Integrating Scanning Lidar with LES for Wake Characterization in Complex Terrain

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Problem Definition

We would like to characterize wind turbine wakes using scanning lidars. Specifically, how can the scanning geometry be chosen to maximize accuracy of wake characteristics? How is this accomplished in complex terrain environments?

From Mike Courtney/DTU Wind Energy.
https://www.nature.com/news/world-s-largest-wind-mapping-project-spins-up-in-portugal-1.21481
Motivation – Complex Terrain

Why complex terrain?

Features of terrain introduce **new flow effects**, which can be taken advantage of

- Flow speed up in up-sloping terrain
- But, higher uncertainties in AEP → need to study further

Countries like China have lots of mountainous terrain

Source: https://globalwindatlas.info/about/method
Motivation – Lidar

Why use lidar?

• Addresses market need for replacing expensive met-masts

• Tip heights are approaching 200 m. Lidars can probe wind at distances > 1 km

• Vast majority wake models assume horizontally homogeneous conditions and no flow separation → not accurate in complex terrain!

Wakes need to be studied experimentally...
Specifically, how can the scanning geometry be chosen to maximize accuracy of wake characteristics?
Approach

How is accuracy determined?

Need a reference for the “true” wake metric values

Use **Large-Eddy Simulation data** as the wind field, and sample the LES in space and time as a scanning lidar would

“**Synthetic lidar**” = sampling of simulated wind field in with a virtual lidar

From a cloud of lidar measurement points, extract wake characteristics, and compare to same characteristics derived from LES fields

→ Taking the LES as ground truth gives an “error” of the lidar’s wake metrics
Approach

• Use previously generated LES data for flow in **Perdigão, Portugal**, a complex terrain site with a wind turbine.
  Field experiments performed in 2016-2017

• Develop synthetic lidar model to based off the field lidar characteristics

• Create new scan geometries and test their accuracy
  → Potential to **optimize scanning geometry** for wake metric accuracy

Lidar measurements in complex terrain present several challenges...
Challenges – from Lidar

- Lidar scans represent **neither instantaneous nor mean velocity fields**

Which type of LES fields should be used as the ‘truth’? Instantaneous? Averaged over scan cycle?

- Movement of wake during a scan will result in a “distorted” wake shape, making wake metrics lose accuracy

*Synthetic lidar scan, normalized radial velocity field. Negative $u_r$ = towards the lidar*
Building the Synthetic Lidar Model

Sample the LES field like a real scanning lidar

**Interpolate** the LES data at time and space coordinates of lidar points

**In space:**
- Linearly interpolate lidar points from LES points in 3D

**In time:**
- Linearly interpolate in time between LES time steps
Wake Characterization Methods

Focus on two metrics: Wake center location and wake center velocity
Assume: Wake center coincides with point of maximum velocity deficit

Create wake center detection routine
Creating Test Geometries

• Which parameters to vary?
  Scan point density
Creating Test Geometries

• Which parameters to vary?

Scan path: PPI and RHI

**PPI**: Hold elevation angle $\phi$ constant & vary azimuth $\theta$

**RHI**: Hold azimuth $\theta$ constant & vary elevation angle $\phi$
Vary the density $\Delta \theta, \Delta \phi$ (resolution) and scan path to make 10 new geometries:

- 5 different “resolutions” (20m, 30m, 40m, 60m, 70m)
- 2 different scan paths (PPI & RHI)
Results

Remember, synthetic scan field ≠ inst. fields nor mean fields. So, which type of LES field to use?

Will compare to 2 types of LES fields:

- Instantaneous at $t_0$
- Averaged over the scan
Error—Wake center velocity

- Performance of resolutions depends on downstream location

- **Trade-off** in spatial & temporal resolution:
  - **Low spatial res.** → less precise wake location ✗
  - High time res. → less distorted wake ✓
  - **High spatial res.** → more precise wake location ✓
  - Low time res. → more distortion due wake movement ✗
Analysis - Error

Enter your analysis and error here.

**Instantaneous LES Fields**

- Wake detection method sensitive to fast velocity fluctuations
  
  → Method sometimes misplaces wake center in slow pocket of air outside wake.

  High time res. → **More accurate for fast moving wakes**

**Averaged LES fields**

Averaging distorts wake shape and misplaces wake center location

Low time res. → **More accurate for slower moving wakes**

- Need to know more about the time scales of the wake to decide between the two
- Further work: investigate time scales through an FFT of the wake center position
If we assume in our case, a slow moving wake $\rightarrow$ PPI,30m geometry is the most accurate fast moving wake $\rightarrow$ RHI,40m
Conclusions

• Developed a synthetic lidar model & wake detection algorithm
• Quantified accuracy of 10 geometries using the same LES wind field to get unbiased error estimation
• A trade-off between spatial and temporal resolution is a key component of accuracy for a scan geometry
• Have shown that the choice for ‘true’ LES field is not trivial, and requires further knowledge of wake time scales
Future Work

• Improve wake detection/characterization method
  More sophisticated definition of wake center, based on velocity deficit distribution
• Vary more geometrical parameters, e.g. different scan paths
• Enhance the LES model
  Add stability effects, study relation to geometrical parameters
Thank you!

Questions and comments
Appendix

Synth. Lidar scan, Corresponding to 1\textsuperscript{st} Inst. LES field in Slide 21
(a) GAL geometry

(b) PPI, resolution = 20 m

(c) PPI, resolution = 70 m
Figure 29: Turbine axis aligned four hour ensemble-averaged $u$ with interpolation plane locations (only every other plane is shown)
Figure 52: LES velocity field time-averaged over $T_{LES}$. Black circle: turbine rotor $y - z$ position. Red ‘X’: location of maximum velocity deficit.
Synthetic Scans

\[ u^w(x, t) \times N_c \rightarrow \text{Wake center detection} \rightarrow \langle X_s, u_s \rangle \]

LES, 1st Fields

\[ u^w(x, t_0) \times N_c \rightarrow \text{Wake center detection} \rightarrow \langle X_{\text{LES,1st}}, u_{\text{LES,1st}} \rangle \]

LES, Cycle-Averaged Fields

\[ \widetilde{u}^w(x) \times N_c \rightarrow \text{Wake center detection} \rightarrow \langle X_{\text{LES,c}}, u_{\text{LES,c}} \rangle \]

LES, All Fields

\[ u^w(x, t) \times N_s = 4000 \text{ fields} \rightarrow \text{Wake center detection} \rightarrow \langle X_{\text{LES,t}}, u_{\text{LES,t}} \rangle \]

Figure 53: Procedure for field averaging, wake detection, and wake metric calculation