Lecture: GLOW radio interferometry school.

Low frequency interferometry

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Time-line of Low Frequency Radio Astronomy

1931-1935 Jansky. Birth of radio astronomy, CMB was discovered at (ν ~ 15-30 MHz)

1935-1940 Reber discovered the non thermal emission (ν ~ 150 MHz)

1942 Hey discovered the Solar radio emission

1946 First 2 element interferometer was build by Ryle

1955 Kraus et. al made the first all sky survey (ν ~ 80 MHz)

1955 Burke et al. discovered the first planetary radio emission (ν ~ 10-100 MHz)

1958 – 88 Erickson built the Clarke Lake TPT (ν ~ 100-1400 MHz)

1962-1963 Bennet completed the 3C catalog (ν ~ 160 MHz)

1963 Hazard Schmidt Sandage discovered the first quasar (ν ~ 178 MHz)

1967 First VLBI fringes (ν ~ 20-1400 MHz)

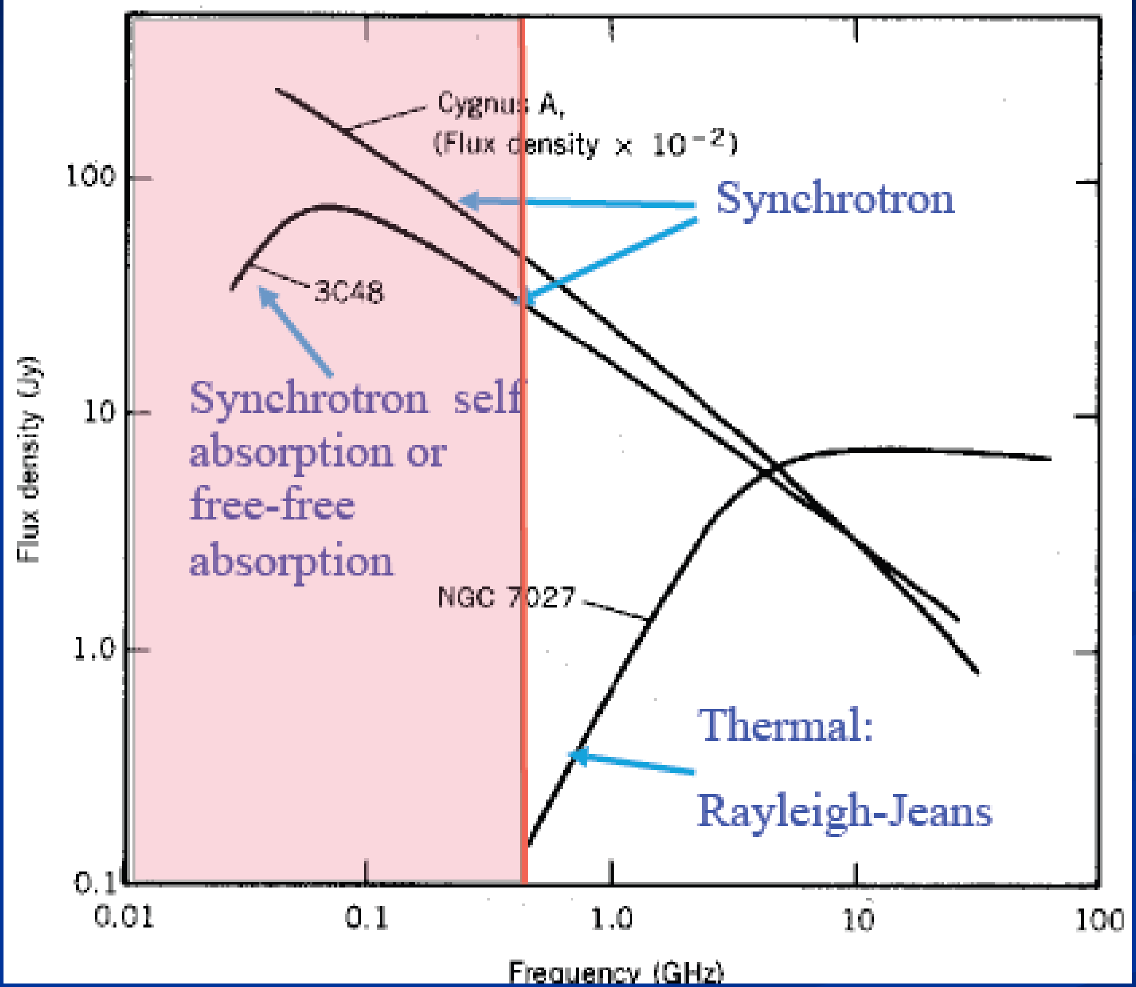
1968 Bell discovered the first pulsar (ν ~ 81 MHz)

1980 Dedication of the VLA

1990 Implementation of the **74 MHz** system at the VLA

2000´s LOFAR & LWA & MWA

Key science unique to low frequencies:



Synchrotron

Synchrotron self absorption or free-free absorption

Thermal:

Rayleigh-Jeans

Key science unique to low frequencies:

Ionospheric studies
Solar Burst studies

Interstellar Mediu , HII regions, SNR, pulsars)
Galaxy Evolution (d starburst galaxies)
transient searches (inc extrasolar planets)

Early Structur mation (high z RG)
Large Scale Stru volution (diffuse emission)
Wide Field (up to) mapping
Large surveys

Epoch of Reionization (highly redshifted 21 cm lines)

Serendipity (exploration of the unknown)

STANDARD interferometry observations, @ ν>1 GHz

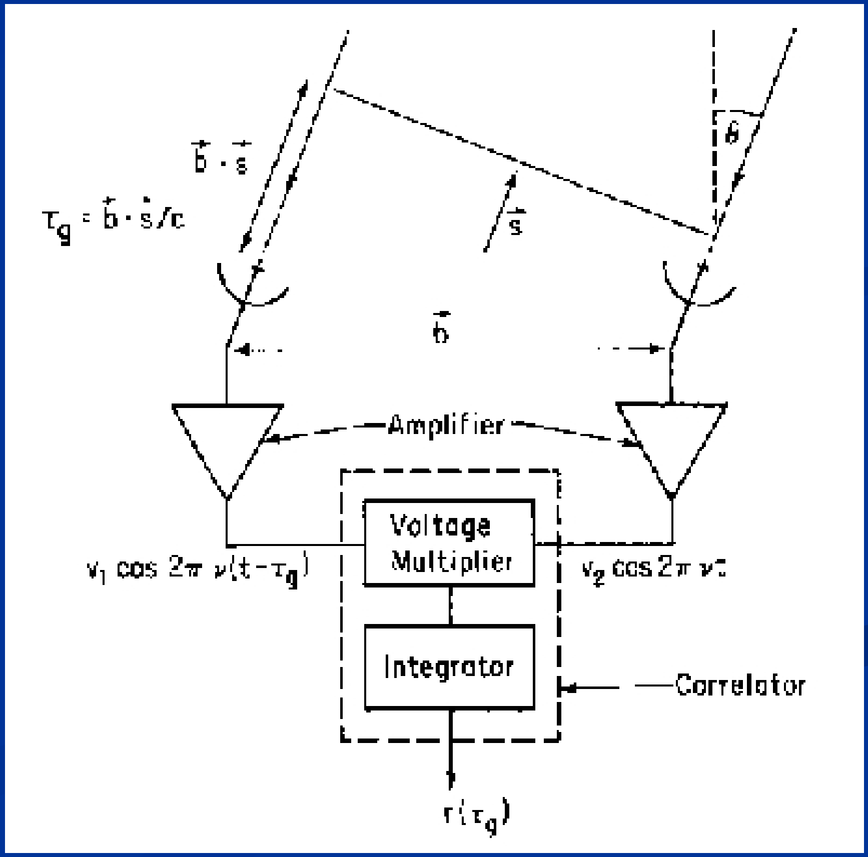
Correlate signals coming from two or more antennas

$V(u,v) \xrightarrow{FT} I(\alpha,\delta)$

Complex function
Amplitude & Phase

The PHASE give the position of the source on the sky at the each time.

How we correct phase error?



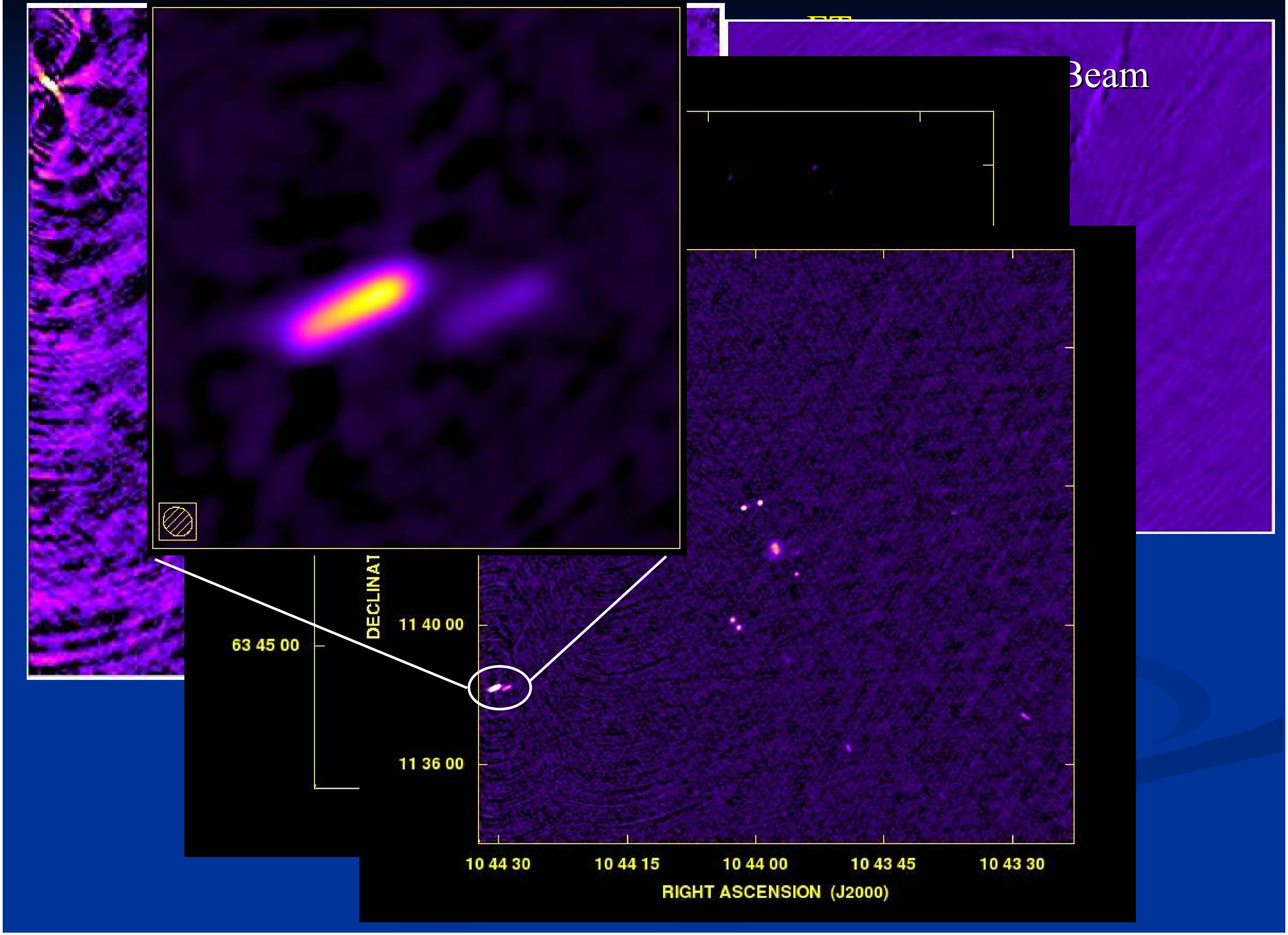
Typical observation at 1.4 GHz: BW 50 MHZ

Amplitude calibrator ~5 min
Phase calibrator~3 min
Source~20 min
Phase calibrator~3 min
Source~20 min
Phase calibrator~3 min
Source~20 min
Amplitude calibrator ~5 min

Additional effects..

Primary beam attenuation ⟶ the answer of the interferometer is modulated with respect to the answer of a single antenna: attenuation of the signal in the edges

Bandwidth smearing ⟶ observations are affected by the chromatic aberration caused by the bandwidth: sources at the edges show a radial distortion.


Beam
DECLINAT
63 45 00
11 40 00
11 36 00
10 44 30
10 44 15
10 44 00
10 43 45
10 43 30
RIGHT ASCENSION (J2000)

Low frequency interferometry

First observations with the Very Large Array

- 327 MHz → λ=90 cm → 1990 → 6" res FOV 2.5°
- 74 MHz → λ=4 m → 1998 → 20" res. FOV 11°

First to " break the ionospheric barrier"

First to obtain resolutions < 1' below 100 MHz

Why only now?.......

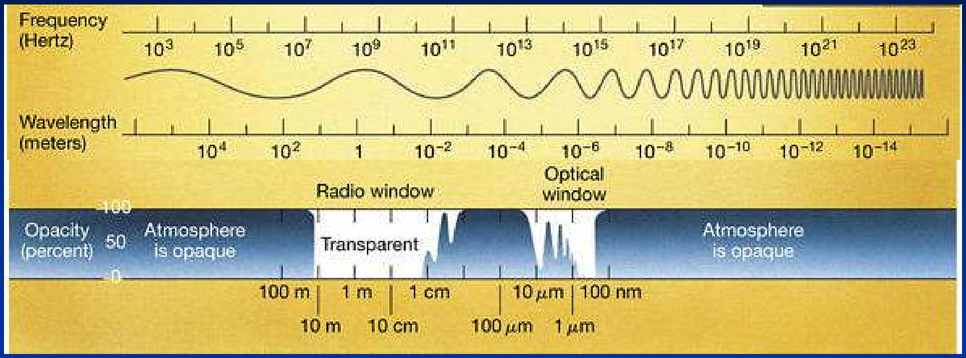
In practice…

- Phase coherence through ionosphere
- Large Fields of View
- Bandwidth smearing
- Radio Frequency Interferences
- Finite Isoplanatic Patch Problem

Ionosphere

$$n_r \propto \sqrt{1-n_e\varpi^2} \propto \sqrt{1-\left(\frac{\nu_p}{\nu}\right)^2}$$

n_e depends on:
latitude, day-time, season etc

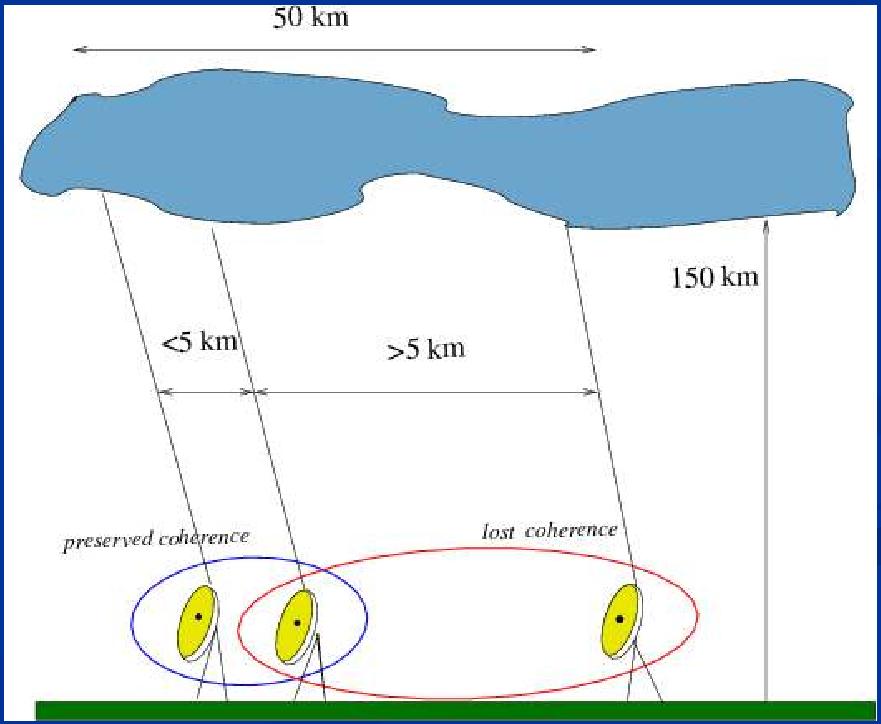


Ionospheric barrier

$\nu_p \approx$ 10 MHz

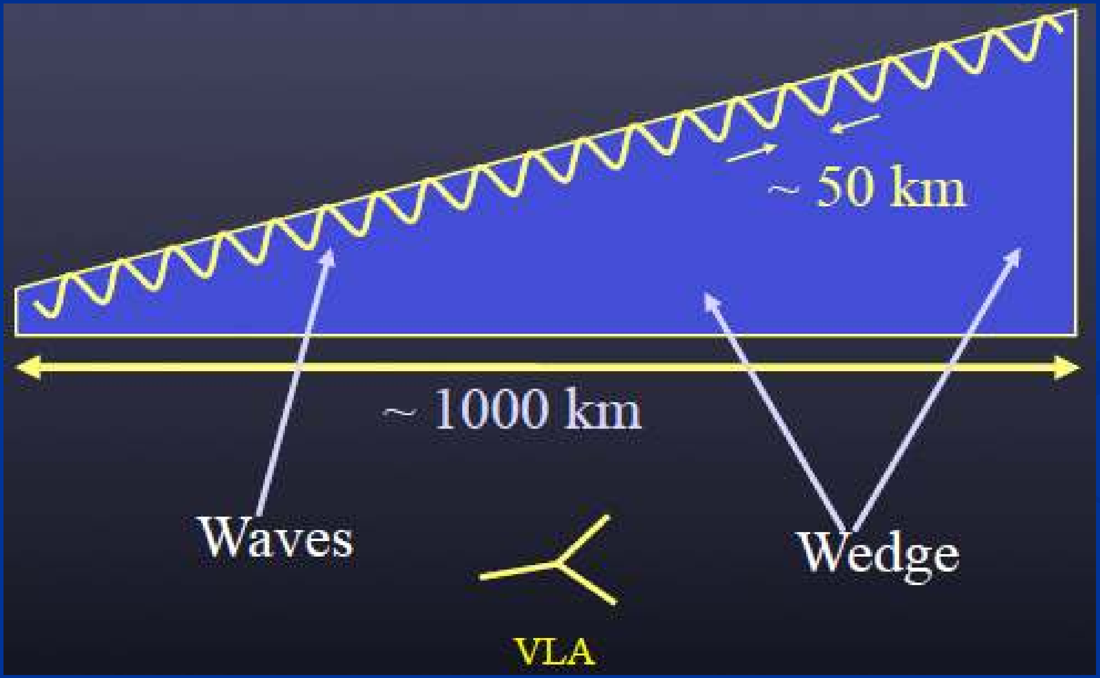
Loss of
phase coherece

Low angular
resolution



Wedge Effects: Faraday rotation, refraction, absorption below ~ 5 MHz (atmospheric cutoff)

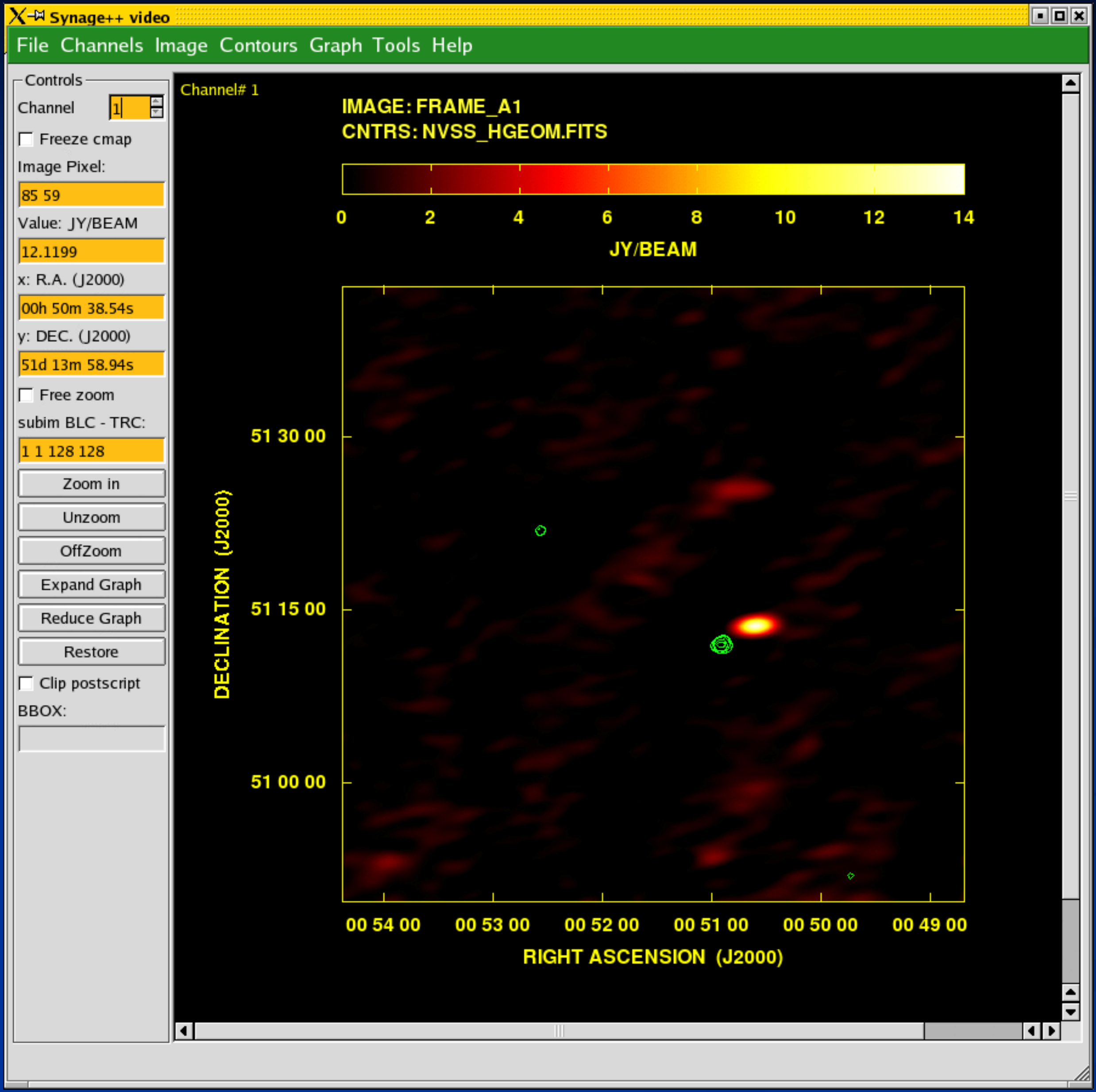
Wave and Turbulence Effects: Rapid phase winding, differential refraction, source distortion, scintillations



Wedge: characterized by
TEC = $\int n_e dl \sim 10^7$ m^{-2}
Extra path length adds extra phase
$\Delta L \propto \lambda^2 * \mathrm{TEC}$
$\Delta\phi \sim \Delta L/\lambda \sim \lambda * \mathrm{TEC}$
Waves: tiny (<1%) fluctuations superimposed on the wedge
VLA

- The wedge introduces thousands of turns of phase at 74 MHz

- Interferometers are particularly sensitive to difference in phase (wave/turbulence component)



Synage++ video

Channel: 1

☐ Freeze cmap

Image Pixel: 85 59

Value: JY/BEAM 12.1199

x: R.A. (J2000) 00h 50m 38.54s

y: DEC. (J2000) 51d 13m 58.94s

☐ Free zoom

subim BLC - TRC: 1 1 128 128

☐ Clip postscript

BBOX:

Channel# 1

IMAGE: FRAME_A1

CNTRS: NVSS_HGEOM.FITS

- Both global and differential refraction seen.

- Time scales of 1 min. or less.

Different approach for calibration…??

- Equivalent length scales In the ionosphere of 10 km or less.

Wide Field of View

- Primary Beam (PB) ($45'/\nu_{GHz}$) → 74MHz ~ 2.5°
327 MHz ~ 11°

Problems . . .

Non-complanar baseline → **V(u,v,w) 3D Fourier transform 3D**

Important if FOV is large compared to resolution

Essential for all observations below 1 GHz and for high resolution, high dynamic range even at 1.4 GHz

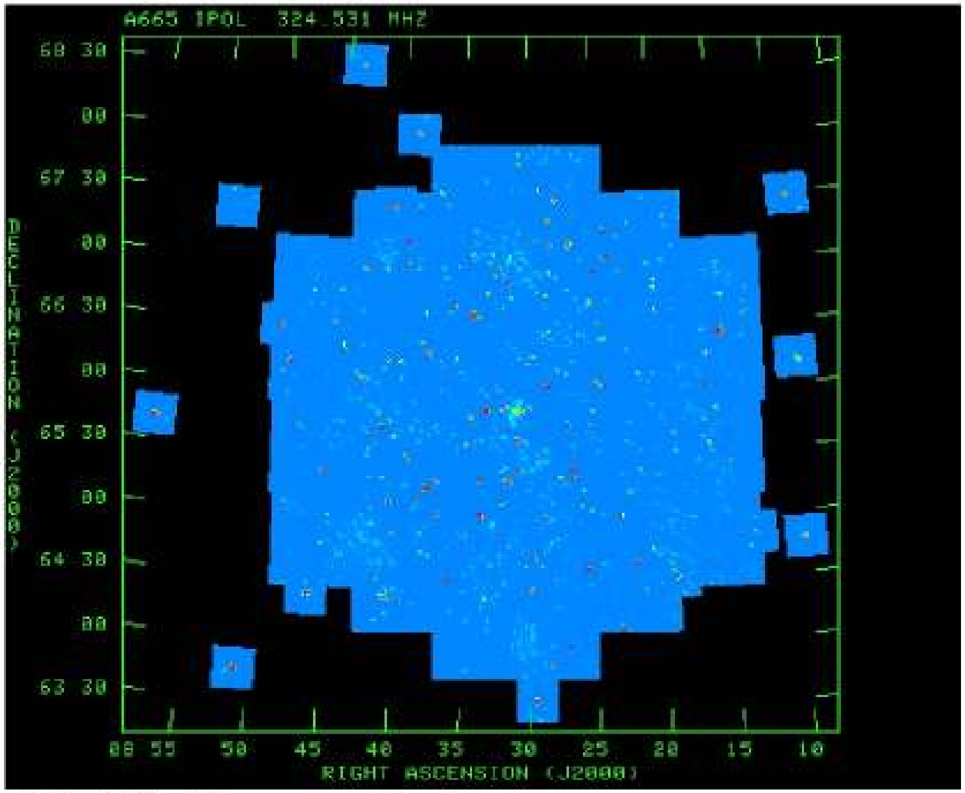
Requires lots of computing power and disk space

Bandwidth smearing → not negligible effects at low frequency with wide FOV

HOW THESE HAVE BEEN OVERCOME?

Multi-facet images

- enormous processing required to image entire FOV
- reduce processing by targeting facets on selected sources (still large number!)
- overlap a fly's eye of the central region and add individual outliers



BEAM 68" x 59" rms=1 mJy

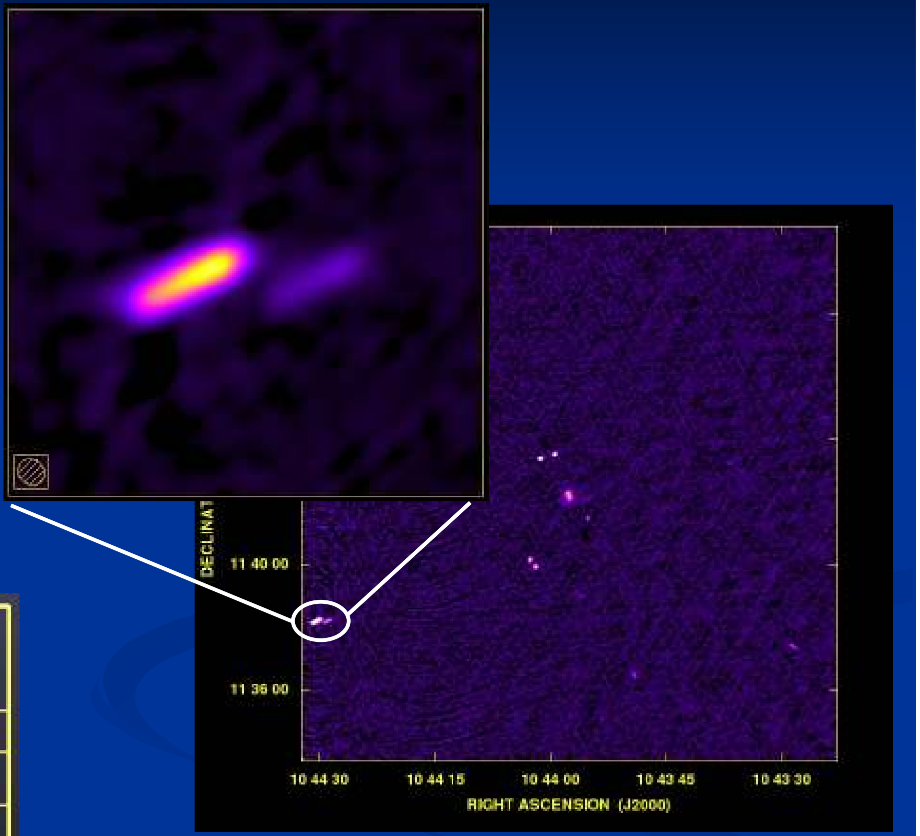
Example: VLA B array 74 MHz:
~325 facets
A array requires 10X more:
~ 3000 facets
~108 pixels

FT → Cellsize=12"; imsize=1700 pixels

Bandwidth Smearing

- Averaging visibilities over finite BW results in chromatic aberration worsens with distance from the phase center => radial smearing

$(\Delta\nu/\nu_o)$x$(\theta_o/\theta_{synth}) \sim 2 \Rightarrow I_o/I = 0.5 \Rightarrow$ worse at higher resolutions



Freq. (MHz)	BW (MHz)	A-config. θ_{synth} (")	Radius of PB_{FWHM} (')	θ_{MAX} (') for 50% degradation
74	1.5	25	350	41
330	6.0	6	75	11
1420	50	1.4	15	1.3

Solution: spectral line mode (already essential for RFI excision)

Radio Frequency Interferences (RFI) :

As at cm wavelengths, natural and man-generated RFI are a nuisance
– Getting "better" at low freq., relative BW for commercial use is low

VLA
74 MHz → origin in VLA (comb predictable), some are external.
.327 MHz → externally generated (completely random)
Can be wideband (C & D configurations), mostly narrowband

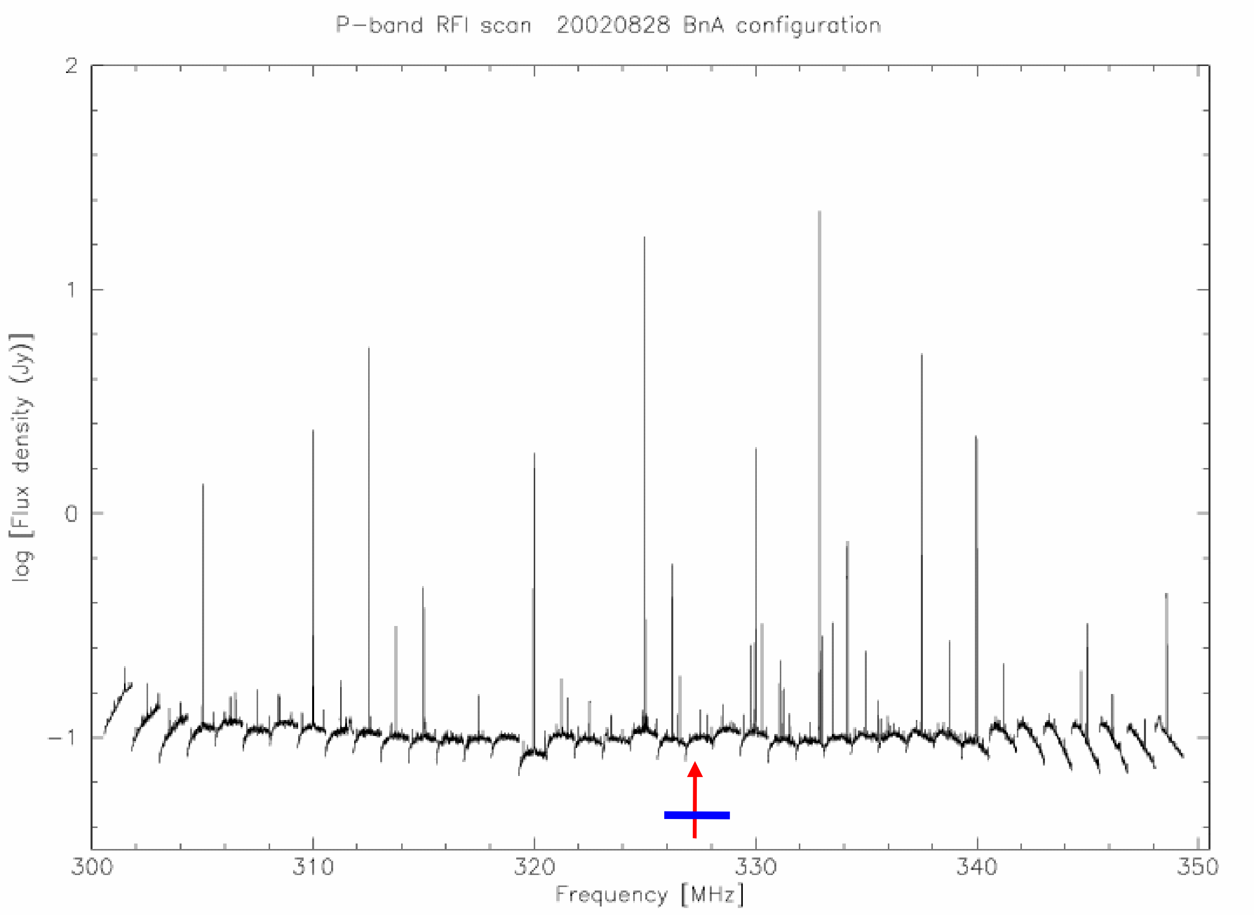
Solar effects (non predictable): Sun bursts, geomagnetic storms, scintillations

IONOSPHERE: partially stable in daytime and nigh time
unstable at the sunrise and sunset

... Mitigated observing in `LINE MODE`

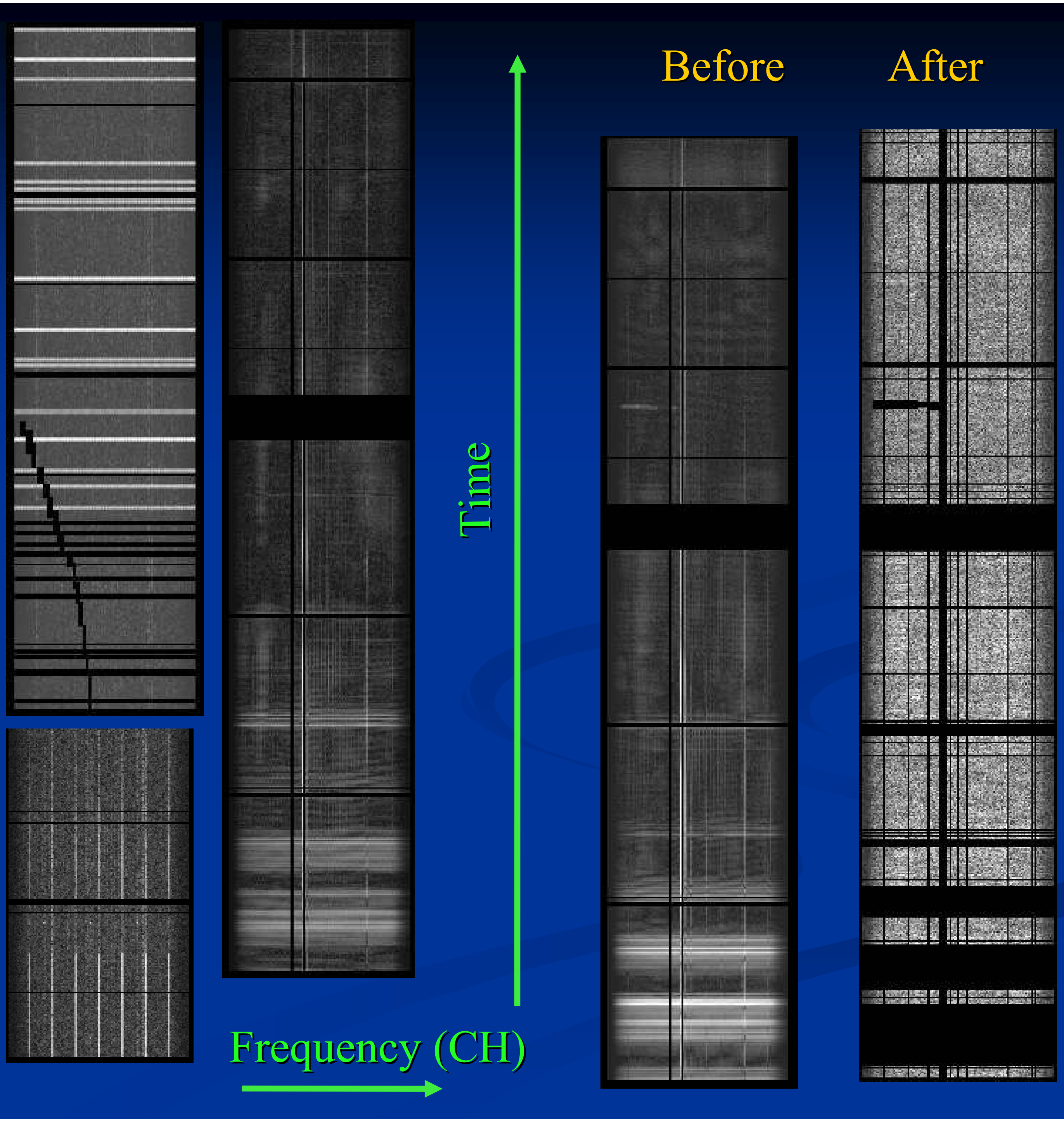
RFI can usually be edited out – tedious but "doable"

Radio Frequency Interferences (RFI) :



RFI EXCISION

For each baseline →



RFI EXCISION

Approach: averaging data in time and/or frequency makes it easier to isolate RFI, which averages coherently, from Gaussian noise, which does not

- Once identified, the affected times/baselines can be flagged in the un-averaged dataset

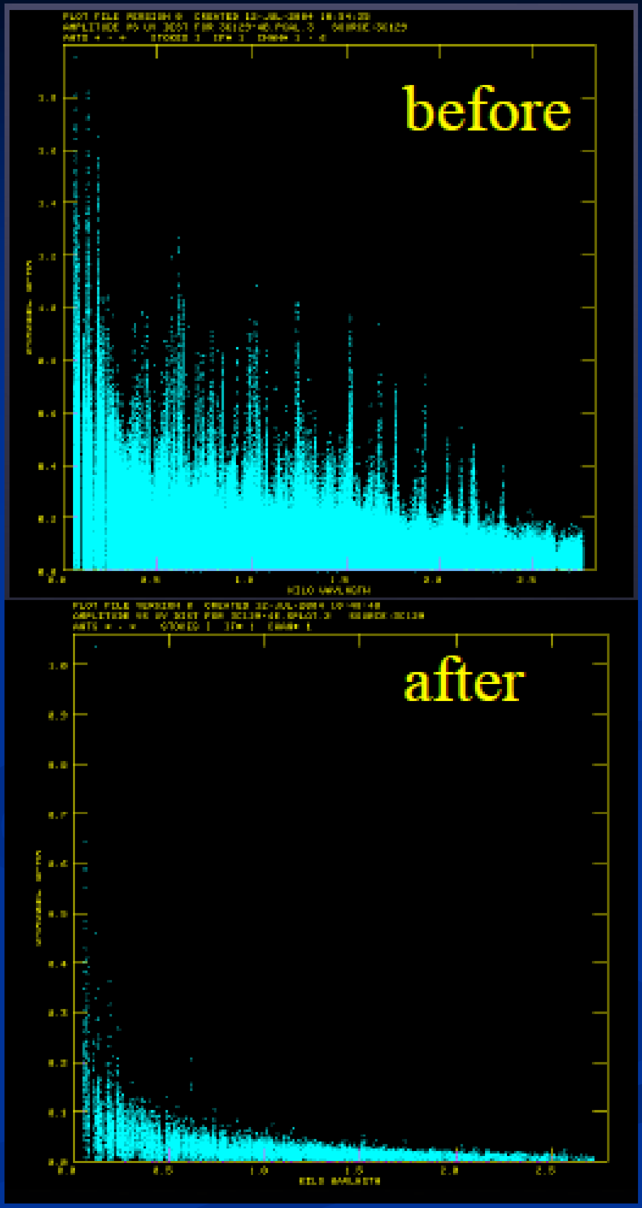
- Where to start?

AIPS tasks: QUACK, SPFLG, TVFLG, UVPLT, UVFND, UVFLG, UVSUB, CLIP, FLGIT, FLAGR, RFI, ...

CASA tasks: plotxy, flagdata

Obit tasks: AutoFlag, MednFlag

- Stokes V can be helpful to identify interference signals



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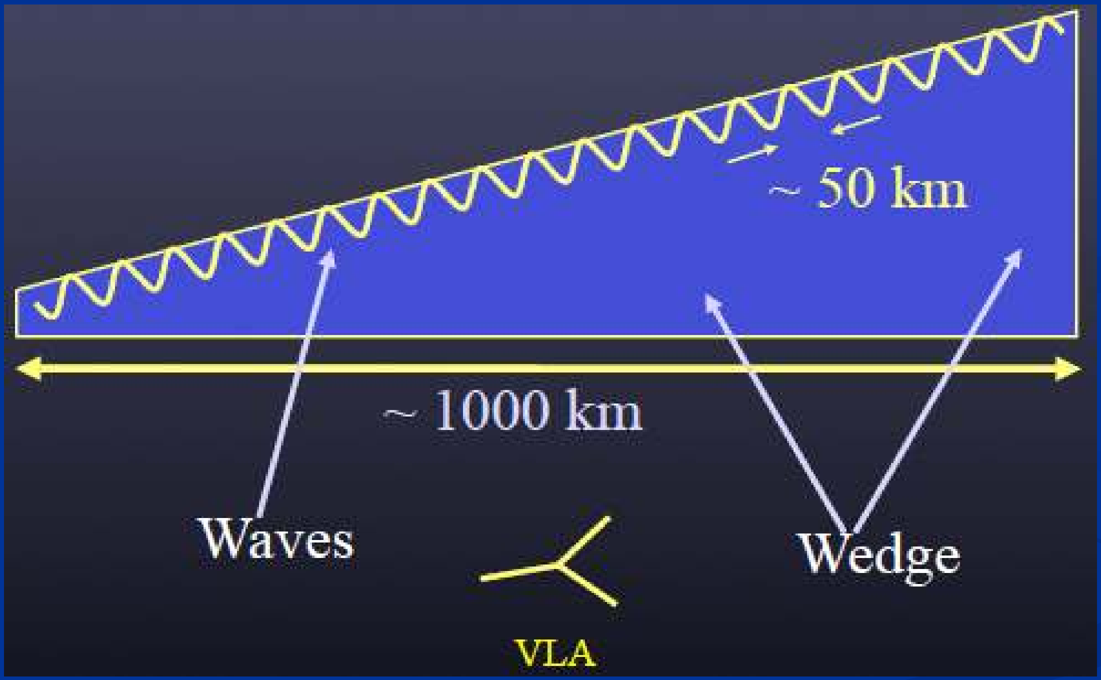


Isoplanatic patch

DEF: The area where the wavefront remain plane.

- At low frequency, the wide FOV is characterized by several isoplanatic patches. The IONOSPHERE behave as a variable refractive medium.
- Effect is contained in small dimension telescopes.
- Estimated isoplanatic patch size at 74 MHz is ~ 4°, the FOV~12°.

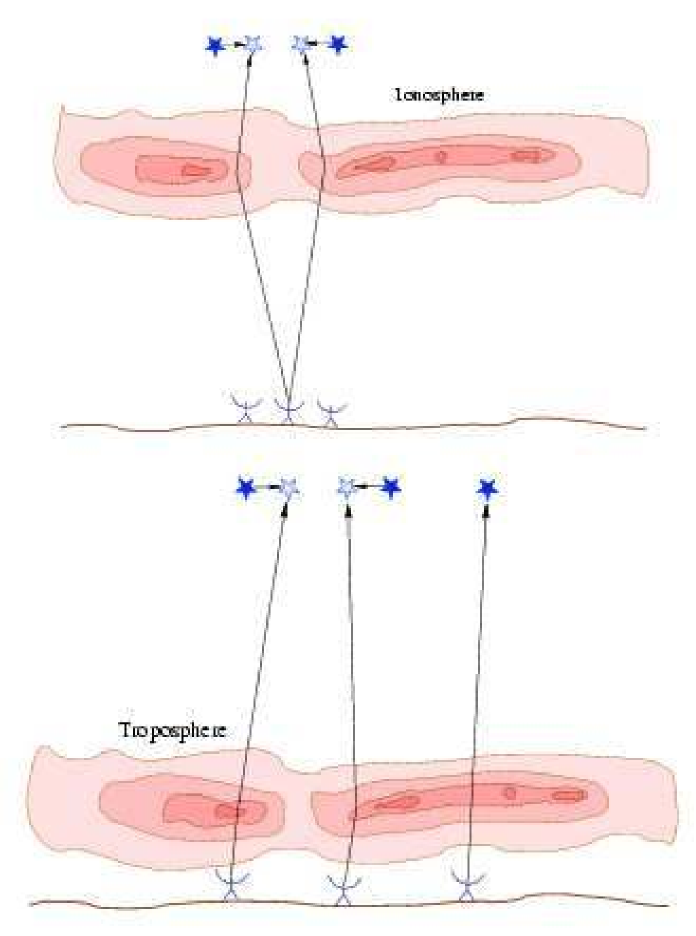
↓

- Needed a new technique of calibration:

the phase calibrator must be in the same isoplanatic patch of the target source.

Analogy with the optical astronomy…

Isoplanatic patch



WIDE FIELD OF VIEW from PROBLEM to ADVANTAGE

...observing in continuous LINE MODE:
dividing the bandwidth in channels → solve bandwidth smearing

Wide FOV + low frequency = huge n° of sources in the field

↓ ↓ ↓

SELF CALIBRATION at 330 MHz

MODEL for the IONOSPHERE at 74 MHz

Self Calibration :'Dealing' with the Ionosphere

- Self-calibration models ionosphere as a time-variable antenna based phase: $\phi_i(t)$
- Loop consisting of imaging and self-calibration

Typical approach is to use a priori sky-based model such as NVSS, WENSS, or higher frequency source model (AIPS: SETFC, FACES, CALIB, IMAGR)

freezes out time variable refraction and ties positions to known sky-model

This method assumes a single ionospheric solution applies to entire FOV

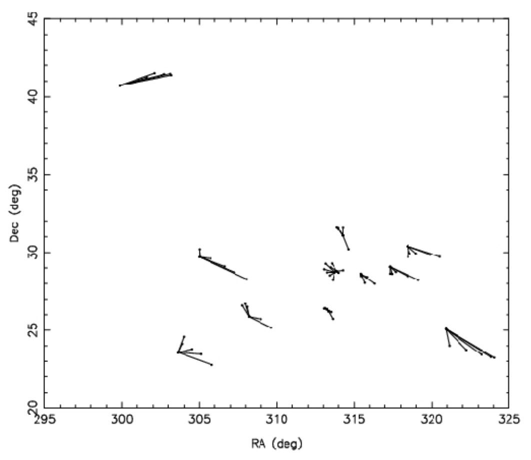
- Problems remain with standard self-calibration:

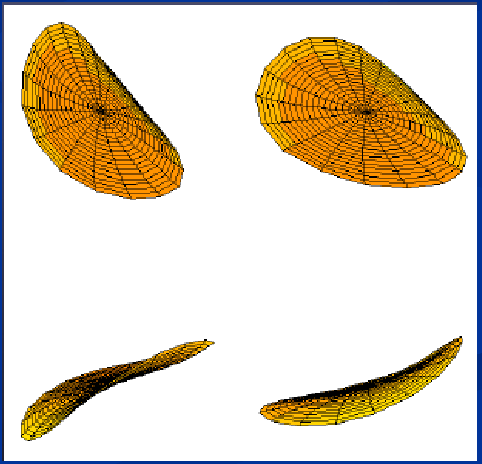
– often fails if target is not brightest source in FoV
– also issues of differential refraction, image distortion, reduced sensitivity
– Ultimate solution: selfcal solutions with angular dependence $\phi i(t) \longrightarrow \phi i(t, \alpha, \delta)$

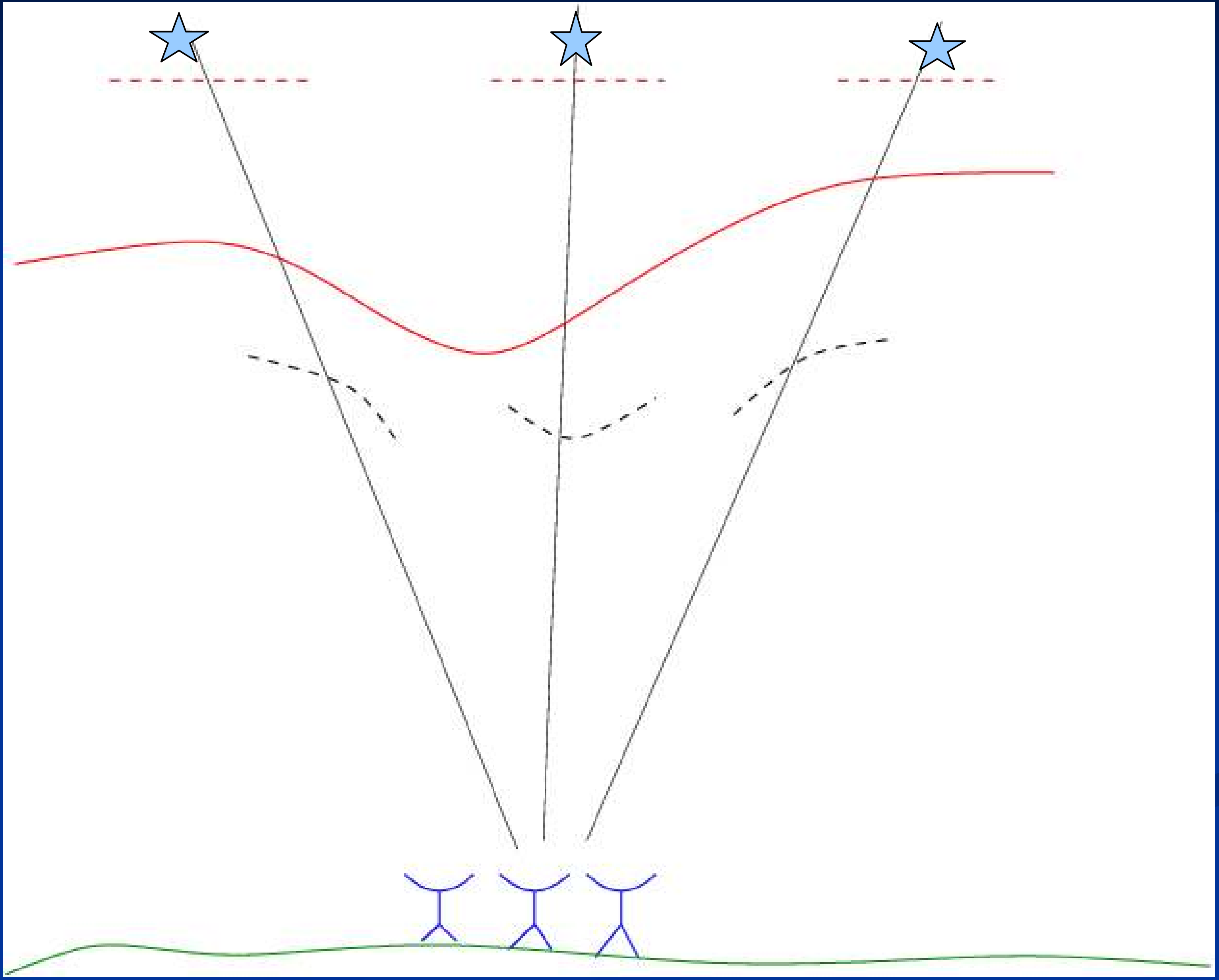
Developed by Bill Cotton (NRAO)

Field Based Calibration

- Zernike polynomial phase screen
  - Delivers astrometrically correct images
  - Takes snapshot images of bright sources to compare to NVSS positions
  - Fits phase delay screen rendered as a plane (3-D viewed from different angles)
  - Apply time varying phase delay screens while imaging







Field Based Calibration

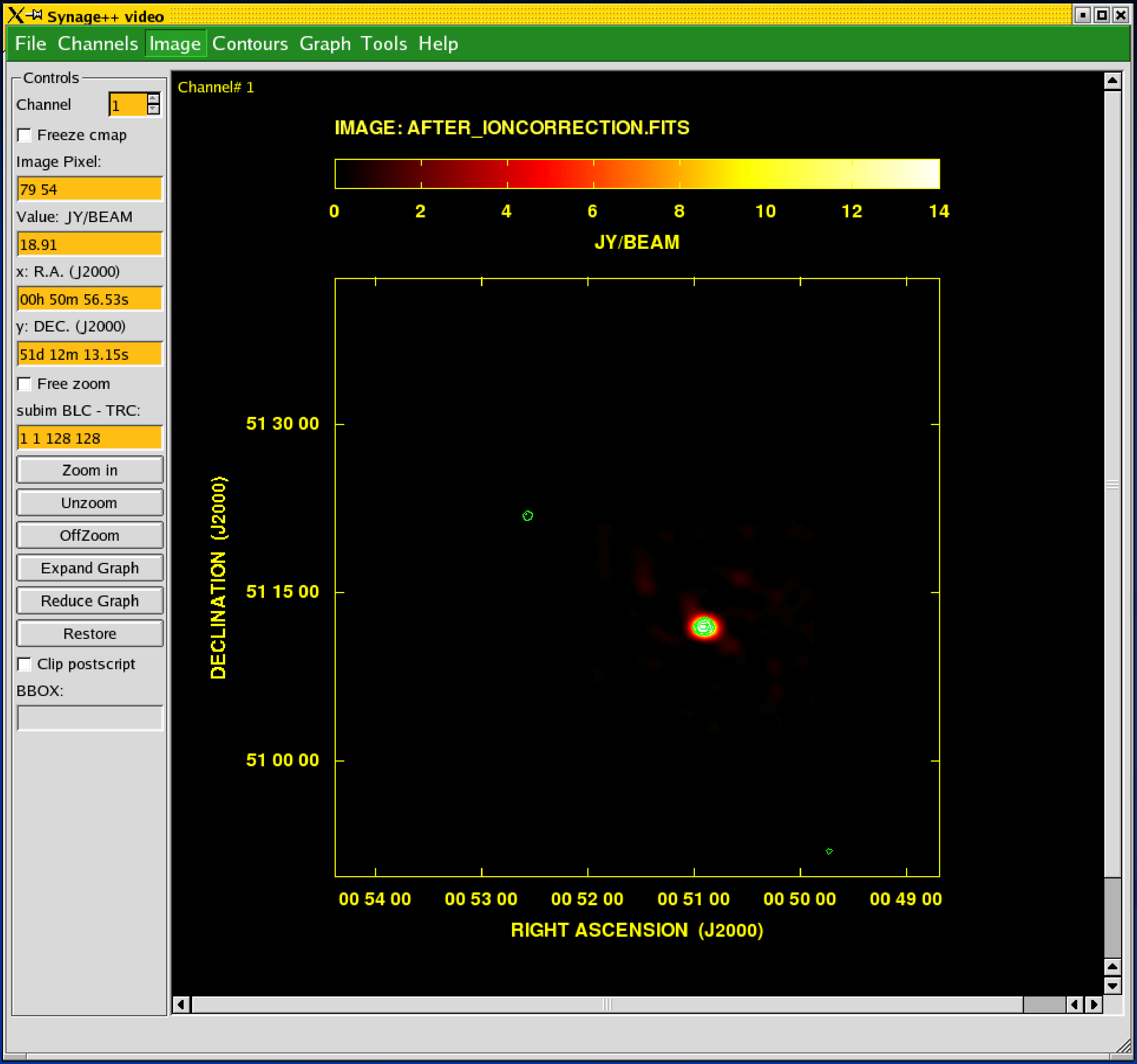
Problems remain with field based calibration: :

Need high S/N, significant data loss under poor ionospheric conditions

Total flux should be dominated by point sources

Good for baselines < 12 km

New tools needed for next generation of instruments with BL > 200 km



Channel 1

☐ Freeze cmap

Image Pixel: 79 54

Value: JY/BEAM 18.91

x: R.A. (J2000) 00h 50m 56.53s

y: DEC. (J2000) 51d 12m 13.15s

☐ Free zoom

subim BLC - TRC: 1 1 128 128

☐ Clip postscript

BBOX:

Summary

"Line Mode" observations	correction for the bandwidth smearing mitigation for RFI
Wide FOV	permits to create a model for the ionosphere calibration & self-calibration

IN CONTINUOUS EVOLUTION

Data Reduction: AIPS
CALIBRATION: Amplitude, Phase , Bandpass
EDITING: task SPFLG, UVLFG, CLIP… ~ 10-30% flagged data
SPLAT

74 MHz
Wide Field Imaging
Ionospheric correction with VLAFM (B. Cotton)
Self Calibration

327 MHz
Wide Field Imaging
(SETFC+IMAGR)
Self Calibration

Current Low Frequency Interferometers

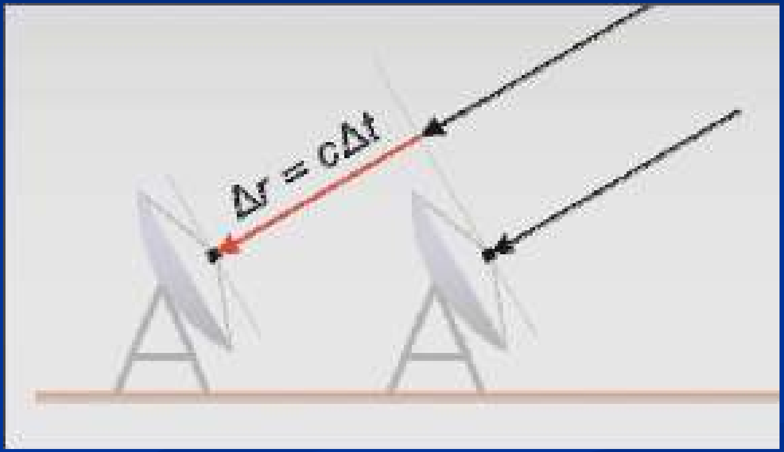
Two Receivers:
330 MHz = 90cm
PB ~ 2.5O (FOV ~ 5° -- res ~ 6")
74 MHz = 400cm
PB ~ 12O (FOV ~ 14°-- res ~ 24")

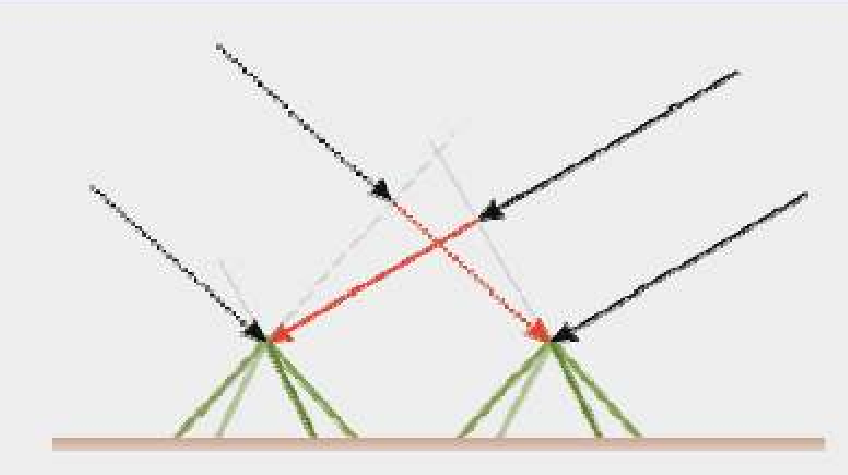
Five Receivers:
153 MHz = 190cm
PB ~ 3.8° (res ~ 20")
235 MHz = 128cm
PB ~ 2.5° (res ~ 12")
325 MHz = 90cm
PB ~ 1.8° (res ~ 9")
610 MHz = 50cm
PB ~ 0.9° (res ~ 5")

Next Generation of Low Frequency Instruments

- Next generation low frequency telescopes will have no moving parts:

- traditional interferometry uses delays
to combine signals from different antennas
- instantaneously limited to a single
look-direction on the sky





- dipole arrays are sensitive to the entire sky
- different delays allow systems to
simultaneously **beam form in multiple different directions**

LOw Frequency Array (LOFAR)

- Under construction in the NL
+ DE..EU..

- Two frequency bands:
- low band -- 30-80 MHz
- high band -- 120-240 MHz

- Baselines to 100 km with
European expansion to 1000 km

- Science Drivers:
- Epoch of Reionization
- Extragalactic Surveys
- Transients and Pulsars
- Cosmic Rays

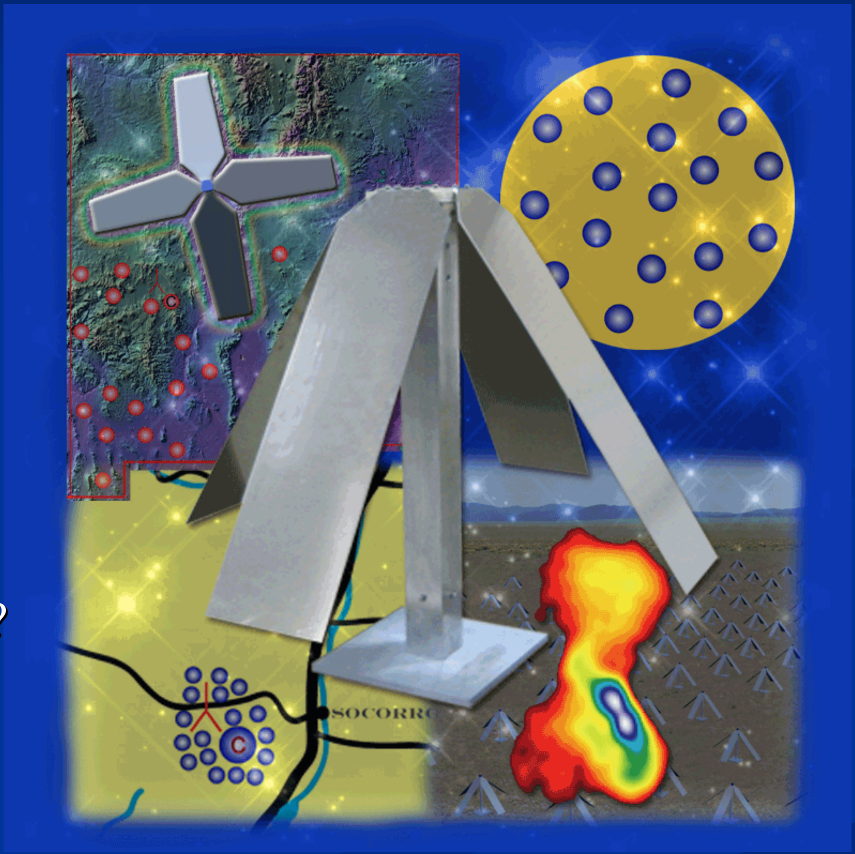
Long Wavelength Array (LWA)

- Under construction in New Mexico:
- Frequency range: 20-80 MHz, BL < 400 km
- Science Drivers:

- Cosmic Evolution & The High Redshift Universe
- pre-reionization – Dark Ages
- 1st super-massive black holes
- LSS - Dark Matter & Dark Energy
- Acceleration of Relativistic Particles in:
- SNRs in normal galaxies up to 10^{15} eV
- Radio galaxies & clusters up to 10^{19} eV
- Ultra high energy cosmic rays up to 10^{21} eV?

-Plasma Astrophysics & Space Science
- Ionospheric waves & turbulence
- Solar, Planetary, & Space Weather Science
- Acceleration, Turbulence, & Propagation

-Exploration Science
- Maximizes the opportunity for Discovery Science through flexibility



Murchison Widefield Array (MWA)

- Under construction in W. Australia:

- Frequency range: 80-300 MHz, BL < 3 km (most < 1.5 km)

- Science Drivers:

- Epoch of Reionization
- Solar, Heliosphere and Ionosphere

References:

Emanuela Orru´ PhD Thesis: *Low Frequency spectral studies of extragalactic radio sources.*

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From Clark Lake to the Long Wavelength Array: Bill Erickson's Radio Science,
ASP Conference Series 345

The 74 MHz System on the Very Large Array, Kassim et al. 2007, ApJS, 172, 686

Tracy Clarke Talk: *Low Frequency Interferometry, Eleventh Synthesis Imaging Workshop*
Socorro, June 10-17, 2008