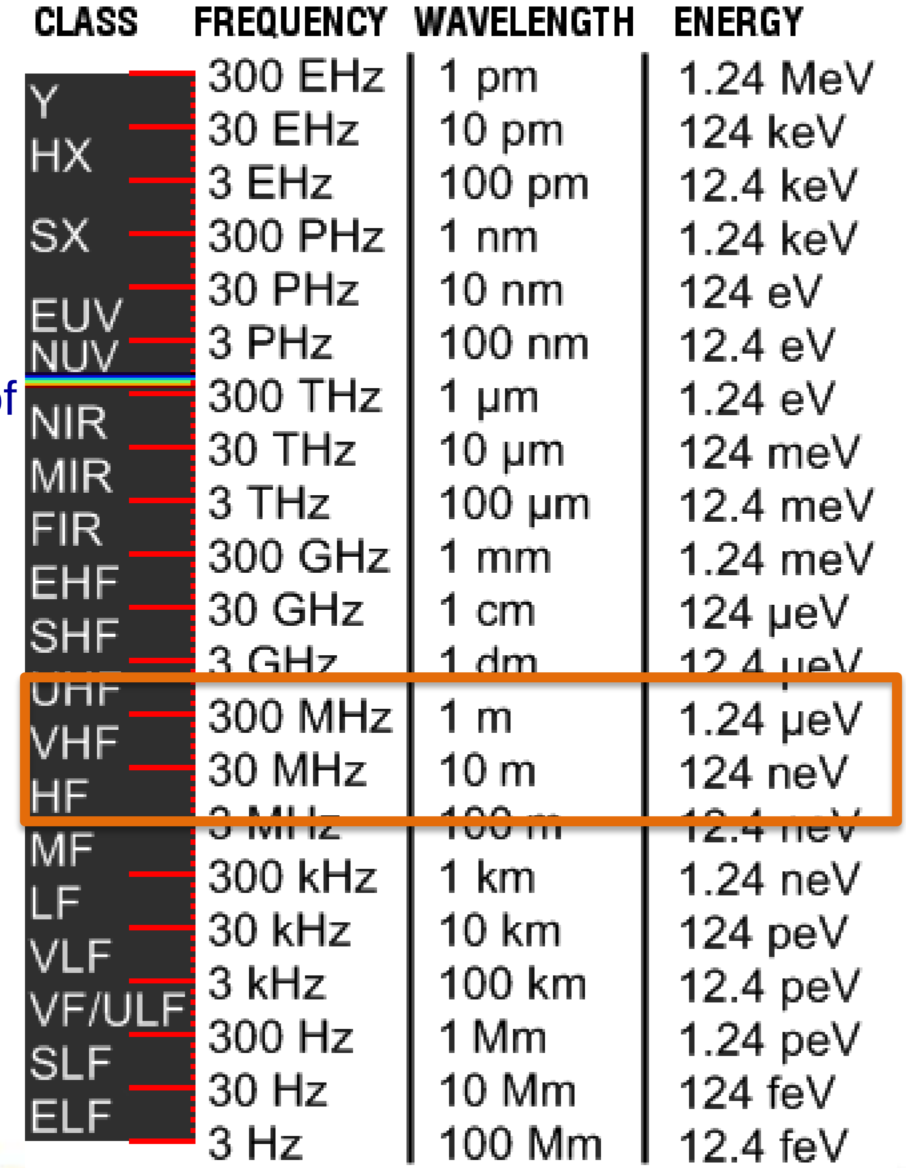
What do we mean by Low Frequency?

- Low frequency:
  - HF (3 MHz – 30 MHz),
  - VHF (30 MHz – 300 MHz),
  - UHF (300 MHz – 3 GHz)
- Ground-based instruments rarely probe below 10 MHz due to the impact of ionospheric effects





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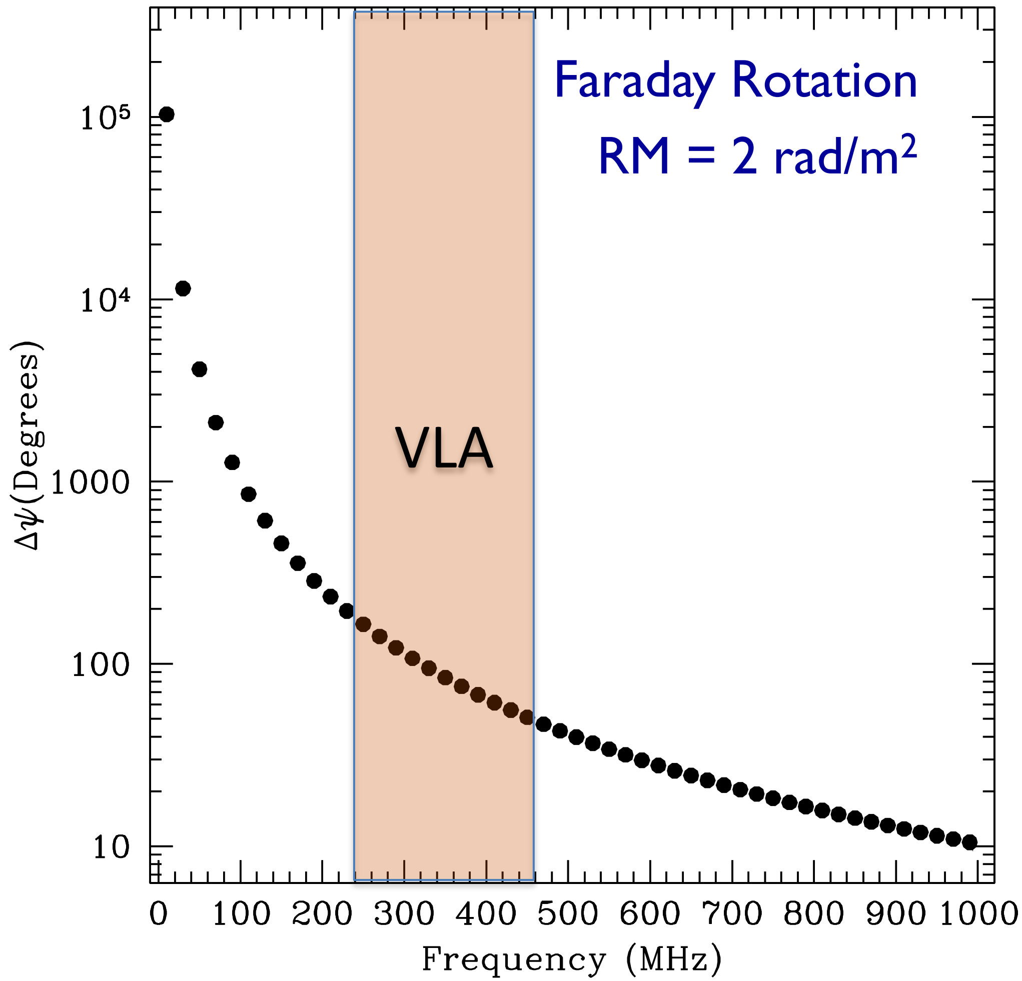
Ionosphere and Radio Astronomy (Briefly)

$$\nu_p \simeq 9\sqrt{n_e}\ kHz, n_e \sim 10^4 - 10^5 cm^{-3}$$
$$\nu_p \sim 10 MHz$$

- Ionospheric Cutoff
  - Plasma opacity

- Quiescent Ionosphere
  - Refraction
  - Faraday Rotation

- Disturbed Ionosphere
  - Scintillation
  - Image distortion
  - Rapid position shifts



Moellenbrock Talk

Brentjens Talk

Outline

- LF Emission: Continuum & Line
- Brief & biassed overview of LF Science
- LF Instruments: Dishes and Dipoles
- Recent LF Sky Surveys
- LF in Practice:
  - Confusion
  - Ionosphere
  - Radio Frequency Interference
  - Large Field of View (Myers Talk)
  - Wide Bandwidth (Rau Talk)
  - Polarization (Brentjens Talk)

Low Frequency Emission

Synchrotron Continuum:

- Best observed at $\nu < 1$ GHz
- Relativistic e$^-$ in magnetic fields
- F(energy of the e$^-$, density, B)
- Emission is polarized
- Coherent or incoherent

Redshifted 21cm Line:

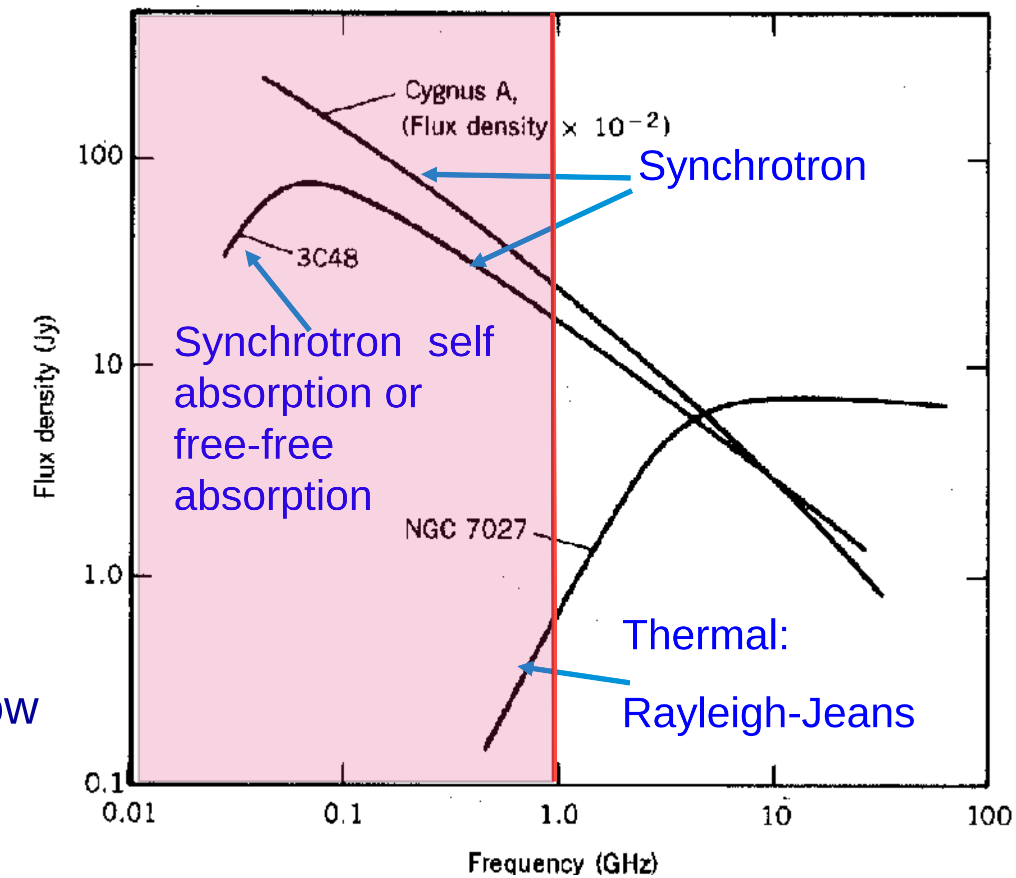
- ν = 1420/(1+z) MHz

Radio Recombination Lines:

- Probe of ISM conditions: low temp, low density

Bremsstrahlung: (thermal free-free):

- Best observed at $\nu > 1$ GHz
- Acceleration of free electrons by ions



Thompson, Moran, & Swenson

Low Frequency 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)
  - Evolution of Dark Matter & Dark Energy (LSS & Clusters)
  - Large Sky Surveys for Population Studies
  - Transient Searches (including extrasolar planets)
  - Galaxy Evolution (distant starburst galaxies)
  - Interstellar Medium (CR, HII regions, SNR, pulsars)
  - Solar System Planetary Emission
  - Solar Burst Studies
  - Ionospheric Studies
  - Ultra High Energy Cosmic Ray Airshowers
  - Serendipity (exploration of the unknown)

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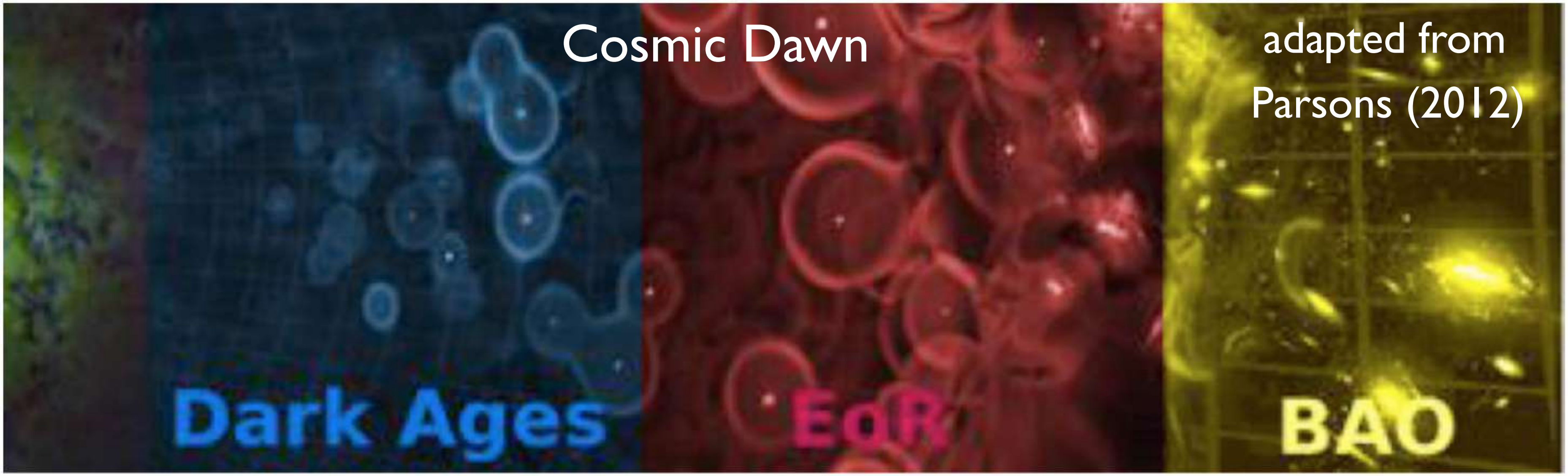
Low Frequency Science

Neutral hydrogen absorbs CMB & imprints inhomogeneities

Hydrogen 21 cm line during EoR

Measure HI power spectrum to get BAO peaks vs z



z = 100 to 20
15 to 70 MHz

z = 20 to 5
70 to 240 MHz

z = 5 to 0
240 to 1400 MHz

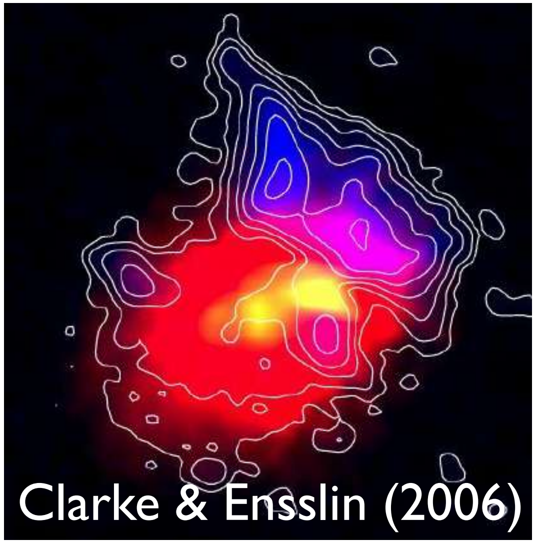
LEDA, HERA
DARE

MWA,PAPER
Edges, LOFAR,
GMRT, 21CMA

GBT, CHIME

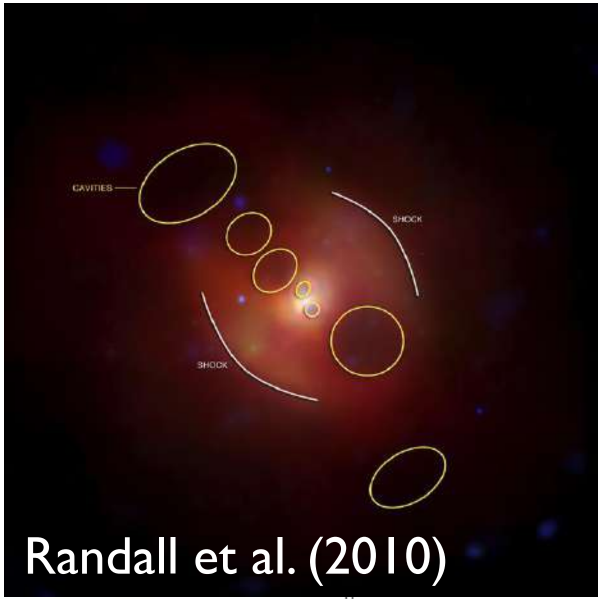
Low Frequency Science

- LSS forms in a cosmic web with galaxy clusters at nodes. Structure growth drives shocks and turbulence generating relics and halos
- Study of plasma microphysics, dark matter and dark energy
- Emission is steep spectrum and best traced at low frequencies



Clarke & Ensslin (2006)

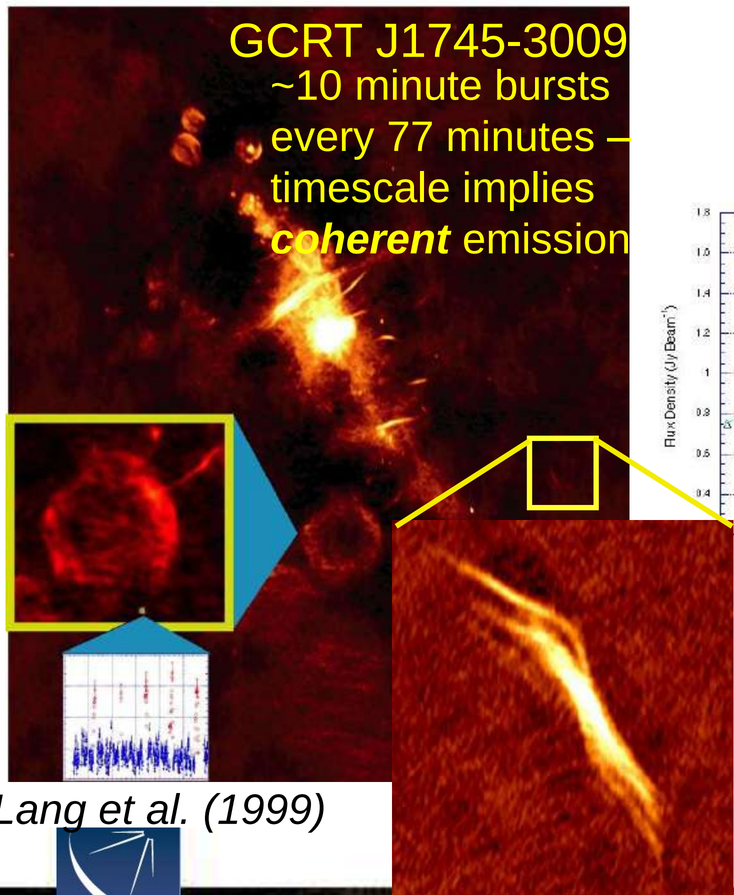
- Supermassive black-hole driven AGN feedback in clusters can offset catastrophic cooling and limit the size of the host galaxy
- Low Frequencies trace older outbursts as they are sensitive to particles which have undergone significant aging



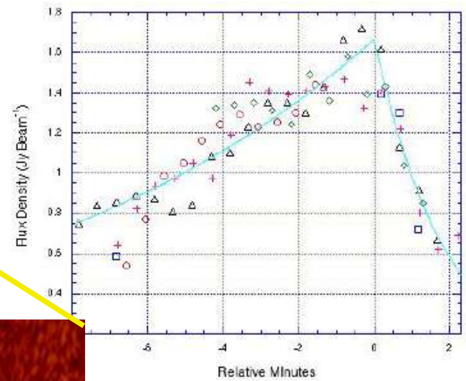
Randall et al. (2010)

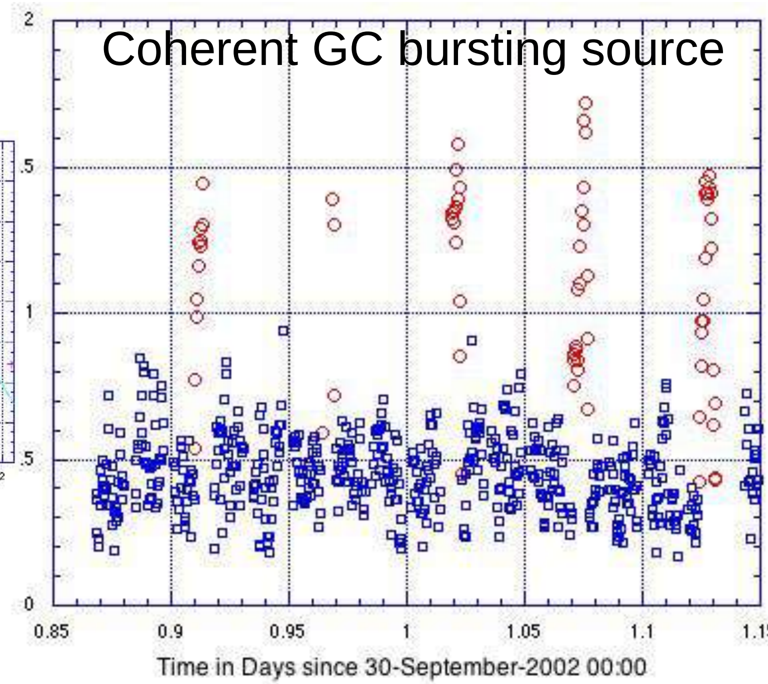
Transients: Galactic Center

- ➢ Transients: wide fields at low frequencies provide powerful opportunity to search for new transient sources - **VLITE**
- ➢ Candidate coherent emission transient discovered near Galactic center



Lang et al. (1999)



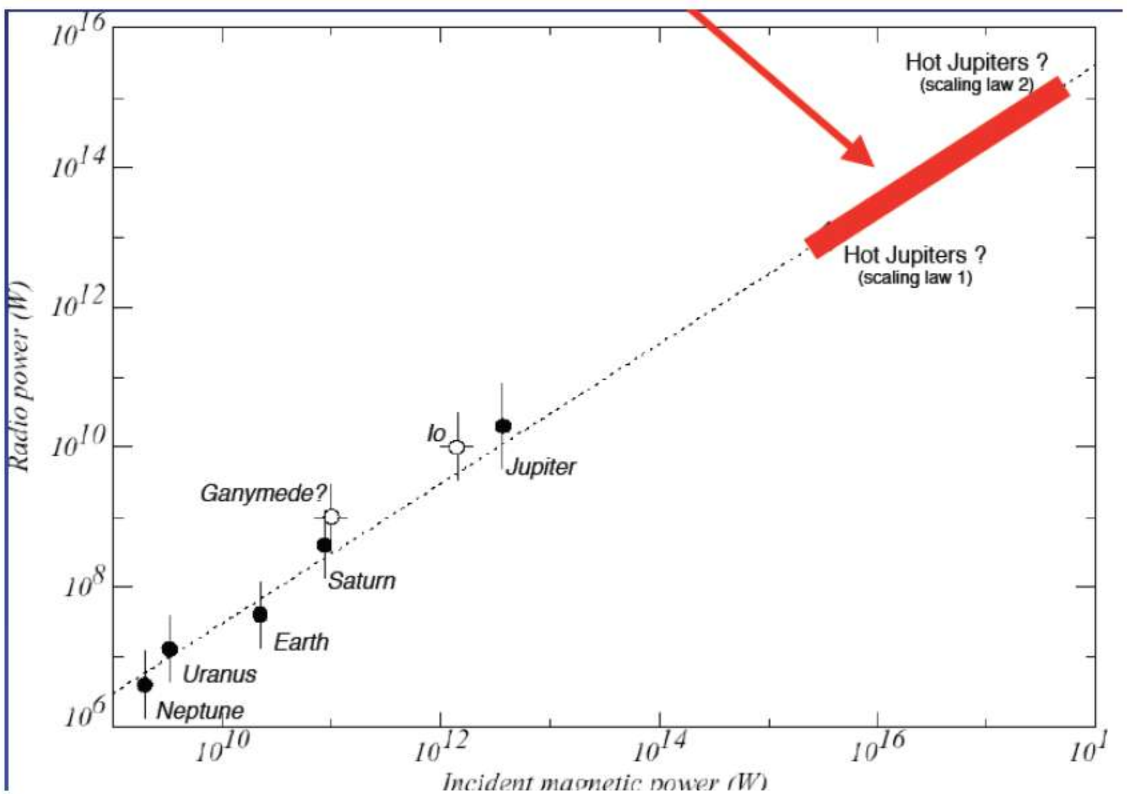


Hyman, et al., (2005) - Nature;
Hyman et al. (2006, 2007)

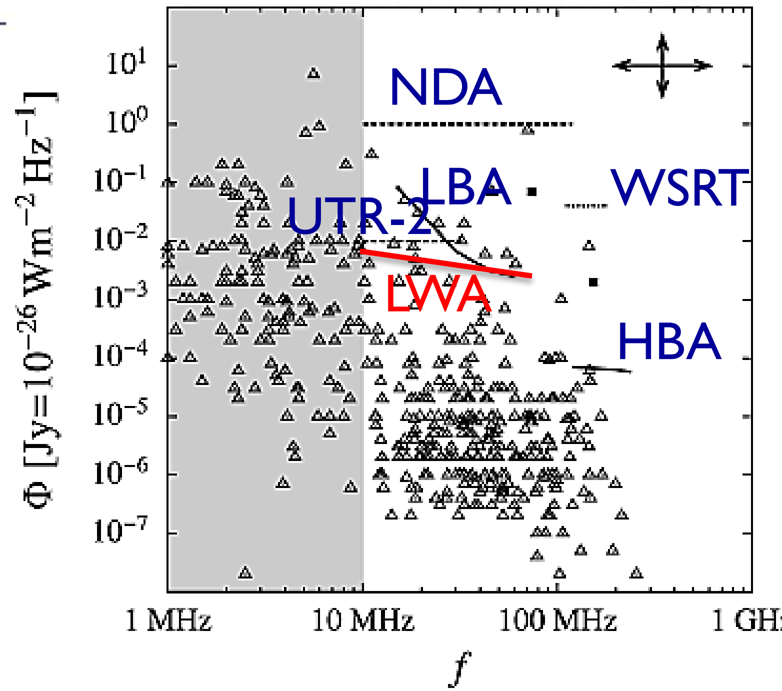
Jupiter and Extrasolar Planets

- ➢ Jupiter's coherent cyclotron emission: complex interaction of Jupiter's magnetosphere with Io torus
- ➢ Future instruments will resolve Jupiter and may detect extra-solar planets

POSSIBLE TO DETECT BURST EMISSION FROM DISTANT "JUPITERS"



Adapted from Zarka et al. (2001)



Grießmeier et al. (2011)

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Low Frequency Arrays

➢ Advances in ionospheric calibration, wide-field imaging, and radio frequency interference excision have led to a new focus on low frequency arrays

	Instrument	Location	{ range (MHz)	Resolution (arcsec)	FoV (arcmin)	Sensitivity (mJy)
Dishes	VLA	NM	73.8, 330	24-5	700-150	20-0.2
	GMRT	IN	151-610	20-5	186-43	1.5-0.02
	WSRT	NL	115-615	160-30	480-84	5.0-0.15
	…					
Dipoles	LOFAR-Low	NL	10-90	40-8	1089-220	110-12
	LOFAR-Hi	NL	110-250	5-3	272-136	0.41-0.46
	LWA1	NM	10-88		600-180	1000
	MWA	WAu	80-300	180-60	1482-1162	10
	…..					

Note: Table numbers are not apples-apples comparison!

Low Frequency Receivers: VLA

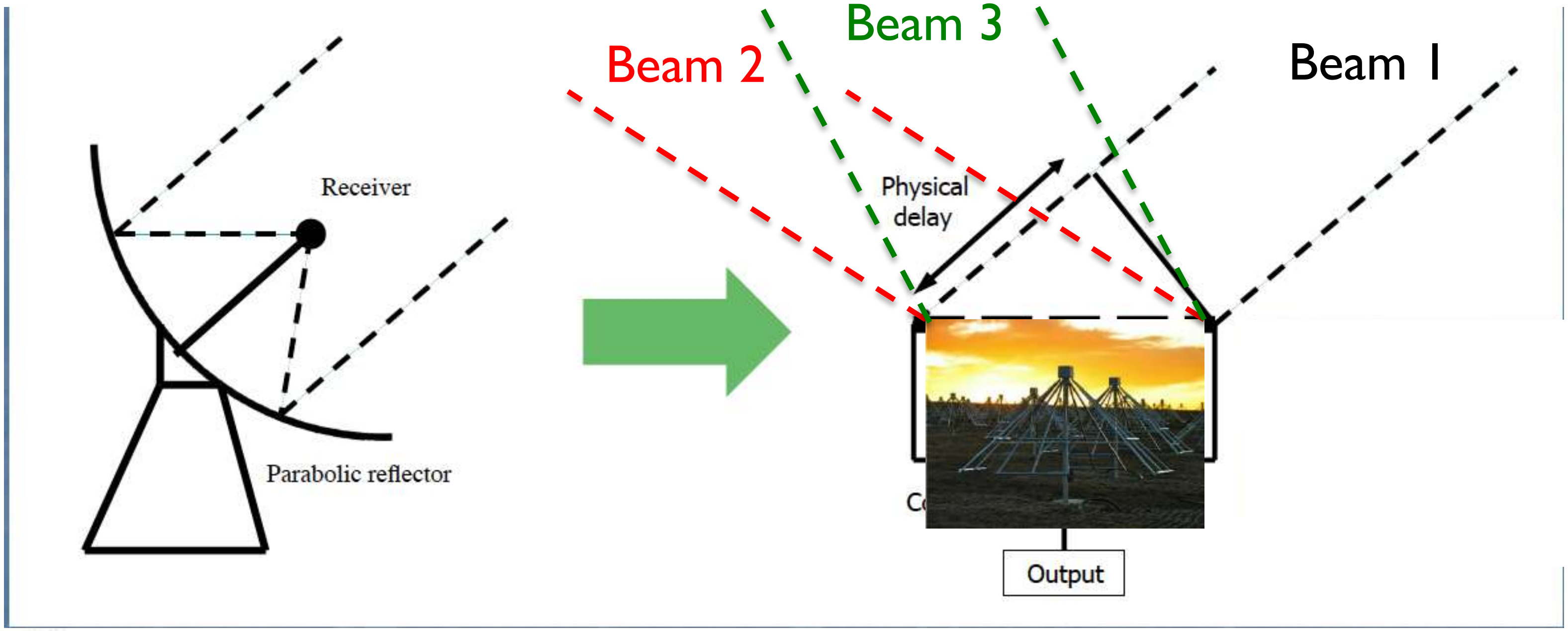
- ➢ VLA low band (dish + dipole) system transitioned to wide-bandwidth (2013)
- ➢ Replaces narrow band receivers but still using legacy feeds:
  - ➢ **P band: 240 – 470 MHz**
  - ➢ 4 band: 50 – 86 MHz
- ➢ New 4 band feed design being tested by NRAO for continuous deployment

Low Frequency Receivers: GMRT

- Giant Metrewave Radio Telescope feeds located at prime focus on a rotating turret + 50 MHz feeds on support legs
    - 150 MHz
    - 235/610 MHz: dual band on same face of turret,
    - 330 MHz
    - 610 MHz
- GMRT wide-band upgrade: 50-1500 MHz with 400 MHz instantaneous BW

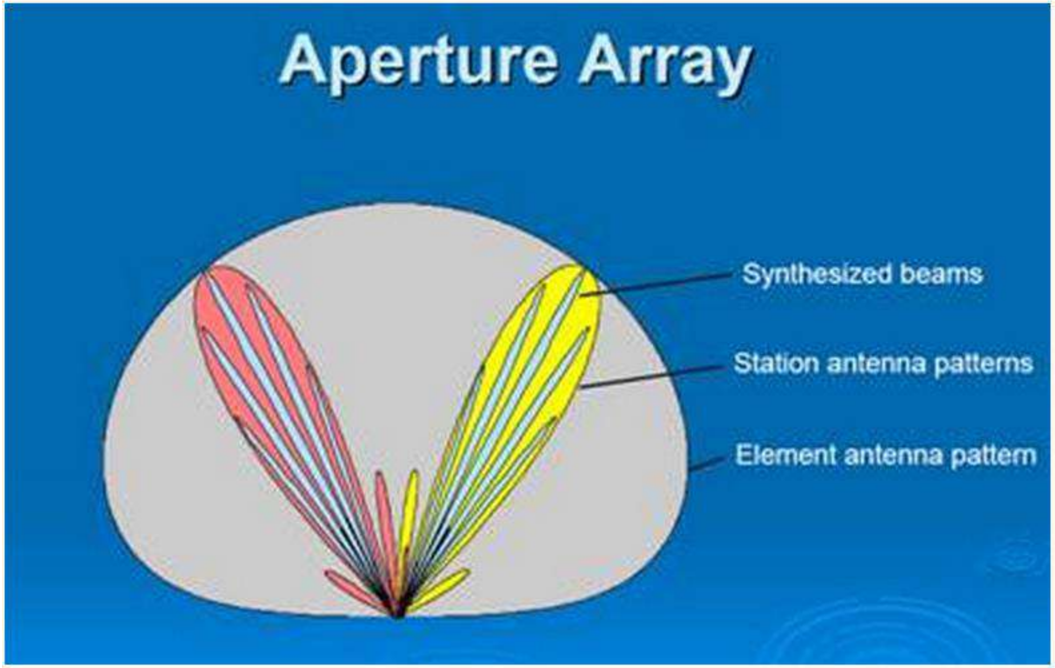
Re-Energizing Low Frequencies: Dipole Arrays

- Low frequencies are very forgiving, no need for an accurate dish surface
- Bare dipoles + ground screens are much cheaper to build and maintain compared to dishes
- Electronic beamforming of dipole arrays allows flexibility to image anywhere on the sky and have multiple, independent and simultaneous beams!



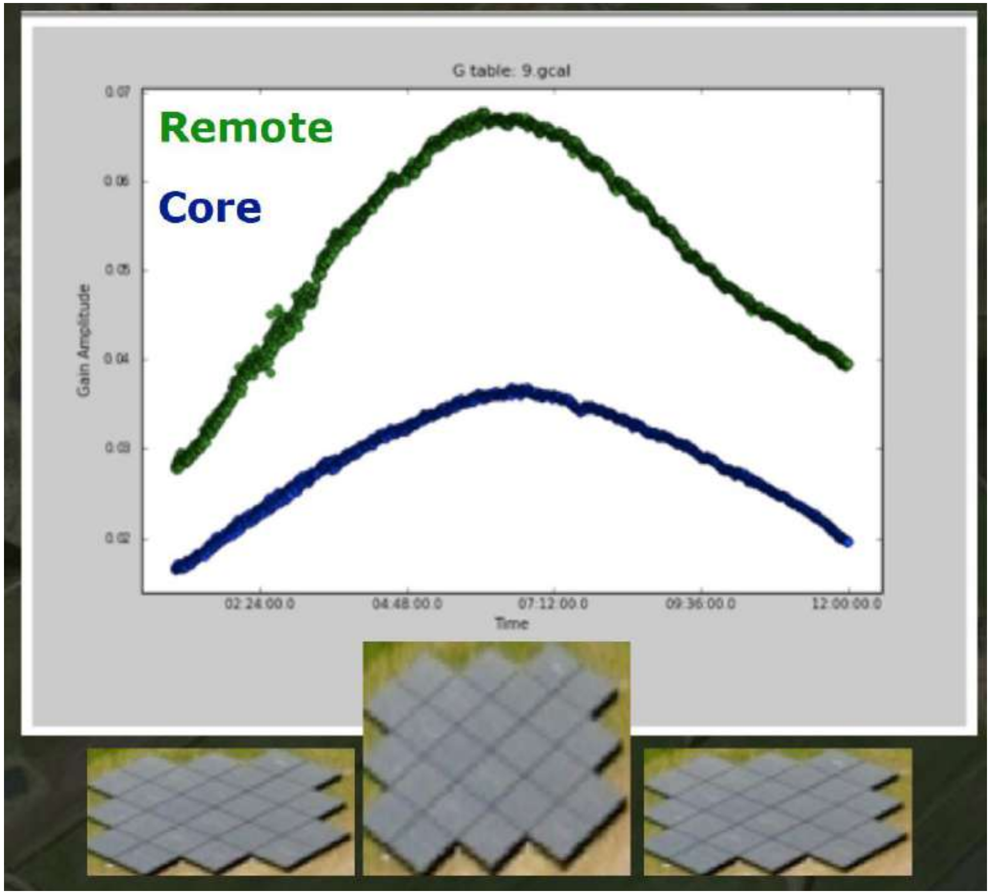
Dipole Array Beams

- A single dipole sees the entire sky (element pattern)
- Station of dipoles (e.g. LWA1) can be combined to create station beams
- Multiple stations combined (e.g. LOFAR) to create synthesized beams



Dipoles: Changing Gain with Time

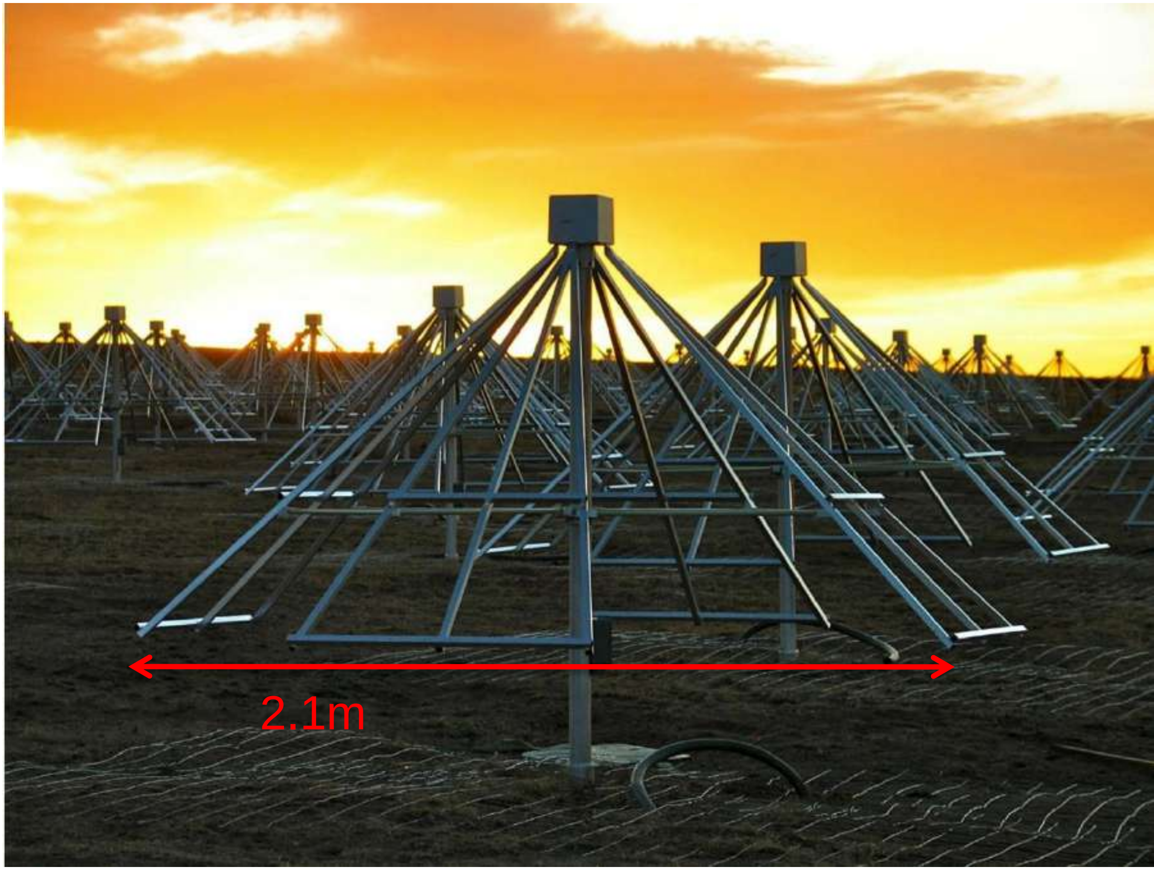
- dipoles see the entire sky
- projected area of dipole station changes with zenith angle, result is a gain change with time
- different parts of a large instrument can have different area so different gain change with time: e.g. LOFAR core and remote stations



McKean (2013)

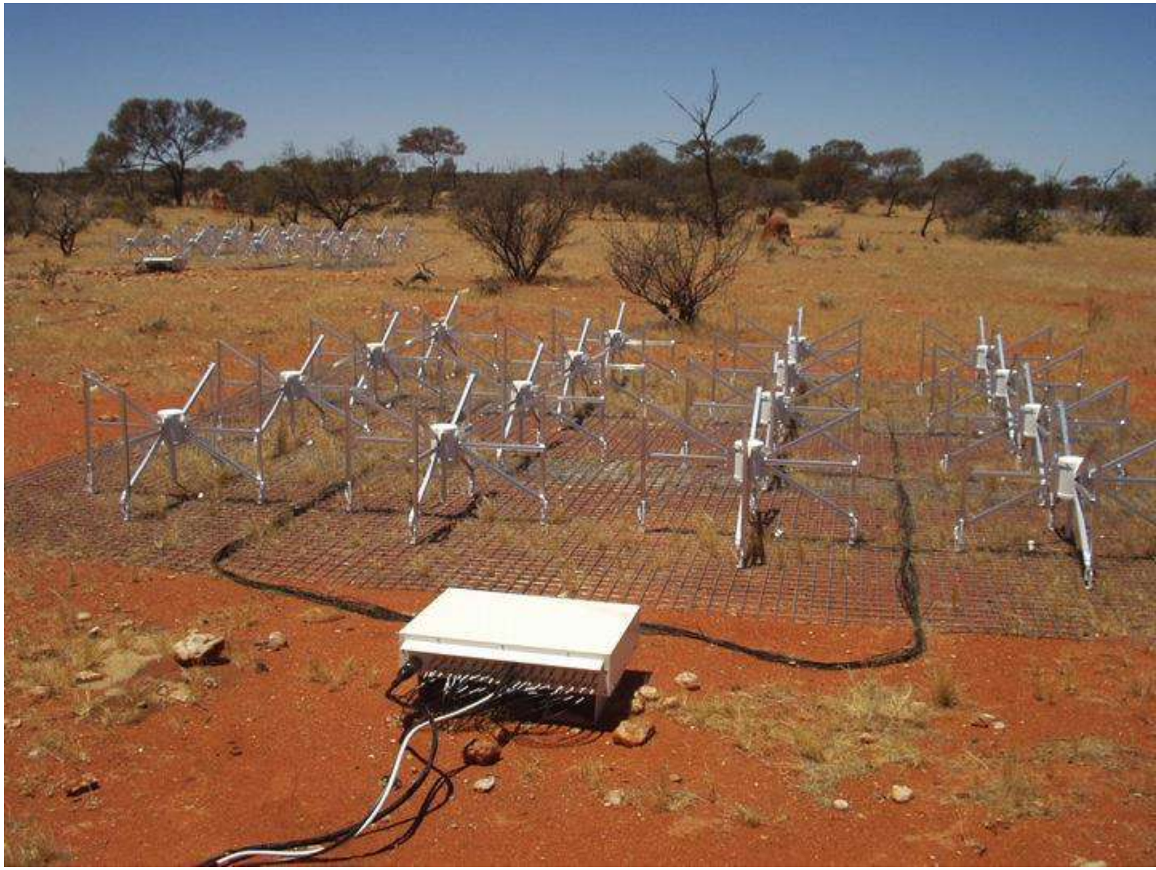
Low Frequency Receivers: LWA1

- LWA1
  - Long Wavelength Array Station 1
  - 256 dipoles in 100x110m station
  - Operates 10-88 MHz
  - 4 simultaneous beams with two tunings + dual orthogonal polz.
  - All-sky buffers
  - Range of science
  - open access facility (CfP5 due Aug 15, 2014)
  - http://www.phys.unm.edu/~lwa/index.html



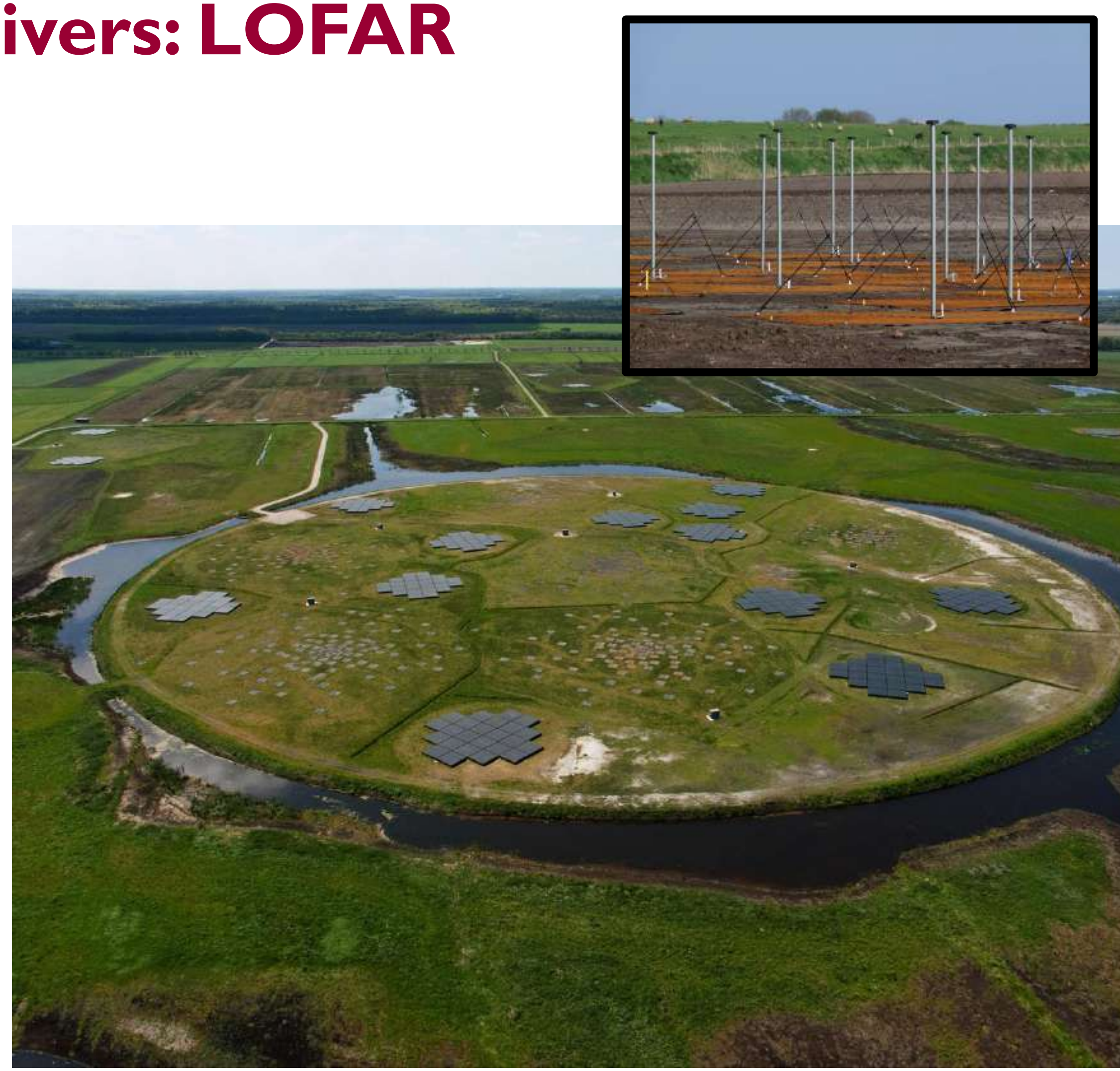
Low Frequency Receivers: MWA

- MWA
  - Murchison Wide-field Array
  - 80-300 MHz, BW=31 MHz
  - bowtie geometry
  - 128 tiles of 16 dipoles
  - tiling increases A_e (~20 m^2)
  - EOR, SNR, transients, Solar and space weather
  - complicated beam pattern
  - mwatelescope.org



Low Frequency Receivers: LOFAR

- LOFAR
  - Low Frequency Array
  - Low band: 30-90 MHz
  - High band: 110-240 MHz
  - 8 beams per station
  - Core, remote and international stations
  - EOR, surveys, transients, CRs, Solar and Space Weather, magnetism
  - http://www.astron.nl/lofar-telescope/lofar-telescope
  - Van Haarlem et al. (2013)



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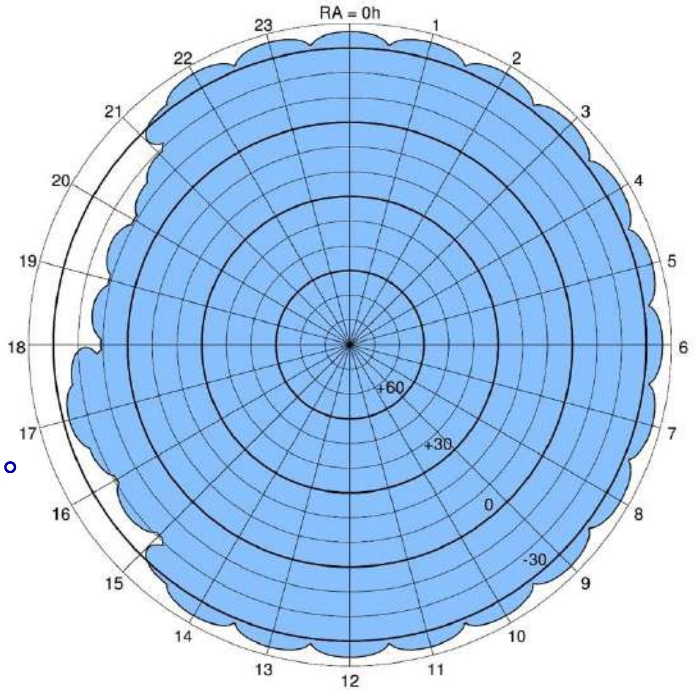
VLA Low Frequency Sky Survey Redux: VLSSr

- Survey Parameters: { = 74 MHz, ™> -30° ,
  ◡= 75” resolution, σ~100 mJy/beam
- Status: completed, re-released
- Reprocessed with new RFI excision software,
  original survey as ionospheric model,
  improved primary beam



Lane et al. (2012, 2014)

- Final catalog: N ~ 92 964 sces in ~ 95% of sky ™> -30°
  Statistically useful samples of sources
  => fast pulsars, distant radio galaxies, cluster radio halos and relics, unbiased view of parent populations for unification models

- Important calibration grid for VLA, GMRT, LOFAR, etc
- Data online at NRAO VLSSr server

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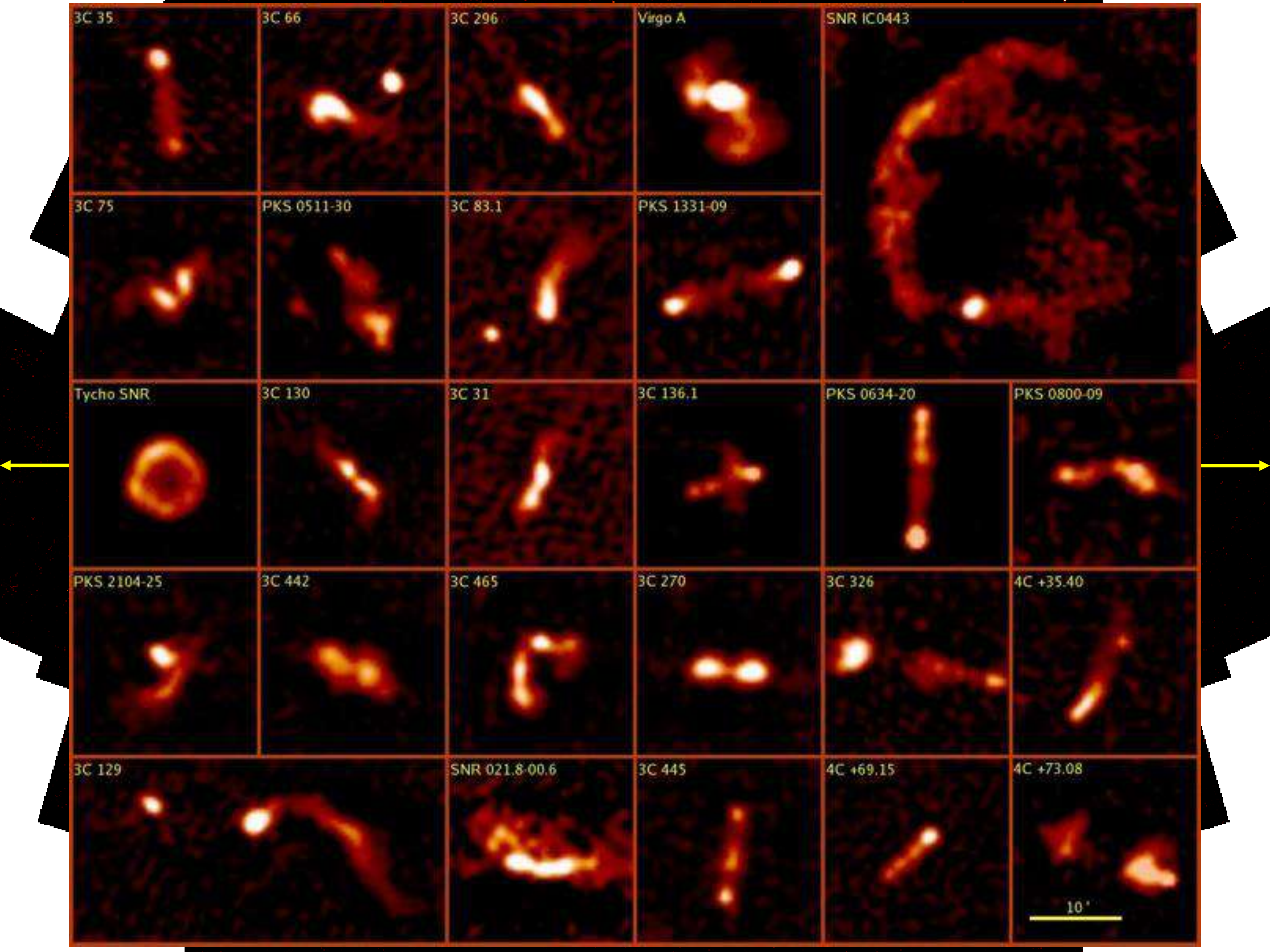
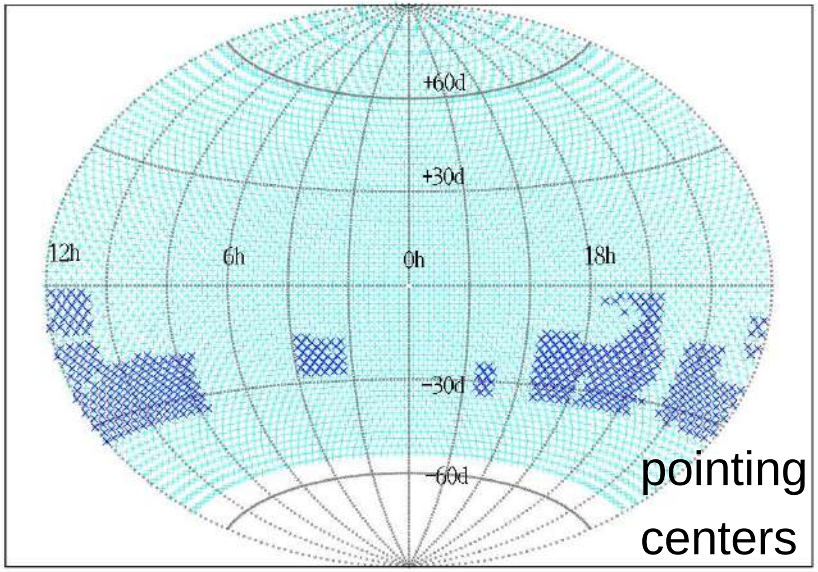
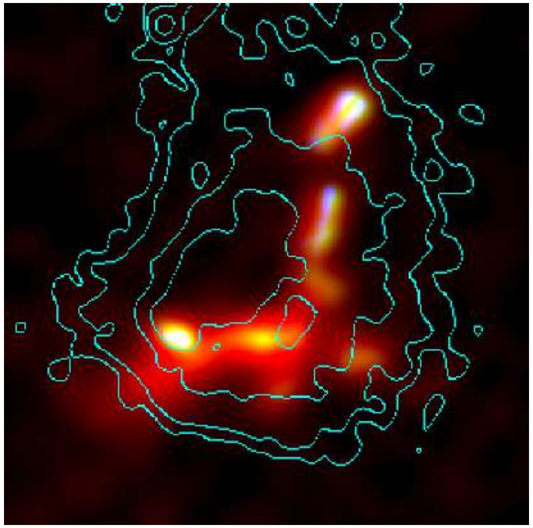

3C 35
3C 66
3C 296
Virgo A
SNR IC0443
3C 75
PKS 0511-30
3C 83.1
PKS 1331-09
Tycho SNR
3C 130
3C 31
3C 136.1
PKS 0634-20
PKS 0800-09
PKS 2104-25
3C 442
3C 465
3C 270
3C 326
4C +35.40
3C 129
SNR 021.8-00.6
3C 445
4C +69.15
4C +73.08
10'

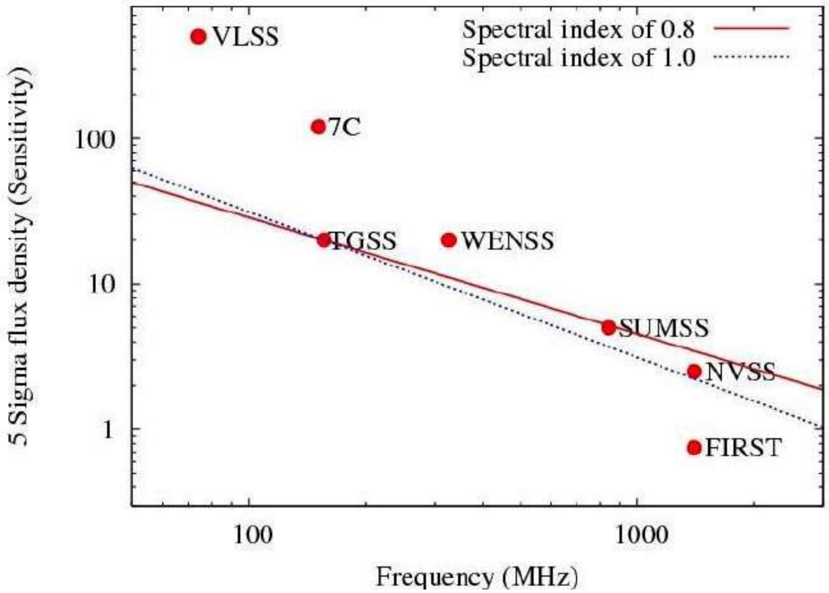
TIFR GMRT Sky Survey: TGSS

- 150 MHz survey of ™> -55˚
- Status: in progress
- survey parameters:
  - ⎝ = 20″, σ ~ 10 mJy/beam

- enhances low-freq. calibration grid
- data online at http://tgss.ncra.tifr.res.in/150MHz/





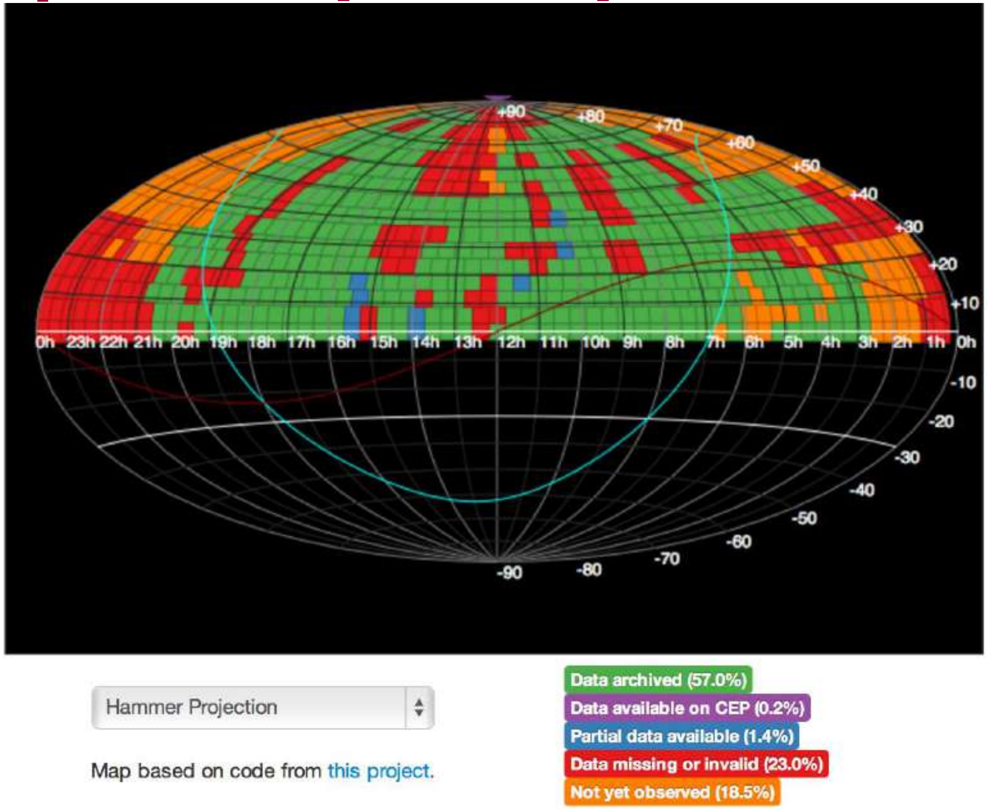


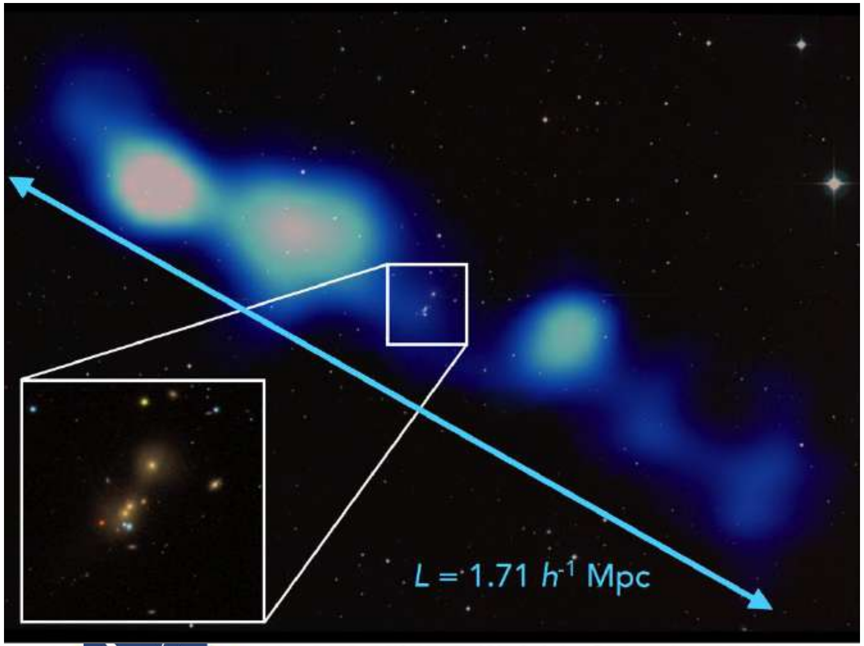
Sirothia et al.

LOFAR Multifrequency Snapshot Sky Survey: MSSS

- Covers 20,000 deg^2
- LBA: σ<15 mJy, θ ~100"
- HBA: σ<5 mJy, θ ~120"
- Status: in progress

- data online at http://msss.astron.nl



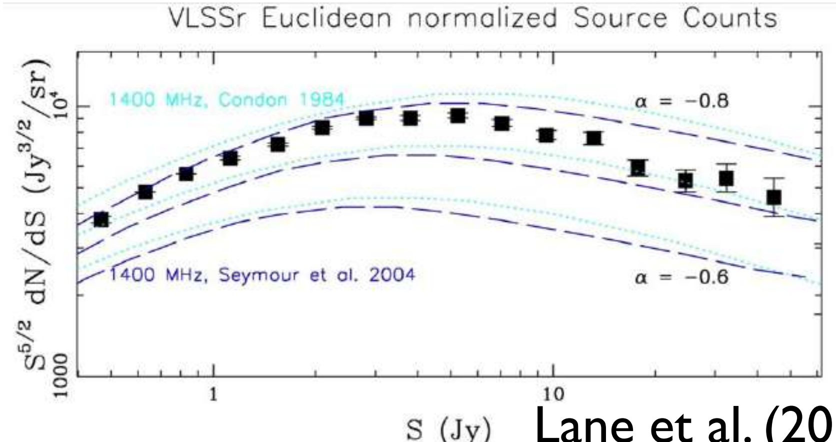


Low Frequency Interferometry In Practice:

- Confusion: source blending at lower resolutions – need long baselines to overcome confusion
- Ionosphere: single self-cal. phase correction per FoV often fail at LF
  - *Quiescent*: Refraction, Faraday Rotation
  - *Disturbed*: Scintillation, Image Distortion, Position Shifts
- Radio Frequency Interference:
  - Severe at low frequencies
- Large Fields of View: (Myers Talk)
  - Non-coplanar array (*u,v, & w*)
  - *Dipoles see entire sky: Demixing for A-team with LOFAR*
- Wide Bandwidth: (Rau Talk)
- Polarization: (Brentjens Talk, Moellenbrock Talk)

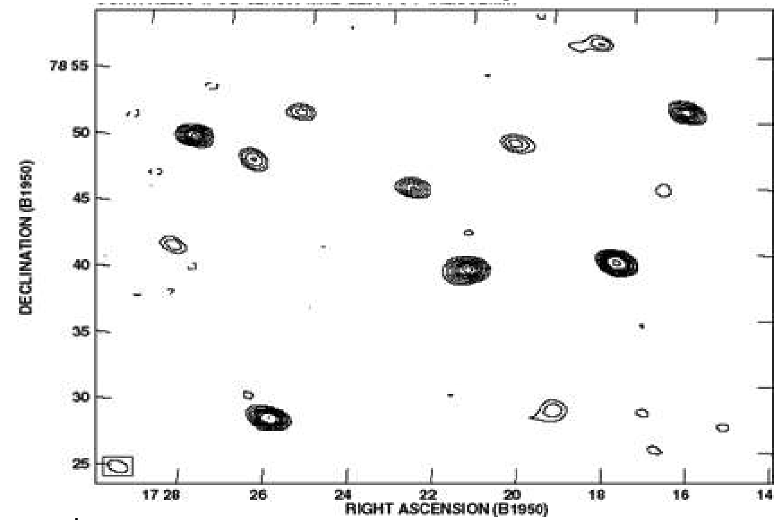
Confusion: Need Long Baselines

- source counts rise to mJy level

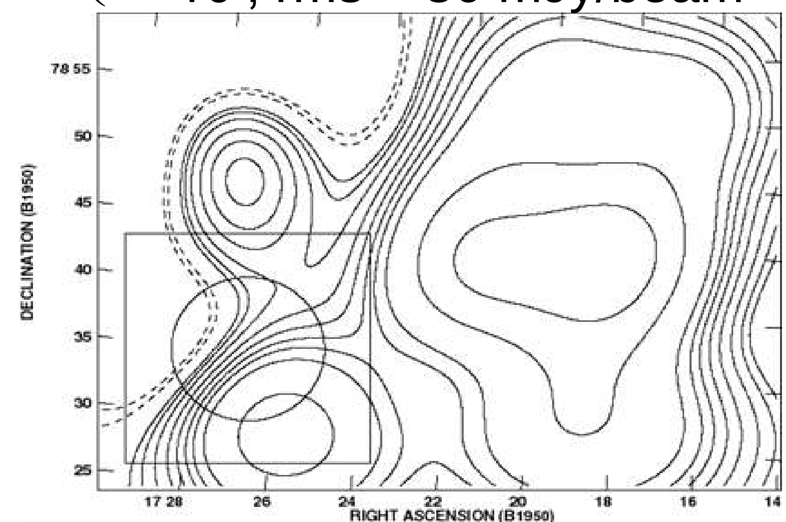


Lane et al. (2012)

~ 1', rms ~ 3 mJy/beam



~ 10', rms ~ 30 mJy/beam



- for any angular resolution θ
  - there is a confusion limit
  - individual weak sources blend
  - the resulting sky noise may exceed thermal noise
  - such cases are “confusion limited”

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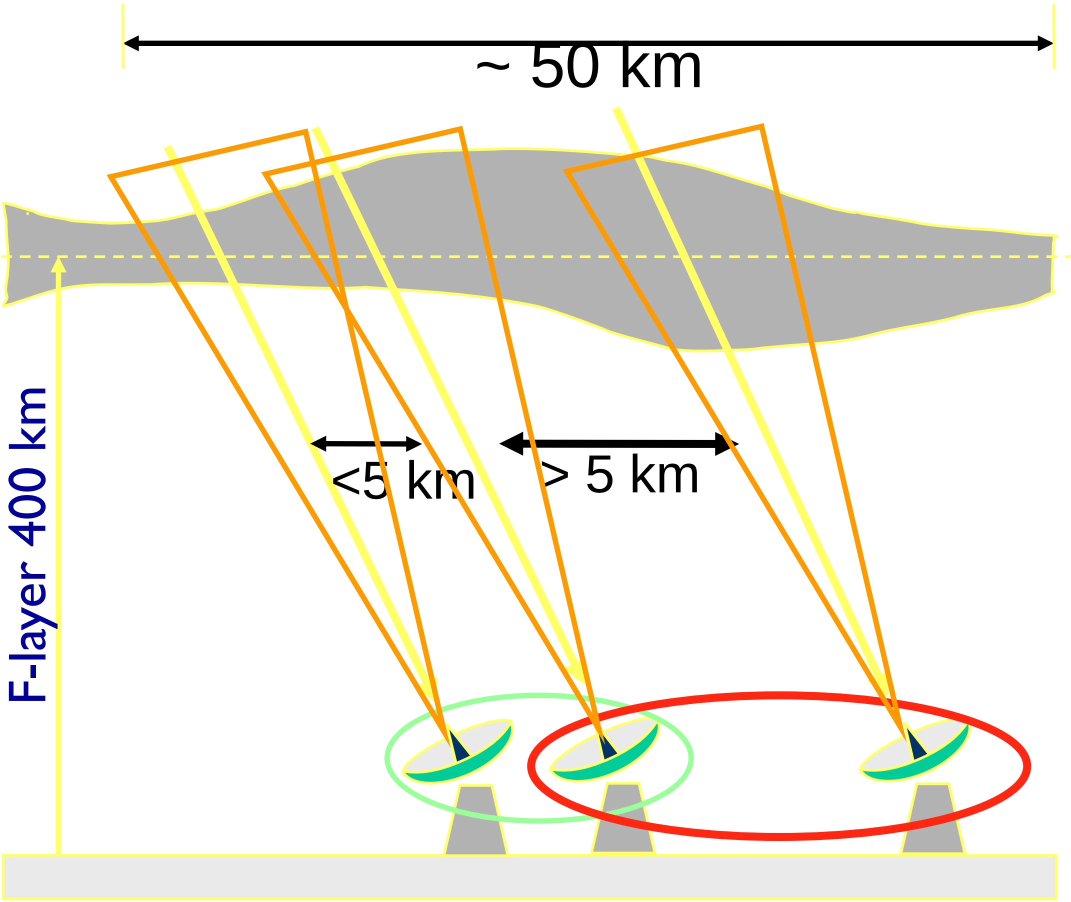
Ionosphere

- Ionosphere introduces phase errors in radio signal

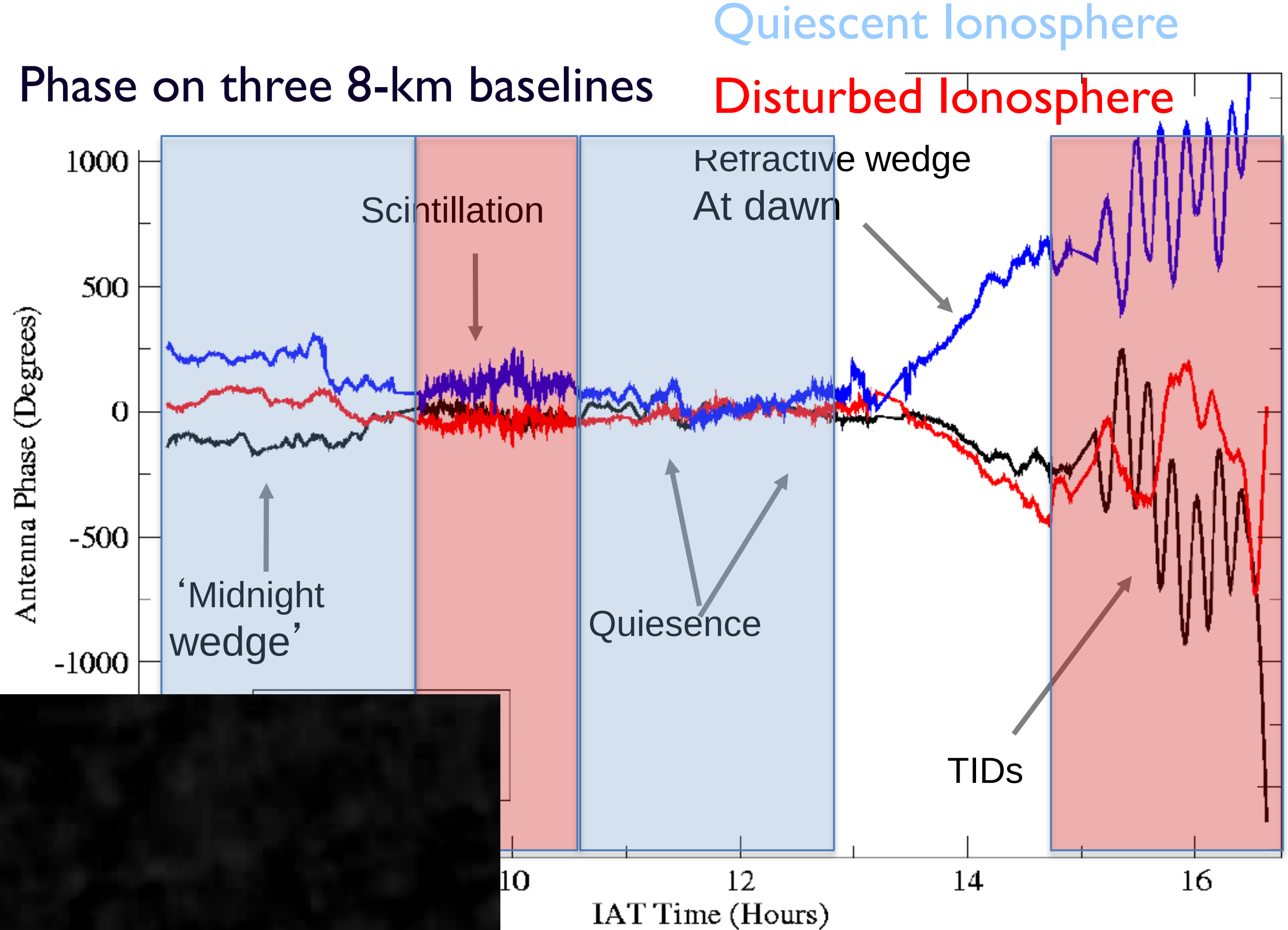


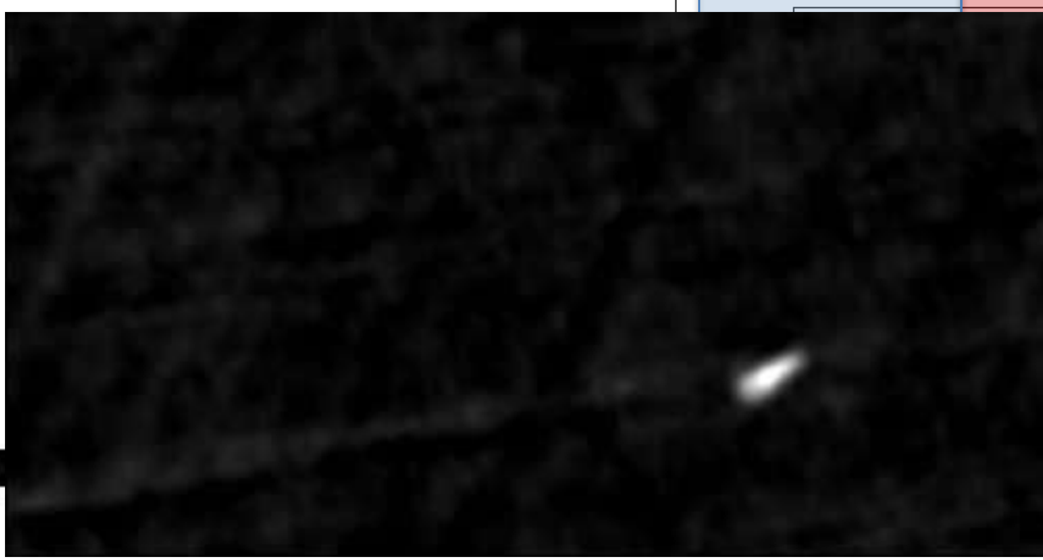
Correlation preserved Correlation destroyed

- 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

Disturbed Ionosphere: Antenna Phase vs Time

- A wide range of phenomena were observed over the 12-hour observation
- Often daytime (not dawn) has stable conditions but more RFI





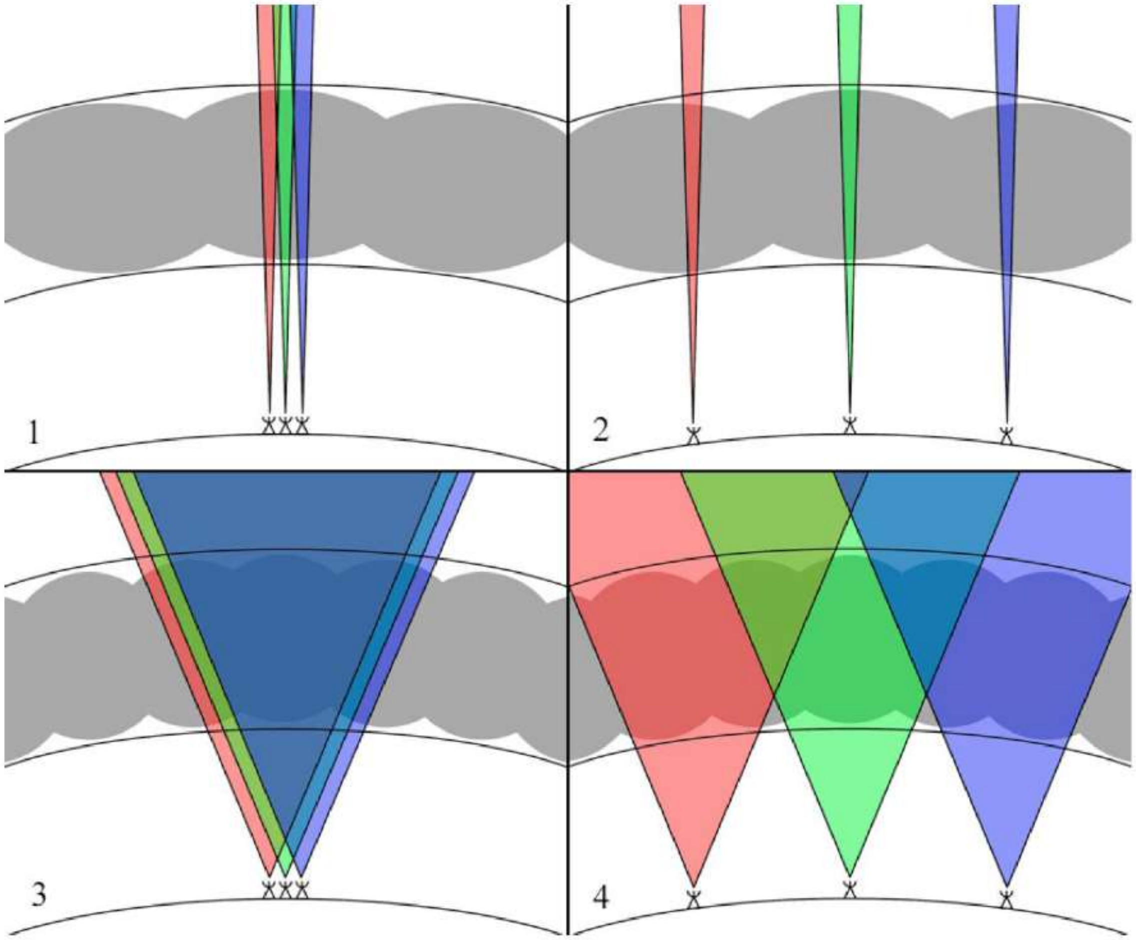
Ionosphere in Practice: What Regime?

- Lonsdale (2005) identified different calibration regimes for ionosphere

- Regimes 1 & 2 ionospheric phase error has no FoV variation – self cal OK

- Regimes 3 & 4 have varying phase over FoV – need direction dependent algorithms

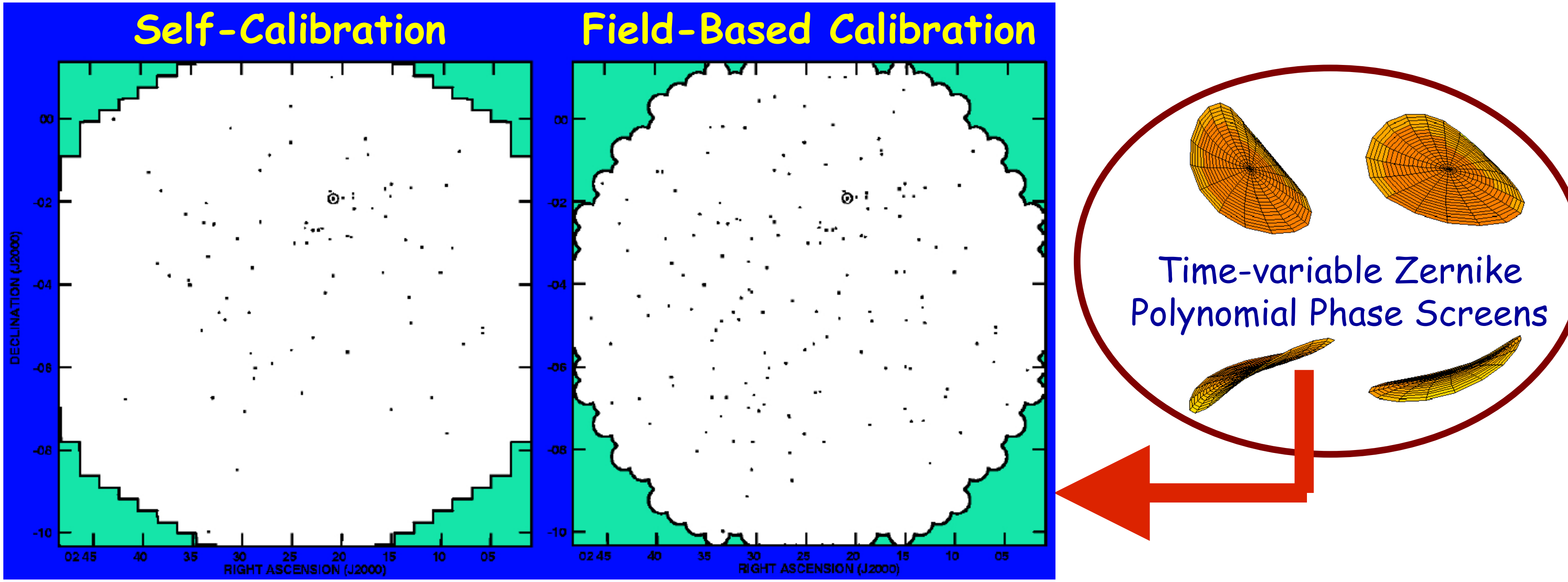
Significant effort underway: field-based, source peeling, global model, multiple scale height models, …



Intema et al. (2009)

Ionosphere: Field-Based Calibration

- Compare bright sources to sky model positions (5-10 sources per FoV)
- Fit phase delay screen (Zernike polynomial) & apply to correct image



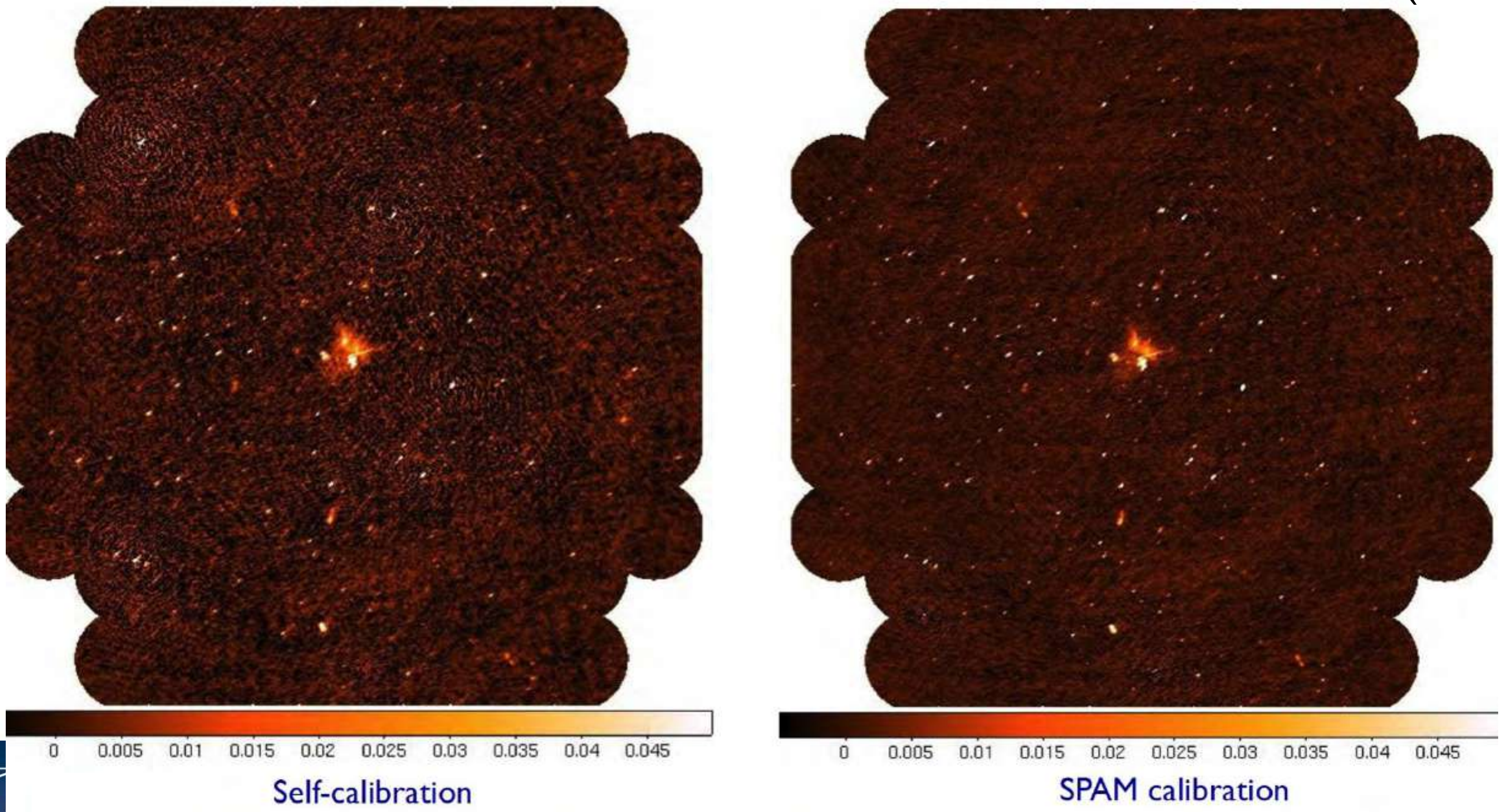
Average positional error decreased from ~45” to 17”

Obit: IonImage [for Obit see B. Cotton (NRAO) webpage]

Ionosphere: SPAM

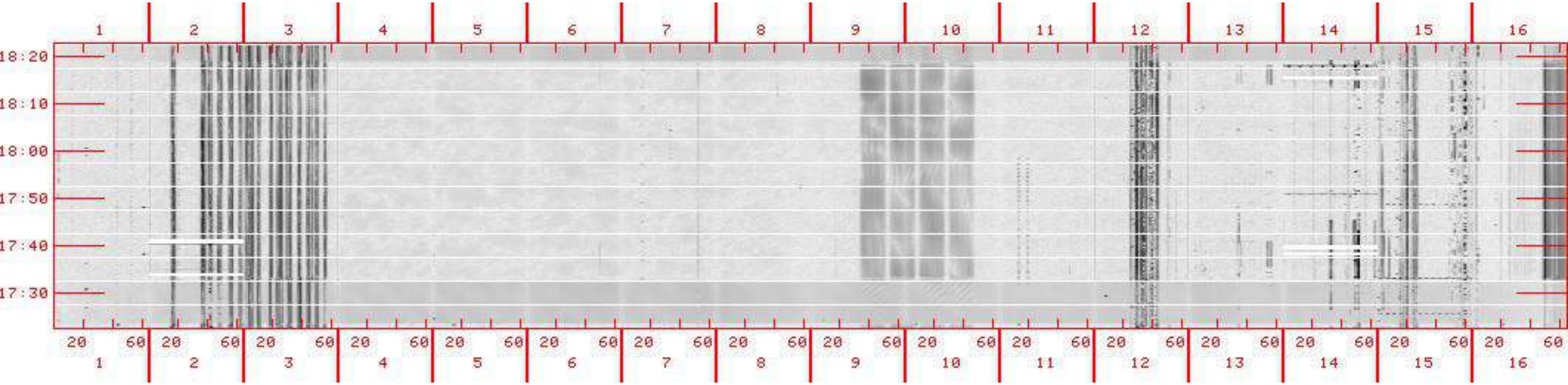
- Source Peeling and Ionospheric Modeling: SPAM (python + AIPS)
- Constrain ionospheric phase model based on calibration phases from ‘peeling’ (sequential self-calibration) of bright sources
- Fit a phase screen to pierce point solutions and apply to imaging

Intema et al. (2009)



Radio Frequency Interference: RFI

- Natural & man-generated RFI are at best a nuisance



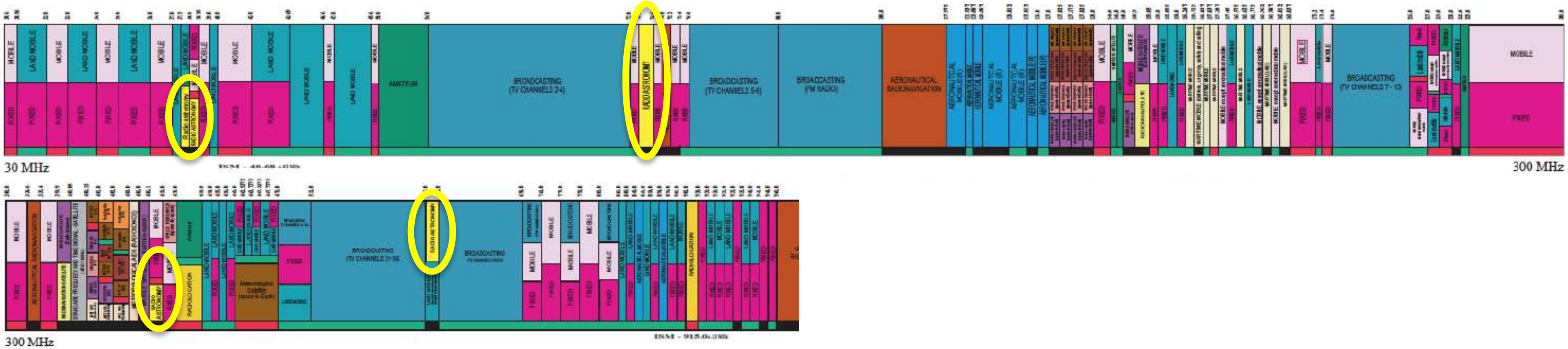
- Many different signatures seen:

  narrowband, wideband, time varying, ‘wandering’

- Best to deal with RFI at highest spectral resolution before averaging for imaging.

When do you deal with RFI?

- Pre-detection: coordination & frequency spectrum regulation, RQ zones, …



- US Spectrum allocation to Radio Astronomy between 30 MHz and 1 GHz (2011):
  - 37.5 - 38.25 MHz (0.75 MHz)
  - 73.0 – 74.6 MHz (1.6 MHz)
  - 406.1 – 410.0 MHz (3.9 MHz)
  - 608.0 – 614.0 MHz (6.0 MHz)

  Total of 12.25 MHz over 990 MHz (1.2% of spectrum)

RFI In Practice: Options! Options! Options!

- AIPS: RFLAG, FLAGR, EDITA, FLGIT, SPFLG, CLIP, WIPER, UVLIN, …
- CASA: flagdata (manual, clip, tfcrop, rflag, …), plotms (by hand), …
- Obit: AutoFlag, MednFlag, SrvrEdt, RFIFilt, UVFlag, …
- RfiX, UVRFI: Fringe stopping to separate celestial and terrestrial signals
- AOFlagger: Generalized tool using Offringa et al. (2010, 2012) techniques
- RFI Nulling: adaptively place beam nulls on RFI
- General Notes:

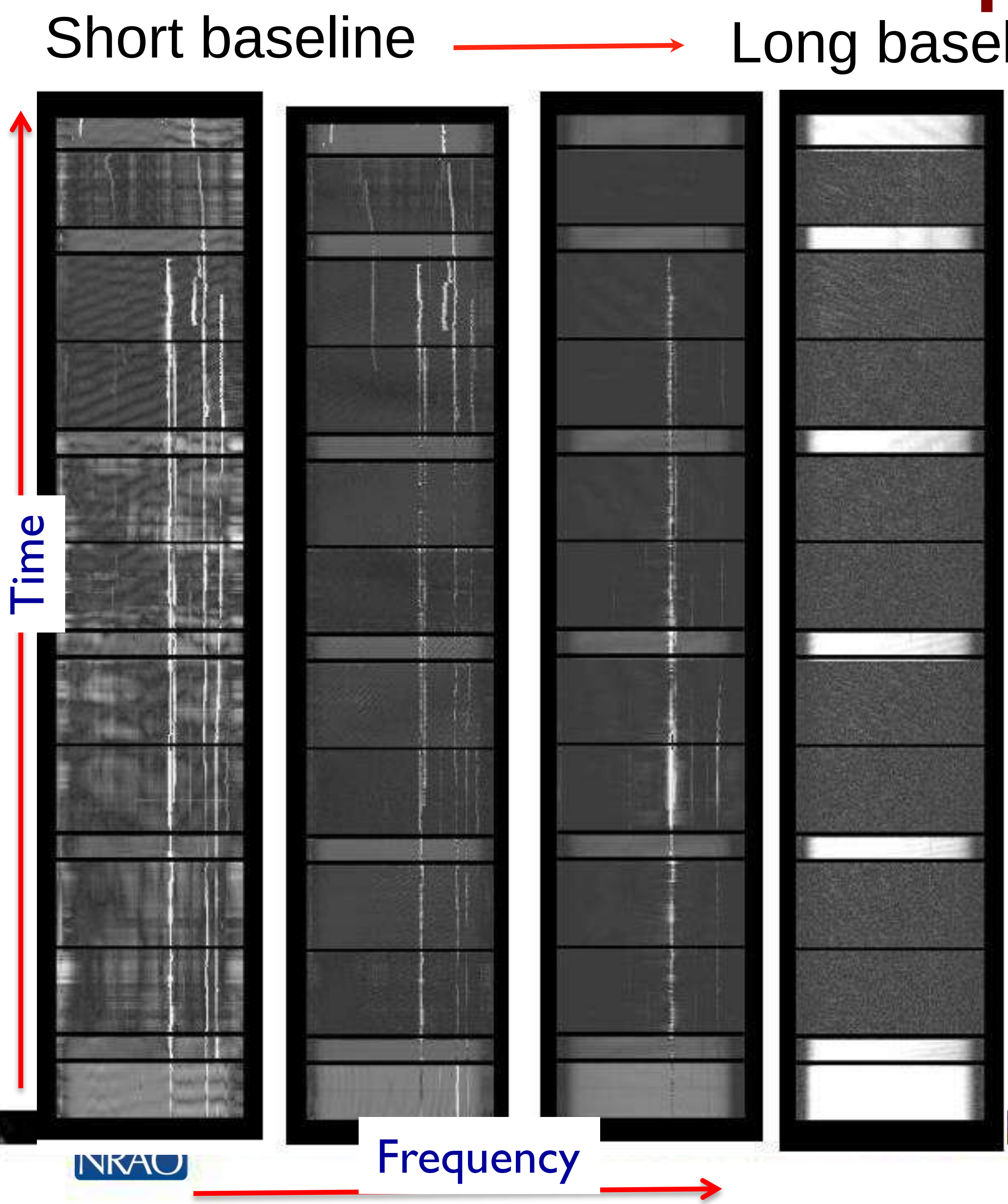
✓ RFI is generally circularly polarized – <u>Look at Stokes V</u>!

✓ Collapse data to a single channel so low level RFI adds up

✓ Look at image residuals for lower-level RFI

✓ Image analysis of errors (**talk by Taylor**)

RFI Examples



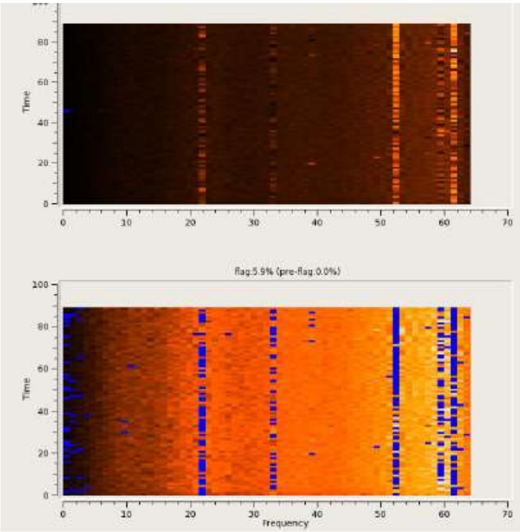
- RFI environment worse on short baselines
- Several 'types': narrow band, wandering, wideband, ...
- Wideband interference hard for some automated routines

RFI Excision: AIPS

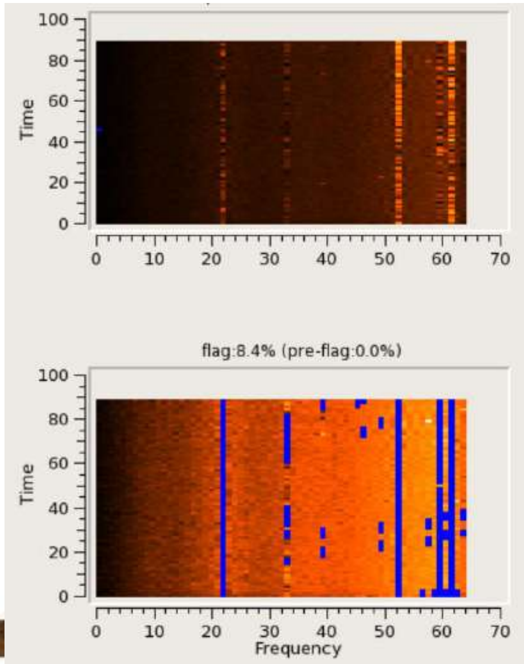
- TVFLG: manual flagging visual of time vs baseline cycle channels
- SPFLG: manual flagging visual of time vs channels cycle baselines
- WIPER: visual diagnostic tool
- UVFLG: manual command-line flagging
- EDITA: manual flagging visual to flag on antenna gains, Tsys or SysPower
- CLIP: cut the top off (not generally a good idea)
- FLGIT: removed continuum from channels
- RFLAG: automated task to ID RFI via rms vs time
- FLAGR: automated, converts baseline-based to antenna-based
- …
- In desperation ZAP – really not recommended but deleting ALL uv data does get rid of RFI!

RFI Excision: CASA flagdata modes

- <u>tfcrop</u>: detects amp. outliers in 2D freq-time plane
  - operates on uncalibrated or calibrated data
    - average data in time
    - fit piecewise polynomial to background
    - identify and flag deviant points
    - repeat for frequency dimension
    - 'spiky' RFI is relatively easy, wider RFI need more tuning



- <u>rflag</u>: detects outliers in sliding windows in frequency and time
  - operates on calibrated data (2 passes)
    - for each channel calc. rms of Re and Im vis in sliding window
    - calculate median rms and deviations across time windows
    - flag on outliers



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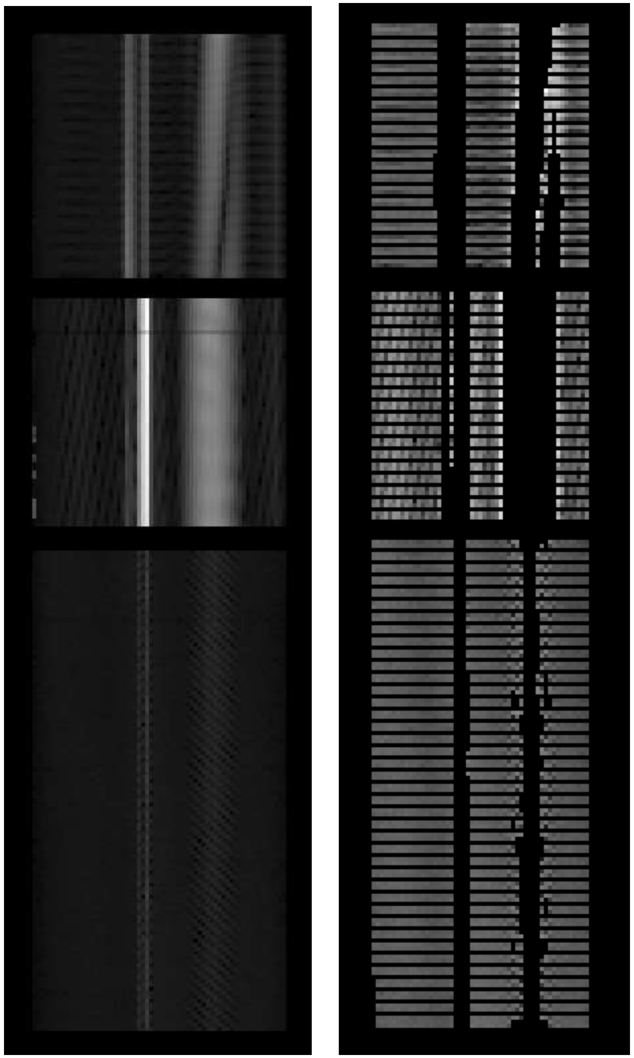
See Urvashi Rau's web pages

RFI Flagging: Obit

- Pipeline processing: Developing a new low band reduction pipeline for VLA & VLITE*
- One 16 MHz IF shown
- LF Pipeline:
  - Drops end channels and applies manually defined flags (PFlag)
  - Removes beginning and end of scans (Quack)
  - Flags shadowed antennas (UVFlag)
  - Edits on median window over time (MednFlag)
  - Edits on median window over frequency (AutoFlag)



*VLITE – VLA Ionospheric and Transient Experiment

- 3 yr, 10 antenna through software correlator

B. Cotton (NRAO)

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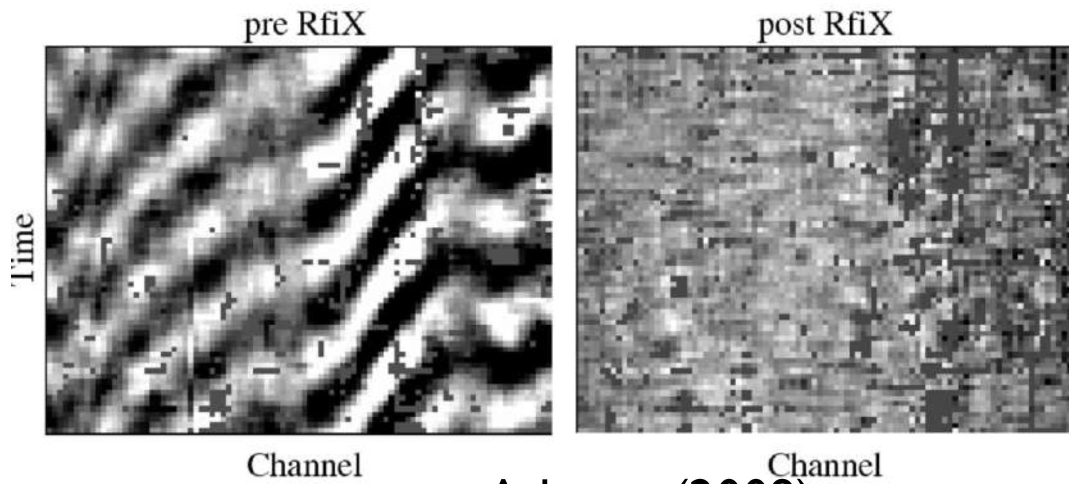
Fringe Stopping: RFI Cancellation (RfiX)

➢ Exploit different fringe rates of sky and terrestrial RFI

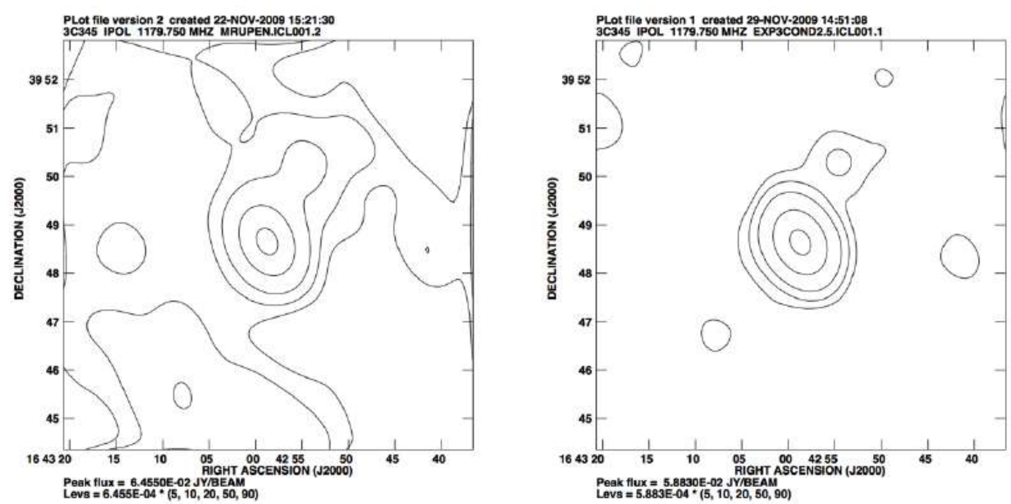
➢ removes ground-based, constant amplitude RFI from visibilities



Athreya (2009)

Fringe Stopping: AIPS UVRFI

➢ Athreya algorithm modified to allow amplitude variations and multiple sources of RFI moving at different speeds (i.e. ground and satellite-based)

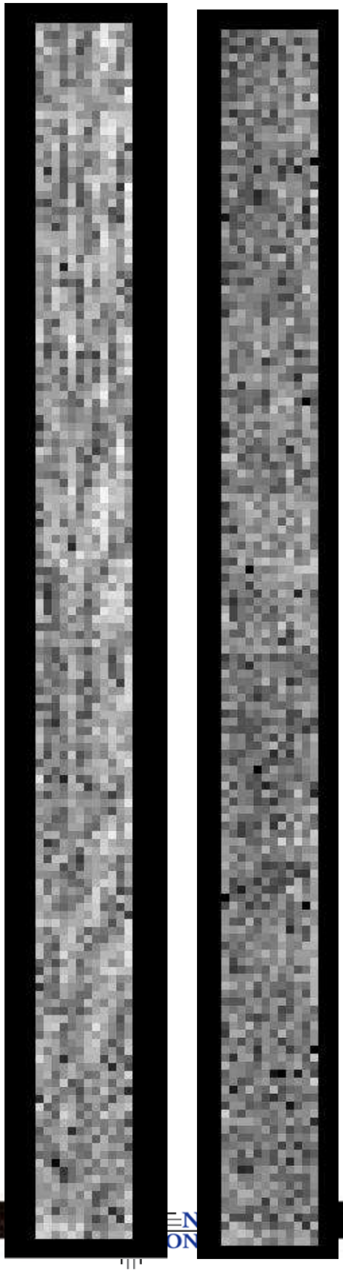


Kogan & Owen AIPS memo #116

Fringe Stopping: Obit

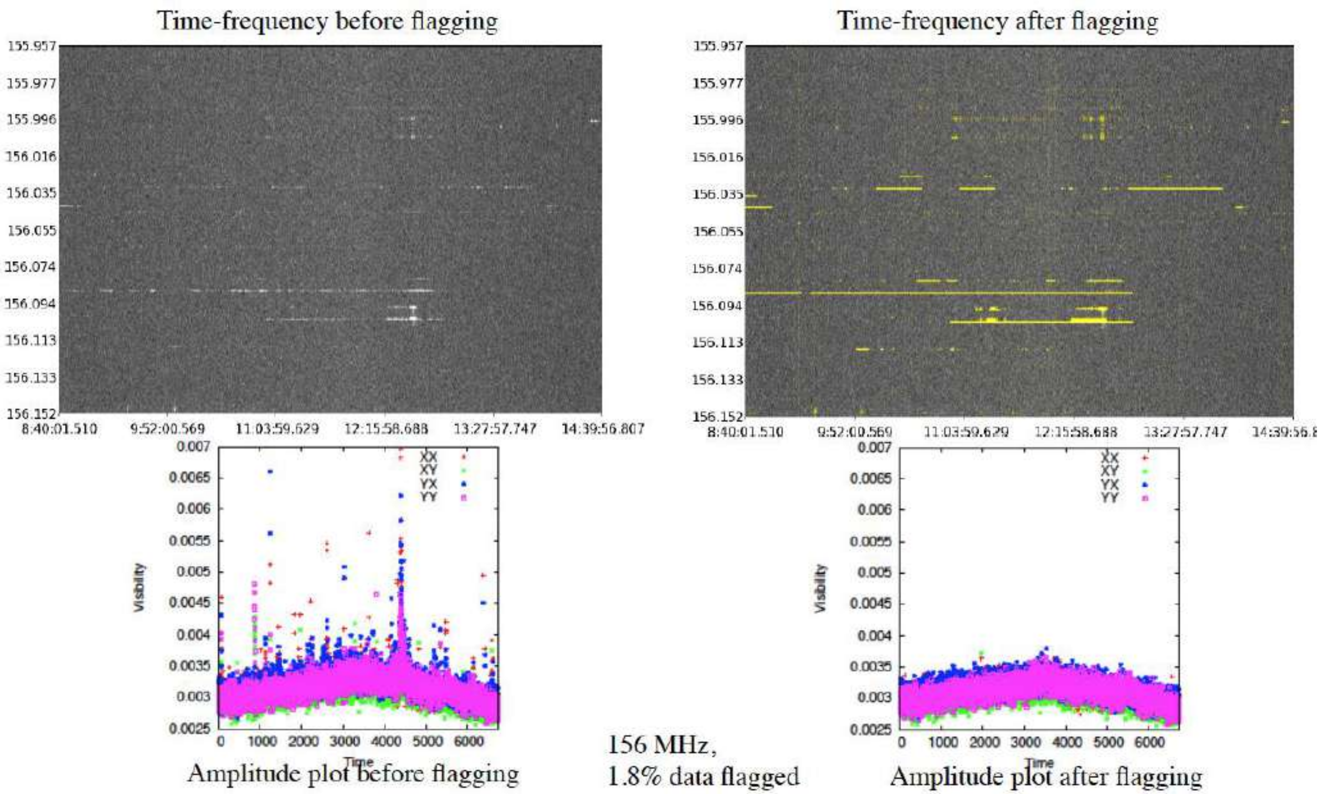
- RFI subtraction 74 MHz VLSSr survey data.
- Obit class UVRFIXize: (Obit memo # 16)
  - Differs from Athreya's code as this works on the residuals visibilities
  - Counter-rotate residuals to make constant terrestrial RFI zero phase
  - Time average to smear celestial signal and get RFI model
  - Filter the RFI model as desired to application to visibilities (sub or flag)
  - Interpolate filtered RFI model to time of each observed visibility and subtract or flag

✓ Obit Task: LowFRFI



RFI Flagging: AOFlagger

- ‘*SumThreshold*’ method to detect series of samples with high values
- Iterative analysis for entire obs., per subband and spectral channel
- Used for LOFAR but available as stand-alone package

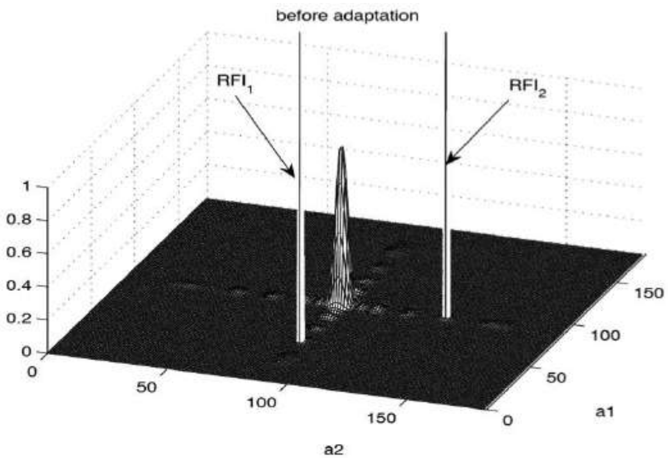


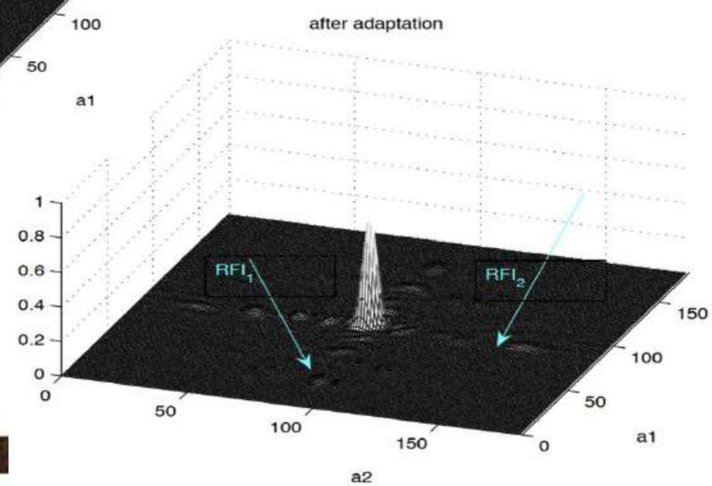
156 MHz,
1.8% data flagged

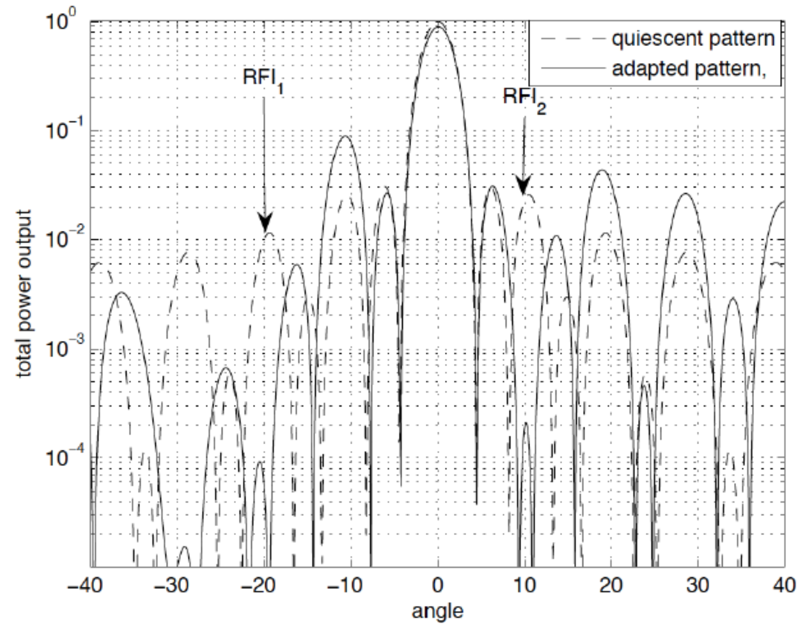
Offringa et al. (2010, 2012)

RFI Nulling

- Low frequency dipole arrays are electronically steered to source of interest
- Beamforming coefficients can be adaptively modified to place beam null(s) at locations of RFI sources







Fridman (2010)

Wide Field of View (Myers Lecture!)

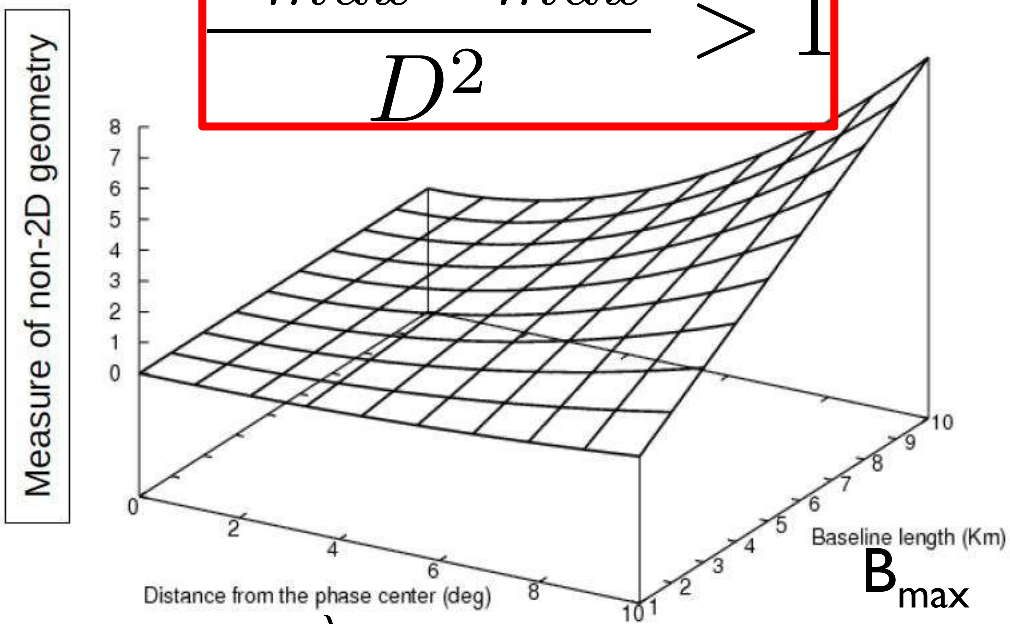
- Need to image bright sources over the entire primary beam and even into the far out sidelobes

- 2D Fourier inversion of visibilities is only true if the visibilities lie in a plane (no *w* term) and the FOV is a small angular region.

$$\boxed{\frac{\lambda_{max} B_{max}}{D^2} > 1}$$

- Deviation from 2D approx. increases with distance from phase center and baseline length

- Limits DR in full field by deconvolution errors from distant sources



B_{max}

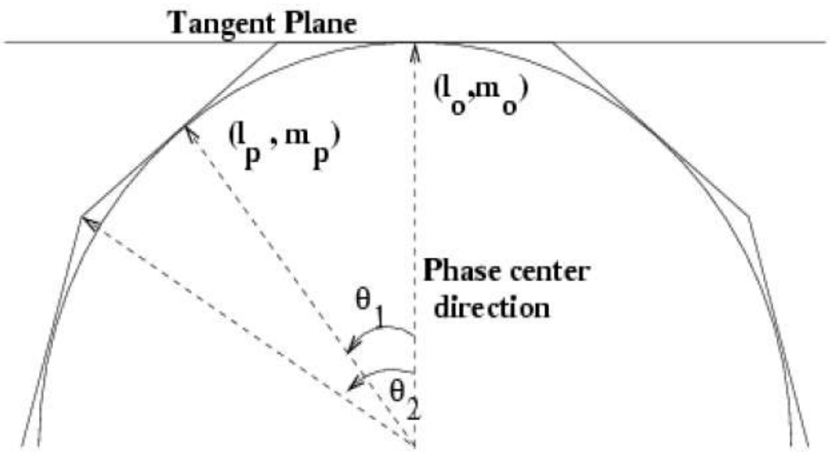
$$\theta \sim \frac{\lambda}{D}$$

Wide Field of View

- Approaches to Wide Field Imaging:
  - Facets: phase rotate uv data to different positions on the celestial sphere
    - 3D: facets not co-planar
    - 2D: facets projected to common plane tangent to phase center
  - W-Projection: use *w*-dependent convolution function in gridding to get corrected image in 2D FFT
  - A-Projection: adds direction dependent gain to the W-Projection method for dipole arrays
  - Full 3D Fourier Transform: Too computationally expensive, not used
- Primary beam changes with frequency, polarization, and time, must be incorporated into wide field, wide bandwidth, direction-dependent techniques! (Myers Lecture)

Wide Field of View: Faceting

- 3D faceting:
  - FoV broken into smaller facets which satisfy 2D approx.
  - Image each facet separately then project to a single image at the tangent plane
  - ✓ CASA: clean
  - ✓ AIPS: IMAGR
  - ✓ Obit: Imager, MFImager

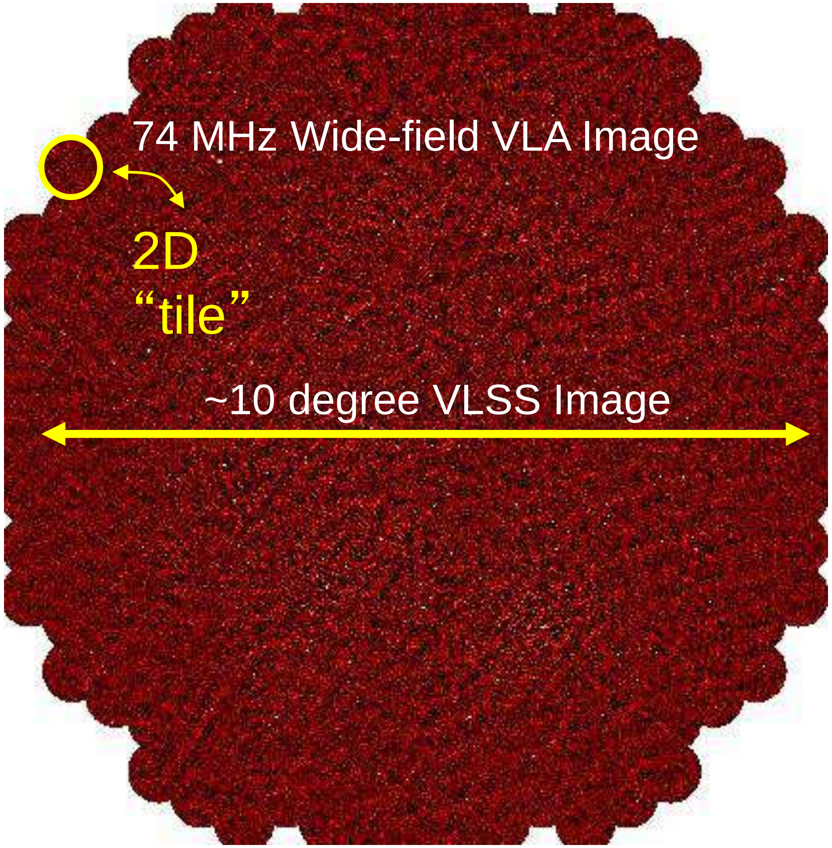


- 2D faceting:
  - Project facets to a common plane (1 tangent) with a common grid
  - ✓ Obit: do3D = False
  - ✓ AIPS: DO3DIMAG = -1

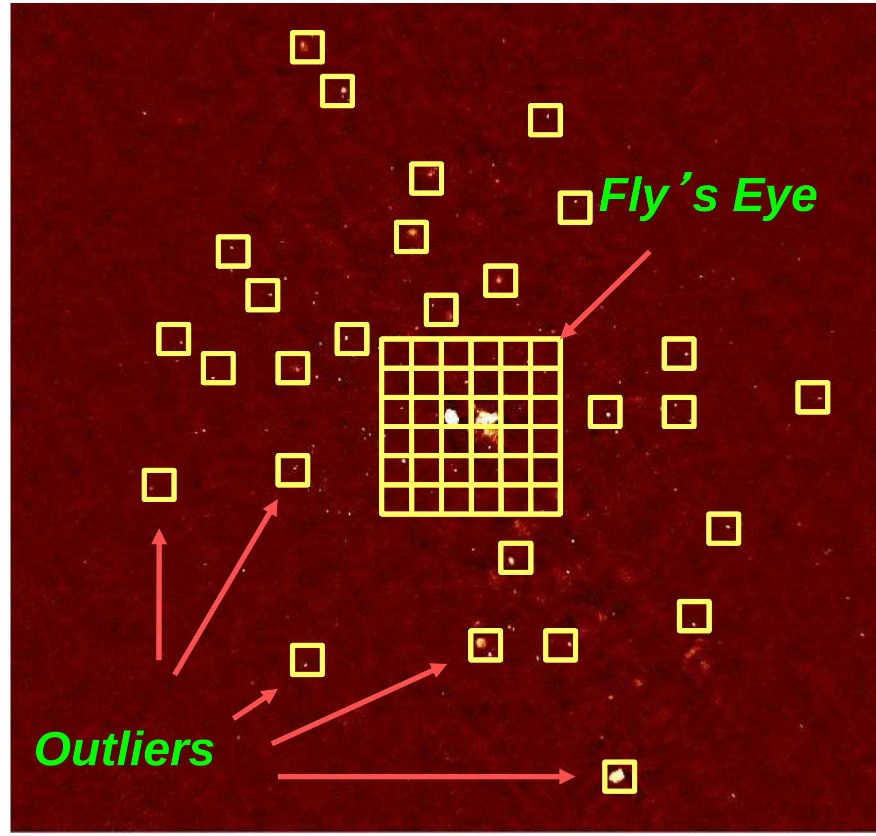
Cotton (2009) Obit memo # 15

Kogan & Greisen (2009) AIPS memo #113

Full Field vs Targeted Imaging



A array requires ~10,000 pixels!



- ➢ 2D faceted imaging of entire FoV is very computationally expensive
- ➢ Fly’s eye of field center and then targeted facets on outlier is less demanding BUT potential loss of interesting science

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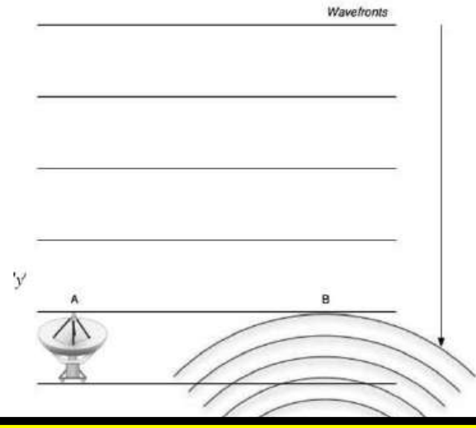
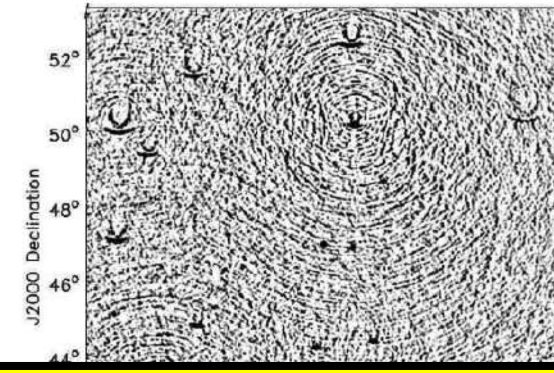
Wide Field of View: W-Projection

Cornwell et al. (2008)

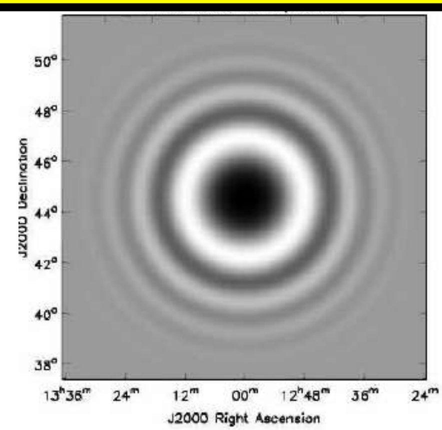
- ➤ Coplanar array A and B would be a 2D FT
- ➤ Propagation to B' in a non-coplanar array experiences diffraction

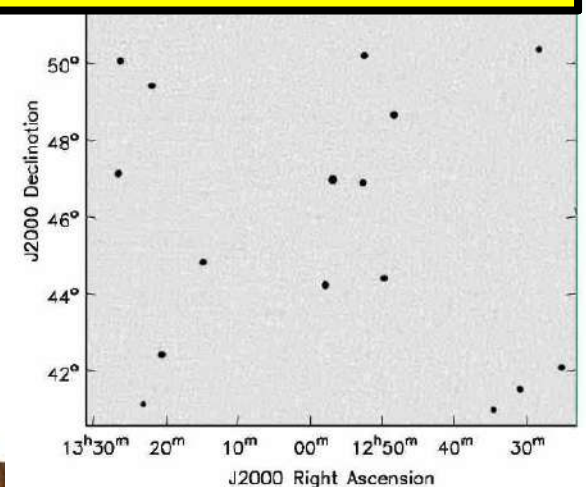




At low frequencies with very large field of view you would need many w-planes. A hybrid approach of faceting and w-projection is best.

- ➤ ba co di space before Fourier transform
  - ✓ CASA: clean





Myers Lecture

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Wide Field of View: WB A-Projection

- w-Projection deals with wide FoV but not direction-dependent effects

- A-Projection (Bhatnagar et al. 2008) developed a narrow-band technique to deal with DD primary beam effects

  - corrects for time and polarization of PB

- WB A-Projection (Bhatnagar et al. 2013) expands algorithm to handle wideband primary beam DD effects

  - corrects for time, polarization and frequency of PB

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Summary

- Next generation of low frequency instruments is being built while current instruments (such as the VLA) are being upgraded

- Low frequency interferometers are powerful and we know a lot about problems but we don't have all the tools in our calibration toolkits:
  - Fully automated RFI mitigation
  - Time, direction and frequency dependent ionospheric corrections
  - Time, direction, frequency, polarization and element depended gain corections

- Advances will lead improved scientific capabilities for studies from Dark Ages through Cosmic Dawn to our Solar system

✓ Great time to incorporate low frequency information into your research

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Looking Forward: