Bonn, ERIS , 13-Sep-2007

Low frequency interferometry (< 400 MHz)

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Acknowledgements:

ionospheric slides: James Anderson & Bob Campbell (JIVE), Perley, Lazio a.o

RFI : Albert-Jan Boonstra, Stefan de Koning,

Others: Gianni Bernardi , Frank Briggs

Outline:

- some history
- ionosphere
- low frequencies FOV are large --> all-sky imaging
- non-isoplanaticity and selfcalibration over wide fields
- bandwidth, RFI and noise
- polarization issues
- classical confusion issues

Roots of Radio Astronomy lie at LOW frequencies

(see e.g. WCE74 symposium, Santa Fe, Sep 04, Ed Kassim et al)

1932	20 MHz	Karl Jansky
1940-45		Grote Reber
1948-1962	178 MHz	Cambridge (3C, 4C) (Ryle ...
1965-1980	26 - 57 MHz	Clark Lake (California, Bill Erickson)
1975-1990	38 MHz	Cambridge (e.g. 8C)

Many other telescopes: Puschino, UTR2-Ukraine, Ooty, Gauribidanur, Nancay-DAM, Mauritius, Texas, Arecibo, ... (10 - 365 MHz)

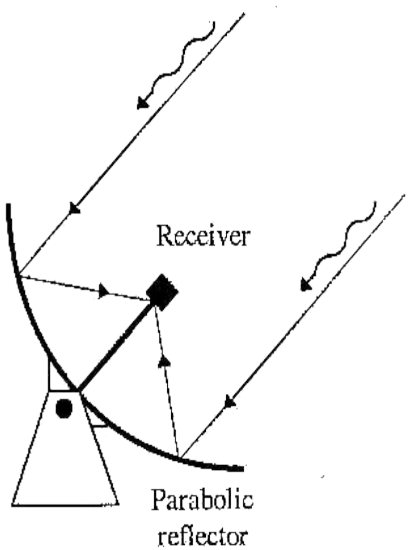
Modern sensitive interferometers (dishes)

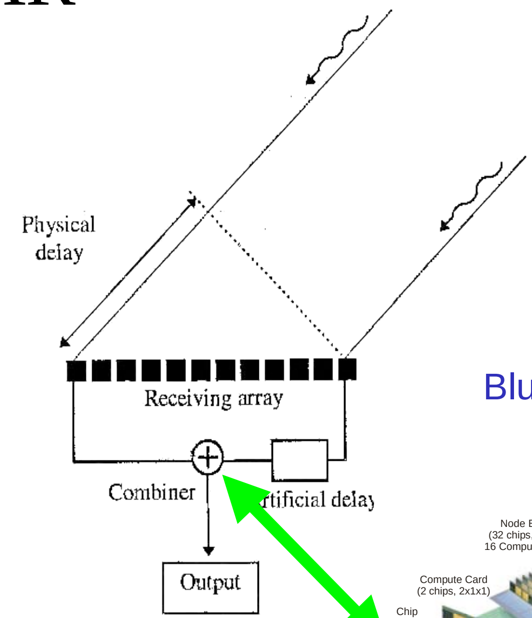
WSRT:	270 - 390 MHz	later also 115-180 MHz
VLA	300 - 350 MHz	later also 74 MHz
GMRT	150, 232, 325 MHz	future 50 MHz

Future arrays (of dipoles!)

LOFAR (NL-Europe)	10 - 240 MHz	100 - 1000km
LWA (New Mexico US)	10 - 80 MHz	400 km (?)
MWA (Western-Australia)	80 - 300 MHz	1.5 km
SKA	<100 --> 20000 MHz (?)	

Arrays of dipoles provide enormous flexibility: electronic beamforming and 'software telescope' e.g. LOFAR

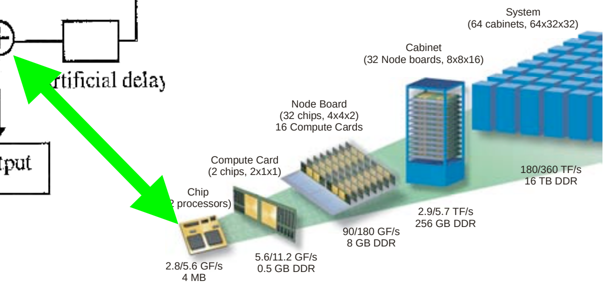




0.5 Tbit/s

25 Tflops

Blue Gene™ (IBM)



Principles:

a) **E** is detected, interference can be performed (off-line) in computer

b) No quantum shot noise: extra copies of the signal are free!

Consequences:

a) Can replace mechanical beam forming by electronic signal processing

b) Put the technology of radio telescopes on *favorable cost curve*

c) Also: multiple, independent beams become possible

Low frequency radio astronomy has been done for 50 years: what is new ?

Well,...

1) We want to do it with ~1000x better sensitivity (i.e. to thermal noise)
2) with an appropriate image quality (>10^4 dynamic range)
3) at a resolution of 0.25-1.0 arcsec over the whole sky,
4) do it in full polarization and do spectroscopy at z=10,
5) record down to 5 nanosec resolution,
6) In somewhat harsh RFI conditions,
7) and do this for many users simultaneously !!

So there are a few challenges ahead !!

Low frequency astronomy requires imaging and (self)calibrating the whole sky ! That is both good and bad.

For example at 100 MHz:

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

2) There are very bright sources, e.g. the A-team:

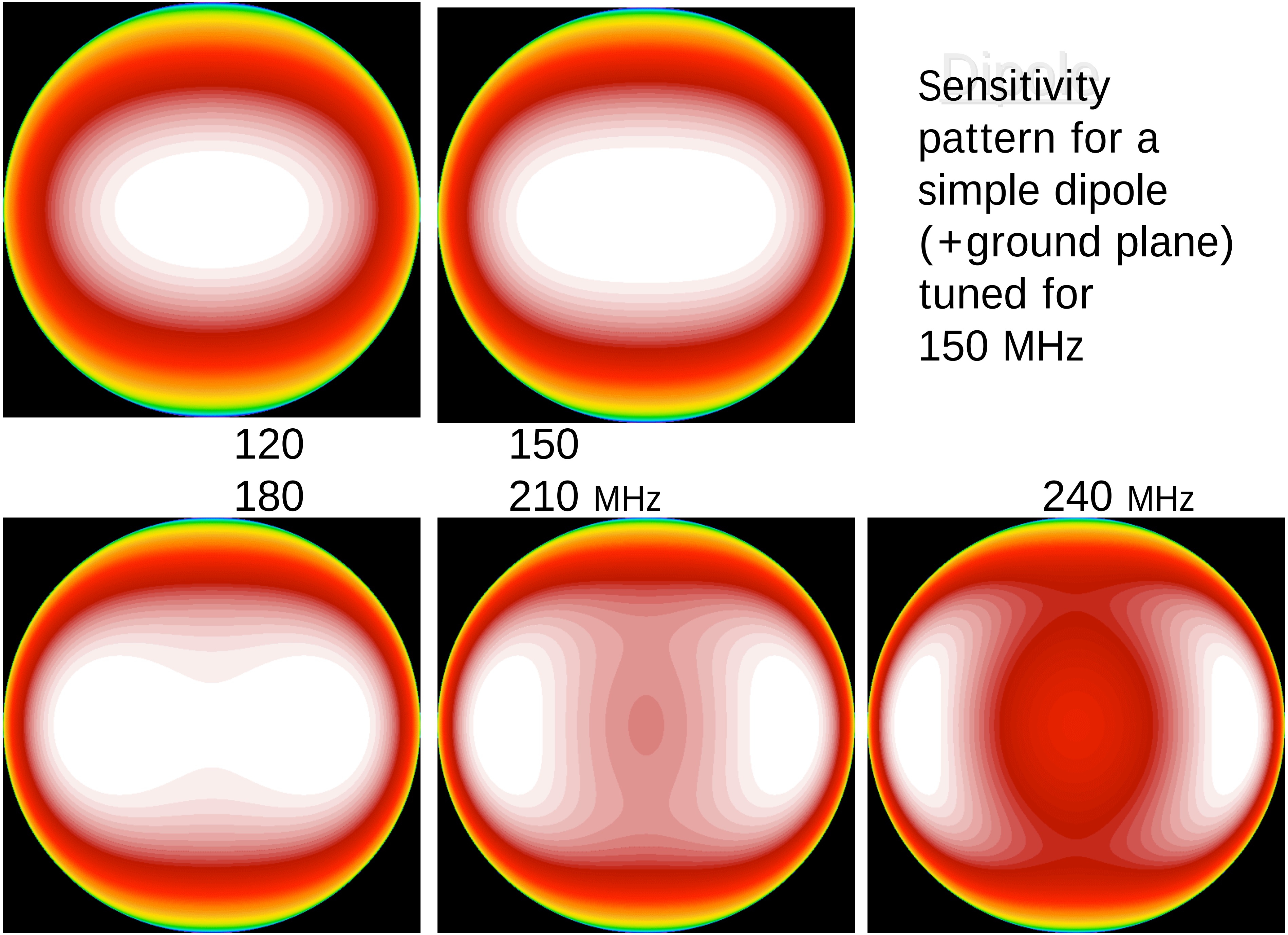
   Sun > 10,000 - 1000,000 Jy   CasA, CygA ~ 10,000 Jy

   VirgoA, TauA ~ 1000 Jy

3) Distant sidelobe levels are typically -20 to -30dB (= 0.01 - 0.001)

4) Thermal sensitivity of an array < ~ 1 mJy after 12h

For phased arrays (like LOFAR) this is even 'worse': a dipole 'sees' most of the sky down to the horizon . Telescope made up from arrays of dipoles, e.g. through analog or digital beamforming, certainly need to worry about the whole sky.



Sensitivity pattern for a simple dipole (+ground plane) tuned for 150 MHz

Some relevant past VLBI - low frequency experiments

	frequency	baseline	sources
Clark et al (1975)	111 MHz	2500 km	3C286,287
Hartas et al (1983)	81 MHz	1500 km	3C48,147,216,380
Global VLBI (>1980)	327 MHz	~ 8000 km	hundreds

The sensitivity of the system was such that we could measure the fringe visibility of 3C 48 (73.2 Jy at 81.5 MHz) with a signal-to-rms noise ratio of about 50 : 1 in the absence of scintillation on short baselines in 100 s, using eight antennas in each polarization at the remote site.

3 The observations

We observed a total of 33 of the brightest 3C radio sources between 1981 June and 1982 September. The results will be analysed in detail elsewhere; here we present our measure-

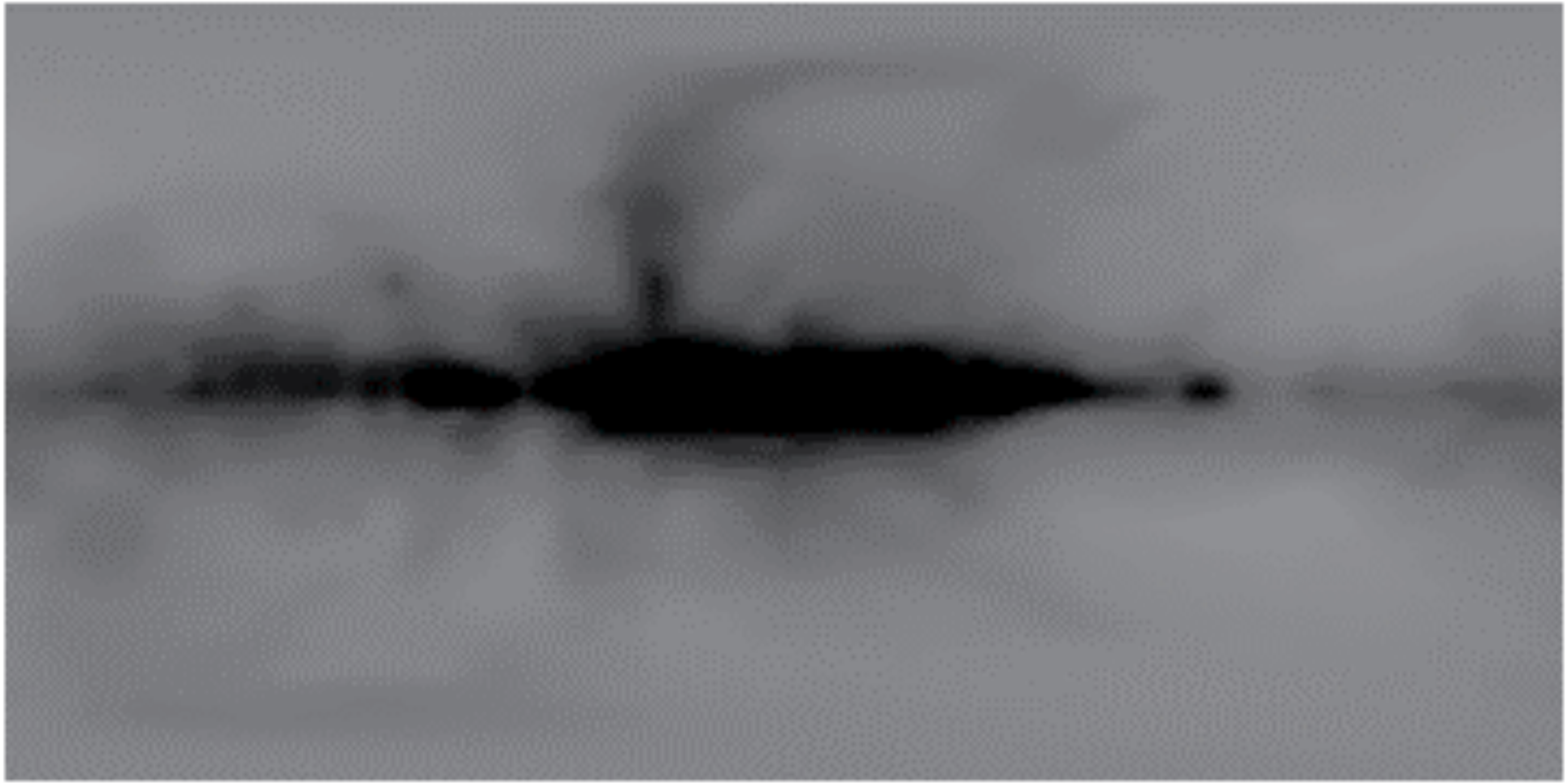
Figure 2. The baselines (a) within the UK and (b) within Europe.

Very simple 'images' were made at 81 MHz with a portable dish in 1981-82

Hartas et al, MNRAS 205, 625 (1983)

The sky at 150 MHz

Landecker and Wielebinski, 1970



Radio astronomical imaging (which works at diffraction limit ~ λ/D) is possible only once we 'control' phase-stability.

Phase corruptions have two main parts:

- instrument (geometry+electronics)
- atmosphere = troposphere +ionosphere

Troposphere (0-10 km): phase $\propto$ ν

Ionosphere (100-1000 km): phase $\propto$ ν^{-1}

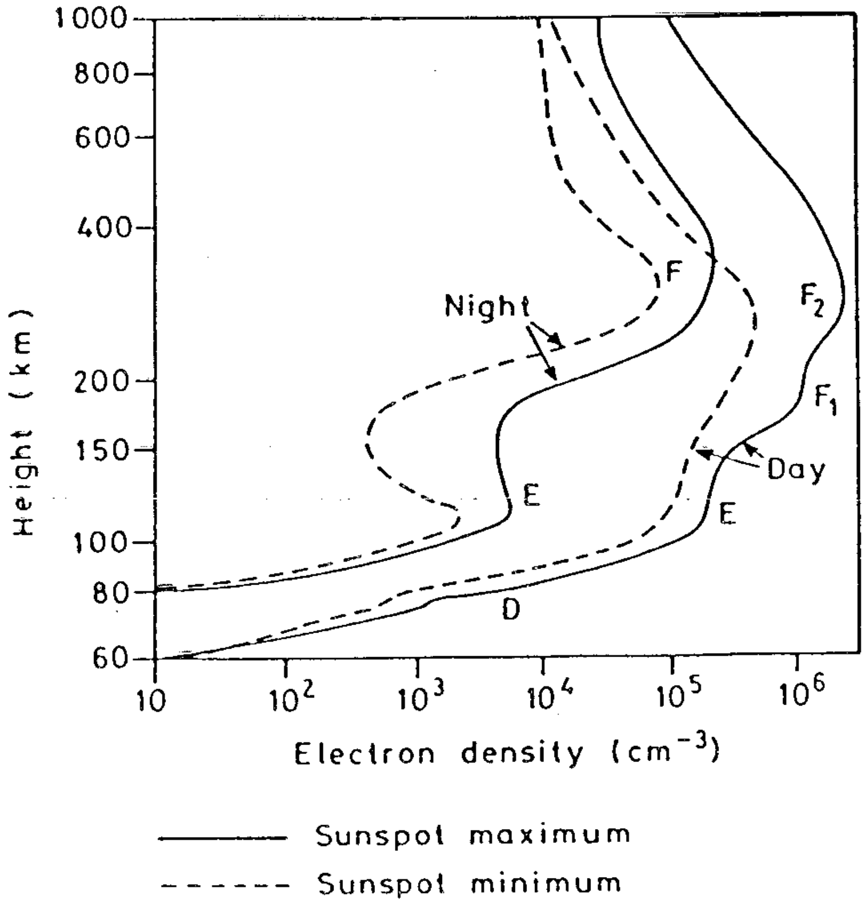
Typically equal contributions at baselines of 10 km at ~ 1 GHz

So at ~100 MHz the ionosphere is our worst enemy.

Reason to look at ionosphere in detail. !

Ionosphere

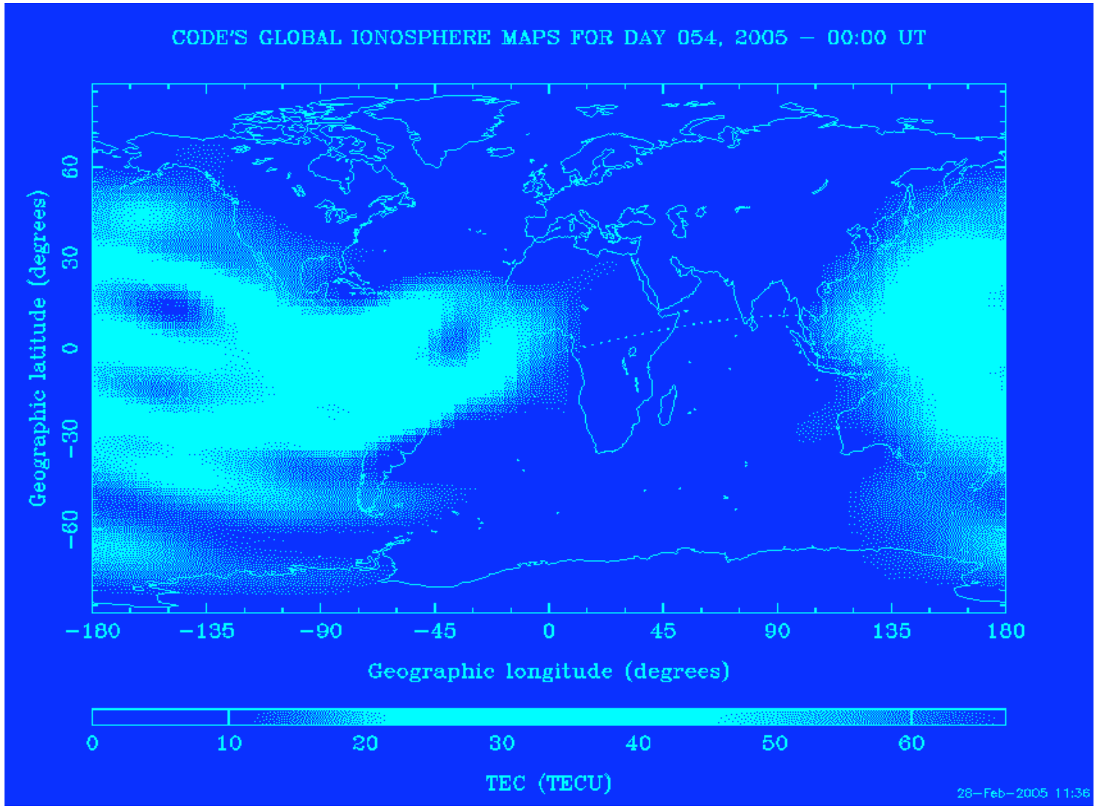
Ionospheric density profile



- Solar radiation ionizes during daytime
- Recombination at night
- --> Egg-shaped structure inside which Earth rotates

  --> refracting wedges at disk and dawn
- Peak electron density around 300 km
- Plasma frequency: 9 kHz $\sqrt{n_e}$
- Ionosphere reflecting at ν < 3-10 MHz

Vertical Total Electron Content behaviour



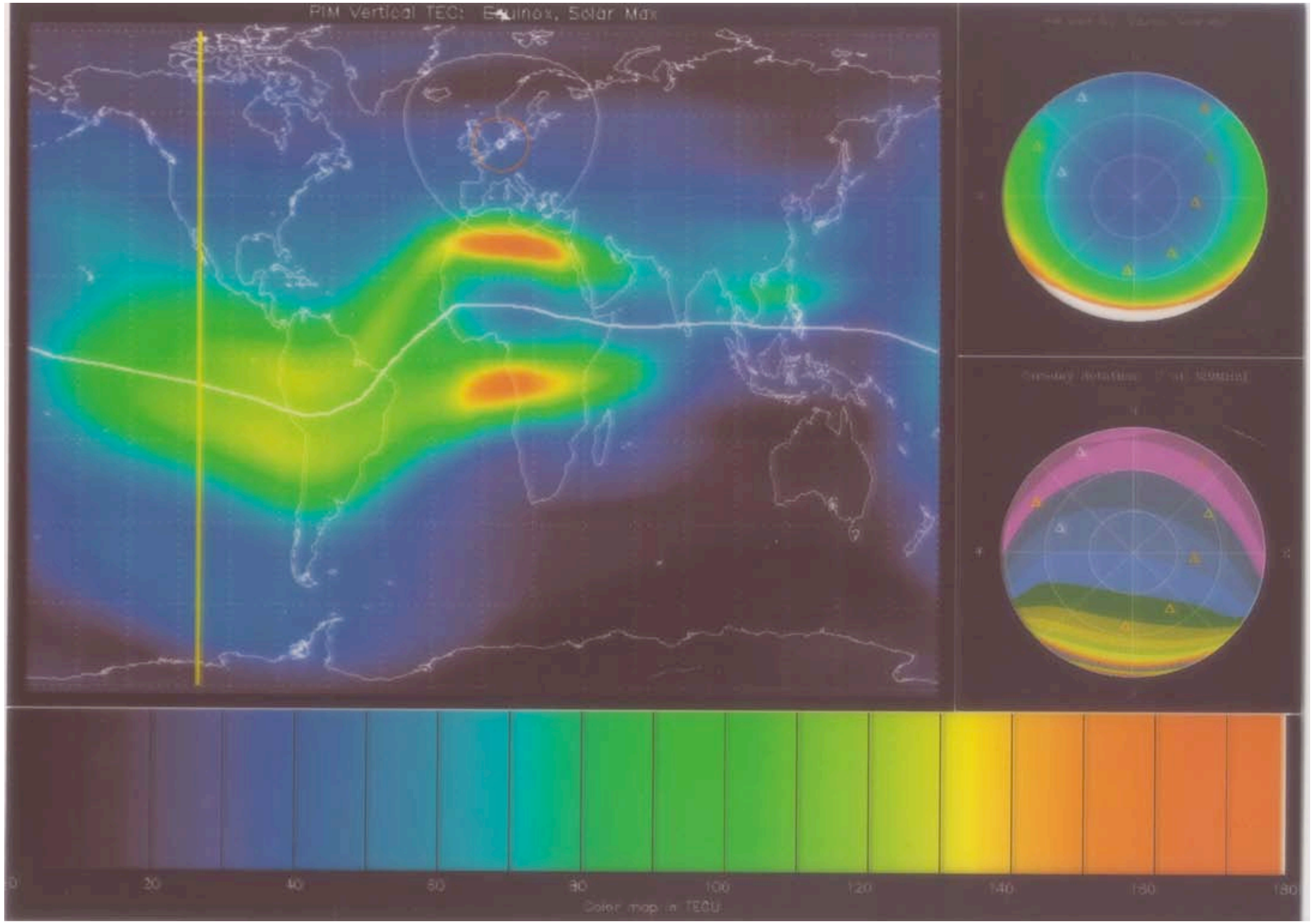
- 1 TECUnit = 10^{12} el/cm^2
- Typically 5-10 TECU at intermediate latitudes. Much higher at equator
- 1 TECU causes:

4/3 turn of phase at 1 GHz

40/3 turns at 100 MHz !!

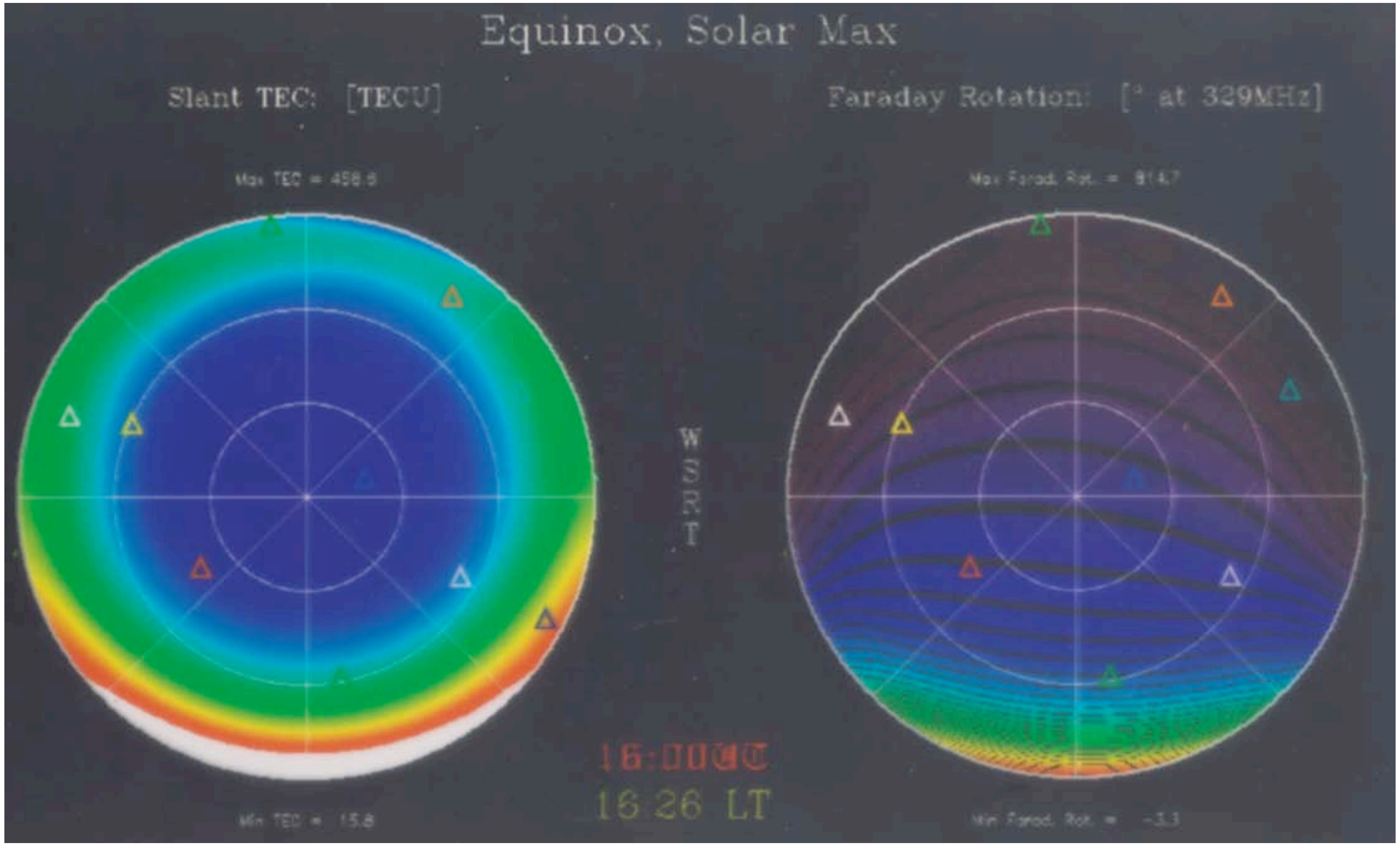
- Ionization fraction slightly lags Solar noon
- Electrons raised in equatorial fountain fall along flux lines to either side of equator

Slant Total Electron Content for Westerbork *(Bob Campbell, JIVE)*



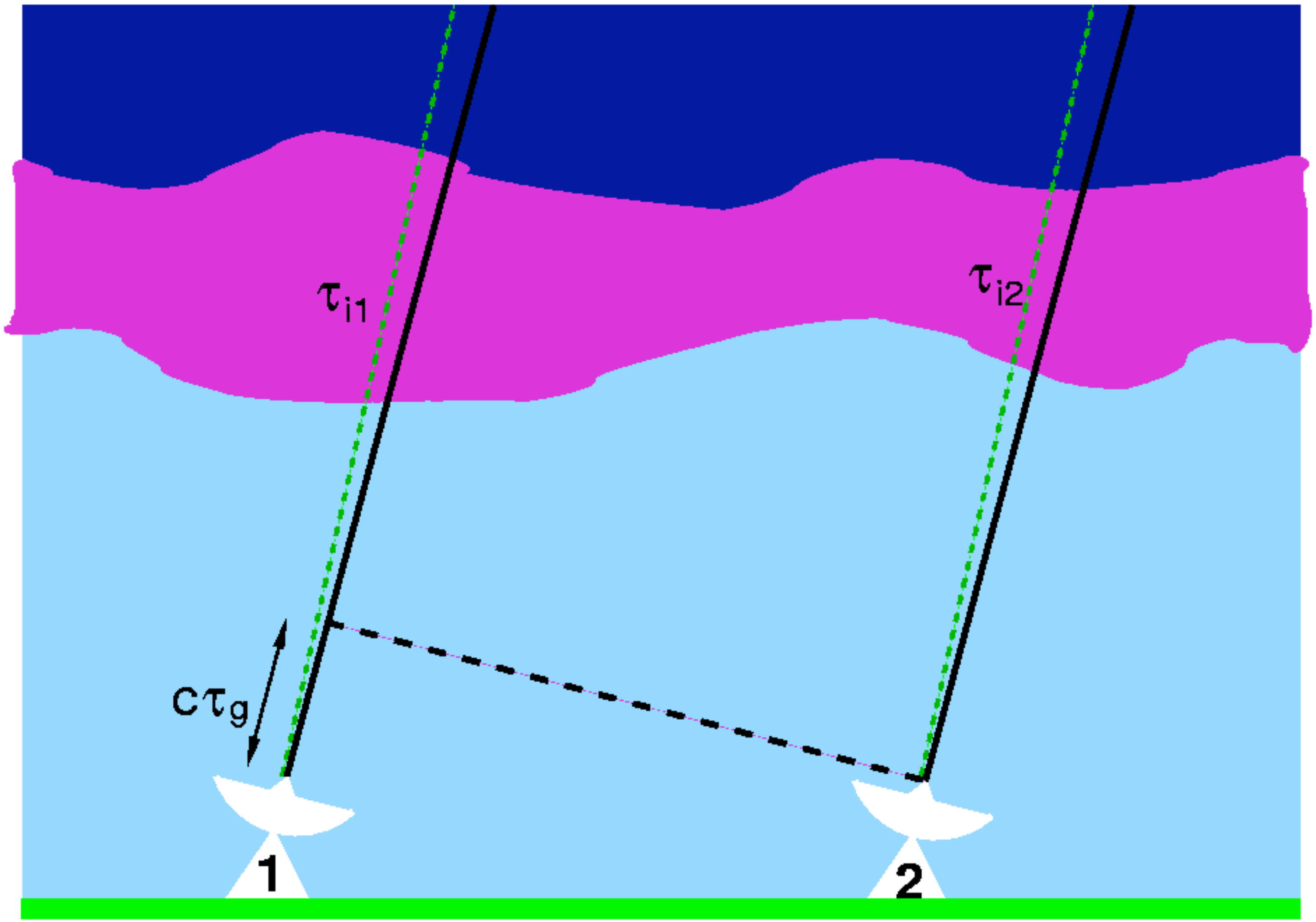
- Vertical TEC at left
- Slant TEC upper right
- TEC values very large near horizon

Slant Total Electron Content for Westerbork: Afternoon

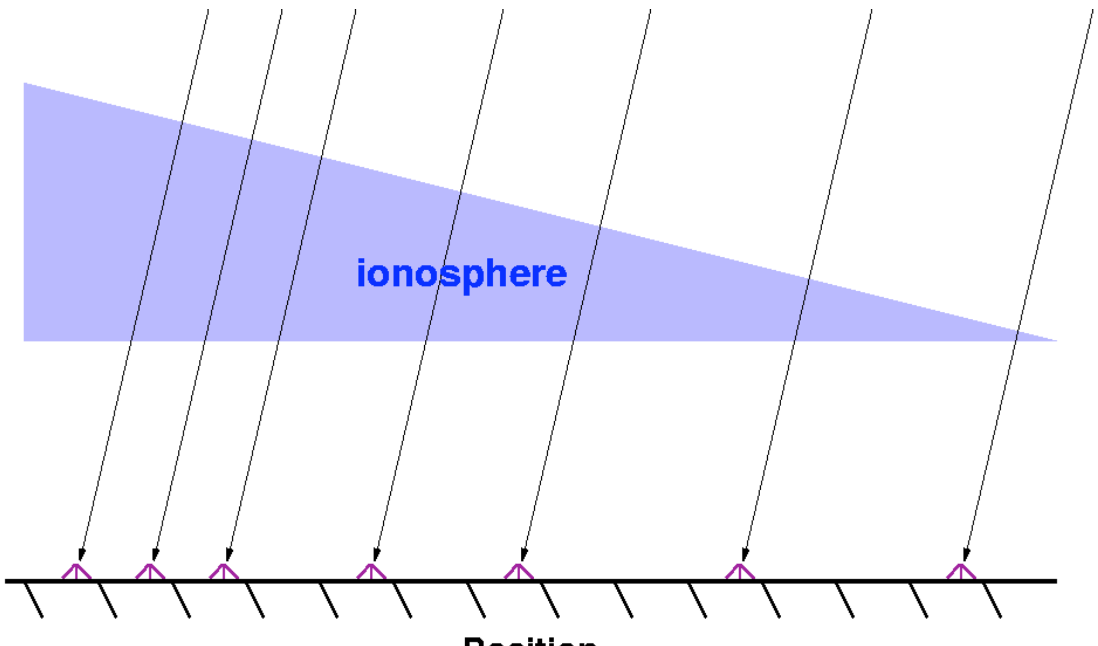


- Slant TEC at left
- Triangles show locations of GPS satellites

Interferometry basics plus ionosphere

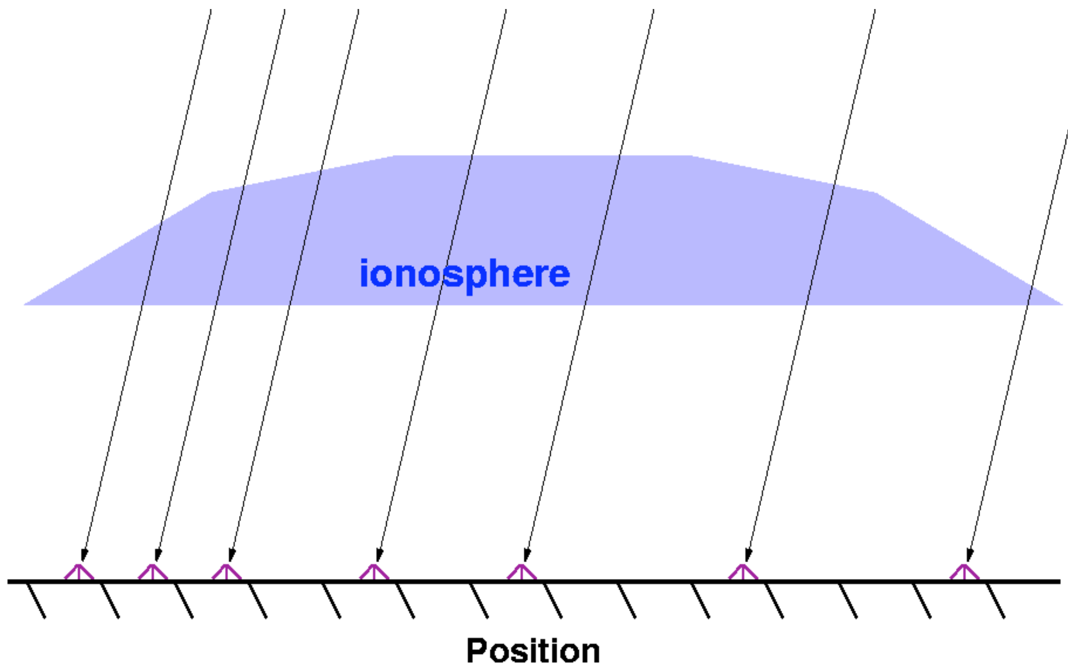


Ionospheric wedge model



- Assume differential delay related to ionospheric density GRADIENT, so $\varphi = (x_1 - x_2) * K$
- Depends on BASELINE length, not station or ionosphere POSITION

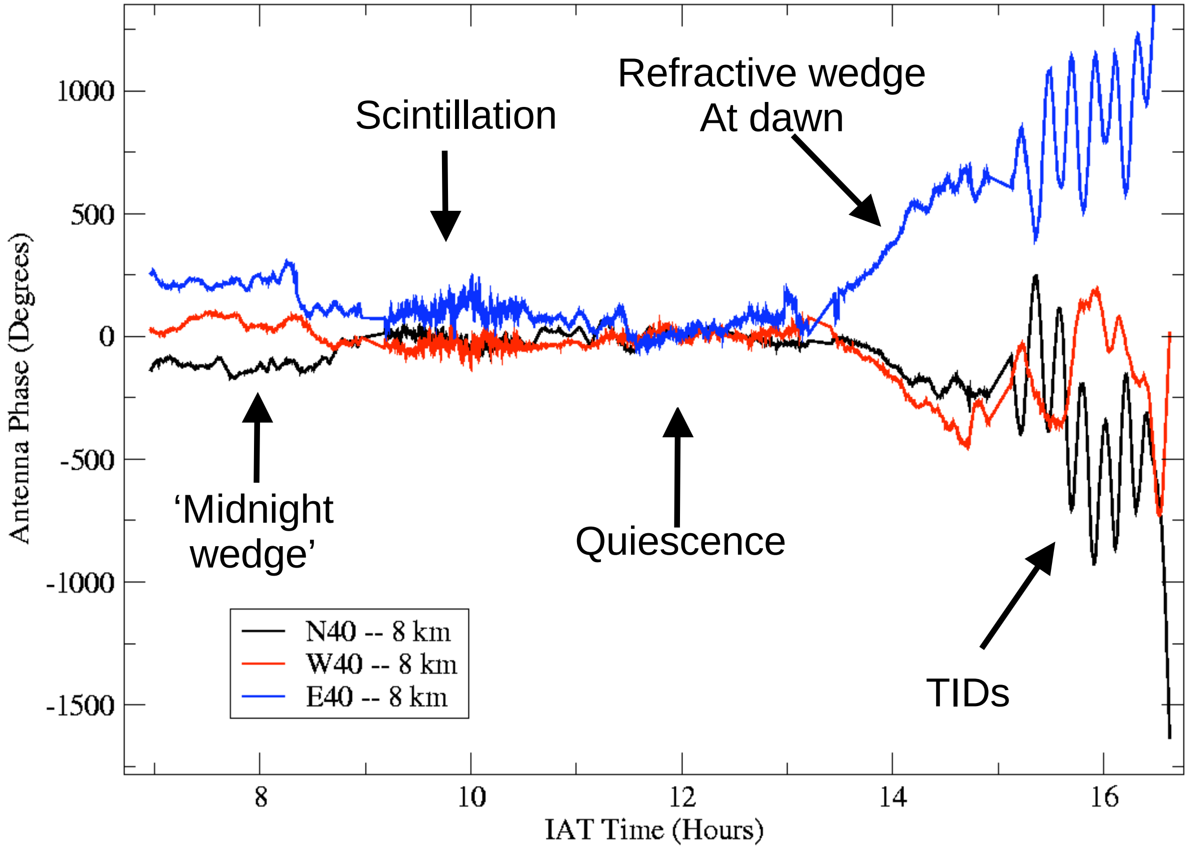
Gradient model breaks down for long baselines



- For stations at great distances, large-scale ionospheric structure and ionospheric waves cause gradient approach to fail
- Gradient approach also fails for large angular separations on sky

Ionospheric delay over the VLA (74 MHz)

phase behaviour can get very ugly !



TID =

Travelling Ionospheric Disturbance

(caused by Acoustic Gravity Wave)

Typical timescales 10-15m

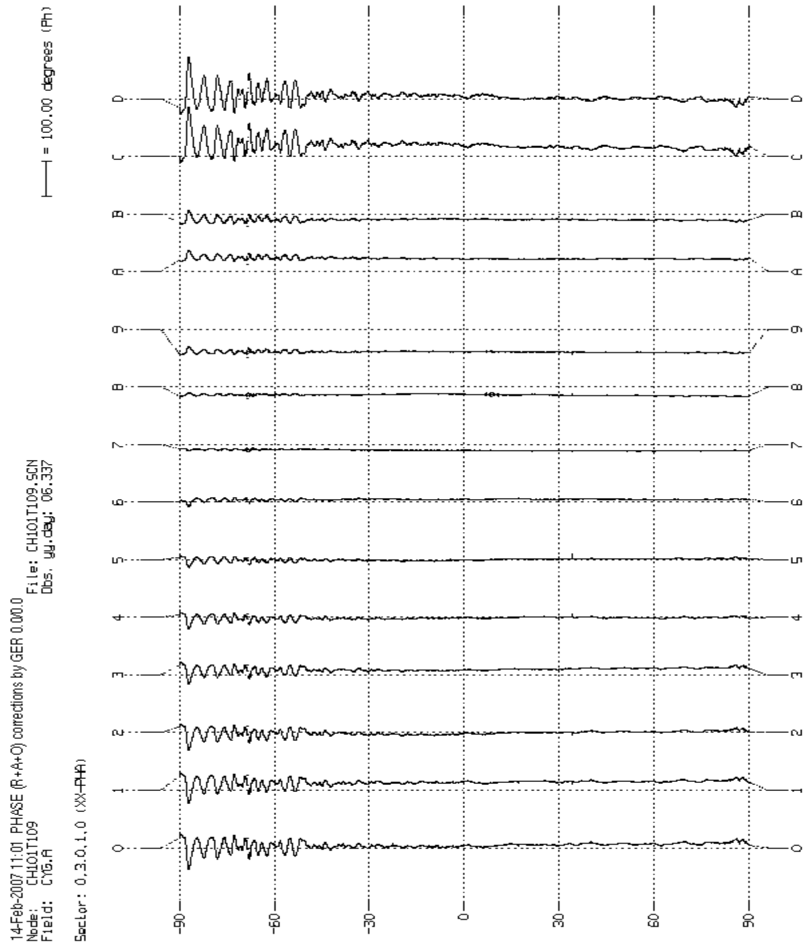
Speeds 500 km/h

Occur at ~ 250 km height (bottom F1 layer)

Lazio, 2005: data from Perley

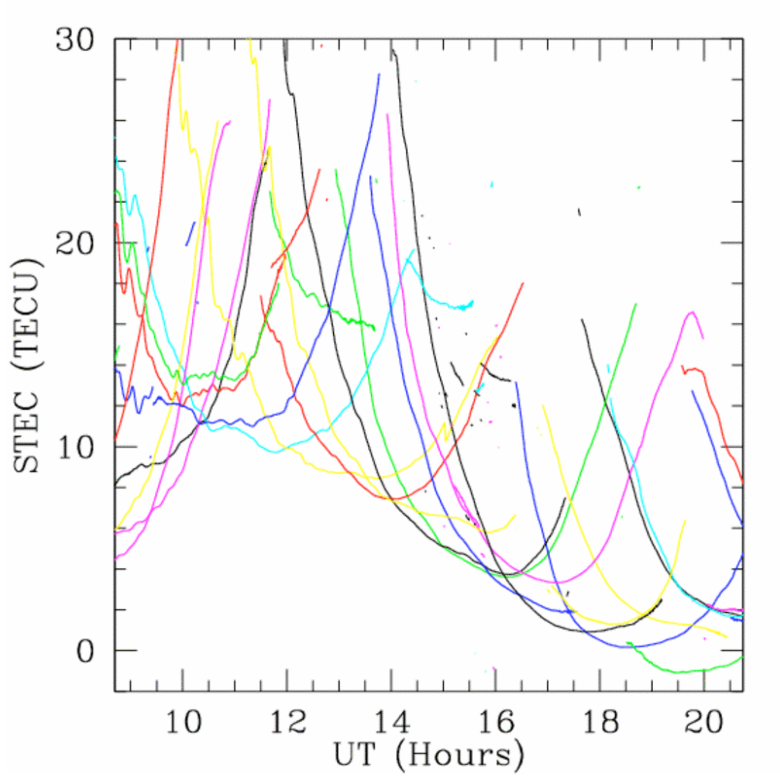
GPS Data show same TIDs measured with WSRT at 140 MHz (CygA, Dec06)

Phase slope

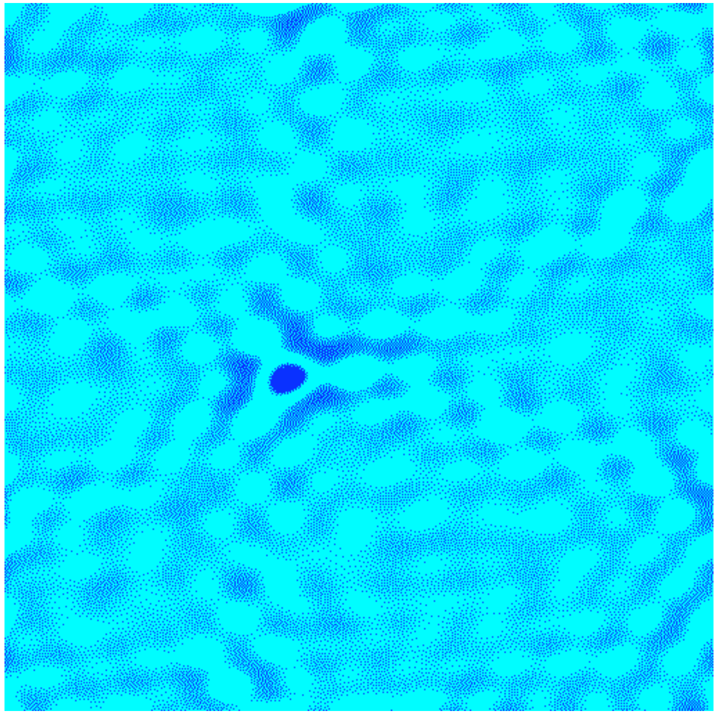


12h

hence TIDs are a very significant perturbation in TEC



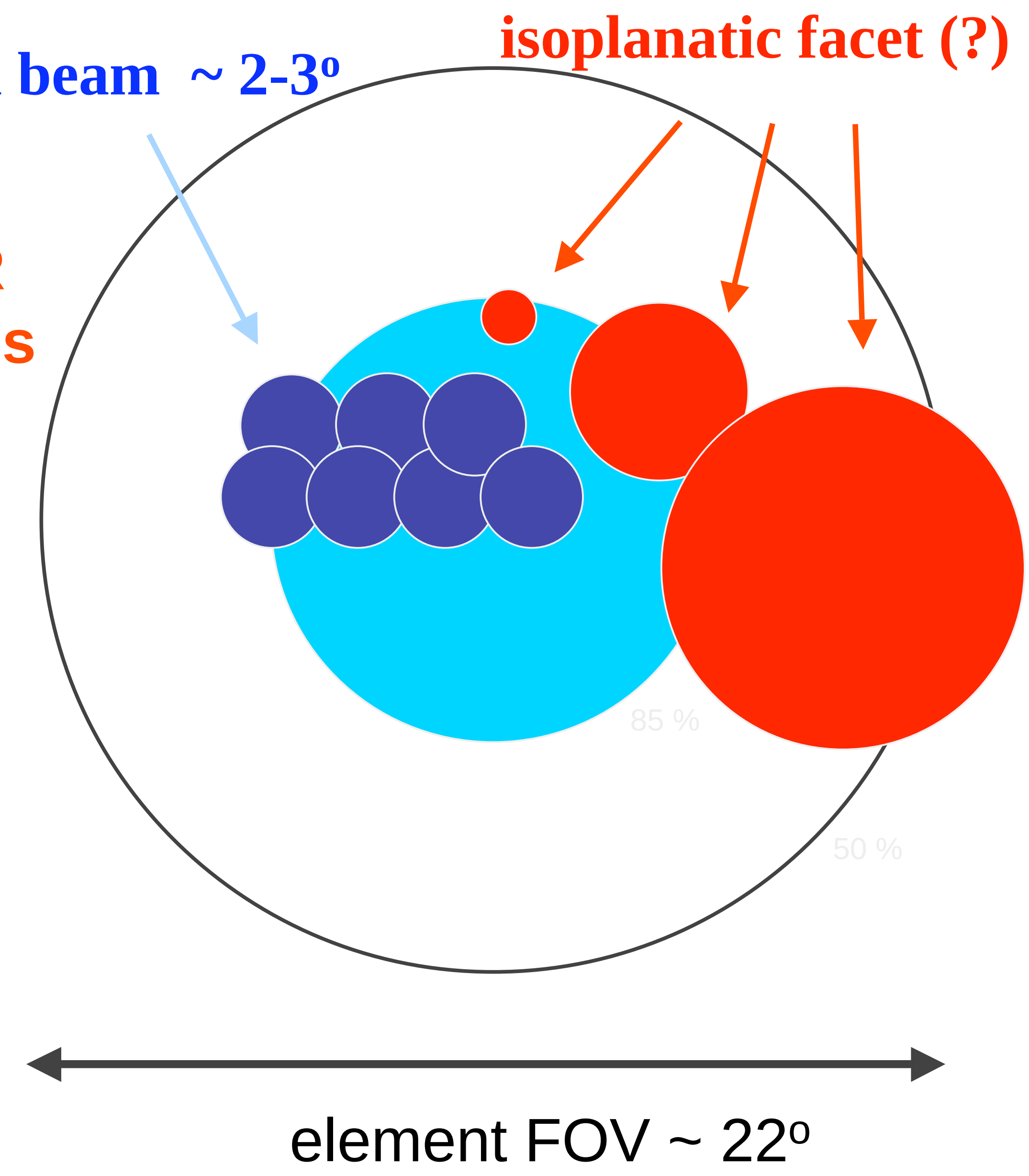
Dealing With a Variable Ionosphere: Waves



- Simulated VLA observation with sinusoidal ionospheric wave
- Large position motions replicated
- Beam shape changes replicated
- 2 sinusoidal waves in different directions reproduce the complex behavior of actual observations

MeqTree simulation by O. Smirnov

Angular scales in LOFAR 120-240 MHz observations



Note:

All scales are more or less frequency dependent but in different - timevariable - ways

WSRT-LFFE results

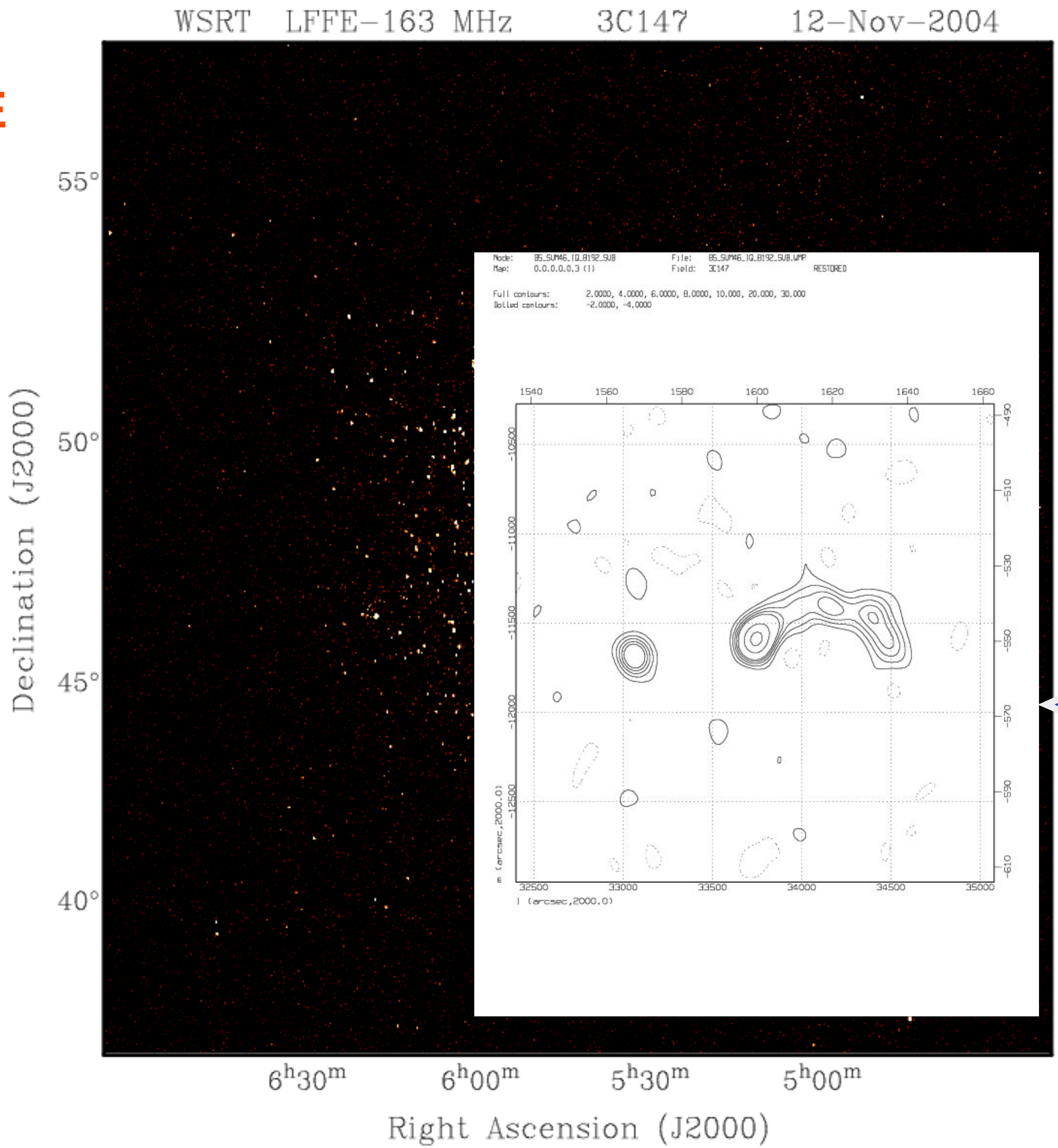
3C147

163 MHz

(z=7.7)

$20^o \times 20^o$

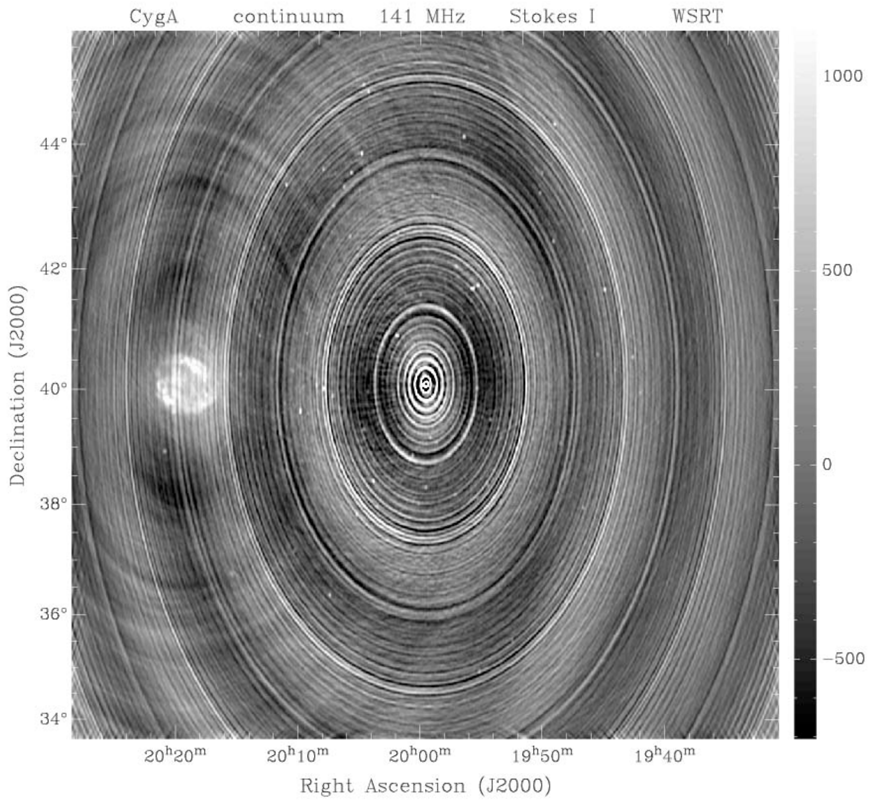
(4 mJy noise)



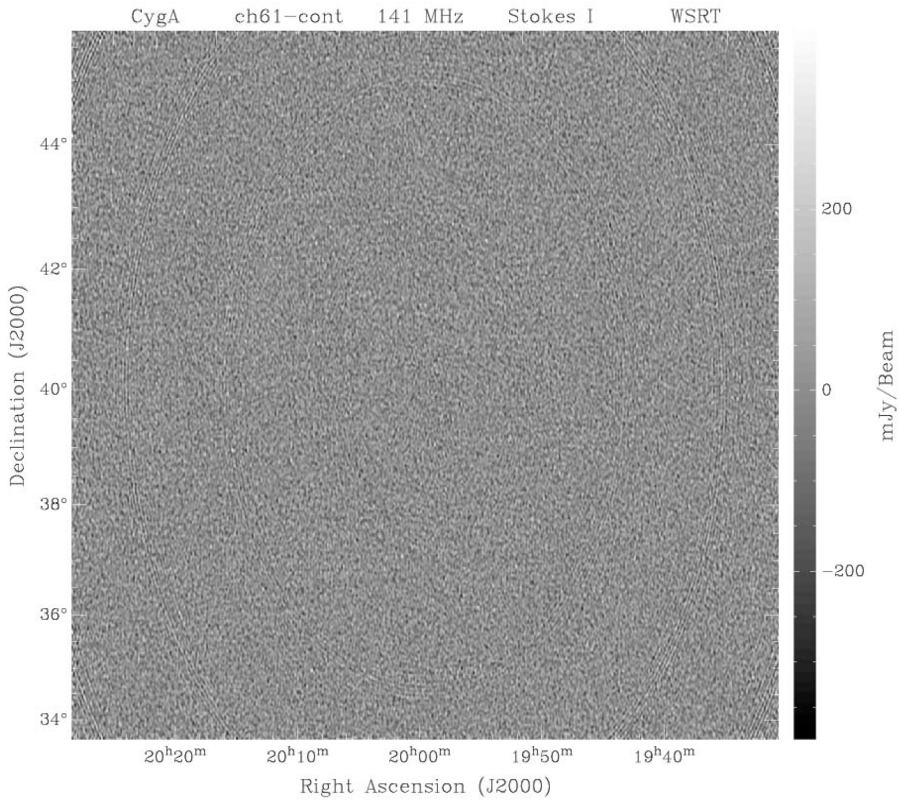
3C129/129.1

Very high dynamic range imaging of Cyg A at 141 MHz with the WSRT low frequency receivers

CONT (B=0.5 MHz)



LINE (10 kHz) - CONT



(Original) peak: 11000 Jy

noise 70 mJy

dynamic range = ~ 150,000:1 !!

RFI = Radio Frequency Interference

Issues:

- usable spectrum (time-frequency occupancy)
- linearity and saturation

lots of monitoring data, preparing for LOFAR

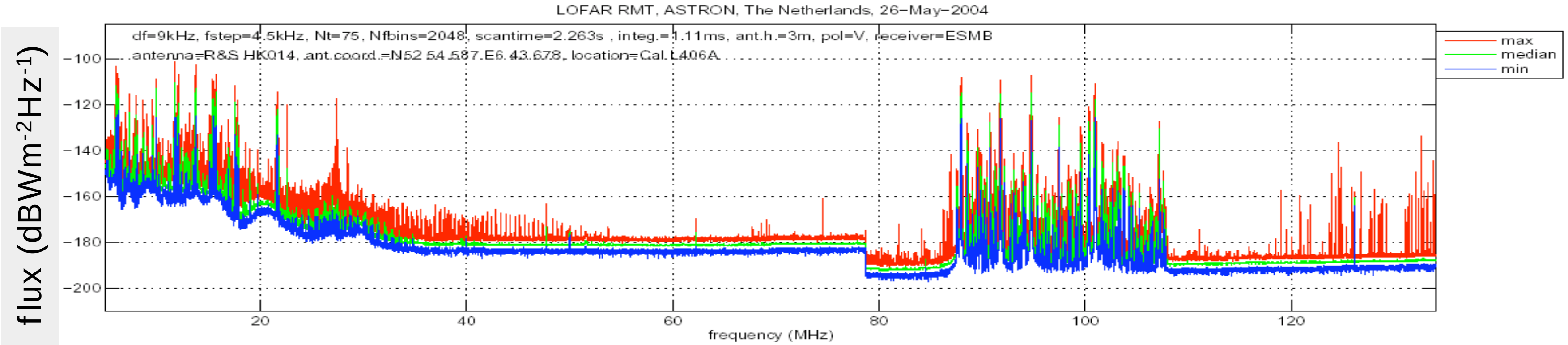
Main sources of RFI (Europe)

- TV 50 - 700 MHz
- FM radio 88 - 108 MHz
- Digital Audio Broadcast (spread spectrum, 174 -230 MHz, Europe)
- Satellites (amateur, military, weather,...

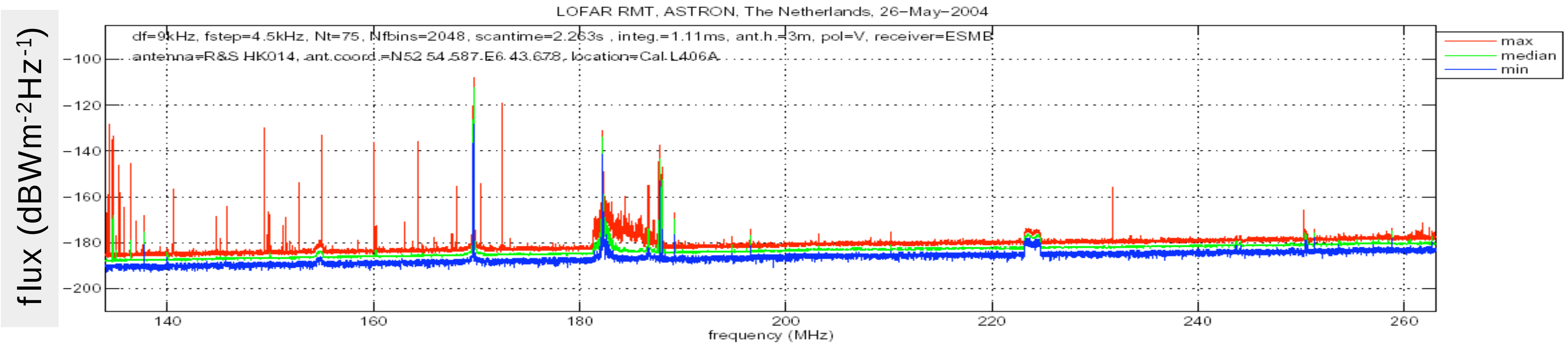
- Receiver/computer electronics (i.e. often your own RFI !)
- Mobile services

- Many signals, but not all, are very narrowband (~ 1 kHz)

RFI data in the Netherlands (not untypical for Europe)



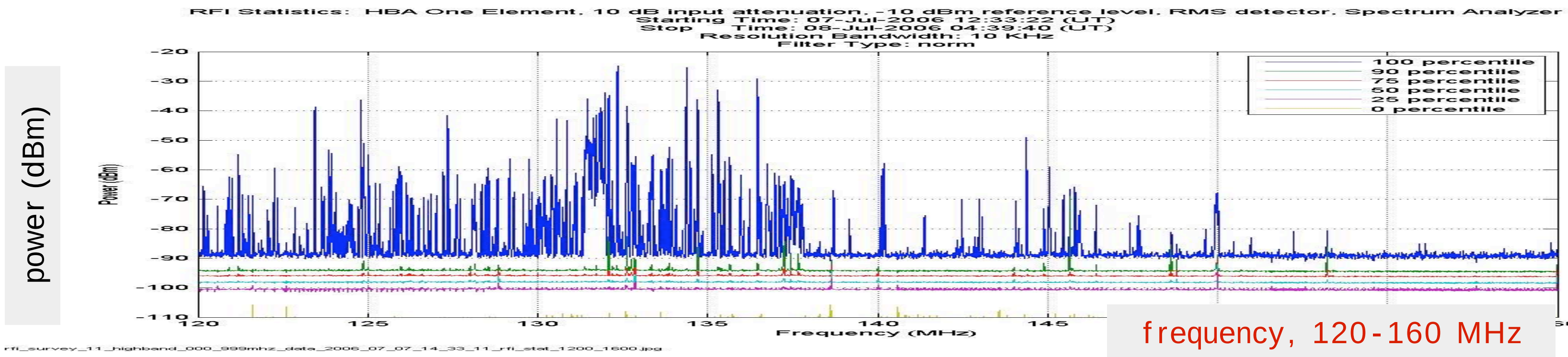
frequency 5-135 MHz

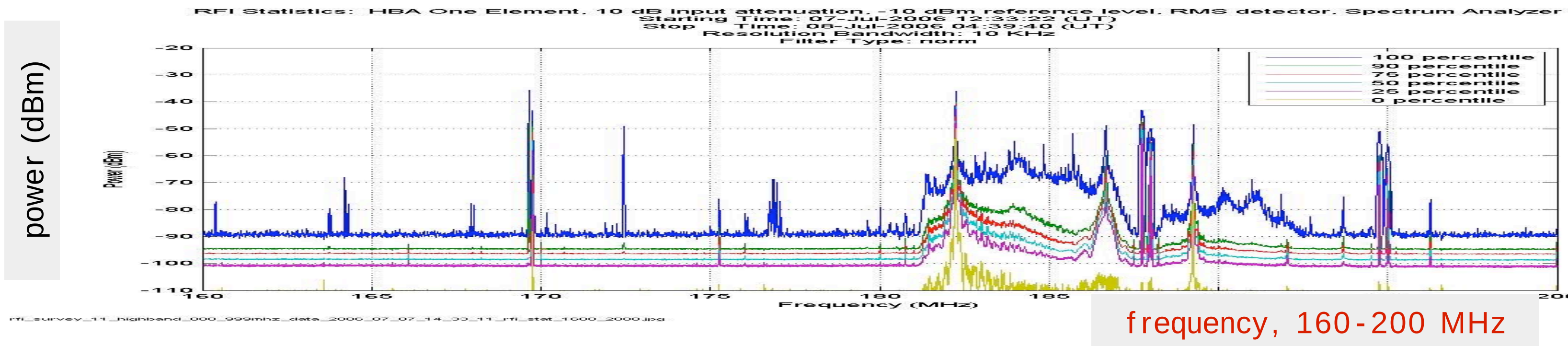


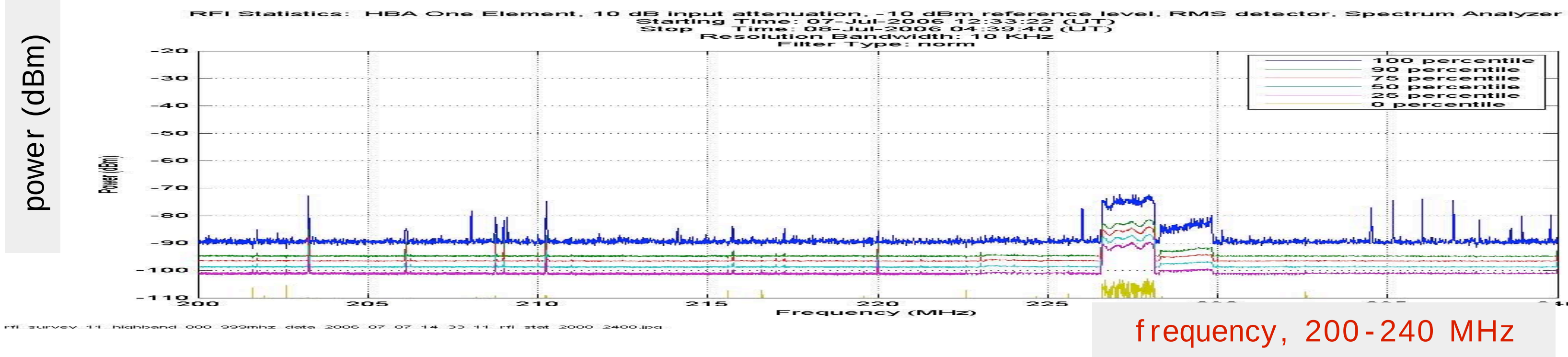
frequency 135-265 MHz

Max. observed RFI signal level:	~ -110 $dBWm^{-2}Hz^{-1}$	~ 10^{15} Jy	(at 169 MHz)
0 dBμVm-1, Δf=1 kHz:	~ -176 $dBWm^{-2}Hz^{-1}$		(at 150 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)

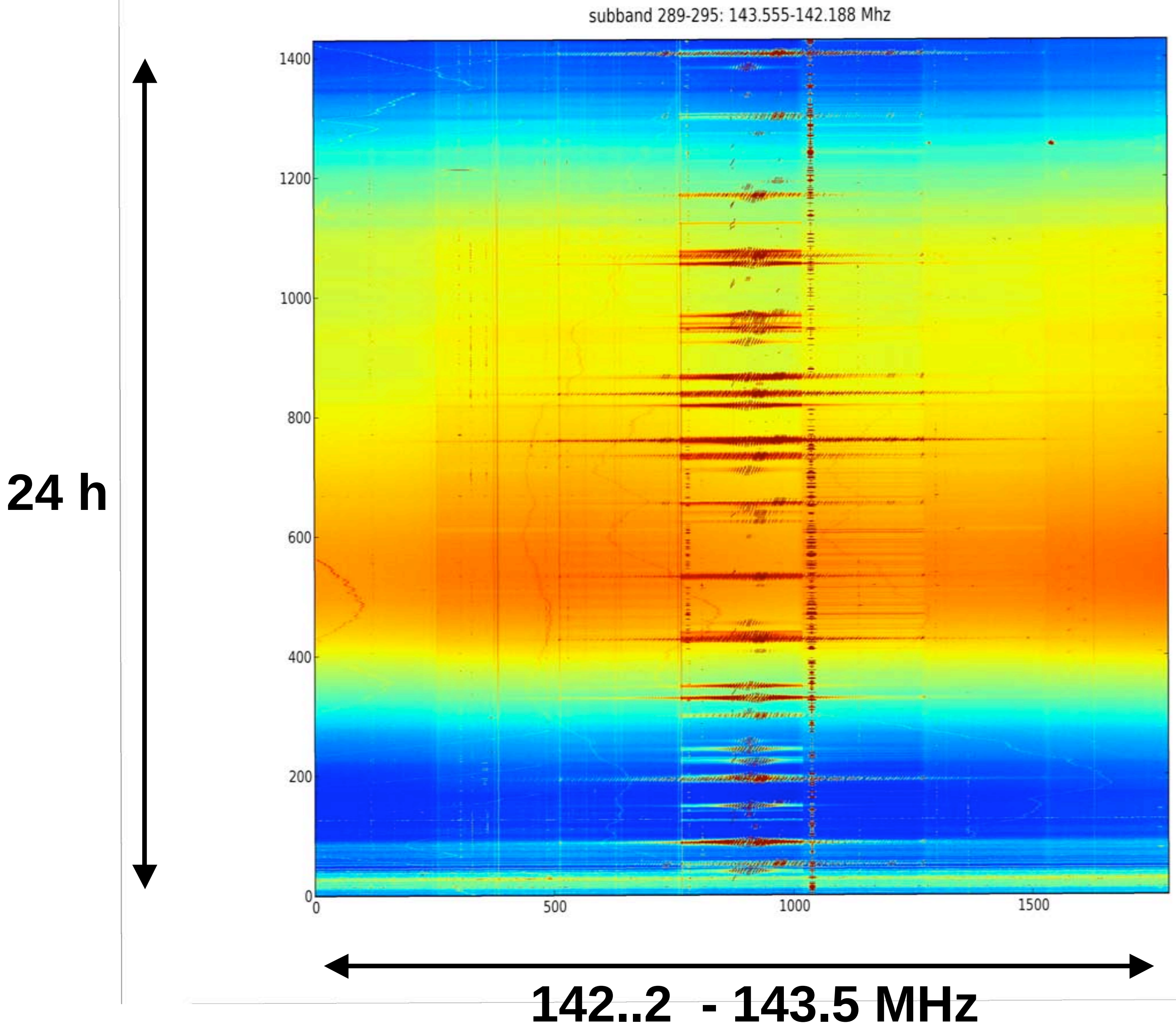
Initial LOFAR antenna measurement results (July 2006)
NB: analog TV 180-188 MHz disappeared in Dec 06!))



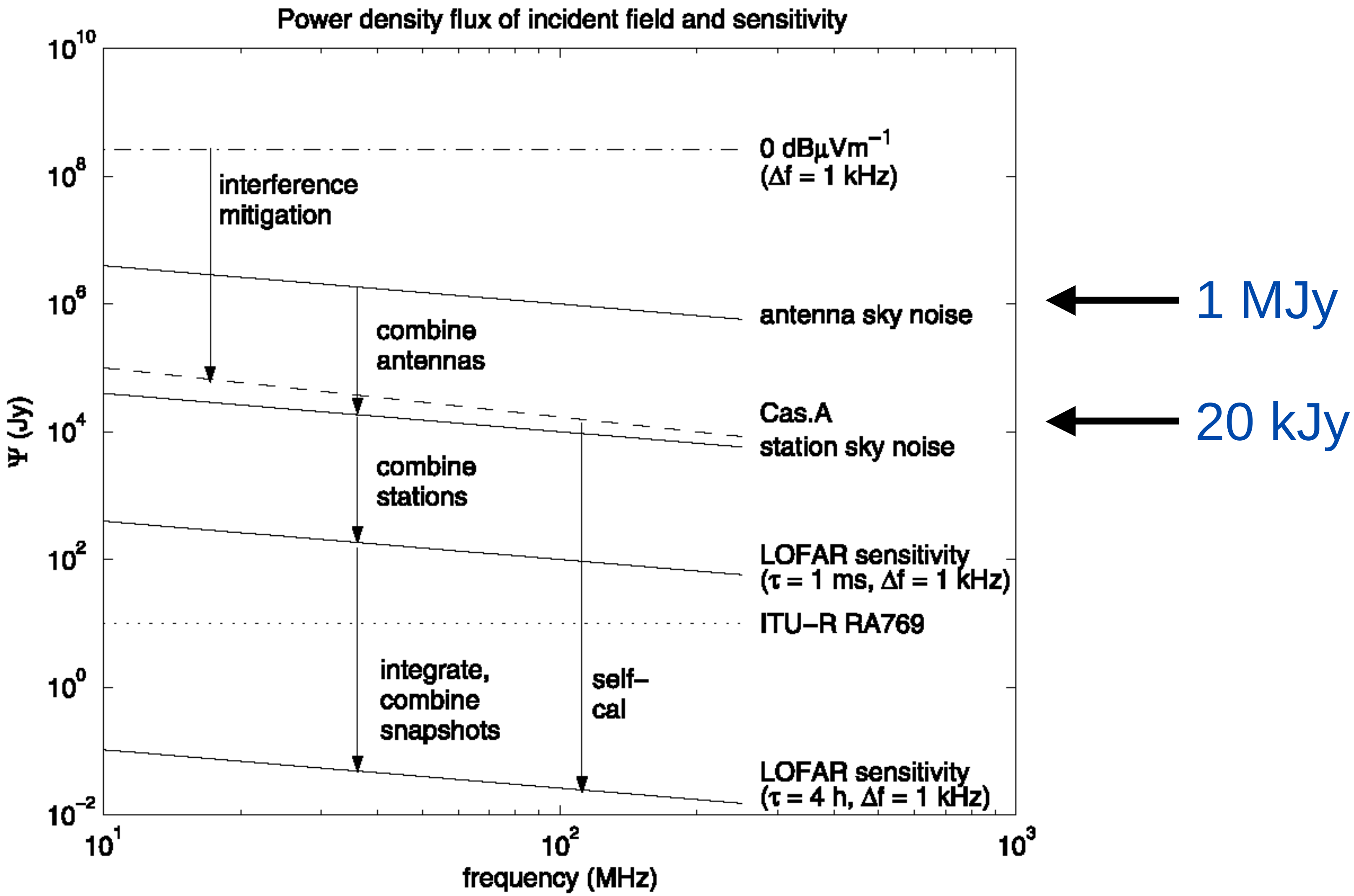




LOFAR dingle dipole monitoring at   1s, 1 kHz



LOFAR RFI mitigation approach



Spectrum allocation and use

DAB-T, band I I I

Drenthe/Groningen

- 6, 7C, 11C, 12C

Friesland/Overijssel

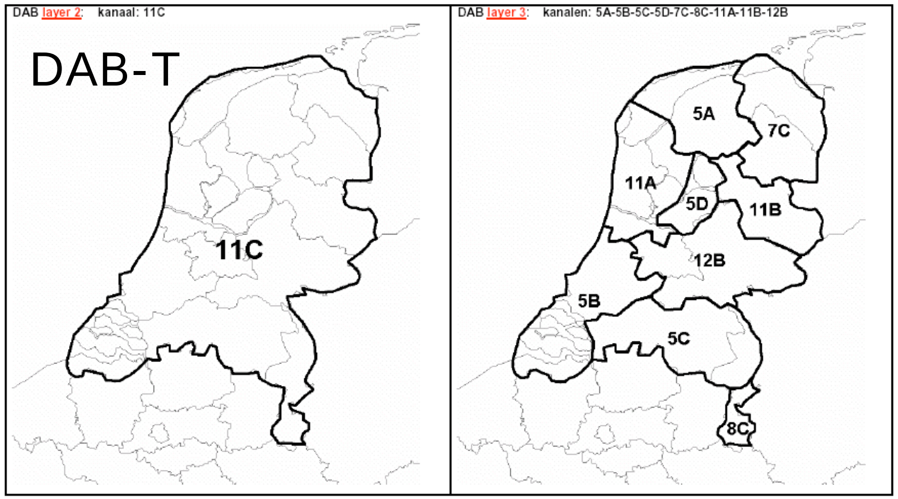
- 5A, 9, 11B

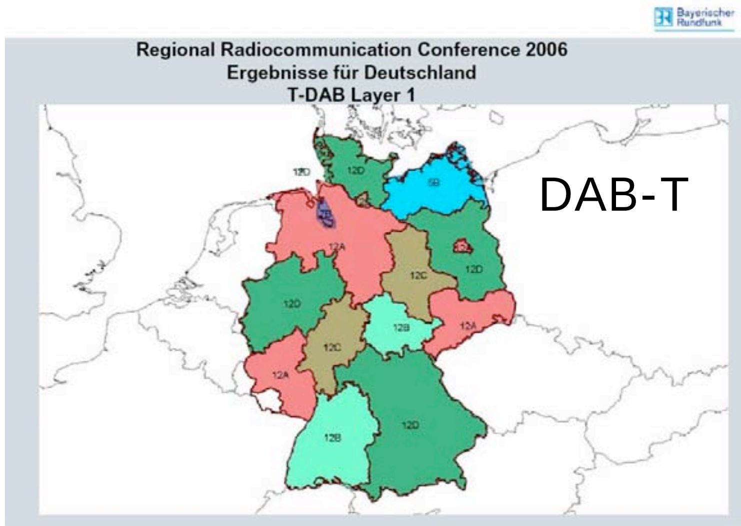
Lower Saxony:

- 5C, 5D, 10, 11A, 12A, 12B

DAB-T, band I I I.
174-230 MHz, ch.5-12.
7 MHz channels split into
four 1.75 MHz channels A-D.

Ch.5: 174-181	Ch.9: 202-209
Ch.6: 181-188	Ch.10: 209-216
Ch.7: 188-195	Ch.11: 216-223
Ch.8: 195-202	Ch.12: 223-230





Scattering at low frequencies: worrying?

Density fluctuations in ionized medium --> refractive index changes

Cause: waves (which cascade to) turbulence: Kolmogorov: $P \propto k^{-5/3}$

Observational consequences:

Scattering angular size $\theta_{ISS} \propto \lambda^{2.2}$

Angular resolution: $\theta \propto \lambda / L_{max}$

--> the maximum 'useful' baseline scales as: $L_{max} \propto \lambda^{-1.2}$

Multipath scattering leads to time-smearing (pulsars): $\Delta t \propto \lambda^{4.4}$

Decorrelation bandwidth is the inverse of this

Contributions to scattering

CygX3 :
2.8” at 408 MHz

- IGM ?
- ISM strong Galactic latitude dependence
- IPM depends on Solar elongation /Solar cycle
- Ionosphere occasional periods of scintillations

Strong versus Weak scattering

Parameters: screen distance, turbulence level C_N^2, wavelength, transverse velocities

Transition between weak to strong scattering when R_{diff} <~ $R_{Fresnel}$

- Strong (= diffractive) size << 1μ arcsec (Pulsars, Planets, Flarestars ?
- Weak (= refractive) almost everything else (AGN, ...)

Polarized radio emission

Linear polarization at (very) low frequencies

- New frontier !
- Great diagnostic value

Faraday rotation: $\Delta\Phi \propto \int n_e B_{//} dl \; . \; \lambda^2$

Contributions: - source

- intervening plasmas (IGM,ISM)
- ionosphere (time variable part!)

Low frequency polarimetry; technical aspects:

- Propagation and instrumentation lead to various depolarization effects:

  → beam → *use longer baselines*

  (WSRT 3 km, VLA-GMRT 30 km, LOFAR ~ 100 - 1000 km)

  → bandwidth → *use multi-channel backends*

  → depth → *separate Faraday (thin/thick) layers in RM-space*

- Use wide-field RM synthesis. (Coherent addition of polarization vectors)

Beam depolarization due to spatial RM- gradients around source or intervening media

1) ISM RM-gradient of 1 rad/m^2 per degree

--> at 50 MHz: 34^o / arcmin

--> NO PROBLEM with standard LOFAR-100km

2) source RM-gradient of 1 rad/m^2 per arcmin (e.g. double-double giant B1834+62)

--> at 50 MHz: 34^o / arcsec

--> this requires ~1000 km baselines.

Bandwidth depolarization:

$\mathbf{d(\Delta\theta_{Far})} \sim 2\ \mathrm{RM}\ .\ \lambda^2\ .\ \Delta\nu/\nu$ $\quad\quad$ **($\propto\nu^{-3}$!)**

at 150 MHz:	0.03° / kHz	for RM=10 rad/m^2
50	0.8	
30	3.8	

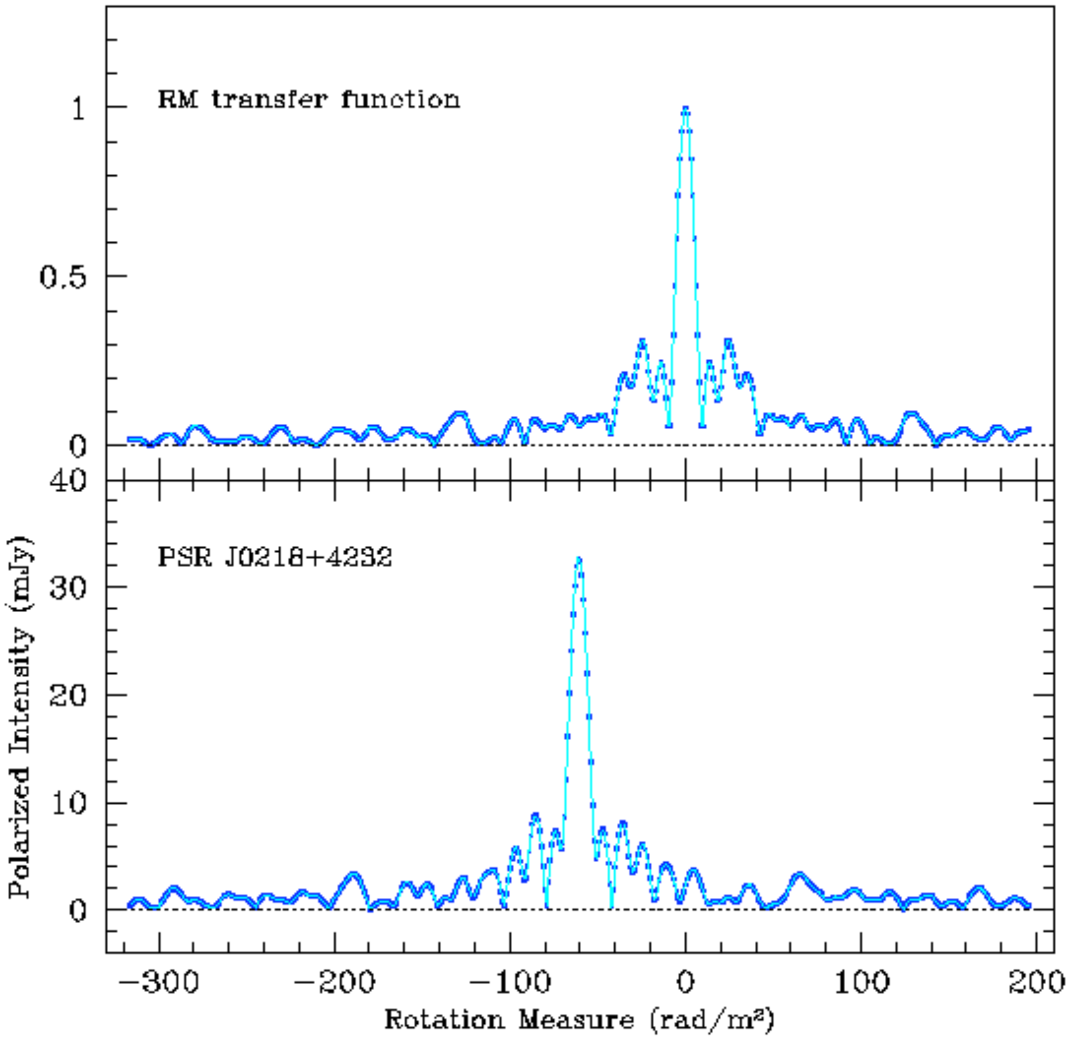
LOFAR will have 1 kHz resolution

--> RM synthesis techniques usable and required

An example of the use of RM-synthesis,

on a single source

Brentjens & de Bruyn, 2005



WSRT 315-375 MHz

PSR J0218+4232

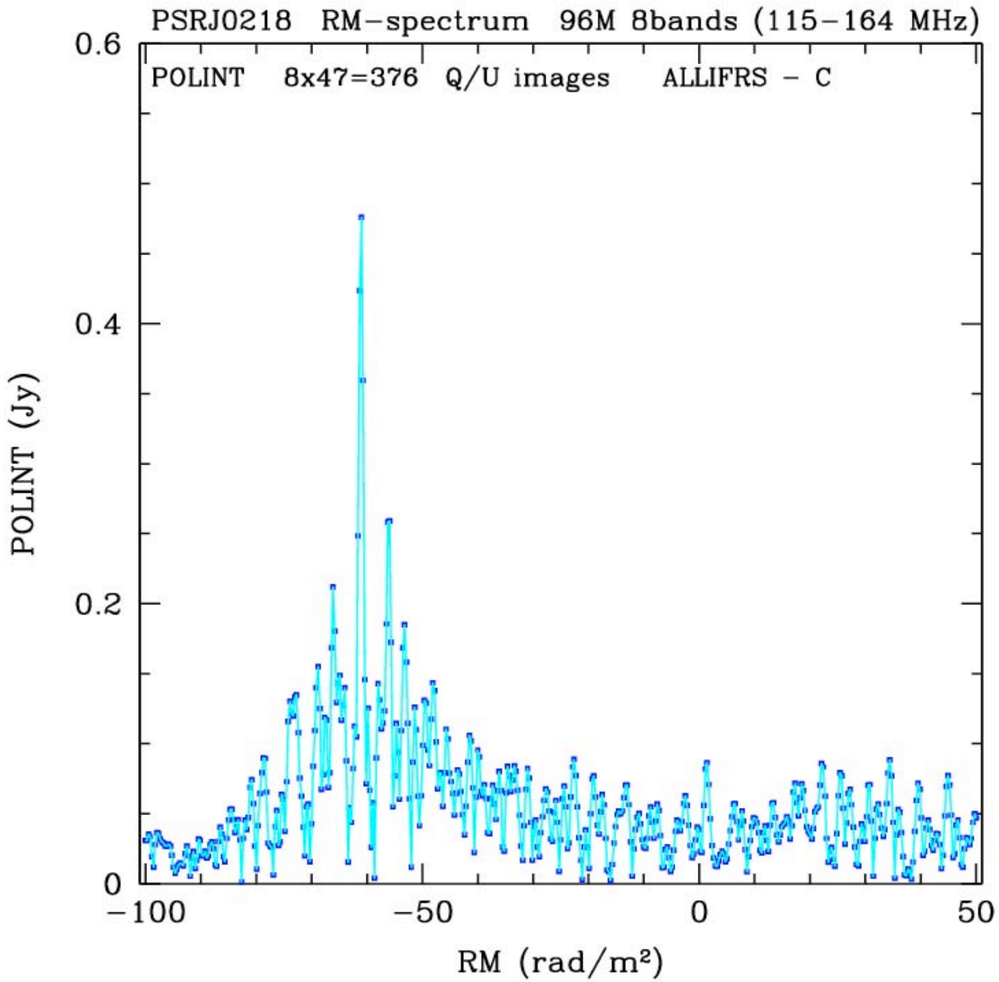
RM = - 61 rad/m^2

RM-synthesis at still lower frequency

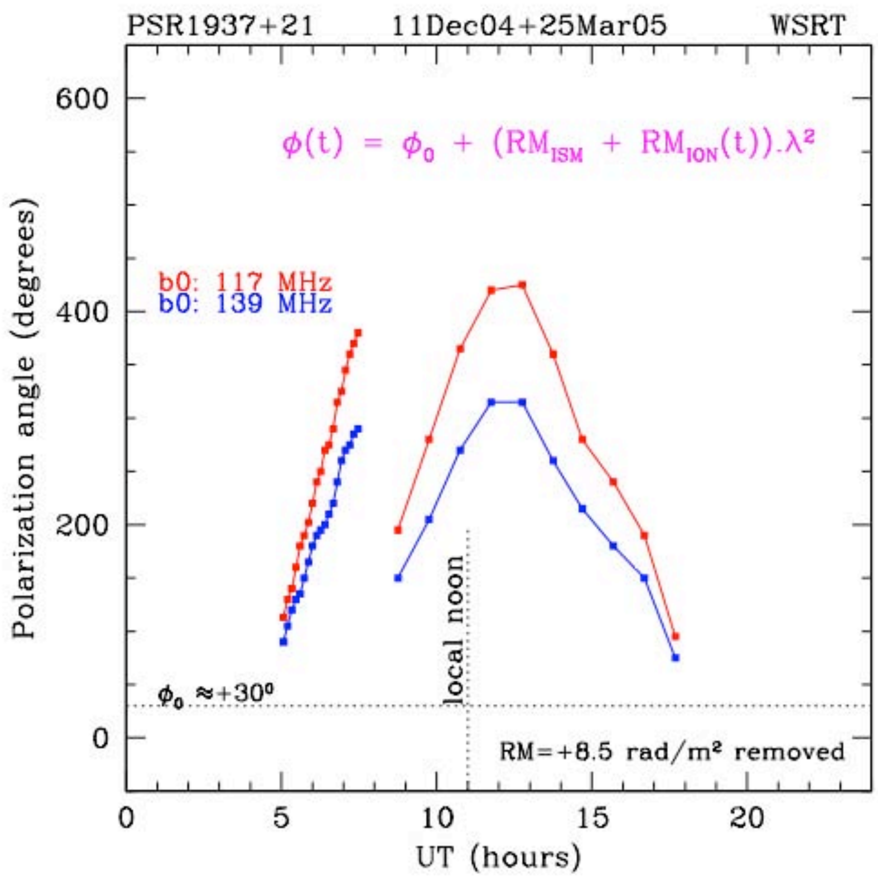
WSRT 115-164 MHz

PSR J0218+4232

RM = - 61 rad/m^2



Ionospheric Faraday rotation variability



WSRT-LFFE

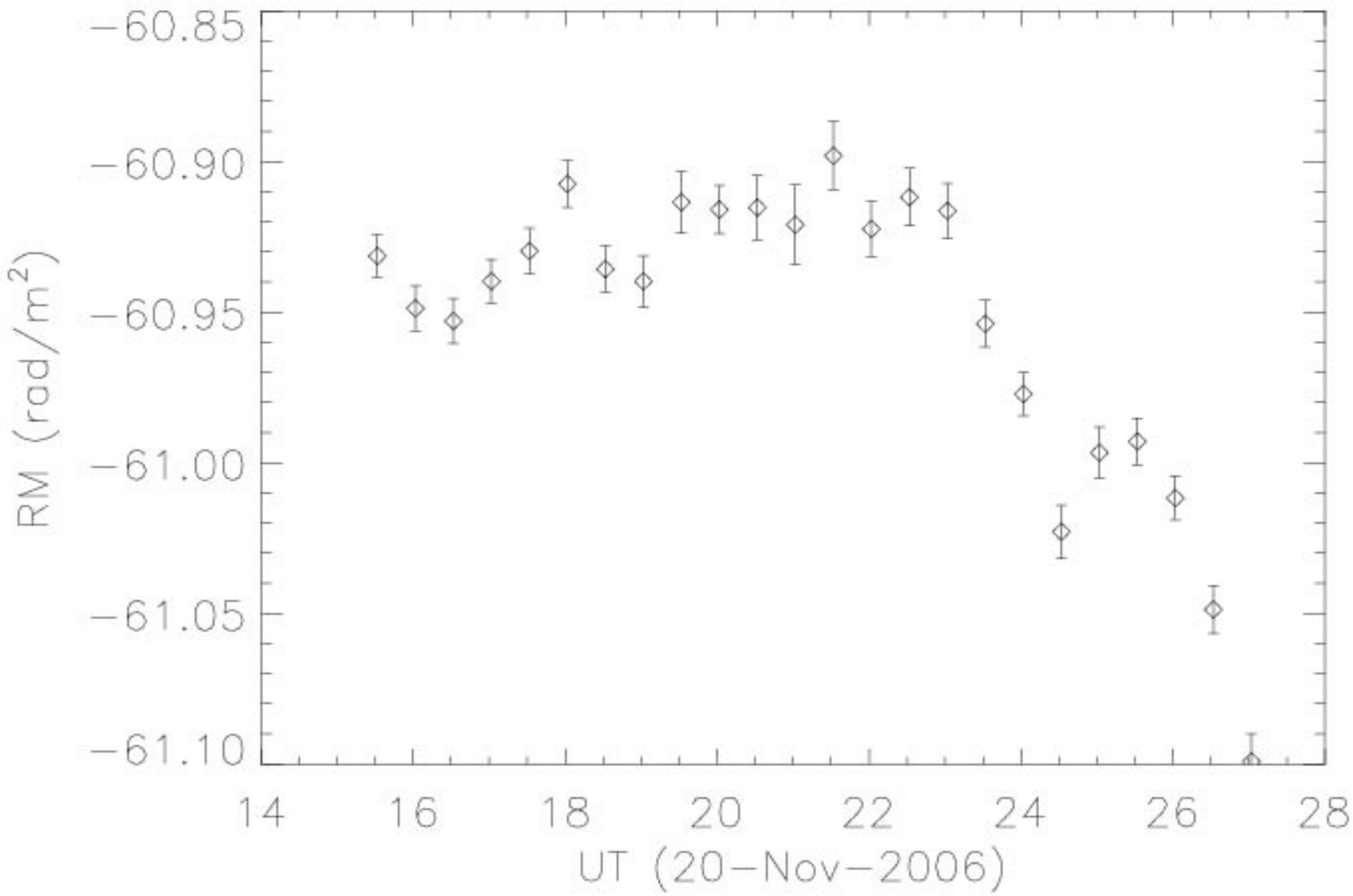
dawn gradient in angle rotation

at 117 MHz ~ 2.5^o / minute

→ at 60 MHz ~ 10^o / minute

→ at 30 MHz ~ 40^o / minute

Nightly variations of ionospheric Faraday rotation variations
PSRJ0218+4232



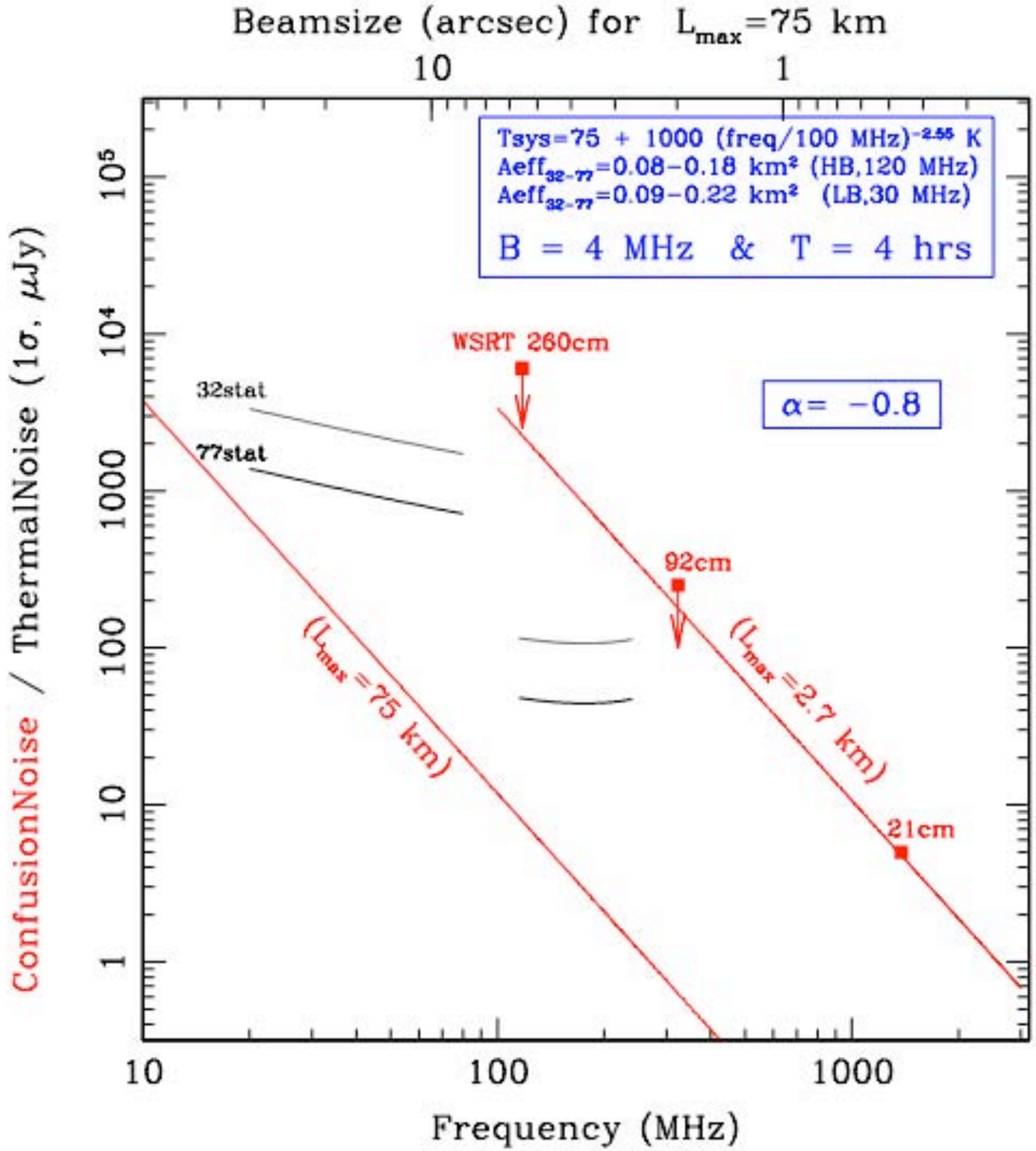
Classical source confusion

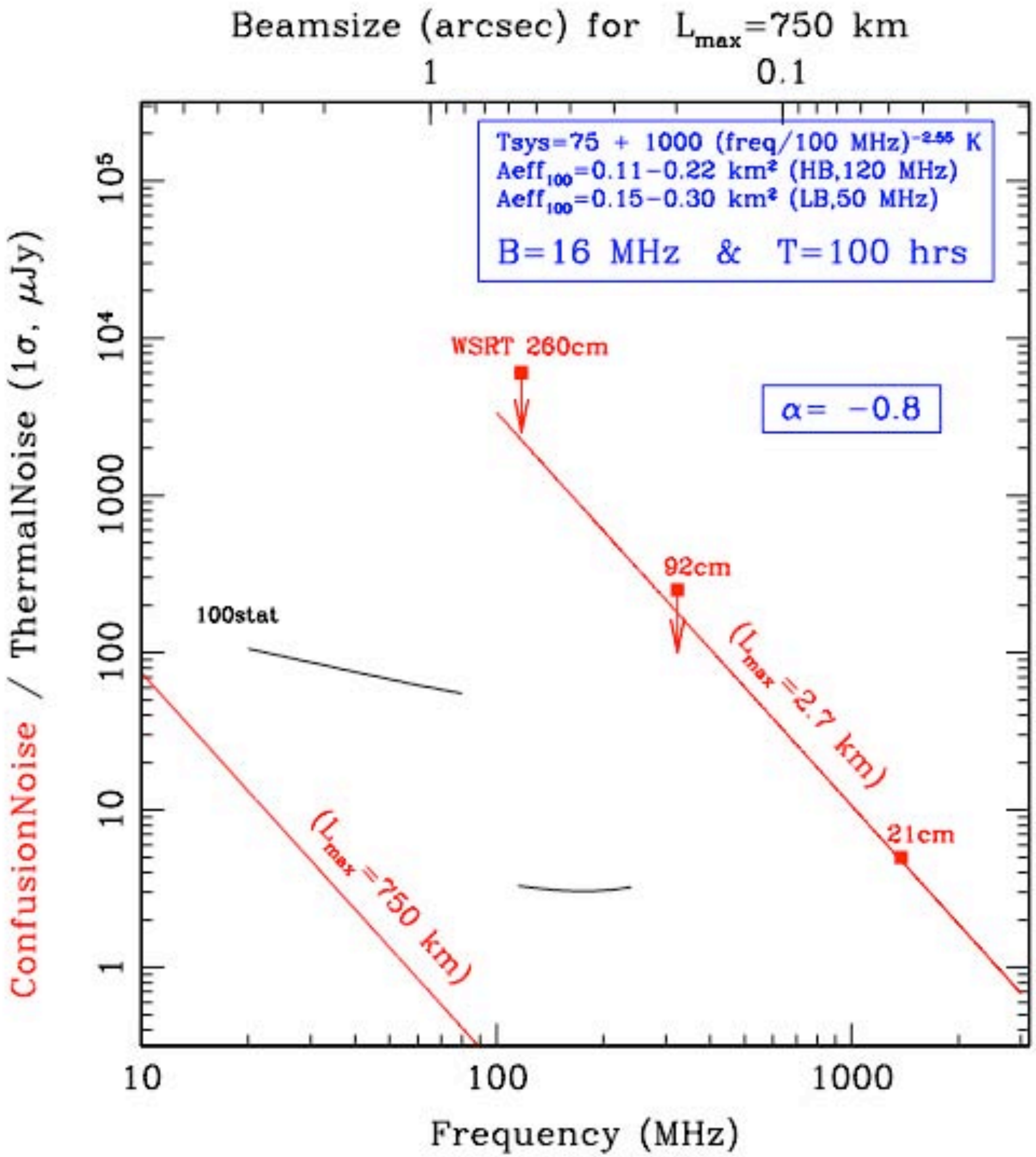
at (very) low frequencies

Approaching one source per beam -->

'classical confusion'

LOFAR 100km baseline





Beamsize (arcsec) for L_{max}=750 km
1
0.1
Tsys=75 + 1000 (freq/100 MHz)$^{-2.55}$ K
$Aeff_{100}$=0.11-0.22 km^2 (HB,120 MHz)
$Aeff_{100}$=0.15-0.30 km^2 (LB,50 MHz)
B=16 MHz & T=100 hrs
WSRT 260cm
α= -0.8
92cm
100stat
(L_{max} =2.7 km)
21cm
(L_{max} =750 km)
10^5
10^4
1000
100
10
1
10
100
1000
Frequency (MHz)
ConfusionNoise / ThermalNoise (1σ, μJy)