Influence of Open-path Gas Analyzer Flow Distortion on Ultrasonic Wind Measurements

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Introduction

The **eddy-covariance** method is a micrometeorological technique for measuring turbulent exchange between the ecosystem and the atmosphere. It relies on fast-response, synchronous and co-located measurements of 3D wind and gas concentration measurements provided by a **sonic anemometer/thermometer (SAT)** and an **infrared gas analyzer (IRGA)**. To avoid flow distortion effects, the open-path analyzer has to be mounted a certain distance away from the SAT transducer array.

Tradeoff	Separation distance	Potential negative effect
	Large	Lack of covariance
	Small	Flow distortion

Motivation

Most flow distortion investigations have focused on the sonic anemometer.

Dyer et al. (1982) concluded that sensors (gas analyzers and their support structures) could potentially introduce significant distortion of the flow and that "**considerable care must be taken in the basic design of the turbulence sensors**".

Little is known about the aerodynamic properties of open-path analyzers and their effect on the flow through the sonic measurement path.

Wyngaard (1988) finds that sensor-induced flow distortion could cause amplification or attenuation of the vertical velocity due to flow blocking and suggests that this error can be minimized by designing horizontally symmetrical housing structure with minimal stagnation loss in the streamwise speed. **"The need for vertical symmetry**" (of eddy covariance sensors) "seems not to be stressed in the literature" Wyngaard (1988).

Kaimal (1986) recommends **incorporating "as much vertical symmetry as possible into the probe design".**

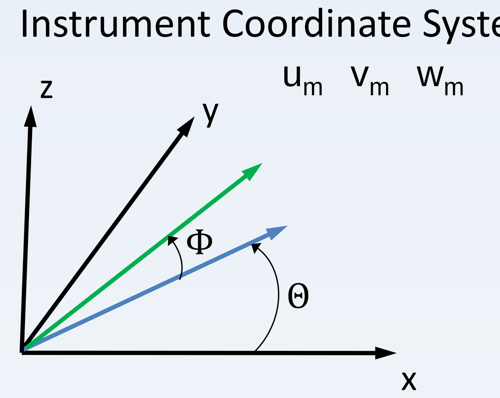
Research Objectives

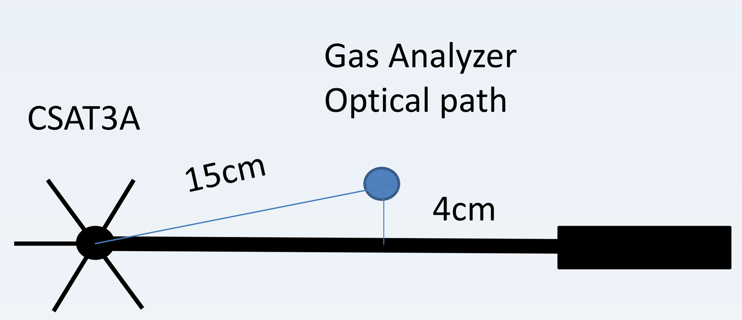
- Compare the flow distortion effects of two commonly used open-path CO_2 and H_2O gas analyzers with horizontally symmetrical and non-symmetrical housing geometries.
- Provide a methodology to identify wind direction segments with potential flow distortion problems

Methods

We conducted a field experiment with a SAT over flat gravel area (50x50 m) with three experimental setups: stand-alone CSAT3A, CSAT3A anemometer and LI-7500 gas analyzer and CSAT3A and EC150 gas analyzer

Instrument Coordinate System and Streamwise Rotation Angles





1. Rotation of x and y around z:

$u_1 \quad v_1 \quad w_1$

$\Theta = \tan^{-1}(v_m / u_m)$ yaw angle

$u_1 = u_m \cos\Theta + v_m \sin\Theta$

$v_1 = -u_m \sin\Theta + v_m \cos\Theta$

$w_1 = w_m$

2. Rotation of x and z around y:

$u_2 \quad v_2 \quad w_2$

$\Phi = \tan^{-1}(w_1 / u_1)$ pitch angle

$u_2 = u_1 \cos\Phi + w_1 \sin\Phi$

$v_2 = v_1$

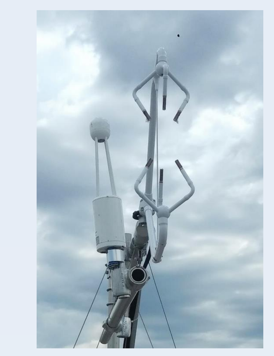
$w_2 = -u_1 \sin\Phi + w_1 \cos\Phi$

Setup A – CSAT3A standalone

Unobstructed, standalone CSAT3A sonic anemometer installed 2.5 m above a flat 50x50 m gravel covered area. The position and the orientation of the anemometer remained the same for setup B and C. This setup is used as a reference.

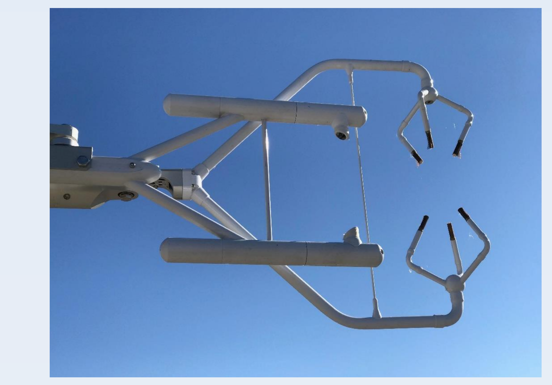
Setup B – Analyzer with Non-symmetrical Design

CSAT3A sonic anemometer and a **horizontally asymmetrical** open-path gas analyzer (LI-7500) with 6.5 cm and 4 cm lower and upper housing diameters, respectively. The distance between the two housings is 12.5 cm and forms the sensing path of the analyzer that is positioned 15 cm behind the sonic path (+x direction) on the same horizontal plane.



Setup C – Analyzer with Vertically Symmetrical Design

CSAT3A sonic anemometer and a **horizontally symmetrical** open-path gas analyzer (EC150) with 3.2 cm lower and upper housing diameters separated 21 cm apart. The optical path length is 14.4 cm and is positioned 15 cm behind the sonic transducer array (+x direction) on the same horizontal plane.

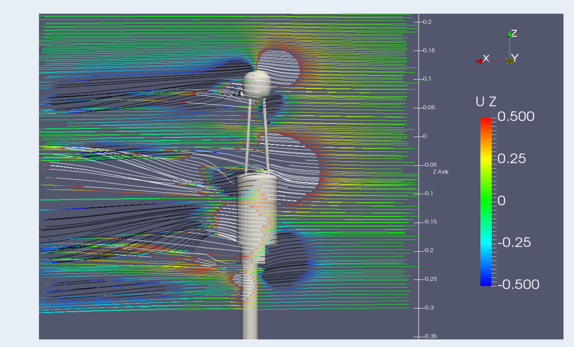


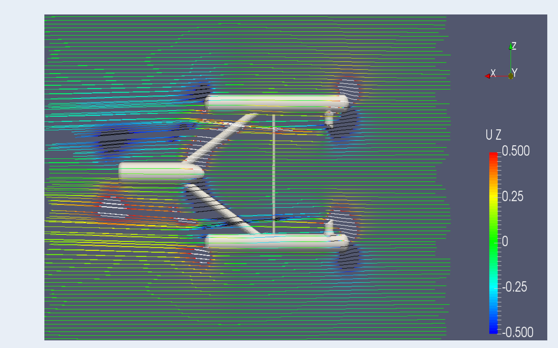
Computational Fluid Dynamics (CFD) Simulations

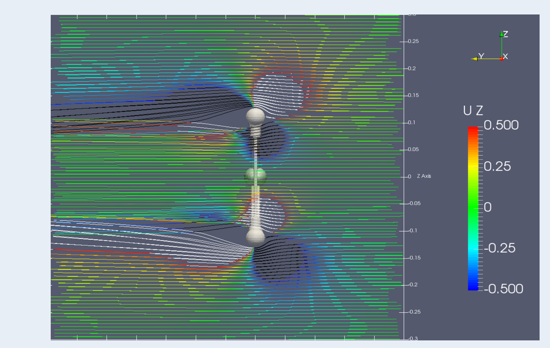
Turbulence model: Large Eddy Simulation, k-omega, SST DES

Model parameters and settings: steady state, incompressible fluid (air v=1.51e^{-5} m^{2}s^{-1})

Boundary conditions: Inlet velocity 10 ms^{-1} , zero gradient pressure, 5% turbulence intensity, no slip velocity, five layers boundary mesh, standard wall function for turbulence effects in boundary layer, outlet at zero gage pressure, solve for outlet velocity and turbulence values

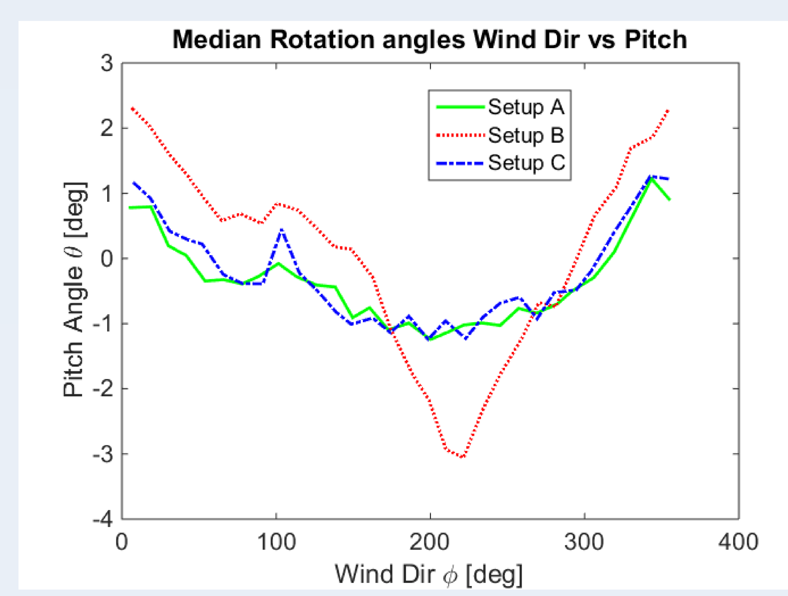


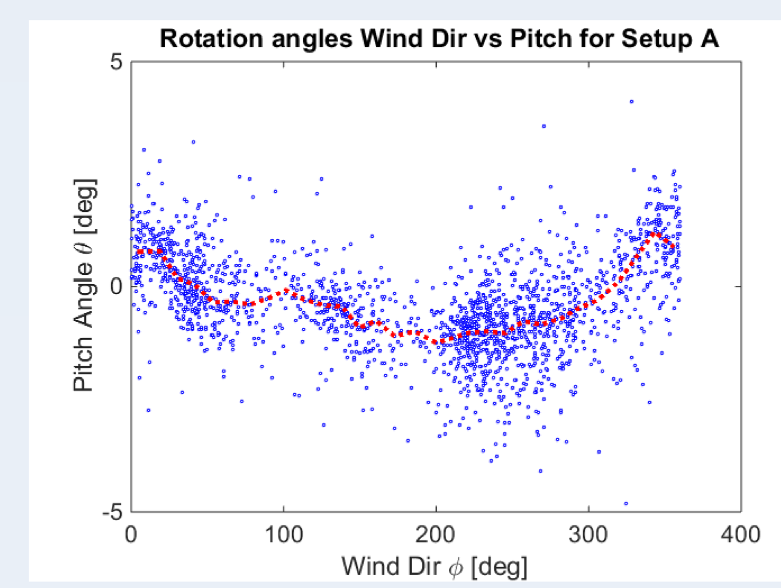


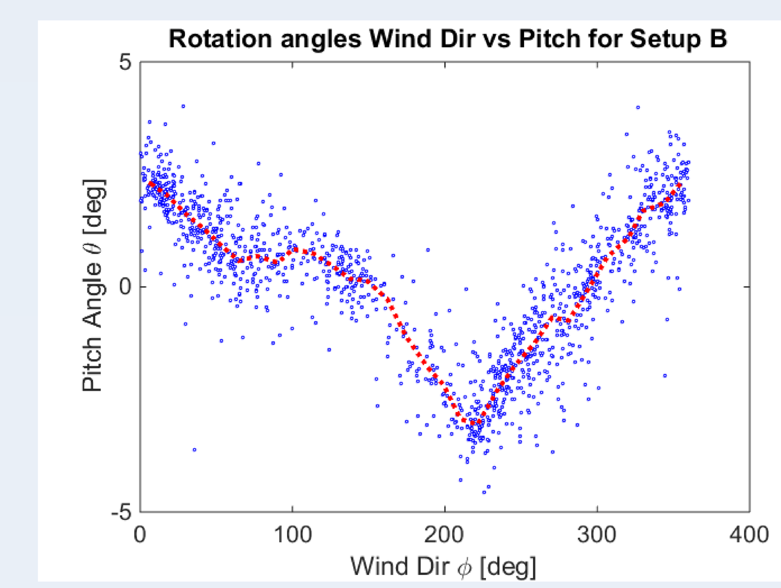


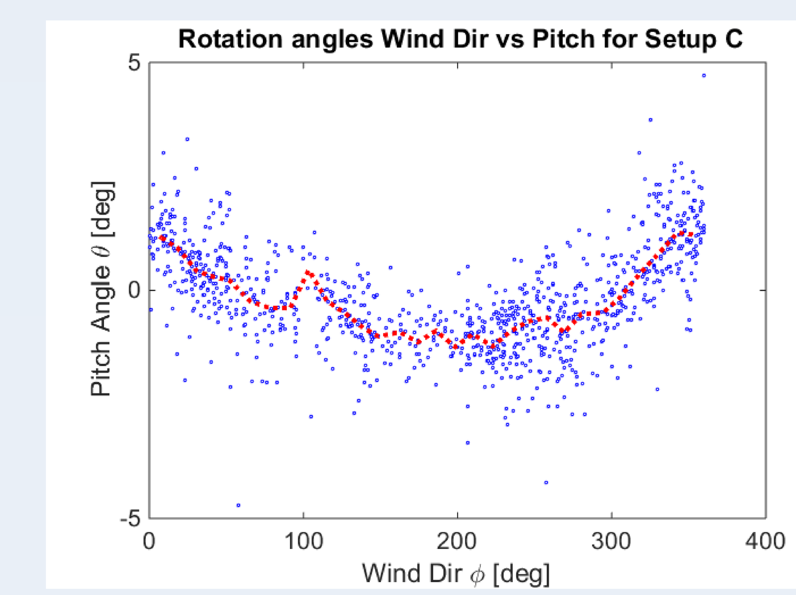
Results

Comparison of scatter plots of wind direction (azimuth) and pitch angles from the double rotation between setup A, B and C are presented below. Changes of rotation angles due to bluff body effects are seen in setup B.





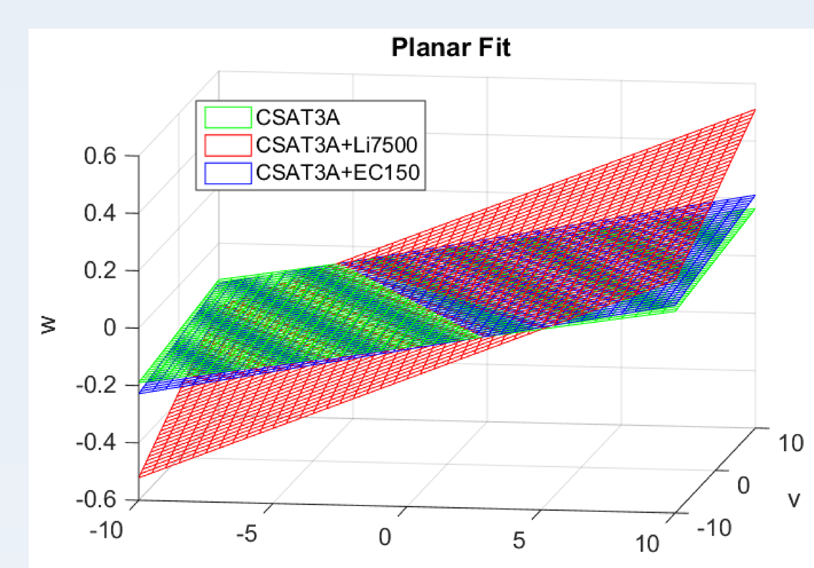




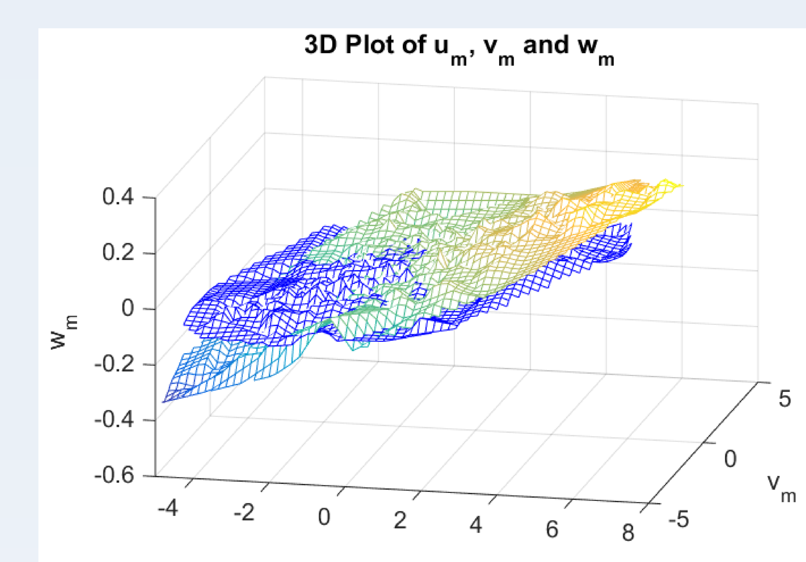
Comparison of planar fit angles for the three setups using the algorithms proposed by Wilczak (2001)

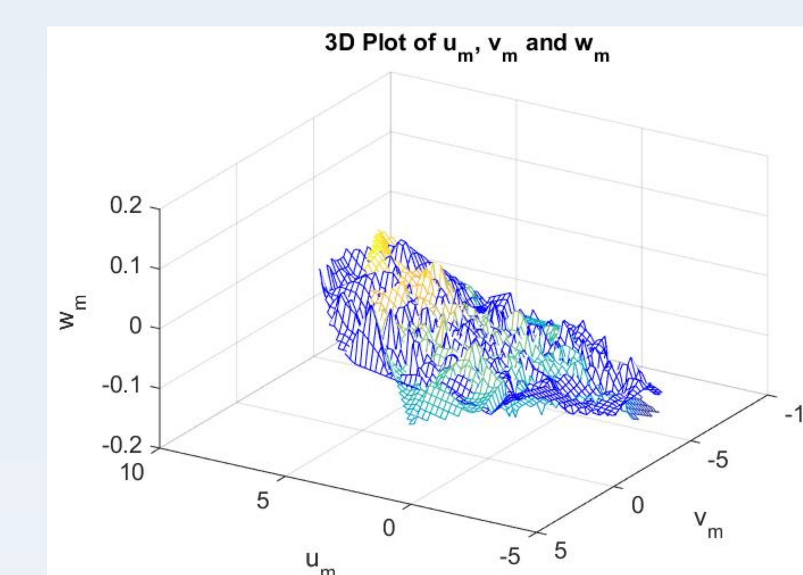
Planar Fit Results: Tilt Angles and Offset			
Setup	α (xy plane)	β (yz plane)	Offset [ms^{-1}]
A	-0.84°	0.18°	-0.012
B	-2.10°	0.86°	-0.006
C	-1.01°	0.25°	-0.008

Results from the planar fit method Wiczak (2001).



Plots of wind vector components in sonic coordinate system for setup A&B (left) and A&C (right).





Conclusions

- Results of our study support the recommendations of Wingaard (1988) and Kaimal (1986) for the need of **vertical symmetry in the design of turbulence sensors.**
- Flow distortion effects caused by turbulence sensors, including open-path gas analyzers, can be minimized by designs with aerodynamic, vertically symmetrical upper and lower housings. Sensors with smaller diameter housings have less stagnation loss and can be mounted closer to the sensing path of the sonic anemometer.
- Analyzers with larger separation distance between the upper and lower housings have less influence on the sonic anemometer measurements, because the housings are further away from the sonic transducer array.
- For open-path gas analyzer and sonic anemometer setups, the planar fit and the double rotation methods can be used to identify potential flow distortion issues associated with the analyzers and the supporting structures.

References

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