Optimization of turbulence measurements for radar, lidar and sonic anemometers

A.C.P. Oude Nijhuis, C.M.H. Unal, O.A. Krasnov, H.W.J. Russchenberg and A. Yarovoy

Outline

Introduction and motivation

Turbulence retrieval methods

Cascade turbulence model

Experiments

I. Number of samples
II. Inertial range check
III. Cloud structure and beamwidth
IV. Noise

Conclusions and outlook

Introduction and motivation

We all want a safe flight…

Introduction and motivation

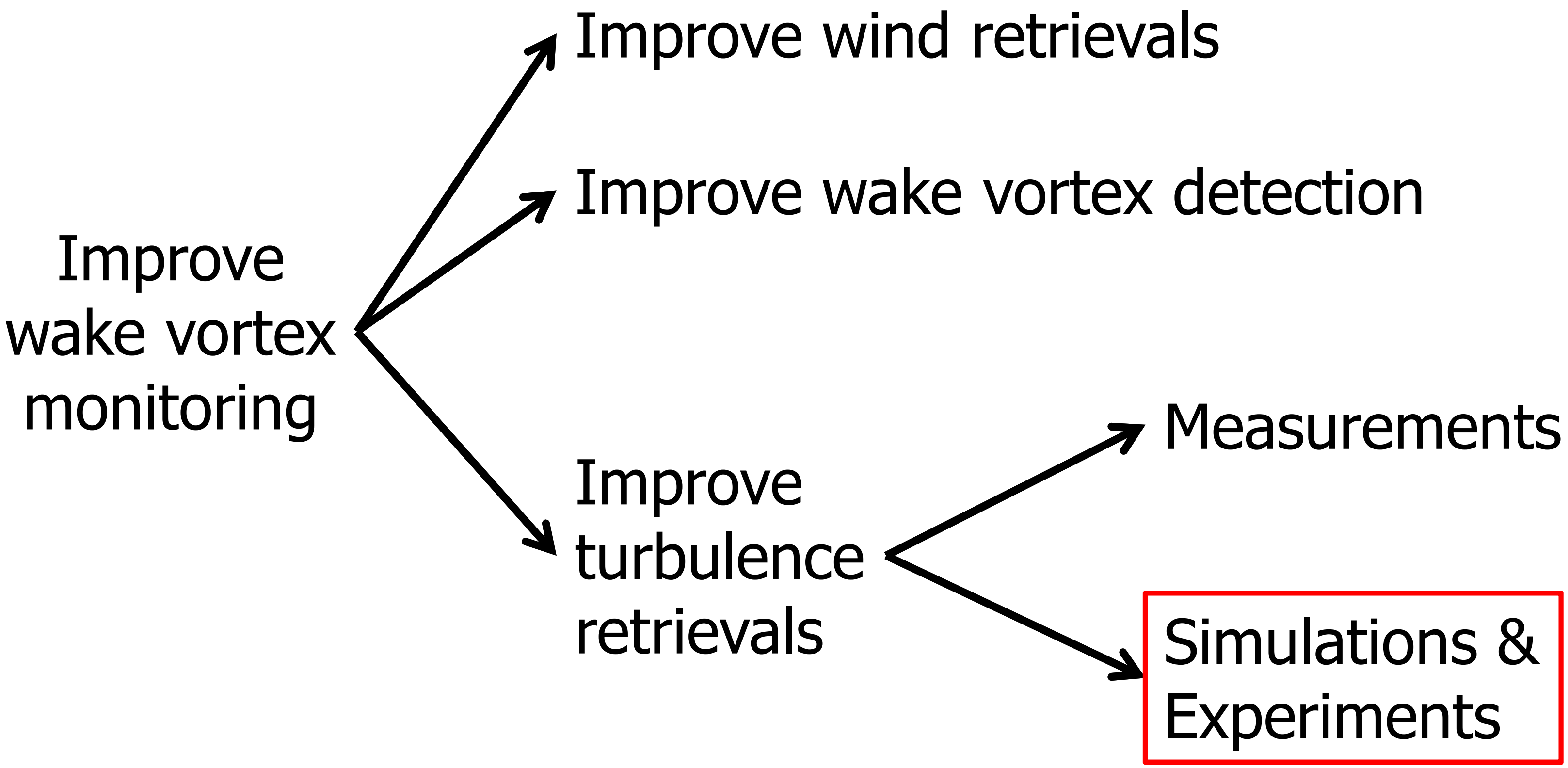
Solution to mitigate wake vortex and weather hazards. Potentially increase the airport capacity.

Monitoring under all weather conditions by using scanning radars and lidars.

Does it work???!!!???

Introduction and motivation

We would like to improve turbulence retrievals and improve wake vortex monitoring. How to do this?



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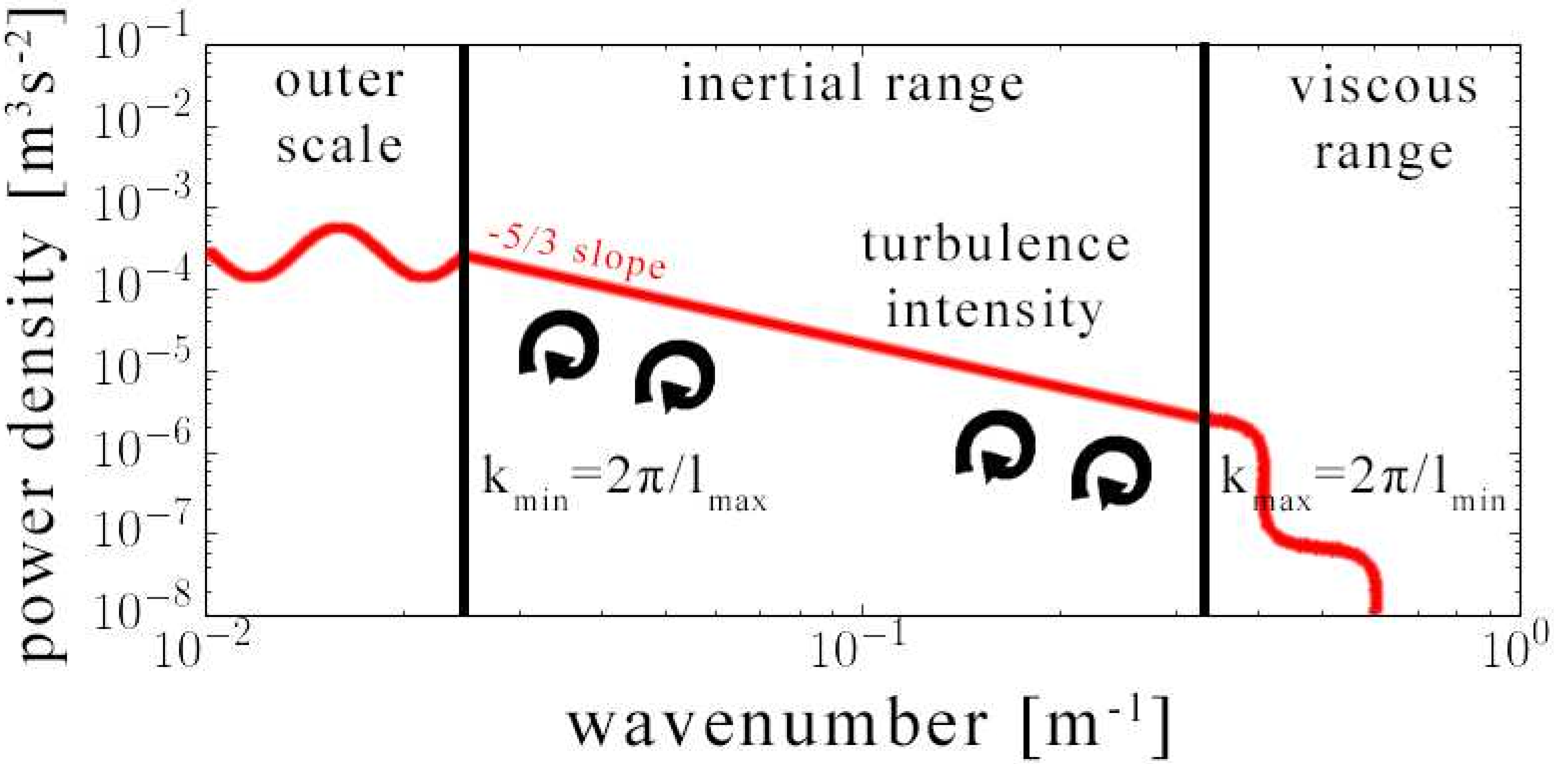
Turbulence retrieval methods

Turbulence is quantified by the Eddy dissipation rate (EDR)

- Assumption on homogenous isotropic frozen turbulence
- In inertial range the dissipation goes with the Kolmogorov -5/3 power.



Turbulence retrieval methods

EDR can be derived from velocity measurements from radar, lidar or sonic anemometers.

EDR retrievals

- A sequence of velocities
  - Power spectrum

    $$E(\kappa) = C\,\varepsilon^{2/3}\kappa^{-5/3}$$

  - Structure function

    $$D_{LL}(r) = \langle [v(x+r) - v(r)]^2 \rangle = C_2(\varepsilon r)^{2/3}$$

  - Variance

    $$\sigma^2 = \frac{3}{2} C\,\varepsilon^{2/3}\left[\kappa_1^{-2/3} - \kappa_2^{-2/3}\right]$$

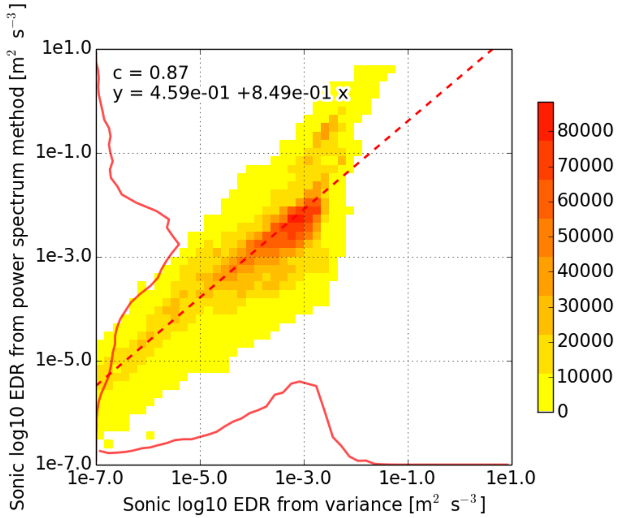
- Doppler Spectral width

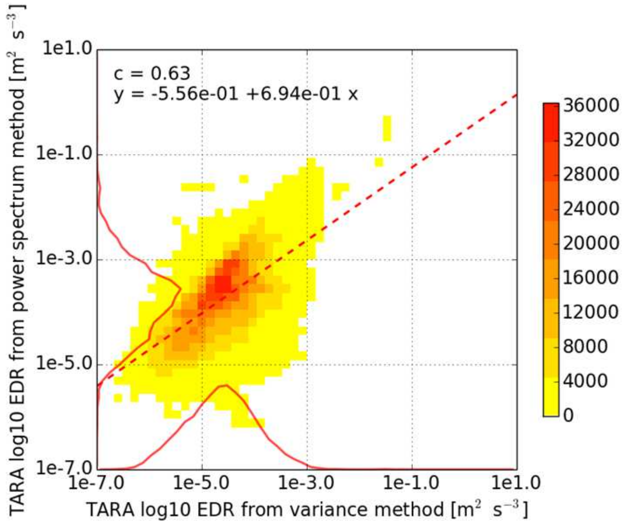
Turbulence retrieval methods

- When different EDR retrieval methods are applied, we find biases…

TARA S-Band

Sonic





EDR comparison for 2012

- Can we better understand turbulence retrievals?
- What does (in)consistency of retrieval methods mean?

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IV. Signal-to-noise ratio and minimal detectable EDR

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Cascade turbulence model

To understand the nature of turbulence retrievals

- we prefer the most simple turbulence model!

Model	**synthetic clean signal**	**isotropic direct numerical simulation (DNS)**	**large eddy simulation (LES)**	**more advanced (e.g. LES forced with weather model)**	**real world**
Features	Kolmogorov power spectrum	Navier-Stokes equation	Inhomo-geneities	weather systems	

simpel ⟶ **complex**

Models of turbulence in order of complexity

Cascade turbulence model

- Input: *N* samples
- Periodic Nyquist sampling interpolation
- Velocity is a sum over *n* scales

$$f(t) = \sum_{i=-\infty}^{\infty} f(i) \frac{\sin \pi(t-i)}{\pi(t-i)}$$

$$f(i+N) = f(i)$$

Leads to an analytic interpolating function Ξ

$$v = \sum_n v_n = \varepsilon^{1/3} \sum_n 2^{5n/6} \sum_{i=0}^{N-1} a_i \Xi(2^{-n}x, i, N)$$

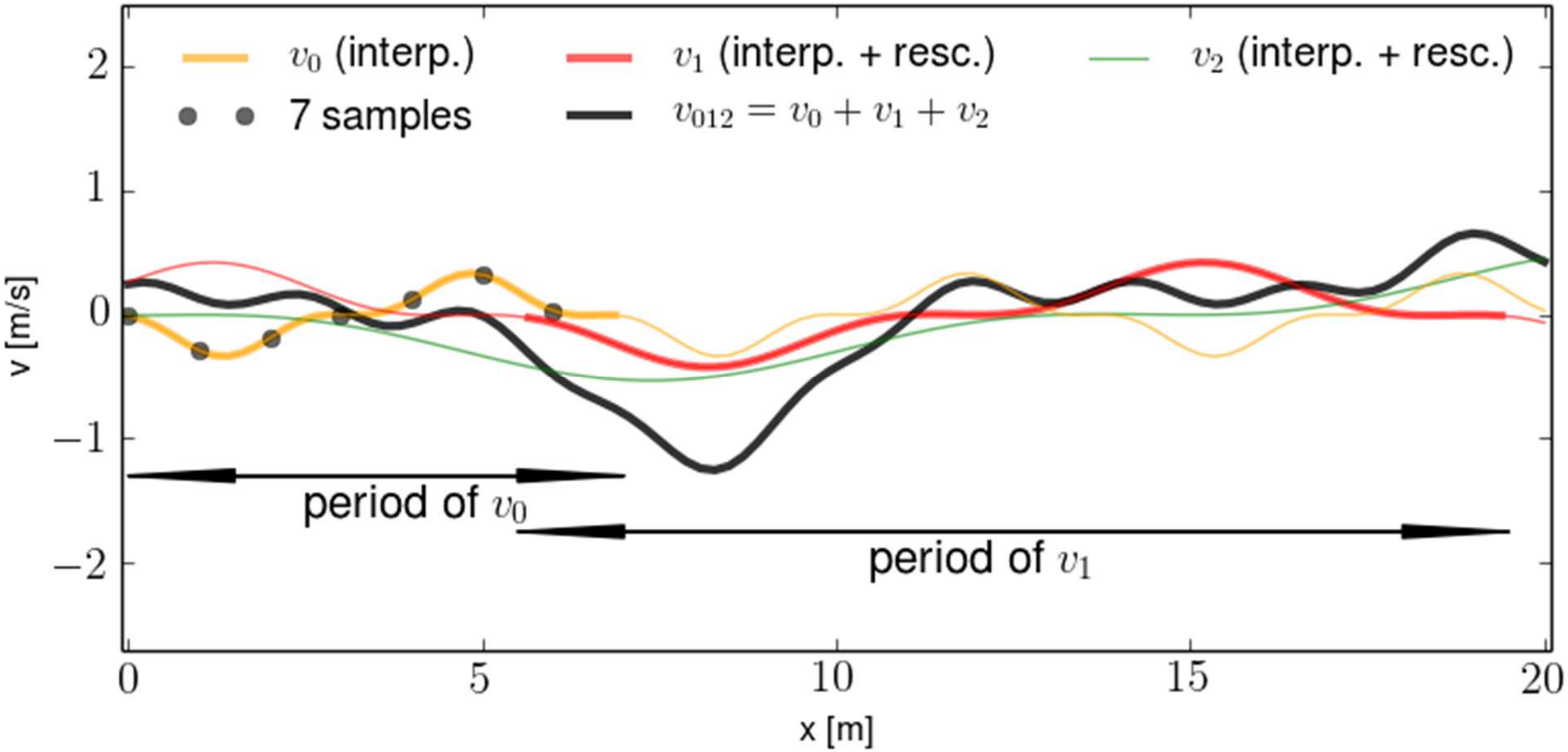
rescaling

Eddy dissipation rate

samples

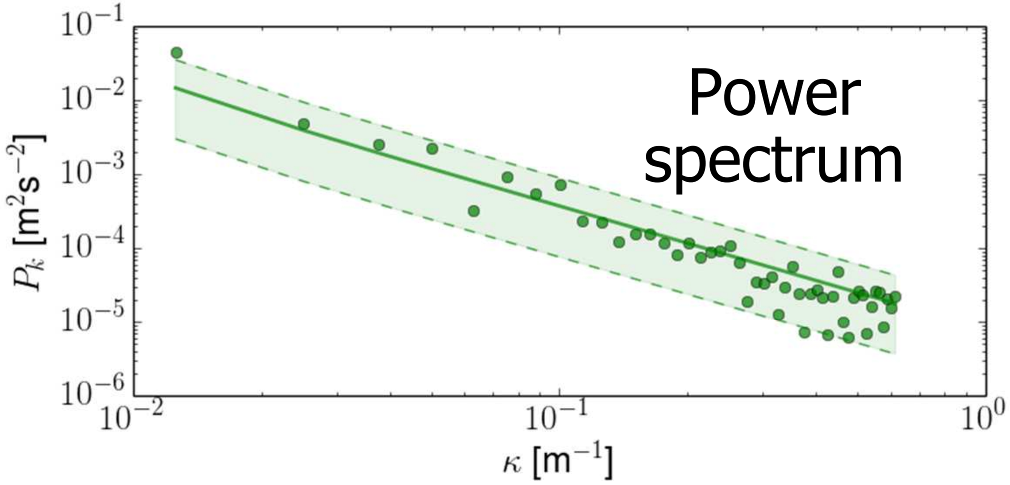
Cascade turbulence model

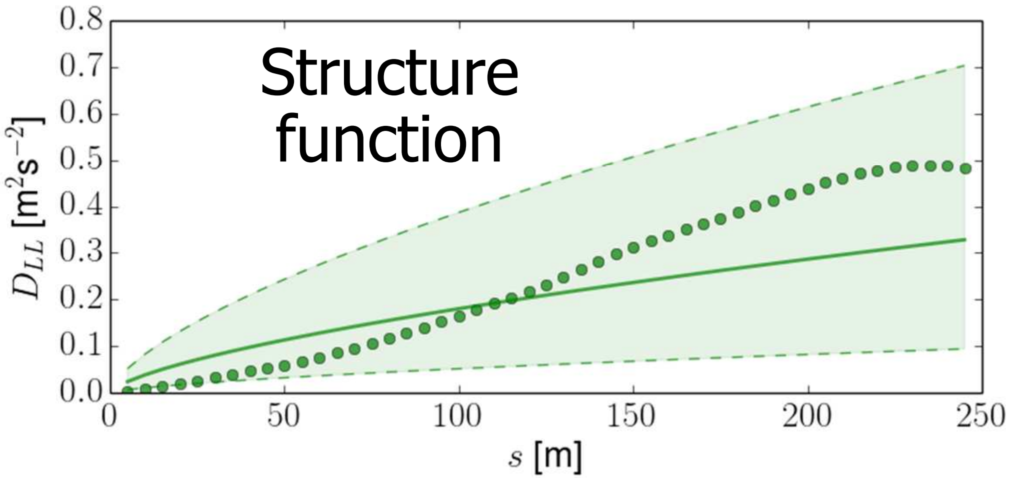
- Example N = 7



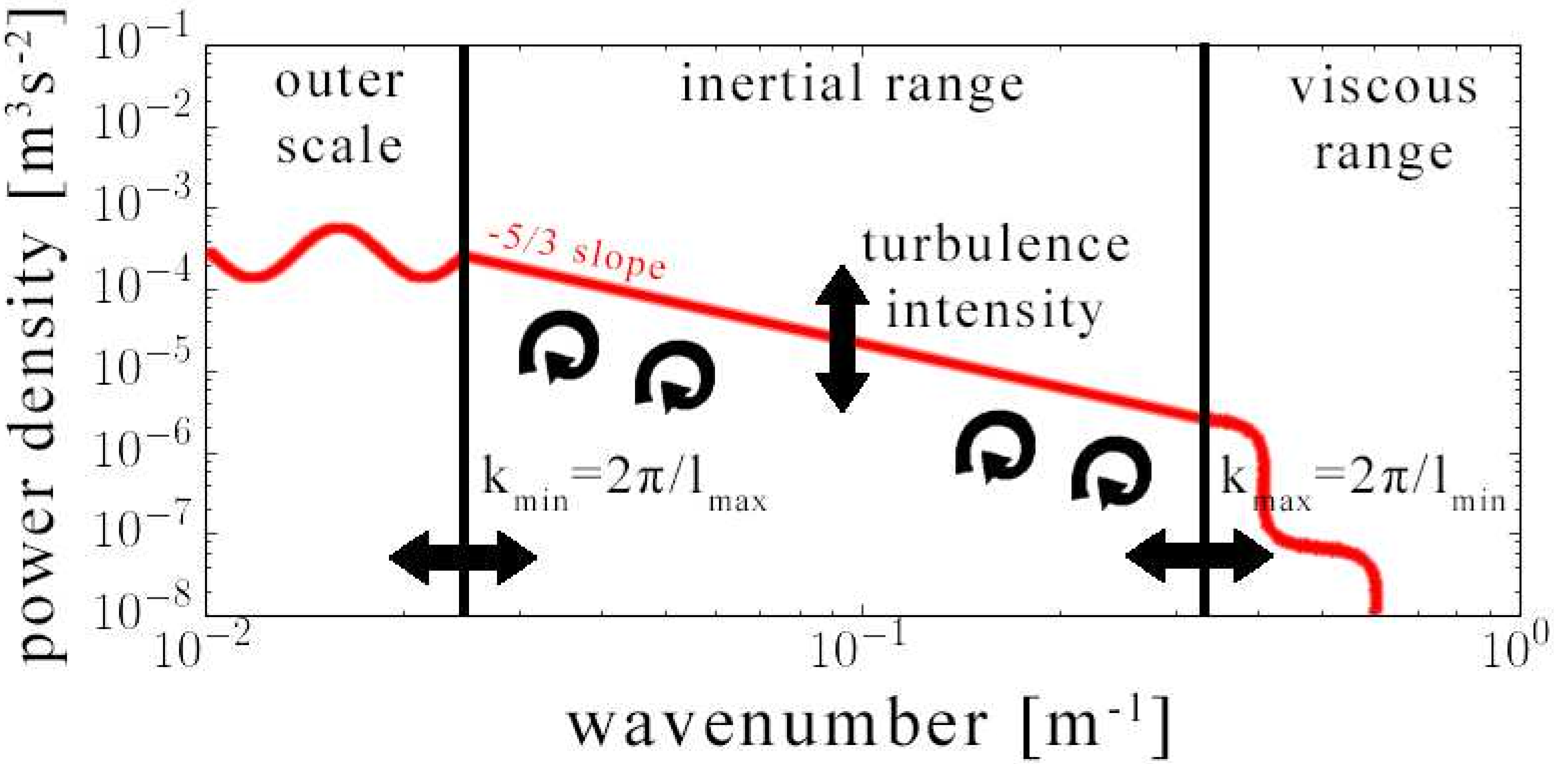
Cascade turbulence model

Basic validation





Cascade turbulence model



Summary:

- Turbulent velocity (u, v, w) defined on $(x, y, z, t) \in \mathbb{R}^4$
- Input: $l_{max}(x, y, z, t)$ and $\varepsilon(x, y, z, t)$
- $l_{min}(x, y, z, t) \ll l_{max}(x, y, z, t)$

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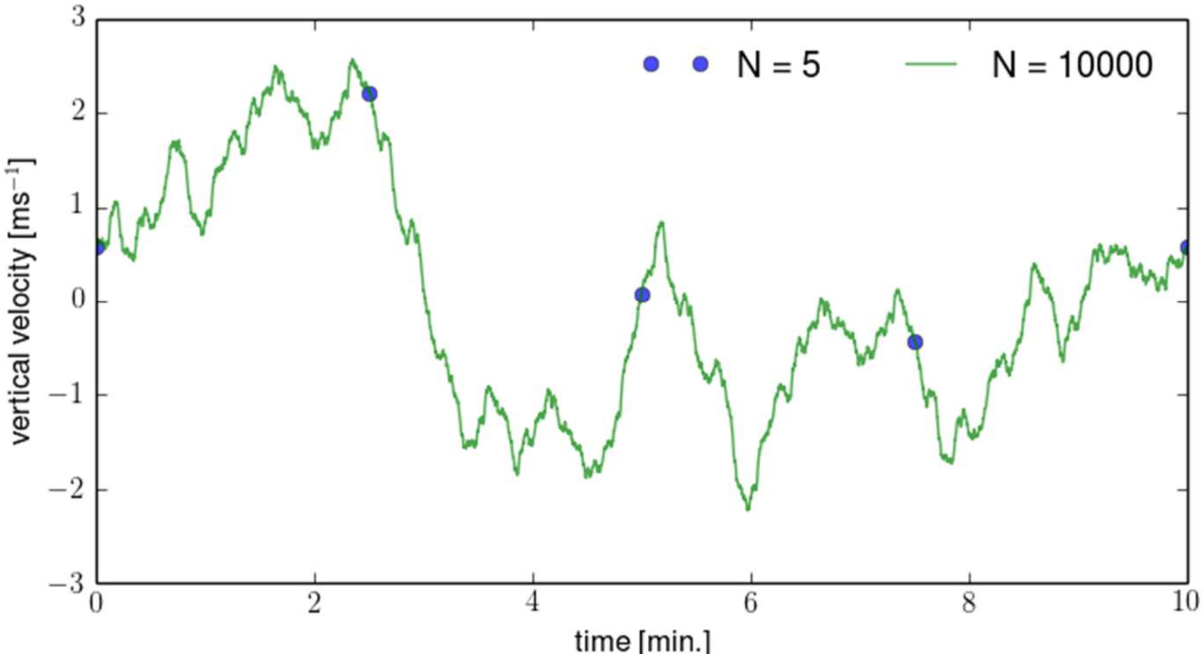
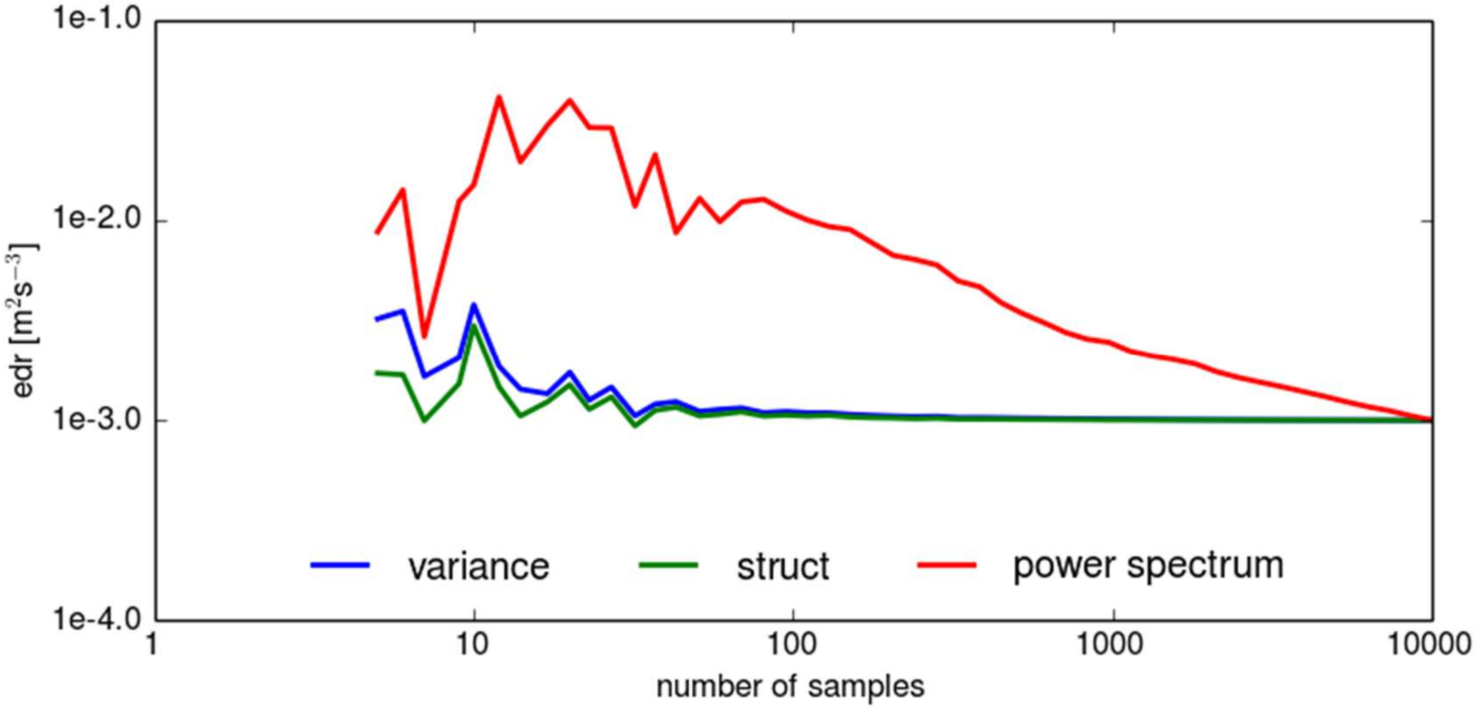
Experiment I: Number of samples

- Number of samples: varying
- Time window: 10 minutes
- Horizontal wind speed: 10 m/s
- Instrument: No noise, no space weighting.
- In the inertial range, $l_{max} = 100\ l_{retr}$



Experiment I: Number of samples

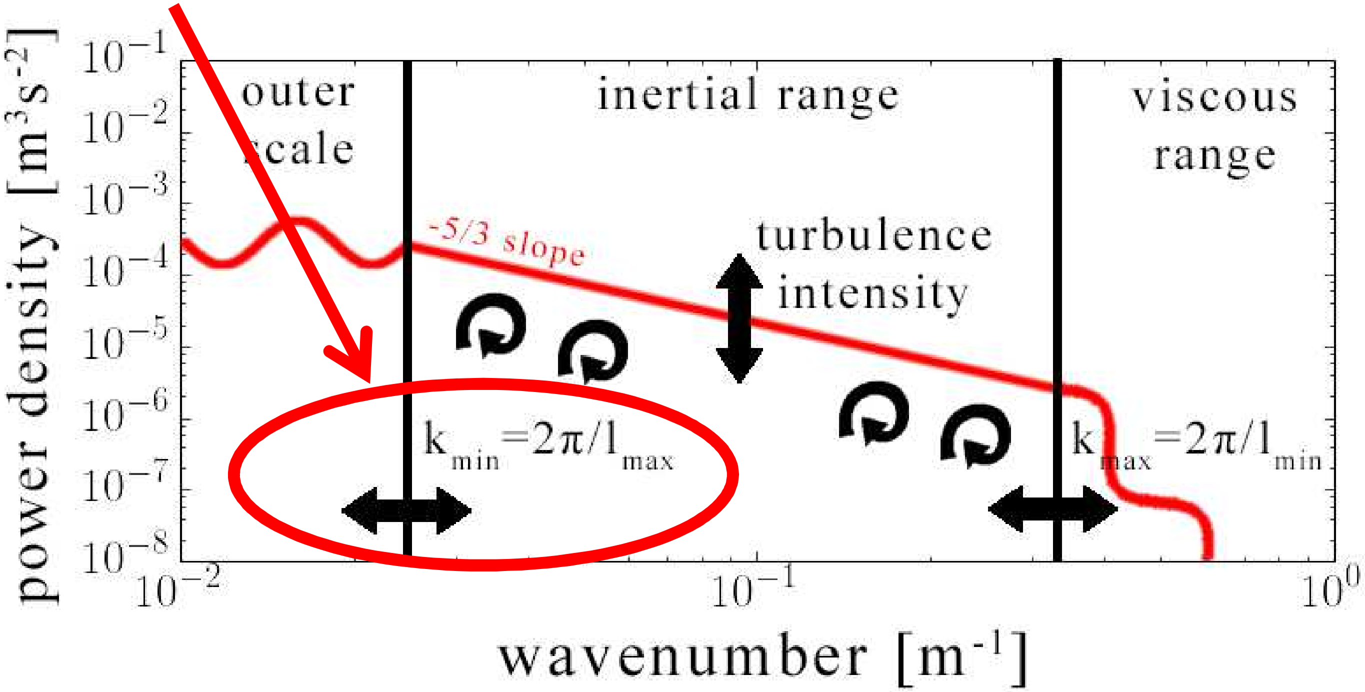


Result:

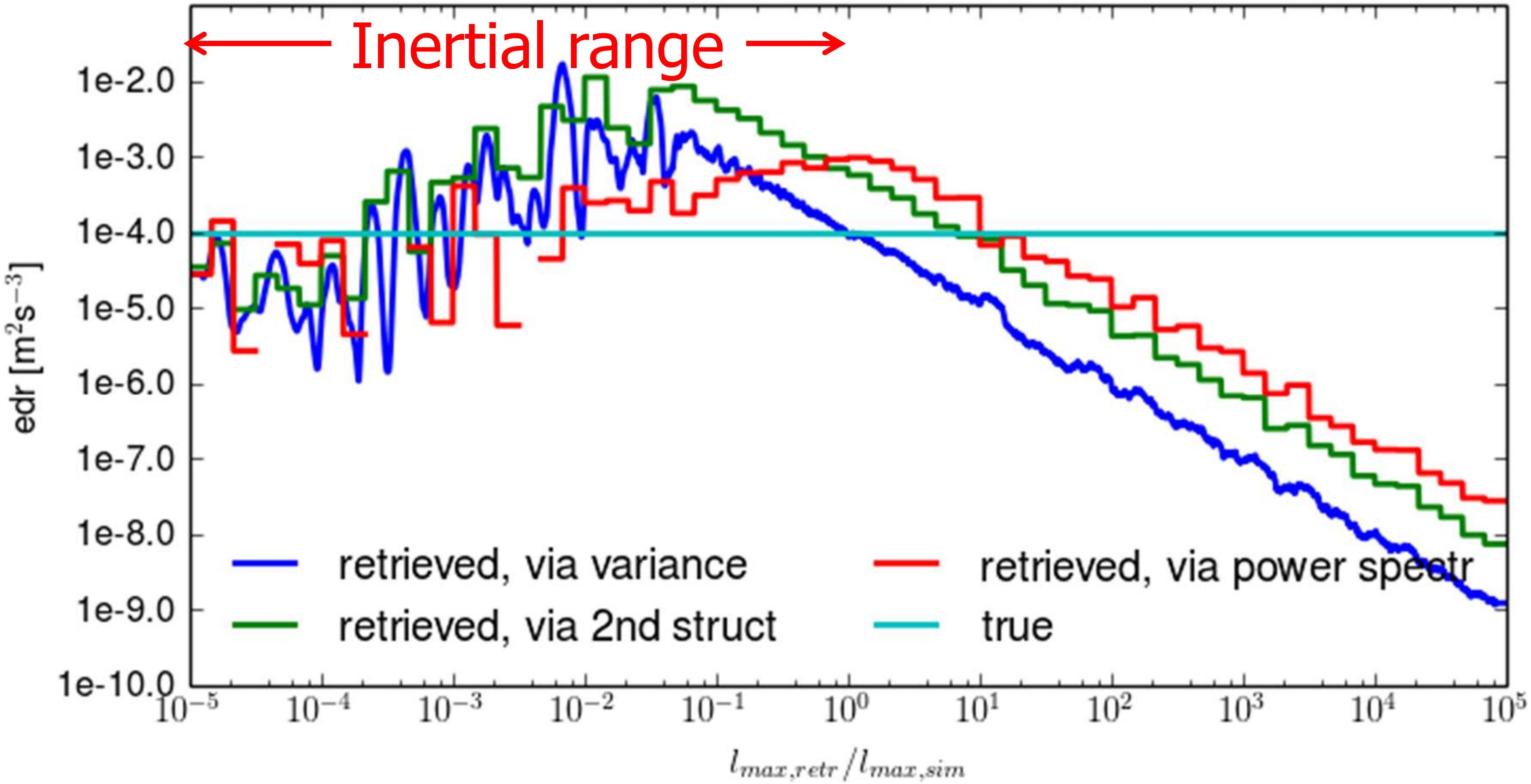
- About 50 samples sufficient for variance method
- About 50 samples sufficient for structure function
- Power spectrum methods has a positive bias and needs much more samples for consistency!

Experiment II: Inertial range check

- Number of samples: 100
- Time window: 10 minutes
- Horizontal wind speed: 10 m/s
- Instrument: No noise, no space weighting.
- l_{max} varying.



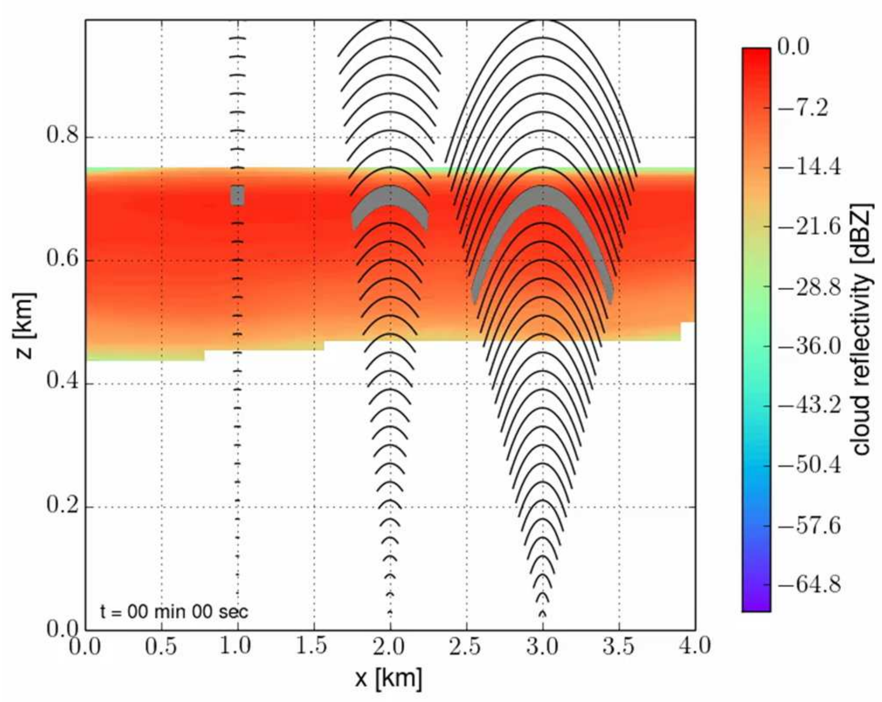
Experiment II: Inertial range check



- Inside the inertial typical error is an order of magnitude
- **Different methods consistent, even outside the inertial range!**

Experiment III: Cloud structure and beamwidth

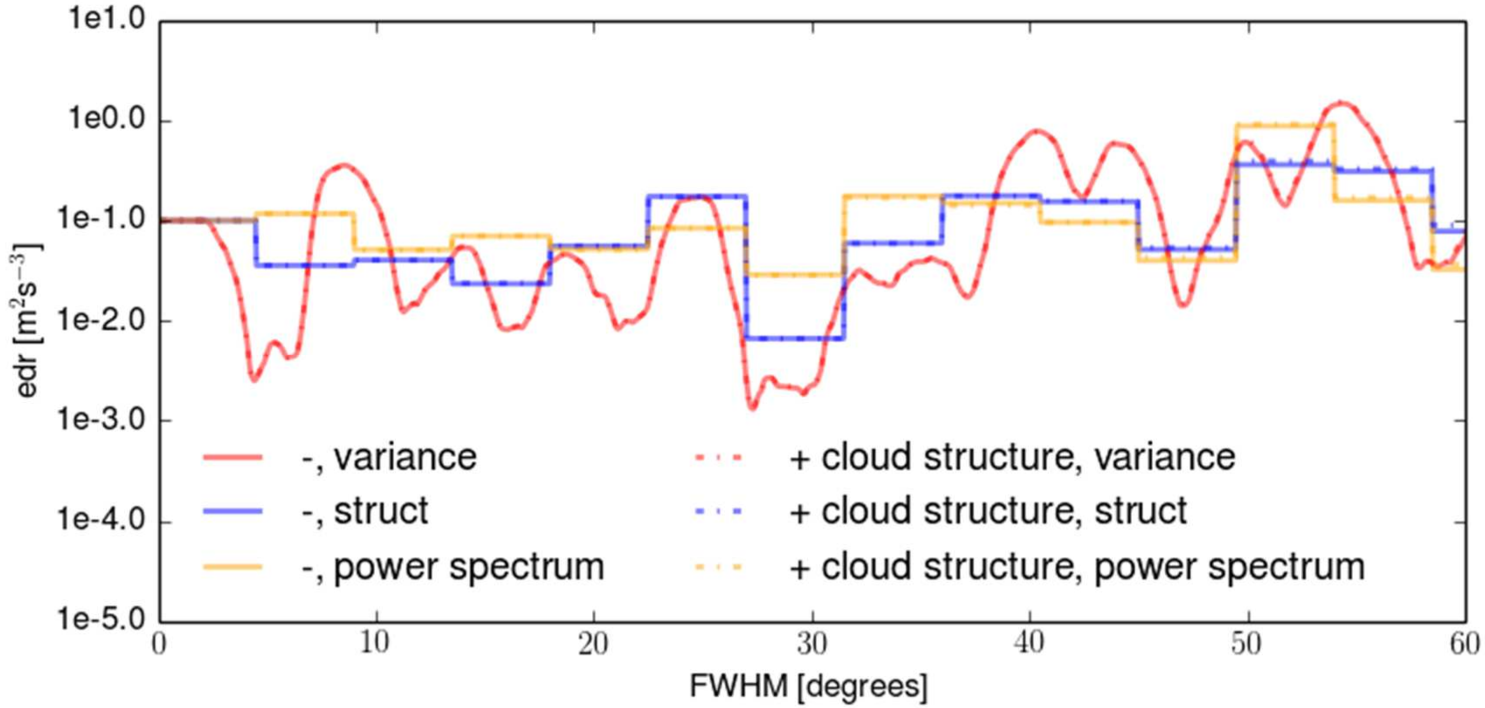
- Number of samples: 100
- Time window: 10 minutes
- Horizontal wind speed: 10 m/s
- Instrument: No noise, vary beam width, cloud structure
- In the inertial range, $l_{max} = 100\ l_{retr}$



Stratocumulus cloud, see Hogan et al. (2005).

dBZ obtained via simple LWC-dBZ relation, see Hagen et al. (2003).

Experiment III: Cloud structure and beamwidth



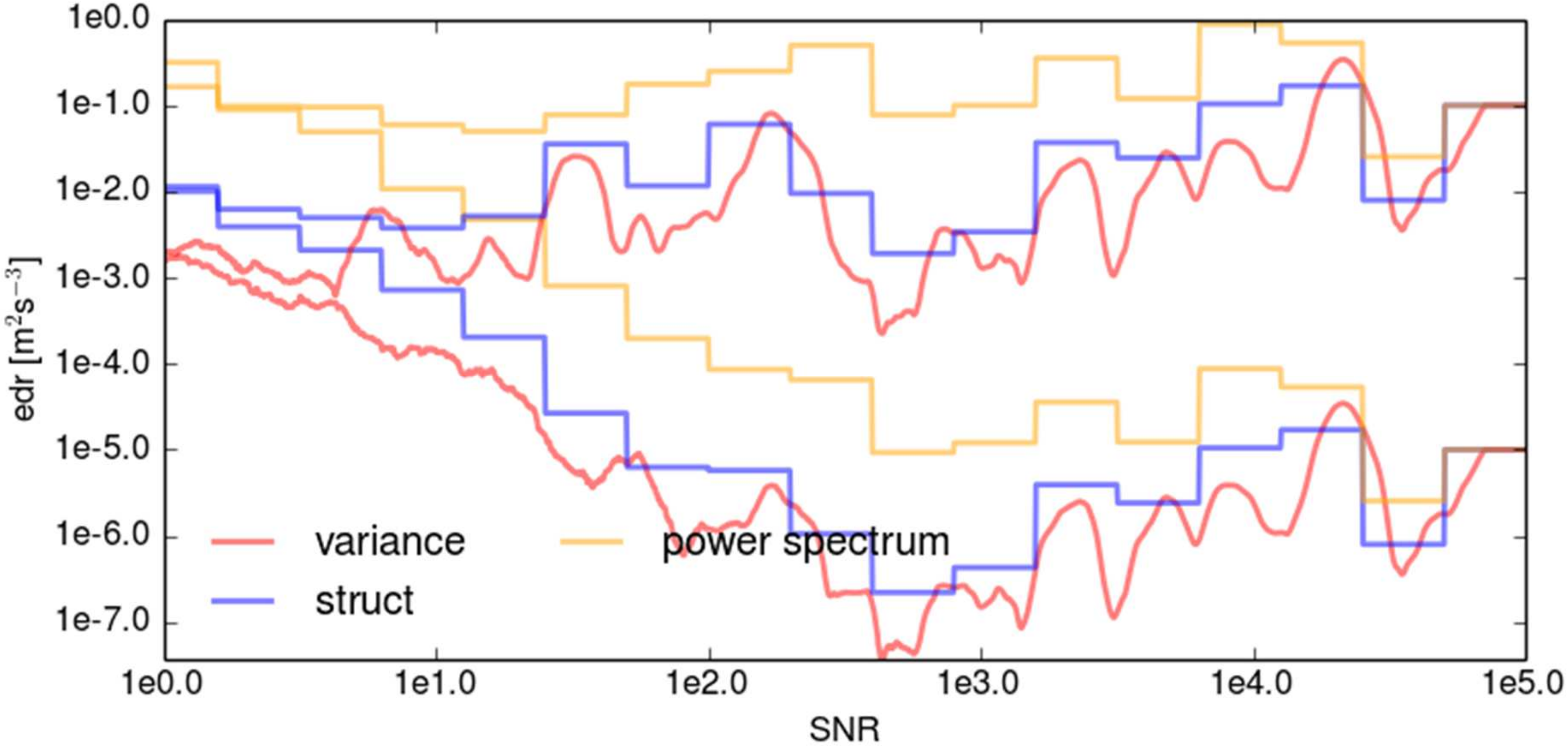
Result:

- With practical all methods EDR is well retrieved.
- Cloud structure or weighting does not prove to be a problem for statocumulus clouds.

Experiment IV: Noise

- Number of samples: 100
- Time window: 10 minutes
- Horizontal wind speed: 10 m/s
- Instrument: Vary noise intensity
- In the inertial range, $l_{max} = 100\ l_{retr}$

Experiment IV: Noise



Result:

- SNR of 100 sufficient for variance and structure method
- SNR of 1000 sufficient for all methods

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- Cascade turbulence model (CTM) is a new tool (under developement) for simple modelling of turbulence.
- CTM can be used for simple turbulence retrieval experiments for radar, lidar and sonic anemometers

- Turbulence nature causes errors in EDR of up to 100%.
- Consistency of methods does not prove anything!
- Stratocumulus cloud structure or beam width has little influence on the retrieved EDR.
- From the available methods, the power spectrum is most challenging. For consistency a high S/R is required and a high number of samples.

- Future work: consider convective clouds; include scatterer modelling.

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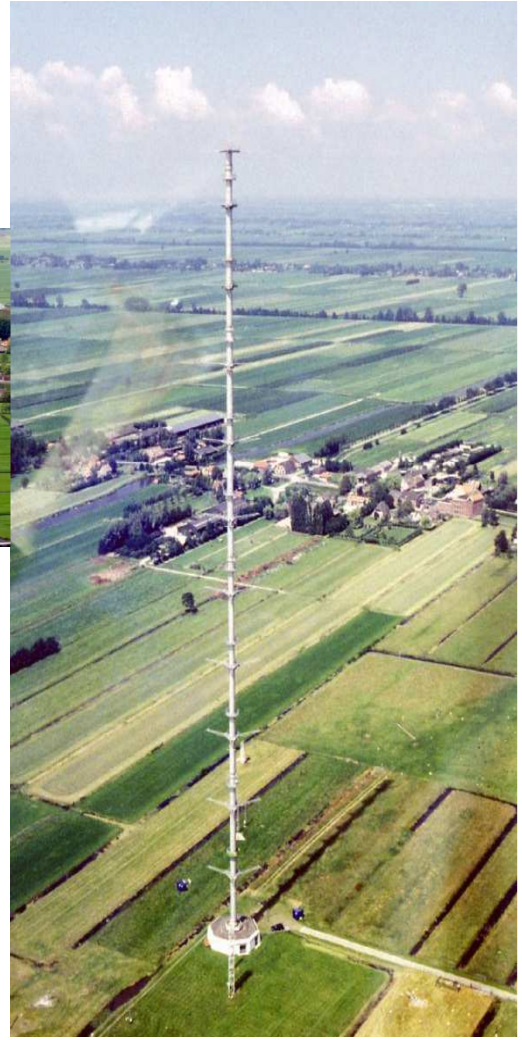
- M. Hagen and S.E. Yutter, “Relations between radar reflectivity, liquid-water content, and rainfall rate during the MAP SOP,” Q. J. R. Meteorol. Soc., 2003.

- Questions?

Backup-slide: Cabauw research site

Atmospheric Profiling between 180 m and ~ 15 km.

Tower with sonic anemometer



330 m

TARA (S-band RADAR) measures the vertical Doppler verlocities at Cabauw.