Wind measurement with a 5 Hole Probe

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Outline

- Wind measurement with the 5 hole probe
- Error estimation of the pressure transducer
- Wind Vector Uncertainty
  - Error estimation of the spectral resolution of wind turbulence
  - Absolute error of the wind vector
- Results of Measurement Flights in 2012


Introduction

UAV MASC (multi-purpose automatic sensor carrier):

- two temperature sensors
- humidity sensors
- 5 hole probe (5HP)
- GPS receiver
- inertial measurement unit (IMU)

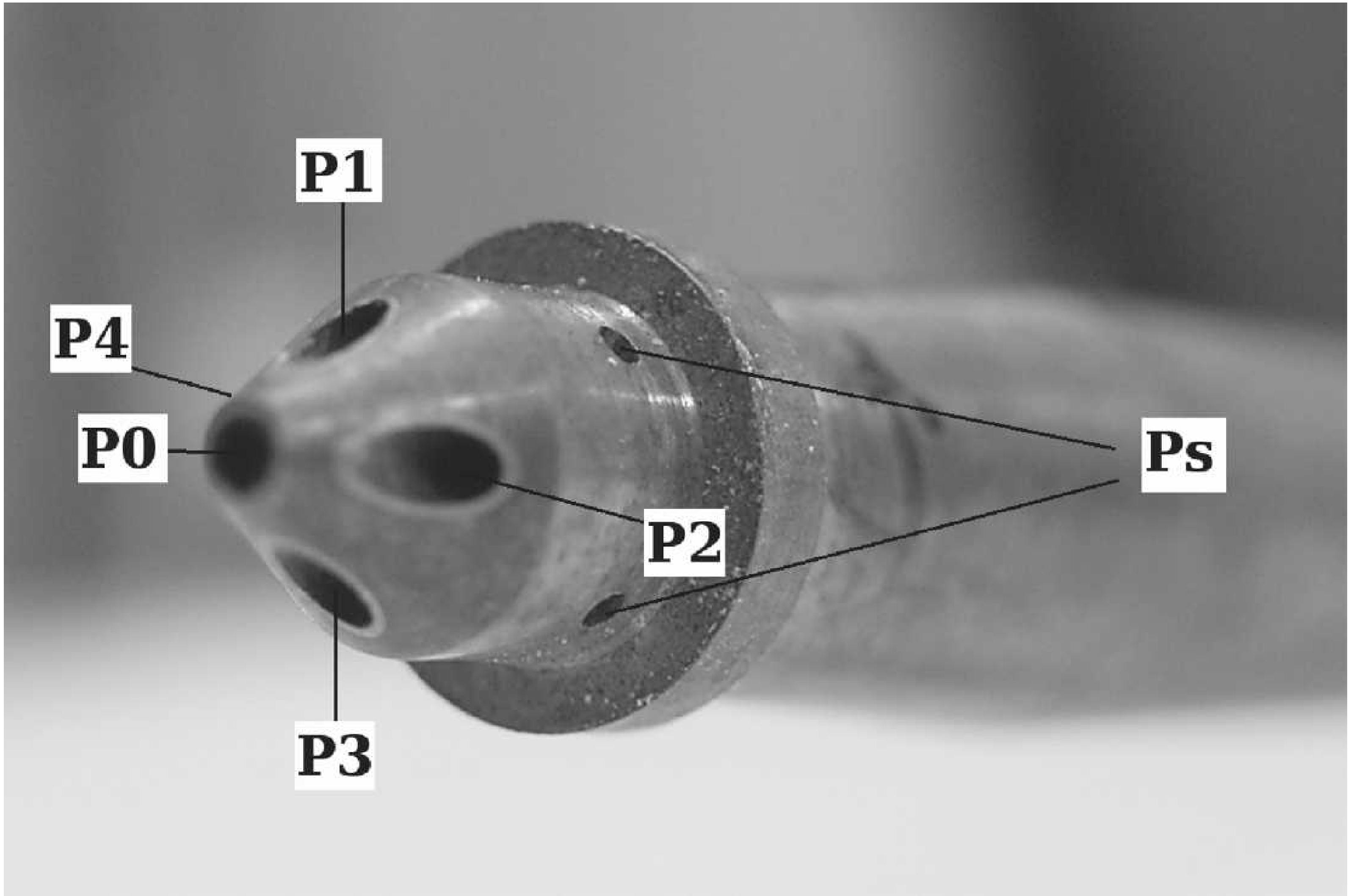
Wind Vector

The wind vector $\boldsymbol{W}_g$ defined in geodetic coordinate system is the vector difference between the inertial velocity vector $\boldsymbol{V}_g$ and the true airspeed $\boldsymbol{U}_a$

$$\boldsymbol{W}_g = \boldsymbol{V}_g + \boldsymbol{M}_{gb}\boldsymbol{M}_{ba}\boldsymbol{U}_a$$

IMU/GPS 5 hole probe

5 hole probe



Pressure sensor sampling frequency $f_s = 100\text{Hz}$

5 hole probe

True airspeed and airflow angles are calculated by the pressure measurements:

$$|\boldsymbol{U}_a| = f_u(\Delta p_{01}, \Delta p_{02}, \Delta p_{03}, \Delta p_{04}, \Delta p_{0s}) \tag{1}$$

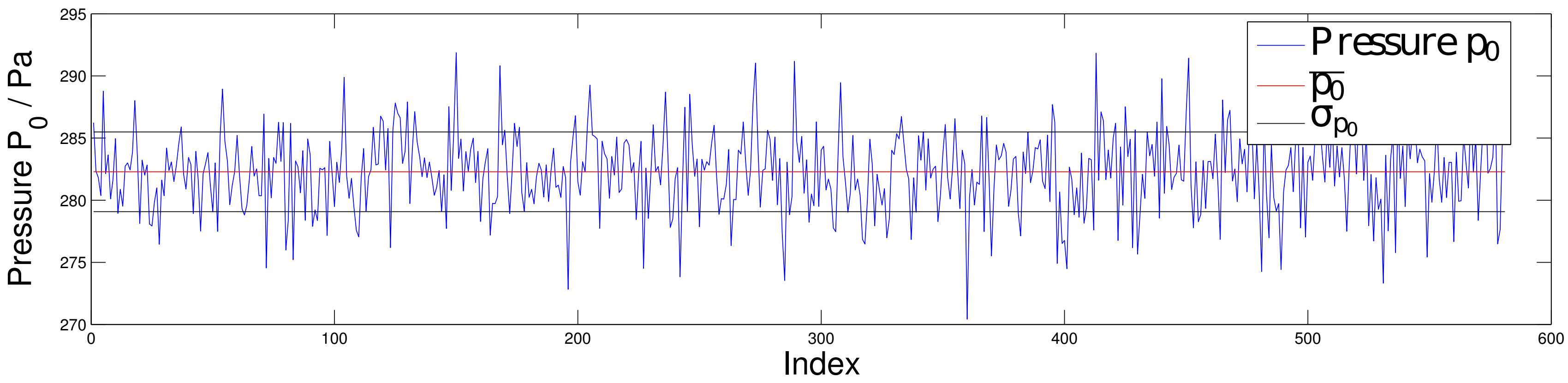
$$\alpha = f_\alpha(\Delta p_{01}, \Delta p_{02}, \Delta p_{03}, \Delta p_{04}, \Delta p_{0s}) \tag{2}$$

$$\beta = f_\beta(\Delta p_{01}, \Delta p_{02}, \Delta p_{03}, \Delta p_{04}, \Delta p_{0s}) \tag{3}$$

where Δp_{0x} is the difference between the pressure measured at the Hole x of the 5HP and the pressure (P_0) measured at the tip.

Error only by Pressure Transducers

Laminar wind tunnel with a turbulence intensity $I = \frac{\sigma_u}{\overline{u}} = 1\%$ with $\overline{u} = 17$ m/s.

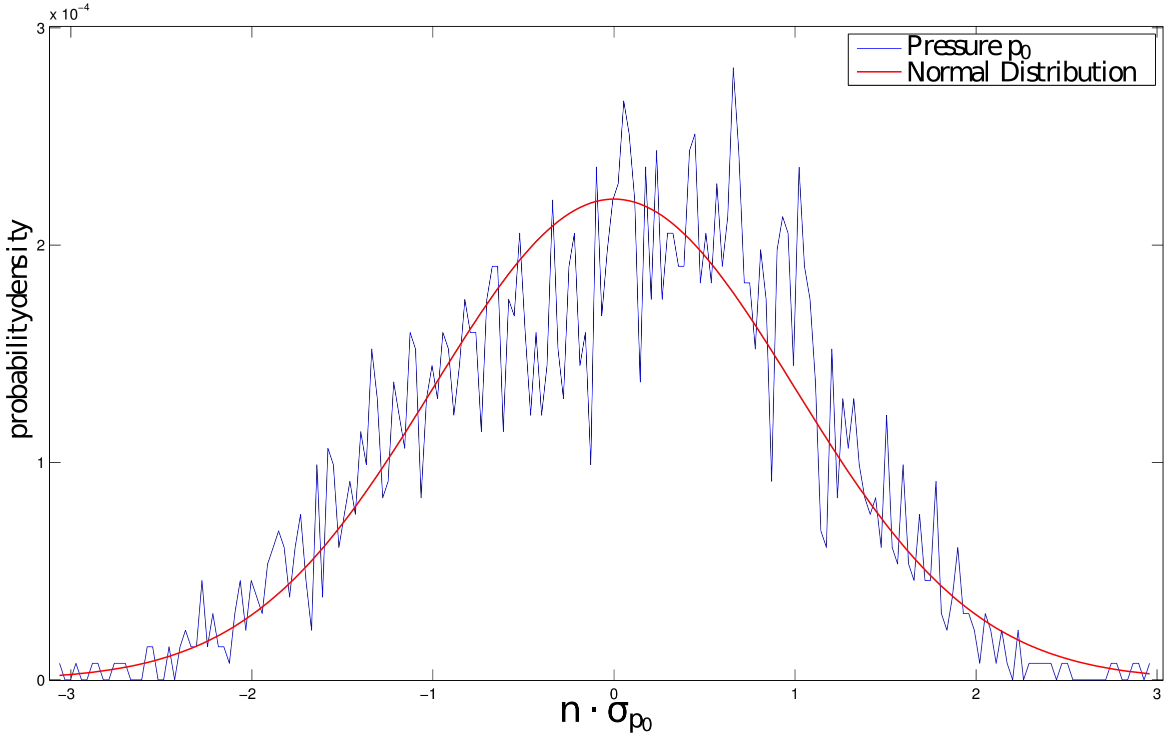


Pressure signal p_0 measured with 5 hole probe in the laminar jet wind tunnel

$$\overline{u} = 17\mathrm{m/s}: \ \sigma_{p_0} = 2.9\mathrm{Pa}, \ \overline{p_0} = 283.1\mathrm{Pa} \Rightarrow I_m = \frac{\sigma_{u_m}}{\overline{u_m}} = \frac{\sigma_{\sqrt{p_0}}}{\overline{\sqrt{p_0}}} = 0.7\%$$

$$\overline{u} = 0\mathrm{m/s}: \ \sigma_{p_0} = 0.5\mathrm{Pa}, \ \overline{p_0} = 0\mathrm{Pa} \Rightarrow \text{elctrical thermal noise of the sensors}$$

Normal Distribution of Sensor Noise



To simulate the error due to noise, random numbers with gaussian distribution (ε) and a specific standard deviation (σ_{noise}) are added to the measurement:

$$\Delta\tilde{p}_{xy,i} = \Delta p_{xy,i} + \sigma_{p,noise} \cdot \varepsilon_{p,i}$$

Simulation of noise error by pressure ransducers

$$|\tilde{\boldsymbol{U}}_a| = f_u(\Delta\tilde{p}_{01}, \Delta\tilde{p}_{02}, \Delta\tilde{p}_{03}, \Delta\tilde{p}_{04}, \Delta\tilde{p}_{0s}) \quad (4)$$

$$\tilde{\alpha} = f_\alpha(\Delta\tilde{p}_{01}, \Delta\tilde{p}_{02}, \Delta\tilde{p}_{03}, \Delta\tilde{p}_{04}, \Delta\tilde{p}_{0s}) \quad (5)$$

$$\tilde{\beta} = f_\beta(\Delta\tilde{p}_{01}, \Delta\tilde{p}_{02}, \Delta\tilde{p}_{03}, \Delta\tilde{p}_{04}, \Delta\tilde{p}_{0s}) \quad (6)$$

$$\mathrm{RMS}_{\mathrm{U_a}} = \sqrt{\frac{1}{n-1}\sum\nolimits_{i=0}^{n}(|\boldsymbol{U}_a|_i - |\tilde{\boldsymbol{U}}_a|_i)^2} \quad (7)$$

$$\mathrm{RMS}_\alpha = \sqrt{\frac{1}{n-1}\sum\nolimits_{i=0}^{n}(\alpha_i - \tilde{\alpha}_i)^2} \quad (8)$$

$$\mathrm{RMS}_\beta = \sqrt{\frac{1}{n-1}\sum\nolimits_{i=0}^{n}(\beta_i - \tilde{\beta}_i)^2} \quad (9)$$

Error only by pressure transducers

S_A power spectrum of a time series $\Rightarrow$ White noise: $S_A = \text{const.}$

$$\sigma^2 = \int_0^N S_A(n)dn \tag{10}$$

with N as the upper bound frequency, is the half of the sampling frequency ($f_s = 100\text{Hz}$).

$$S_A = \frac{\sigma^2}{N} = \frac{\sigma^2}{f_s/2} = \frac{\sigma^2_{p0_{noise}}}{f_s/2} = \frac{0.5\text{Pa}^2}{50\text{Hz}} = 0.01\text{Pa}^2\text{Hz}^{-1} \tag{11}$$

Error only by pressure transducers

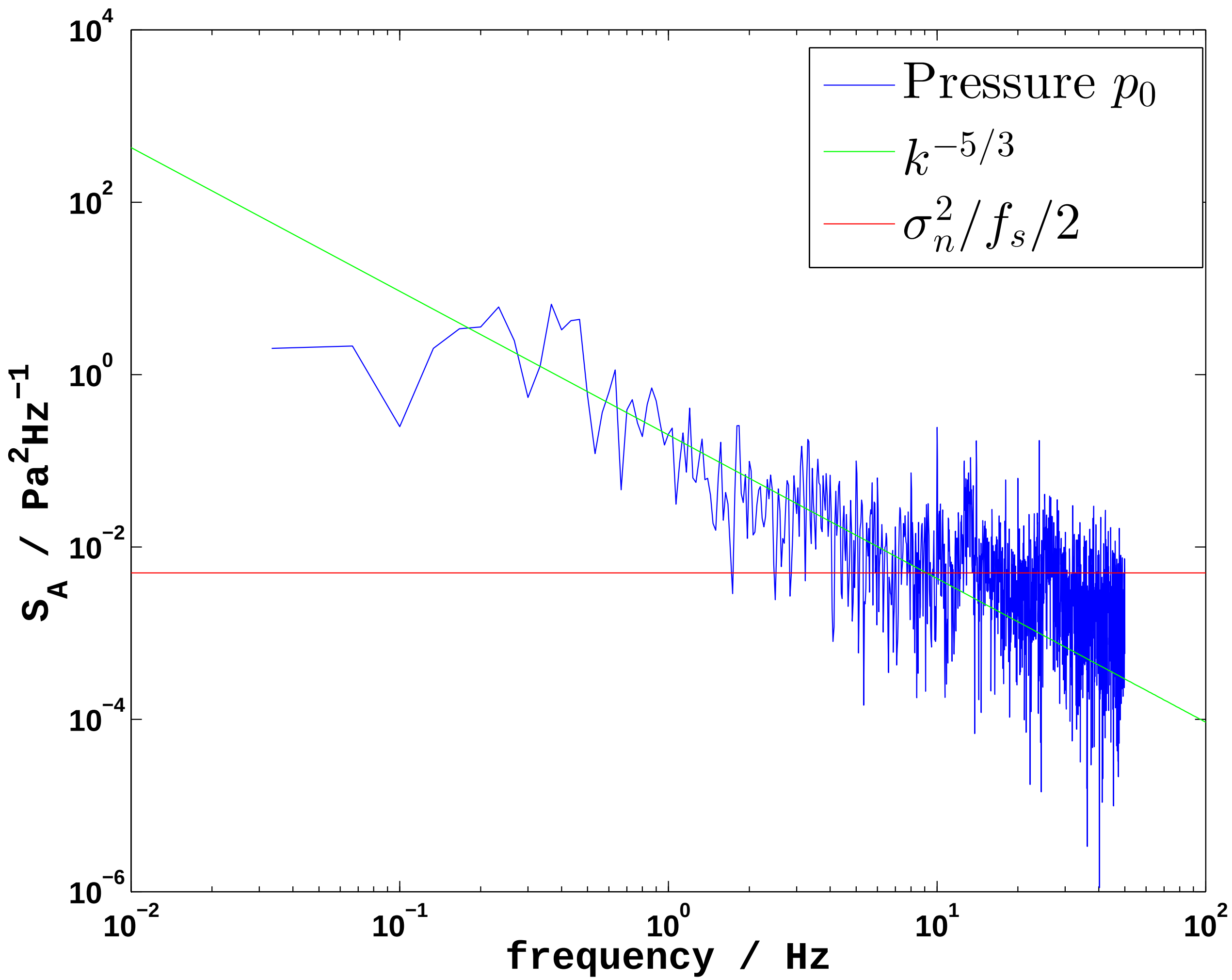


Abbildung 1: Power spectrum of p_0 pressure measurement with theoretical noise level (red).

Wind Vector Uncertainty

Variable	σ
$\|\boldsymbol{U}_a\|$	0.04 ms^{-1}
α	0.07°
β	0.05°
Φ	1 °
Θ	1 °
Ψ	1 °
$\boldsymbol{V}_g$	$[0.1\ 0.1\ 0.1]$ms^{-1}

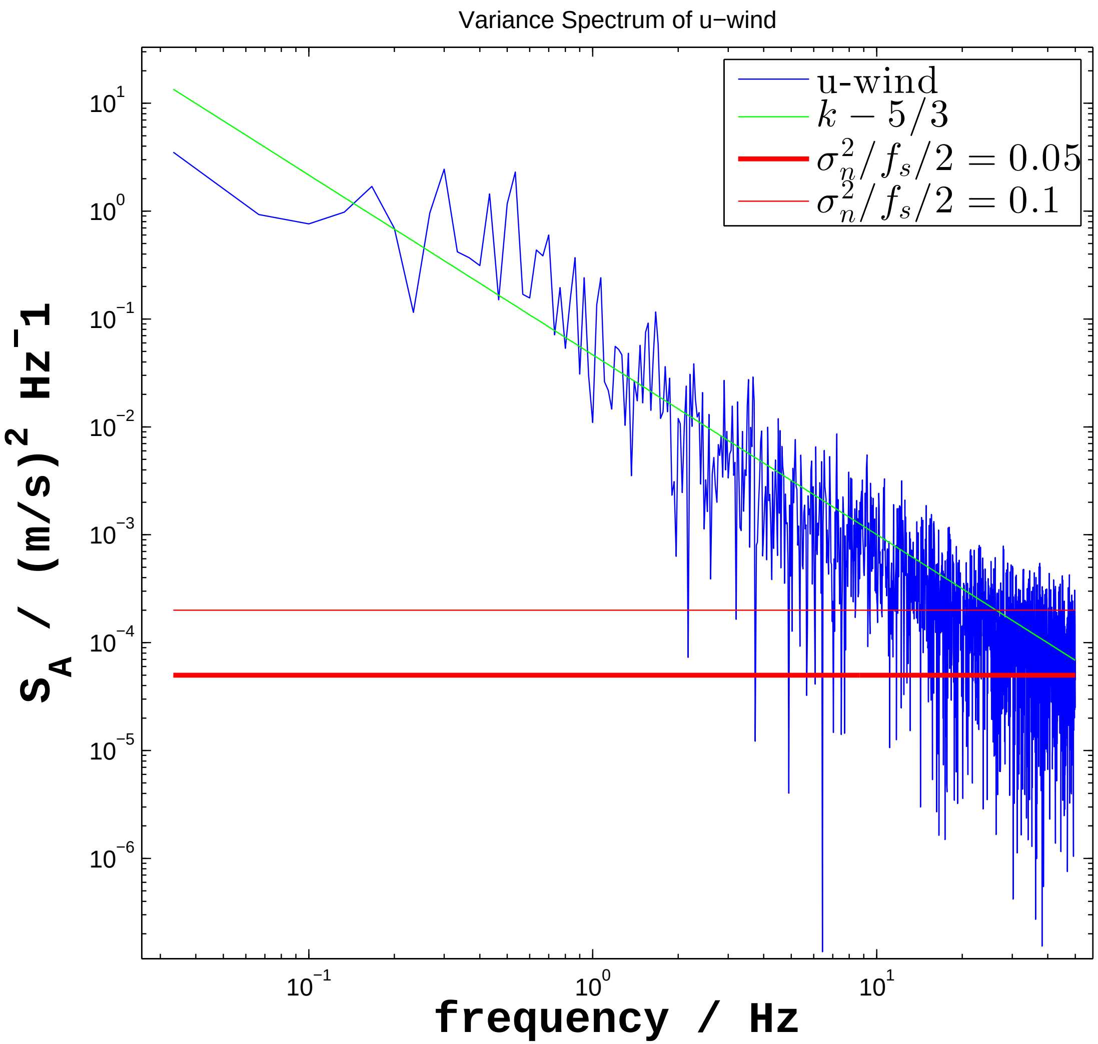
Gaussian error estimation: $\Longrightarrow$ $\boxed{\sigma_{u,v,w} \approx 0.4 \text{ m/s}}$

$\sigma_\Phi = 0°$, $\sigma_\Theta = 0°$, $\sigma_\Psi = 0°$, $\sigma_{\boldsymbol{V}_g} = 0$ m/s $\Longrightarrow$ $\boxed{\sigma_{u,v,w} \approx 0.05 \text{ m/s}}$

Problem: Φ, Θ, Ψ, $\boldsymbol{V}_g$ are no noise errors

Errors are NOT Gaussian normal distributed

Spectral Resolution



$\Longrightarrow$ Expect **spectral resolution of turbulence** fluctuation of ≈ 20 Hz^{-1}

Absolute Error of the Wind Vector

Maximum Error Estimation

Linear Error Analysis with Taylor expansion of first order

$$\varepsilon_{total_{MAX}} = \left|\frac{\partial f}{\partial x}\right| \cdot \Delta x + \left|\frac{\partial f}{\partial y}\right| \cdot \Delta y + ... \tag{12}$$

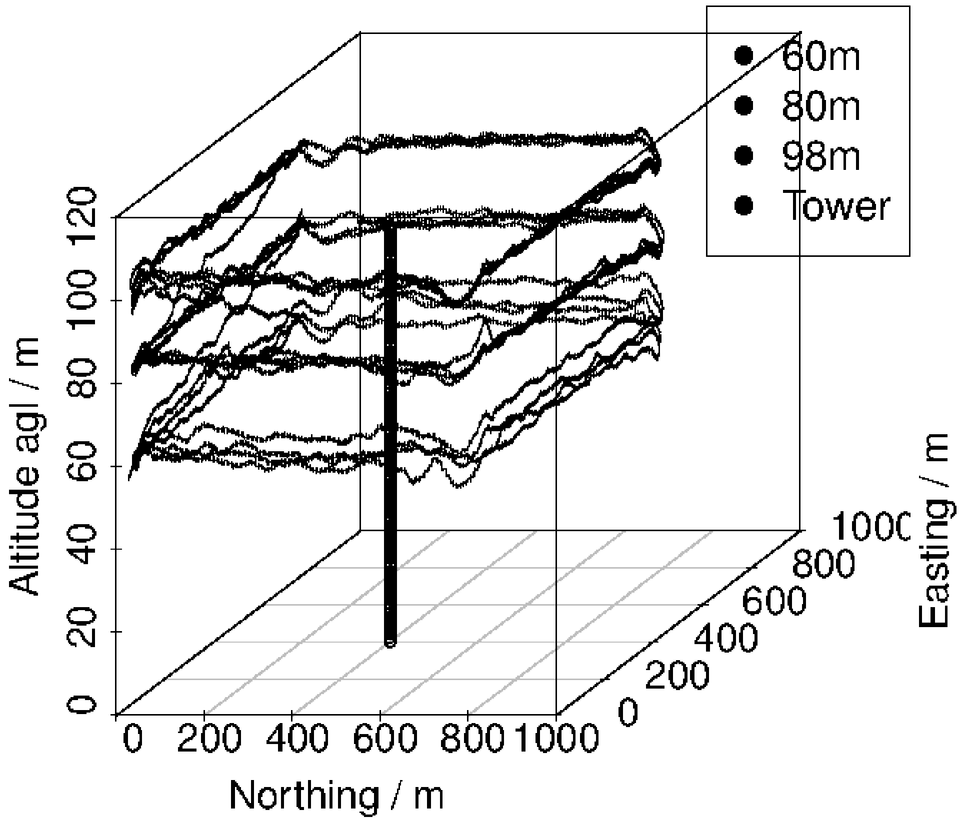
With $\Delta\Phi = 1°$, $\Delta\Theta = 1°$, $\Delta\Psi = 1°$, $\Delta\boldsymbol{V}_g = 0.1$ m/s

$$\Longrightarrow \boxed{\varepsilon_{total_{MAX}} = \pm 0.49 \text{ m/s}}$$

Flight Test

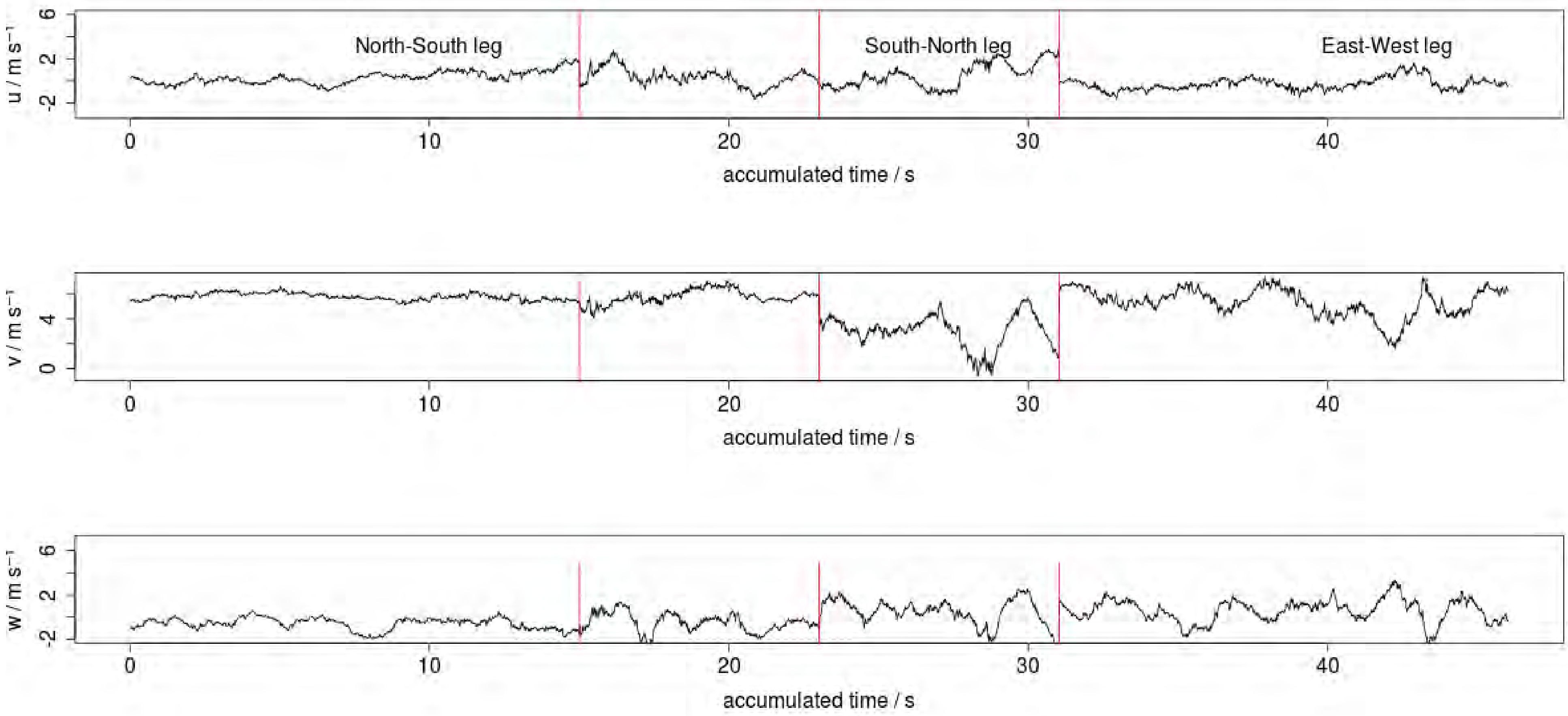
Flight Test

Flight measurements were carried out on 21- 23 September 2012 in Lindenberg near Berlin.



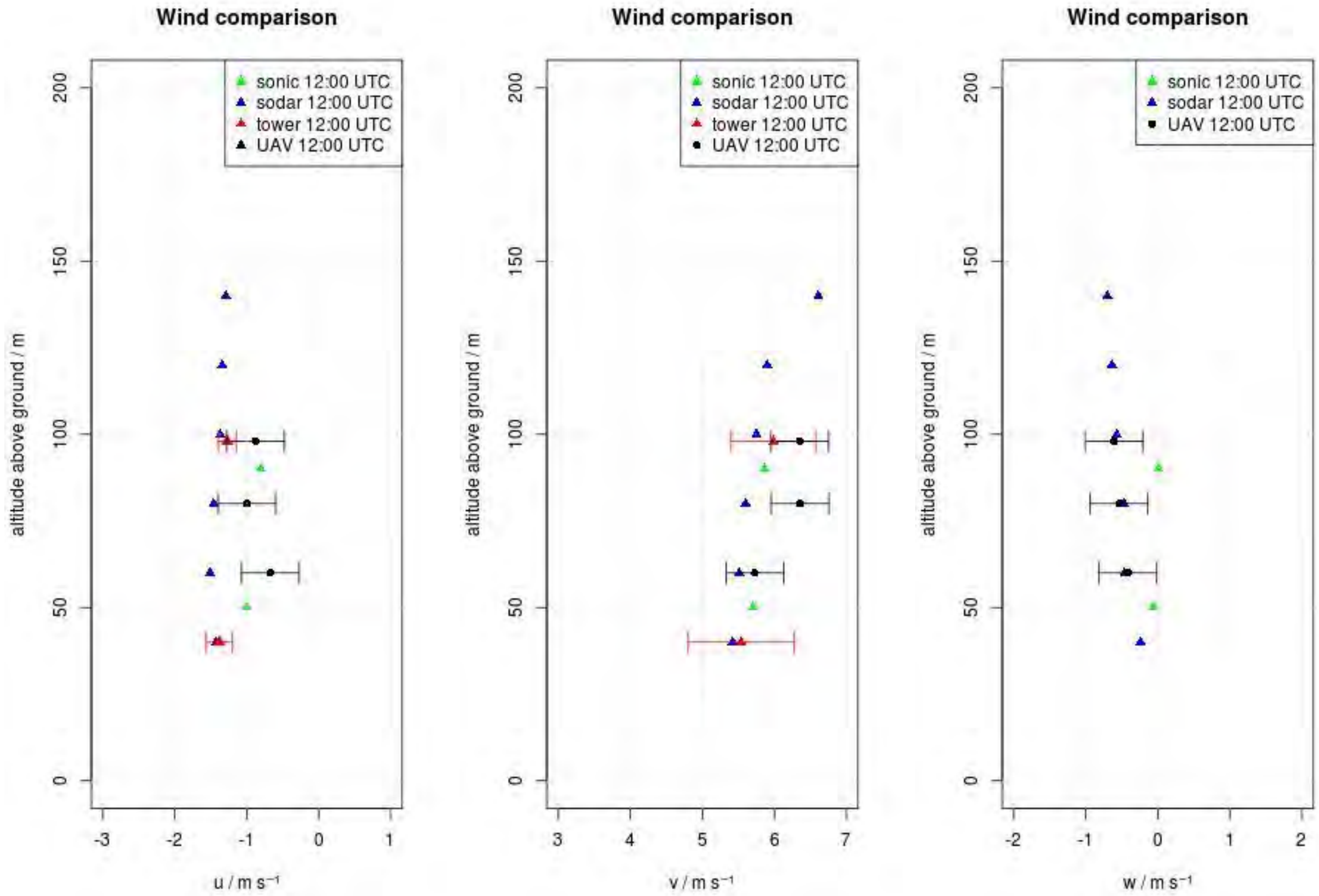
Results

Flight on 21st September 12:00 UTC



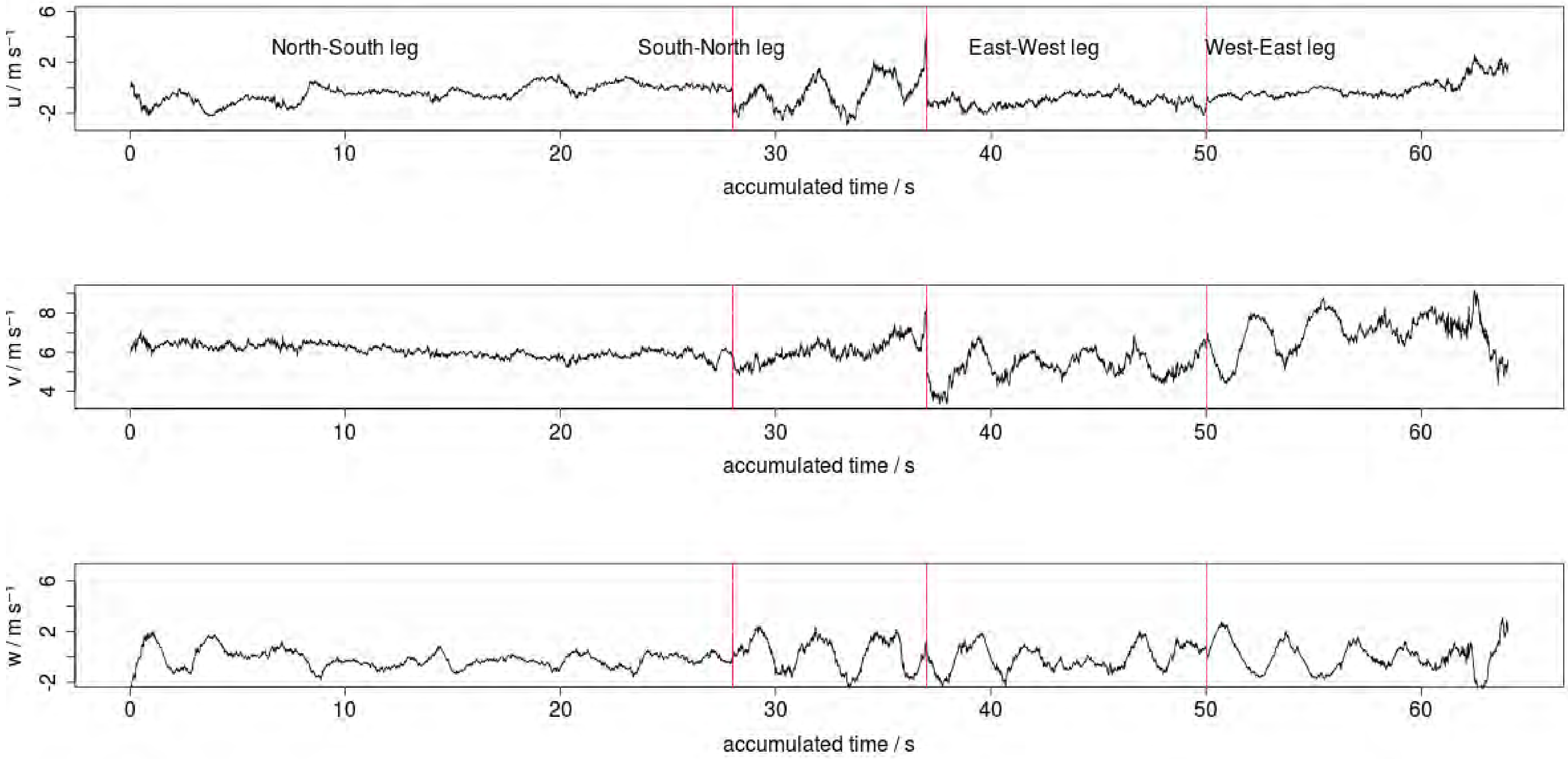
Results

Flight on 21st September 12:00 UTC



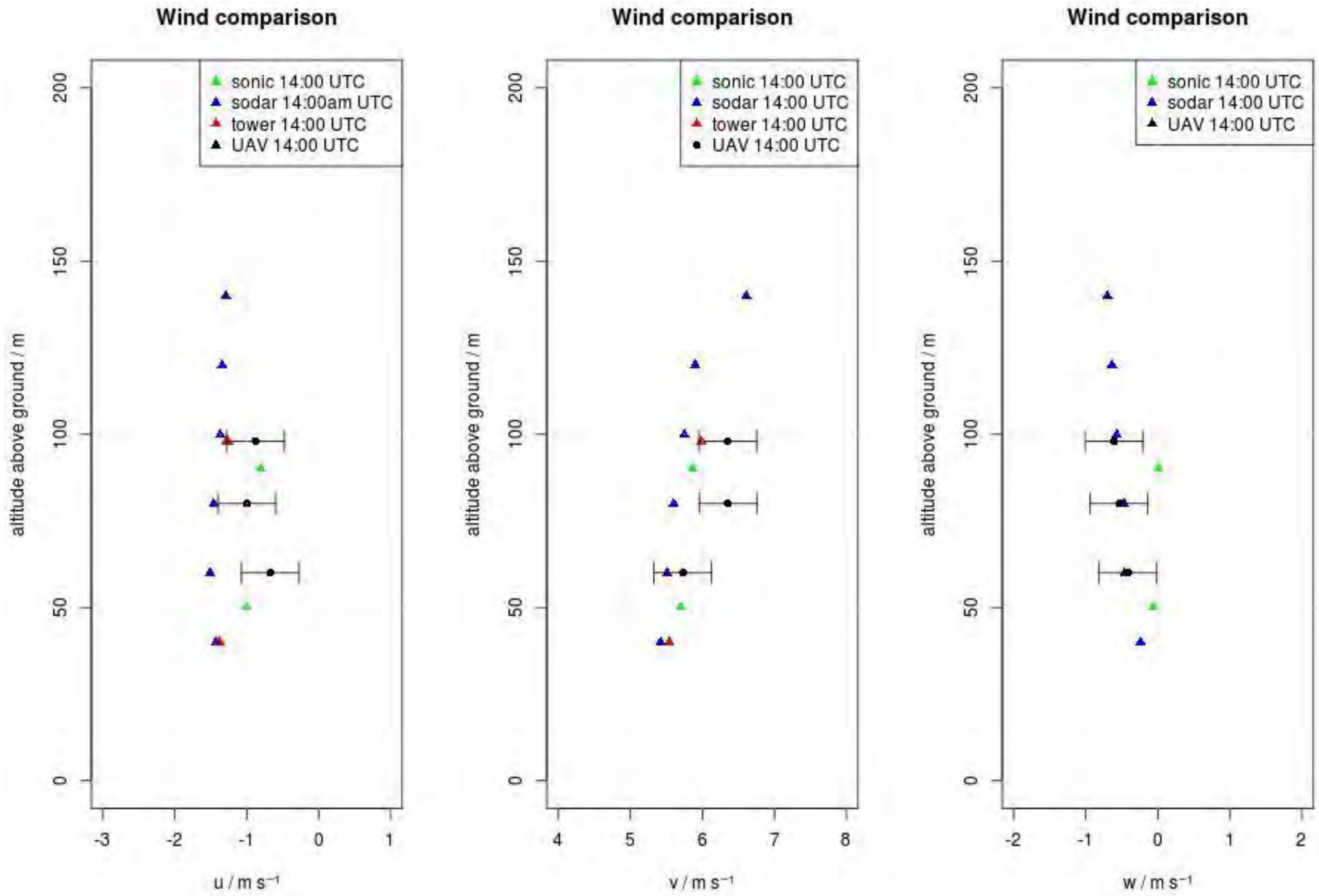
Results

Flight on 21st September 14:00 UTC



Results

Flight on 21st September 14:00 UTC

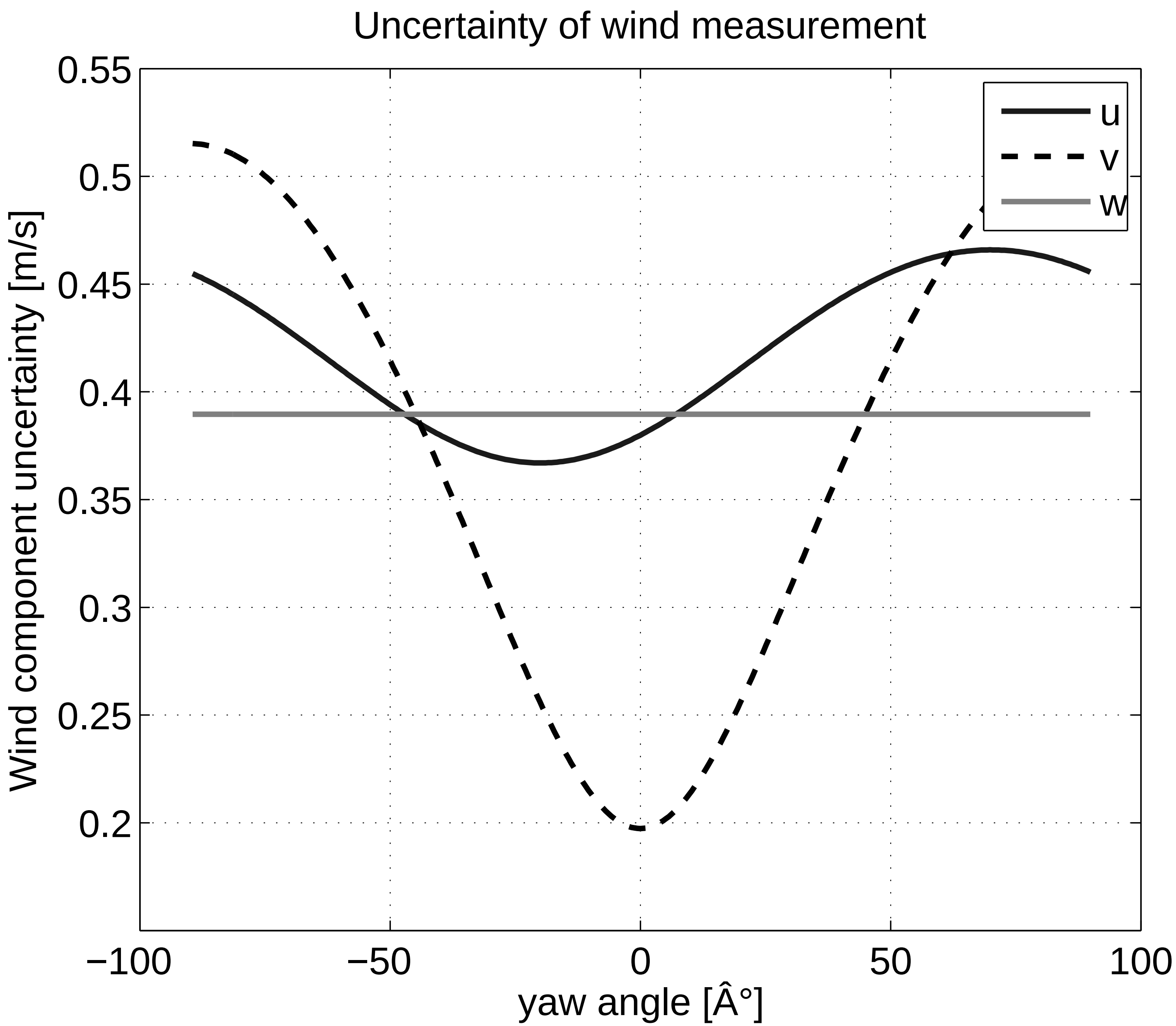


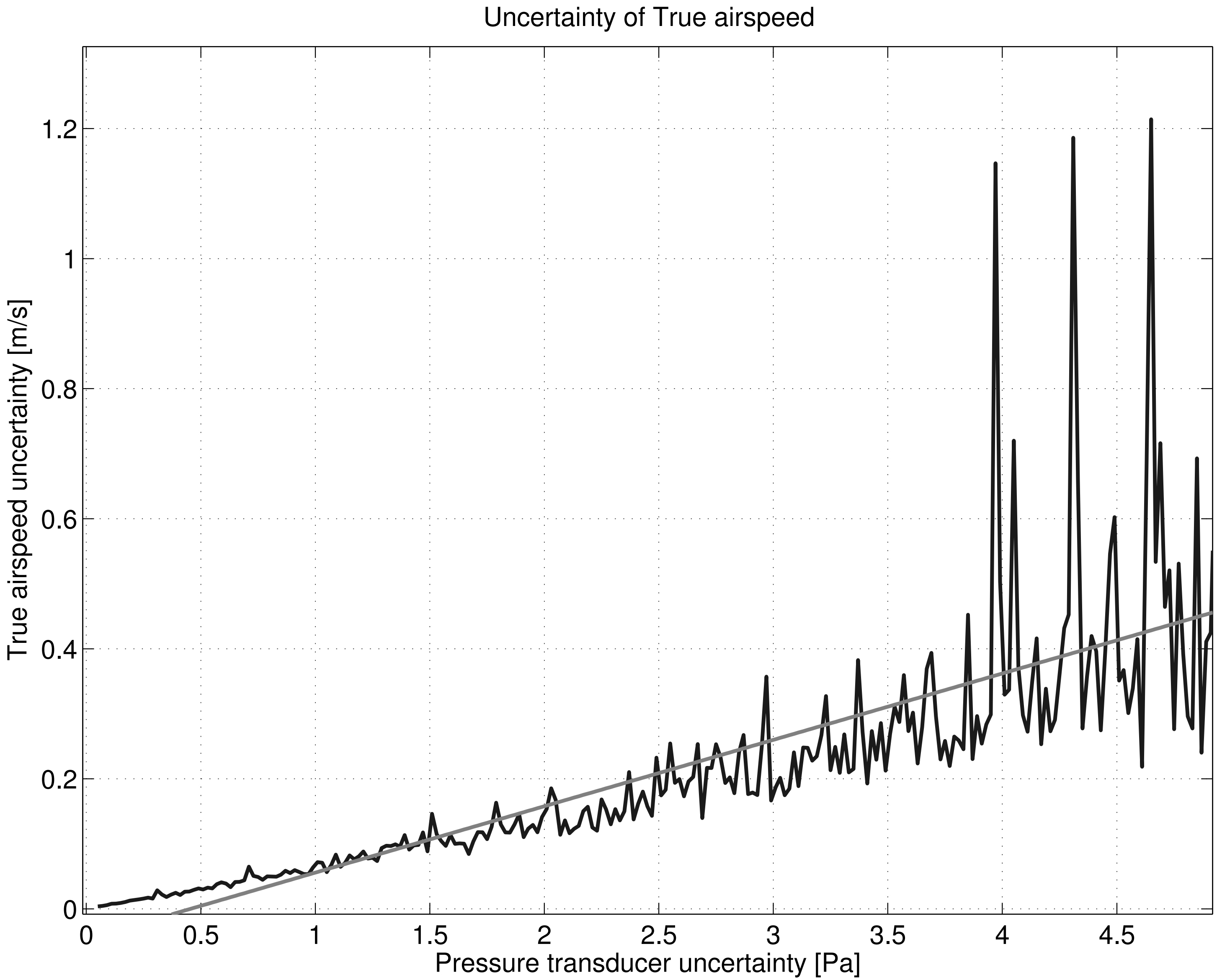
Conclusion and Outlook

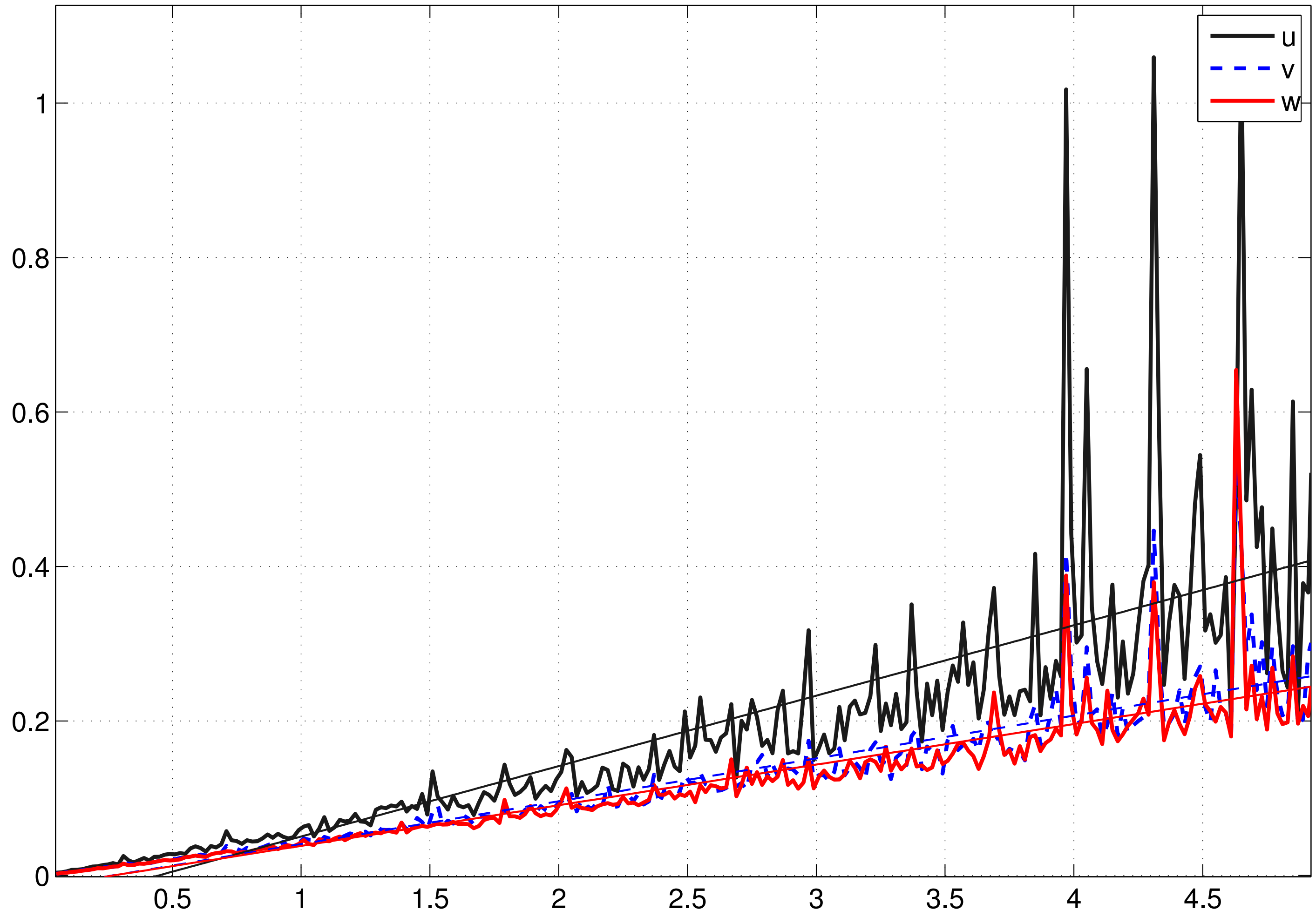
- **spectral resolution of turbulence** fluctuation of $\approx \mathbf{20}$ Hz^{-1}
- Absolute wind error: $\varepsilon_{total_{MAX}} = \pm\mathbf{0.49}$ m/s
- Average wind fits good with ground based measurements

- Mathematical error propagation of the IMU error
- Spectral resolution of turbulence fluctuation depending on the turbulence intensity of the atmosphere
- Compare turbulence measurements with ground based measured turbulence fluxes

Appendix


Uncertainty of wind measurement
Wind component uncertainty [m/s]
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
−100
−50
0
50
100
yaw angle [Â°]
u
v
w


Uncertainty of True airspeed
True airspeed uncertainty [m/s]
Pressure transducer uncertainty [Pa]
0
0.2
0.4
0.6
0.8
1
1.2
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5


u
v
w
1
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5

In-flight Calibration

$\Longrightarrow$ **in-flight calibration** to minimize these errors

Square Pattern: Legs: North-South, West-East, South-North, East-West

For every horizontal leg mean values of the measured time series are calculated.

$\overline{\tilde{\boldsymbol{U}}}_a$, $\overline{\alpha}$, $\overline{\beta}$, $\overline{\Theta}$, $\overline{\Psi}$, $\overline{\Phi}$, $\overline{u}_{Ag}$,$\overline{v}_{Ag}$ and $\overline{w}_{Ag}$

$$\Theta \Rightarrow \overline{\Theta} + \Delta\Theta' \tag{13}$$

$$\Psi \Rightarrow \overline{\Psi} + \Delta\Psi' \tag{14}$$

$$\boldsymbol{U}_a \Rightarrow \overline{\boldsymbol{U}}_a f_{\boldsymbol{U}_a} \tag{15}$$

In-flight Calibration

$$\overline{u}^n - \overline{u}^s = 0 \, , \qquad \overline{v}^n - \overline{v}^s = 0 \tag{16}$$

$$\overline{u}^w - \overline{u}^e = 0 \, , \qquad \overline{v}^w - \overline{v}^e = 0 \tag{17}$$

$$\overline{w}^n = \overline{w}^s = \overline{w}^w = \overline{w}^e = 0 \tag{18}$$

where n, s, w, and e indicate north, south, west, or east flight direction.

The unknown angles $\Delta\Theta'$, $\Delta\Psi'$, and $f_{\boldsymbol{U}_a}$ are calculated from (13-15) where u,v , and w are calculated by (5) using the substitutions from (10-12). The Levenberg–Marquardt least squares fit method (Press et al. 1992) is used to solve the equations.