# 2D VAR single Doppler LIDAR vector retrieval and its application in offshore wind energy

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## Introduction

- Doppler lidars can map the winds with high spatial and temporal resolutions
- One of the potential applications of lidars is in adaptive wind turbine control techniques to maximize the power output of a wind farm
- One limitation of a Doppler lidar is its ability to measure only the line of sight (LOS) component of velocity (radial velocity)
- Hence, a reliable wind vector retrieval technique with real-time running capability is a necessary first step in this process
- Existing vector retrievals either rely on the homogeneous wind field assumption (which does not preserve small scale structure) or on computationally expensive 4D-VAR methods (which are impractical for real-time applications)
- A new 2D-VAR method for low elevation PPI scans was devised to address this issue

## Formulation

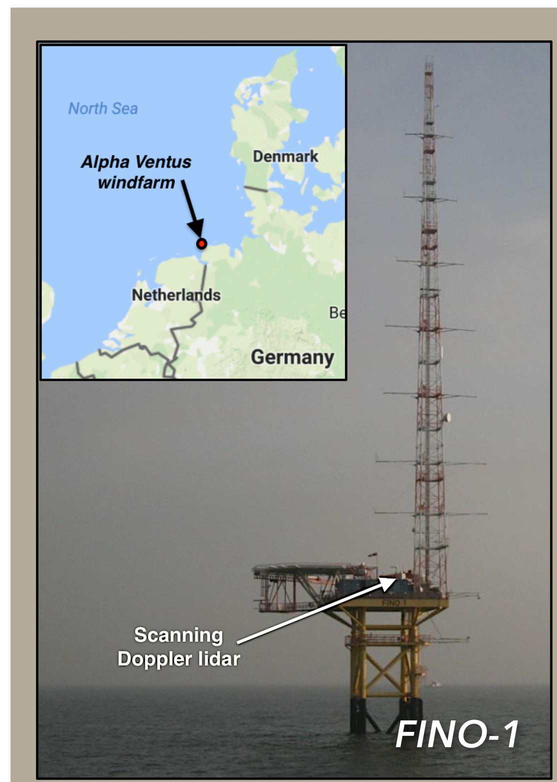
- The 2D-VAR retrieval is based on a parameter identification technique in which the vector field (u,v) is determined such that the cost function (J) composed of a set of constraint equations is minimized
- Apart from the radial velocity, background and the radial velocity advection equations, a new constraint corresponding to the tangential velocity at low elevation angles is formulated by differentiating the radial velocity equation
- The weights were chosen based on the relative importance of the respective terms
- A quasi-Newton method was implemented for minimization

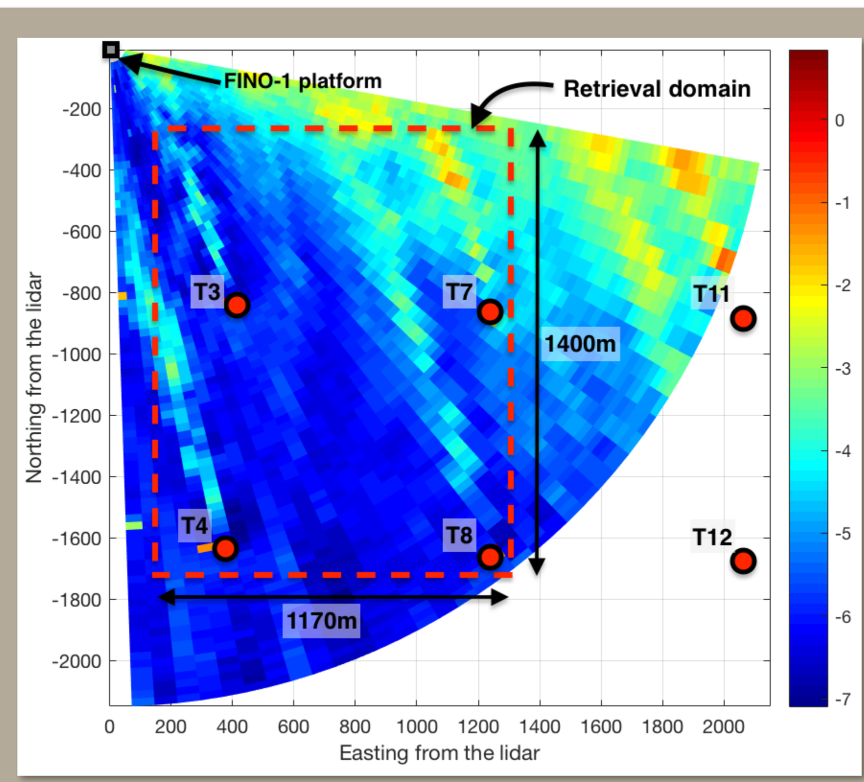
$$\mathrm{J}(\mathrm{u},\mathrm{v},\mathrm{P}) = \frac{1}{2\Omega}\int (W_a\,\mathrm{A}^2 + W_b\,\mathrm{B}^2 + W_c\,\mathrm{C}^2 + W_d\,\mathrm{D}_a^2 + W_d\,\mathrm{D}_b^2 +)\; d\Omega$$

$$(\Omega = retrieval\ domain)$$

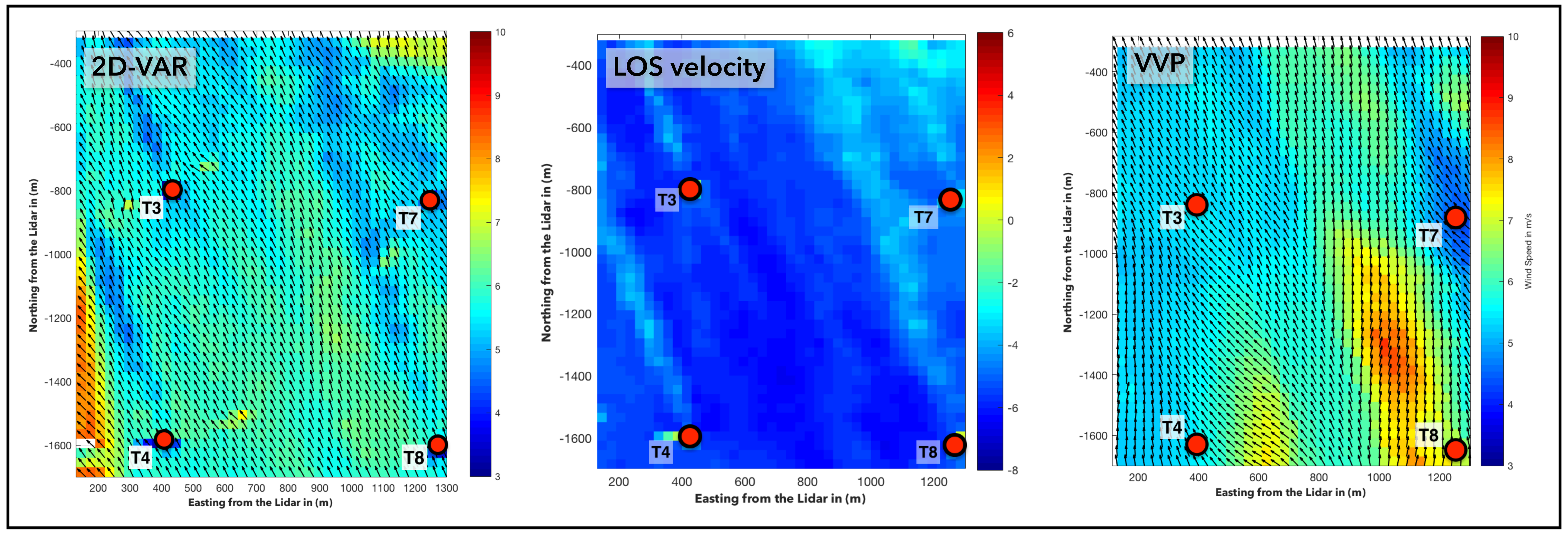
| Term | Expression | Description |
|---|---|---|
| A | $\left(\frac{ux}{r}+\frac{vy}{r}\right) - V_r^{obs}$ | Radial velocity |
| B | $\left(-\frac{uy}{r}+\frac{vx}{r}\right) - \frac{\partial V_r^{obs}}{\partial\theta} + \mathrm{P}$ | Tangential velocity |
| C | $\frac{\partial \widetilde{V}_r}{\partial t} + u\,\frac{\partial \widetilde{V}_r}{\partial x} + v\,\frac{\partial \widetilde{V}_r}{\partial y}$ | Radial velocity advection |
| $\mathrm{D}_a$ | $u - u_b$ | Background from VVP |
| $\mathrm{D}_b$ | $v - v_b$ | |

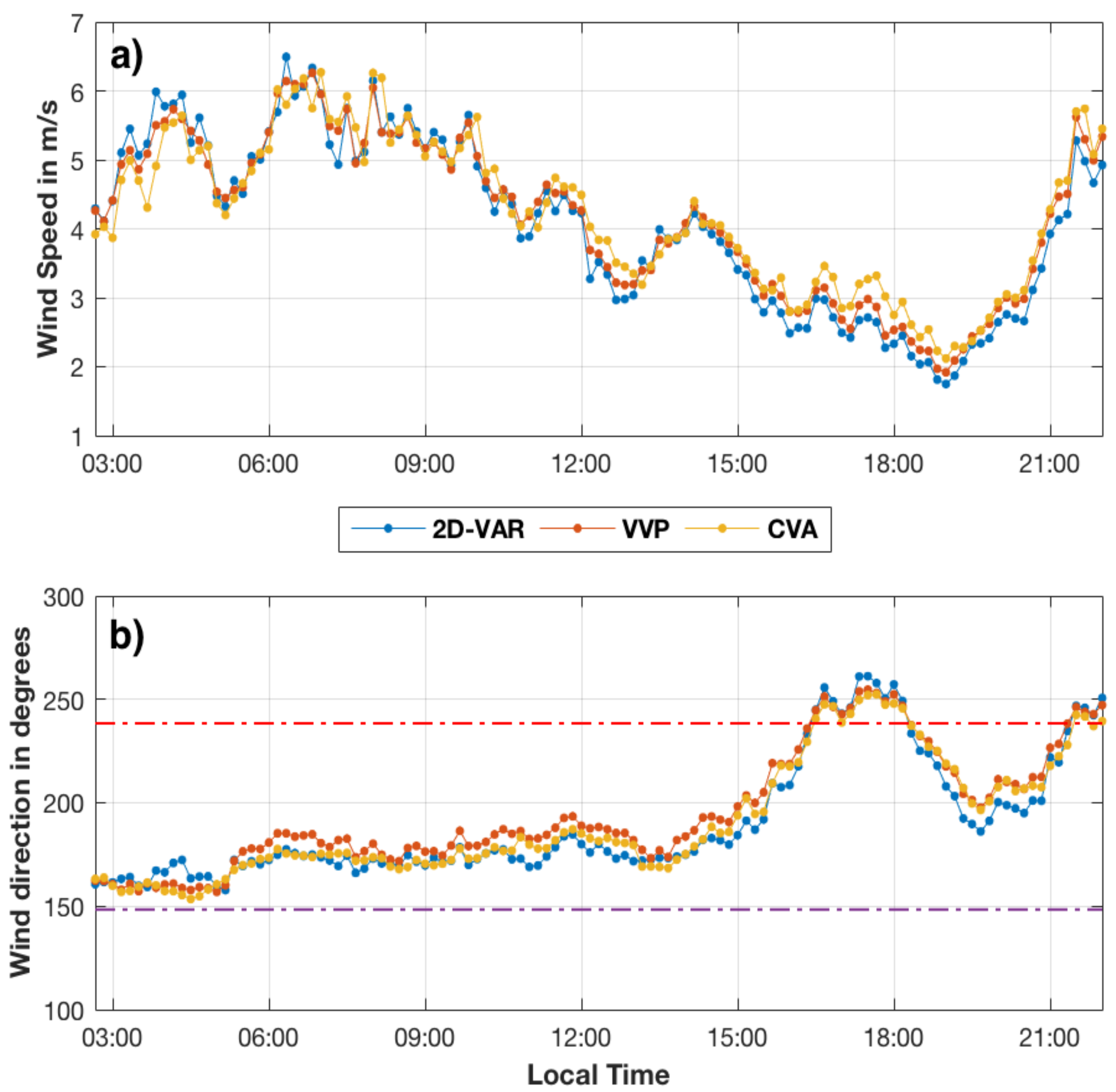
## Test Case




- FINO-1 (Forschungsplattformen in Nord- und Ostsee Nr.1) is a German offshore wind energy research platform located close to the Alpha Ventus wind farm in the North Sea
- A scanning Doppler wind lidar (Leosphere's windcube 100s) was configured to perform repeated low elevation angle (0.5°) PPI scans (90° sector) in the direction of the wind farm
- The 2D-VAR and Volume Velocity Processing (VVP) algorithms were applied in a 1170m x 1400m domain and the results were corroborated with a cup and vane anemometer (CVA) measurements




**ABOVE:** Comparison of the 2D-VAR and VVP retrievals against radial velocity (Line of sight- LOS velocity) as measured by the lidar

**LEFT:** Comparisons of (a) wind speed and (b) wind direction, retrievals from 2D-VAR, VVP and cup and vane anemometer. These are 10-minute averaged values corresponding to the mean flow

**BELOW:** Error statistics corresponding to the 10-minute averaged quantities from 2D-VAR and VVP, with the cup and vane anemometer measurements.

| Algorithm /Variable | Wind speed error | Wind speed correlation | Wind direction error | Wind direction correlation |
|---|---|---|---|---|
| 2D-VAR | 0.383 m/s (5.04%) | 0.96 | -1.4° | 0.98 |
| VVP | 0.290 m/s (2.01%) | 0.98 | 4.3° | 0.99 |

## Discussion

- The 10-minute averaged wind data from the cup and vane anemometer (CVA) situated at 33m LAT on the meteorological mast was used for corroborating and validating the wind retrieval from both 2D-VAR and VVP algorithms
- Since the lidar and the met mast were both located on the FINO-1 platform, retrieved wind vector from the grid point closest to the platform was considered to construct the 10-minute averaged time series
- It is evident that both VVP and the new 2D-VAR methods estimate the mean flow with good accuracy
- VVP performs slightly better that 2D-VAR in capturing the mean flow primarily due to its underlying formulation which is designed to obtain the mean quantities under the homogeneous wind field assumption
- It is evident from this figure that the wind vectors estimated by the 2D-VAR algorithm corroborate well with the radial velocity measurements, especially in capturing small scale flow structures, including what appear to be wakes behind the wind turbines

## Future work

- From this study, it is evident that the true merit of the new 2D-VAR algorithm lies in its ability to preserve small scale flow features, while capturing the mean flow as good as VVP
- However, spatial errors could not be estimated from this dataset primarily due to the lack of instrumentation in the lidar scan region. Data from a lidar simulator running on a background LES windfield could be used to study these errors
- The assignment of weights in the cost function was fixed for all time steps. This could be improved by assigning weights dynamically based on the underlying flow- E.g. the residuals from the VVP stage could be used to increase (or decrease) the weightage of the background term in the cost function

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