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Atmospheric boundary layer wind profile from a Doppler lidar using an Optimal Estimation method

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Background

Coherent Doppler lidar (CDL) make measurements of radial velocity and attenuated backscatter coefficient profiles in the lower troposphere from aerosol backscattered signals.

Mean wind profiles are retrieved from scanning CDL plan-position-indicator (PPI) or step-stare scans using the Velocity-Azimuth Display (VAD) technique [1]. Assuming horizontally homogenous and stationary wind flow at a given range gate, the wind velocity components are retrieved by fitting a sinusoid to the radial velocity data. The amplitude, phase and offset of the sinusoid gives the wind speed, wind direction and vertical velocity, respectively.

$$\psi^2 = \sum_{i=1}^{N} \frac{(x_o k_i - y_i)^2}{\sigma_i^2}$$

Where $\boldsymbol{y_i}$ is a radial velocity measurement, $\boldsymbol{\sigma_i}$ is the measurement uncertainty, $\boldsymbol{N}$ is the number of beams in the PPI scan and $\boldsymbol{x_o} = (\boldsymbol{u_o}, \boldsymbol{v_o}, \boldsymbol{w_o})$ is the mean wind vector. The $\boldsymbol{k_i}$ represent the beam pointing geometry and is given by

$$k_i = (sin\alpha_i cos\theta;\; cos\alpha_i cos\theta;\; sin\theta)$$

where $\boldsymbol{\alpha}$ is the azimuth angle, and $\boldsymbol{\theta}$ is the elevation angle ($\theta = 90 - \phi$ in Figure 1).

This layer-by-layer traditional VAD (tVAD) retrieval enables filtering bad radial velocity estimates at each layer using signal-to-noise ratio (SNR) threshold. However, it ignores the vertical correlation in the atmospheric wind profiles.

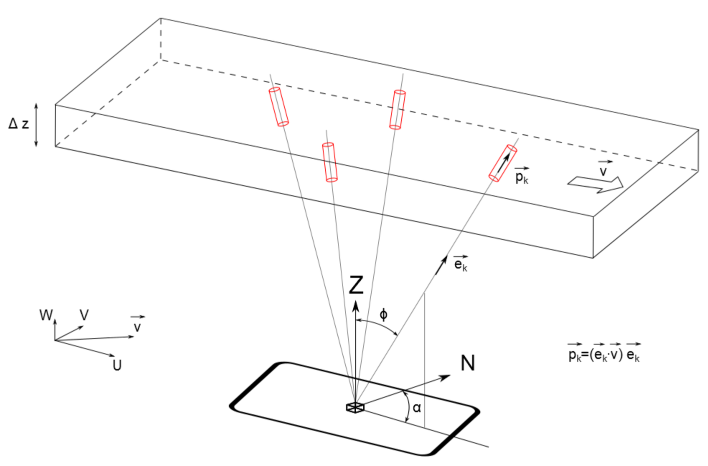

Figure 1: Schematics showing Doppler lidar VAD sampling with 4 beams [2].

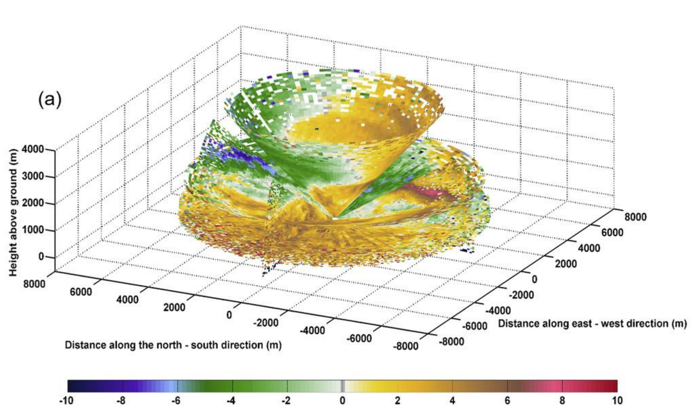

Figure 2: Example Doppler lidar measurements with multiple PPI at different elevation angles and range-height-indicator (RHI) scans used for retrieving wind profile.

Optimal Estimation Method

In Optimal Estimation method [3], a set of measurements, $\boldsymbol{y}$ are related to the state vector, $\boldsymbol{x}$ by the forward model, $\boldsymbol{F}$

$$y = F(x, b) + \epsilon$$

where $\boldsymbol{b}$ and $\boldsymbol{\epsilon}$ are model parameters that are not retrieved and error respectively. The state vector, $\boldsymbol{x}$ contains all the parameters that are retrieved. The error term consists of errors which are not related to the forward model parameters. The forward model includes all the physical and instrumental factors that describe the measurements. The optimal estimation technique has been extensively used for retrievals of atmospheric constituent profiles (e.g. temperature, trace gases) from passive remote sensing measurements where the problem is generally ill-determined. A priori information in the form of mean state vector and covariance around this mean is used as a constraint to provide a solution.

In case of the scanning CDL measurements of radial velocities at different azimuth ($\boldsymbol{\alpha}$) and elevation angles ($\boldsymbol{\theta}$) for wind profile measurements ($\boldsymbol{x} = \boldsymbol{u}, \boldsymbol{v}$ and $\boldsymbol{w}$ components of wind), the forward model $\boldsymbol{F}$ is simply the geometry of the measurement, and independent of $\boldsymbol{x}$. If we assume the vertical velocity $\boldsymbol{w}$ =0, $\boldsymbol{F}$ reduces to

$$F = [\sin\boldsymbol{\alpha} \;\; \cos\boldsymbol{\alpha}]$$

Since, $\boldsymbol{F}$ is independent of the state vector, $\boldsymbol{x}$, the jacobian of $\boldsymbol{F}$ is

$$K = \frac{dF}{dx} = F$$

The maximum aposteriori solution is then given by

$$x = x_a + (K^T S_\epsilon^{-1} K + S_a^{-1})^{-1} K^T S_\epsilon^{-1} (y - K x_a)$$

where x_a is the a priori profile and S_a and S_ϵ are the a priori and measurement error covariance matrices, respectively.

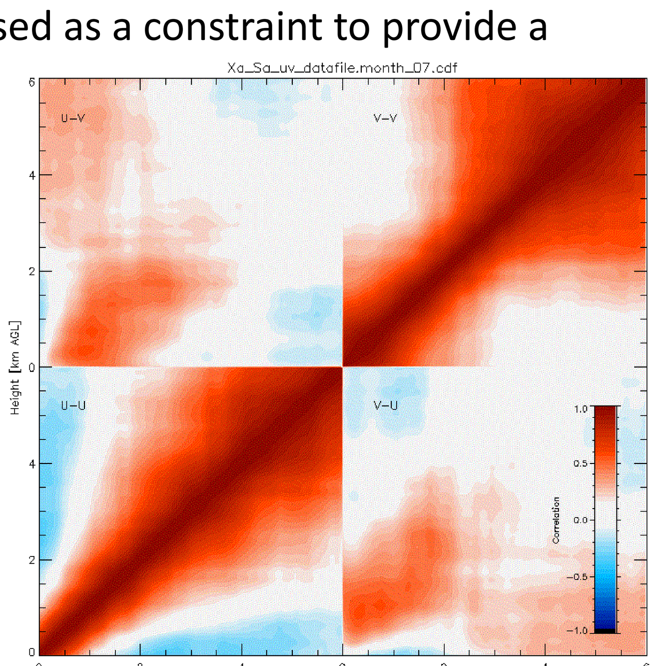

Figure 3: u and v correlation matrix for the month of July determined from radiosonde measurements at the ARM SGP C1 site.

The optimal estimation VAD (OE-VAD) retrieves the vertical profile of horizontal wind vector simultaneously and takes advantage of the vertical correlation in atmospheric winds to provide additional information compared to tVAD method. We used scanning CDL measurements at the DOE ARM Southern Great Plains central site (C1) to test the OE-VAD method, and used 15 years radiosonde wind measurements from 2004-2019 to calculate a unique prior and the covariance for each month.

The Optimal Estimation VAD retrieval of wind profiles from CDL measurements provides additional information compared to traditional VAD algorithm, and it does not degrade the results where traditional VAD provides a valid output.

Results

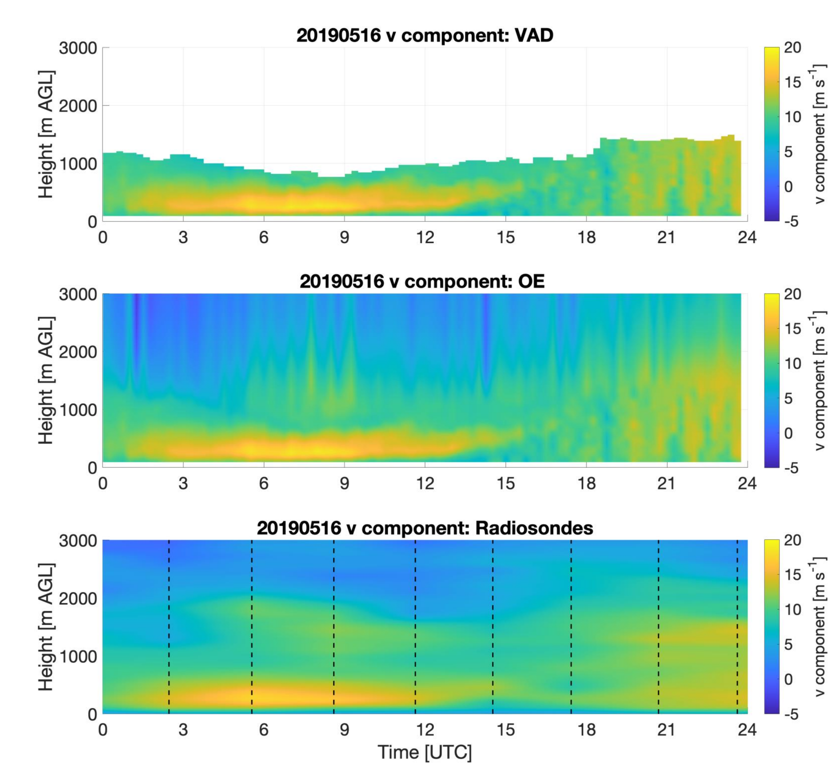

Figure 4: Time-height cross sections of the v-component of wind on 16 May 2019 as retrieved using tVAD (top), OE-VAD (middle), and radiosonde (bottom). Radiosondes were launched every 3 hours at the times indicated by dashed lines in the bottom panel.

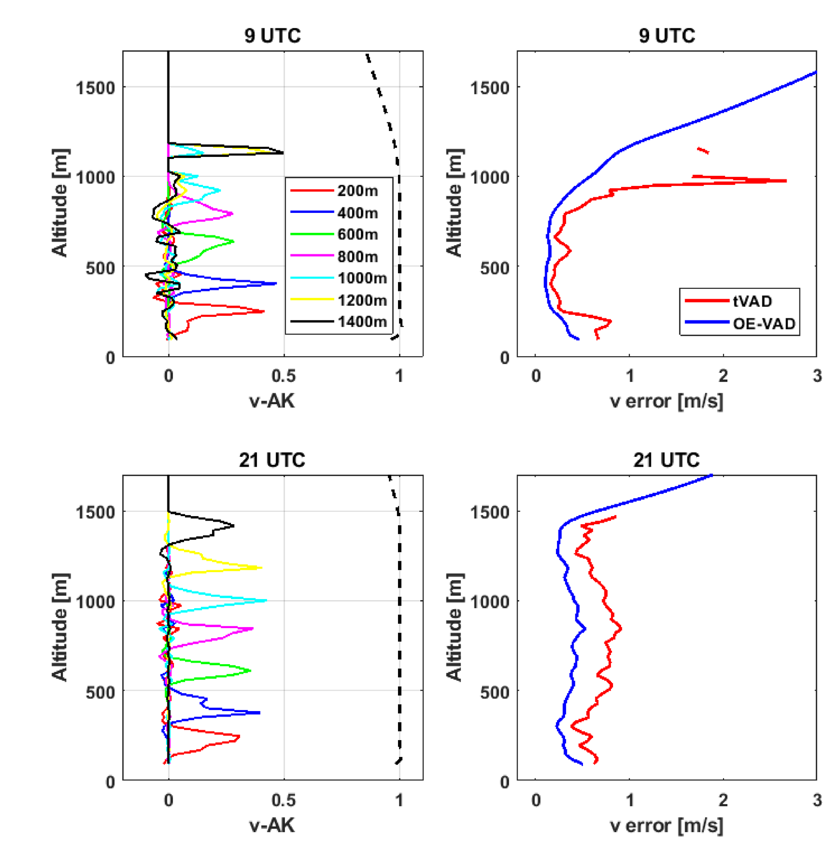

Figure 5: Averaging kernels (left) and error (right) for the v-component of wind for the measurements at 9, and 21 UTC on 16 May 2019. For clarity, the averaging kernels are only shown every 200m in altitude up to 1500 m. The black dashed lines show the summation of rows of the averaging kernel matrix at each altitude.

- OE-VAD does not degrade results where tVAD provides a valid output.
- OE-VAD provides results in regions where tVAD do not provide a valid result. Observational information from adjacent layers, where valid tVAD exists, and prior information are used to provide results in those regions.
- OE-VAD results at higher altitudes are representative of the atmospheric state with bias < 2 m/s.
- OE-VAD provides a framework for combined wind retrievals using measurements from multiple instruments (e.g. Doppler lidar, radar, and sodar).

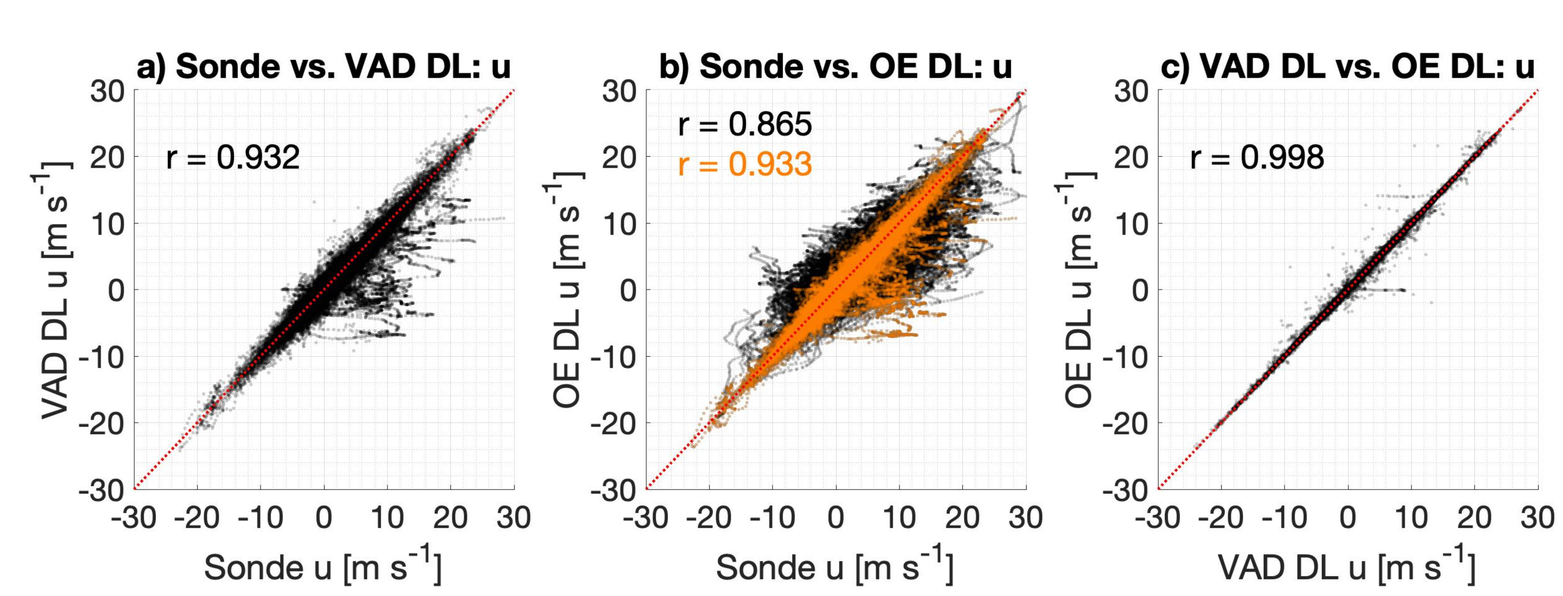

Figure 6: Scatter plots of the u-component of wind at SGP C1 site during 2019 for (a) radiosonde vs. tVAD, (b) radiosonde vs OE-VAD, and (c) tVAD vs. OE-VAD. The dotted red line is the 1:1 line. Points in orange indicate the subset of OE-VAD observations for which a valid tVAD results also exists.

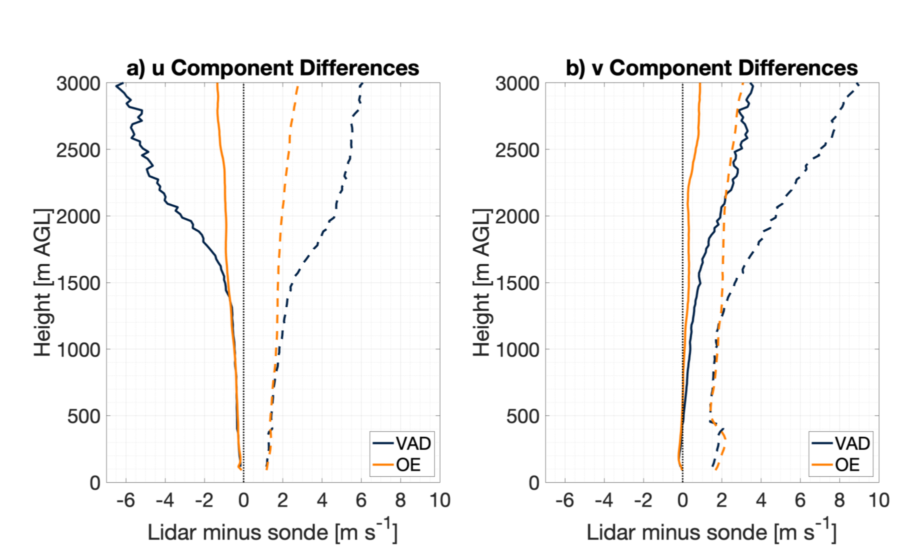

Figure 7: Vertical profiles of the bias (solid line) and 1-σ uncertainty (dashed line) for OE-VAD (orange) and tVAD (black).

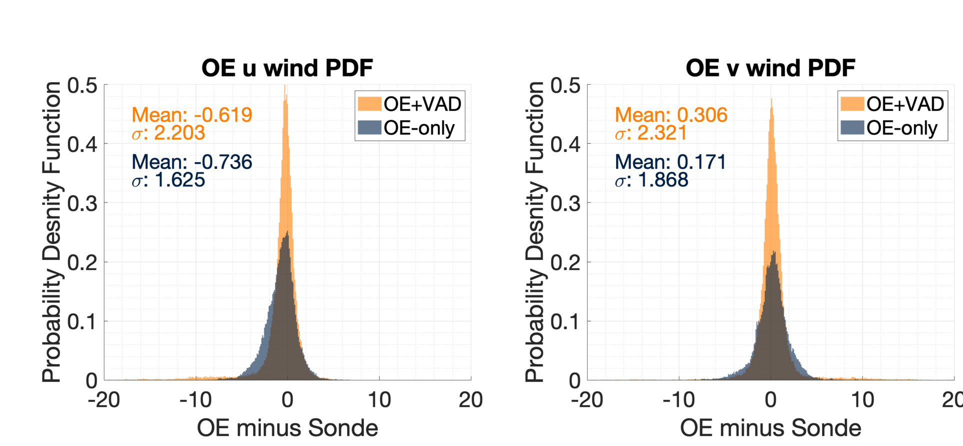

Figure 8: Probability density functions of the OE-VAD minus sonde differences for the u (left) and v (right) component of wind for OE observations without a corresponding tVAD observations (blue), and those with a corresponding tVAD observations (orange).

Acknowledgements and References:

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1. K. A. Browning, and R. Wexler (1968) The determination of kinematic properties of a wind field using Doppler radar, J. Appl. Meteor., 7, 105-113.
2. G. Teschke, and V. Lehmann (2017) Mean wind vector estimation using the velocity-azimuth display (VAD) method: an explicit algebraic solution, Atmos. Meas. Tech., 10, 3265-3271.
3. C. D. Rodgers (2000) Inverse Methods for Atmospheric Sounding: Theory and Practice, World Scientific.