Getting Ionospheric Information from LOFAR Data

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outline

- LOFAR data → ionospheric information
  - calibration data:
    - phases → diffractive delay
    - (differential) Faraday Rotation
    - structure function
      - diffractive scale
  - image analysis:
    - position shifts of sources → phase gradient over array in different directions

Using Calibration data

- Full Jones solution in direction of bright calibrator
- main effects:
  - delay error: clock ~ ν
  - ionospheric delay: dTEC ~ $1/\nu$
  - Differential Faraday rotation: rotation angle $\alpha \sim 1/\nu^2$

    decompose full Jones solution matrix (per subband)

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

  -

dTEC from calibration phases

$$\begin{pmatrix} G_{xx} & 0 \\ 0 & G_{yy} \end{pmatrix} = \begin{pmatrix} A_{xx}e^{i\phi_{yy}} & 0 \\ 0 & A_{yy}e^{i\phi_{yy}} \end{pmatrix}$$

- separate clock from TEC phases making use of wide bandwidth

$$d\phi = 2\pi \cdot clock \cdot \nu - 8.45 \cdot dTEC/\nu \ \ rad$$

+ 2nd order effects

+ 3rd order TEC ($1/\nu^{3}$, LBA)

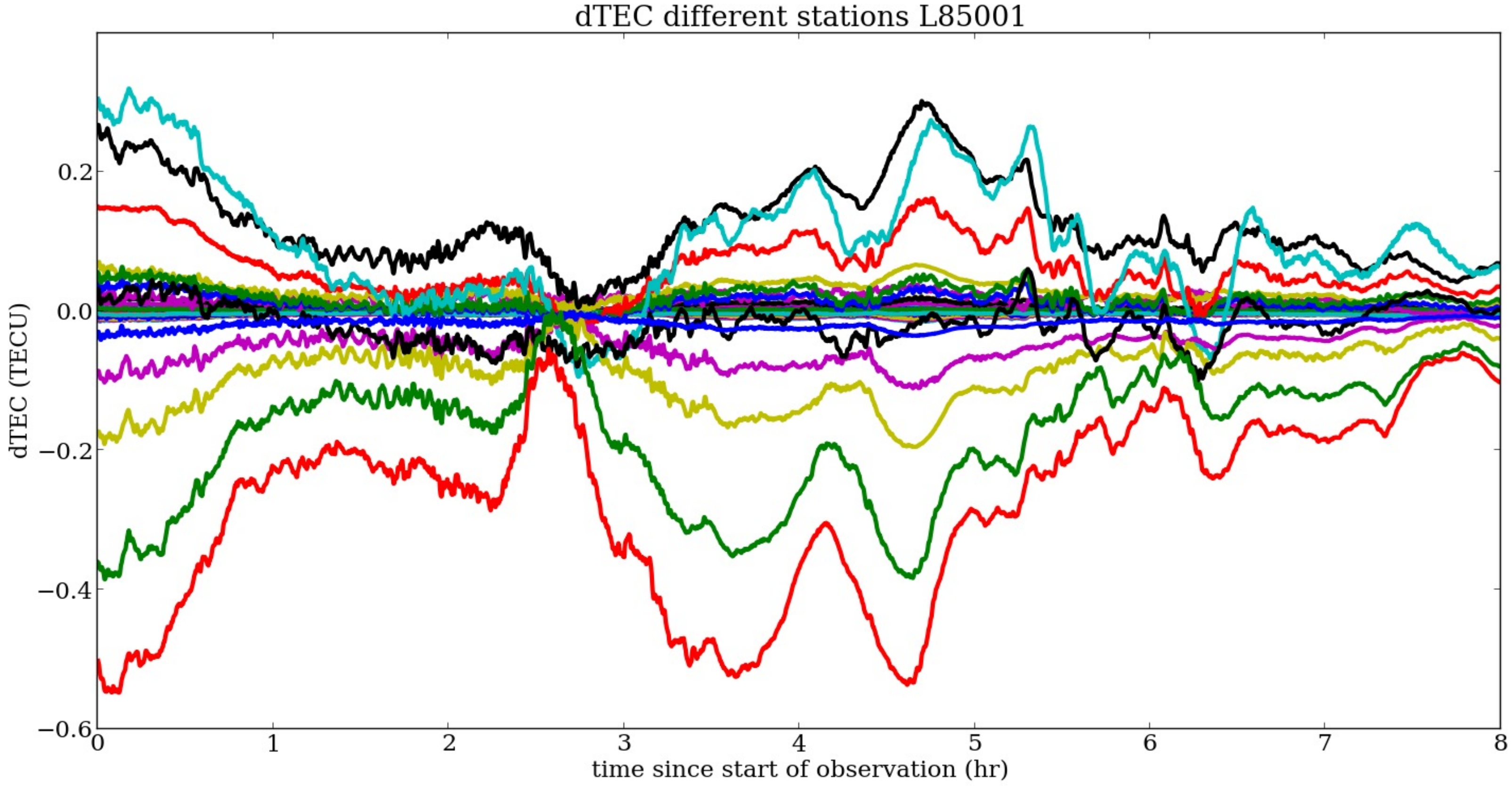
ν in GHz, clock in ns, dTEC in TECU

independently fit each timeslot

example: 10s data, HBA, 3C196

TEC solutions

dTEC solutions versus time, HBA all stations



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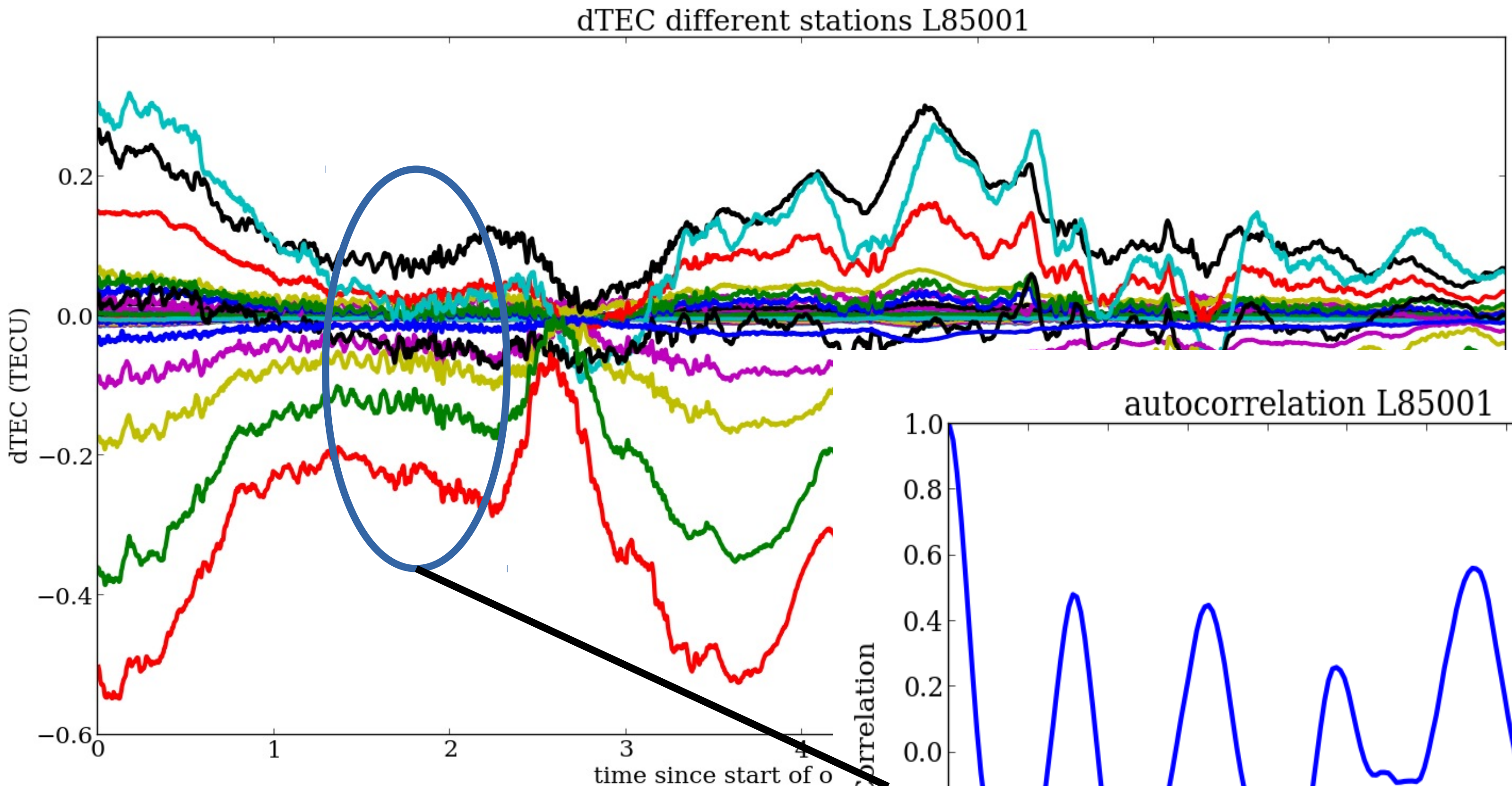
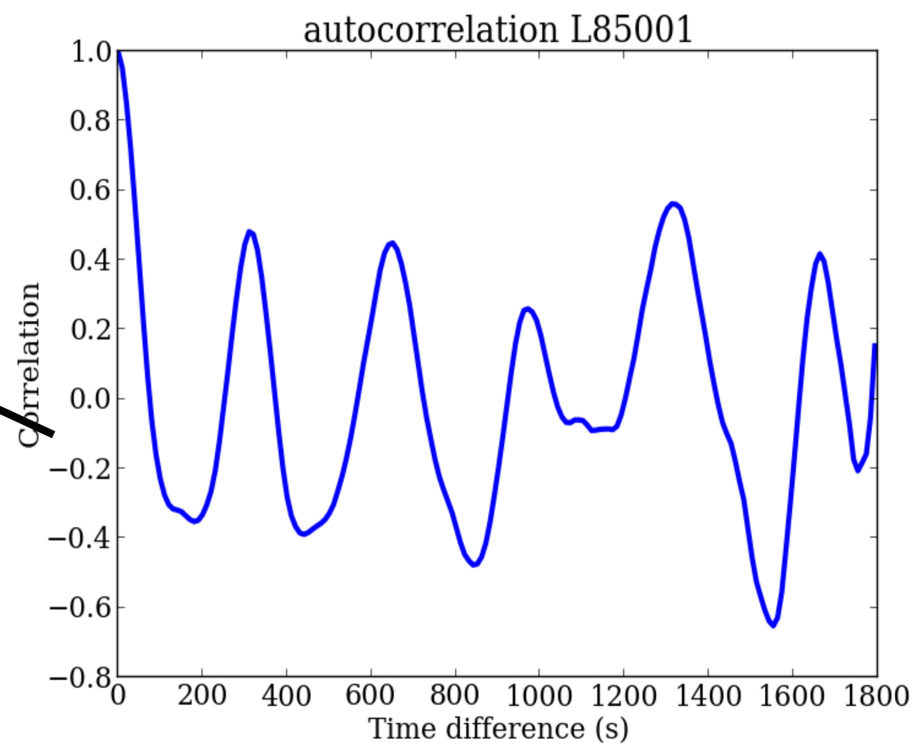




timescale ~5 min

Structure function

Spatial fluctuations:

$D_\varphi(||r_1 - r_2||) = \langle(\varphi_1 - \varphi_2)^2\rangle$

Kolmogorov turbulence, thin layer approximation:

$D_\varphi(\mathbf{r}) = (\mathbf{r} / s_0)^\beta$

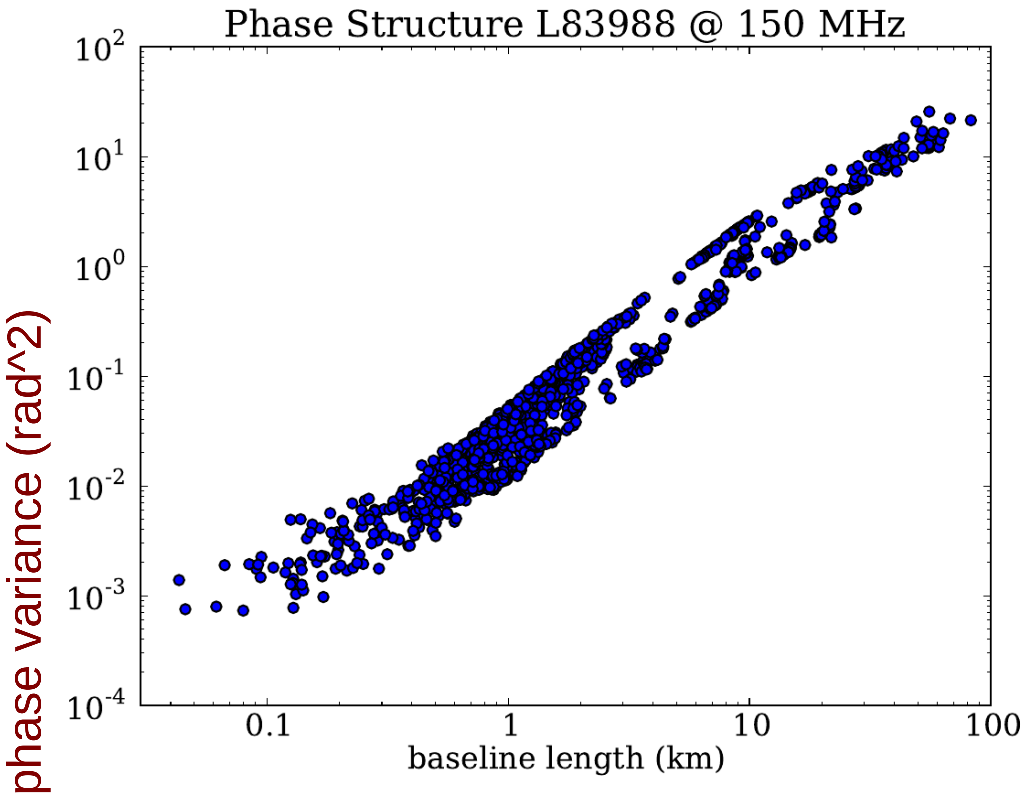
$\beta = 5/3$,

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

variance removes mean → filters global scale



baseline length (km)

Structure function

Spatial fluctuations:

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

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power law over long range of distances ~ 80 km

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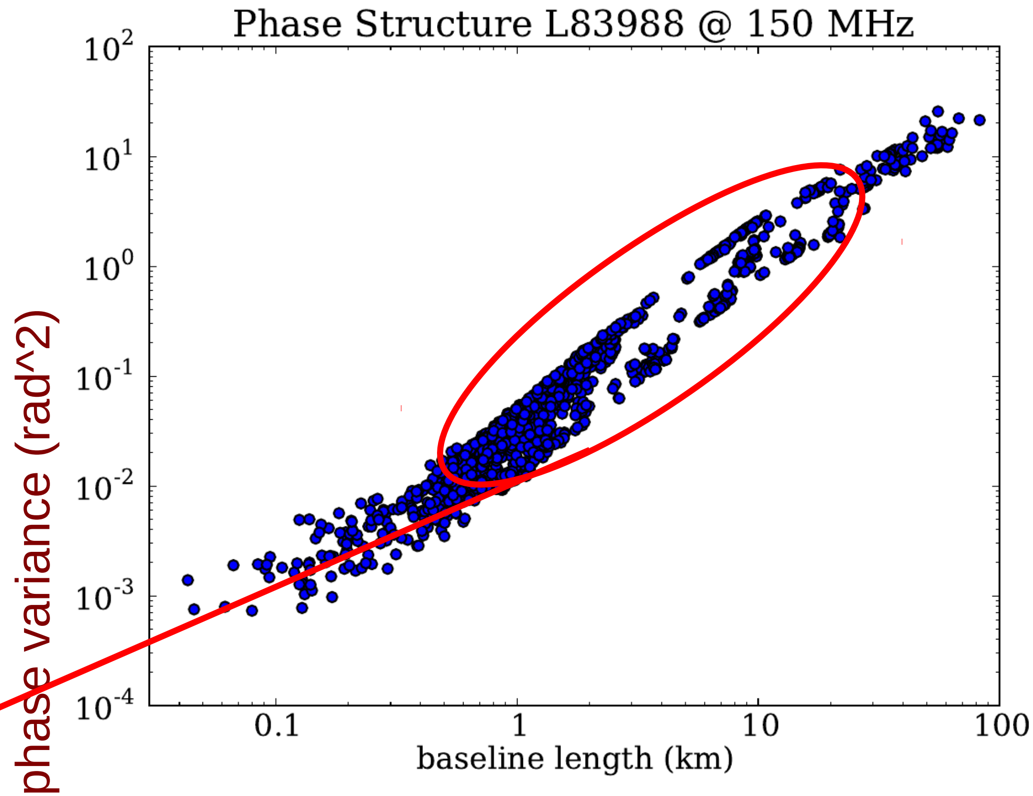

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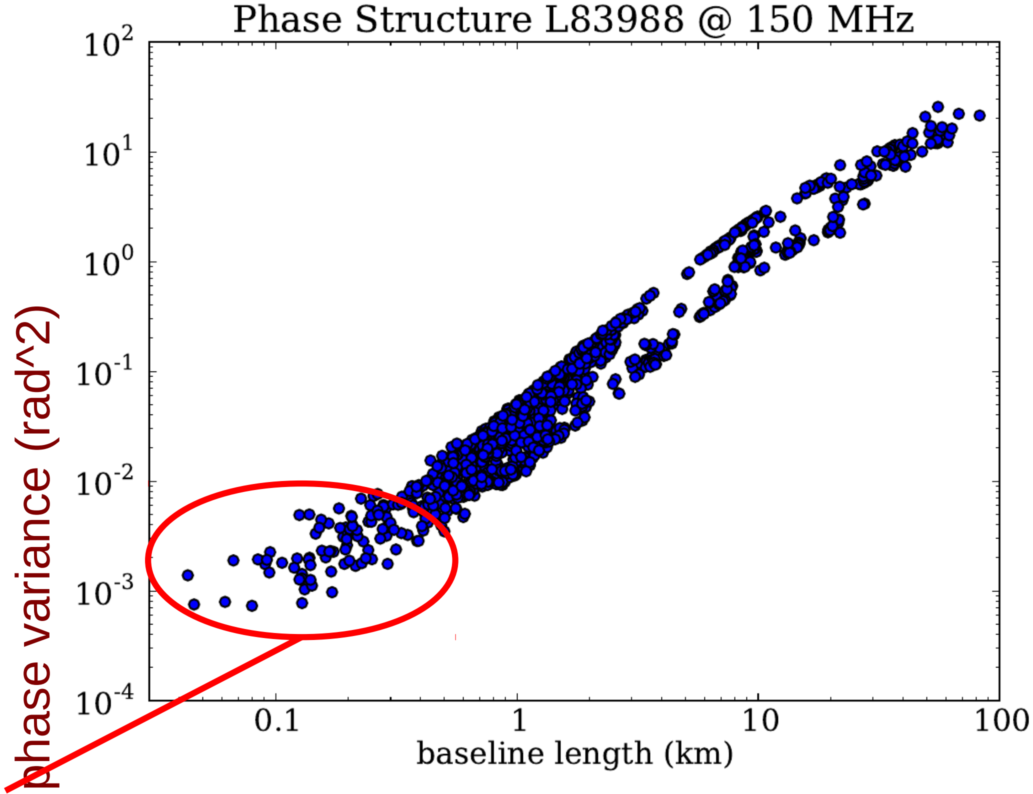

noise floor
~ 1mTEC

baseline length (km)

Structure function

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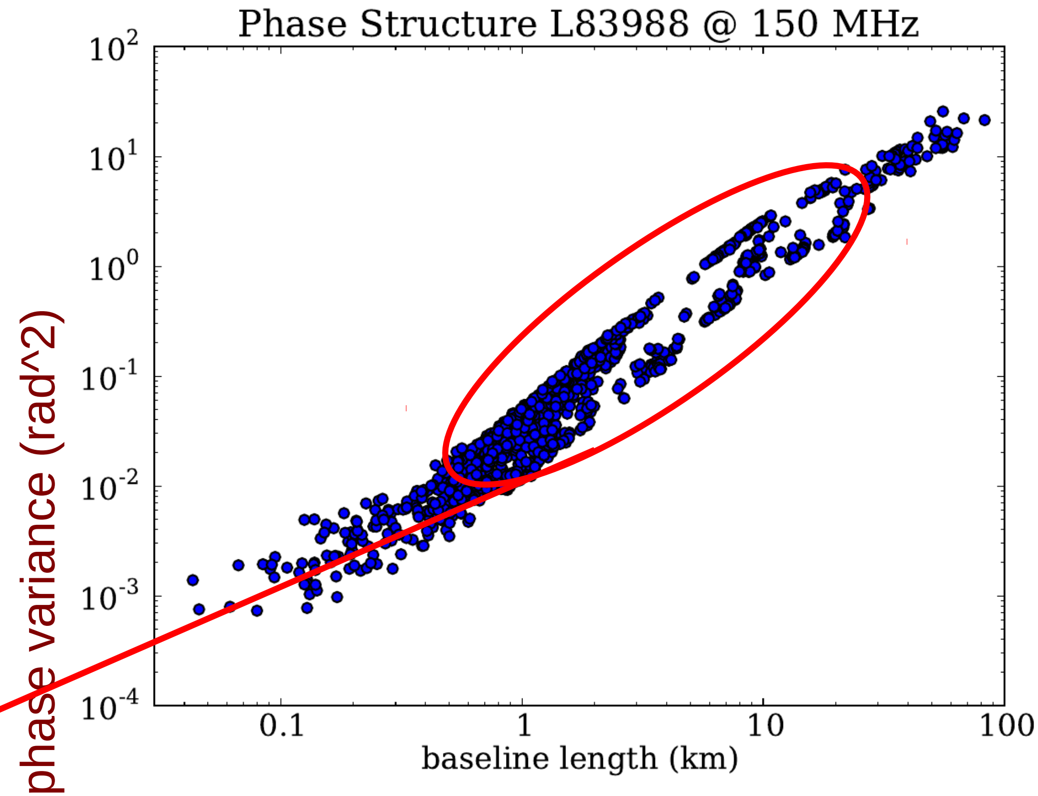
bandlike structure: diffractive scale depends on baseline orientation

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

variance removes mean → filters global scale



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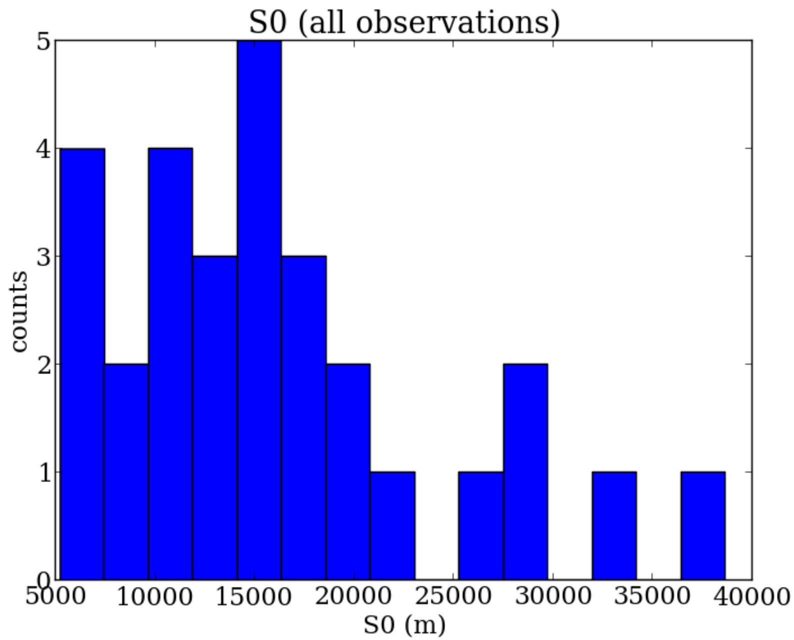
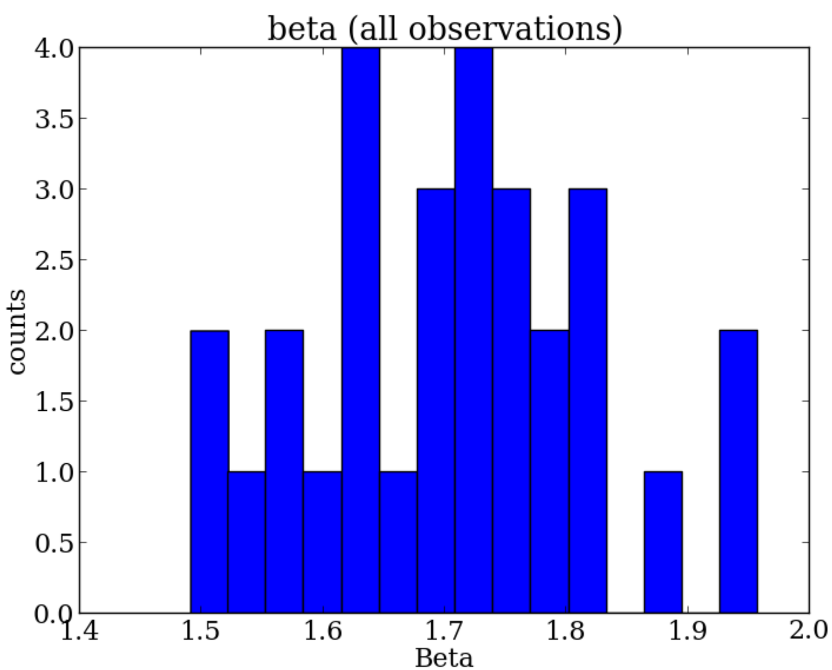


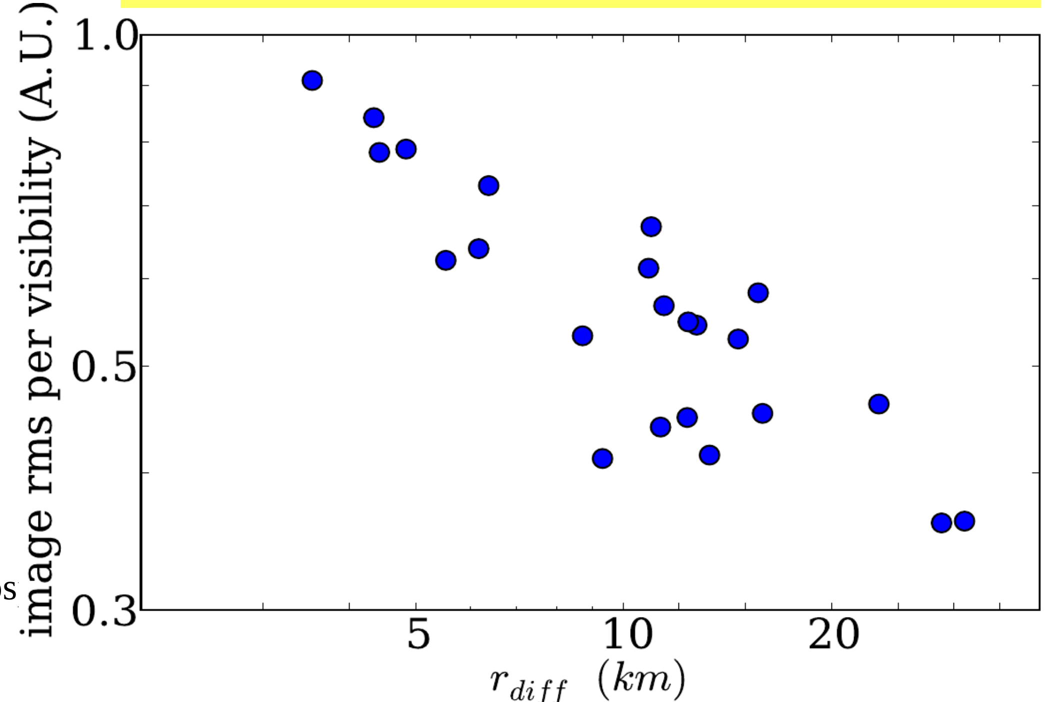
Analyzed 29 nighttime winter observations (2013/2013)

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

- scintillation conditions S_0<2km

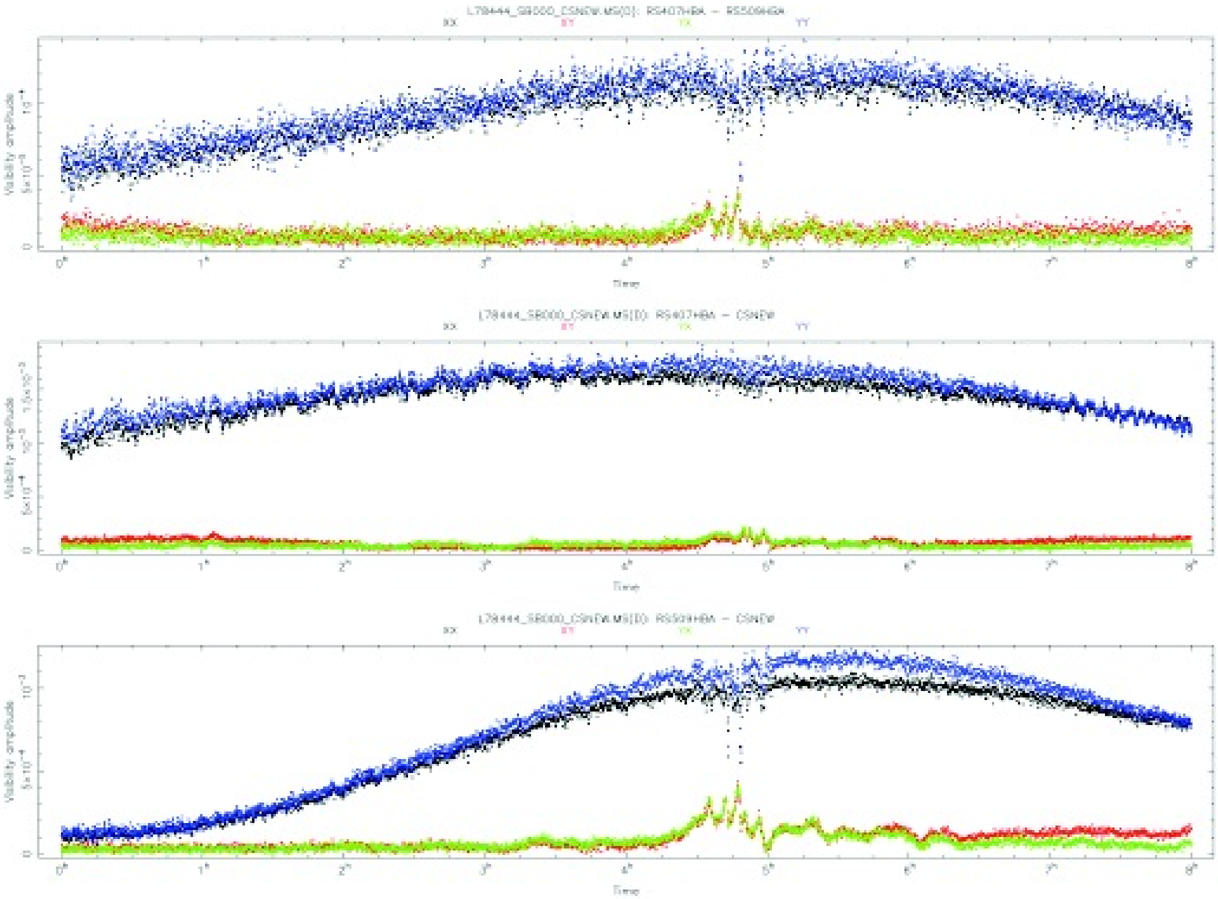


Correlation image noise S_0



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

$$\begin{pmatrix} cos(\alpha) & sin(\alpha) \\ -sin(\alpha) & cos(\alpha) \end{pmatrix}$$

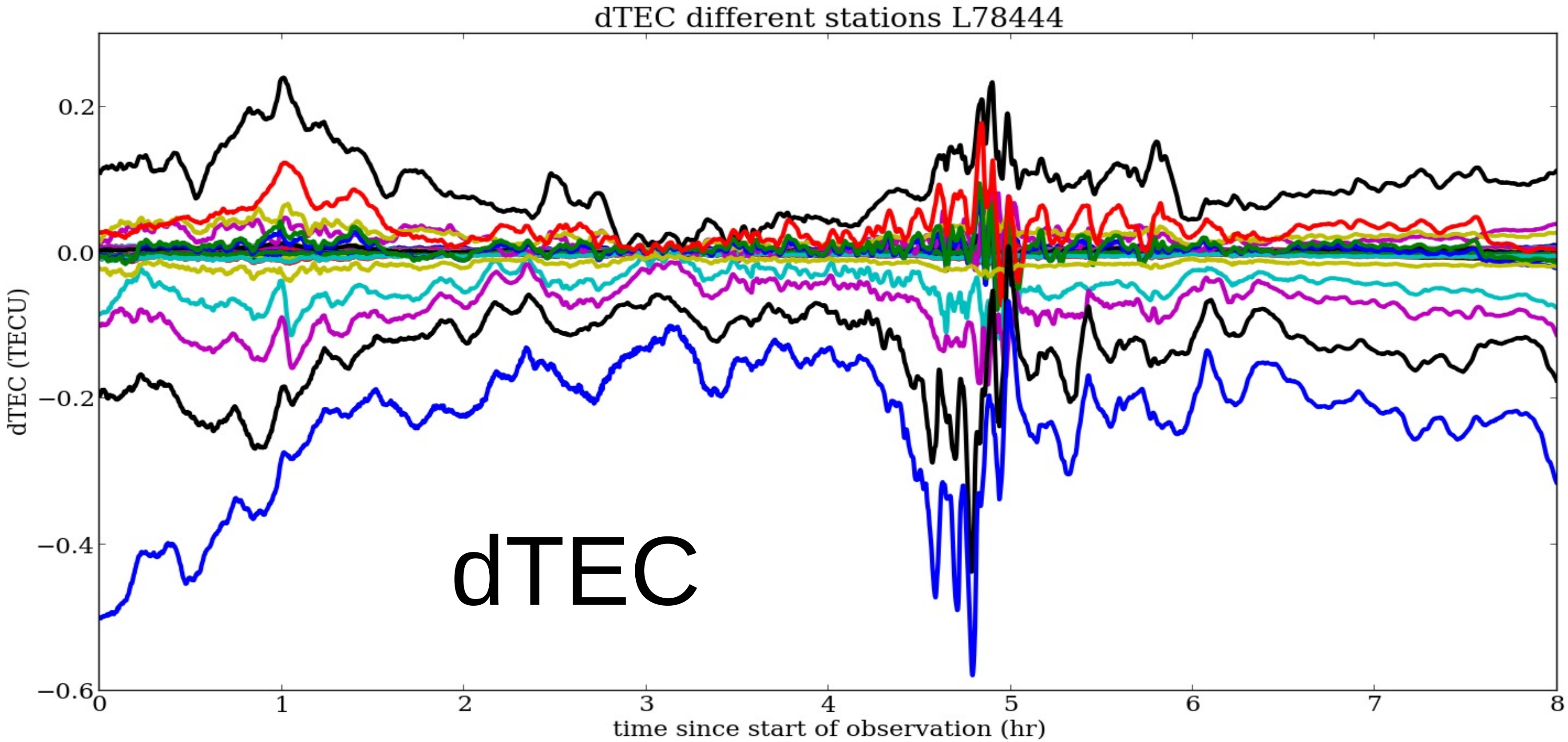


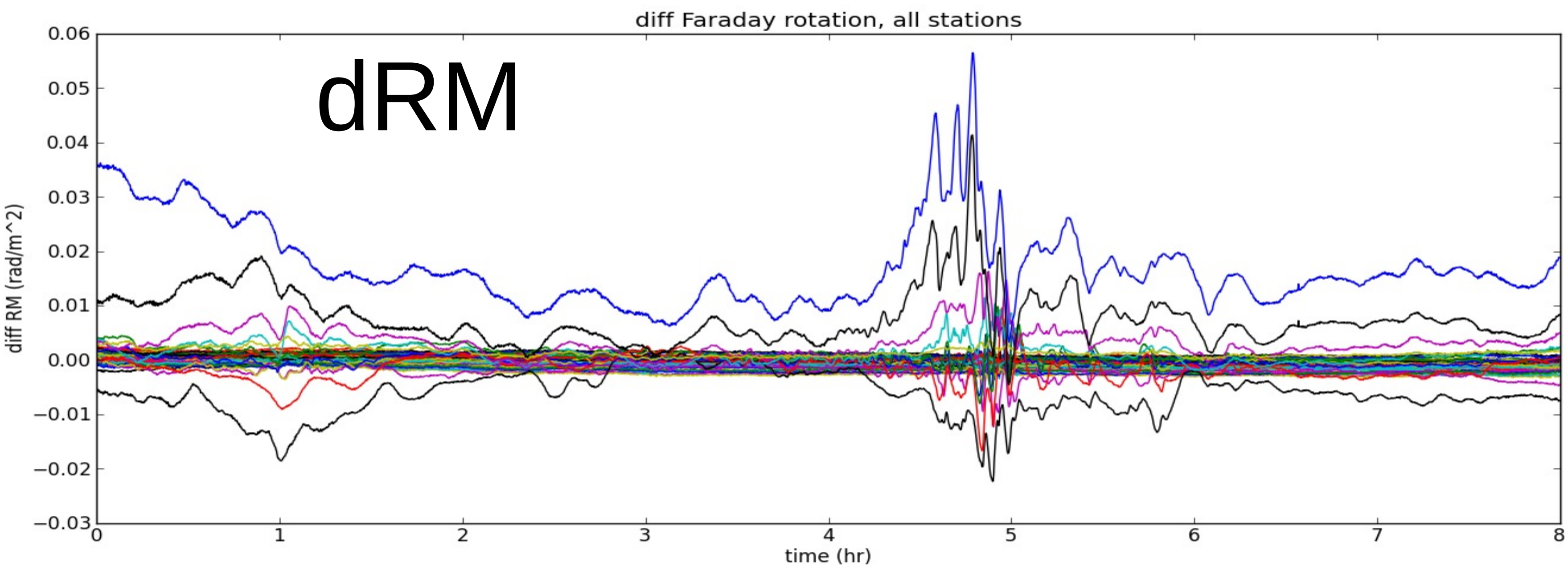
Rotation of the signal from XX,YY to XY,YX due to different Faraday rotation angles for different antennas

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

fit RM (α~RM/ν^2) for every timeslot

10s, HBA, 3C196


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

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

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

In principle possible to extract absolute TEC via:

$$\Delta RM_{ij} \sim TEC_i \cdot B_{||i} - TEC_j \cdot B_{||j}$$

$$= (TEC_i - TEC_j) \cdot B_{||j} + TEC_i \cdot (B_{||i} - B_{||j})$$

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

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from calibration phases

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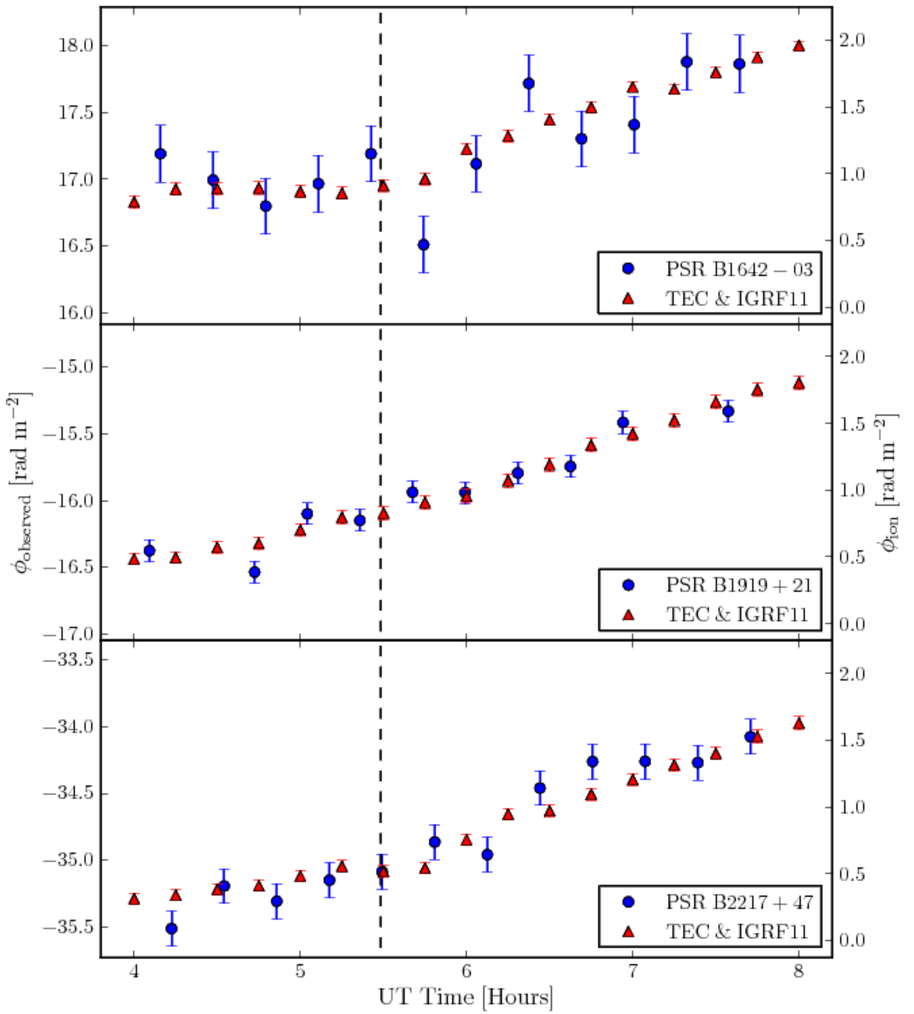
In practice large uncertainty on $\Delta B_{||}$

from models (WMM)

TEC using polarized source

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

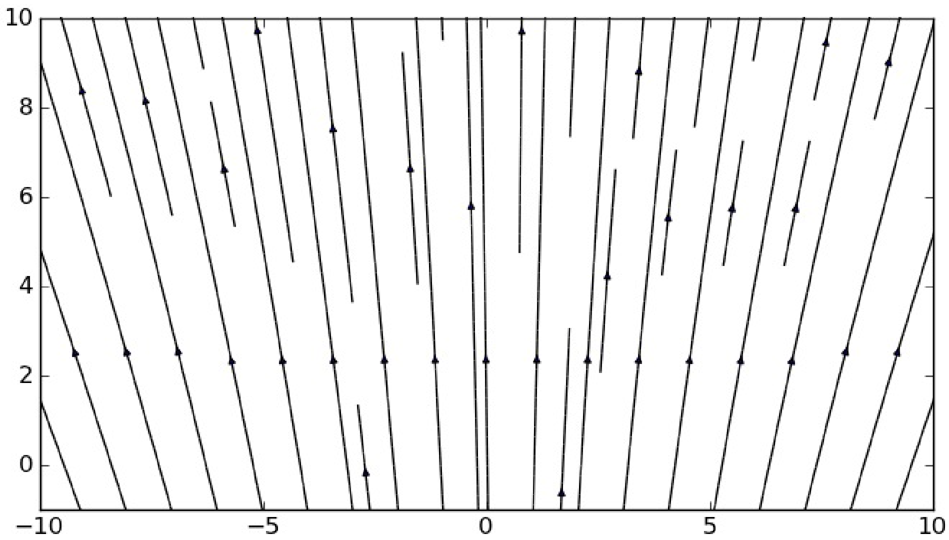
Brentjens et al (in preparation)

Field Aligned Structure

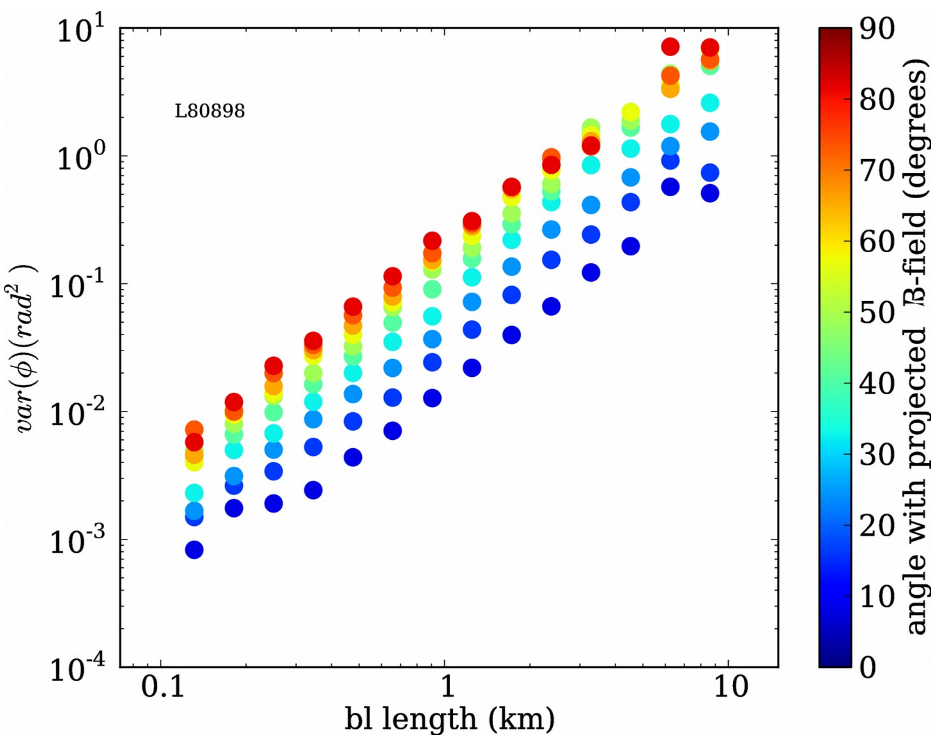
bandlike structure → orientation of the baseline

Earth magnetic field aligned?

projected field lines along LOS single ionospheric height



Earth magnetic field lines along viewing angle (NS/EW beam angle, zenith = 0,0)



perspective view → time dependent orientation
bin data in according to angle wrst projected field lines
field aligned structure observed in ~ 50 % of the observations

Earth magnetic field : WMM

Imaging Structures

ionosphere: linear gradient → position shift

higher order term → distorted source

use only short baselines: CS only

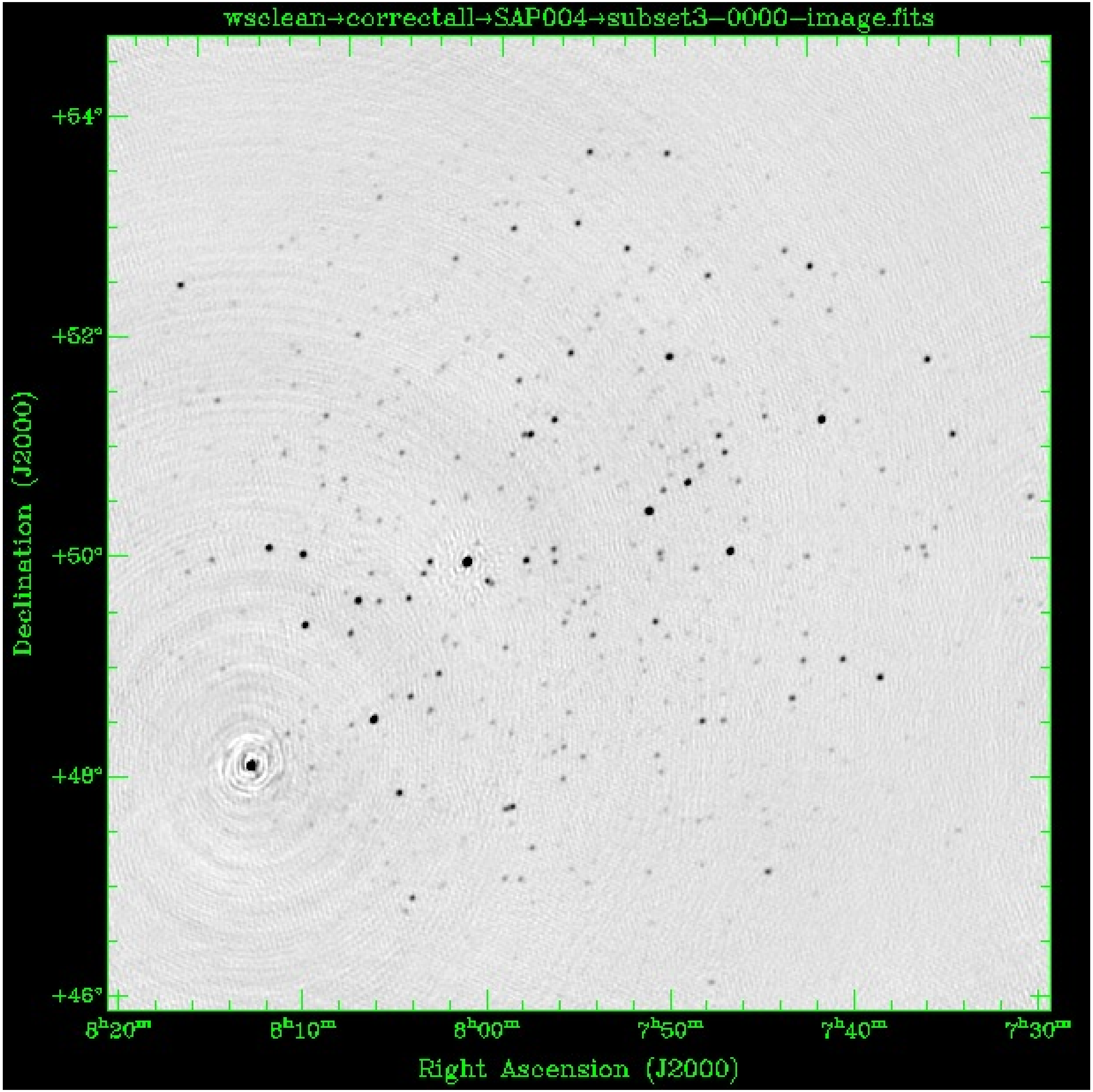
$\Delta\theta = C/\nu^2 \, \nabla_\perp \, TEC$

I. correct all with calibration gains of central field

- subtract 3C196 from central field

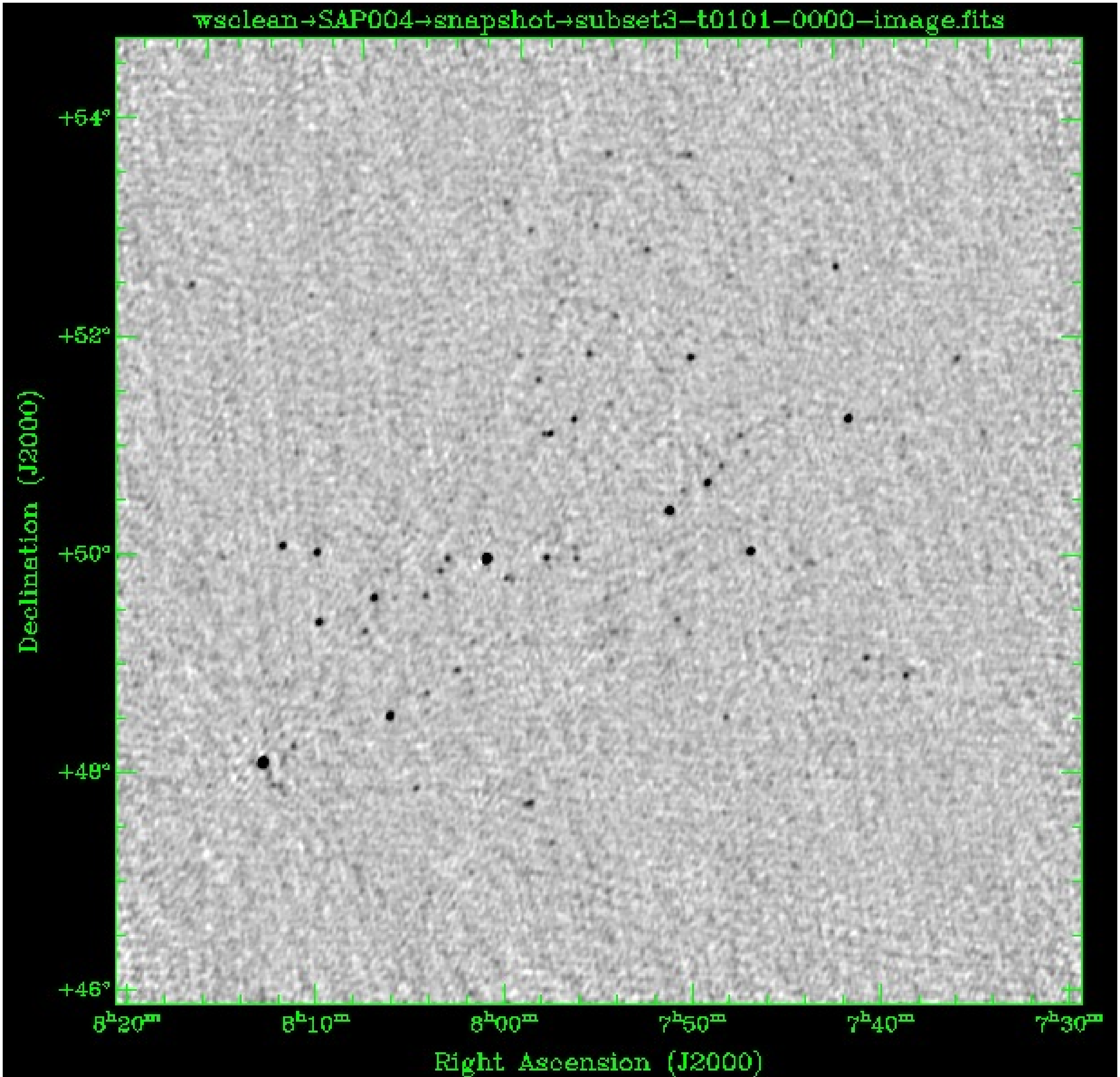
II. image corrected data (wsclean) → extract sources for reference (pybdsm)

III. remove TEC-phases from calibration gains, correct all



wsclean: combine SBs to create 3 images with different frequency

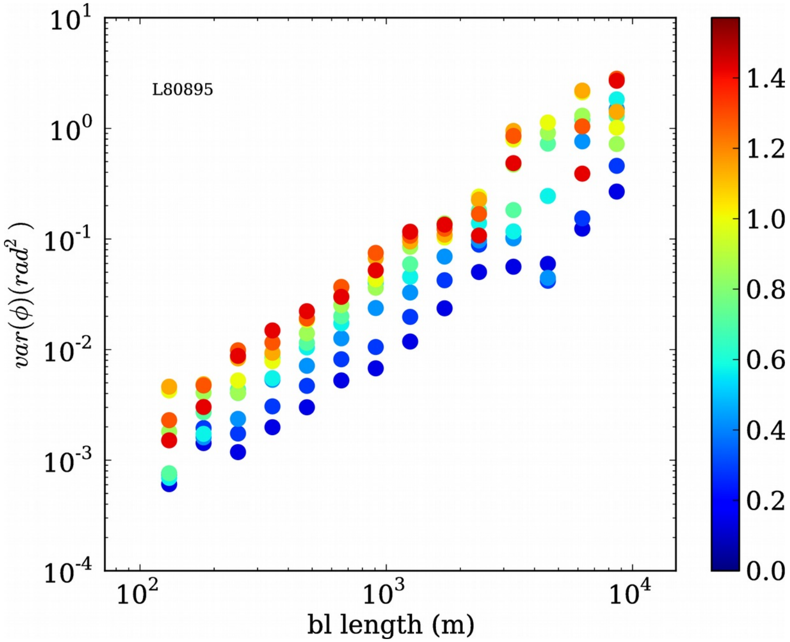
~ 4 SB each, due to missing files

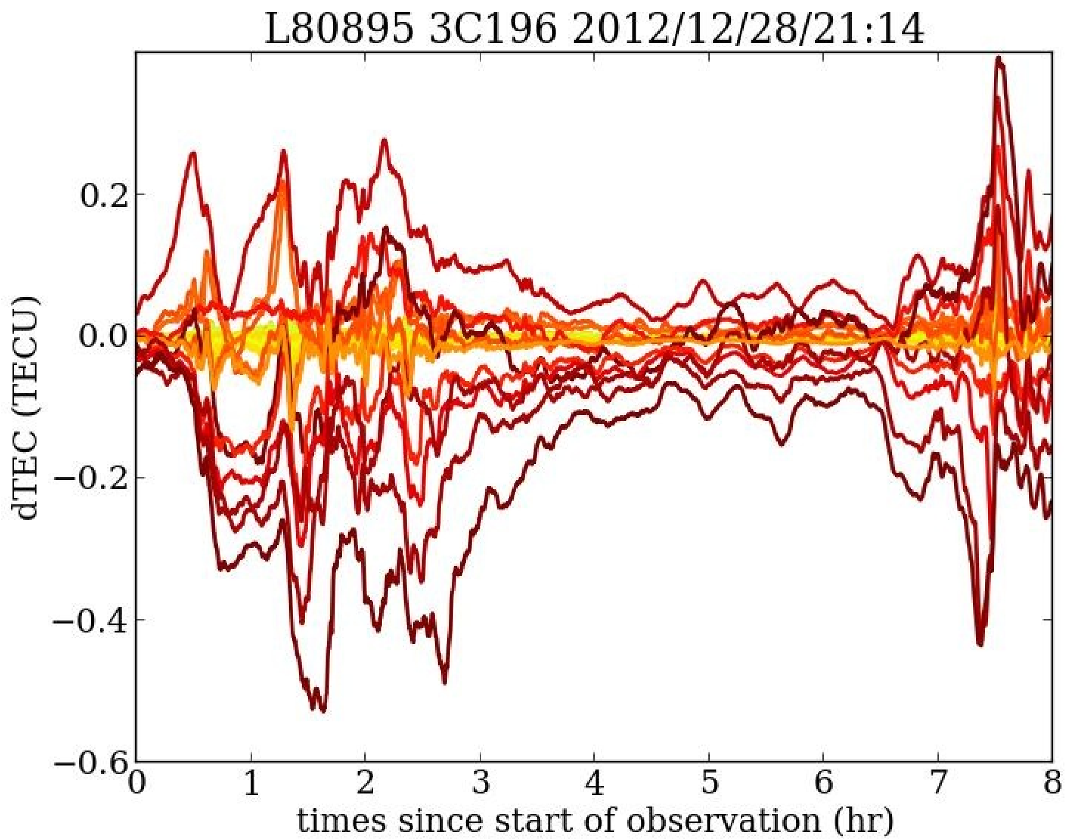


1 minute snapshot image

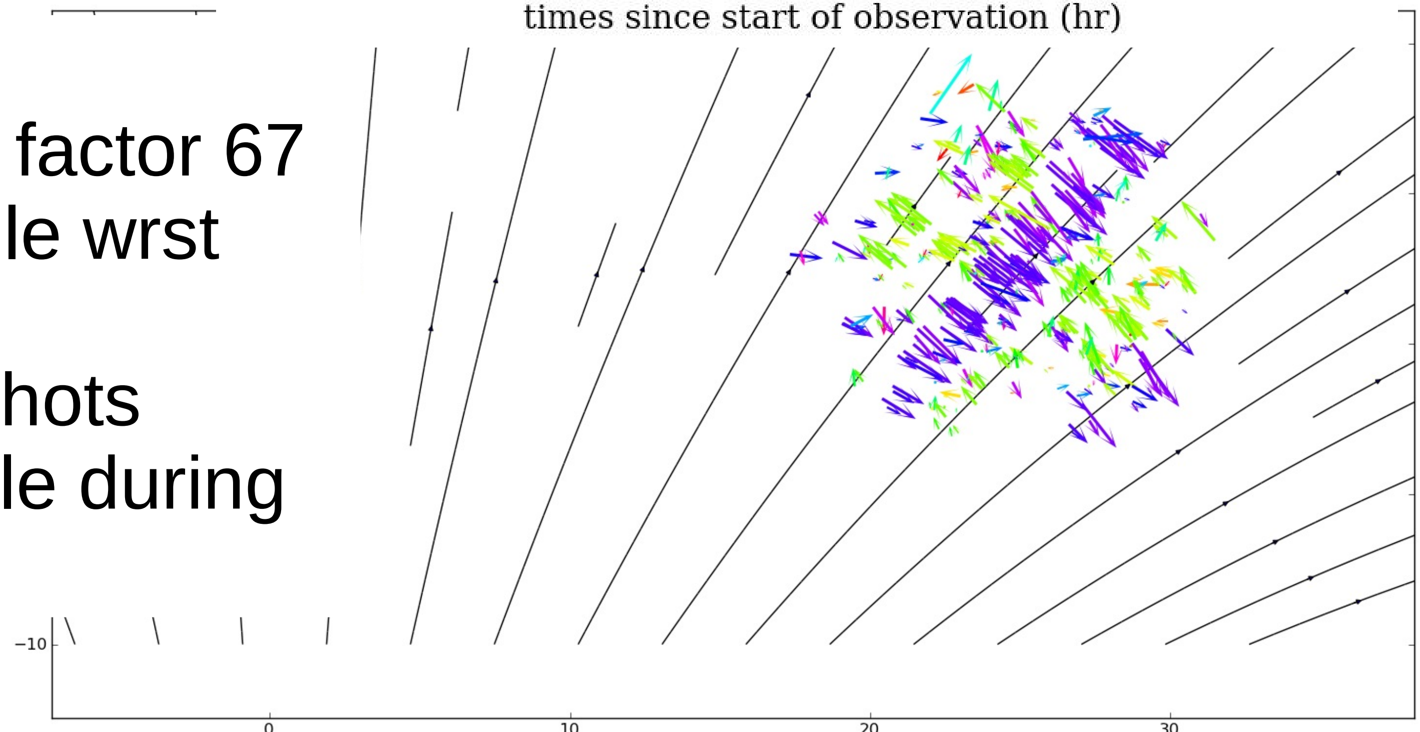
SAP004

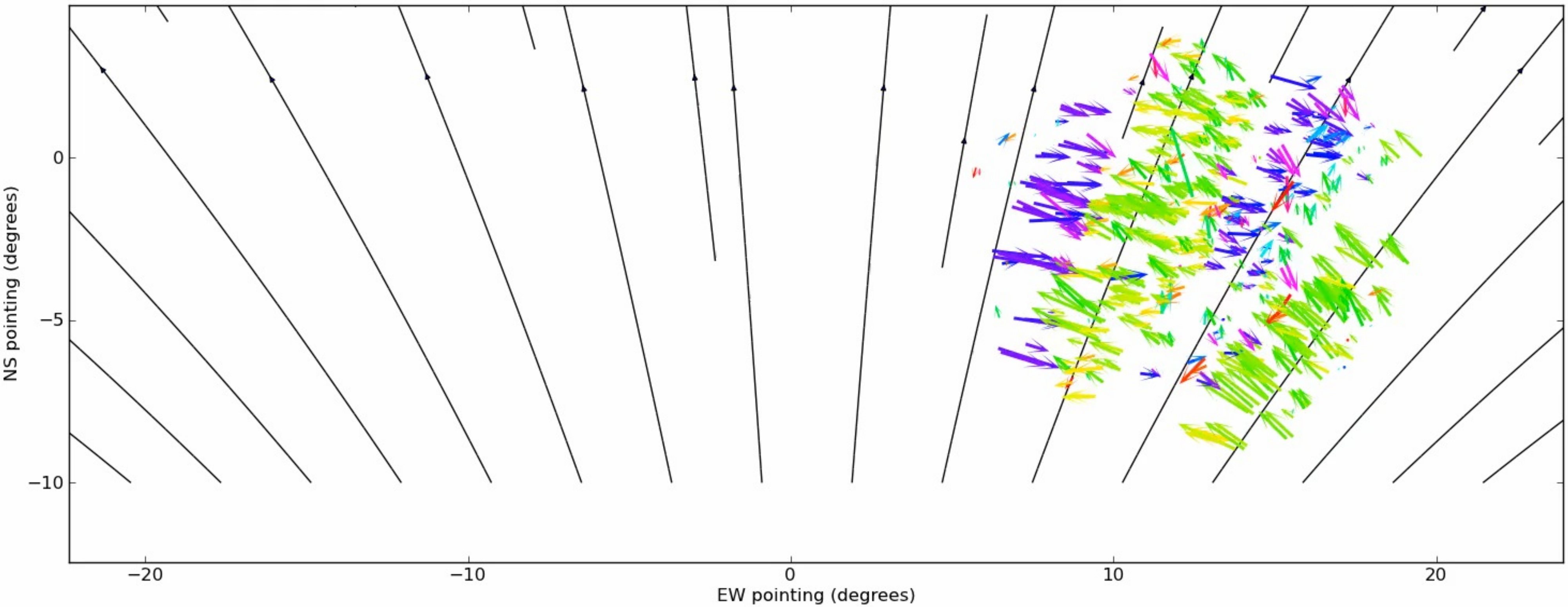
L86767





L80895
arrows scaled with factor 67
color indicates angle wrst
local field lines
2 (1 minute) snapshots
structure only visible during
first hour





0
−5
−10
NS pointing (degrees)
−20
−10
0
10
20
EW pointing (degrees)

Summary

- methods to gather info on ionosphere:
  - calibration parameters:
    - dTEC
    - dRM
    - 3rd order effects
  - structure functions:
    - diffractive scale measure of “wildness” of ionosphere
  - image analysis:
    - source positions → instantaneous image of small scale TEC gradients
  - absolute TEC:
    - using Faraday rotation of polarised source
    - using differential Faraday rotation/dTEC and B-field

Extra

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:

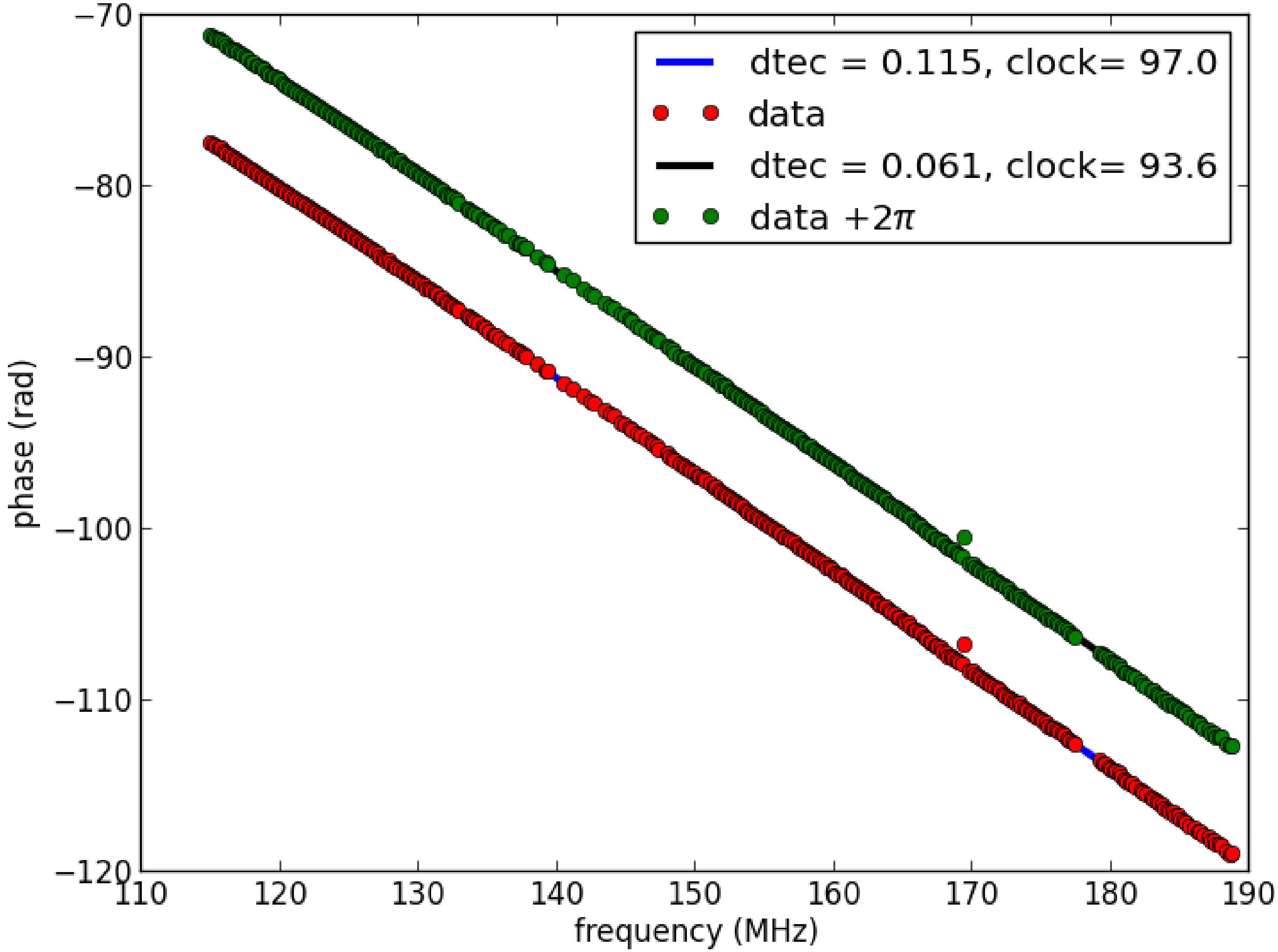
if φ is a solution so is φ+2π

corresponds to fixed offset in clock and TEC

Clock/TEC separation

Start from selfcal phases over wide frequency range.

Fit for



Compl

i

c

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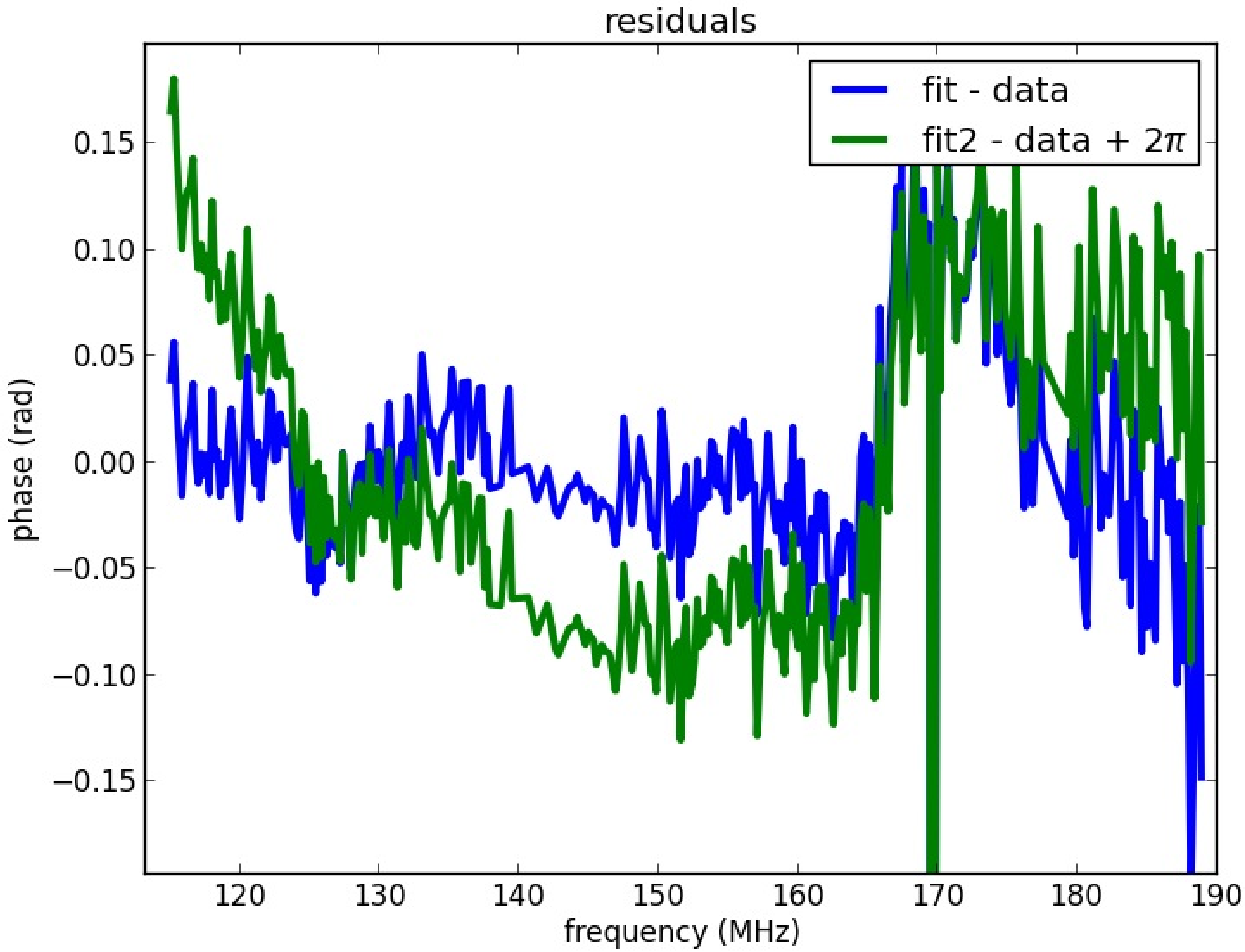
Start from selfcal phases over wide frequency range.

Fit for



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Clock/TEC separation

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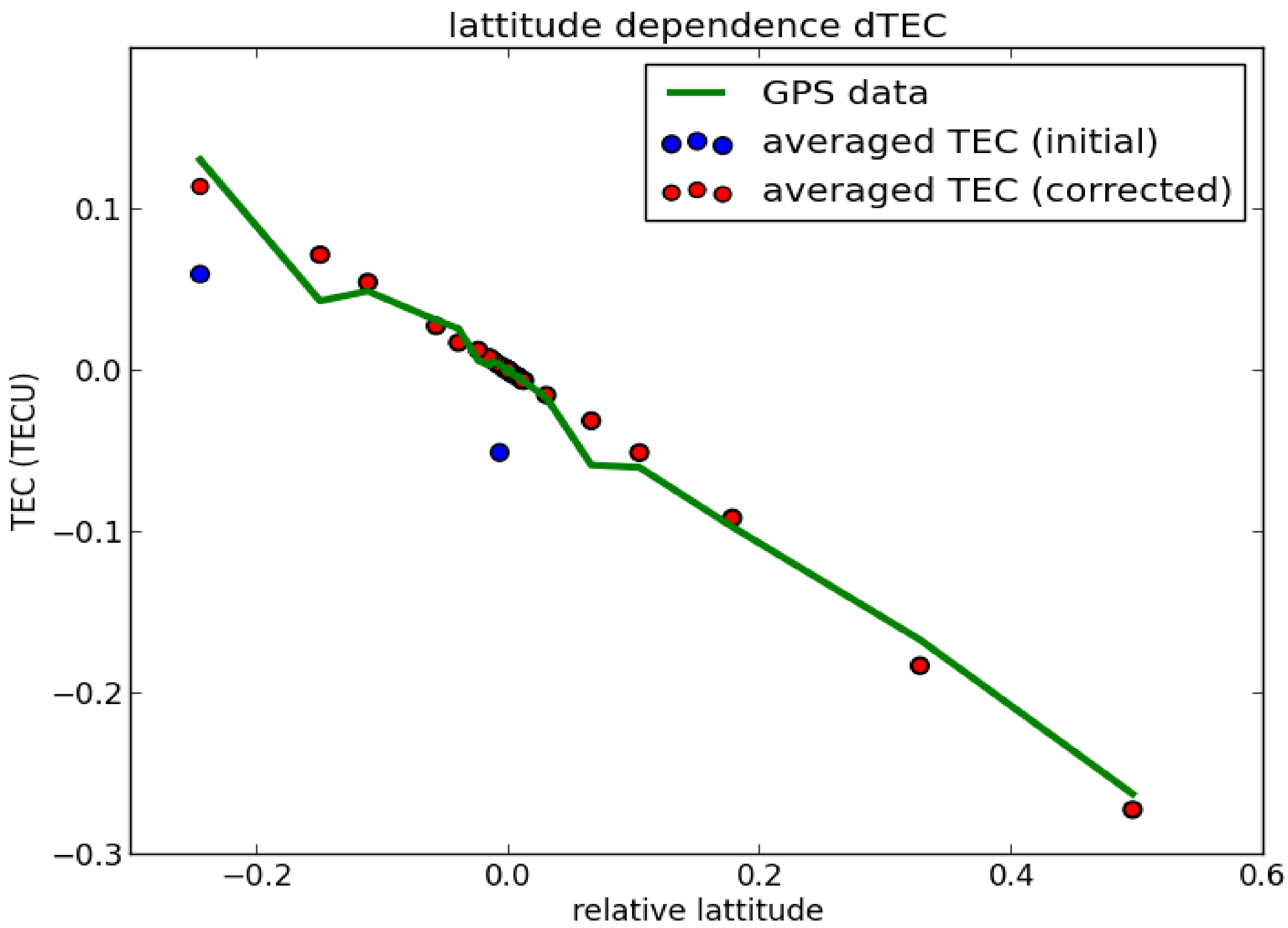
Fit



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wit

Correct remaining wraps by inspecting residuals/spatial correlation