Probing Ionospheric Structure Using LOFAR

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LOFAR

ASTRON

NWO
Netherlands Organisation for Scientific Research

erc
European Research Council
Established by the European Commission
Supporting top researchers from anywhere in the world

Outline

- Goal: accumulate many nights of data, remove foreground with best possible calibration
- Ionospheric errors: 1 of the main issues of calibration
- In the process of removing those errors you gain information about the ionospheric structure
- Ionospheric structure functions:
  - side product of calibration
  - useful in estimating remaining phase errors → rms noise
- Investigate night to night structure variations
- Anisotropy due to Earth magnetic field

Observations

3C196 HBA

27 observations winter 2012/2013

2 observations winter 2013/2014

6hr/8hr nighttime

all observations aligned in time around transit

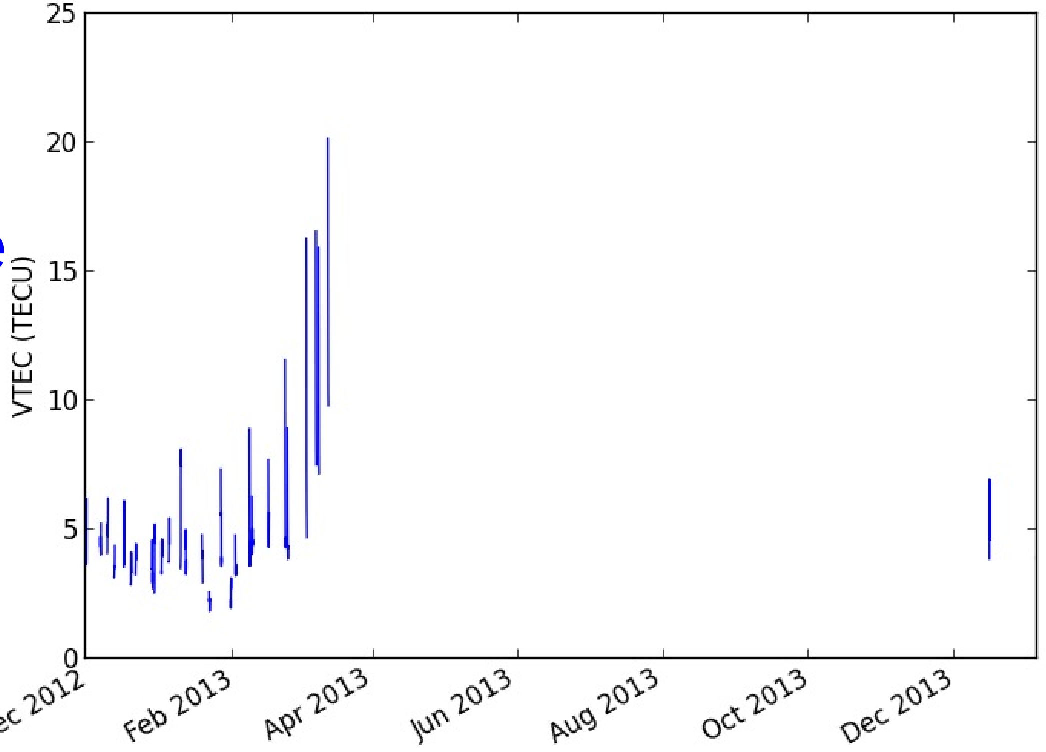
30 SB distributed over 115-175 MHz

1 channel per SB

time resolution: 10s

VTEC @ LOFAR-CORE

(IONEX data from CODE)



Extracting TEC information

- Start from calibration phases:
  - 3C196 dominant:
    - single (4 component) source in skymodel
    - calibrate full polarization matrix gains with 10s time resolution
    - separate in differential Faraday rotation angle + diagonal amplitude + phases
- phases errors:
  - clock/cable length
  - ionospheric delay
  - cable reflections
  - beammodel errors
  - skymodel

Clock/TEC separation

separate clock phases
from ionospheric effects:

use large bandwidth

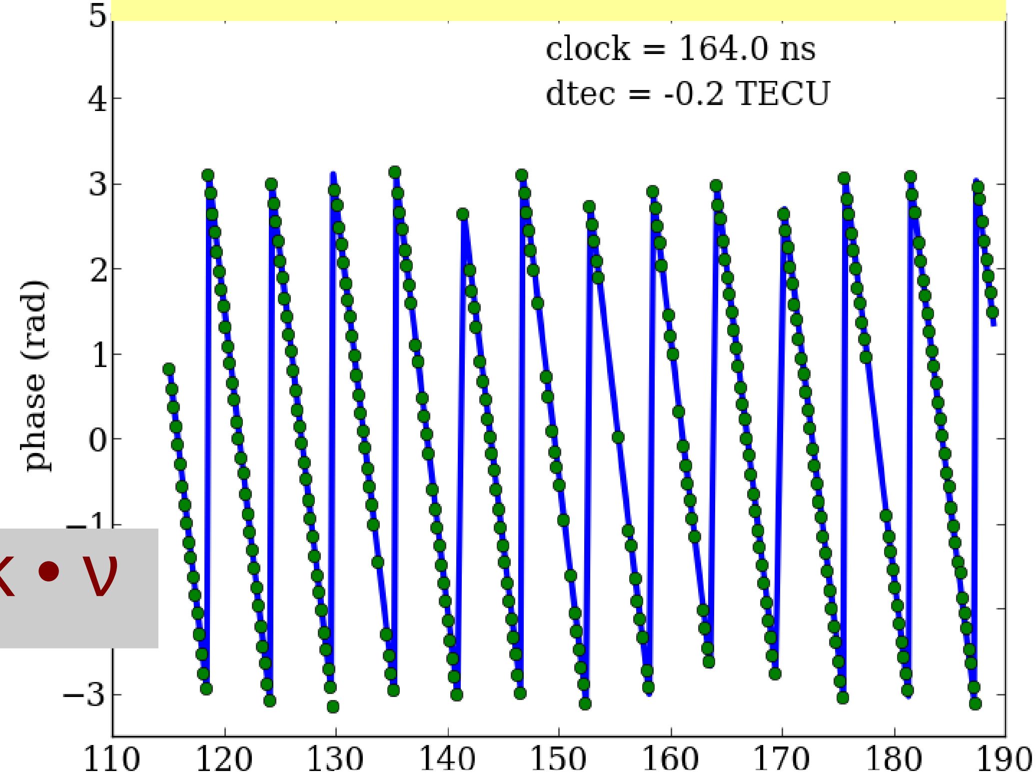
+

different frequency
behaviour:

$$d\varphi = c_1 \cdot dTEC/\nu + c_2 \cdot dclock \cdot \nu$$

dφ vs frequency 1 timeslot

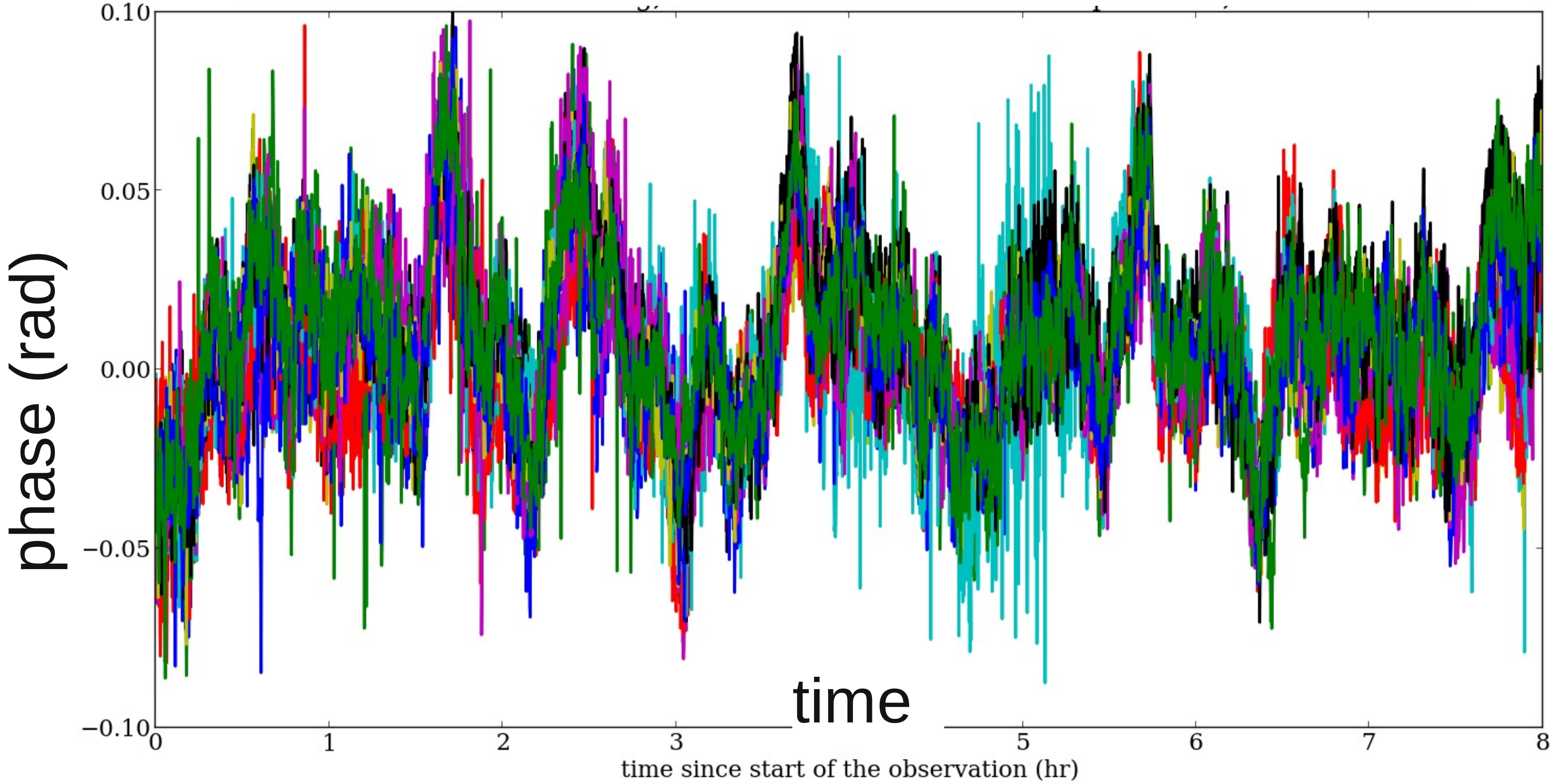
~40 km baseline



frequency (MHz)

interferometer: only sensitive to TEC differences

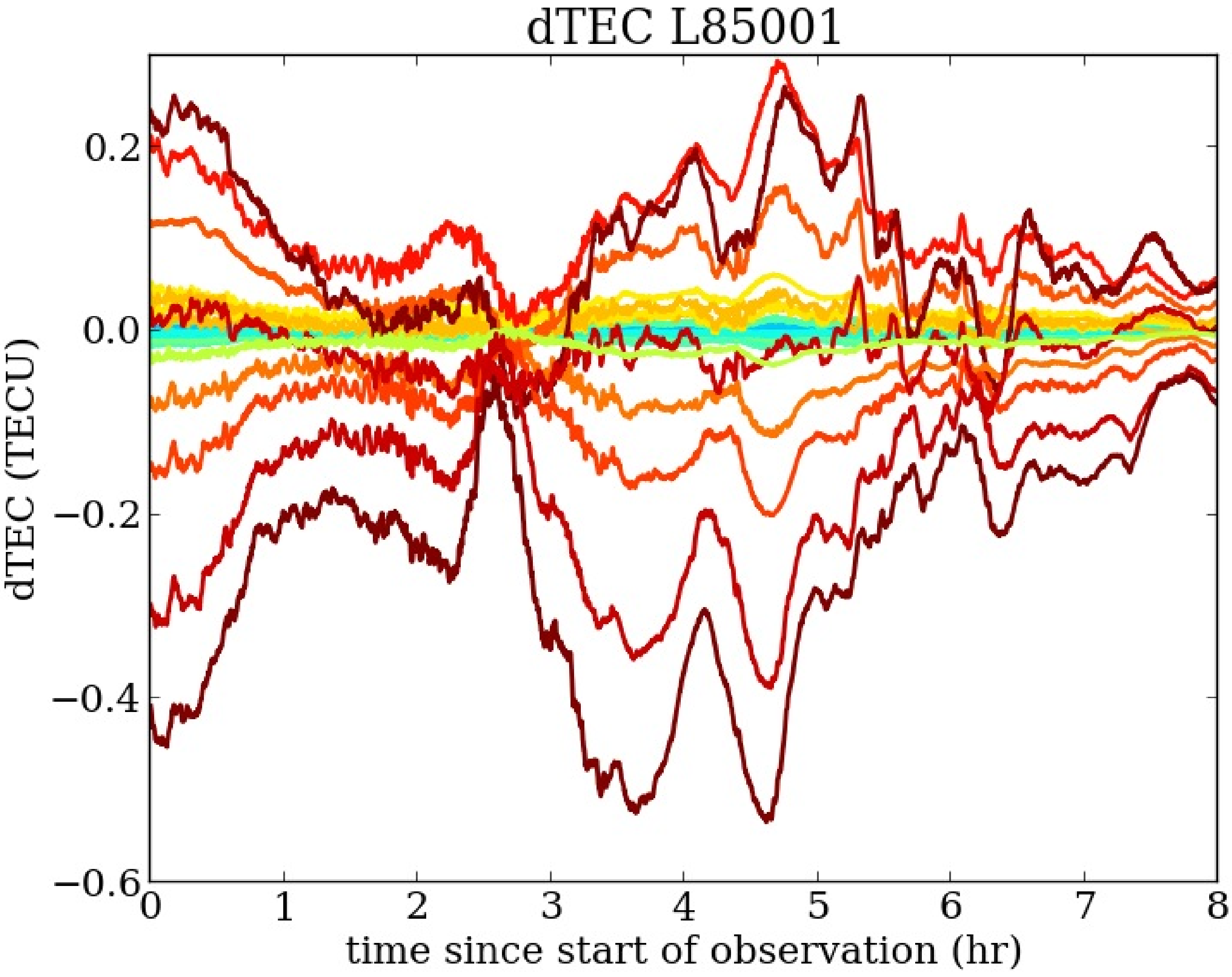
residuals of clock/tec fit versus time (CS017-CS001)
ignoring other phase effects
1 baseline (~1km), 1 channel
different colors: different observations
all observations aligned in SRT



correlation between residuals: beam-/skymodel effects
ignoring rest of the sky mainly source of error @ short baselines

dTEC solutions versus time, all stations (reference station: CS001)

color coding according to baseline length



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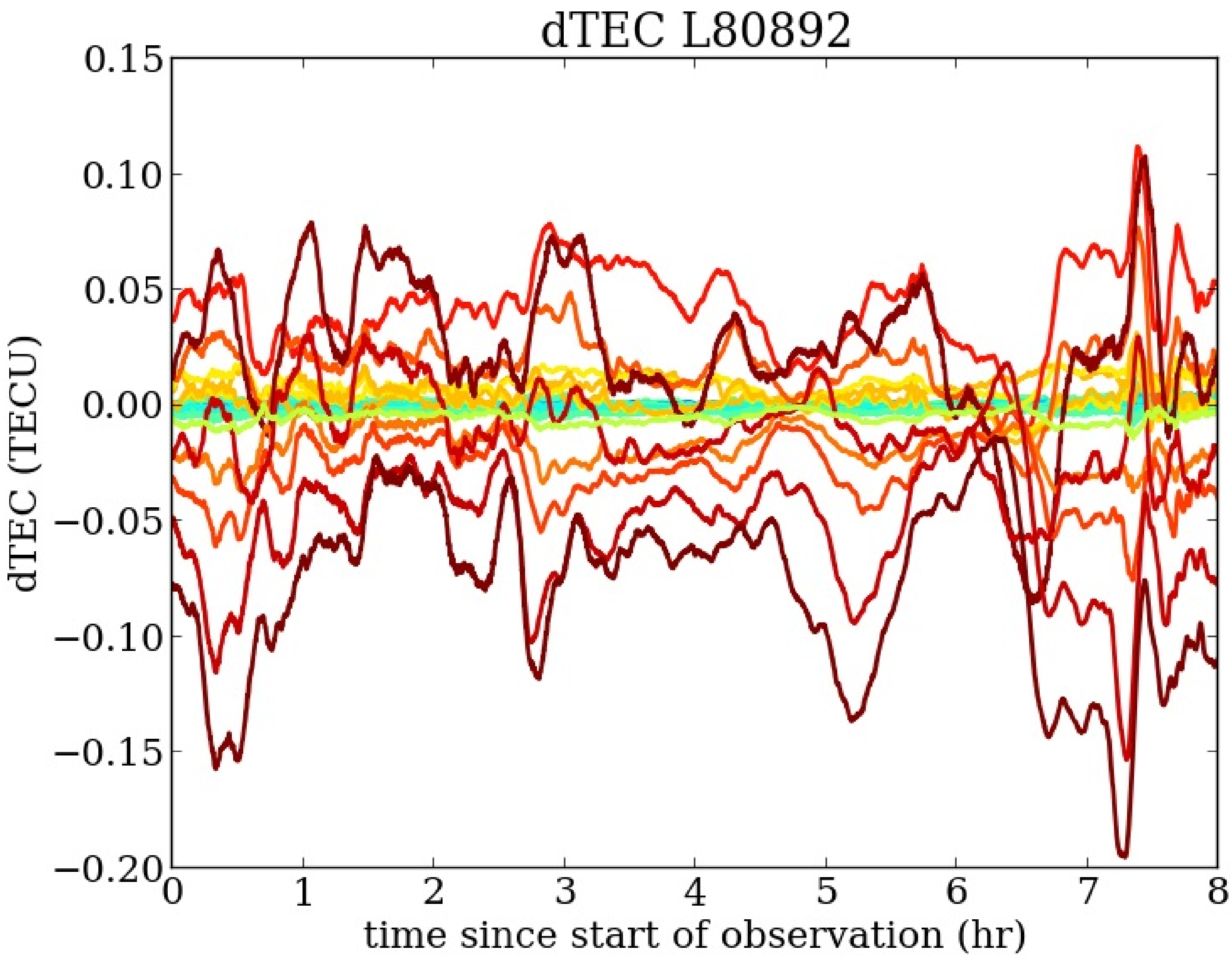

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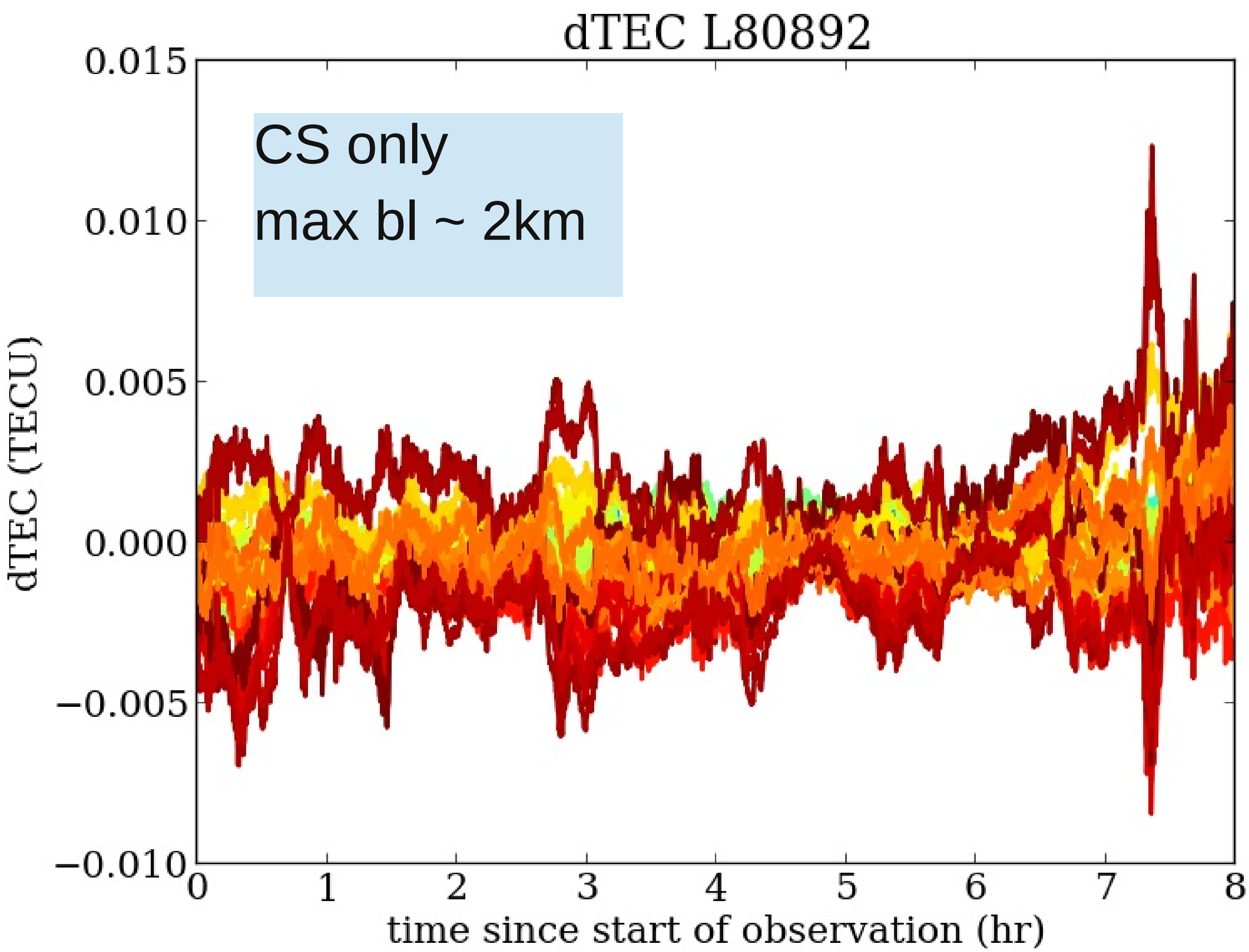

Ionospheric information from dTEC solutions

phase structure: convert dTEC to dφ @150 MHz

calculate time variance of dφ per baseline

Kolmogorov turbulence: $<\varphi>=(S/S_0)^{\beta}$,

$\beta=5/3$, S_0 diffractive scale

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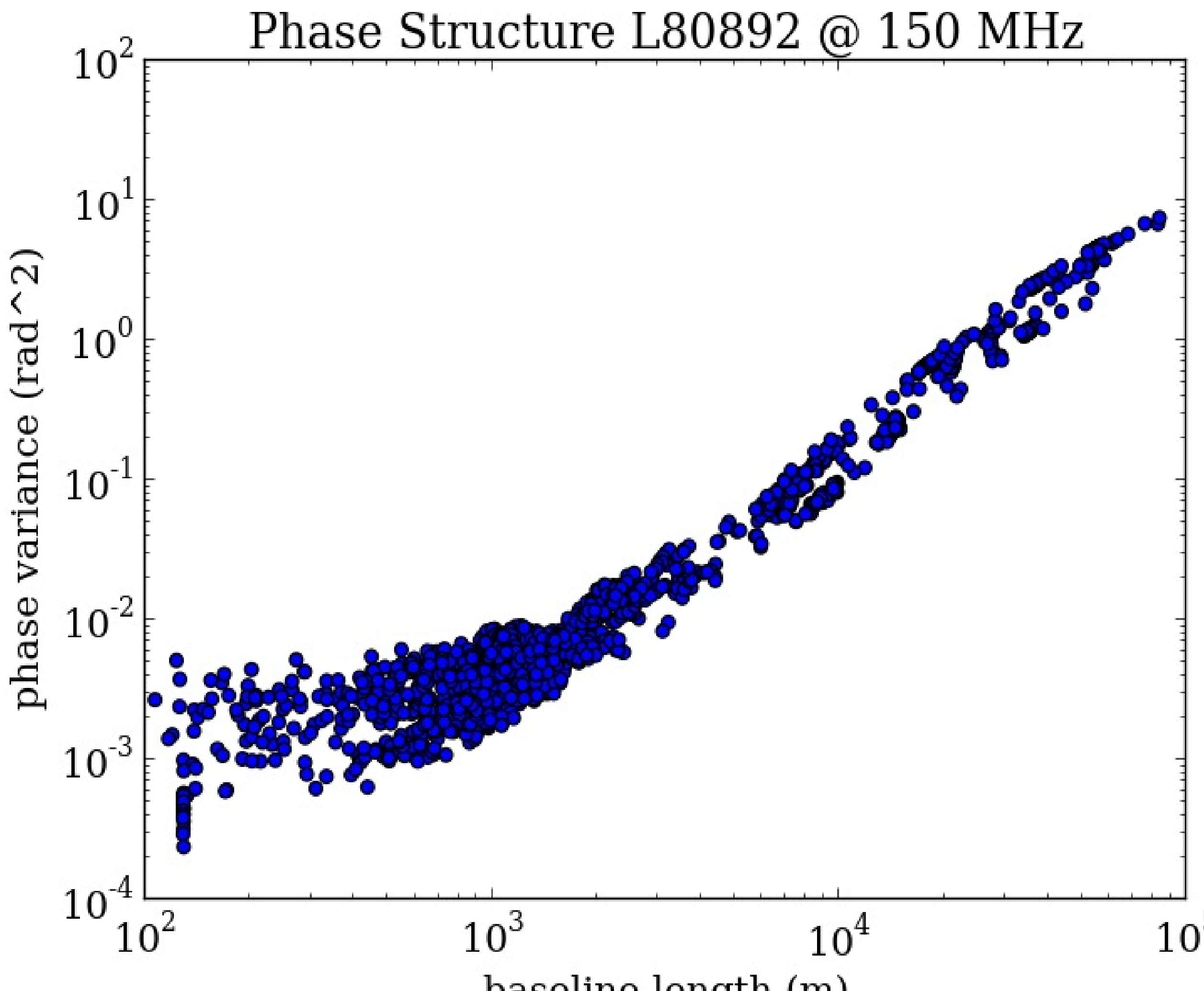

Ionospheric information from dTEC solutions

phase structure: convert dTEC to $d\varphi$ @150 MHz

calculate time variance of $d\varphi$ per baseline

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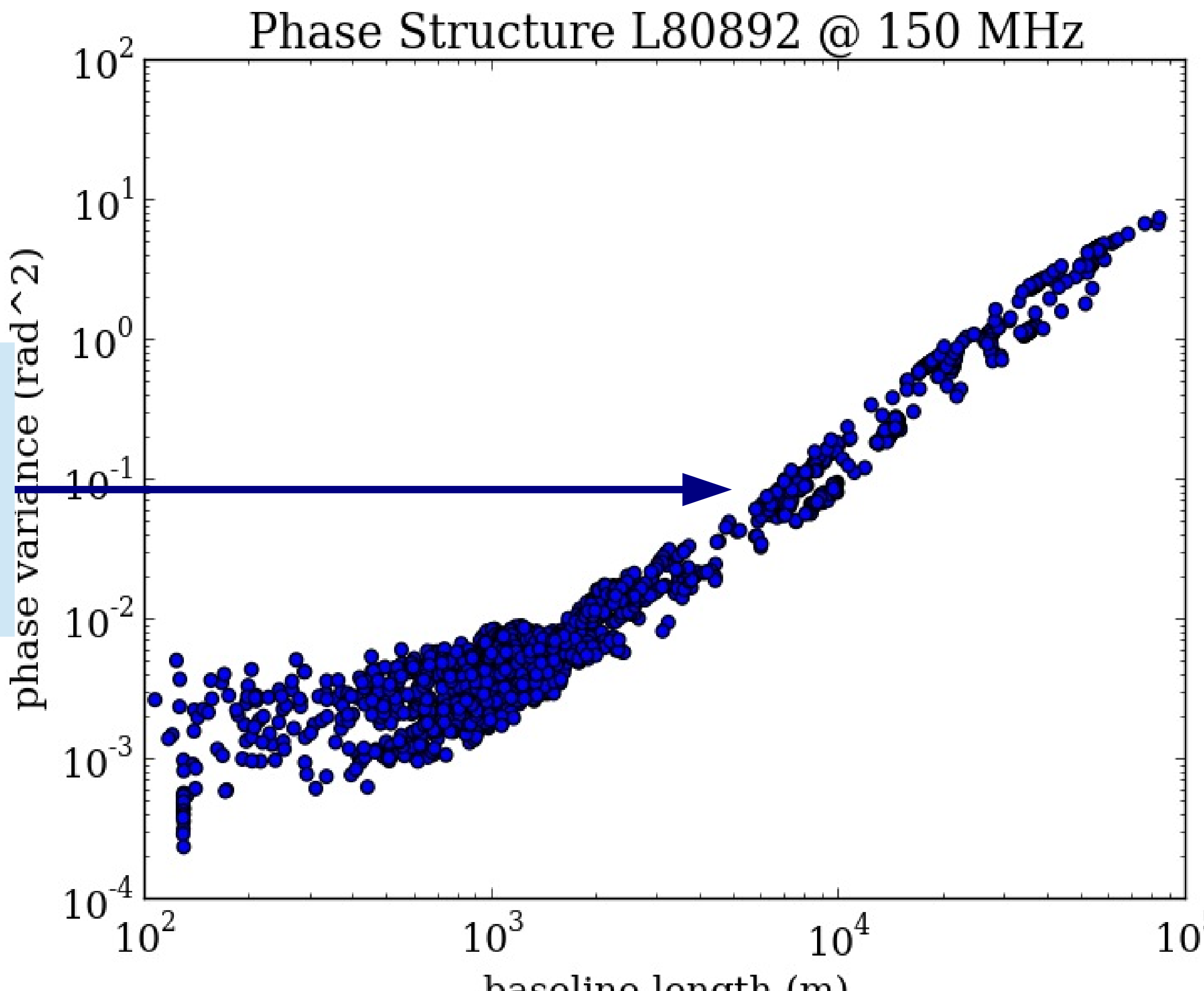
Power law over large range of distances

~1km – 80 km



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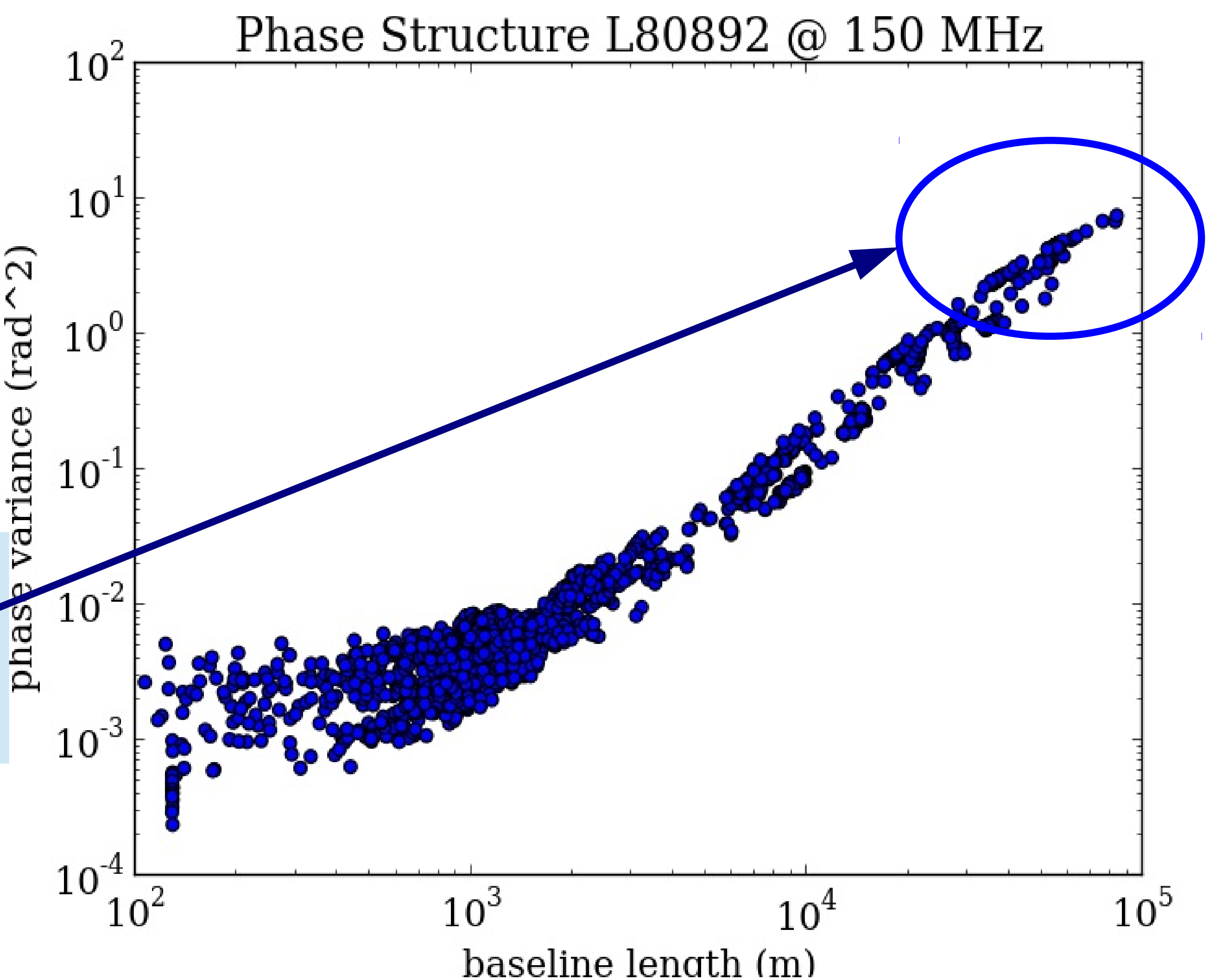

turn over at largest distances(?)

Ionospheric information from dTEC solutions

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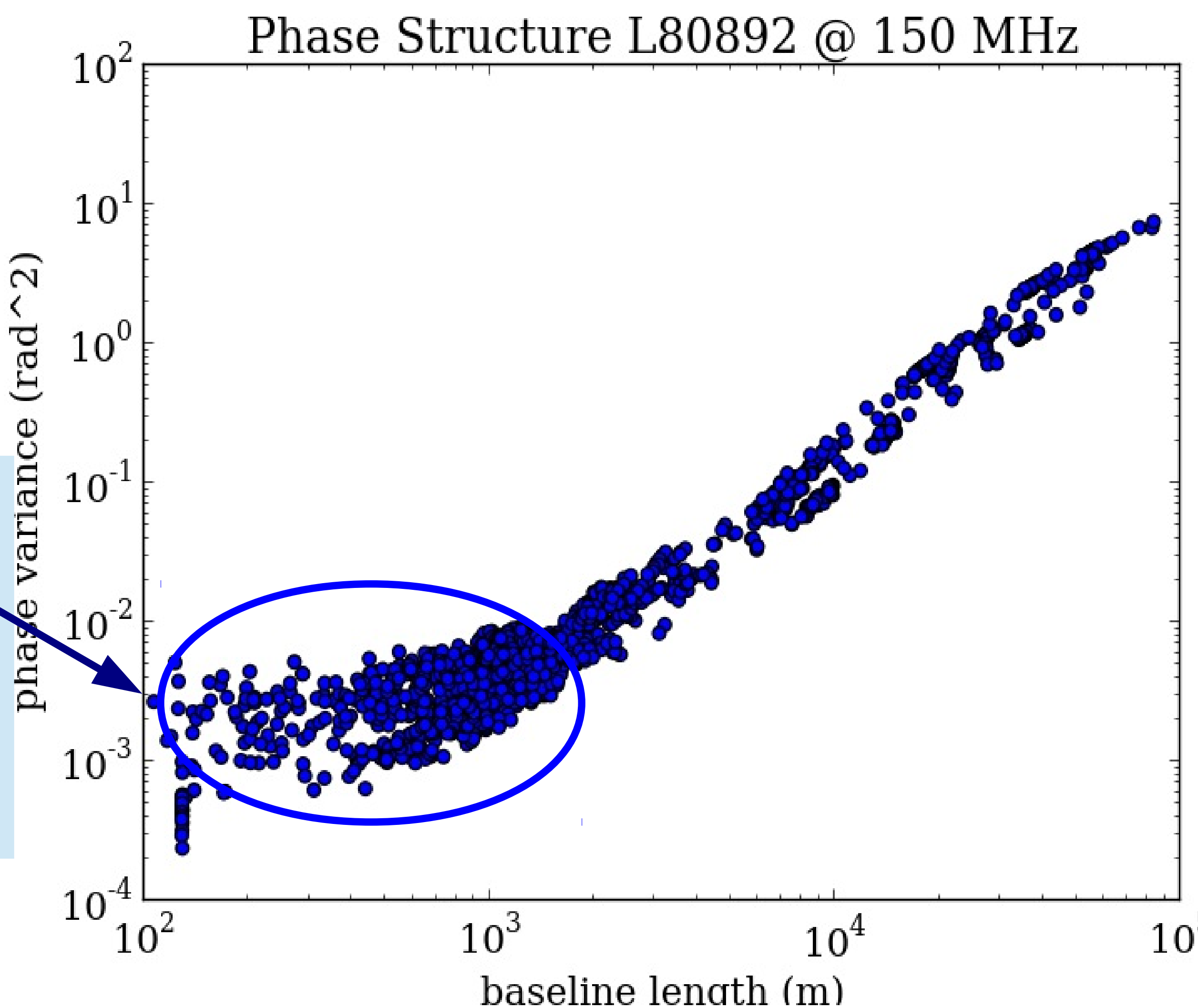

noise floor

constant level for all observations

~1mTEC

Ionospheric information from dTEC solutions

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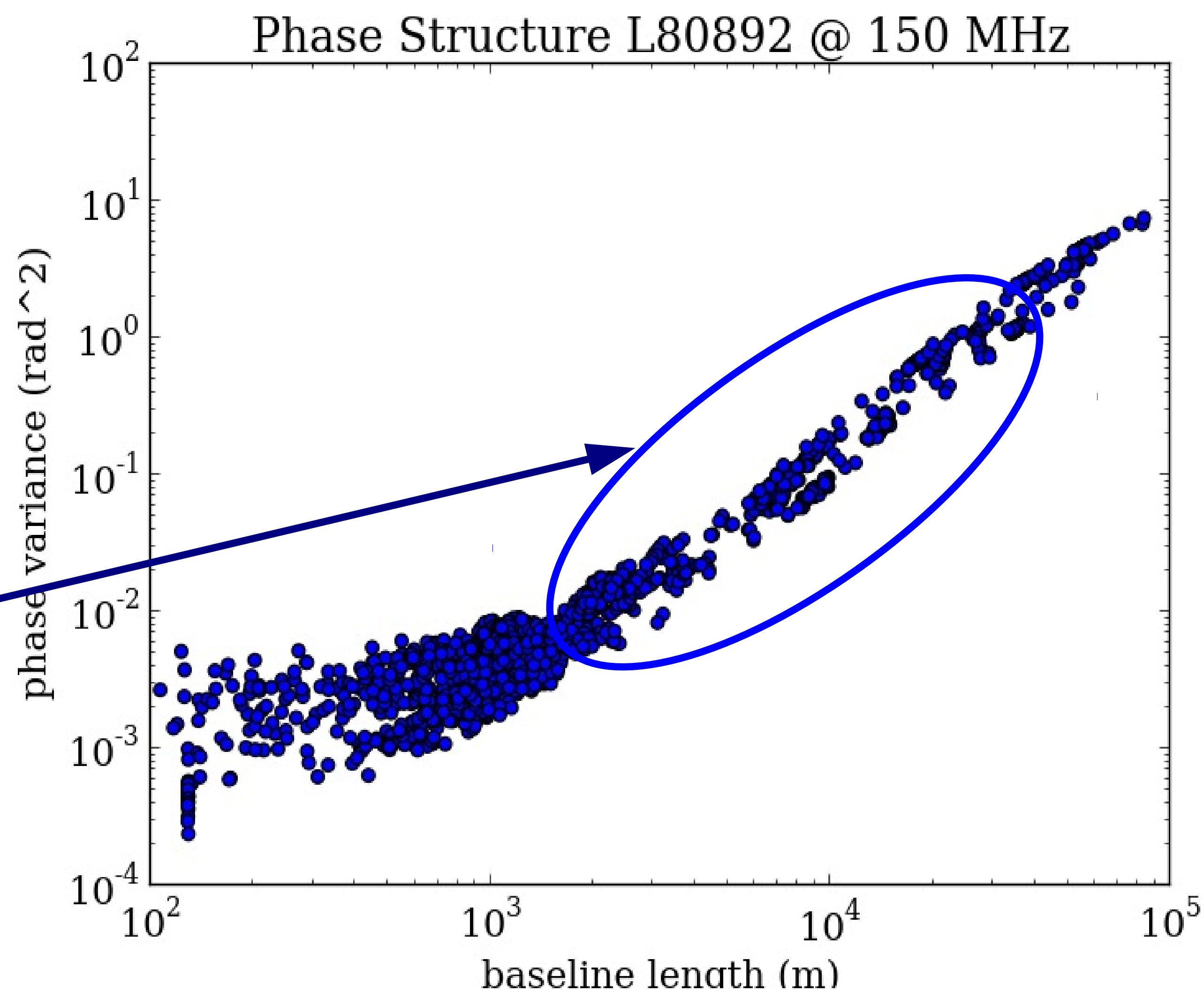
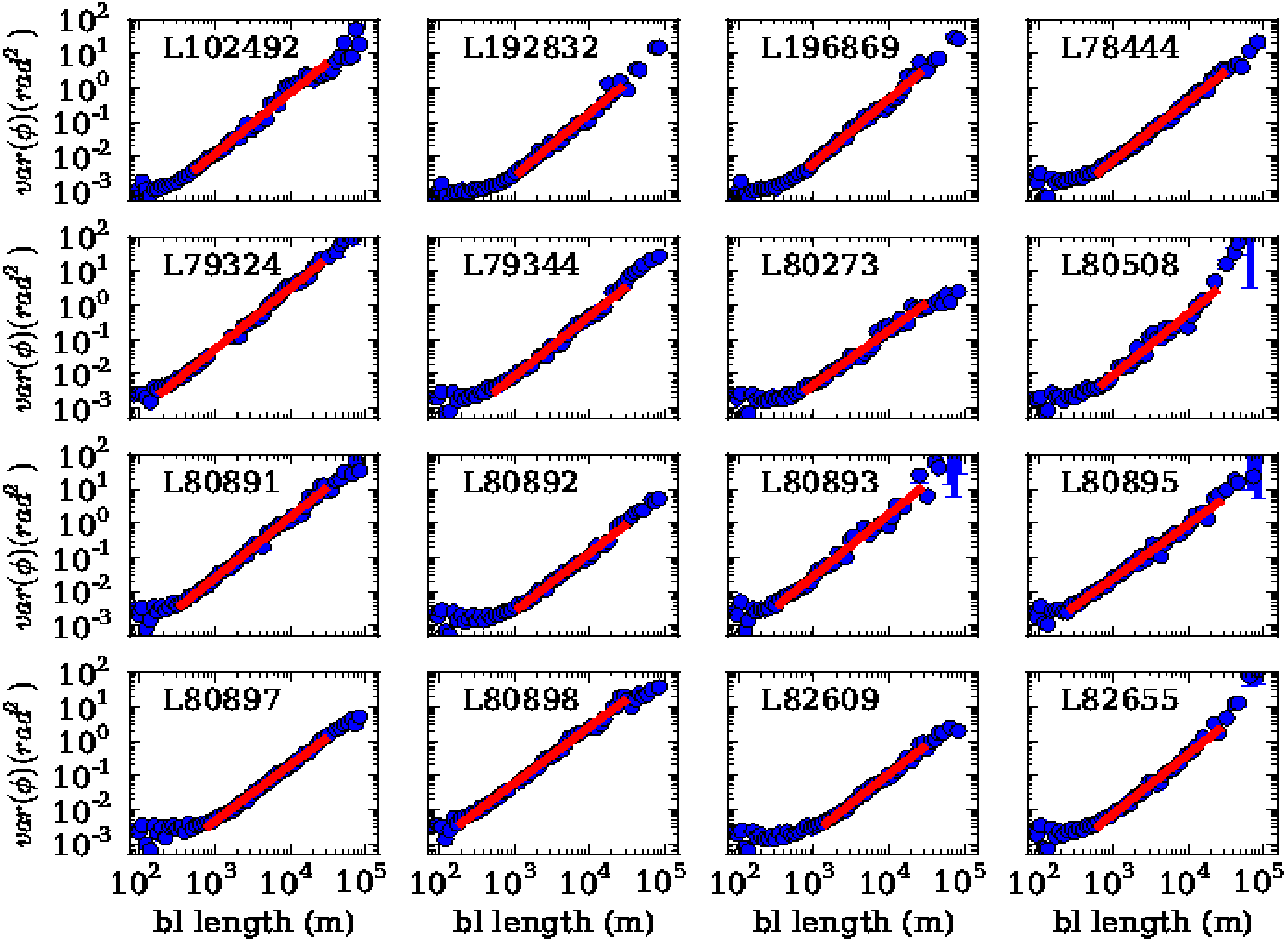
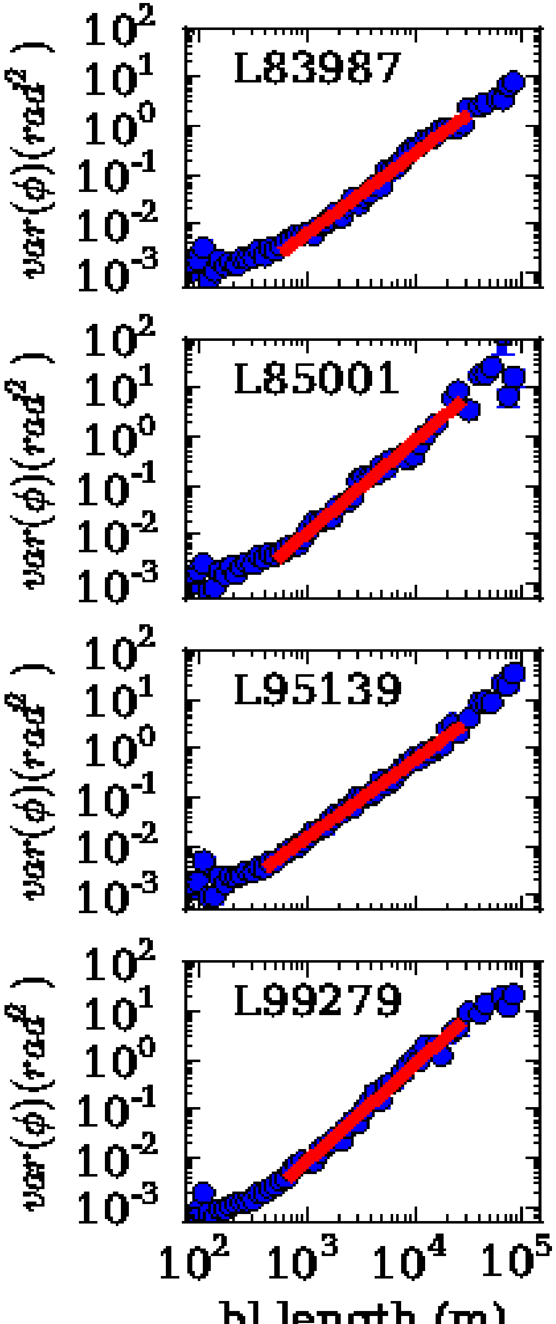


bandlike structure

Structure function all observations



Structure function all observations

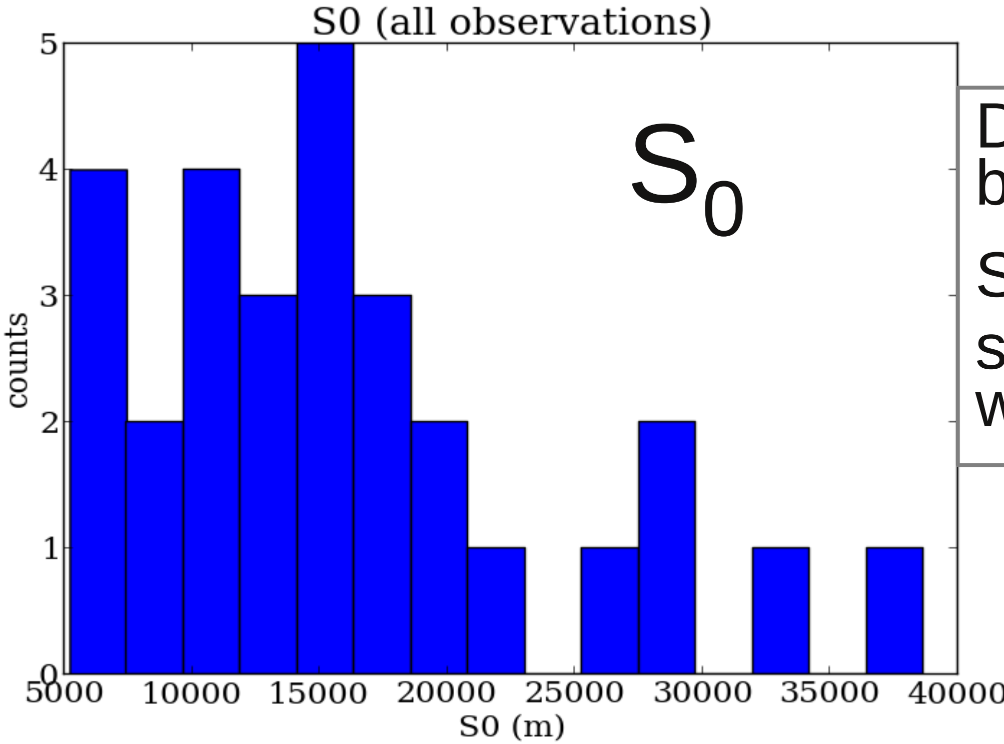


Clear power law structure for all observations

Main variation in offset (S0)

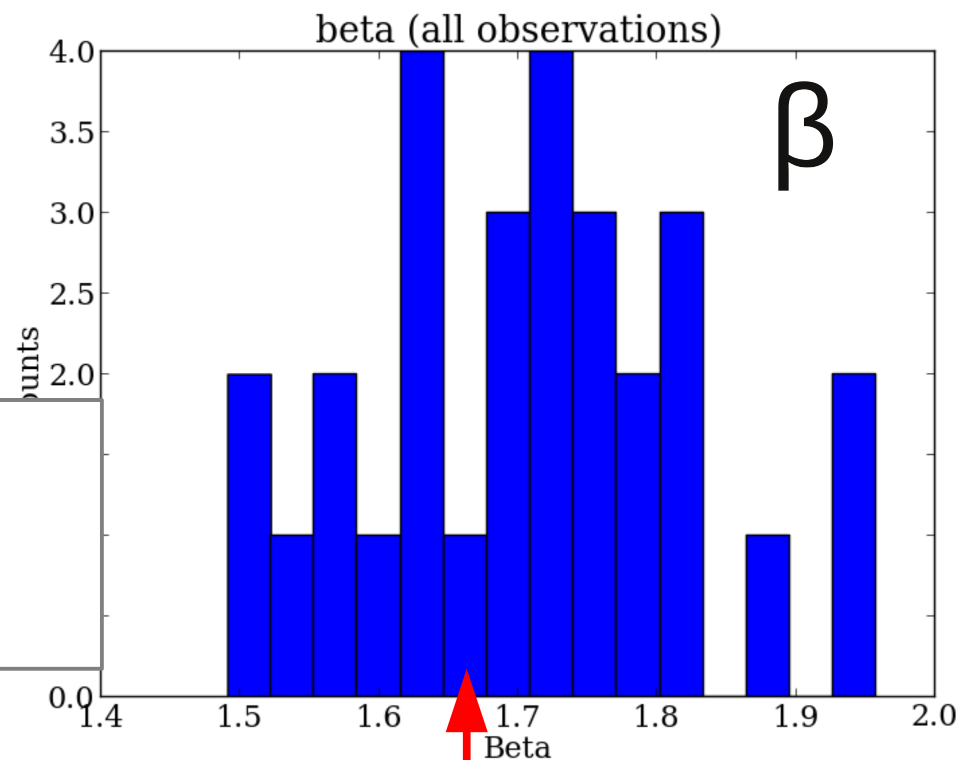
error bars statistical only

Fit Parameters



Diffractive scale variations between 5-40 km

S_0<2km (Fresnel scale)leads to scintillation (not observed in winter 12/13)



Fitted β on average larger than 5/3

(large scale non Kolmogorov structures,TIDs?)

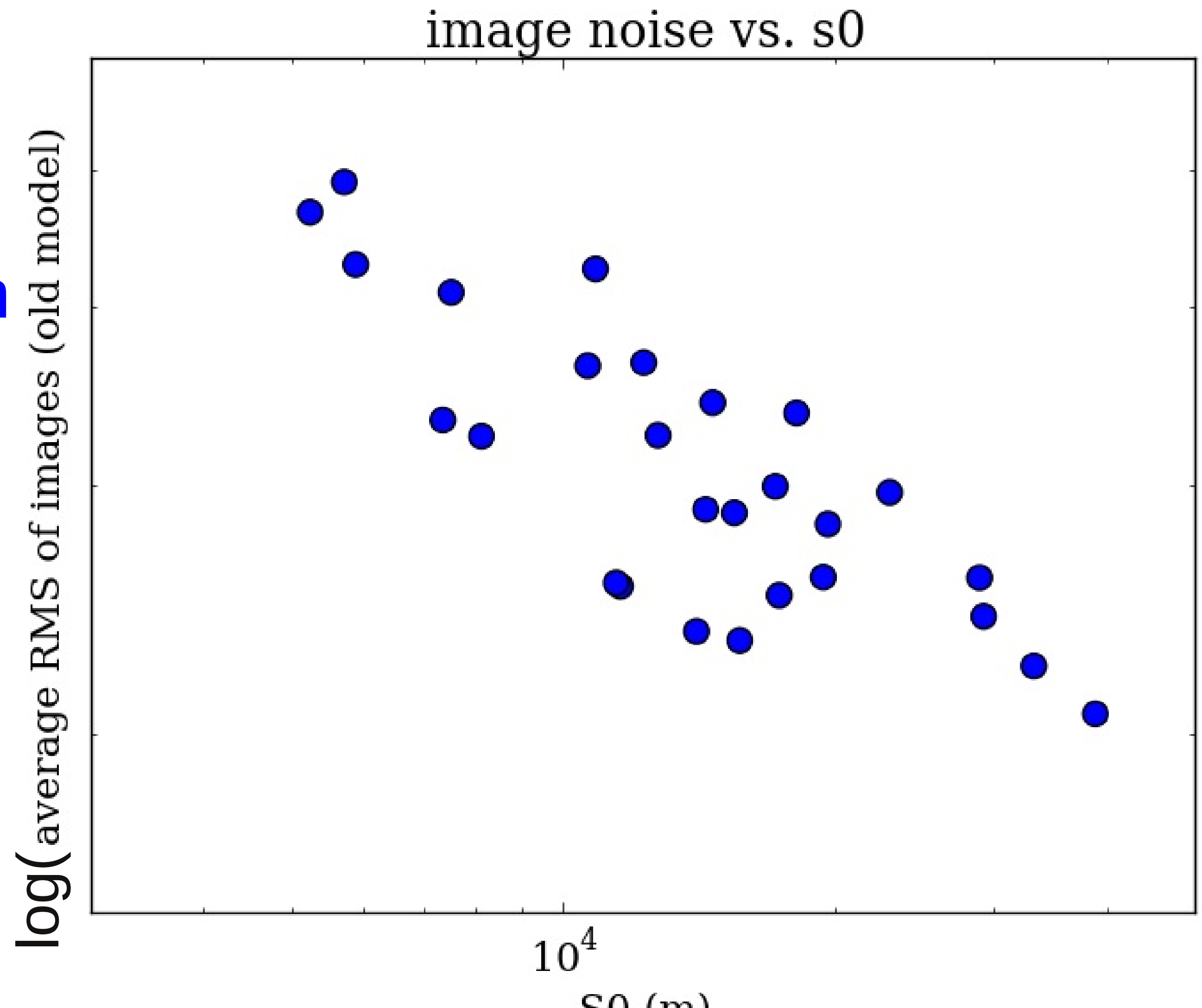
Correlation with RMS image noise

- Night to night fluctuations in image noise
  - direction independent calibration only

Diffractive scale anti-correlates with image noise

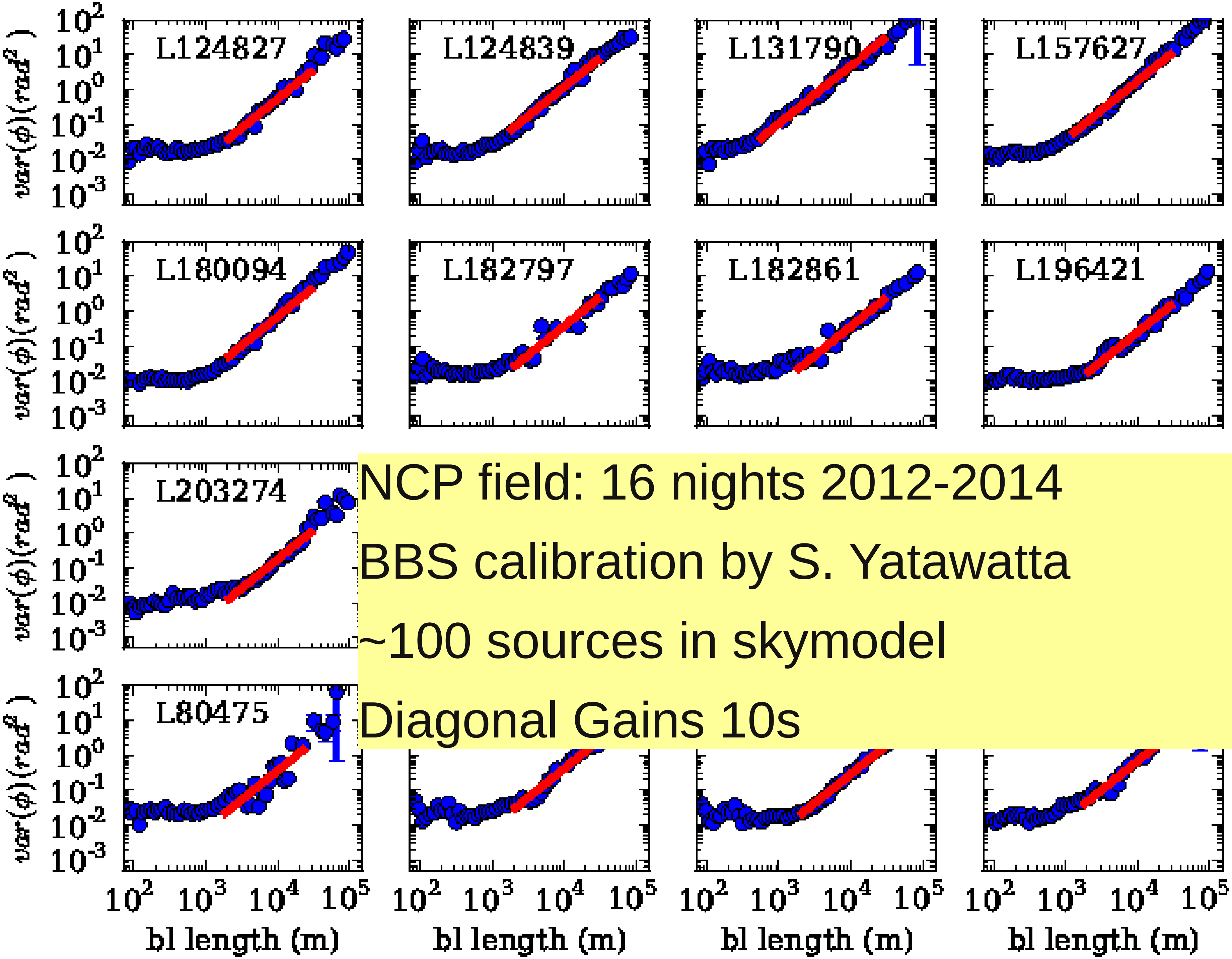
Measure for remaining noise after calibration

(see: Vedantham et. al. 2014, submitted to MNRAS)



non calibrator fields

- Diffractive scale is a measure of ionospheric quality of data
  - easily extracted from calibrator data
  - few solutions (~20) over large frequency range
- Can also be extracted from selfcal phase solutions of weaker fields
  - NO phase transfer from calibrator
  - TEC from Clock/TEC separation will be the determined by (flux weighted) average TEC over the field of view
- Mind: flux ratio can vary with frequency
  - eg. bright source at the edge of the beam
  - issue issue for “wild” nights, when ionosphere varies significantly over field of view
- example NCP

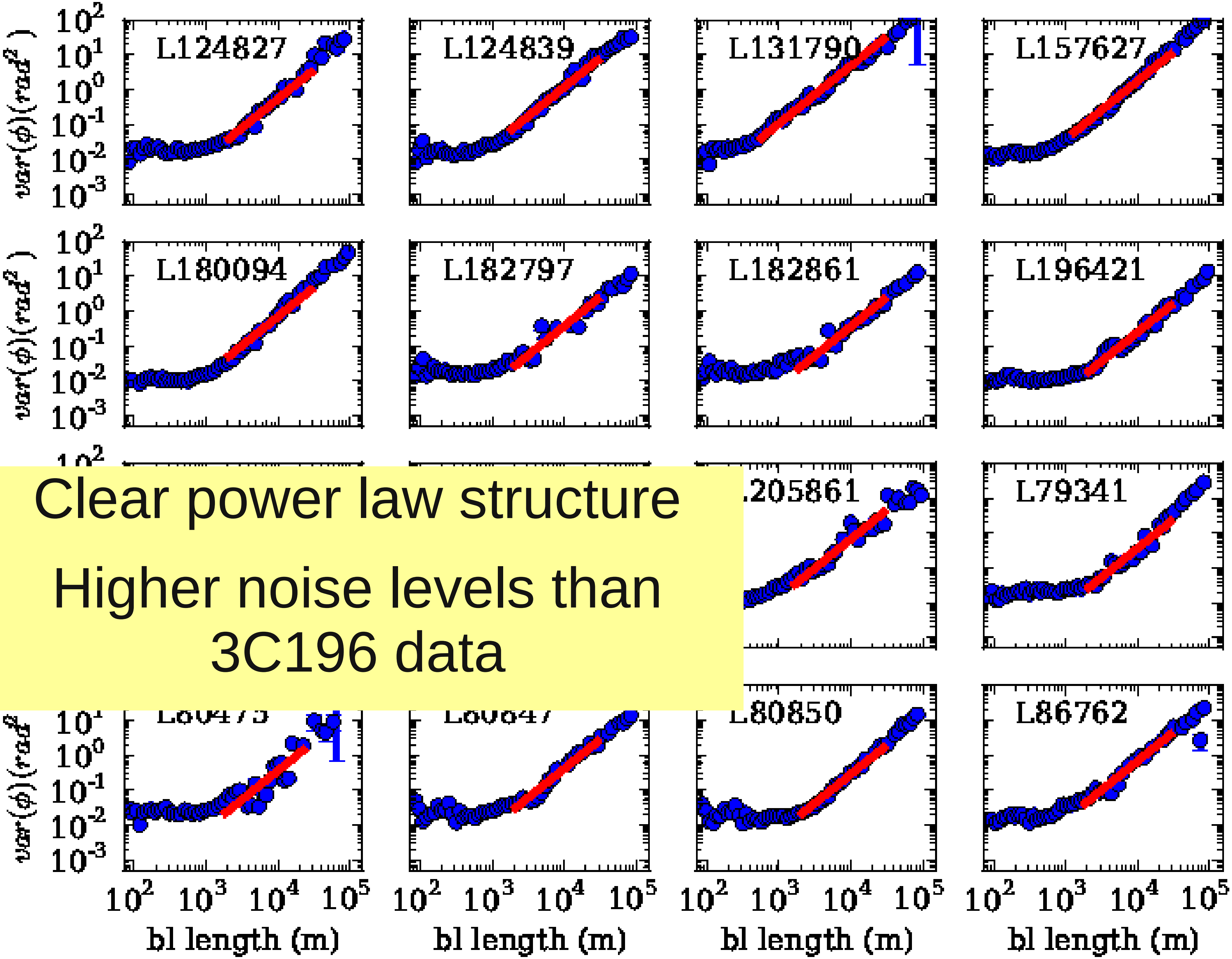


NCP field: 16 nights 2012-2014

BBS calibration by S. Yatawatta

~100 sources in skymodel

Diagonal Gains 10s

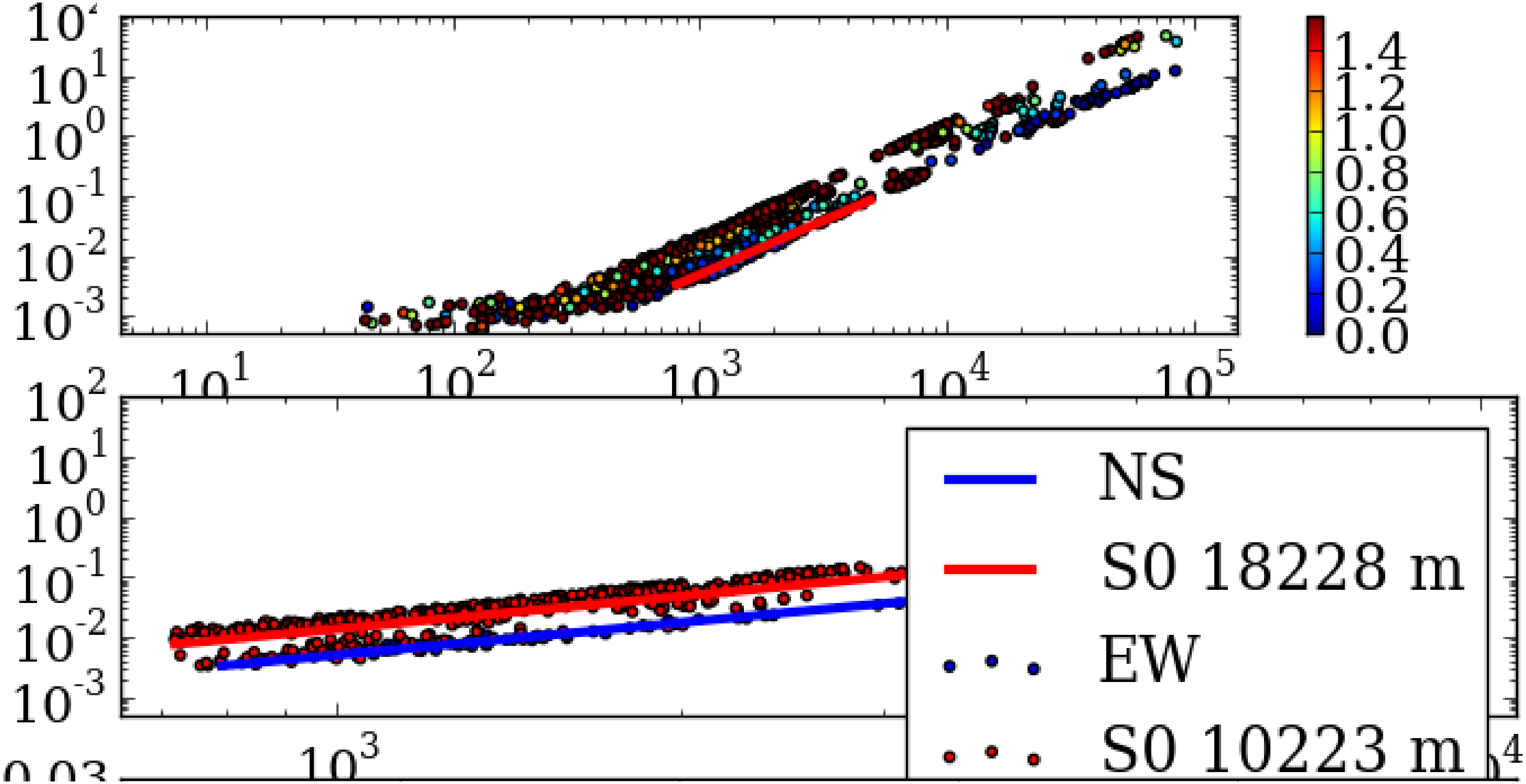


Clear power law structure

Higher noise levels than 3C196 data

Bandlike structure

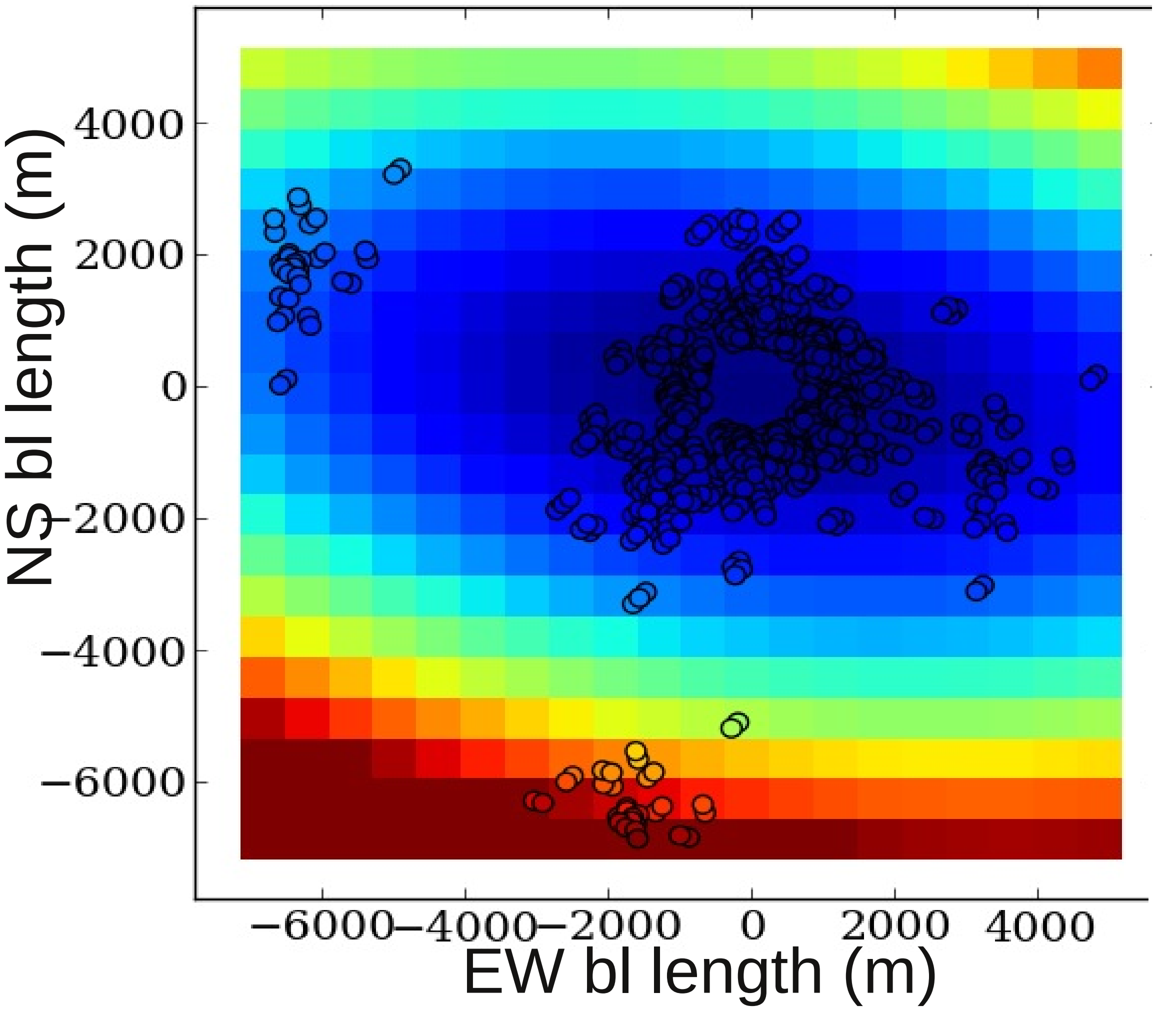
Orientation dependent
Anisotropic structure

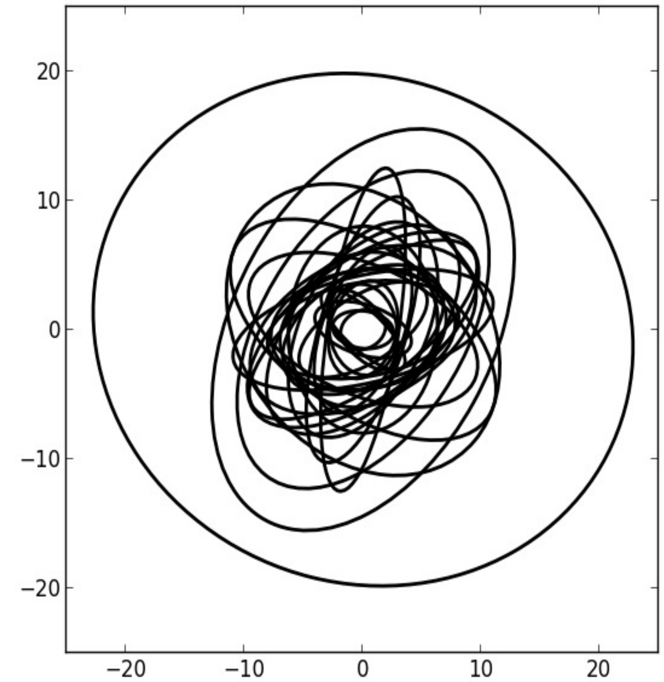


2D structure

Fit 2D structure all observations

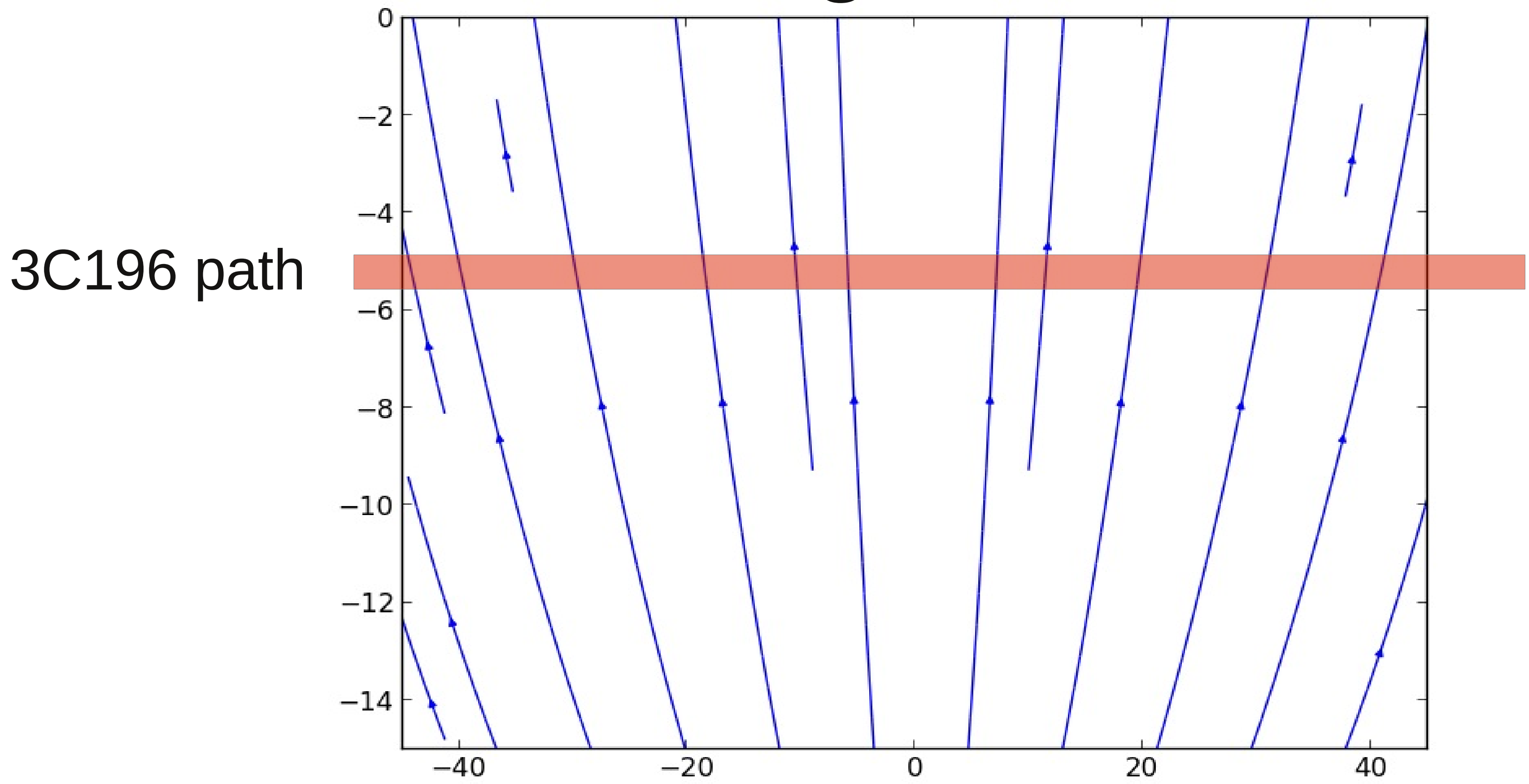
$$<\varphi>=(S^{EW}/S_{0EW}+S^{NS}/S_{0NS})^{\beta}$$





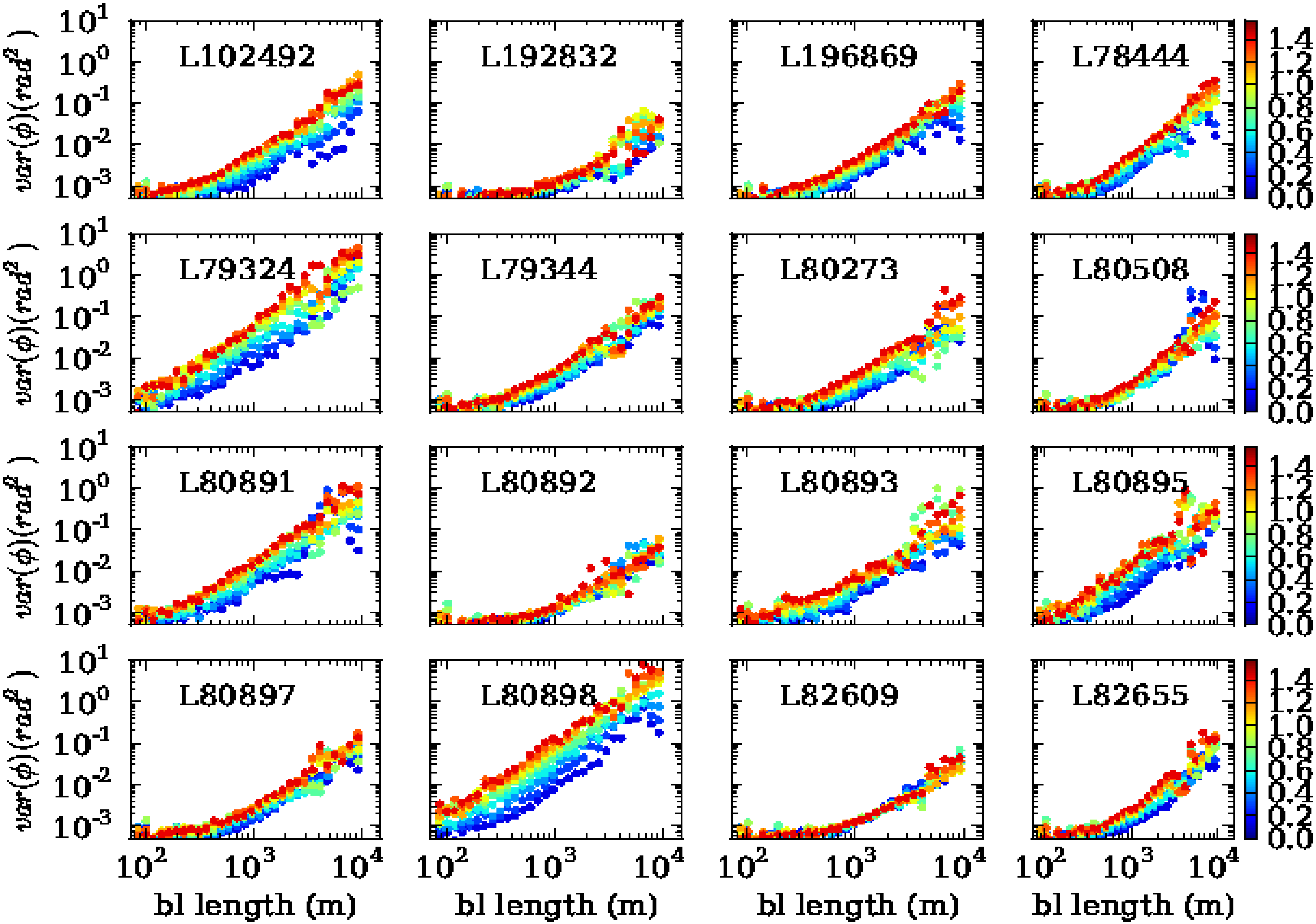
- Orientation dependent structures
- No clear preferred (NS/EW) direction

Geomagnetic Field

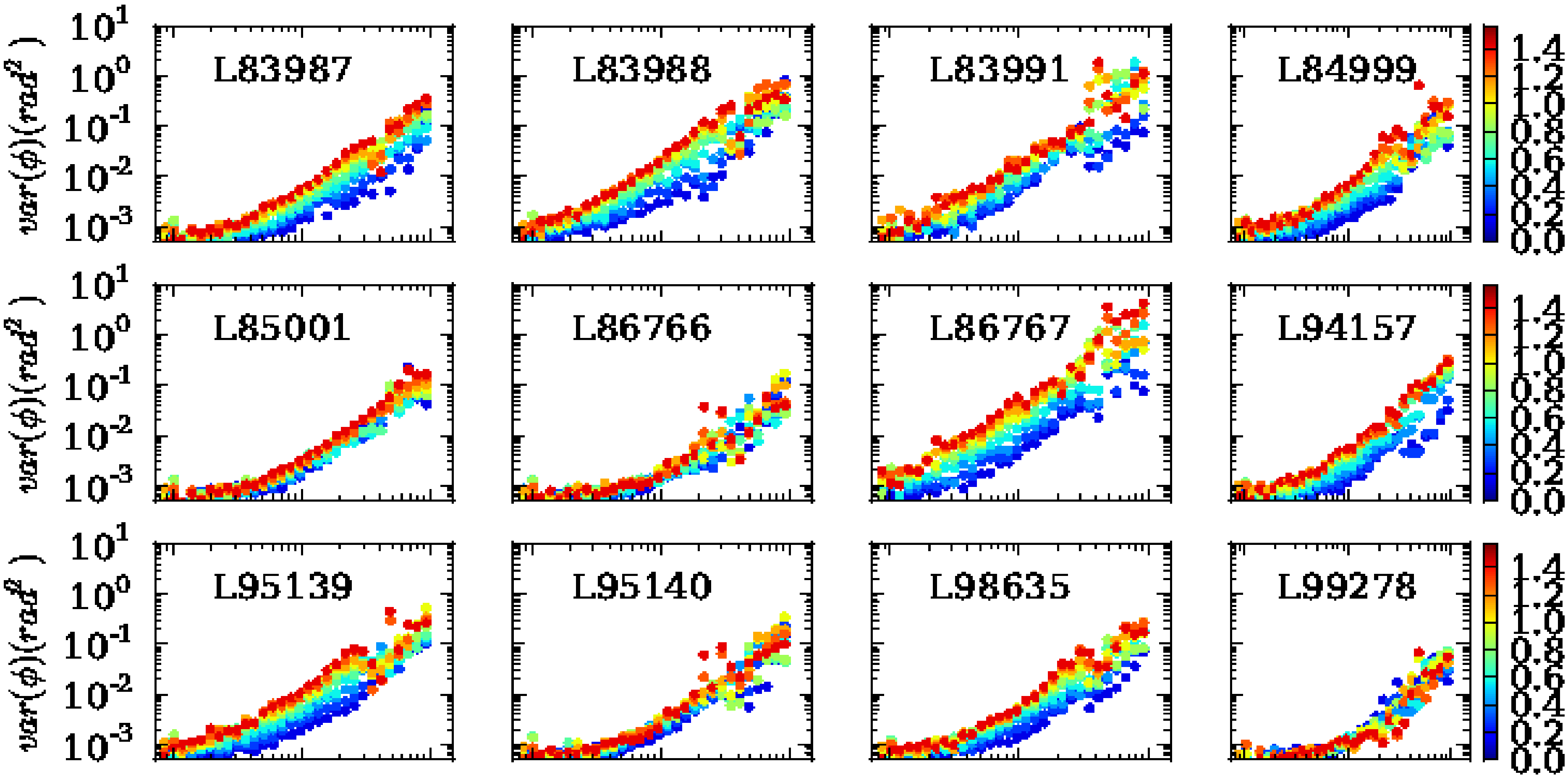


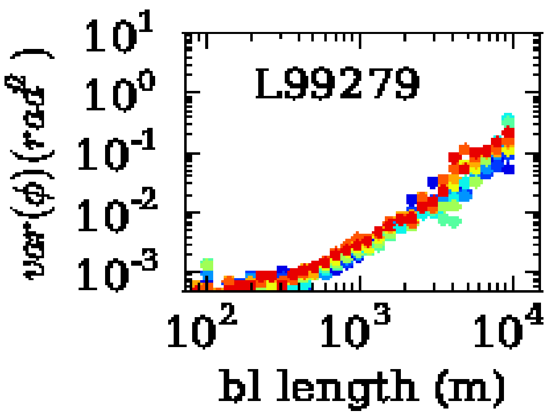
- Projected geomagnetic field lines
- projected along LOS
- axes are beam pointing angles in degrees (0,0 = zenith)
- Structure function binned according to orientation wrst Earth magnetic field

Geomagnetic Field Orientation



Geomagnetic Field Orientation





Red: perpendicular
Blue: parallel
Structures tend to be elongated along the magnetic field lines (leading to smaller S_0 values)

Conclusion

- LOFAR calibration data can be used to probe turbulent structure of the ionosphere over a long range of scales (~1-80 km)
- Diffractive scale is a measure of the ionospheric quality of the night
  - diffractive scale correlates with rms noise of the image
- Observed anisotropy in turbulent structure aligned with Earth magnetic field
  - structures elongated along magnetic field lines