Wind turbine aerodynamic measurements using a scanning lidar

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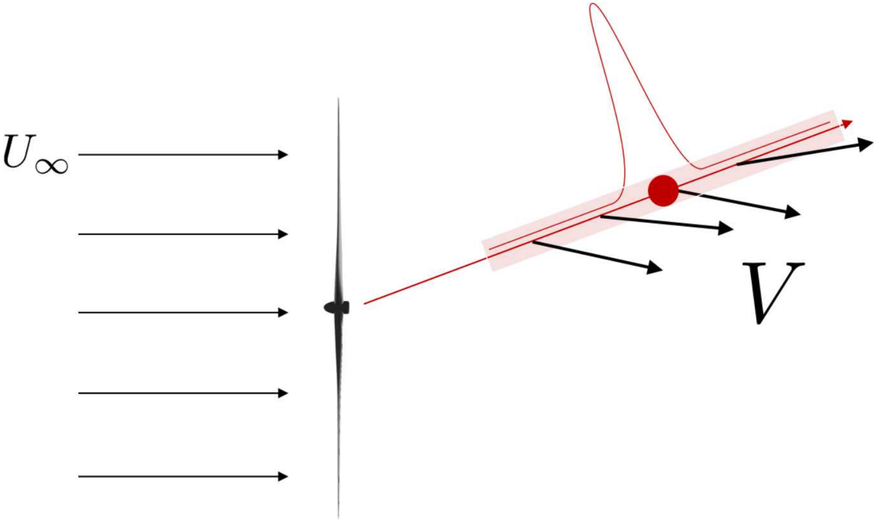
How accurately can you calculate wind turbine aerodynamics from a scanning lidar measurement of the wake?

Motivation

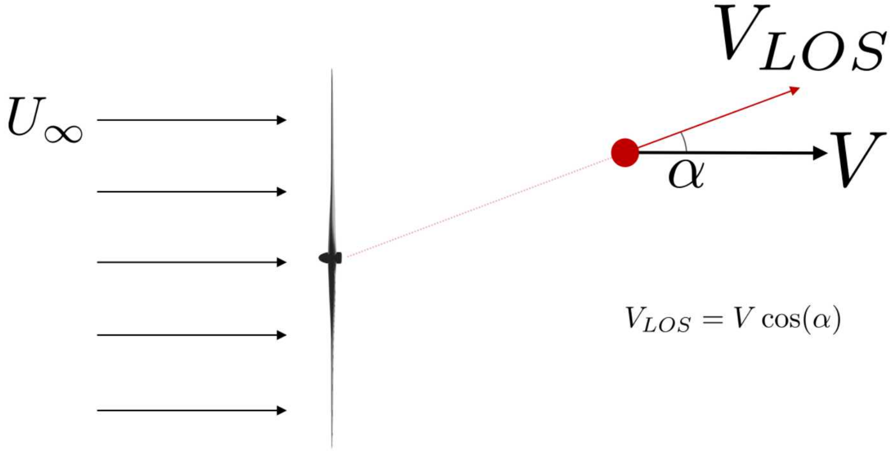
- DTU SpinnerLidar deployed at Sandia's SWiFT site
- wake steering experiment quantified wake deflection for different inflow conditions
- can a simple technique correct issues with a lidar measurement?

Volumetric Averaging Error



Volumetric weighting is Lorentzian distribution with FWHM = 12.1 m for $f = 3D$

Projection Error



$$V_{LOS} = V\cos(\alpha)$$

lidar line-of-sight velocity, V_{LOS}, is measured
actual velocity, V, is unknown

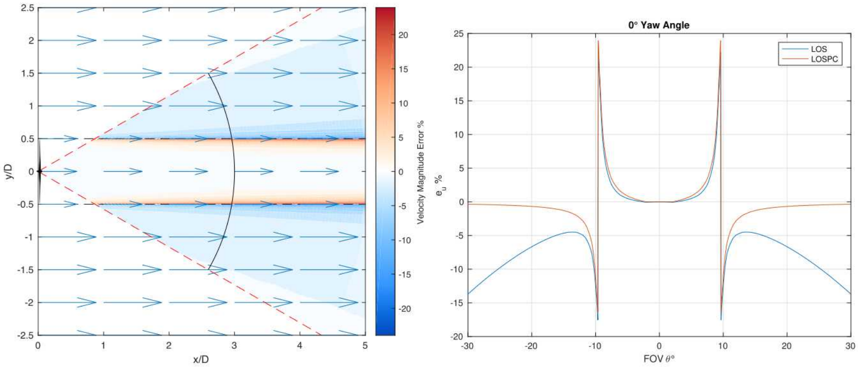
Projection Correction

- Assume average wind direction is known
- Assume $\mathbf{V} \parallel U_\infty$
- Therefore α is the angle between the wind direction and the instantaneous lidar beam
- the line-of-sight projection correction is

$$|\mathbf{V}_{LOSPC}| = \frac{|\mathbf{V}_{LOS}|}{\cos(\alpha)}$$

- Does this correction work and reduce error?

Test on simple velocity field



- Volumetric averaging error is greatest in regions of high shear
- LOSPC effective at reducing error near edge of field of view

Test Correction with Large-eddy Simulation

- exact velocity is known from simulation so error can be calculated
- 200 seconds in SOWFA simulation
- V27, zero yaw
- virtual DTU SpinnerLidar - 984 point rosette pattern, 2 seconds / scan, 100 scans total
- $U_\infty = 6.5$ m/s, shear exponent 0.29, $TI = 8.5\%$

Compare Axial Velocity with Different Methods

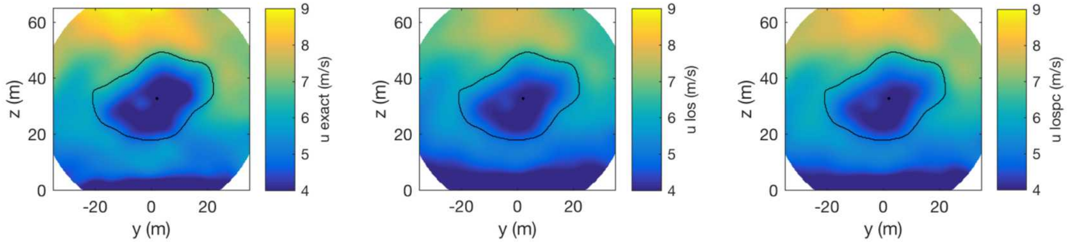


Figure: Axial velocity field a) exact, b) line of sight, and c) line of sight projection correction for one scan of the field of view.

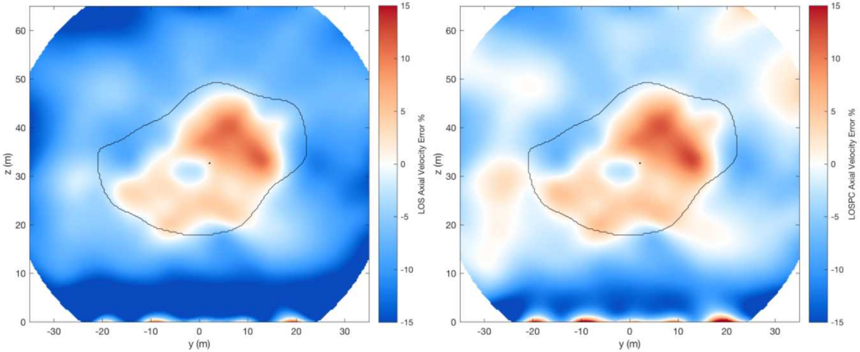
- wake - locus of points of equal velocity | $A_{wake} = 2\pi R^2$
- exact axial velocity, u_{ex}
- line-of-sight axial velocity, $u_{LOS} = V_{LOS}$
- line-of-sight axial velocity with projection correction, $u_{LOSPC} = \frac{V_{LOS}}{\cos(\alpha)}$

Axial Velocity Error for One Scan

$$e_{u_{LOS}} = \frac{u_{LOS} - u_{ex}}{u_{ex}} \tag{1}$$

and

$$e_{u_{LOSPC}} = \frac{u_{LOSPC} - u_{ex}}{u_{ex}}. \tag{2}$$



Axial Velocity Error for 100 Scans

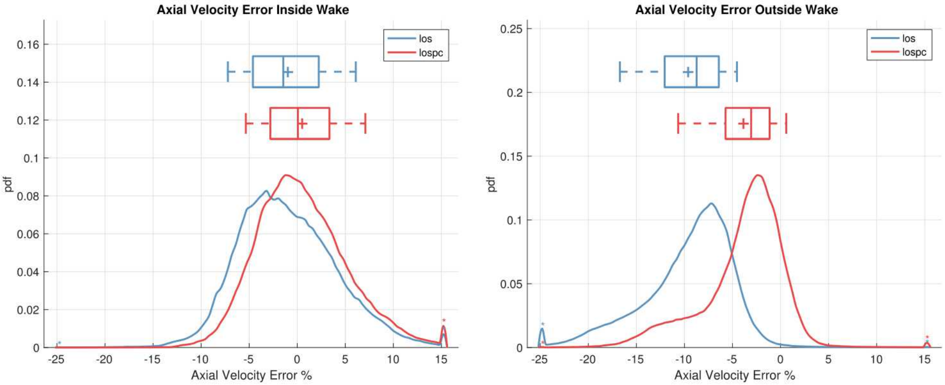


Figure: Distribution of axial velocity error at $3D$ for 100 lidar scans a) inside the wake b) outside the wake.

Freestream Velocity Estimation

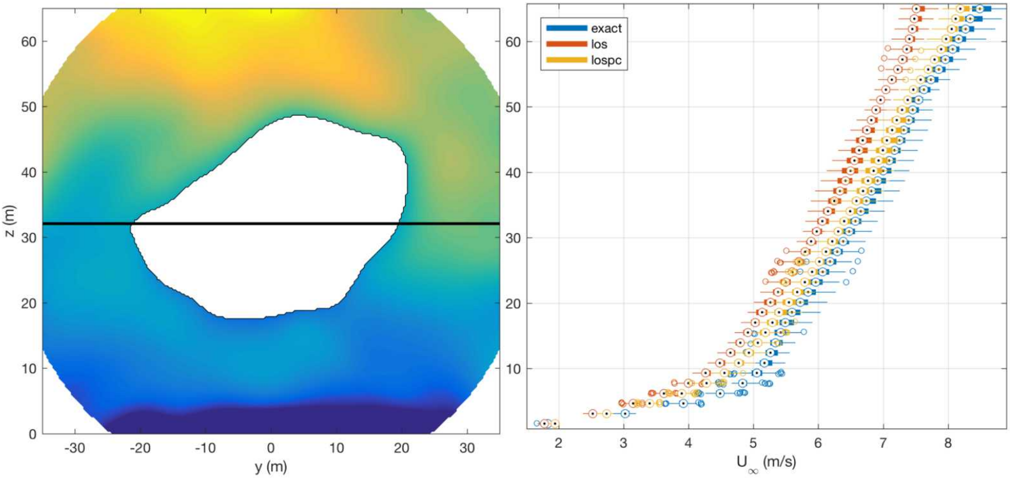


Figure: Atmospheric boundary layer a) vertical plane $3D$ downstream and b) freestream velocity from 100 lidar scans.

Azimuthal Average Wake Induction

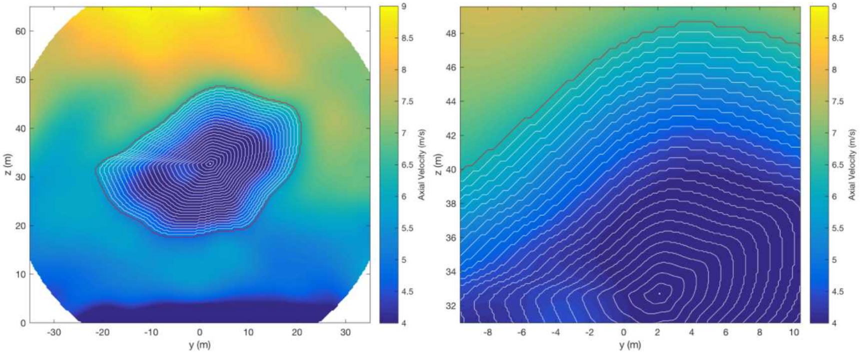


Figure: Distorted wake shape annuli and zoomed view.

$$\overline{a} = \frac{1}{2\pi} \int_0^{2\pi} \left(1 - \frac{u_{wake}}{U_\infty}\right) \, \mathrm{d}\theta \tag{3}$$

Azimuthal Average Wake Induction

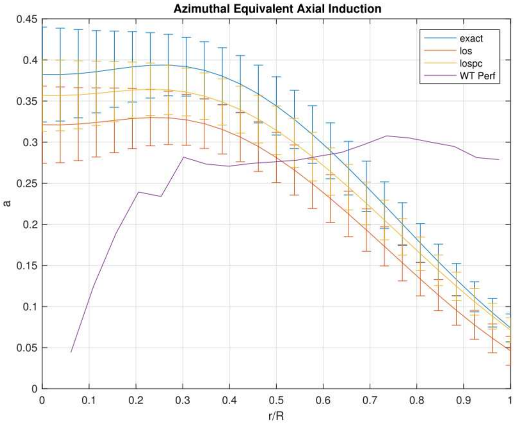


Figure: Azimuthal averaged wake induction for 100 lidar scans.

Thrust Coefficient Estimation

$$C_{T_{wake}} = \frac{2}{\pi R^2} \iint_{wake} \frac{u(z,y)}{U_\infty}\left(1 - \frac{u(z,y)}{U_\infty}\right) \mathrm{d}z\,\mathrm{d}y \tag{4}$$

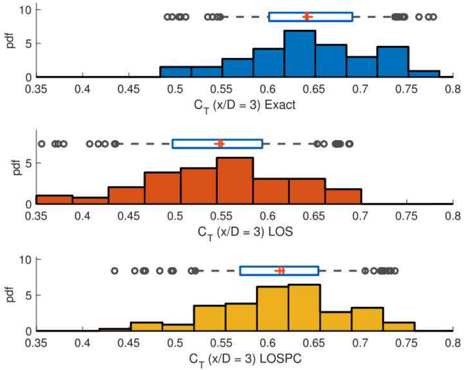


Figure: Probability density of thrust coefficient from 100 lidar scans at $f = 3D$.

Power Coefficient Estimation

$$C_{P_{wake}} = \frac{1}{\pi R^2} \iint_{wake} \frac{u(z,y)}{U_\infty} \left(1 - \frac{u^2(z,y)}{U_\infty^2}\right) \mathrm{d}z \, \mathrm{d}y \tag{5}$$

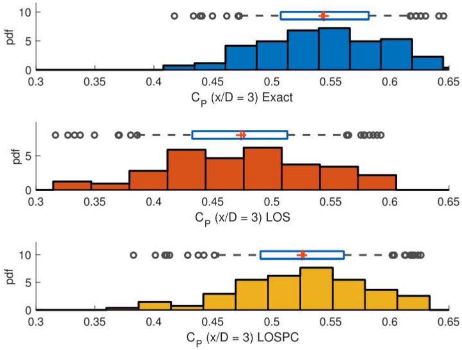


Figure: Probability density of power coefficient from 100 lidar scans at $f = 3D$.

Summary of Error Improvement

Table: Summary of Error for Average Values of 100 Lidar Scans.

Method	u (m/s)	u_{error}	$\overline{a}$	$\overline{a}_{error}$	U_∞ (m/s)	$U_{\infty error}$	C_T	$C_{T_{error}}$	C_P	$C_{P_{error}}$
Exact	6.0	—	0.29	—	6.5	—	0.64	—	0.54	—
LOS	5.6	-7.4%	0.24	-18.7%	5.9	-9.2%	0.55	-15.1%	0.47	-13.2%
LOSPC	5.9	-2.8%	0.27	-7.6%	6.2	-3.5%	0.61	-4.6%	0.53	-3.5%

Suggestion to Correct Volumetric Averaging

for a V27 wake with $TI = 8.5\%$ the following correction would average 0 error for axial velocity:

$$u = \frac{1.028\, u_{LOS}}{\cos(\alpha)} \tag{6}$$

Conclusions

- assumed exact velocity is parallel to wind direction
- found angle between lidar beam and wind direction
- projection correction improved error from -7.4% to -2.8% for axial velocity

Future Work

- comparison of LINCOM could show if extra computational cost is necessary
- use turbulence measurements from lidar to improve thrust and power

$$C_{T_{wake}} = \frac{2}{\pi R^2} \iint\limits_{wake} \frac{u(z,y)}{U_\infty} \left(1 - \frac{u(z,y)}{U_\infty}\right) - \frac{2}{\pi R^2} \iint\limits_{wake} TI^2(z,y)\, \mathrm{d}z\, \mathrm{d}y \tag{7}$$

$$C_{P_{wake}} = \frac{1}{\pi R^2} \iint\limits_{wake} \frac{u(z,y)}{U_\infty} \left(1 - \frac{u^2(z,y)}{U_\infty^2}\right) \mathrm{d}z\, \mathrm{d}y - \frac{1}{\pi R^2} \iint\limits_{wake} \frac{5u(z,y)}{U_\infty} TI^2(z,y)\, \mathrm{d}z\, \mathrm{d}y \tag{8}$$