Investigating the potential of turbulence measurements with the RPAS SUMO

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Outline

- Motivation
- The SUMO system
  - The 5-hole probe
- Wind tunnel testing
  - Comparison to hot-wire anemometer
  - Tubing length variation
- Calculation methods
  - 3D turbulent wind vector
- BLLAST
  - Comparison to 60 m tower (TKE and u*)
  - TKE profiles from SUMO
- Summary
- Future work

- New sensors available for RPAS
- RPAS: small, inexpensive and flexible
- Operation close to the ground
- Operation in and around wind farms
- SUMO (GFI)

Picture by Jesper Hjelme, IWAL.

- Wind tunnel experiments (2013)

- Two SUMO turbulence datasets available:

BLLAST field campaign (2011)

Nøjsomheds Odde wind farm (2011)

http://Map-France.com

Giebel et.al (2011)

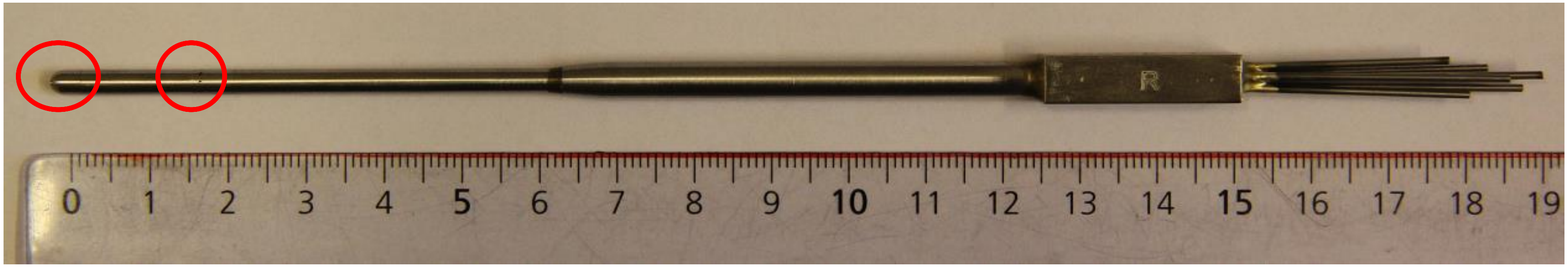
The 5-hole probe (OTF)

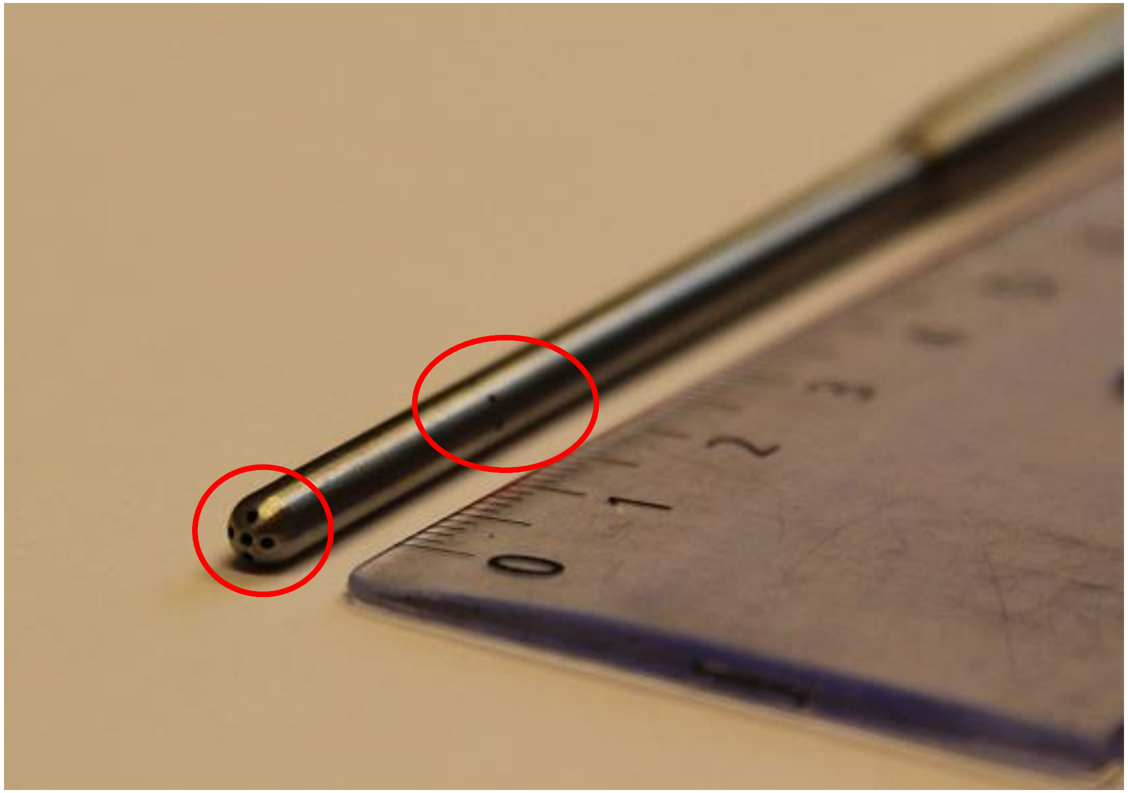
- Newly integrated sensor
- 3D turbulent wind
- 100 Hz temporal resolution
- Static and differential pressure

Reuder et. al (2012)

On-The-Fly user manual (2011)

Figures from Reuder et. al (2012) and Reuder & Jonassen (2012)

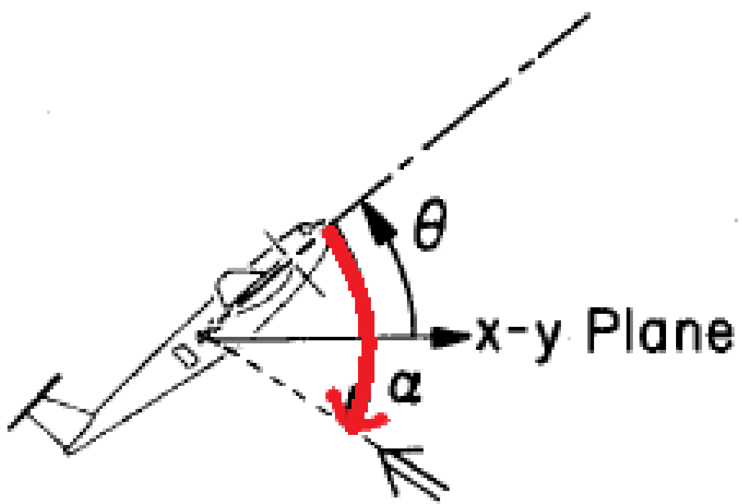


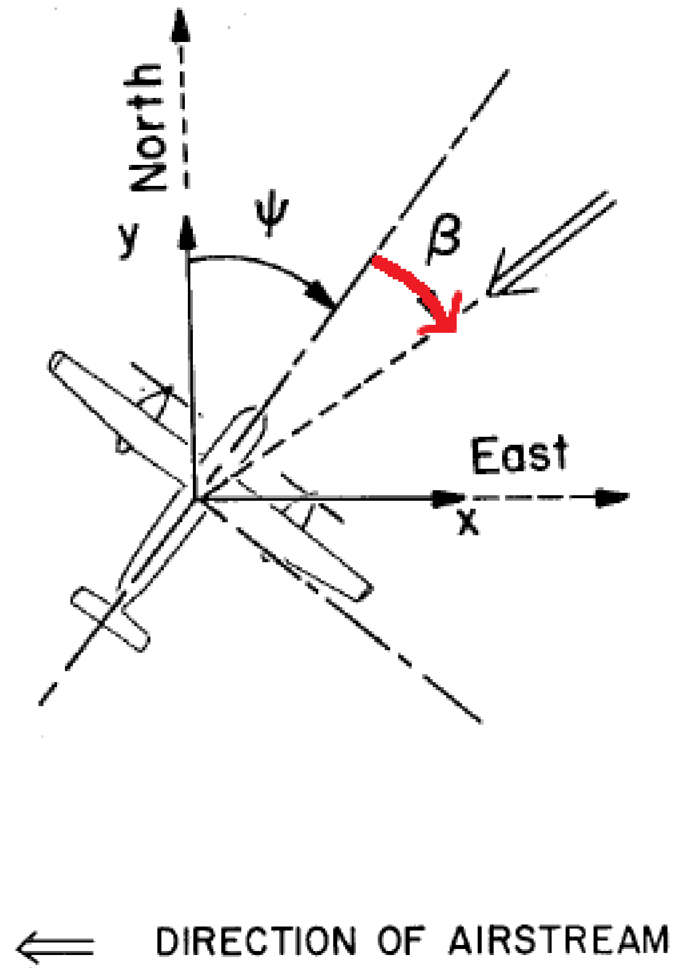


Pictures by Joachim Reuder

Output from the 5-hole probe

- True airspeed, U_a
- Angle of attack, α
- Angle of sideslip, β
- Altitude

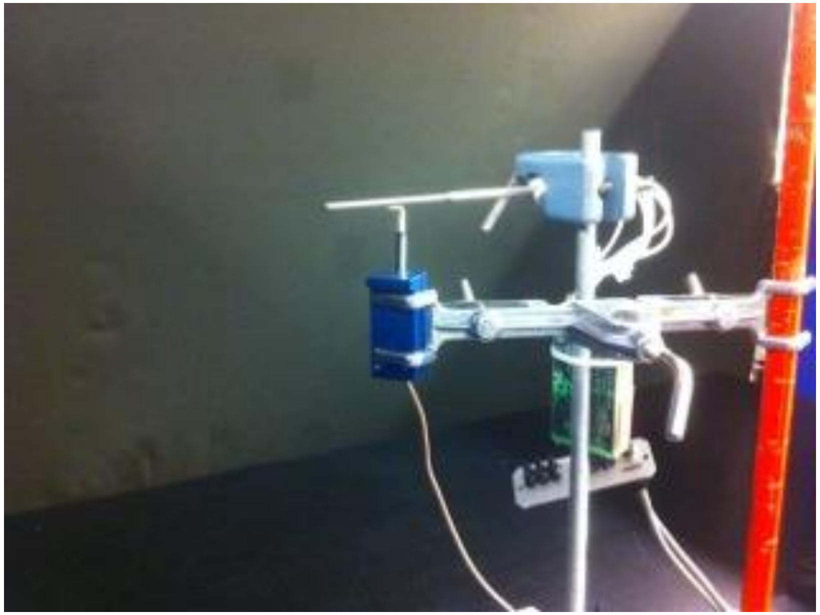


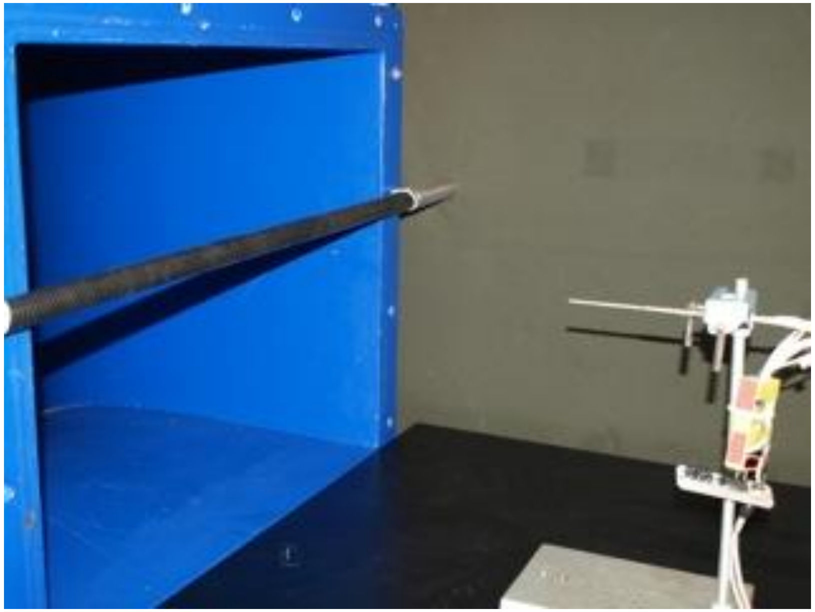


Figures from Lenschow (1986)

Wind tunnel experiments

- Comparison to hot-wire anemometer (HD)
- Tubing length variation

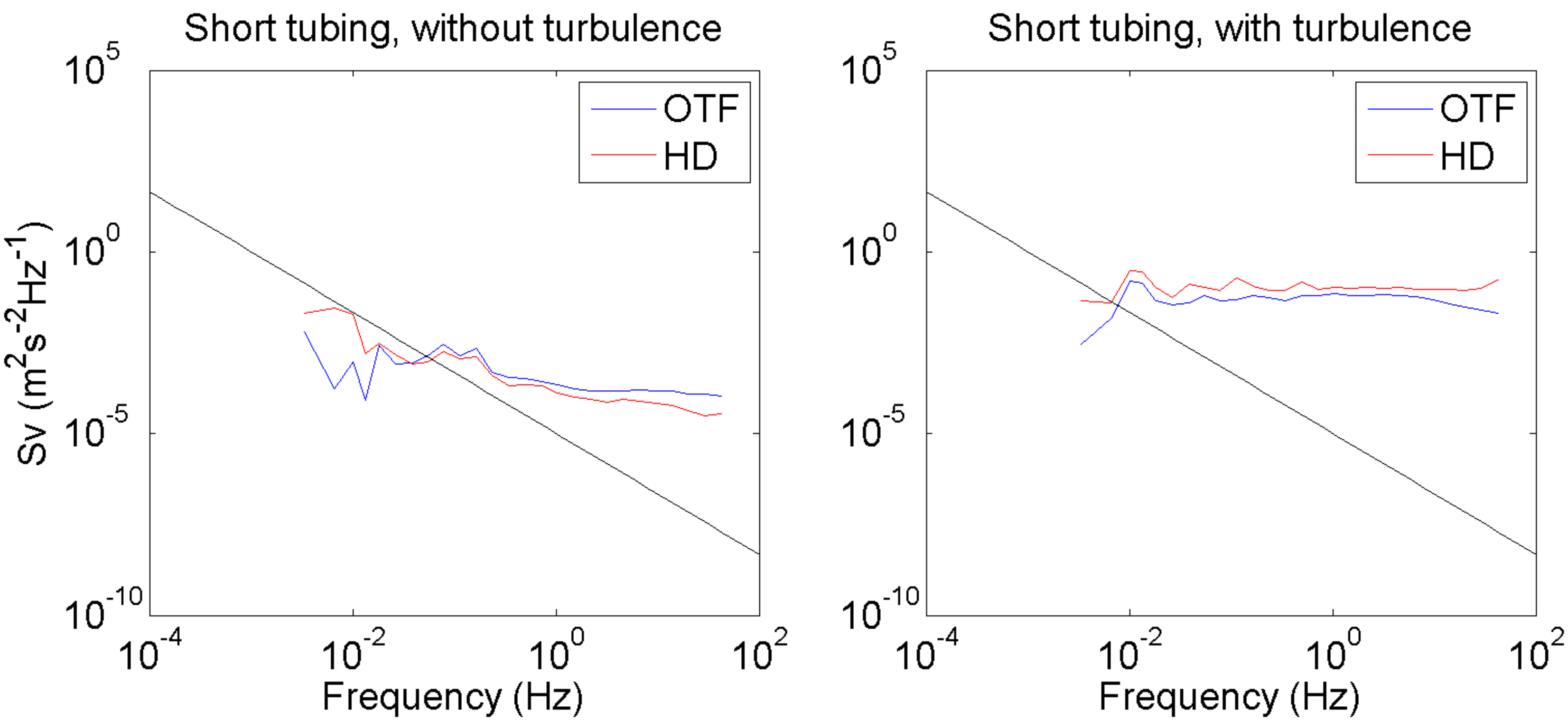




Pictures by Sebastian Wein

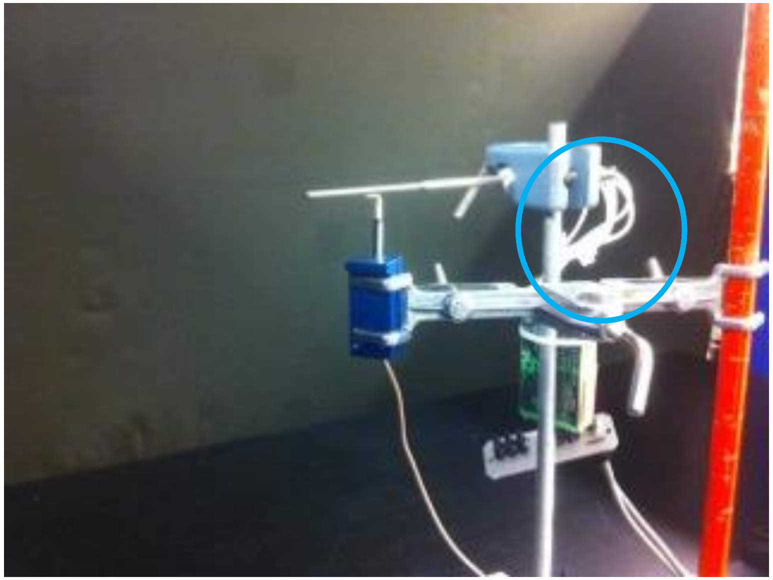
Comparion to hot-wire anemometer

- OTF responds to energy shift
- Similar response as the HD
- Difference in variability



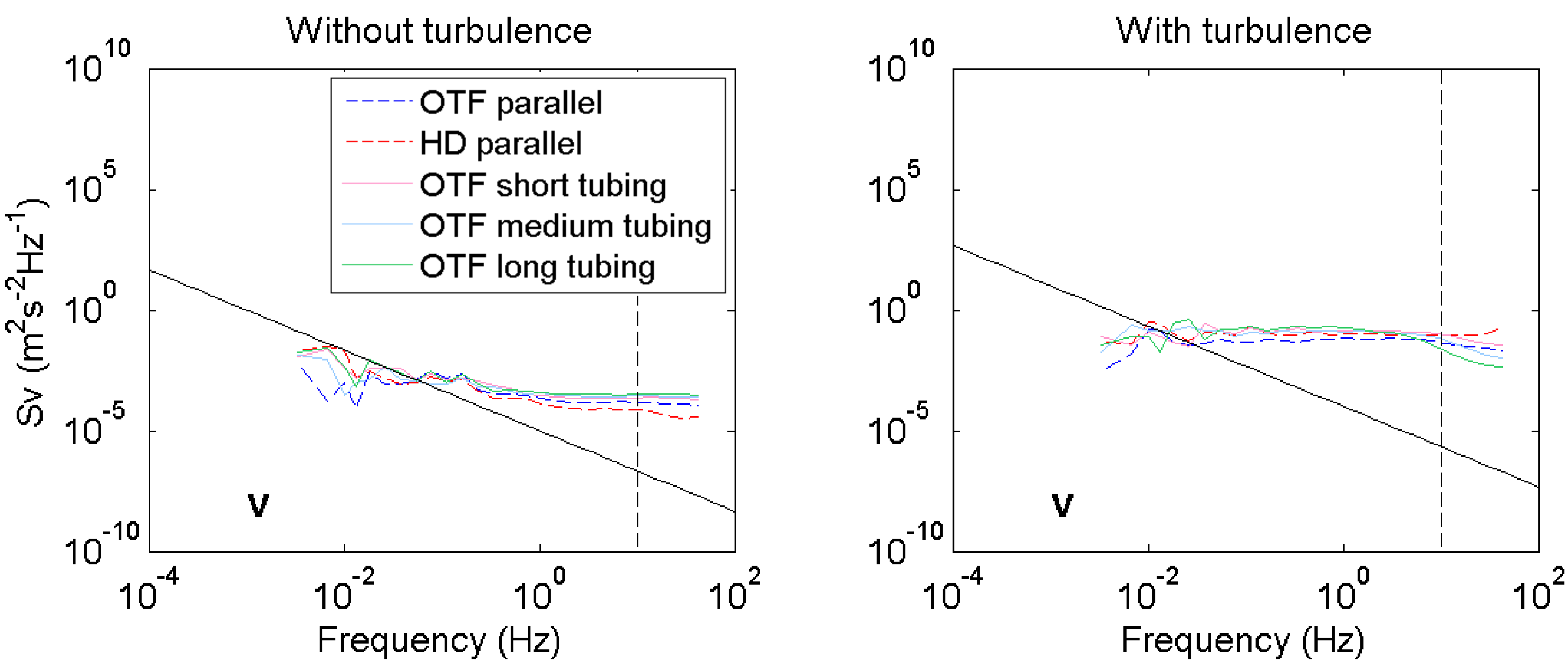
Tubing length variation

- 15 cm
- 30 cm
- 90 cm



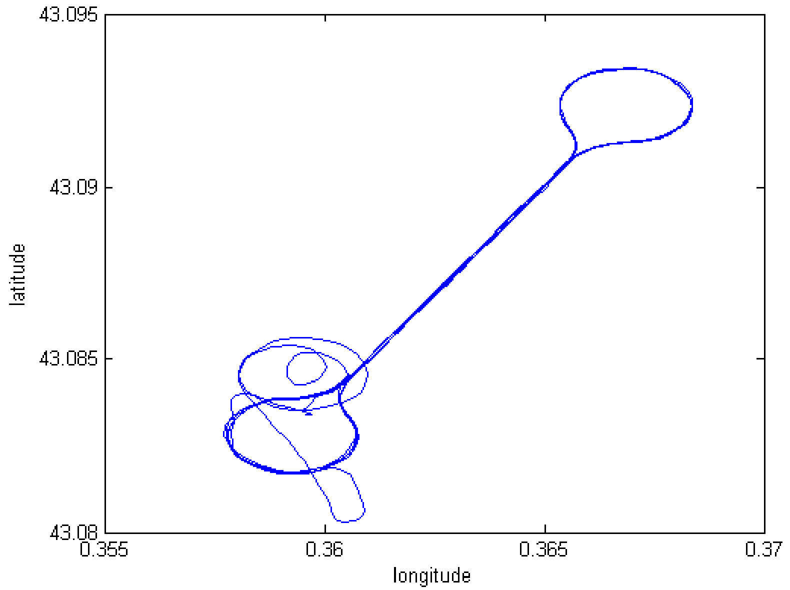
Tubing length variation

- Non-turbulent: similar behavior
- Turbulent: difference from around 10 Hz
- Similar for α and β



Theory and methods

- Synchronization of 5-hole probe and attitude information
- Select straight flight segments
- Calculate $\vec{v}$ = (u,v,w)



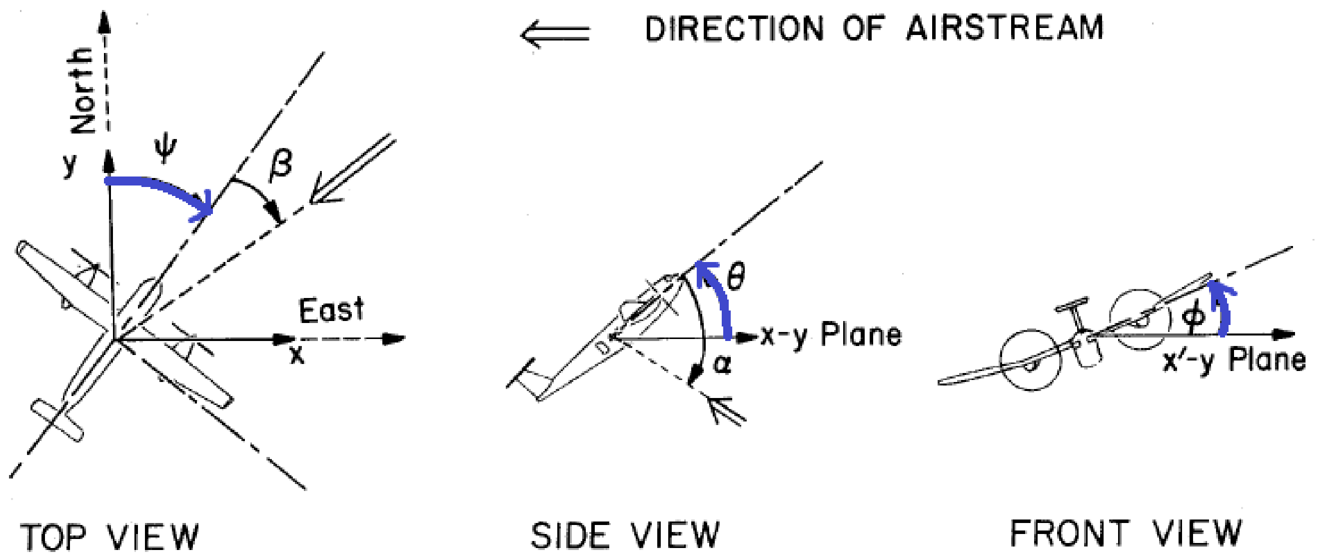
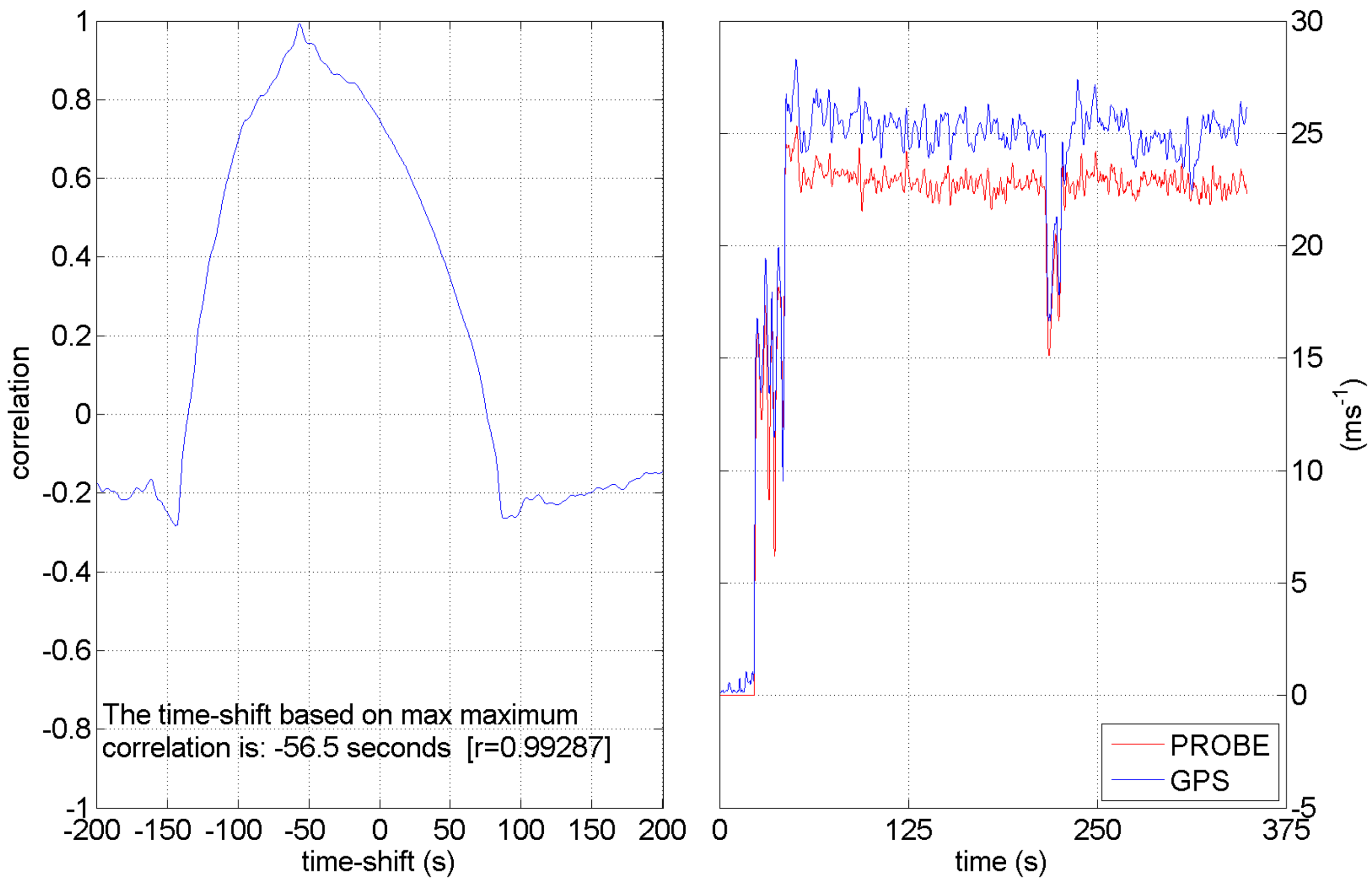
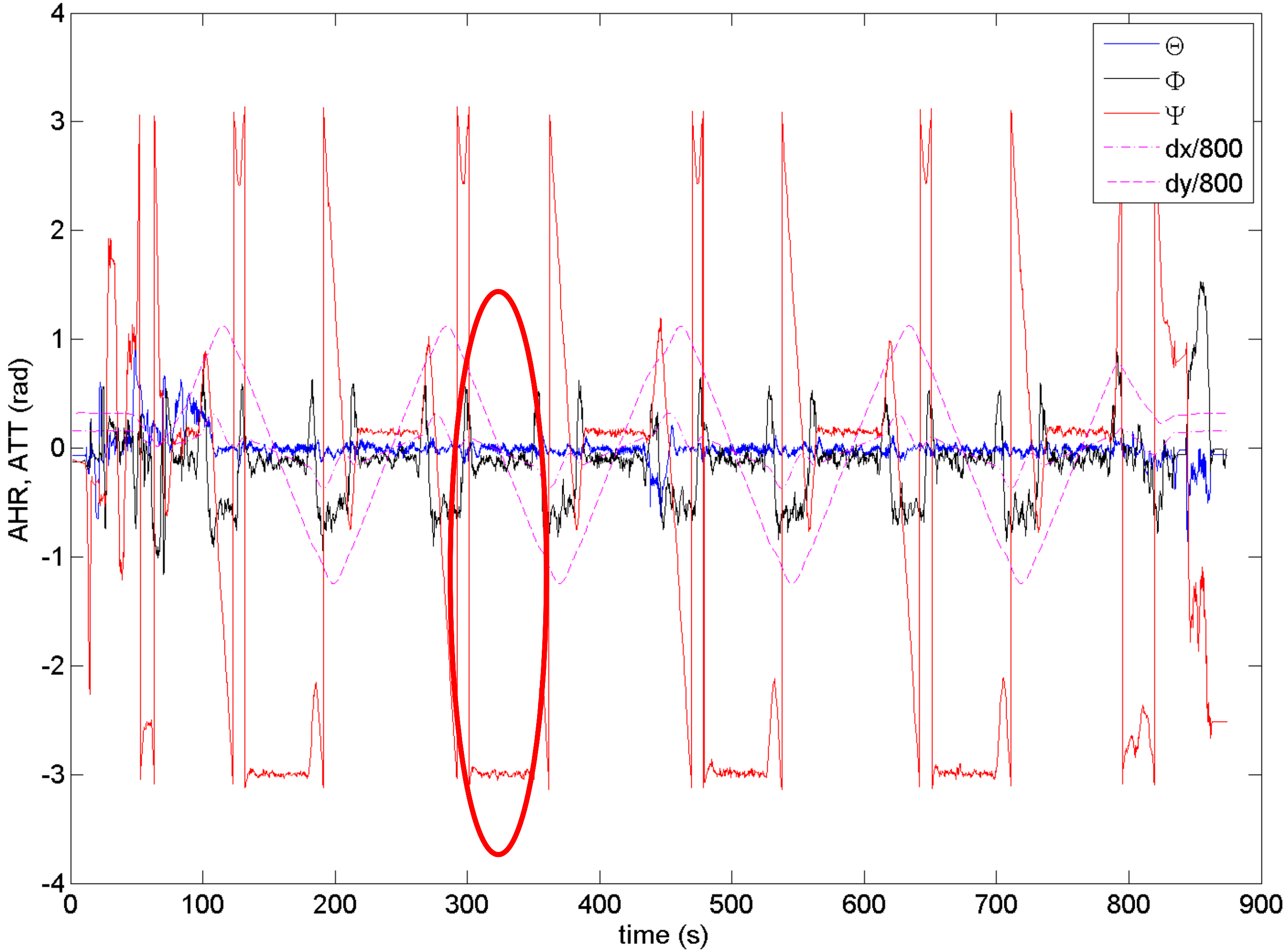


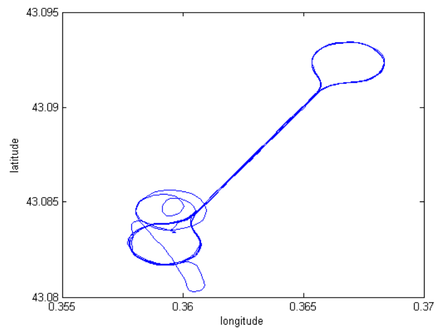
Figure from Lenschow (1986)

Synchronization of 5-hole probe measurements and attitude information



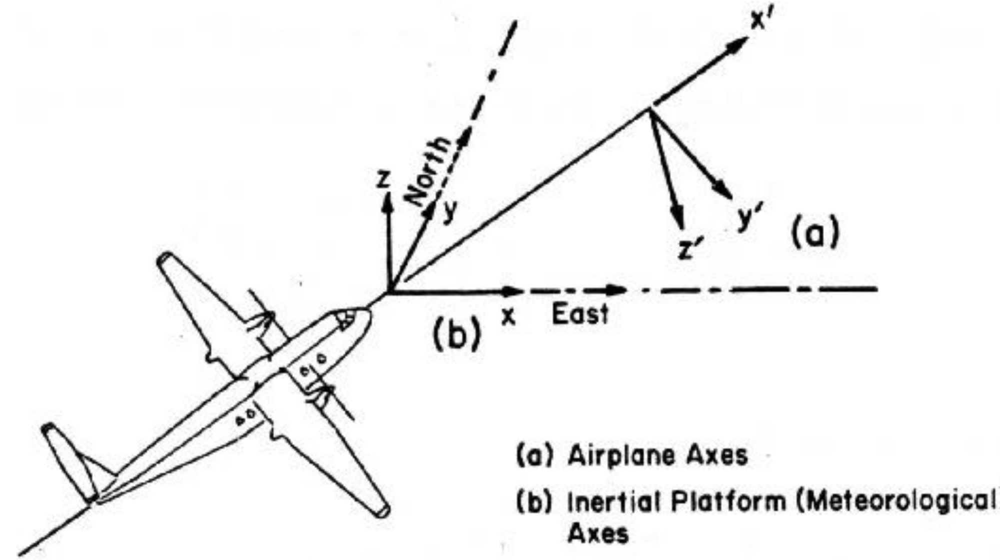
Selecting the straight flight segments

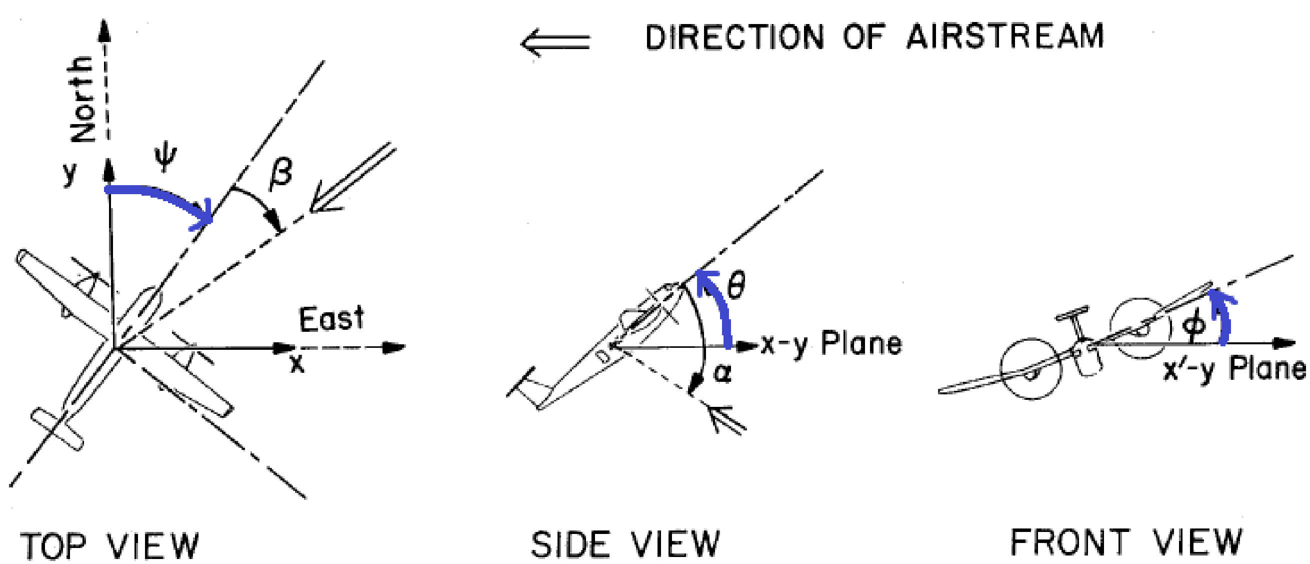




Calculating $\vec{v}$

- $\vec{v} = \vec{v}_p + \vec{v}_a$
- $\vec{v} = \vec{v}_p + \vec{v}_a + \vec{\Omega}_p \times \vec{R}$





Figures from Lenschow (1986)

Calculating $\vec{v}$

$$u = -UaD^{-1}\begin{pmatrix}\sin\Psi\cos\theta + \tan\beta\,(\cos\Psi\cos\Phi + \sin\Psi\sin\theta\sin\Phi) \\ +\tan\alpha\,(\sin\Psi\sin\theta\cos\Phi - \cos\Psi\sin\Phi)\end{pmatrix}$$
$$+up - L(\dot{\theta}\sin\theta\sin\Psi - \dot{\Psi}\cos\Psi\cos\theta)$$

$$v = -UaD^{-1}\begin{pmatrix}\cos\Psi\cos\theta + \tan\beta\,(\sin\Psi\cos\Phi - \cos\Psi\sin\theta\sin\Phi) \\ +\tan\alpha\,(\cos\Psi\sin\theta\cos\Phi + \sin\Psi\sin\Phi)\end{pmatrix}$$
$$+vp - L(\dot{\Psi}\sin\Psi\cos\theta + \dot{\theta}\cos\Psi\sin\theta)$$

$$v = -UaD^{-1}(\sin\theta - \tan\beta\cos\theta\sin\Phi - \tan\alpha\cos\theta\cos\Phi)$$
$$+wp + L\dot{\theta}\cos\theta$$

$$u = -UaD^{-1}\sin(\Psi + \beta) + u_p$$

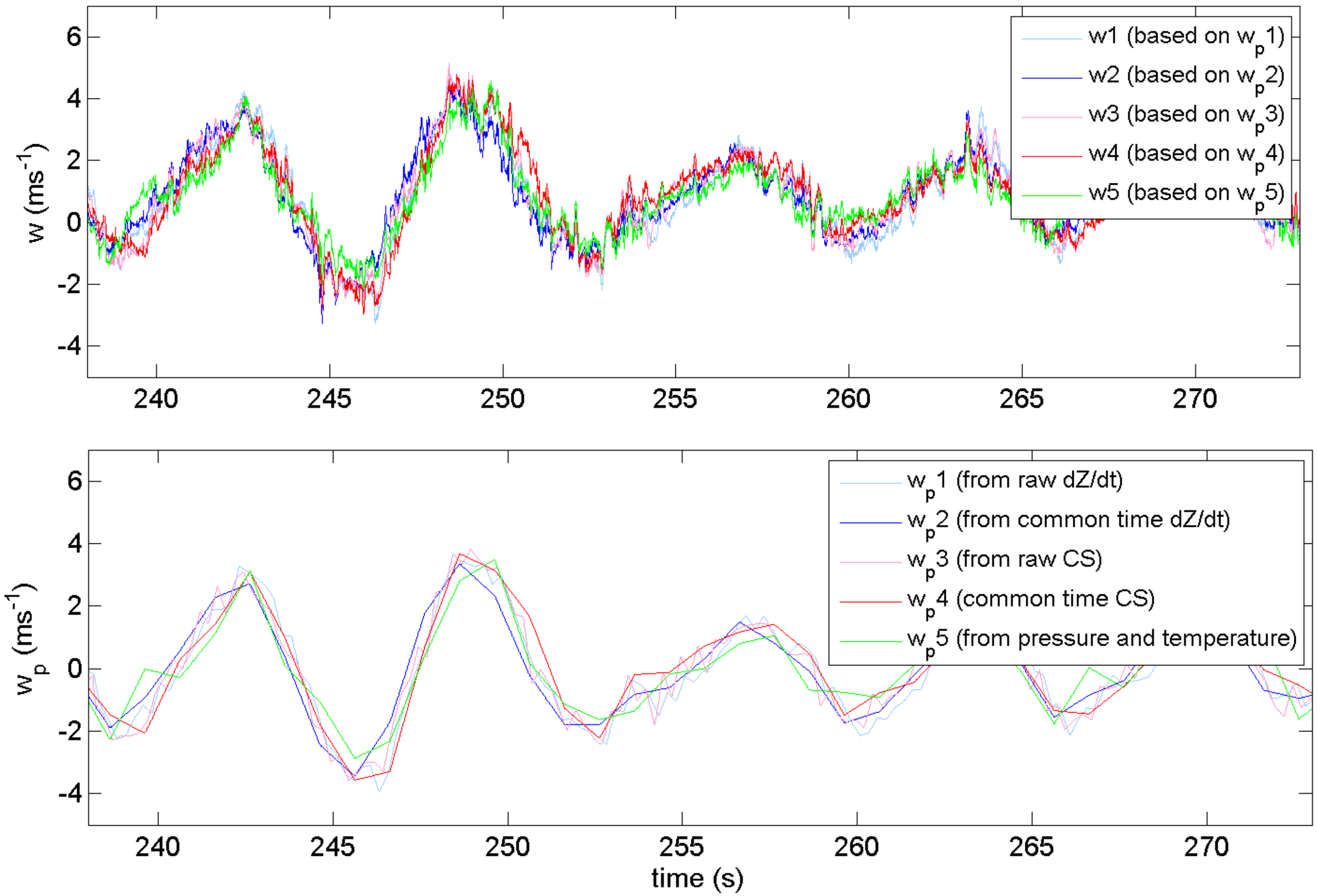
$$v = -U_aD^{-1}\cos(\Psi + \beta) + v_p$$

$$w = -U_aD^{-1}\sin(\theta - \alpha) + w_p$$

$$D = \sqrt{1 + \tan^2\alpha + \tan^2\beta}$$

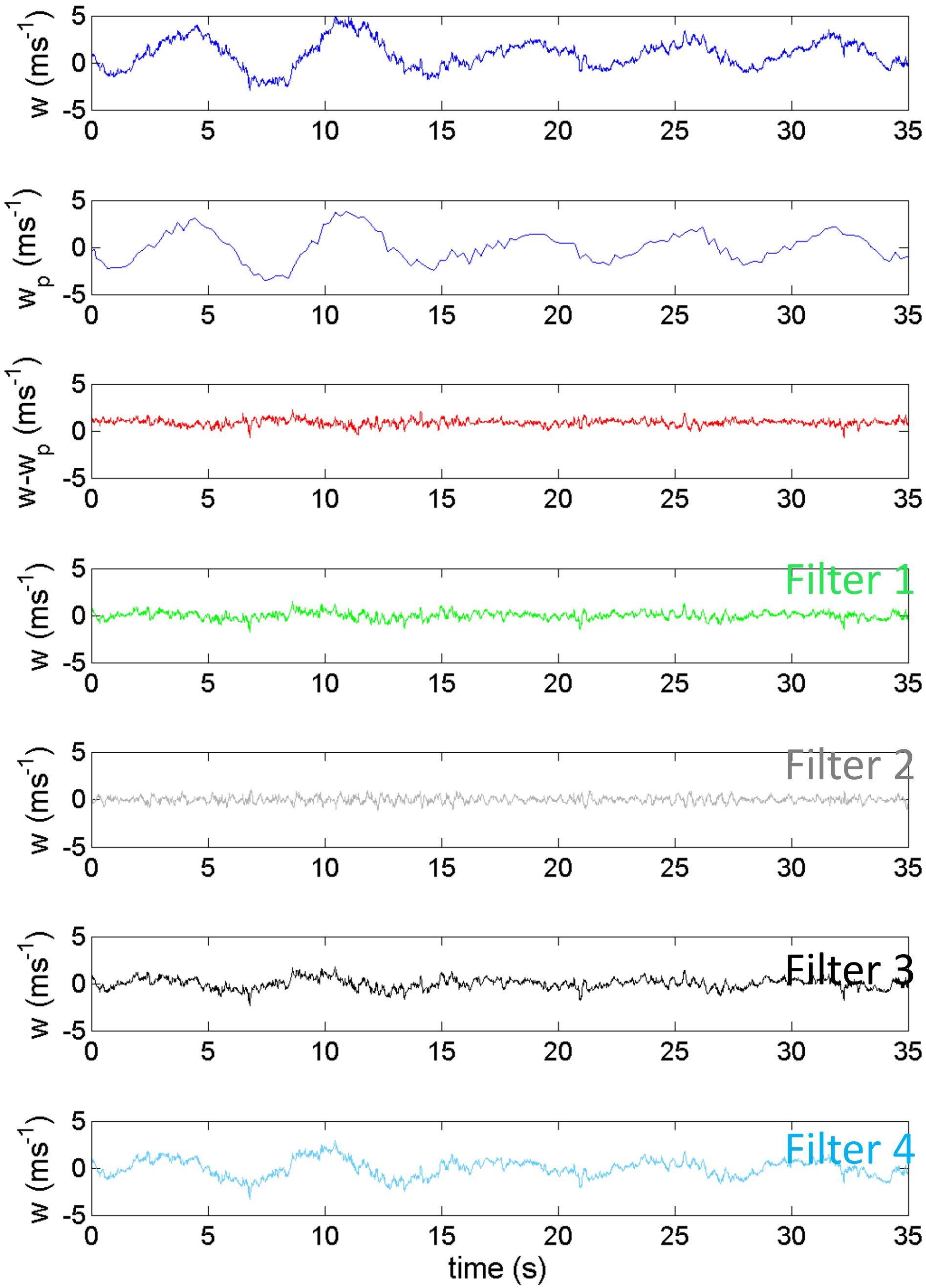
Calculating $\vec{v}$

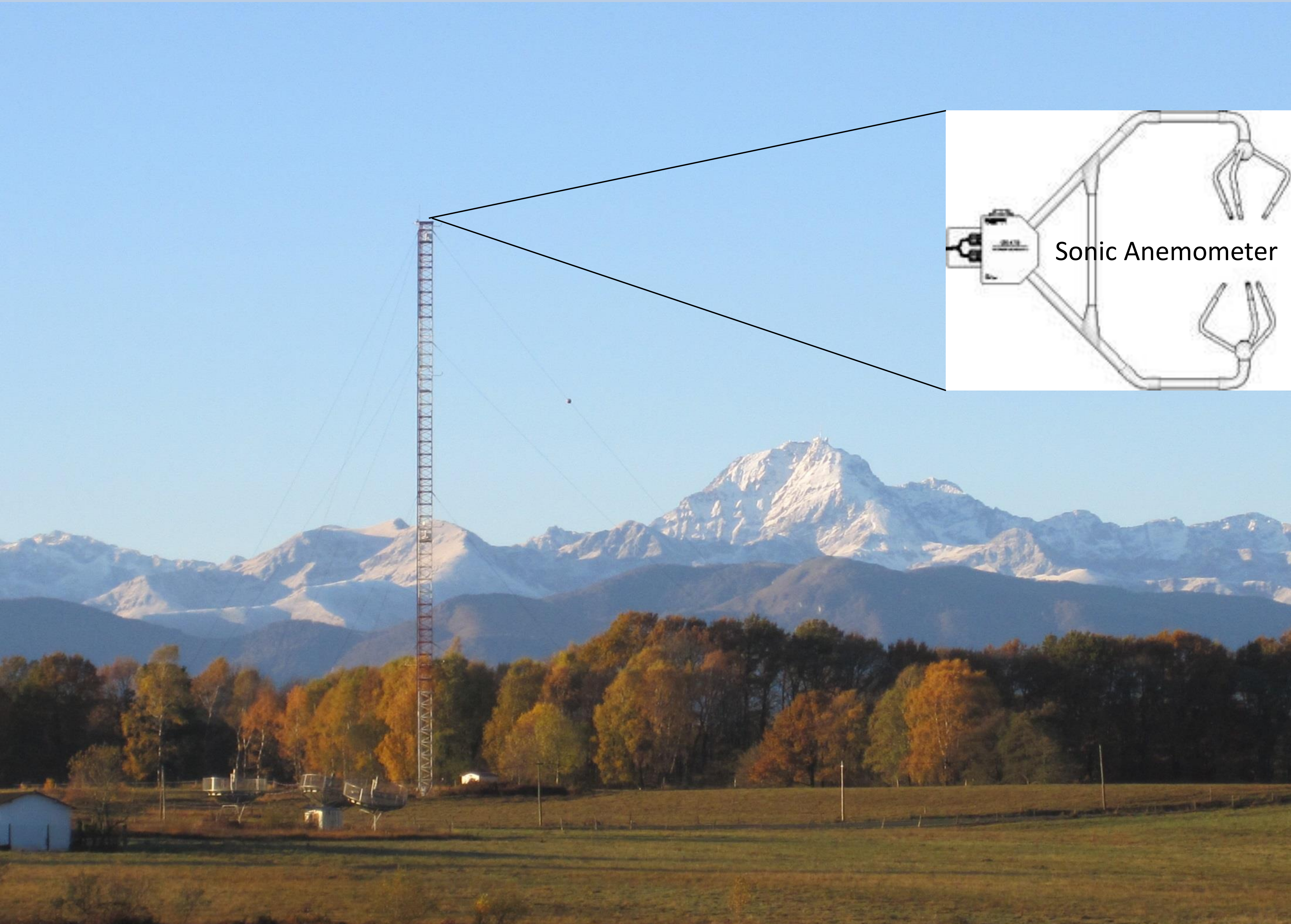
$$w = -UaD^{-1}\sin(\theta - \alpha) + w_p$$



Calculating $\vec{v}$: Highpass filter

- Remove $\vec{v}_p$
- Butterworth filter
- Different cutoff frequency and filter order



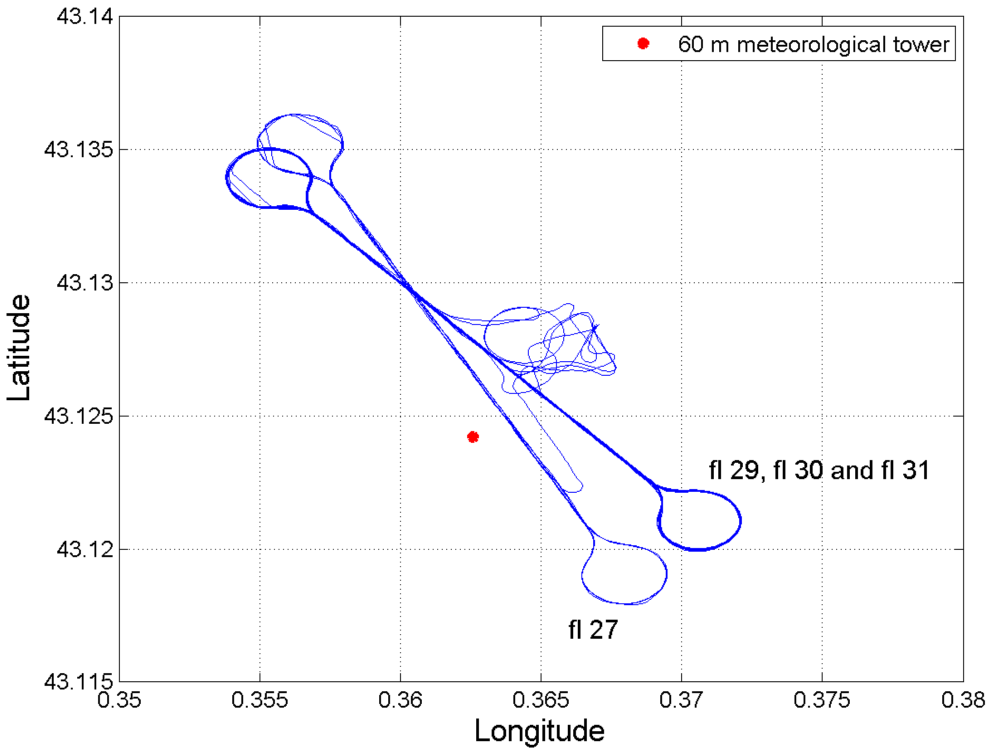

Sonic Anemometer

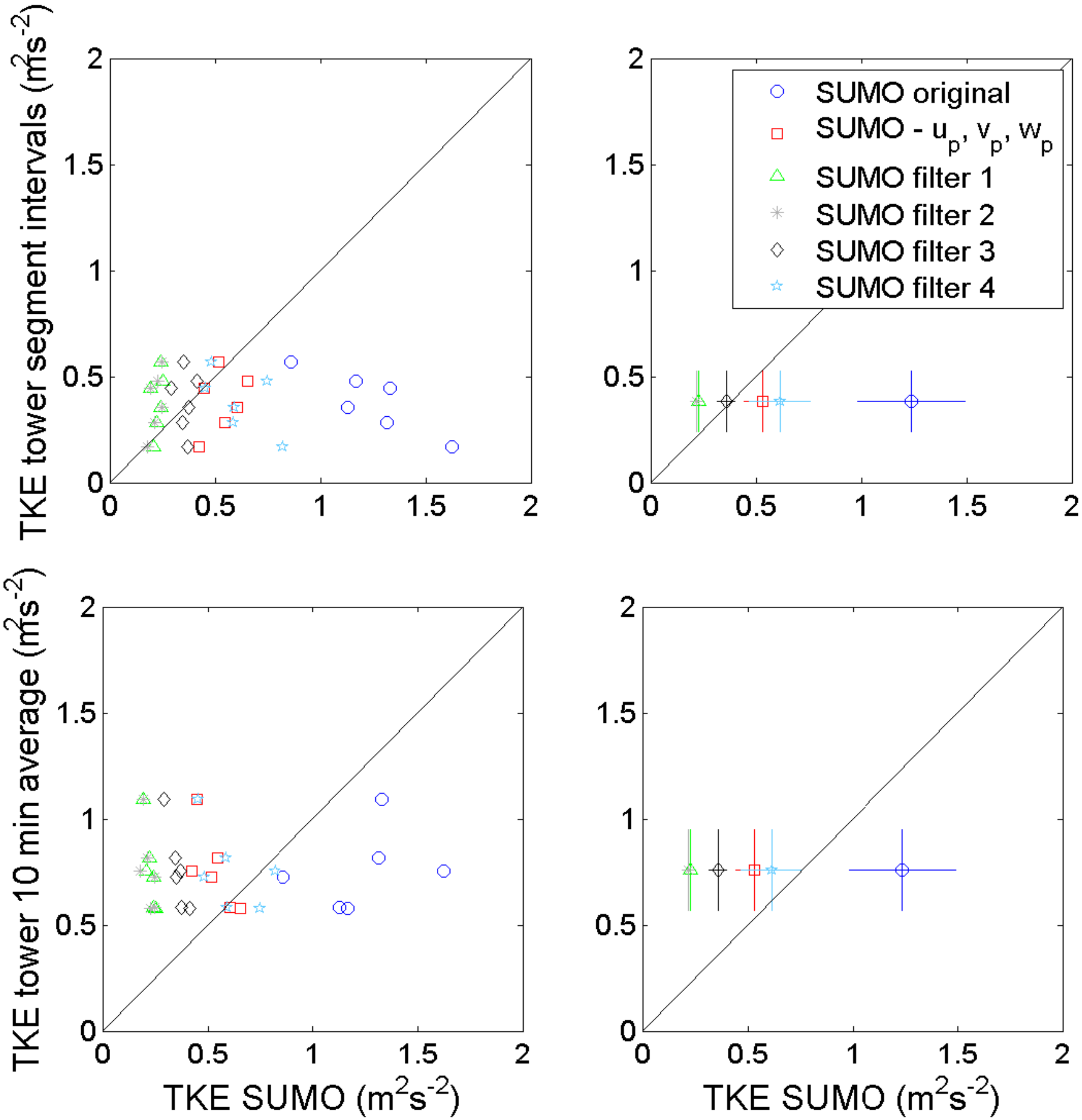
Comparison to a 60 m meteorological tower

- 17 flights in the vicinity of the tower
- 4 flights available for comparison (26 segments)

- $\frac{TKE}{m} = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$

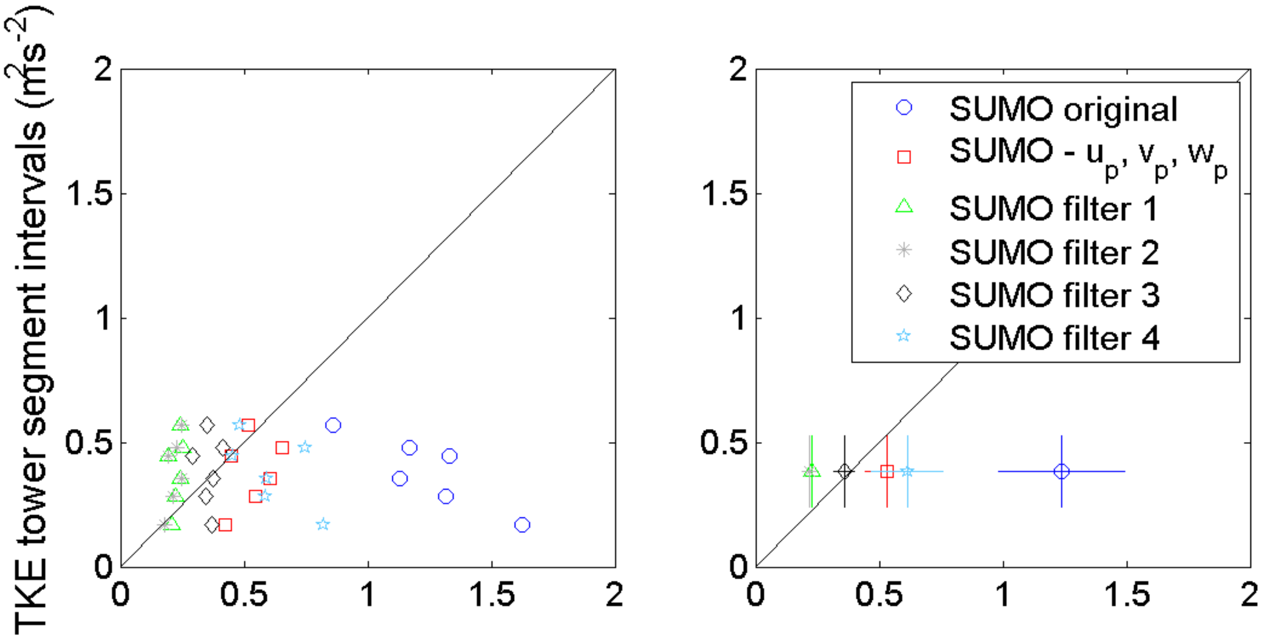
- $u^* = \left(\overline{u'w'}^2 + \overline{v'w'}^2\right)^{1/4}$





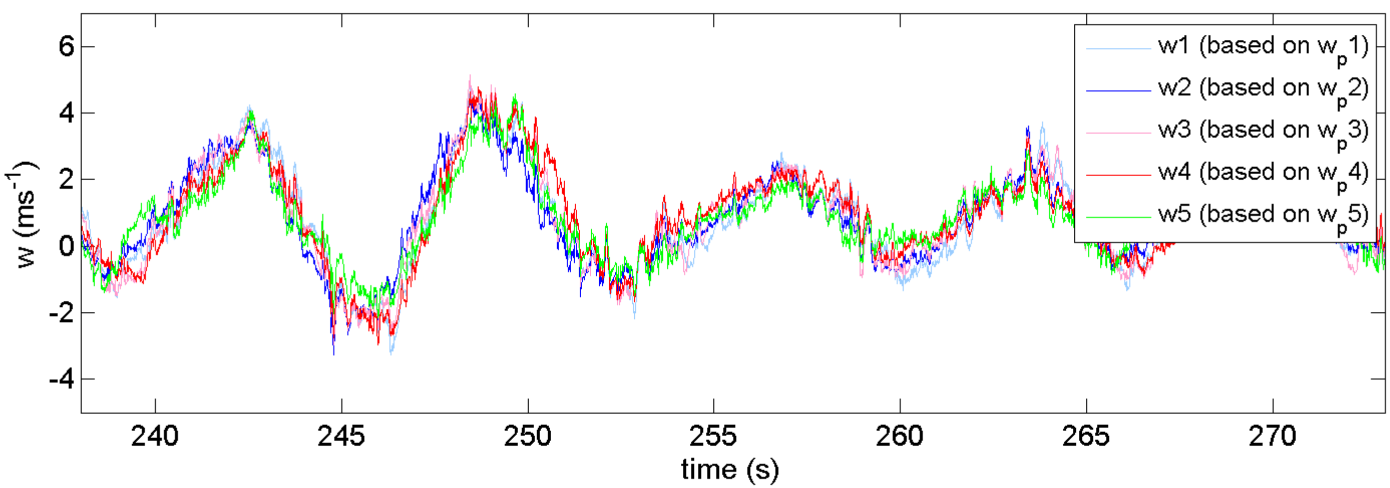
TKE
FL 29

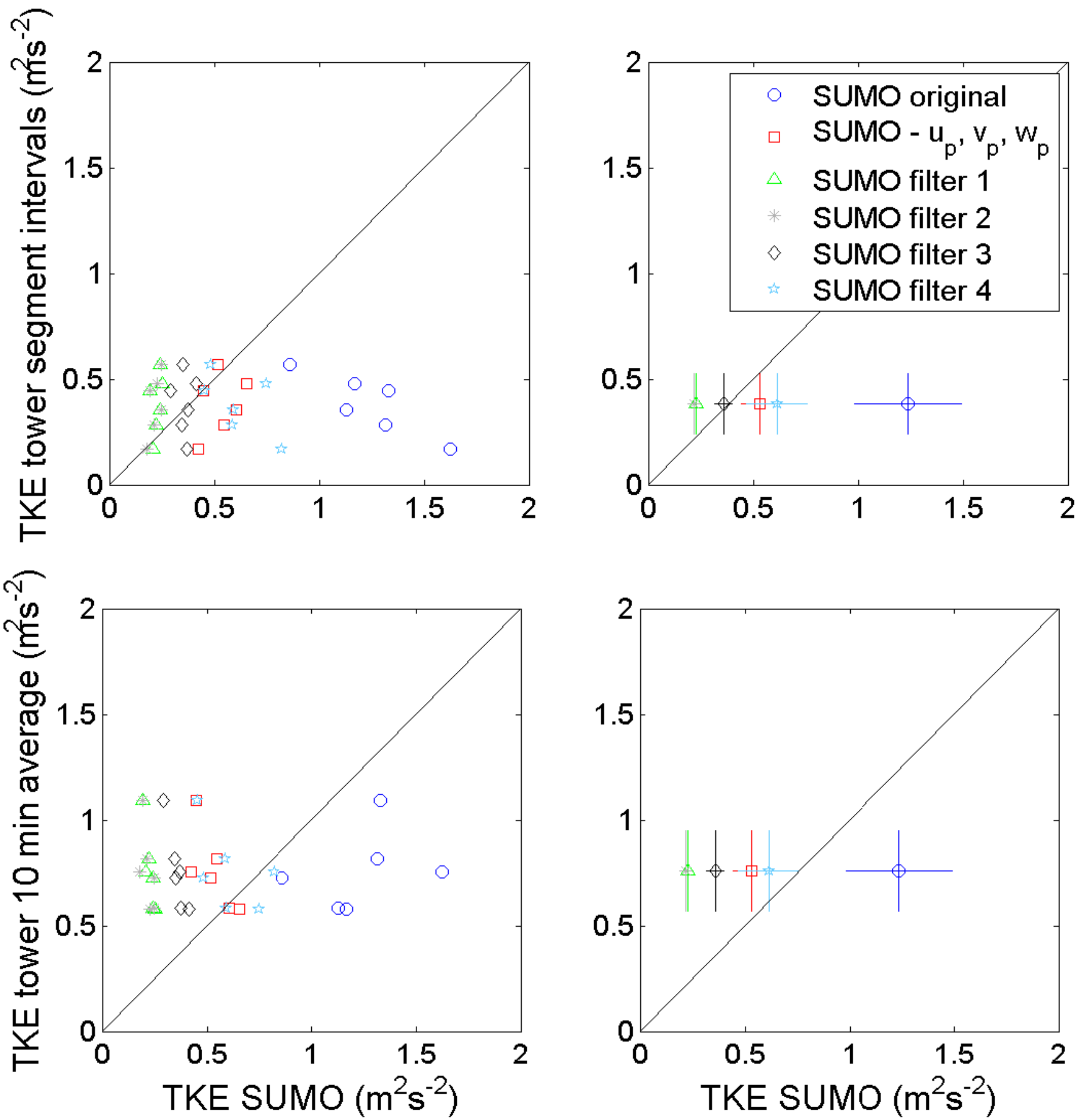
- 6 straight flight segments



TKE
FL 29

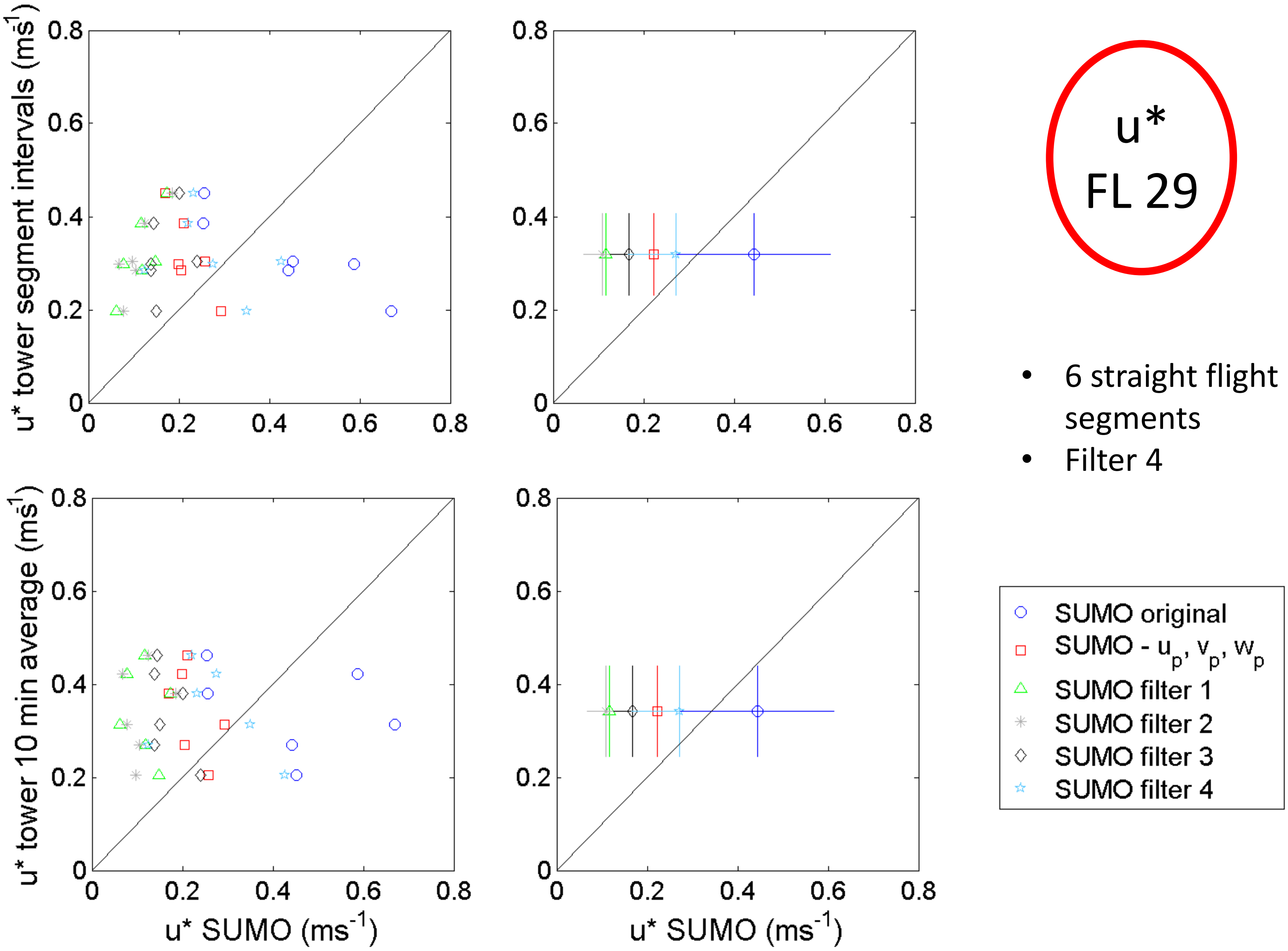
- 6 straight flight segments





TKE
FL 29

- 6 straight flight segments
- Filter 3

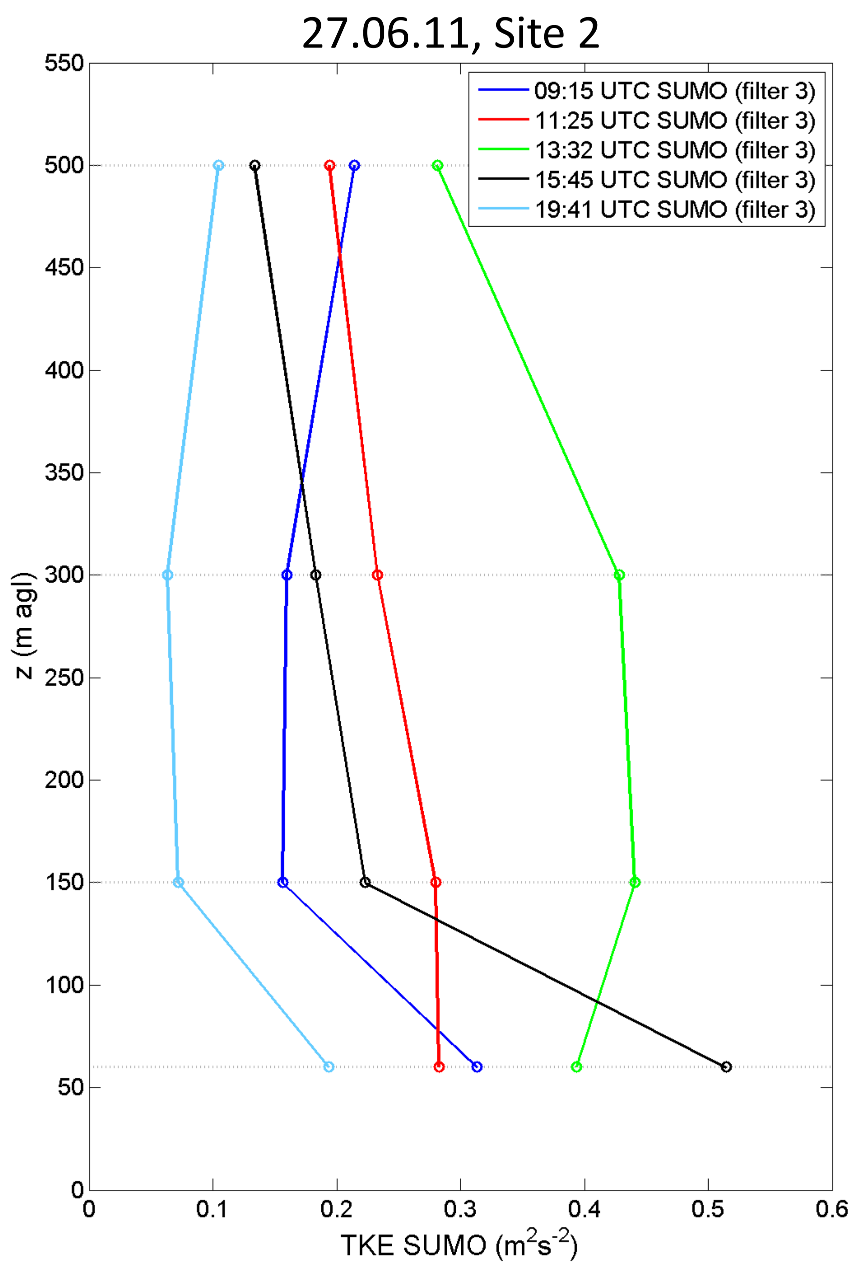


u*
FL 29

- 6 straight flight segments
- Filter 4

TKE profiles

- Low TKE in morning/ evening
- Maximum early afternoon
- Daily evolution mainly driven by buoyancy
- Shear production close to the ground



Summary

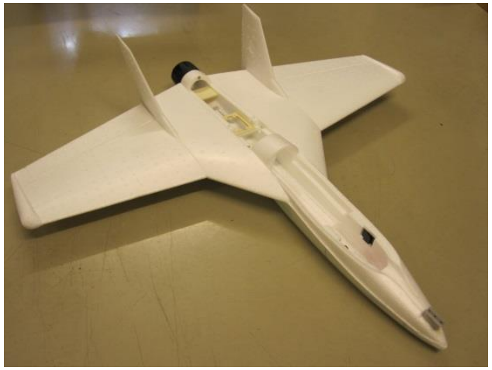
- A new 5-hole probe sensor

- Wind tunnel testing
  - 5-hole probe able to react to turbulence ($\sim$20 Hz)
  - Tubing of 15 cm

- BLLAST
  - SUMO overestimate TKE and u* due to aircraft movement
  - Highpass filter improve the results
  - SUMO capture daily TKE evolution by profiles

Future work

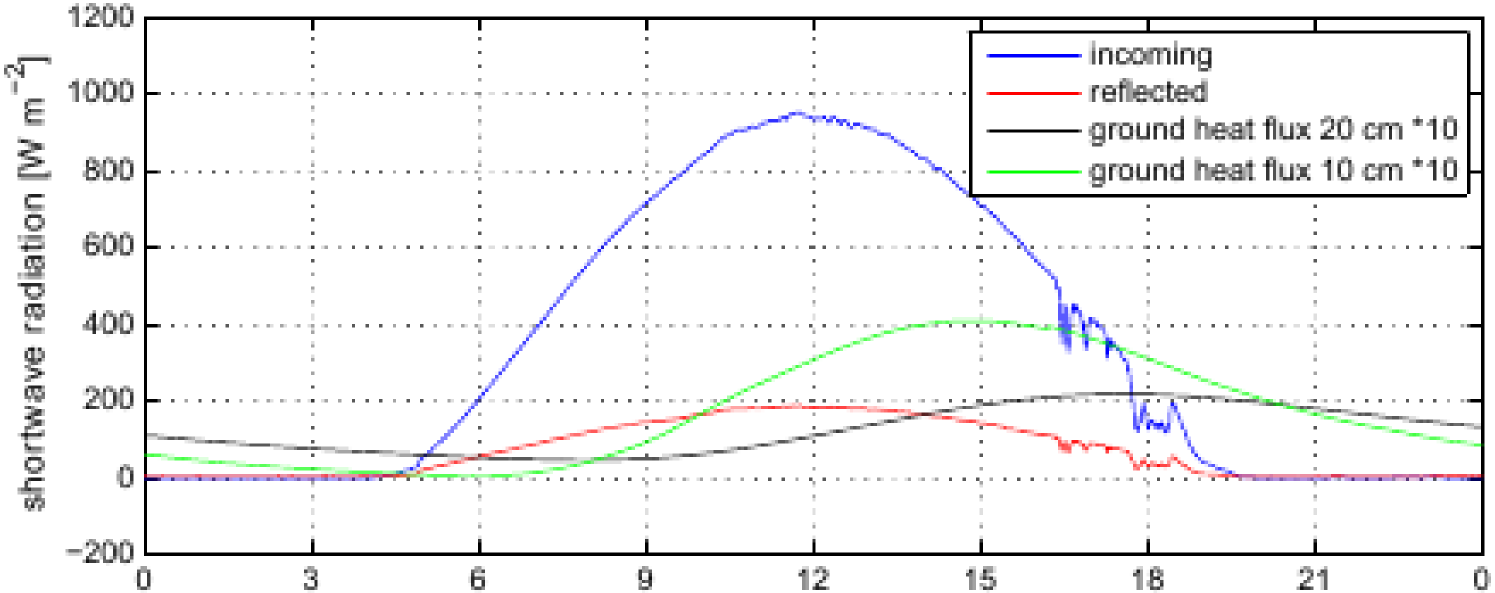
- New version: 5-hole probe and attitude on common datalogger with 100 Hz temporal resolution
- Wind tunnels tests with higher turbulence intensity (whole airframe due to flow distortion)
- In-flight calibration maneuvers to detect offsets in 5-hole probe measurements of angles/airspeed
- Small test campaign under planning: SUMO mounted on a car together with 2 sonic anemometers
- Campaign in the vicinity of wind turbines together with a Lidar (Netherlands)

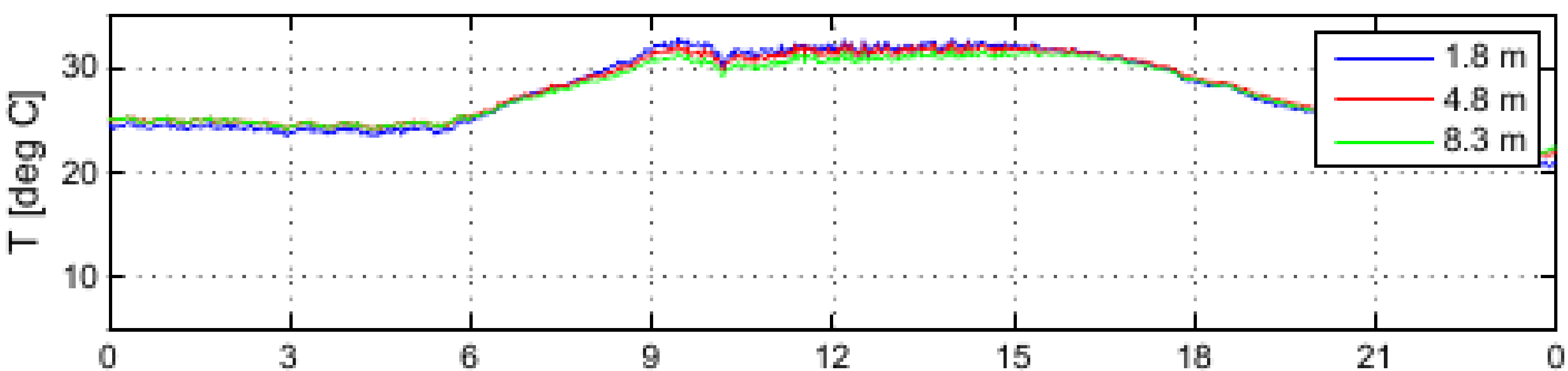


Thank you!

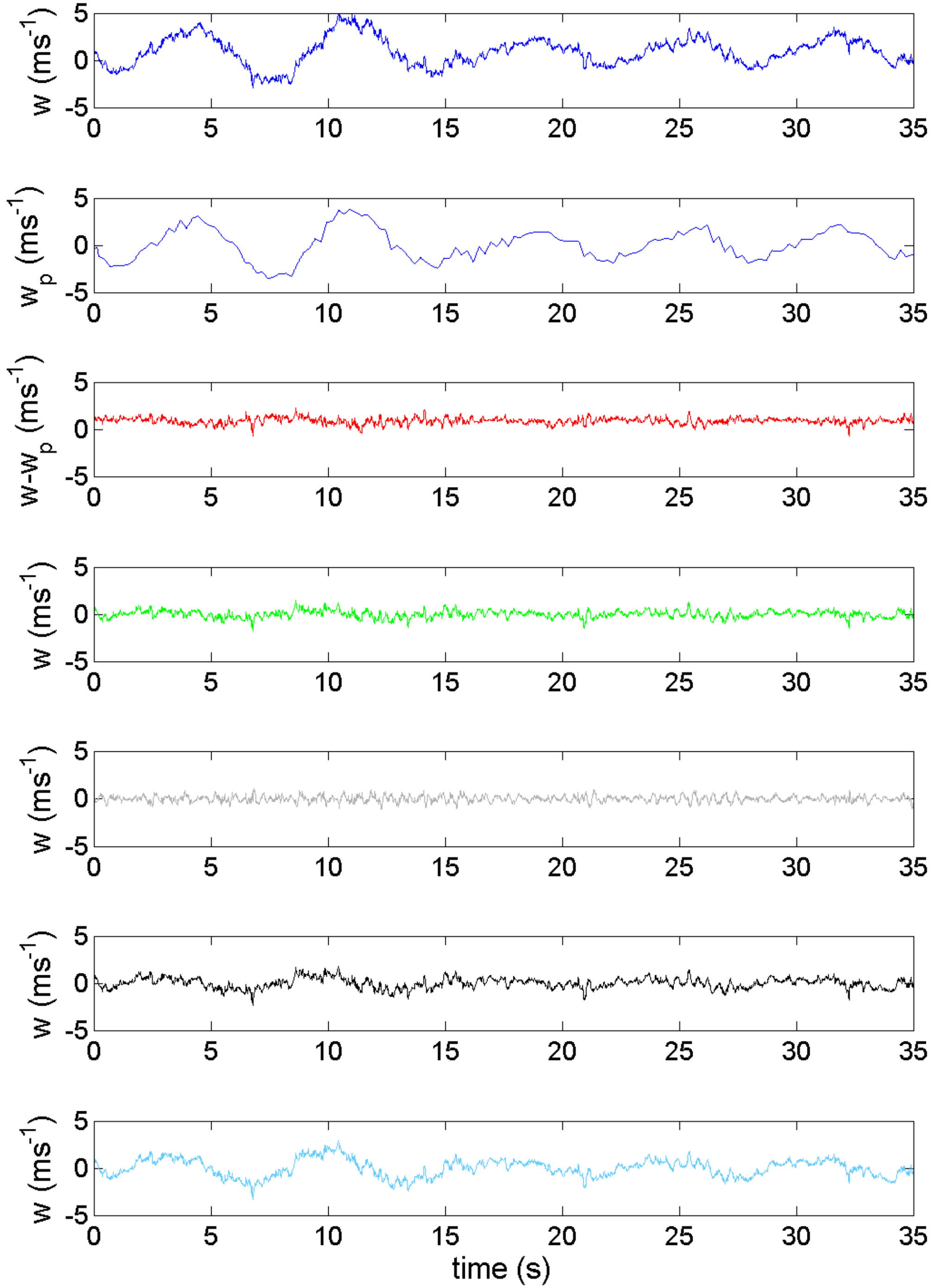
Picture by Jesper Hjelme, IWAL

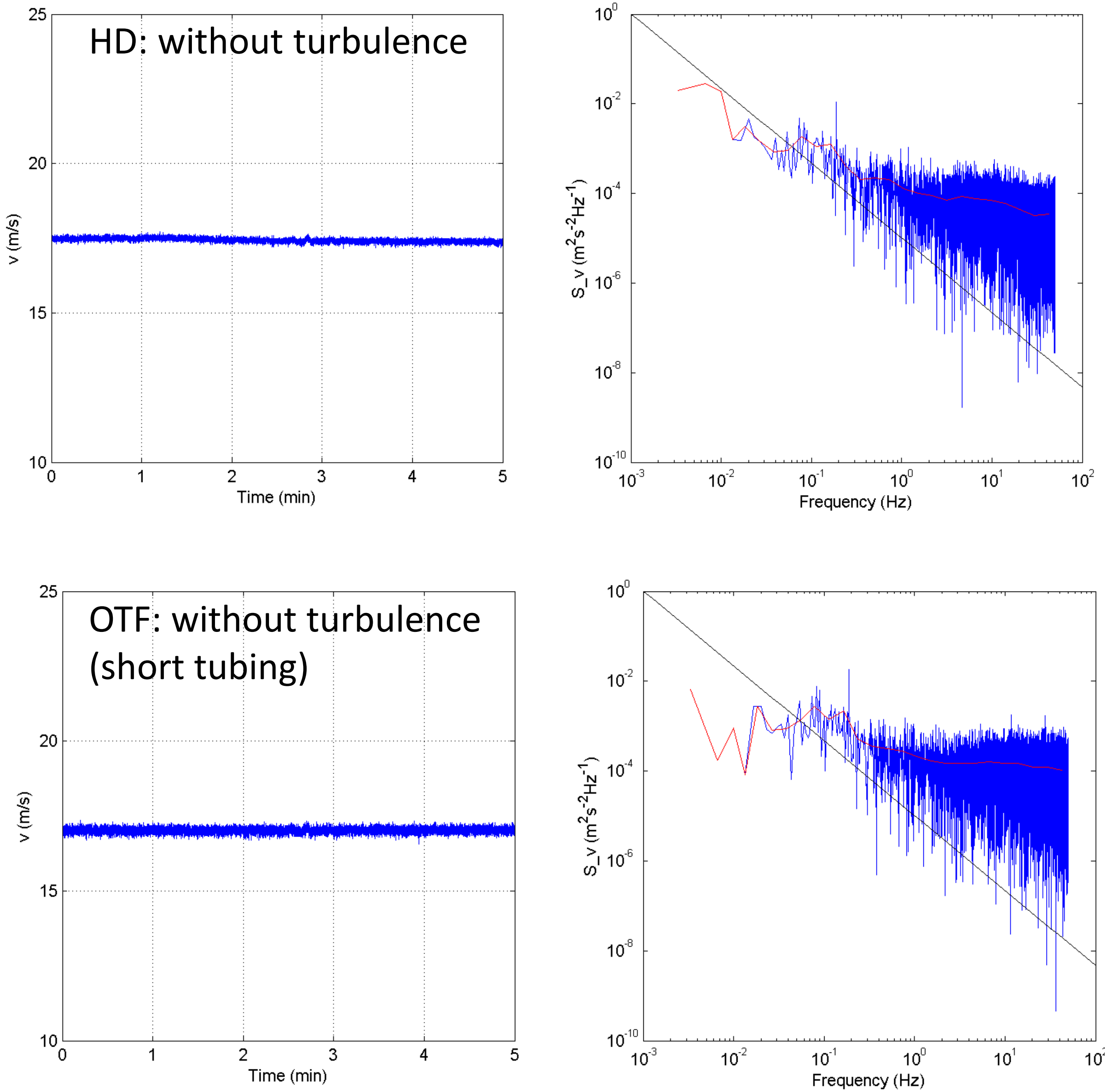
Meteorological conditions at Site 1, 27.06.11

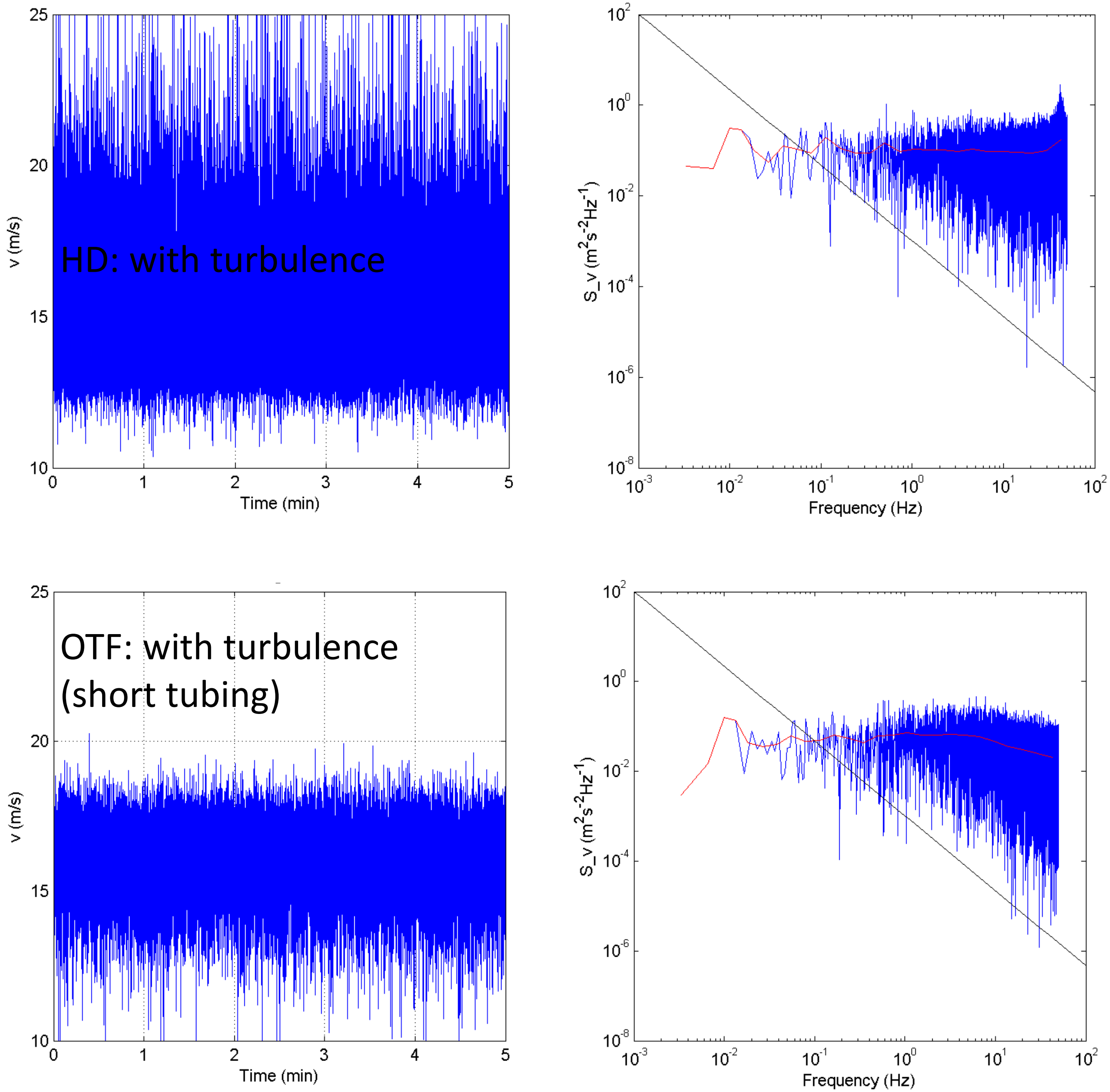




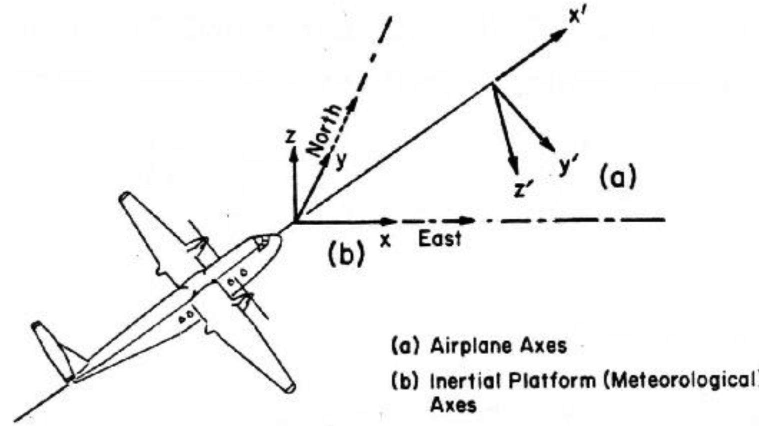
- Filter 1 (N=1, Wn=1 Hz)
- Filter 2 (N=10, Wn=1 Hz)
- Filter 3 (N=1, Wn=0.5 Hz)
- Filter 4 (N=1, Wn=0.2 Hz)




HD: without turbulence
v (m/s)
Time (min)
S_v (m^2s^-2Hz^-1)
Frequency (Hz)
OTF: without turbulence
(short tubing)
v (m/s)
Time (min)
S_v (m^2s^-2Hz^-1)
Frequency (Hz)


HD: with turbulence
OTF: with turbulence
(short tubing)
v (m/s)
Time (min)
S_v (m2s-2Hz-1)
Frequency (Hz)

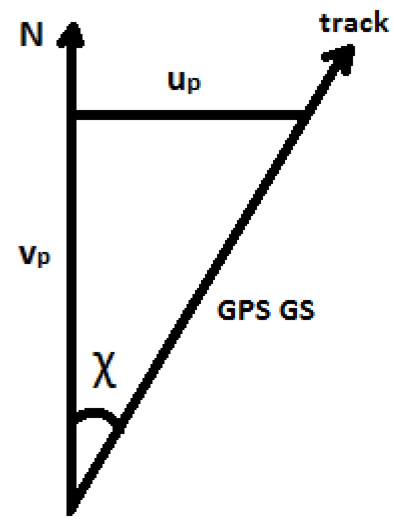
Calculating the velocity of the aircraft with respect to the ground ($\vec{v}_p$)



1 (dx/dt,dy/dt and dz/dt)

X = GPS_utmE
Y = GPS_utmN
Z = altitude

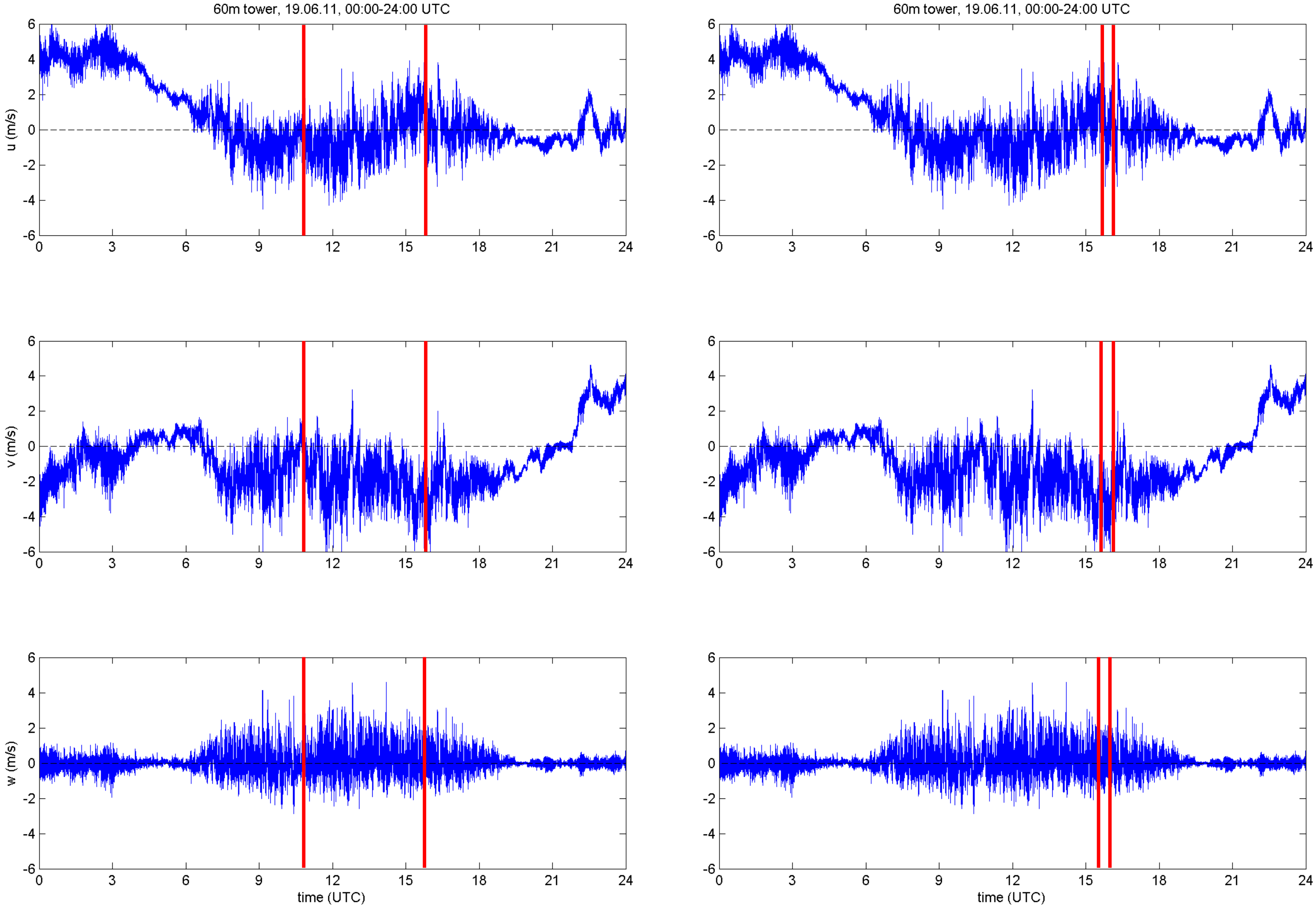
2 (GS, CS, χ)

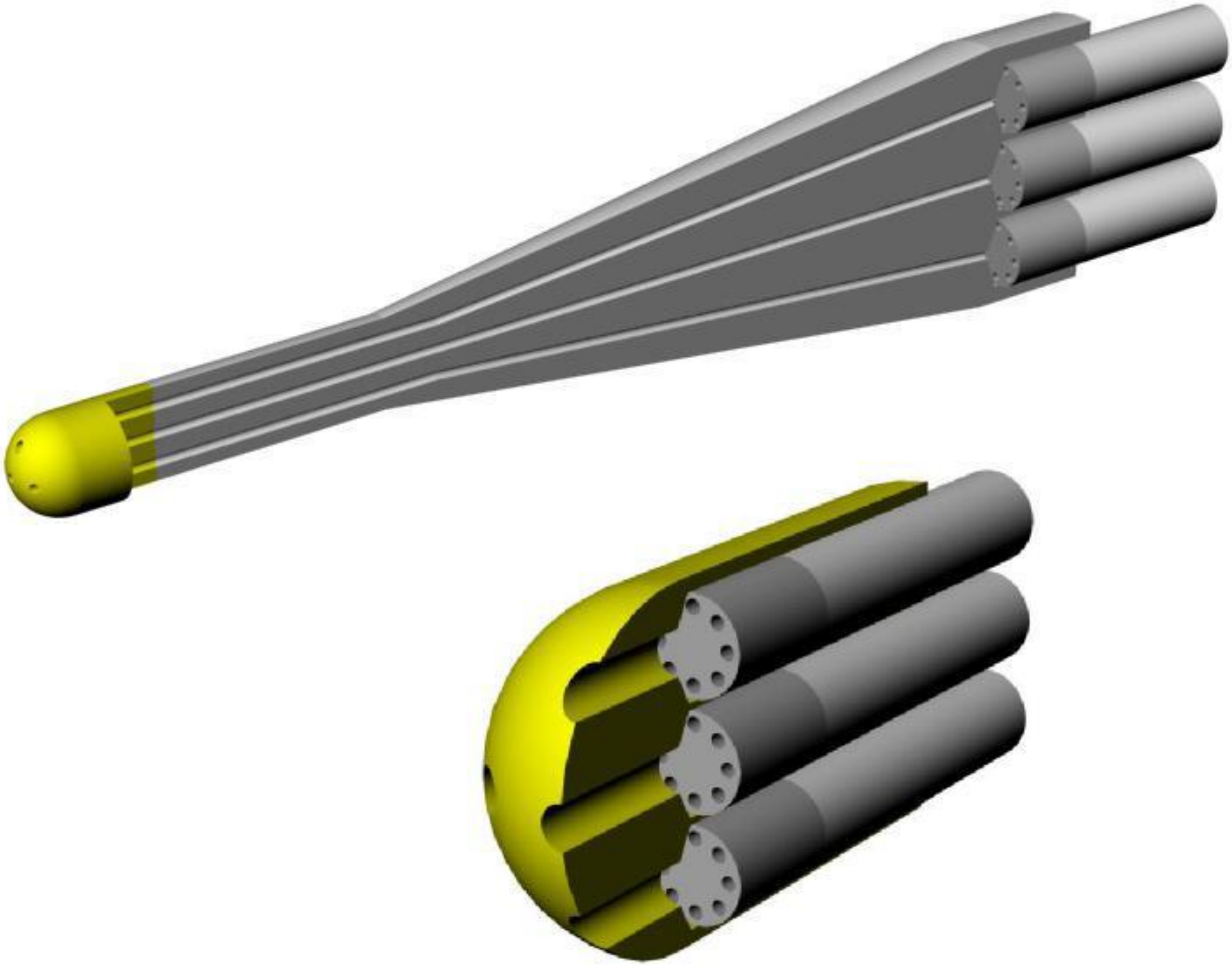


Up = GPS_GS*sinχ
Vp = GPS_GS*cosχ
Wp = GPS_CS

3 (temperature SHT_T and pressure SCP_P)

$$w_p = \frac{dz}{dt} = -\frac{RT}{pg}\frac{dp}{dt}$$


60m tower, 19.06.11, 00:00-24:00 UTC
60m tower, 19.06.11, 00:00-24:00 UTC
u (m/s)
v (m/s)
w (m/s)
time (UTC)
time (UTC)



http://www.alava-ing.es/repositorio/f425/pdf/2100/2/fast-response-probes.pdf?d=1