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Sensitivity analysis of the 2D VAR retrieval method in the application to the wind turbine wakes

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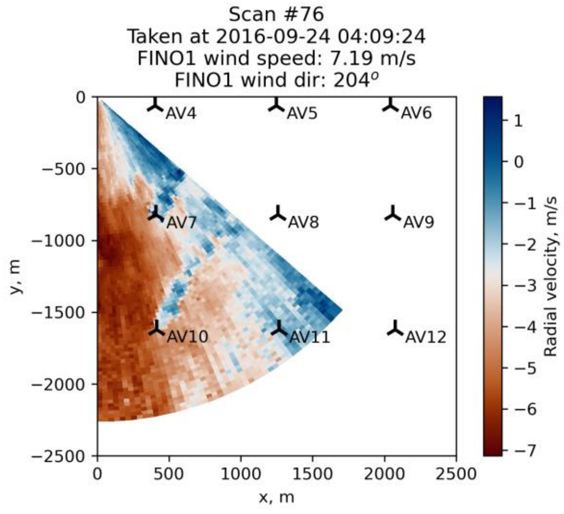
Motivation

- Scanning lidars measure **radial velocity** – a projection of the actual wind speed to the line of sight.

  $$V_r = u \sin\varphi \cos\psi + v \cos\varphi \cos\psi + w \sin\psi$$

  where φ – azimuth, ψ – elevation angle.
- The original wind field is reconstructed via **lidar retrieval**.
- The most common methods were originally developed for homogeneous fields and do not perform well for wake fields.
- A **2D-VAR method** was suggested as a fast alternative, consisting of Volume Velocity Processing (VVP) and cost function optimization [1, 2].

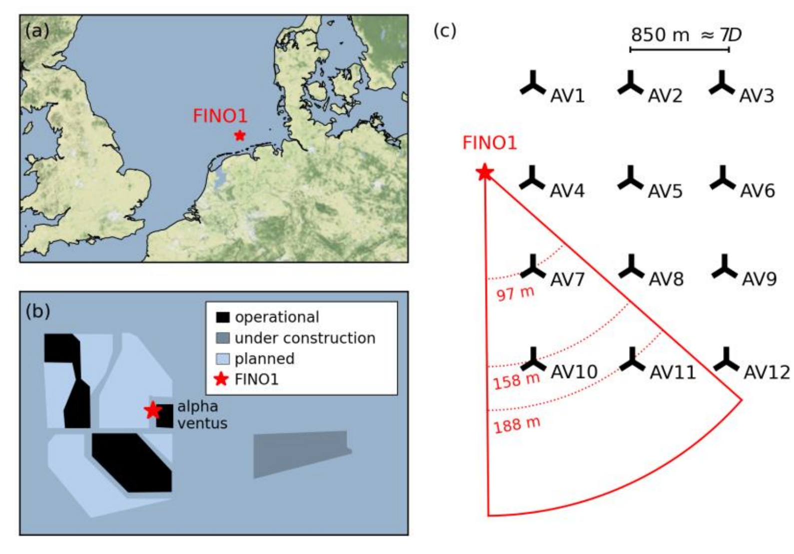


1. Cherukuru NW, Calhoun R, Krishnamurthy R, Benny S, Reuder J, Flügge M. 2D VAR single Doppler lidar vector retrieval and its application in offshore wind energy. *Energy Procedia 2017*; 137: 497–504. doi: 10.1016/j.egypro.2017.10.378

2. Cherukuru NW. *Doppler Lidar Vector Retrievals and Atmospheric Data Visualization in Mixed/Augmented Reality*. PhD thesis. Arizona State University, 1151 S Forest Ave Tempe, AZ 85281, USA; 2017

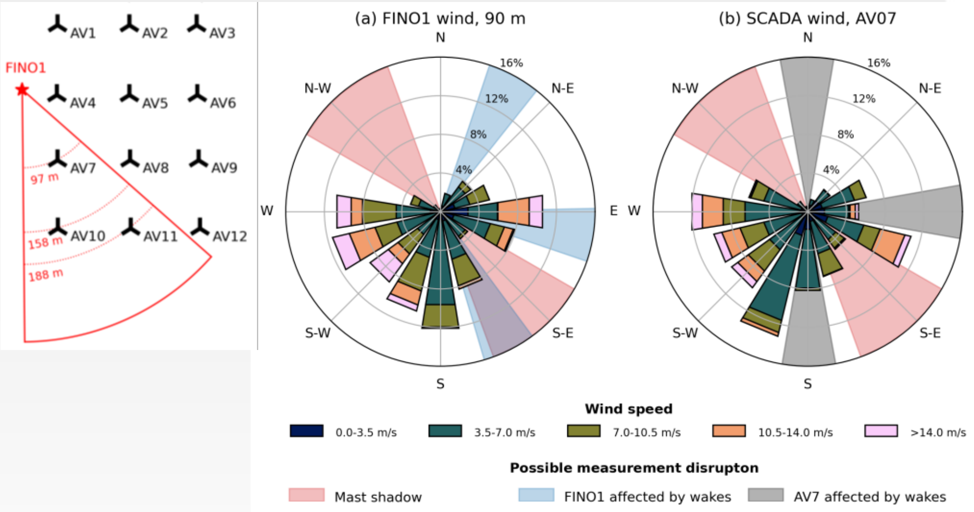
Datasets: Description

- Period: September 2016
- Cup anemometer, vane and at FINO1 (10-minute averages).
- Lidar: Leosphere WindCube 100S (OBLEX-F1)
  - Non-continuous dataset
  - Only elevation angle of 4.62º
  - **AV7 is scanned at the hub height**
  - ~55 seconds between scans
- SCADA system (installed at each turbine)



Datasets: Wind roses

- Wind roses show wake effect on AV7
- Possibility of a 5-10º *wind direction offset* between FINO1 and AV7
  - Vertical veer effect?
  - FINO1 data averaging?
  - Lidar orientation?
- The offset was observed regardless of the wind direction [3]
- We do not account the possible wind direction offset for now – this needs more studying.



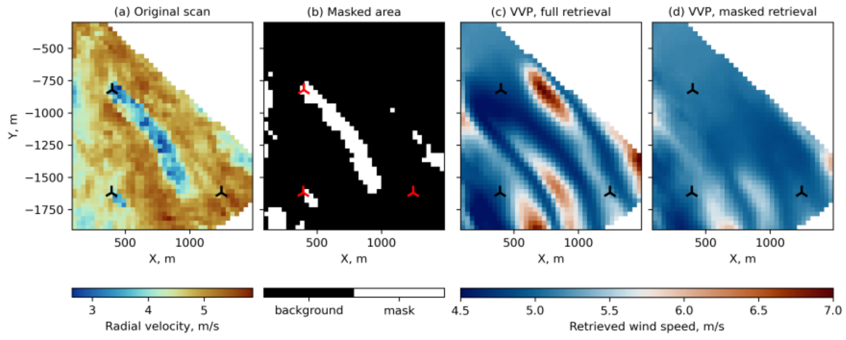
2D-VAR retrieval: VVP retrieval

- First step: VVP retrieval to estimate the background flow
  - Reduce $V_r = u \cos\varphi \cos\psi + v \sin\varphi \cos\psi + w \sin\psi$ to $V_r = u \cos\varphi + v \sin\varphi$
  - Minimize solution for consecutive scans i and $i+1$

$$V_r^{(i)} = u \cos\varphi + v \sin\varphi$$

$$V_r^{(i+1)} = u \cos\varphi + v \sin\varphi$$

- The VVP solution is rather stable but smooths the wakes.
- The solution depends little on the initial guess and more on the retrieval domain size.
- May require wake masking to avoid non-physical wind speed increase along the wakes.



2D-VAR retrieval: Cost function

- Second step: cost function optimization for the actual flow (u, v) and deviation from the constant wind P.
- The VVP solution serves as one of the inputs (u_b, v_b).

$$J = \int (W_a A^2 + W_b B^2 + W_c C^2 + W_d D_a^2 + WdD_b^2) d\Omega / 2\Omega$$

- Where W_a, W_b, W_c and W_d are weights (detailed in [2])
- And the components are:

  $A = u \cos \varphi + v \sin \varphi - V_r$ (radial velocity residuals)

  $B = - u \sin \varphi + v \cos \varphi - \partial V_r/\partial \theta + P$ (tangential velocity)

  $C = \partial V_r/\partial t + u\, \partial V_r/\partial x + v\, \partial V_r/\partial y$ (advection equation)

  $D_a = u - u_b$, $D_b = v - v_b$ (deviation from the background flow)

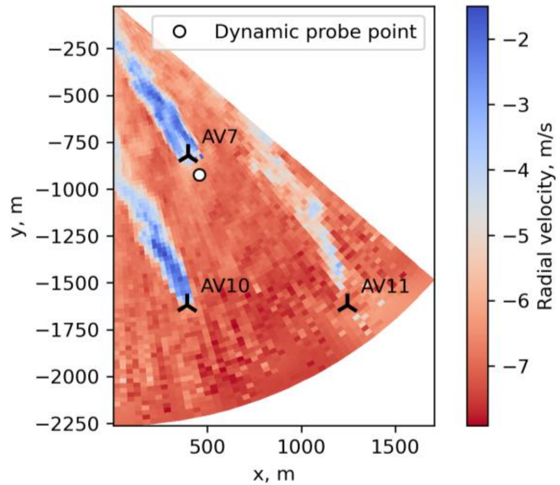
- Initial guess: (u_0, v_0) as uniform field from FINO1 90-100 m data, P – zero matrix.

Verification

- Compare radial velocity residuals
  - Observed vs. calculated from the retrieved field

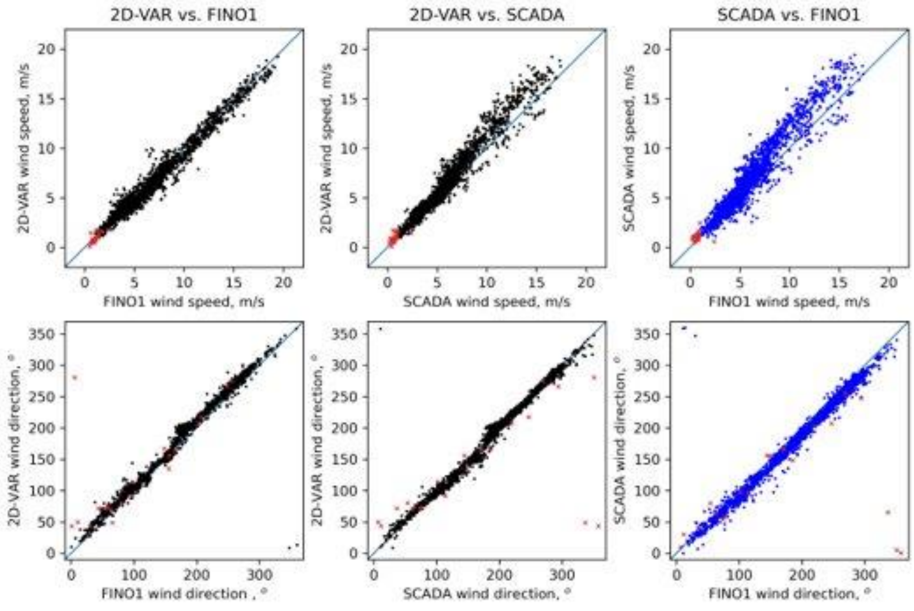
    $$\Delta V_r = V_r^{(obs)} - V_r^{(ret)}$$

  - Shows, whether **the retrieved flow corresponds to the lidar scan**.
- Compare time series
  - Even if the retrieved flow is not 100% accurate, we can still **evaluate local results**.
  - AV7 SCADA data vs. retrieval (AV7 hub height)
  - FINO1 data vs. retrieval (AV7 hub height)
  - AV7 inflow is probed dynamically at *1D* in front of a wind turbine to account the wind direction.



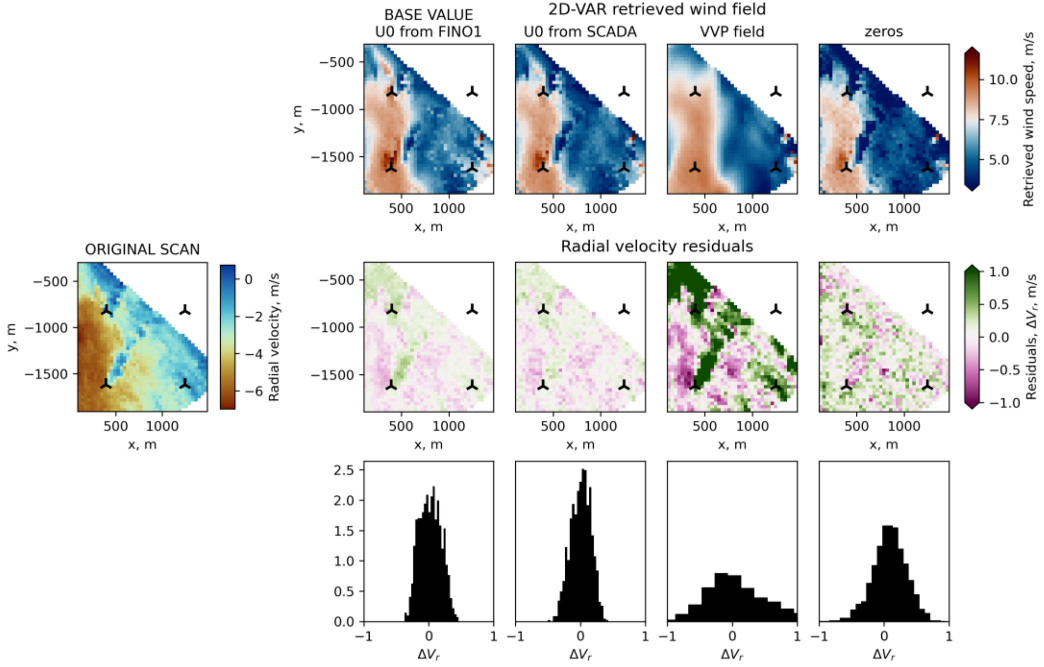
Results

- 2D-VAR algorithm runs over all valid September 2016 scans (elevation angle 4.62º, <60 s interval, <50% data missing).
- **Initial guess – FINO1 data** at 90-100 m.
- Compare 10-minute averages for FINO1, SCADA AV7 and retrieval series near AV7.
- Exclude points with wind speed <1 m/s – prone to erroneous estimation due to uncertainty.
- Wind direction agrees well.
- Wind speed near AV7 is more similar to FINO1 than SCADA.
- Initial guess influence? – **very likely**



Sensitivity: Initial guess

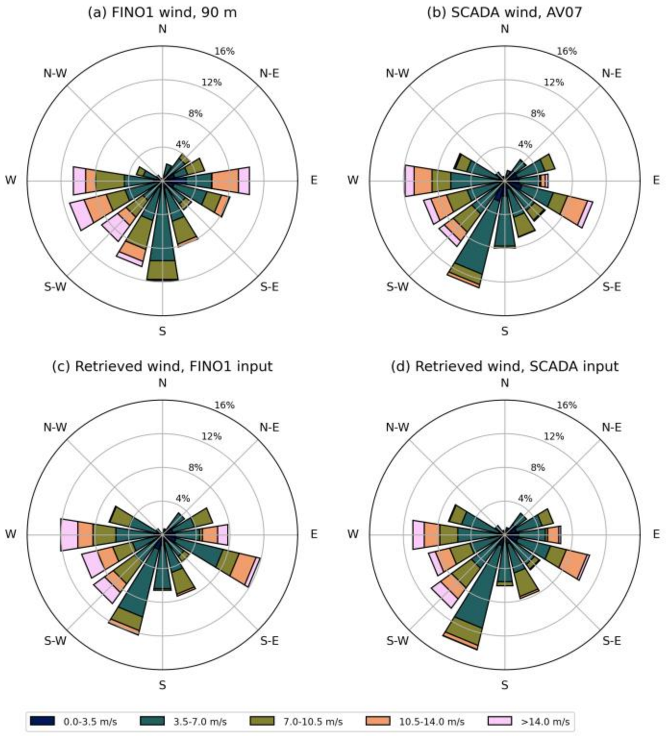
- Basic initial guess (u_0, v_0):
  - uniform field from FINO1 data
  - uniform field from SCADA AV7 data
  - background flow from VVP solution
  - constant values, e.g., zeros
- However:
  - **The VVP solution** does not work as an initial guess if already used as background flow.
  - **Zero matrix** as initial guess performs close to fields from measurement data but the solution is not stable and stronger depends on the weights.



Sensitivity: Initial guess

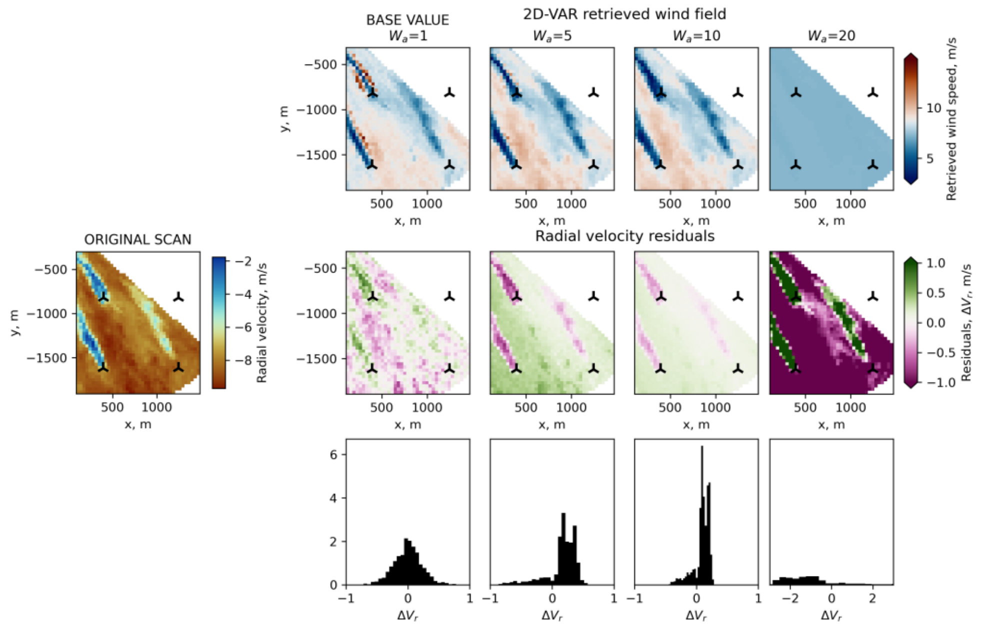
- Basic initial guess (u_0, v_0):
  - uniform field from FINO1 data
  - uniform field from SCADA AV7 data
  - ~~background flow from VVP solution~~
  - ~~constant values, e.g., zeros~~
- The 2D-VAR solution is affected by the initial guess
- Yet, local values may tend to the actual value – see RMSE vs. SCADA data

Series	Wind speed error (RMSE)	Wind direction error (RMSE)
FINO1 vs. SCADA	1.43 m/s (0.961)	12.7º (0.979)
FINO1 as initial guess		
2D-VAR vs. FINO1	0.66 m/s (0.988)	11.5º (0.979)
2D-VAR vs. SCADA	1.08 m/s (0.977)	6.83º (0.996)
SCADA as initial guess		
2D-VAR vs. FINO1	1.04 m/s (0.965)	13.17º (0.985)
2D-VAR vs. SCADA	0.74 m/s (0.979)	5.0º (0.992)



Sensitivity: Weight W_a

- Puts significance on residuals
- Original source value: $W_a = 1$
- $W_a = 1$ may return high wind speeds along the wakes.
- Higher weight => lower residuals
- **BUT**: Very high weight => cost function locks at the initial guess.
- $W_a = 1...5$ is fine for solution tuning, but higher values are not recommended.



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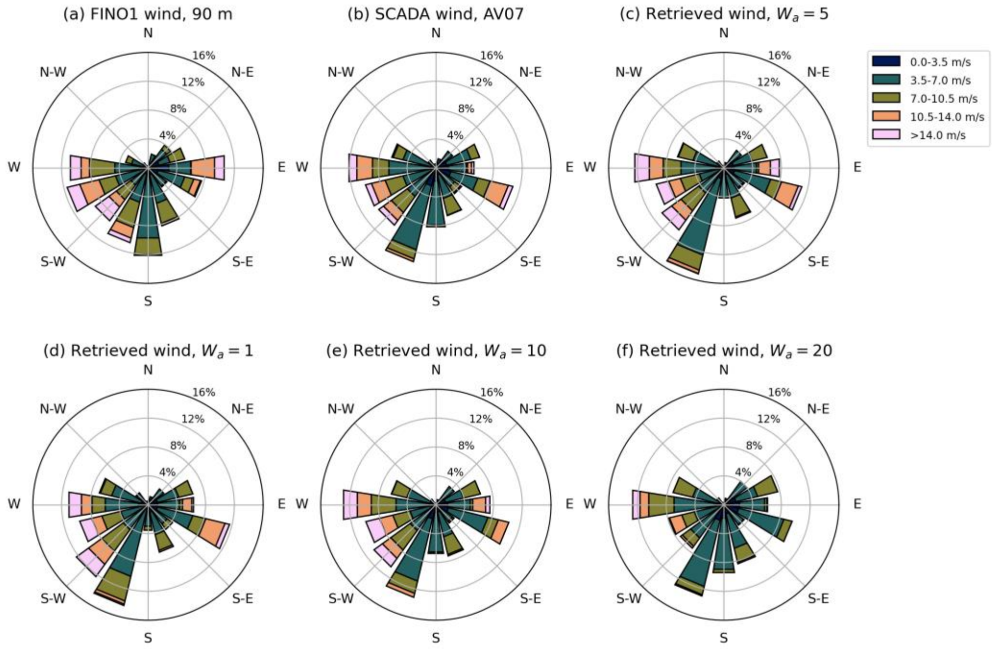
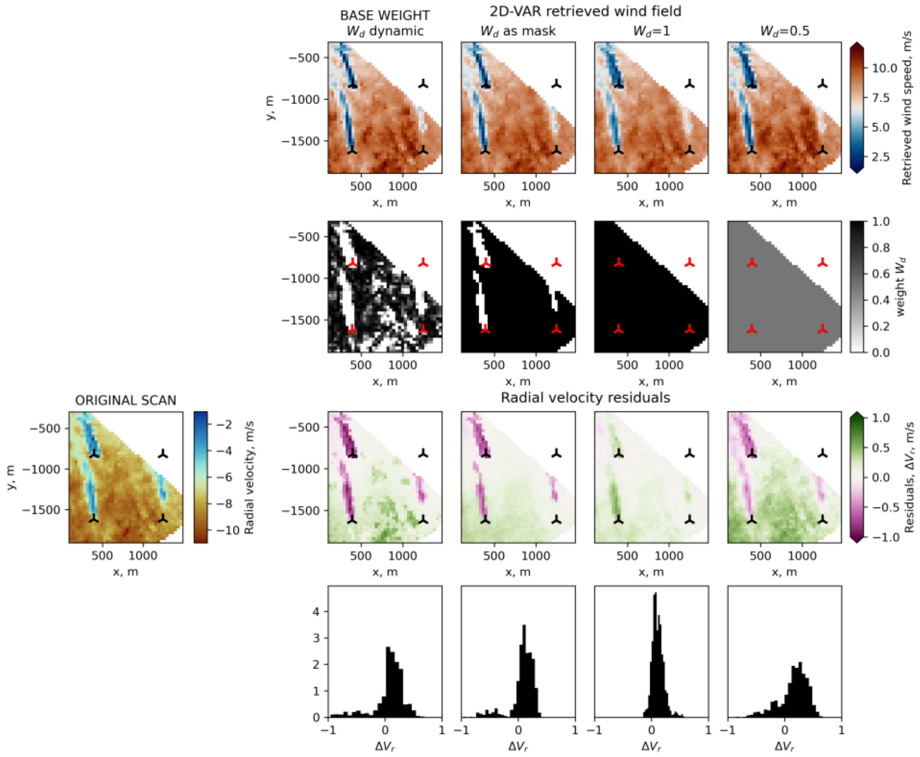


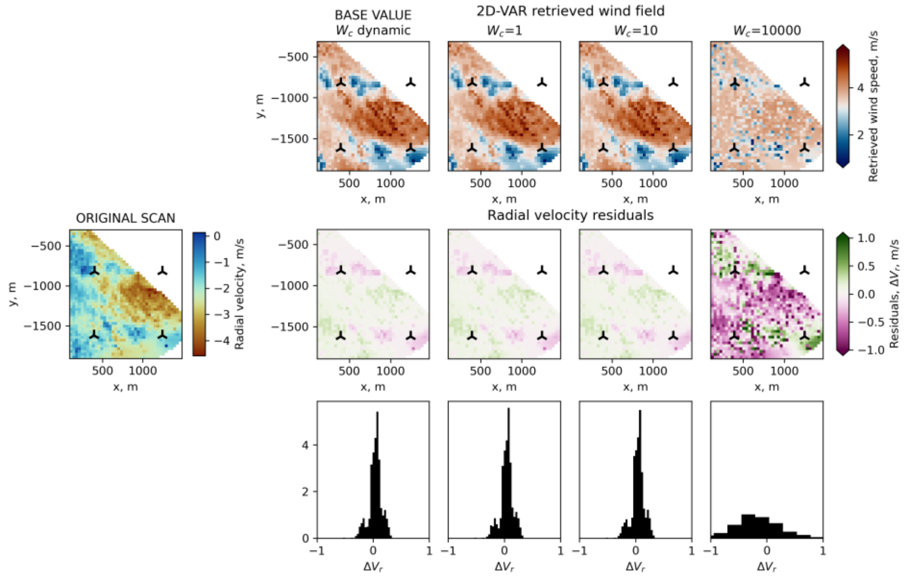
Sensitivity: Weights W_b and W_d

- The weights are complementary $W_b + W_d = 1$
- W_d is derived from the difference between V_r observed and V_r calculated from VVP-field
- For W_b, it is more important that the field was smoothed for calculation of $\partial V_r/\partial\theta$.
- W_d acts similarly to a wake mask, but also accounts fluctuations in the background flow
- Alternatives:
  - W_d as wake mask
  - $W_d = 1, W_b = 0$
  - $W_d = W_b = 0.5$
- Constant value weights may perform differently depending on the flow



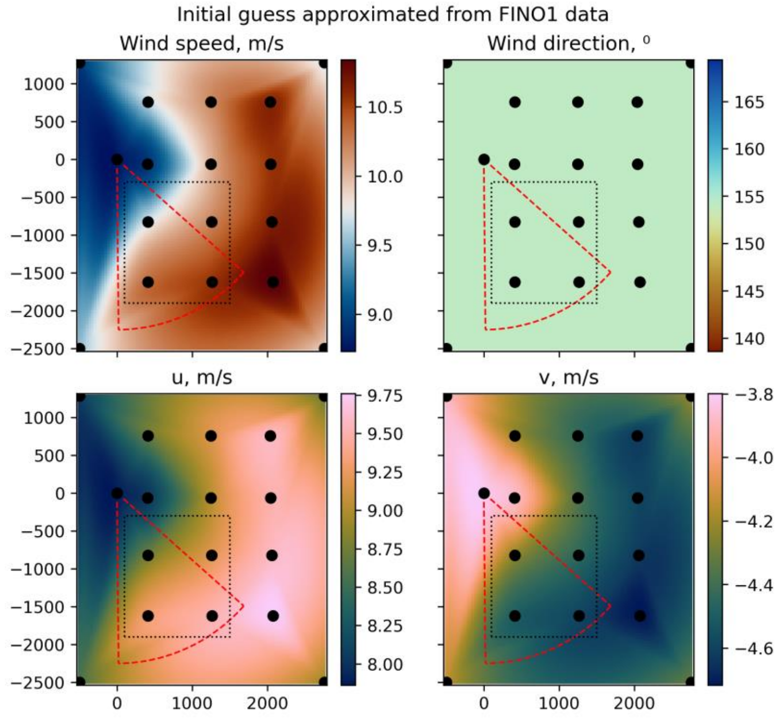
Sensitivity: Weight W_c

- The weight ensures that the advection equation is solved only where the radial velocity can be assumed stationary.
- Binary matrix
  - 0 – advection distance > grid spacing, do not solve the advection equation
  - 1 – advection distance < grid spacing, solve the advection equation
- In some flows (low speed, crosswind), W_c may be uniform.
- Overall, **the contribution of W_c is low.** Needs an increase by several orders to have an effect on the solution.



Test of a concept: Non-uniform initial guess field

- **Initial guess is important.**
- FINO1 series can give only a constant field.
  - Good for real time processing, but not full field retrieval for wake research
- SCADA data cover several turbines.
- Approximate 2D field from FINO1 and SCADA.
- Elevated scan: **extrapolate wind speed** to corresponding heights based on wind profile.
- Wind direction is not yet extrapolated.
- Example: FINO1 constant field adjusted to height.
  - Adding SCADA data accounts local fluctuations
  - Very crude approximation – only **an initial guess**

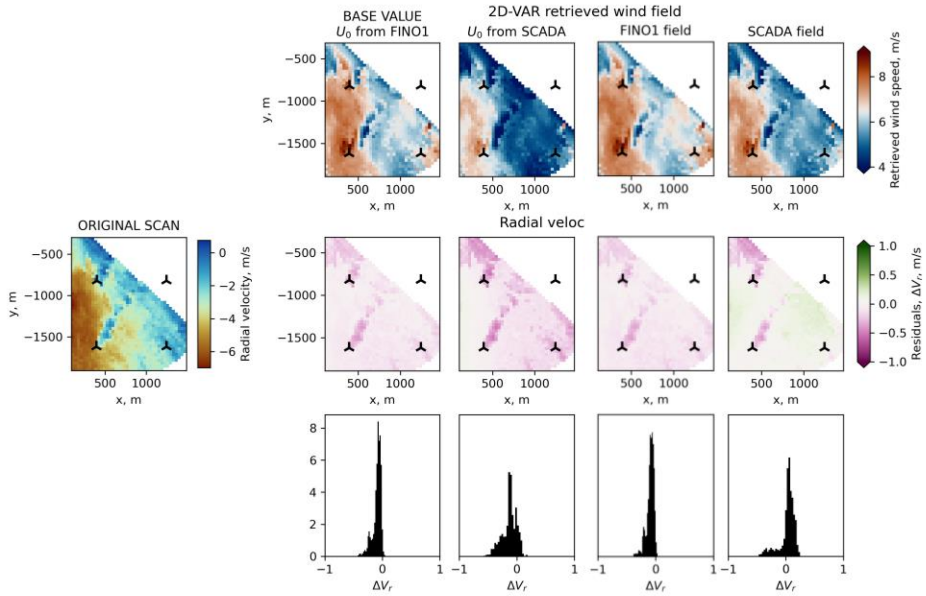


Test of a concept: Non-uniform initial guess field

- Non-uniform initial guess is extrapolated from FINO1 and SCADA point data

Results

- Non-uniform initial guess moves residuals.
- Far range shifts residual bias, if SCADA data are used for non-uniform field.
- Near range – lidar measurement artifacts or too high resolution?
- Non-uniform initial guess may perform better than constant values
- There is a potential to improve full field retrieval
  - But it may not be applicable in real time



Conclusions

- The 2D-VAR solution is **the most sensitive to the residuals weight** W_a – this weight should be altered carefully.
- Other weights affect the solution less and may be replaced by simplified definitions.
- Initial guess is very important. Constant value is compromise, but good enough for local values
- **Future work**:
  - Retrieval on the simulated wind fields ('true' data)
  - Initial guess adjustment for the full field retrieval
  - Weight adjustment depending on the meteorological conditions

References

1. Cherukuru NW, Calhoun R, Krishnamurthy R, Benny S, Reuder J, Flügge M. 2D VAR single Doppler lidar vector retrieval and its application in offshore wind energy. *Energy Procedia 2017*; 137: 497–504. doi: 10.1016/j.egypro.2017.10.378

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3. Krutova M, Bakhoday-Paskyabi M, Reuder J, Nielsen FG. Development of an automatic thresholding method for wake meandering studies and its application to the data set from scanning wind lidar. Wind Energy Sci. 2022; 7(2): 849–873. doi: 10.5194/wes-7-849-2022

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