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# Estimation of rotor-effective wind speed from turbine-mounted LiDAR for real time applications


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## Abstract / Objectives


Turbine mounted LiDARs have proven to be a good remote sensor candidate for use in wind turbine control applications (e.g. reducing structural loads) since it estimates incoming wind speed before it reaches the rotor plan [1]. Current scientific challenges involve improving accuracy of such device based on signal processing tools and precise system modeling [2,3,4,5].

Two identified drawbacks associated with Light Detection And Ranging (LiDAR) remote sensors:

1. Measurement related noise
2. Spatial integration along the entire laser beam (range weighting function) [6]
   ➔ major filtering impact on the measurement

Objectives

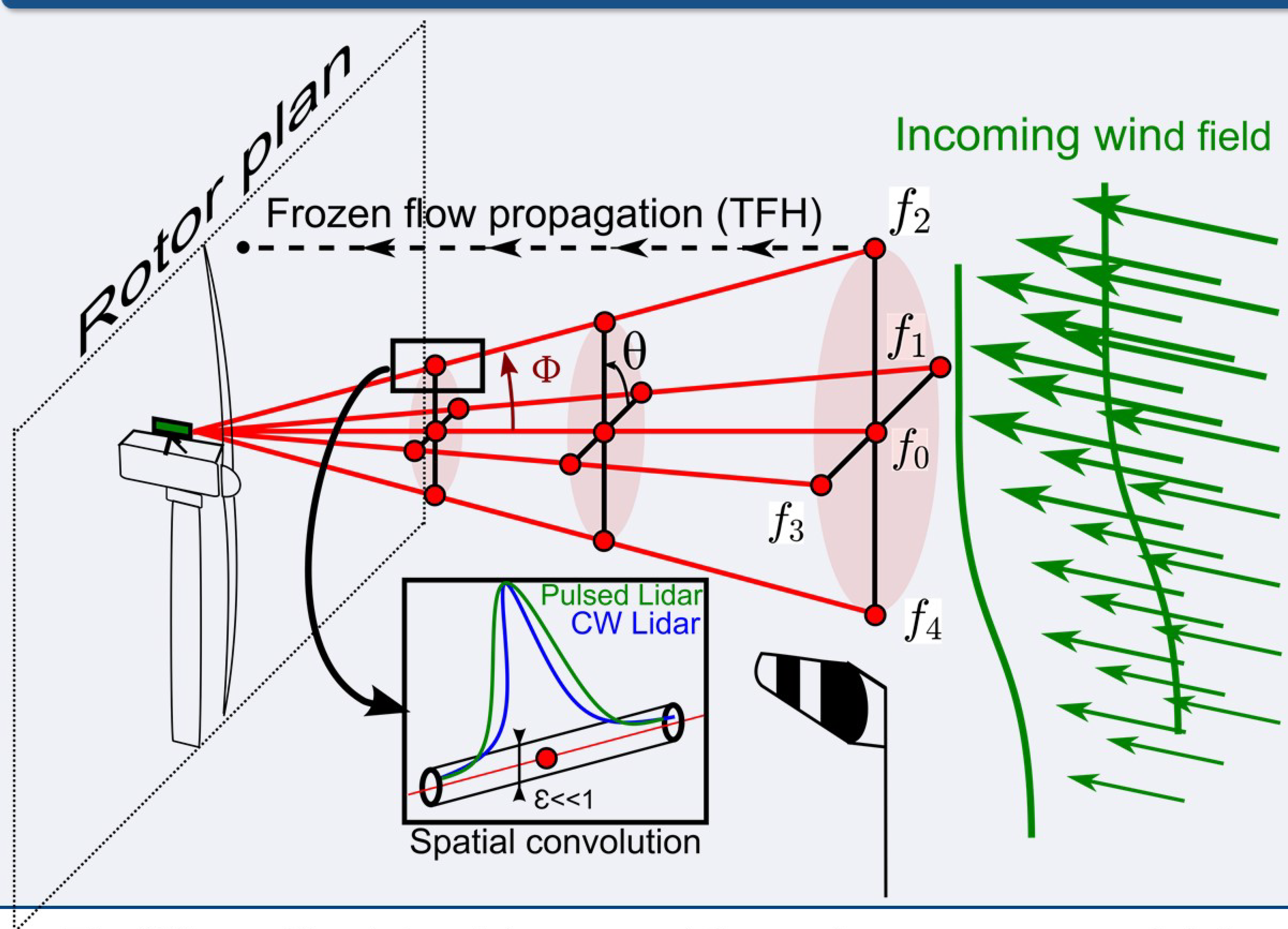
1. Real time estimation of rotor-effective wind speed [7]
2. Representative, generic, efficient and low complexity method

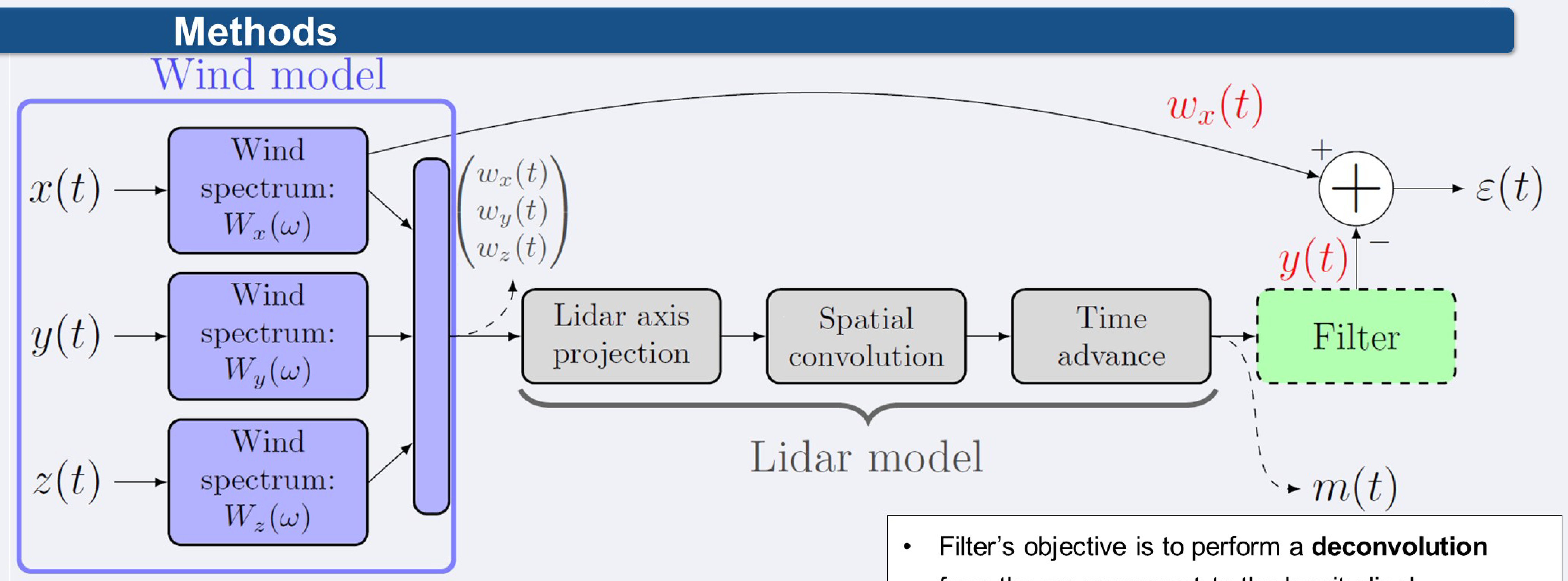
Proposed approach:

- Numerical 3D wind and LiDAR simulators
- Adaptive Wiener filter design to estimate the rotor-effective wind speed from turbine-mounted LiDAR measurement,
- Instantaneous wind speed filtering for various wind and measurement conditions.

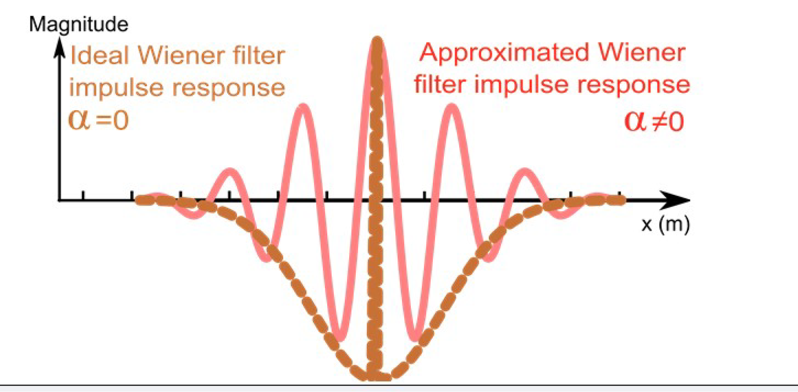



## Methods




- Filter's objective is to perform a **deconvolution** from the measurement to the longitudinal component of the wind field,
- *Remove contributions from upstream and downstream (past & future) wind from the measurement,*
- For horizontal beam in a noiseless environment, the Wiener filter can be seen as follow :




- The Wiener filter takes into account **time advance**, **range weighting function** as well as **PSD models**, **TFH** and **geometry characteristics**,
- The filter is designed such that it minimizes the PSD of the estimation error $\varepsilon(\omega) = W_x(\omega) - F(\omega)M(\omega)$ (Least squares solution),
- To avoid a pure model inversion (noise sensitivity issues) a tunable gain appears in the filter expression $\alpha$.

$$F_x(\omega) = \overbrace{e^{-2i\pi\omega\frac{l_0 \sin(\Phi)}{\bar{w}}}}^{delay} \overbrace{\frac{L W_x^2 \sin(\Phi)}{L^2\left(\sin^2(\Phi) W_x^2 + \cos^2(\Phi)\left(\cos^2(\Phi)\cos^2(\theta) W_y^2 + \sin^2(\Phi)\sin^2(\theta) W_z^2\right)\right) + \alpha^2}}^{magnitude}$$

**Adaptive filter** (Updated values) $\overline{w(t)}, W_{x,y,z}(t), \alpha(t) = f(\overline{w(t)}, \sigma(t), CNR, \ldots)$

Where $L$ is the Fourier transform of the spatial convolution, which are resp. given by:

$$l_{pulsed}(t) = \frac{\bar{w}}{\sin(\Phi)} \beta e^{-}\alpha \left(\frac{t\bar{w}}{\sin(\Phi) - l_0}\right)^2 \quad \text{and} \quad l_{CW}(t) = \frac{K}{\left(\frac{t\bar{w}}{\sin(\Phi)}\right)^2 + \left(1 + \frac{t\bar{w}}{l_0}\right)^2 R_r^2}$$

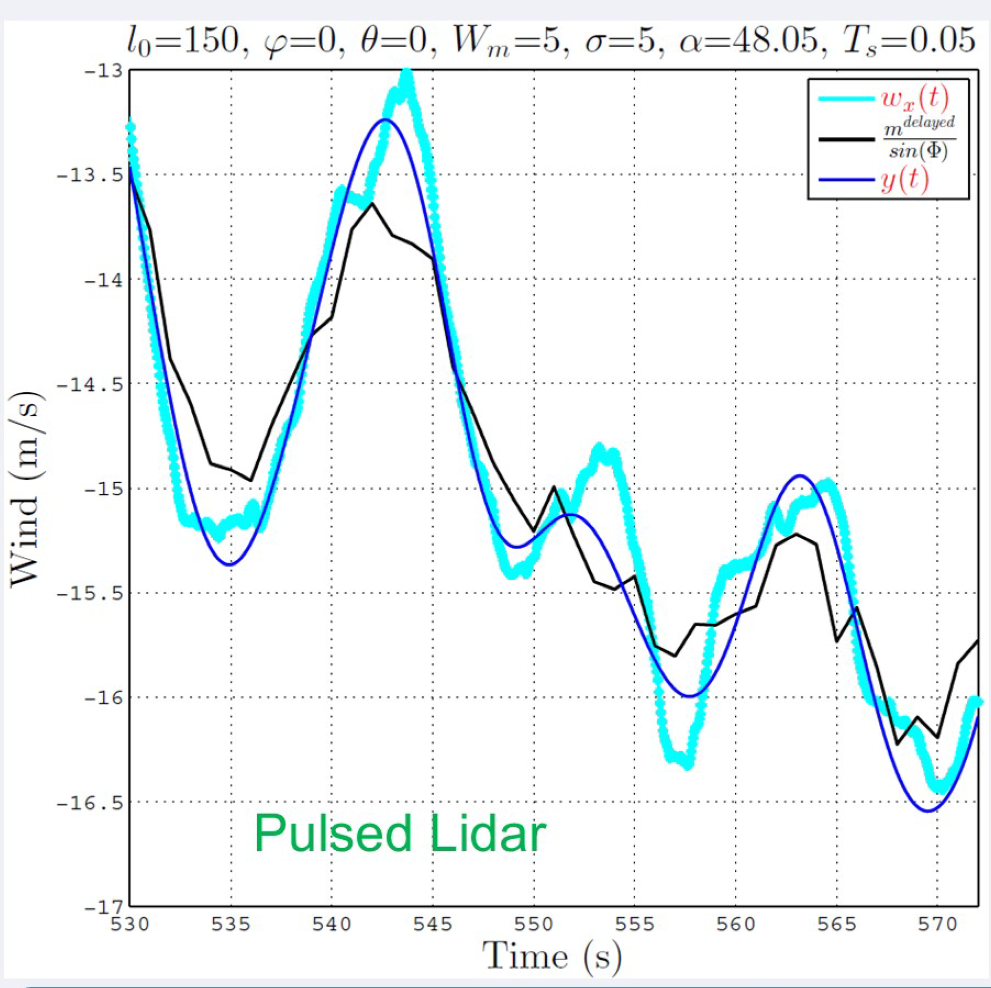
With $\alpha = \frac{\text{FWHM}^2}{4ln(2)}$, $\beta = \frac{2}{\text{FWHM}}\sqrt{\frac{ln(2)}{\pi}}$, FWHM $= 29m$ for a Wind Iris and $R_r$ is the Rayleigh length.

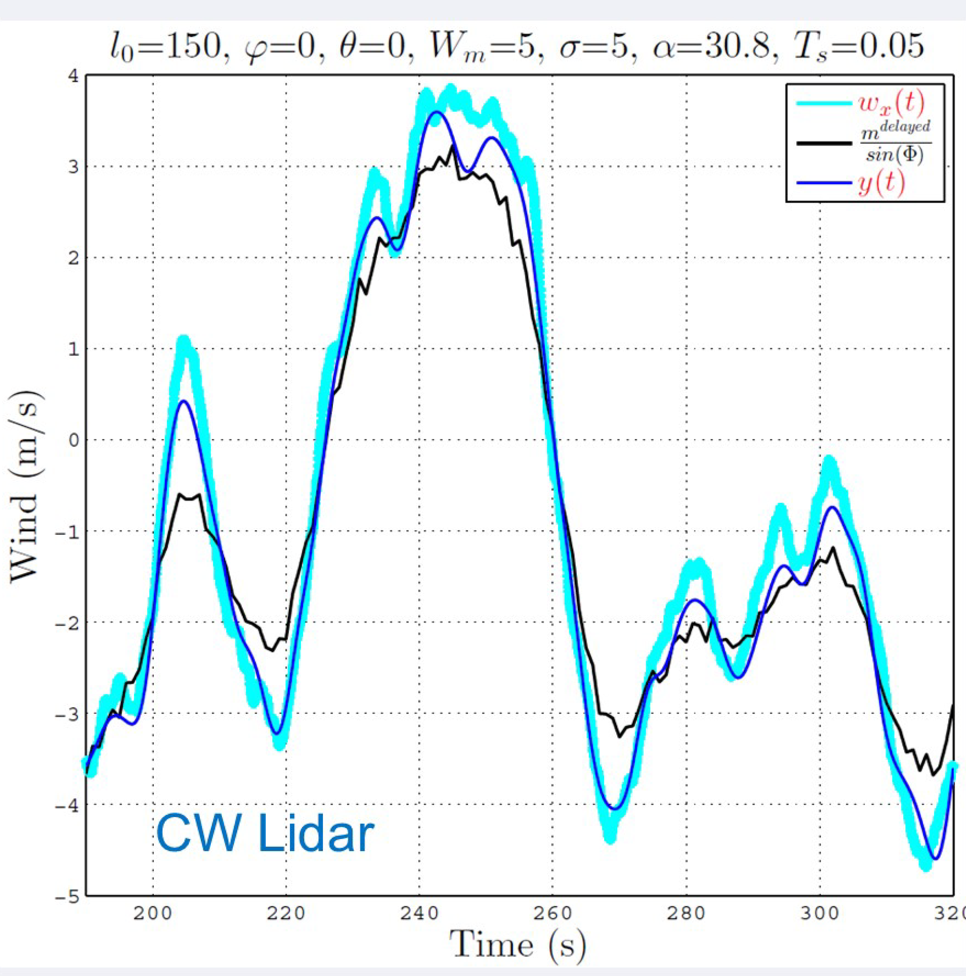
- Hann window is applied to approximate the ideal Wiener filter as a FIR filter → Implementation aspects (**limited complexity**)

**Simulations**: Relative gain on squared error (%)

$$100\left(1 - \frac{\sum_{k=1}^{N}\left(y(k) - w_x(k)\right)^2}{\sum_{k=1}^{N}\left(\frac{1}{\sin(\Phi)} m\left(k + \frac{l_0}{\bar{w}T_s}\right) - w_x(k)\right)^2}\right)$$

## Results




**Pulsed Lidar**

| Measurement distance on x-axis (m) | $f_0$: 5 | $f_0$: 15 | $f_0$: 25 | $f_1$: 5 | $f_1$: 15 | $f_1$: 25 | $f_2$: 5 | $f_2$: 15 | $f_2$: 25 |
|---|---|---|---|---|---|---|---|---|---|
| 50 | 49.77 | 30.71 | 21.60 | 3.29 | 3.22 | 3.11 | 26.42 | 10.48 | 10.39 |
| 70 | 53.24 | 30.11 | 22.10 | 3.95 | 2.54 | 1.31 | 18.65 | 19.45 | 6.02 |
| 90 | 49.17 | 24.60 | 20.47 | 9.53 | 5.84 | 3.93 | 21.49 | 9.86 | 7.77 |
| 110 | 51.21 | 22.08 | 14.92 | 8.79 | 5.95 | 6.51 | 12.66 | 12.46 | 9.98 |
| 130 | 53.42 | 26.44 | 21.10 | 1.92 | 5.37 | 8.45 | 18.00 | 12.43 | 11.31 |
| 150 | 52.07 | 27.47 | 19.16 | 1.67 | 14.29 | 6.26 | 20.32 | 19.76 | 2.30 |

Mean Wind speed (m/s)

**CW Lidar**

| Measurement distance on x-axis (m) | $f_0$: 5 | $f_0$: 15 | $f_0$: 25 | $f_1$: 5 | $f_1$: 15 | $f_1$: 25 | $f_2$: 5 | $f_2$: 15 | $f_2$: 25 |
|---|---|---|---|---|---|---|---|---|---|
| 50 | 26.94 | 9.67 | 5.93 | 5.35 | 2.94 | 3.32 | 17.83 | 12.17 | 5.01 |
| 70 | 41.07 | 15.81 | 10.35 | 3.65 | 2.75 | 0.46 | 12.75 | 11.55 | 12.96 |
| 90 | 43.94 | 20.84 | 14.71 | 7.84 | 8.91 | 5.18 | 18.58 | 9.51 | 7.04 |
| 110 | 60.35 | 27.78 | 19.77 | 9.50 | 5.33 | 4.94 | 17.10 | 15.19 | 8.99 |
| 130 | 62.23 | 36.00 | 31.94 | 6.91 | 6.50 | 9.25 | 33.27 | 17.94 | 15.31 |
| 150 | 65.17 | 45.32 | 34.30 | 7.63 | 4.75 | 7.28 | 45.31 | 36.60 | 5.77 |

Mean Wind speed (m/s)

## Conclusions

- Improved instantaneous wind speed precision for CW & Pulsed Lidars (gains up to 65%),
- Easy to implement and computationally efficient method

## Perspectives

- Adaptive $\alpha(t)$ (online tuning procedure)
- Experimental validation on wind turbine
- TFH and directional bias improvements
- Lidar based blade pitch control

## References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