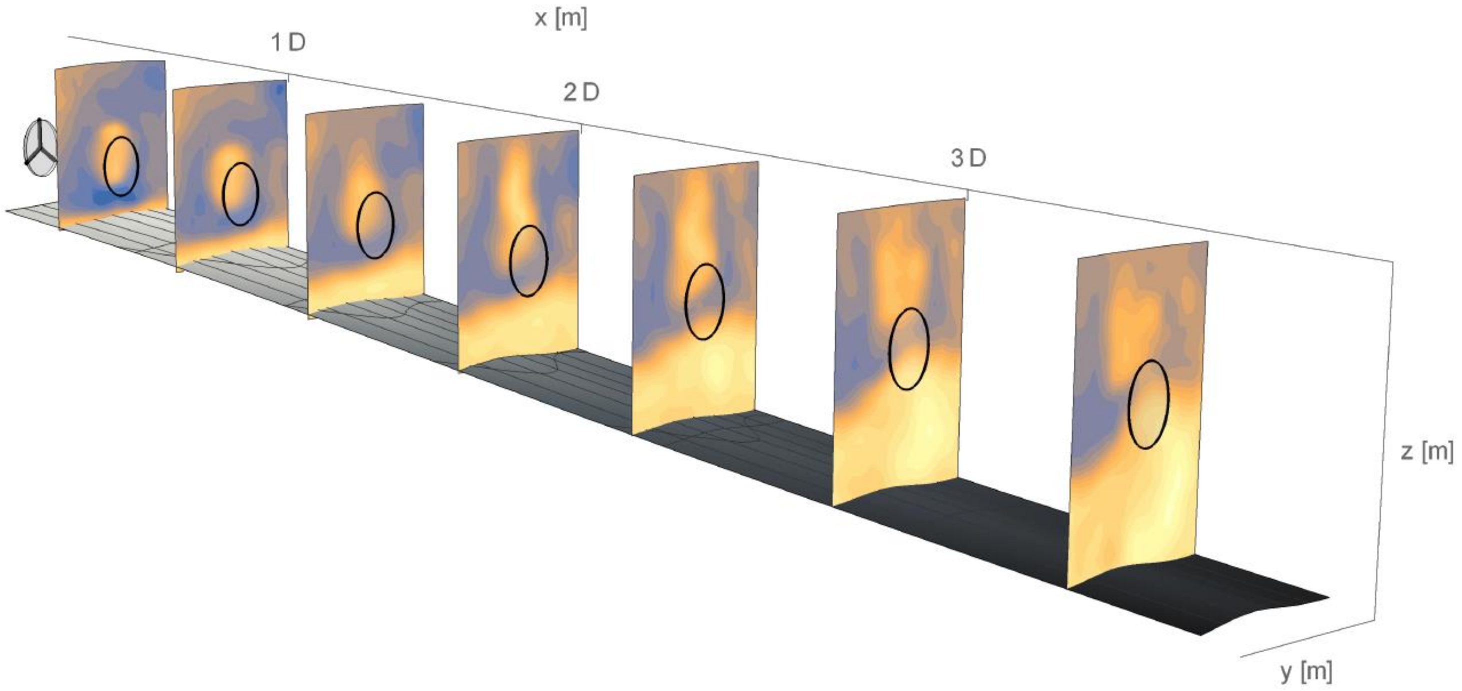
Integrating Scanning Lidar with LES for Wake Characterization in Complex Terrain

MSc Thesis, Erik Haugen



Part of the **European Wind Energy Master's Programme** (EWEM) with:

Technical University of Denmark (DTU)

Delft University of Technology (TU Delft)

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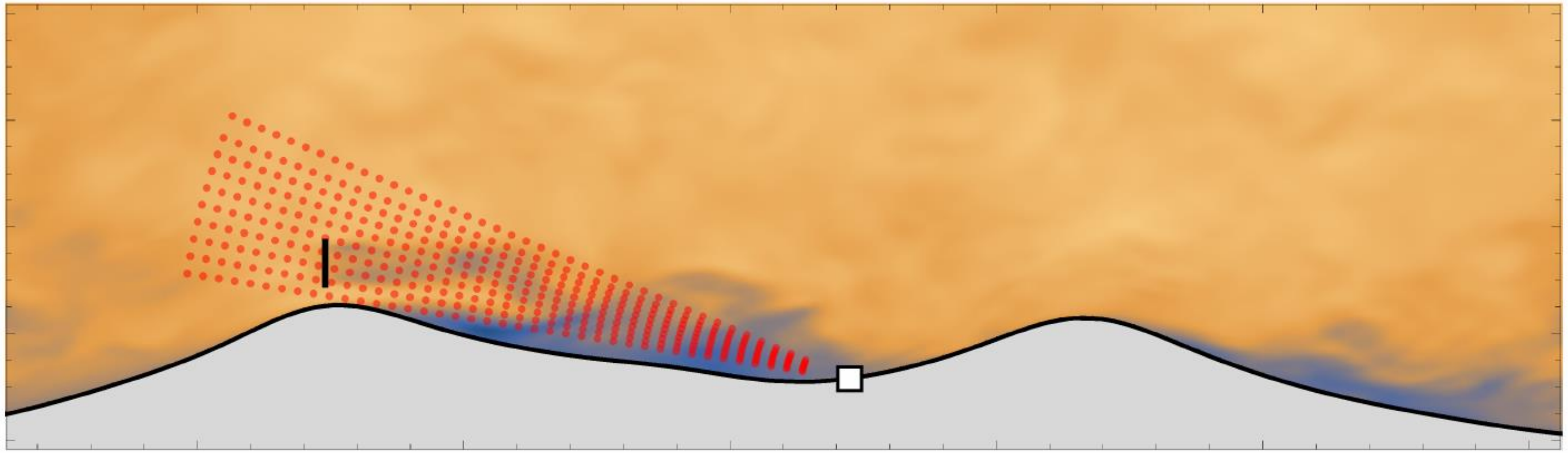

Problem Definition

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

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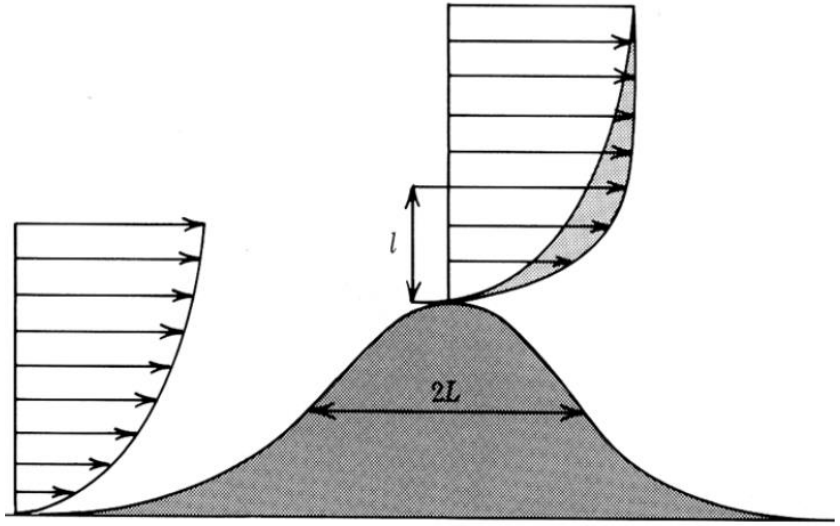
Motivation – Complex Terrain

Why complex terrain?

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

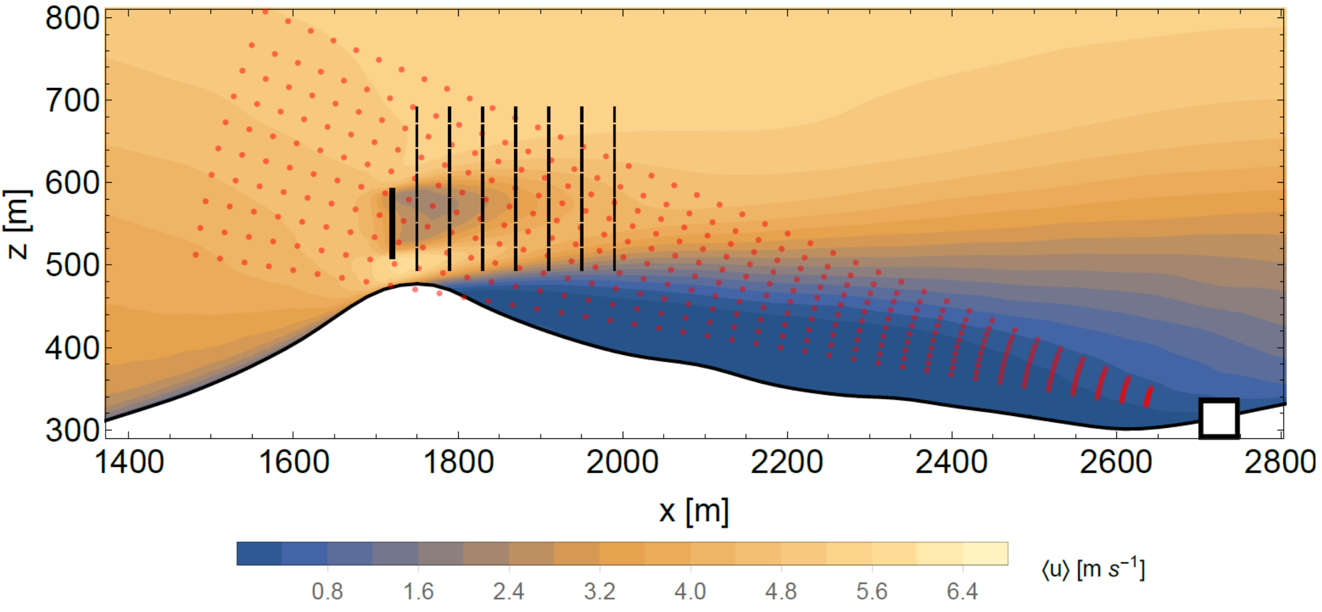
- Flow speed up in up-sloping terrain
- But, higher uncertainties in AEP → need to study further

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**?

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

Approach

How is accuracy determined?

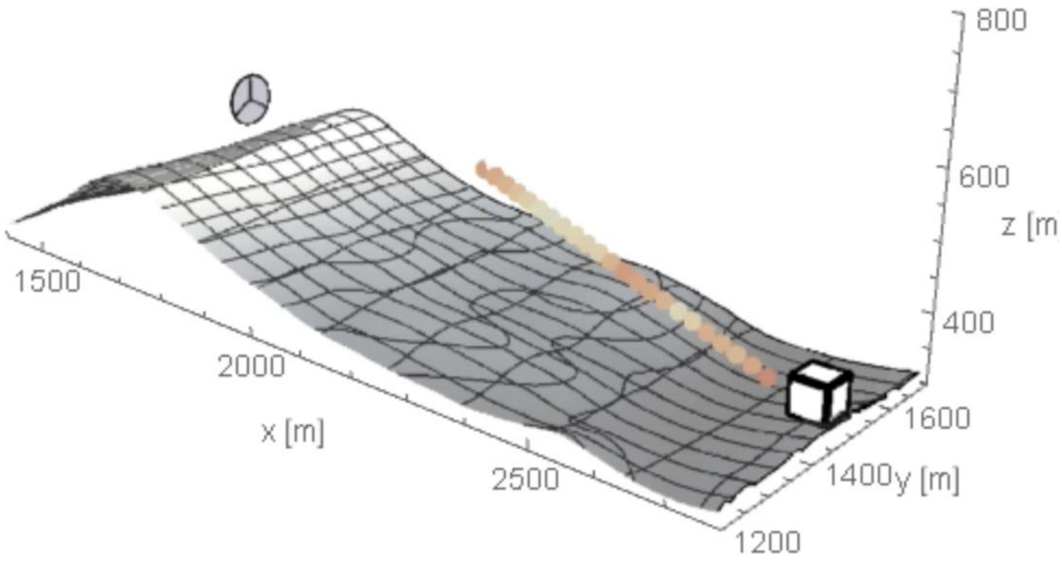
Need a reference for the “true” wake metric values

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, <u>extract wake characteristics, and compare to same characteristics derived from LES fields</u>

→ **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.

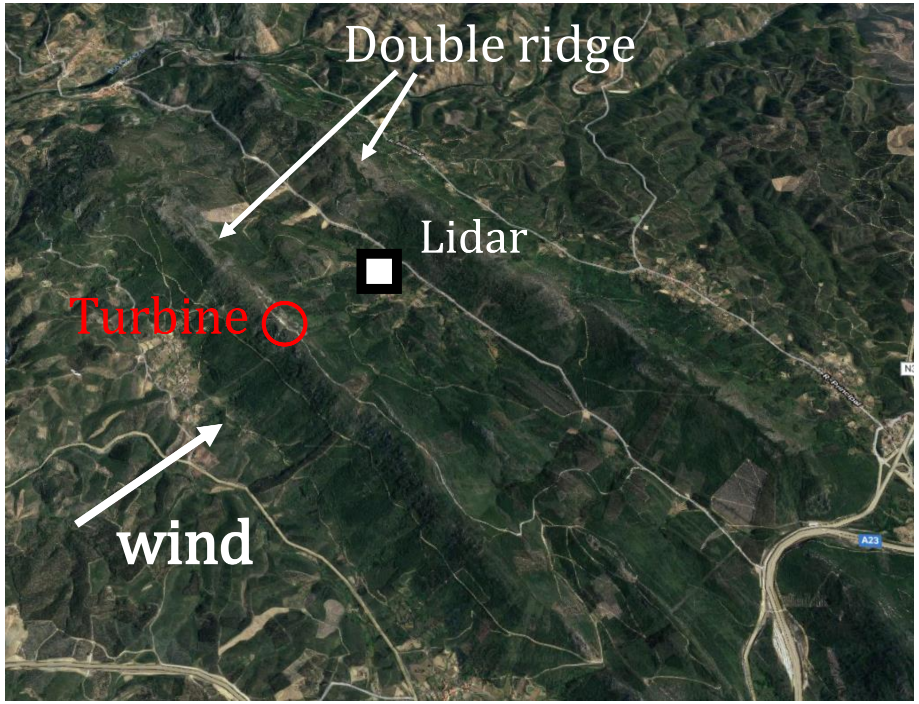
  Field experiments performed in 2016-2017

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

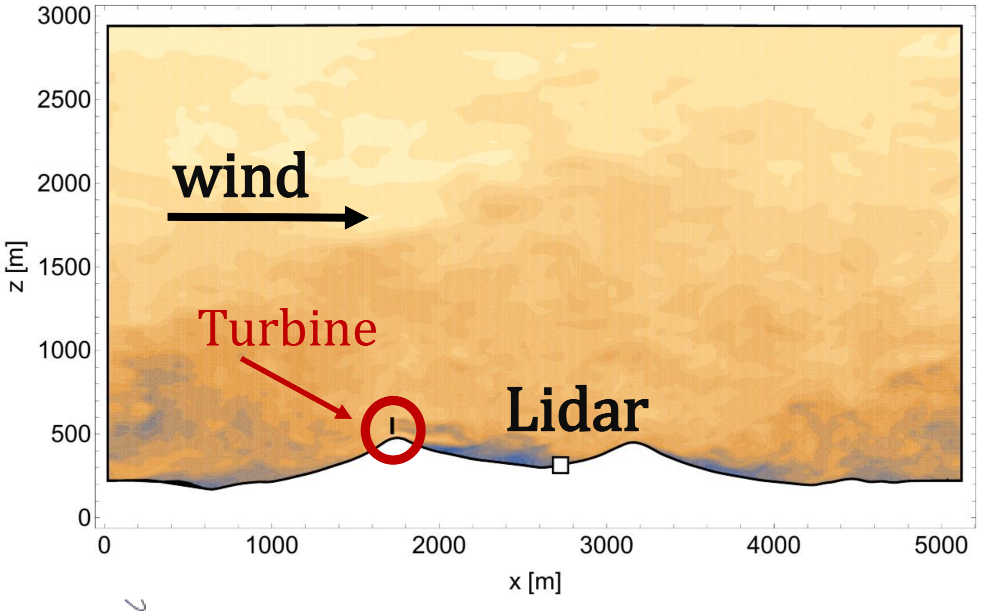
- Create new scan geometries and test their accuracy

  → Potential to **optimize scanning geometry** for wake metric accuracy

Lidar measurements in complex terrain present several challenges…



Source: Google maps, 2018



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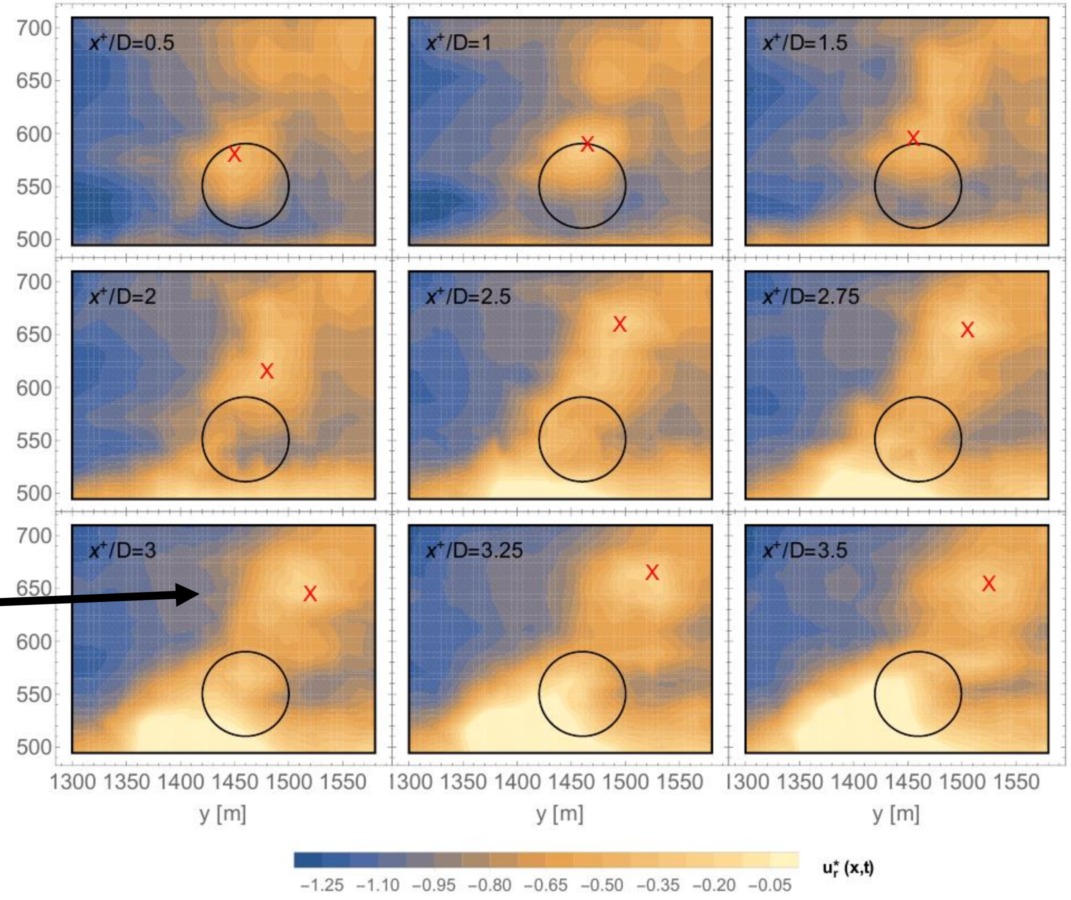
Challenges – from Lidar

- 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

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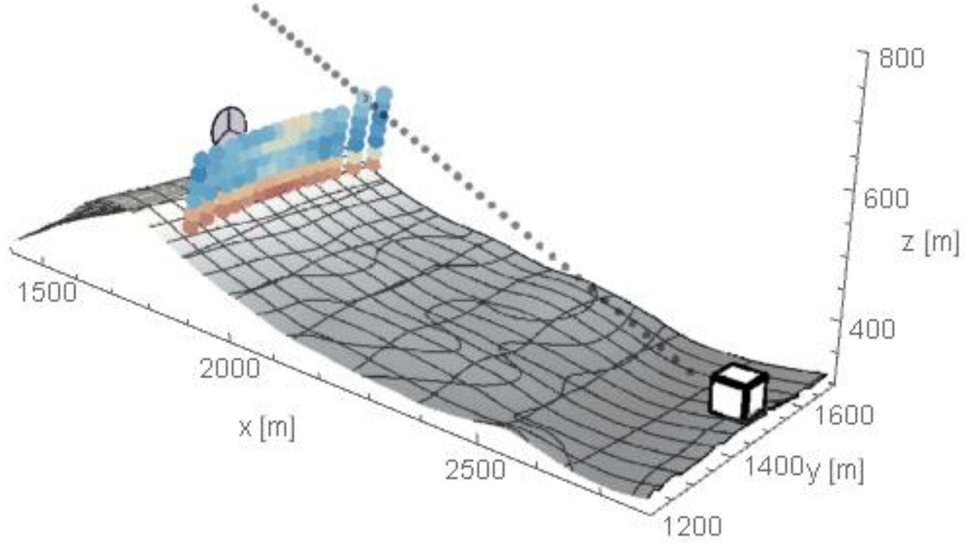
Building the Synthetic Lidar Model

Sample the LES field like a real scanning lidar

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

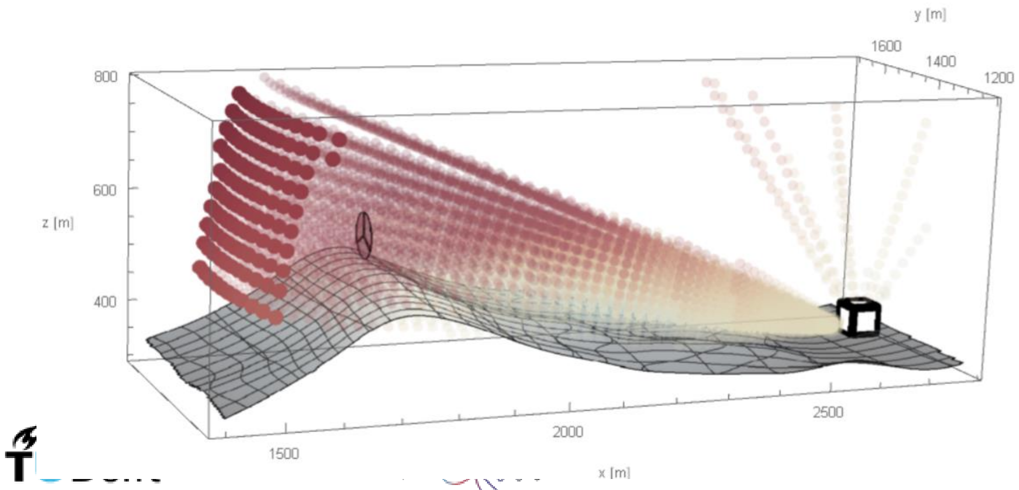
<u>In space:</u>

- Linearly interpolate lidar points from LES points in 3D



<u>In time:</u>

- Linearly interpolate in time between LES time steps

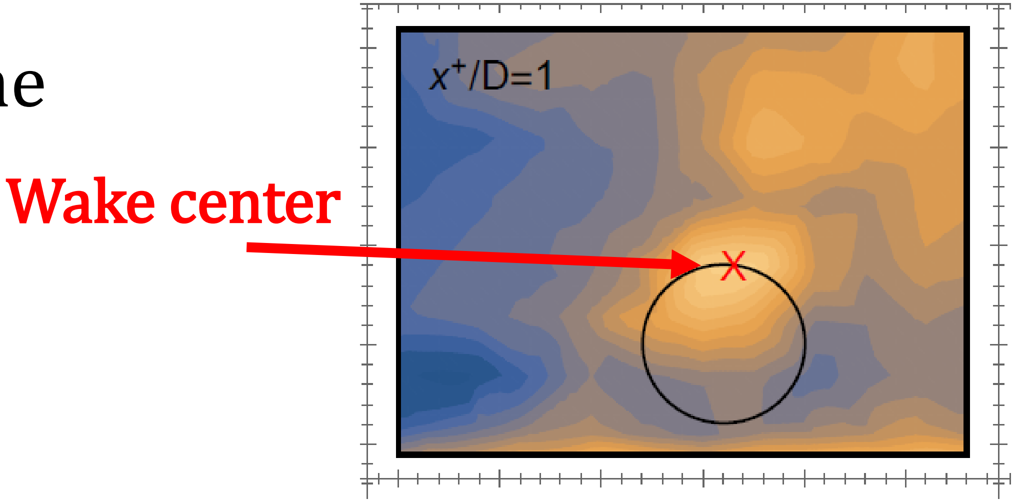


Wake Characterization Methods

Focus on two metrics: Wake center location and wake center velocity

Assume: Wake center coincides with point of maximum velocity deficit

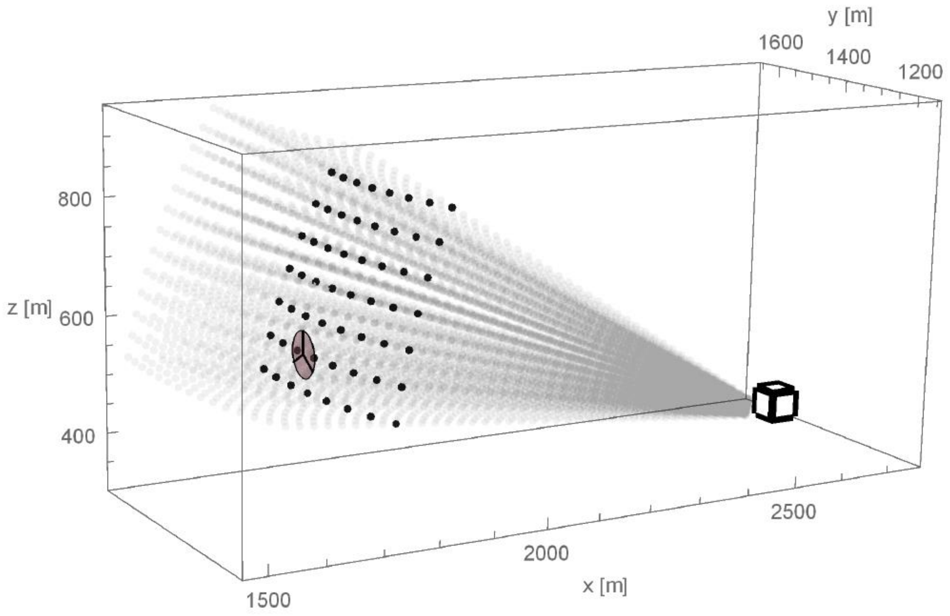
Create wake center detection routine

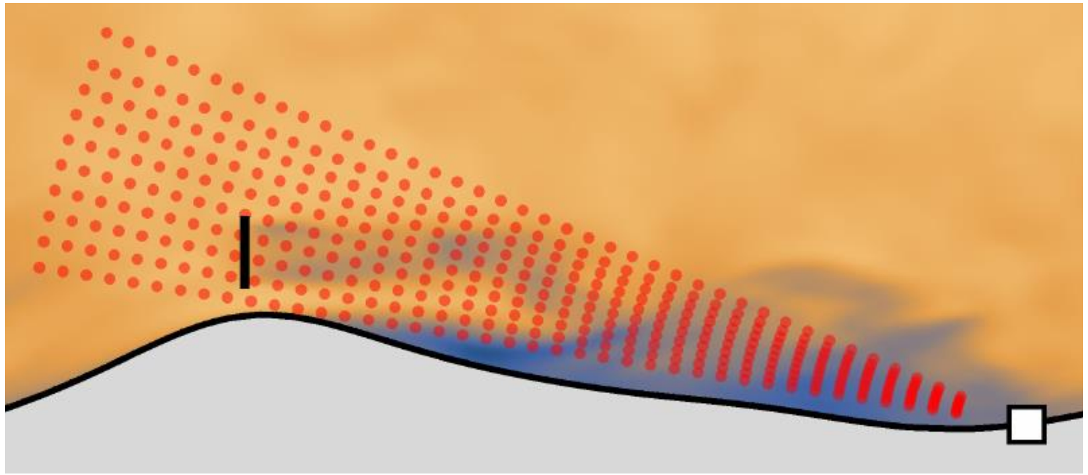


Creating Test Geometries

- Which parameters to vary?

Scan point density



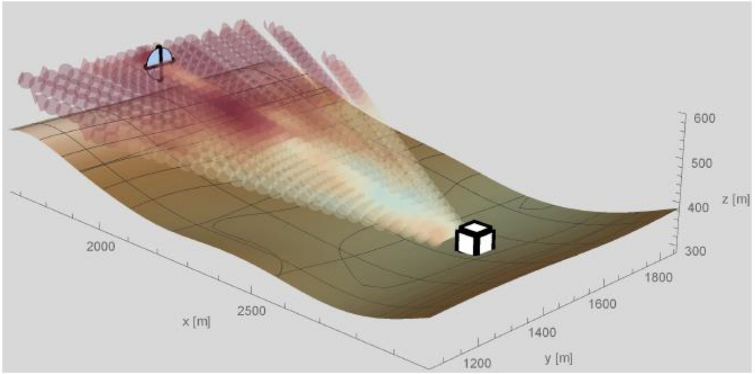


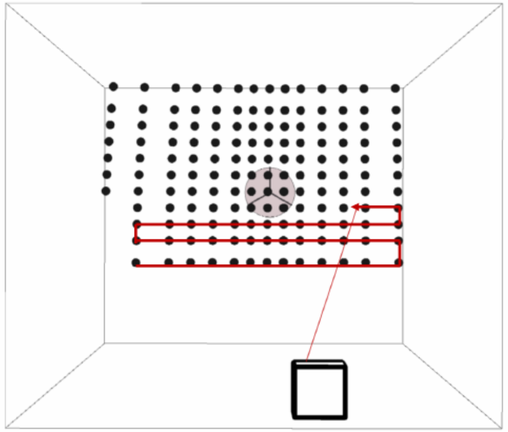
Creating Test Geometries

- Which parameters to vary?

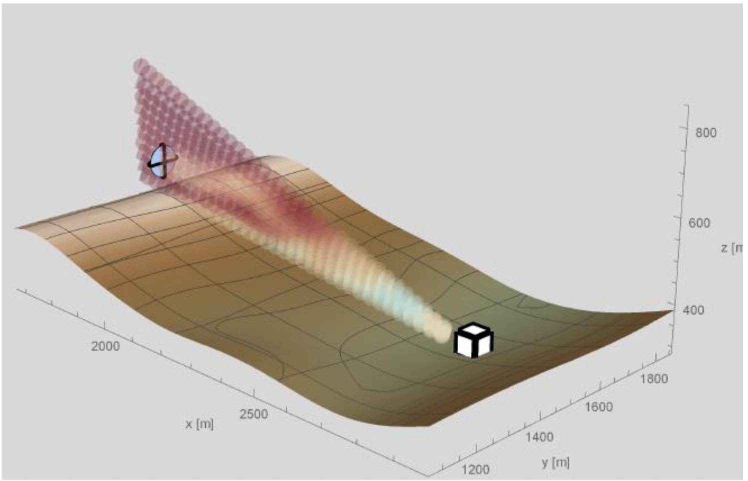
Scan path: PPI and RHI

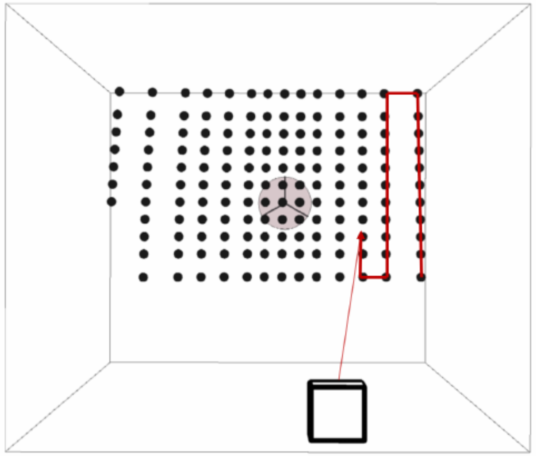
PPI : Hold elevation angle ϕ constant & vary azimuth θ





RHI : Hold azimuth θ constant & vary elevation angle ϕ





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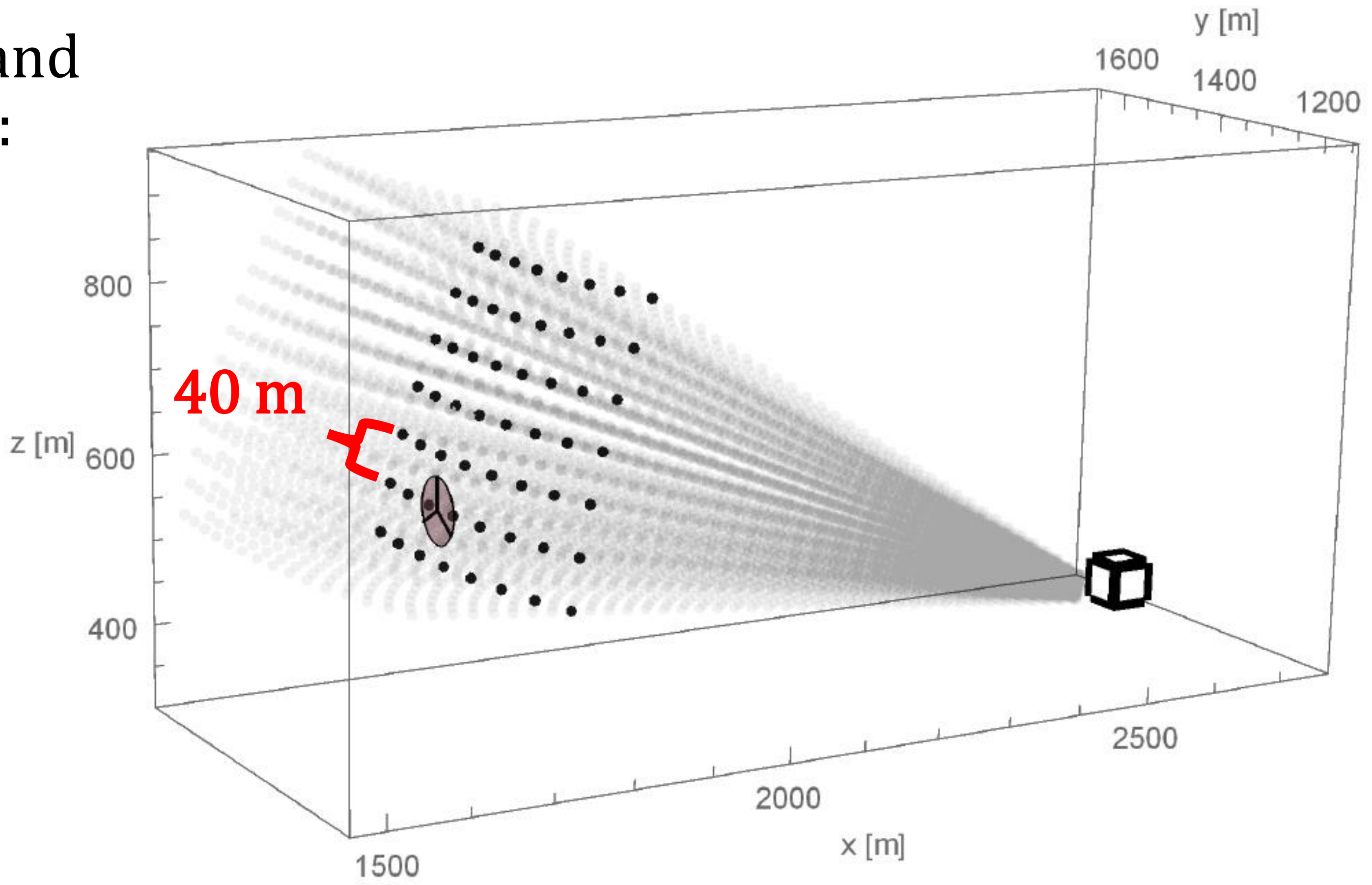
Vary the **density** Δθ, Δϕ (resolution) and **scan path** to make **10 new geometries**:

- 5 different "resolutions" (20m,30m,**40m**,60m,70m)

- 2 different scan paths (PPI & RHI)

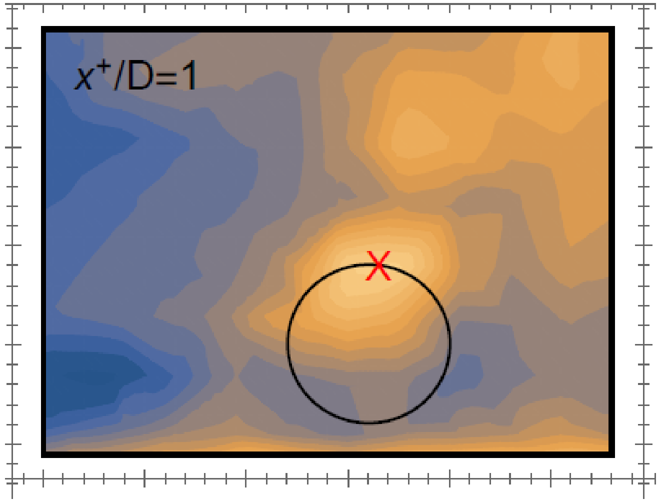


Results

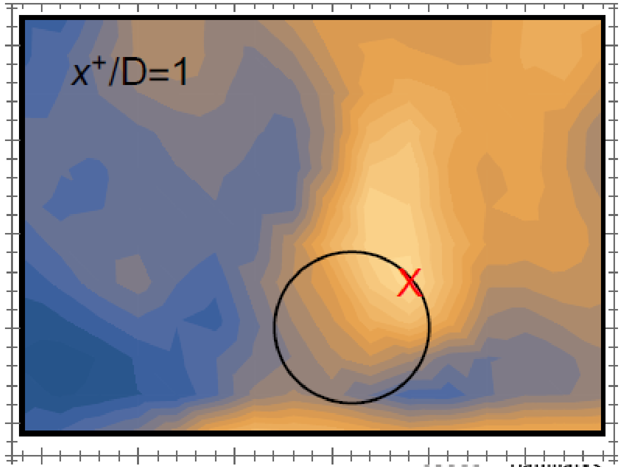
Remember, synthetic scan field ≠ inst. fields nor mean fields. So, **which type of LES field to use?**

Will compare to 2 types of LES fields:

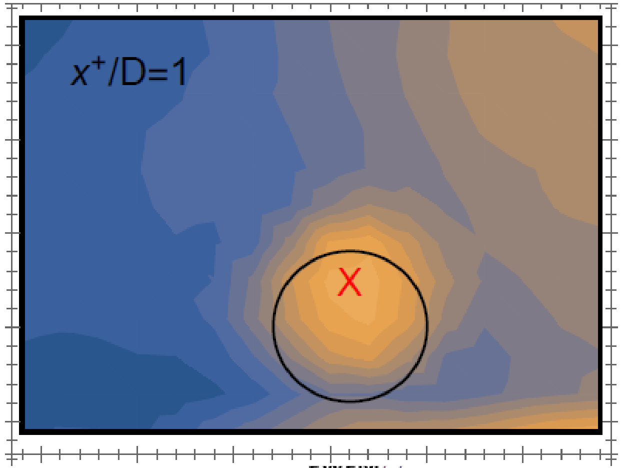
Synthetic scan



Instantaneous at t_0



Averaged over the scan



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Error—Wake center velocity

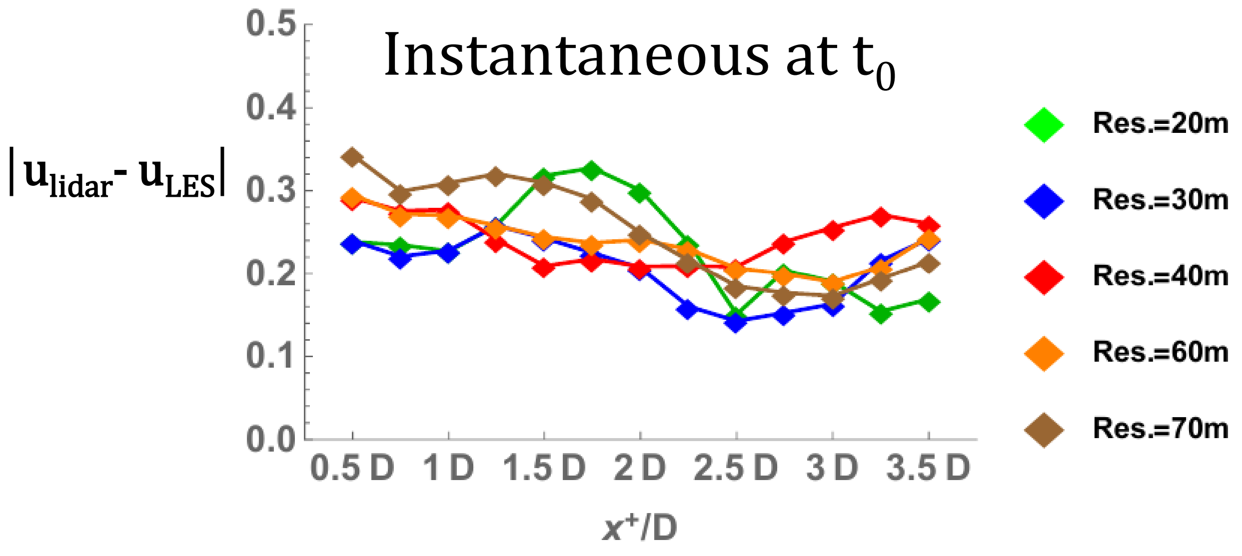
- Performance of resolutions depends on downstream location
- **Trade-off** in spatial & temporal resolution:

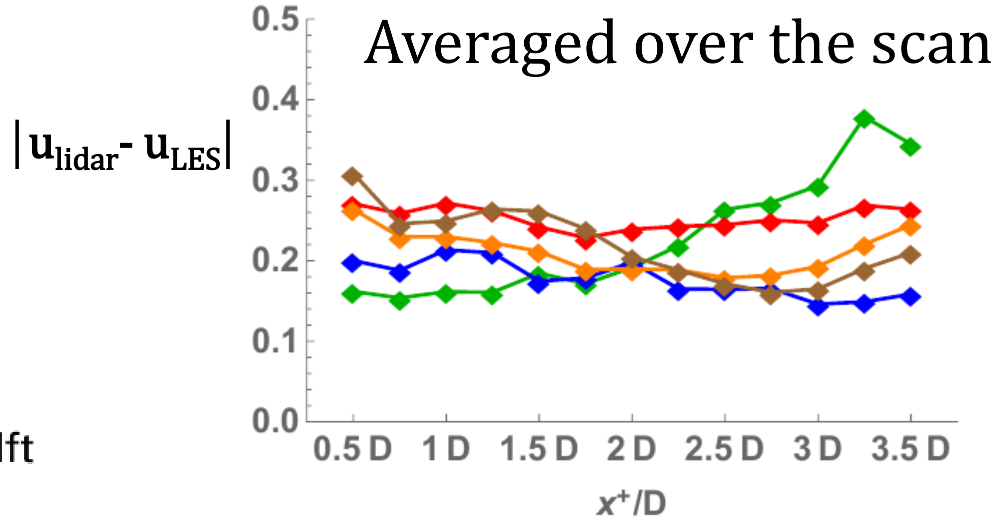
<u>**Low spatial res.**</u> → less precise wake location ✗

High time res. → less distorted wake ✓

<u>**High spatial res.**</u> → more precise wake location ✓

Low time res. → more distortion due wake movement ✗





Analysis - Error

Instantaneous LES Fields	**Averaged 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**	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

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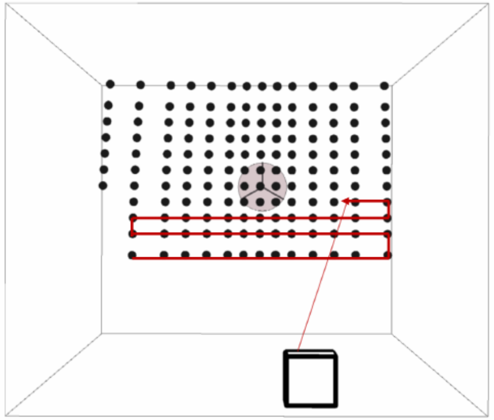
Analysis – Optimal Geometry

If we assume in our case,
a **slow moving wake** → PPI,30m
geometry is the most accurate

fast moving wake → RHI,40m

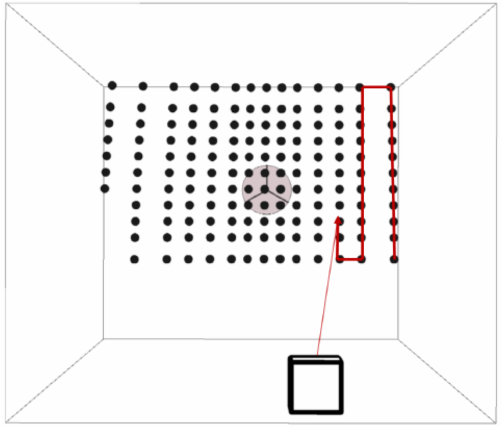
PPI Geometries

	Instantaneous		Averaged	
Resolution	E_{u_r} [–]	E_x [m]	E_{u_r} [–]	E_x [m]
Res=20m	0.25	0.45 D	0.19	0.36 D
Res=30m	0.21	0.44 D	0.19	0.34 D
Res=40m	0.24	0.57 D	0.25	0.42 D
Res=60m	0.25	0.51 D	0.21	0.48 D
Res=70m	0.27	0.64 D	0.23	0.62 D



RHI Geometries

Resolution	E_{u_r} [–]	E_x [m]	E_{u_r} [–]	E_x [m]
Res=20m	0.25	0.51 D	0.26	0.33 D
Res=30m	0.19	0.50 D	0.21	0.41 D
Res=40m	0.19	0.47 D	0.22	0.34 D
Res=60m	0.25	0.49 D	0.21	0.45 D
Res=70m	0.27	0.61 D	0.23	0.58 D



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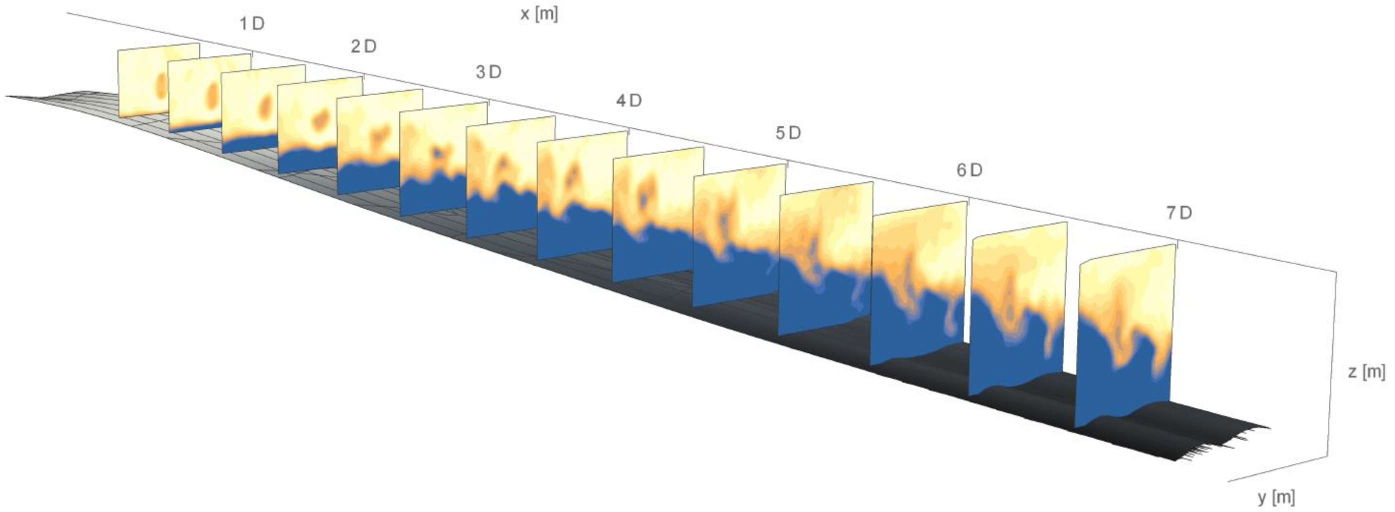
Conclusions



- 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

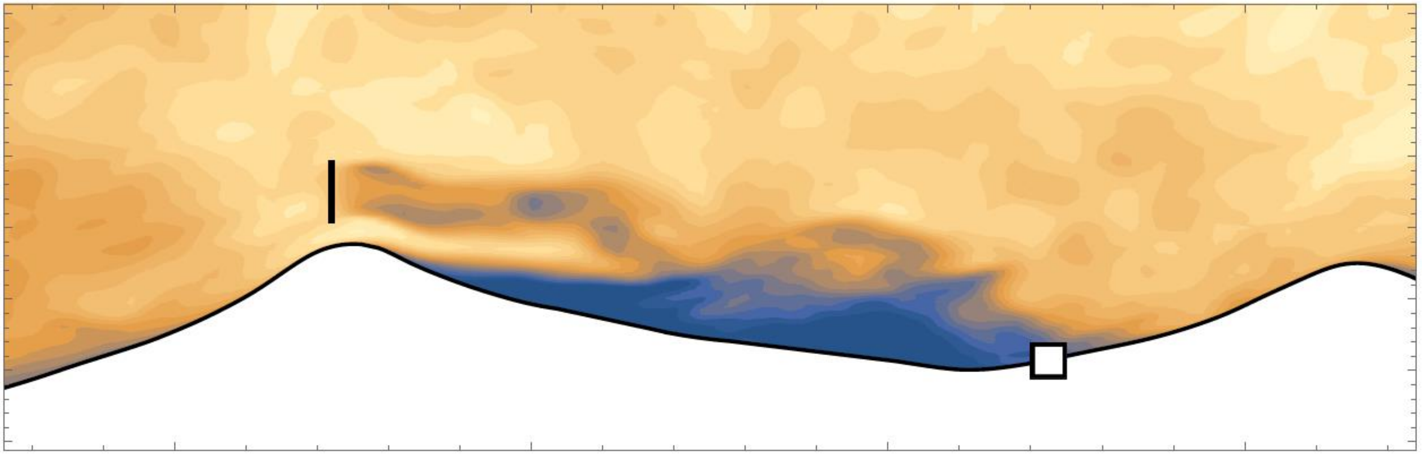
Future Work

- 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

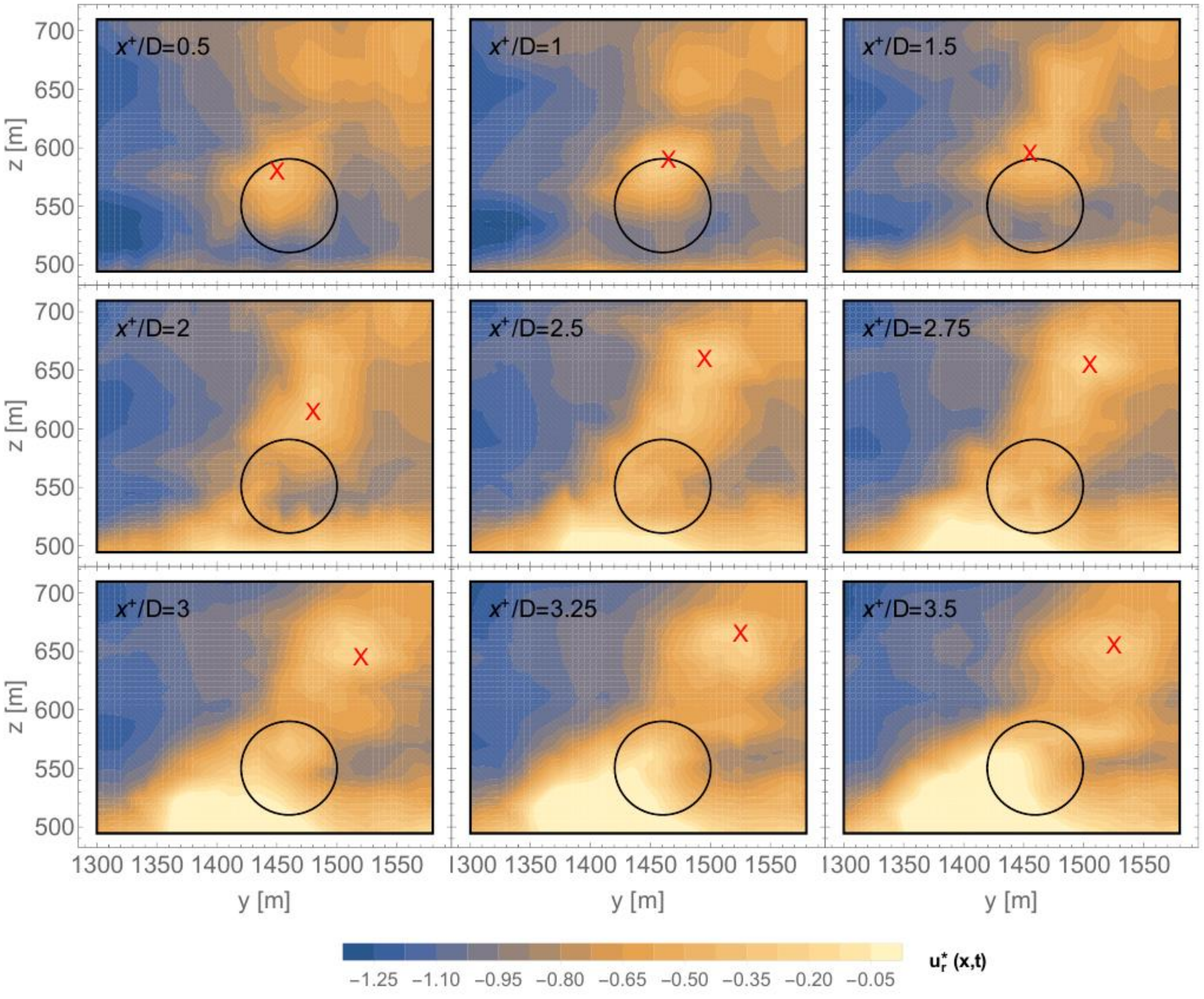


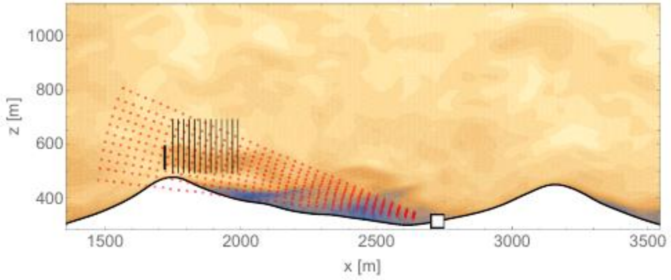
Thank you!

Questions and comments

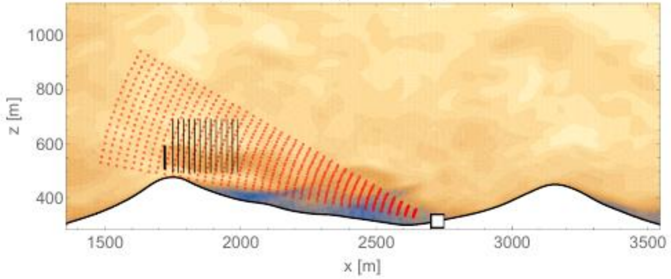
Appendix

Synth. Lidar scan, Corresponding to 1^{st} Inst. LES field in Slide 21

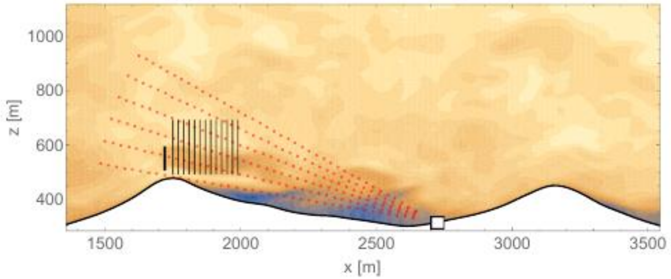




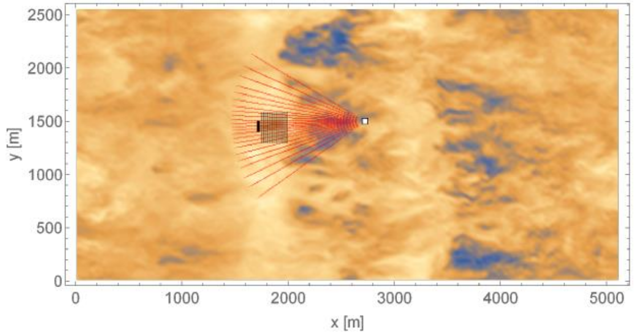
(a) GAL geometry



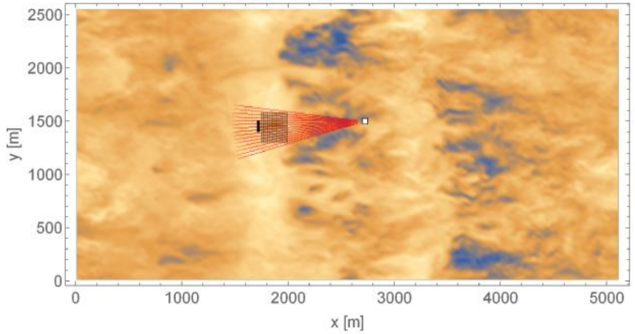
(b) PPI, resolution = 20 m



(c) PPI, resolution = 70 m



(a) GAL geomtery



(b) PPI, resolution = 30 m

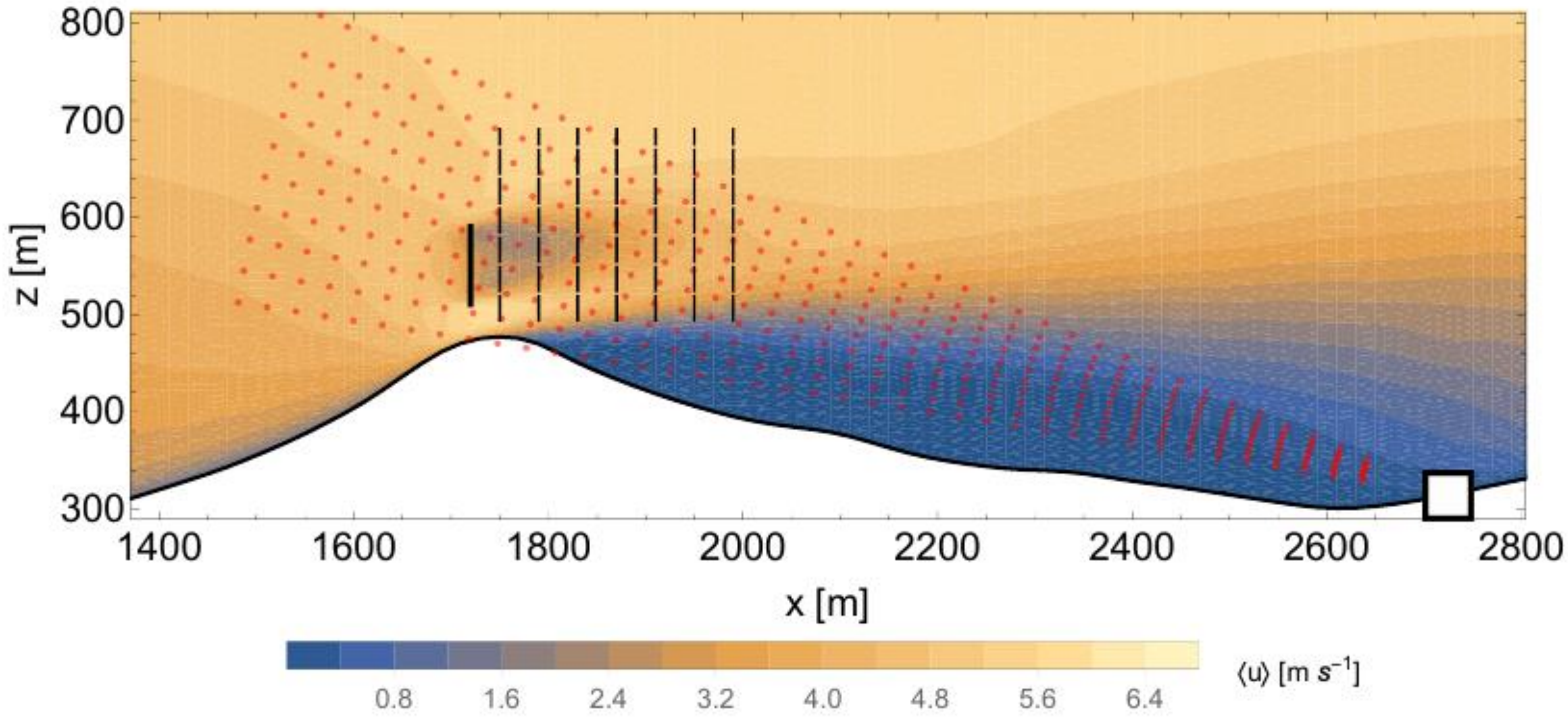


Figure 29: Turbine axis aligned four hour ensemble-averaged u with interpolation plane locations (only every other plane is shown)

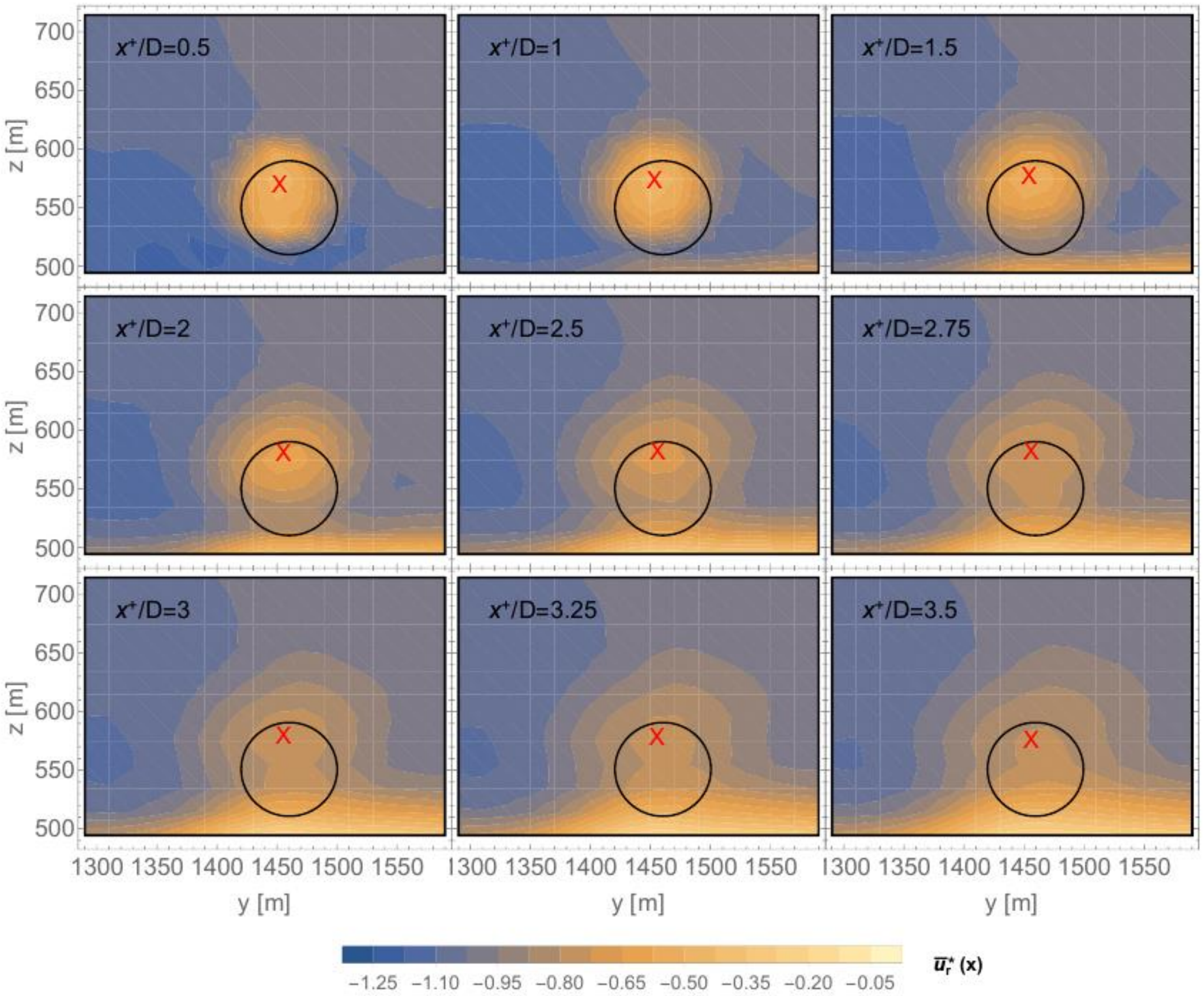


Figure 52: LES velocity field time-averaged over T_{LES}. Black circle: turbine rotor $y-z$ position. Red 'X': location of maximum velocity deficit.

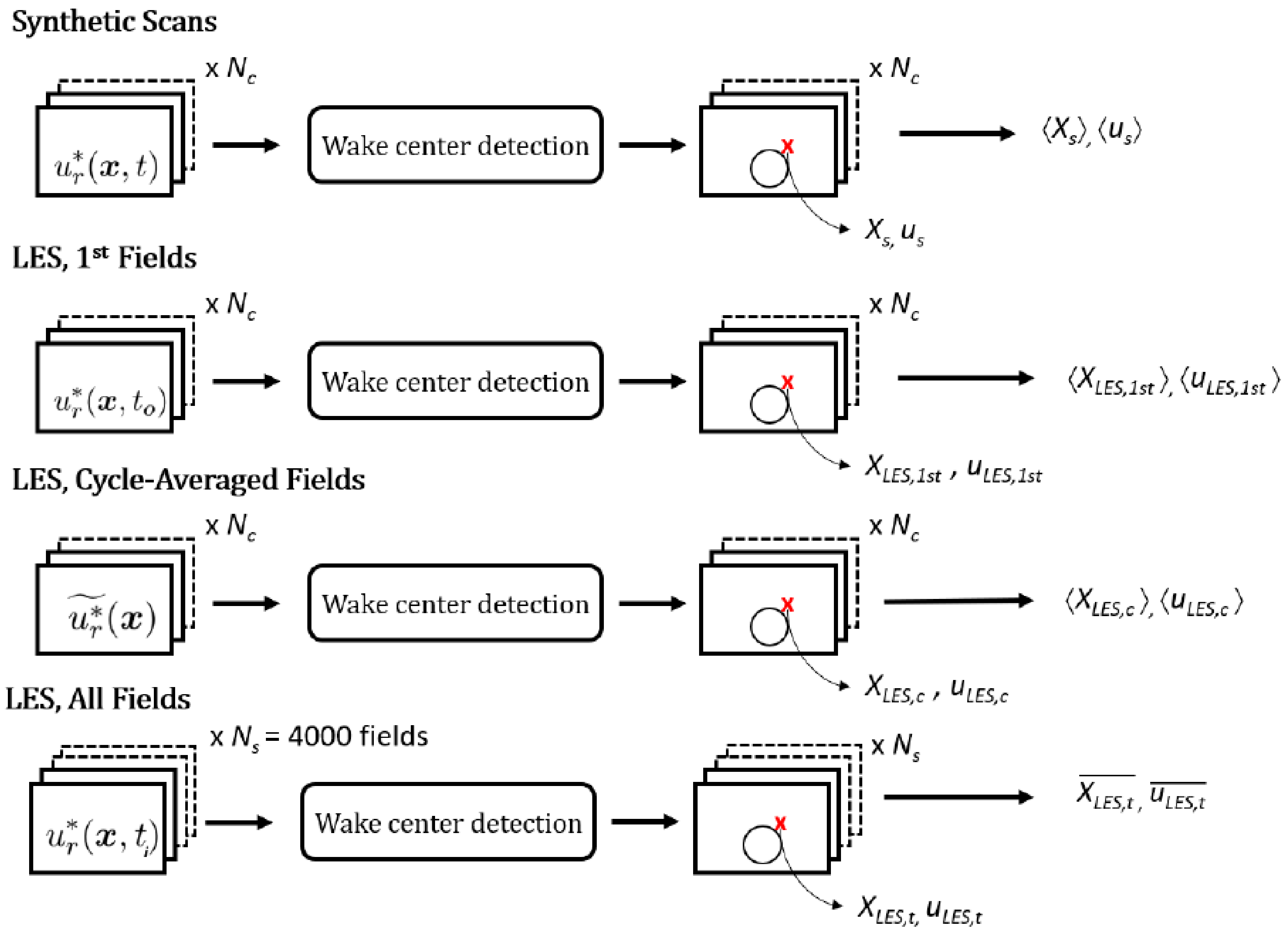


Figure 53: Procedure for field averaging, wake detection, and wake metric calculation