Wind Physics Measurement Project
SS 2016

Lecture 4:
Lidar measurements

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Outline

- Introduction
- Continuous-wave and pulsed Lidar
- Vertical profilers
- Advanced applications
- Summary
- Task

Introduction

Lidar: Light detection and ranging

- Remote sensing device (like radar)
- Several types and applications of Lidar:
  - Lidar speed guns used by the police
  - Elevation maps by airborne Lidar
  - Lidar for distance measurements in physics and astronomy
  - Lidar for wind energy
- Wind Lidars are Doppler Lidars

Lidar systems

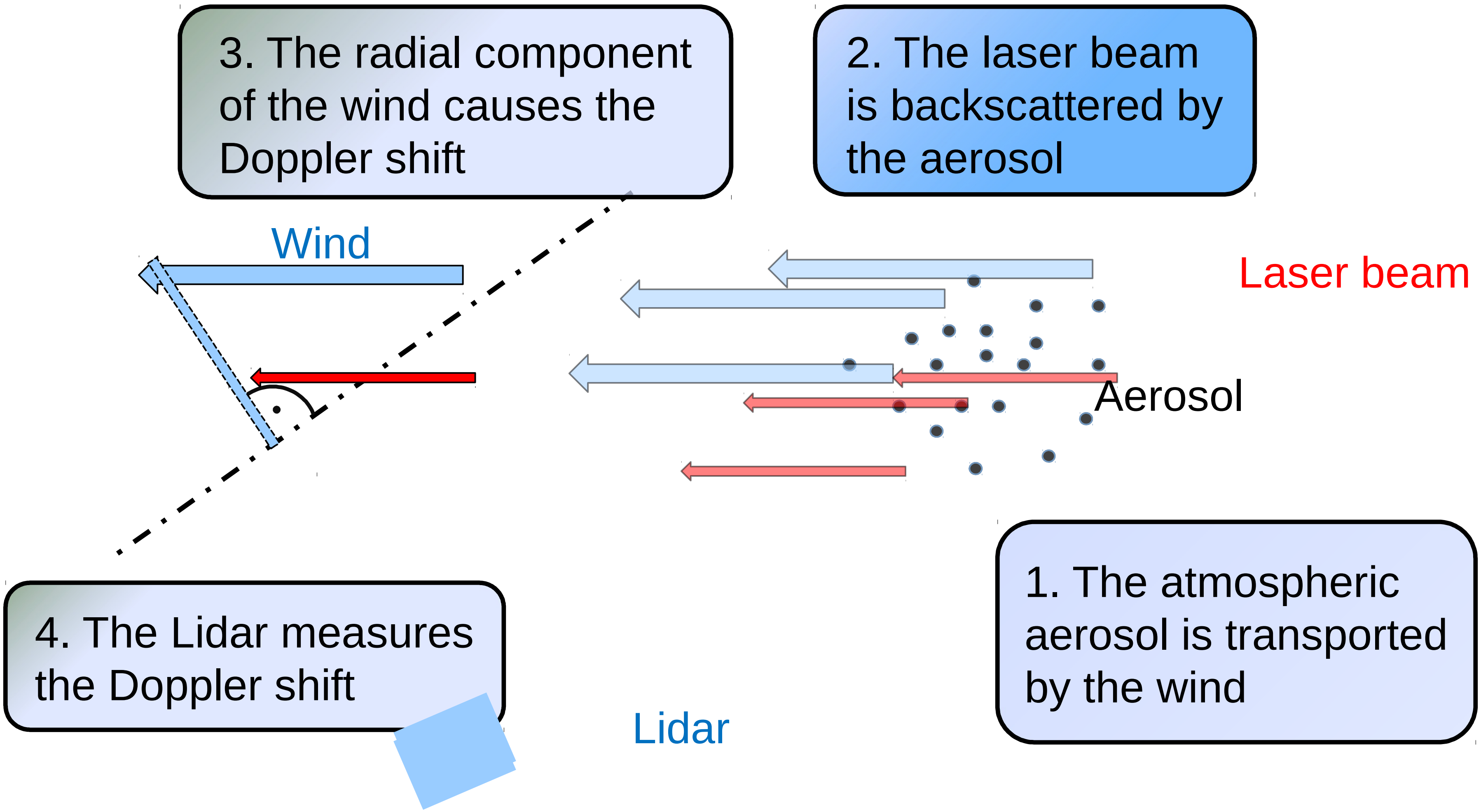

[Fig.:Zephir]

[Fig.:DTU]

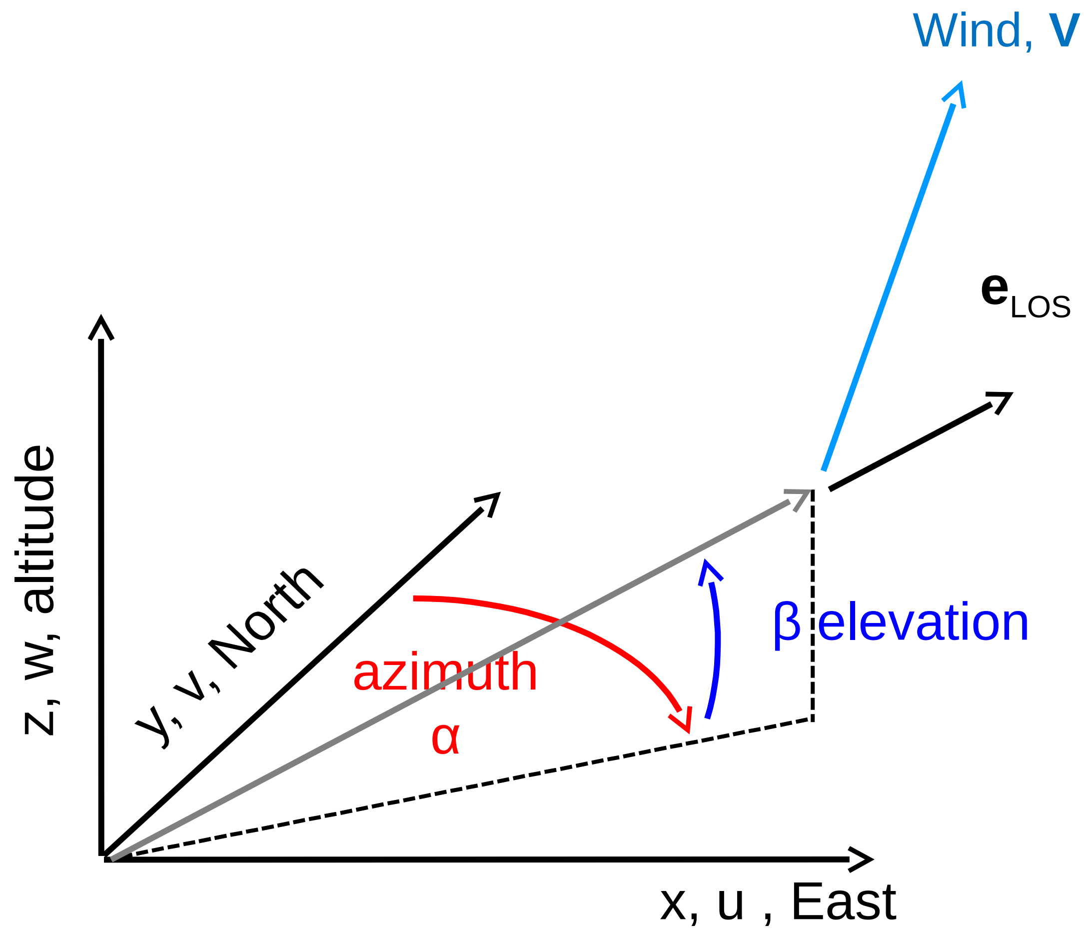

[Fig.:ForWind WeSYS]

[Fig.:FLidar]

Measurement of the radial wind speed



Measurement of the radial wind speed



$$V_{rad} = V \cdot \ e_{LOS} = [u\ v\ w] \cdot [\cos(\beta)\sin(\alpha)\ \ \cos(\beta)\cos(\alpha)\ \ \sin(\beta)]$$

Doppler effect: principle

- A frequency shift is measured if there is relative movement between the wave source and the receiver
- Knowing the frequency of the source (f_0), it is possible to compute the relative velocity from the measured frequency (f_r)

$$f_r = f_0\left(1 + \frac{v}{c}\right) = f_0 + f_D$$

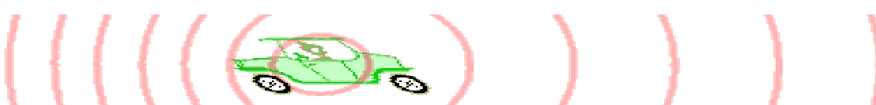


Fig. Charly Whisky

Doppler effect: exercise

$$\lambda_0 = 1.5\ \mu m$$
$$c = 3 \cdot 10^8\ {}^{m}/_{s}$$
$$v_{rad} = 0.1\ {}^{m}/_{s}$$
$$f_0 = ?$$
$$f_D = ?$$
$$f_r = ?$$

The aerosol does not emit spontaneously light
⇒ the Doppler effect applies on both ways to and from the particles

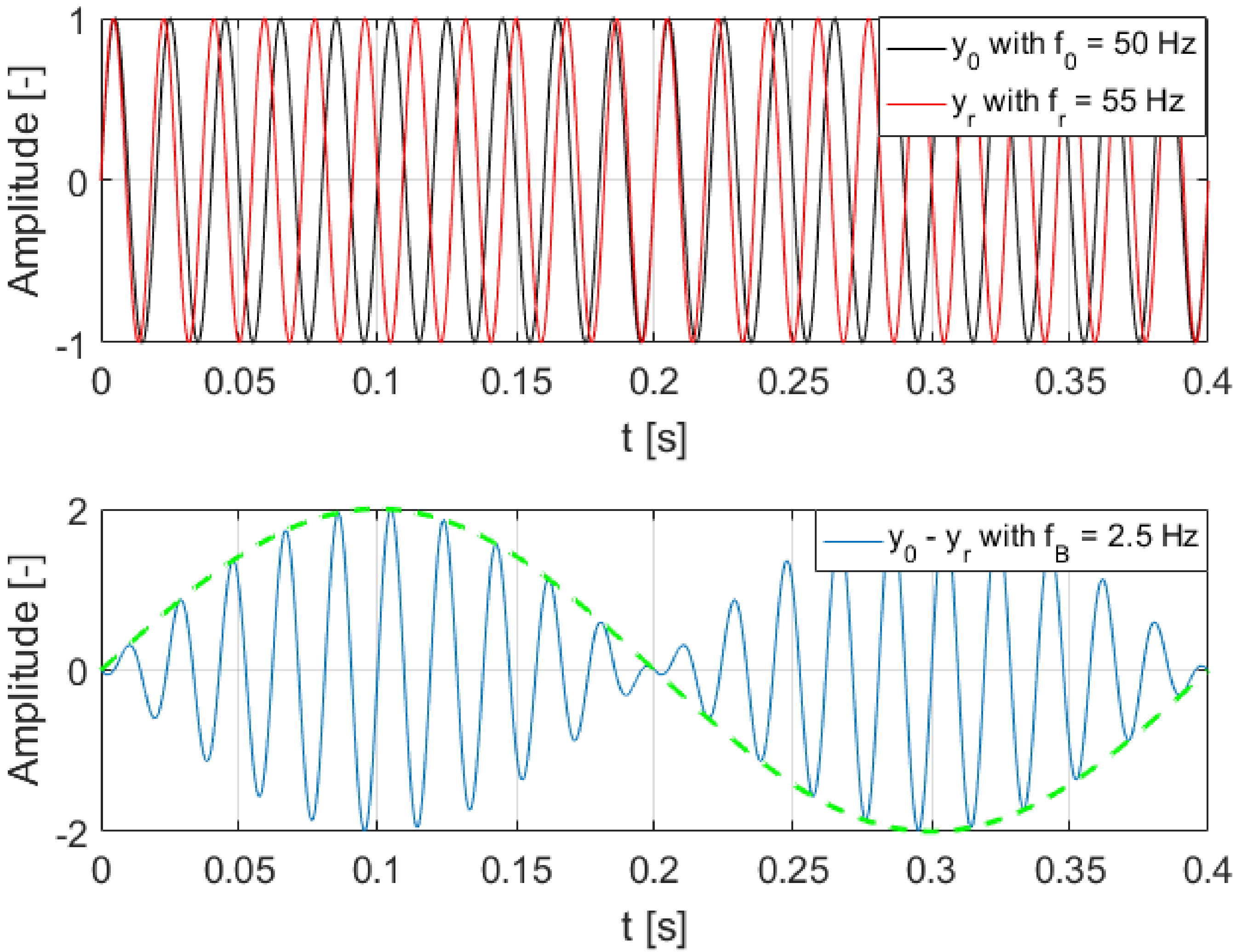
$$f_r = f_0 + \frac{2v_{rad}}{\lambda_0} = f_0 + f_D$$

Doppler effect: exercise

$$\lambda_0 = 1.5\ \mu m$$
$$c = 3 \cdot 10^8\ {}^{m}/_{s}$$
$$v_{rad} = 0.1\ {}^{m}/_{s}$$
$$f_0 = 2 \cdot 10^{14} = 200\ THz$$
$$f_D = 1.33 \cdot 10^5 = 133\ KHz$$
$$f_r \approx 200\ THz$$

$$f_r = f_0 + \frac{2v_{rad}}{\lambda_0} = f_0 + f_D$$

Heterodyne detection: the beat tone



$$f_B = \frac{|f_0 - f_r|}{2}$$

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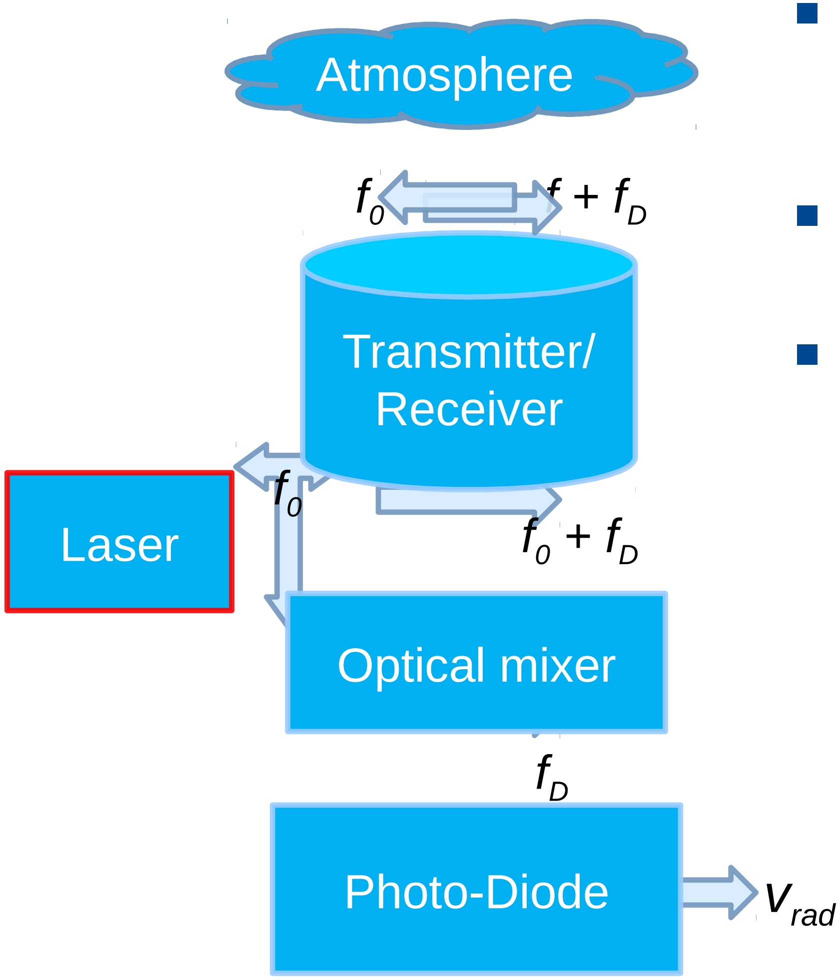
Heterodyne detection: application



- A reference beam and the received backscattered light are merged in an optical mixer
- The interferece of the two waves generates a beating signal
- A photo-diode samples the beating signal

f_0 : Laser frequency

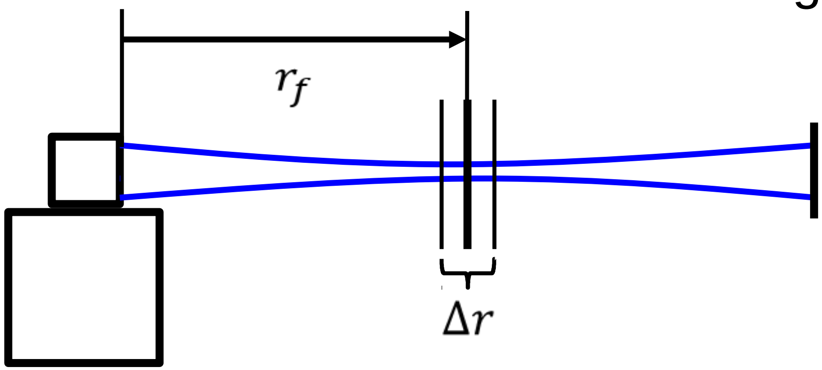
f_D : Doppler frequency

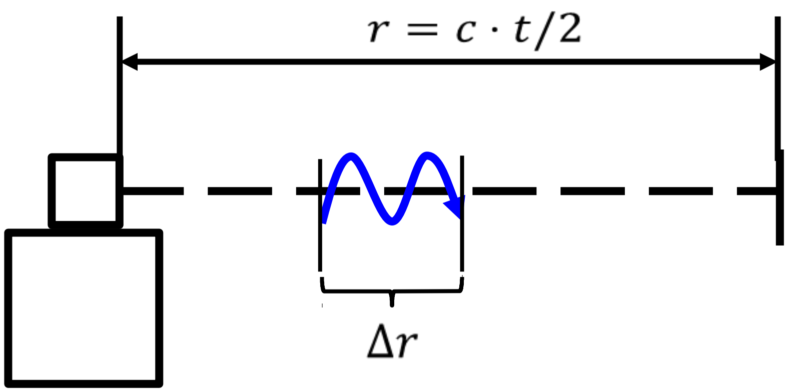
Continuous-wave and pulsed Lidar

Laser source

Wind-lidar categories:

- Continuous wave, cw $\rightarrow$ distance = focus point
- Pulsed $\rightarrow$ distance = time of flight





- Range up to a few hundred metres
- High sampling rate

$$\Delta r = \frac{4r^2\lambda}{A}$$

- Focus length r
- Wavelength λ
- Aperture Surface A

- Range up to a few kilometres

$$\Delta r \approx t_p/2$$

- Pulse length t_p

Continuous wave lidars (i)

- The focus distance defines the position of the measured point
  - ⇒ different focus distances have to be set sequentially
- The length of the sample volume Δr depends on:
  - The focus distance r
  - The wavelength λ
  - The telescope aperture surface

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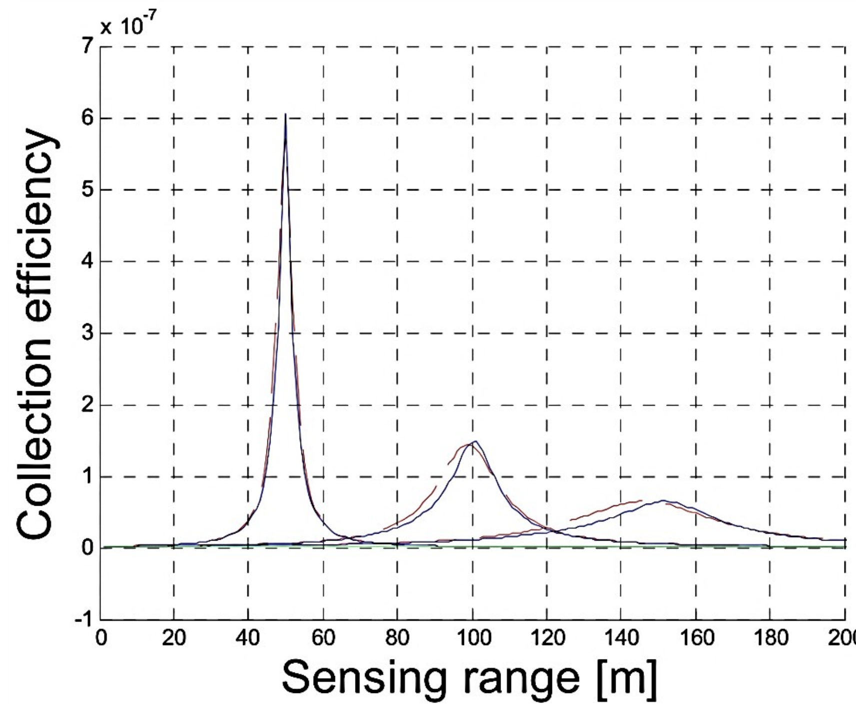
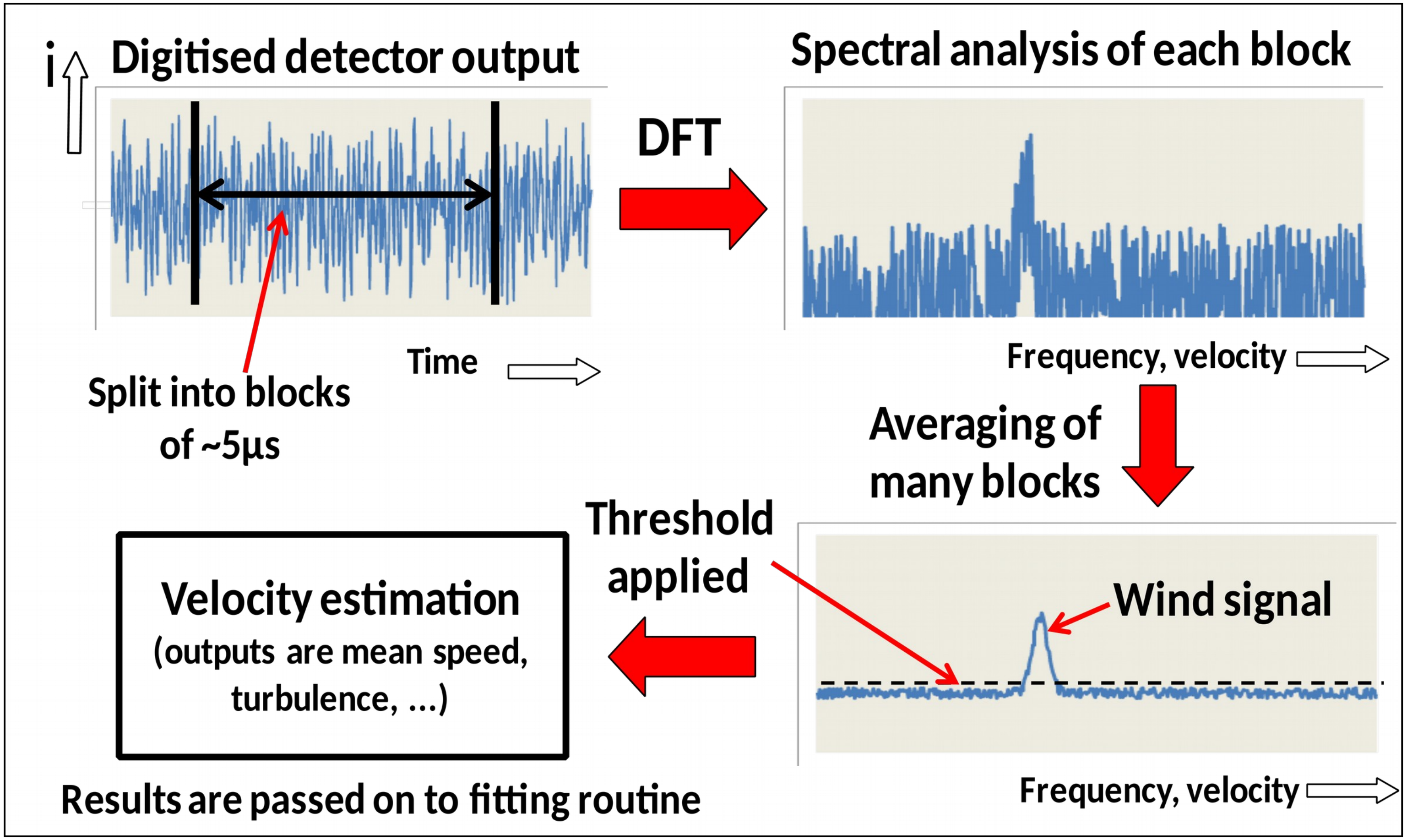


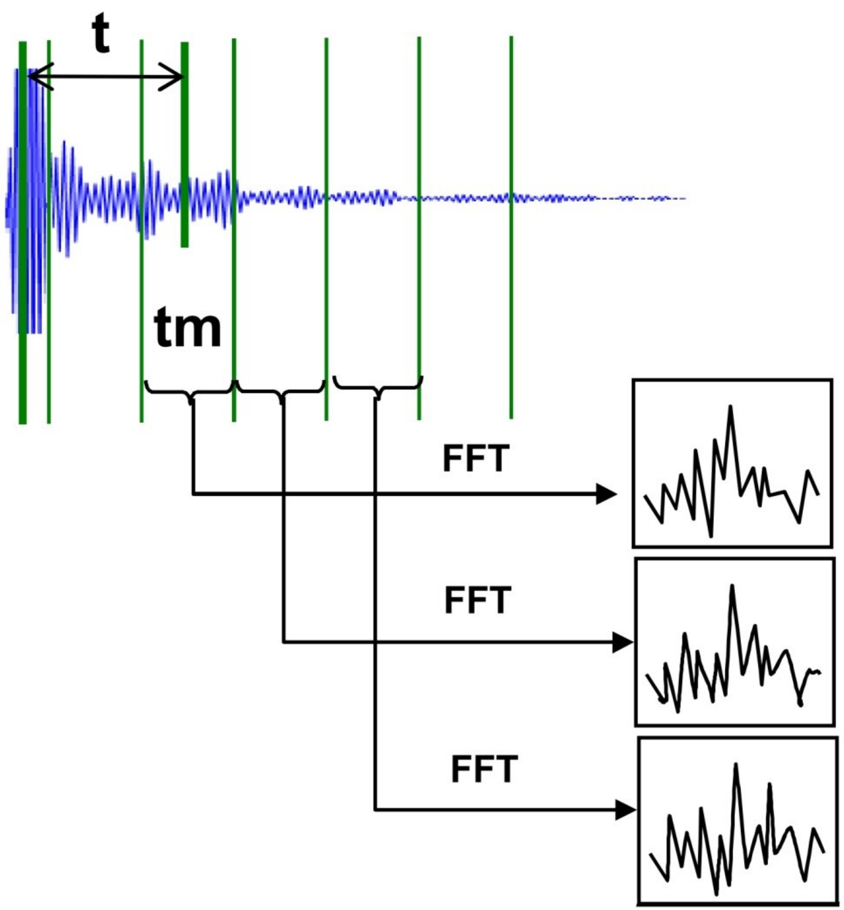
Fig.: Lindelöw, 2007

Continuous wave lidars (ii)



Slide: M.Harris, Natural Power

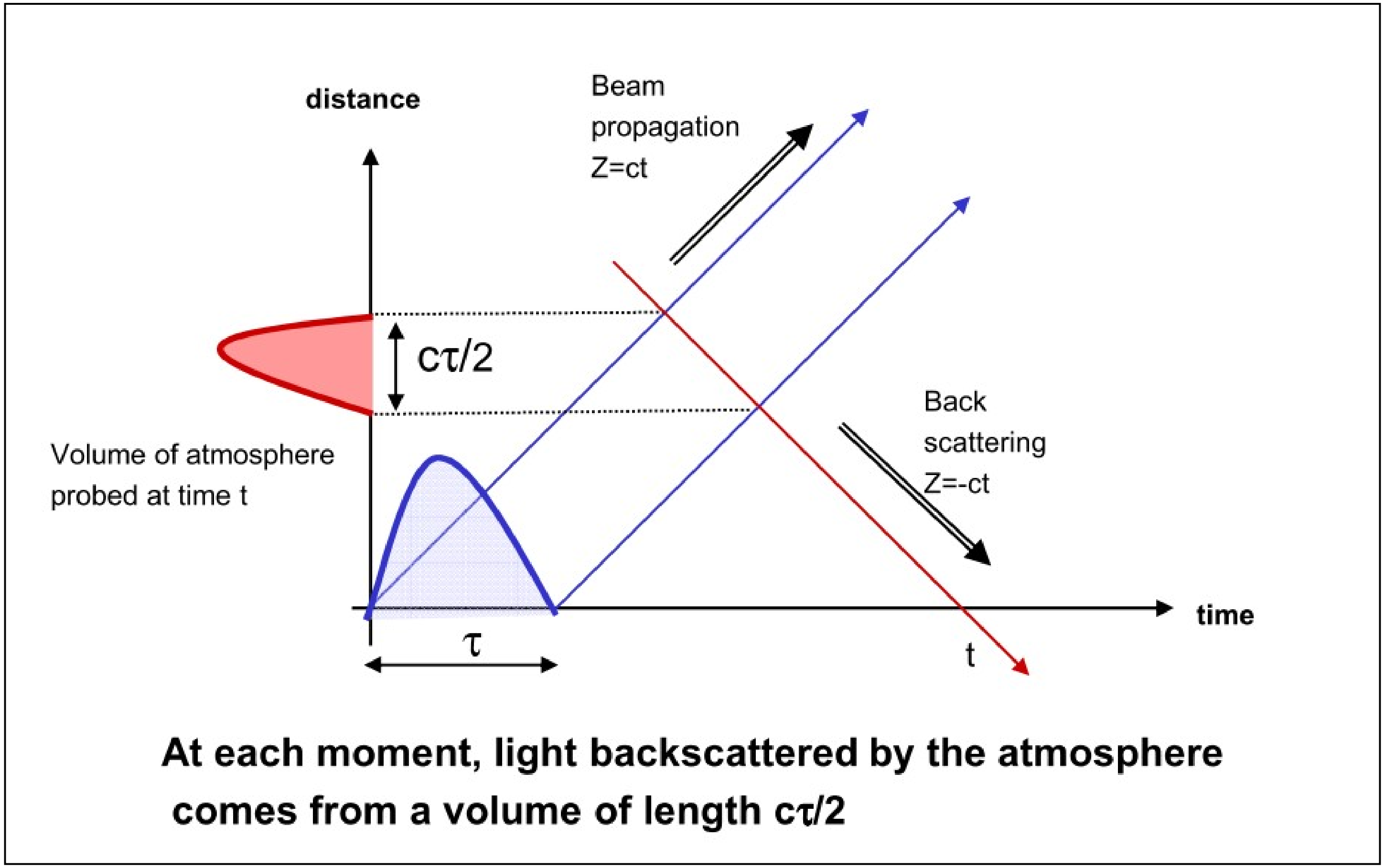
Pulsed lidars (i)



- For each pulse the heterodyne signal is segmented
- For each segment **tm** (range gate) the power spectrum is computed.
- From the time **t** the distance of the measurement point is evaluated
- For each range gate, the power spectrum is calculated
- Noise is filtered out by averaging the spectrum of n laser pulses
- The Doppler peaks are identified

Fig.: J.-P. Cariou, Leosphere.

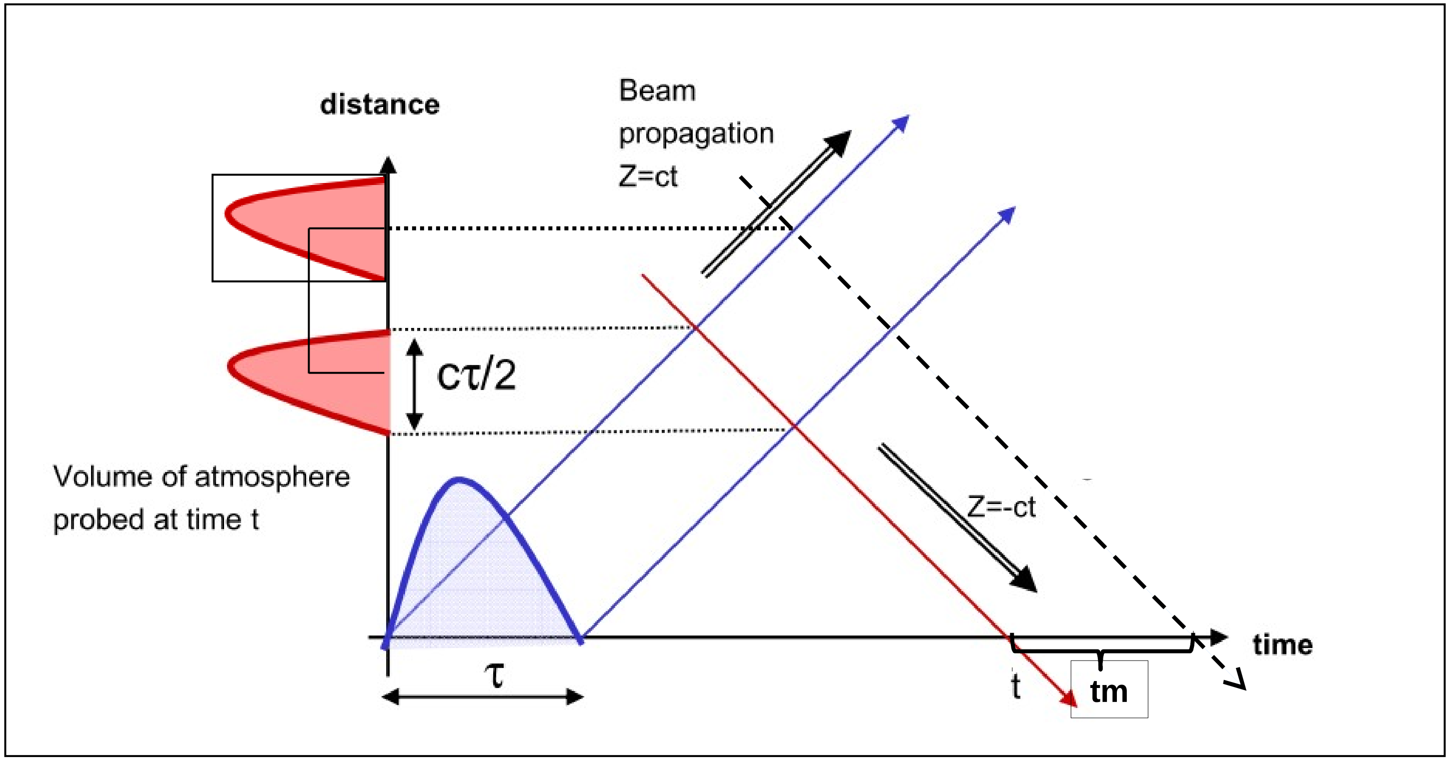
Pulsed lidars (ii)



Slide: J.-P. Cariou, Leosphere, mod.

Slide: J.-P. Cariou, Leosphere.

Pulsed lidars (ii)



Slide: J.-P. Cariou, Leosphere, mod.

- The weighting function is the convolution of the pulse and the range gate window
- The weighting function is the same for all range gates
- The probe volume is defined by the weighting function

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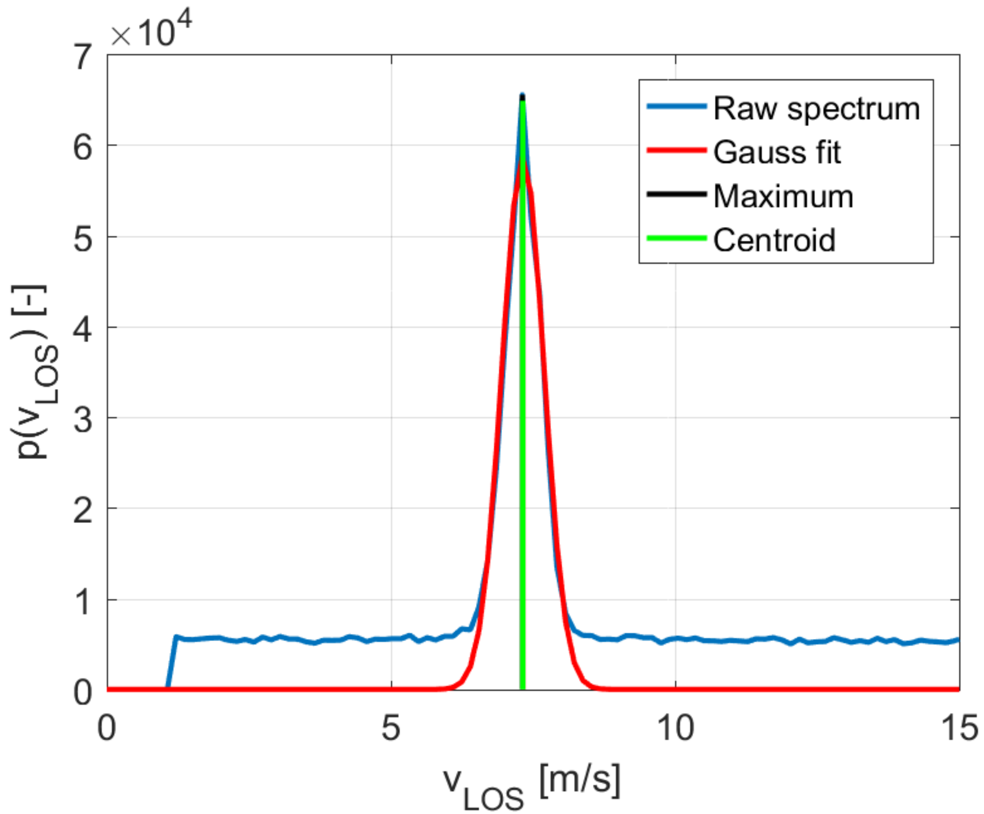
Peak detection in the spectra

- There is no unique Doppler frequency directly measured by a Lidar, but a spectrum representing the fluctuations within the probe volume
- The line-of-sight velocity is defined by a so-called ‚peak detection‘ algorithm, of which the most common is the centroid method:

$$f_{peak} = \frac{\int f \cdot p(f) df}{\int p(f) df}$$



Peak detection in the spectra

- The spectra are normally only providing the power as a function of an amount of N bins (e.g. 256). The frequency bandwith and the laser wavelength define the wind speed magnitude of each bin:

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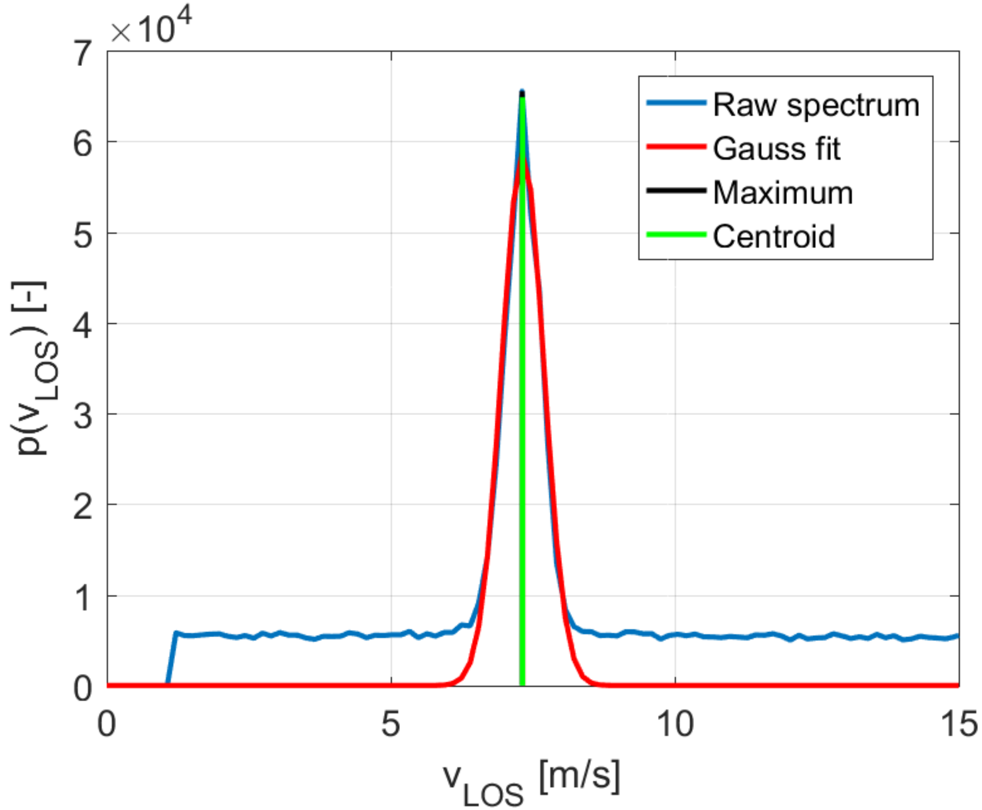
$$\Delta f = \frac{bandwith}{N_{bins}}$$

$$\Delta v_{LOS} = \Delta f \cdot \lambda_{laser}$$

The first bin corresponds to zero:

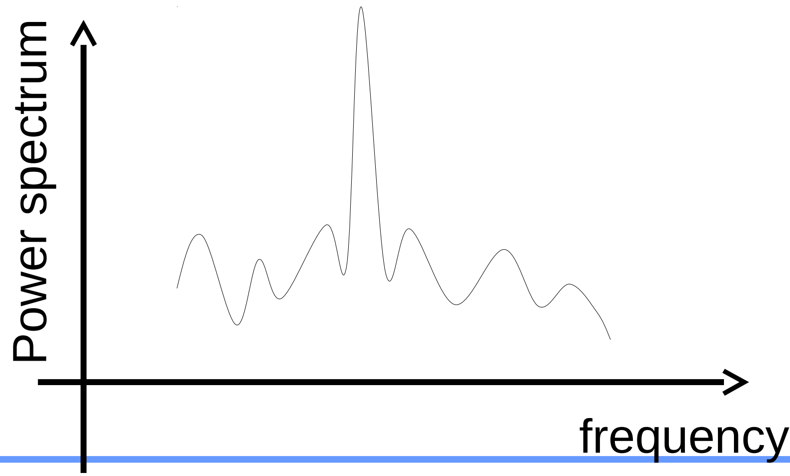
The first bin corresponds to zero:

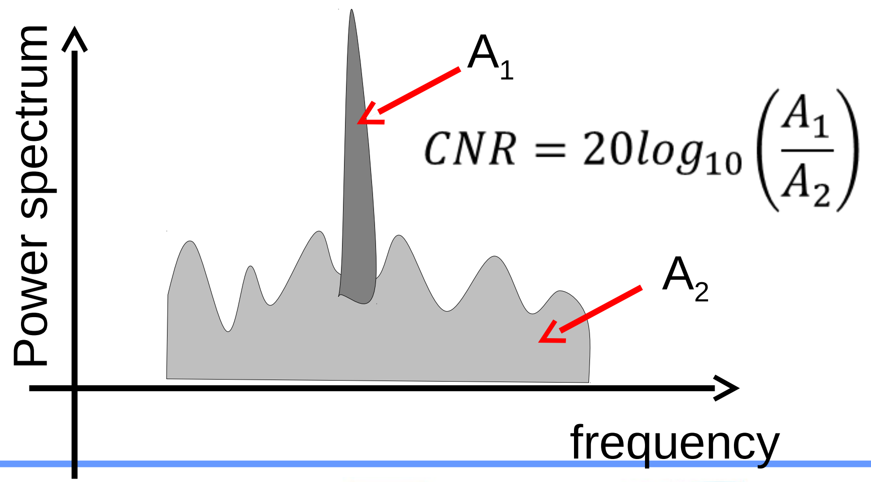
$$v_{LOS} = (bin - 1) \cdot \Delta v_{LOS}$$



The Carrier-to-Noise-Ratio (CNR)

- It is defined in decibel (dB)
- Ratio between noise and signal power
- It depends on the backscatter intensity
  - ⇒ on the distance of the range gate
  - ⇒ on the visibility
  - ⇒ on the aerosol concentration
- Increase with the number of averaged spectra
- Data below a certain threshold should be discarded





Vertical profilers

From radial wind to wind vector
Vertical profilers

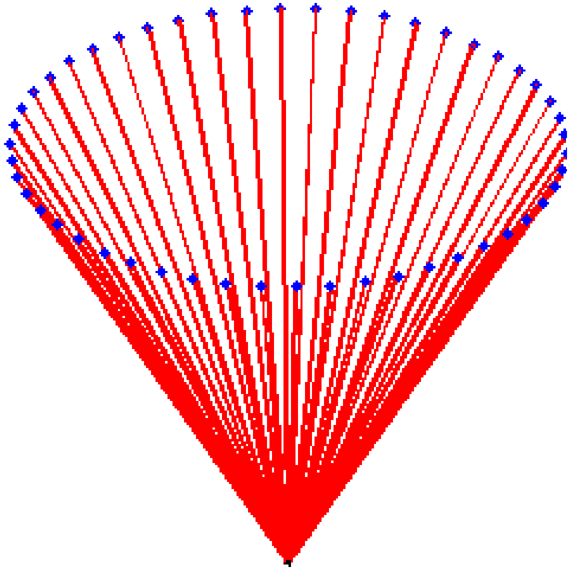
- One measurement = One radial wind speed
- At least three measurements in three not linearly dependent directions are required

Standard approach of vertical profiler:

- cw ⇒ Velocity Azimuth Dislplay (VAD):
  Radial wind speed at several points scanning a vertical cone
  (one height per scan)

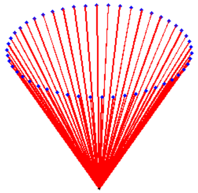
Hypothesis: homogeneous wind field

* three or five directions are also used



VAD

From radial wind to wind vector
Velocity Azimuth Display (VAD, cw)



- Radial wind speed commonly sampled at 50Hz
- There is direction anbiguity (the cosinus is an even function)
- New focus distance required to scan a different height

Fit function:

$$v_{rad} = \mathrm{b}\cos(\varphi - \theta) + a$$

Horizontal and vertical wind speed:

$$v_{hor} = \frac{b}{\cos(\vartheta)}\ ; w = \frac{-a}{\sin(\vartheta)}$$

Wind direction:

Wind direction:

$$D = b \pm 180$$

is the azimuth and the cone angle

φ is the azimuth and ϑ the cone angle

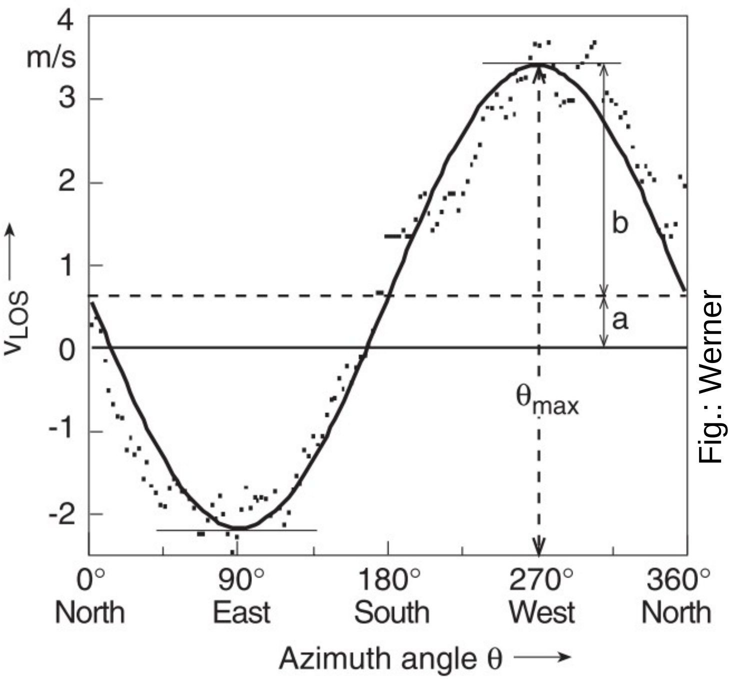
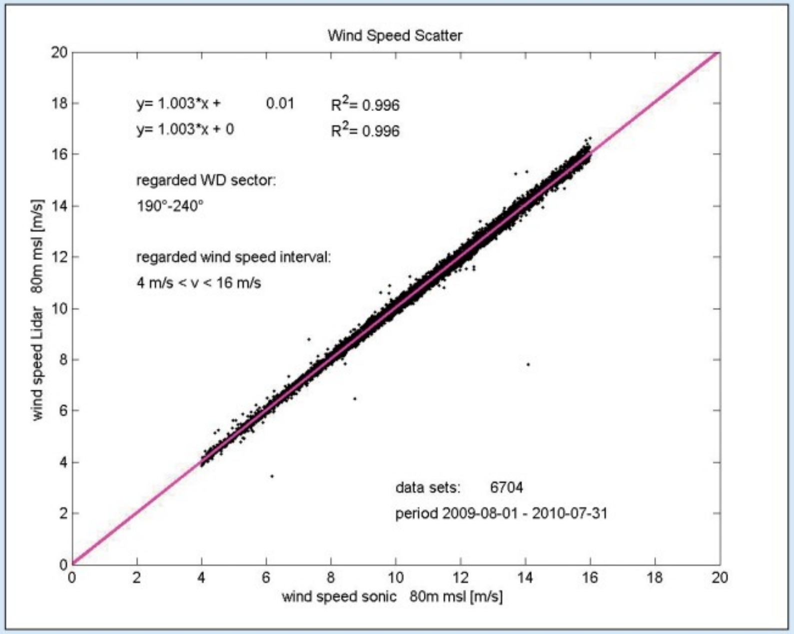


Fig.: Werner

From radial wind to wind vector
Comparison with standard anemometer (calibration)

- 10-min average of the horizontal wind direction and speed
- Scatter plot and linear regression of standard anemometry and lidar statistics
- 10-min average fits well
- For the standard deviation it is not so straight-forward...



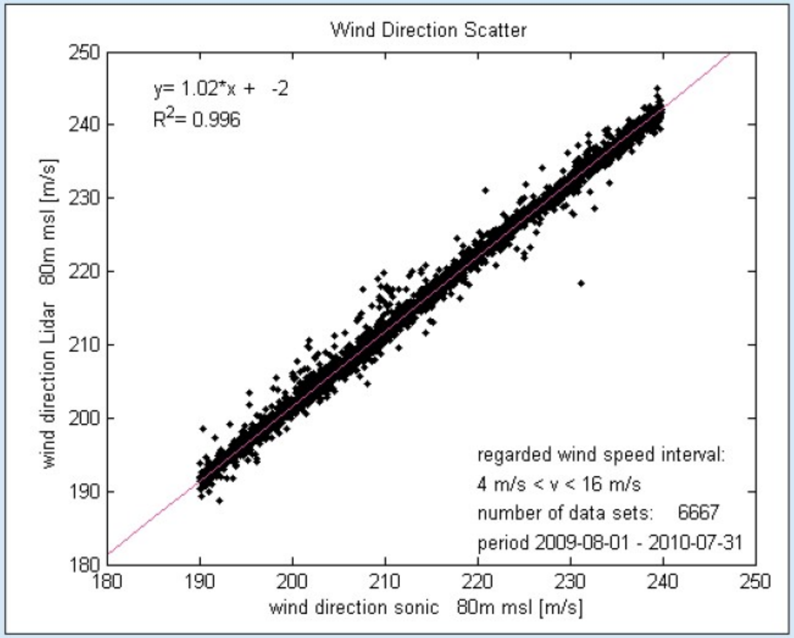


Fig.: B. Canadillas.

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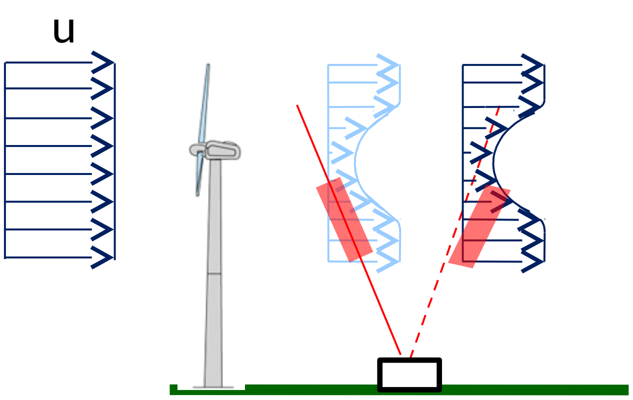
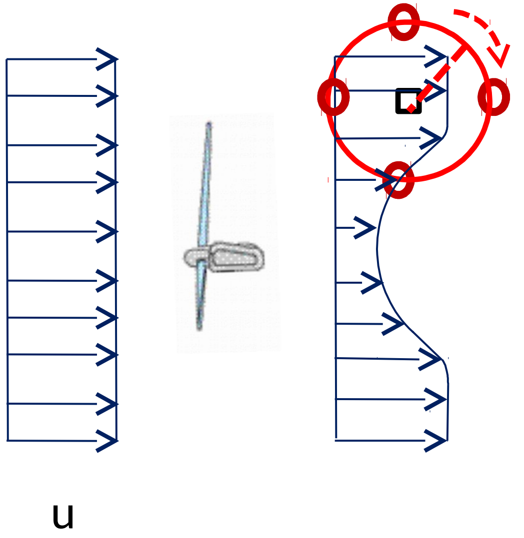
From radial wind to wind vector:
Discrepancies with standard anemometer

- Breakdown of the homogeneity model of the flow
  complex terrain, wakes, shear, veer, turbulent structures
- Atmospheric conditions
  inhomogeneous scatter distribution, clouds, rain, veer
- Accuracy of device components/installation
  cone angle, sensing range, tilt mounting,
- Accuracy/installation of standard anemometry





From radial wind to wind vector
The standard deviation...

- generally shows a larger scatter
- sometimes has a positive offset

Why?

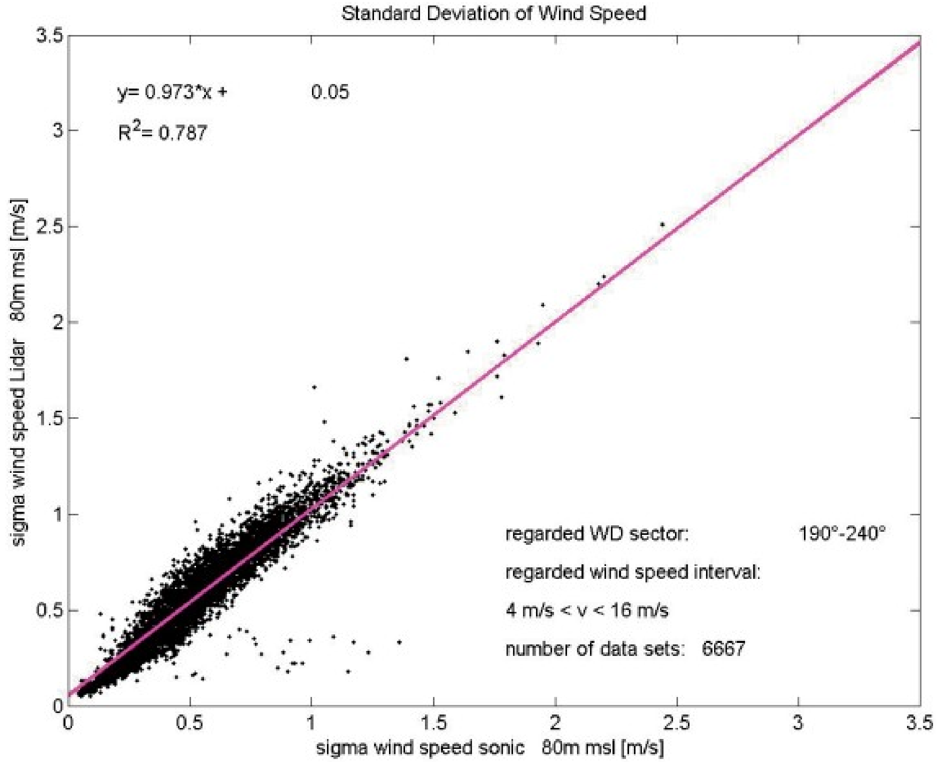
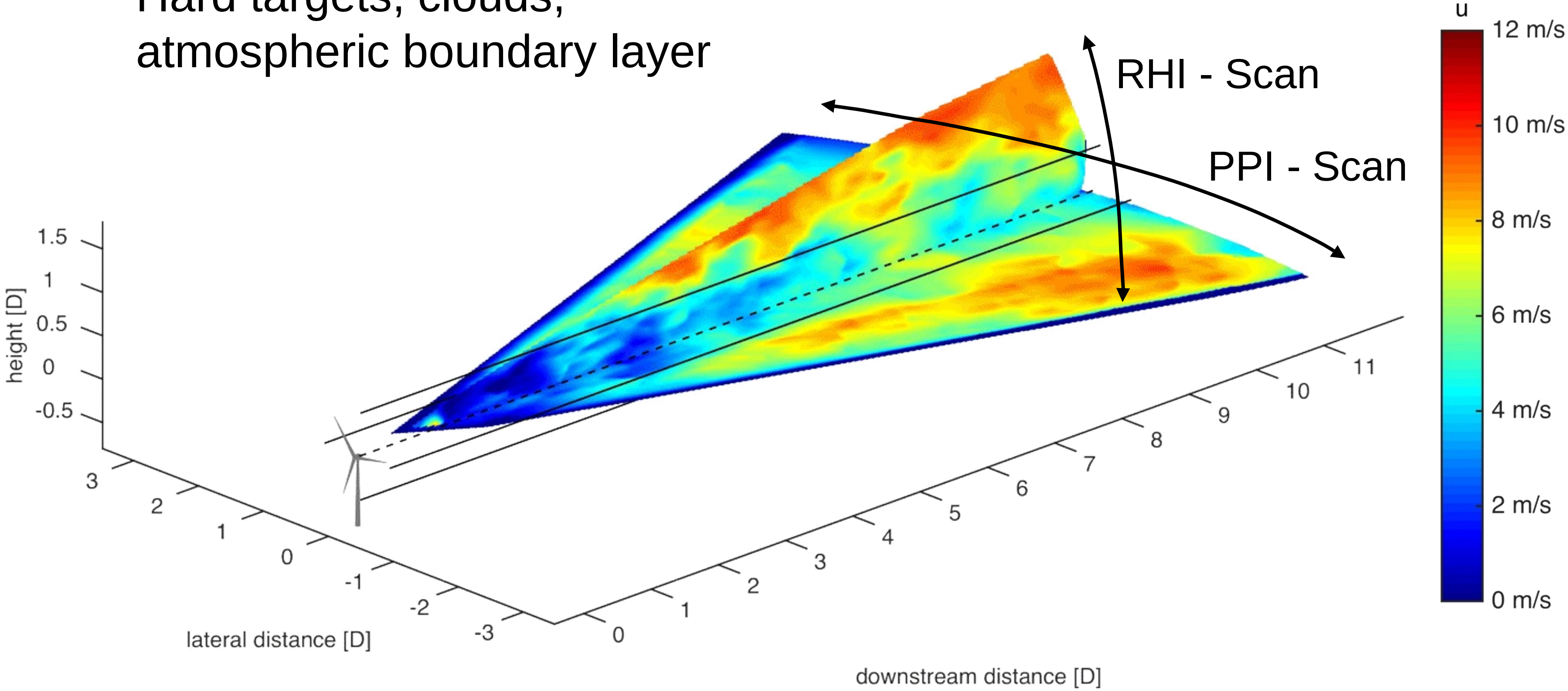


Fig.: B. Canadillas.

Advanced applications

Lidars, not only profilers
Scanning Lidar

- Wind field measurements
- Flexible trajectories
- Vortex detection
- Hard targets, clouds, atmospheric boundary layer



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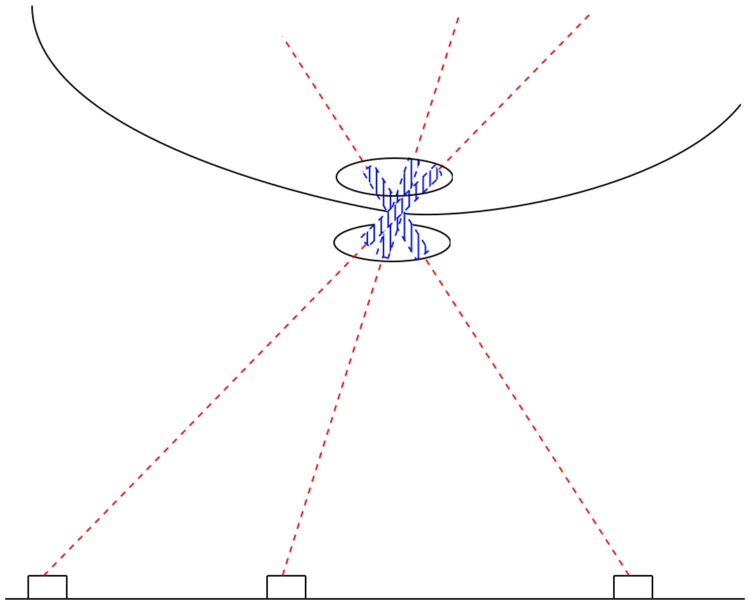
Lidars, not only profilers

Multi-Lidar

- Retrieval of the 3D wind vector
- Reduced probe volume
- Higher sample rate



Three concurrent lidars:

$$V_{rad,\mathbf{1}} = [u\ v\ w] \cdot [\cos(\beta_1)\sin(\alpha_1) \quad \cos(\beta_1)\cos(\alpha_1) \quad \sin(\beta_1)]$$

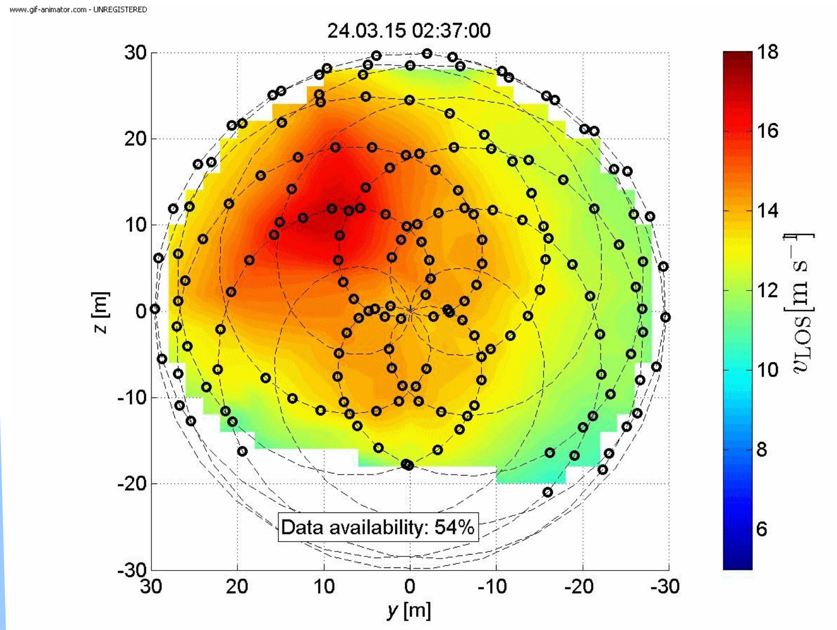
$$V_{rad,\mathbf{2}} = [u\ v\ w] \cdot [\cos(\beta_2)\sin(\alpha_2) \quad \cos(\beta_2)\cos(\alpha_2) \quad \sin(\beta_2)]$$

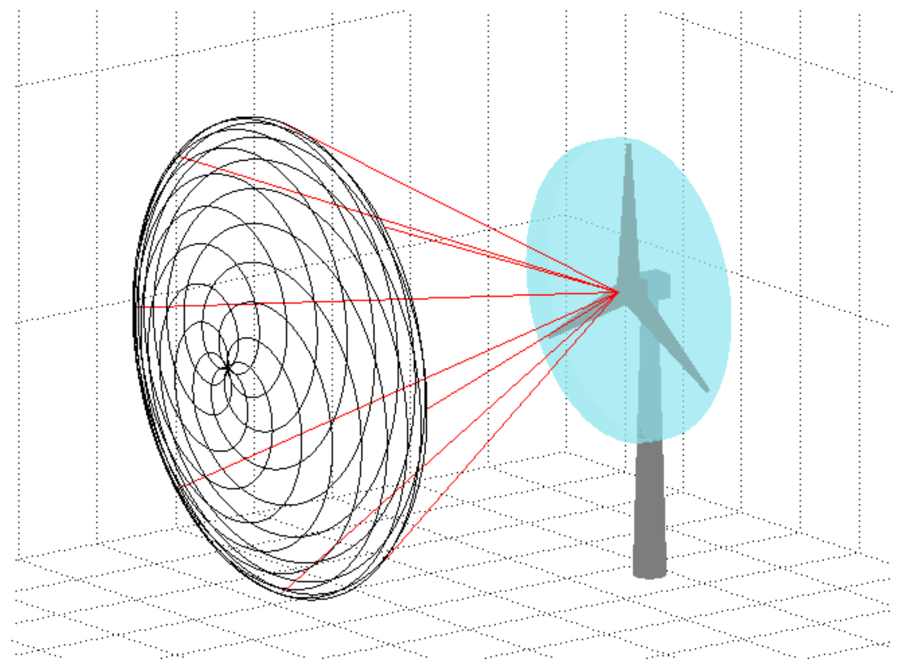
$$V_{rad,\mathbf{3}} = [u\ v\ w] \cdot [\cos(\beta_3)\sin(\alpha_3) \quad \cos(\beta_3)\cos(\alpha_3) \quad \sin(\beta_3)]$$

Linear system in the form [**A**] · **b** = **c**
A meaningful solution exists for three linearly independent $\mathbf{e}_{LOS}$

Lidars, not only profilers
2D SpinnerLidar

- 2D wind fields in the inflow of wind turbines
- Feed-forward rotor control
- Detection of incoming gust events





Lidars, not only onshore
Floating wind profilers

- Easy deployable
  (compared to a mast)
- Power supply issue
  (small wind turbines, photovoltaic panels, battery, generator)
- Sea-state compensation
  (relative speed, beam inclination, wave height)

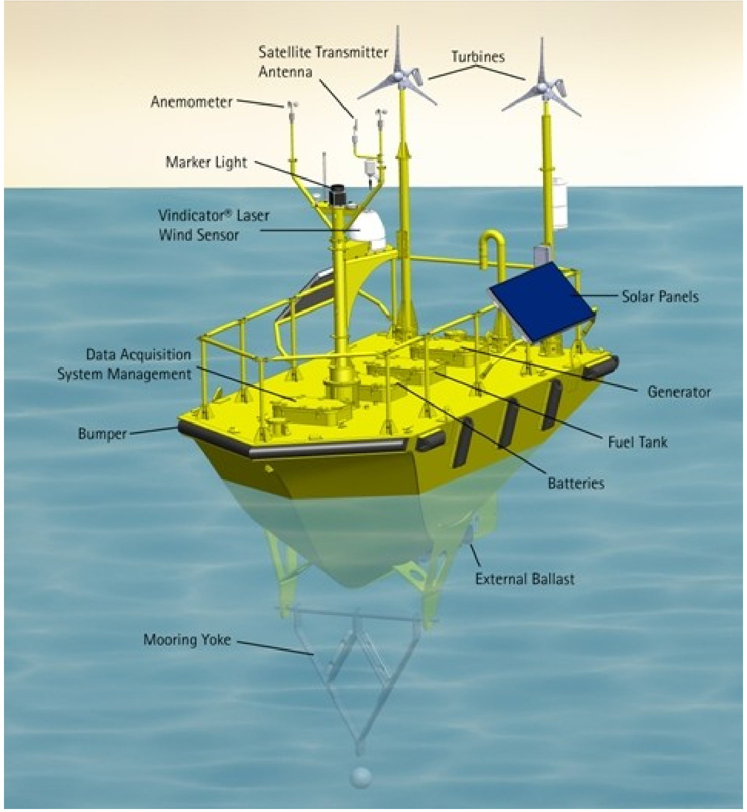


Fig.,AXYS, WindSentinel.

Fig.3E, Flidar .

Fig.,Zephir LTD, SeaZephir©

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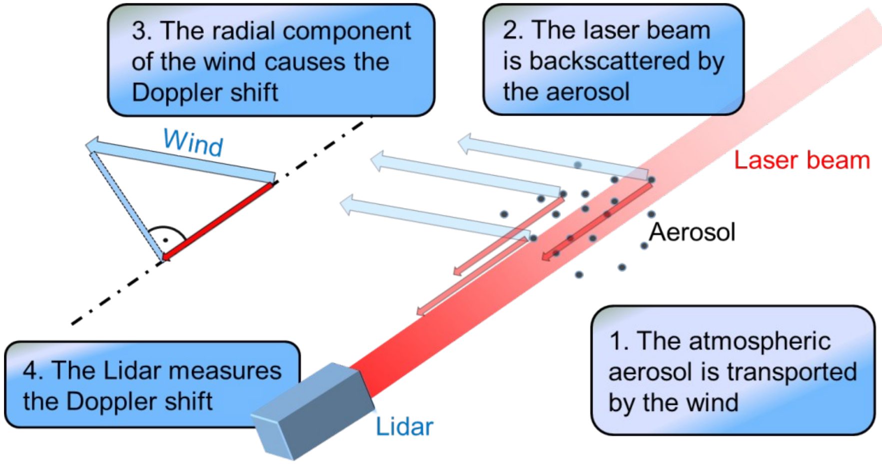
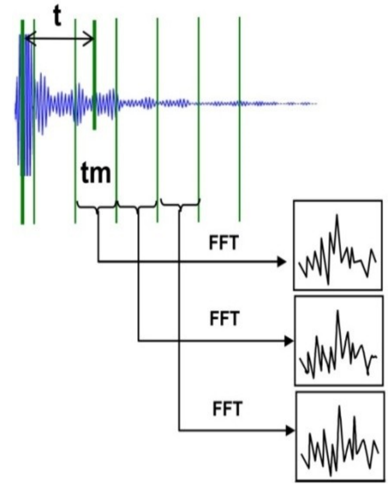
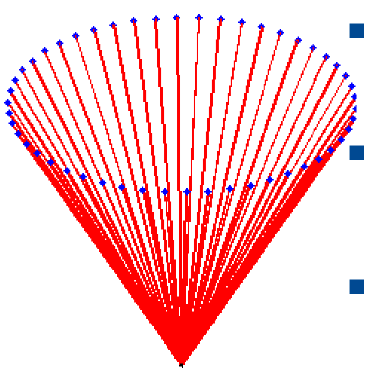
Summary



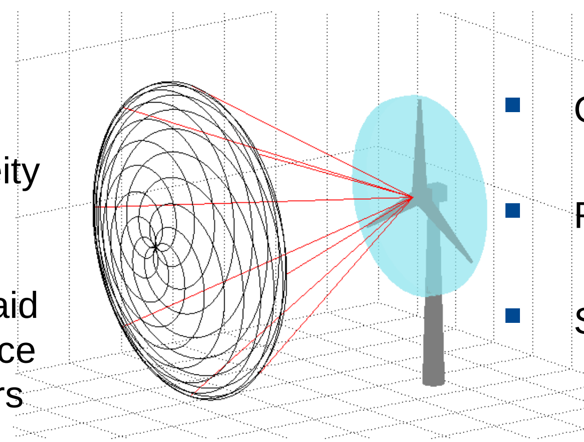


- FFT analysis of received signal
- Division of signal in range gates for pulsed Lidar
- Averaging over several pulses and indentification of Doppler Peak

- Lidar make use of the Doppler Effect
- The Doppler effect applies to the radial speed only
- Continuous and pulsed Lidars define range differently



- VAD wind profiler
- Requires homogeneity of the wind flow
- Attention must be paid to evaluate turbulence properties with Lidars



- Other applications for Lidar
- RHI/PPI Scans
- SpinnerLidar, Multi-Lidar

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Tasks

Tasks

1. SpinnerLidar Spectral Analysis
   - Peak finding in raw spectra
   - Define the of each spectra and filter outliers
   - Plot the wind field

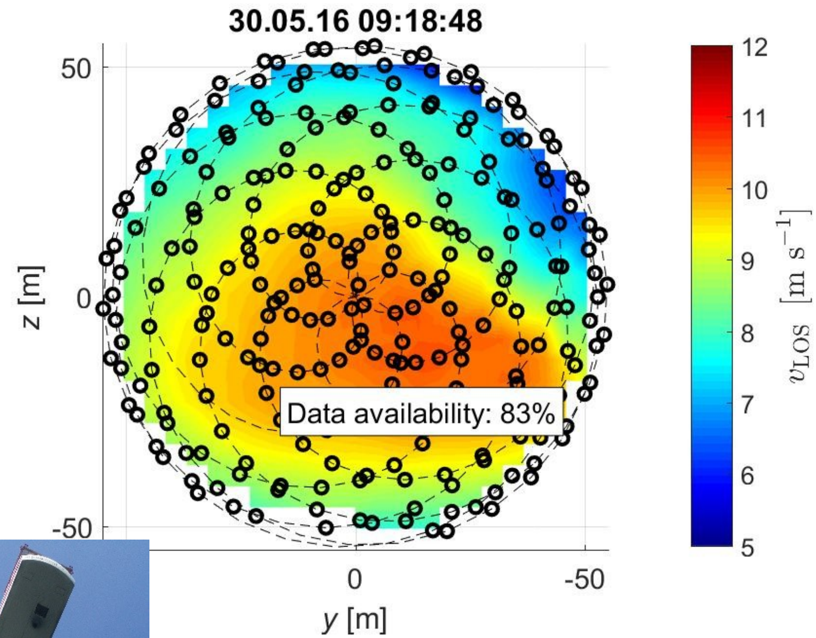
2. Comparison
   - Wind Lidar vertical profiler (pulsed system)
   - Meteorological met-mast anemometry

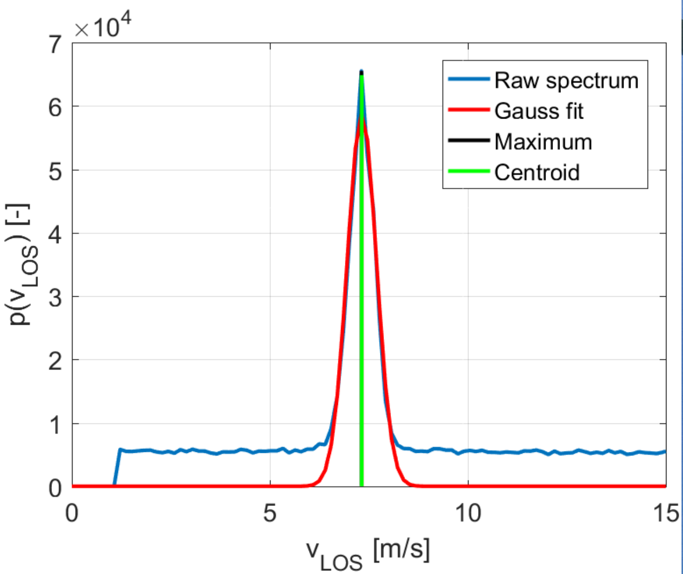
3. 3D vector calculation
   - Triple-Lidar systems of WindScanners
   - Calculate [u v w] from three measurements

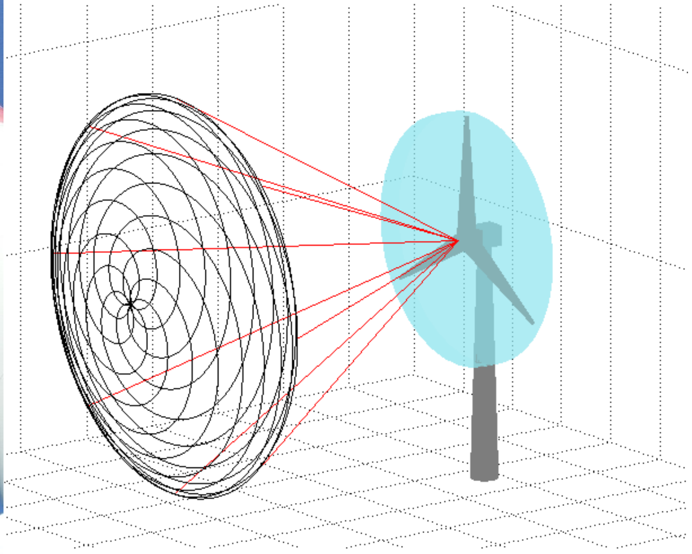
1. SpinnerLidar Spectral Analysis
   - Peak finding in raw spectra
   - Define the v_{LOS} of each spectra and filter outliers
   - Plot the v_{LOS} wind field
2. Comparison
   - Wind Lidar vertical profiler (pulsed system)
   - Meteorological met-mast anemometry
3. 3D vector calculation
   - Triple-Lidar systems of WindScanners
   - Calculate [u v w] from three v_{LOS} measurements

* The datasets are produced by means of lidar simulation in a wind field generated by a LES implementation

Task 1
Measurement description





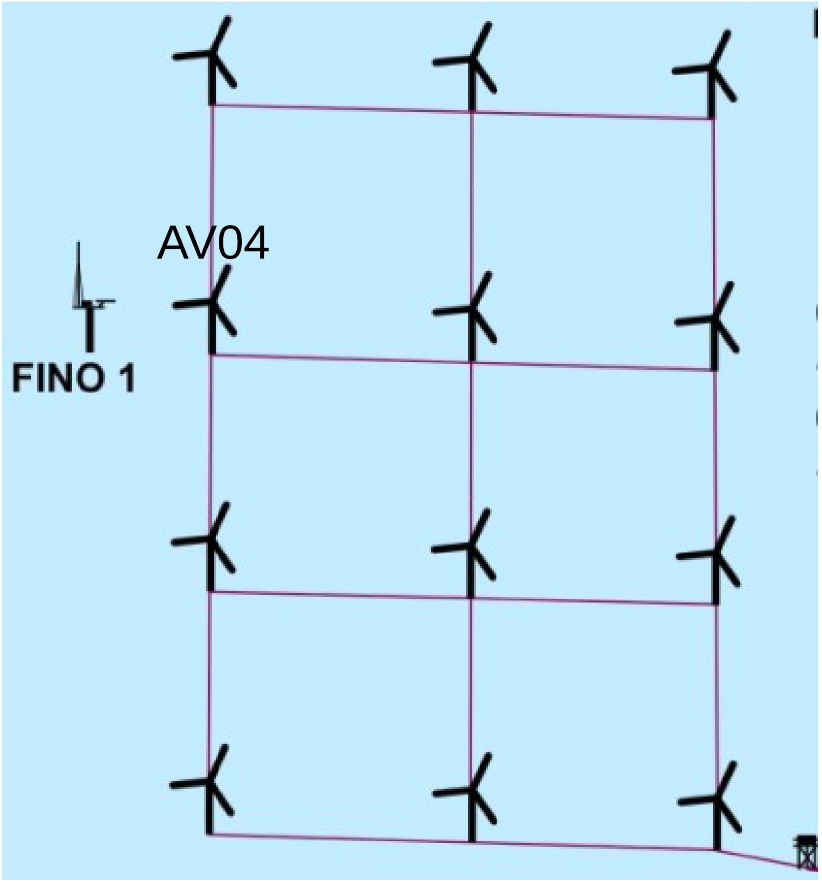


Task 1
Measurement setup

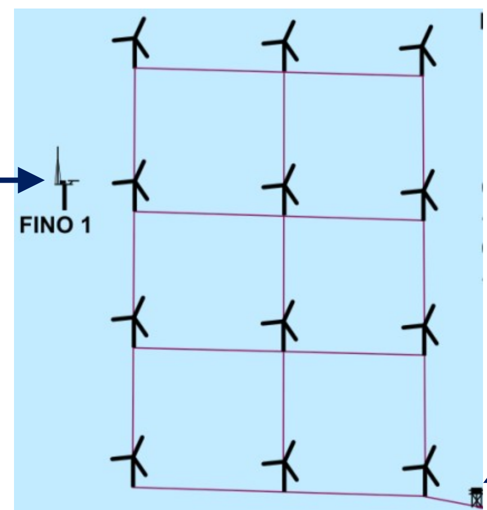
AV04

- Turbine closest to FINO1
- Inflow measurements
- 1 Hz scans of wind fields with 312 Hz samping rate of points
- Measurements at different distances
- Not installed in spinner but on nacelle: BLADE interference

alpha ventus



Task 2
Measurement description

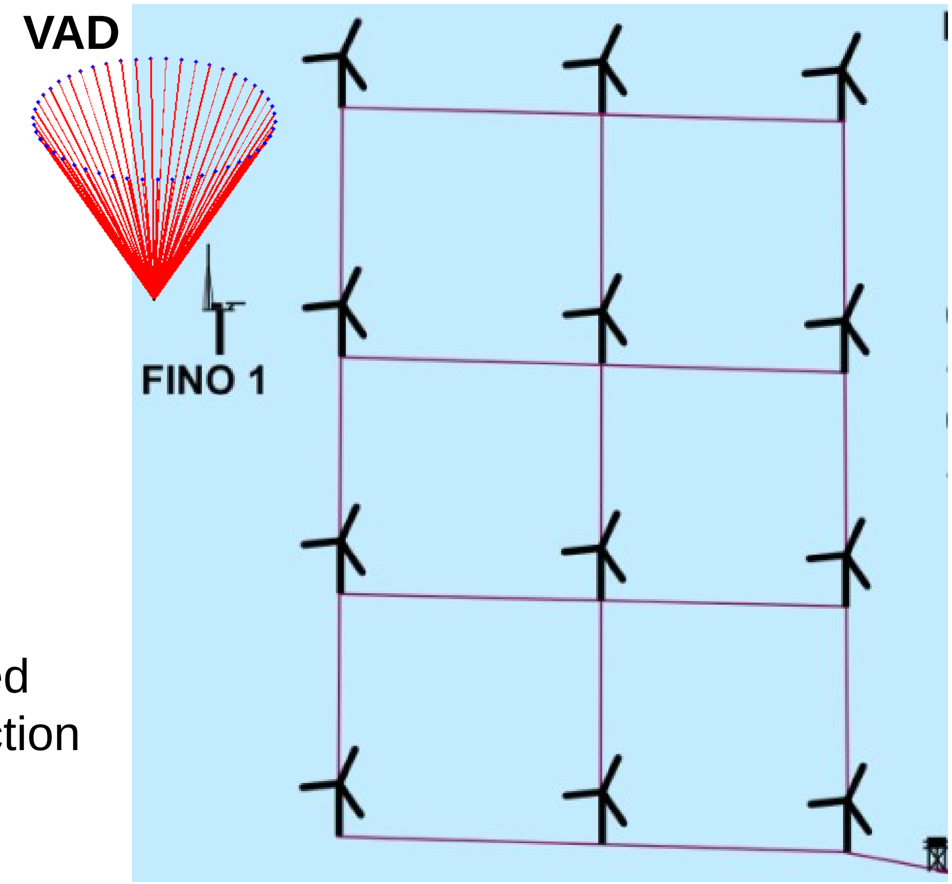


Task 2
Measurement setup

VAD

- **Pulsed system**
- 0.4 s acc. time

  (2.5 Hz)
- 25°/s
- **Average over scanned sector (!)**



Fino

- 10-min average wind speed
- 10-min average wind direction

Task 2

Hint cosine fitting matlab

Fit function:

Fit function:

$$v_{rad} = \mathrm{b}\cos(\varphi - \theta) + a$$

Define function in Matlab

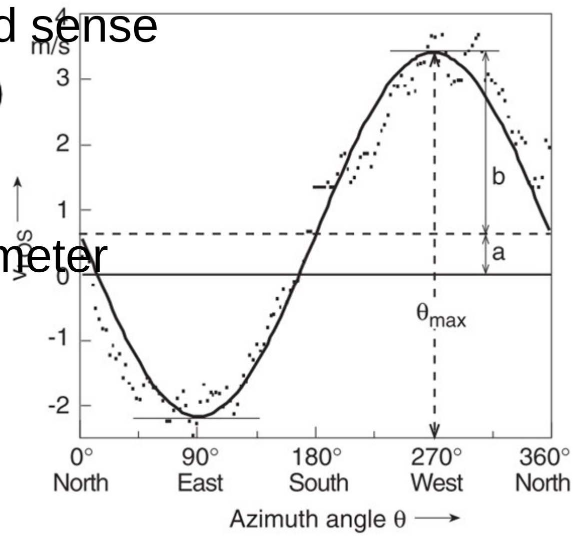
Define function in Matlab

$$VADCos = @(param, \varphi)\ param(1) * \cos\big(\varphi\ - param(2)\big) + param(3)$$

Solve function with lsqcurvefit in least squared sense

Solve function with lsqcurvefit in least sqared sense

$$fitparam = lsqcurvefit(VADCos, startvalues, \varphi, v_{LOS})$$



Rember to define start values for each parameter

Rember to define start values for each parameter

i.e. $startvalues = [2\ 10\ 1]$

i.e.

Task 3
Measurement setup

Multi-Lidar

- Three short-range cw WindScanners
- 3D wind vector measurements at h = 90 m
- 100 Hz samping rate
- Location: Test field at DTU Risø Campus