Flow Observations using Nacelle Lidars: A Study on the University of Stavanger Campus

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Session 2B: Metocean conditions

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Instruments on campus

2 ZXTM horizontally scanning nacelle lidars

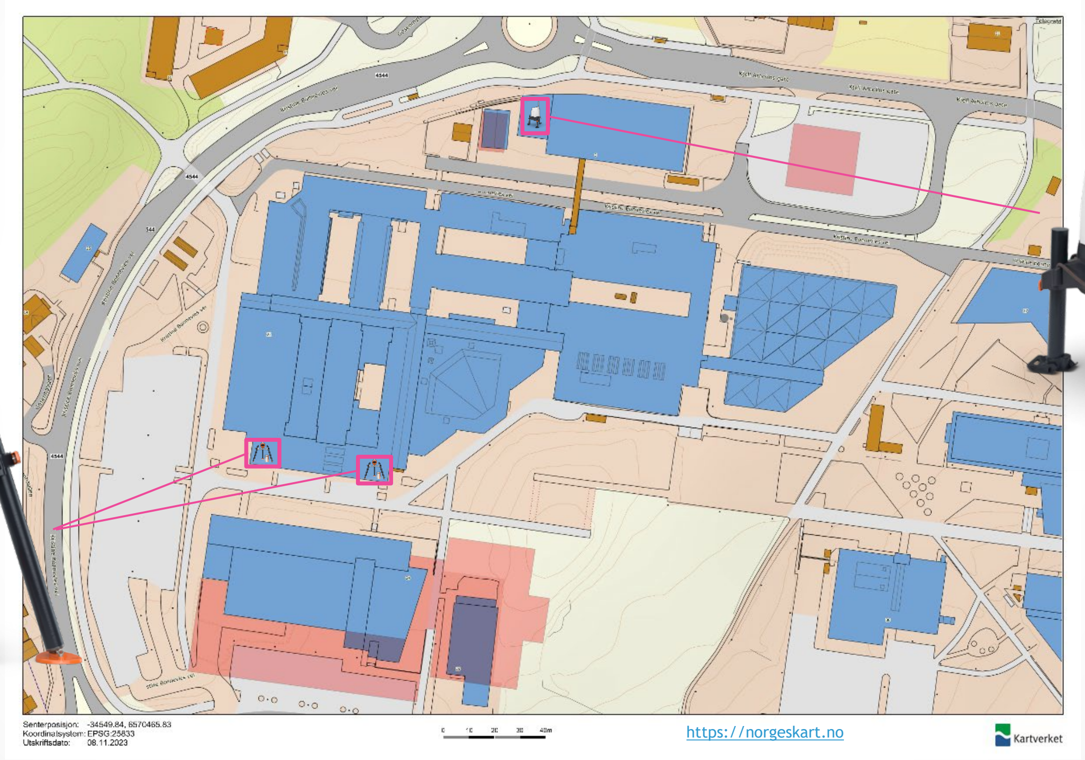
1 ZX300 vertically profiling lidar

https://www.zxlidars.com/wind-lidars/

Sonic anemometers

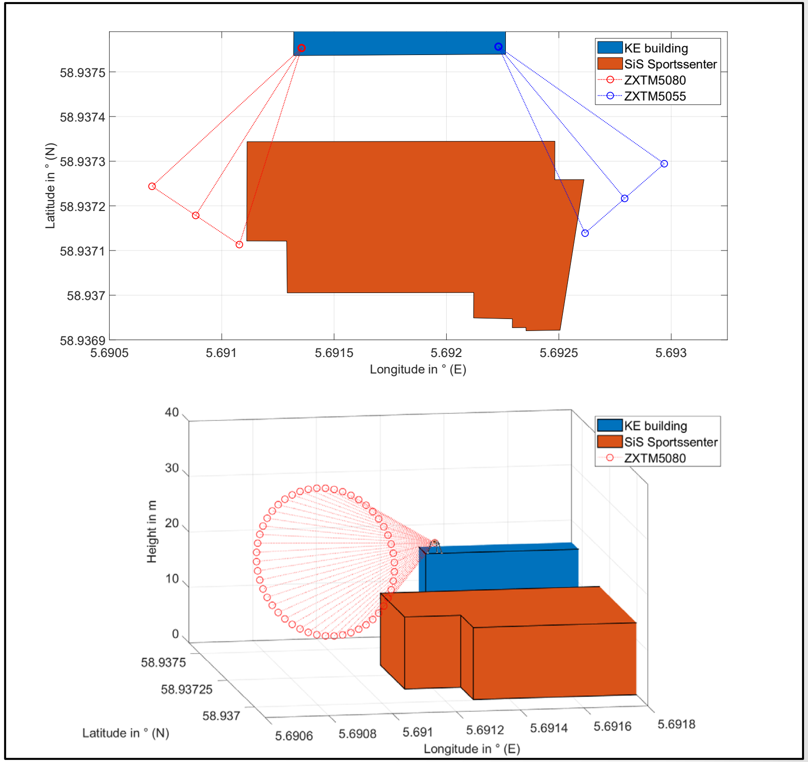
https://www.zxlidars.com/wind-lidars/

Instruments on campus



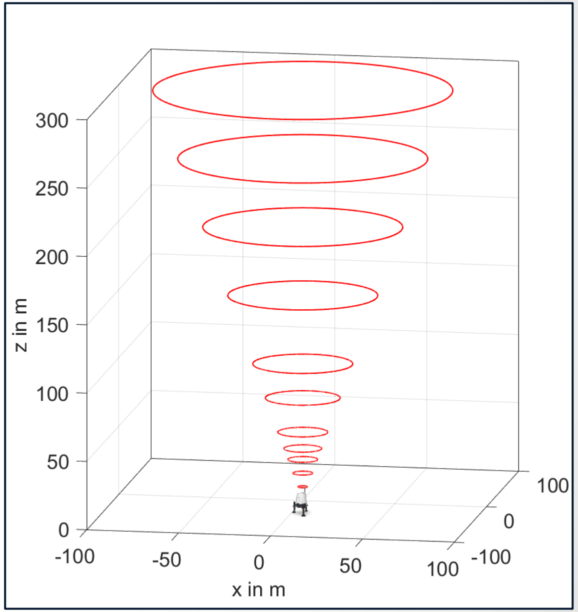
ZXTM nacelle lidar specifications

▪ Half cone opening angle	15°
▪ Scanning distance	50 m
▪ Scanning circle radius	13.4 m
▪ Number of scanning points	50
▪ Sampling rate	50 Hz
▪ Lidar inclination	5.3°



ZX300 profiling lidar specifications

Half cone opening angle	15°
Scanning heights	10 m, 20 m, 30 m, 38 m, 50 m, 75 m, 100 m, 150 m, 200 m, 250 m, 300 m
Sampling rate at each height	0.06 Hz



Objectives of the study

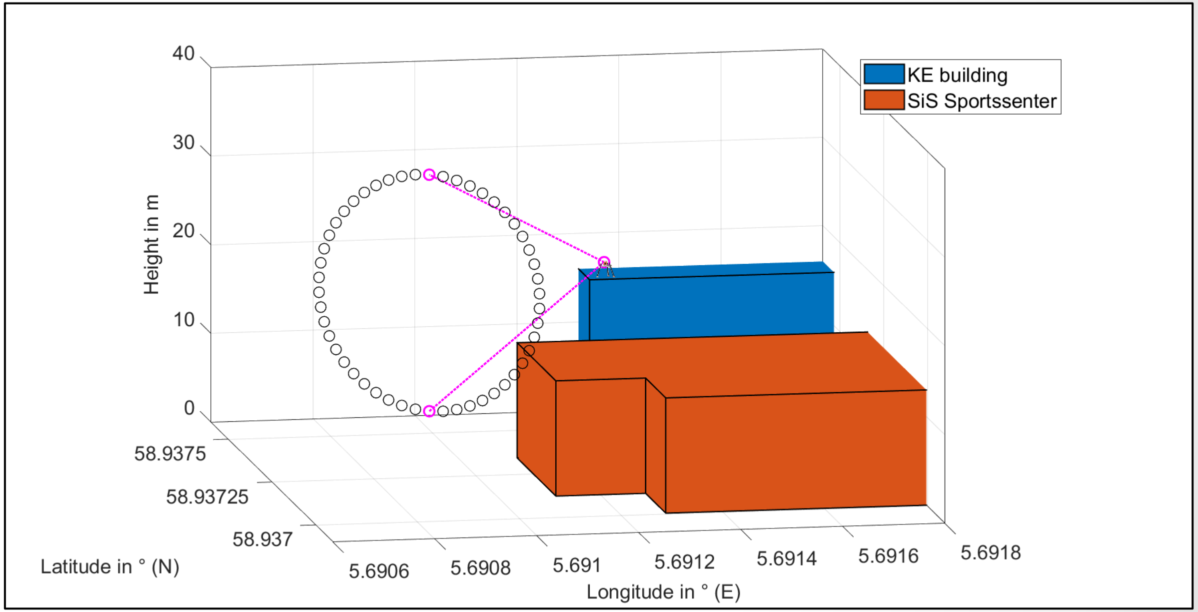
- Experience in instrument use and data processing
- Evaluation of instruments’ potential for:
  - flow characterization in urban environment
  - turbulence characterization
- Investigation of flow conditions on campus

Time series from radial velocity observations

Estimate:

a. u and v from horizontal beams

b. u and w from vertical beams



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Time series from radial velocity observations

- Estimation of 10-min wind direction

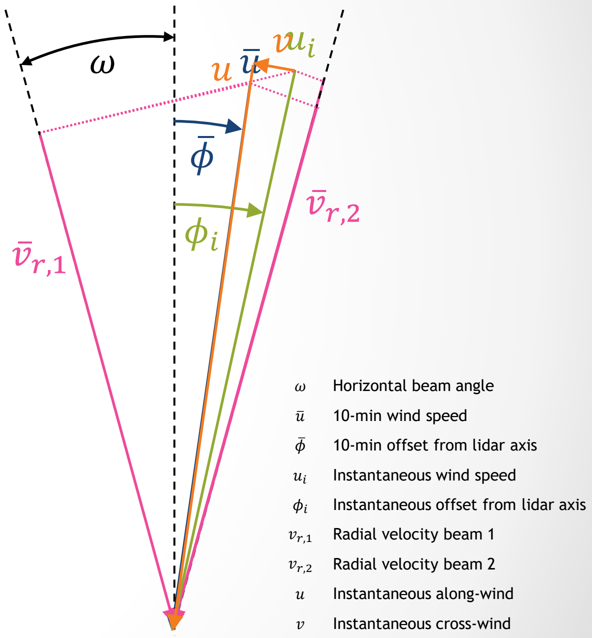
$$\bar{v}_{r,1} = \bar{u}\cos(\omega + \bar{\phi})$$
$$\bar{v}_{r,2} = \bar{u}\cos(\omega - \bar{\phi})$$

- Calculation of instantaneous wind speed and direction

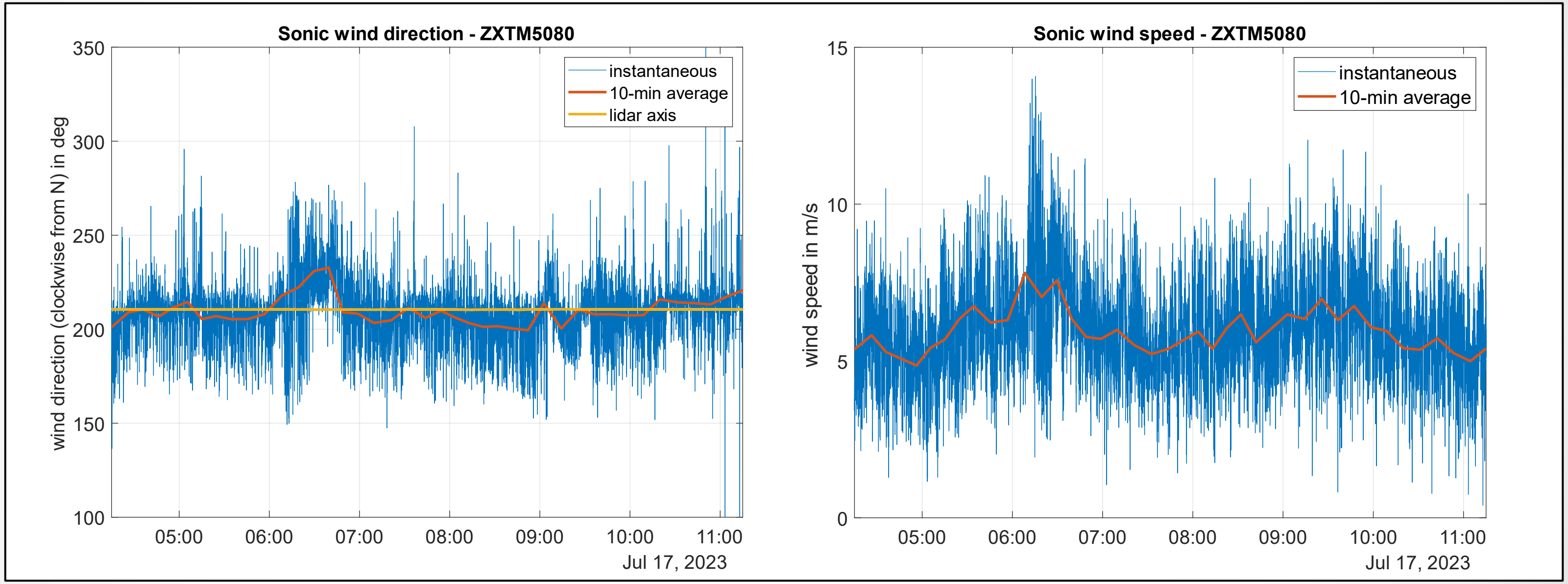
$$v_{r,1} = u_i \cos(\omega + \phi_i)$$
$$v_{r,2} = u_i \cos(\omega - \phi_i)$$

- Decomposition into instantaneous along- and cross-wind components

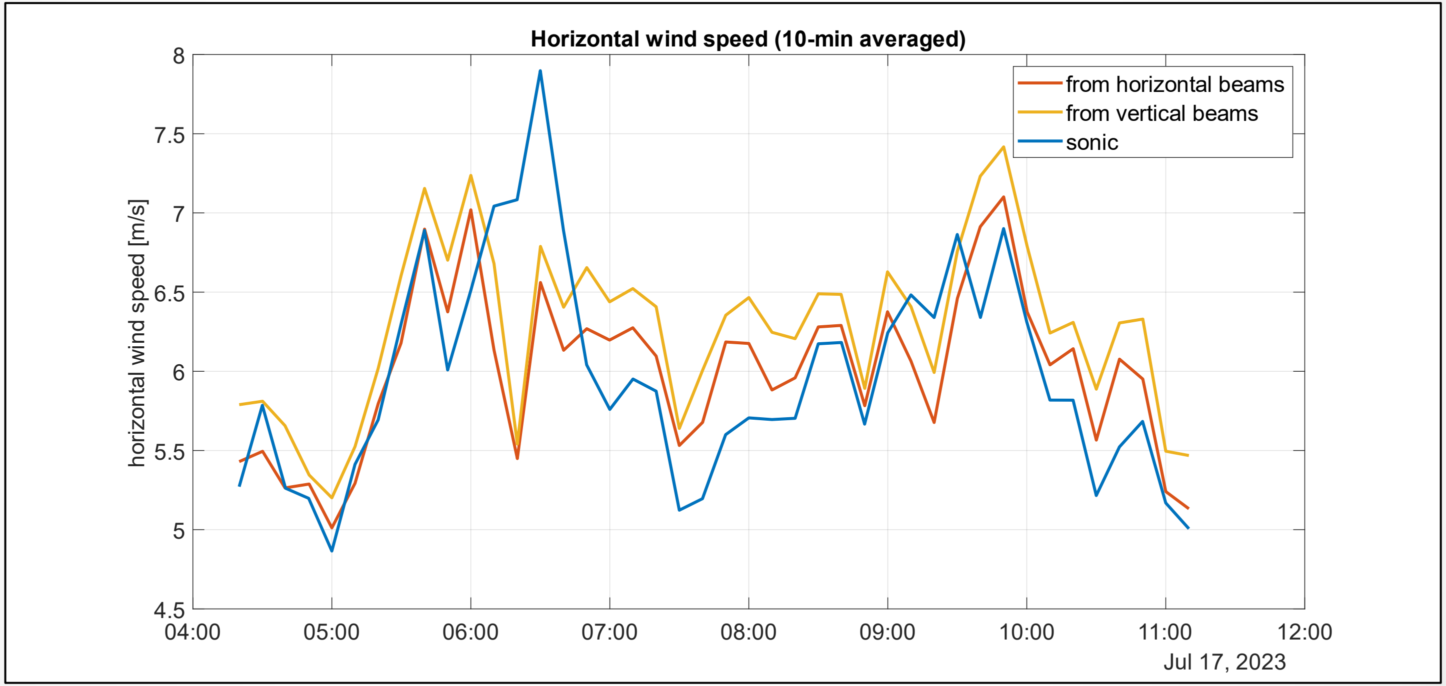
$$u = u_i \cos(\bar{\phi} - \phi_i)$$
$$v = u_i \sin(\bar{\phi} - \phi_i)$$



Exemplary case

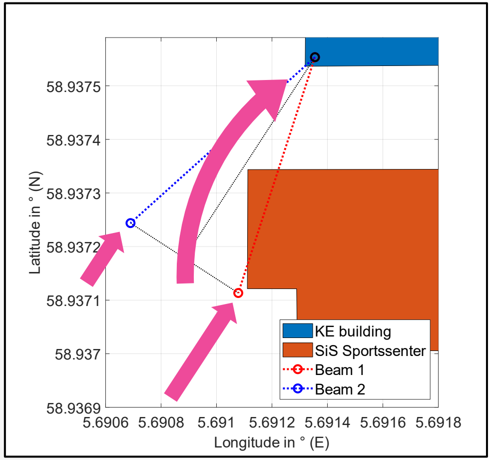


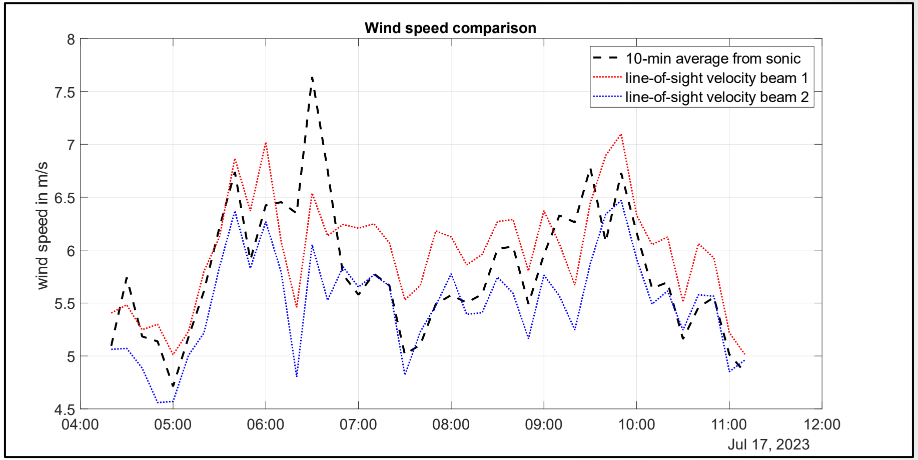
Wind speed comparison



Wind speed comparison

- Systematic difference between radial velocities of horizontal beams

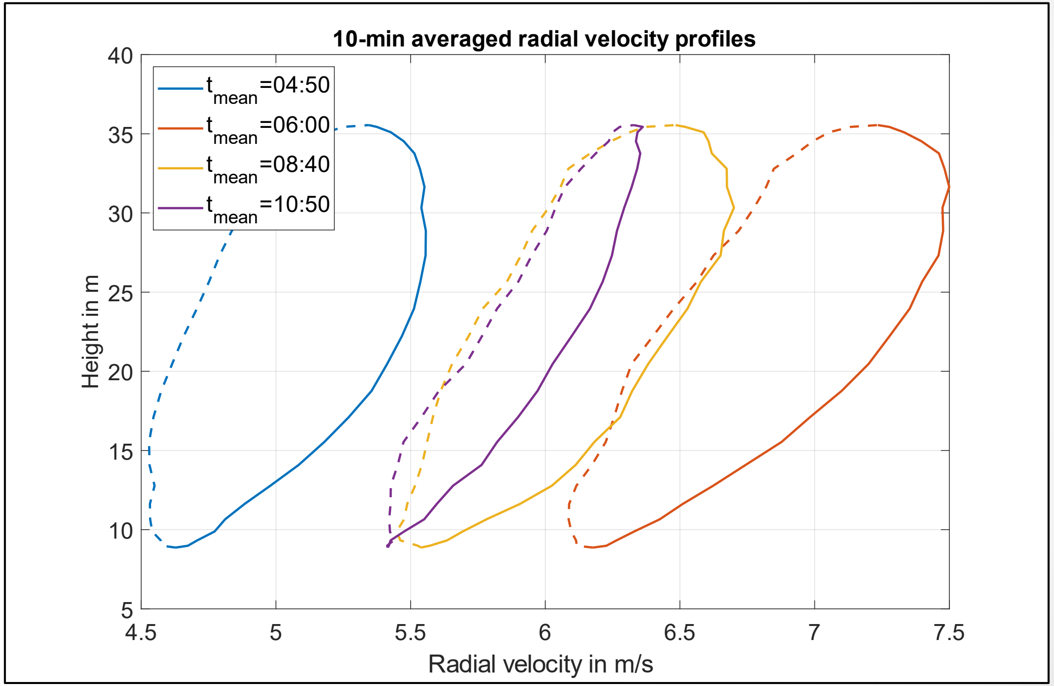




- Likely caused by interference with sports centre
  A. Local speed-up
  B. Directional change
  C. Combination of both

Wind profiles from nacelle lidar

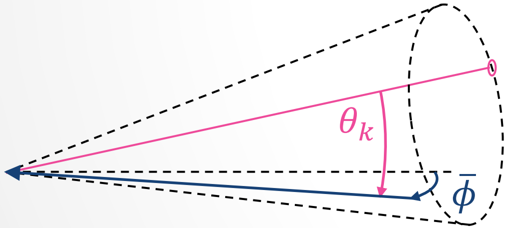
- Solid lines: left side of the scanning circle
- Dashed lines: right side of the scanning circle



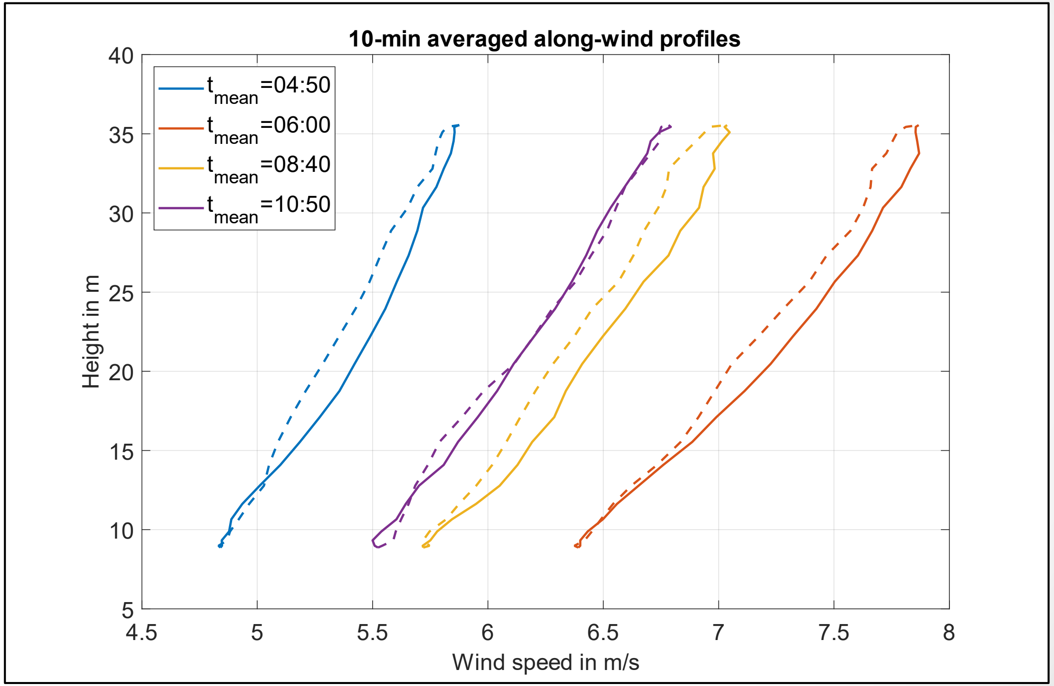
Wind profiles from nacelle lidar

- Yaw and tilt corrected profiles

$$u_k = \frac{v_{r,k}}{\cos\theta_k}$$



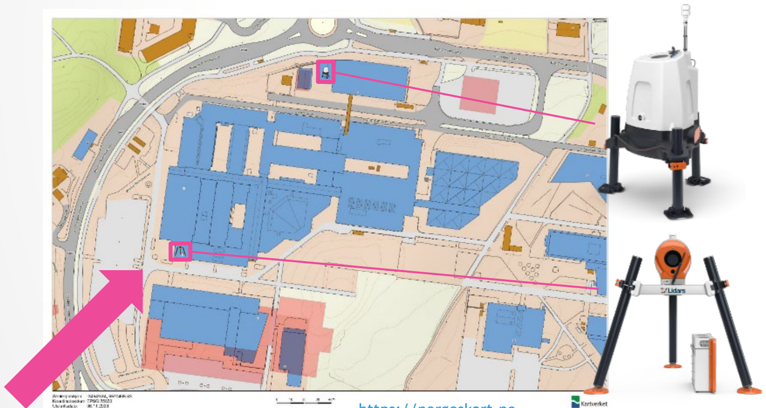
$\bar{\phi}$	10-min offset from lidar axis
$v_{r,k}$	Radial velocity of beam k
θ_k	Along-wind angle of beam k



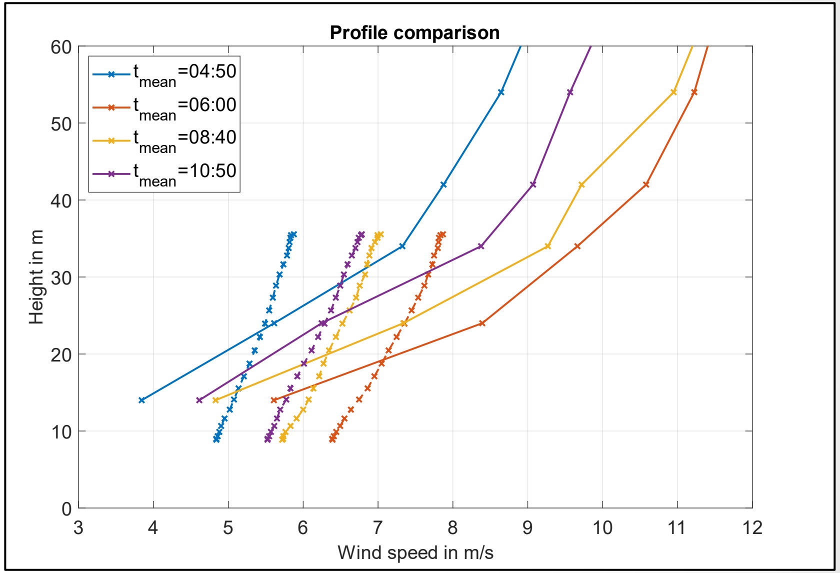
Wind profile comparison

- Wind reaches profiler after passing KE building

→ boundary layer with steep gradients



https://norgeskart.no



- solid lines: profiling lidar
- dashed lines: nacelle lidar

Fitting of standard wind profiles

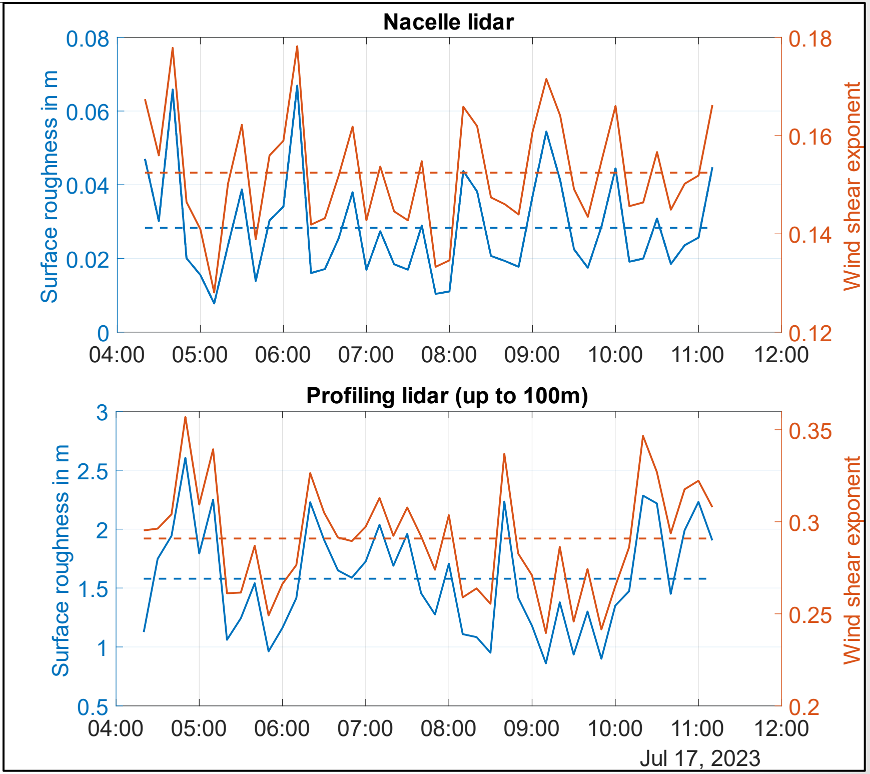
- Power law

$$\bar{u}(z) = \bar{u}_{ref} \cdot \left(\frac{z}{z_{ref}}\right)^{\alpha}$$

- Logarithmic profile

$$\bar{u}(z) = \bar{u}_{ref} \cdot \left(\frac{\ln \frac{z}{z_0}}{\ln \frac{z_{ref}}{z_0}}\right)$$

$\bar{u}(z)$	Wind speed at height z
$\bar{u}_{ref}(z)$	Wind speed at reference height z_{ref}
α	Wind shear exponent
z_0	Surface roughness

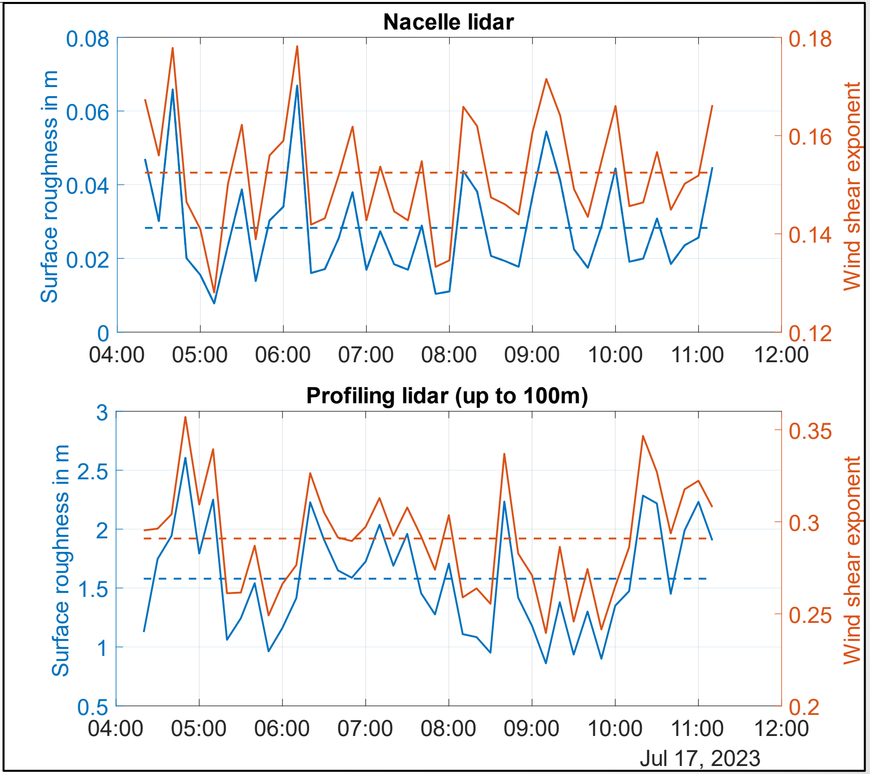


Fitting of standard wind profiles

- Nacelle lidar:
  - $z_0 = 0.01 \ldots 0.07$ m
  - $\alpha = 0.13 \ldots 0.18$
- Profiler:
  - $z_0 = 1 \ldots 2.5$ m
  - $\alpha = 0.24 \ldots 0.36$
- Literature values:

Type of terrain	Surface roughness in m	Wind shear exponent
Mown grass	0.001 ... 0.01	
Low grass	0.01 ... 0.04	0.13
High grass	0.04 ... 0.1	0.19
Forest and woodland	0.1 ... 1	
Built up area, suburb	1 ... 2	0.32
City	1 ... 2	

Nacelle lidar (Low grass, High grass)
Profiler (Built up area, suburb; City)



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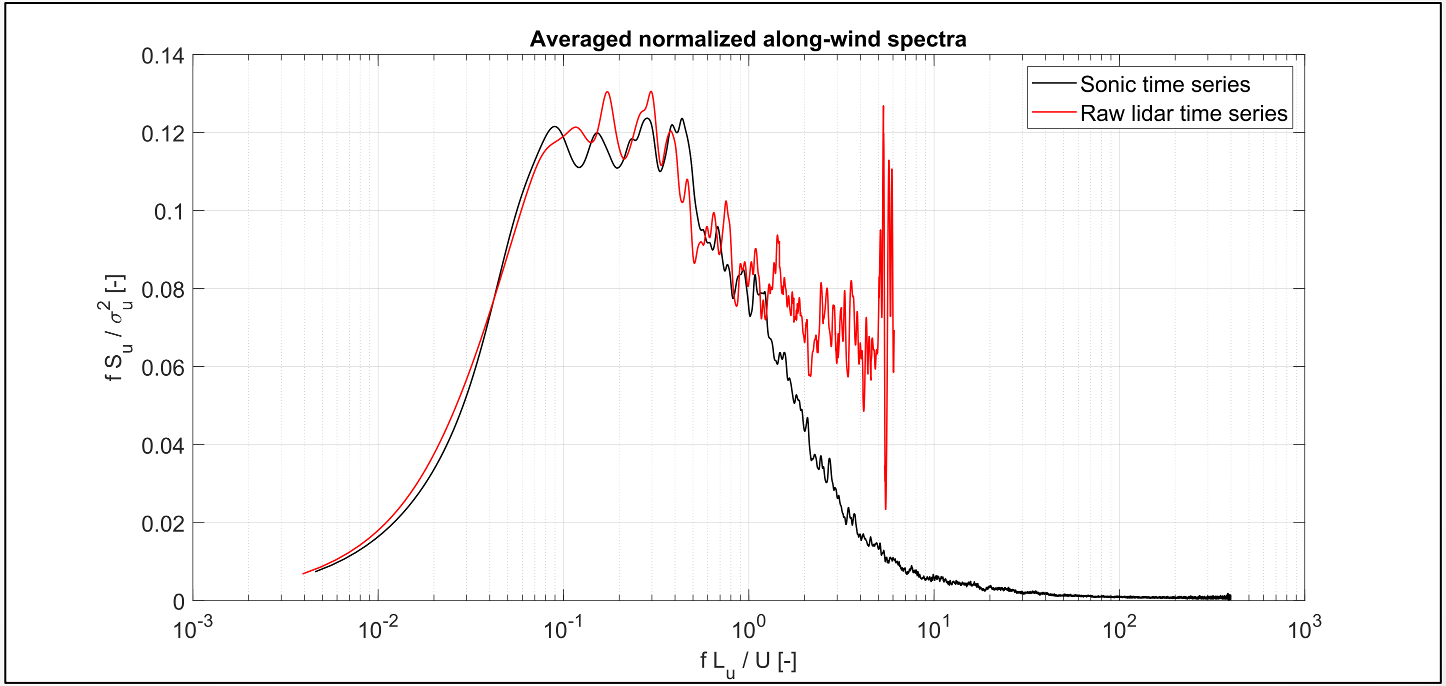
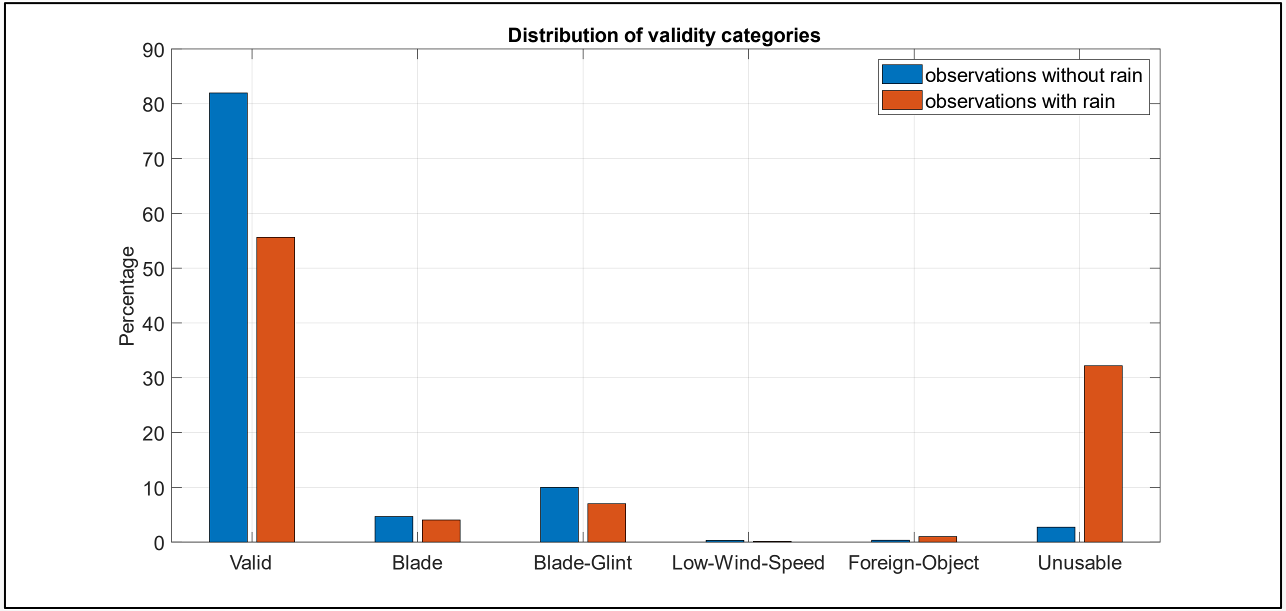
Spectral estimates

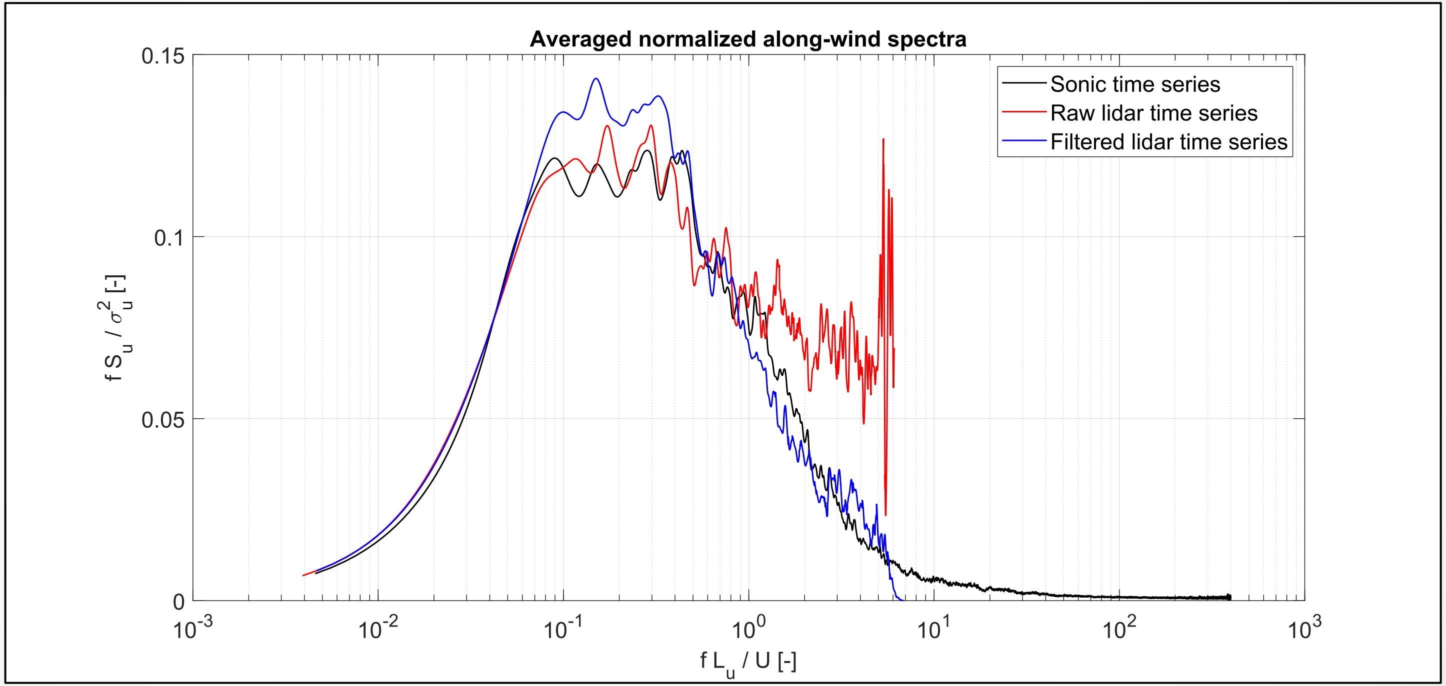


Spectral estimates

- Large share of data flagged as “unusable”



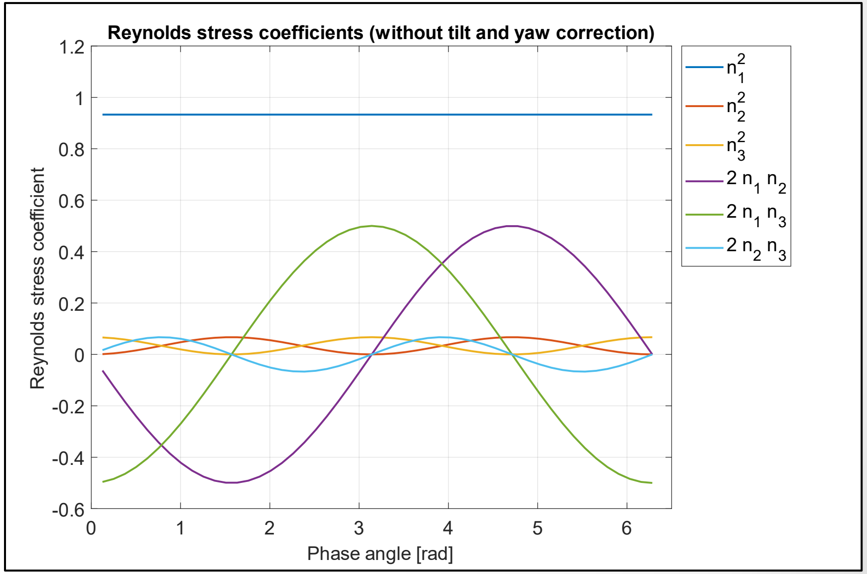
Spectral estimates



Estimation of Reynolds stresses

$$\sigma_{v_r}^2 = \sigma_u^2\, n_1^2 + \sigma_v^2\, n_2^2 + \sigma_w^2\, n_3^2 - \langle u'v' \rangle\, 2\, n_1 n_2 - \langle u'w' \rangle\, 2\, n_1 n_3 + \langle v'w' \rangle\, 2\, n_2 n_3$$

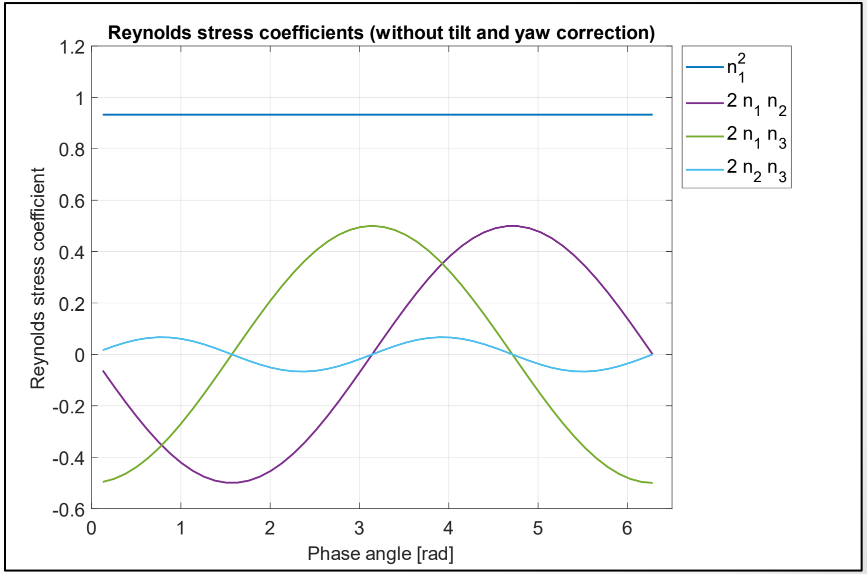
- fitting procedure is poorly conditioned in case of lidars with a single opening angle



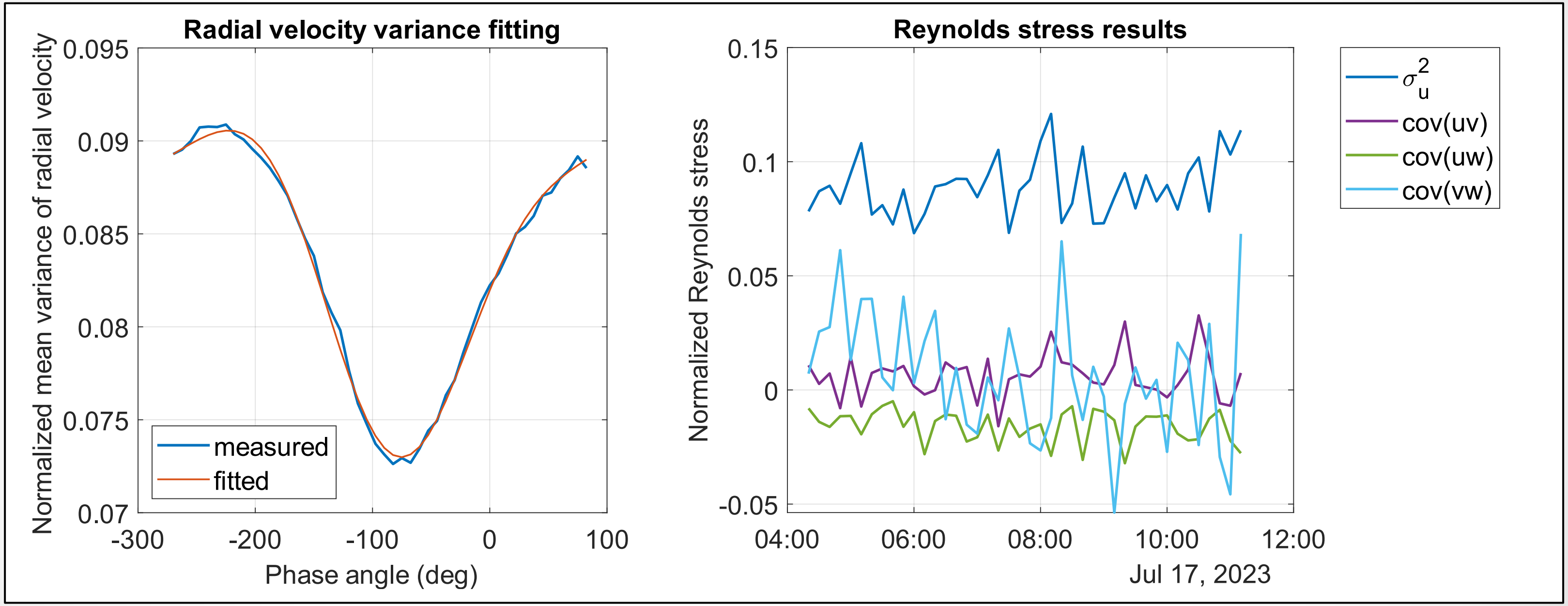
Estimation of Reynolds stresses

$$\sigma_{v_r}^2 = \sigma_u^2\, n_1^2 - \langle u'v' \rangle\, 2\, n_1 n_2 - \langle u'w' \rangle\, 2\, n_1 n_3 + \langle v'w' \rangle\, 2\, n_2 n_3$$

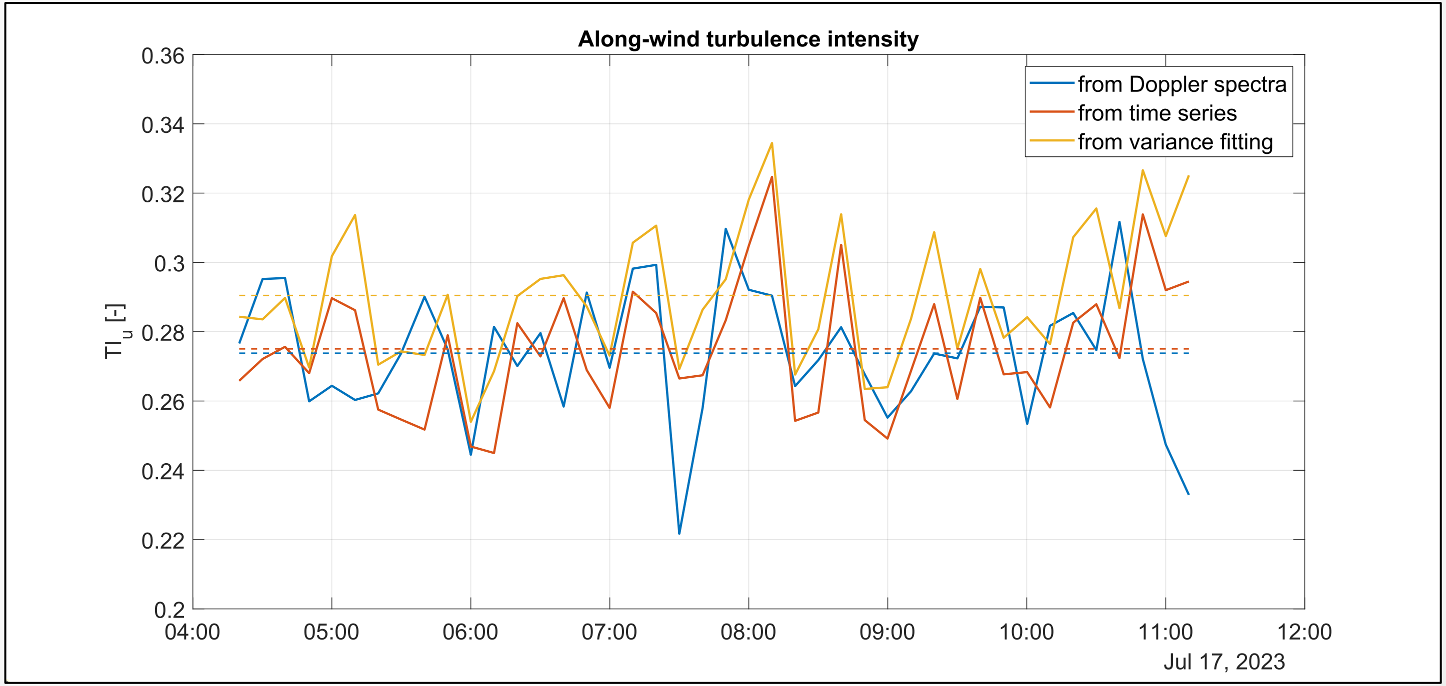
- simplified estimate of σ_u^2 (as well as $\langle u'v' \rangle$, $\langle u'w' \rangle$ and $\langle v'w' \rangle$) by neglecting the terms $\sigma_v^2 n_2^2$ & $\sigma_w^2 n_3^2$



Estimation of Reynolds stresses



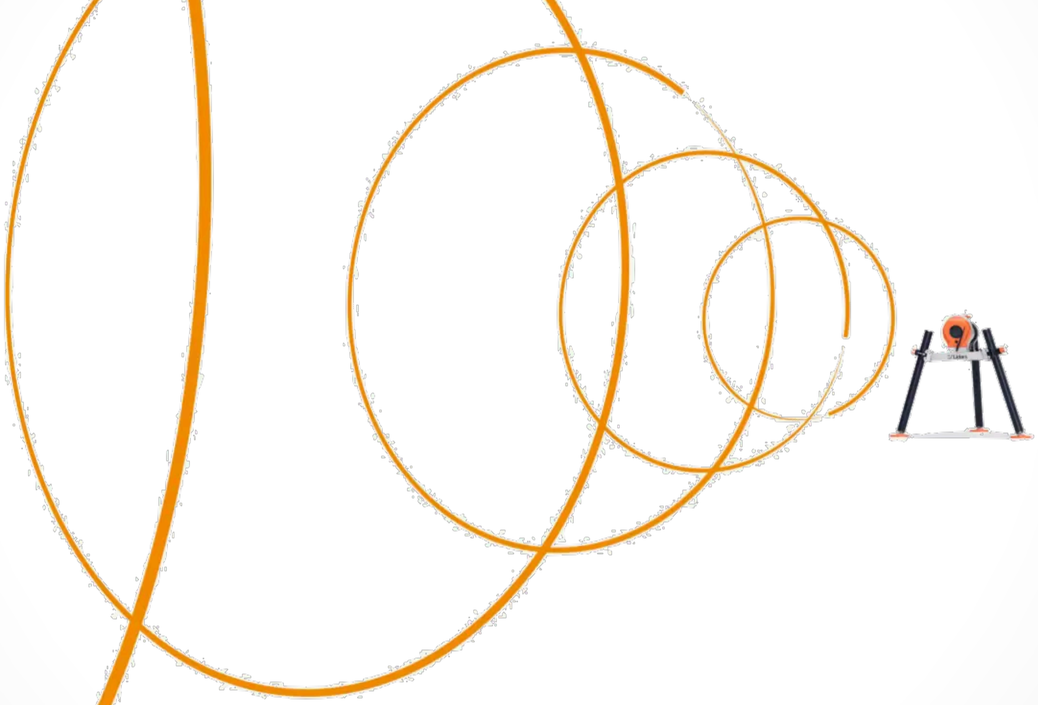
Turbulence intensity estimates



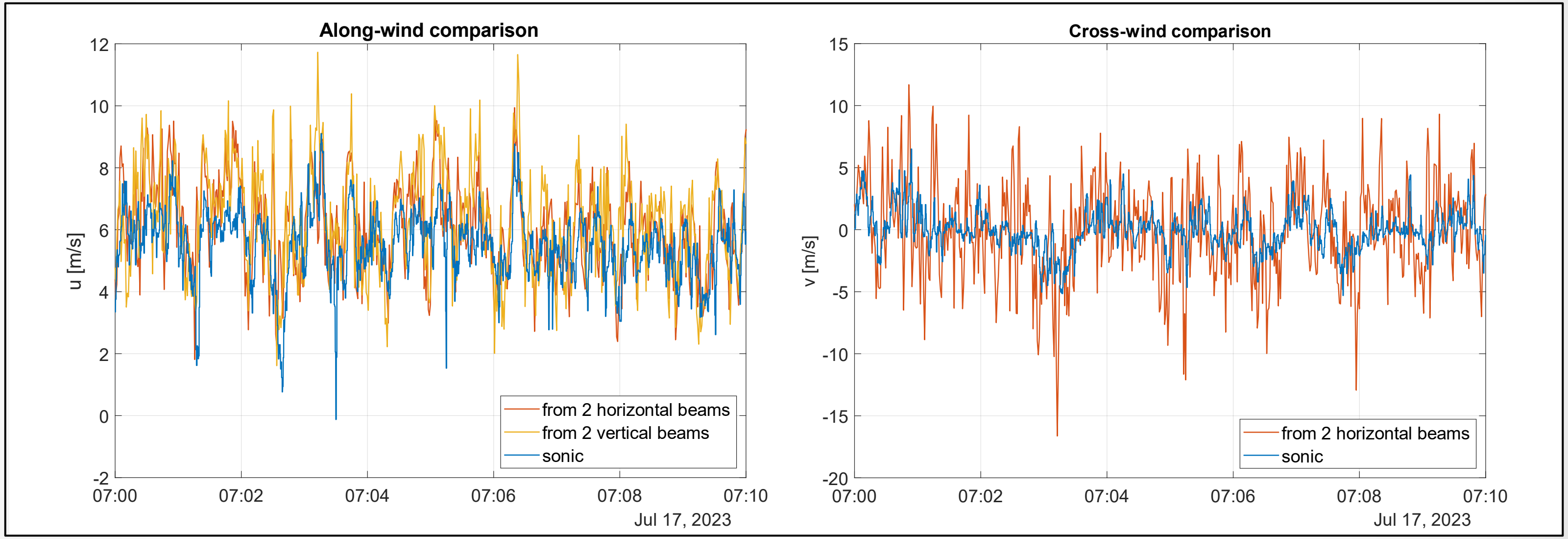
Conclusion

- 2 horizontal lidars (ZXTM) and 1 profiler (ZX300) deployed on the UiS campus, in an urban environment
- The 3 lidars give insights on:
  - Flow interference with buildings
  - Wind profile
  - Surface roughness estimates
- The horizontal lidars provide:
  - Line of sight time-series in 50 points on the scanning circle, at 1 Hz in each point
  - Time-series of the along-wind turbulence from the data in the horizontal plane
  - Turbulence characteristics in terms of:
    - Reduced Reynolds stress tensor including turbulence intensity
    - Radial and along-wind turbulence spectra
  - Influence of rain on the data quality identified and accounted for

Thank you for your attention.



Wind speed comparison



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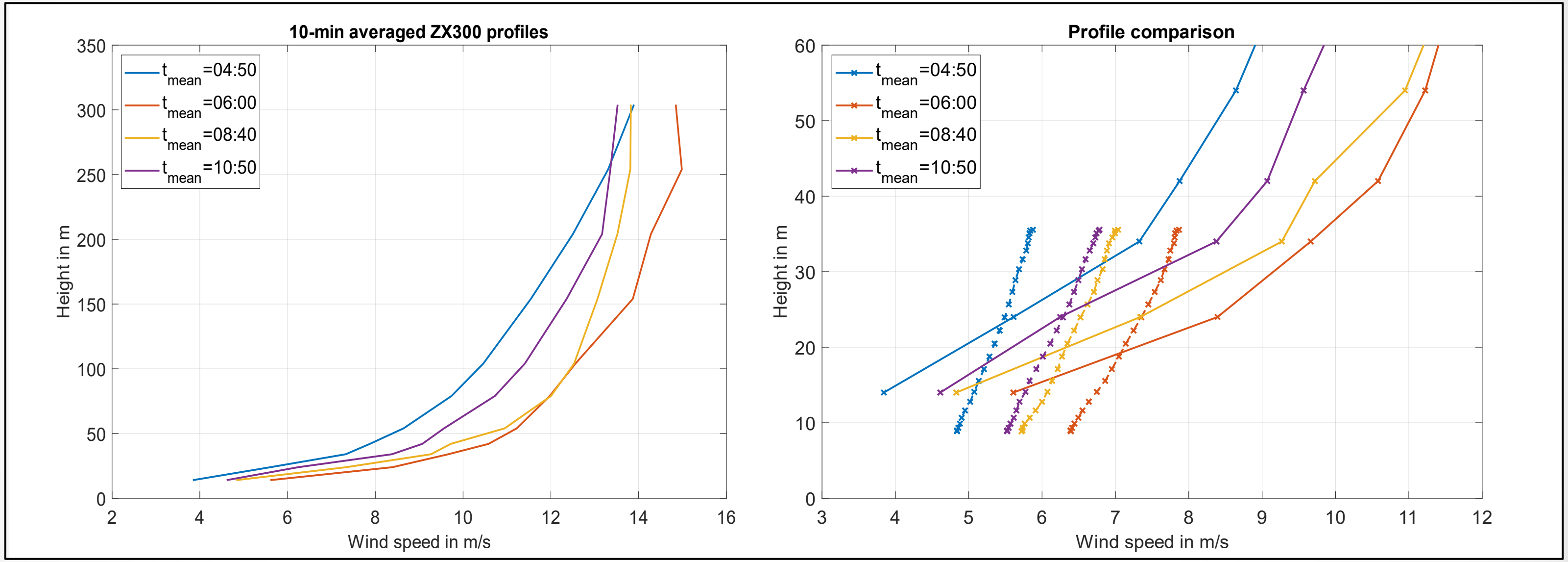
Wind profiles from profiling lidar

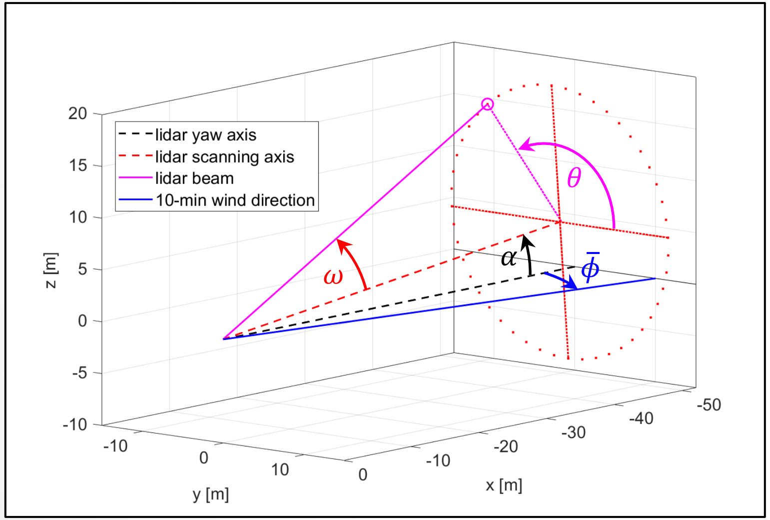


- solid lines: profiling lidar
- dashed lines: nacelle lidar

Estimation of Reynolds stresses

- Unit vector:

$$\boldsymbol{n}(\theta) = [-\cos\omega \quad \cos\theta\,\sin\omega \quad \sin\theta\,\sin\omega] \cdot \underbrace{\begin{bmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{bmatrix}}_{\text{tilt correction}} \cdot \underbrace{\begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{yaw correction}}$$



ω	half cone opening angle
α	tilt angle
ϕ	yaw error
θ	scanning point phase angle

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Estimation of Reynolds stresses

- Radial velocity:

$$v_r = u\,n_1 + v\,n_2 + w\,n_3$$

- Radial velocity variance:

$$\sigma_{v_r}^2 = \sigma_u^2\,n_1^2 + \sigma_v^2\,n_2^2 + \sigma_w^2\,n_3^2 - 2\langle u'v'\rangle\,n_1 n_2 - 2\langle u'w'\rangle\,n_1 n_3 + 2\langle v'w'\rangle\,n_2 n_3$$

- Reynolds stress tensor:

$$\boldsymbol{R} = \begin{bmatrix} \sigma_u^2 & \langle u'v'\rangle & \langle u'w'\rangle \\ \langle v'u'\rangle & \sigma_v^2 & \langle v'w'\rangle \\ \langle w'u'\rangle & \langle w'v'\rangle & \sigma_w^2 \end{bmatrix}$$