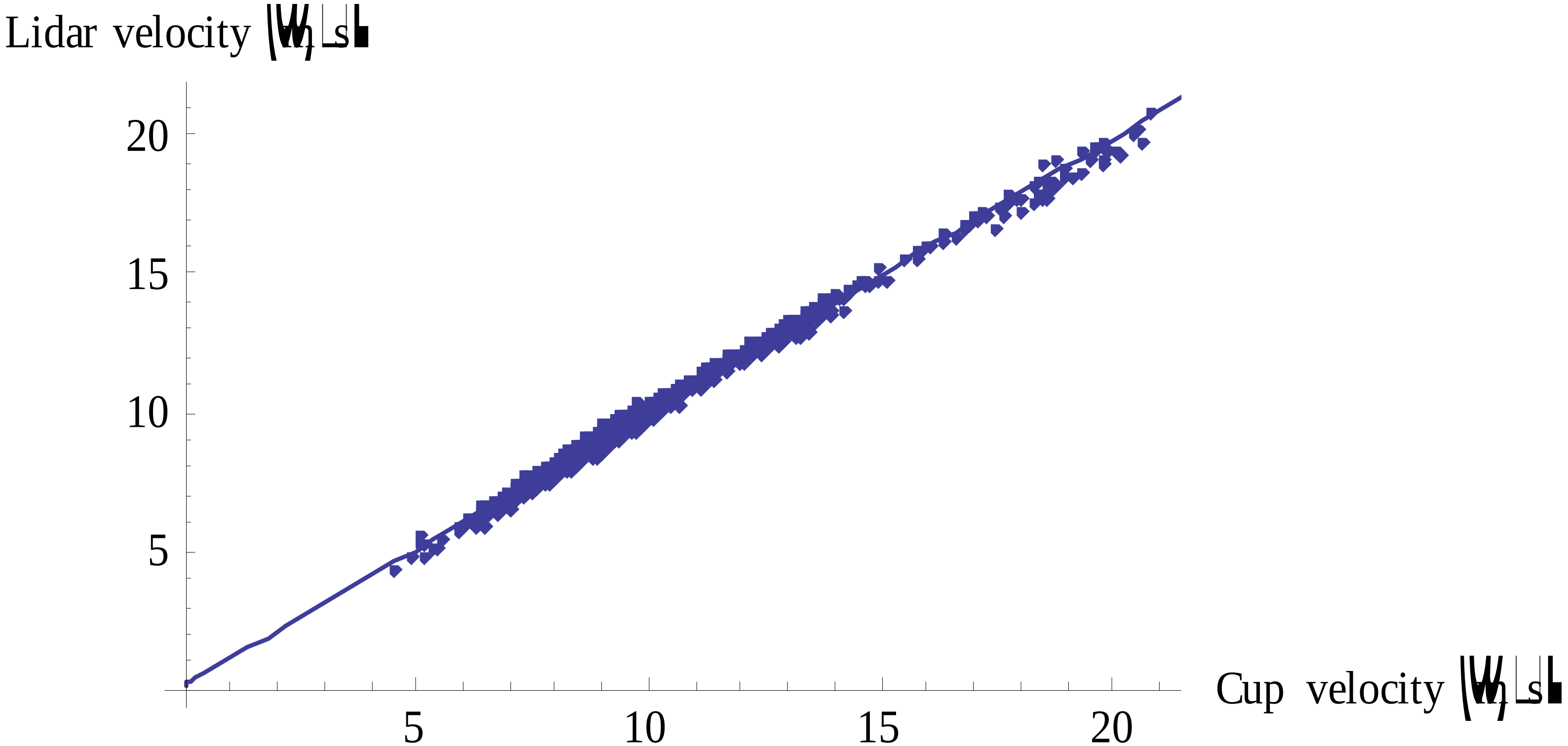
LIDAR PRECISION



Outline

- Plausible sources for biases and deviations in remote sensing of wind with lidars
    - Complex terrain
    - Cone angle errors
    - Altitude errors
- Statistic analysis of lidar-cup comparisons
- The numbers

DTU RISØ

The Basic Coherent Wind Lidar Principle and Verification

$$v_{LOS} = \frac{\lambda}{2} f_{Doppler}$$

Heterodyne detection:

To deduct the radial wind velocity with 1% precision →

Know and maintain λ and meas $f_{Doppler}$ with less than 1% deviation :

Theory: Difficult

Practice: Easy (in fiber), **selfcalibrating** but expensive

Much more to a lidar than heterodyne detection.

Construct horizontal wind velocity from at least three LOS measurements.

Know angles better than 0.3°, know altitude better than 5 m

Assume laminar flow (at least on average)

Theory: Simple geometrics

Practice: Not so easy, needs veification

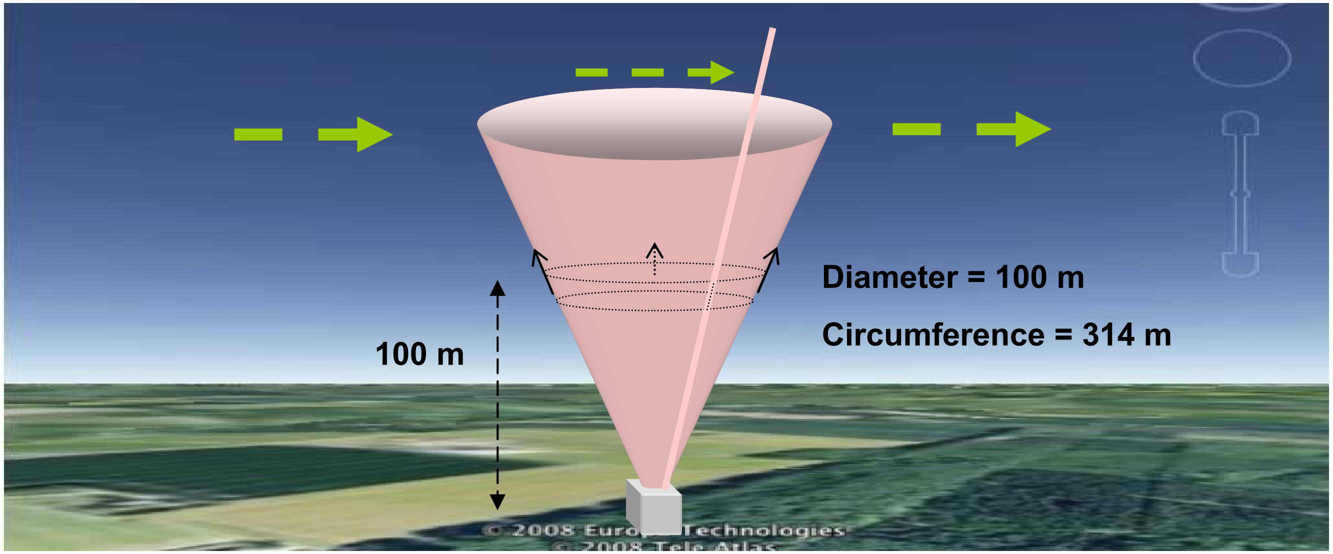
Standard Deviation from a ”perfect” lidar

Flat terrain, perfect conically scanning lidar.

<u>Constructing the u vector:</u>

Inhomogeneous flow over scan perimeter

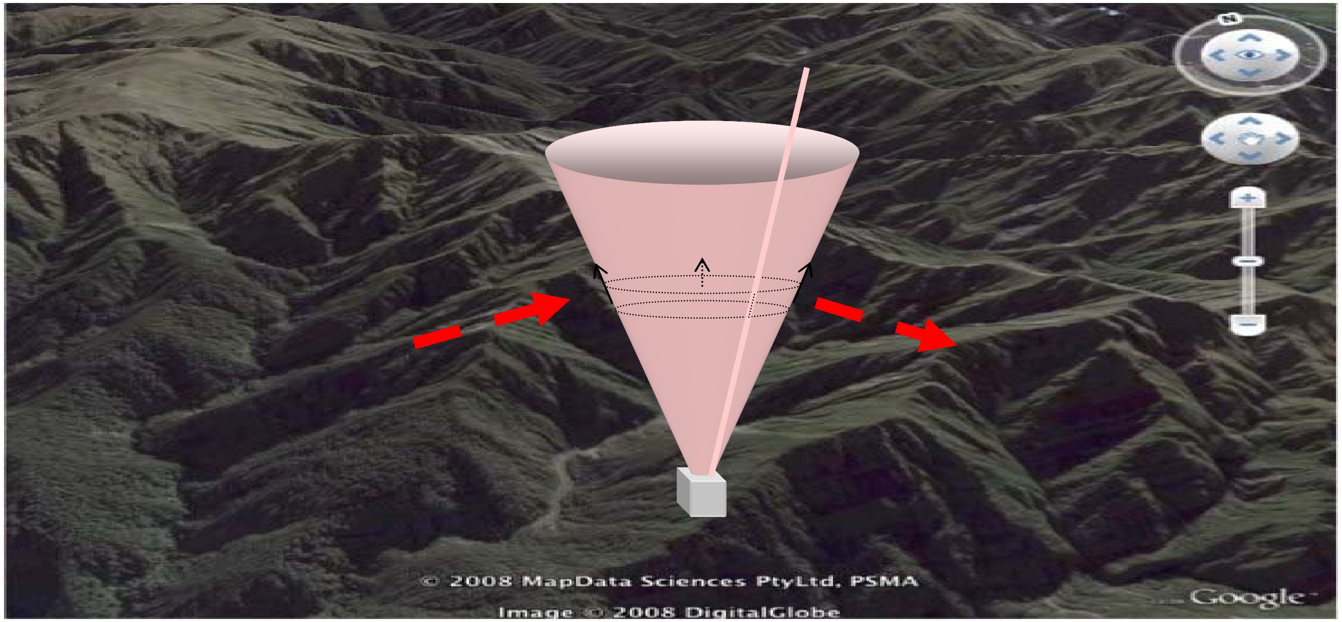
Spatial differences:	Zephir: 50 directions	Windcube: 4 directions
Time difference:	Zephir: 1 s/revolution	Windcube: 6 s/revoltion



In average over flat terrain **no BIAS** but introduction of a **standard deviation** which **depends on the turbulence at the site**.

BIAS from a ”perfect” lidar

Complex terrain, perfect conically scanning lidar.



The accuracy of the constructed horizontal wind velocity drastically decreses with the complexity of the terrain.

Moderately complex terrain: 10-20% bias in cup comparisons
Different errors in different directions. Site specific.

Lidars can, to some degree, self-evaluate the complexety of the flow

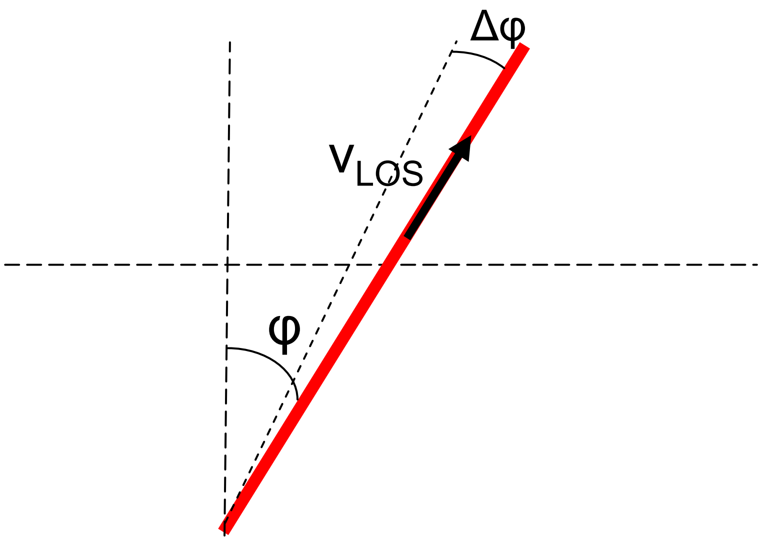
Bias due to error in cone angle

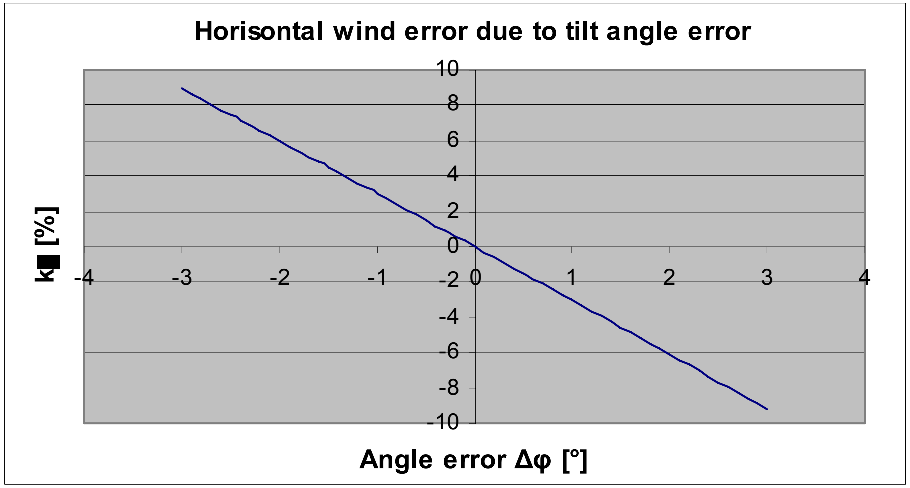
Assumption for now, vertical wind = 0

$u_1 = v_{LOS}/\sin(\varphi)$

$\Delta\varphi < 0.3°$ → <1% wind velocity error

$$\varepsilon_{lidar} = \left(\frac{\sin(\varphi - \Delta\varphi)}{\sin(\varphi)} - 1 \right) \cdot u$$





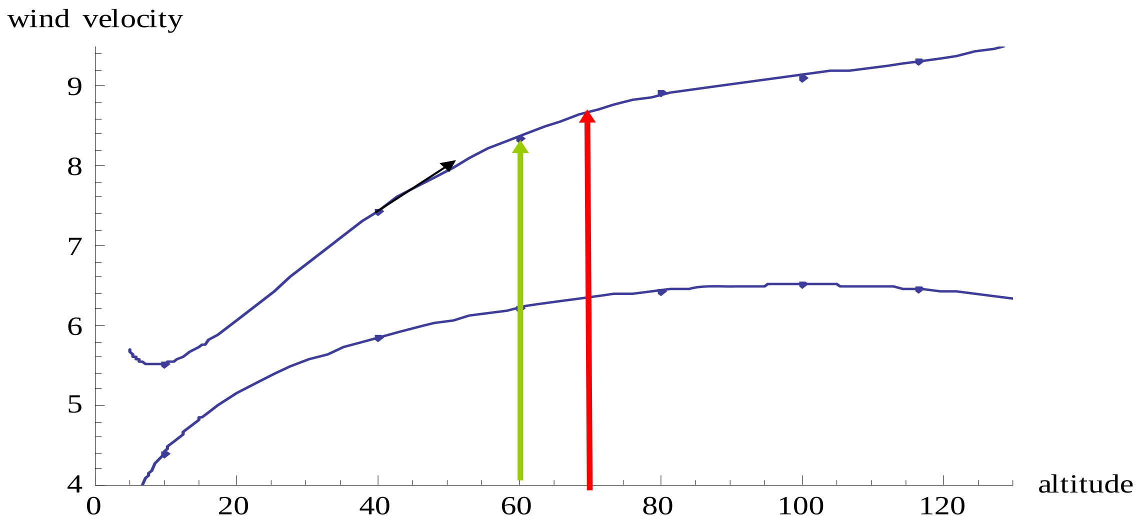
Error in cone angle →

Error proportional to u

which is similar at all heights

Also introduces altitude error

Altitude errors



Stronger positive wind shear → More overestimated wind velocity

Error with + 5 m in altitude → 0.03*5 = 0.15 m/s positive bias

Small errors in altitude can give significant wind velocity bias

Limited altitude errors →Linear relation between lidar error and wind shear

Random due to atmosphere, biases due to machine (?)

Wind shear dependencies

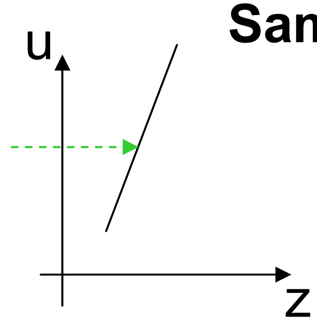
The significantly contributing sample volume lenght ≈ 50 m

Projected vertically ≈ 50 m cos(30) ≈ 40 m

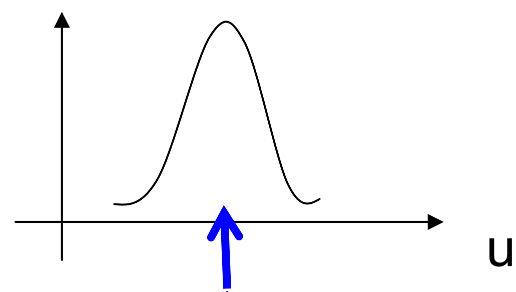
Typical shear 0.04 m/s per m altitude → Wind spectrum width ≈ 1.5 m/s.

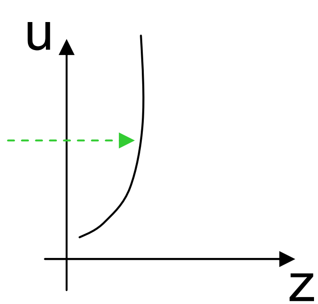
Estimator: Selects one velocity, e.g by centroid or peak of a fitted function.

Same wind at cup height, different shear

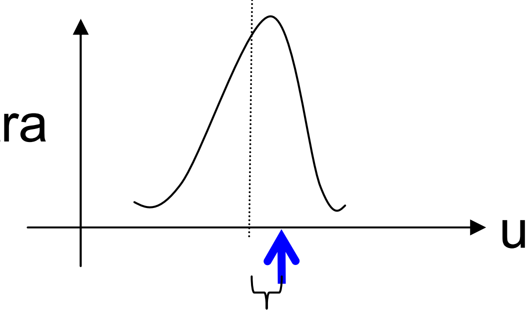


Linear shear →
Symmetric wind spectra





Non-linear shear →
Non-symmetric wind spectra



Non-linear (?) dependency on wind shear

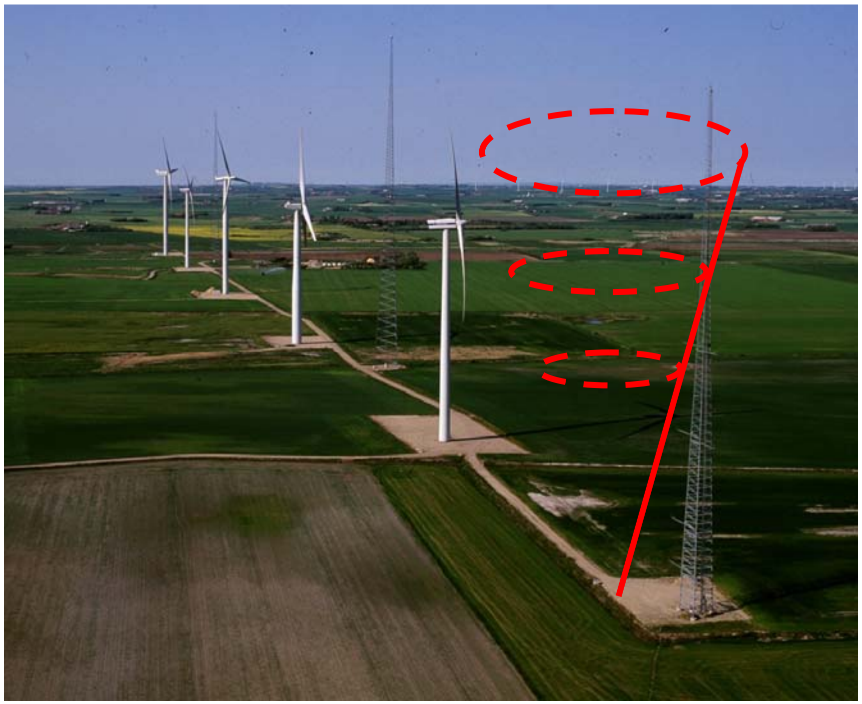
Plausible error sources in lidar sensing: Due to "atmosphere"

Error	Implication	Magnitude	Which instrument
Turbulence Spatial and temporal	Standard Deviation No bias in flat terrain(?)	< 0.1 m/s in Høvsøre?	Conically scanning
Complex terrain	Complex errors Direction dependent biases	Depends (10-20%)	Any one unit system More directions, more options
Rain	Bias on w Standard deviation increase	? From 15 to 50 cm/s	Both
Clouds	Typically positive bias	Mitigated with cloud correction (but gives σ?)	Zephir
Inhomogenuous aerosol distribution (backscattercoeff and correlation duration)	Random distribution Standard deviation Depletion or propagation losses Negative bias	? ?	Both, Zephir more sensitive(?)
Shear in sample volume	Probably overestimation for typical shears	Minor?	Both
…			

Plausible bias sources in lidar sensing: Due to ”machine”

Error	**Implication**	**Which instrument**	**Which instrument**
Error in scan angle	• Gain • Altitude Errror	• +- 3 % < 2 m	Windcube and Zephir (mitigated in 2008?)
Error in center of sample volume	Altitude error	< 5 m in Zephir < 10 m in Windcube	Zephir: Focus error Windcube: Range gate distortion, trigger offset and/or unsymmetric pulse shapes
RIN	Positive Bias for low LOS velocities	Low for wind >4 ms	Zephir
Chirp in pulse	Offset in radial, but solved in construction of u	< 0.5 m/s	Windcube
System tilt	Small gain and irregular altitude errors.	Minor?	Windcube and Zephir
…			

Testing LIDARs in Høvsøre



Høvsøre Large Wind Turbin Test Facility

- West coast of Denmark, flat terrain, wide range of horisontally homogeneous wind speed.
- Site equipped with rain and cloud sensors
- **14** Zephirs and Windcubes tested
- **45** months of comparison with class 1 cup anemometers @ 40-116 m (160 m)
- Data from 2 other flat sites evaluated

Definitions and Data sets

10 min horizontal wind speed averages

Lidar Error = lidar-cup at intended height

Mean, STDEV (σ)

Dependencies vs wind speed, wind shear

Residual analyses

<u>Data screened on :</u>

Rain

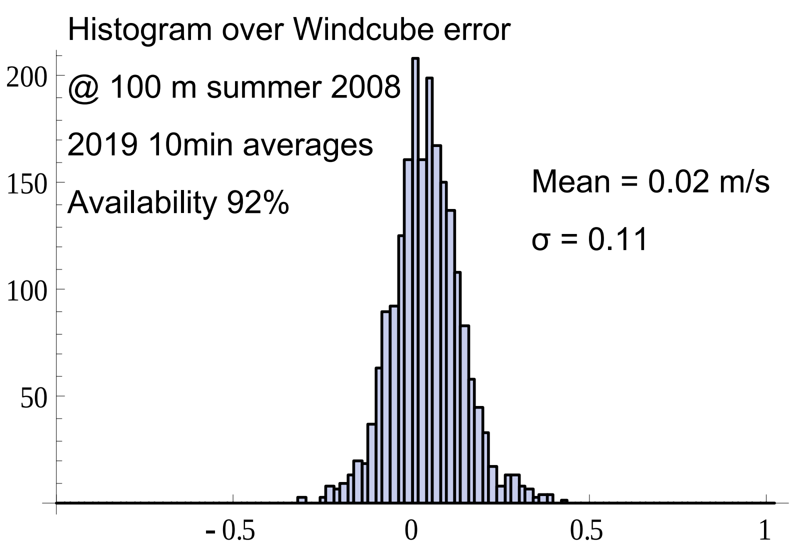
Clouds (when cloud correction inactive)

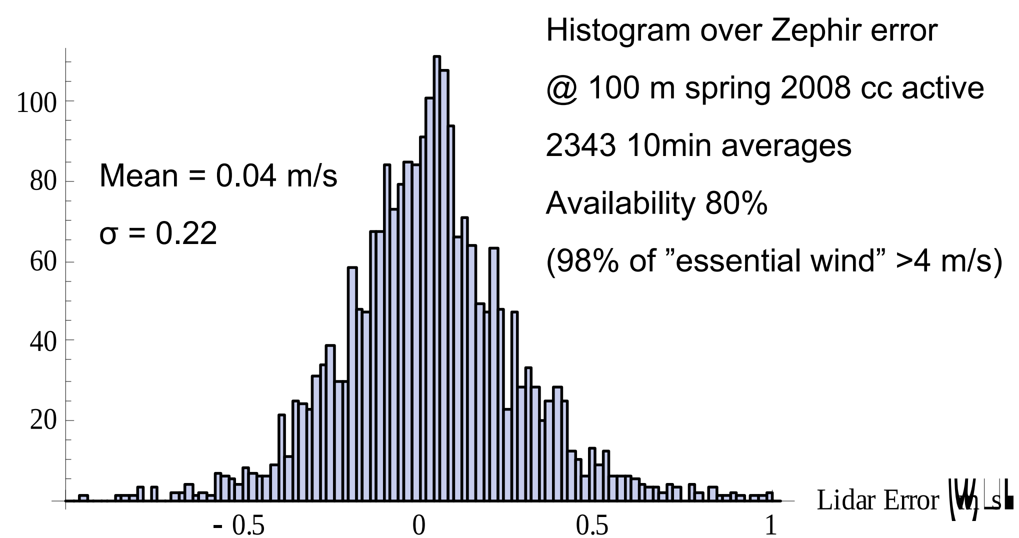
Undisturbed wind directions

Min wind speed >4 m/s for Zephirs

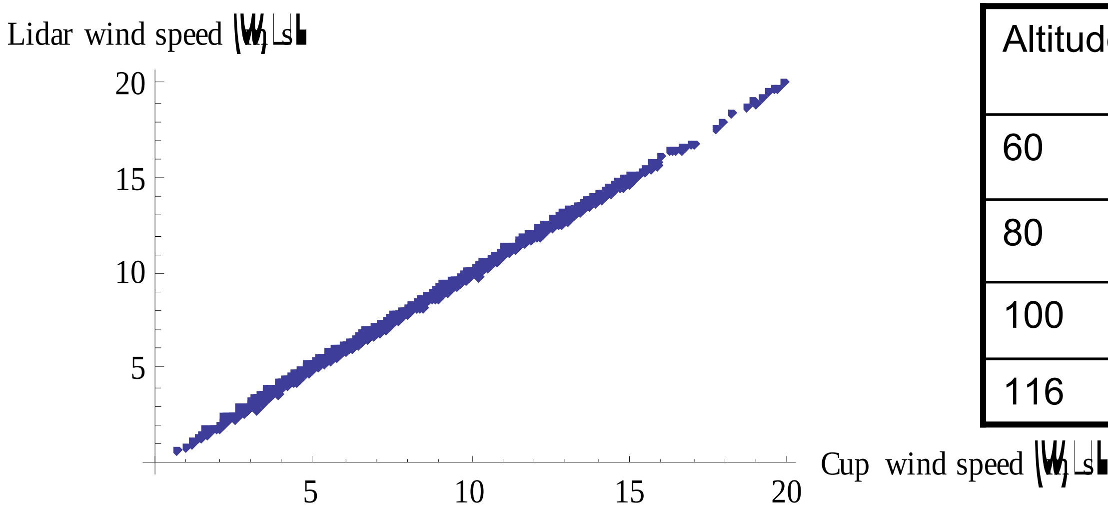
10 min recovery ratio >80% for WC

State of the art in remote wind sensing accuracy 2008

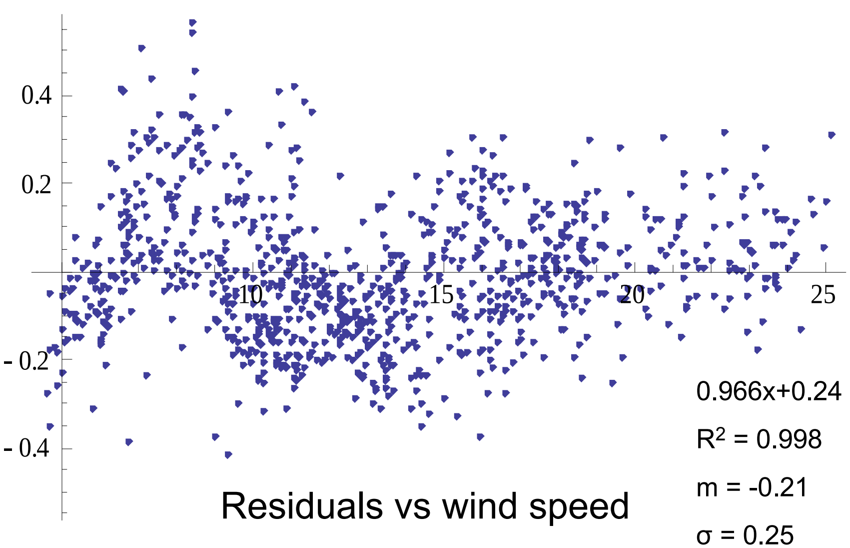


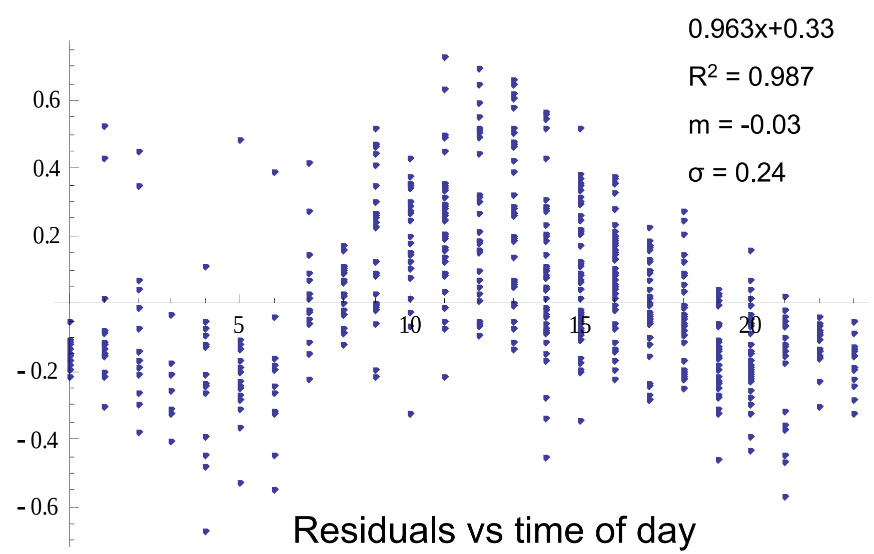


Limitations of linear regression plots



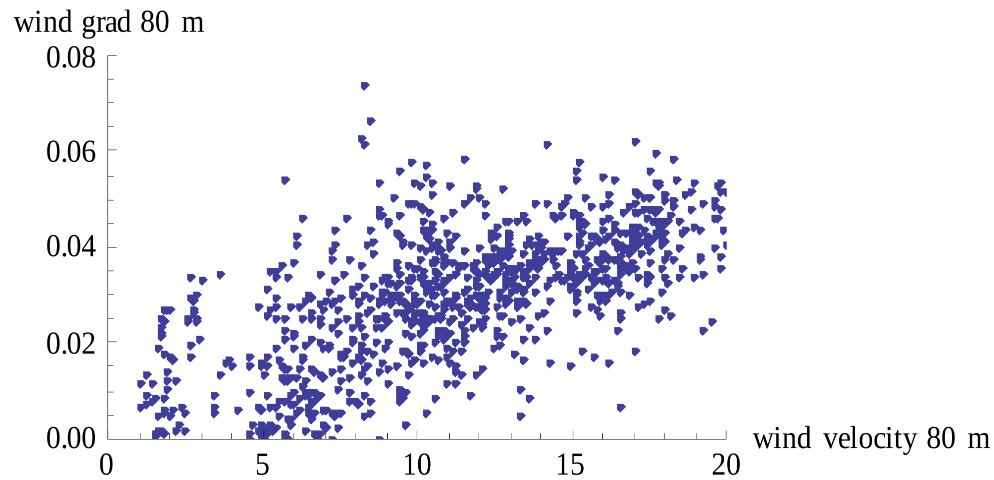
Altitude	Gain	Offset [m/s]	R^2	Availability [%]
60	1.000	0.06	0.999	0.92
80	0.994	-0.01	0.998	0.92
100	0.997	0.06	0.999	0.92
116	0.979	0.24	0.998	0.91

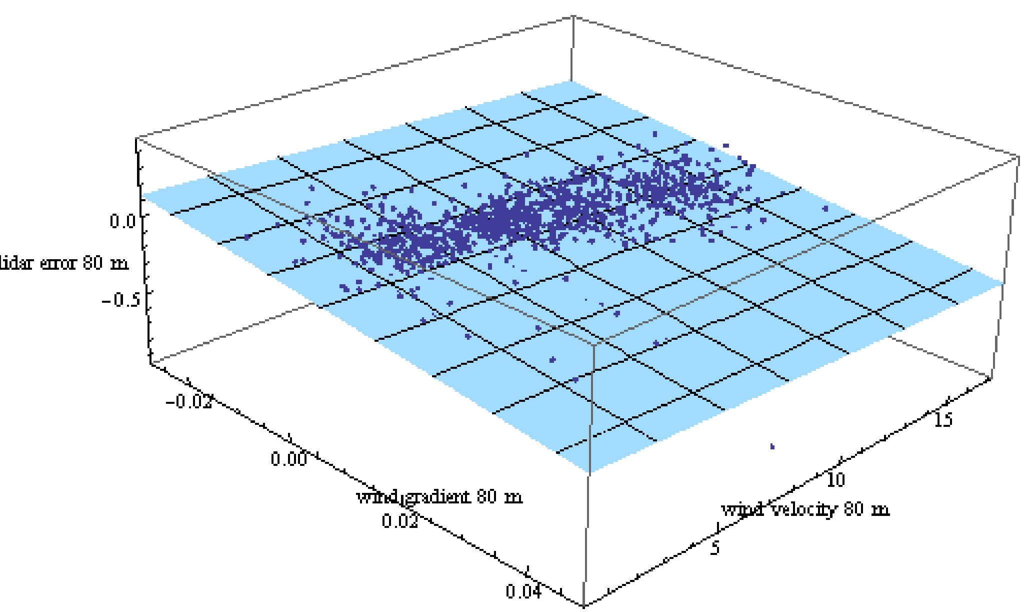




Wind shear dependency example

Wind shear and wind velocity are typically not uncorrelated:
2-parametric regression analysis.





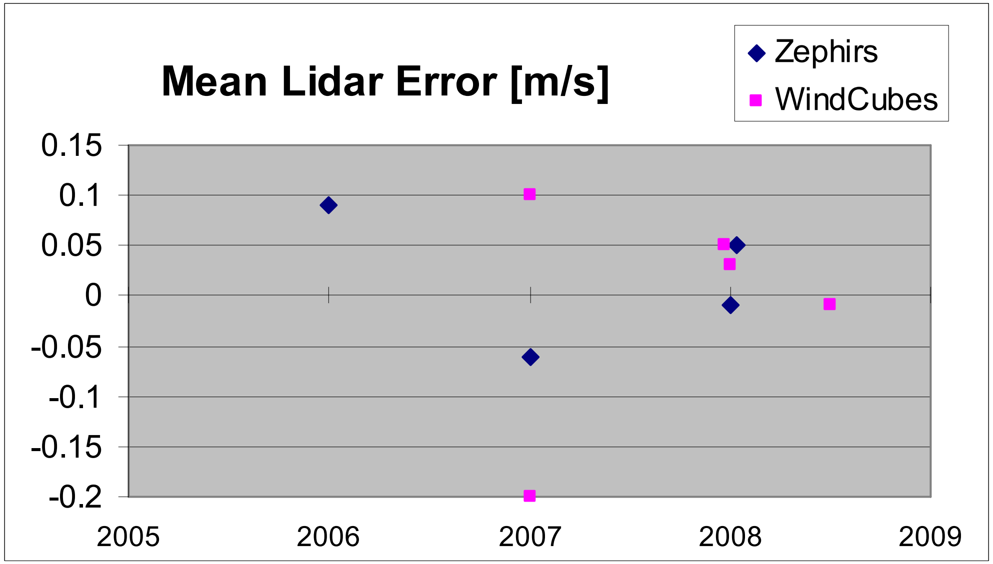
Windcube @ 80 m summer 2008
Non-conclusive
(Low shear period < 0.25m/s per meter)

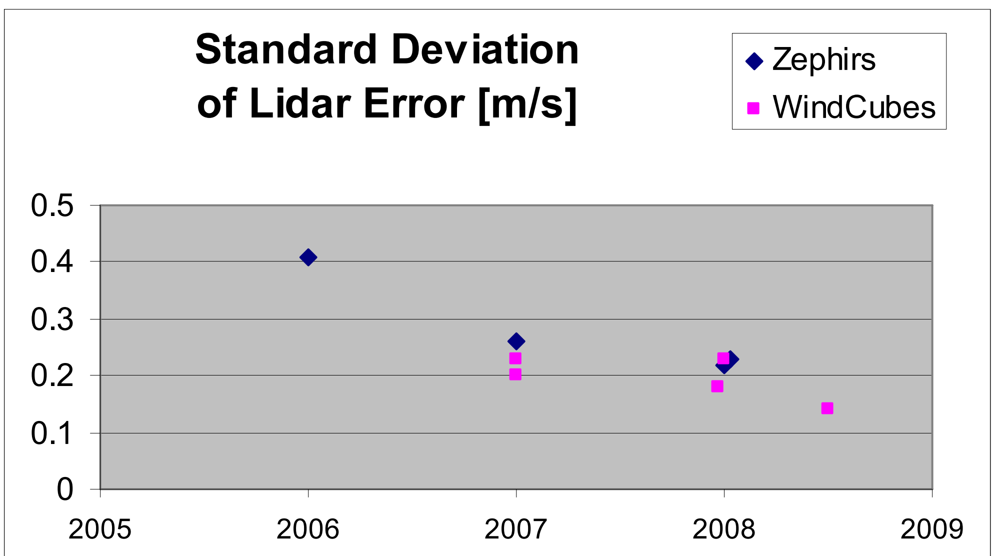
"Altitude error": - 4.2 ± 1.1 m
"Cone angle": 0.7 ± 0.2 %

Zephir @ 80 m spring 2008

"Altitude error": - 4.0 ± 0.7 m
"Cone angle": - 2.9 ± 0.3 %

Development of Wind Sensing Lidars





2006: Zephir commercial model introduced. Hardware issues.

2007: Ceilometer installed, screening on clouds: positive bias and σ reduced, availability drops.
Leosphere introduces Windcube.

2008: Cloud correction: availability increases.
Cone angle accuracy: bias reduced.

2008.5: ?.
Estimator improved: nonlinear problems reduced.
Introduction of the Windicator

Mean < ~±0.05 m/s σ ~0.25

Mean < ~±0.05 m/s σ ~0.15

Conclusions: Precision and Biases in Lidars 2008

Typical results in flat terrain 2008

- **Mean:** **< 0.1 m/s**
- **STDEV:** **< 0.25 m/s**
- **Gain:** **< ± 2%,** observed [-6 to +2%] mitigated
- **”Altitude” error:** < **± 5 m** observed [-6 to +9]

Complex terrain → Complex errors observed 10-20%.

Conically scanning lidar concept (soon) mature for stand alone site evaluation in flat terrain! (?)

However is the hardware and the price, include power supply and repairs?

Can they offer added value?

Does lidars need calibration/verification/audit?

Heterodyne detection is selfstabilizing, lidars are not.

Hardware calibrations/verifications + acceptance tests traceable to cups on masts.

Conclusions: What should be done before (and is ongoing)

”The other lidar challenge”

- **Perform rigurous analysis, with tolerances, of plausible lidar errors**
  - Find good statistical measures which can reveal them

- **Determine the required accuracy in 2008 standards** Estimate their influence in the full chain of Annual Energy Production predictions: wind measurement, correlation to a wind atlas, forecasting of future winds and the measured power curve. Cost/benefit calculations for the different techniques.

- **Evaluate the added value lidars can offer in future standards** Taking into account the wind over the whole rotor area in AEP predictions.

- **Establish complex terrain warning flags**

- **Find complex terrain solutions:** WindScanners or combinations with flow modeling.

SUPPORT SLIDES

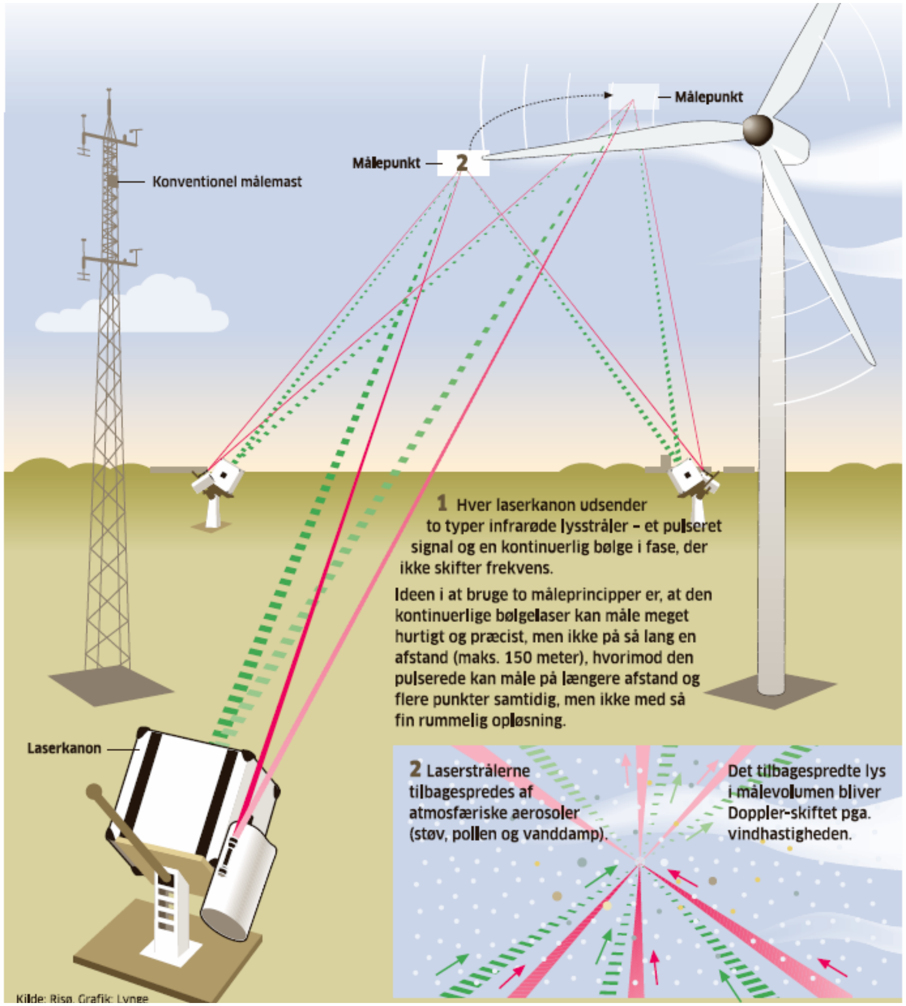
- The WindScanner
- Complex Terrain, some numbers
- Turbulence
- Clouds
- Rain, the numbers
- Power Curves
- Wakes

WindScanner (Torben Mikkelsen)

For u and w: LOS measurements in at least three directions.

One conically scanning lidar

1 LOS measurement at **3** locations



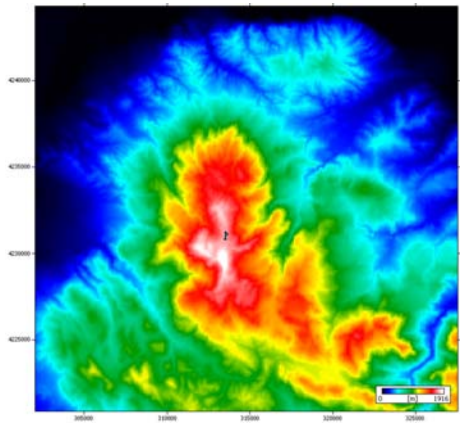
www.windscanner.dk

Three Zephirs, (fast scanning ability)

3 LOS measurement at **1** locations

- Complex terrain
- 2D fields in rotor plane.

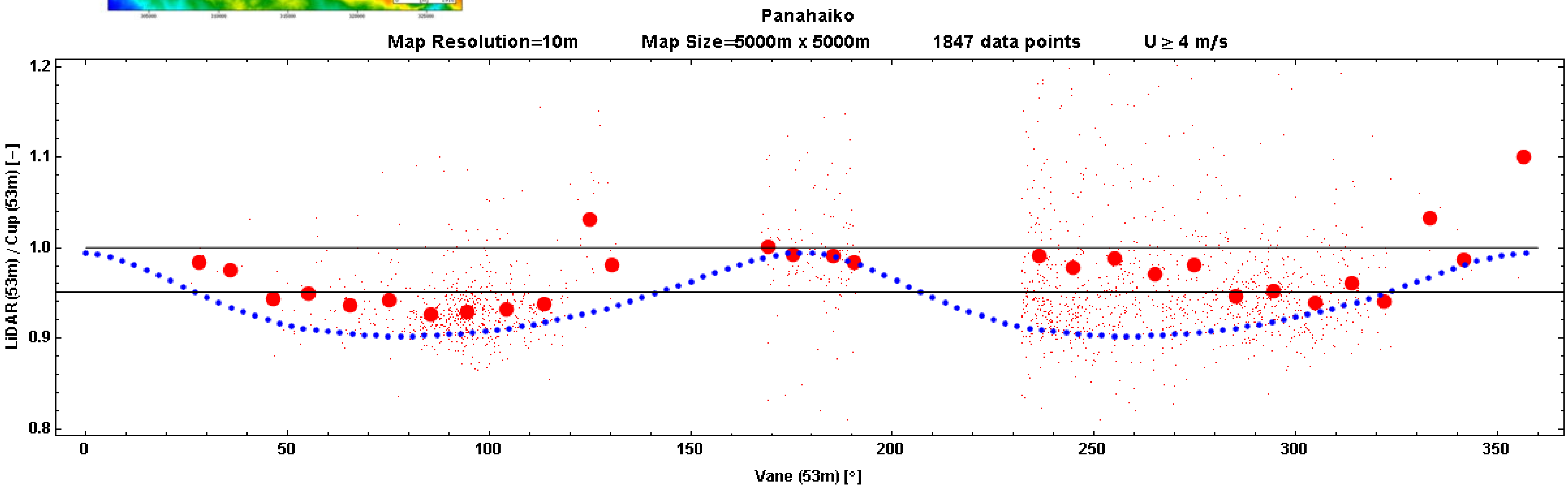
Complex terrain (Ferhat Bingöl)



Panahaiko, Greece

Very complex site

Mast-lidar comparison



Measurement results and WEng predictions for. Small size red dots are 10 minutes averages. Big red dots are the averages in 6° wind directions. Blue line is the WEng error predictions.

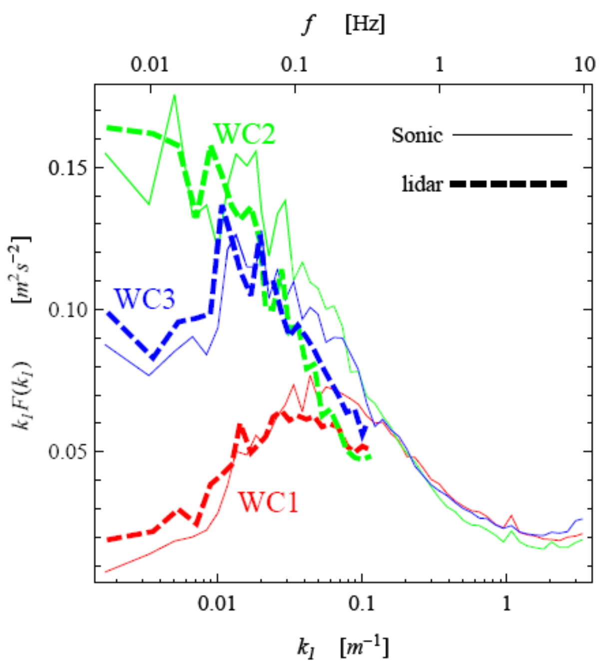
Turbulence (Jakob Mann)

<u>Different ways to asses turbulence with lidars:</u>

1 Look at the time series of the U.

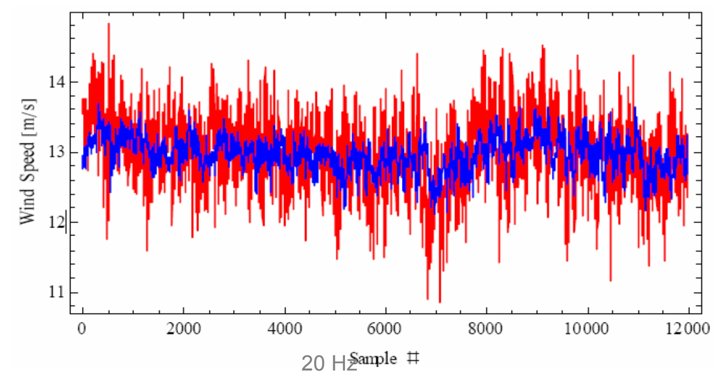
2 Look at difference in opposite directions, or figure of eight fit

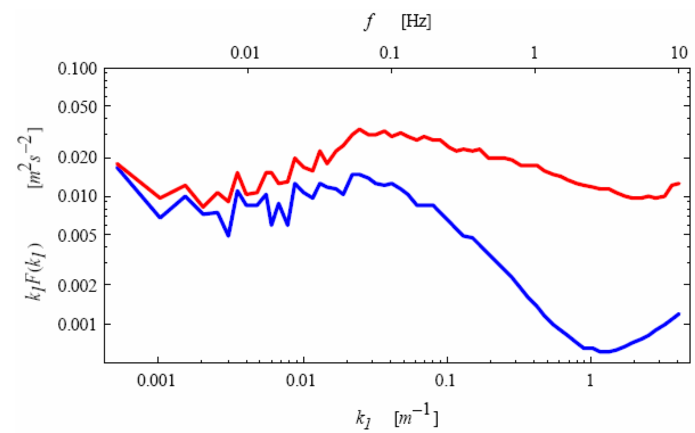
3 Look at spectral width of Doppler spectra



Spectra measured by three WC and the spectra of the corresponding component of the sonic velocity vector.

Zephir prototype 138 m





red: Sonic wind speed in Zephir direction.

Blue: Zephir radial wind speed

Clouds (Non-conclusive)

Due to the non-finite sample volume of the Zephir.

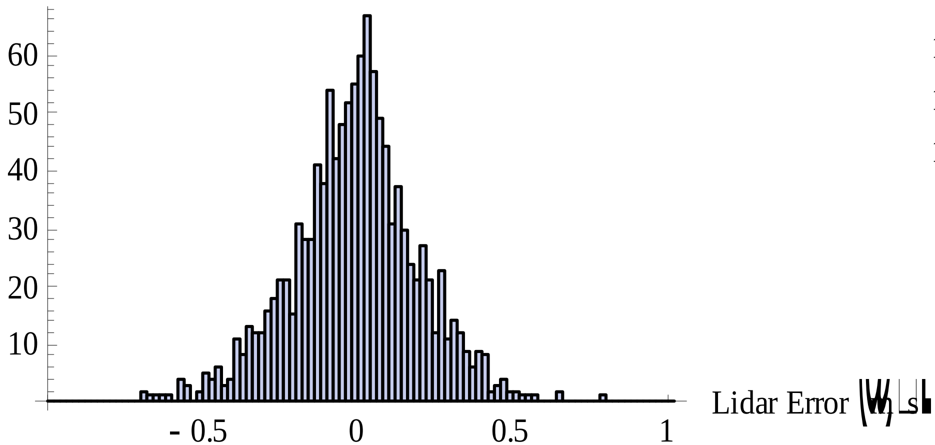
Sensitivity increases with altitude.

If untreated gives positive bias.

1 Get ceilometer and screen on cloud base (lower availability)

2 Use cloud correction (get slightly higher stdev but probably no bias)

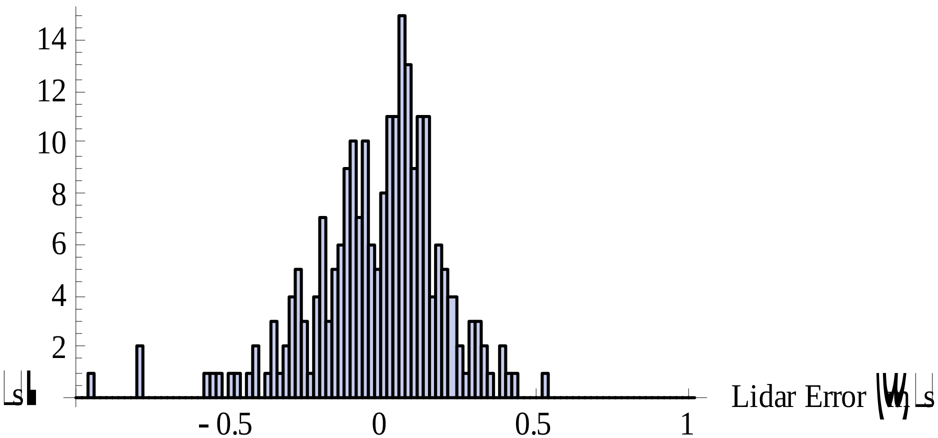
Cloud base >2.5 km



100 m : σ = 0.2   m = -0.01

0.23 – 6.1 m -2.4%

Cloud base < 1 km



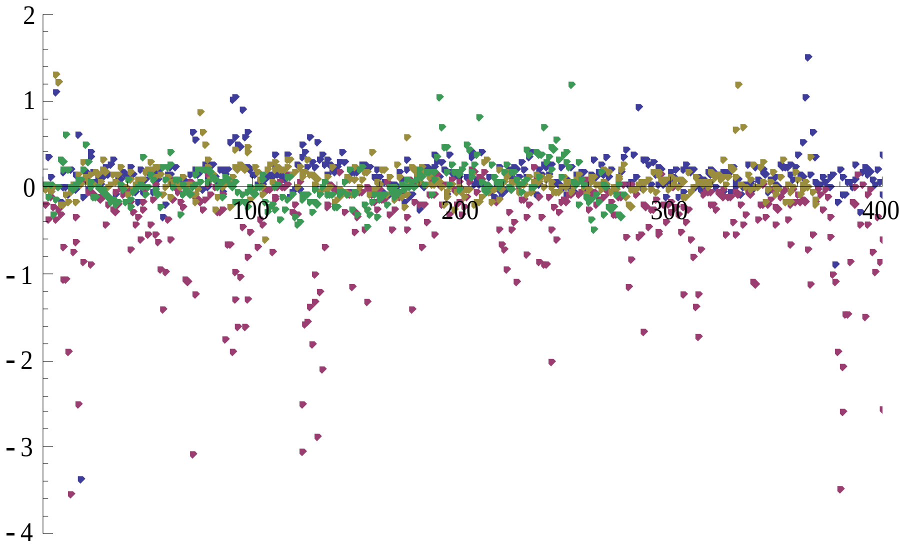
100 m : σ = 0.22   m = -0.02

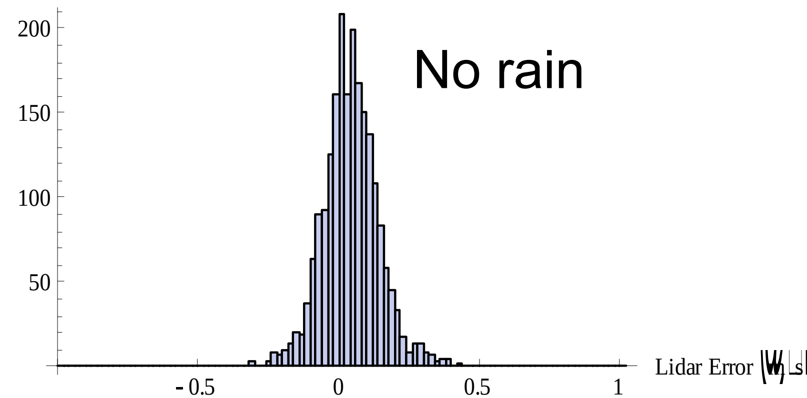
0.22 + 1.7 m -3.0%

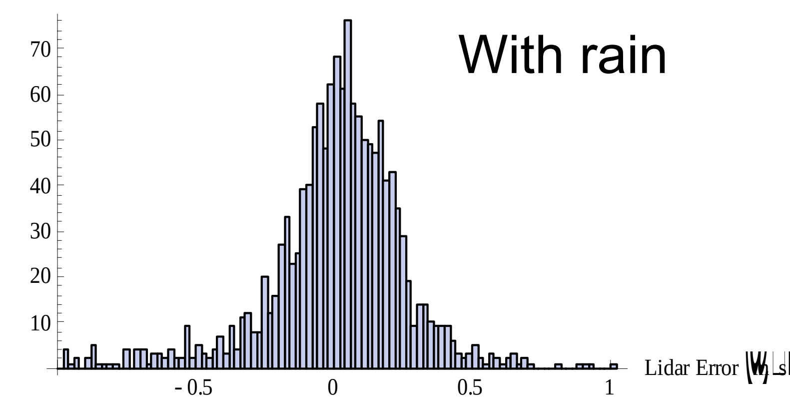
Rain

Standard Deviation of Windcube error during rain: 0.46 m/s (0.15 m/s)

Mean Error of Windcube error during rain: -0.04 m/s (-0.01 m/s)







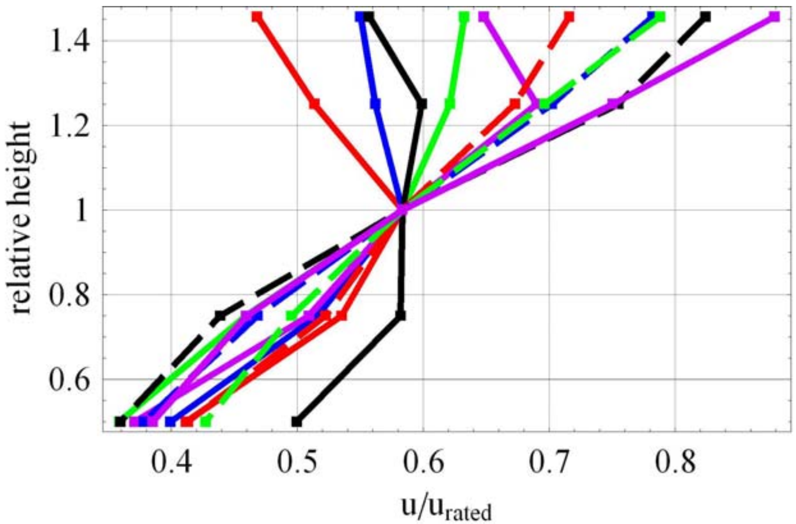
Purple: WIndcube @ 80 m

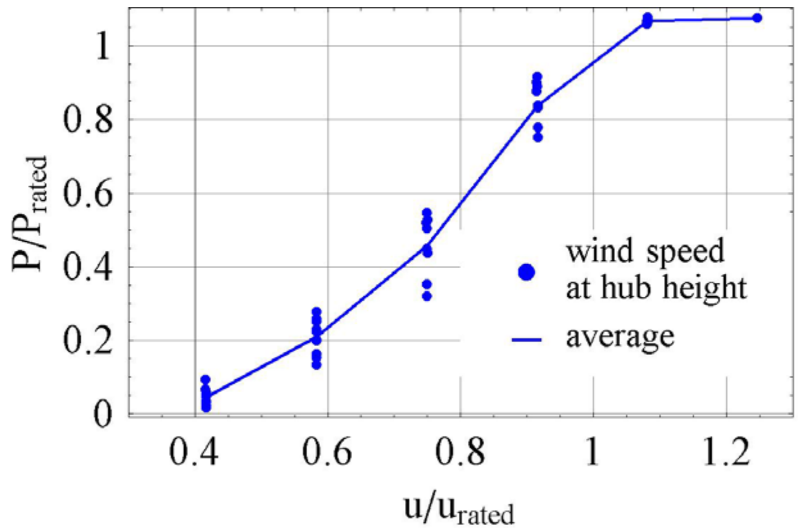
More negative than 60, 100, 116 m?

Not the case without rain.

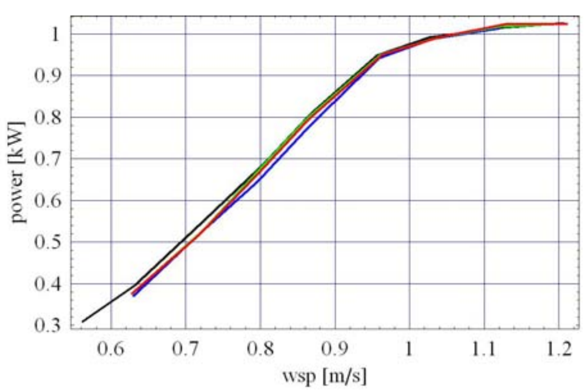
Power curves (Non-conclusive) (Rozenn Wagner)

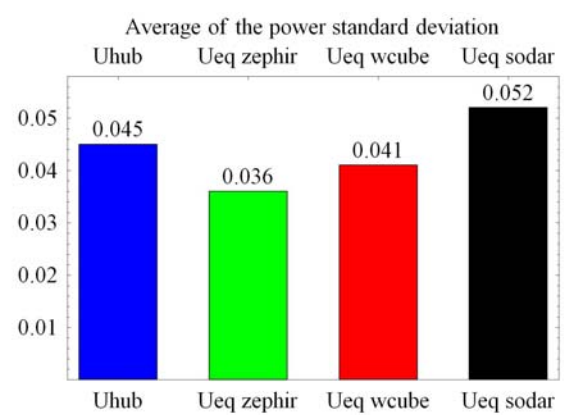
Incentive





Are lidars good enough for power curves? Are power curves good enough for lidars?





Wakes (Ferhat Bingöl)

2D scanning after turbine, Conceptual study

Date 2005–11–15 Time 20:20 Number of Scans 81113

LiDAR				Turbine				Met.Mast							
WS [m/s]				Yaw [°]				WS [m/s]				WD [°]			
Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev	Mean	Min	Max	StdDev
7.66	3.17	12.40	1.58	282.0	267.0	294.0	4.9	9.12	6.51	11.50	1.05	286.0	271.0	294.0	7.3