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: ≈ 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

Overview Terrain
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 on 22 April.
Color code: Normalized horizontal wind speed. Wind speeds $\approx 7$ m/s.
Pronounced updraft region. Low wind speeds 500 m downstream of the escarpment at 75 m a.g.l.
Average of 4 flights on 5 March.
Color code: Normalized horizontal wind speed. Wind speeds $\approx 5$ m/s. Most pronounced updraft region. Region of low wind speeds 350 m downstream of the escarpment.
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 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

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 flow 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

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

<table>
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<tr>
<th>Height AGL [m]</th>
<th>UAV</th>
<th>LiDAR</th>
<th>Offset</th>
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Comparing the time series of inclination angle

Inclination UAV–LiDAR 14:26–15:01 UTC

<table>
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<th>Height AGL [m]</th>
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<th>LiDAR</th>
<th>Offset</th>
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</table>
Conclusions

• With respect to the wind direction and speed we can approximate the locations ...
  o with significant vertical wind
  o with increased turbulence intensity
  o with significant wind shear
  o 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!

The projects “Lidar complex” and “KonTest” are funded by the Federal Ministry for Economic Affairs and Energy based on a decision of the German Bundestag. Webpage WindForS: http://www.windfors.de/
Recommended literature

Autopilot System controlling MASC

Many thanks to Prof. Walter Fichter and his team at

iFR - Institut für Flugmechanik und Flugregelung

University of Stuttgart

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

meteorological wind vector:

\[ \vec{v} = \vec{v}_{gs} + M \left( \vec{v}_{tas} + \vec{\Omega} \times \vec{s}_p \right) \]

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

two coordinate transformations \( M \):

1. aerodynamic → aircraft body
   FHP: flow angles \( \alpha, \tilde{\beta} \),
   dynamic pressure increase \( \Delta p_q \)
2. aircraft body → Earth
   IMU/GPS: Euler angles \( \Phi, \Psi, \Theta \)

measurements:

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