IONOSPHERIC EFFECTS

LOFAR data school 2014

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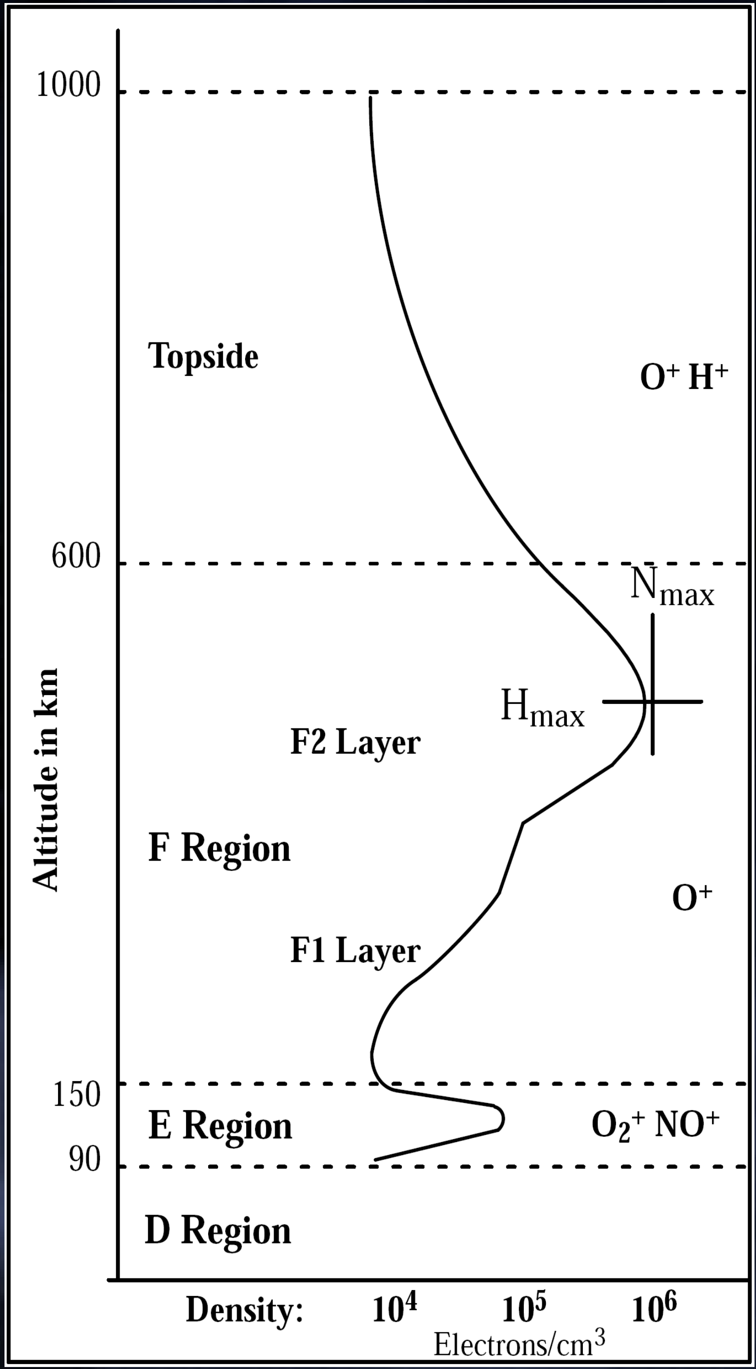
ASTRON

LOFAR

OUTLINE

- Introduction Ionosphere
- Electromagnetic propagation
  - dispersive delay
  - Faraday rotation
- Corrections
  - phase solutions
  - Direction Dependent Solutions
    - TECscreen
  - RM corrections
- Conclusion

Ionosphere

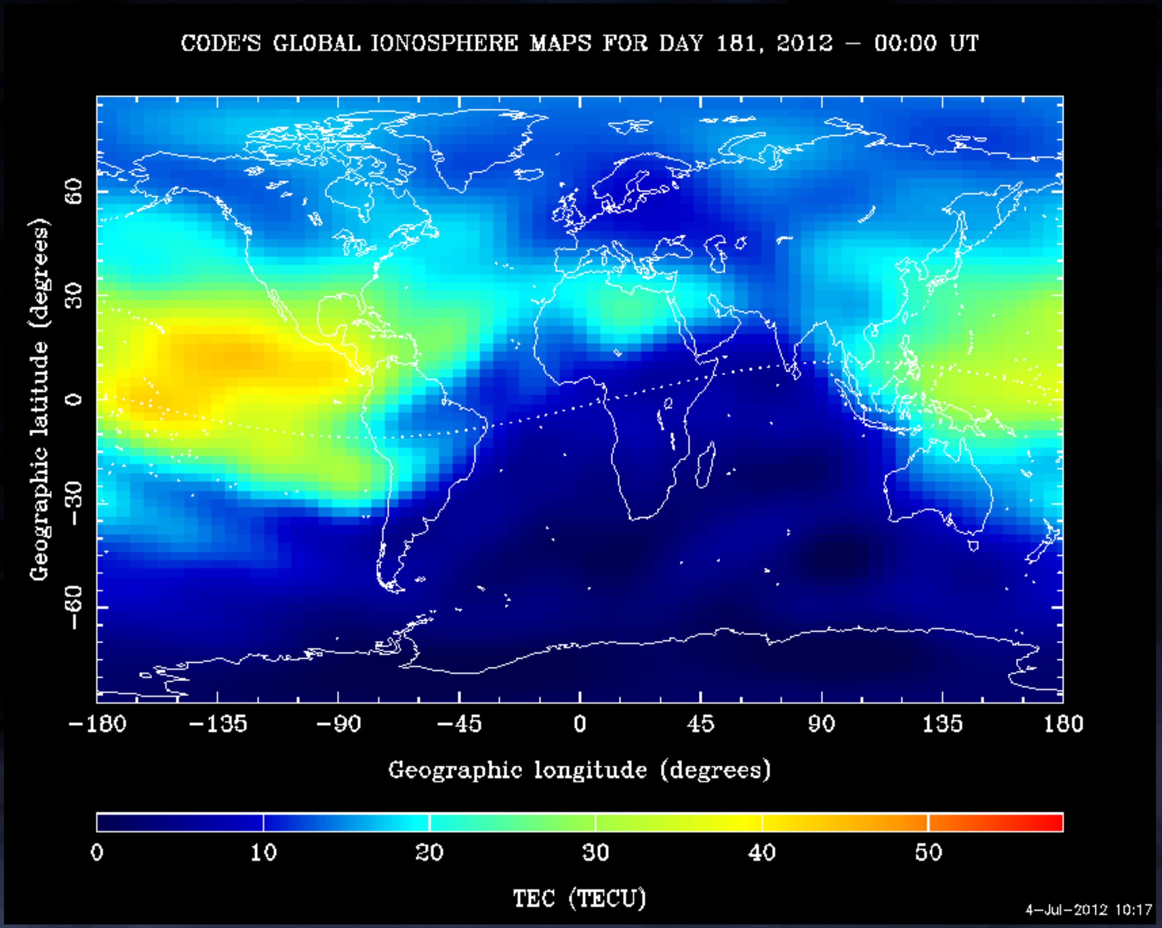


- Appleton 1924:
  - existence of reflecting layer (long wavelengths) in atmosphere (~125 km)
  - ionized
  - shorter wavelengths reflected @ 300-400 km
- ionospheric structure, density changes with altitude
  - height of layer changes during sunset/sunrise
  - ionization due to solar radiation

Measurements

- ionosonde: measure the structure of the different layers by investigating reflections of different wavelengths
- early radio astronomy
  - signals pass completely through
- nowadays: satellites +GPS receivers
  - GPS data online available
  - fit to GPS data of many stations also online: IONEX data
    - low time (1~2hr) and spatial (2.5 x2.5 degrees) resolution
    - thin layer approximation

CODE ionospheric data



Total Electron Content (TEC)

Typical values @ 52° for integrated TEC along LOS:
5(night)- 50(day) TECU (10^{16} e/m^2)

Structure

The ionosphere is highly dynamic:

Ionization through solar radiation (UV+X-ray)
Recombination at night
=> diurnal pattern

Solar activity cycle

Scintillation (high turbulence):
(mostly) after sunset

Pressure + composition lower atmosphere
Travelling Ionospheric Disturbances (TIDs)

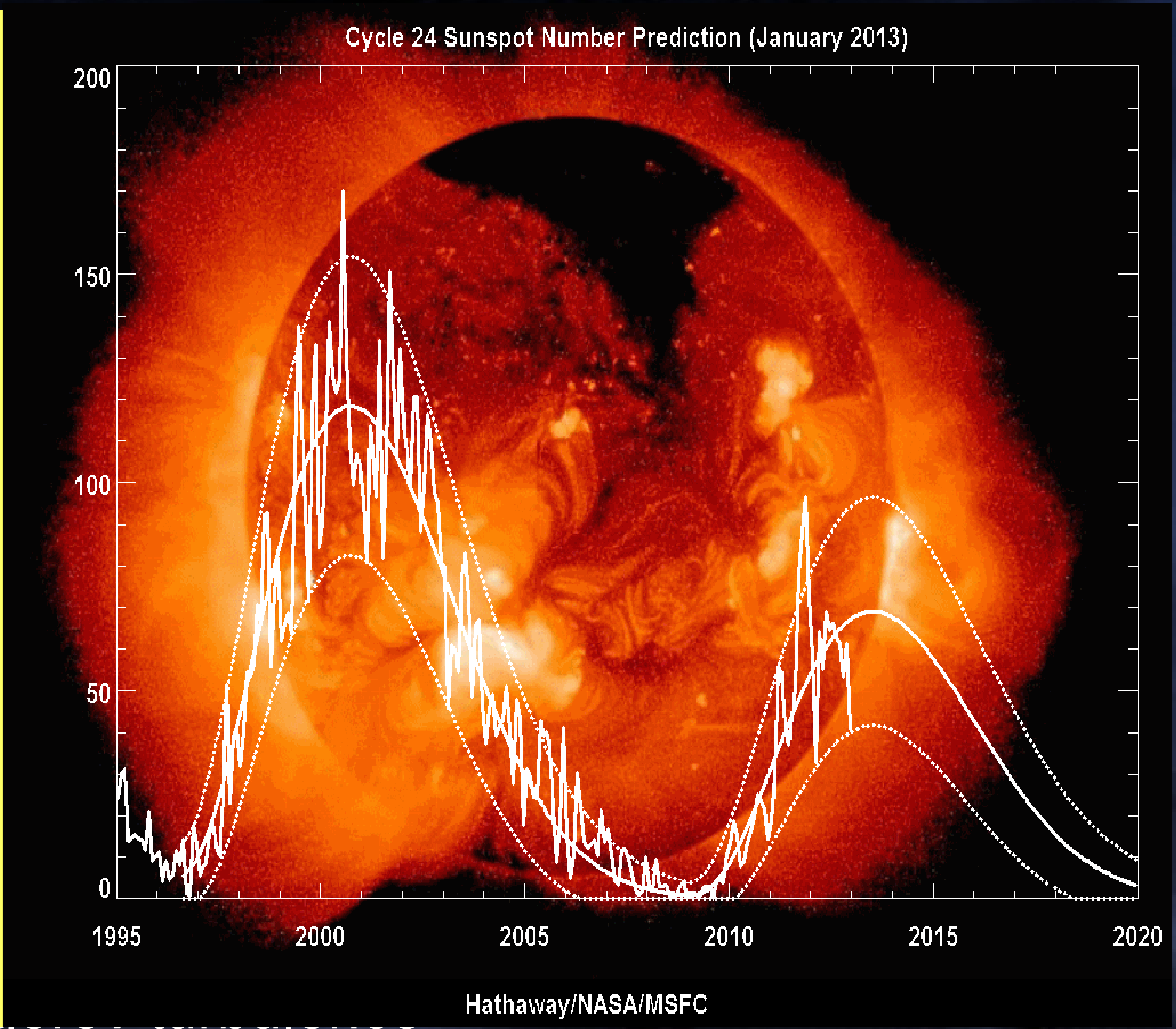
Structure: Kolmogorov turbulence

Structure

Solar activity follows a 12 year cycle:

Currently we are in a maximum

the current maximum appears to be much lower than in previous cycles.



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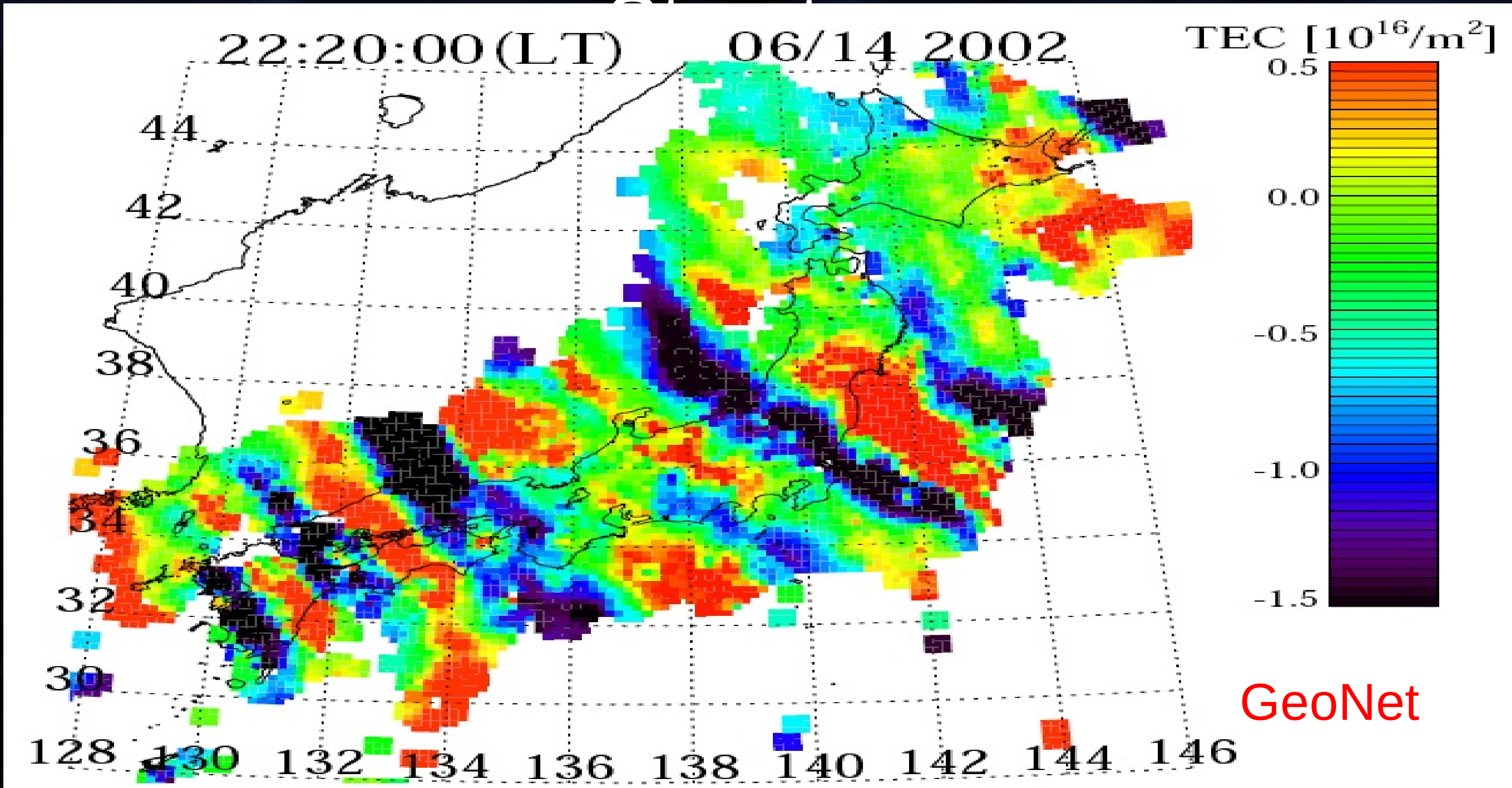

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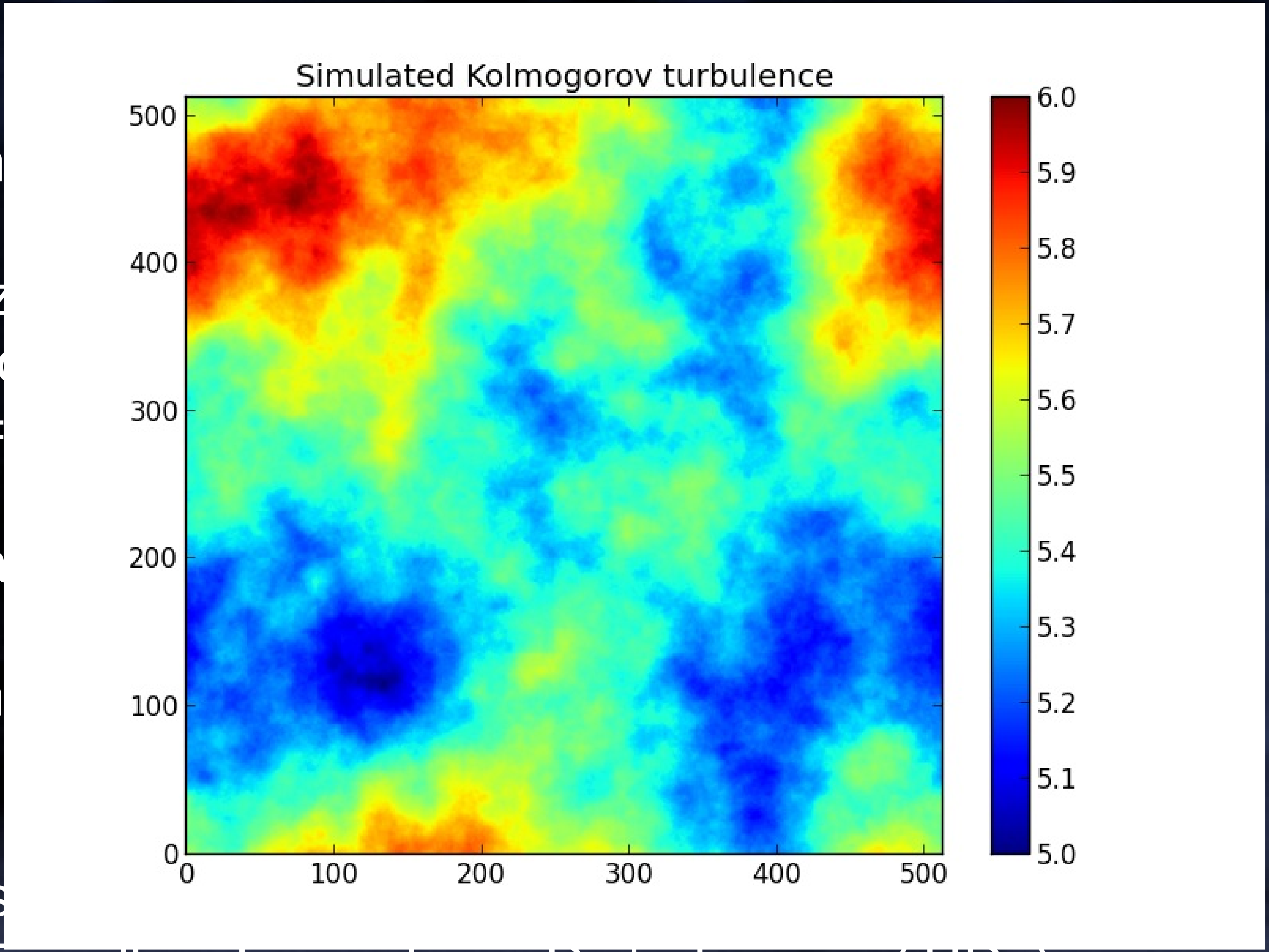
Travelling Ionospheric Disturbances (TIDs)



Structure: Kolmogorov turbulence

Electromagnetic Propagation

refractive index in ionized plasma:

$$n_{ph} = \sqrt{1 - \left(\frac{f_p}{f}\right)^2} \simeq 1 - \frac{1}{2}\left(\frac{f_p}{f}\right)^2 = 1 - \frac{40.3}{f^2} N_e$$

if frequency *f (ν)* >> plasma frequency f_p(~10 MHz)

N_e = electron density

excess path length $$40.3/\nu^2 \cdot \int N_e dl$$

phase error: $\varphi_{ion} \approx 8.45e9$ dTEC/ν

dTEC in TECU (10^{16} e/m^2)

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dispersive

Faraday Rotation

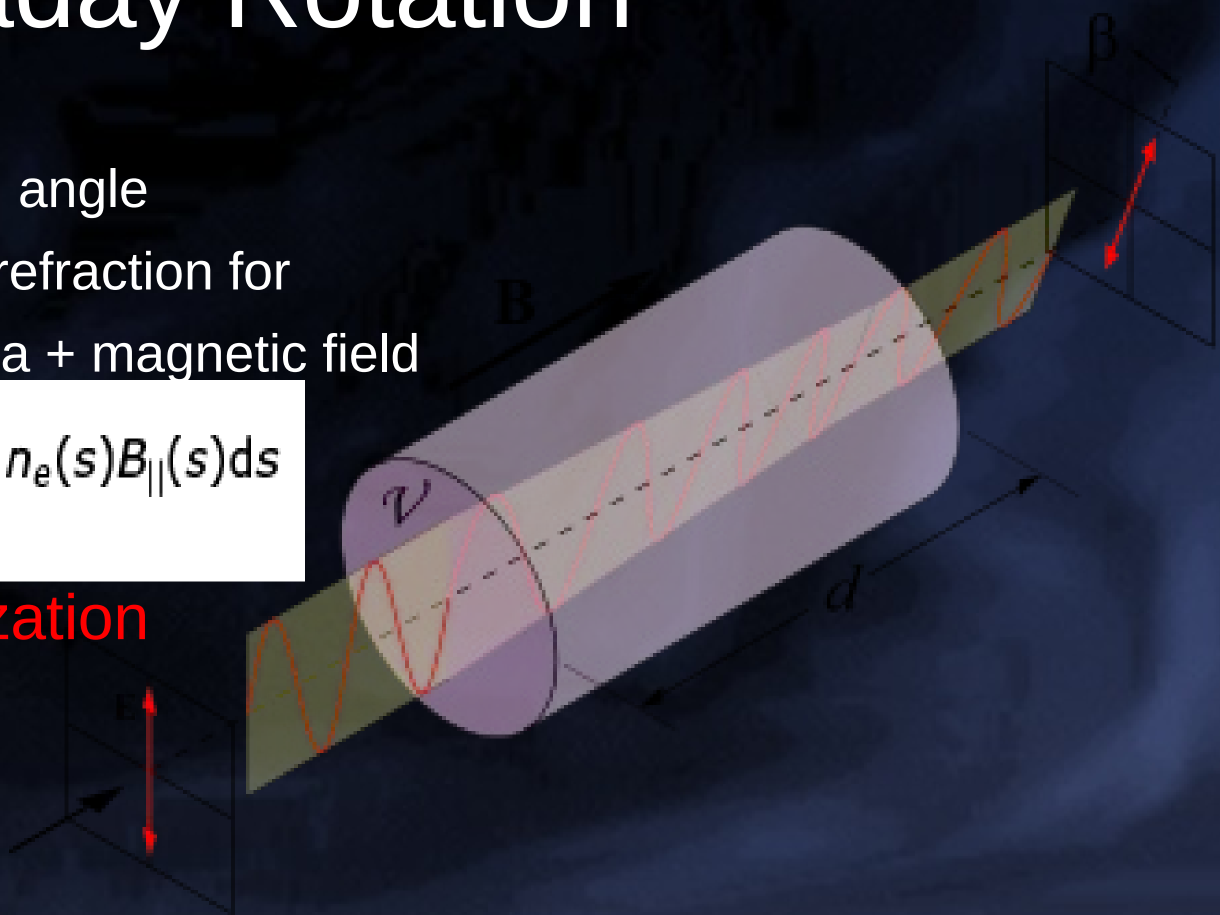
Rotation of linear polarization angle

Due to difference in index of refraction for

R and L polarization in plasma + magnetic field

$$\beta = \mathrm{RM}\nu^{-2}\ ,\ \mathrm{RM} = \frac{e^3}{8\pi^2\epsilon_0 m^2 c^3}\int_0^d n_e(s)B_{||}(s)\mathrm{d}s$$

see presentation on polarization (Thursday, M. Brentjens)



Typical Rotation Measure:

- 0.5 rad/m^2 for ~10 TECU
- Depending on viewing direction (parallel B-field)

Absolute TEC can be determined from polarized source (with known intrinsic RM) and Earth Magnetic Field

Differential Faraday Rotation also significant effect on longer baselines (>10 km)

Effects on radio propagation

- Dispersive delays
  - Direction dependent/frequency dependent effect on differential phases
    - Sensitive to differential TEC
- Faraday Rotation
  - Rotation of polarization angle of polarized signal
    - Sensitive to absolute TEC
  - Differential Faraday Rotation:
    - Sensitive to relative TEC and (relative) B-field
- Differential refraction (second order)
  - Displacement of relative source positions due to refraction
    - absolute TEC

Dispersive delays @ LOFAR

phase error: $\varphi_{ion} \approx 8.45\ 10^9\ dTEC/\nu$

typical variation LOFAR (NL) 80 km: 0.5- 1TECU

within a single HBA beam: ~0.1 TECU

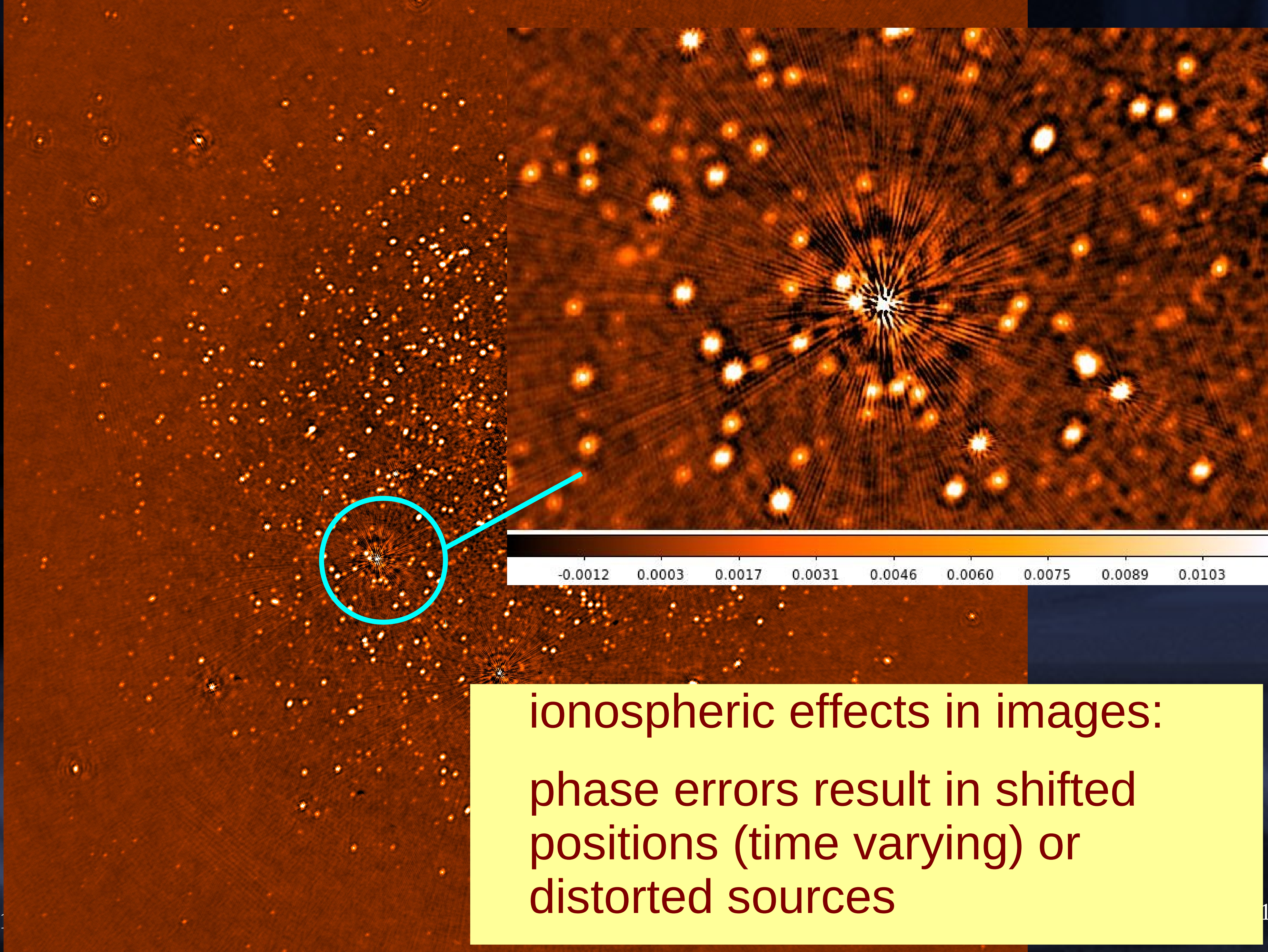
110-180 MHz (HBA): 1 full 2π rotation @ 0.2 TECU

30-80 MHz (LBA): 1 full 2π rotation @ 0.035 TECU

time variability of ionosphere:

- mTIDs ~ 15 min
- moving turbulence: smaller amplitude, but much faster variations

high time and frequency resolution needed for phase solutions image: V. Pandey



ionospheric effects in images:

phase errors result in shifted positions (time varying) or distorted sources

Dispersive Delay Correction

selfcal phases contain different phase effects

@ LOFAR 2 dominant sources:

- drifting clock errors
- ionospheric phases

use frequency dependence + wide frequency range for clock/TEC separation on phase solutions:

- calibrator: apply clocks only (since ionosphere is different in target field)
- use ionospheric phases to generate phasescreen for interpolation (direction dependent correction)
- inspect ionospheric conditions of observation

Clock/TEC separation

Start from selfcal phases over wide frequency range.

Fit for A(clock) and B(TEC) in:

$$\Delta\phi(\nu) = A \cdot 2\pi\nu + B \cdot 8.4479745 \cdot 10^9/\nu$$

Complication 2π ambiguities:

if φ is a solution so is φ+2π

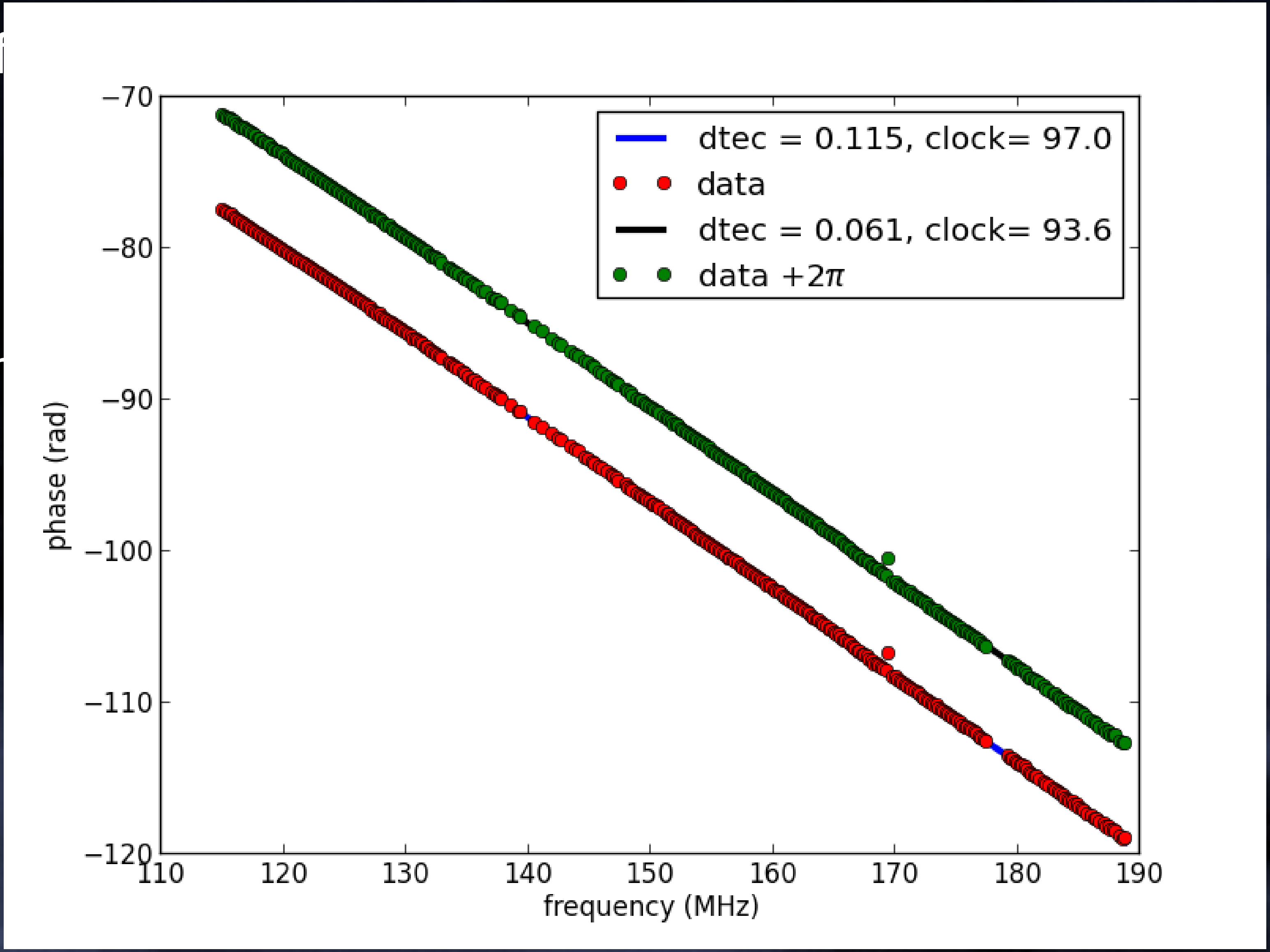
corresponds to fixed offset in clock and TEC

Clock/TEC separation

Start from selfcal phases over wide frequency range.

Fit f

Cor



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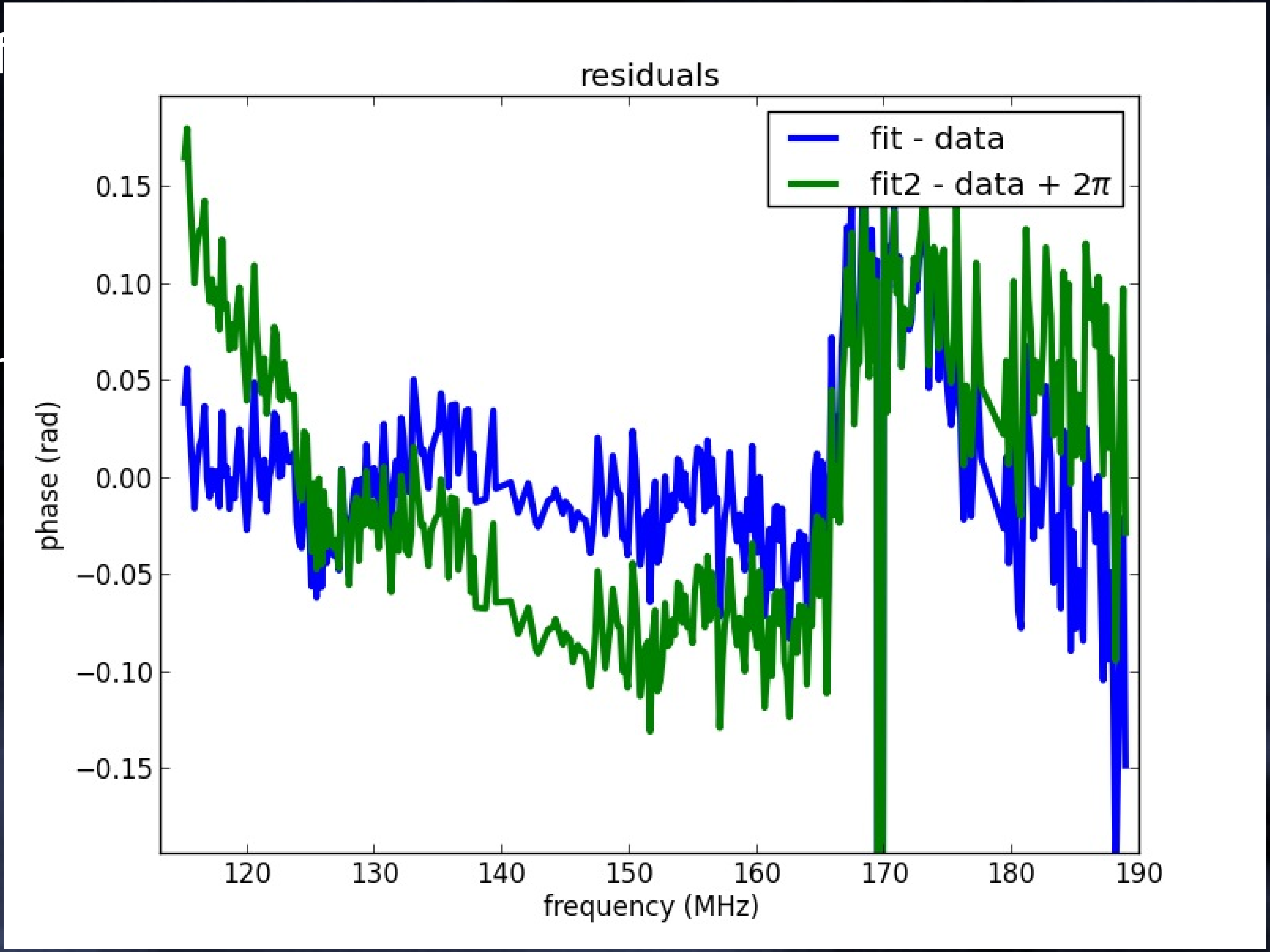

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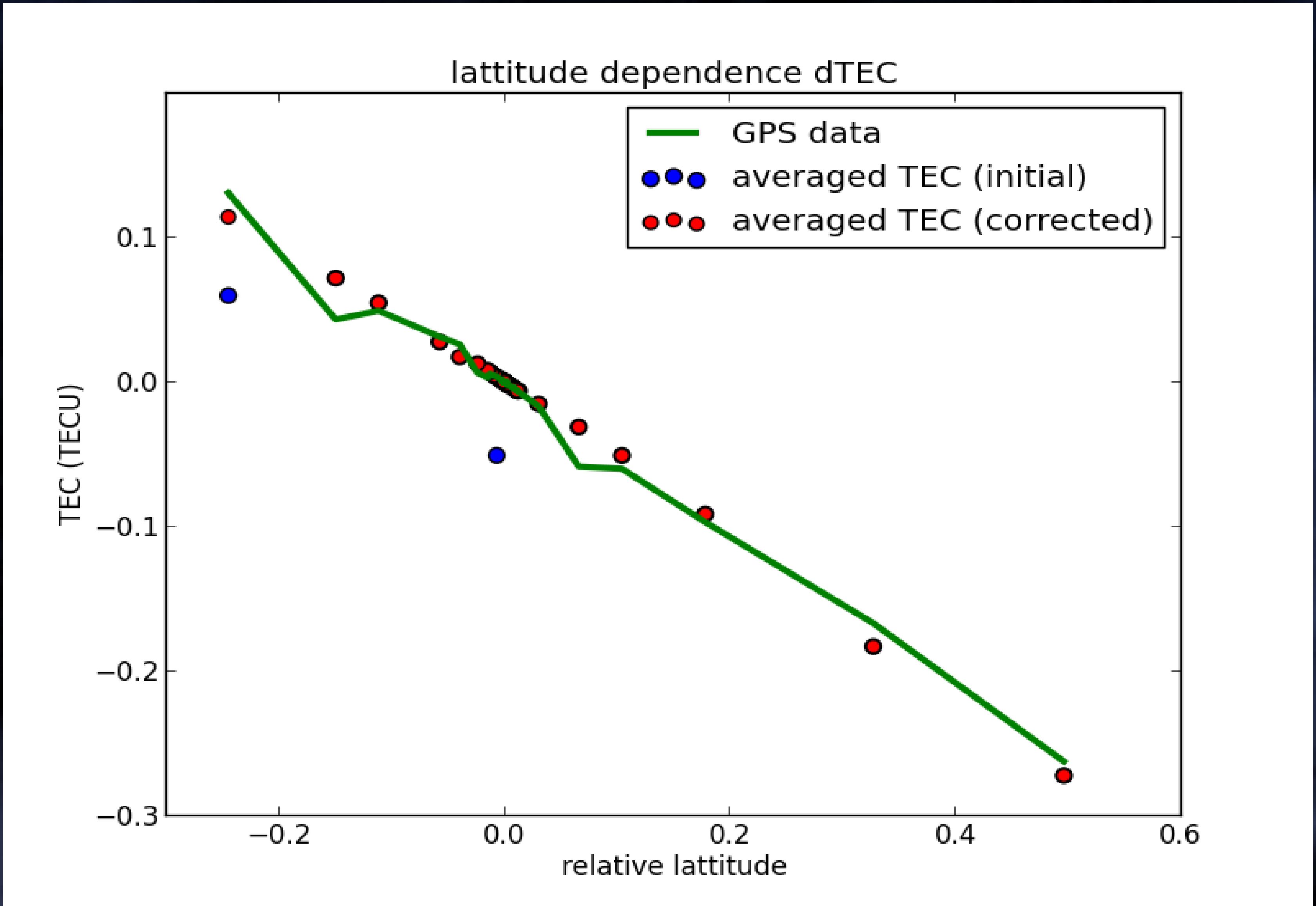
Slow variation of clock/TEC solutions in time:

start with good solution for first timeslot, initialize subsequent with previous solutions

Correct remaining wraps by inspecting residuals/spatial correlation

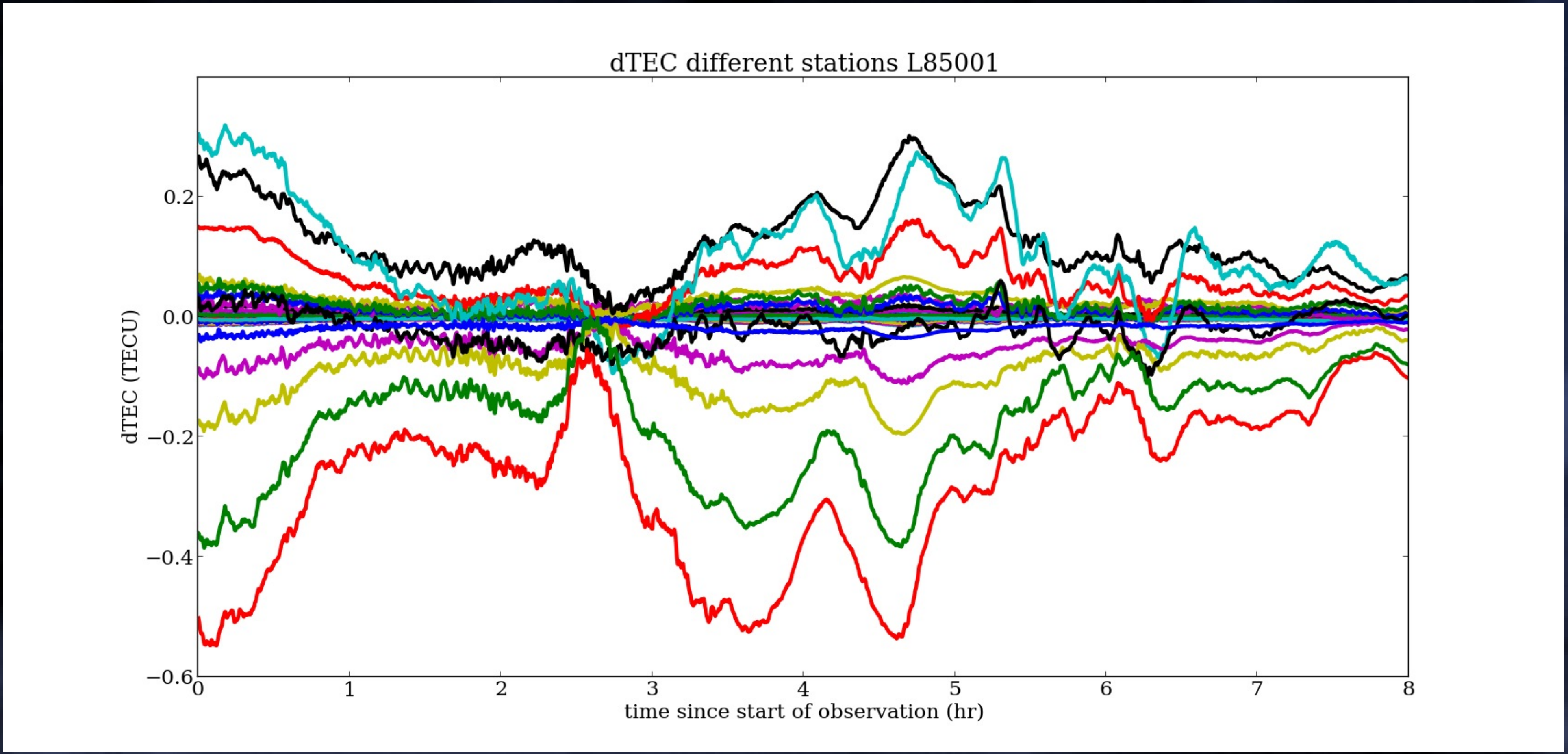
Clock/TEC separation



Correct remaining wraps by inspecting residuals/spatial correlation

TEC solutions

dTEC solutions versus time, HBA all stations



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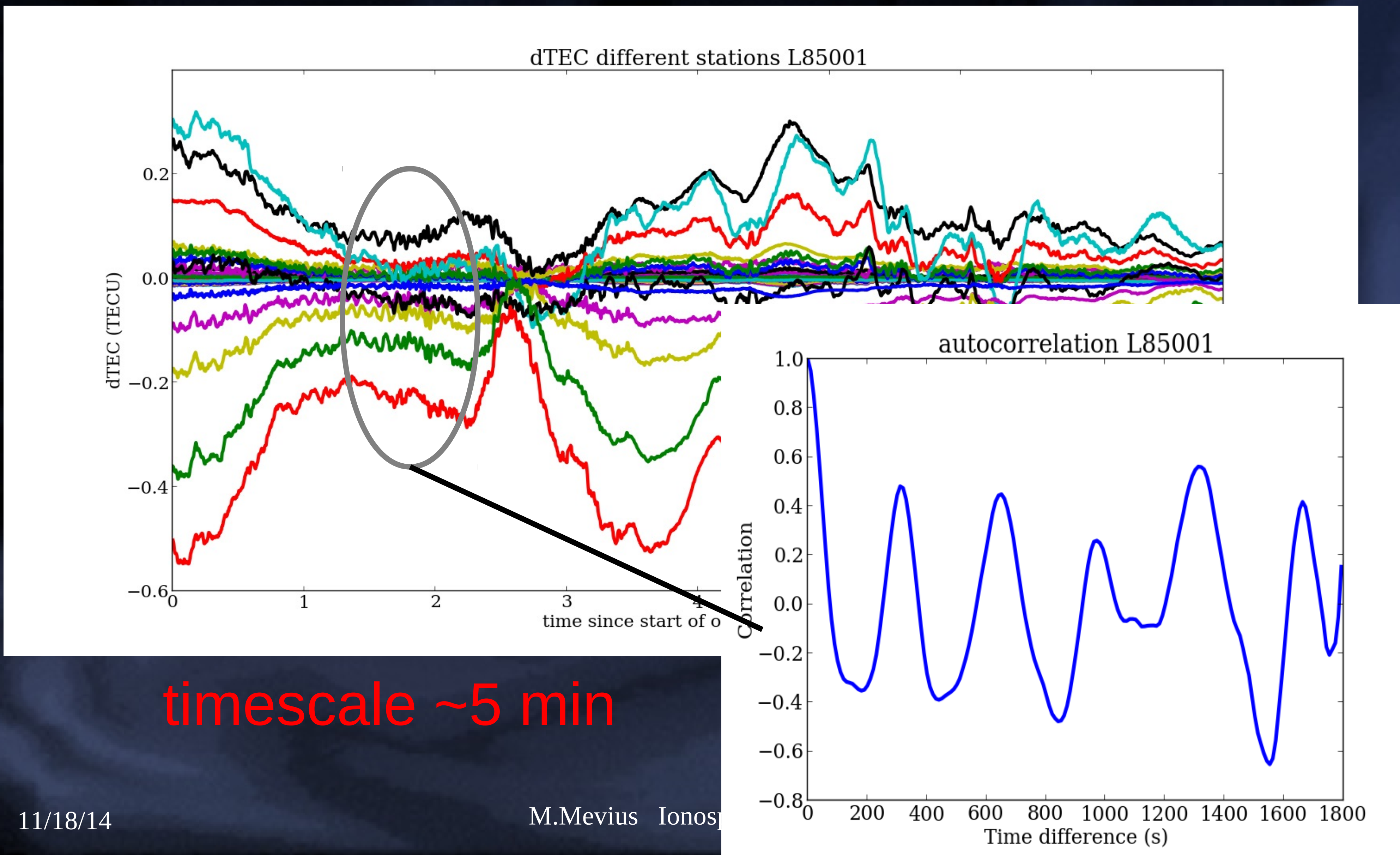


timescale ~5 min

Structure function

Spatial fluctuations:

$$D_\varphi(||r_1 - r_2||) = <(\varphi_1 - \varphi_2)^2>$$

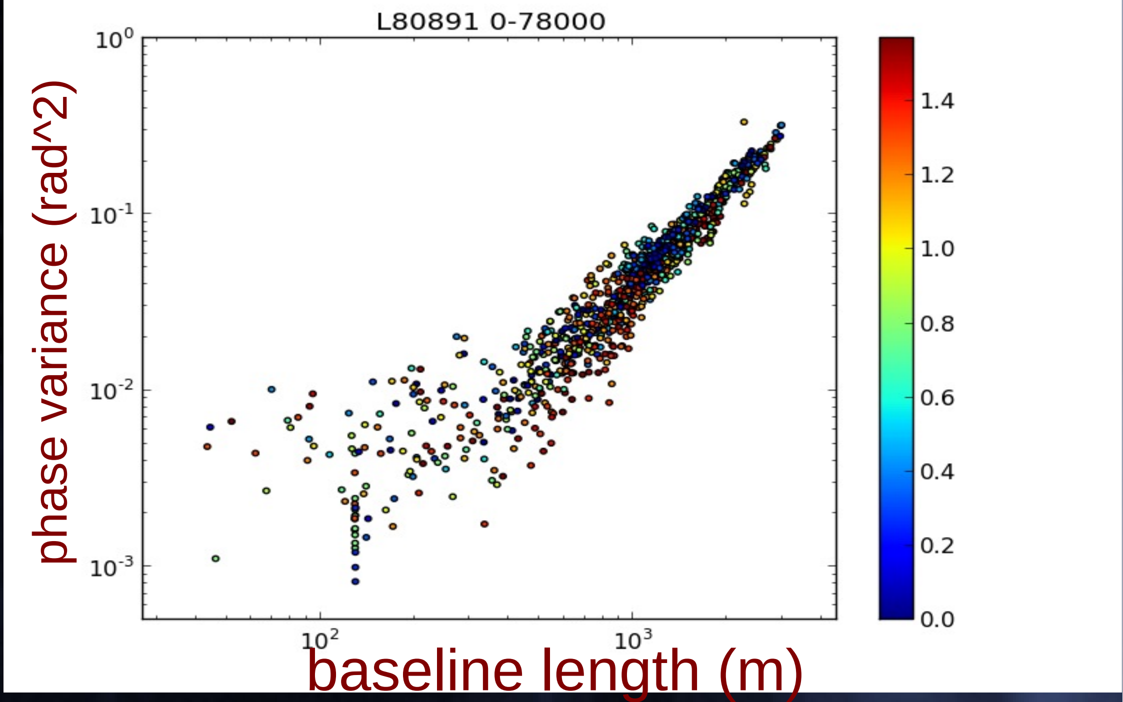
Kolmogorov turbulence, thin layer approximation:

- $D_\varphi(\mathbf{r}) = (\mathbf{r} / s_0)^\beta$
- $\beta = 5/3$,
- s_0: field coherence scale, $D_\varphi(s_0) = 1\ \mathrm{rad}^2$

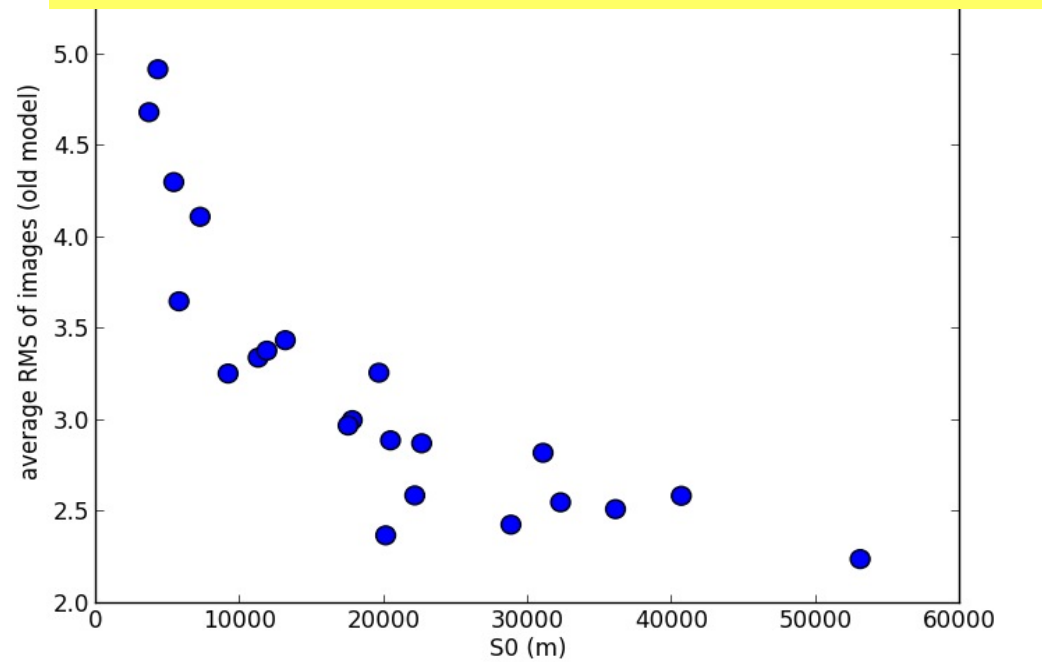
Typical nighttime S_0 values @150 MHz: 2-40 km

scintillation conditions S_0<2km

-

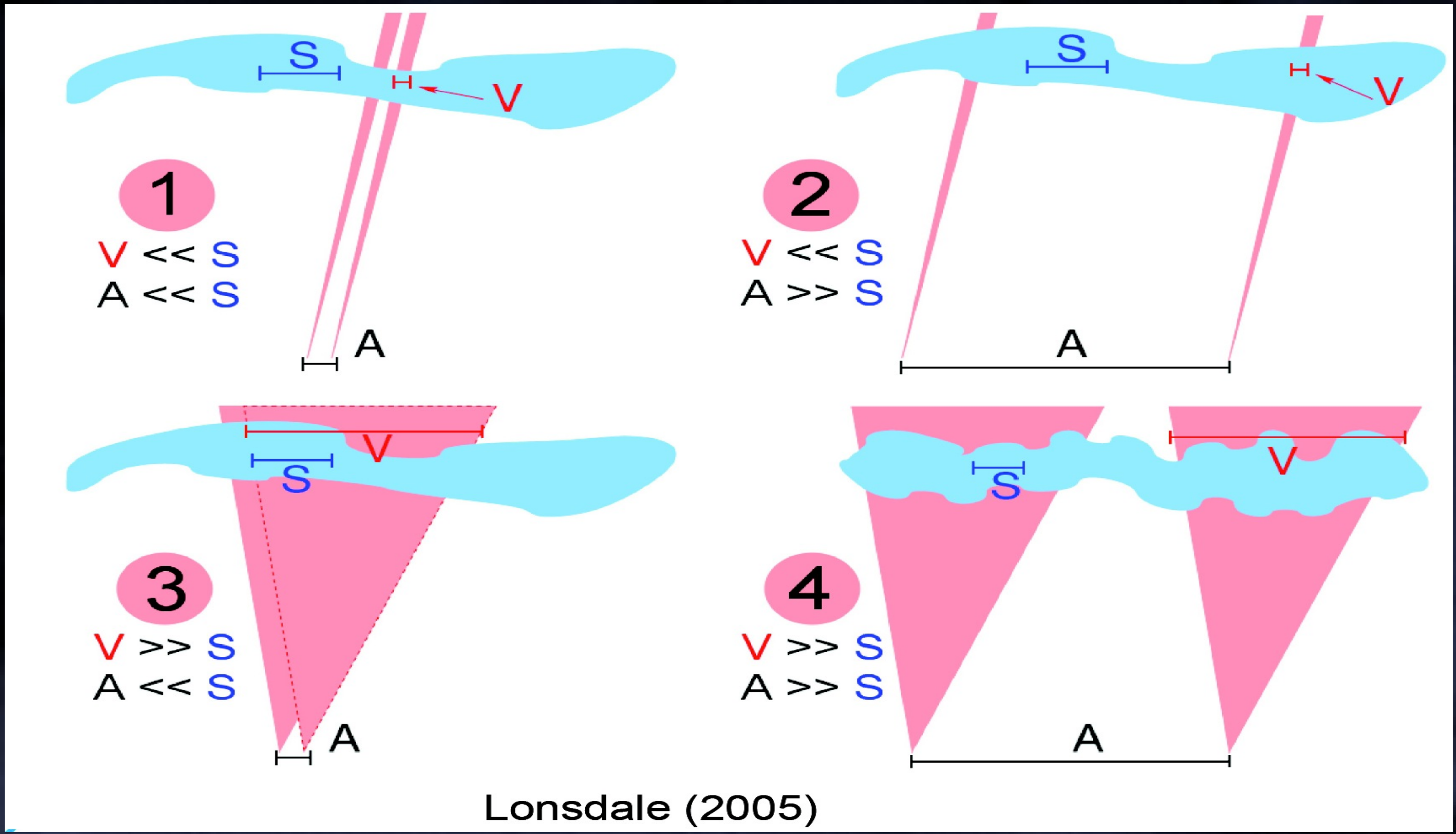


Correlation image noise S_0



Lonsdale regimes

clock/TEC separation: direction independent phases
spatial structure ionosphere:

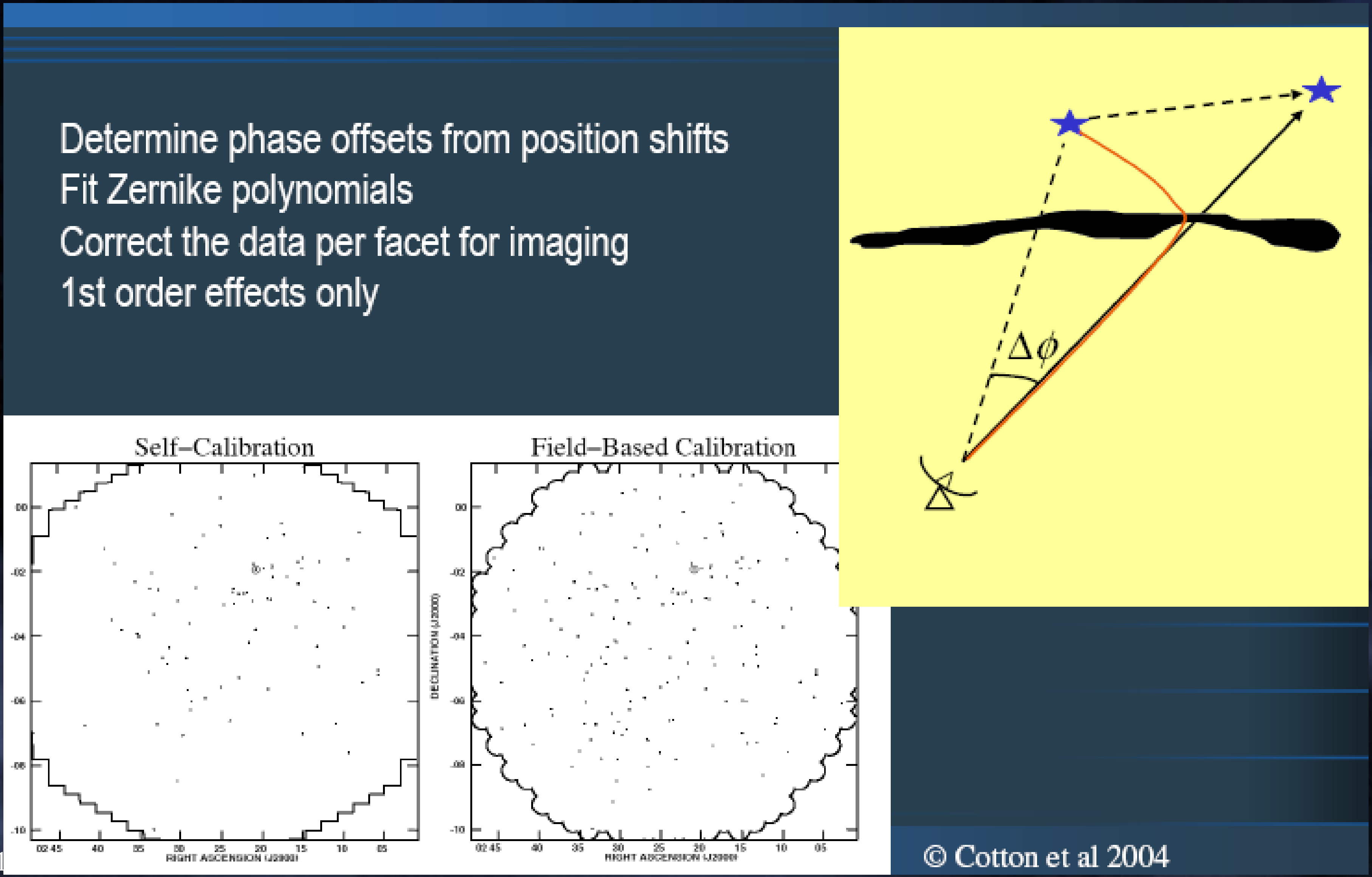


standard selfcal works only in regime 1 or 2

LOFAR: direction dependent effect

Direction dependent correction methods

- Field based calibration *B. Cotton et. Al (2004)*
  - works for linear gradients, higher order effects distort the source



Direction dependent correction methods

Methods that involve direction dependent calibration
(separate gain/phase solutions in direction of several sources/clusters)

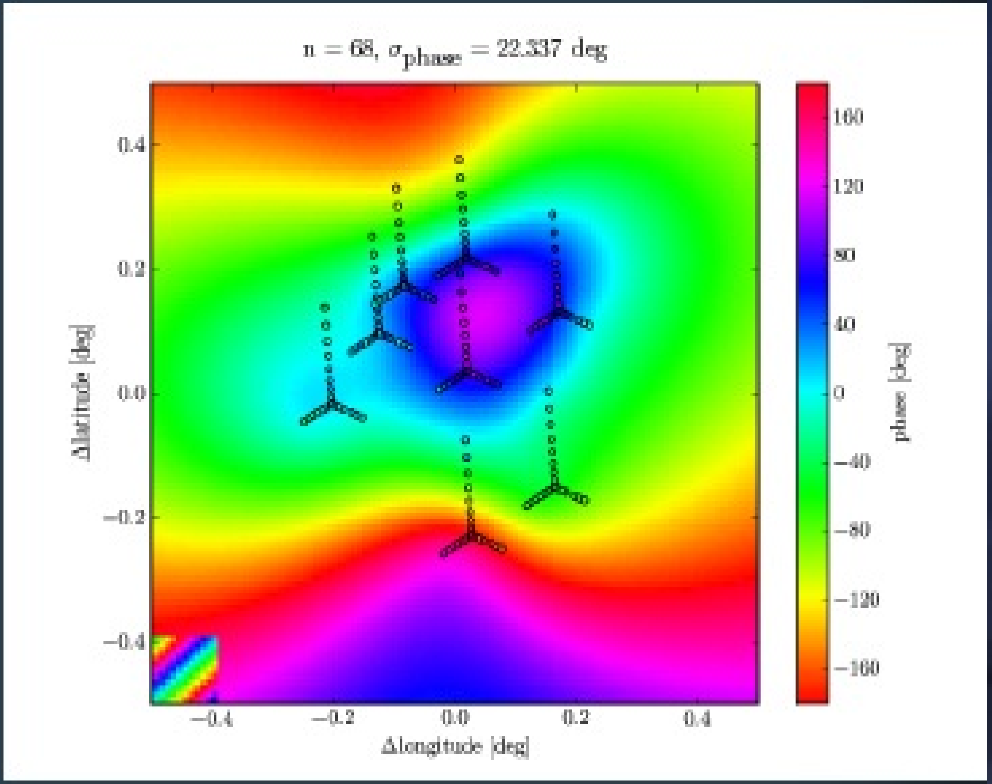
- Multi direction solve + subtract sources with their own solutions (eg. Sagecal):
  - No correction for residuals
- Phasescreen methods:
  - every station-direction pair corresponds to a *piercepoint* on 1 (or more) thin layers
  - fit 2D function on piercepoint solutions and interpolate to get phases in unknown directions
  - apply solutions:
    - facet imaging
    - subtract sky model with interpolated phase correction
    - A projection: apply screen during imaging step

See Wide Field imaging (S. vd. Tol, Wednesday)

Phasescreen examples: SPAM

Source Peeling & Atmospheric Modeling

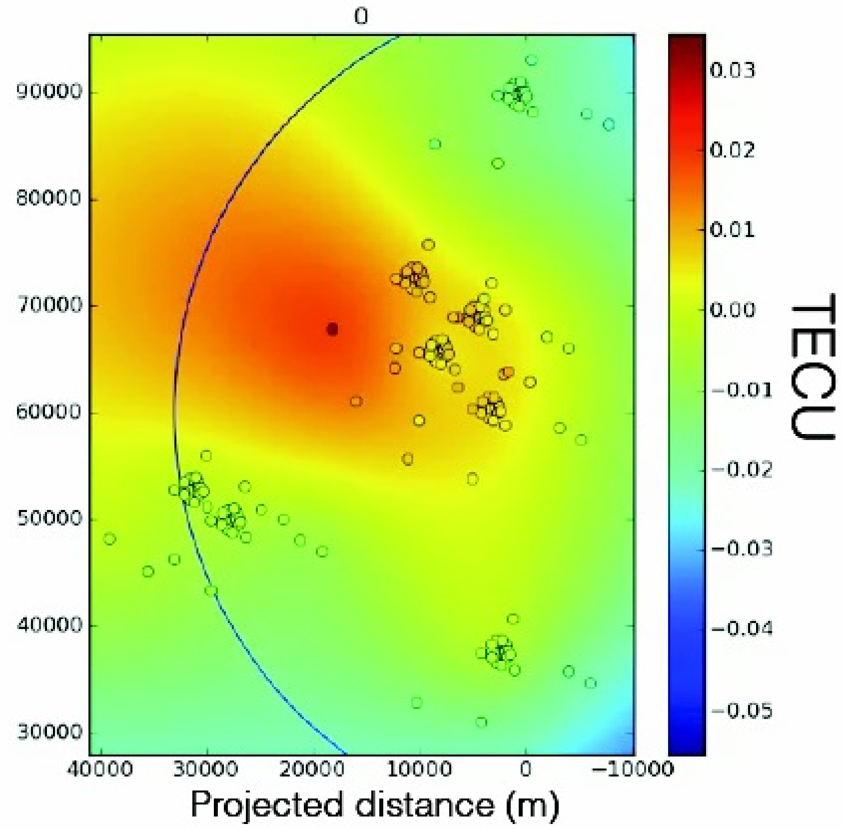
- Get $\varphi_{obs}(t)$ from peeling of calibrators
- Fit model on KL basis
- Correct each facet with model phase
- Make image
- Not limited to gradients only



SPAM + facet imaging *Intema et Al (2009)*

Phasescreen examples:MSSS (LBA)

- TEC value was derived for each pierce point every 10 seconds using fit to phases across all 8 bands
- Core stations + 5 remote stations were used
- 7 11-minute snapshots were used (first two snapshots not used due to poor solutions)
- AWimager used to image + apply screen



D. Rafferty + S. vd. Tol

MSSS TECscreen +

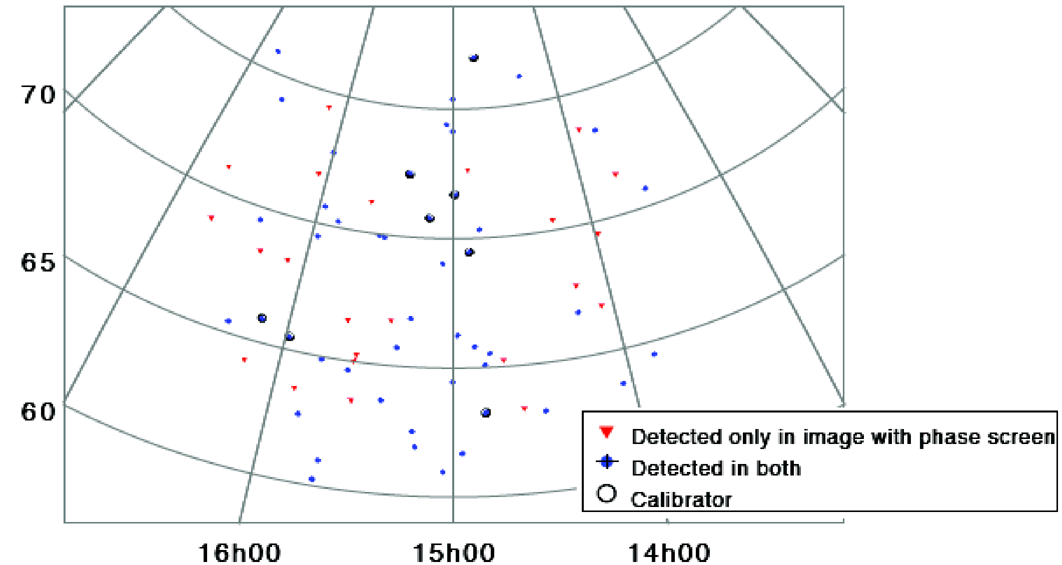
A projection

solutions in 8 directions

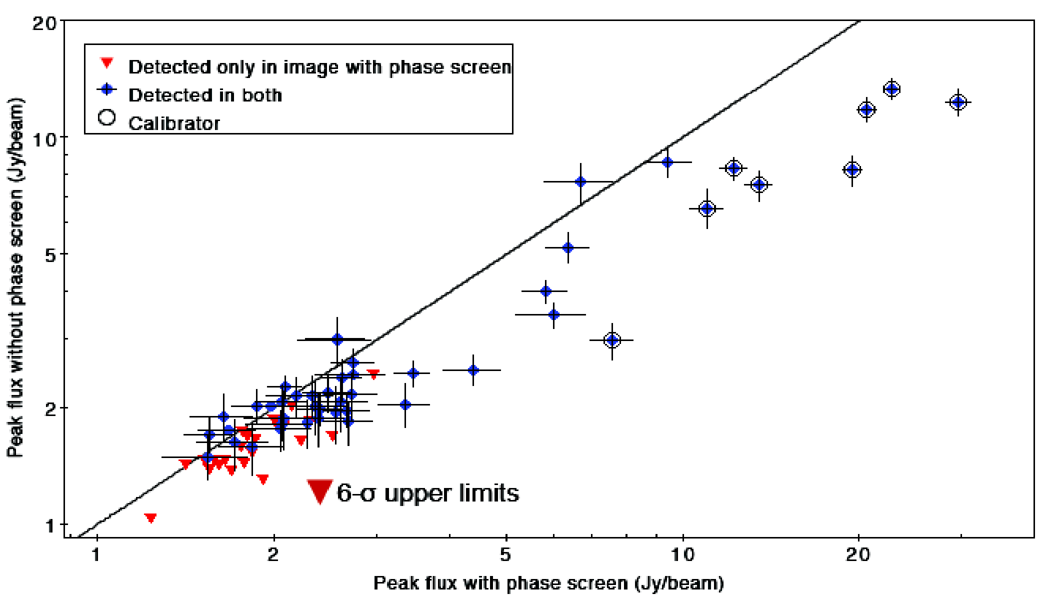
after correction with AWimager:

better focused + more sources detected

Detected Sources at 30 MHz (>6σ peak flux)



- At 30 MHz, ~ 50% more sources detected in image with phase screen (~30% more at 45 MHz)



Phasescreen Methods

issues:

- needs several bright enough sources in FOV
- ignores 3D structure of ionosphere
  - crossing of piercepoints depends on chosen height of layer(s)

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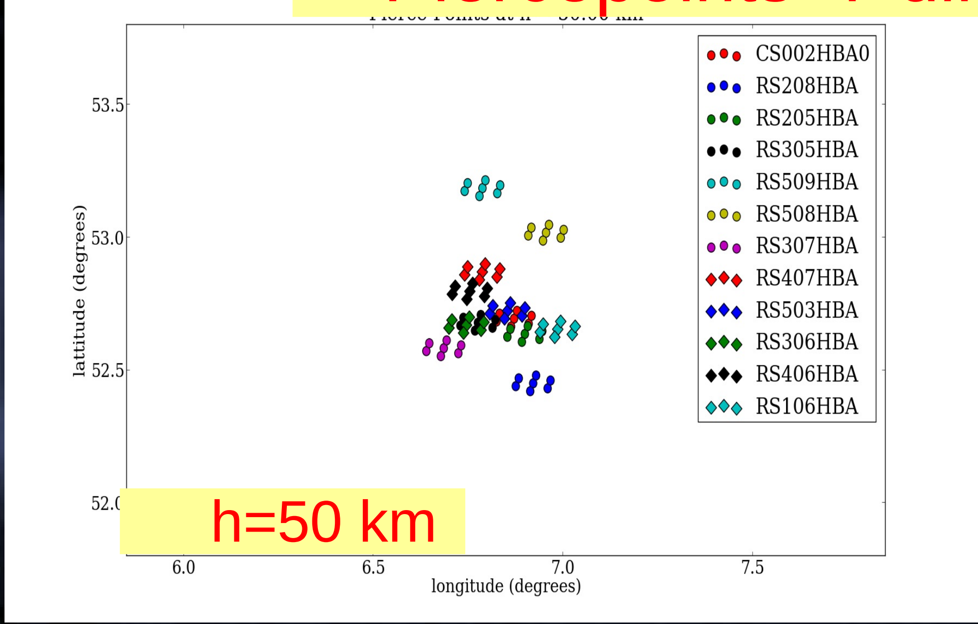
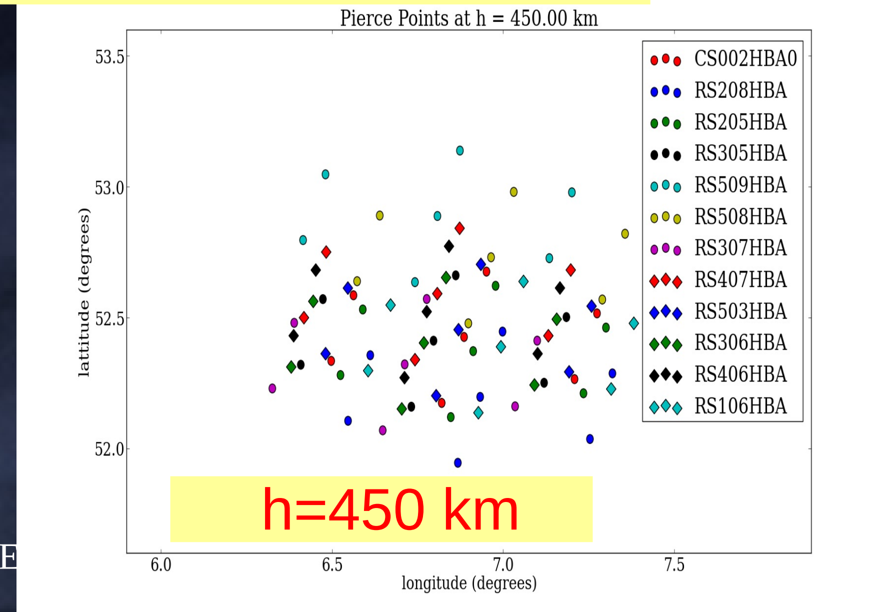
Piercepoints 7 directions Remote stations





Phasescreen Methods

issues:

- needs several bright enough sources in FOV
  - source models
- ignores 3D structure of ionosphere
  - crossing of piercepoints depends on chosen height of layer(s)
  - 3D tomography?
- LOFAR beam errors give also direction dependent phases
  - station dependent
  - makes phasescreen fitting more difficult

Differential Faraday rotation

$$\beta = RM\nu^{-2}$$

Rotation of the signal from XX,YY to XY,YX due to different Faraday rotation angles for different antennas

- HBA: small rotation most of the time
  - sometimes (“wild' ionosphere) visible in RAW uv data
- LBA: significant effect

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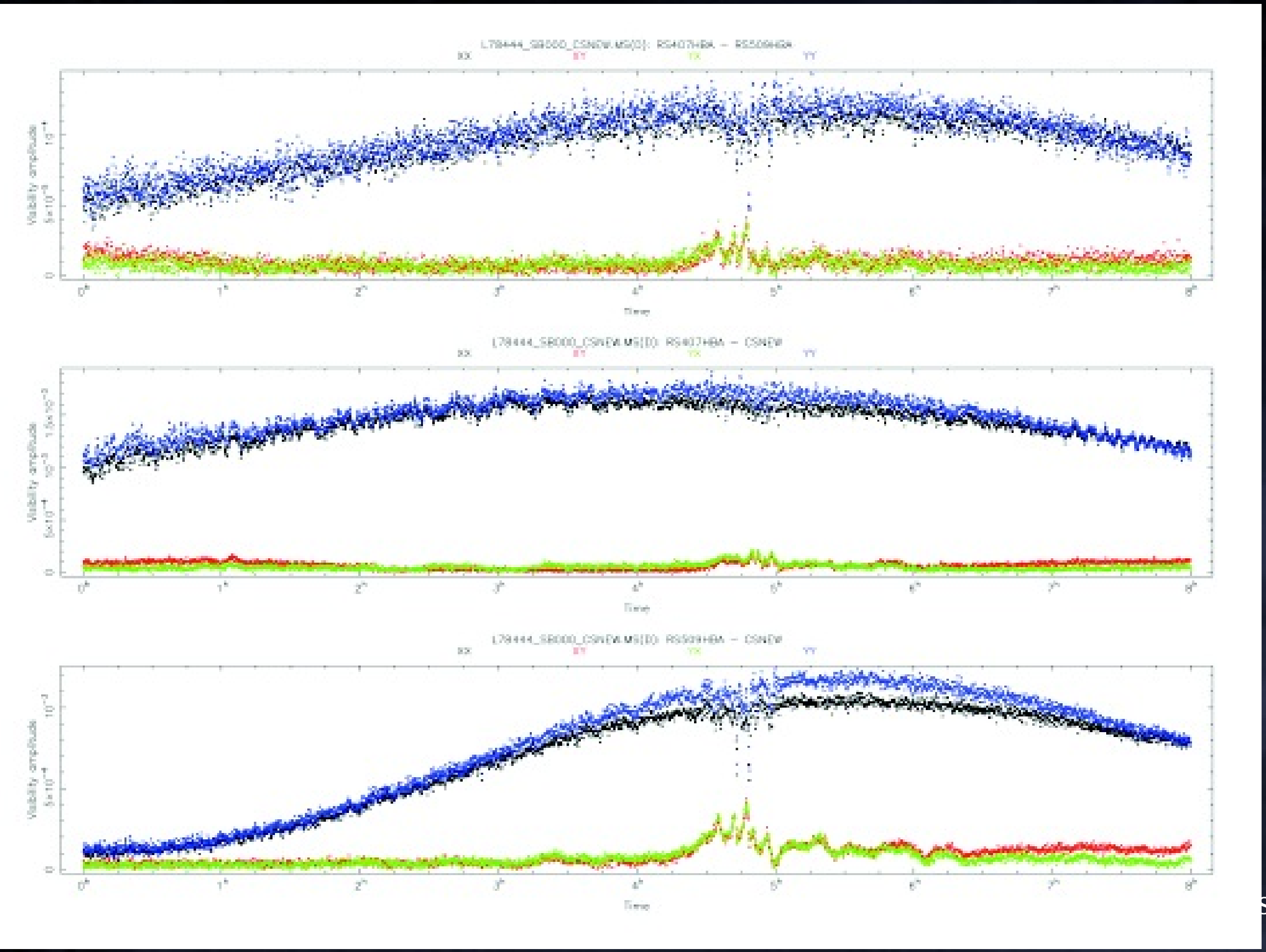

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Selfcal: either solve full polarization matrix or

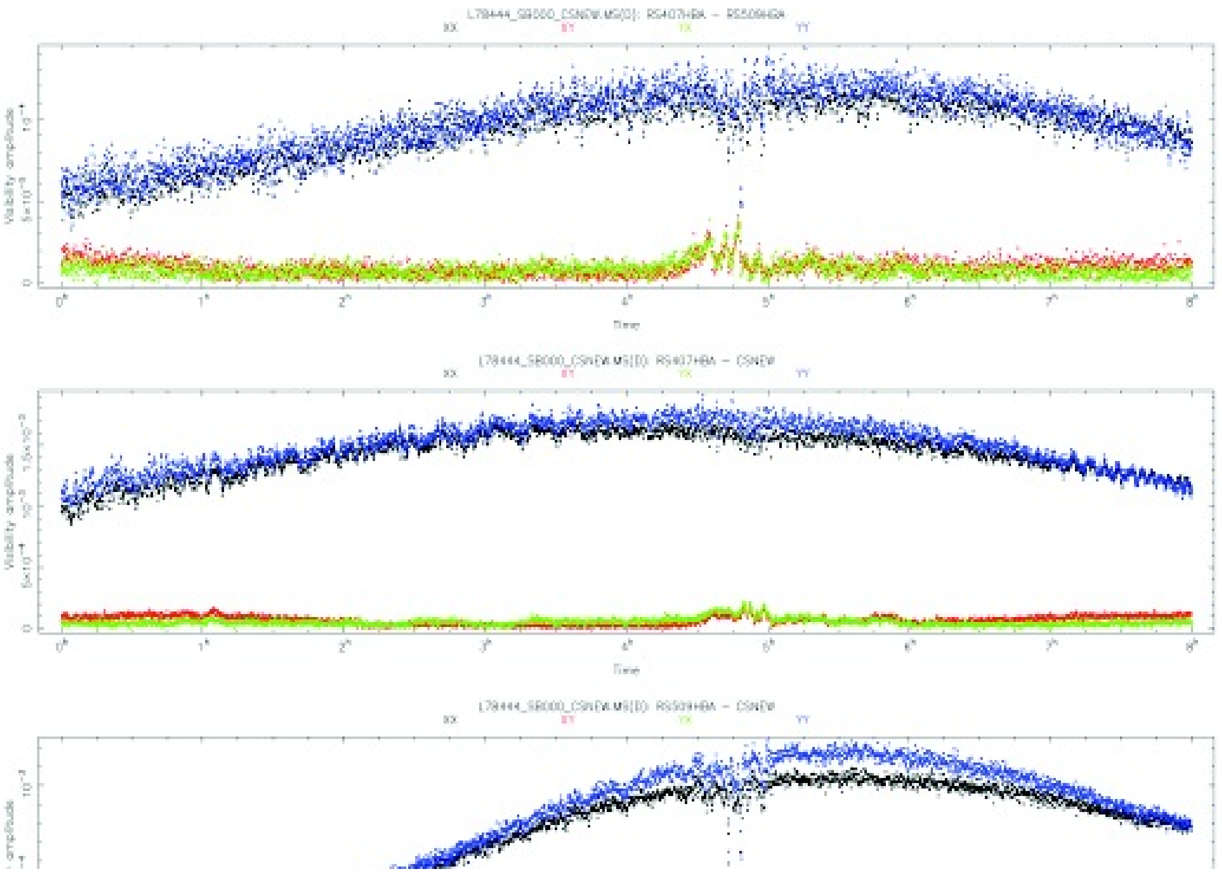
diagonal gains + 1 rotation matrix

Differential Faraday rotation provides clean independent measure of ionospheric fluctuations (ignoring differential B)

In principle possible to extract absolute TEC via:

$$\Delta RM = \Delta TEC \cdot B_{||} + TEC \cdot \Delta B_{||}$$

In practice large uncertainty on $\Delta B_{||}$

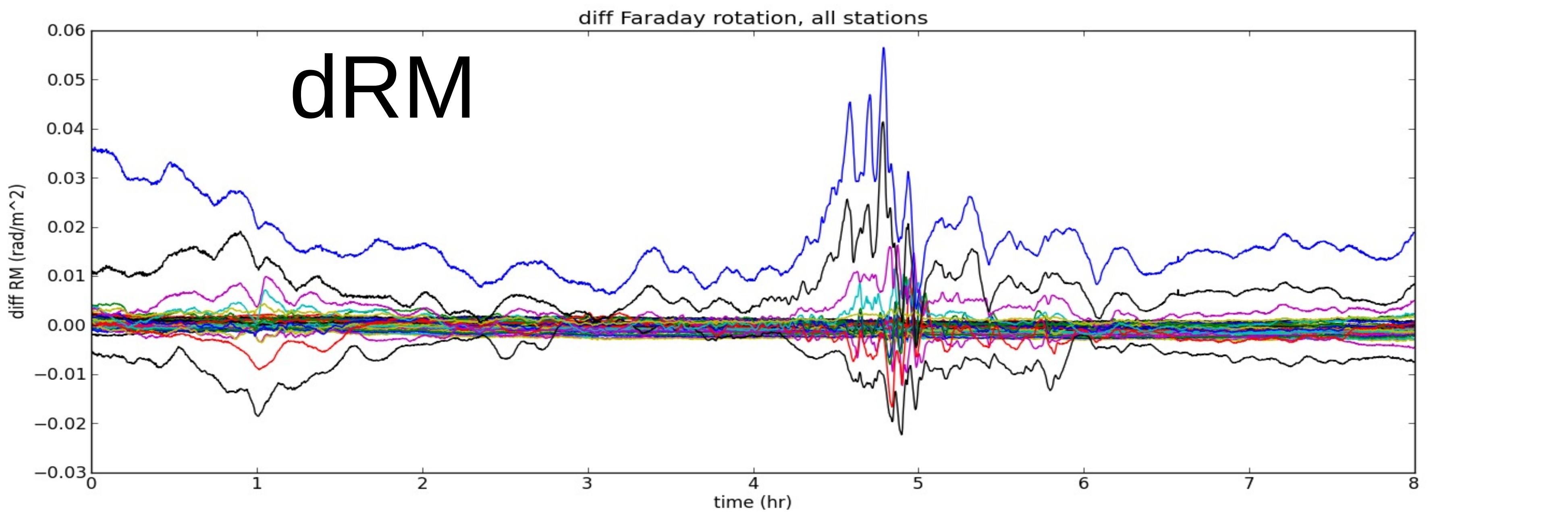


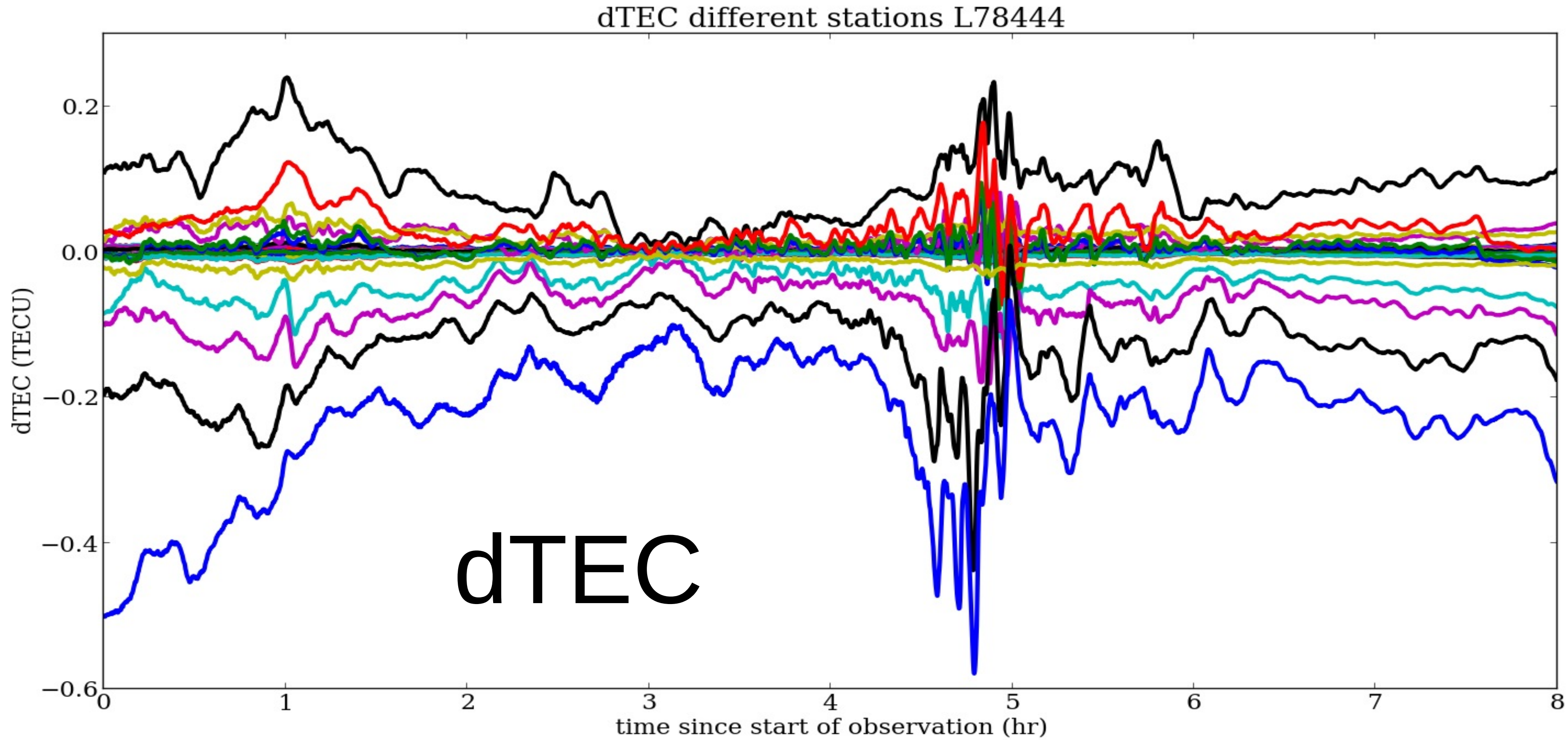
y rotation

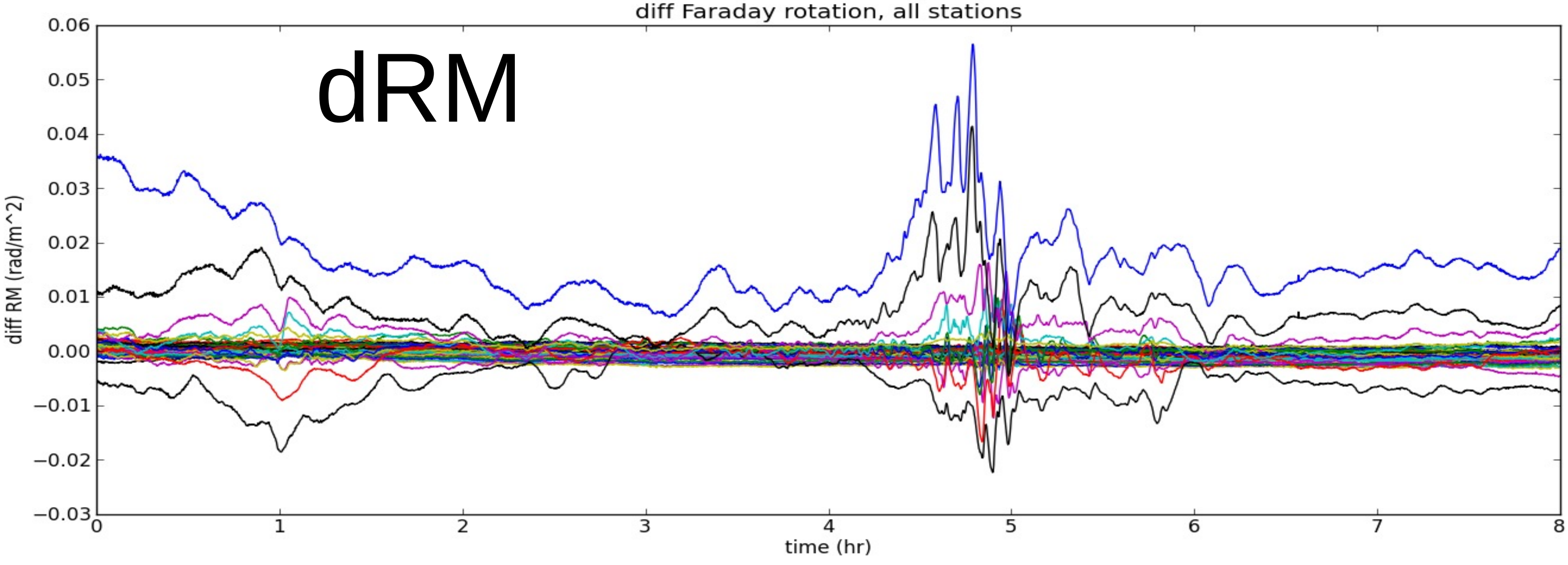
X,YY to XY,YX due
angles for different

t of the time

visible in RAW uv data




dTEC different stations L78444
dTEC (TECU)
time since start of observation (hr)
dTEC


diff Faraday rotation, all stations
diff RM (rad/m^2)
time (hr)
dRM

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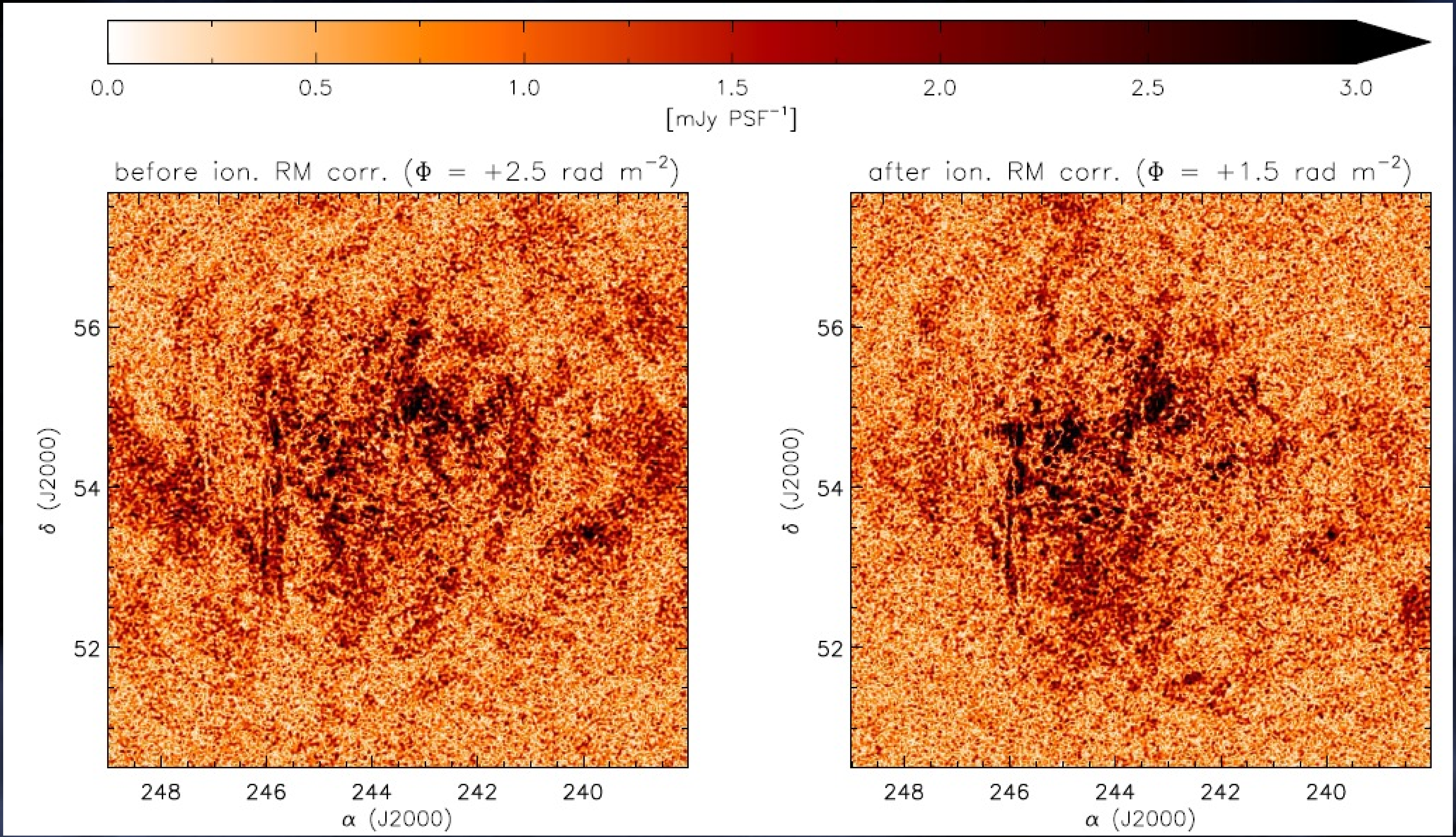
In practice large uncertainty on $\Delta B_{||}$

RM correction

- For polarization studies:
  - correct time variation of ionospheric Faraday rotation
- Calculate RM variation:
  - GPS data
  - Earth Magnetic Model:
    - WMM Maus, S., S. Macmillan, S. McLean, B. Hamilton, A. Thomson, M. Nair, and C. Rollins, 2010, The US/UK World Magnetic Model for 2010-2015, NOAA Technical Report NESDIS/NGDC.
    - IGRF Geophysical Journal International, Volume 183, Issue 3, pages 1216–1230, December 2010
- Correct data using single rotation matrix
  - GPS models do not provide accurate enough resolution to correct spatial variation

Example Elais Field



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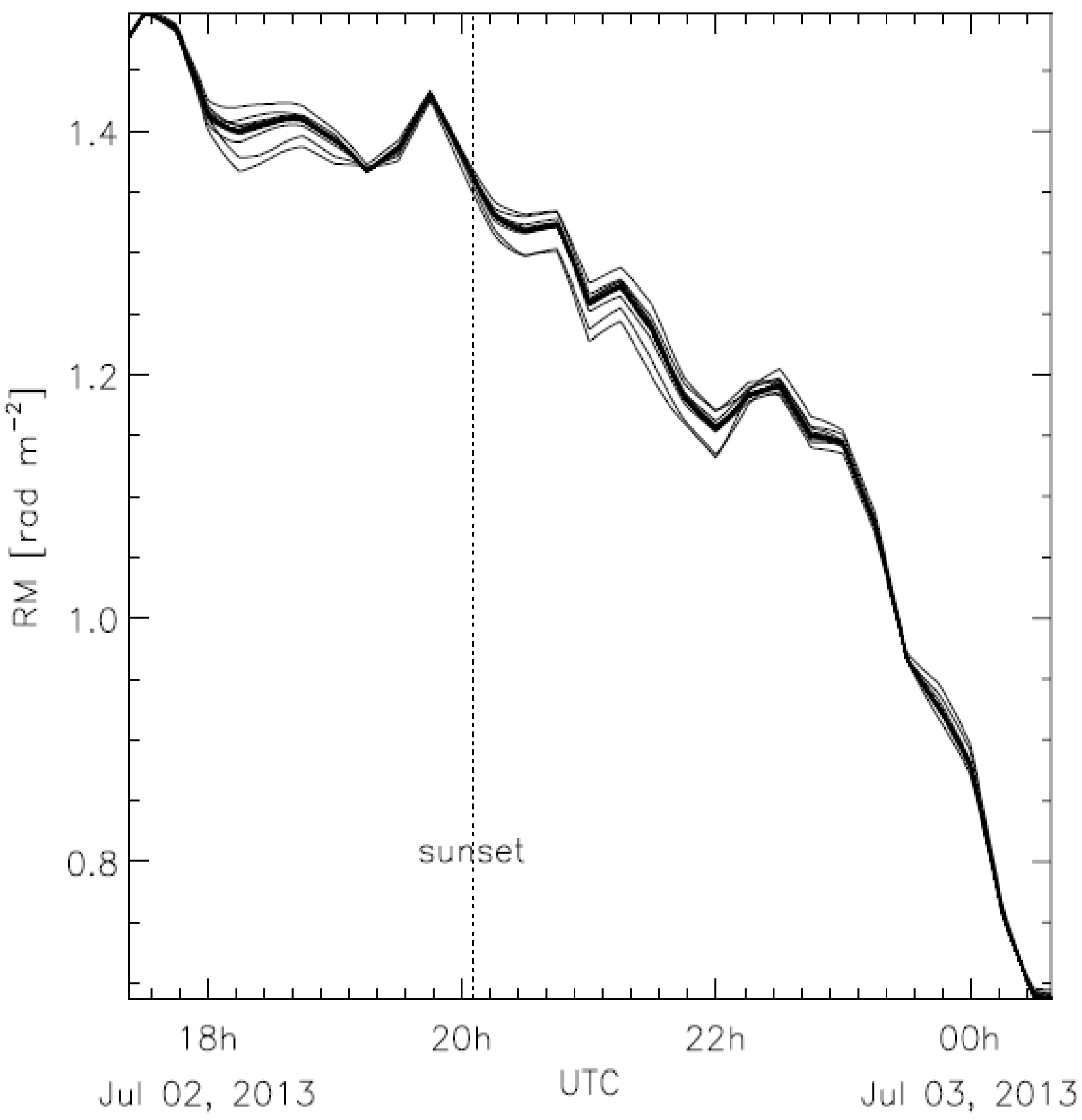
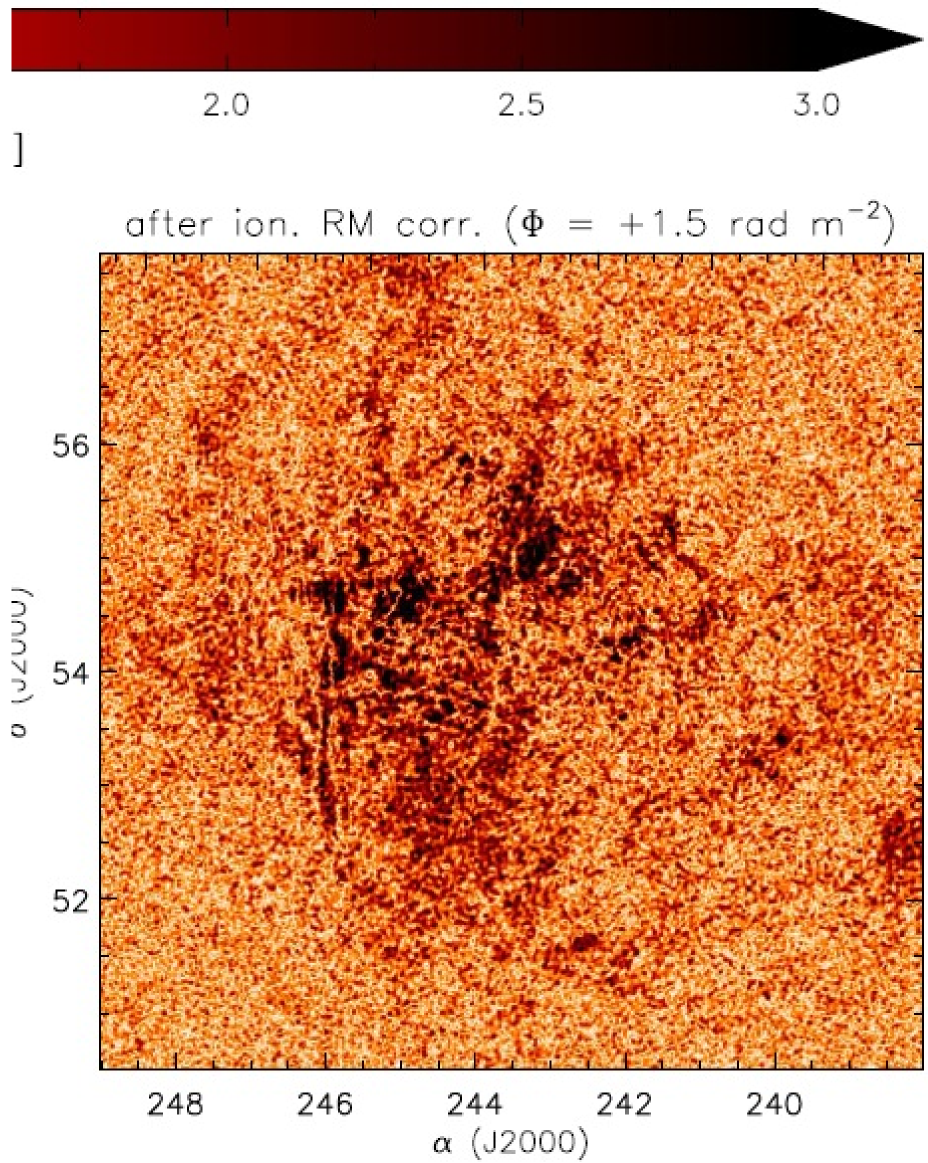
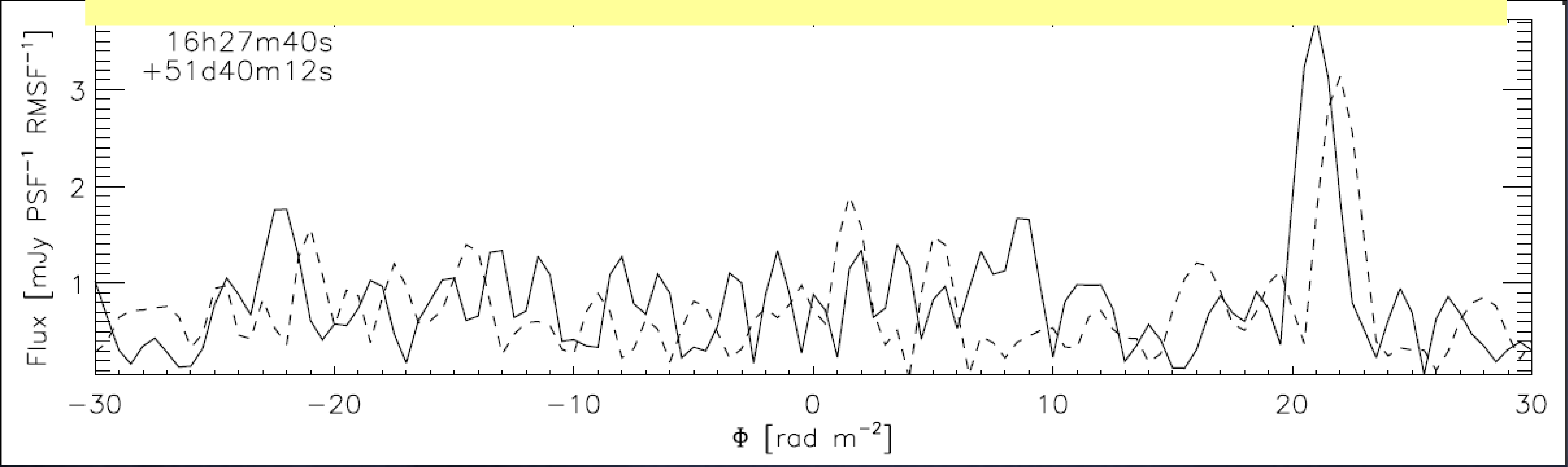




Example Elais Field

Polarized Flux before (dashed) and after (solid) RM correction

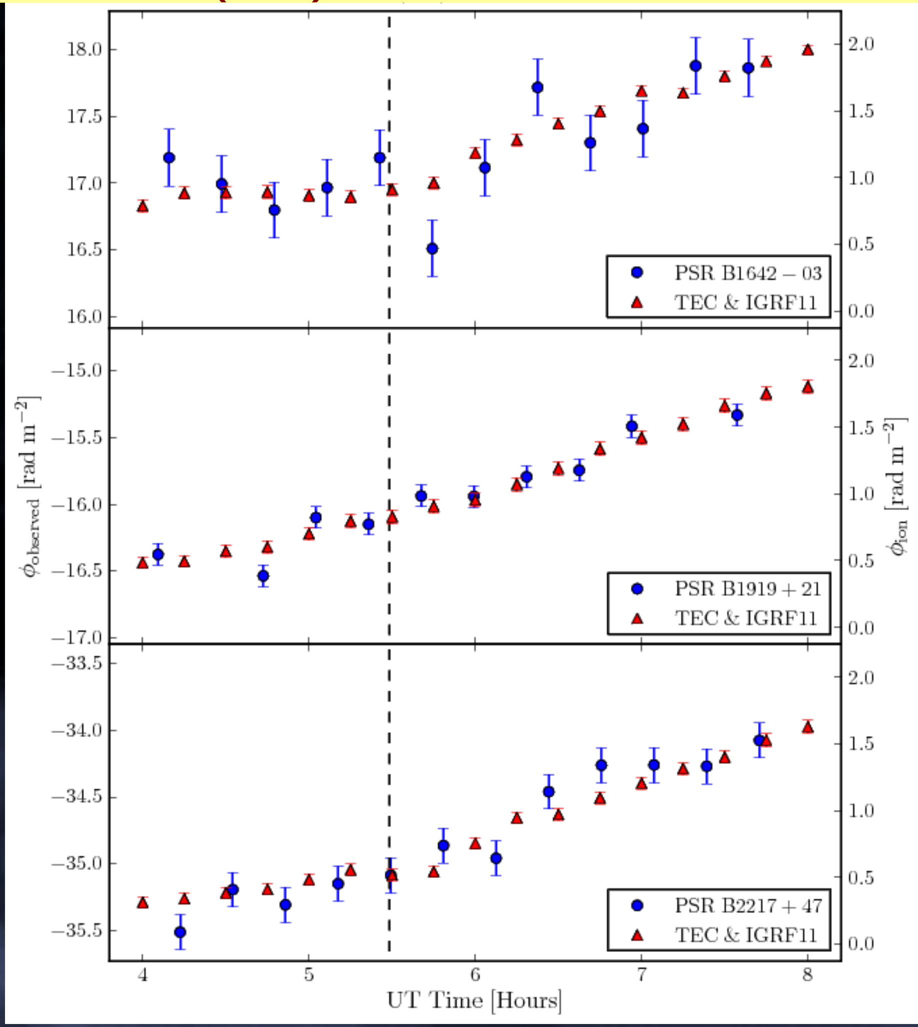


V. Jelic et al (2014)

Initial LOFAR observations of Epoch of Reionization windows: II. Diffuse polarized emission in the ELAIS-N1 field

Other methods

Pulsar (blue) and GPS + IGRF(red) RM variation



use polarized source to determine ionospheric RM

Sotomayor-Beltran et al (2013)

Calibrating high-precison Faraday rotation measurements for LOFAR and the next generation of low-frequency radio telescopes

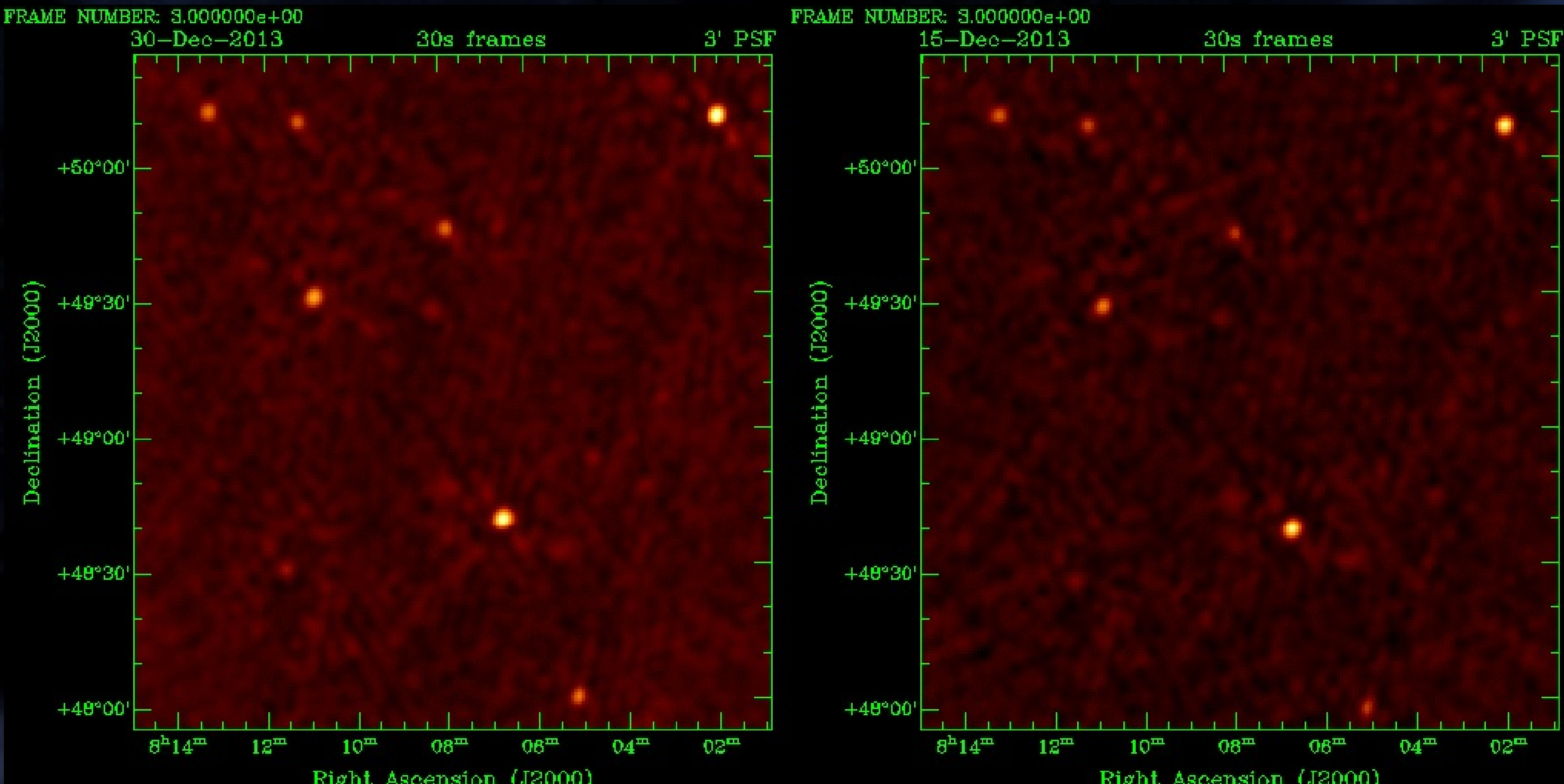
Conclusion

- Effects of ionosphere large at low frequencies
- time variation + frequency dependence requires calibration with high time and frequency resolution
- spatial variation requires direction dependent calibration
- dispersive delays sensitive to differential TEC
- interpolation to other directions via phasescreen approaches

Conclusion (2)

- Faraday rotation:
  - rotation of linear polarization angle
- Differential Faraday rotation
  - significant effect for LBA
  - needs extra rotation matrix in ME
- ionospheric RM correction:
  - using GPS data and Earth magnetic models
  - directly estimate RM from polarized sources

Scintillation



G.de Bruyn