Determination of refractivity variations with GNSS and ultra-stable frequency standards

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Introduction

Atmospheric turbulence:

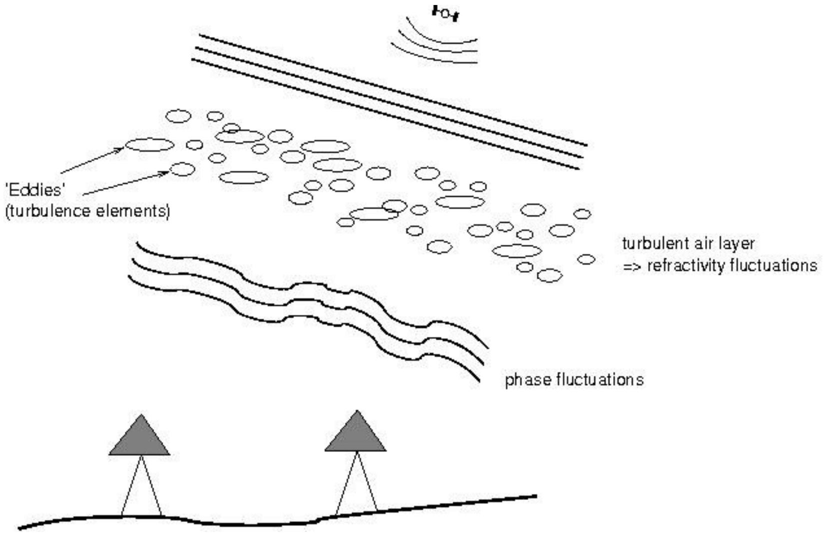
- Occurrence: Atmospheric boundary layer

- Chaotic phenomenon caused by:
  - convection (thermal energy exchange, air pressure changes, wind shear, ...)
  - mechanical obstructions

- temporal scales:
  several minutes to (less than) seconds

- spatial scales:
  from several [km] to [mm]

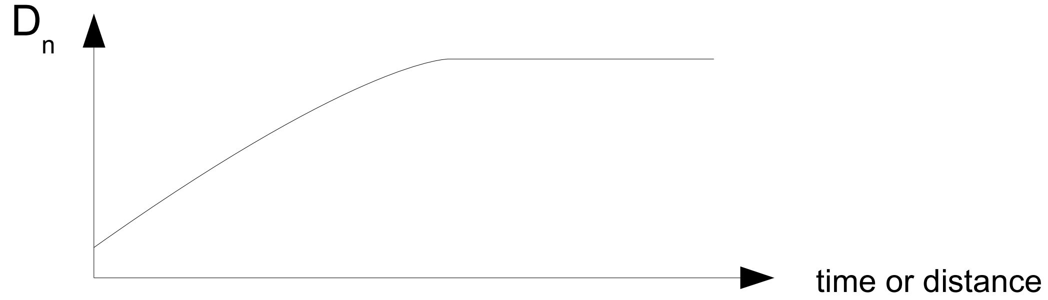
=> high-frequency water vapor variations
=> refractive index / refractivity variations
=> phase fluctuations of electromagnetic waves



Introduction

- Refractivity **structure function** (both temporal and spatial):

$$D_n(\tau) = \langle [n(t+\tau) - n(t)]^2 \rangle$$



- Turbulence theory predicts structure function slopes:
  2/3 spatial and 5/3 temporal power-law behaviour at the beginning, finally 0

Analysis objectives:

1. **Modelling physical correlations** due to atmospheric turbulence
   => Stochastic model GNSS

2. **Determination of atmospheric turbulence from phase fluctuations**
   => GNSS receivers as 'turbulence sensors'

Stochastic model

- No deterministic model of atmospheric turbulence possible (Wheelon 2001)
  => stochastic modelling
- (Co-)Variance model for tropospheric delays T and phase observations φ
  (cf. Schön/Brunner, JGeod 82 (10) 2008):

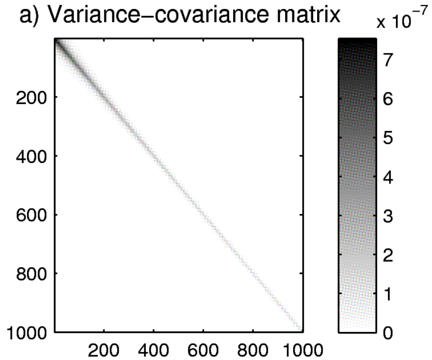
$$\langle T_A^i(t_A), T_B^j(t_B)\rangle = \langle \phi_A^i(t_A), \phi_B^j(t_B)\rangle =$$

$$\frac{0.31\,\kappa_o^{-2/3}}{\sin(\epsilon_A^i)\sin(\epsilon_B^j)} C_n^2 \times \int_0^H \int_0^H (\kappa_0 d)^{1/3} K_{-1/3}(\kappa_0 d)\, dz_1\, dz_2$$

Symbol	Description
T_A^i, Φ_A^i	Slant tropospheric delay / carrier phase observation at station A to satellite i
C_n^2	Structure constant of refractivity (time and location dependent)
ε	Satellite elevation angle
H	Height of wet troposphere (approx. 2000 m)
κ_0	Electromagnetic wave number of signal used

- known geometry and turbulence parameters => variance-covariance matrix $\mathbf{\Sigma_T}$

Simulations



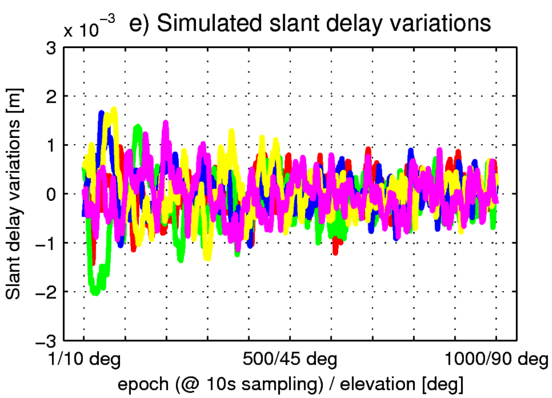
- simulation of time series via eigenvalue decomposition of $\mathbf{\Sigma_T}$:

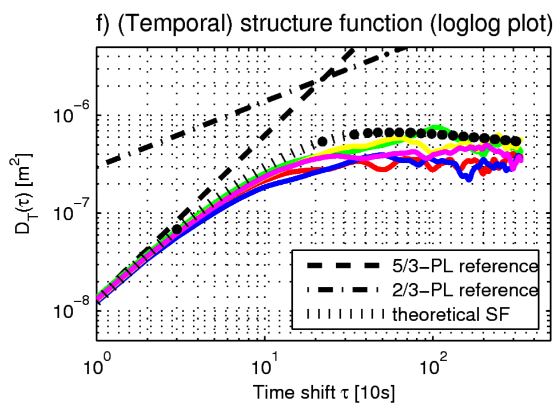
$$T = G\sqrt{\Lambda}\,x$$

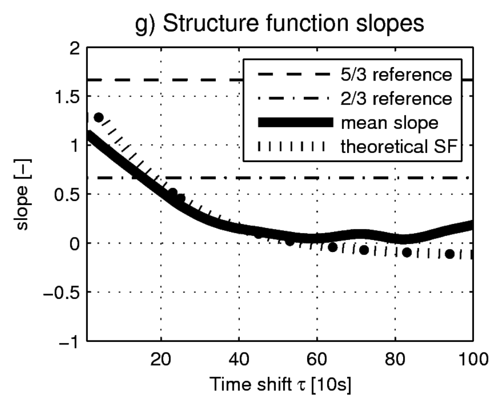
$\mathbf{G}$ = eigenvectors of $\mathbf{\Sigma_T}$, $\mathbf{\Lambda}$ = eigenvalues λ_i of $\mathbf{\Sigma_T}$, $\mathbf{x}$ = random vector N(0, 1)

<u>Example (rising satellite from 10° to 90°):</u>

- 1000 epochs with 10 sec sampling => approximately 3 h
- average turbulence conditions
- peak-to-peak variations: 2 to 4 mm





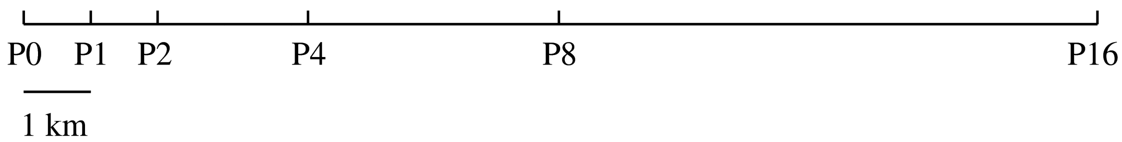


→ Simulated slant delay variations follow predicted 5/3-PL-behaviour (closed-loop test)

PPP results: Overview

Seewinkel network:

- eastern Austria (Burgenland, 47.7 N, 17.E, 160 m ellipsoidal height)
- straight line GPS network with 6 equally equipped stations (Leica SR530/520 receivers, Ashtech choke ring antennas with SCIS radomes



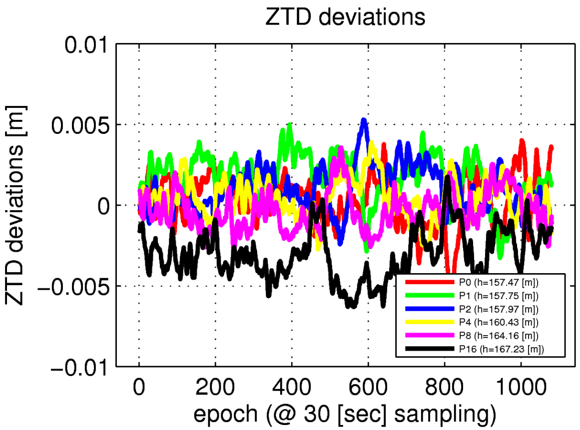
- baseline lengths: 1 km to 16 km
- almost equal heights
- 8 hours data, sampling interval: 30 sec

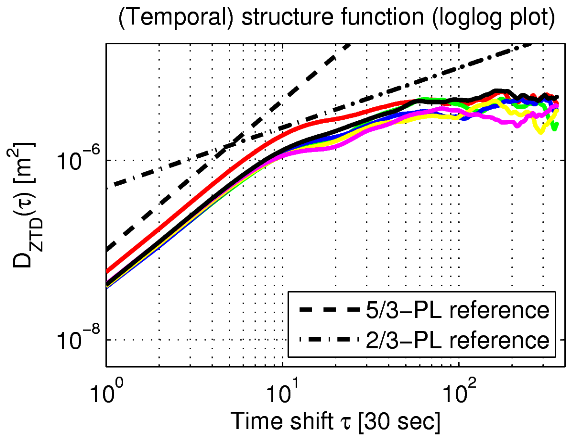
IfE-Precise Point Positioning (PPP) software:

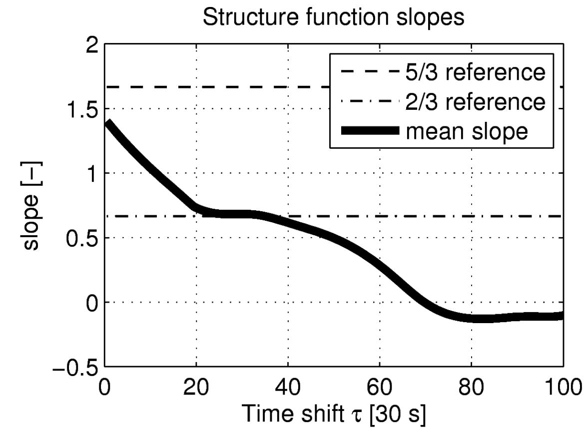
- Kalman filter with backward filtering
- precise ephemeris and 30 s satellite clocks from MIT reprocessing
- zenith tropospheric delays modelled as random walk with system noise 15 mm/√h (large)

PPP results: temporal ZTD behaviour

Seewinkel PPP results:





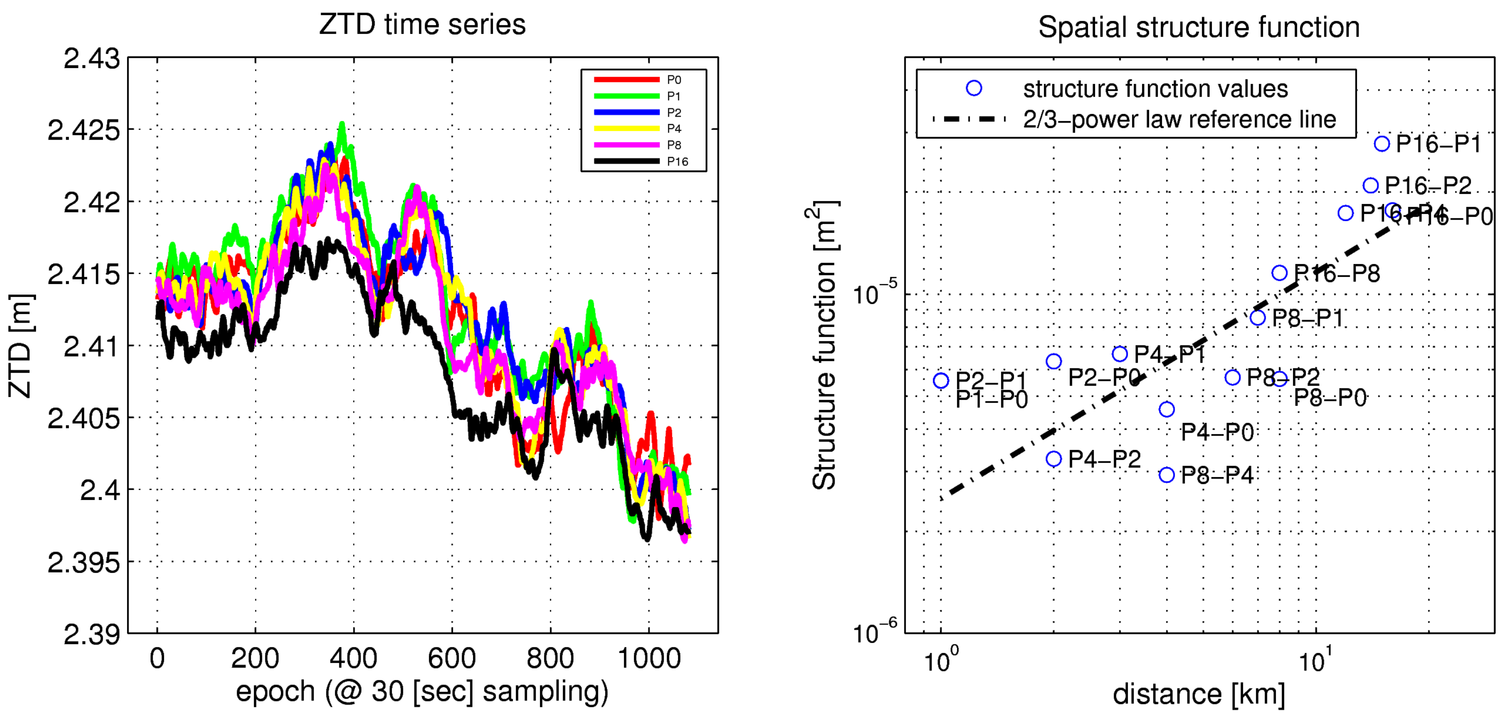


Noise-like with random walk contributions, ZTD variations: up to 5 mm

⟶ Temporal power-law-behaviour of real ZTD: 5/3 (as predicted by turbulence theory)

But: 5/3 power-law is a necessary, but no sufficient condition for turbulence!

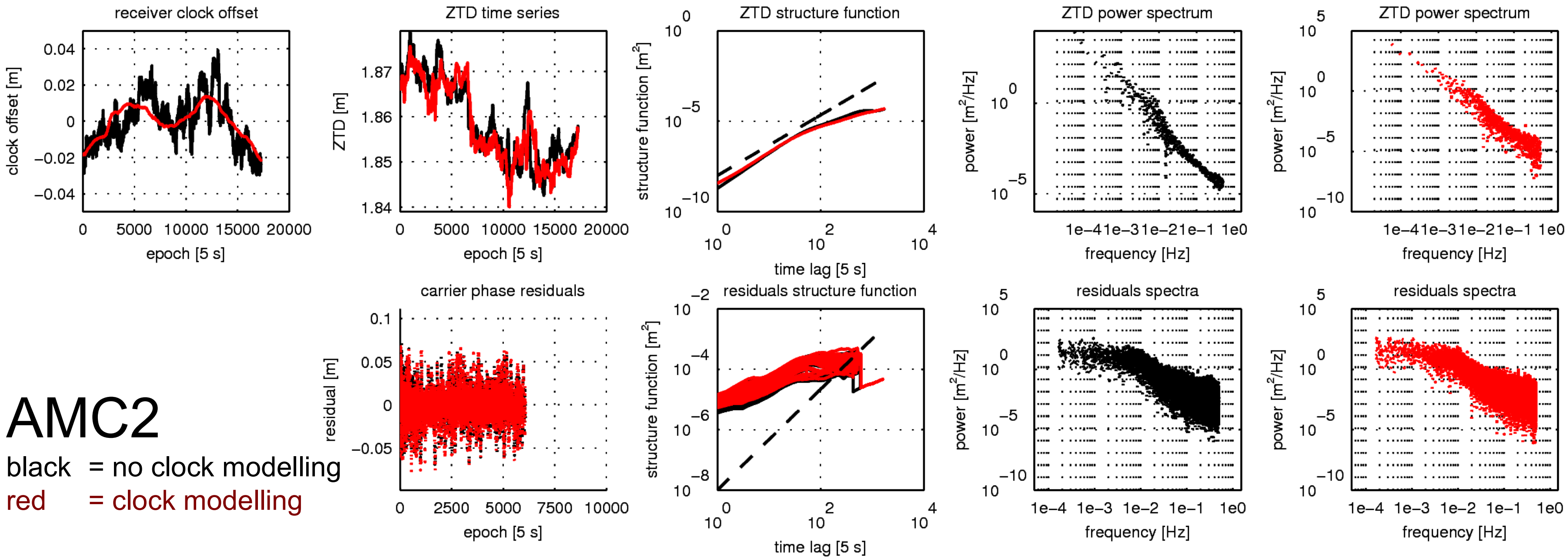
PPP results: spatial ZTD behaviour



→ Spatial power-law-behaviour of real ZTD: 2/3 = 2D turbulence process

Ultra-stable frequency standards

- Remaining effects in ZTD:
  Multipath, receiver clock effects, receiver noise, <u>turbulence effects</u>, …
- stable oscillators enable enhanced clock modelling (Weinbach/Schön 2011)
- Kalman filter clock system noise from Allan variance parameters
- improved separability (of receiver clock and tropospheric delays)



AMC2
black = no clock modelling
red = clock modelling

=> Clock modelling transfers high-frequency effects into ZTD

Summary & Conclusions

General:

- atmospheric turbulence acts (de-)correlating and should be (and can be) modelled

Simulations:

- realistic simulations of turbulence/tropospheric delays possible => full VCM

Real data:

- structure functions of PPP-ZTDs show temporal power-law-behaviour:
  - initial 5/3 power-law temporal behaviour for approx. first 5 minutes
  - 2/3 power-law spatial behaviour (for 16 km network)

Ultra-stable frequency standards:

- clock modelling transferes high-frequency effects to ZTD parameters
  => improves separability
- detection of atmospheric turbulence requires further investigations on remaining effects

References and Acknowledgements

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