A combo (Sonic & 2 x-hot-films) setup for atmospheric turbulence measurements

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Motivation

- Fine resolution measurements of atmospheric turbulence, which enable to determine dissipation, velocity derivatives etc. is an important task.
- The standard instruments used for velocity field measurements such as Sonic anemometer and Lidar have a low temporal and spatial resolution.
- Miniature hot-wires or films are suitable for these purposes, however, they require frequent calibrations of the wires/films.
- The calibration using a specially devised calibrator is a cumbersome procedure in the Laboratory conditions and becomes practically inapplicable in the field.
- The use of in-situ calibration by utilizing a low resolution data from Sonic appears to be very attractive but only in case that an appropriate procedure is developed.

Layout of the talk

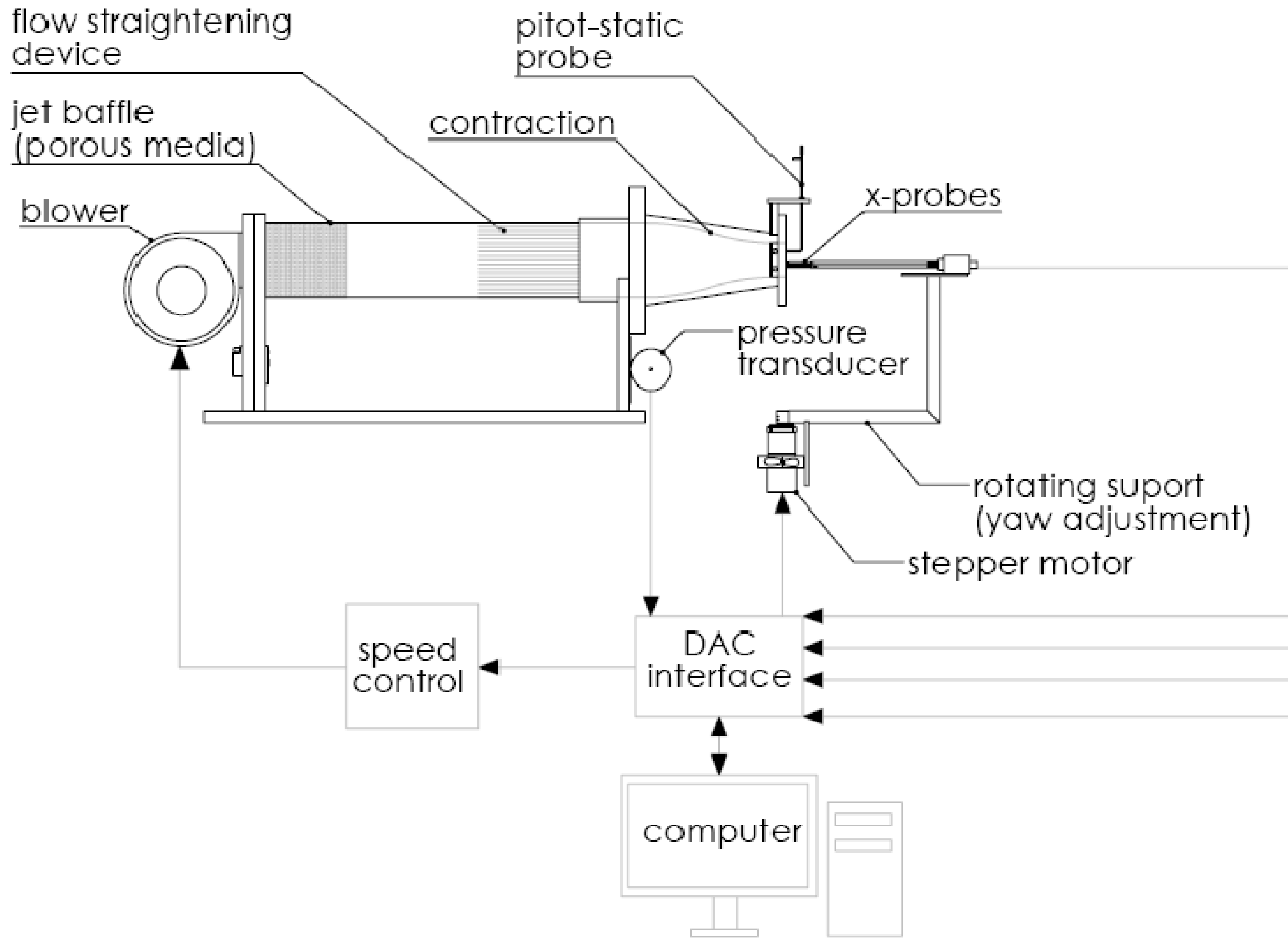
- **Part 1**: Feasibility Study (Work made in ASU)
- Jet facility – calibrator
- Probe yawing for calibration and feedback purposes
- Hot-film and sonic: calibration datasets
- Approximations of input/output relations:
  Polynomial least square **F**it and **N**eural **N**etwork
- Results: Laboratory and Field
- **Part 2**: Angular probability distribution (Recent)
- **Future plans**: the use of UAV and combo setup in mountain terrain turbulence measurements ,
  Three-dimensional calibration (ND)
- Conclusions

Relevant Papers

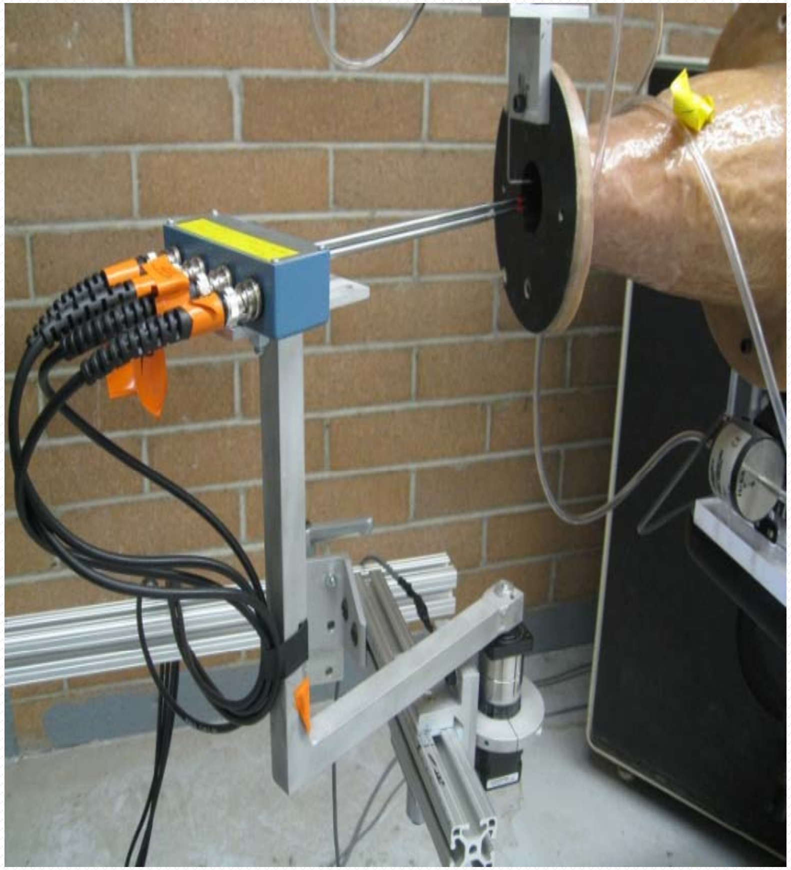
- E. Kit, A. Cherkassky, T. Sant, H.J.S. Fernando. *In-situ* calibration of hot-film probes using a co-located sonic anemometer: Implementation of a neural network. **Journal of Atmospheric and Oceanic Technology-AMS, Vol. 27**, No. 1, 23-41 (2010).
- E. Kit and B. Gritz. *In-situ* calibration of hot-film probes using a co-located sonic anemometer: angular probability distribution properties. **Journal of Atmospheric and Oceanic Technology-AMS, Vol. 28,** 104-110 (2011).

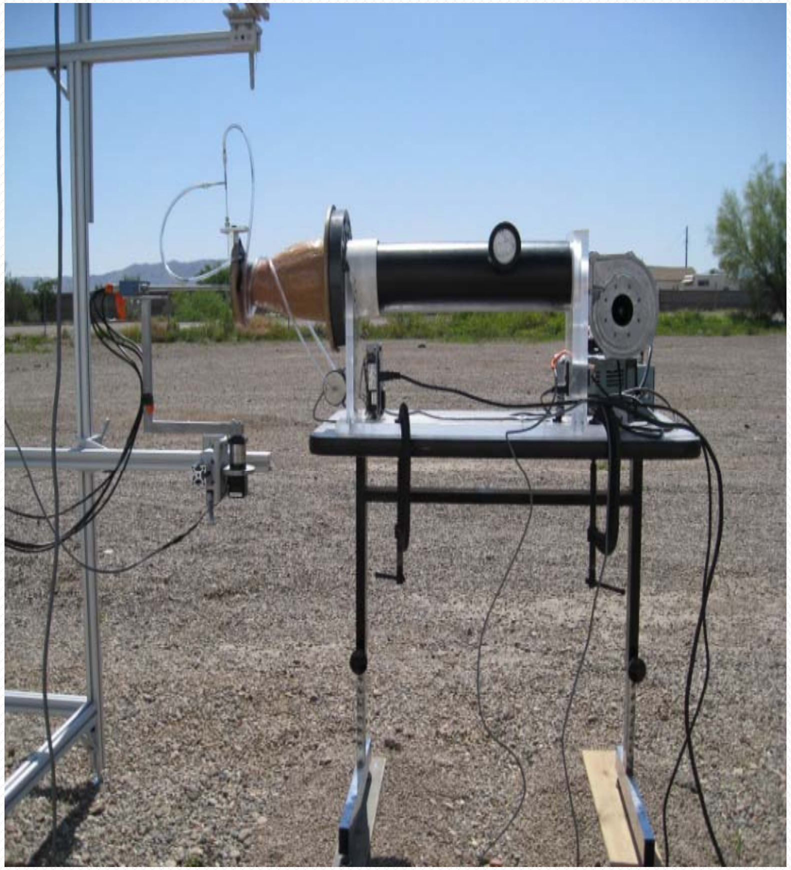
1. Feasibility Study

Jet Facility and traverse for probe yawing

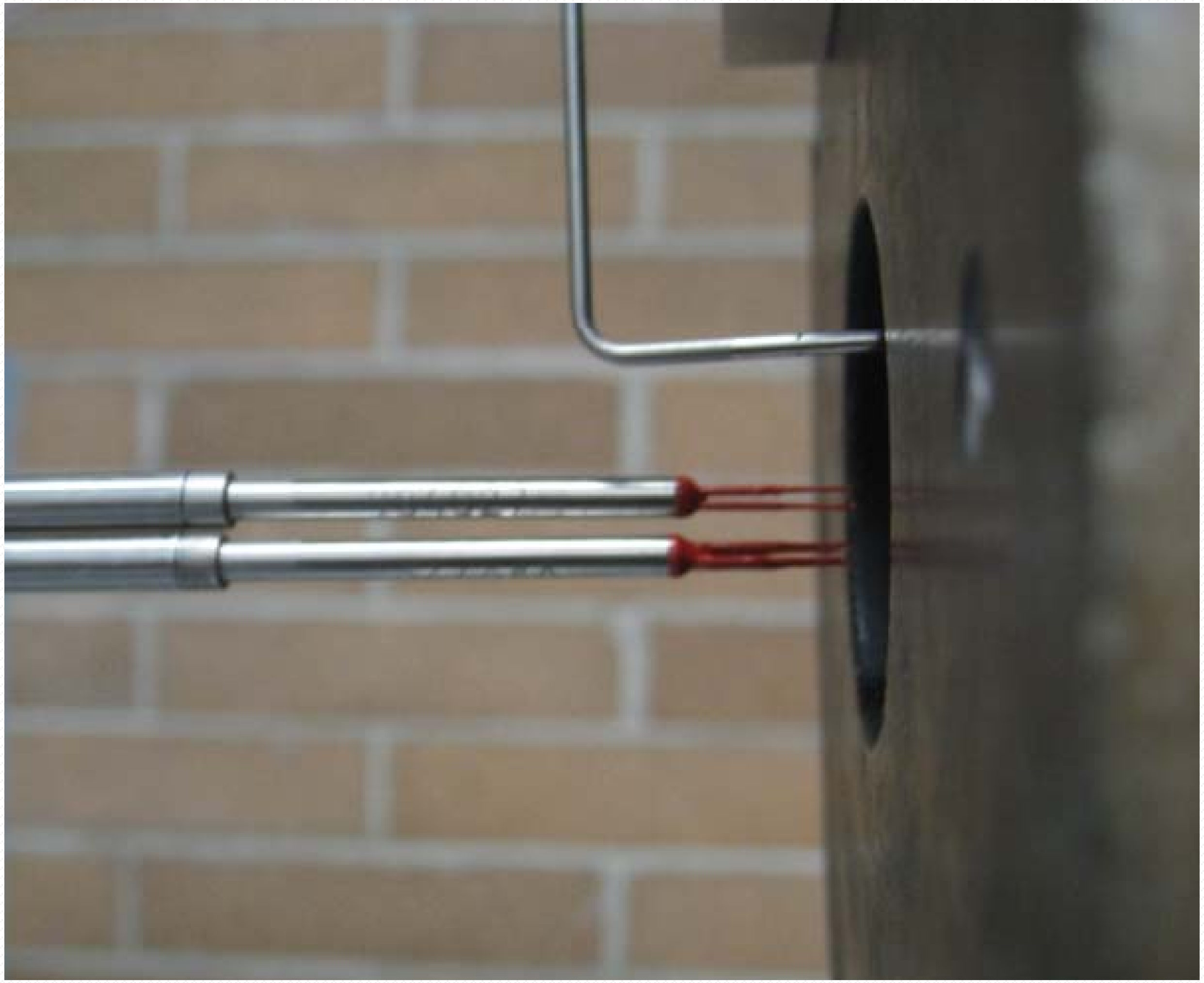


Left: Laboratory - set-up for probe yawing
Right: Calibration in the field - general view





- Hot-films (x-probes) at the jet exit. Miniature Pitot tube for simultaneous mean velocity measurements



Presentation of velocity components as polynomials of voltages across the wires. TKE dissipations and skewness of velocity derivatives

$$U_i = f_i(E_1, E_2)$$

$$f_i(E_1, E_2) = \sum_{kl} c_{ikl} \, P_k(E_1) P_l(E_2); \;\; P_k(E) = E^k, 0 \le k, l \le 4, k + l \le 4$$

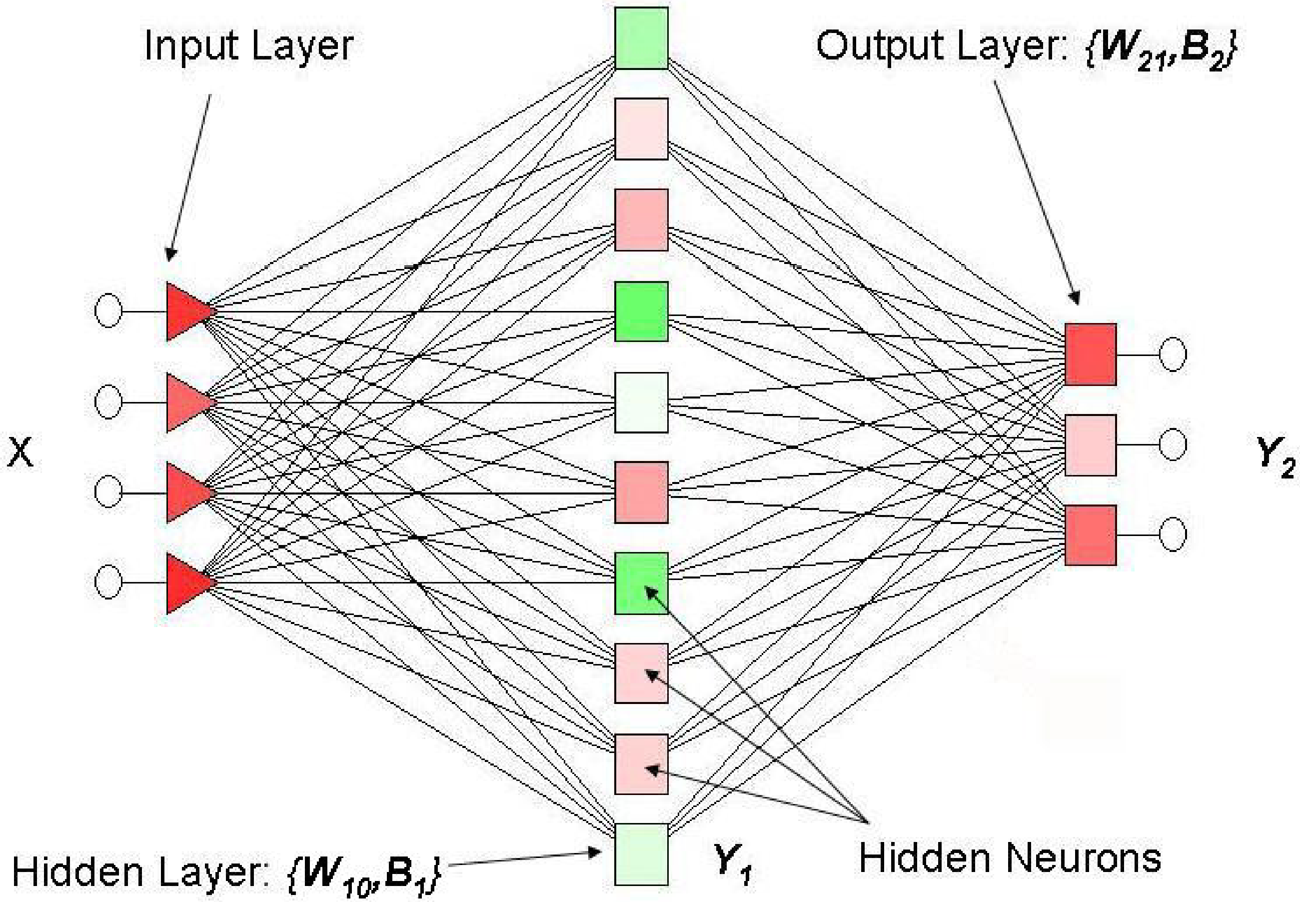
Linear system for determination of polynomial coefficients *c* is obtained from calibration data using the least square fit.

Dissipation: $\epsilon = 15\nu \overline{\left(\frac{\partial u}{\partial x}\right)^2} \; ; \;\; \partial x = -U \partial t$

Skewness of velocity derivative: Sk= $\overline{\left(\frac{\partial u}{\partial x}\right)^3} \Big/ \left(\overline{\left(\frac{\partial u}{\partial x}\right)^2}\right)^{3/2}$

Neural Network

The structure of the generated neural network (3-layer Perceptron)

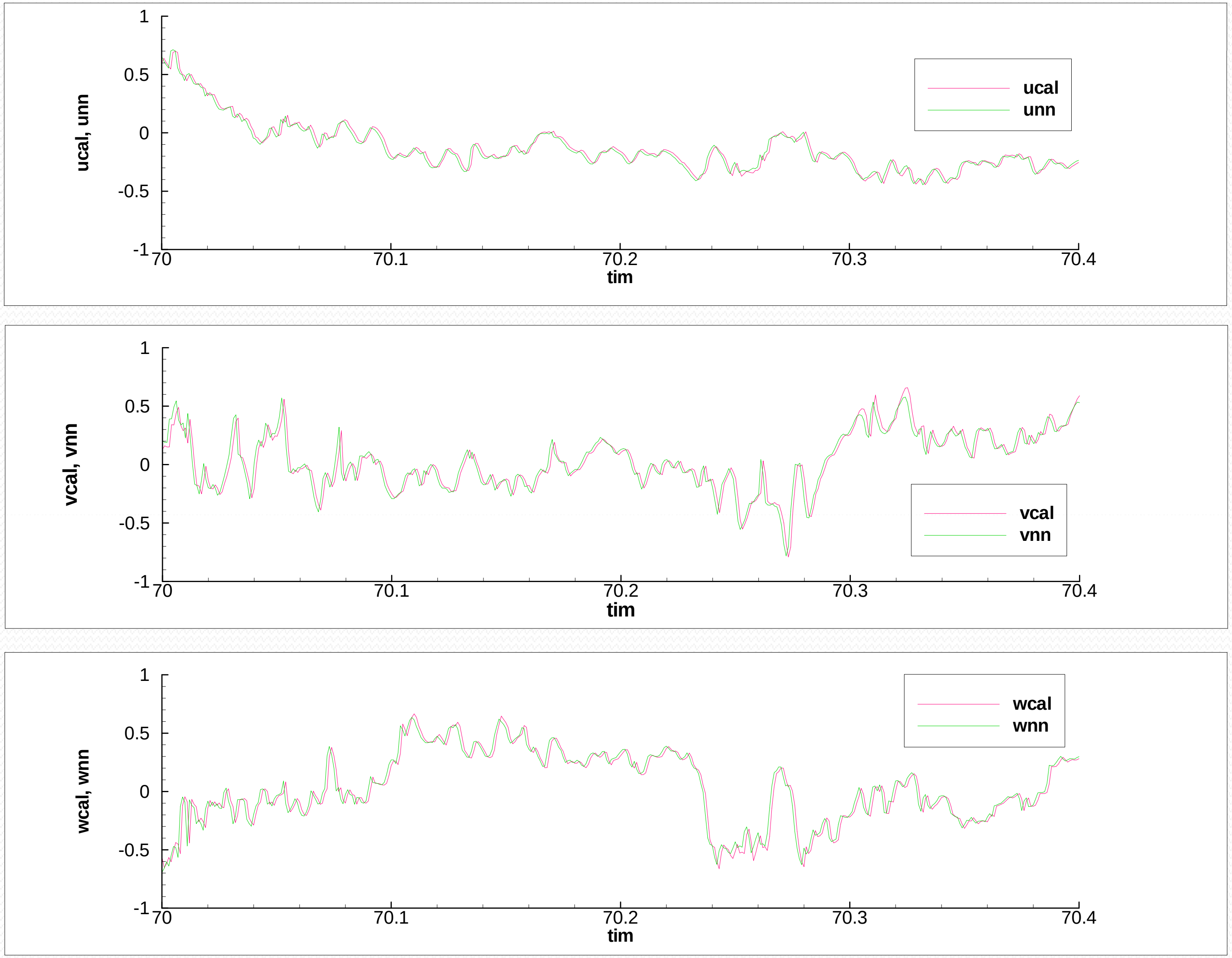


Calibration Data Sets and Approximations

Table 1 List of calibration datasets and procedures.

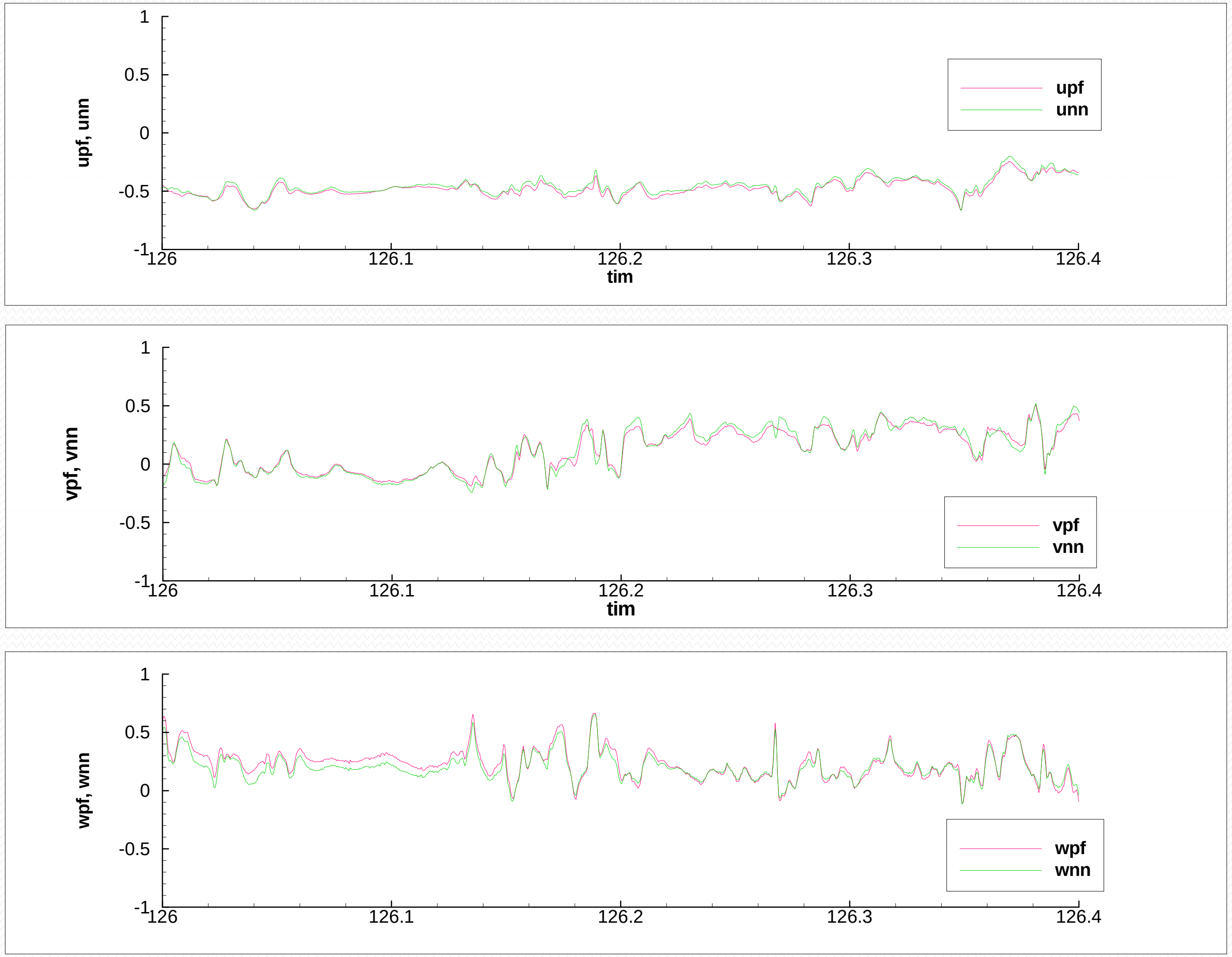
Calibration datasets/Approximations	**Polynomial Fit**	**Neural Network**
CBS (Calibrator Based dataSet)	**1 – PF (CBS)**	**2 – NN (CBS)**
SBS (Sonic Based dataSet)	**3 – PF (SBS)**	**4 – NN (SBS)**

Lab_Exp# 01 L = 3m
Upper: streamwise, mid plot: crosswise, lower: vertical red-PF (CBS), green-NN (CBS).

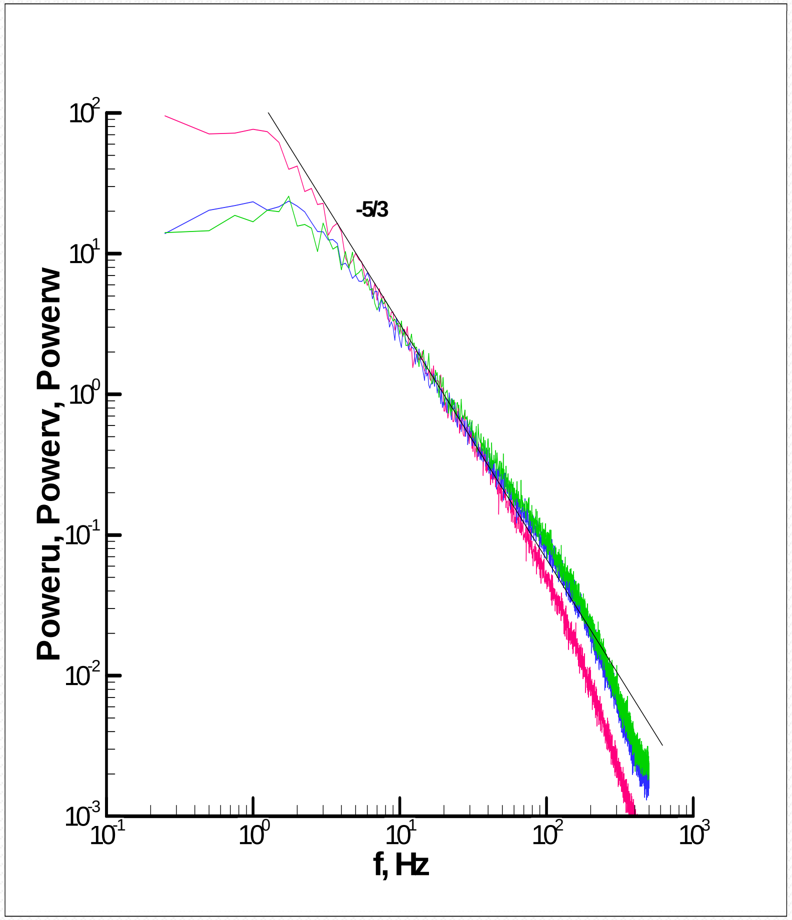


Field_Exp# 02 Night

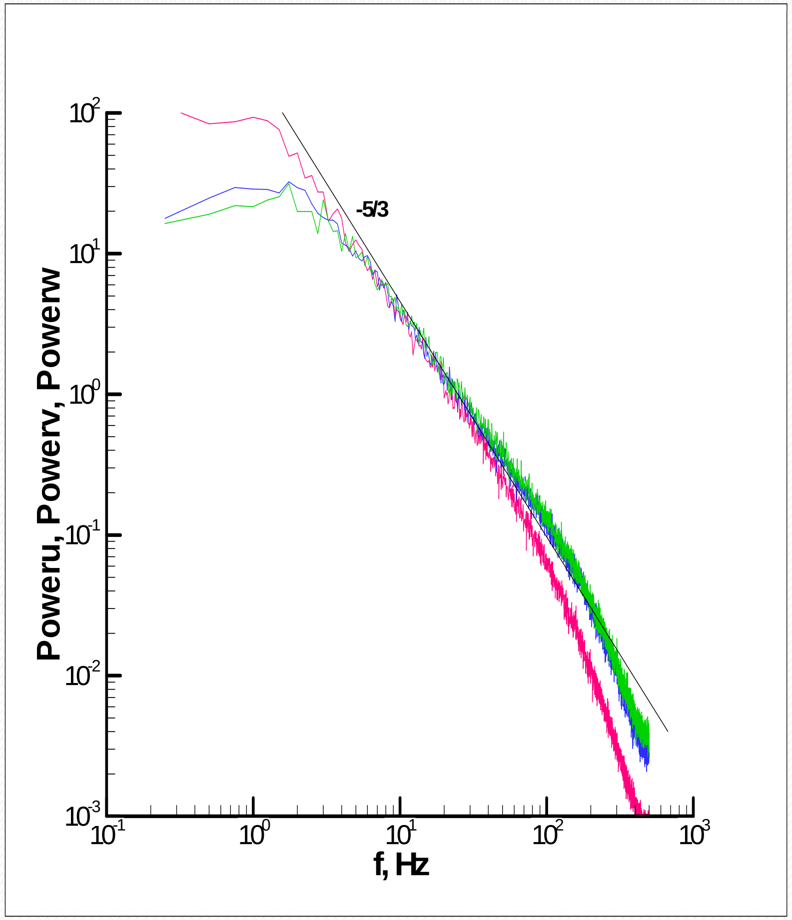
Upper: streamwise, mid plot: crosswise, lower: vertical red-PF (CBS), green-NN (SBS).



Spectra of u-red, v-blue, w-green: a-using NN procedure, b-using PF procedure. Lab_Exp# 1

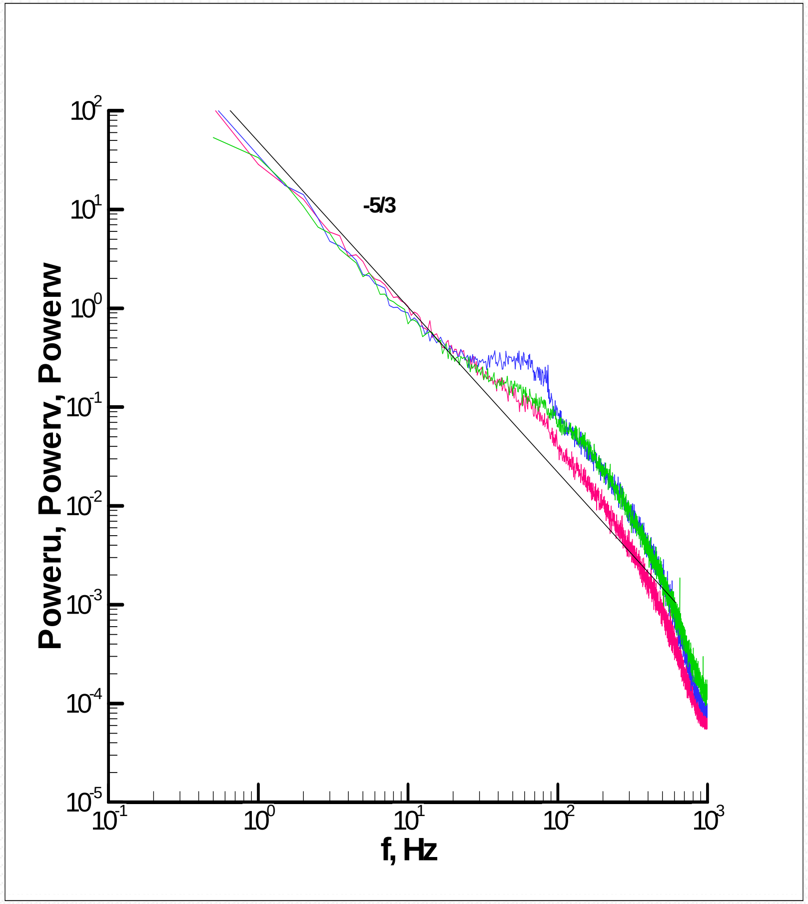


a)

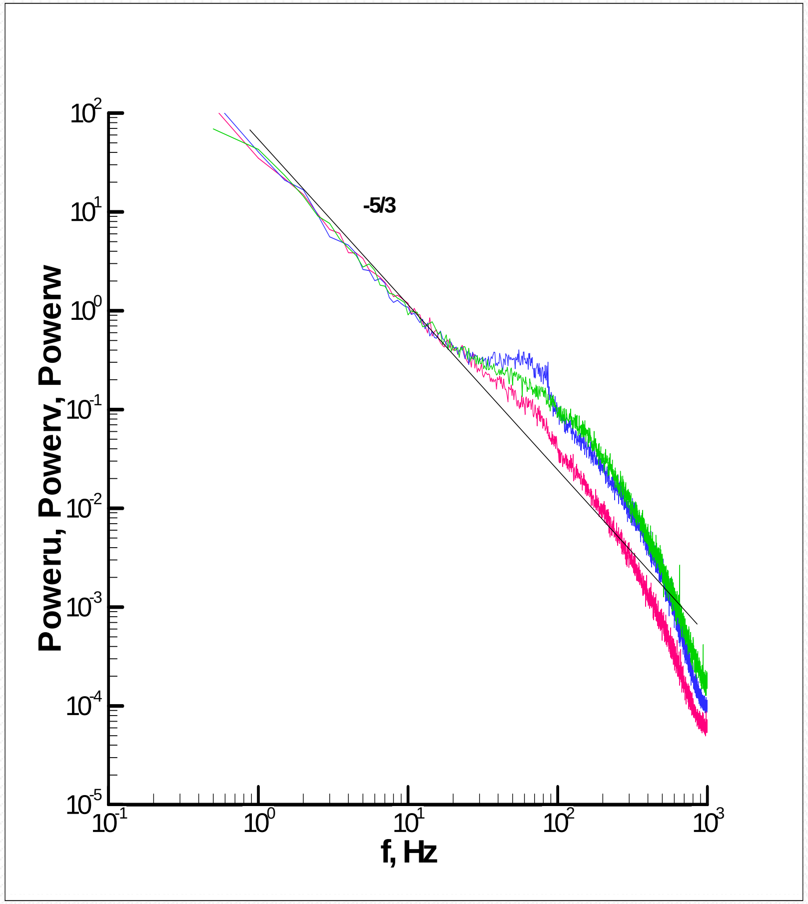


b)

Spectra of u-red, v-blue, w-green: a-using NN procedure, b-using PF procedure. Field_Exp# 2



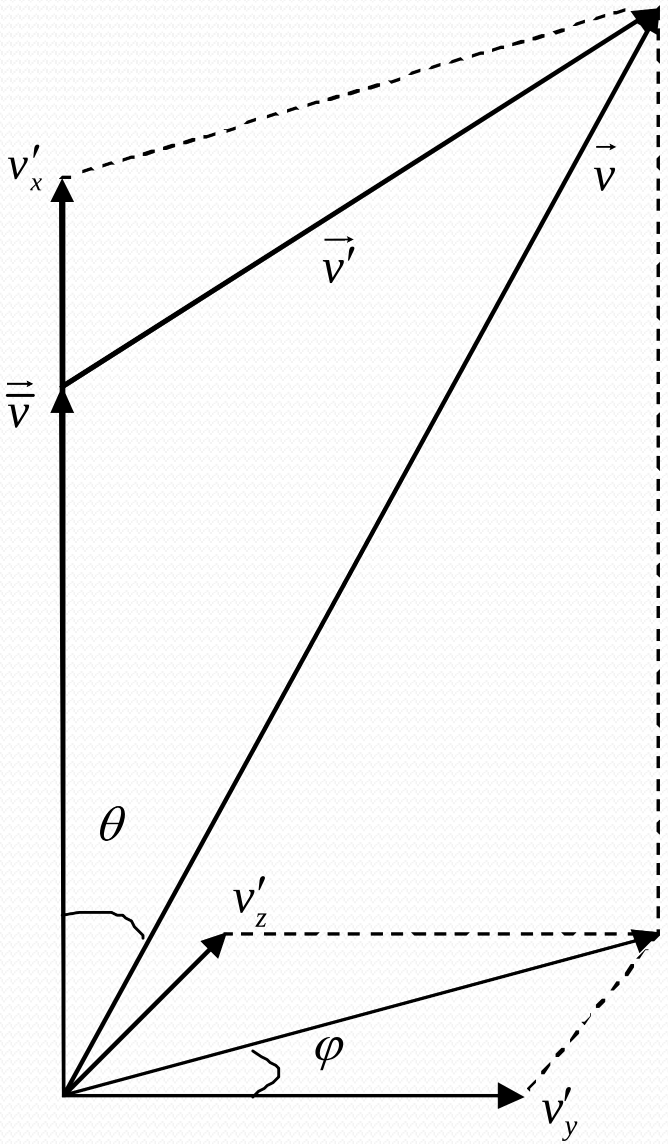
a)



b)

2. Angular Probability Distribution

Sketch of velocity vector, components and angles



Velocities and angles at a given point:

$\vec{\bar{v}}$ - mean velocity,

$\vec{v}\,'$- fluctuating part,

$\vec{v}$ - full velocity;

θ - the deviation angle of full velocity from mean velocity,

ϕ- the azimuth angle.

Angular distribution - development

Assumptions:

- each velocity component obey a Gaussian distribution,
- correlation among components are relatively low

then the probability density for the full velocity

$$P\left(v_x', v_y', v_z'\right) = n \cdot \exp\left(-\frac{\left(v_x'\right)^2}{2\sigma_x^2}\right) \cdot \exp\left(-\frac{\left(v_y'\right)^2}{2k_y\sigma_x^2}\right) \cdot \exp\left(-\frac{\left(v_z'\right)^2}{2k_z\sigma_x^2}\right)$$

n - a normalization factor

k_y and k_z – coefficients for standard deviations in *y* and *z*

Isotropic case: $k_z = k_y = 1$

Axisymmetric case: $k_z = k_y = k$

The integration in spherical coordinate system yields

$$n = \frac{1}{\left(2\pi\right)^{3/2} k \cdot \sigma_x^3}$$

Angular distribution – development, cont…

- using the expressions $(v'_x)^2 = (v \cdot \cos\theta - \bar{v})^2$, $v'_y = v \cdot \sin\theta \cdot \cos\varphi$
- and $v'_z = v \cdot \sin\theta \cdot \sin\varphi$
- The probability density function in spherical coordinate system

$$P(\varphi,\theta,x) = \frac{x^2 \sin\theta}{(2\pi)^{3/2}\,\bar{v}k \cdot \sigma_n^3} \cdot \exp\left(-\frac{(x\cos\theta - 1)^2 + x^2 \sin^2\theta / k}{2\sigma_n^2} \right).$$

Where $x = v/\bar{v}$, $\sigma_n = \sigma_x / \bar{v}$

For isotropic case k= 1,

$$\boldsymbol{P(\varphi,\theta,x)} = \frac{\boldsymbol{x}^2 \sin\boldsymbol{\theta}}{(2\boldsymbol{\pi})^{3/2}\,\boldsymbol{\bar{v}\sigma_n^3}} \cdot \exp\left(-\frac{(\boldsymbol{x} - \cos\boldsymbol{\theta})^2 + \sin^2\boldsymbol{\theta}}{2\boldsymbol{\sigma_n^2}} \right).$$

Angular distribution – development, cont…

Integrating over x and over φ in axisymmetric case yields

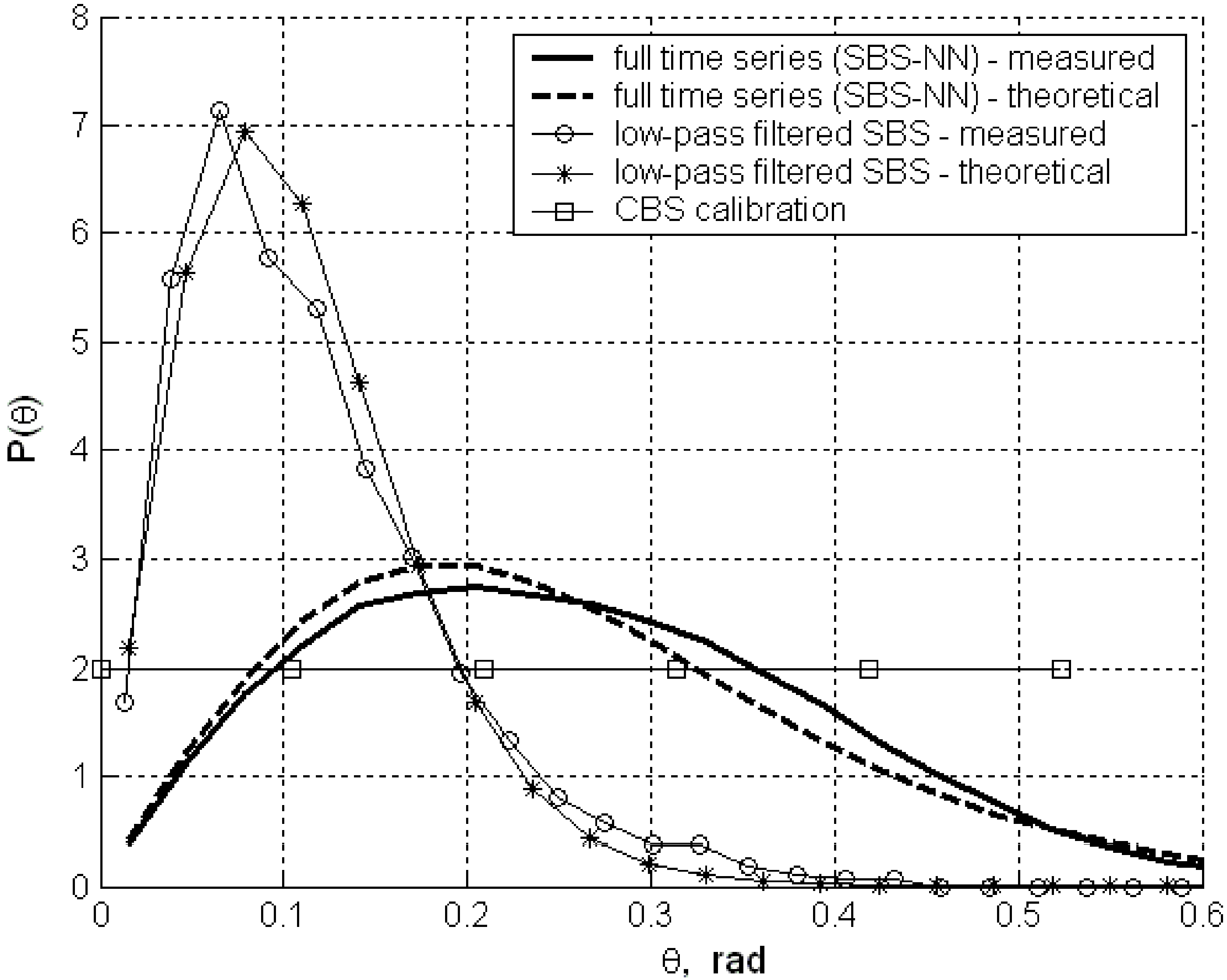
$$P(\theta)=\frac{\tan\theta}{k\sigma_n\cos^2\theta\cdot f^2}\left\{\frac{\exp\left(-\frac{1}{2\sigma_n^2}\right)}{\sqrt{2\pi}}+\frac{\left(f\sigma_n^2+1\right)\exp\left(\frac{f^{-1}-1}{2\sigma_n^2}\right)}{2\sigma_n\sqrt{f}}\cdot\left[1-erf\left(-\frac{1}{\sqrt{2f}\sigma_n}\right)\right]\right\}$$

where $\quad f=1+\tan^2\theta/k$

In the isotropic case (k=1):

$$P(\theta)=\frac{\tan\theta}{\sigma_n}\cdot\left\{\frac{\exp\left(-\frac{1}{2\sigma_n^2}\right)}{\sqrt{2\pi}}+\frac{\left(\sigma_n^2+\cos^2\theta\right)\exp\left(-\frac{\sin^2\theta}{2\sigma_n^2}\right)}{2\sigma_n\cos\theta}\cdot\left[1-erf\left(-\frac{\cos\theta}{\sqrt{2}\sigma_n}\right)\right]\right\}$$

Angular probability: Comparison of model prediction with experimental data



Conclusions

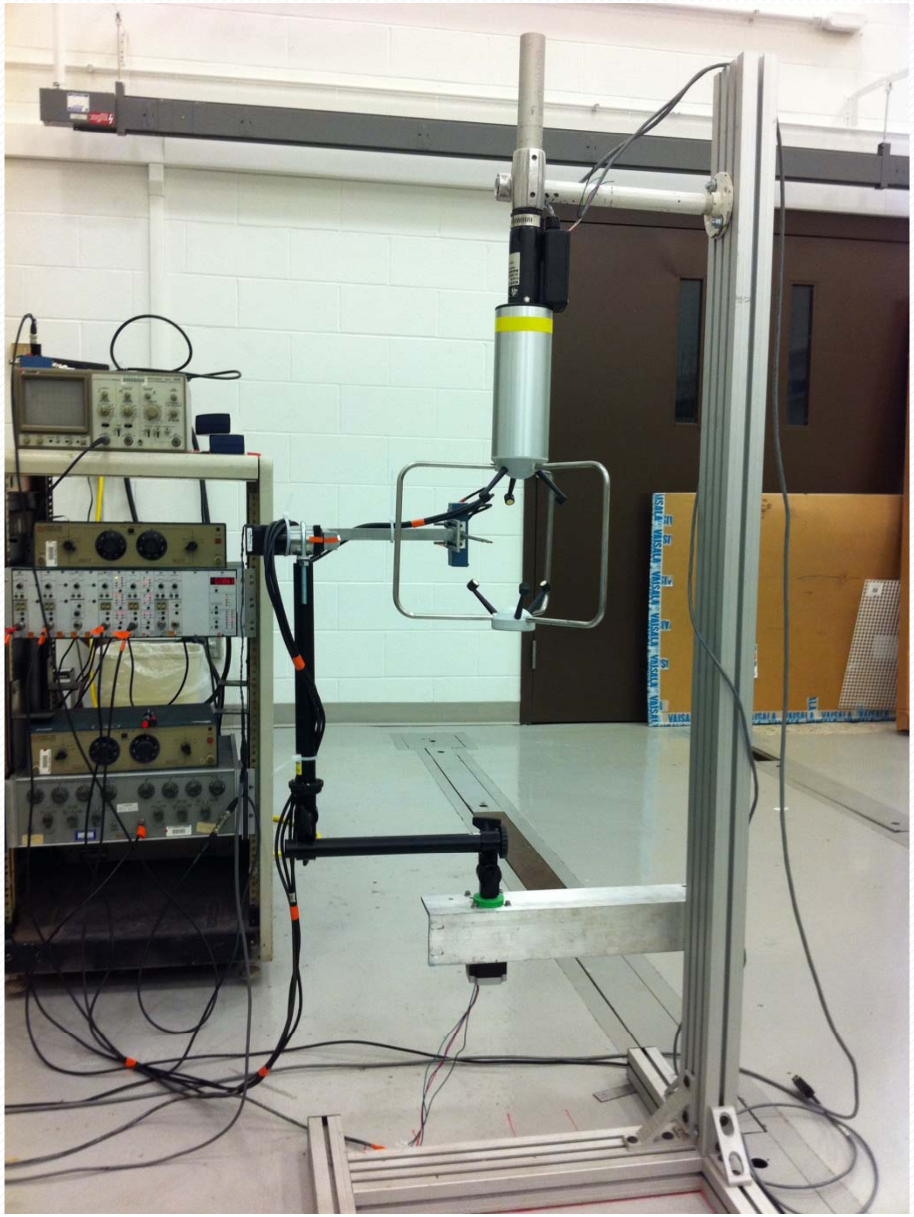
- NN model works with calibration datasets with unevenly distributed data points, PF works only with evenly.
- Field: Nocturnal works best and recommended.
- Very interesting spectra in our short preliminary campaign.
- Model of Angular Density Probability (ADP) is developed based on Gaussian distribution of velocity components.
- Angular Probability Distribution for calibration dataset is twice as narrow as for full signal. PF fails, NN comes through.
- Studying of non-linearity defined as RMS to mean velocity ratio
- The installation of combo setup on UAV for mountain terrain to study the turbulent atmospheric boundary layer.
- Further development of the method: establishing of criteria for data quality.

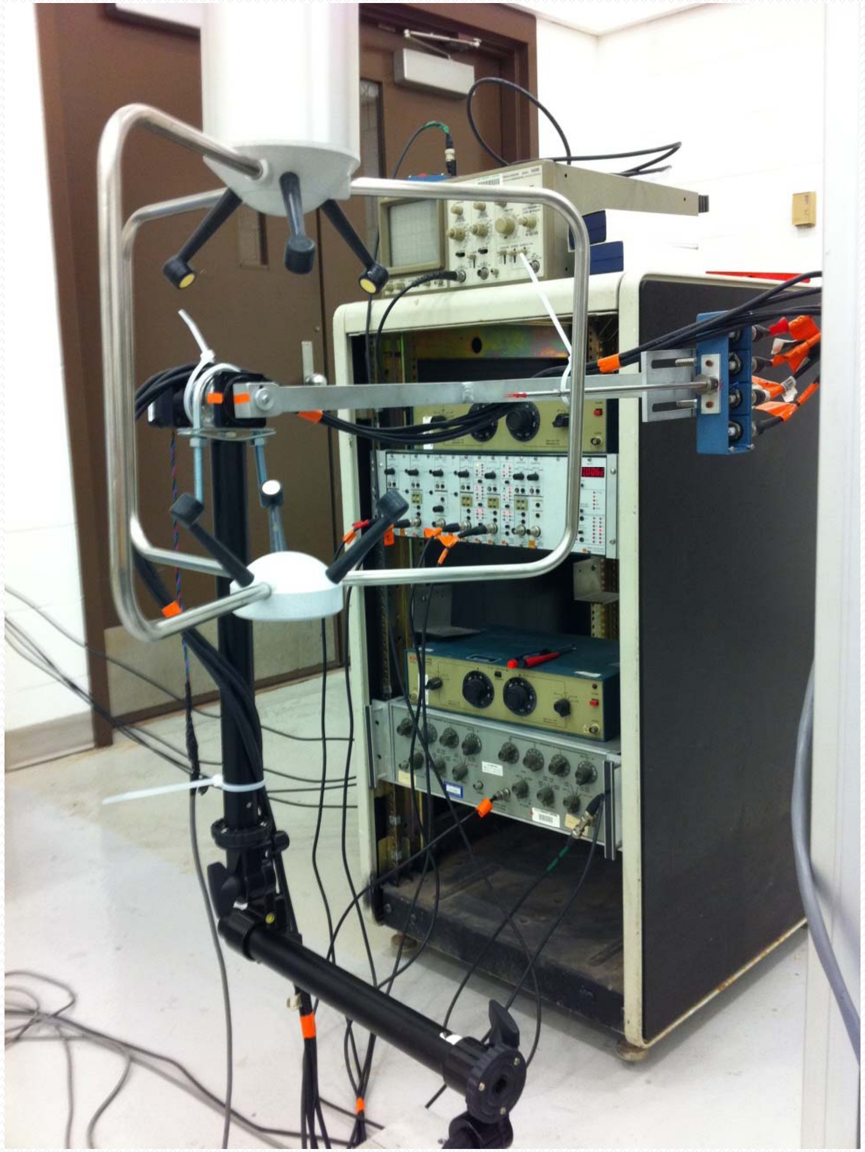
3. Future plans: the use of UAV and combo setup (pair of *x*-hot-films or a triple-sensor fiber-film probe & sonic) for turbulence atmospheric measurements in mountain terrain.

Development of three-dimensional traversing and 3D calibration procedure

A small autonomous UAV: 30 pound payload capacity, airborne for two hours at 30-40 mph.

3D-TRAVERSING & SONIC





THANK YOU!
THE END