Eidgenössische Technische Hochschule Zürich
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Laboratory for Energy Conversion

On the Development of a 7-Sensor Fast-Response for Wind Energy Application

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Outline

- Motivation
- Objectives
- Seven-Sensor Fast Response Aerodynamic Probe (7S-FRAP)
- Results
- Concluding Remarks

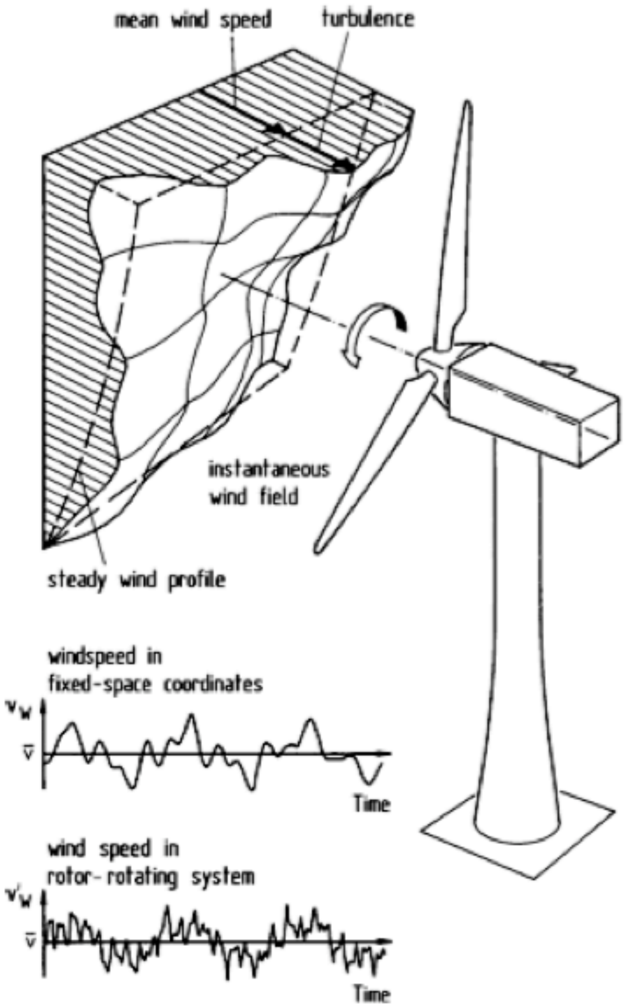
Motivation

- Continued rapid increase of wind energy projects, with hub height exceeding often 90m, requires improved approaches to site assessment

	Range (m)	Resolution (m)	Cost (USD)
Mast	80-90	-	65‘000
SODAR	1‘000 - 2‘000	~ 30 - 40	100‘000
LIDAR profiler	200	~ 40	219‘600
Scanning LIDAR	1‘000 - 2‘000	~ 100	1‘500‘000

Objectives

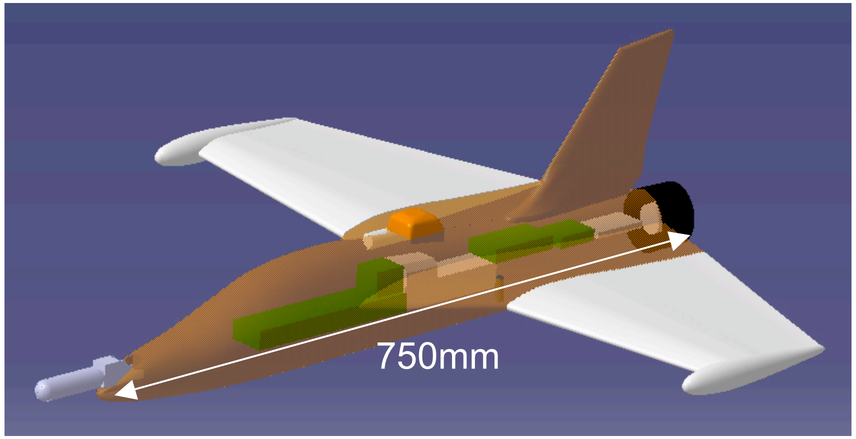
- Develop a light, mobile and cost effective measurement system for time and spatially resolved measurements of wind using an autonomous aircraft
- Provide full-scale measurement data for ETH sub-scale experiment and computational models



Source: Wind Turbines, E. Hau, 2006

Fast Response Probe Requirements

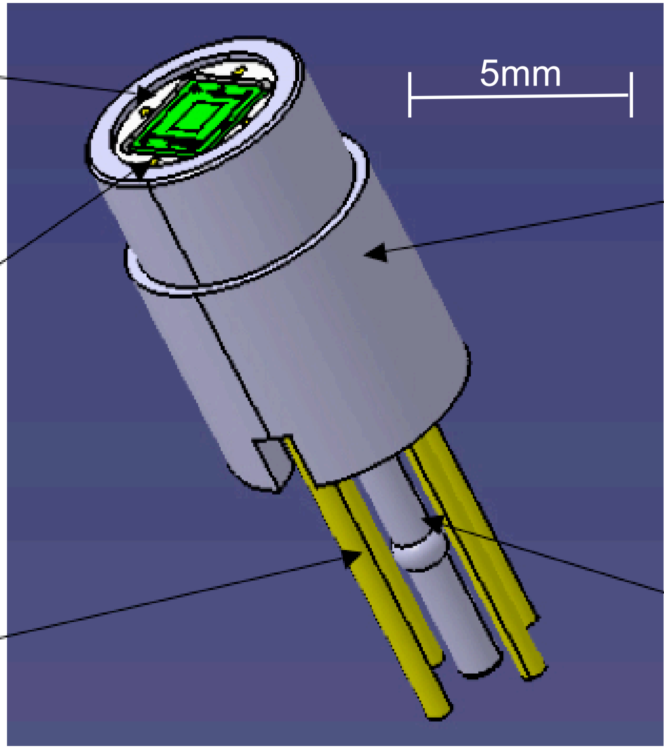
- Light & compact (< 300g)
- Robust for outdoor application
- Low dynamic head;
  - Dynamic head = 0-10mbar (airspeed=0-50m/s)
- Measurement of 3D velocity & turbulence for large flow angles (≤70°)
- High measurement bandwidth (≤1kHz)



UAV's dimensions:

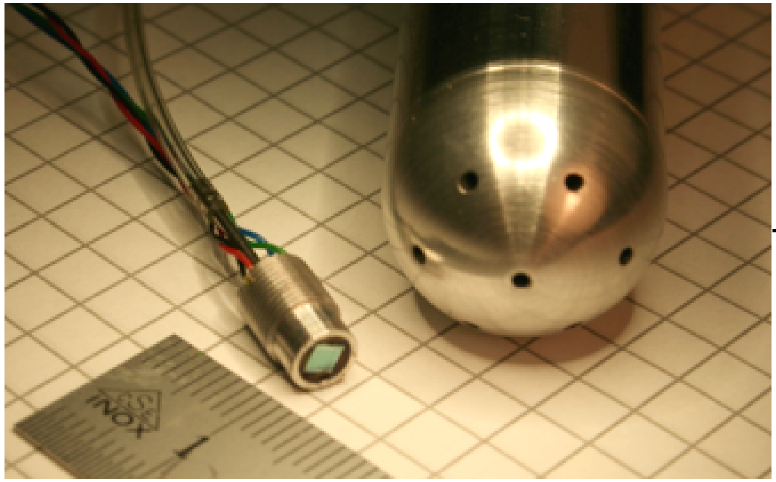
- Wingspan: 800mm
- Lenght: 750mm
- Front payload bay: 40 X 280mm

F7S Sensor Packaging



- Low pressure piezo-resistive pressure sensors ($0 \leq p \leq 50$mbar)
- Sensor installed onto a socket encapsulated in threaded casing
- Threaded casing enables quick replacement of sensor in case of failure

F7S Probe Design



On-board ADC:
- Sampling rate: 3kHz
- resolution: 24 bit

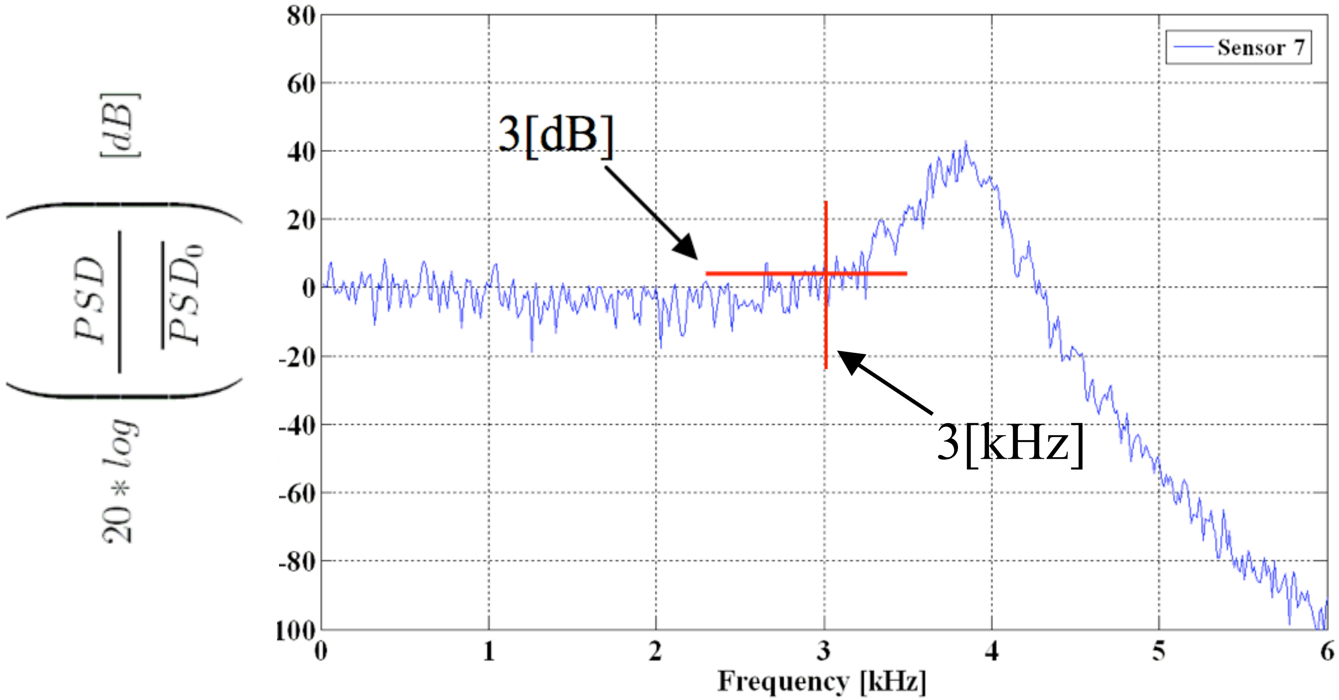
On-board data storage

Telemetry
- Monitoring on GCS

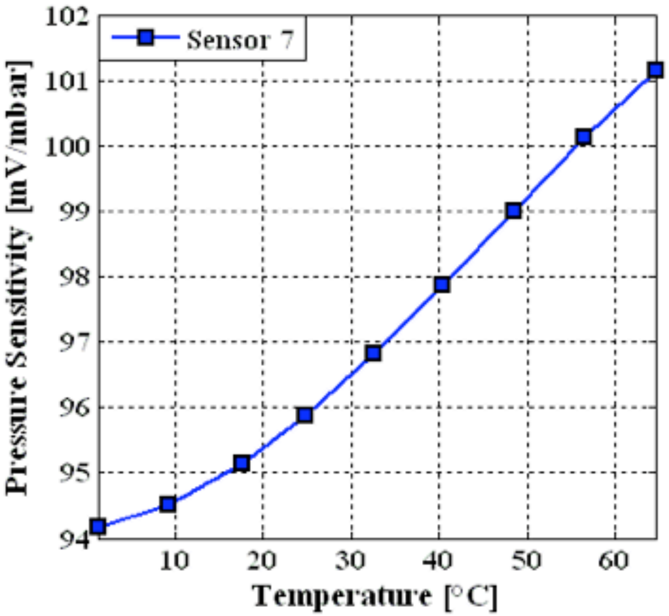
- 7 fast-response pressure sensors embedded beneath pressure taps
- Hemispherical head, diameter D = 20mm
- Overall probe length L = 75mm
  - L/D ≈ 4, minimizing effect of UAV's potential filed on measured flowfield

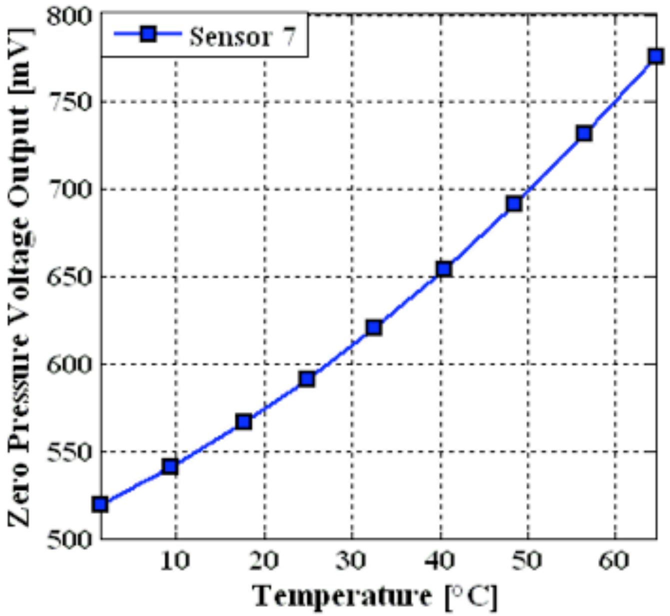
F7S Probe: Dynamic Calibration

- Pneumatic cavity between pressure tap and pressure sensor
- Eigenfrequency of pneumatic cavity measured in freejet
- Peak at 3.8kHz is eigenfrequency of cavity
- Cutoff frequency of 3kHz at 3db amplitude sets bandwidth of F7S probe



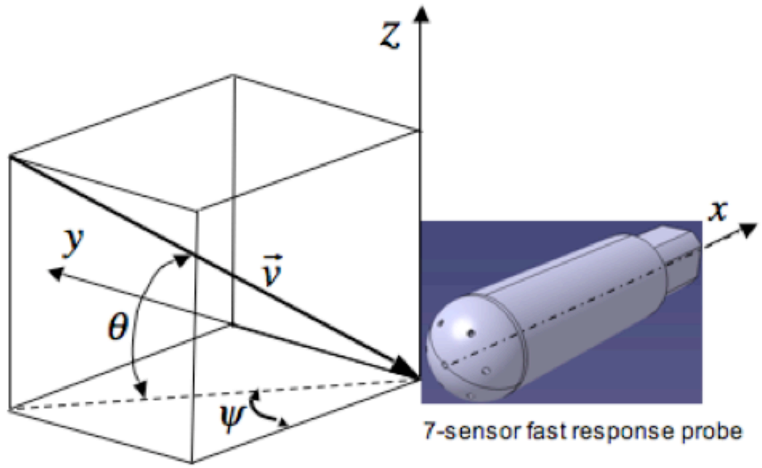
F7S Probe: Static Calibration

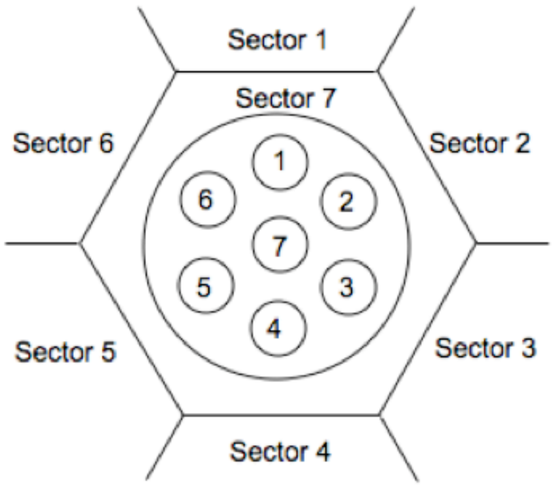




- Pressure calibration range: 2 < p< 32 mbar
- Temperature calibration range: 1< T< 65°C
- 7% and 32 % variation in pressure sensitivity and zero pressure offset
- Pressure sensitivity ~100 mV/mbar
- Effective pressure resolution = ±8.6 10^{-3} Pa (19bits effective ADC)

F7S Probe: AeroCalibration Method





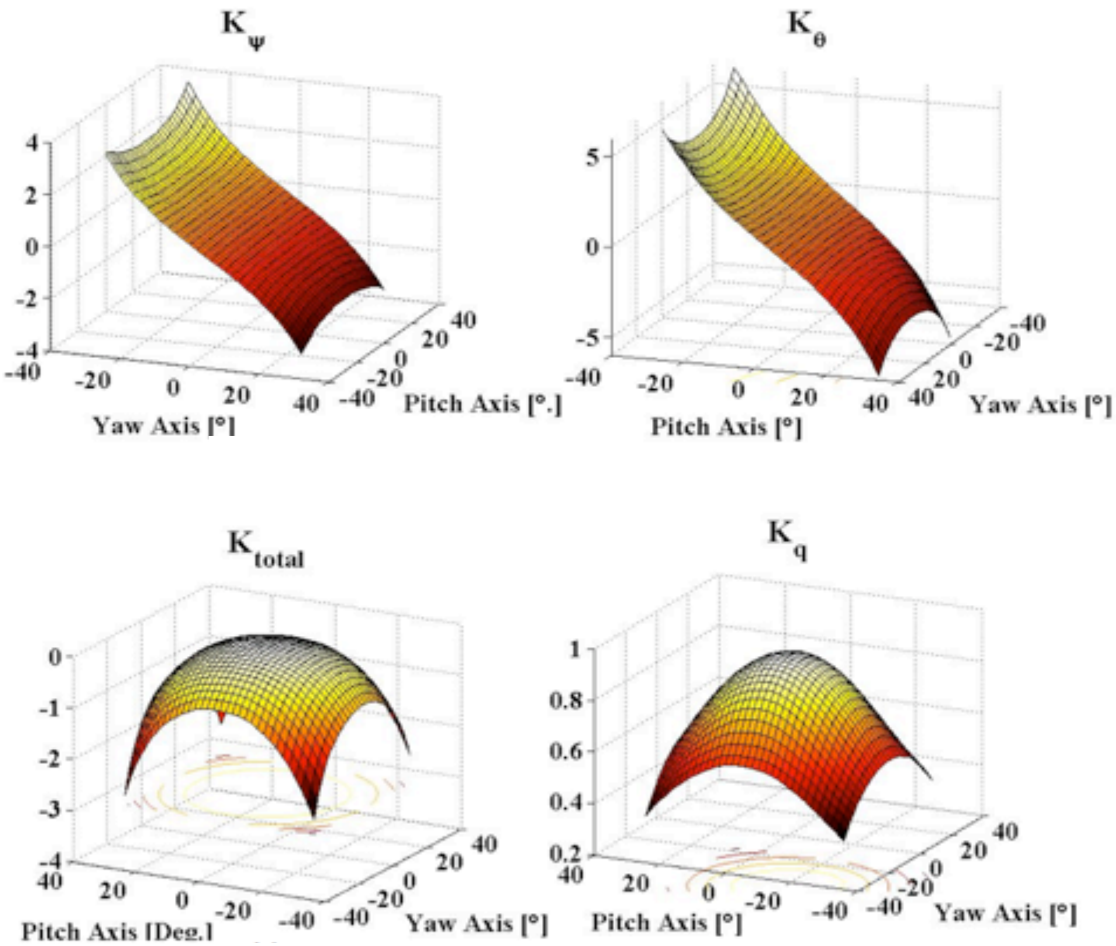
Low flow angles -30< ψ,θ < 30°:

- Center Port 7 (sector 7) reads highest pressure
- Calibration coeffs. computed using P_1 to P_7

Large flow angles 30< ψ,θ <60°:

- Separated flow on leeward side
- Sectored calibration scheme
- Circumferential port n (n = 1 : 6) reads highest pressure
- Subset of 3 pressures P_{n-1}, P_n, P_{n+1} used for calibration coeffs.

F7S Probe: AeroCalibration Method



Calibration conditions:

- Flow speed, 25m/s
- Dynamic pressure, 4mbar
- Ambient temperature, 23ºC
- Mach number, 0.074
- -30° < yaw, pitch < 30°

Model standard deviation:

- $\sigma_\psi = 5.7\times10^{-2}$ °
- $\sigma_\theta = 5.7\times10^{-2}$ °
- σ_{total} = 16.5 Pa
- σ_q = 7.3 Pa

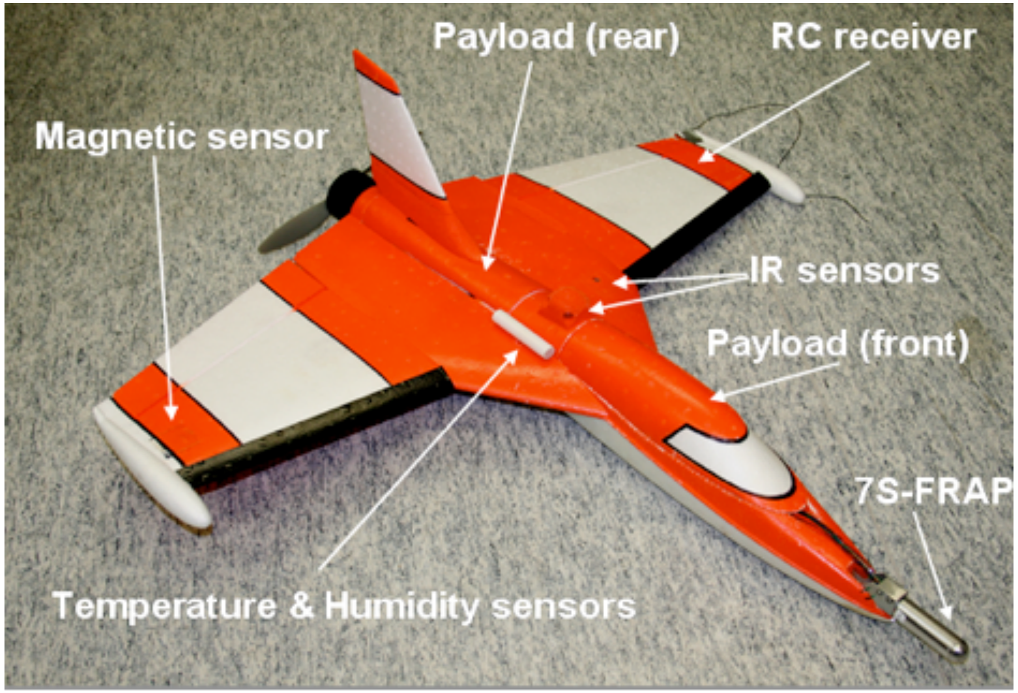
F7S Probe: Uncertainty Analysis

Guide of Uncertainty in Measurements software (GUM):

- Calculation of overall uncertainty by Gaussian error propagation
- Expanded uncertainty (confidence level = 95%)

	Angle [°]		Velocity [m/s]	
	Pitch	**Yaw**	**20**	**25**
Absolute	+/- 1.4	+/ - 2.2	+/- 1.2	+/- 1.2
Relative	2.33%	3.6%	6 %	4.8 %

Instrumented Uninhabited Aerial Vehicle



F7S probe:

- vertical angle of attack
- horizontal sideslip angle
- total pressure (±47Pa)

On-board sensors:

- GPS:
  - horizontal position (±2.5m)
  - vertical position (±5m)
  - ground speed (±0.1m/s)
  - Vertical speed
  - course heading (±0.5°)
- Infrared sensors:
  - pitch angle
  - roll angle
- Magnetometer:
  - sideslip angle
- Absolute pressure sensor :
  - atmospheric pressure (±150Pa)
- Temperature & humidity sensor:
  - static temperature (±0.3°C)
  - humidity (±1.8%RH)

Wind Velocity Measurement Approaches

Time-resolved wind measurements using F7S probe

- Define V_{wind} vector in earth frame of reference S

$$\vec{V}_{wind,S} = \vec{V}_{air,S} - \vec{V}_{plane,S}$$

- $\vec{V}_{air,S}$ from F7S, IR sensors, magnetometer
- $\vec{V}_{plane,S}$ from GPS, IR sensors

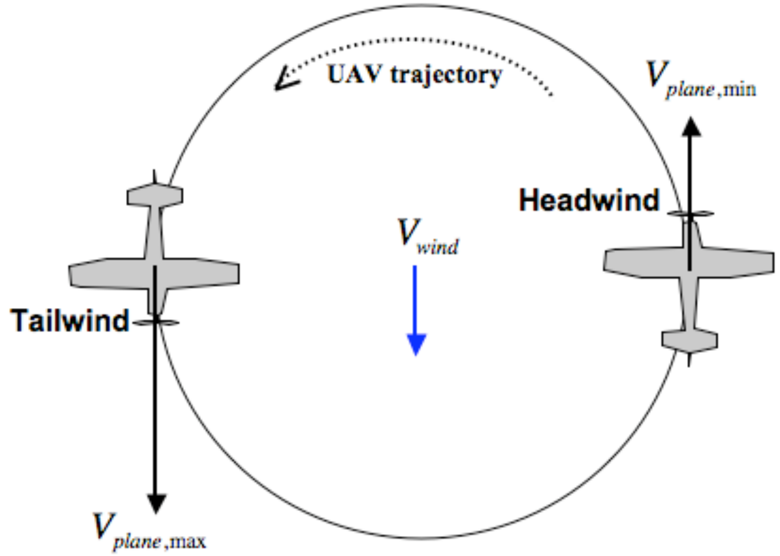
Time-averaged wind measurement using circle flight technique

- circle flights patterns performed at constant altitude
- constant throttle => $V_{plane,\ true\ airspeed}$ = constant
- V_{plane} from GPS

Tailwind: $V_{plane,\max} = V_{plane,true\ airspeed} + V_{wind}$

Headwind: $V_{plane,\min} = V_{plane,true\ airspeed} - V_{wind}$

=> $V_{wind} = \dfrac{V_{plane,\max} - V_{plane,\min}}{2}$



Atmospheric Boundary Layer Measurement Set-uP

Location:

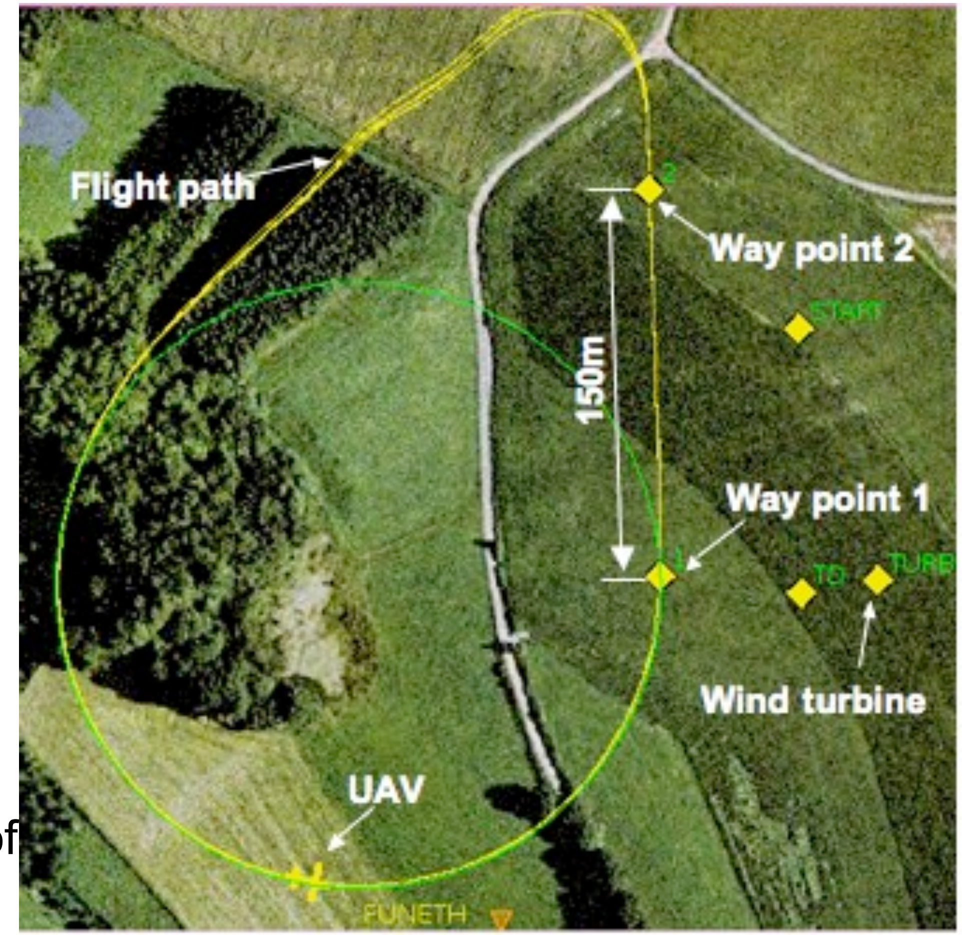
- moderately complex terrain in Northern Germany
- 240m altitude
- area dotted with open agricultural terrain and small forest

Wind Turbine:

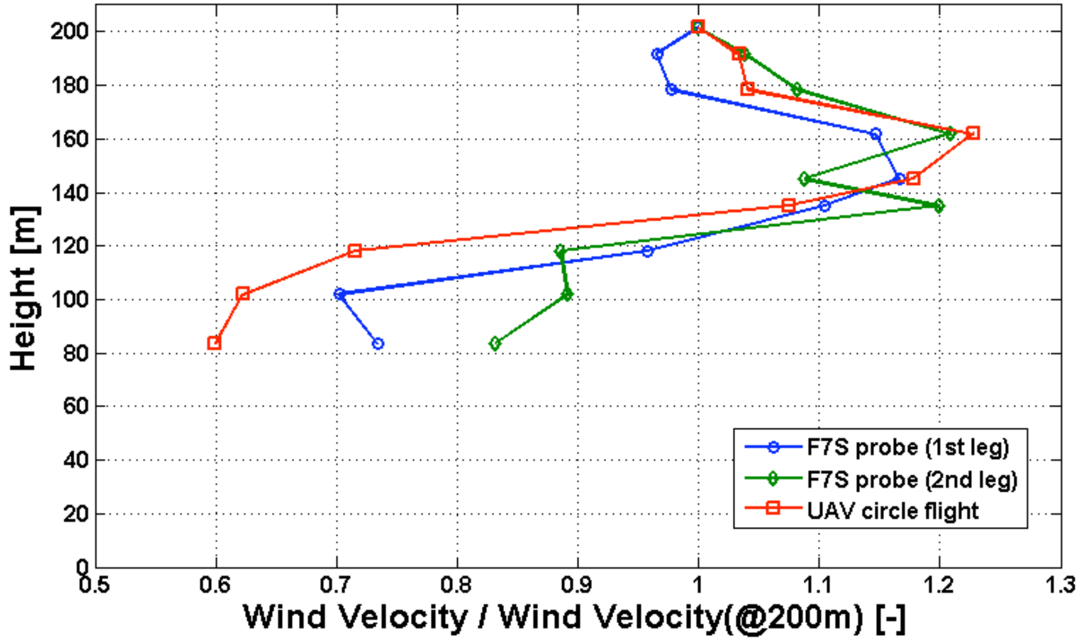
- Vestas V80
- rotor diameter, 80m
- hub height, 100m

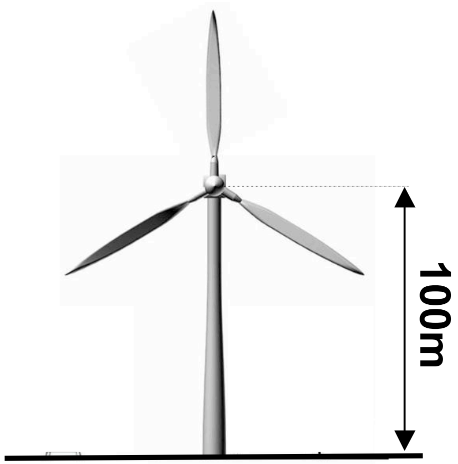
UAV flight path:

- upstream of wind turbine
- level flight over horizontal distance of 150m
- heights: 80 - 200m
- height intervals: 15m



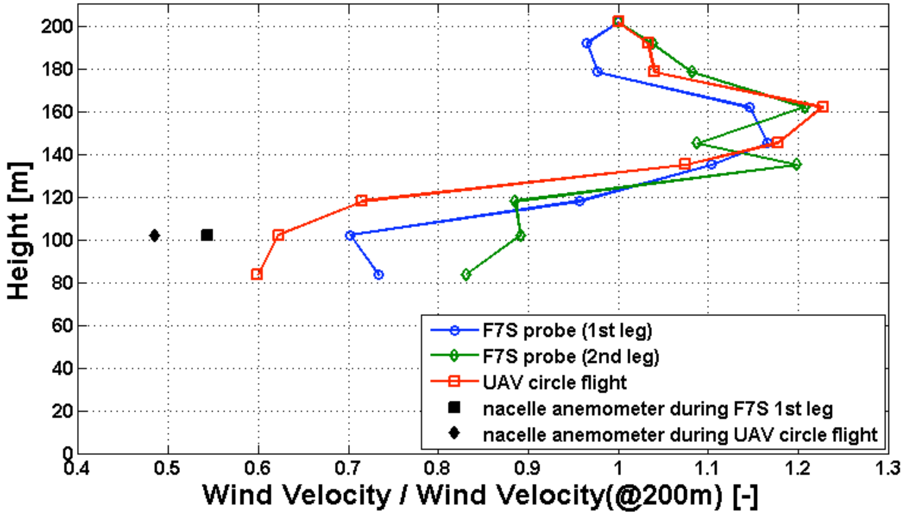
Atmospheric Boundary Layer Measurement

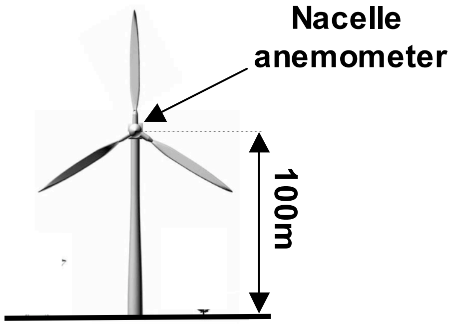




- 2 measurement legs with F7S and 1 measurement leg with circle flight
- measurements capture shear wind profile:
  - accelerated wind profile over 100 and 175m
  - peak velocity around 150m
  - shear factor V_{150}/V_{200} = 1.2

Atmospheric Boundary Layer Measurement

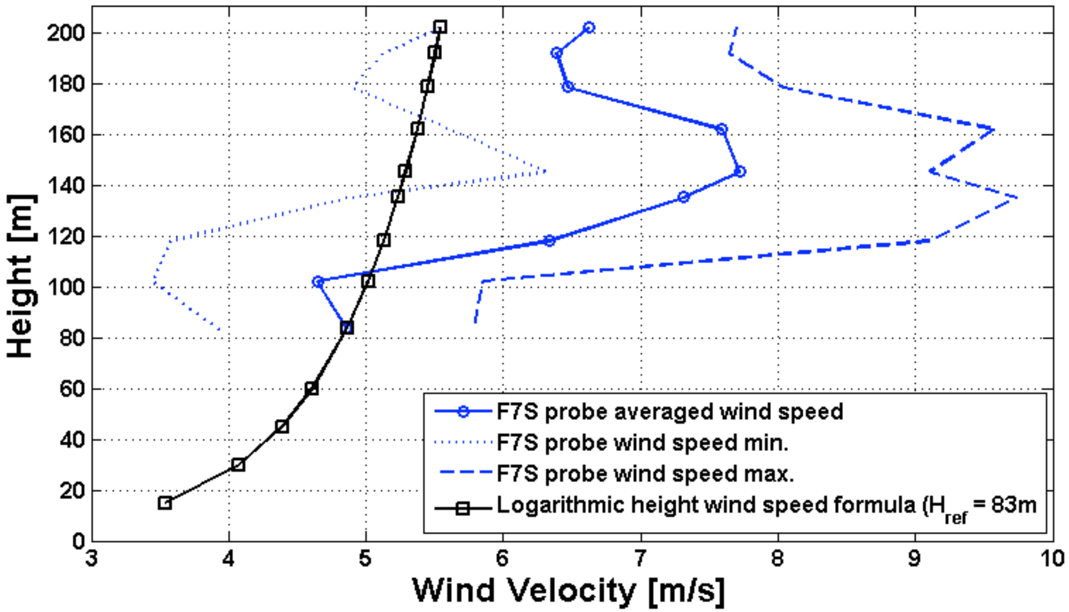




	Measured wind velocity [m/s]	Expected wind velocity [m/s]	Nacelle anemometer [m/s]	Deviation Abs. [m/s] / rel. [%]
F7S	4.65	4.5	3.6	0.15 / 3%
Circle flight	3.14	3.06	2.45	0.08 / 2.6%

- Nacelle anemometer at 100m (10 minute - averaged)
- Modern rotor retards wind speed downstream of rotor plane by approx. 25%
- Measured velocities at 100m in good agreement with nacelle anemometer

ABL Layer Measurement Vs. Logarithmic profile



Logarithmic wind profile formula:

$$\overline{v}_H = \overline{v}_{ref} \frac{\ln \frac{H}{z_o}}{\ln \frac{H_{ref}}{z_o}}$$

- Time-resolved wind profiles show up to 44% velocity fluctuations
- Logarithmic wind profile extrapolated from wind speed at 83m with z_0 = 0.15m
- Logarithmic wind profile compared to measured profile :
  - underestimates wind velocity up to 32% at 143m
  - overestimates sectionnal lift variation at midspan over rotor swept area by 5%
  - underestimates calculated electrical power by 42%

Concluding Remarks

- A novel measurement approach for wind energy applications, which is comprised of an instrumented UAV equipped with F7S probe,has been developed and demonstrated
- Measurements of atmospheric boundary layer have been performed
- F7S shows 3% wind velocity measurement deviation with nacelle anemometer
- Wind profile extrapolated from single point measurement using logarithmic height profile not adequate for wind turbine sitting in moderate and highly complex terrains

Thank you for your attention !