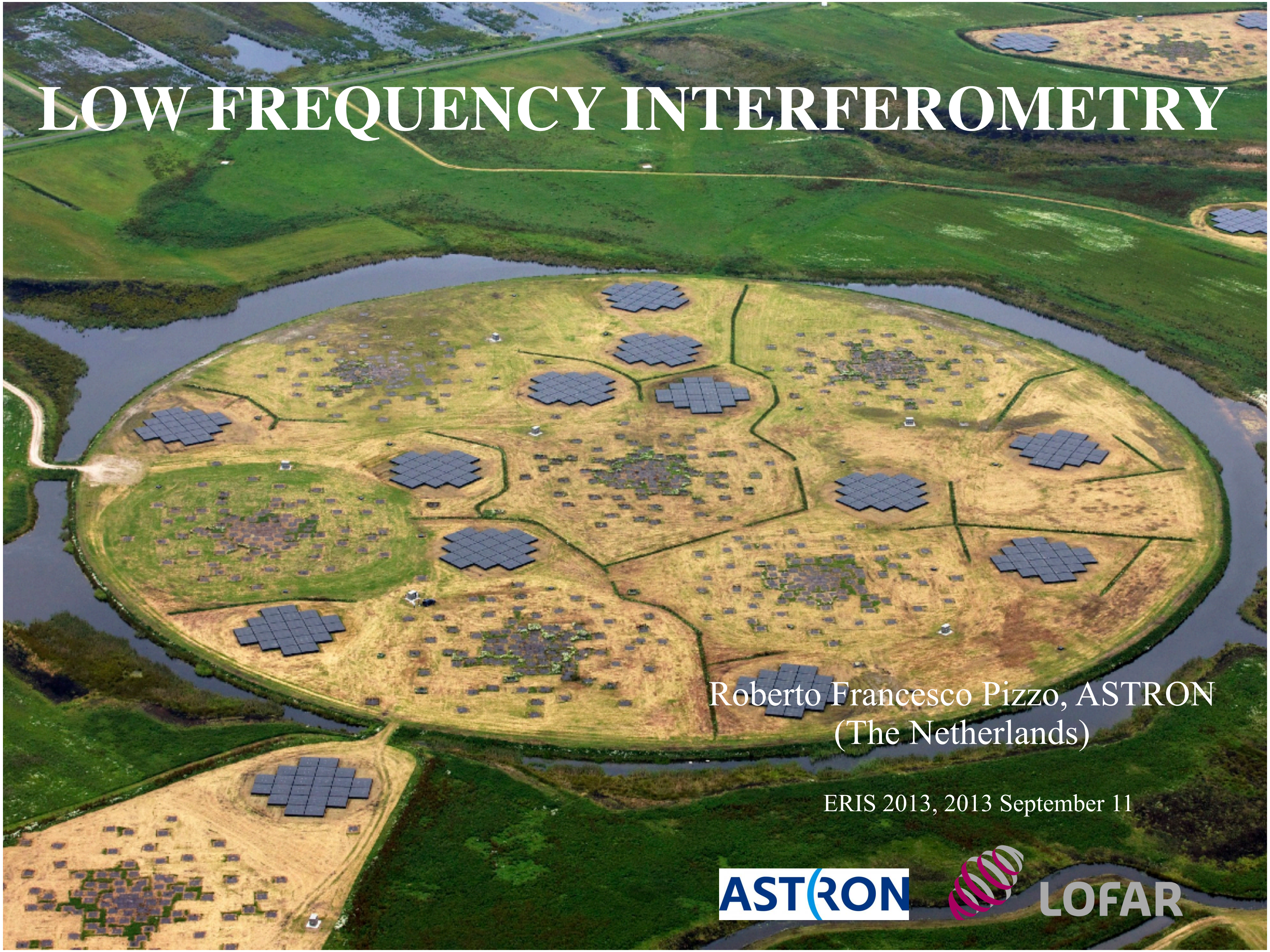
LOW FREQUENCY INTERFEROMETRY



Roberto Francesco Pizzo, ASTRON
(The Netherlands)

ERIS 2013, 2013 September 11

ASTRON LOFAR

OUTLINE

- ✓ Definition
- ✓ History
- ✓ What is to be investigated?
- ✓ The end and the new beginning of LF interferometry
- ✓ Ionosphere
- ✓ RFI
- ✓ A-team removal
- ✓ Large FOV ➔ all-sky imaging
- ✓ Polarization issues

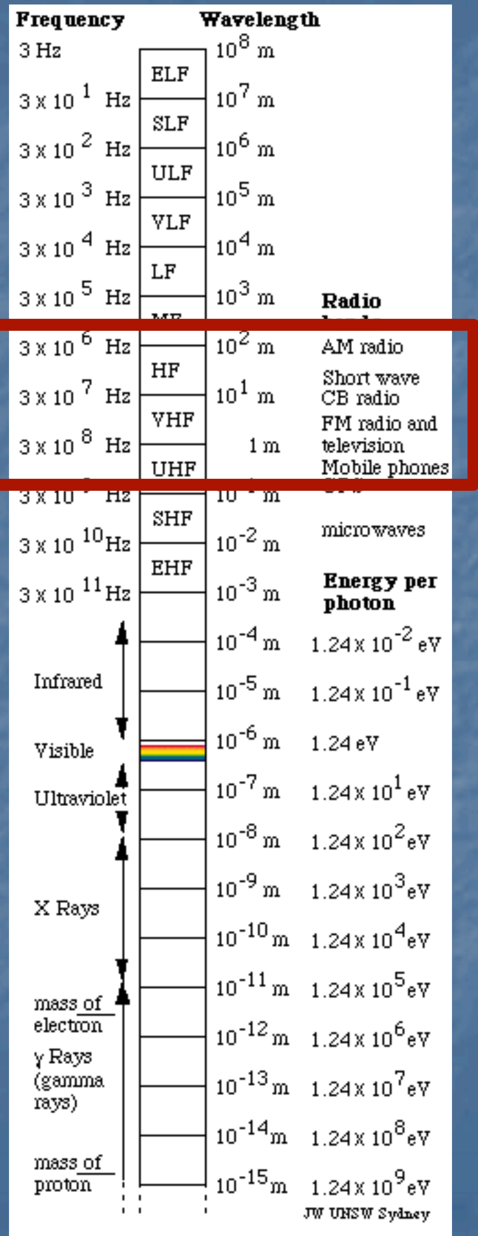
WHAT IS LOW FREQUENCY?

- ✓ The general definition of low frequency is (Wikipedia): "Low frequency or low freq or LF refers to radio frequencies (RF) in the range of 30 kHz–300 kHz"

↓

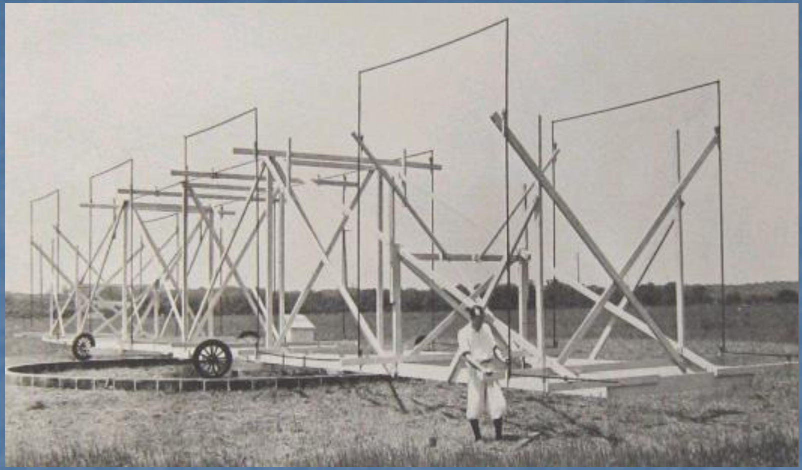
NOT THE GENERAL DEFINITION USED BY ASTRONOMERS

- ✓ LF radio astronomy ranges between 3 - 400 MHz
- ✓ Ground-based instrument have 10 MHz as a lower limit due to reflection of the signal by the ionosphere.

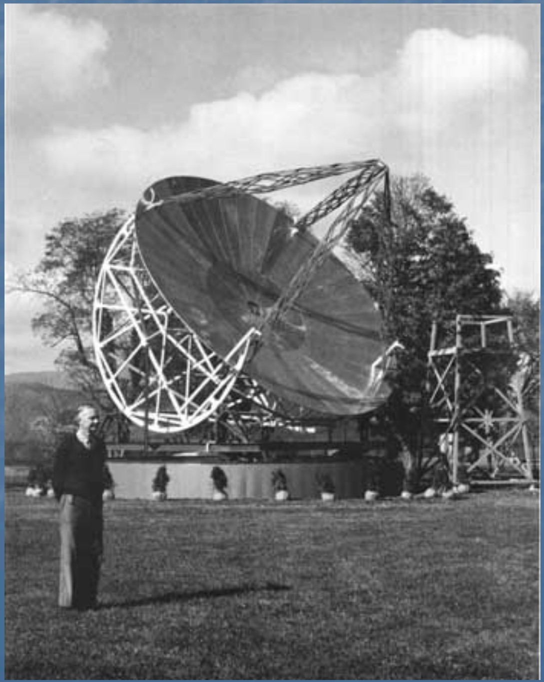


HISTORY OF LOW FREQUENCY INTERFEROMETRY (I)

- ✓ 1931-35 - Jansky: Birth of Radio astronomy, discovery of Galactic emission $\nu \sim 15 - 30$ MHz



- ✓ 1935-45 – Reber: discovery of non-thermal emission



160 MHz, resolution=12°

HISTORY OF LOW FREQUENCY INTERFEROMETRY (II)

- ✓ 1946 – Ryle: construction of the first 2-element interferometer
- ✓ 1955 – Kraus et al.: first all sky survey (ν = 80 MHz)
  Burke et al.: discovery of the first planetary radio emission (ν = 10 - 100 MHz)
- ✓ 1958-88 – Erickson: building of the Clarke Lake TPT (ν = 100 - 1400 MHz)
- ✓ 1962 – Bennet: completion of the first 3C catalogue (ν = 160 MHz)
- ✓ 1963 – Hazard Schmidt Sandage: discovery of the first quasar (ν = 178 MHz)
- ✓ 1967: first VLBI fringes (ν = 20 - 1400 MHz)
- ✓ 1968 – Bell: discovery of the first pulsar (ν = 81 MHz)
- ✓ 1975-90: completion of the Cambridge 8C catalogue

LOW FREQUENCY RADIO INTERFEROMETERS

Modern sensitive interferometers

LOFAR (NL – Europe)	10 - 240 MHz
WSRT (NL)	270 – 390 MHz
VLA (New Mexico - US)	300 – 350 MHz (later also 74 MHz)
GMRT (India)	150, 232, 325 MHz
LWA (New Mexico – US)	10 – 80 MHz
MWA (AUS)	80 – 300 MHz

Future arrays

SKA	< 70 --- 30000 MHz (?)

= with dipoles

LOW FREQUENCY RADIO INTERFEROMETERS

Mode	LOFAR (NL – Europe)	10 - 240 MHz
inter	WSRT (NL)	270 – 390 MHz
	VLA (New Mexico - US)	300 – 350 MHz (later also 74 MHz)

A PERFECT TIME TO DO LF RADIOASTRONOMY !!!

Future arrays	SKA	< 70 --- 30000 MHz (?)

= with dipoles

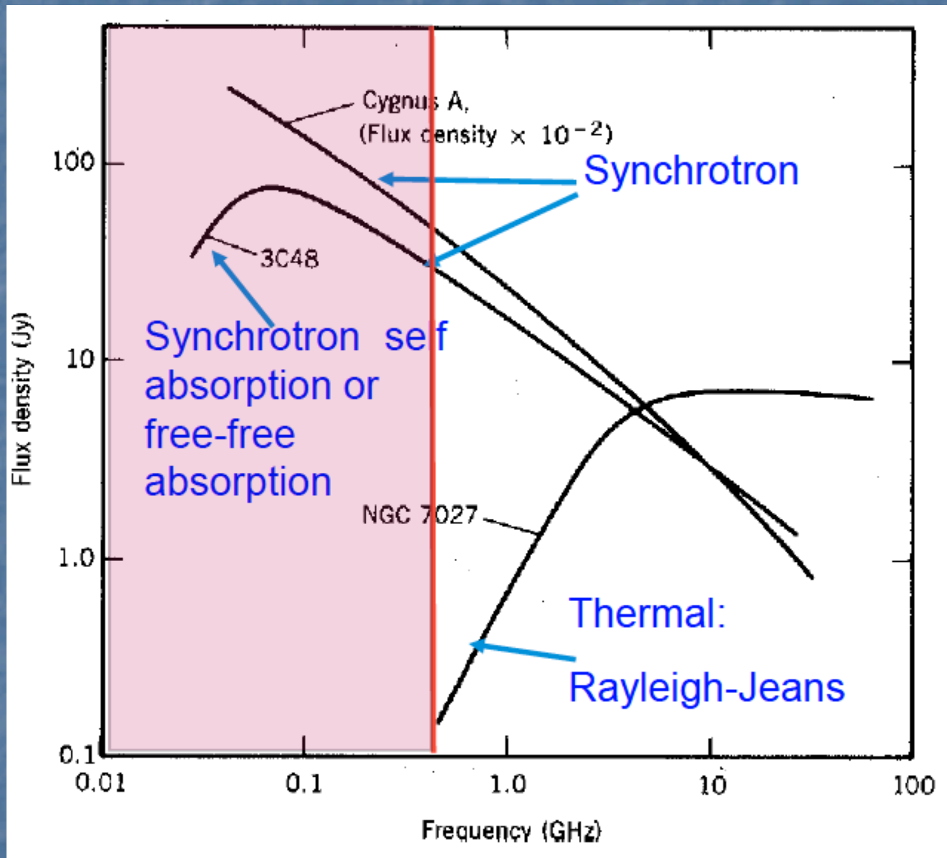
LOW FREQUENCY SKY: WHAT IS TO BE INVESTIGATED?

Synchrotron emission:

- Best detected at ν < 1 GHz ($S \propto \nu^{-\alpha}$)
- Particles spiraling around **B** lines
- Polarized
- Intensity depends on energy of *e* and strength of **B**

Thermal emission (Free-free, Bremsstrahlung):

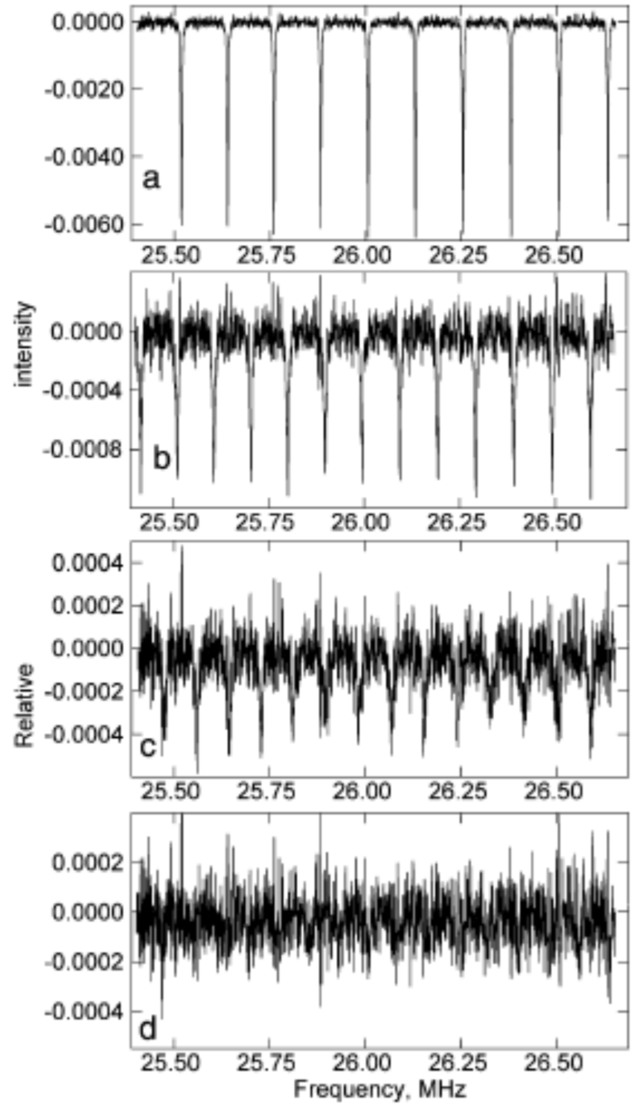
- Best observed at ν > 1 GHz
- Due to deflection of electrons by ions
- Depends on gas temperature



LOW FREQUENCY SKY: WHAT IS TO BE INVESTIGATED?

Radio recombination lines:

- Largely observed toward the Galactic plane and discrete sources. Detected n absorption below 150 MHz
- They provide a diagnostic of the physical condition of the poorly known cold ISM (temperature, density, level of ionization, abundance ratios, etc…



Cas A, 26 MHz Stepkin et al. 2007

SCIENCE UNIQUE TO LF RADIOASTRONOMY

Epoch of Reionization (highly redshifted 21 cm line)

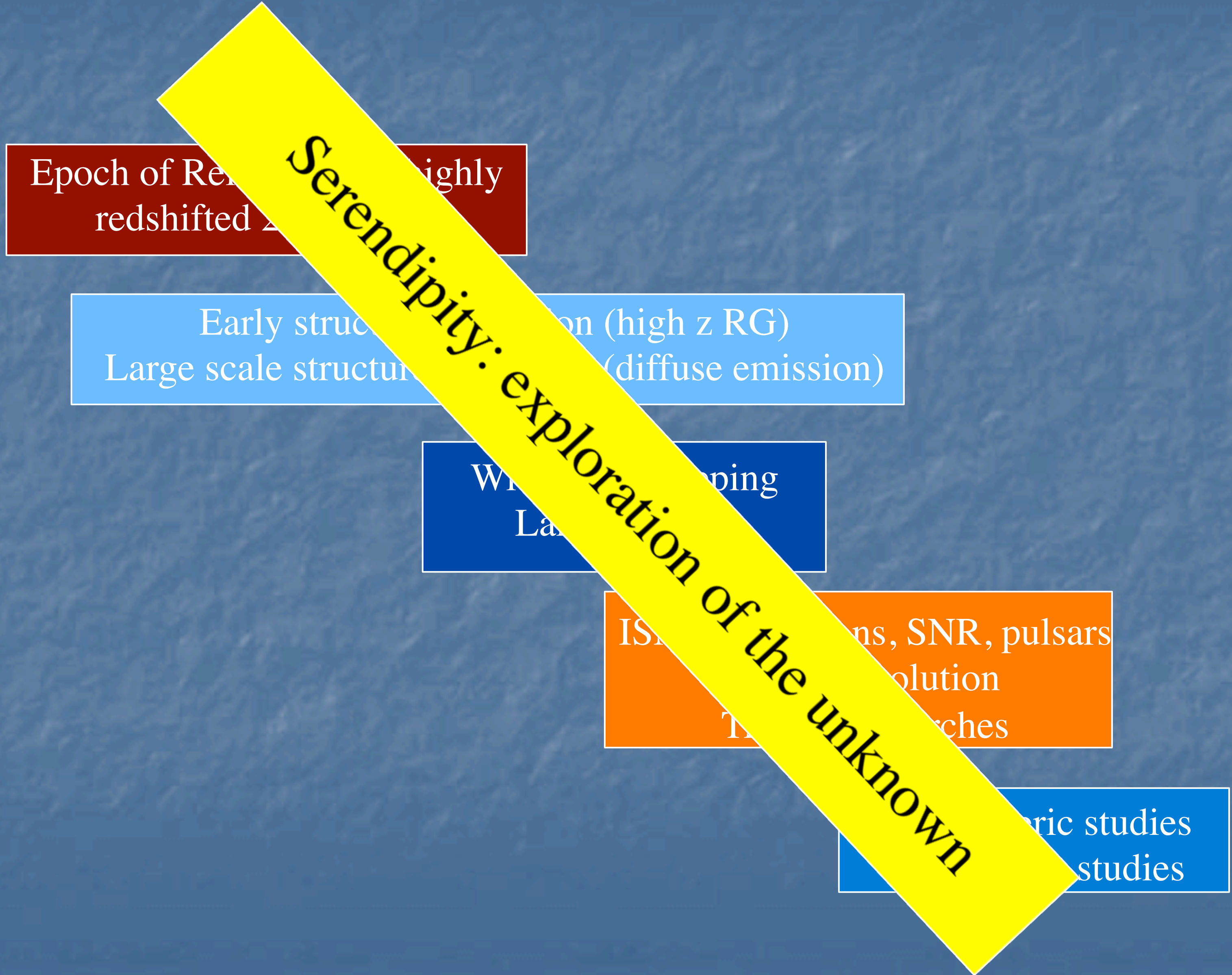
Early structure formation (high z RG)
Large scale structure formation (diffuse emission)

Wide field mapping
Large surveys

ISM, HII regions, SNR, pulsars
Galaxy evolution
Transient searches

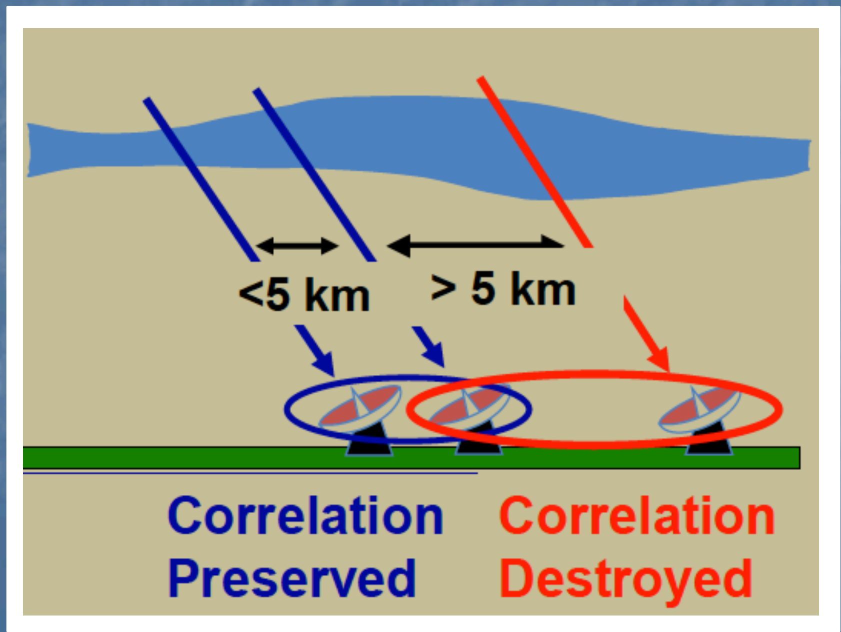
Ionospheric studies
Solar burst studies

SCIENCE UNIQUE TO LF RADIOASTRONOMY



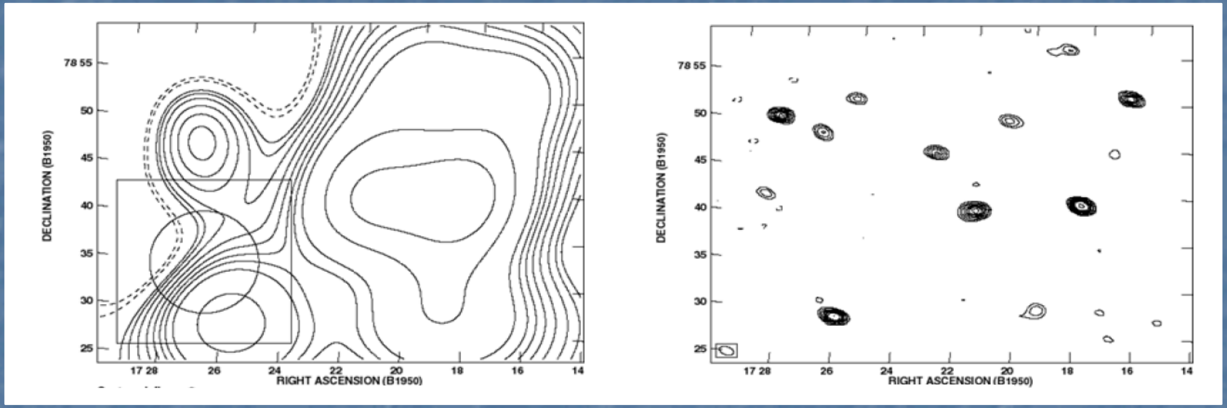
LIMITS OF LF RADIO ASTRONOMY: IONOSPHERIC BARRIER

- ✓ Spatial resolution increases with the antenna interferometer baseline: $\theta \sim \dfrac{\lambda}{D}$
- ✓ Large arrays of mechanically mounted parabolas are very costly!
- ✓ Low frequency instruments needed limited aperture due to the ionosphere (B < 5 km for ν < 100 MHz)



ABANDONING LF RADIO ASTRONOMY

- Confusion: it manifests in several fundamentally different ways, including main-beam, side-lobe, and classical confusion ➔ sensitivity degraded by $\sim \theta^2$



θ = 10', σ = 30 mJy/beam

θ = 1', σ = 3 mJy/beam

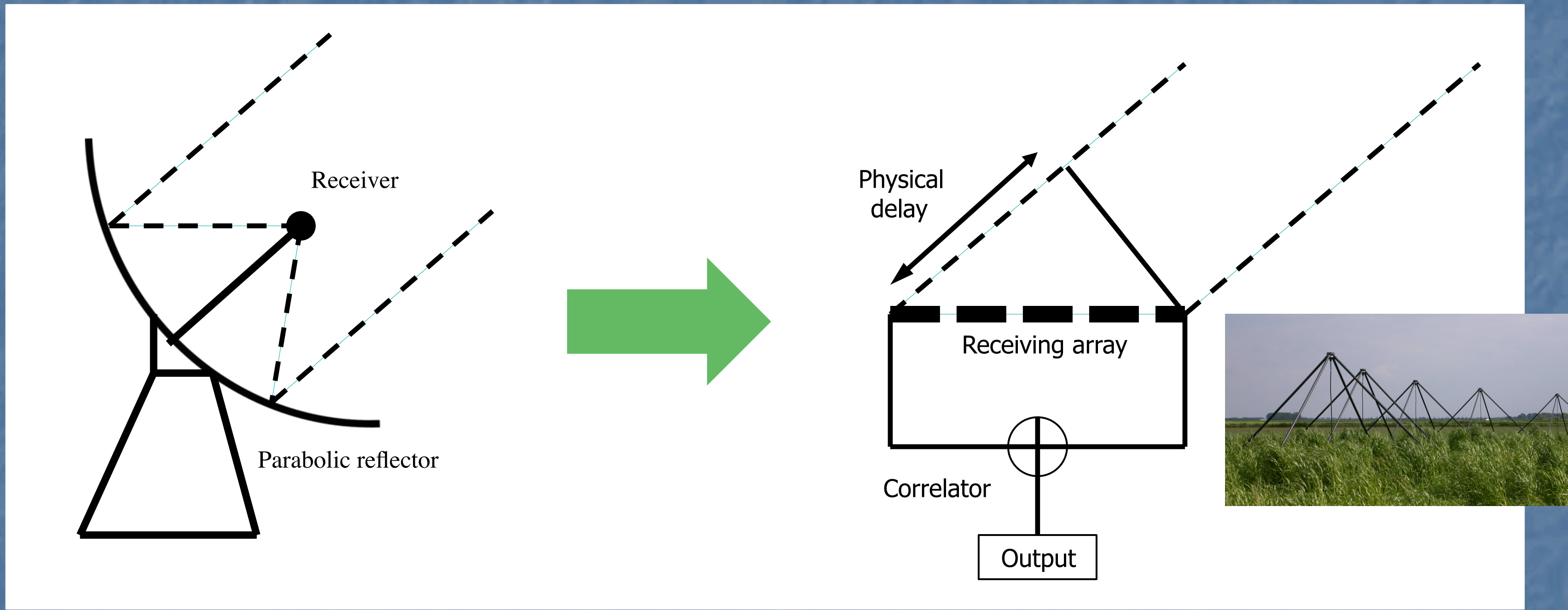
- Imaging of large fields of view posed enormous computing problems

- Removal of RFI (radio frequency interferences) was challenging

- Astronomers pushed for better resolution and continued their work at high frequencies.

WHY NEW INTEREST FOR LF RADIOASTRONOMY ?

We can use phased arrays: antennas in which the relative phases of the respective signals feeding the antennas are varied in such a way that the effective radiation pattern of the array is reinforced in a desired direction and suppressed in undesired directions



Enormous flexibility: electronic beamforming and ‘software telescope’

Advantages: a) replacement of mechanical beam forming by electronic signal processing
b) low frequency telescopes become economically affordable
c) multiple and independent beams can be formed at a time

WHY NEW INTEREST FOR LF RADIOASTRONOMY ?

because with the current capabilities of radio interferometers, we can …

- ✓ achieve 1000x better sensitivity,
- ✓ with an appropriate image quality (>10^4 dynamic range),
- ✓ at a resolution of 0.25-1.0 arcsec over the whole sky,
- ✓ do it in full polarization and do spectroscopy at z = 10,
- ✓ record down to 5 ns resolution,
- ✓ in somewhat difficult RFI conditions,
- ✓ and do this for many users simultaneously.

NOT AN EASY TASK…

The lower the observing frequency, the larger is the field of view (FOV) of your telescope ➔ LF observations require imaging and (self-)calibration of the whole sky.

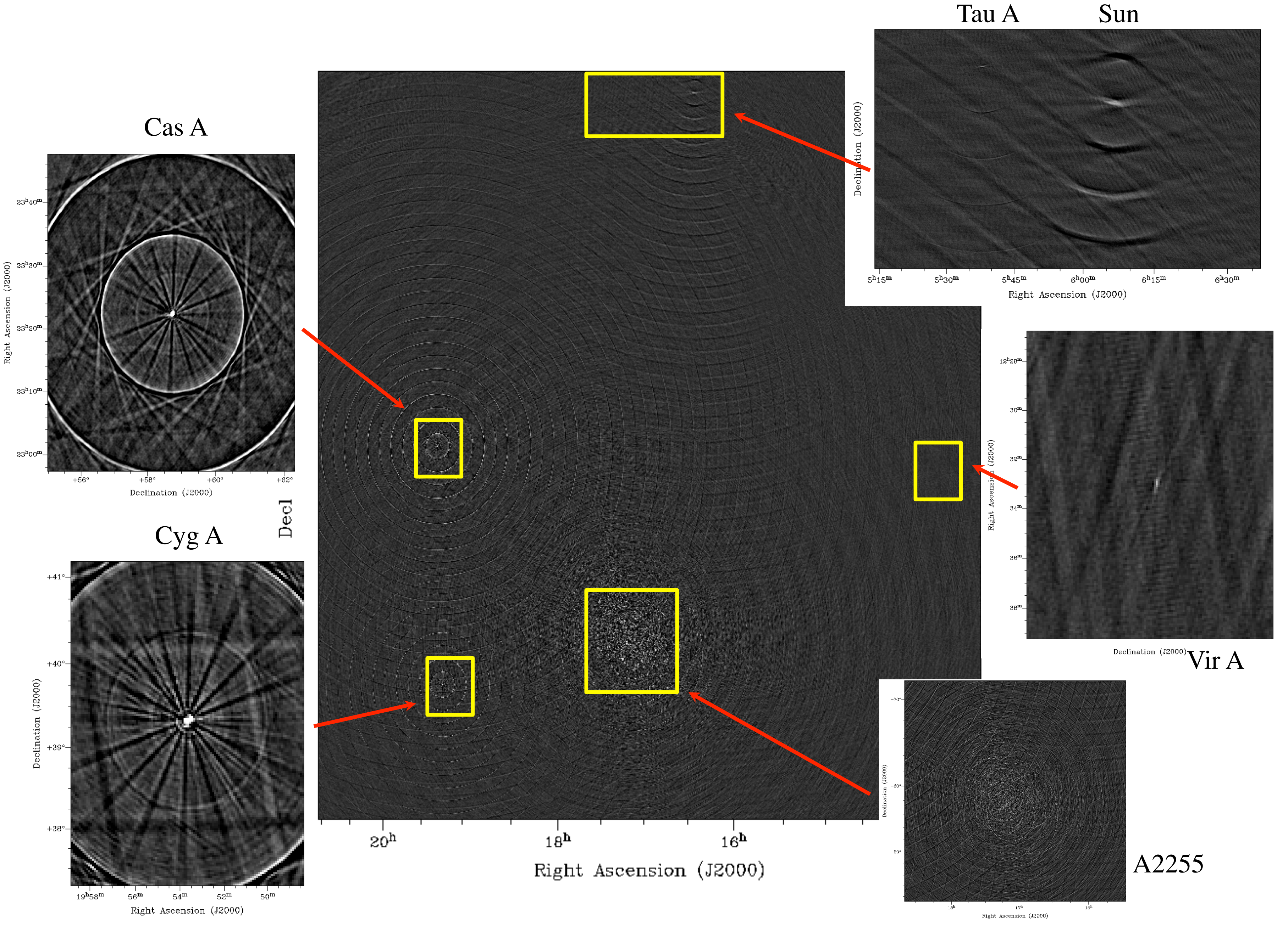
E.g. @ 100 MHz

① HPBW ~ 1.3 λ / D ~ 10° for D = 25 m (WSRT, VLA)

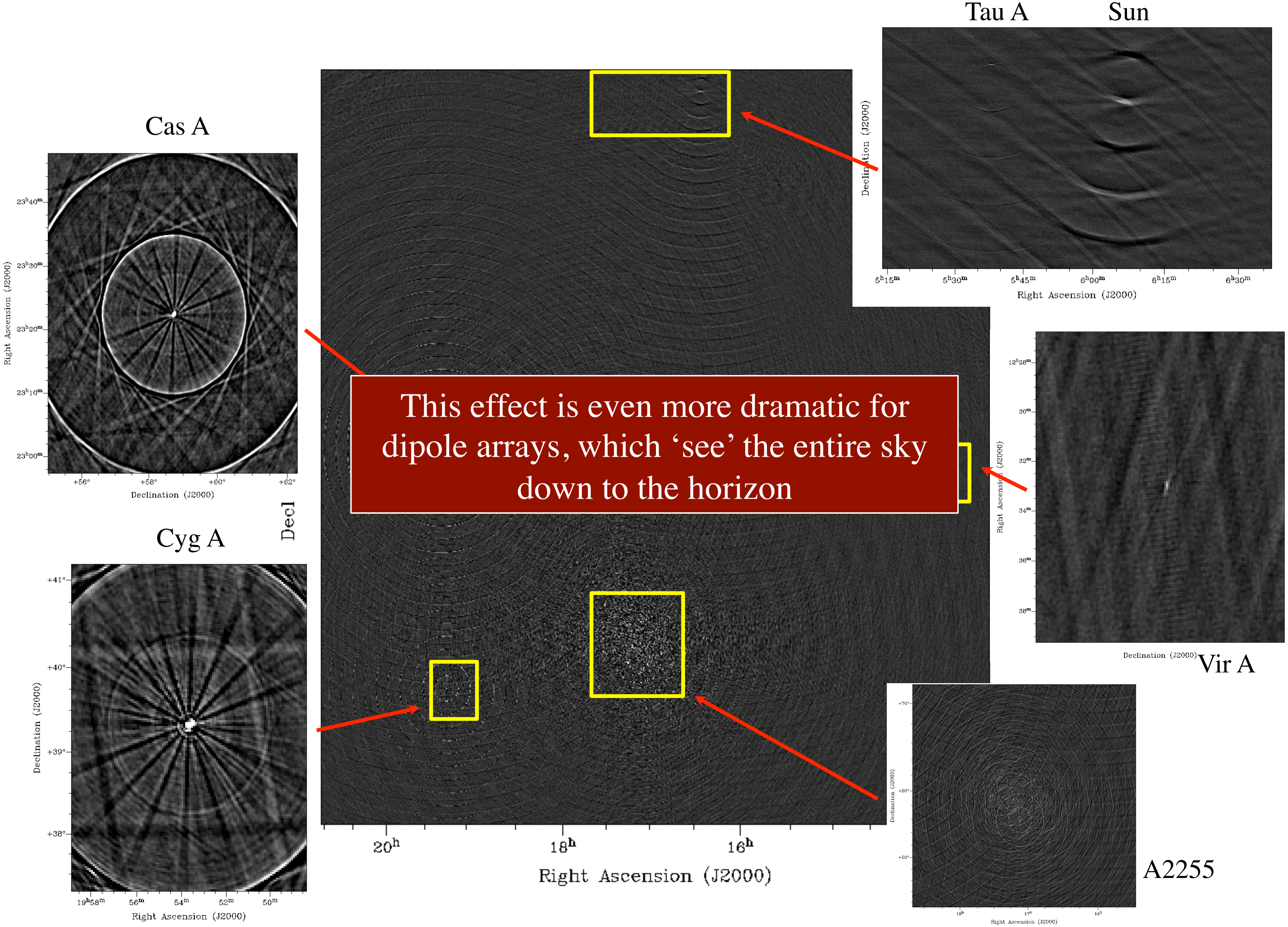
② A-team: CasA, CygA ~ 10.000 Jy
VirA, TauA ~ 1.000 Jy
Sun ~ > 10.000 – 1000,000 Jy

Even far from the field center, the (relatively) high distant sidelobe levels of the primary beam (‘only’ -30 to -40 db) keeps these sources very bright, giving rise to significant sidelobes in the final images.

THE A-TEAM around A2255 @ 115 MHz (WSRT)



THE A-TEAM around A2255 @ 115 MHz (WSRT)



This effect is even more dramatic for dipole arrays, which ‘see’ the entire sky down to the horizon

THE CHALLENGES OF LF RADIO IMAGING

The phase stability of the received signal is an important factor at whatever frequency we are working. Two main factors contribute to corrupt phase stability:

- Instrument (geometry + electronics)
- Atmosphere = troposphere + ionosphere

TROPOSPHERE: 0 - 10 km $\text{phase} \propto \nu$

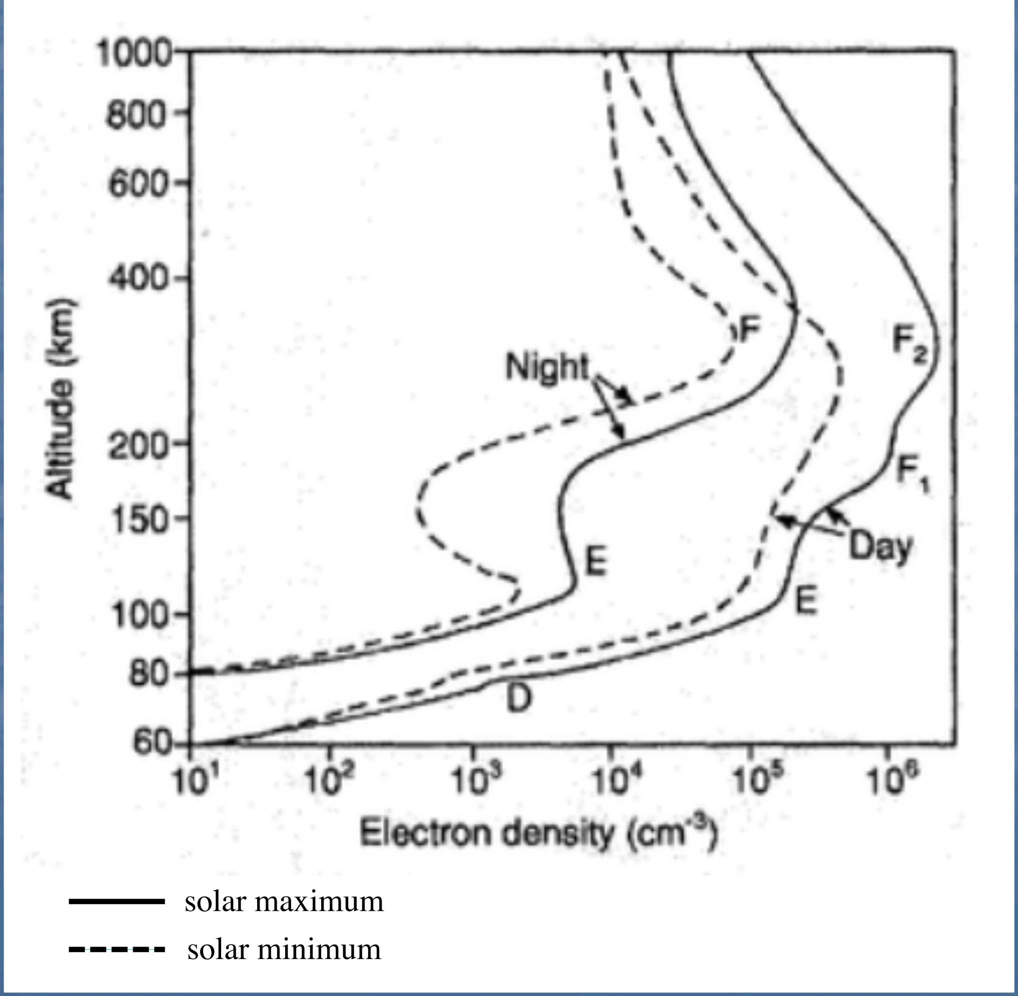
IONOSPHERE: 100 – 1000 km $\text{phase} \propto \nu^{-1}$

The ionospheric disturbances become progressively more important at low frequencies, while the tropospheric effect become negligible

LOOKING AT THE IONOSPHERE IS CRUCIAL

IONOSPHERE

Portion of the upper atmosphere, which extends from about 100 to 1000 km above the Earth, where ions and electrons are present in quantities sufficient to affect the propagation of electromagnetic waves

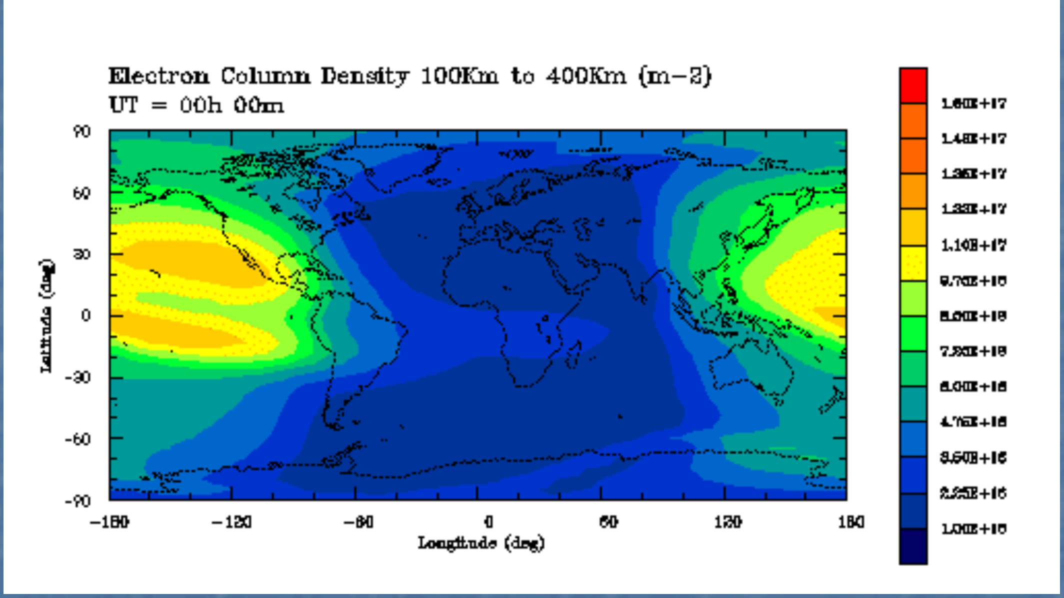


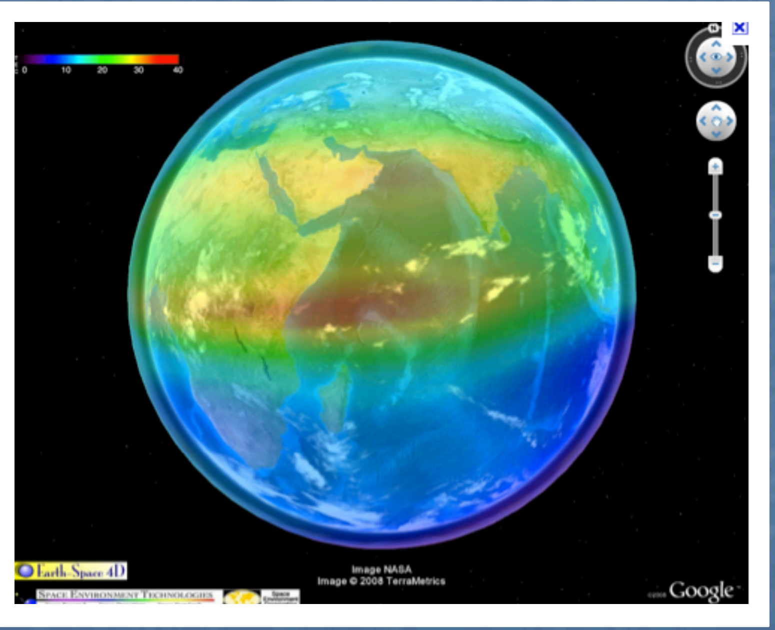
- ✓ During the day, molecules bombarded by solar X-ray and UV radiation ➔ 'ions' are produced. Recombination at night.
- ✓ Degree of ionization varies greatly with time (sunspot cycle, seasonally and diurnally) and geographical location (polar, mid-latitude, and equatorial regions)
- ✓ Refractive index: $n_r \simeq \sqrt{1-\left(\frac{\nu_p}{\nu}\right)^2}$

  where $\nu_p = 9.1\times10^3\sqrt{n_e}$
  When $\nu < \nu_p$, wave reflection
  (ν < 10 MHz)

VERTICAL TOTAL ELECTRON CONTENT

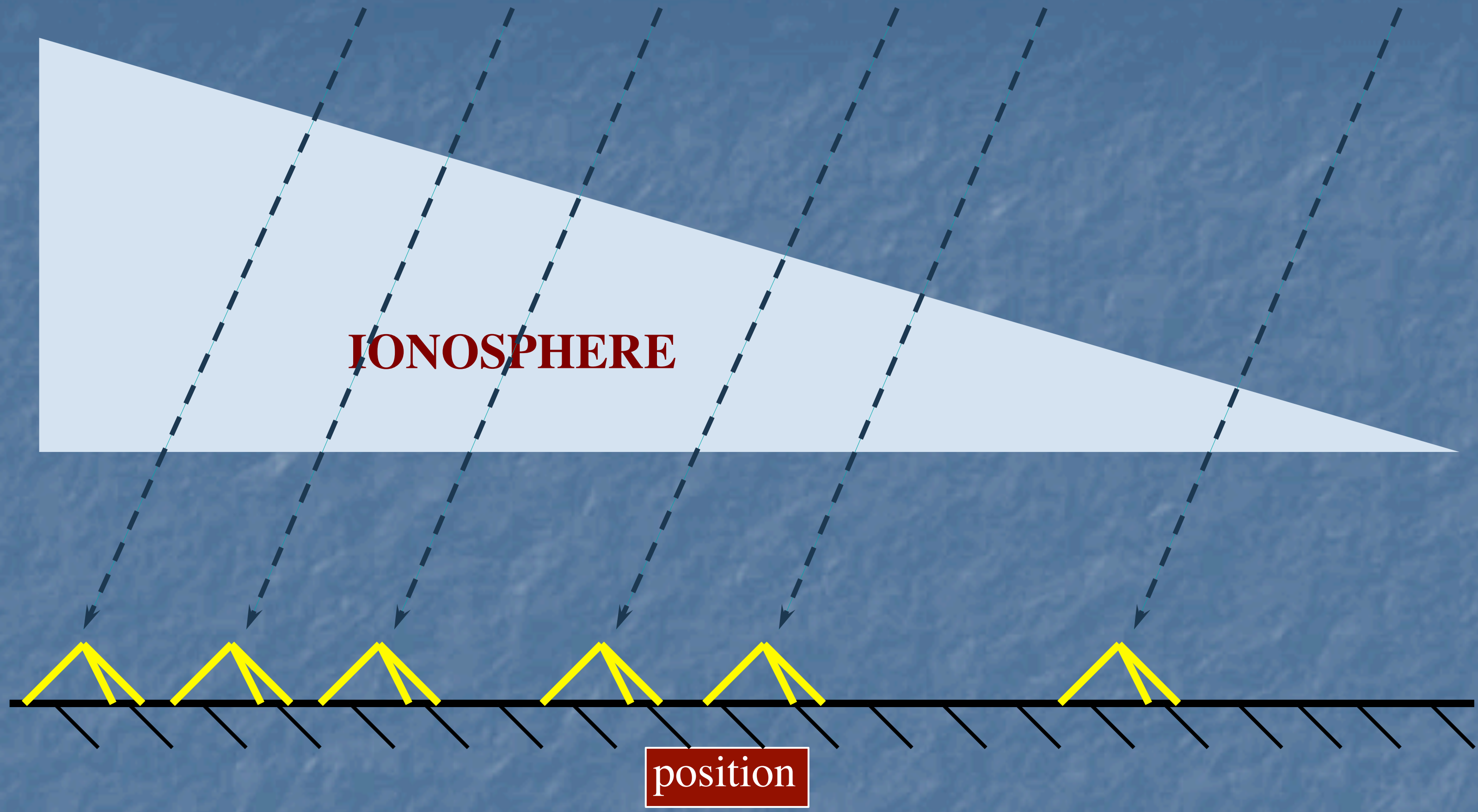
- ✓ Total number of electrons present along a path between two points, with units of electrons per square meter, where 10^{16} electrons/m^2 = 1 TEC unit (TECU)
- ✓ Data obtained through GPS satellites





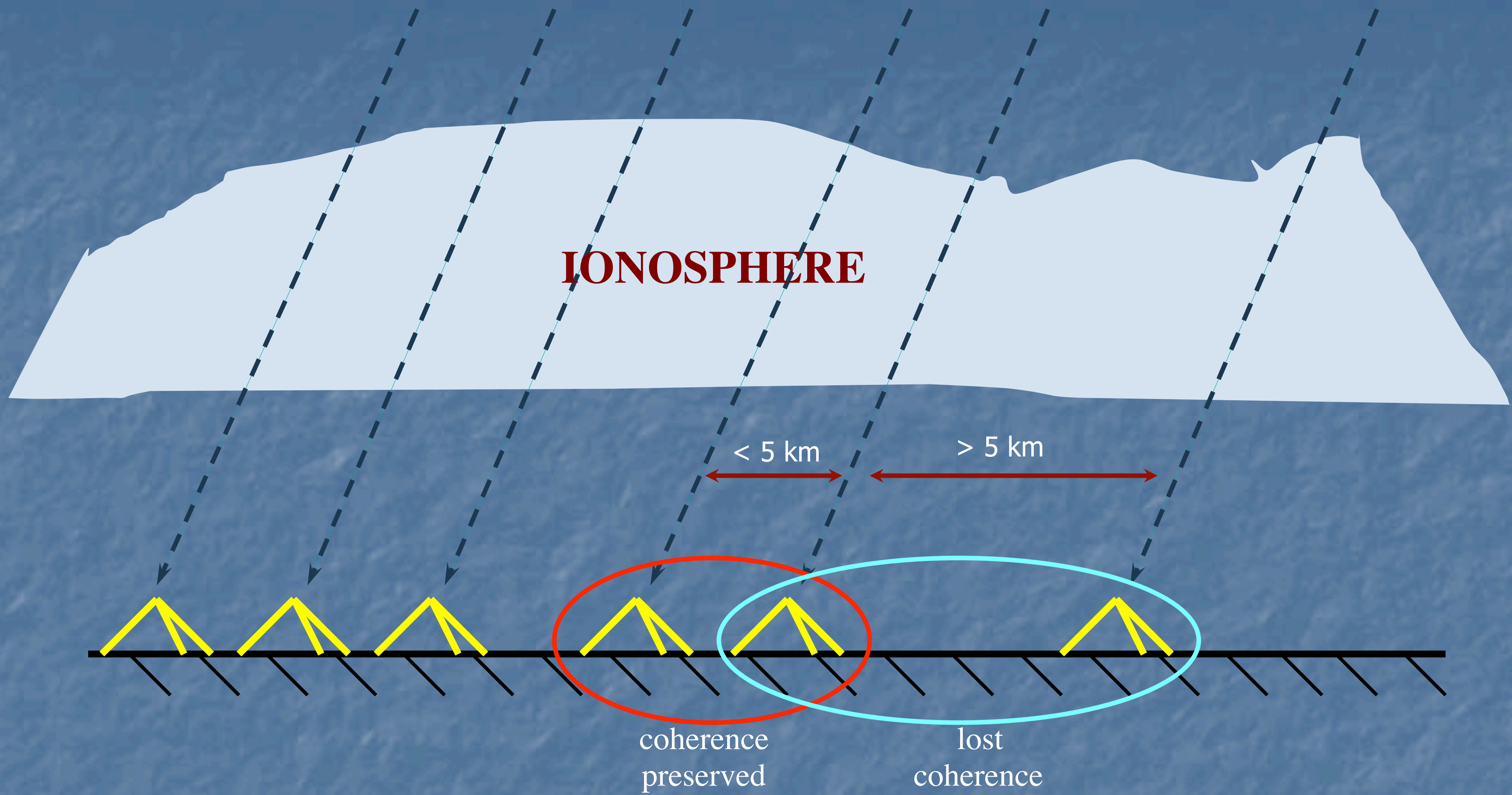
(movie courtesy of A. Burns, T. Killeen and W. Wang at the University of Michigan)

IONOSPHERIC WEDGE MODEL



- ✓ In the case of a simple ionosphere with smooth density fluctuations, the constant excess ionospheric phase can be solved for using self-calibration.

FOR LONG BASELINES…



- ✓ Over long distances, the ionospheric regions crossed by the signal have very different properties ➔ we loose the coherence of the signal – gradient approach fails (also for large separations in the sky)
- ✓ Minimum allowed baseline size given by the size scale of the Traveling Ionospheric Disturbancies (TDIs). For $\nu < 100$ MHz, coherence of the signal preserved for baseline length < 5 km

NON ISOPLANATICITY

- ✓ Variations of the ionospheric phase over the field of view are referred to as non isoplanaticity

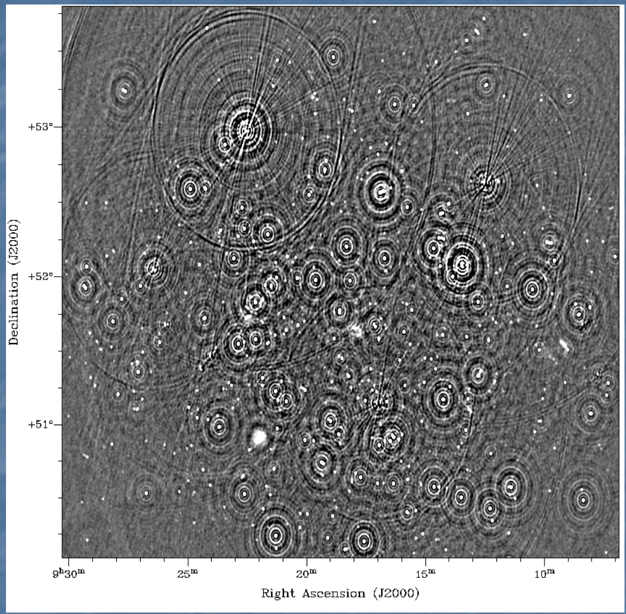
- ✓ At low frequencies, phase fluctuations are dominated by ionospheric effect also because primary beam is larger than the coherence length of the ionosphere

  the primary beam illuminates a portion of sky in which the ionosphere behaves as a *variable refractive medium*. The electromagnetic wave propagates through this wedge with different velocities, therefore with variable refractive indices

- ✓ Area in which the wavefront is still plane: isoplanatic patch

(SELF-)CALIBRATION AT LOW FREQUENCIES

✓ High dynamic range imaging seriously limited by the stability of the ionosphere



A773, WSRT @ 325 MHz

✓ Selfcal algorithm minimizes the differences between model and data by applying an average time-dependent correction to the field ➔ not ok when the FOV is large and samples various isoplanatic patches

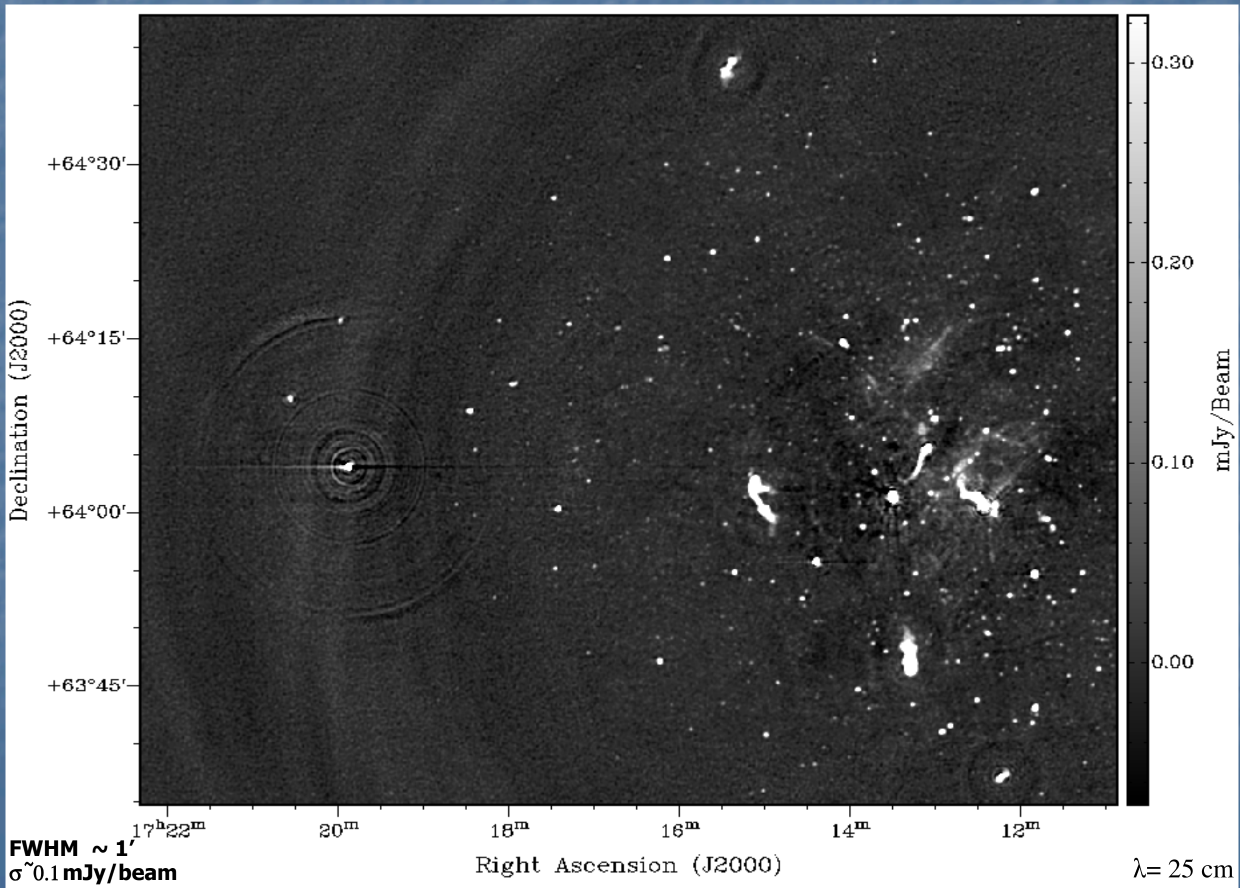
✓ Direction dependent calibration must be applied to the data, by removing the problematic off-axis sources together with their calibration corrections (Cotton et al. 2004, Intema 2009)

⬇

PEELING

AN EXAMPLE: A2255 with WSRT

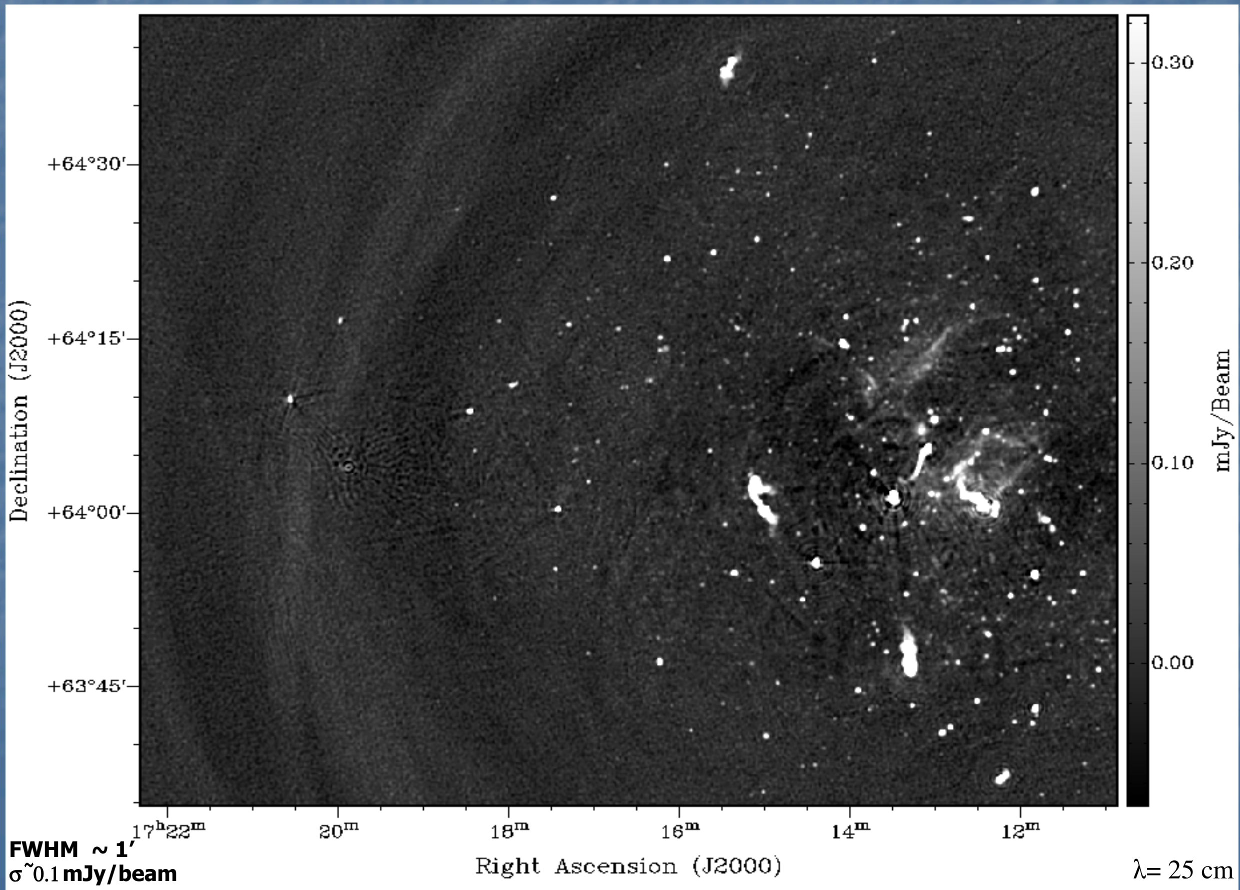
- ✓ Presence of spiky pattern surrounding the brightest off-axis sources . Pattern due to the instantaneous fan beam response of WSRT, rotating clockwise from position angle +90° to +270° in the 12h synthesis



No peeling applied

AN EXAMPLE: A2255 with WSRT

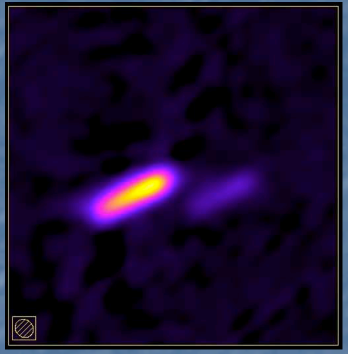
- ✓ Presence of spiky pattern surrounding the brightest off-axis sources . Pattern due to the instantaneous fan beam response of WSRT, rotating clockwise from position angle +90^o to +270^o in the 12h synthesis



Peeling applied

BANDWIDTH SMEARING

- ✓ Averaging the visibilities over finite BW results in chromatic aberration, which worsens with distance from the phase center ➔ radial smearing



point source at 7' from the field center at 20 cm, VLA
Courtesy of E. Orru'

- ✓ Does not affect the target source, but it must be corrected to properly deconvolve the images

- ✓ Effects can be parametrized by the product of the fractional bandwith and the source offset in synthesized beamwidths

$$\frac{\Delta\nu}{\nu_0} \times \frac{\theta}{\theta_{HPBW}}$$

increases with angular resolution and radial distance

when of the order of unity, chromatic aberration becomes an issue:

- ✓ Solution: observe in spectral line continuous mode (which also helps the RFI excision)

RADIO FREQUENCY INTERFERENCE (RFI)

- ✓ One of the most serious problems of low frequency interferometry
- ✓ Two origins:

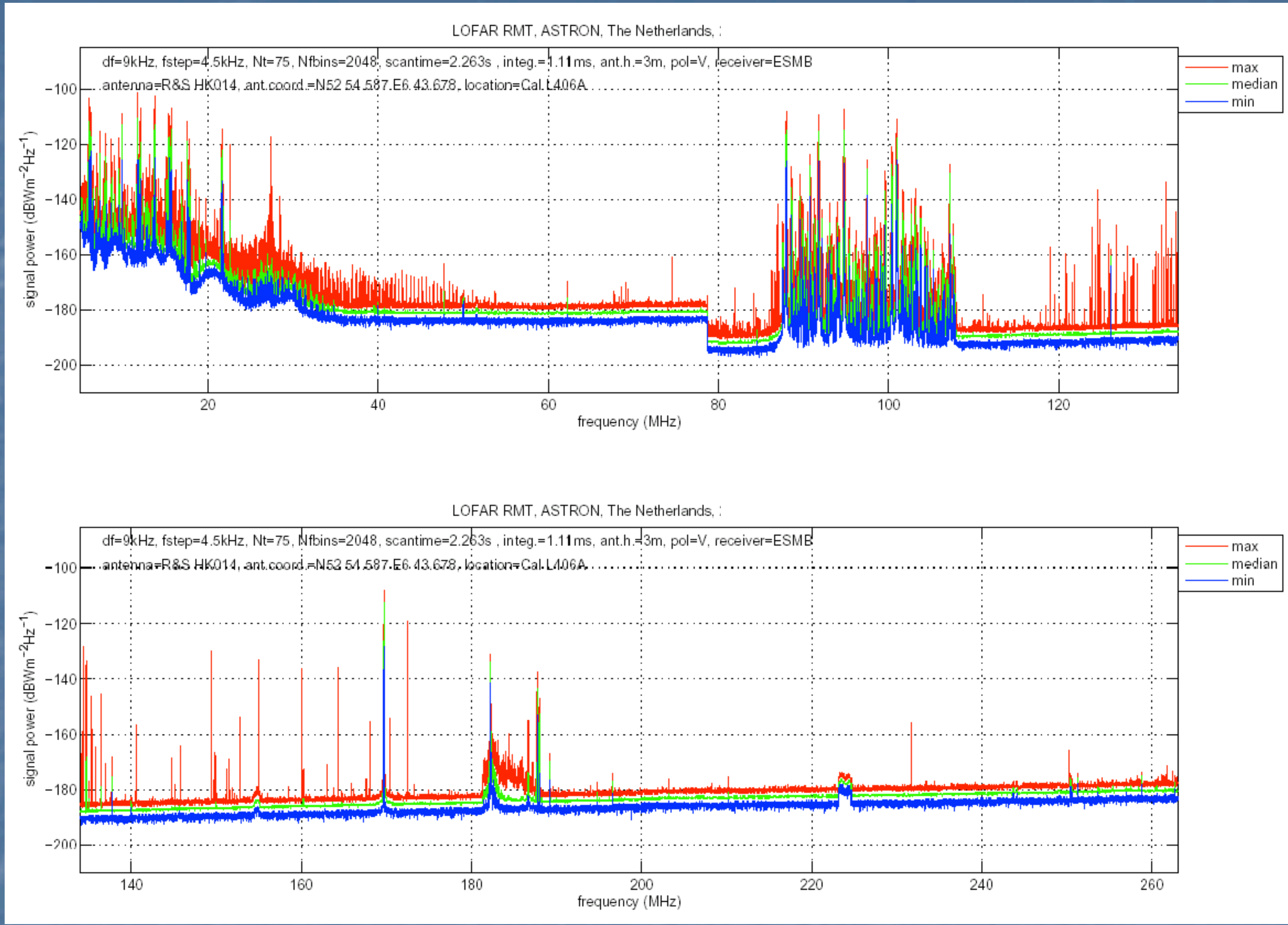
a) natural: lighting static during summer time, dust particles attracting charged particles in the proximity of the antennas.
Solar bursts (night time preferred), geo-magnetic storms, ionospheric scintillations

b) man-made: have various origin, residing in the electronic equipment present in the antennas themselves. At meter wavelengths, significant contribution comes from

- TV	50 – 700 MHz
- FM radio	88 – 108 MHz
- Digital audio broadcast	174 – 230 MHz, Europe
- Satellites	
…	

RFI measurement and monitoring are essential to ensure a good quality of radio data

RFI in THE NETHERLANDS (not untypical for Europe)



Max observed RFI signal level	~ - 110 dbWm^{-2}Hz^{-1}	~ 10^{15} Jy	(at 169 MHz)
Antenna sky noise level	~ - 201 dbWm^{-2}Hz^{-1}	~ 10^{6} Jy	(at 150 MHz)
CasA/CygA	~ - 219 dbWm^{-2}Hz^{-1}	~ 10^{4} Jy	(at 150 MHz)

RFI MITIGATION

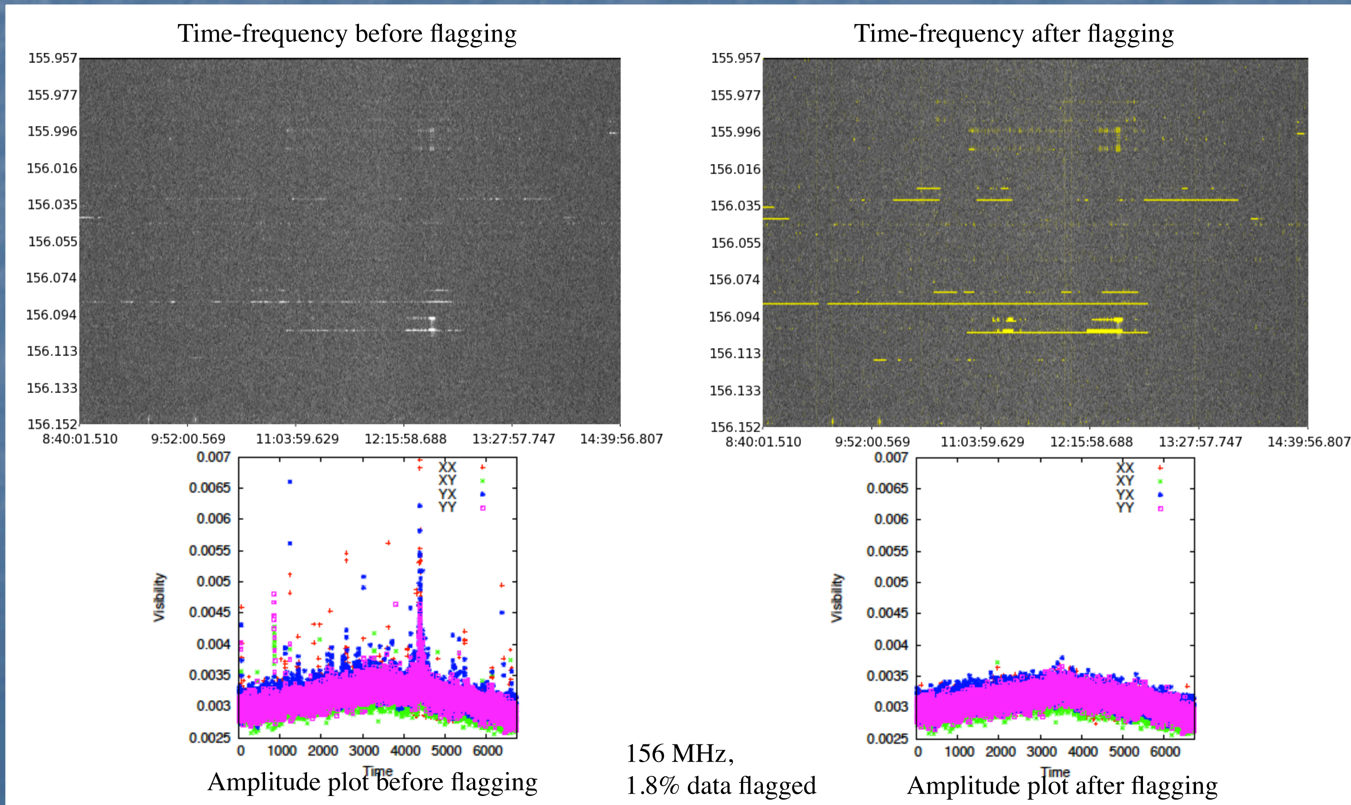
- ✓ Phased arrays are particularly interesting for their capabilities to do interference suppression
- ✓ If the same interfering signal is received by several antenna elements, then by properly phasing and combining the antennas, that signal can be nulled.
- ✓ It can be applied in two different stages: (i) pre-correlation and (ii) post-correlation

  I. Very powerful, as it is applied to full resolution data. Several methods from signal processing to handle this step, e.g., *spatial filtering*: at station level, beamshape modified such that interferer is nulled; at central level, signals combined to null any residual RFI

  II. Manual flagging, but also fringe fitting (Athreya 2009) and post-correlation spatial filtering are possible.

AN *AD HOC* FLAGGER FOR LOFAR DATA

- ✓ AOFlagger (RFIconsole) is based on the '*SumThreshold'* method, which detects series of samples with higher values than expected
- ✓ Analysis done iteratively for the entire observation, per sub band, per baseline
- ✓ Method is very accurate. The algorithm finds RFI invisible by eye on full scale time-frequency diagrams



courtesy of Andre' Offringa

BRIGHT SOURCES REMOVAL – THE A-TEAM

- ✓ The presence of very bright sources in the low-frequency sky (Cyg A, CasA, VirA, TauA, HerA + Sun), combined with the large beam size of LF arrays (LOFAR ➔ ~ 10^o at ν = 80 MHz) seriously limits the dynamic ranges needed for extragalactic surveys (~ 10.000)

- ✓ Two main methods are available to remove the A-team sources:

    a. demixing: based on the assumption that the interfering sources are far from the field center, so their fringe rate is high with respect to the target. Currently, it removes what you select for removal from the uv data and for the entire length of the observation – improvements are in progress;

    b. direction dependent calibration; good source model needed; used to be computationally very intensive, but new softwares make it now more manageable (e.g. SAGECAL).

More in Tutorial LOFAR bits 2

WIDE FIELD IMAGING

✓ The sky brightness is obtained as a 2-D Fourier inversion of the visibilities. True if we assume:

- all the visibilities measurements lie in a plane (*w* term can be neglected)
- FOV limited to a small angular region

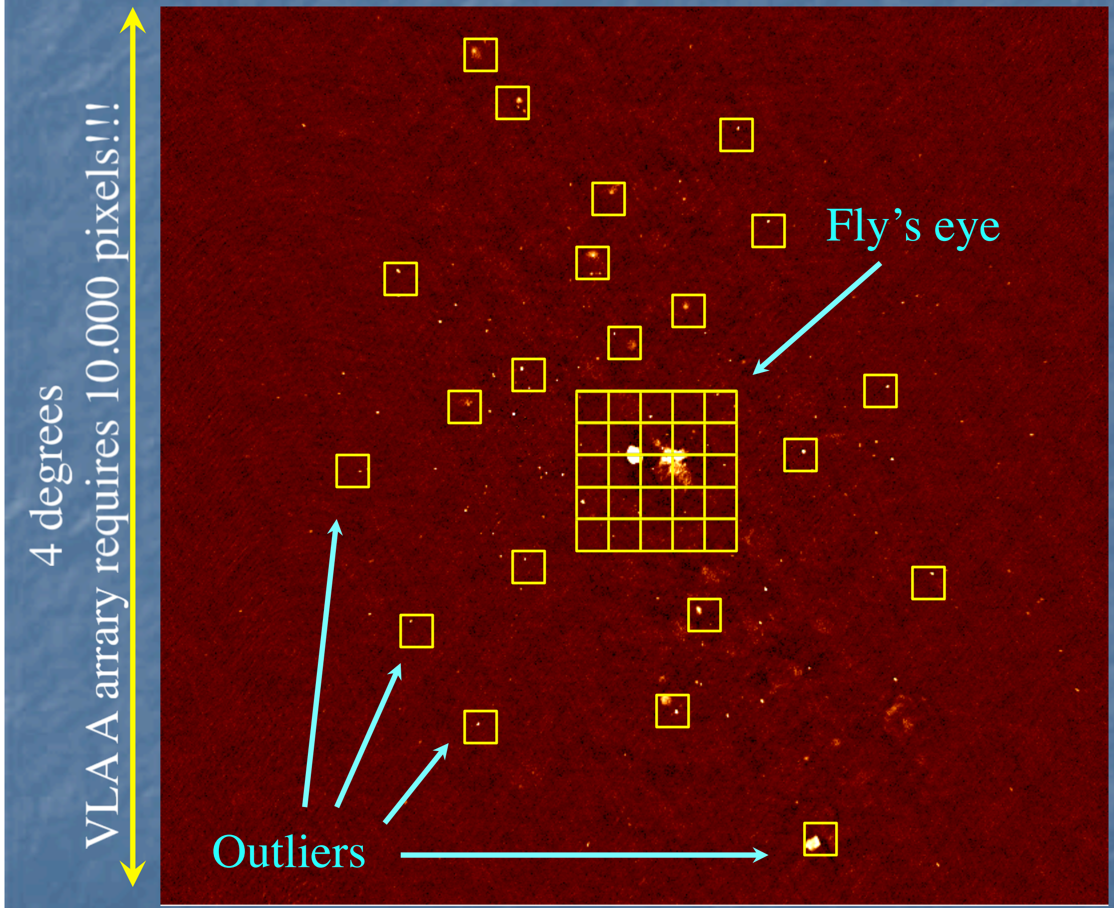
There are two methods of wide field imaging:

- imaging the field in different *facets* or *polyhedron* corresponding to different positions on the celestial sphere by phase rotating the uv data for each one of those.

- W-projection using a w-dependent convolution function in the gridding step to retrieve an undistorted image after a simple 2D fast Fourier transform

More in Tutorial LOFAR bits 2

WIDE FIELD IMAGING (FACETTING)

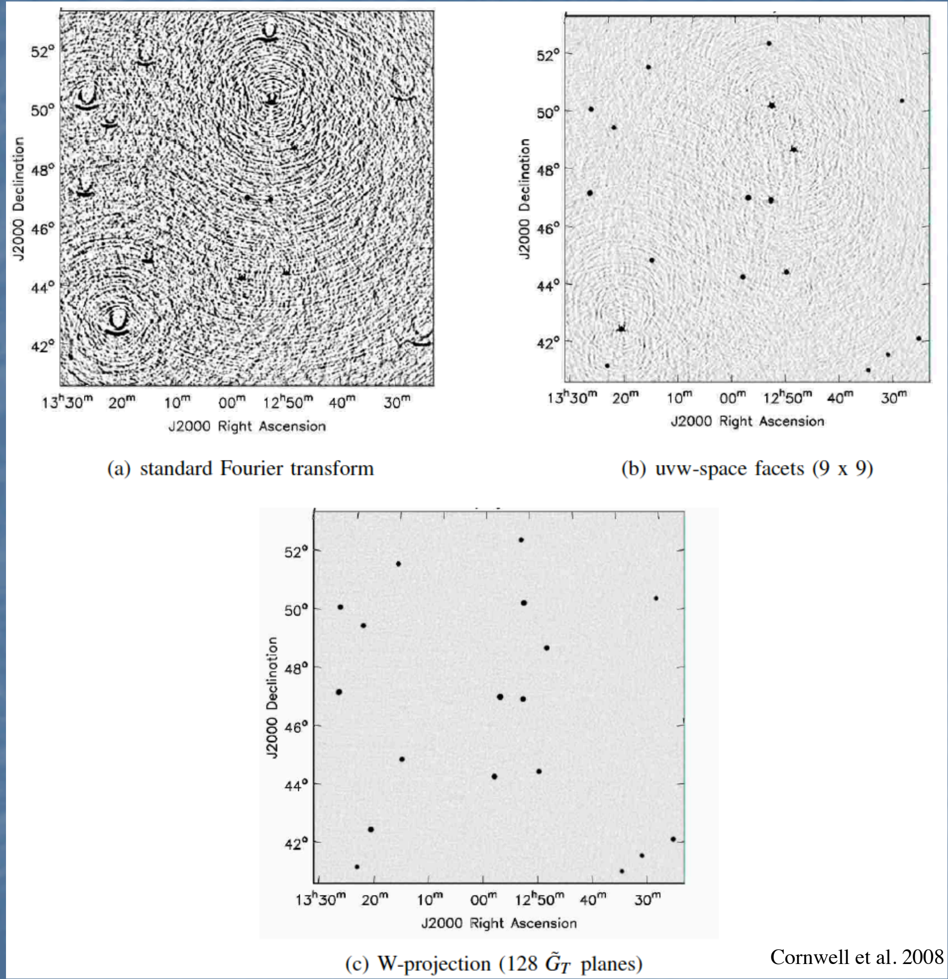


- ✓ Full pixellation is computationally prohibitive!
- ✓ Use NVSS or WENSS to set outliers
- ✓ No need to image empty space (unless you are doing a survey)
- ✓ Loss of potential science

More in Tutorial LOFAR bits 2

WIDE FIELD IMAGING (W-PROJECTION)

- ✓ Simulated observation at 74 MHz with VLA C configuration
- ✓ Sources brighter than 2 Jy taken from WENNS within 12° from phase center
- ✓ W-projection an order of magnitude faster than facets
- ✓ Distortion of sources far from field center for case a) and b)
- ✓ c) much better than b) in case of great sensitivities



(a) standard Fourier transform

(b) uvw-space facets (9 x 9)

(c) W-projection (128 $\tilde{G}_T$ planes)

Cornwell et al. 2008

More in Tutorial LOFAR bits 2

WIDE FIELD IMAGING: A-PROJECTION

- ✓ For LOFAR, antenna gains are direction, time, and frequency dependent. Faceting still holds, but deconvolution scheme is complicated ➔ A-projection, where DDE and non complanarity of the array are corrected in a way similar to the w-projection algorithm.

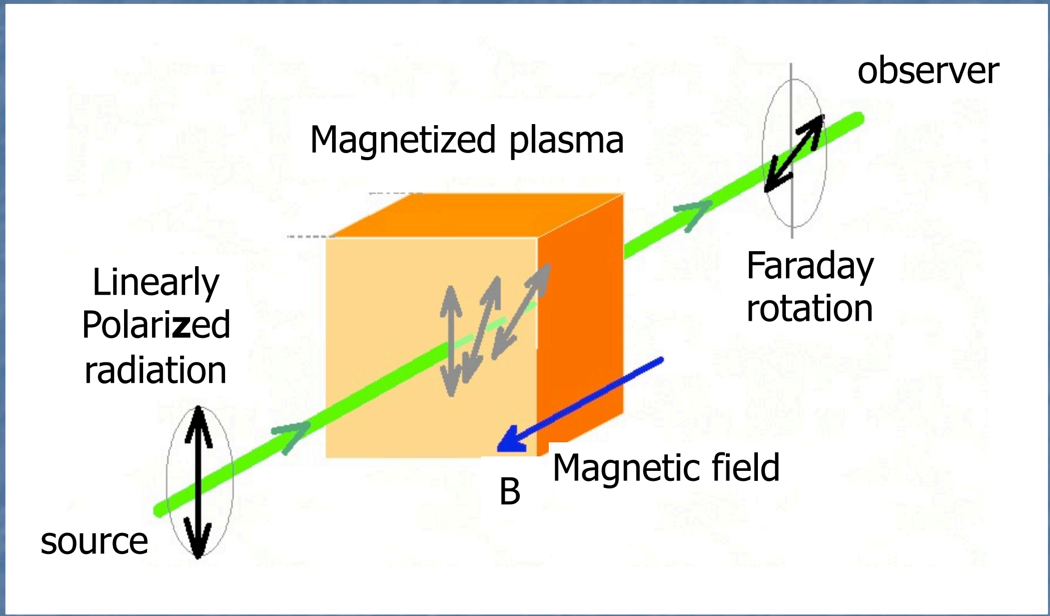
- ✓ Vary in terms of computing efficiency (faster than facet-based algorithms by an order of magnitude), and it can potentially take all DDE into account in the deconvolution steps.

More in Tutorial LOFAR bits 2

POLARIZATION ASPECTES AT LOW FREQUENCY

THE POTENTIAL

- ✓ New frontier !
- ✓ Great diagnostic value to characterize the properties of emitting source and media crossed by its polarized signal (Faraday rotation):
  - ➢ ISM, IGM
  - ➢ Ionosphere (time variable!)



$$RM_{[rad/m^2]} = 812 \int_0^{L_{[kpc]}} n_{e\,[cm^{-3}]} B_{//\,[\mu G]} dl$$

$$\Delta\chi_{[rad]} = \lambda^2_{[m^2]} \times RM_{[rad/m^2]}$$

TECHNICAL ASPECTS AT LOW FREQUENCY

✓ Propagation and instrumentation lead to various depolarization effects:

I. beam ➔ use longer baselines
(WSRT 3 km, VLA-GMRT 30 km, LOFAR ~ 100 – 1000 km)

II. bandwidth ➔ use multi-channel backends

III. Ionospheric Faraday rotation ➔ correct using ionospheric models

BEAM DEPOLARIZATION

✓ when the magnetic field is tangled on scales smaller than the resolution of the observations, the original signal depolarizes inside the observing beam

EXAMPLES:

1) ISM RM-gradient of 1 rad m^{-2} per degree translates at 50 MHz to a rotation of the polarization vector of 34^o/arcmin

⇓

LOFAR-100 km has no problem

2) Source RM-gradient of 1 rad m^{-2} per arcmin translates at 50 MHz into a rotation of the polarization vector of 34^o/arcsec

⇓

1000 km baselines are needed

BANDWIDTH DEPOLARIZATION

✓ observations are carried out in a frequency band with a particular bandwidth $\Delta\nu$

$$d(\Delta\theta_{FAR}) \sim 2RM \times \lambda^2 \times \frac{\Delta\nu}{\nu} \qquad \propto \lambda^3$$

This corresponds to

0.03 ^{o}/kHz at 150 MHz for a RM = 10 rad m^{-2}

0.08 ^{o}/kHz at 50 MHz "

3.8 ^{o}/kHz at 30 MHz "

kHz resolution achieved by LOFAR, for which RM synthesis becomes an obvious tool to adopt to process polarimetric data

IONOSPHERIC FARADAY ROTATION

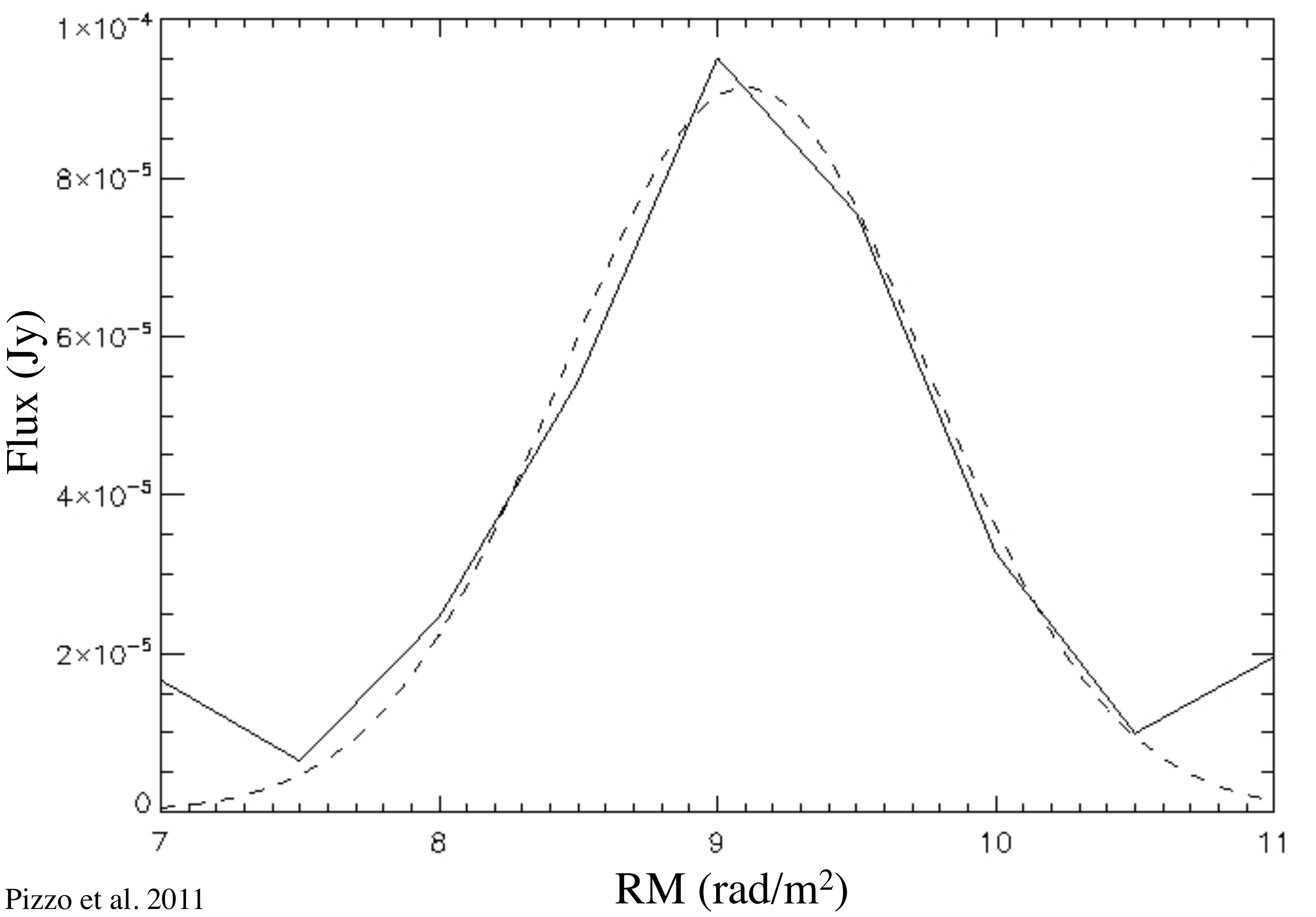
- ✓ Ionospheric Faraday rotation is a time variable phenomenon. The electronic density of the ionosphere varies during the day, depending on the amount of radiation received by the Sun. The most dramatic changes take place during sunset and sunrise

- ✓ Time variable ionospheric Faraday rotation often amounts to several turns of the polarization vector in the QU plane (at low frequencies) and therefore can seriously depolarize the signal: a variation of just 0.5 rad m^{-2} in ionospheric Faraday rotation corresponds to a change in polarization angle of the signal of ~200^{o} at 115 MHz!!

- ✓ Correcting for this effect at low frequencies is very important as it can significantly affect the results of the polarization imaging

IONOSPHERIC FARADAY ROTATION: CALIBRATION APPLIED AT 150 MHZ (Pizzo et al. 2011)

Target observed for 5 nights (for 12 h during each nigh). A polarized calibrator (PSR1937+21) observed 7 time during each target observation run to monitor the ionosphere

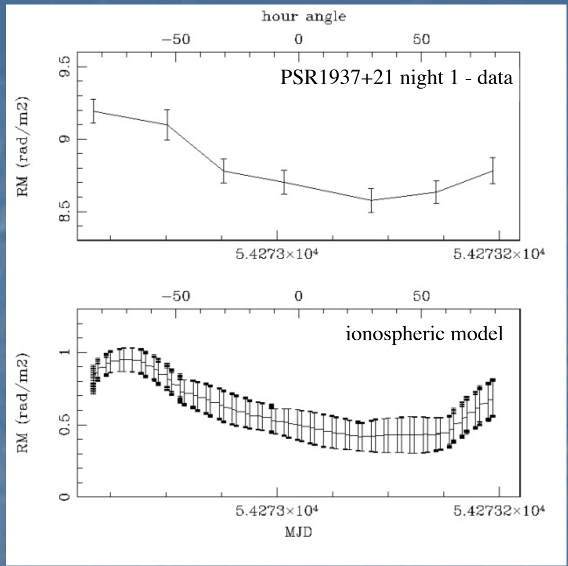


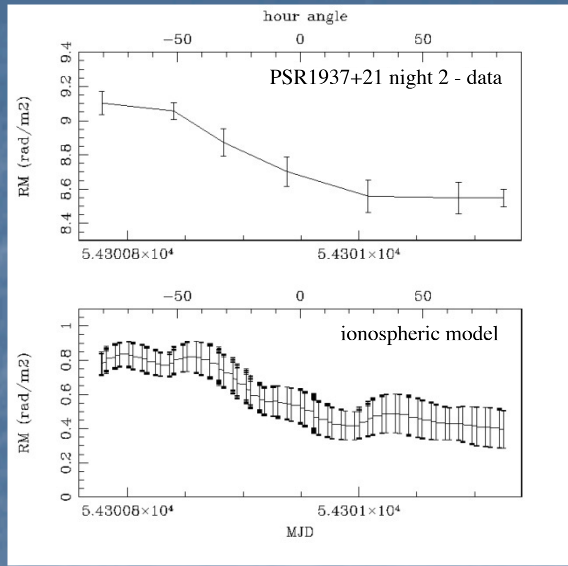
Pizzo et al. 2011

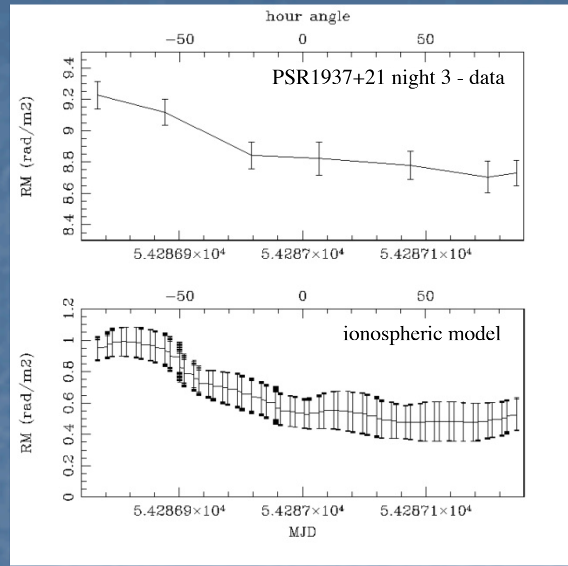
IONOSPHERIC MODEL

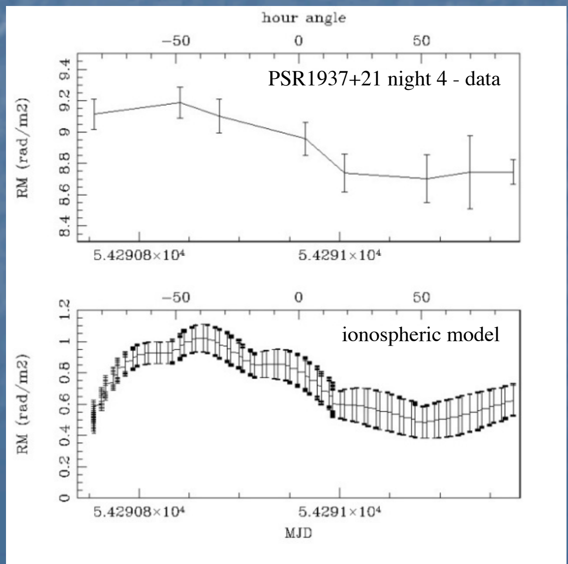
- ✓ The Earth magnetic field modeled through the IGFR (International Geomagnetic Reference Field; series of mathematical models of the Earth's main field and its annual rate of change)
- ✓ The ionospheric electron density derived from GPS data (ionex files) provided by the Center for Orbit Determination in Europe (CODE) of the Astronomical Institute of the university of Bern
- ✓ Ionosphere modeled as a spherical shell of finite thickness and uniform density at an altitude of 350 km above the mean see level
- ✓ Validity of the model first checked for the polarized calibrator

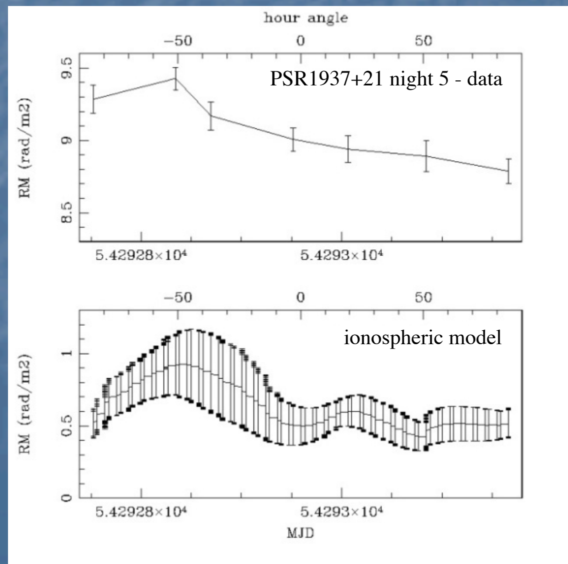
DATA VS MODEL FOR PSR1937+21









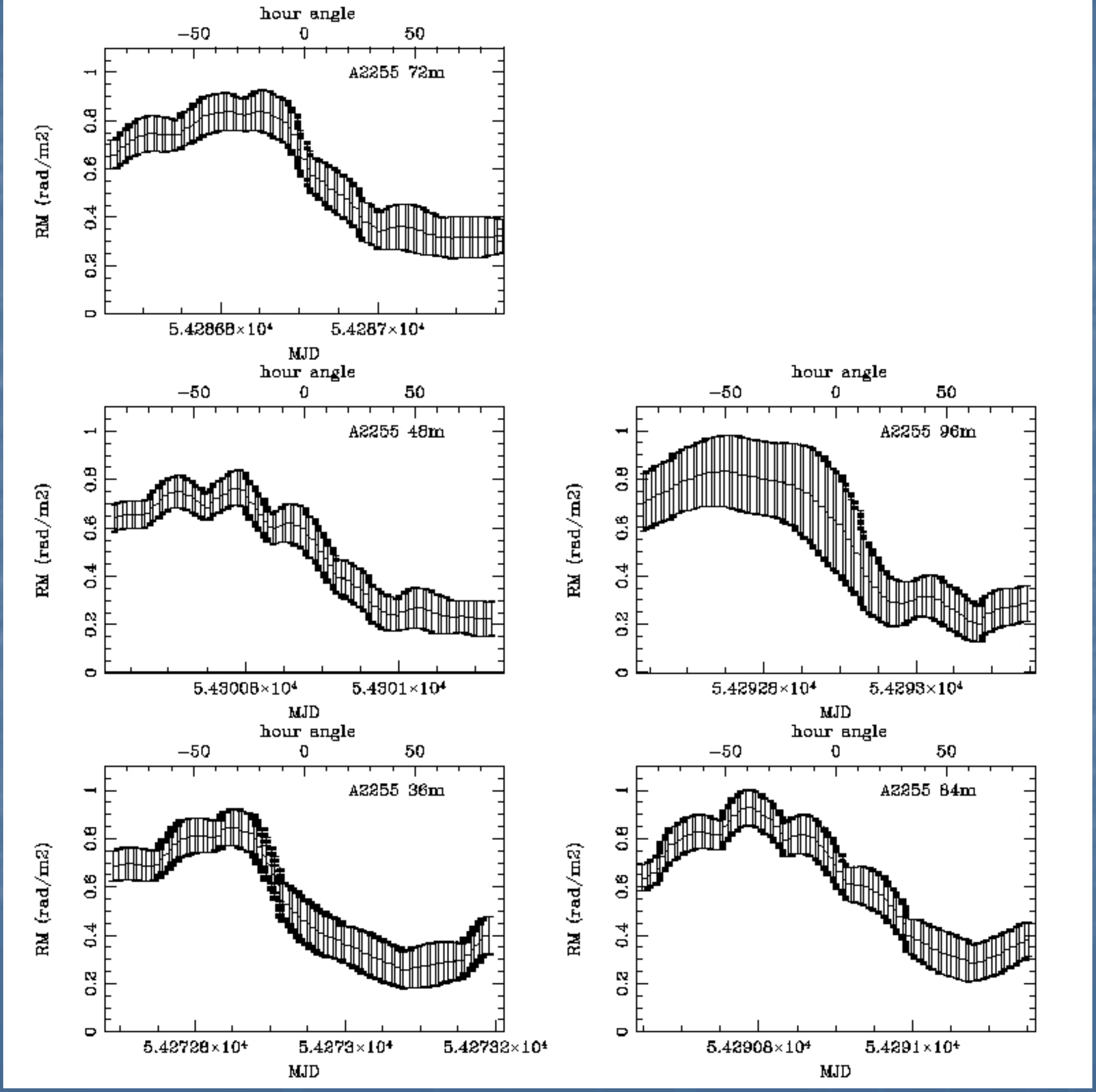


For each night, the observed RM of the pulsar agrees with the predictions within 5 %

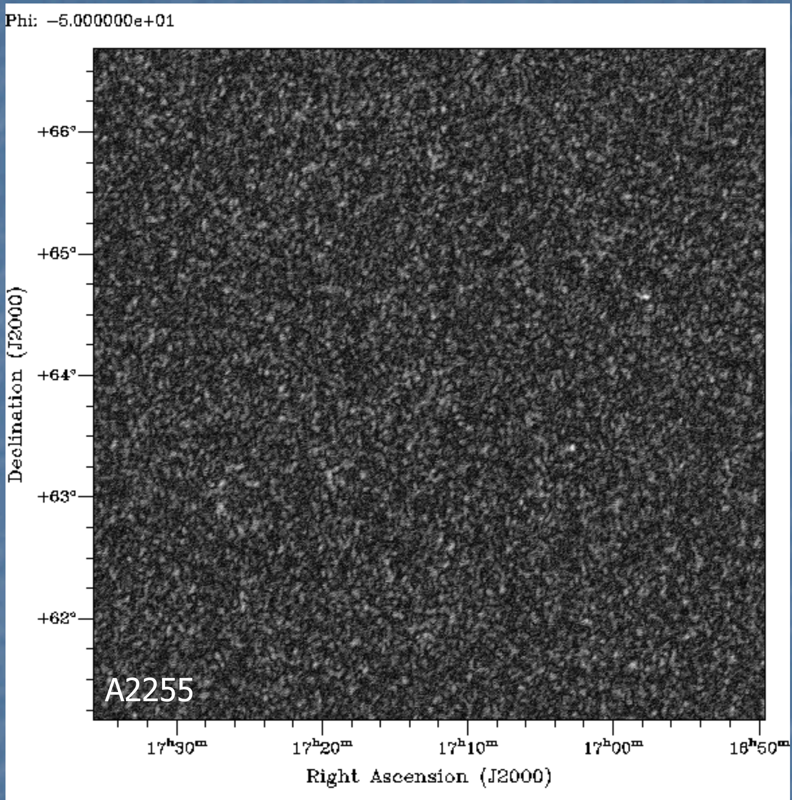
$$RM = 8.19 \pm 0.08 \ rad \ m^{-2}$$

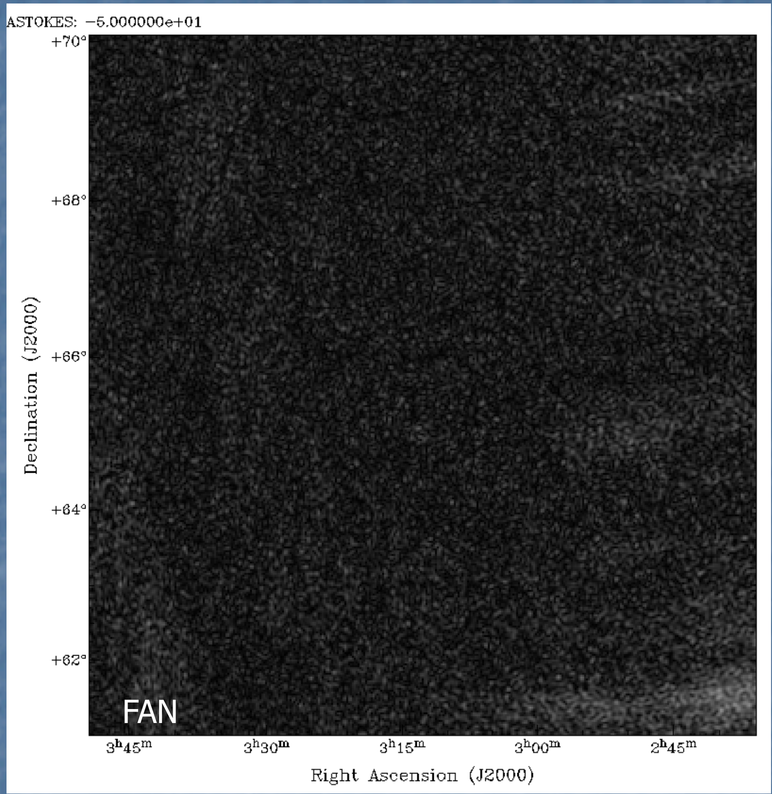
Pizzo et al. 2011

CORRECTIONS TOWARDS A2255



EXAMPLES RM CUBES WITH LOFAR DATA





AND MANY MORE TO COME!

SUMMARY

- ✓ Low frequency interferometry is a powerful tool to answer several interesting question about the history of the universe
- ✓ Several challenges have to be faced when trying to process low frequency data
- ✓ Various techniques have been recently develop to deal with issues related to the ionosphere, large FOV, RFI in low frequency data
- ✓ Low frequency interferometry is undergoing a new golden age, which will surely lead to some important discoveries
- ✓ It is a perfect time to do LF radio astronomy!

REFERENCES

- ✓ Synthesis Imaging in Radio Astronomy II (ASP Conference Series 180, eds Taylor, Carilli & Perley, 1999);
- ✓ On-line lectures of recent NRAO Summer School;
- ✓ Low frequency radio interferometry;
- ✓ The LOFAR Imaging Cookbook - http://www.astron.nl/radio-observatory/lofar/lofar-imaging-cookbook