How small UAS can be used to investigate complex and turbulent flow structures in the Atmospheric Boundary Layer

EUMeTrain Wind Event Week
04.03.2022

Norman Wildmann
Institute of Atmospheric Physics
DLR Oberpfaffenhofen

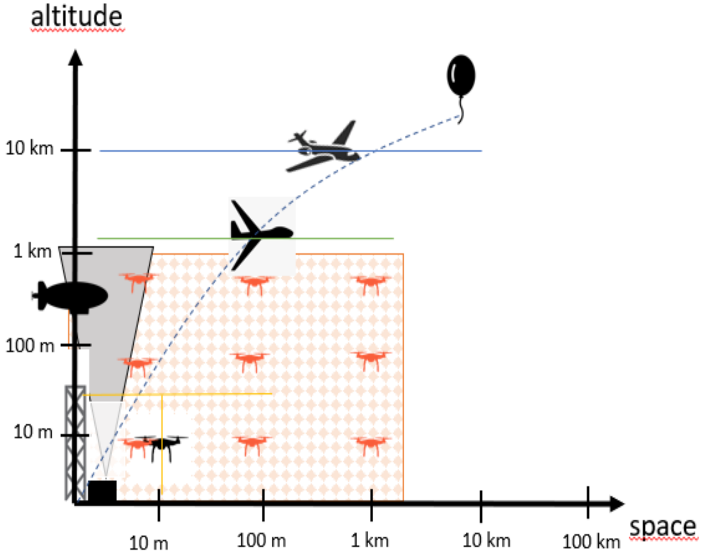
DLR

Content

- Small UAS and their purpose in meteorological observations

- How to measure wind with UAS
  - Fixed-wing UAS
  - Multicopter UAS

- Examples of UAS measurements
  - Complex terrain
  - Wind Energy
  - Distributed measurements



Airborne meteorological measurements

Research aircraft jets
(e.g. DLR Falcon, HALO)

Range,
endurance, flight
height

Small motor aircraft
(e.g. DLR Cessna)

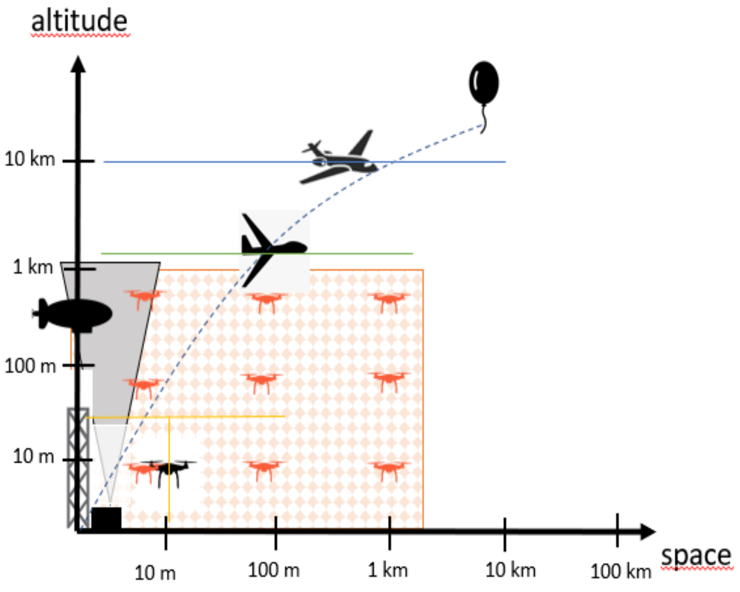
Glider aircraft
(e.g. Stemme S10-VT)

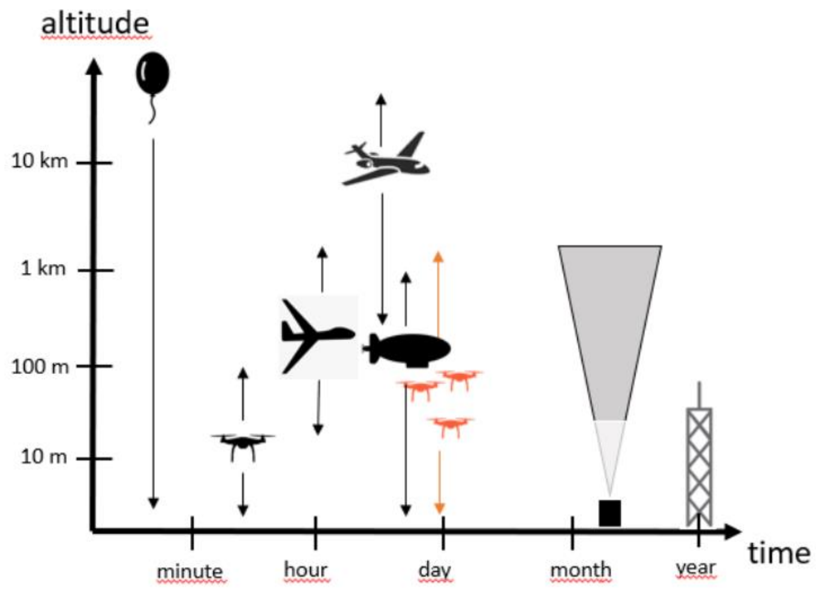
Multicopter
(e.g. SWUF-3D)

Fixed-wing UAS
(e.g. EKUT MASC)

Cost

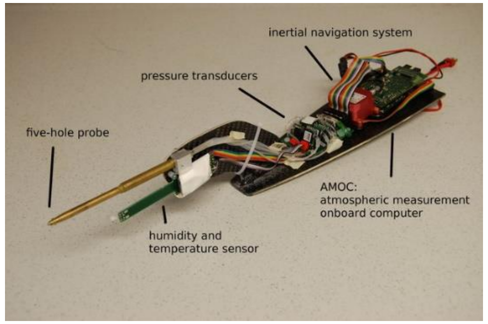
The range and time of meteorological measurements





Wind measurement with fixed-wing UAS

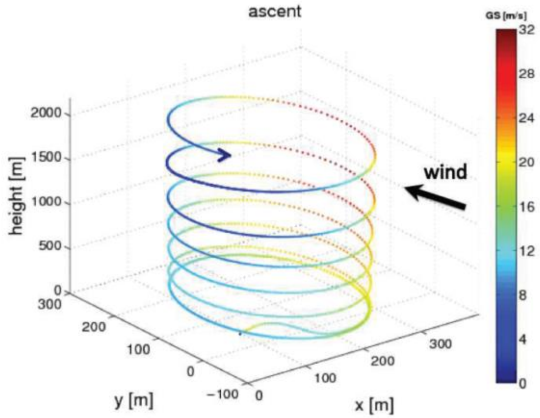
Multi-hole flow probes



Rautenberg et al. 2018,
https://doi.org/10.3390/atmos9110422

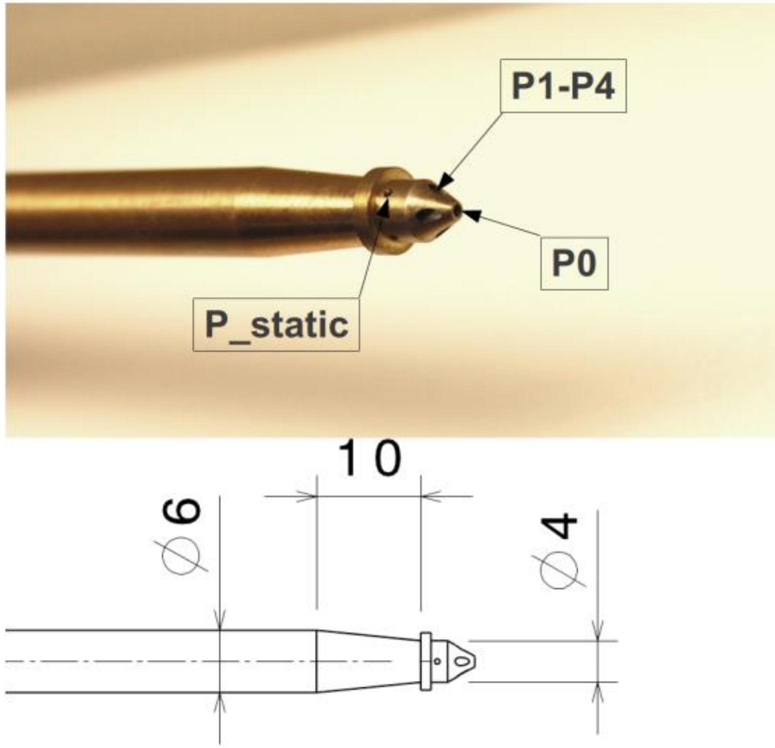
Pitot static probes

No-flow, GPS only



Mayer et al. 2012,
https://doi.org/10.1260/1756-8293.4.1.15

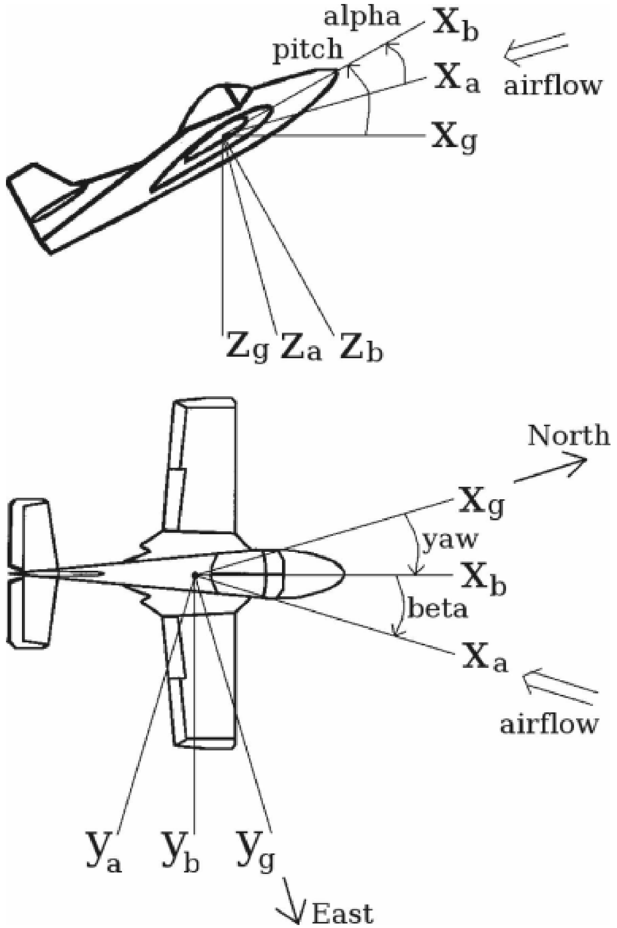
Wind measurement with fixed-wing UAS



$$|\boldsymbol{v}_{\text{tas}}|^2 = 2c_p T_{\text{tot}}\left[1-\left(\frac{p}{p+q}\right)^{\kappa}\right]$$

$$\boldsymbol{v}_{\text{tas}} = -\frac{|\boldsymbol{v}_{\text{tas}}|}{\sqrt{1+\tan^2\alpha+\tan^2\beta}}\begin{pmatrix}1\\ \tan\beta\\ \tan\alpha\end{pmatrix}$$

$$\boldsymbol{v} = \boldsymbol{v}_{\text{gs}} + \mathbf{M}_{\text{mf}}\left(\boldsymbol{v}_{\text{tas}} + \boldsymbol{\Omega}\times\boldsymbol{s}_p\right)$$



Wildmann, N., Ravi, S., and Bange, J.: Towards higher accuracy and better frequency response with standard multi-hole probes in turbulence measurement with remotely piloted aircraft (RPA), Atmos. Meas. Tech., 7, 1027–1041, https://doi.org/10.5194/amt-7-1027-2014 , 2014.

van den Kroonenberg, Aline, Tim Martin, Marco Buschmann, Jens Bange, and Peter Vörsmann. " Measuring the Wind Vector Using the Autonomous Mini Aerial Vehicle M2AV". *Journal of Atmospheric and Oceanic Technology* 25.11 (2008): 1969-1982. https://doi.org/10.1175/2008JTECHA1114.1

Wind measurement with multicopter UAS

Internal avionic data

Wetz et al. 2021,
https://doi.org/10.5194/amt-14-3795-2021

Meteodrone
[from: www.meteomatics.com, 03.03.2022]

External sensors

Molter and Cheng (2020)
http://dx.doi.org/10.1088/1742-6596/1618/3/032049

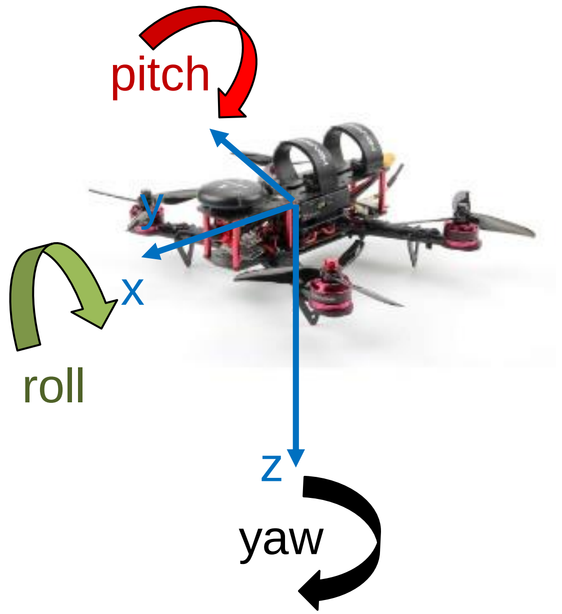
Thielicke et al. 2021,
https://doi.org/10.5194/amt-14-1303-2021

Wind measurement with multicopter UAS

Six degrees of freedom in quadrotor movement

translation $\mathbf{X_b} = [x \quad y \quad z]^T$

rotation $\mathbf{\Phi_i} = [\phi \quad \theta \quad \psi]^T$



Kinematic model for horizontal motion

$$
\begin{aligned}
m(\ddot{x} + q\dot{z} - r\dot{y}) &= -mg[\sin(\theta)] + F_{\mathrm{w,x}} \\
m(\ddot{y} + p\dot{z} - r\dot{x}) &= -mg[\cos(\theta)\sin(\phi)] + F_{\mathrm{w,y}}
\end{aligned}
$$

External forces are wind forces and can be calibrated

$$
\mathbf{V} = \begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} c_x & c_y \end{pmatrix} \begin{pmatrix} F^{b_x}_{\mathrm{w,x}} \\ F^{b_y}_{\mathrm{w,y}} \end{pmatrix} - \begin{pmatrix} \dot{x}_{gps} \\ \dot{y}_{gps} \end{pmatrix}
$$

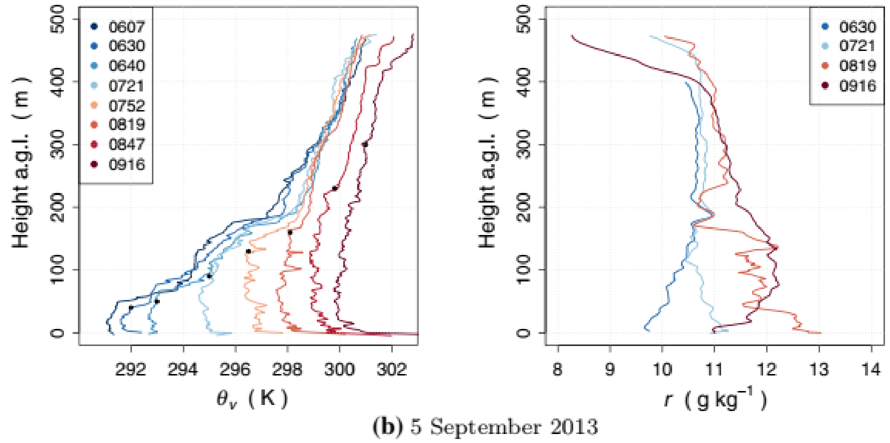
Wetz, T., Wildmann, N., and Beyrich, F.: Distributed wind measurements with multiple quadrotor unmanned aerial vehicles in the atmospheric boundary layer, Atmos. Meas. Tech., 14, 3795–3814, https://doi.org/10.5194/amt-14-3795-2021 , 2021.

Examples of fixed-wing UAS measurements

Fixed-Wing UAS for ABL research

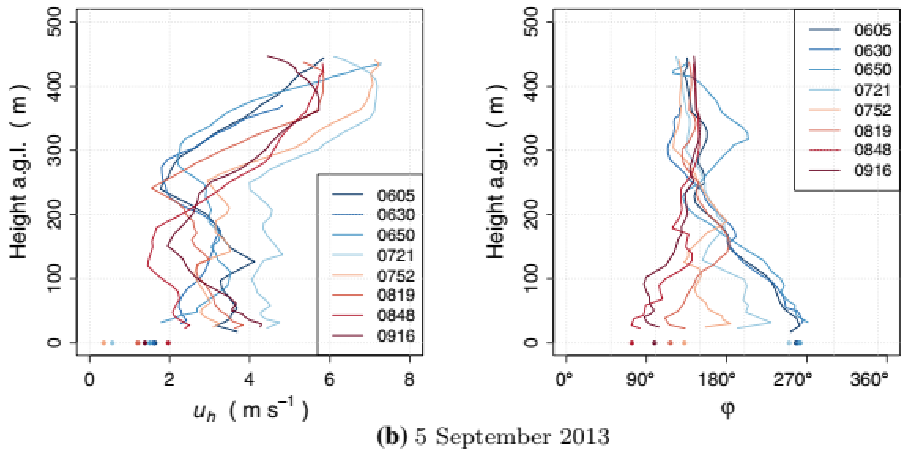
temperature

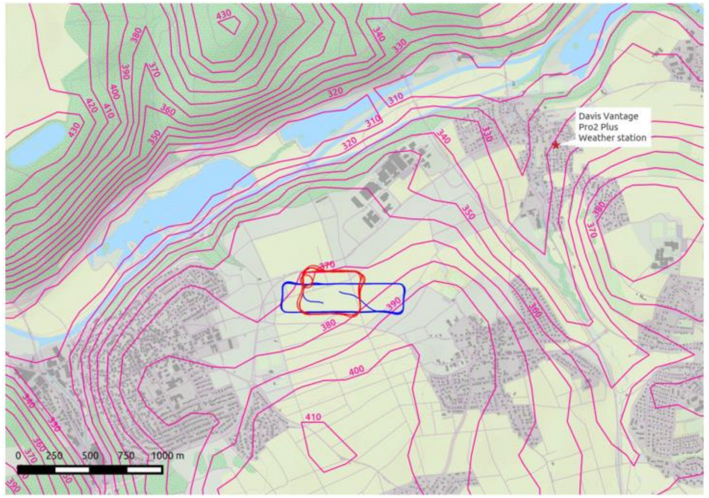
humidity

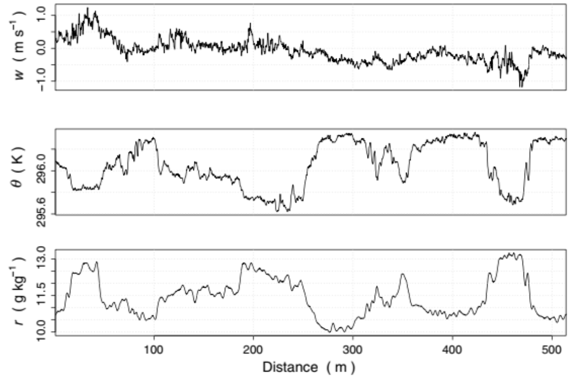


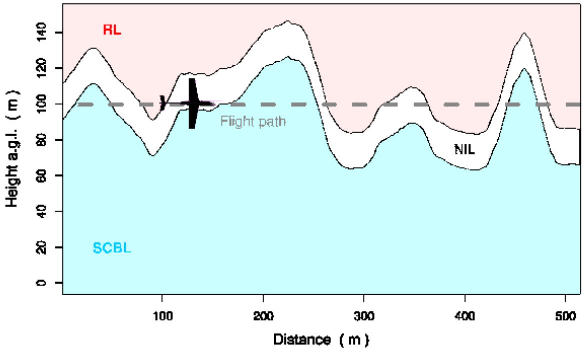
Wind speed

Wind direction



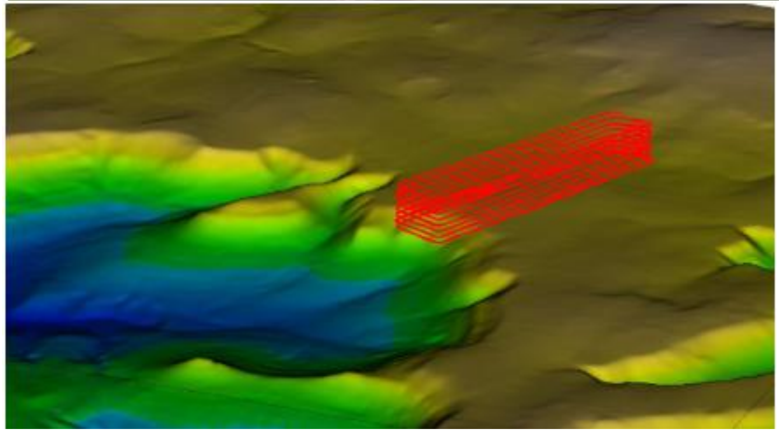


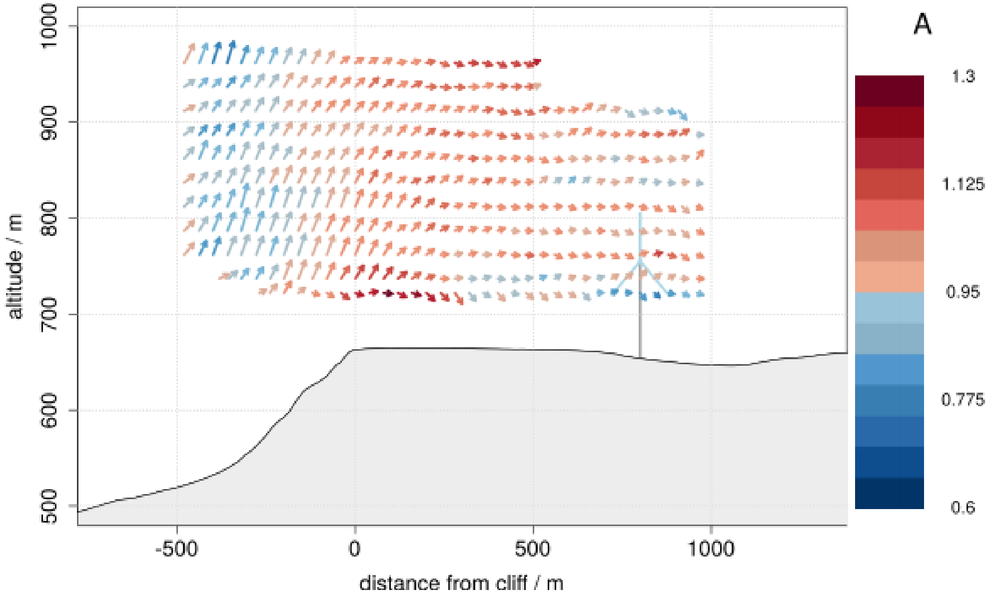


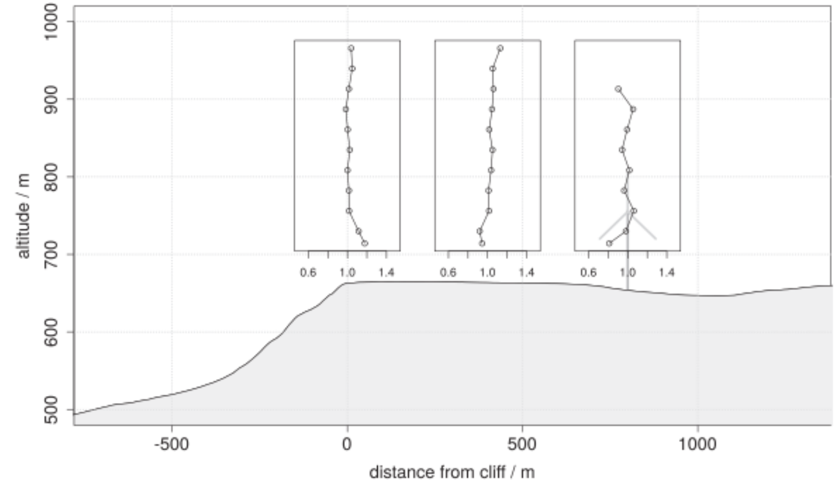


Wildmann, N., Rau, G.A. & Bange, J. Observations of the Early Morning Boundary-Layer Transition with Small Remotely-Piloted Aircraft. *Boundary-Layer Meteorol* **157**, 345–373 (2015). https://doi.org/10.1007/s10546-015-0059-z

Fixed-Wing UAS for Complex Terrain Flow Measurements

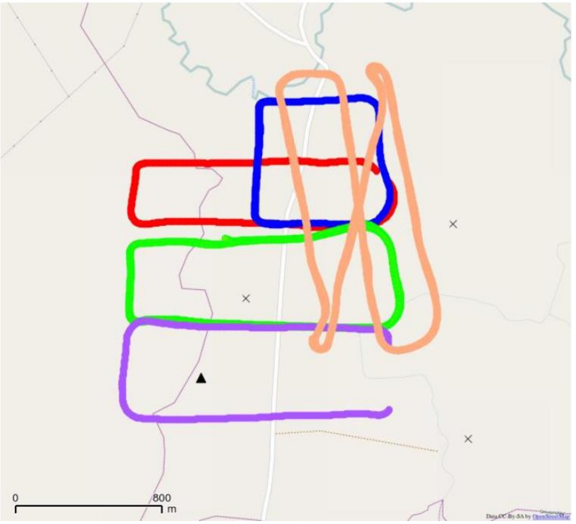


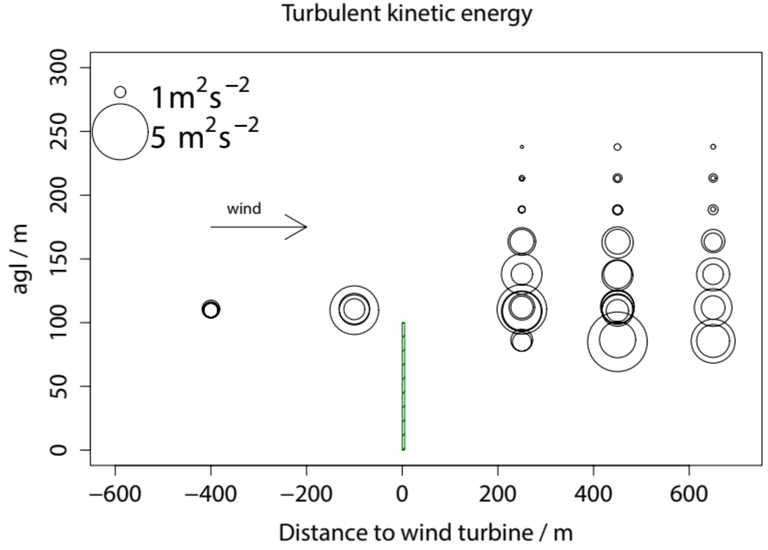


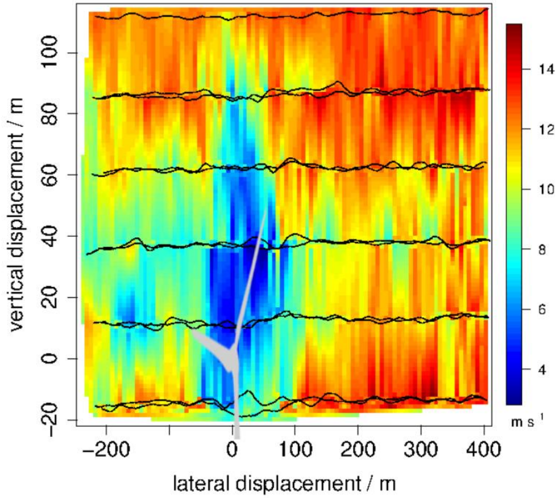


Norman Wildmann, Sarah Bernard, Jens Bange,
Measuring the local wind field at an escarpment using small remotely-piloted aircraft, Renewable Energy, Volume 103, 2017, Pages 613-619, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2016.10.073 .

Fixed-Wing UAS for Wind Energy

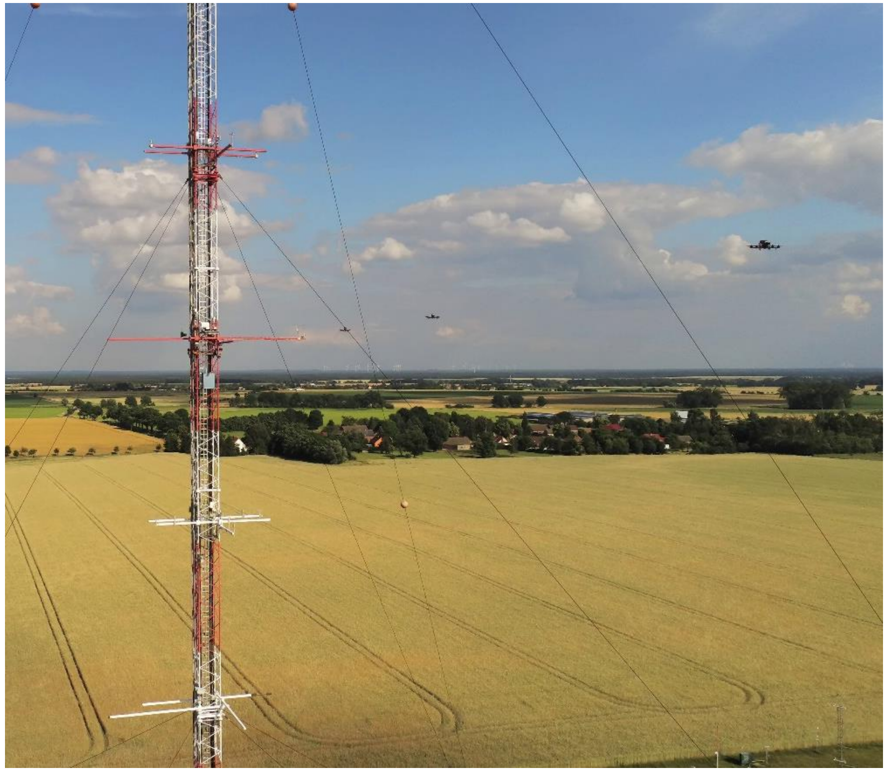






Wildmann, N., Hofsäß, M., Weimer, F., Joos, A., and Bange, J.: MASC – a small Remotely Piloted Aircraft (RPA) for wind energy research, Adv. Sci. Res., 11, 55–61, https://doi.org/10.5194/asr-11-55-2014 , 2014.

Examples of multicopter measurements



2-D Wind algorithm – calibration flights

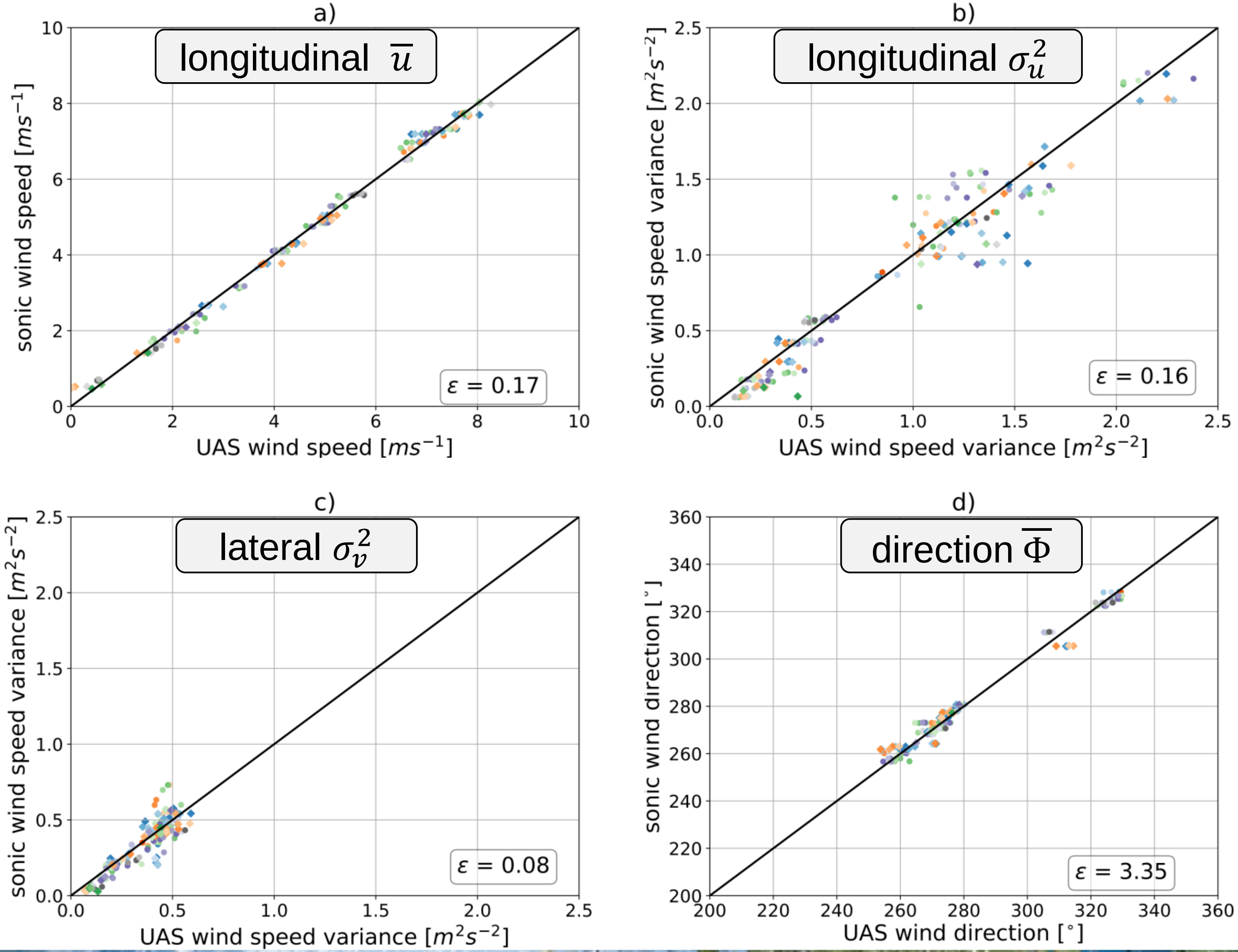
Calbration flights @ DWD MOL-RAO:

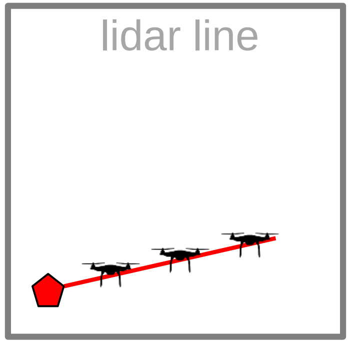
- 99m mast: 50m,90m → sonic
- 185 single flights

New Features:

- lateral wind component
- additional sensor data implemented
- improved calibration
- correction of wind direction

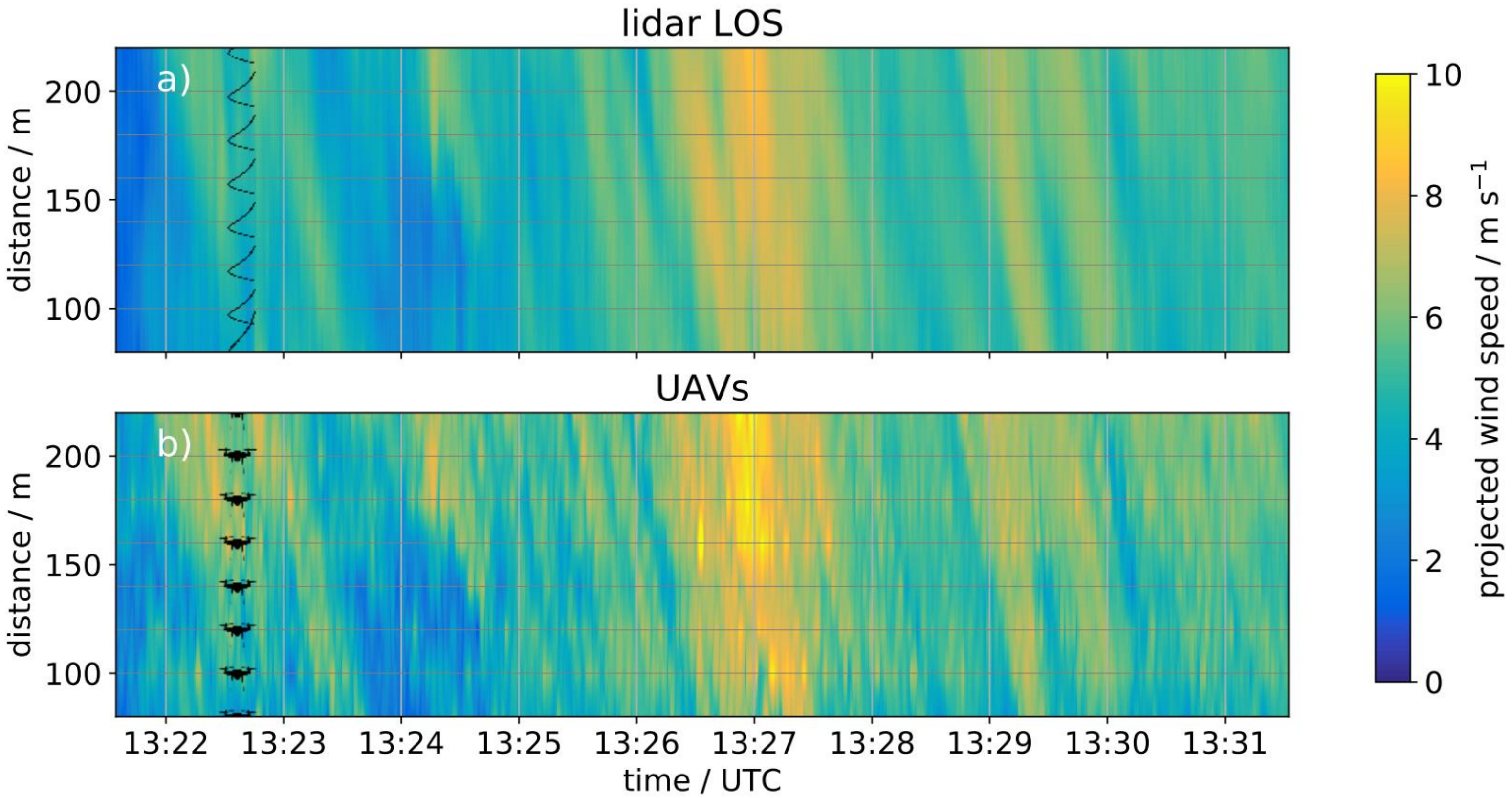
→ improved accuracy of $\overline{u}, \sigma_u^2, \Phi$
→ dynamic behavouir of wind direction





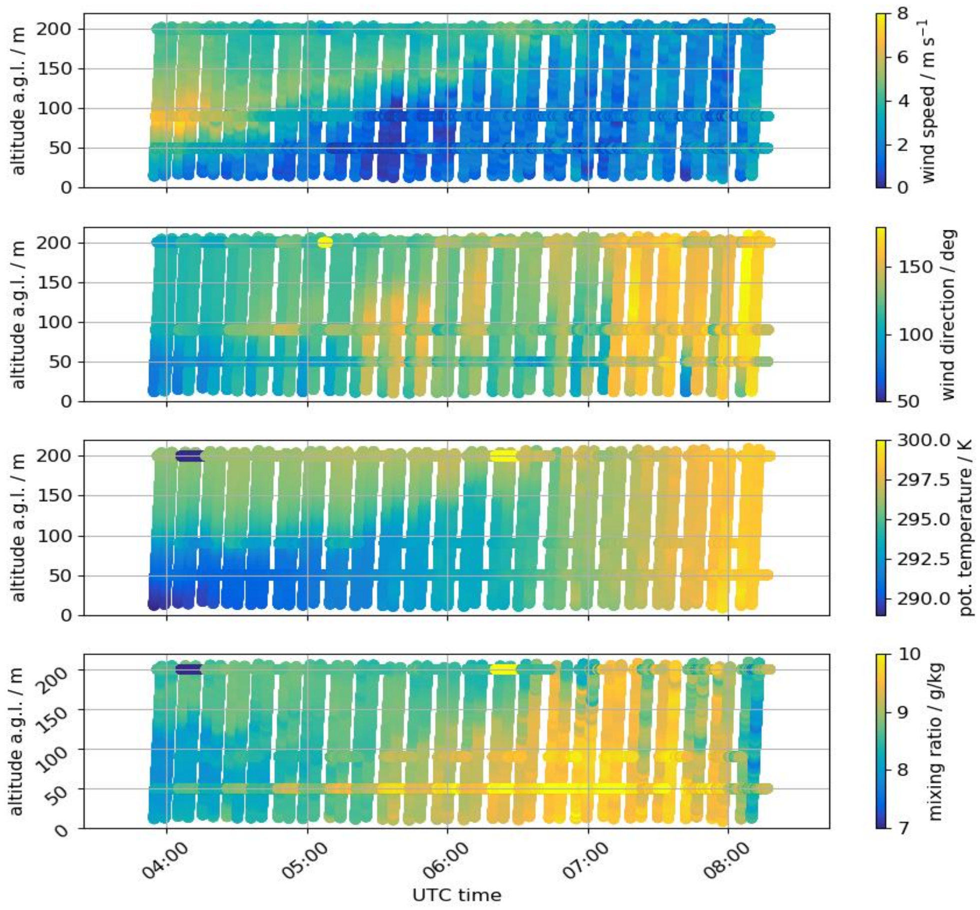
Fleet validation

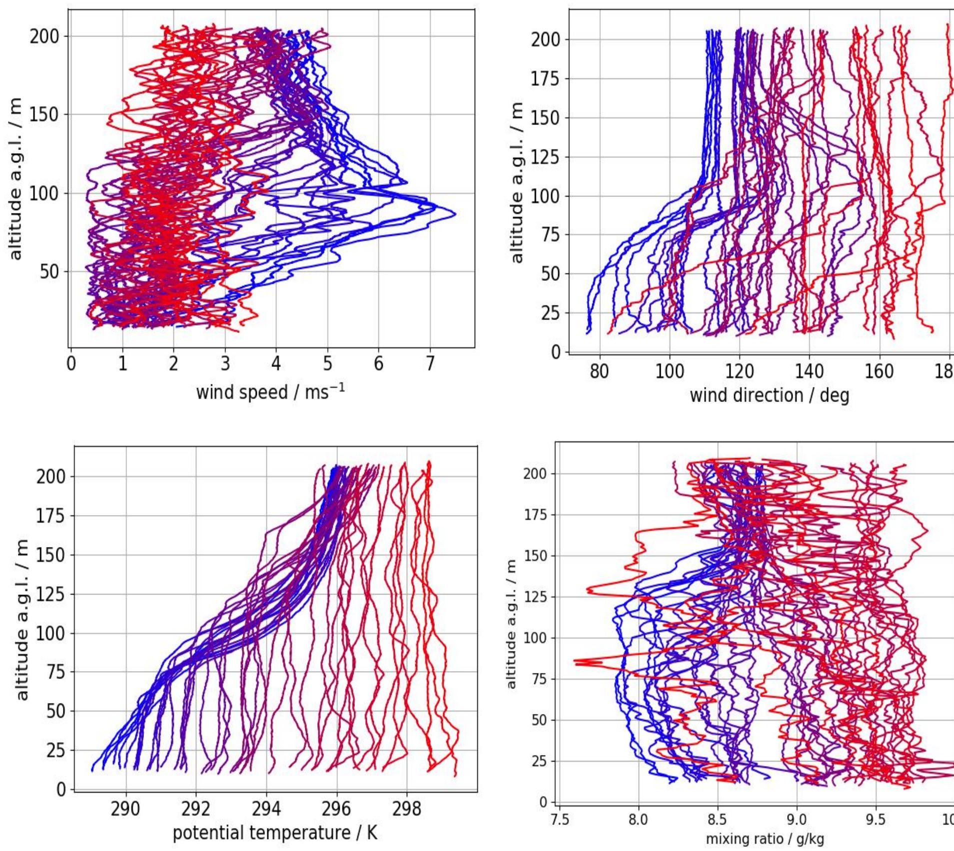
drone vs. lidar - *drone lidar line*



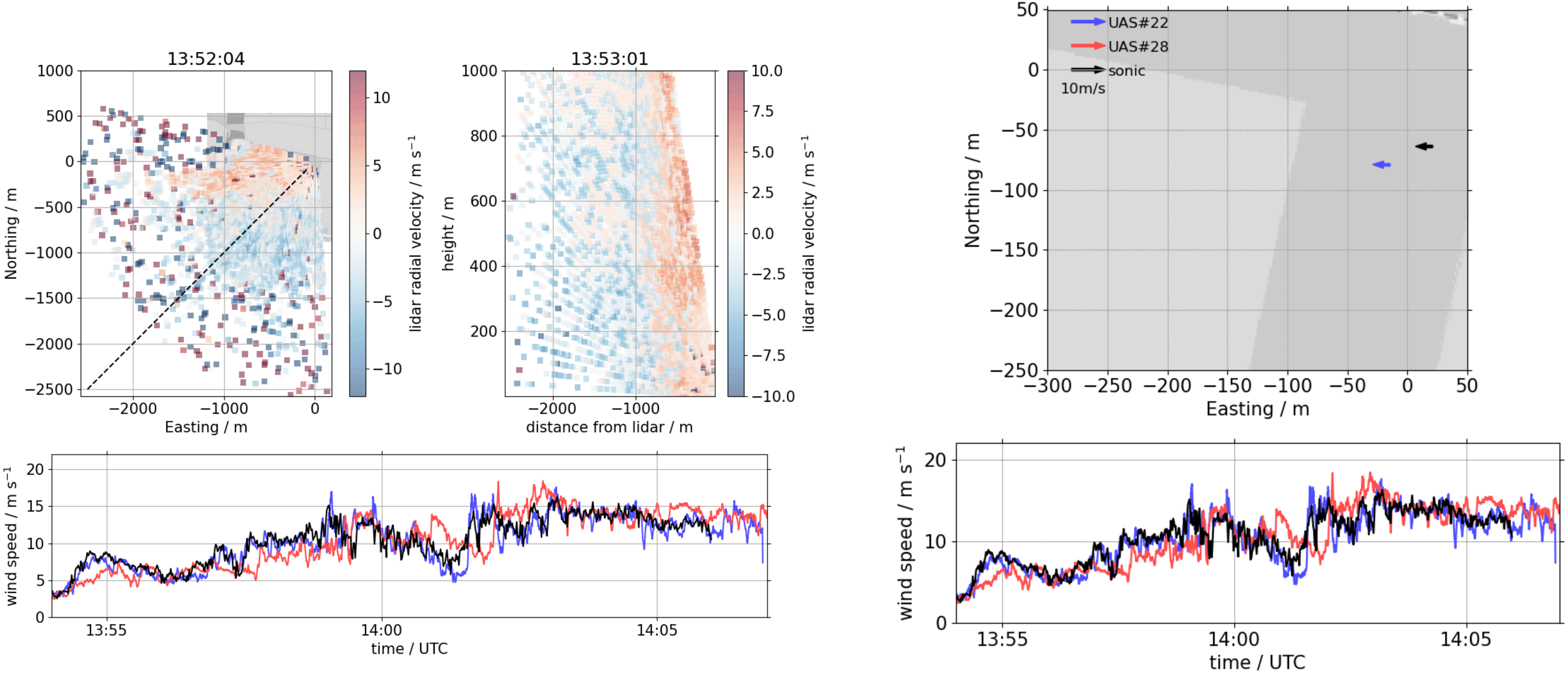
→ Flow structures detected by the lidar can be observed in UAV results

FESSTVaL 2021, 28.06.2021, Morning transition





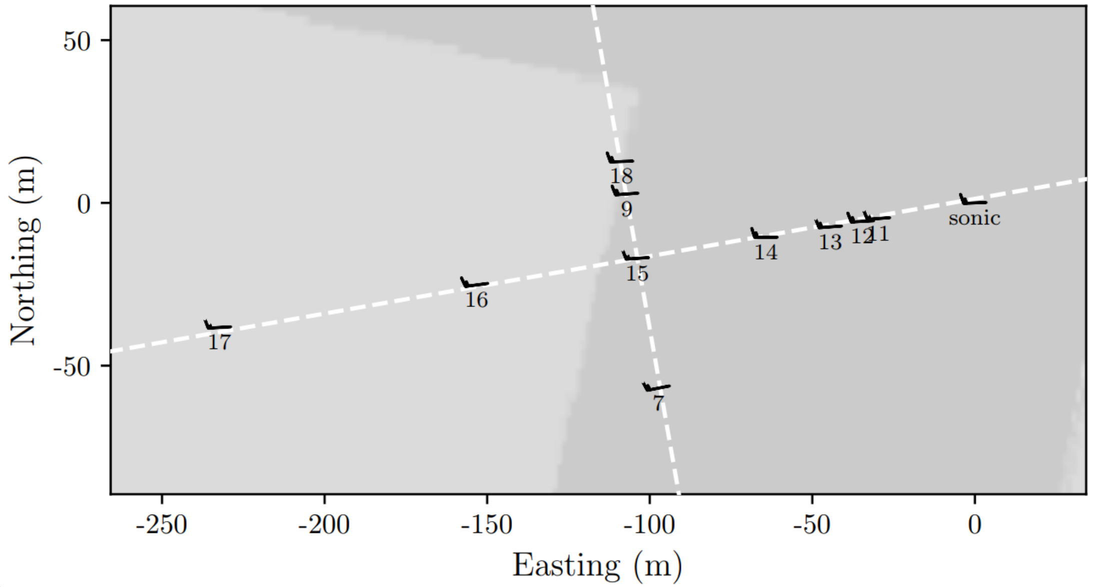
FESSTVaL campaign, MOL-RAO, 29.06.2021, Coldpool „Jogi“

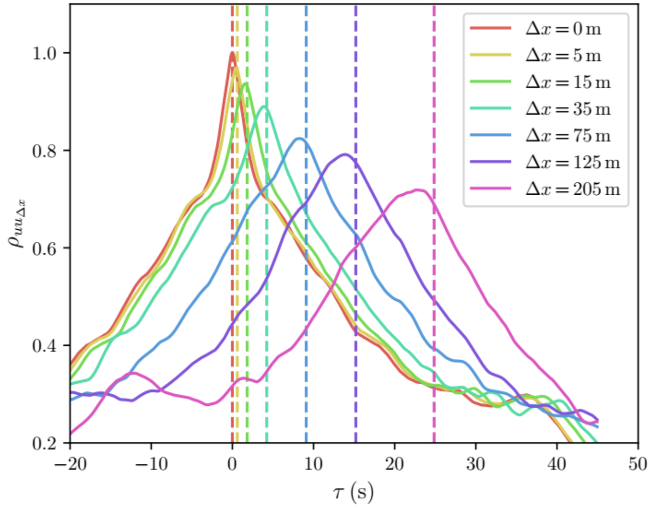


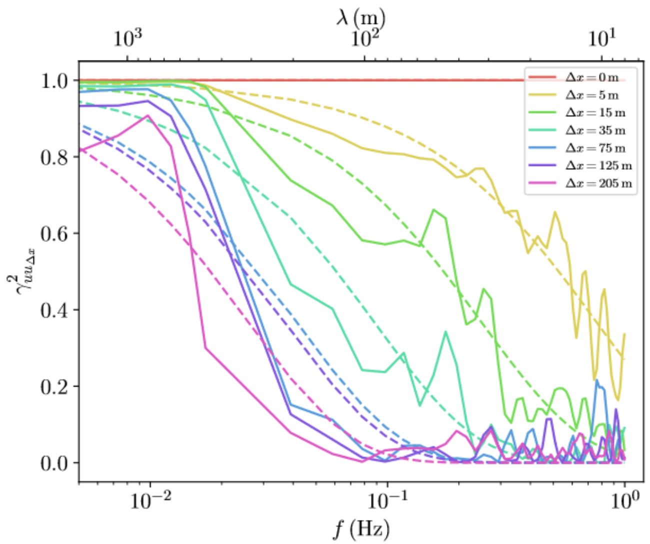
Analysis of spatial turbulence structure on the microscale

- Horizontal flight pattern allows spatially distributed measurements

- Cross-correlation and coherence can be studied for multiple separation distances in lateral and longitudinal direction







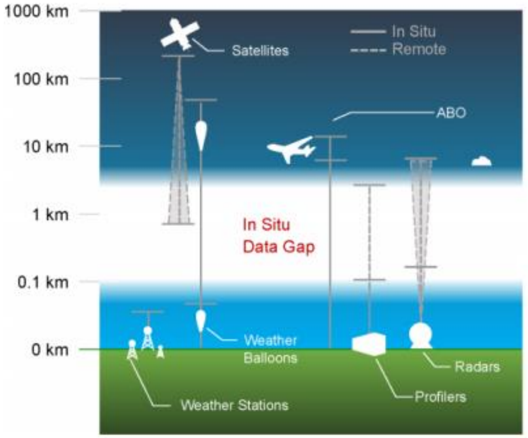
DLR

The future in operational UAS measurements?

Workshop & BAMS Paper – Requirements & Gaps

Requirement & Capability 1 - Higher resolution observations of winds and thermodynamic properties in the lower atmosphere.

*Profiles of wind, temperature, and moisture should extend to **3 km** AGL, and that for the prediction of convection initiation, a time resolution of **15 min**, a vertical resolution of 30 m close to the surface degrading to 100 m at 3 km, a horizontal resolution, **10 km**, and a bias, 5%"* - Profiling Workshop Report to the U.S. National Science Foundation and the National Weather Service



Requirement & Capability 2 – Contribution to provision of soundings from lower stratosphere through to the ground, particularly over oceanic areas.

From BAMS paper, Q1 2021

WMO OMM

World Meteorological Organization

Uncrewed Aircraft Systems

Demonstration Campaign

August 2023 - August 2024

Pinto, J. O. et al.. (2021). The Status and Future of Small Uncrewed Aircraft Systems (UAS) in Operational Meteorology. *Bulletin of the American Meteorological Society* 102, 11, E2121-E2136, https://doi.org/10.1175/BAMS-D-20-0138.1

Thank you for your attention.