A Gappy POD approach to estimate the wind field in an urban environment for air mobility applications

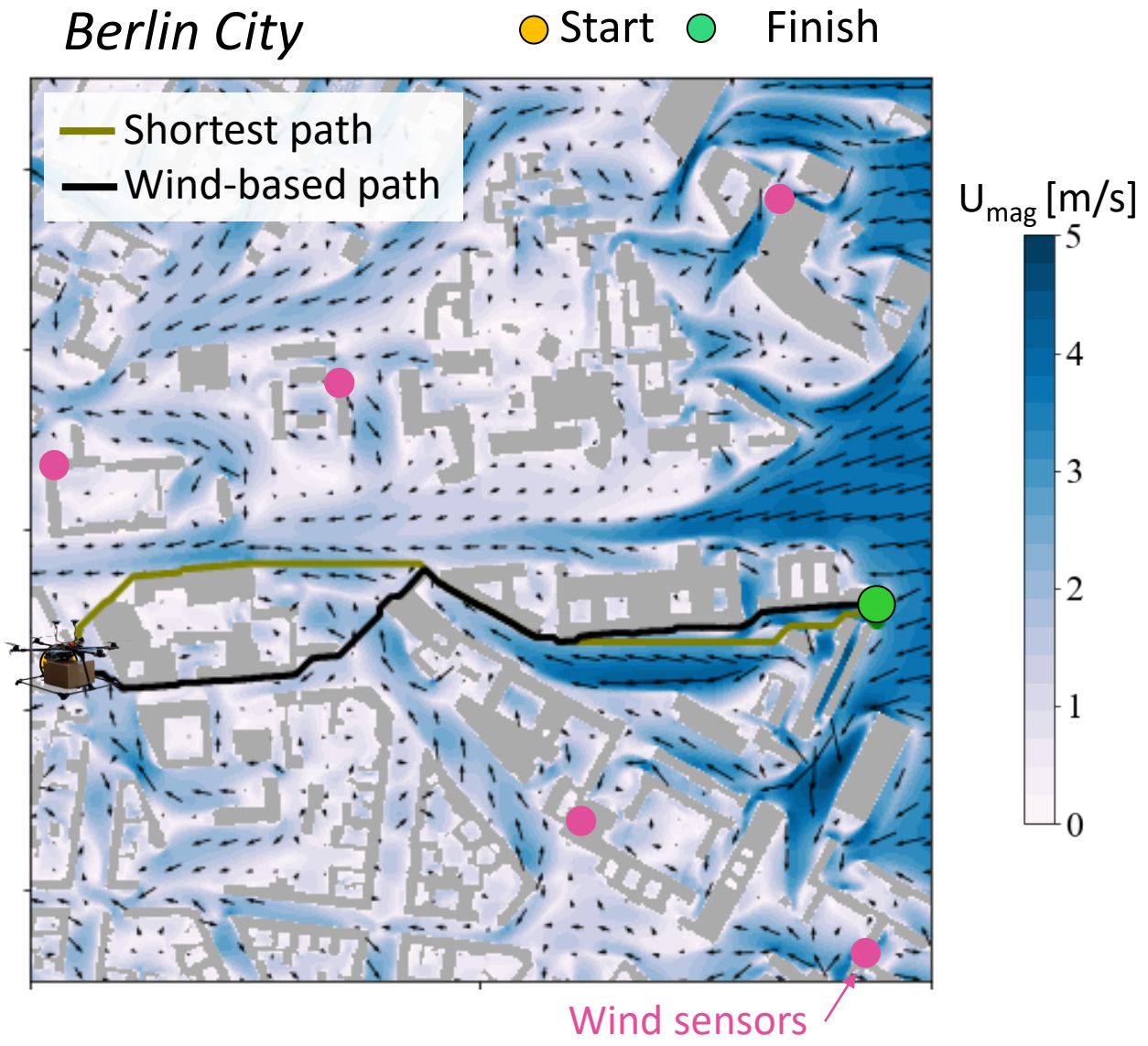
Carola Ebert,
Yana Gorbachova, Maarten Uijt de Haag, Julien Weiss and Dario Milani

Chair of Aerodynamics, Technische Universität Berlin, 10587 Berlin, Germany
DM-AirTech GmbH, Ottenser Hauptstraße 2-6, 22765 Hamburg, Germany
Chair of Flight Guidance and Air Transport, Technische Universität Berlin, 10587 Berlin, Germany

ICWE 16, Florence, August 28-31, 2023

Motivation

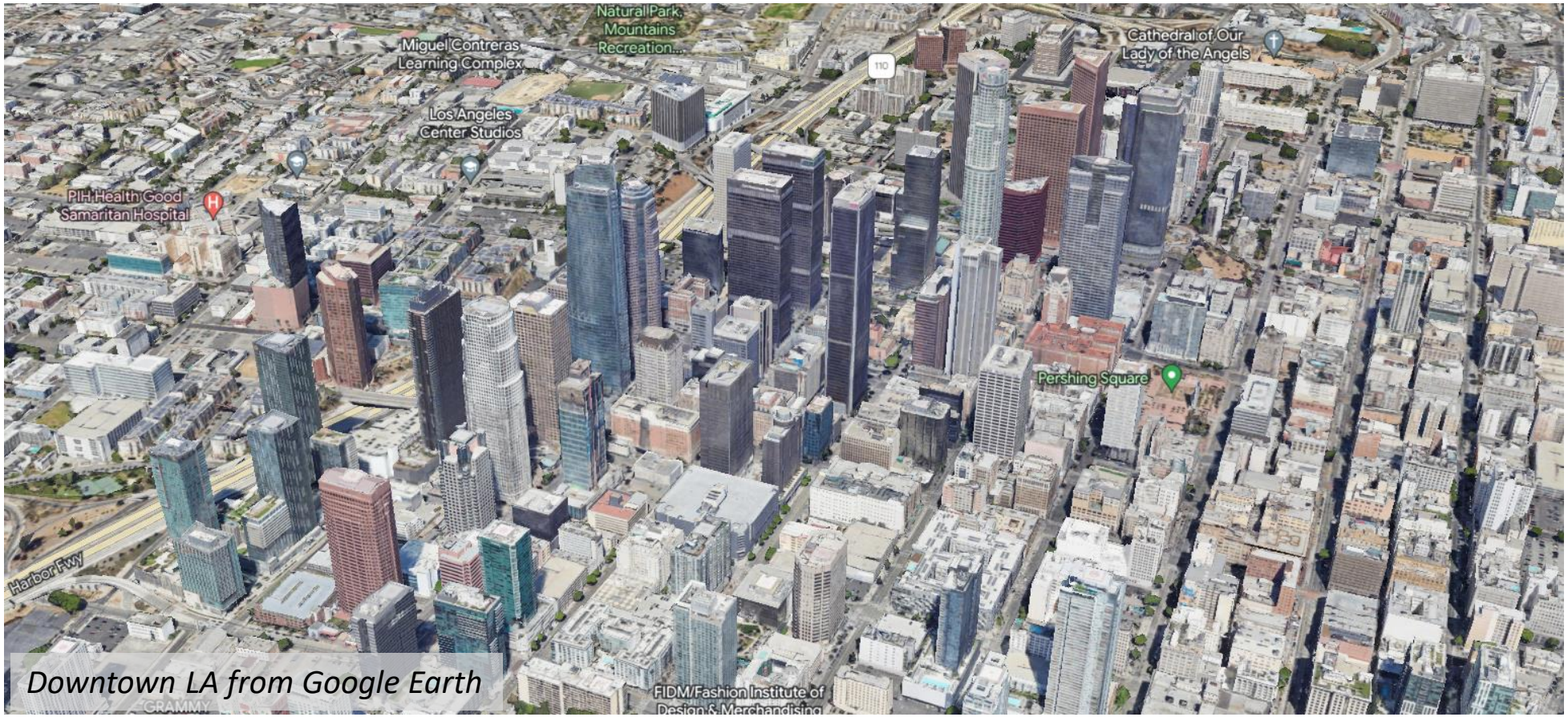
- Real-time wind field estimation from wind sensors for urban air mobility.
- Wind based trajectory optimization: UAVs energy consumption reduced up to 6 %[1].
- Assumption: 2D wind field at a constant wind speed.



[1] Ebert, C., Weiss, J., Uijt De Haag, M., Ruwisch, C., and Silvestre, J., "Trajectory Planning in Windy Urban Environment – a Gappy POD Approach for Wind Field Estimates with Sparse Sensors," *AIAA Journal* 2023.

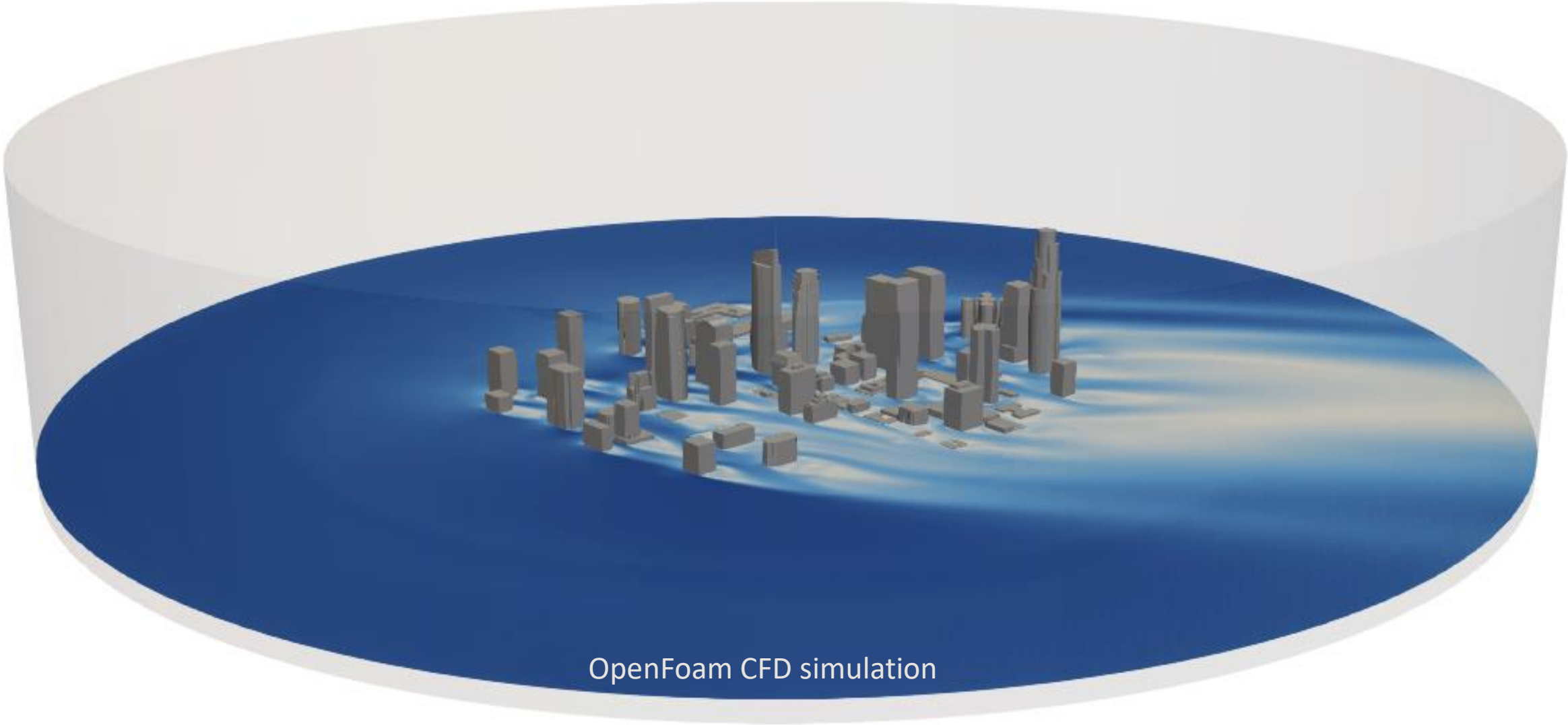
Motivation

- 3D wind field estimation in Downtown Los Angeles
- Different wind speeds U_{ref}



Downtown LA from Google Earth

Real-time Wind Field Estimation



Real-time Wind Field Estimation

Problem

No real-time CFD simulations
~
High computational time

Solution

Data reconstruction methods
~
Trained on CFD simulations
~
Reconstruction time: few seconds

OpenFoam CFD simulation

Objectives

- 3D RANS simulations of an urban area for different *wind directions* and different *wind speeds*.

- *Real-time estimation of an unknown urban wind field* with a data reconstruction method.

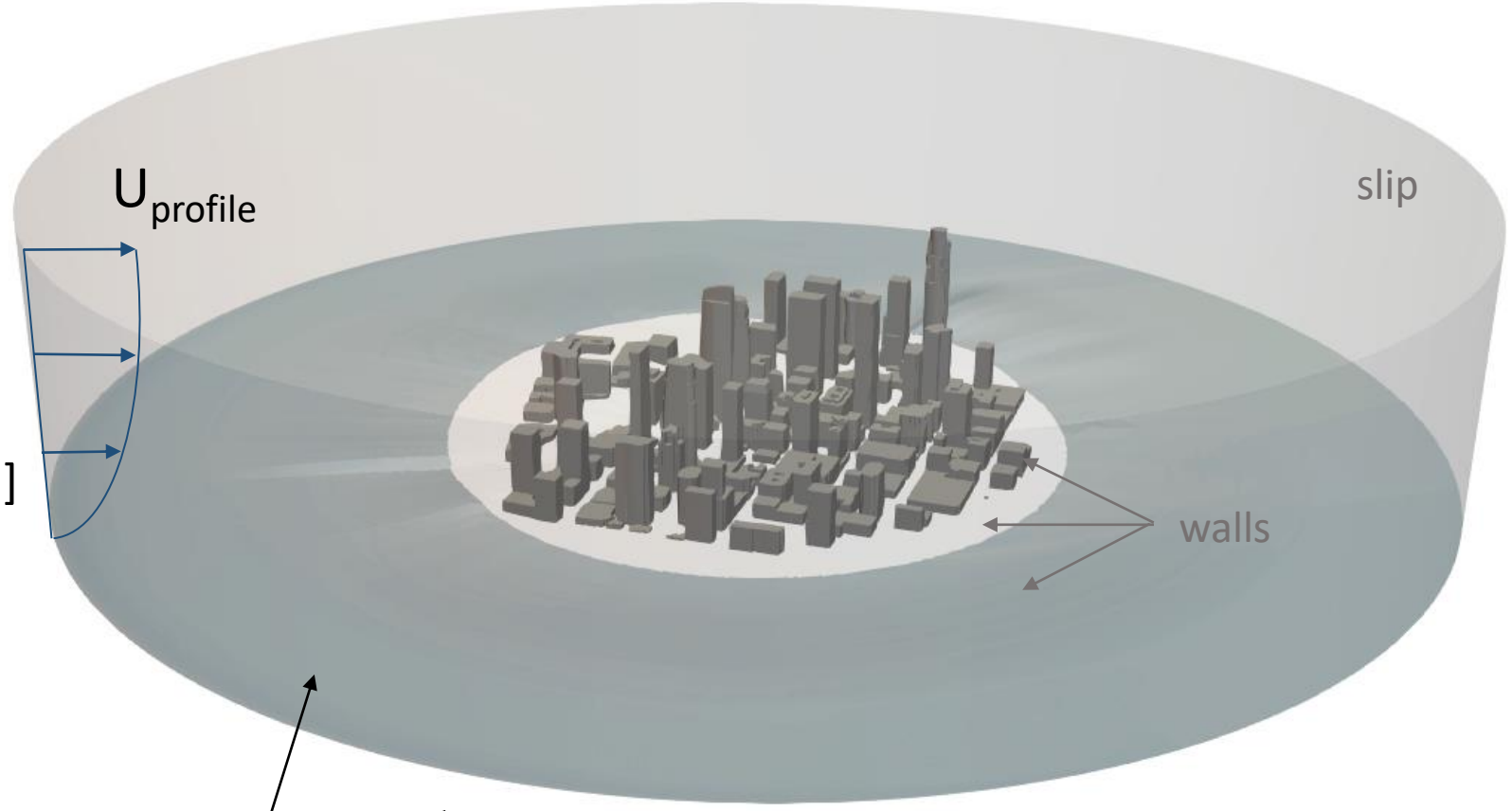
OpenFoam CFD Simulation

- Velocity inlet condition: *atmBoundaryLayerInletVelocity*

Final grid ~15 mio. cells

$$U_{profile} = \frac{u^*}{\kappa} \cdot \ln\left(\frac{z + z_0}{z_0}\right)$$

z_0 = 2 – Aerodyn. roughness length [m]
$U_{profile}$ - wind speed profile [m/s]
u^* - Friction velocity [m/s]
κ = 0.42 - von Kármán constant [-]
z - z coordinate [m]



$z_0 = 2$; (Representative for large town centres with a mixture of low-rise and high-rise buildings.)

Test data

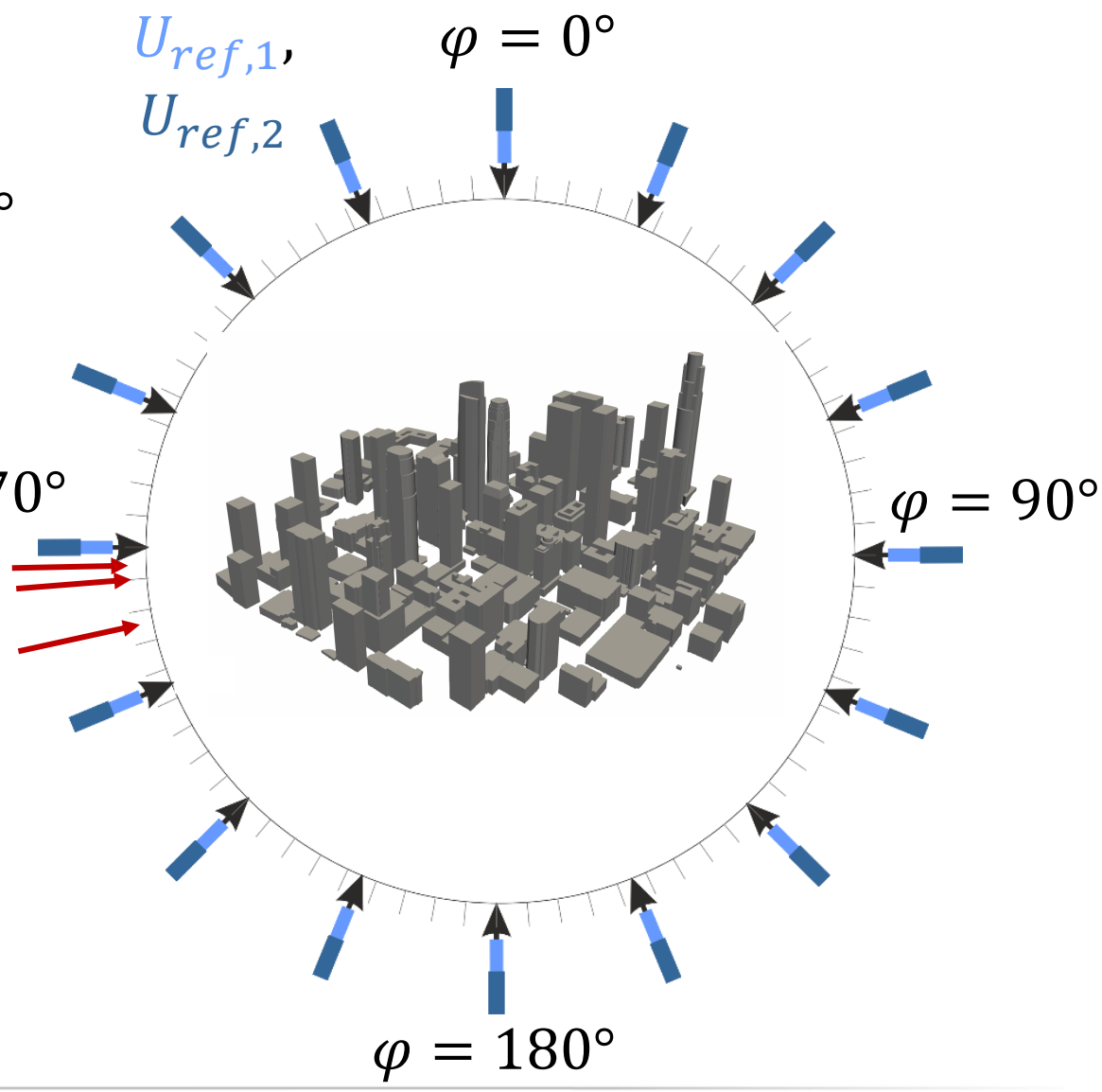
➢ Data basis:

- 16 Wind directions: $\varphi = 0 - 360°, \Delta\varphi = 22.5°$
- 2 wind speeds $@z = 310m$:

$$U_{ref,1} = 8\ m/s$$
$$U_{ref,2} = 16\ m/s$$

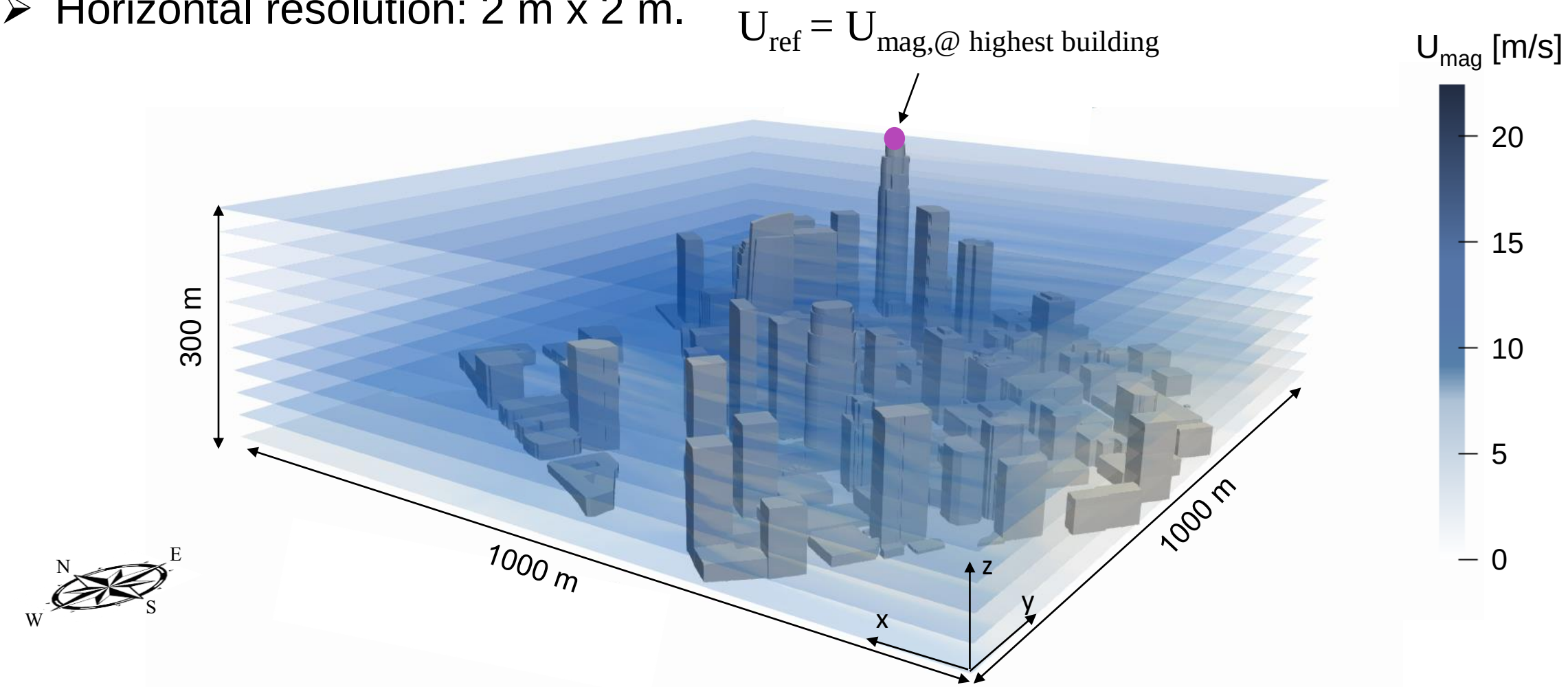
➢ 6 Test cases: (not included in training data)

- $\varphi = 259°, U_{ref} = 17, 19, 23, 31\ m/s$
- $\varphi = 264°, U_{ref} = 31\ m/s$
- $\varphi = 267°, U_{ref} = 31\ m/s$



3D Wind Field

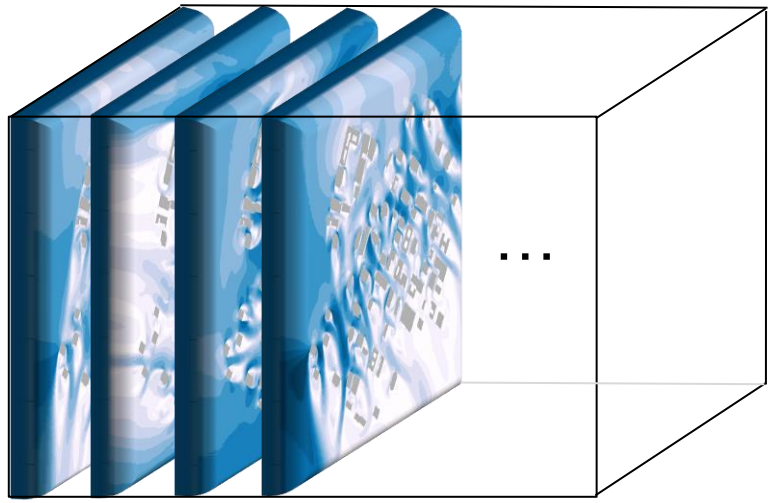
- 11 planes at constant heights of z = 10 m – 310 m, Δz = 30 m.
- Horizontal resolution: 2 m x 2 m.



Data Reconstruction Method

- *Method*: Modal approximation by proper orthogonal decomposition (POD)

3D wind fields = $f(\varphi)$

$\boldsymbol{X_{Uref1}} =$ 

Snapshot matrix

→ **S**ingular **V**alue **D**ecomposition →

POD modes $\boldsymbol{\Psi}$ and POD coefficients $\boldsymbol{A}$

$\boldsymbol{SVD}(\mathrm{X/U}_{ref} - mean_{\varphi}(X))$

Reconstruction:

$\boldsymbol{X} = \boldsymbol{\Psi}(\boldsymbol{\varphi}, \boldsymbol{n}) \cdot \boldsymbol{A}(\boldsymbol{\varphi})$

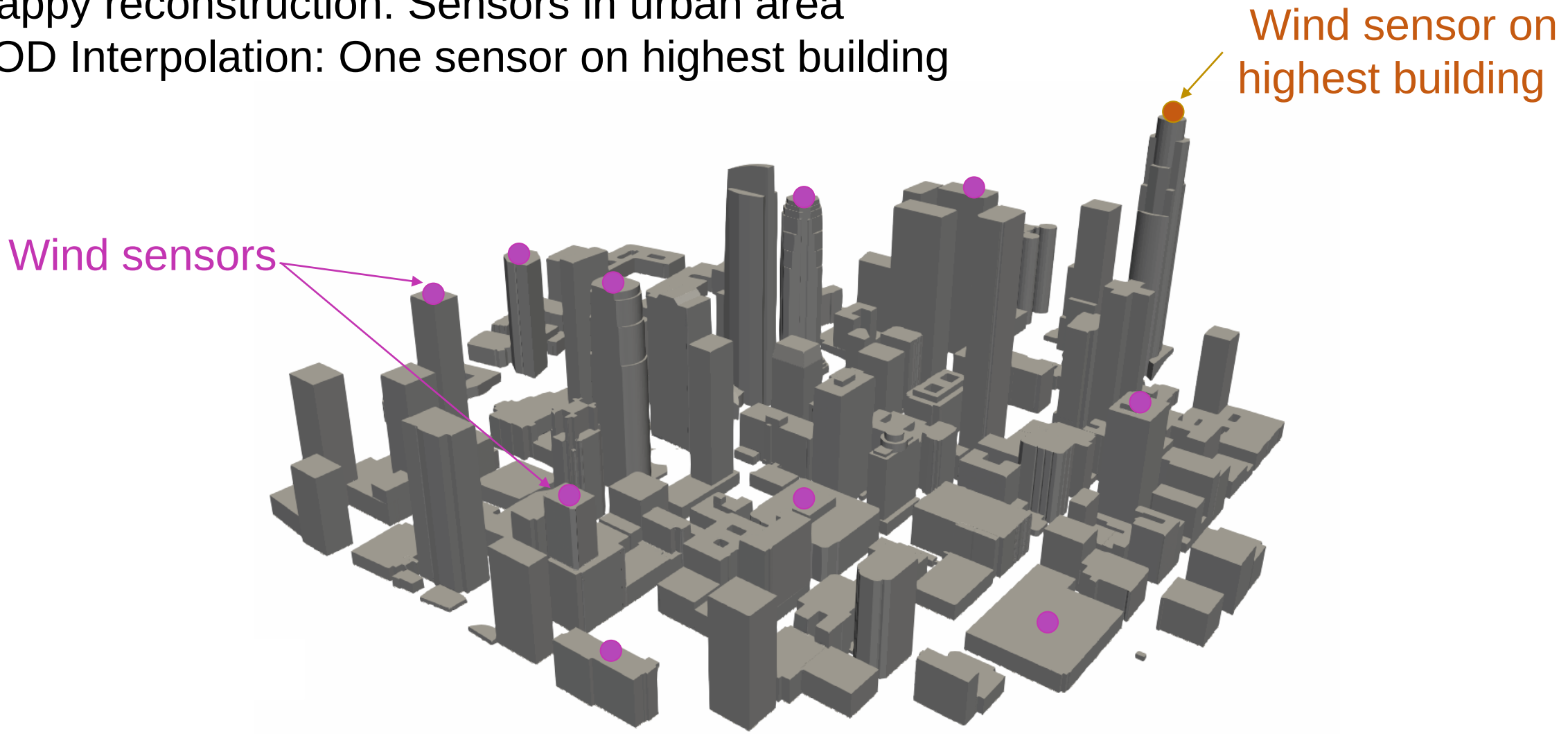
Data Estimation

- Estimation of an *unkown wind field* $\tilde{X}$:
  - Reconstruction: $\tilde{X} = \Psi \cdot \tilde{A}(\varphi_{test})$

    POD modes — **Estimated POD coefficients**
  - Extrapolation $U_{ref,test}$: $\tilde{X}_{U_{ref,test}} = [\tilde{X} + mean_{\varphi}(X)] \cdot U_{ref,test}$
- Two options to *estimate new POD coefficients* $\tilde{A}$:
  1. *Gappy reconstruction* with wind sensors measurements.
  2. *POD Interpolation* as a function of the wind direction (if the φ_{test} is known).

Wind sensors

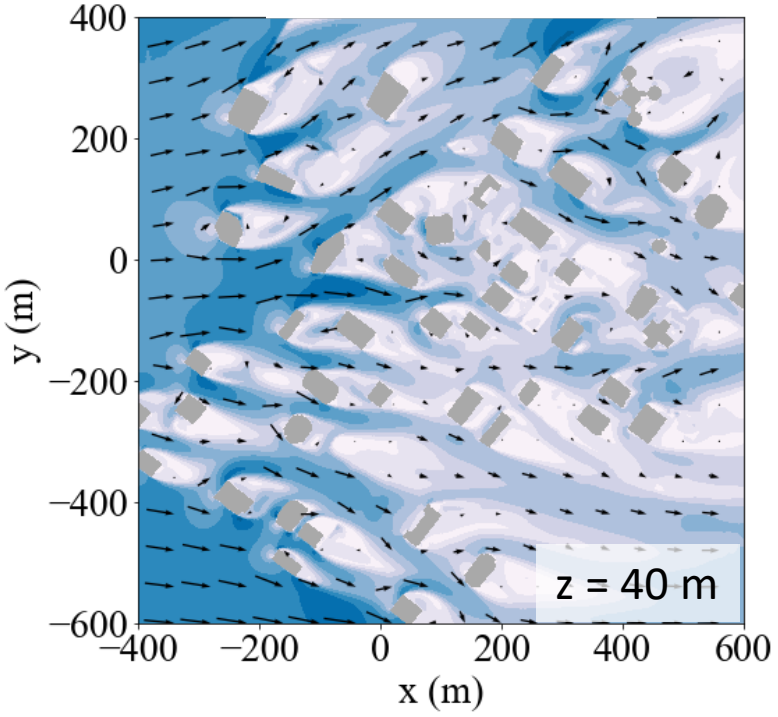
- Gappy reconstruction: Sensors in urban area
- POD Interpolation: One sensor on highest building



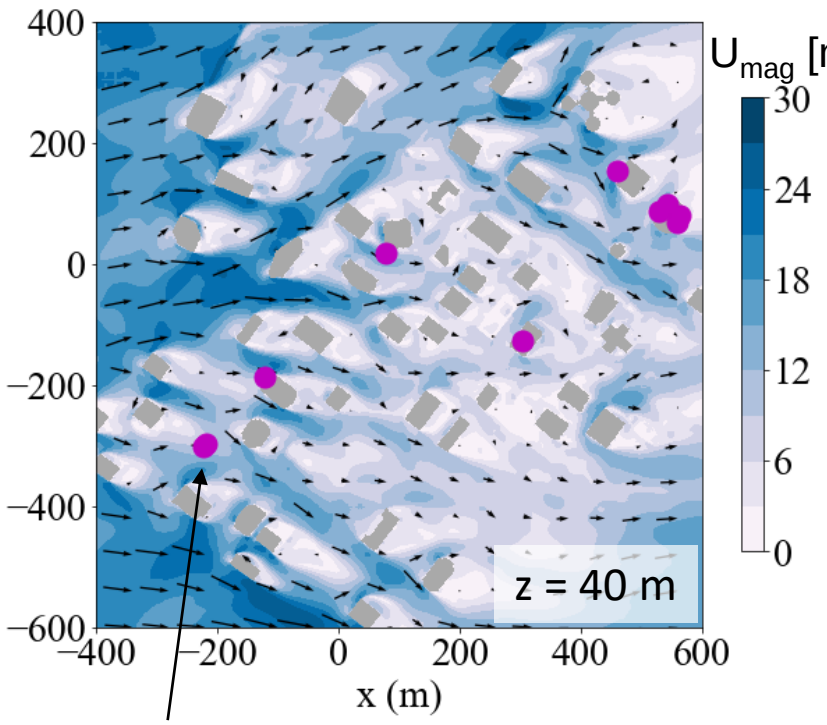
Gappy Reconstruction - U_{mag}

- Test case: φ =267°, $U_{ref} = 31\ m/s$
- Wind sensors = 10

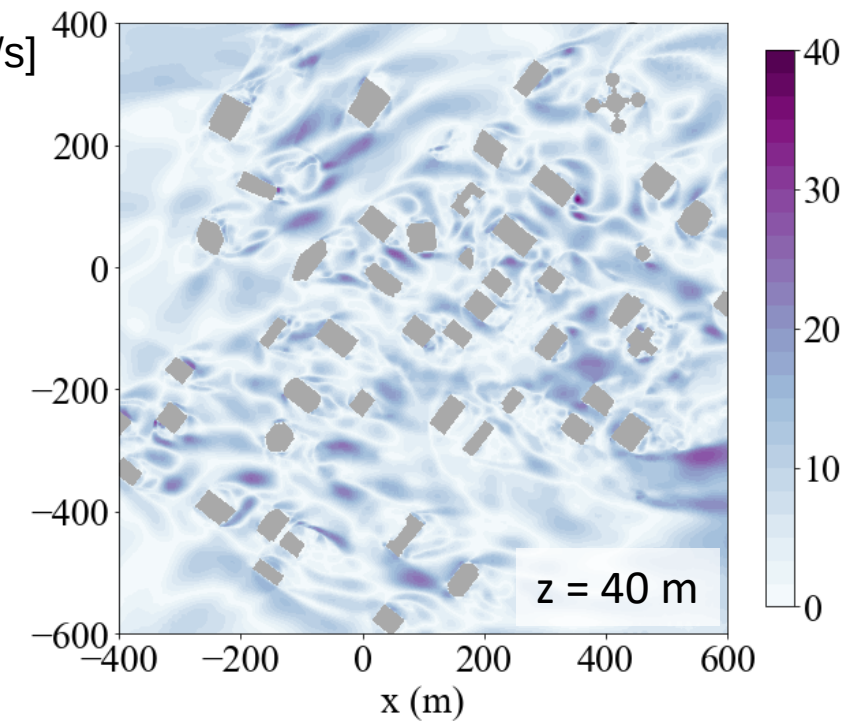
Original



Reconstruction



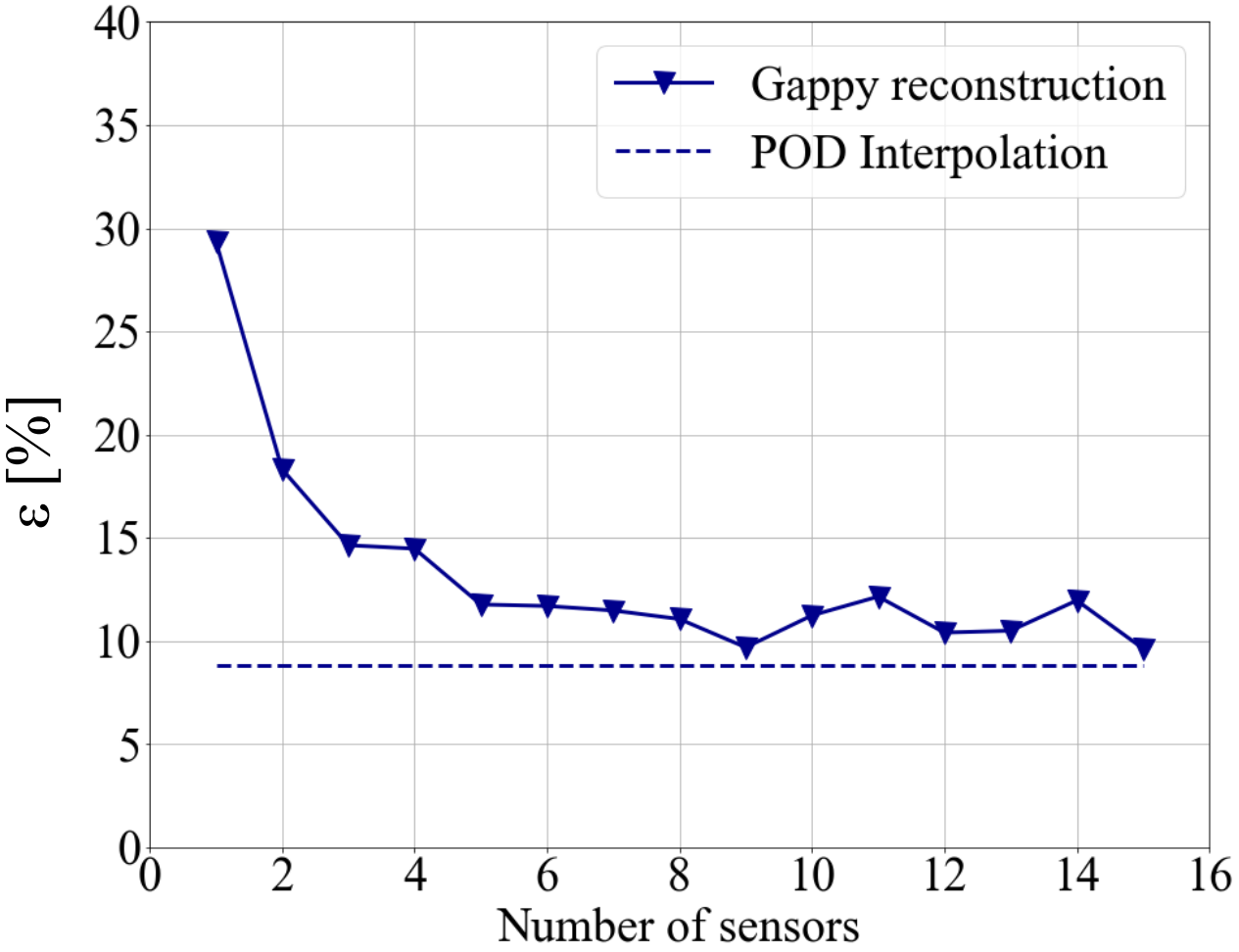
Difference error = $(u_{orig} - u_{recon})/U_{ref}$ *[%]*



Reconstruction Error

- Normalized root-mean-square reconstruction error:

$$\varepsilon = \frac{\left\| \tilde{X} - X_{orig} \right\|_2}{\left\| X_{orig} \right\|_2} \cdot 100\ \%$$



Conclusion

- CFD simulation of urban area for different wind directions and wind speeds.
- 3D wind field estimation with high level of accuracy – Interpolation is slightly more accurate then the Gappy reconstruction.
- Both methods show a fast reconstruction time – suitable for urban air trajectory planning.
- Future: Improvement of interpolation with wind sensors measurements.