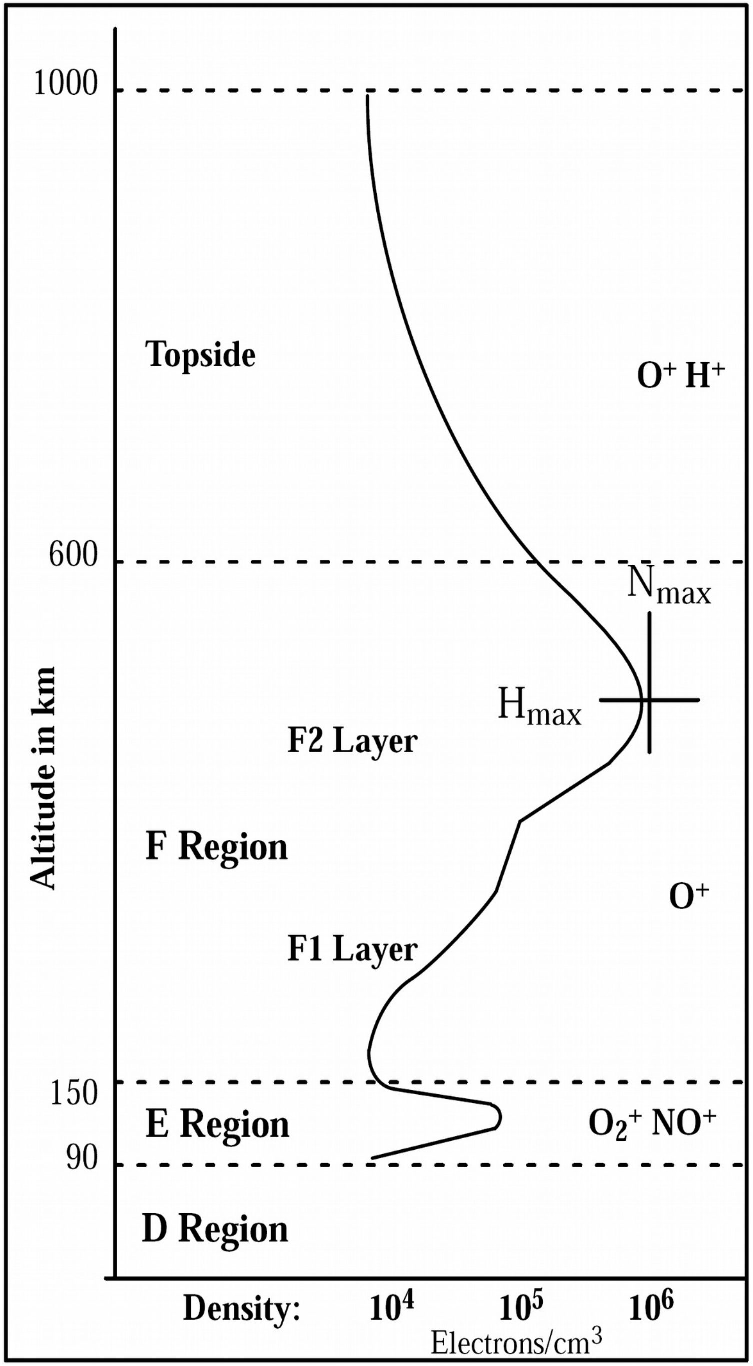
Ionospheric Effects

M.Mevius

Outline

- What is the ionosphere and why do we care?
- Ionospheric delays and calibration strategies:
  - HBA/LBA
  - Direction dependent effect
- Ionospheric Faraday Rotation
  - Polarized signal
  - Differential Faraday Rotation
- Summary

Ionosphere



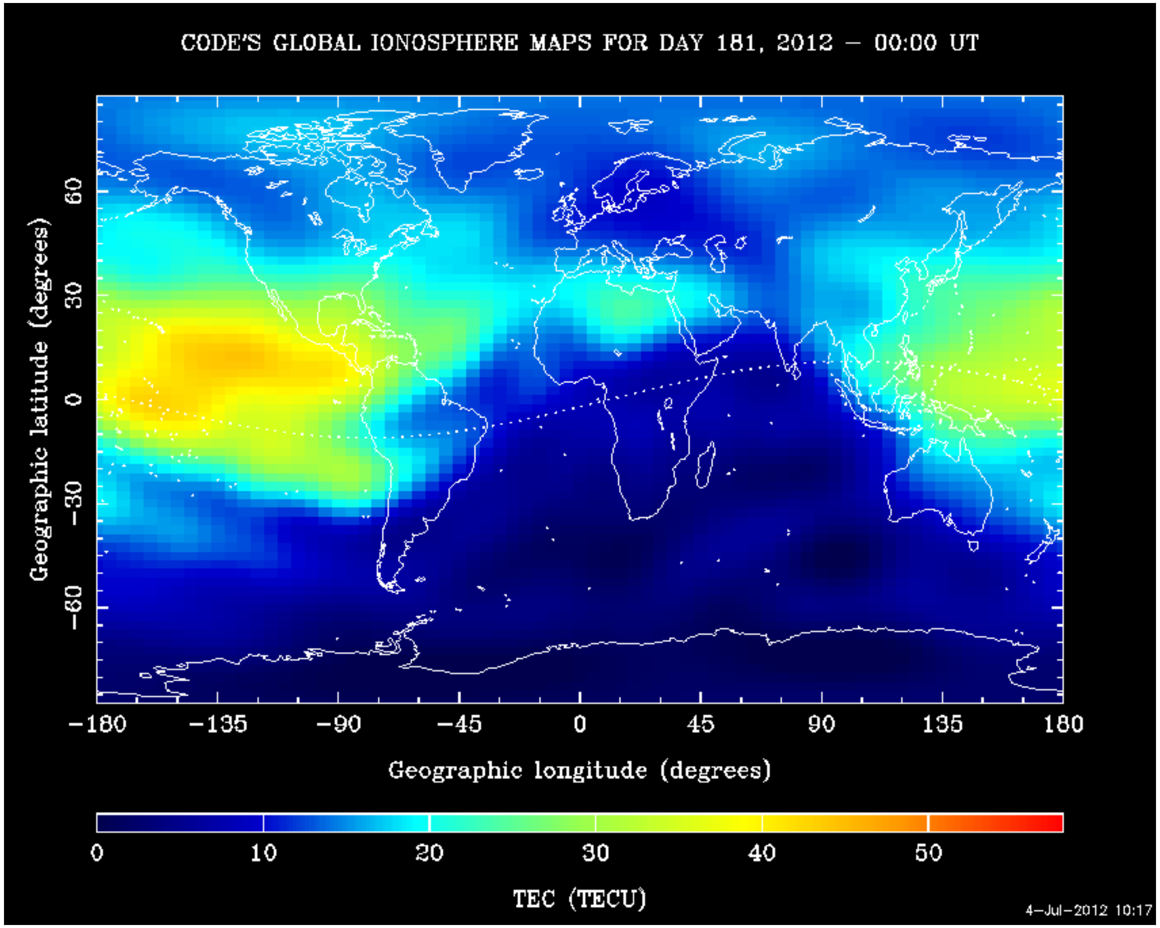
- Appleton 1924:
  - existence of reflecting layer (long wavelengths) in atmosphere (~125 km)
  - ionized
  - shorter wavelengths reflected @ 300-400 km
    - ionospheric structure, density changes with altitude
  - height of layer changes during sunset/sunrise
  - ionization due to solar radiation
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

Ionosphere

Measurements:

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

IONEX data (CODE)



Total Electron Content (TEC)

Typical values @ 52° for integrated TEC along LOS:

5(night)- 50(day) TECU (10^{16} e/m^2)

Ionospheric Variability

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
Traveling Ionospheric Disturbances (TIDs)

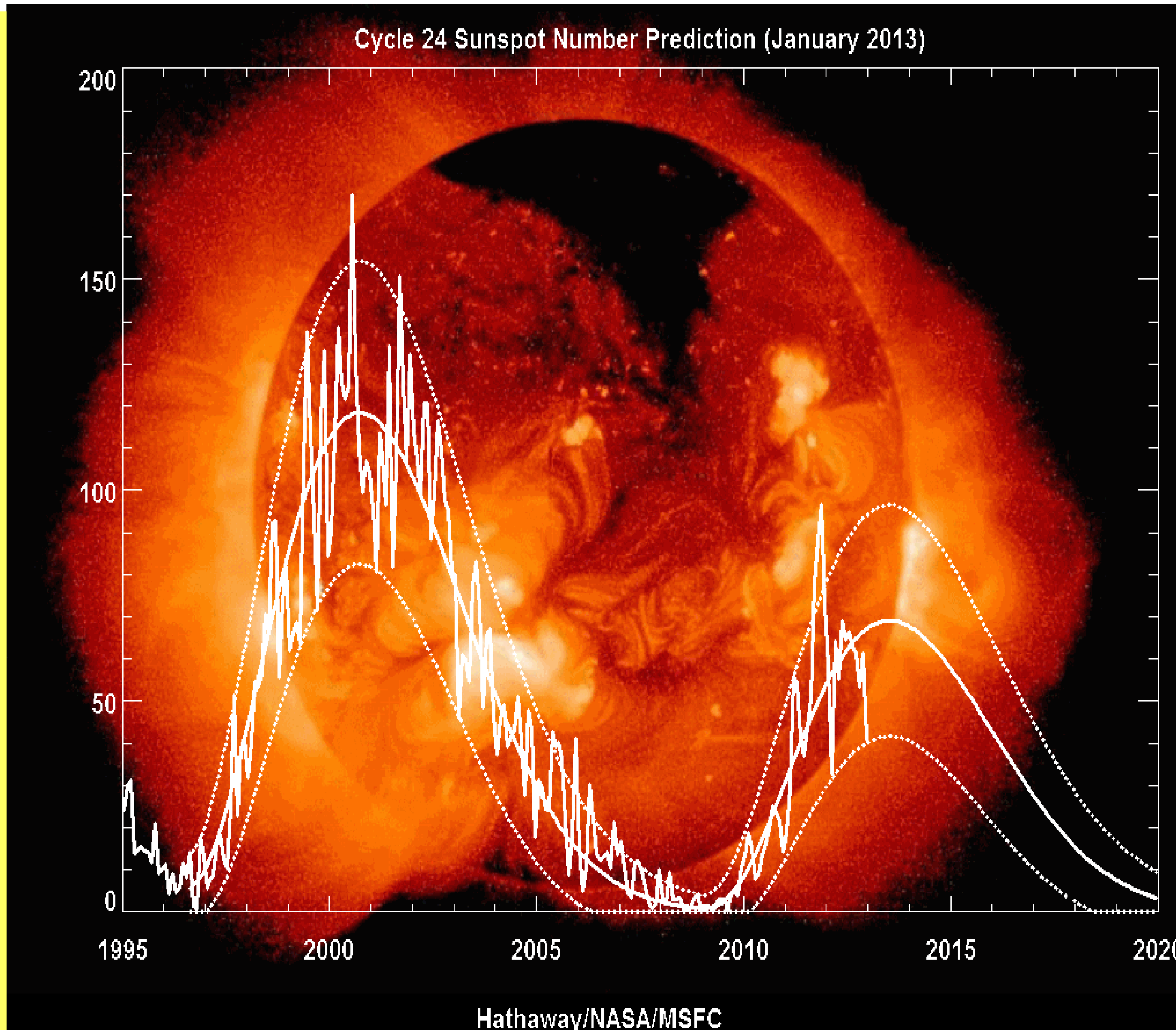
Small Scale Structures: Kolmogorov turbulence

Ionospheric Variability

Solar activity follows a 12 year cycle:

Currently we are past a maximum

the last maximum appeared to be much lower than in previous cycles.



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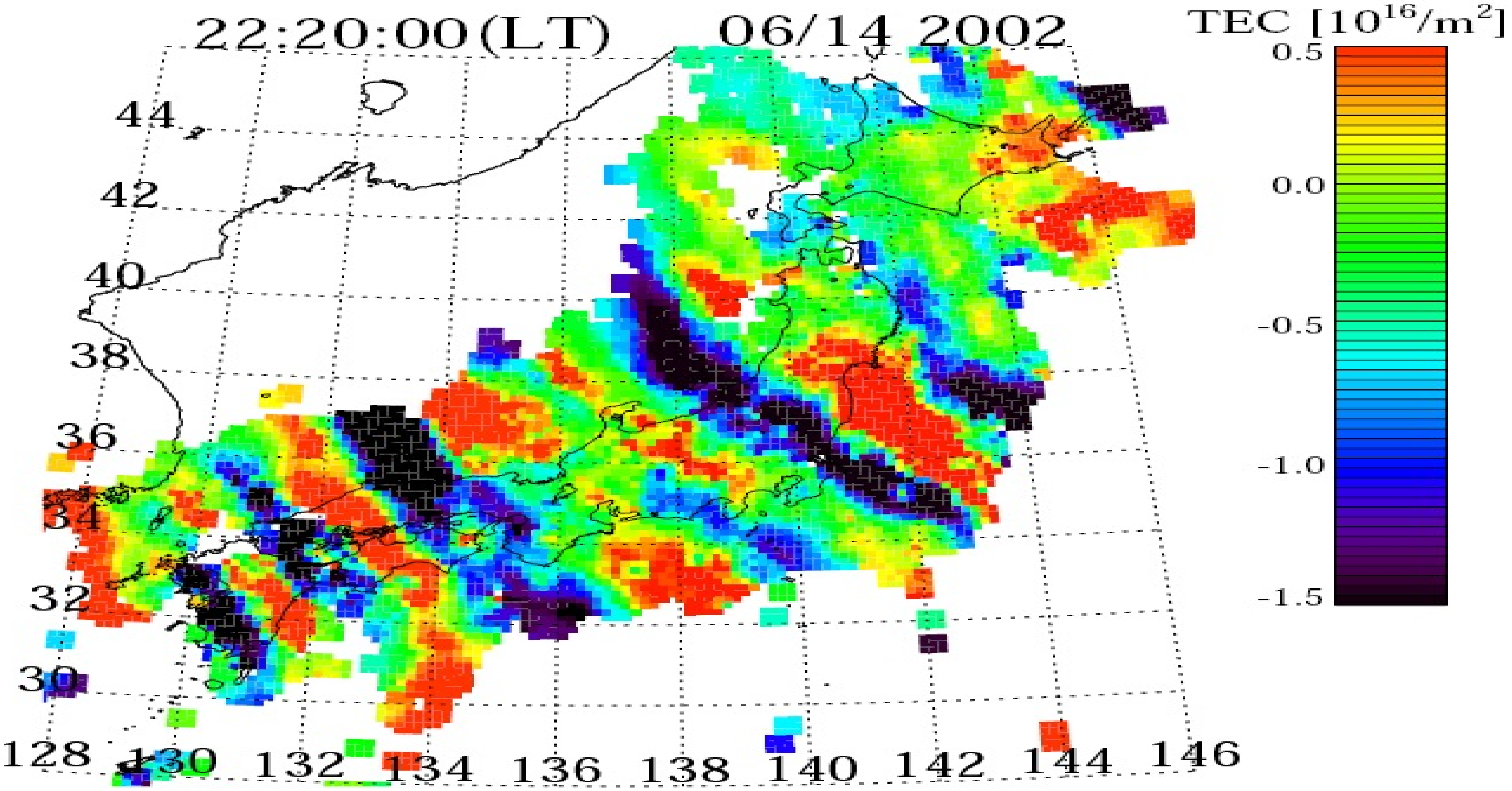

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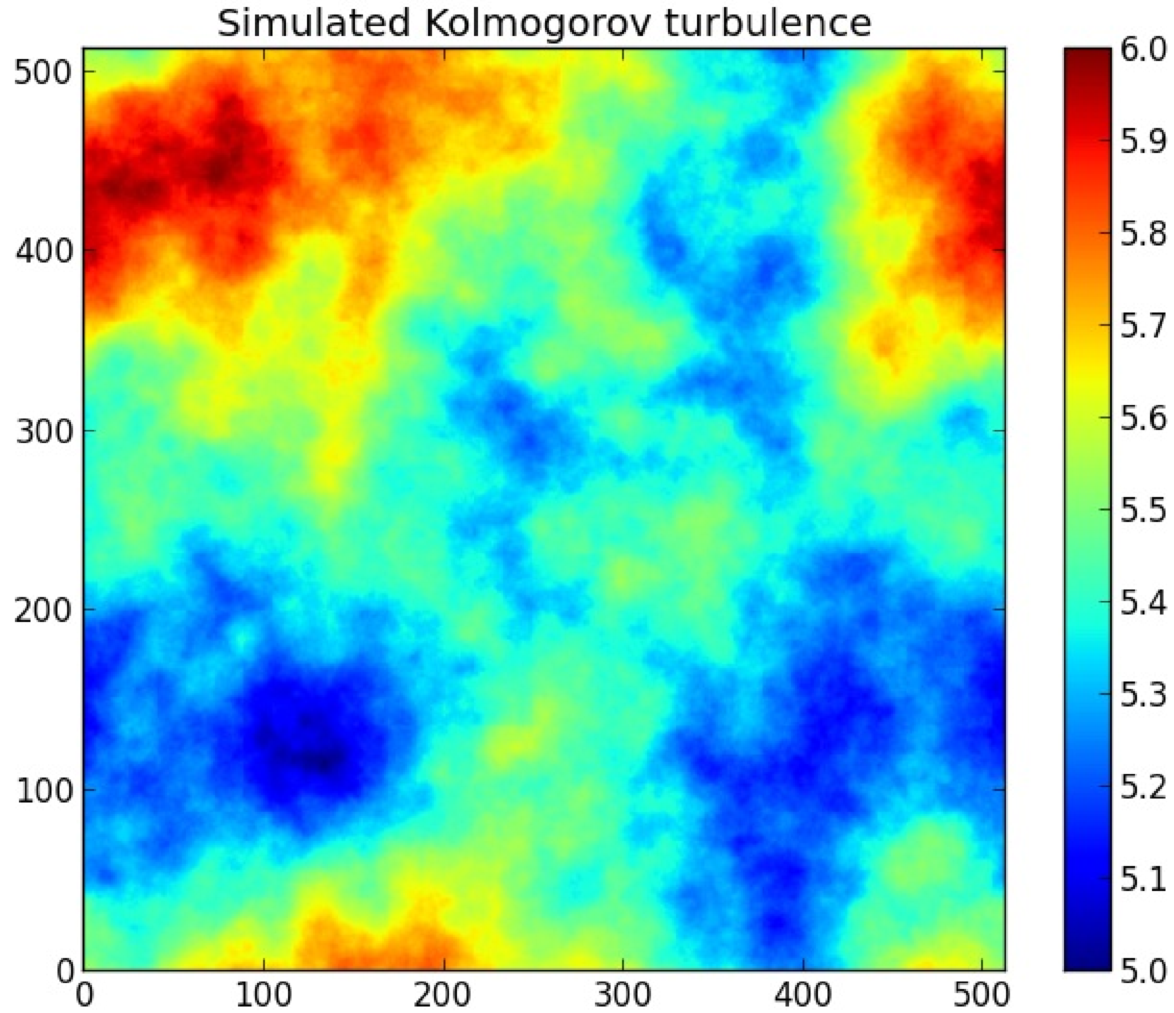


Pres
Traveling Ionospheric Disturbances (TIDs)

Small Scale Structures: 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 signal frequency f >> plasma frequency f_p(~10 MHz)

approximation not valid for lowest LBA frequencies!

N_e = electron density

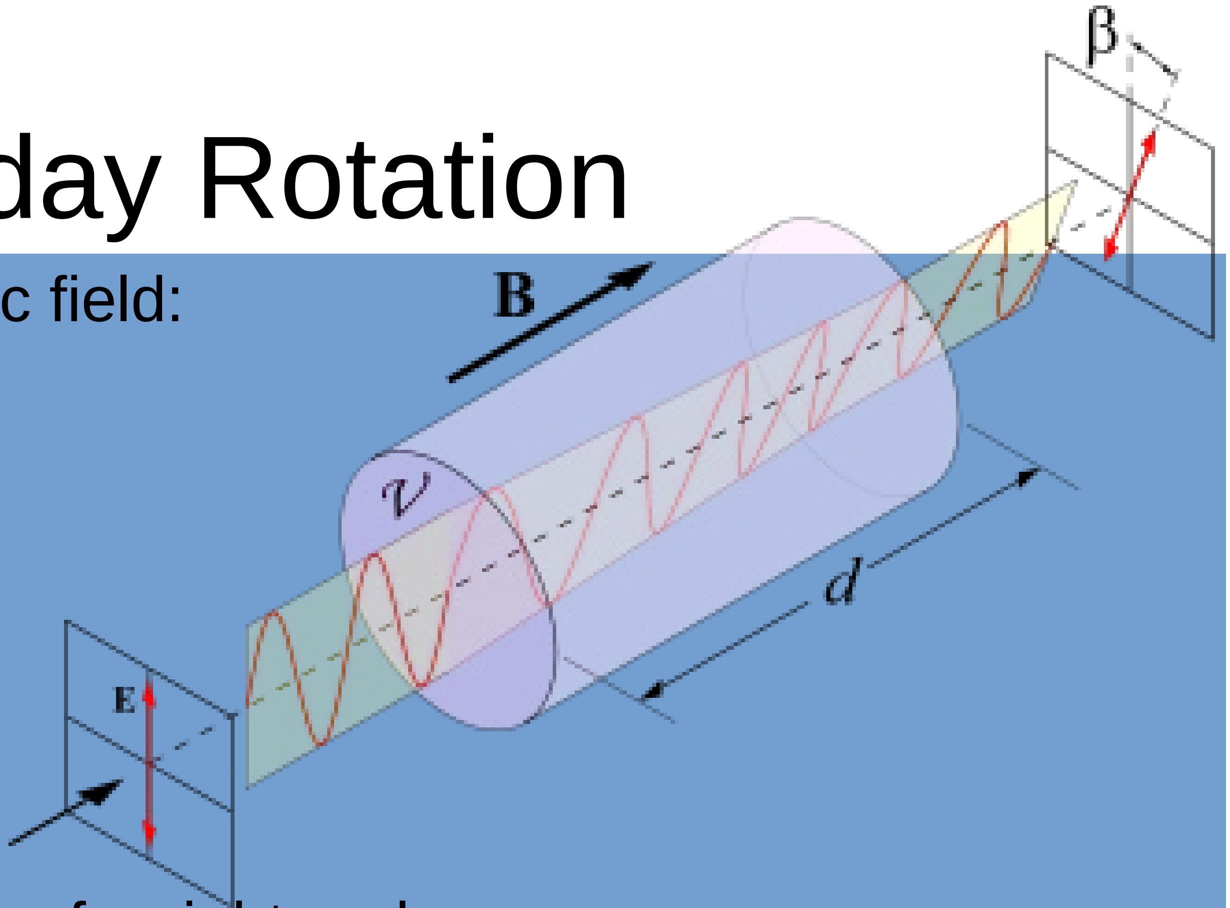
excess path length $40.3/\nu^2 \cdot \int N_e dl$

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

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

Faraday Rotation

In the presence of a magnetic field:



- different refractive index for right and left circularly polarized waves
  - phase shift between right and left circular components
  - equivalently: rotation of linearly polarized components
  - rotation angle:

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

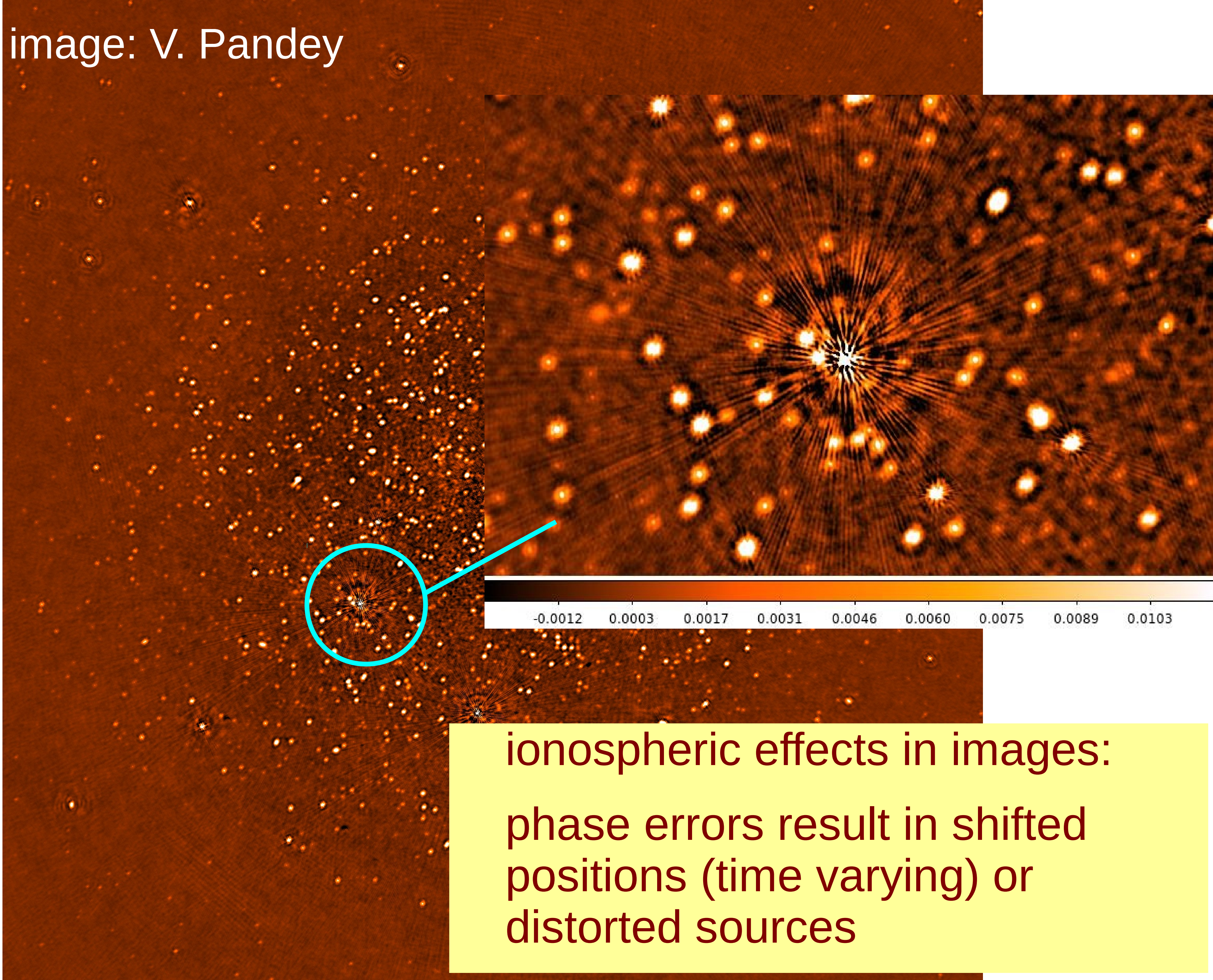
Scintillation

- Amplitude de-correlation due to very turbulent conditions
- Typical size of ionospheric irregularities < Fresnel scale $\sqrt{2\lambda d}$
- Occasional in HBA observations
- Very frequent in LBA

Low Frequency Radio Astronomy

- interferometer measures phase differences:
  - ionospheric delay only visible if the excess path length is different for signal at different receivers
  - ionosphere is highly variable in space and time
  - low frequency radio telescope sensitive to small ionospheric disturbances
    - with LOFAR HBA calibrator data we are able to measure ionospheric variations <0.001 TECU
    - orders of magnitude better than GPS
  - differential integrated TEC of 0.2 TECU →
    - 1 full 2π rotation between 110-180 MHz (HBA)
    - 3.5 full 2π rotations between 40-80 MHz (LBA)

typical variation LOFAR (NL) 80 km: 0.5- 1TECU
within a single HBA beam: ~0.1 TECU



ionospheric effects in images:

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

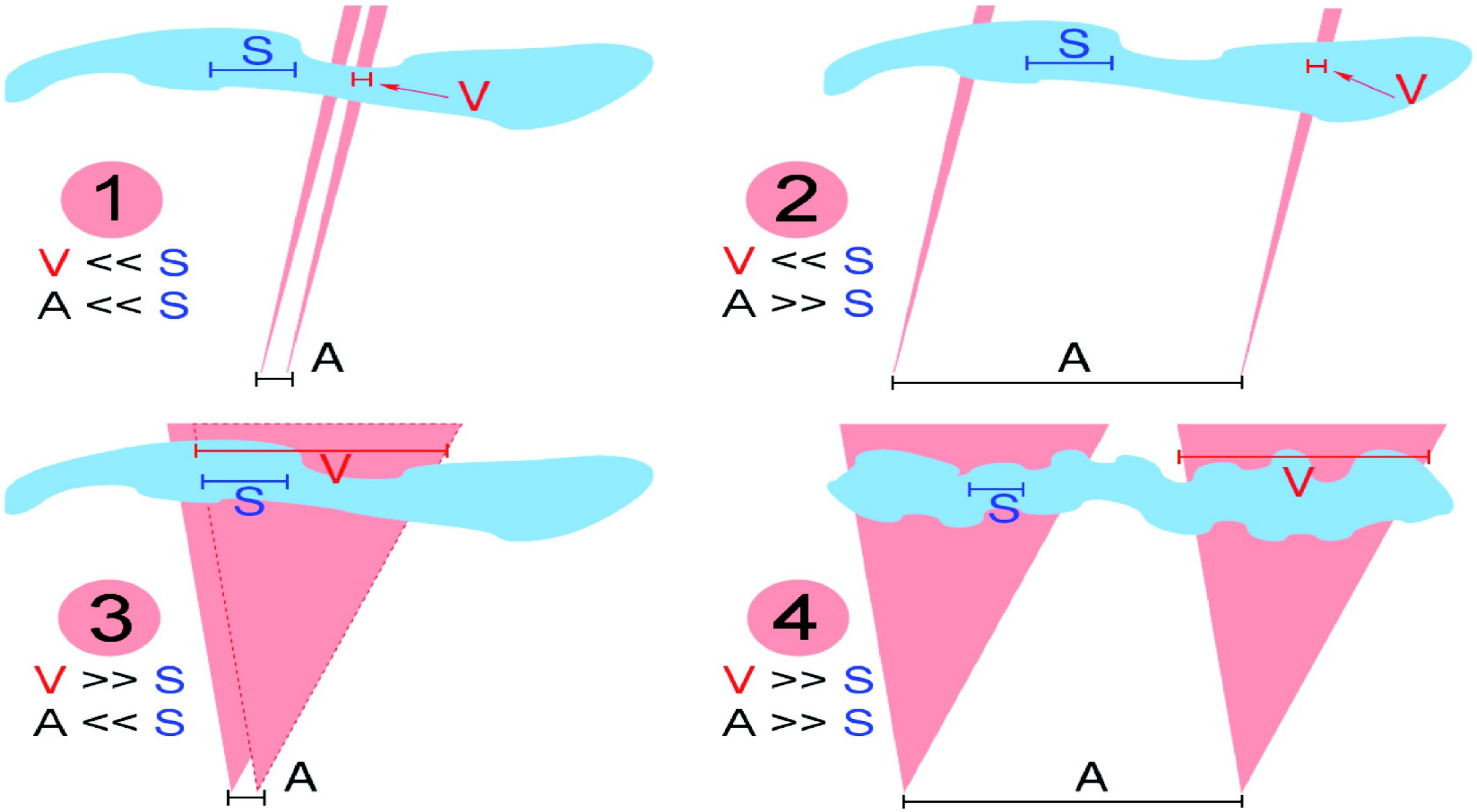
Calibration Strategies

- Calibration strategies of the ionospheric distortions depends on your science goal
- In general:
  - dispersive delay requires high frequency resolution
  - time variability requires high time resolution
    - TID timescales ~ 15 min
    - moving turbulence: smaller amplitude but faster variations
  - spatial variability requires direction dependent calibration
- In practice S/N can complicate above
  - Calibrator phases cannot always directly be applied to target field due to spatial variations

Ionospheric Calibration

Standard direction independent calibration takes care of ionospheric phases in direction of the calibrator

Wide FOV/large area: extra calibration steps needed



Lonsdale (2005)

Dispersive delay correction

direction independent calibration phases contain different phase effects

@ LOFAR 2 dominant sources:

- drifting clock errors
- ionospheric phases

– second order effects are cable reflections,beam and source model errors

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:

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

For LBA <40MHz third order term is also important!

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 fc

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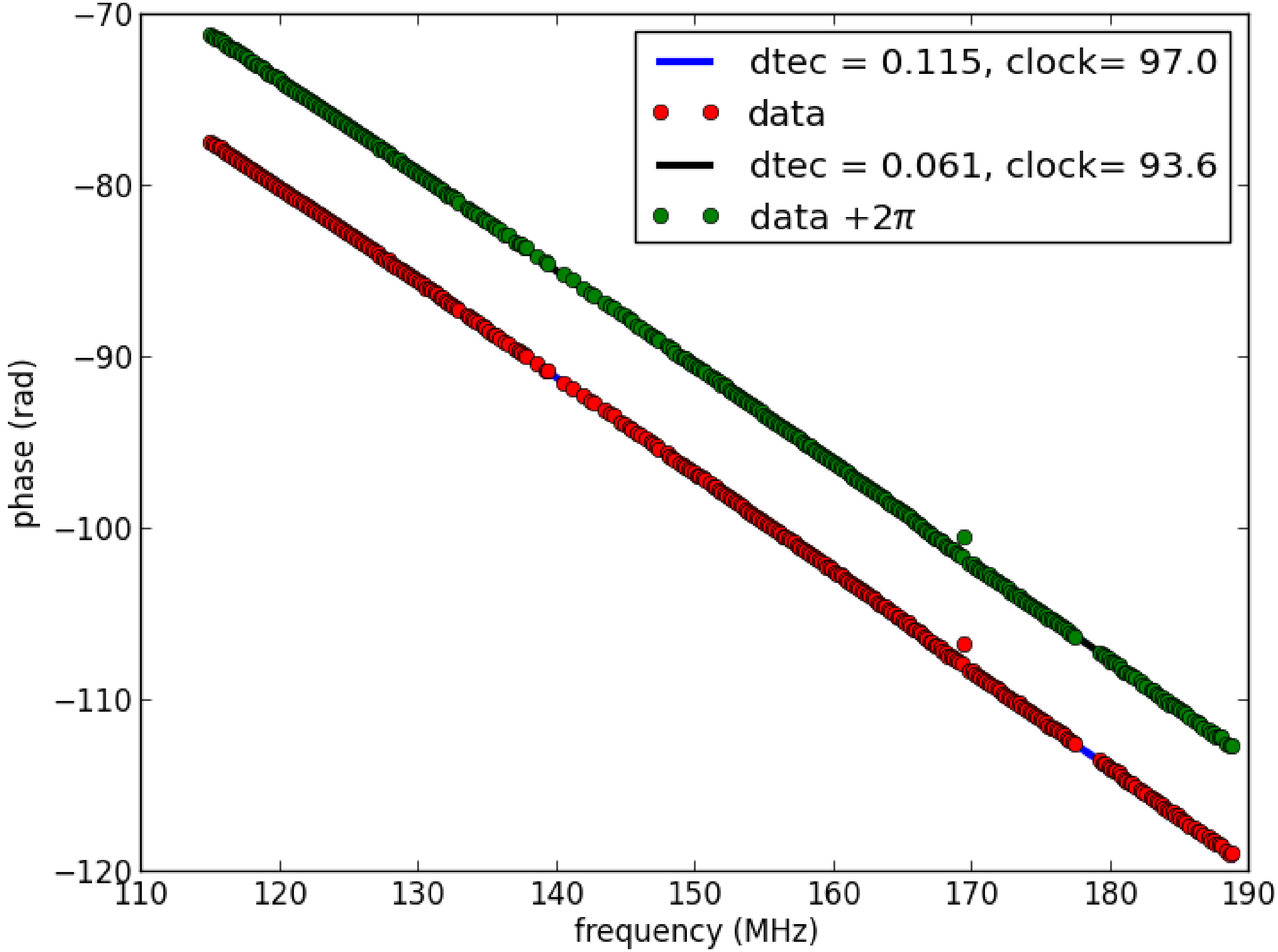

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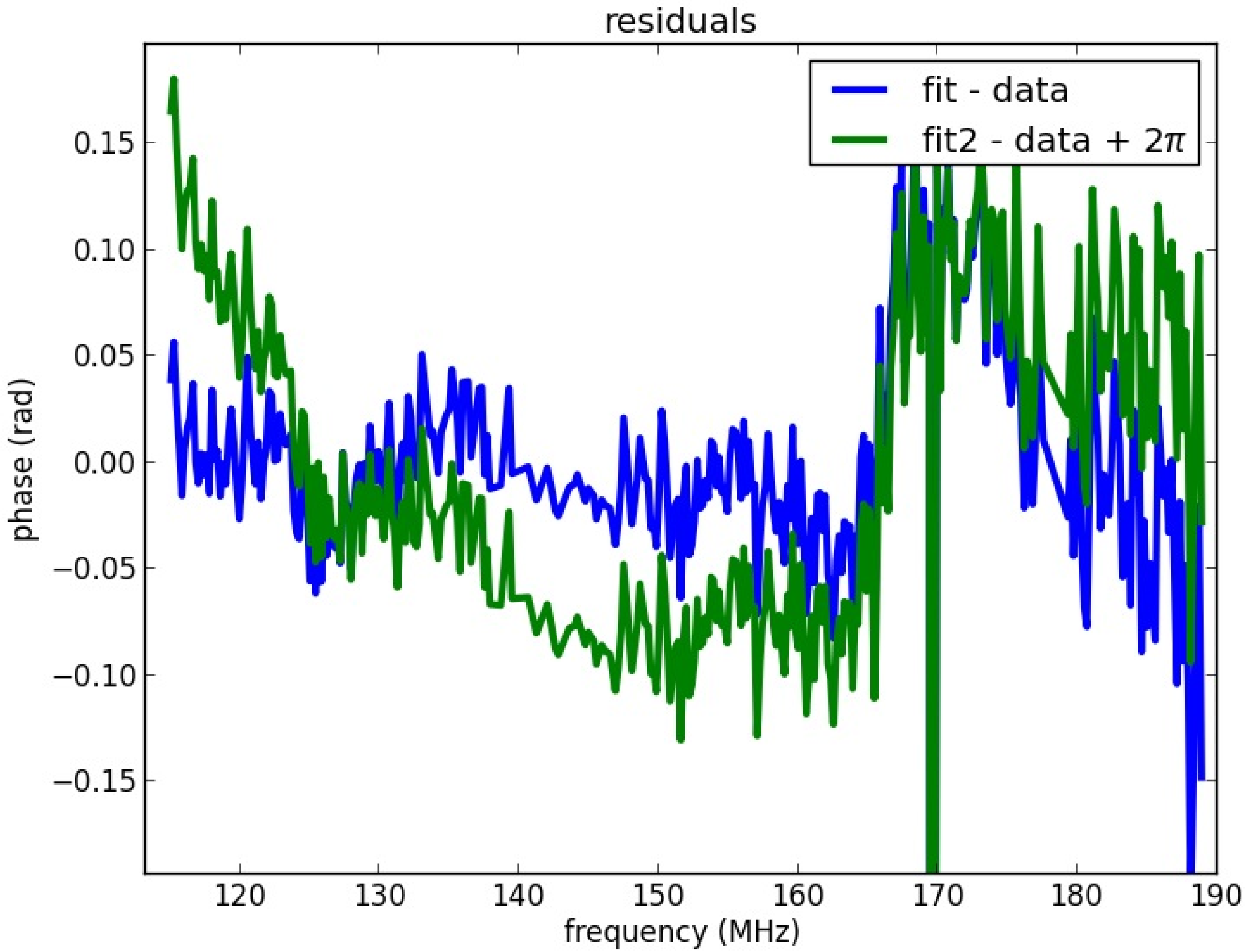

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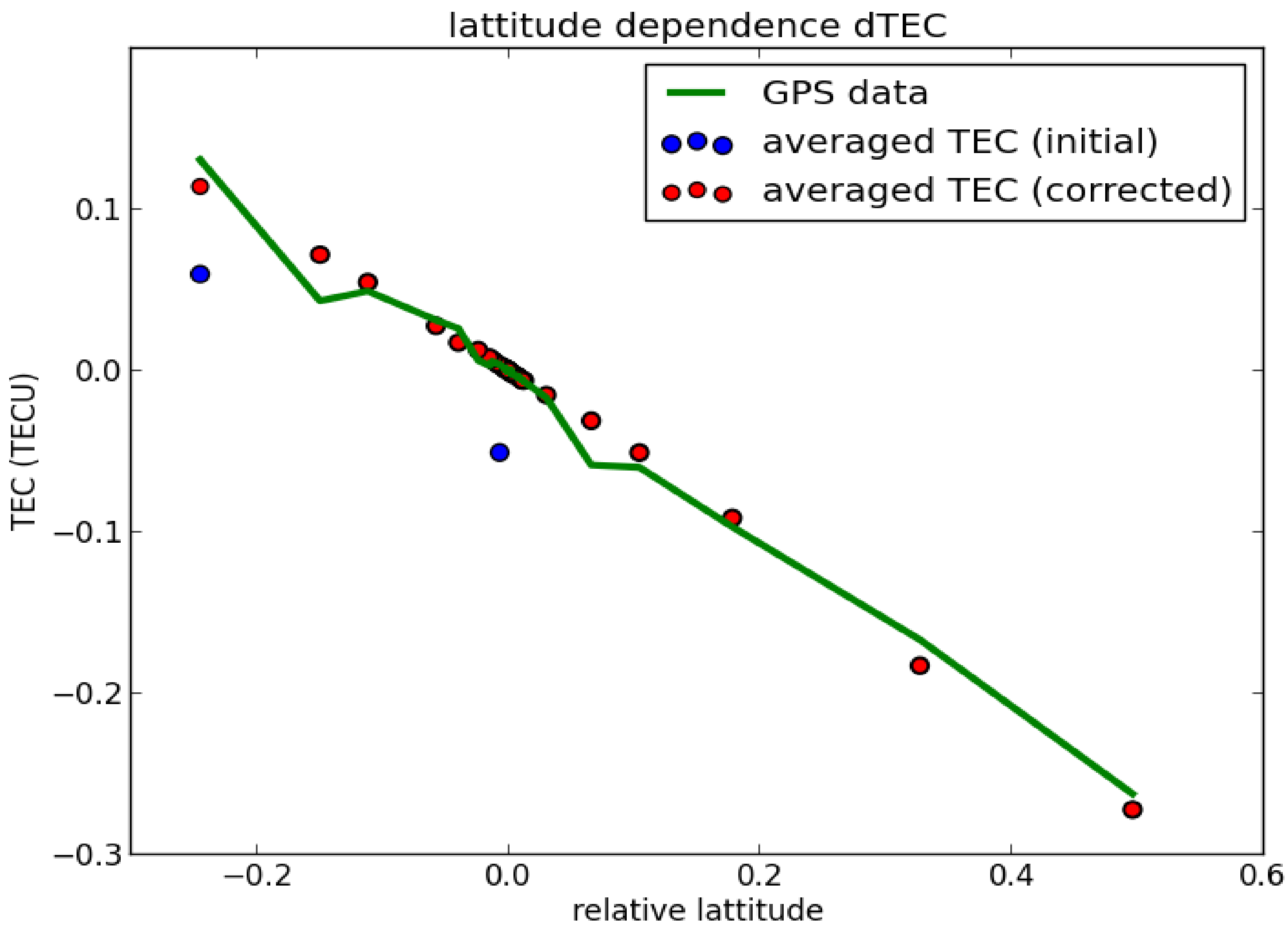
Slow variation of clock/TEC solutions in time:

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

Correct remaining wraps by inspecting residuals/spatial correlation

Clock/TEC separation



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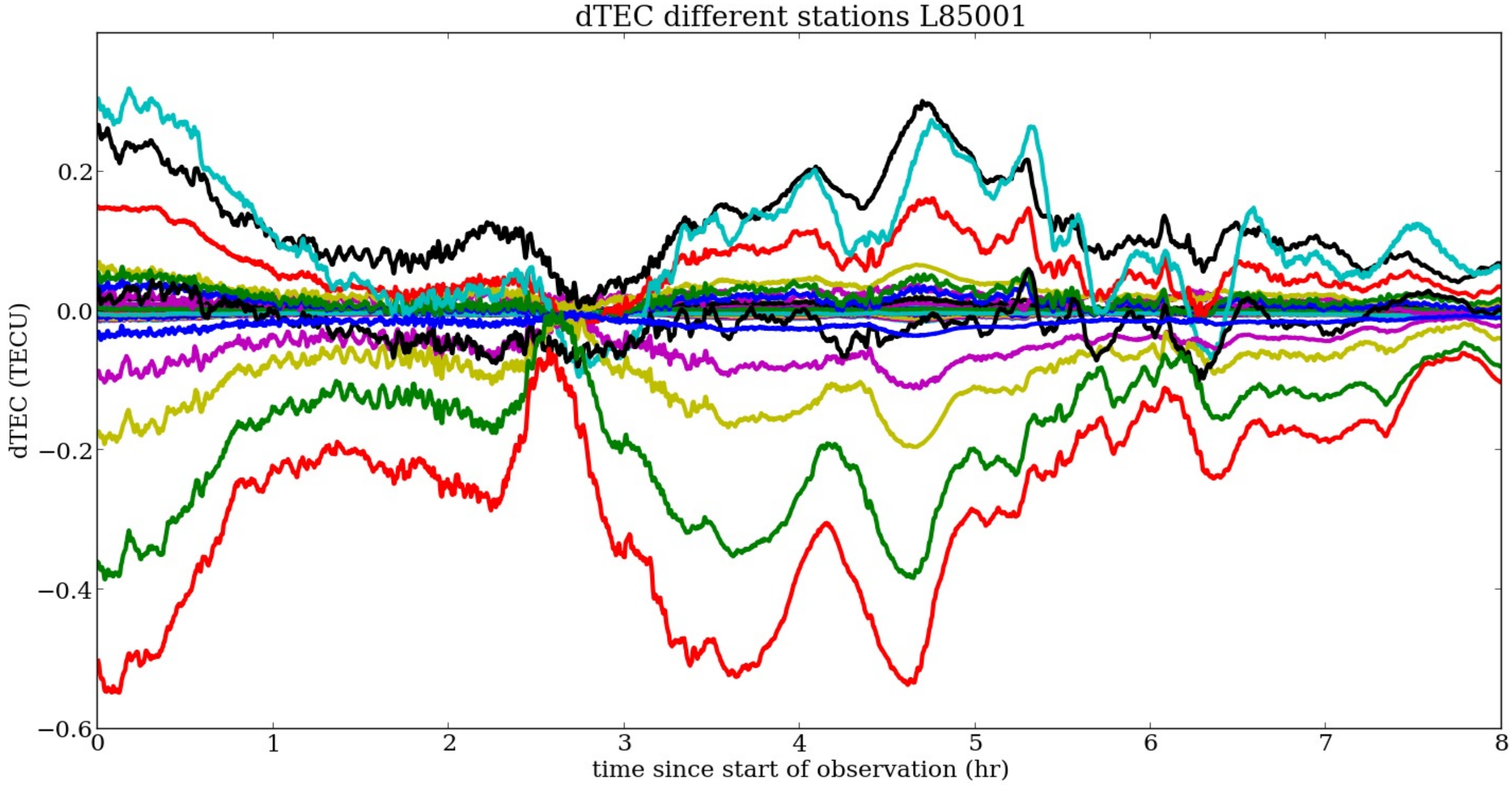
Clock/TEC separation script available in Losoto/prefactor

TEC solutions

dTEC solutions versus time, HBA all stations



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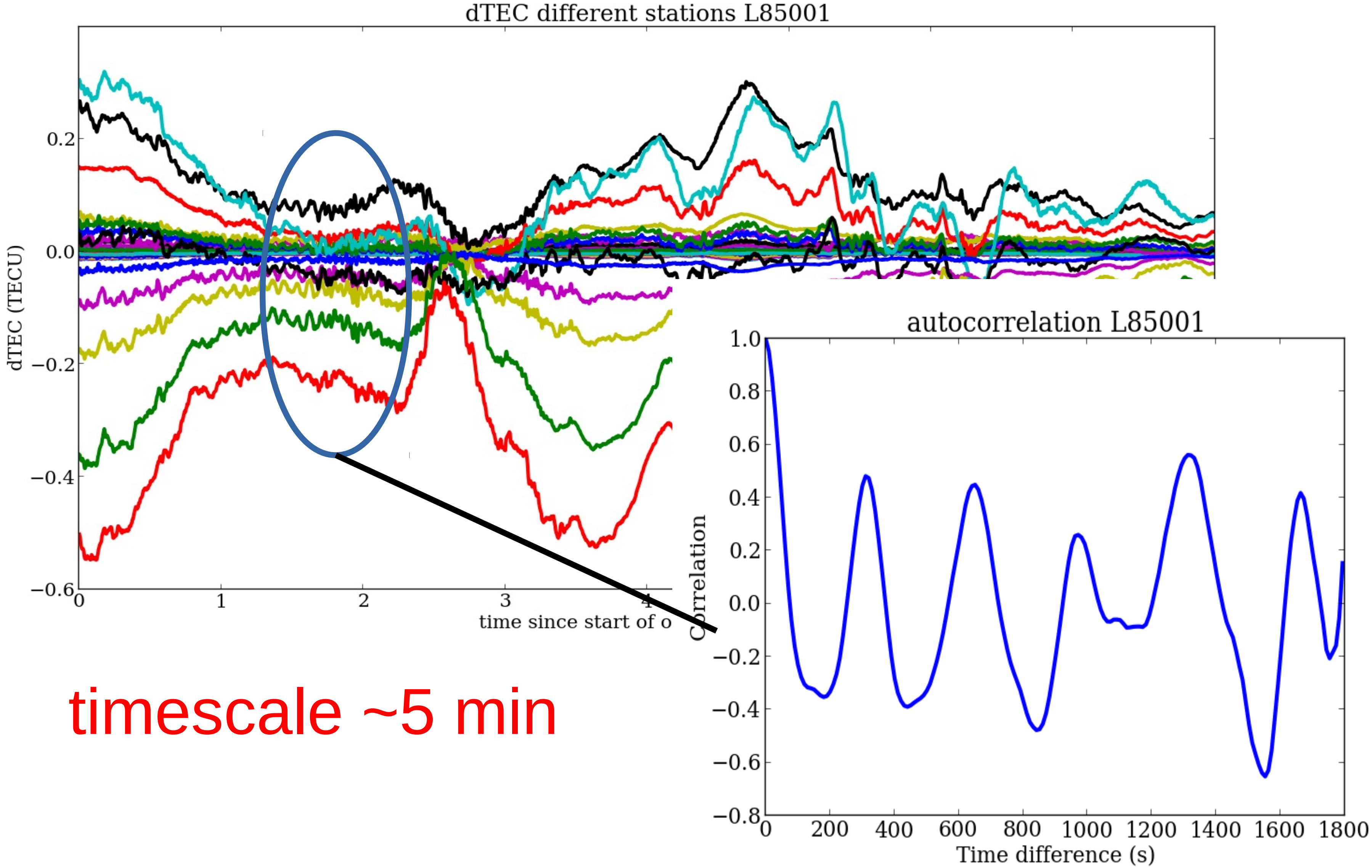


timescale ~5 min

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: diffractive scale,

$D_\varphi(s_0) = 1\ \mathrm{rad}^2$

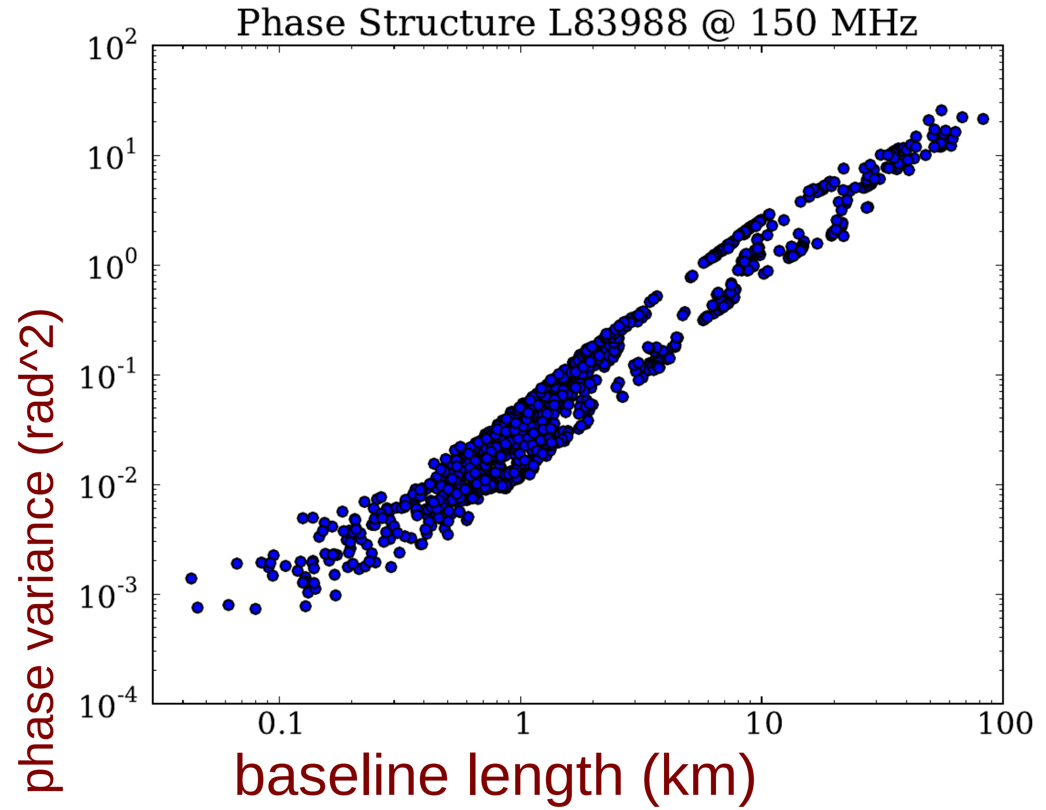
Measure structure function by calculating variance of dTEC vs. time for all baselines

Typical nighttime S_0 @150 MHz: 2-40 km

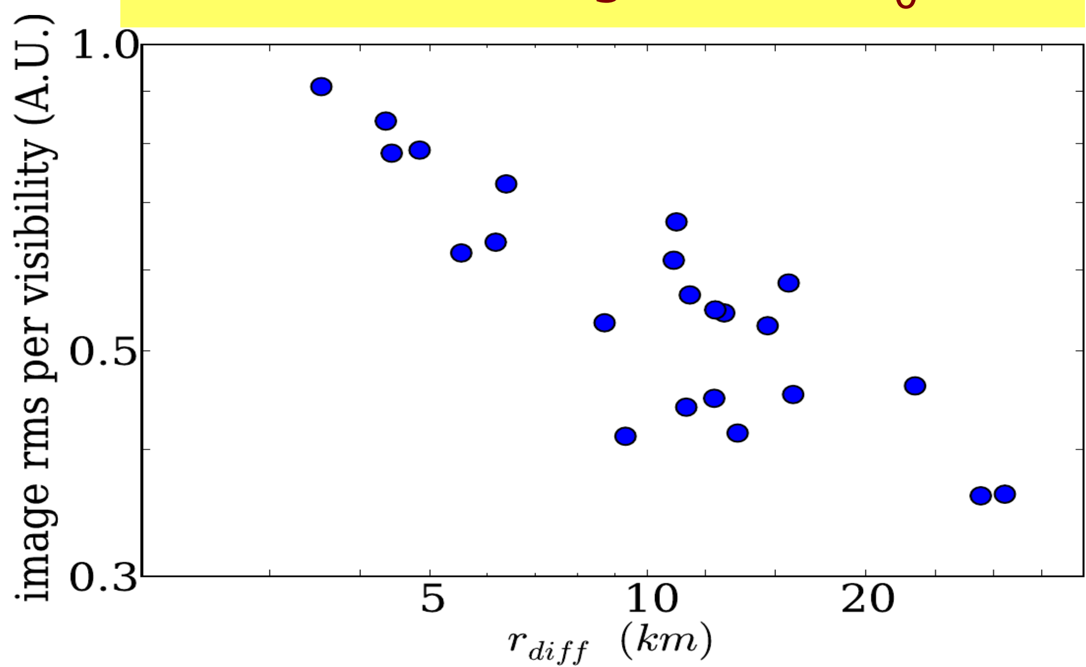
scintillation conditions S_0<2km

Characterize ionospheric quality

Diffractive scale calculation from calibration phases available in Losoto/prefactor



Correlation image noise S_0



Initial Calibration steps

- Get high time/freq resolution calibration phases from calibrator: HBA: 10s 1ch/SB LBA:10s 3ch/SB
- If calibrator outside target field:
  - clock/TEC separation
  - subtract TEC phases from phase solution, apply remaining on target field
- Start selfcal loop on target:
  - use 1/ν frequency dependence to combine several channels/SBs

    available in DPPP
  - high time resolution for phases
  - LBA: scintillation effects: also the amplitudes show fast variations
- Start direction dependent calibration

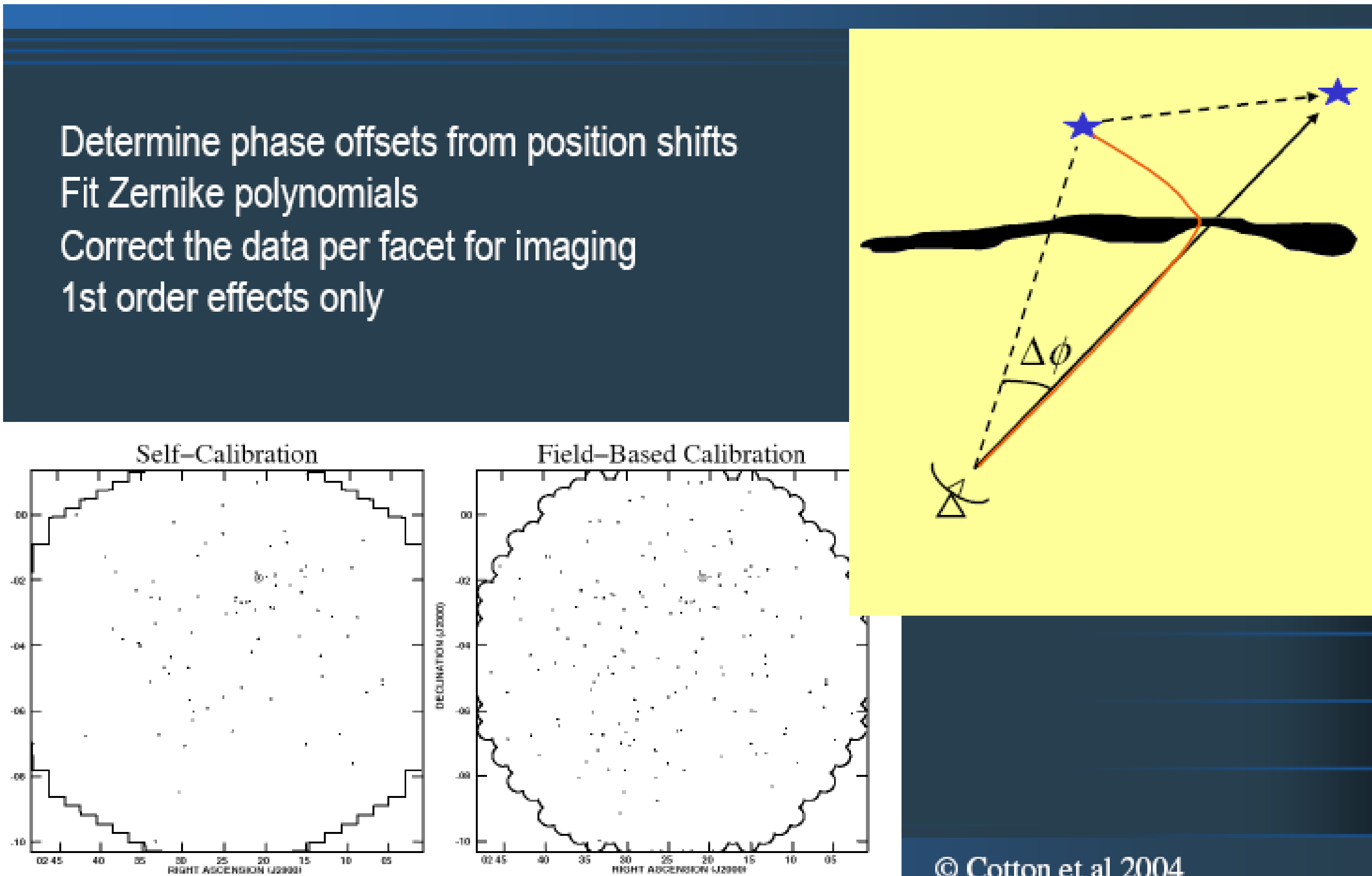
Direction Dependent Calibration

- For deep imaging: ionospheric variation over FOV needs to be taken into account
- First remove global ionospheric phases via direction independent selfcal
- Direction dependent calibration
  - High time resolution phases
  - use $1/\nu$ frequency dependence to combine channels/SBs
  - lower time resolution for beam effects
- Factor or Sagecal for DDE calibration

  (see presentation de Bruyn)
- Correction of direction dependent effects:
  - interpolation between different directions

Direction dependent correction methods

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



Position shifts

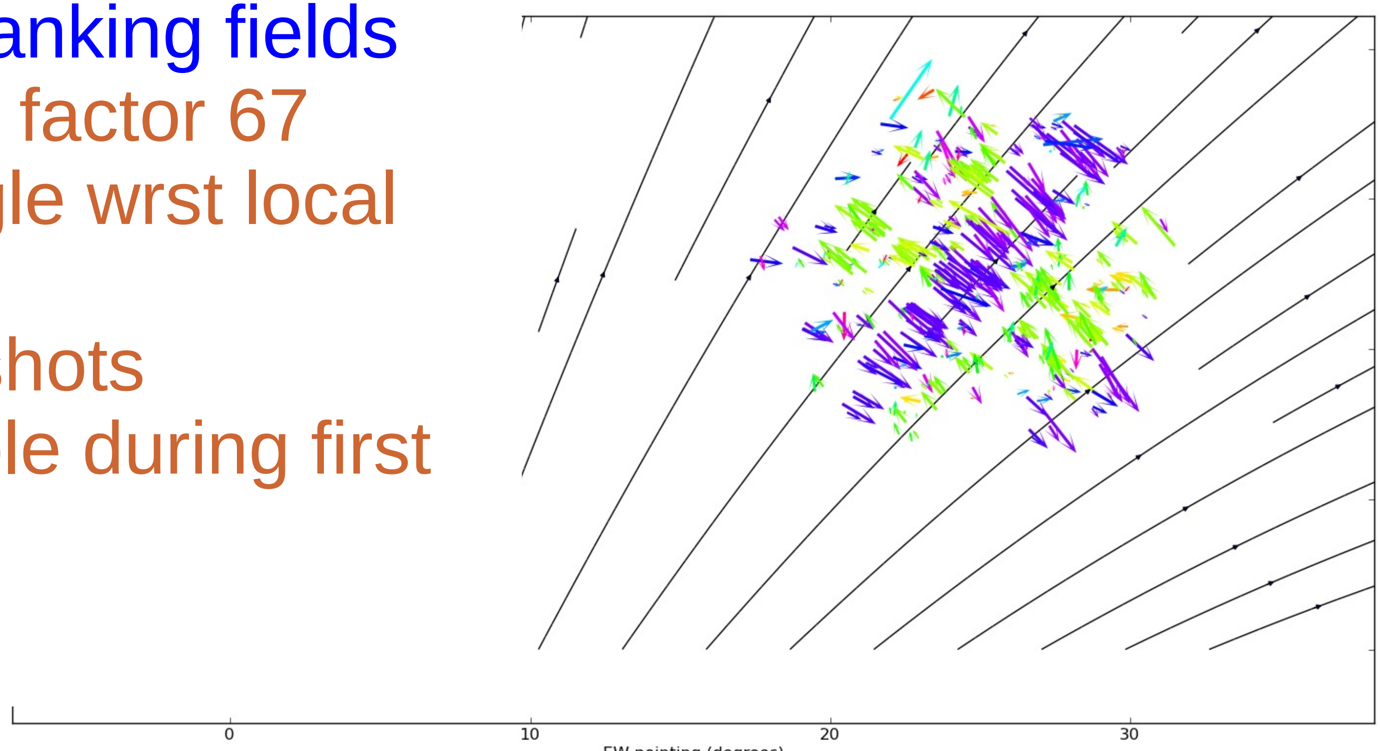
ionosphere: linear gradient over array → position shift

higher order terms → distorted source

LOFAR use only short baselines: CS only

$\Delta\theta = C/\nu^2 \, \nabla_\perp \, TEC$

HBA: 3C196 + 6 flanking fields
arrows scaled with factor 67
color indicates angle wrst local field lines
2 (1 minute) snapshots
structure only visible during first hour



Direction dependent correction methods

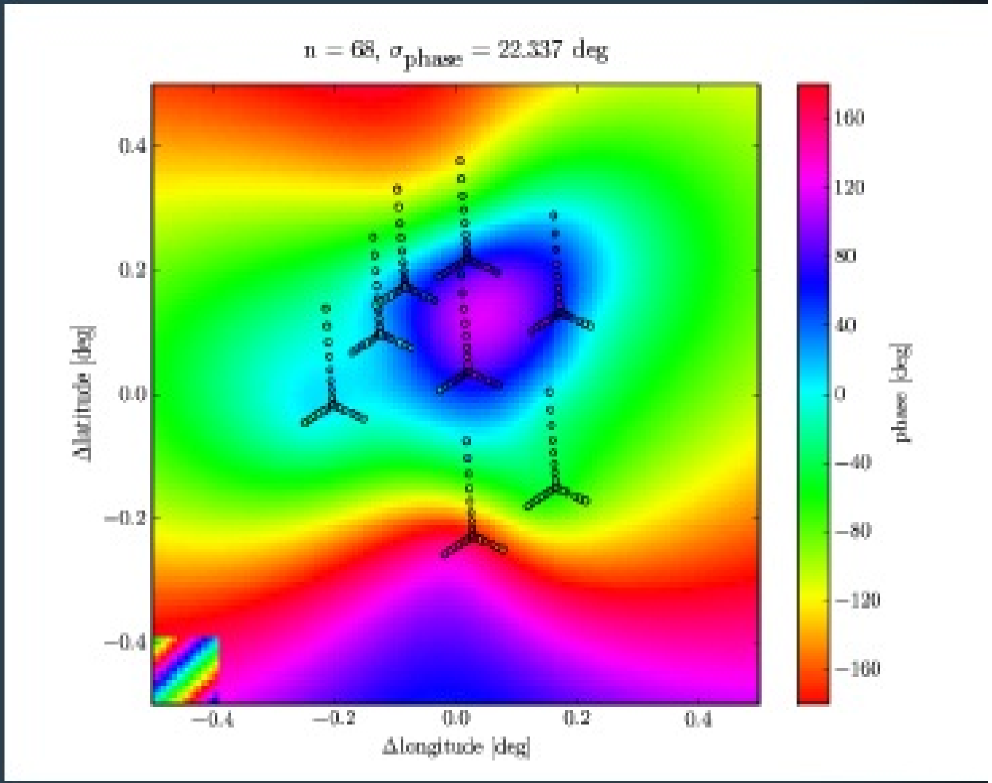
Methods that involve direction dependent calibration
separate gain/phase solutions in direction of several sources/clusters

- Multi direction solve + subtract sources with their own solutions (e.g. Sagecal)
- Facet calibration and correction: Factor
- 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

Phasescreen examples: SPAM

Source Peeling & Atmospheric Modeling

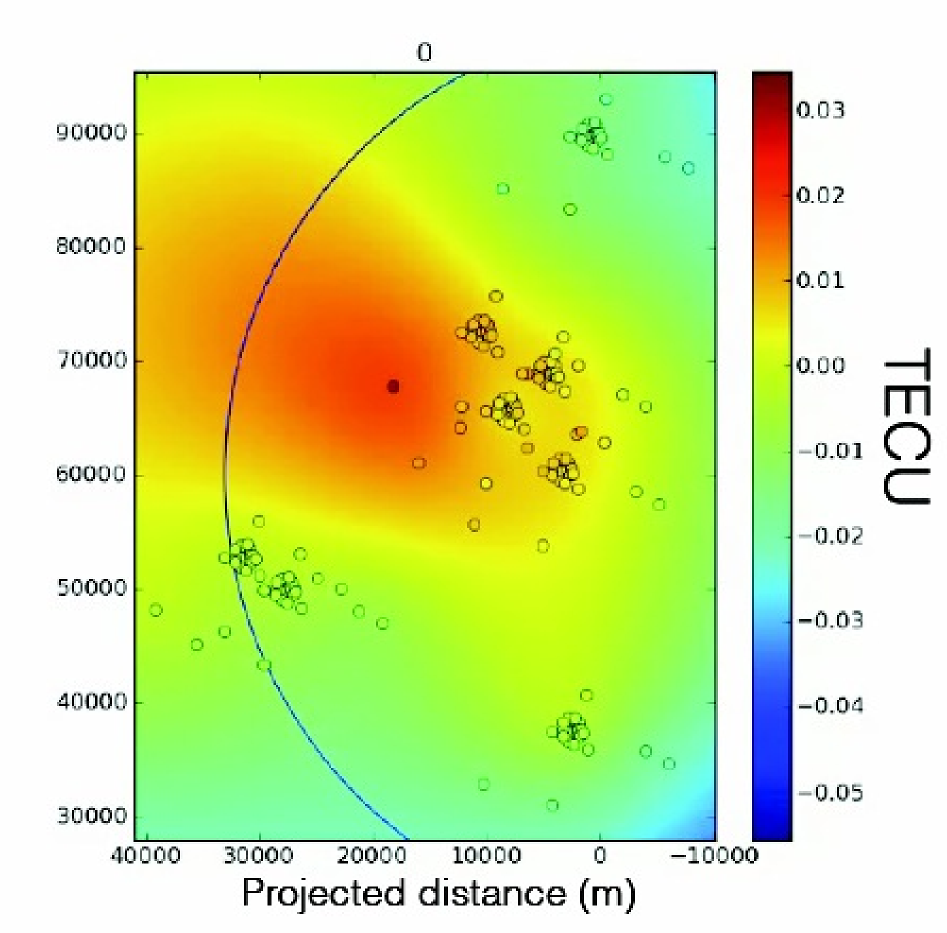
- Get $\varphi_{obs}(t)$ from peeling of calibrators
- Fit model on KL basis
- Correct each facet with model phase
- Make image
- Not limited to gradients only



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

Phasescreen examples: MSSS

- 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

Phasescreen Methods

issues:

- needs several bright enough sources in FOV
  - selfcal source models need good ionospheric calibration
- 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
  - complicates phasescreen fitting

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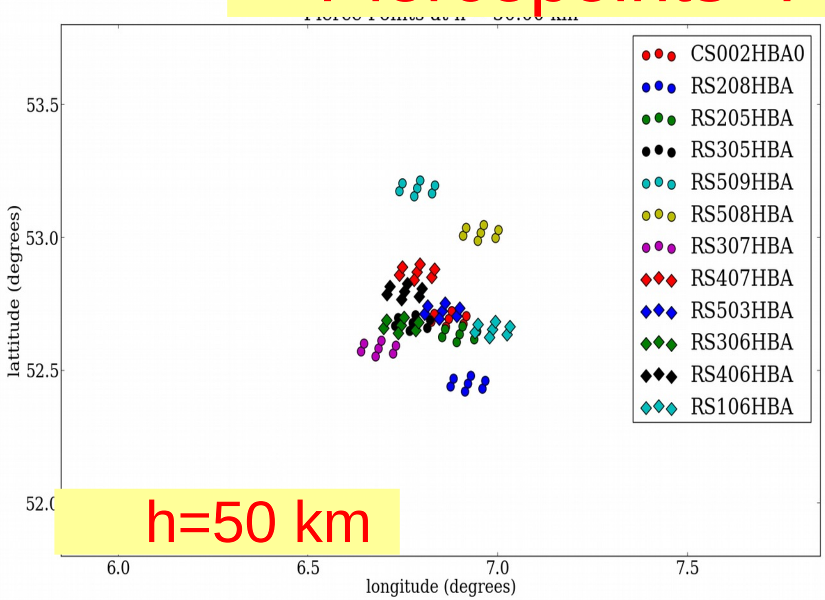
Piercepoints 7 directions Remote stations



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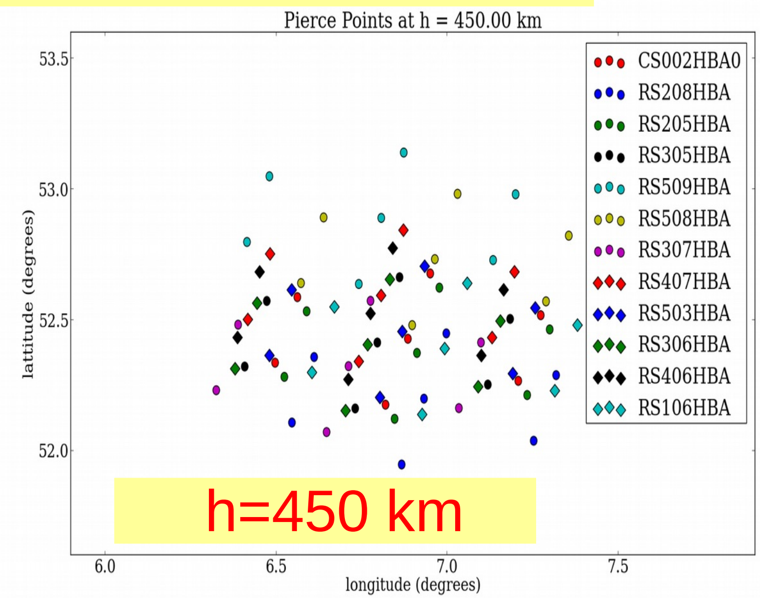

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Differential Faraday rotation $\beta = \mathrm{RM}\nu^{-2}$

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

$$\begin{pmatrix} G_{xx} & G_{xy} \\ G_{yx} & G_{yy} \end{pmatrix} = \begin{pmatrix} cos(\alpha) & sin(\alpha) \\ -sin(\alpha) & cos(\alpha) \end{pmatrix} \cdot \begin{pmatrix} G_{xx} & 0 \\ 0 & G_{yy} \end{pmatrix}$$

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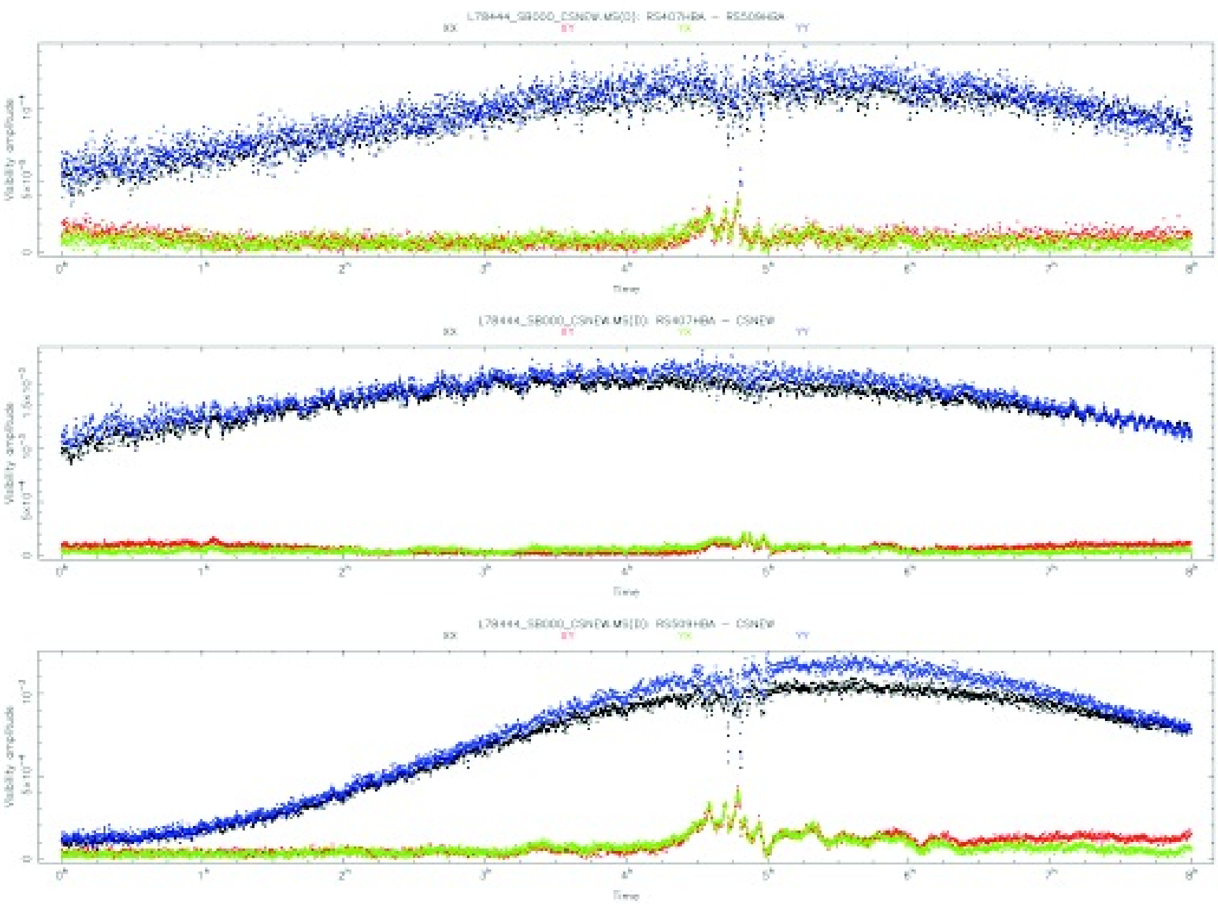

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Selfcal: either

solve full polarization matrix or

diagonal gains + 1 rotation matrix or

convert to circular polarization:

difference in R and L phases gives Faraday rotation angle

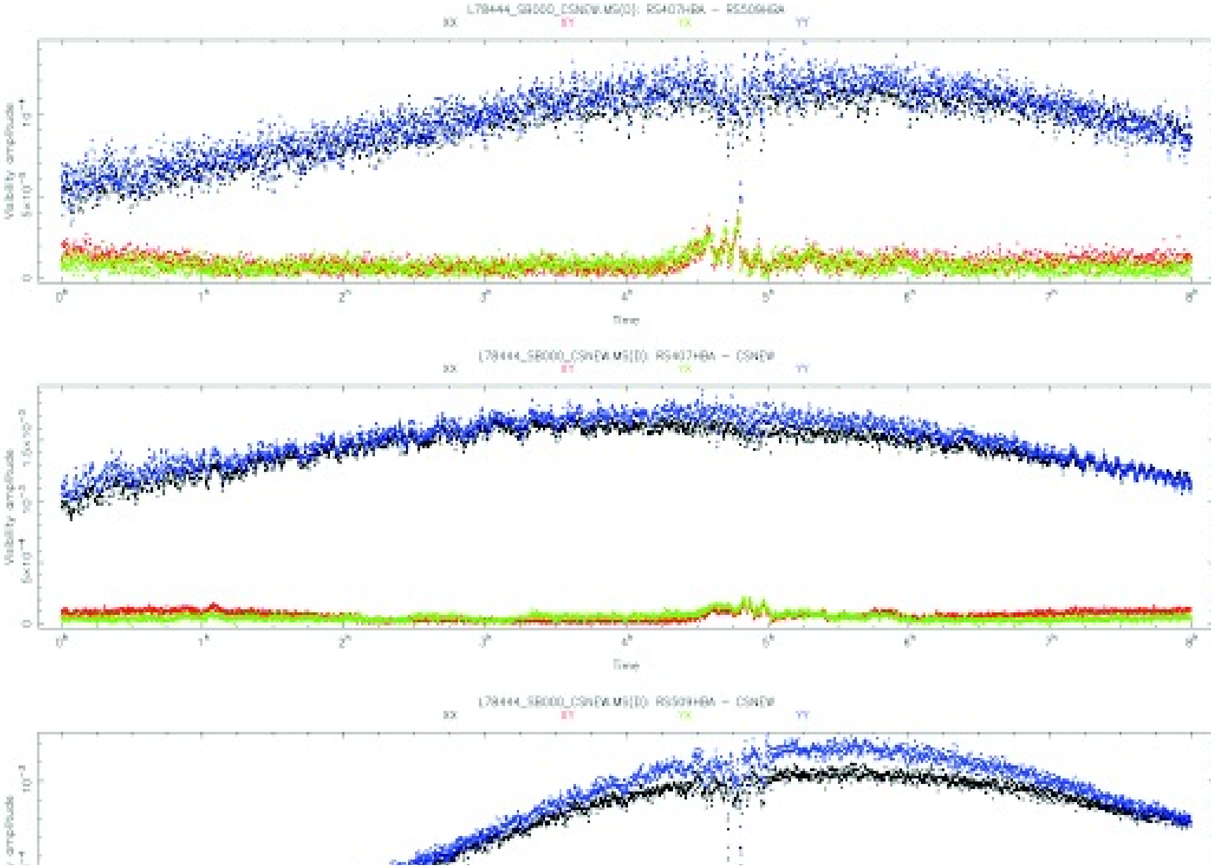
Differential Faraday rotation provides clean independent measure of ionospheric fluctuations (ignoring differential B)

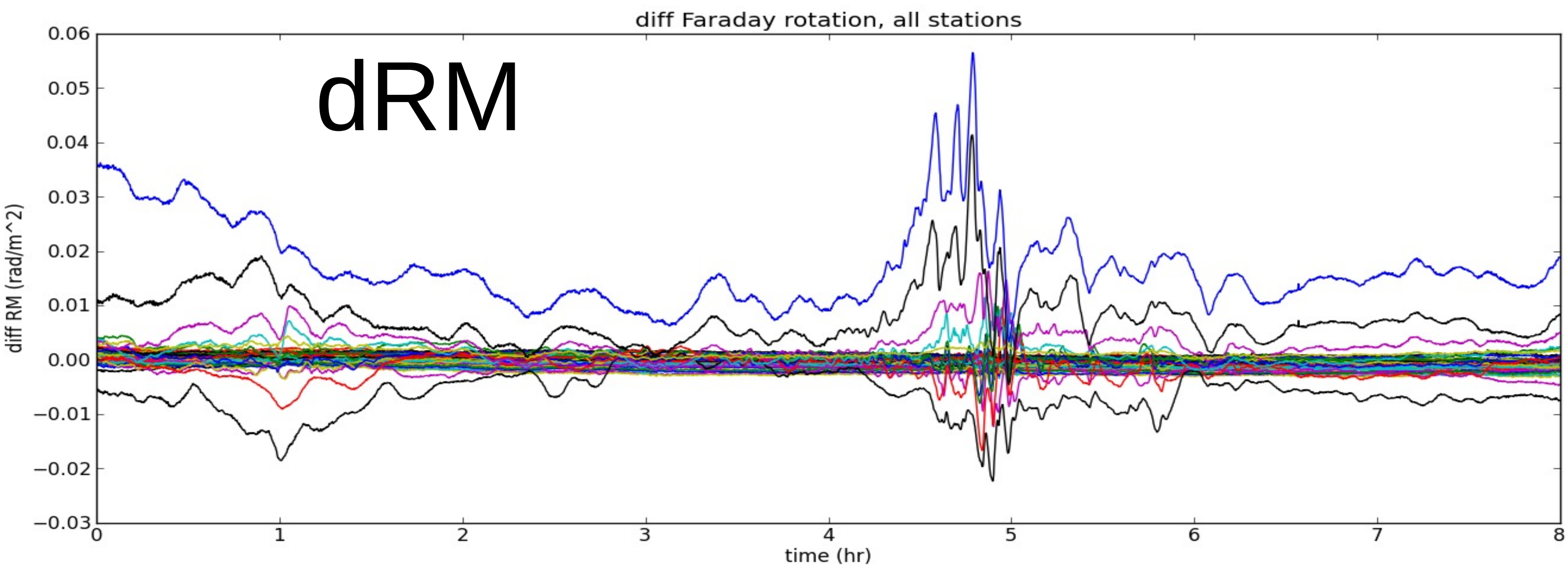
In principle possible to extract absolute TEC via:

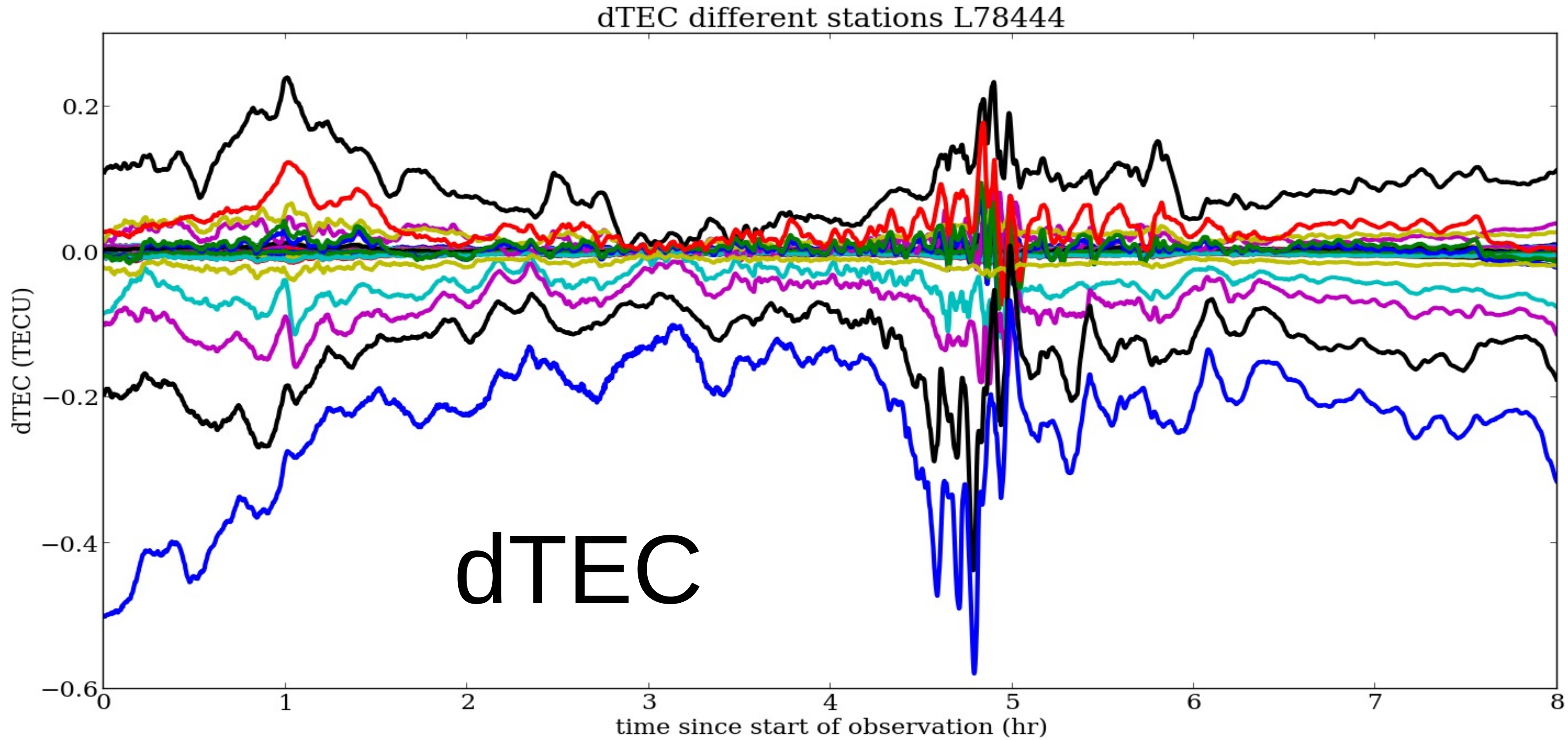
$$\Delta RM = \Delta TEC \cdot B_{||} + TEC \cdot \Delta B_{||}$$

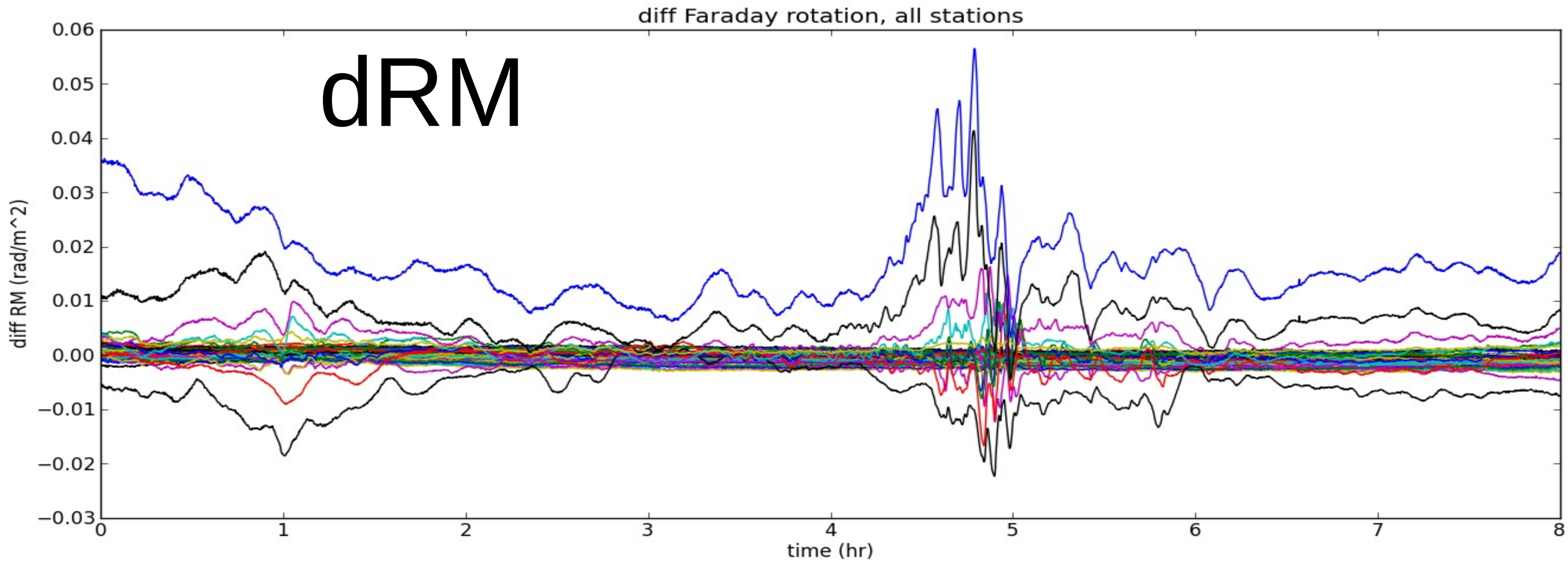
In practice large uncertainty on $\Delta B_{||}$

y rotation




diff Faraday rotation, all stations
dRM
diff RM (rad/m^2)
time (hr)
0.06
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
0
1
2
3
4
5
6
7
8


dTEC different stations L78444
dTEC (TECU)
time since start of observation (hr)
dTEC
0.2
0.0
−0.2
−0.4
−0.6
0
1
2
3
4
5
6
7
8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0
1
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3
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5
6
7
8

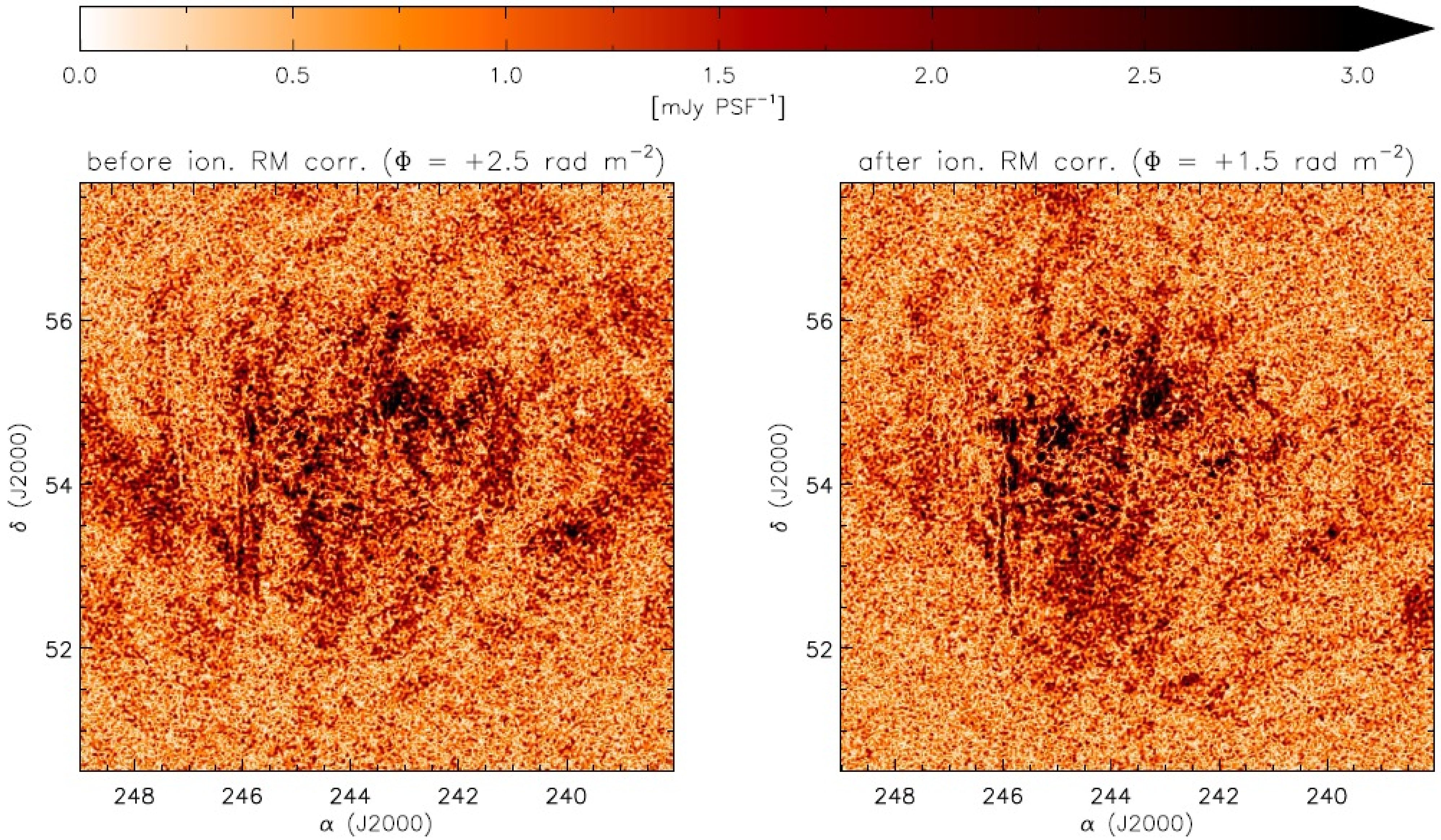
Absolute Faraday Rotation

- 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

www.github.com/maaijke/RMextract:

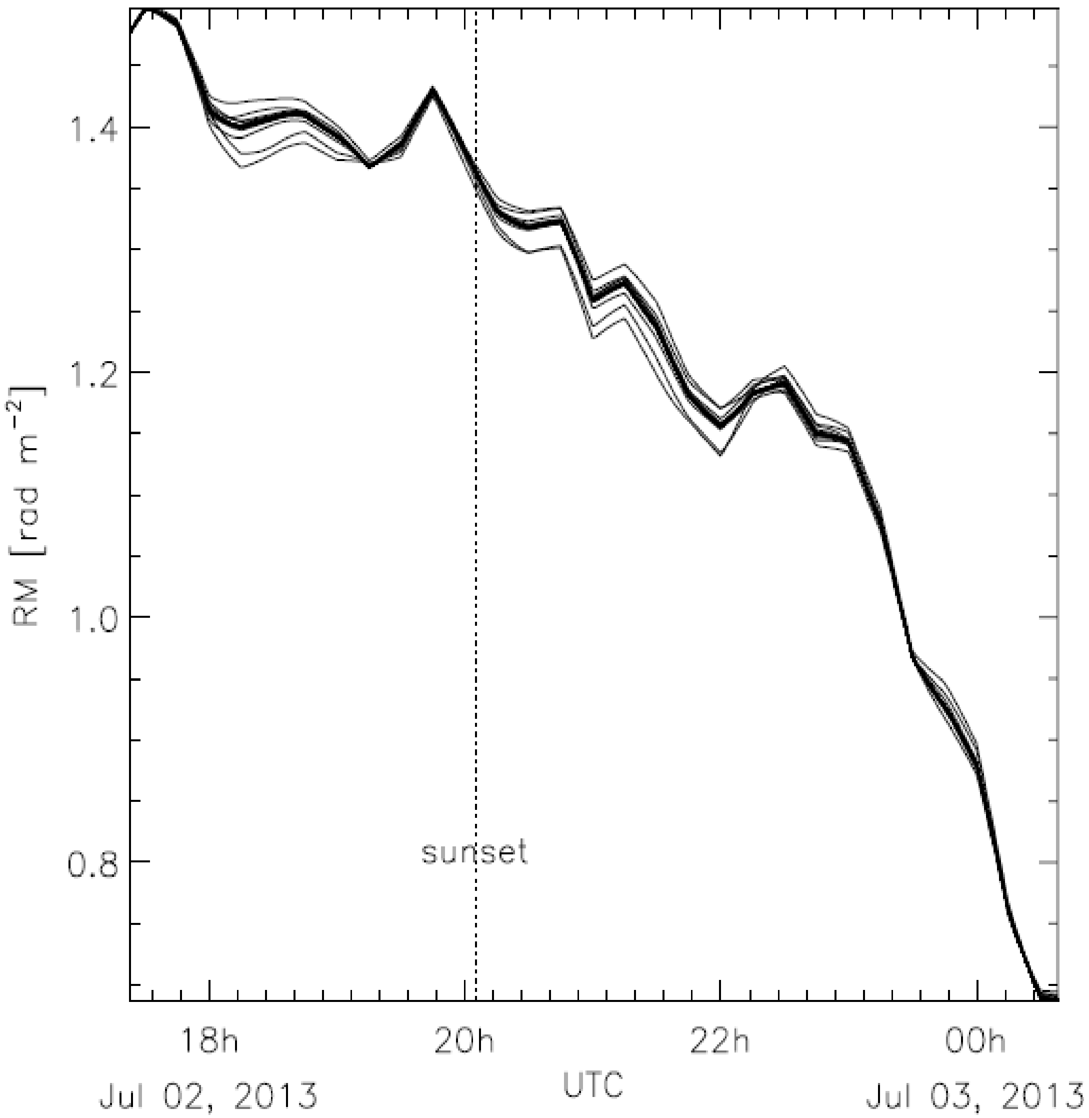
implementation in prefactor available

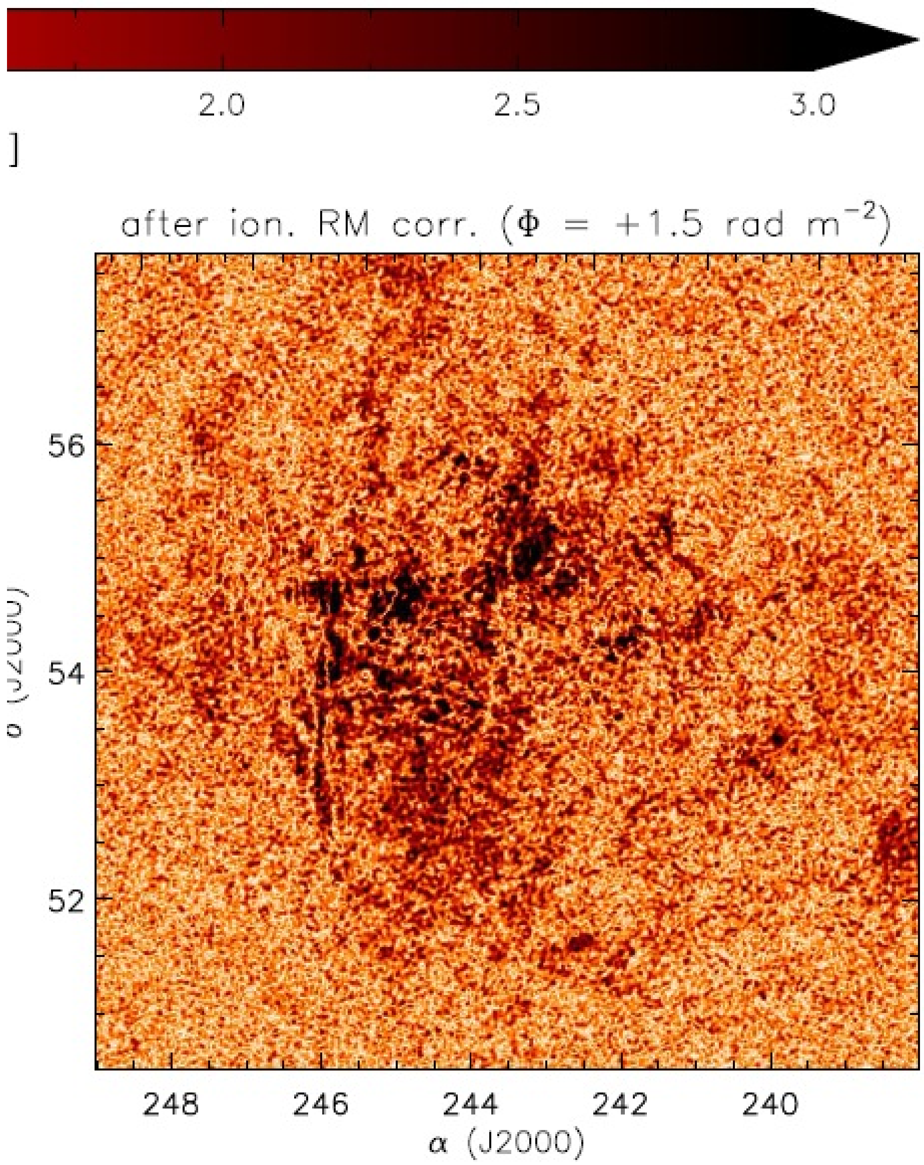
Example Elais Field



V. Jelic

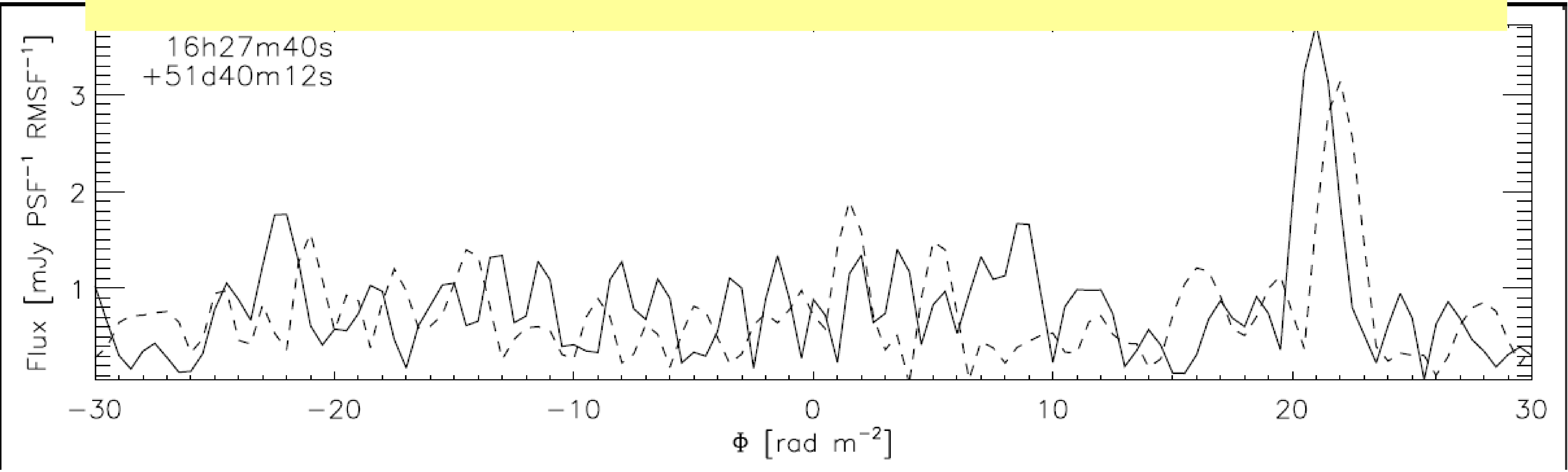
Example Elais Field





V. Jelic

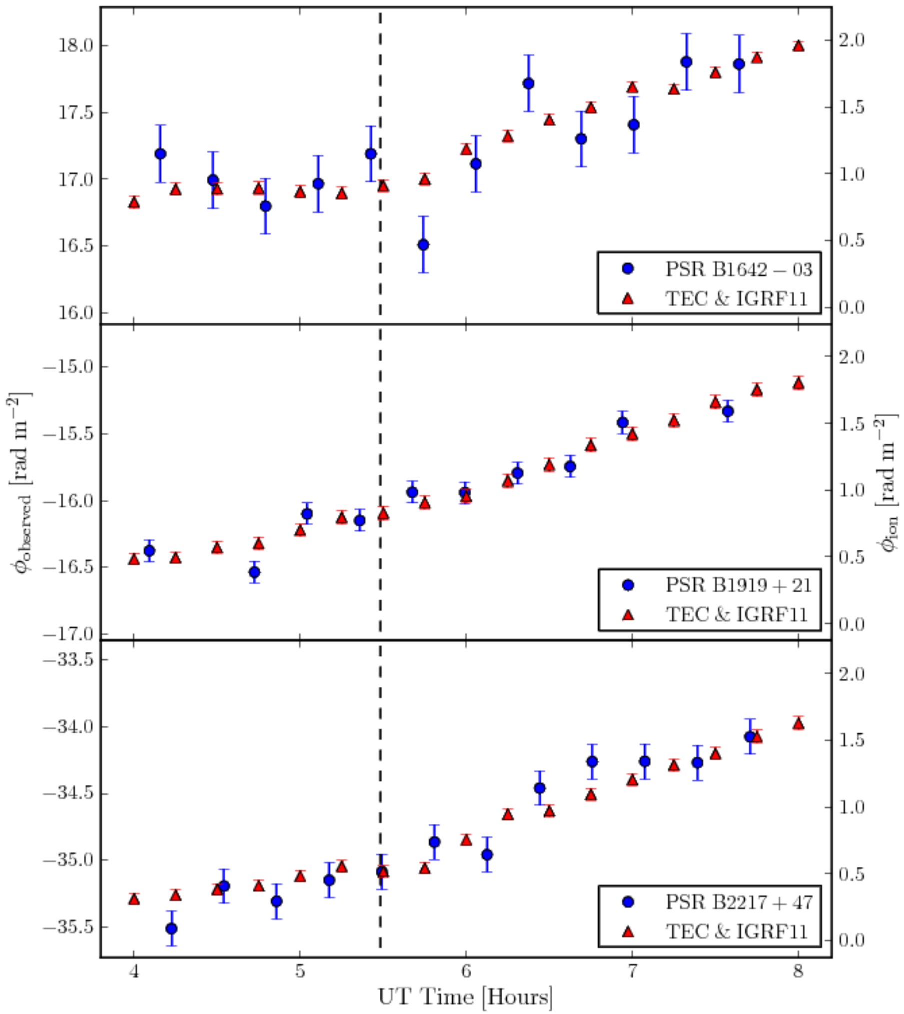
Polarized Flux before (dashed) and after (solid) RM correction



V. Jelic et al (2014)

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

Summary

- Ionosphere is a highly dynamic medium
- radio waves propagating through the ionosphere experience diffractive delay → issue @ low frequencies
- calibration strategies:
  - frequency resolution
  - time resolution
  - direction dependent calibration
- differential Faraday rotation:
  - rotation of unpolarized signal into XY and YX correlations
- absolute Faraday rotation:
  - polarized signals
  - correct using GPS data + Earth Magnetic Model