Investigation of the flow in complex terrain with regard to wind-energy research using the small remotely piloted aircraft MASC

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MASC: Multi-purpose Airborne Sensor Carrier

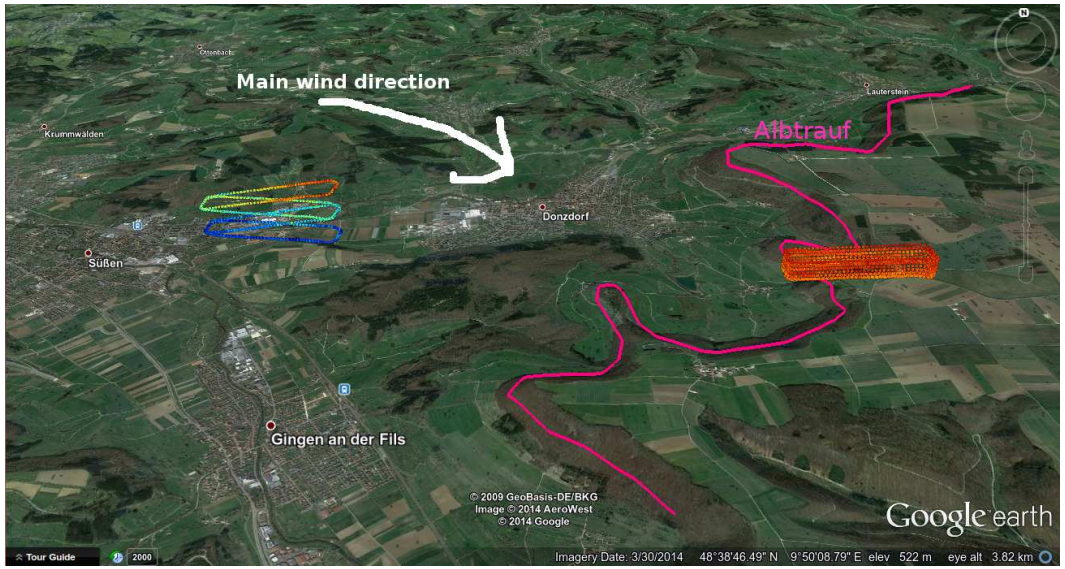
wingspan:	2.7...3.5 m
total weight:	$<$ 6 kg
incl. sci. payload:	1.5 kg
cruising speed:	25 m/s
endurance:	$\approx$ 1 hour
electrical engine	
autopilot:	Uni Stuttgart

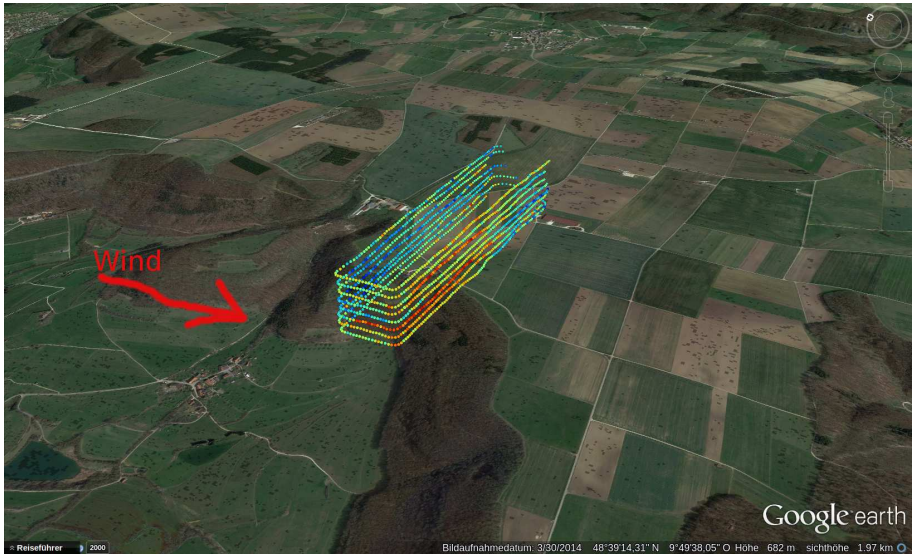
Turbulence measurements:

- 3D wind vector (30 Hz)
- air temperature (30 Hz)
- water vapour (5 Hz)
- data link to ground station

Lidar Complex And KonTest. WindForS Projects

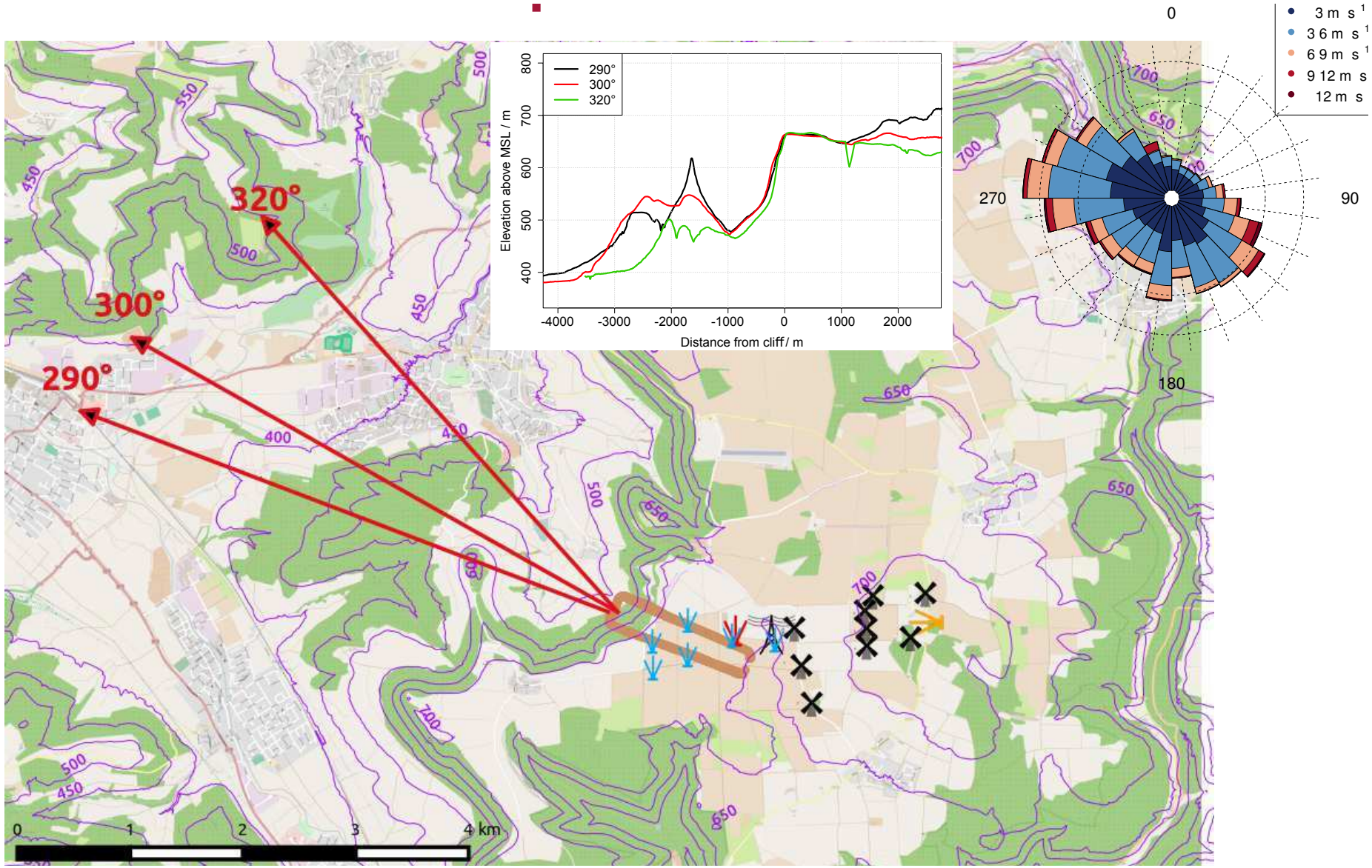
- Conceptual design of a test field for wind energy in complex terrain
- Measuring the wind field and turbulence using RPA in combination with LiDAR and towers
- Calculation of turbulence intensity, shear, fluxes
- Characterization of potential locations for wind turbines



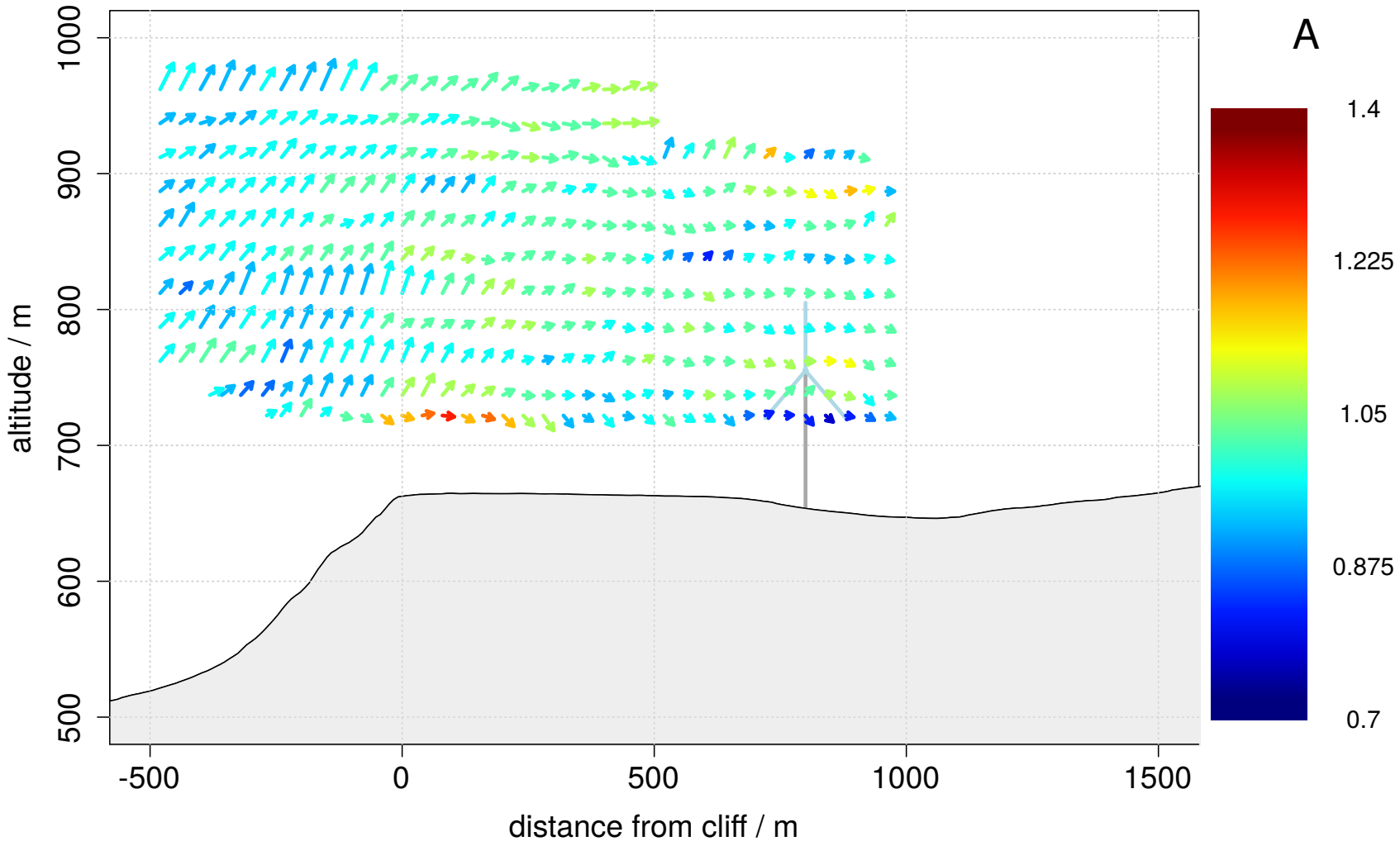


- Focus is on the **flow over the escarpment**
  → Racetracks from 75 m to 300 m in vertical steps of 25 m

Terrain with evaluated wind direction

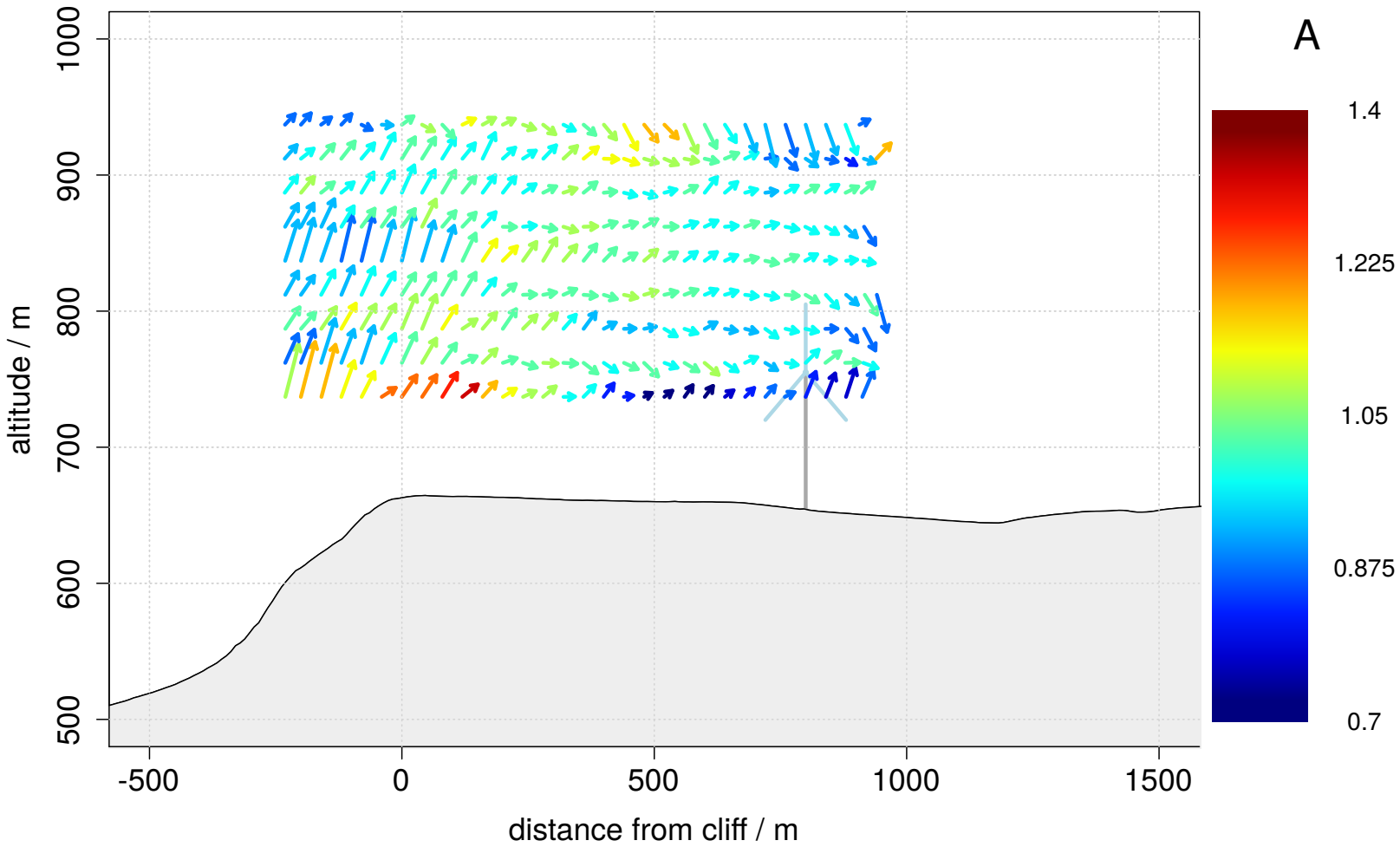


Average of 11 flights with wind direction 290°



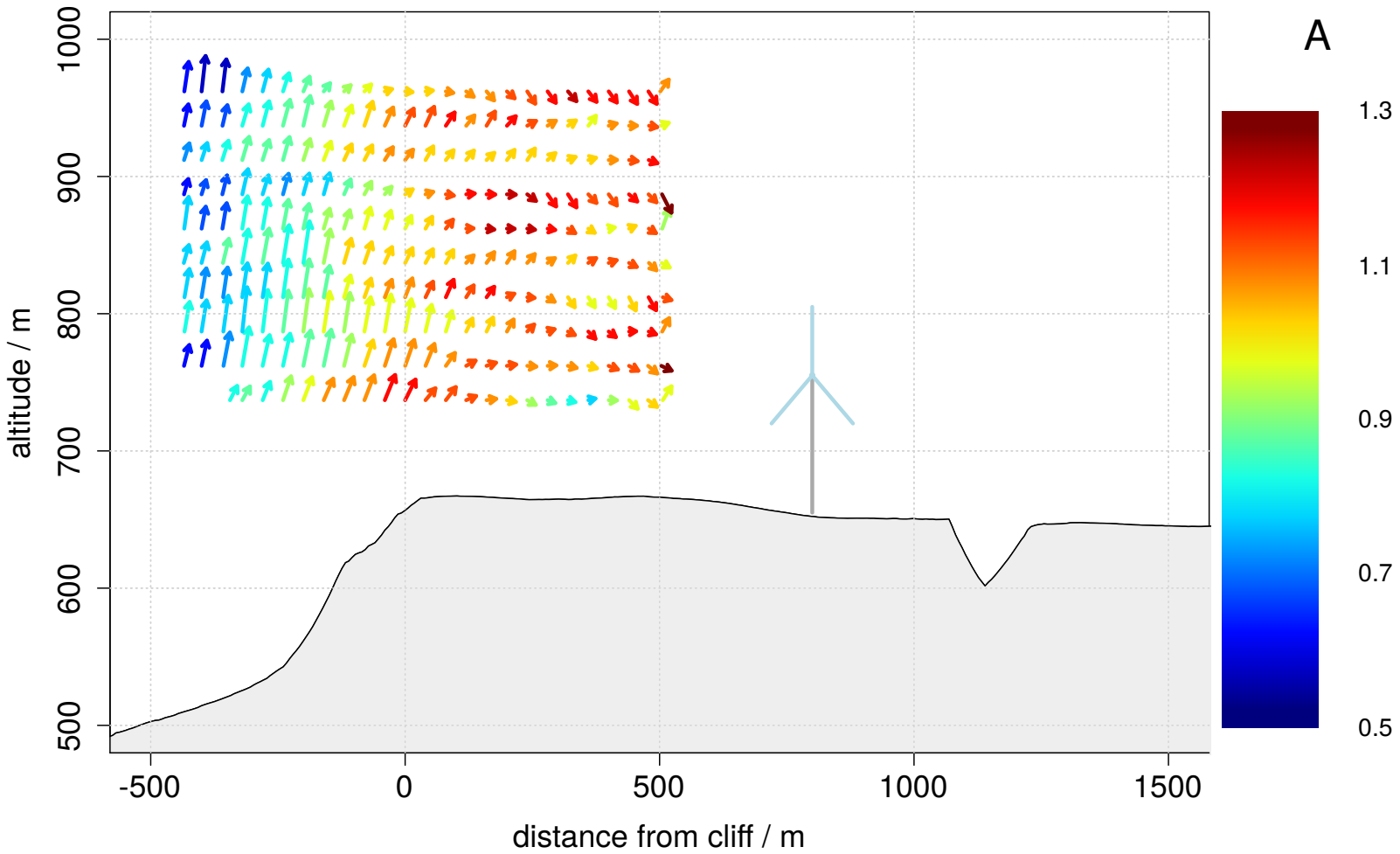
Average of **11** flights on 27 March, 5 May and 7 May.
Color code: Normalized horizontal wind speed. Wind speeds 5-9 m/s.
Strong updrafts over the edge up to 5 m/s. Acceleration of the flow up to 40 %.

Average of 3 flights with wind direction 300°



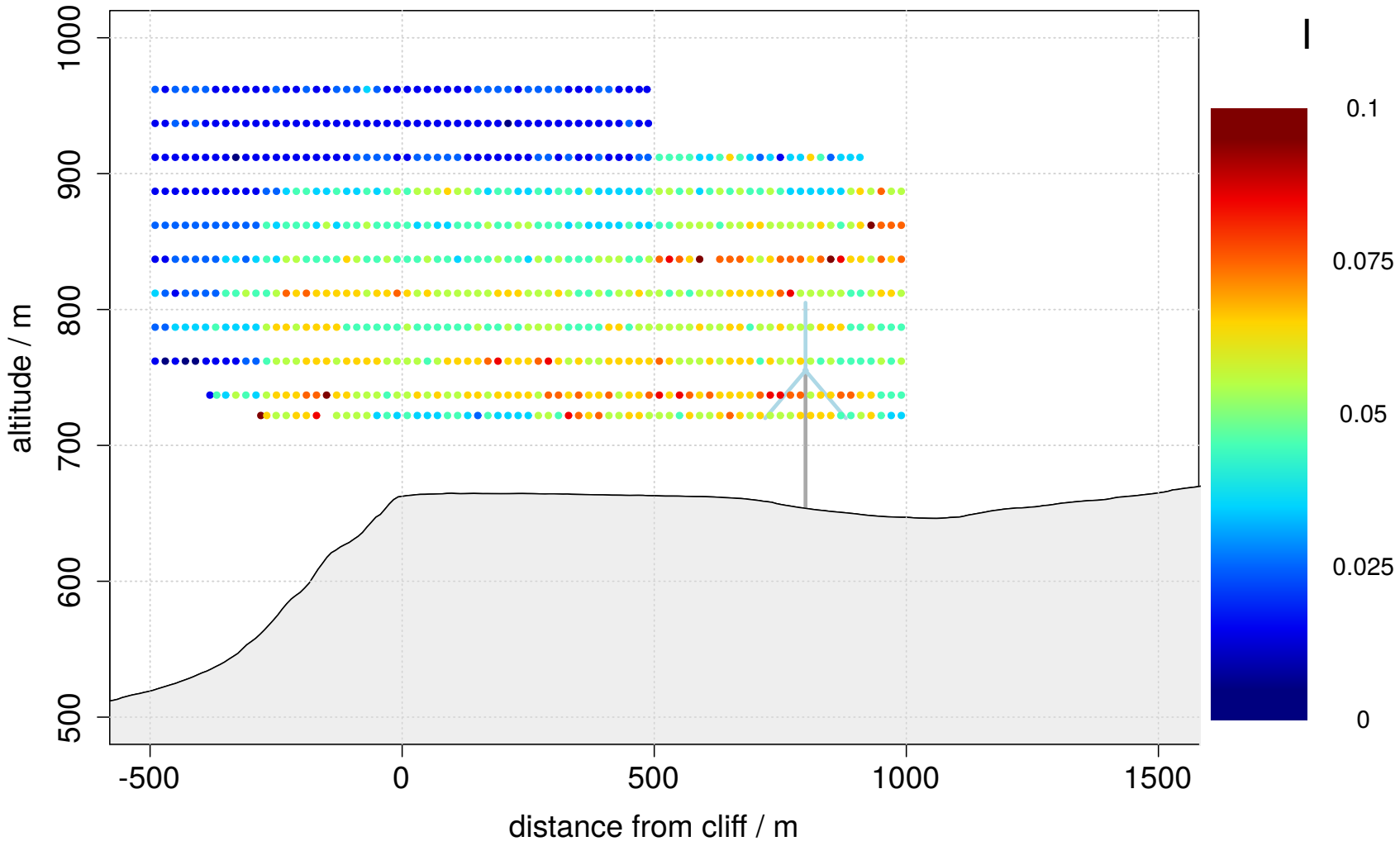
Average of **3** flights on 22 April.
Color code: Normalized horizontal wind speed. Wind speeds ≈7 m/s.
Pronounced updraft region. Low wind speeds 500 m downstream of the escarpment at 75 m a.g.l.

Average of 4 flights with wind direction 320°



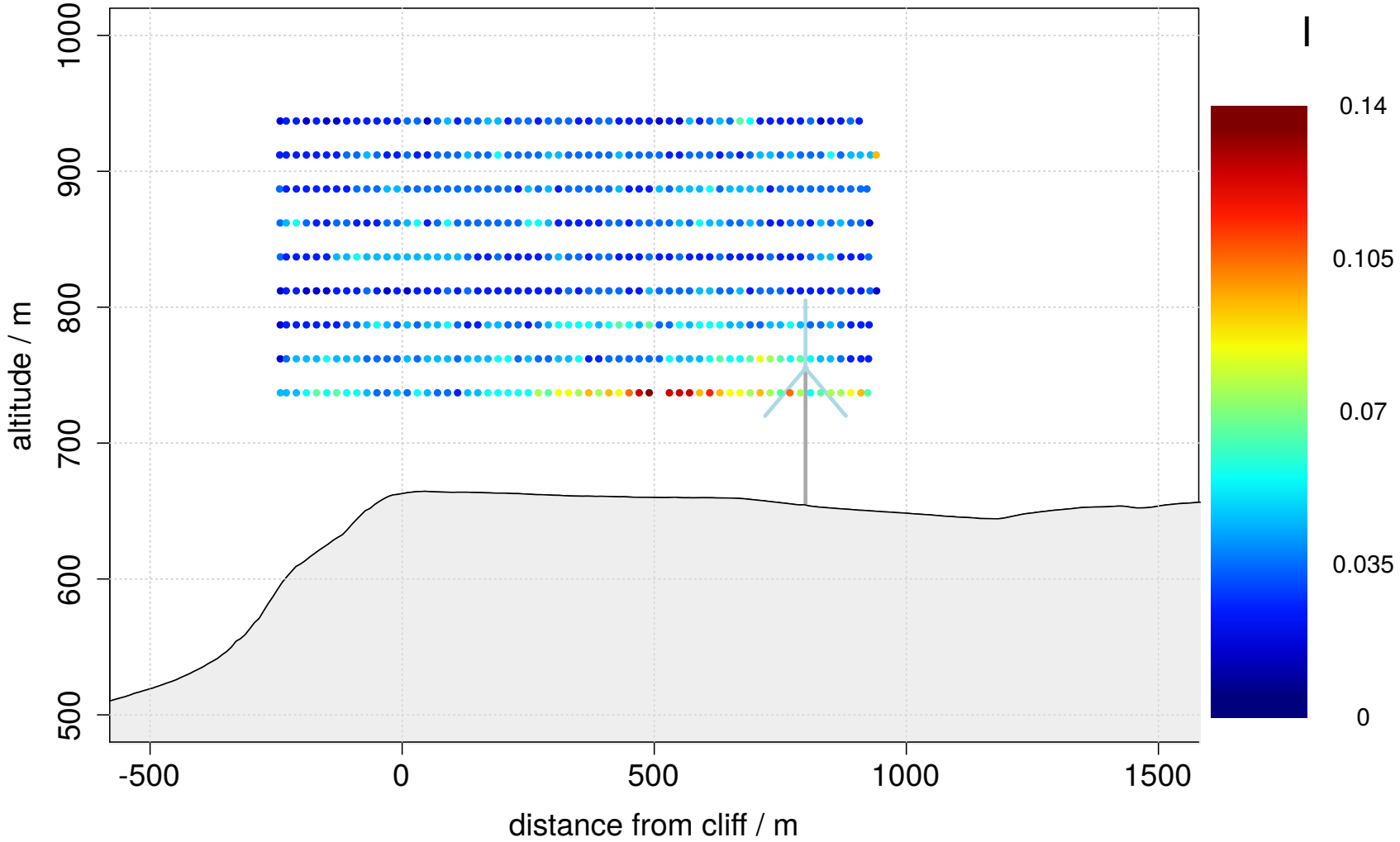
Average of **4** flights on 5 March.
Color code: Normalized horizontal wind speed. Wind speeds ≈5 m/s.
Most pronounced updraft region. Region of low wind speeds 350 m downstream of the escarpment.

Average of 11 flights with wind direction 290°



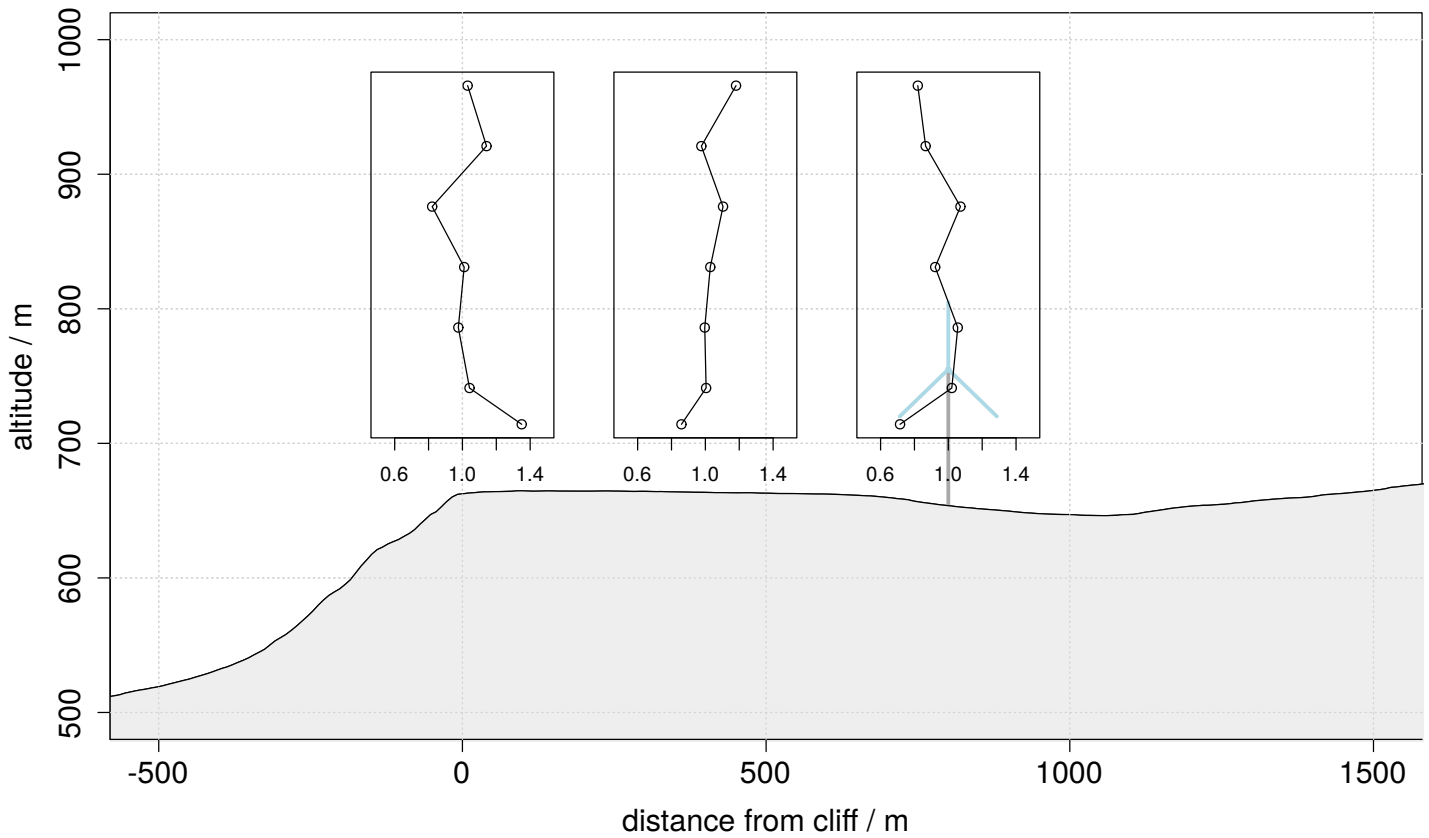
Average of **11** flights on 27 March, 5 May and 7 May.
Color code: Turbulence intensity with 50 m window.
Increased I downstream of the escarpment.

Average of 3 flights with wind direction 300°



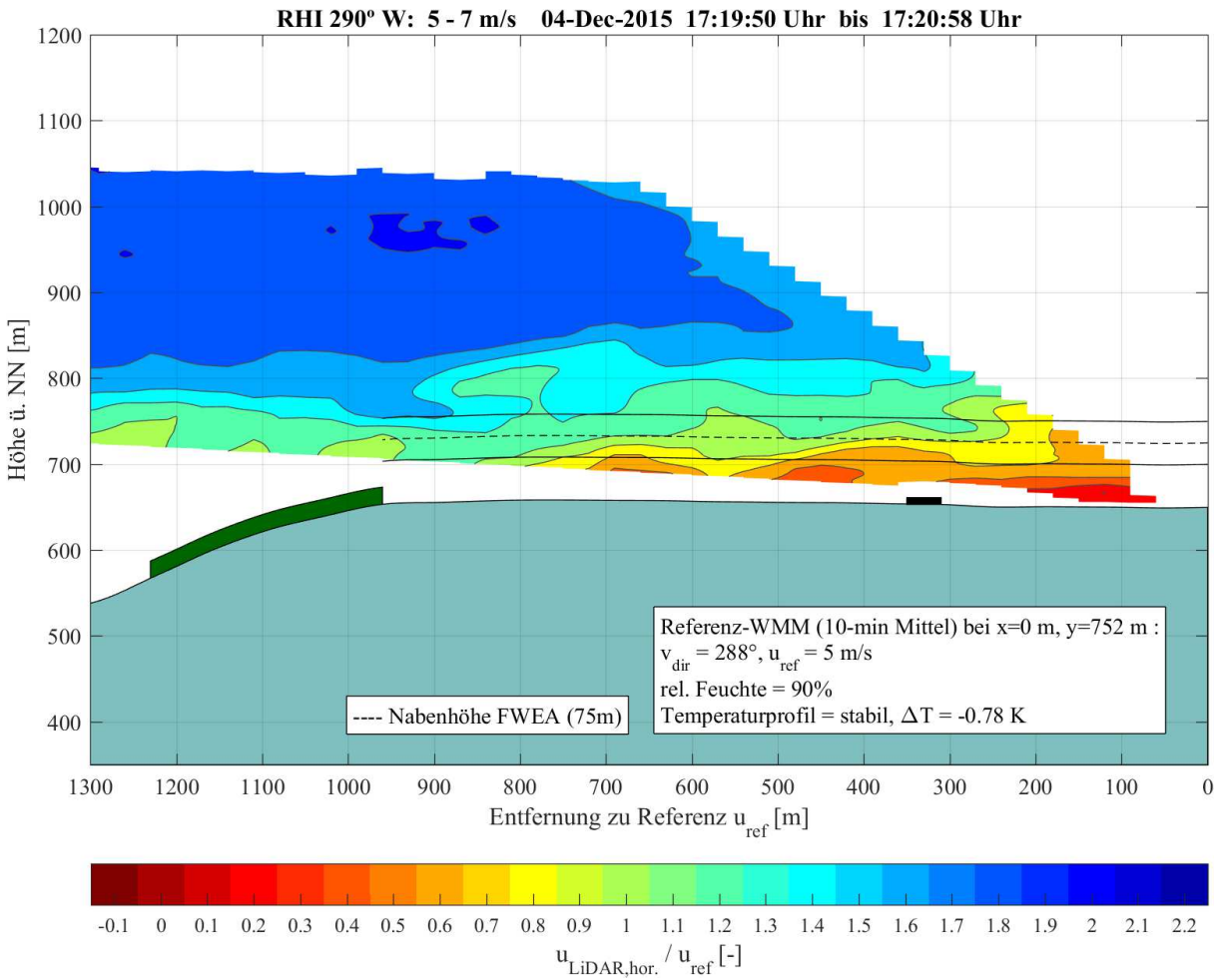
Average of **3** flights on 22 April.
Color code: Turbulence intensity with 50 m window.
Increased I especially in the region of low horizontal wind speed.

Average of 11 flights with wind direction 290°



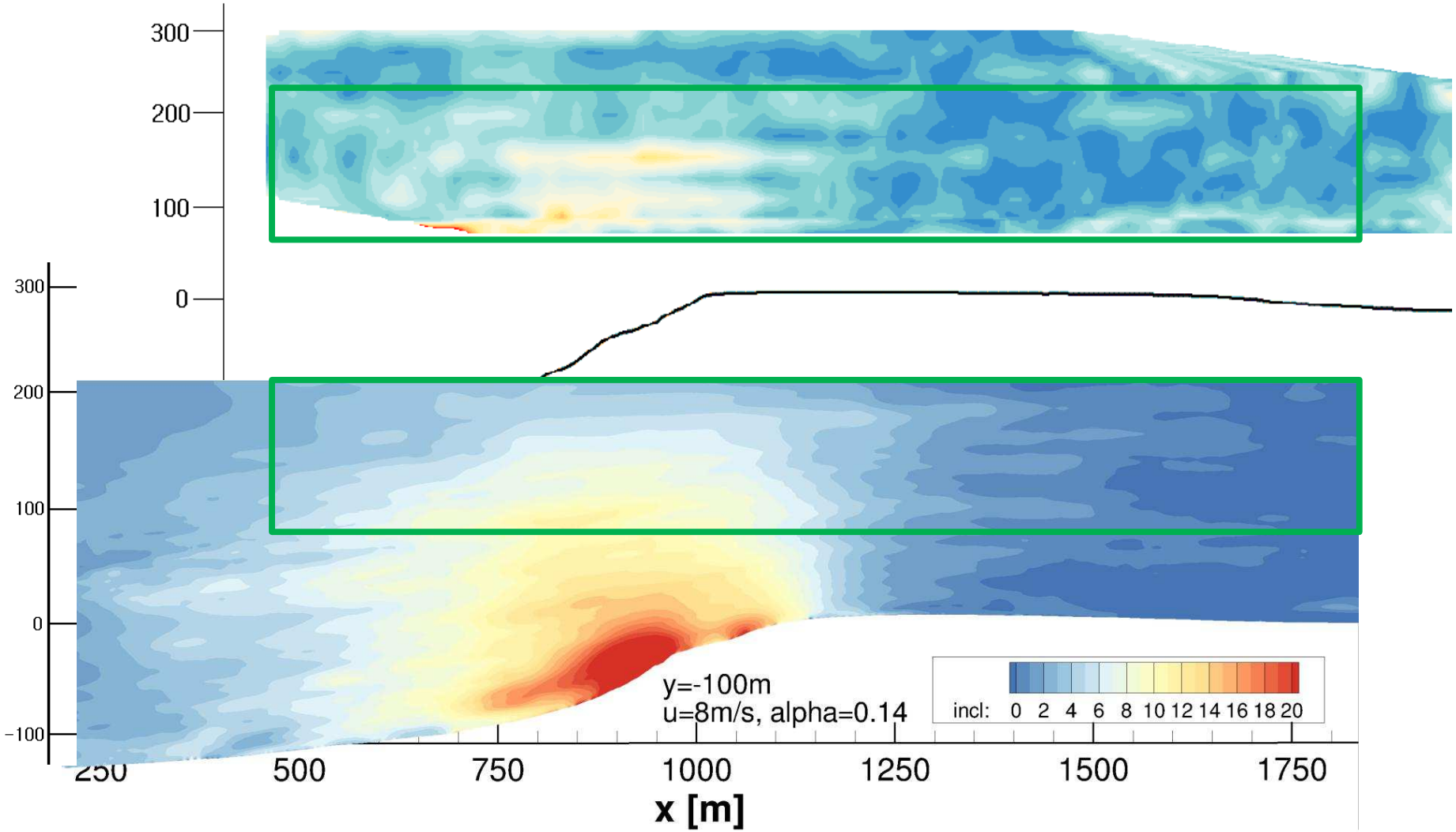
Average of **11** flights on 27 March, 5 May and 7 May.
The vertical profile of horizontal wind speed differs, depending on the position.

Comparing the wind array with LongRange-LiDAR measurements

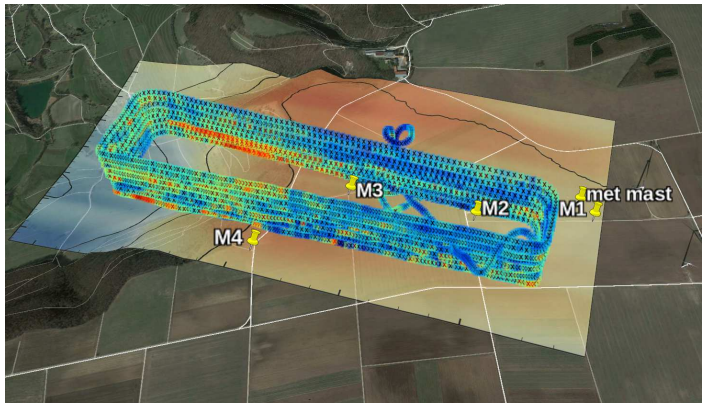


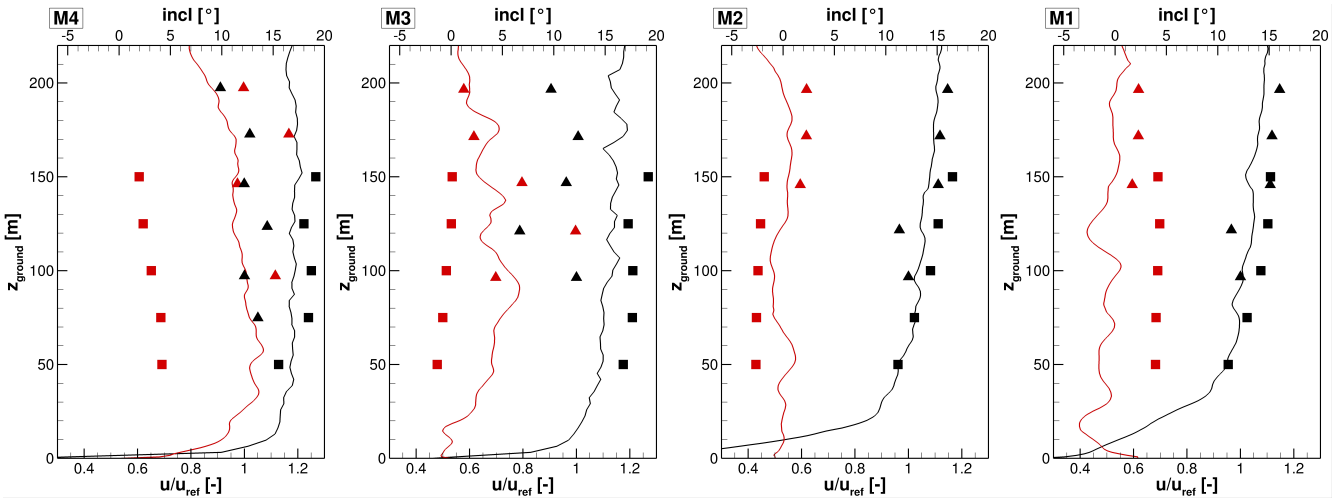
- LongRange-LiDAR Galion
- Ranges up to 4 km
- RHI-Scan (RHI - Range Height Indicator)
- Simultaneous measurement every 30 m along the laser beam
- Normalized with met mast data at 100m height

Comparing the inclination angle with DES-simulation



Height profiles of UAV, LiDAR and DES-simulation

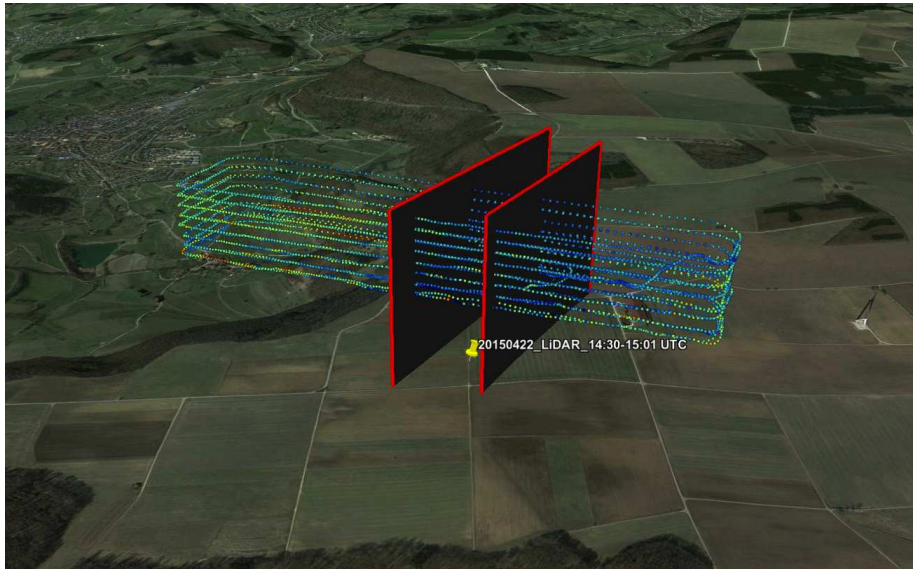


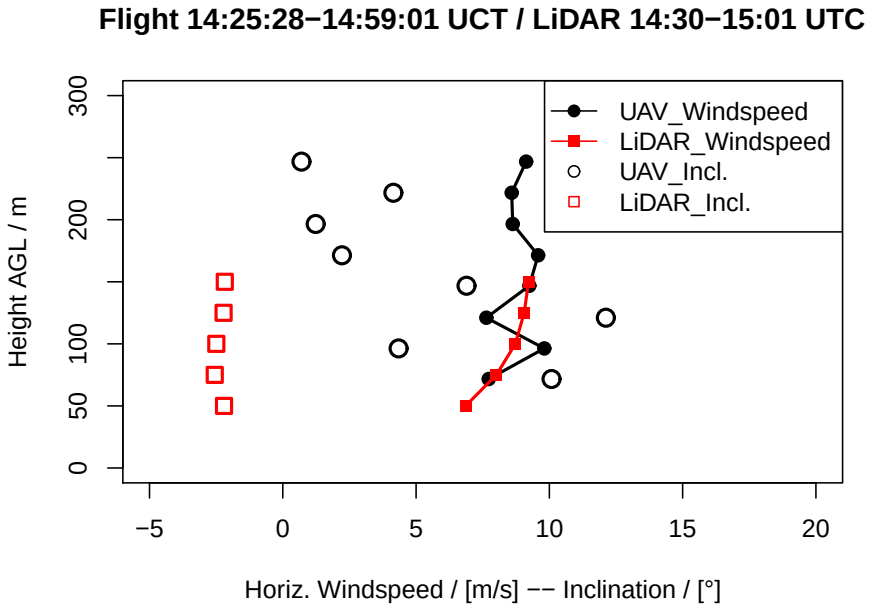


(a) Postion M4 (b) Postion M3 (c) Postion M2 (d) Postion M1

Figure 2: Normalized wind speed of measurements (LiDAR ◆, UAV ▲) and simulation (—) at different positions at the test site. Relative velocity in black and inclination angle — the angle of the f ow against the horizontal plane — in red.

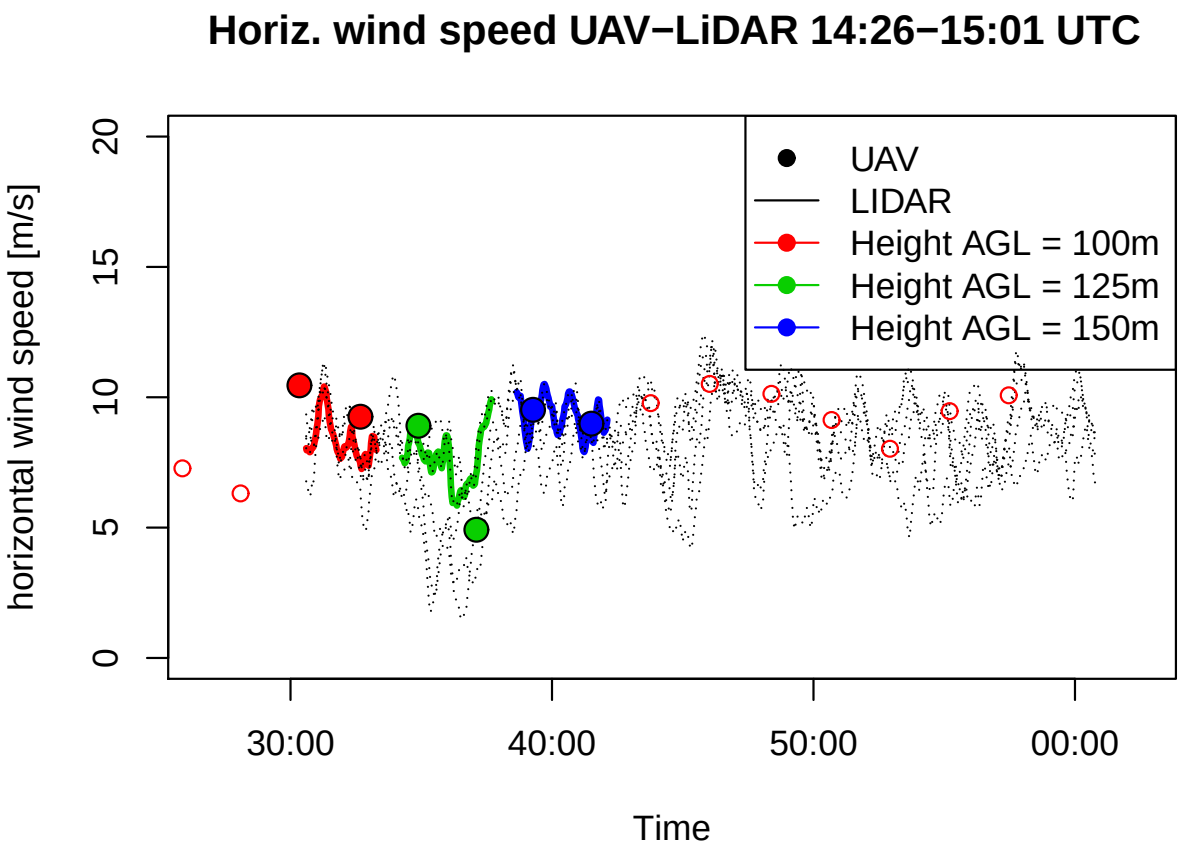
Comparing one UAV flight to one LiDAR profile





- Fast LiDAR wind scanner based on a Leosphere Windcube V1 system with adapted scanner
- Velocity azimuth display with five points in a circle and one point in the center only used for the vertical wind component acquisition was performed
- $\approx$ 0.5 Hz sampling rate

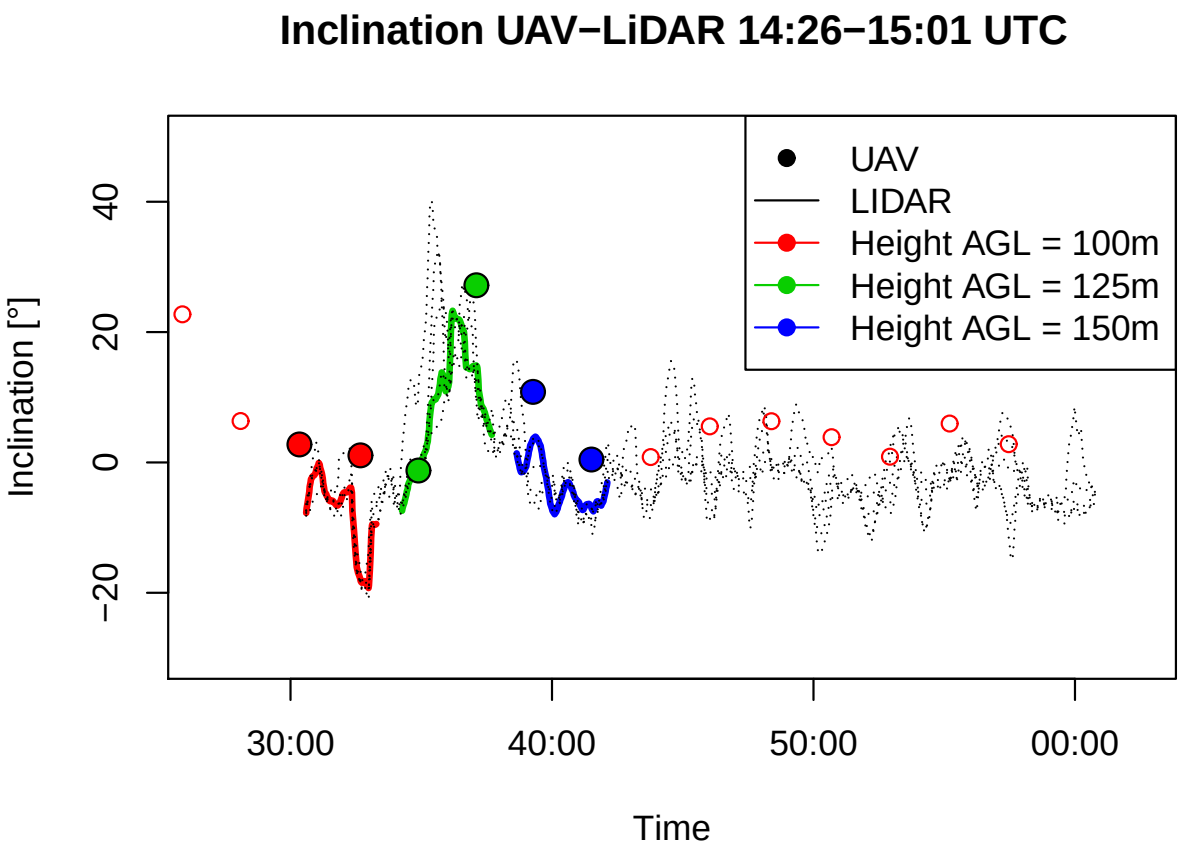
Comparing the time series of horizontal wind speed



Height AGL [m]	UAV	LiDAR	Offset
100	10.46	10.78	-0.32
100	9.25	8.16	1.09
125	8.91	6.07	2.84
125	4.92	6.03	-1.11
150	9.52	9.94	-0.42
150	8.99	8.98	0.01

- LiDAR data as moving average with 20 data points
- UAV data is average of $\approx$ 8 s flight through the 100 m window

Comparing the time series of inclination angle



Height AGL [m]	UAV	LiDAR	Offset
100	2.76	-5.80	8.56
100	1.09	-9.88	10.97
125	-1.24	2.30	-3.54
125	27.18	6.21	20.97
150	10.82	-0.11	10.93
150	0.45	-8.31	8.76

Conclusions

- With respect to the wind direction and speed we can approximate the locations ...
  - with significant vertical wind
  - with increased turbulence intensity
  - with significant wind shear
  - with accelerated and decelerated flow
- The wind field and turbulence is very sensitive to the wind direction
- The temporal and spatial resolution of the wind measurements affects the results especially in complex terrain
- Combining UAV and LiDAR in a beneficial way increases and strengthens the findings

Thank you for your attention!

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Bundesministerium für Wirtschaft und Technologie

Recommended literature

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- Wildmann, N., Mauz, M., and Bange, J.: Two **fast temperature sensors** for probing of the atmospheric boundary layer using small remotely piloted aircraft (RPA), Atmos. Meas. Tech., 6, 2101-2113, doi:10.5194/amt-6-2101-2013, 2013.
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Autopilot System controlling MASC

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iFR - Institut für Flugmechanik und Flugregelung

University of Stuttgart

`http://www.ifr.uni-stuttgart.de`

Research Onboard Computer System

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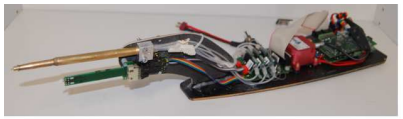
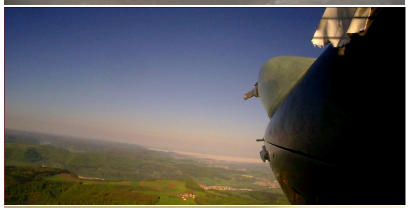
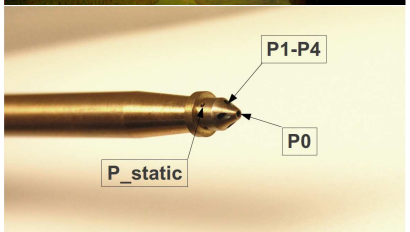
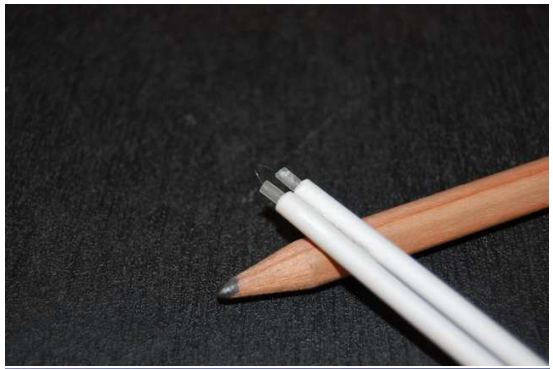
MASC sensor system

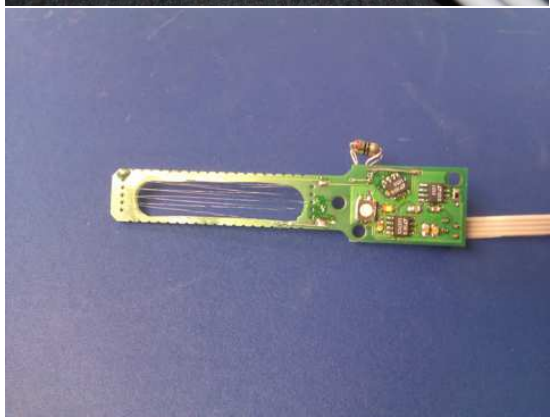


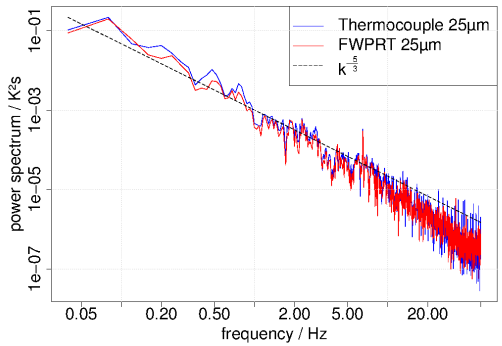




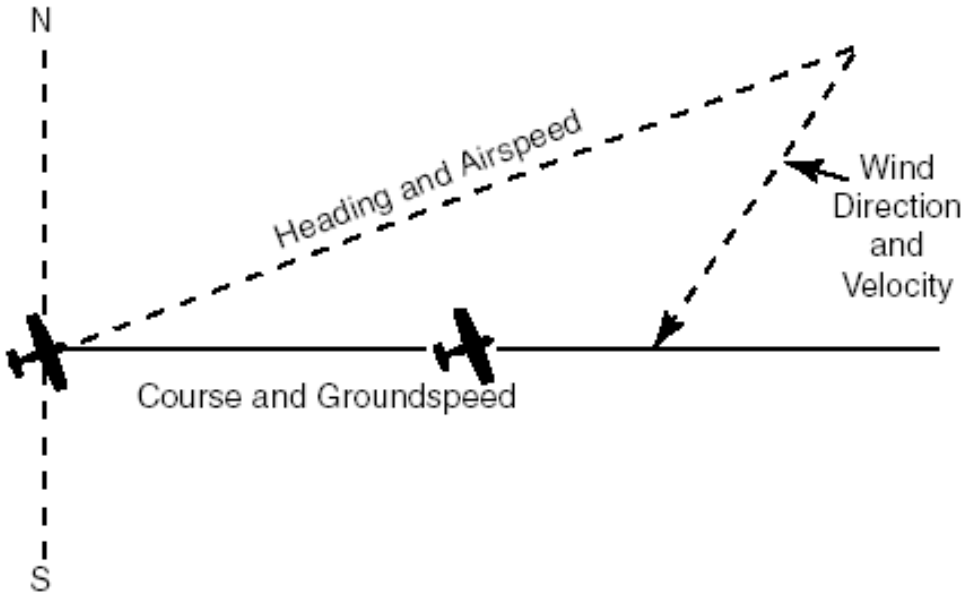
- complete thermodynamic sensor package:
  - thermocouple
  - fine wire resistance thermometer
  - capacitive humidity sensors
  - flow probe
  - inertial measurement unit (IMU)
  - GNSS position and velocity
- turbulence measurement
  up to 30 Hz
- live data observation
  on ground-station computer
- 100 Hz on-board log to SD-card







Measuring the wind vector



measurements:

- ground speed $\vec{v}_{\text{gs}} = (u_{\text{gs}}, v_{\text{gs}}, w_{\text{gs}})$
  by IMU/GPS combination in Earth's system
- true airspeed $\vec{v}_{\text{tas}}$
  by FHP in aerodynamic system

meteorological wind vector:

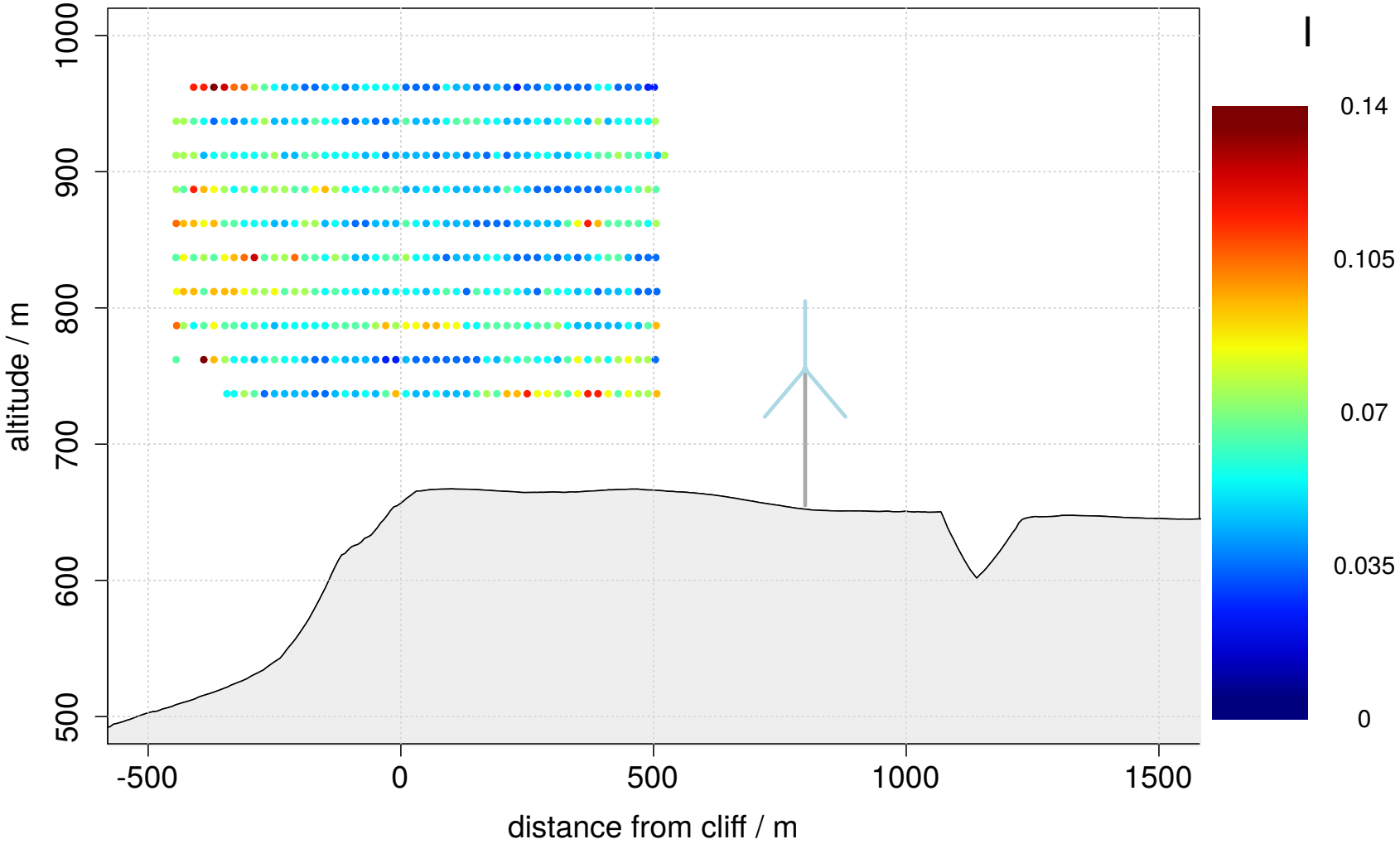
$$\boxed{\vec{v} = \vec{v}_{\text{gs}} + \mathbf{M}\left(\vec{v}_{\text{tas}} + \vec{\Omega} \times \vec{s}_p\right)}$$

with lever arm $\vec{\Omega} \times \vec{s}_p$
between IMU and FHP (often negligible)

two coordinate transformations M:

1. aerodynamic $\rightarrow$ aircraft body
   FHP: flow angles α, $\tilde{\beta}$,
   dynamic pressure increase Δp_q
2. aircraft body $\rightarrow$ Earth
   IMU/GPS: Euler angles Φ, Ψ, Θ

Example: wind direction 320°, turbulence



Average of **4** flights on 5 March. Color code: Turbulence intensity with 50 m window. Increased I especially in the region of low horizontal wind speed.