A combo (Sonic & 2 *x*-hot-films or 3D-multisensor probe) setup for atmospheric turbulence measurements

Eliezer Kit
Tel-Aviv University
Chris Hocut
University of Notre Dame

In collaboration with: Joe Fernando
Dan Liberzon

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 use of in-situ calibration by utilizing a low resolution data from Sonic and NN algorithm appears to be very attractive but only in case that an appropriate procedure is developed.

Layout of the talk

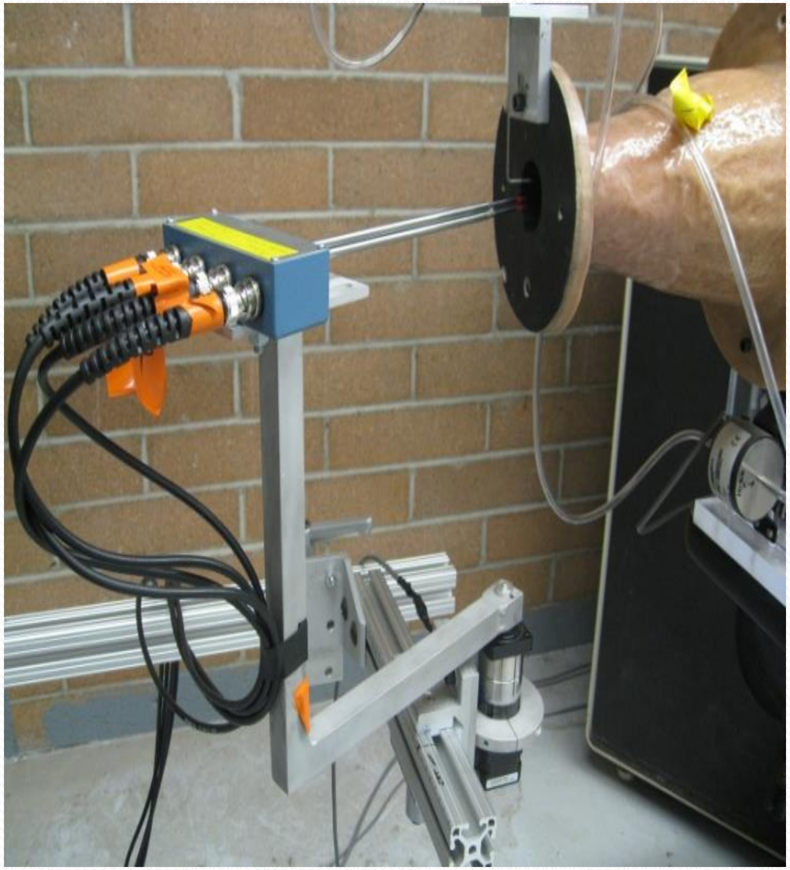
- **Part 1**: Short recall: Feasibility Study (Work in ASU)
- Approximations of input/output relations:
  Polynomial least square **F**it and **N**eural **N**etwork
  Laboratory and Field Results from ASU
- Angular probability distribution
- "Virtual" Probe algorithm (hot-film modeling using "effective velocity" approach) to establish the range of the method applicability (Recent work in TAU)
- **Part 2**: Combo deployment in Dugway and
  Preliminary results from fall experiments in Dugway.
- First estimates from spring experiments.
- **Conclusions**

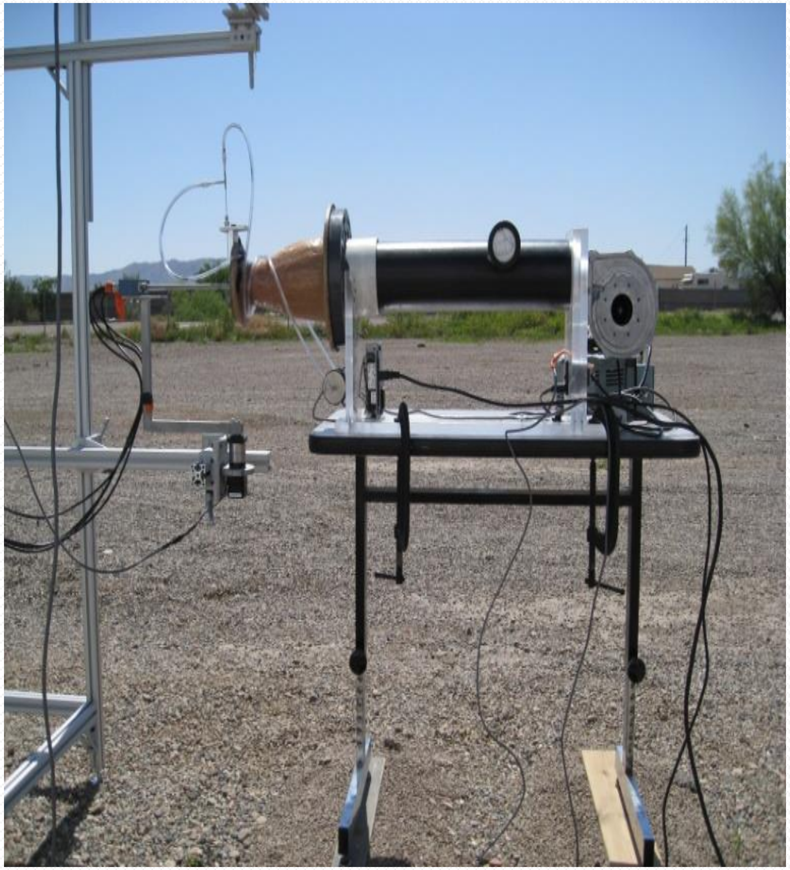
Relevant Papers

- 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).
- L. Vitkin, D. Liberzon, B. Grits and E. Kit. Study of *in-situ* calibration performance of co-located multi-sensor Hot-Film and Sonic anemometers using a "virtual probe" algorithm. **Submitted 2013**

1. Feasibility Study

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





Presentation of velocity components as polynomials of voltages across the wires.

TKE dissipations and skewness of velocity derivatives

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

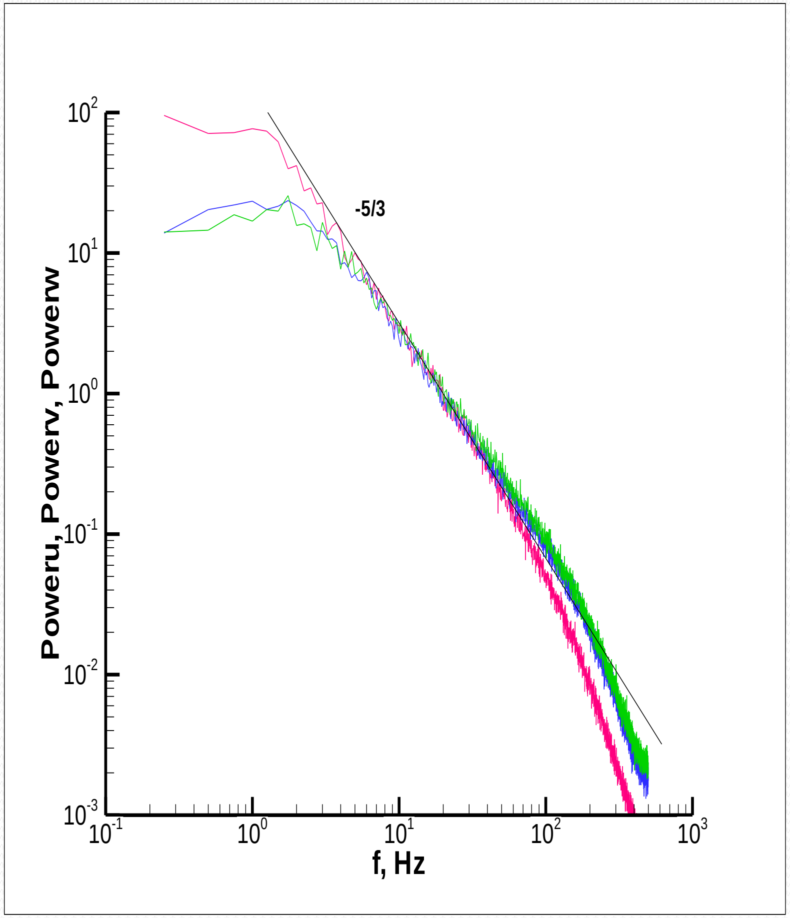
$$f_i(E_1, E_2) = \sum_{kl} c_{ikl}\, P_k(E_1) P_l(E_2); \;\; P_k(E) = E^k, 0 \le k, l \le 4, k + l \le 4$$

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

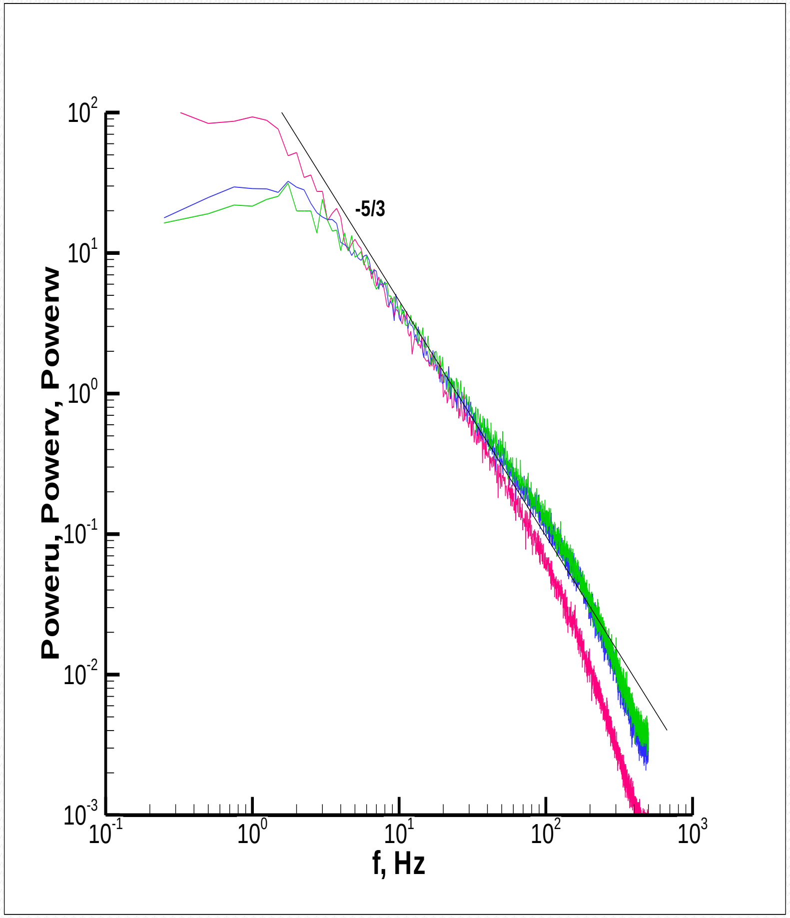
Dissipation: $\epsilon = 15\nu \overline{\left(\frac{\partial u}{\partial x}\right)^2}$; $\partial x = -U\partial t$

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

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

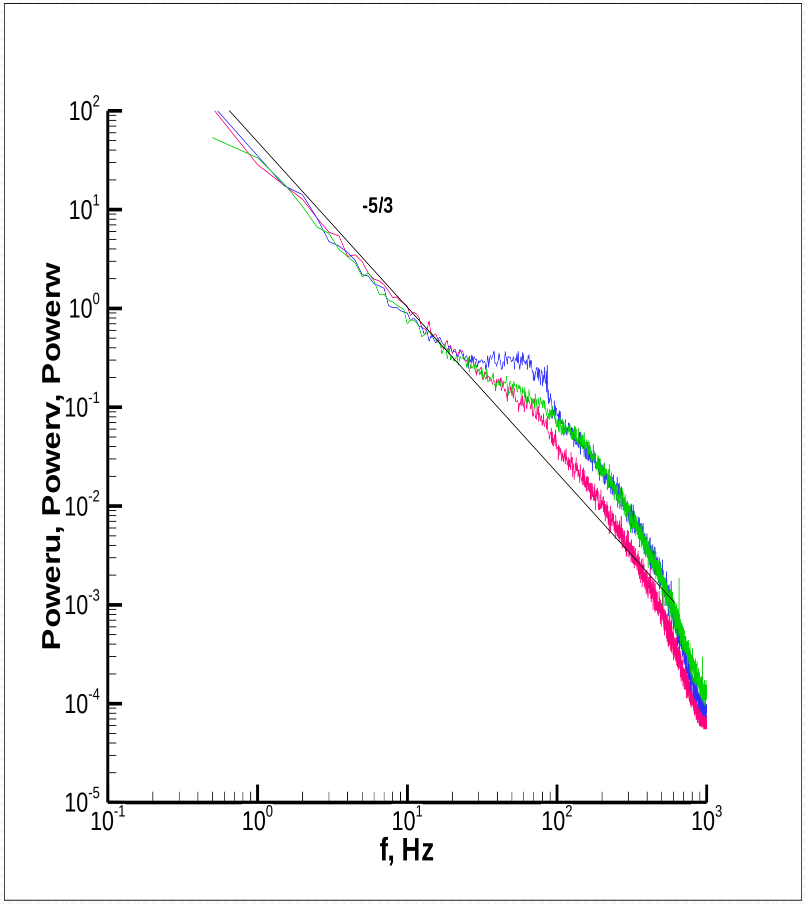


a)

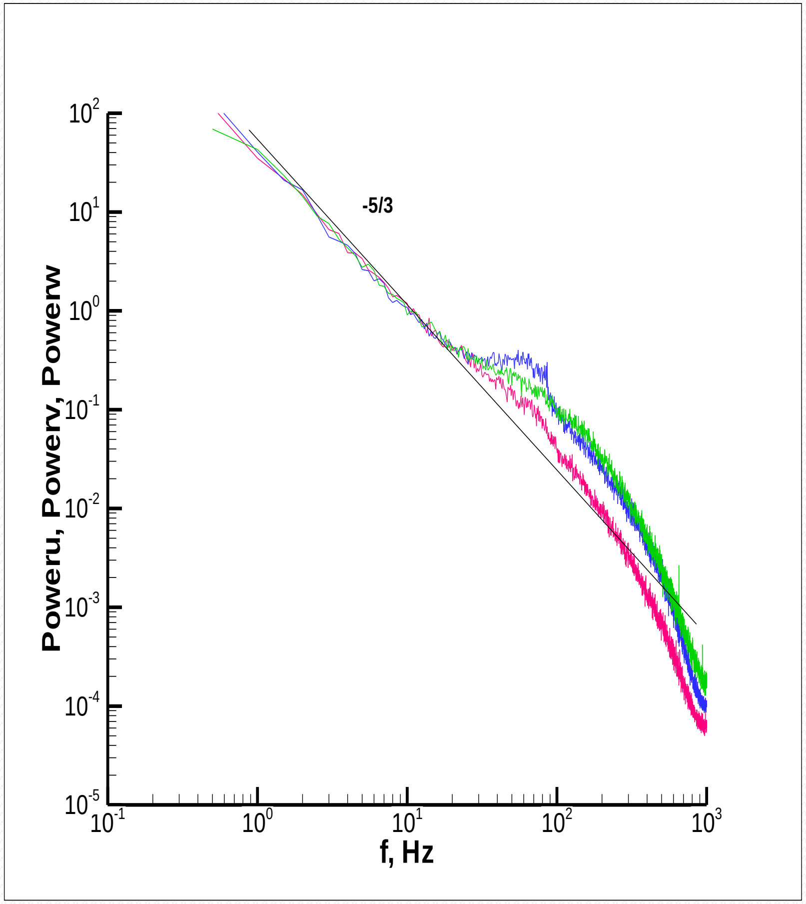


b)

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



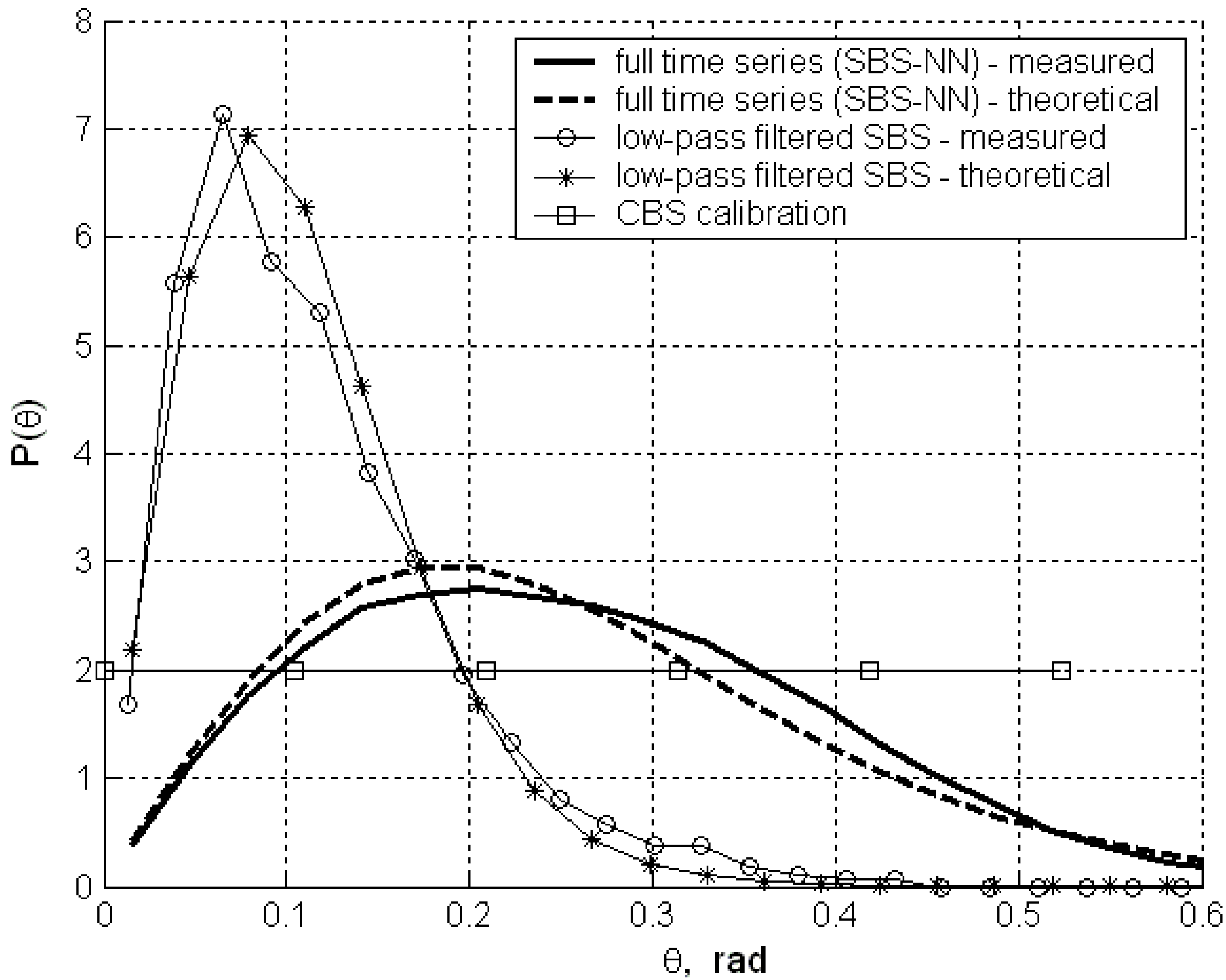
a)



b)

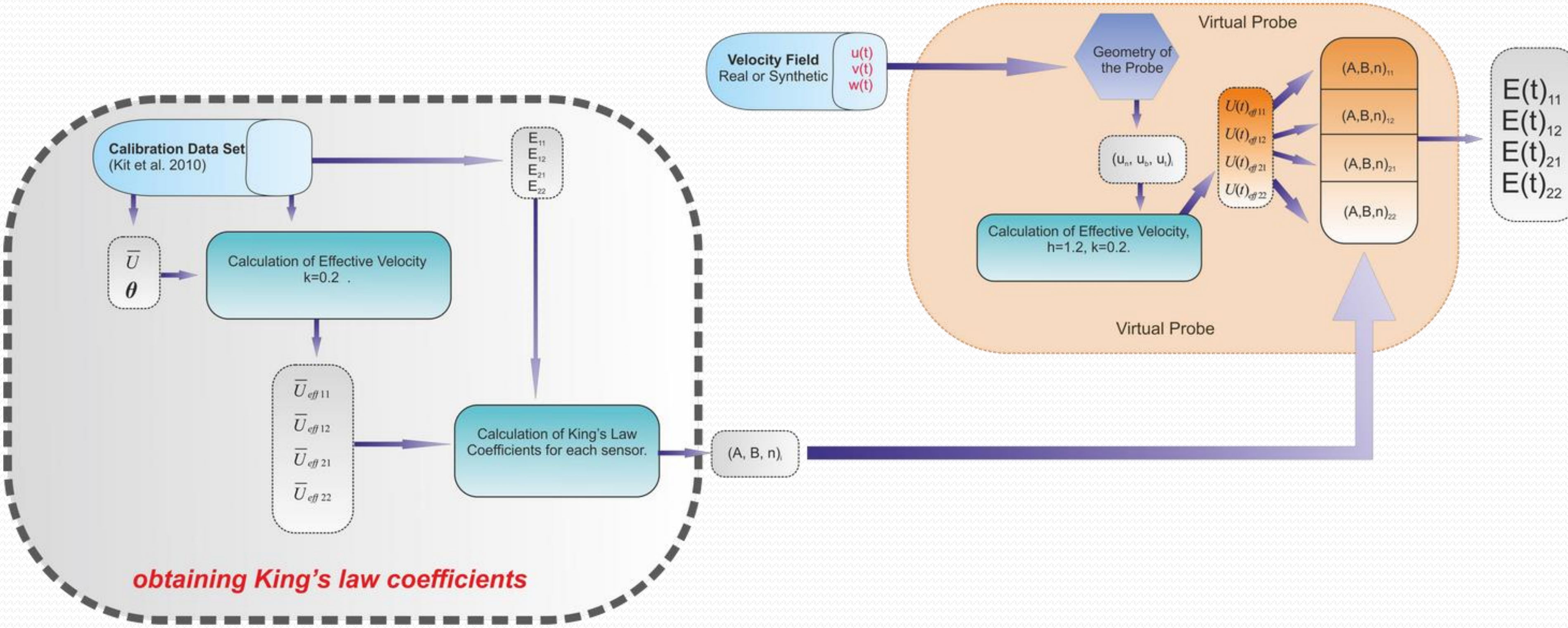
Angular Probability Distribution

Angular probability: Comparison of model prediction with experimental data



VIRTUAL PROBE ALGORITHM

Virtual Probe

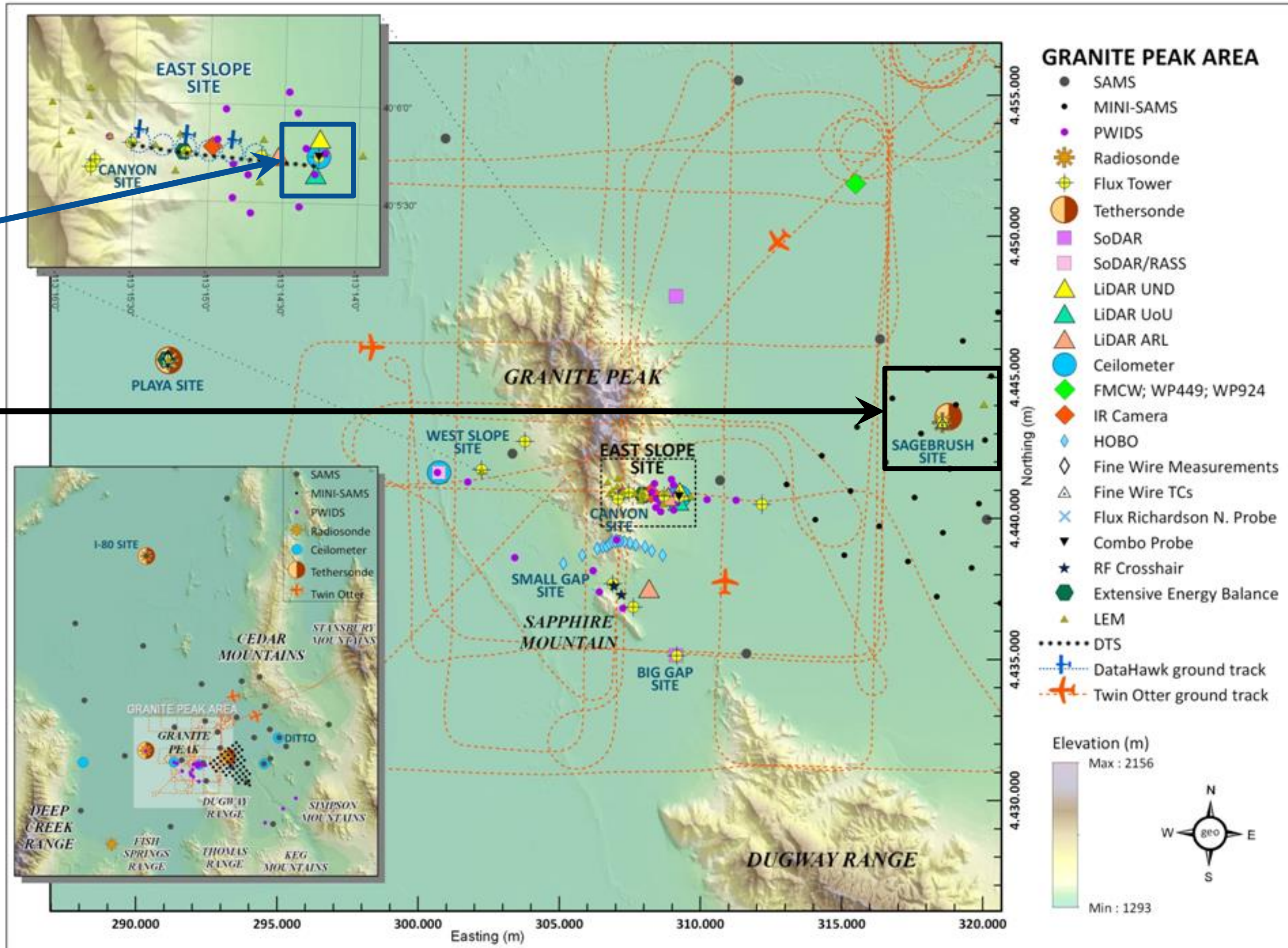


- **MATERHORN-X Combo Probe Deployment**

Combo Probe Placement

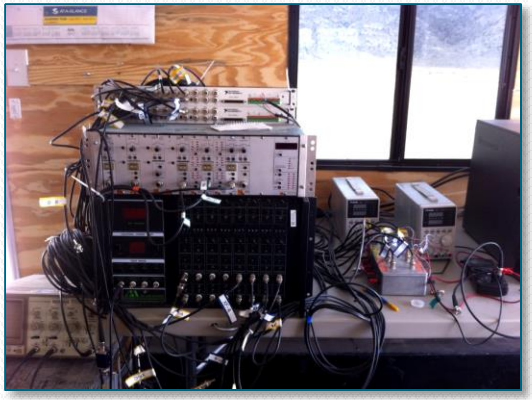
MATERHORN-X-1

MATERHORN-X-2



MATERHORN-X-1

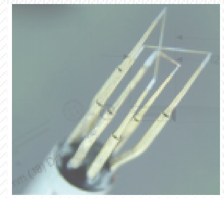
Combo probes located at 2m and 6m



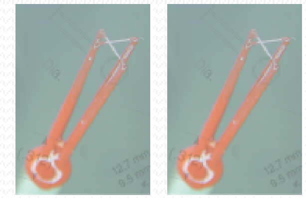
Combo probe electronics

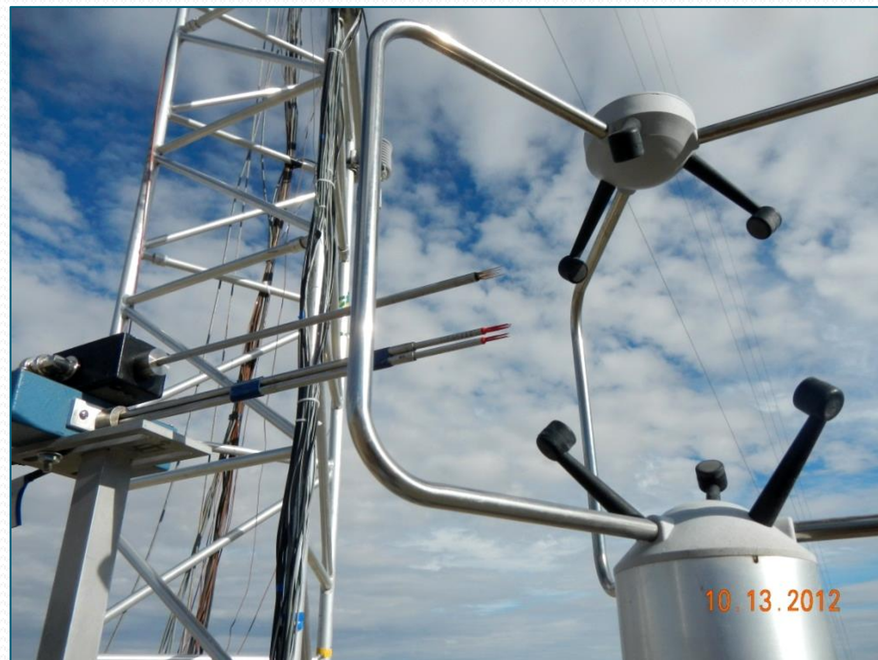
Probe Performance Tested

3D Probe



2-X Probes





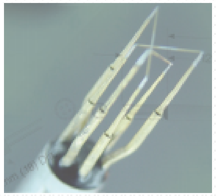
Technology Improvements

Optical Encoders

Provides position feedback with 0.1° accuracy

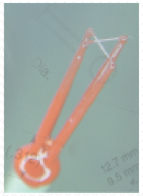
MATERHORN-X-2

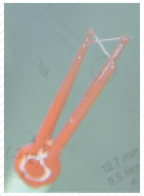
3D Probe



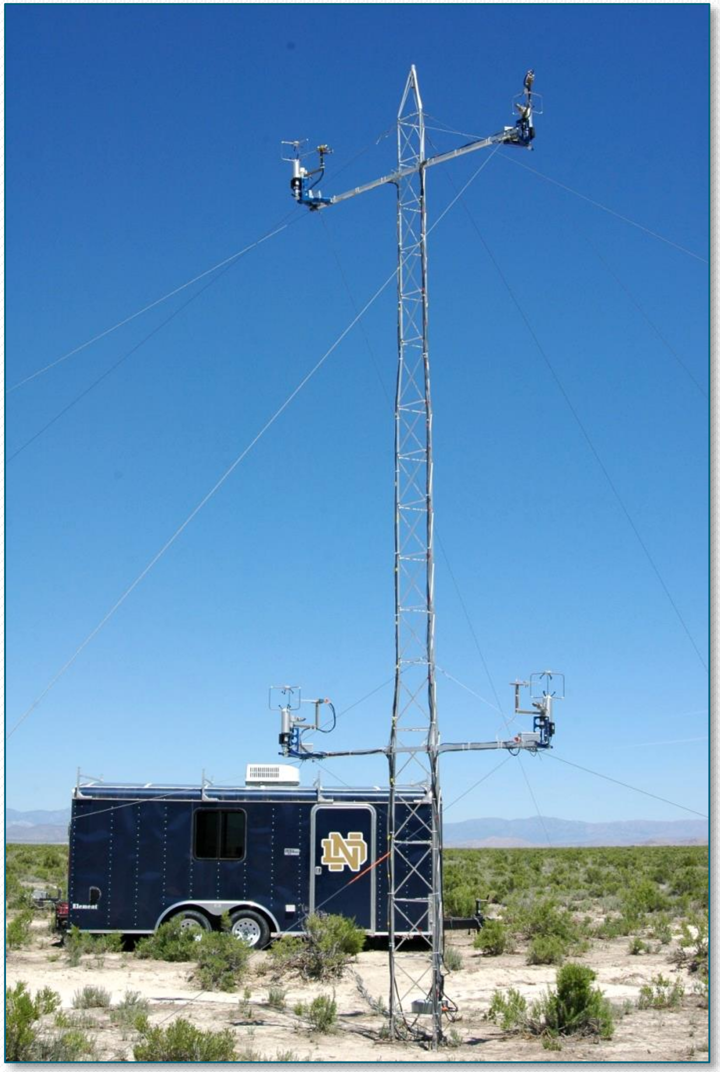
Combo probes located at 3m and 8m

2-X Probes

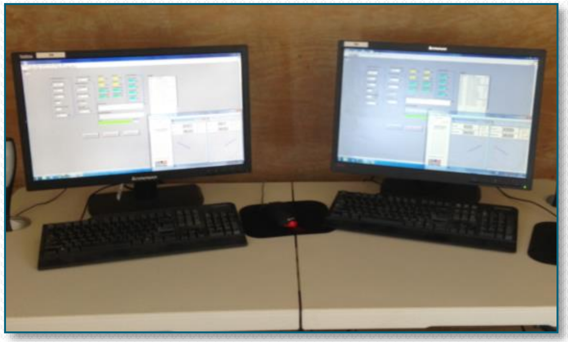




MATERHORN-X-2



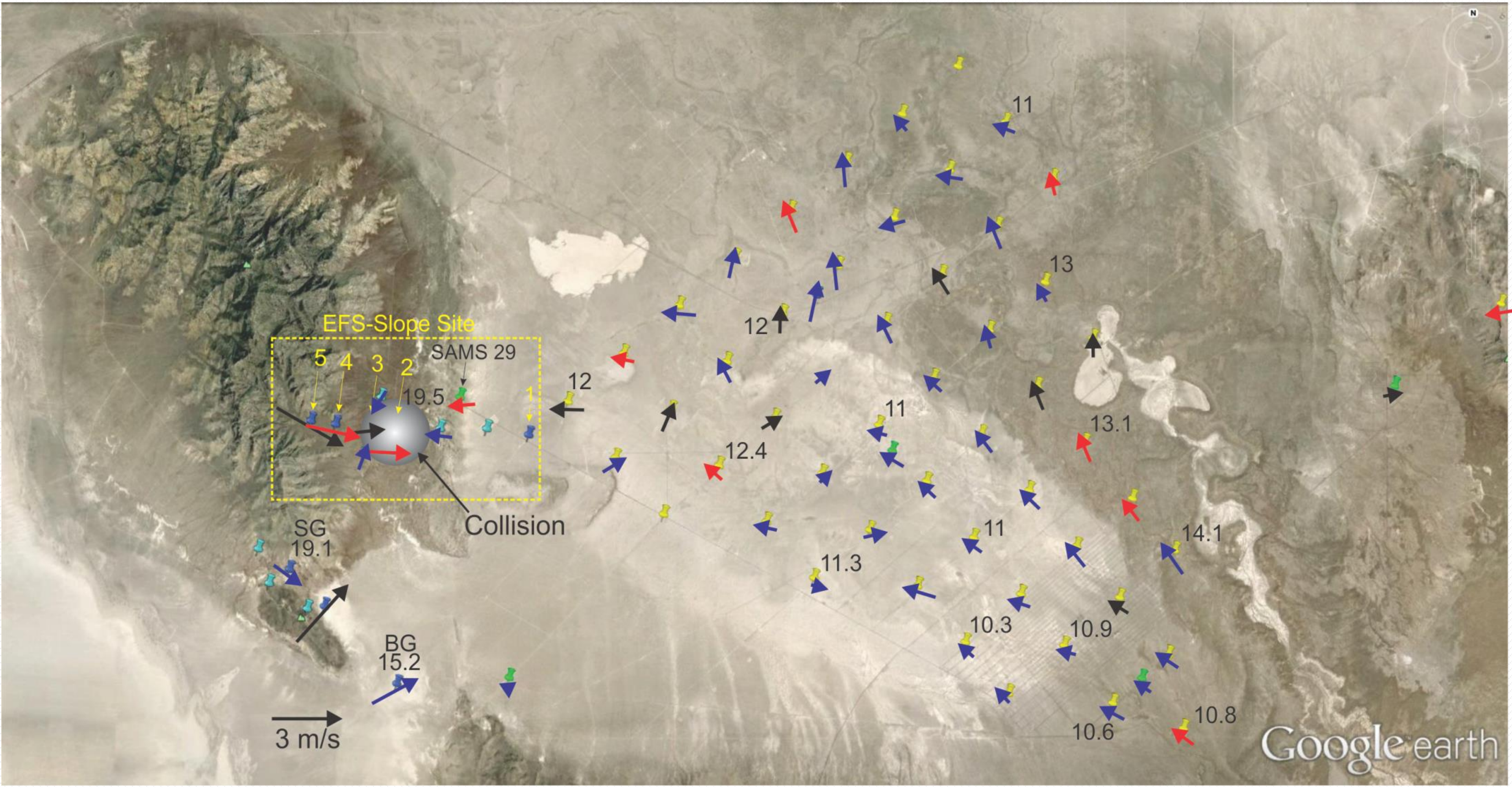
Combo probe electronics



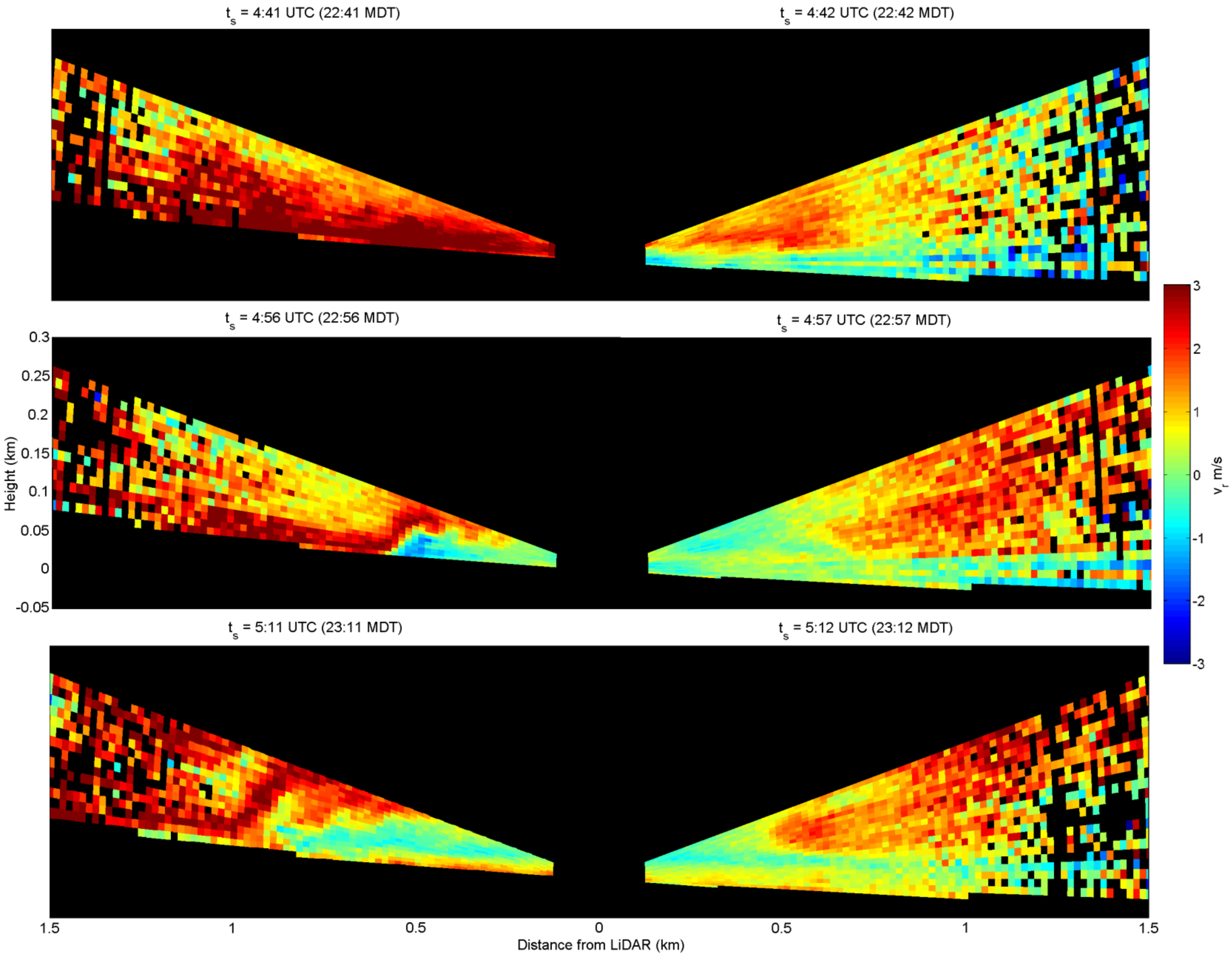
- **Quiescent IOP Turbulence Production Events**

DPG GMAST and Towers

IOP 2, 4:45 UTC (22:45 MDT): Collision occurs between slope and valley flow



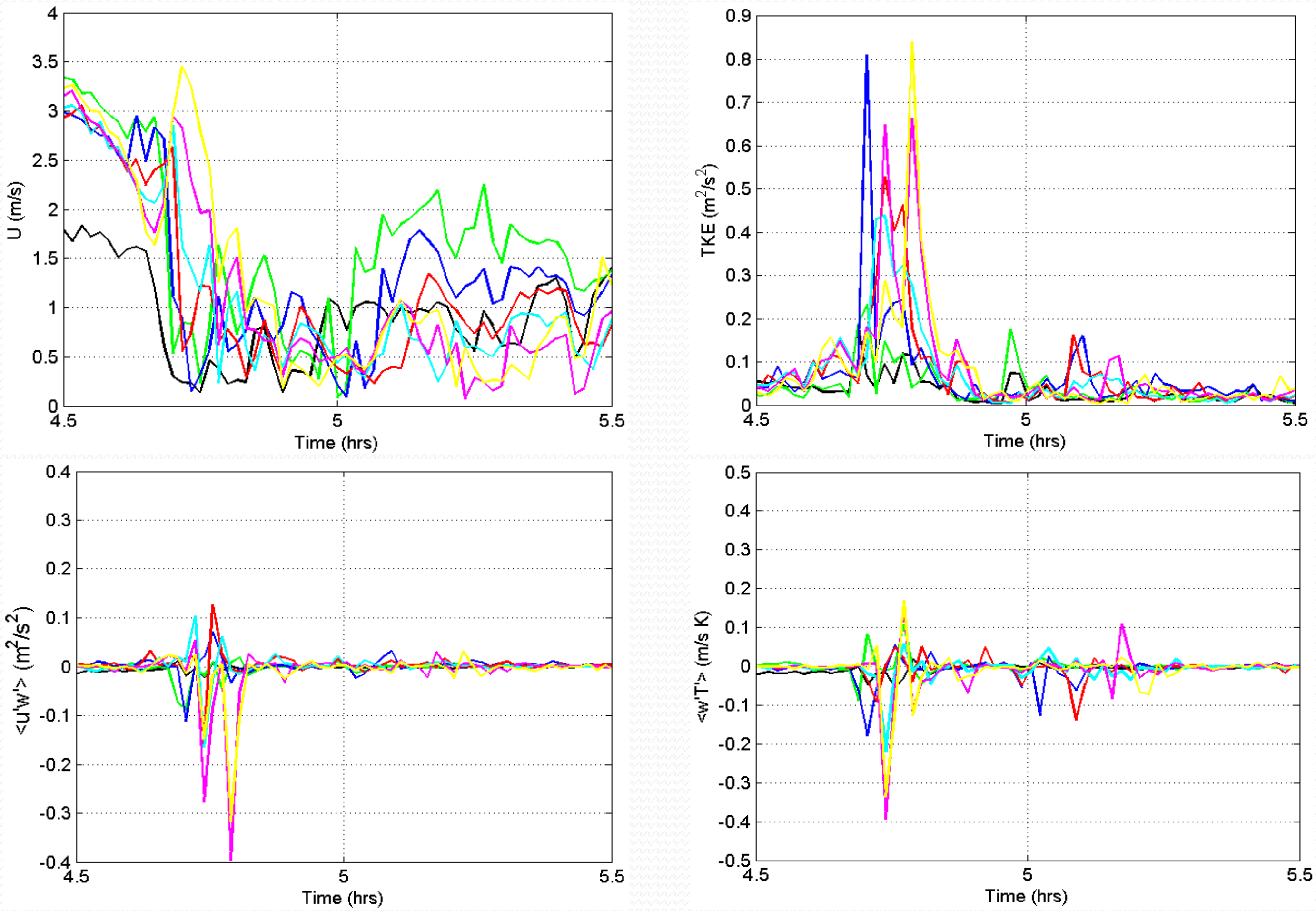
UU LiDAR



t_s = 4:41 UTC (22:41 MDT)
t_s = 4:42 UTC (22:42 MDT)
t_s = 4:56 UTC (22:56 MDT)
t_s = 4:57 UTC (22:57 MDT)
t_s = 5:11 UTC (23:11 MDT)
t_s = 5:12 UTC (23:12 MDT)
Height (km)
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
v_r m/s
3
2
1
0
-1
-2
-3
1.5
1
0.5
0
0.5
1
1.5
Distance from LiDAR (km)

EFS-Slope Site ES2 Tower

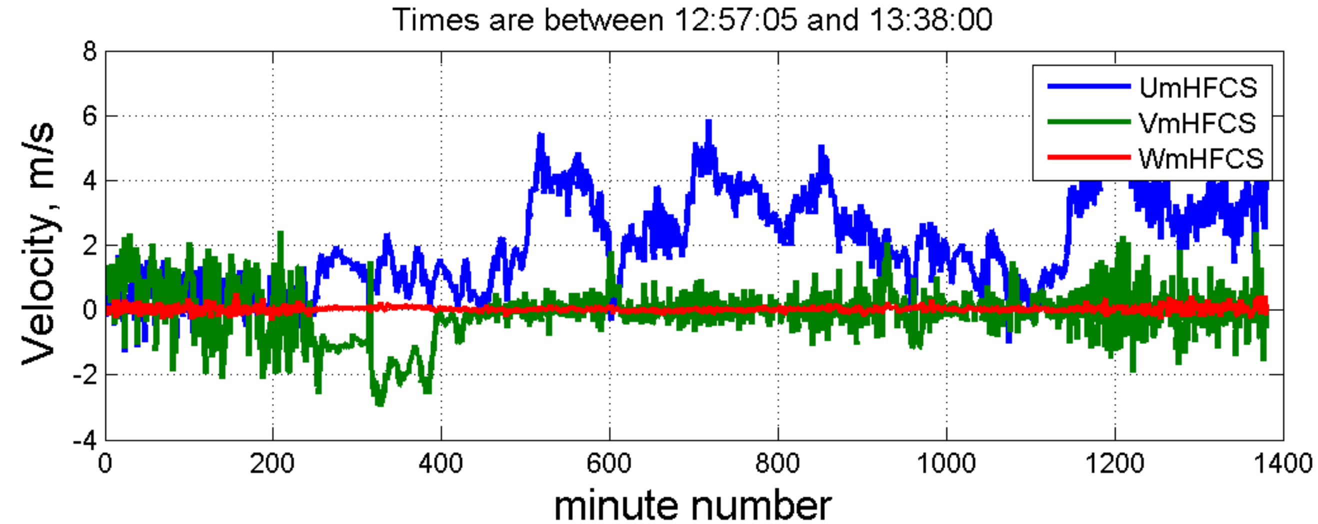
IOP 2, 4:45 UTC (22:45 MDT): Collision occurs between slope and valley flow

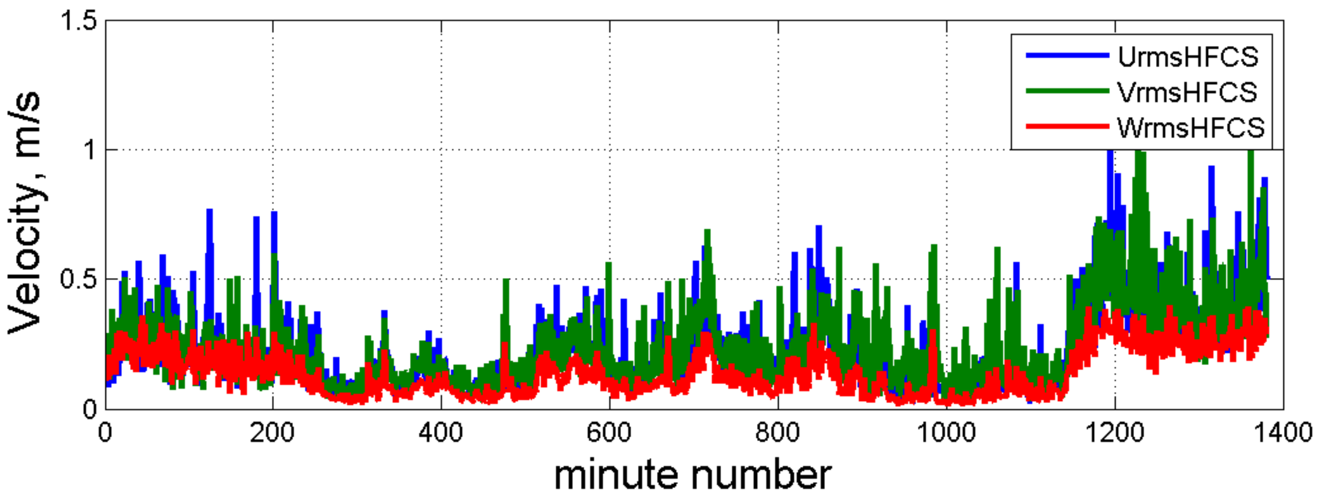


- **Fall Experiment Results**

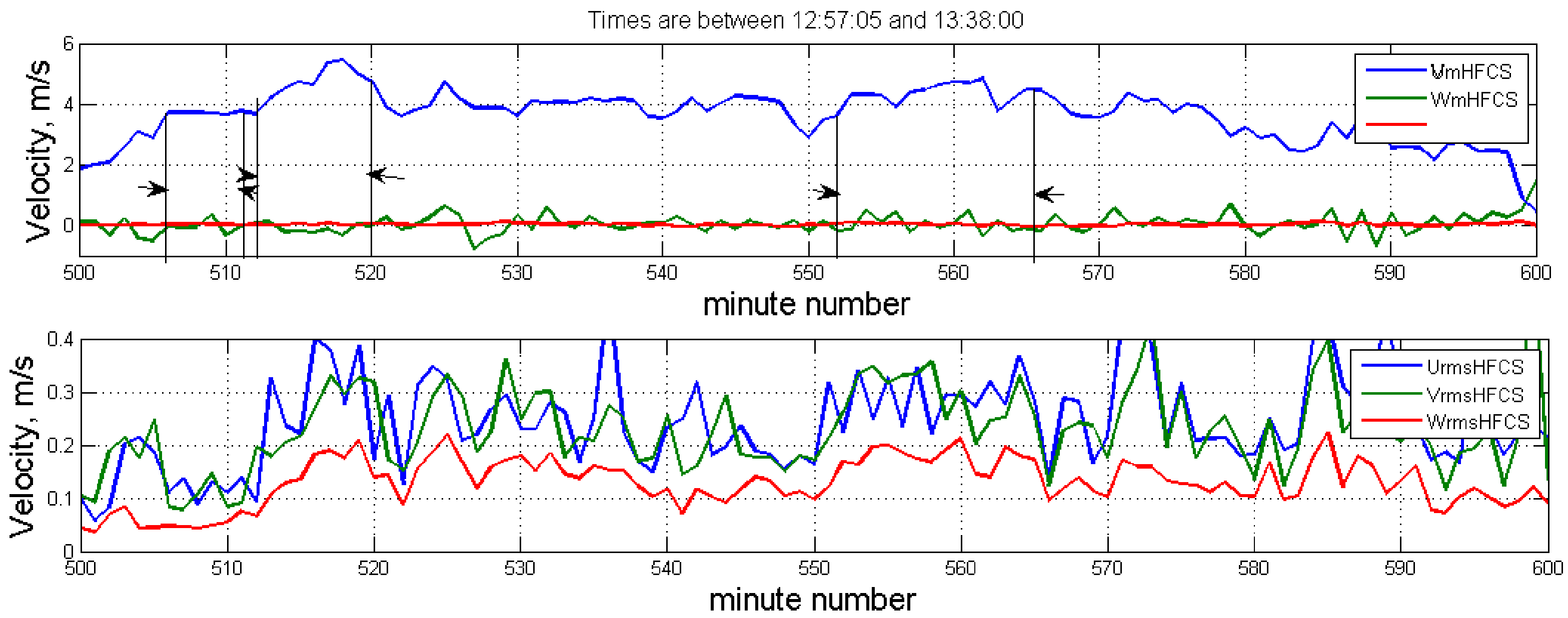
“What Sonic Anemometers Miss”

Sonic time series at October 19-20 (from 12:57 to 13:38)

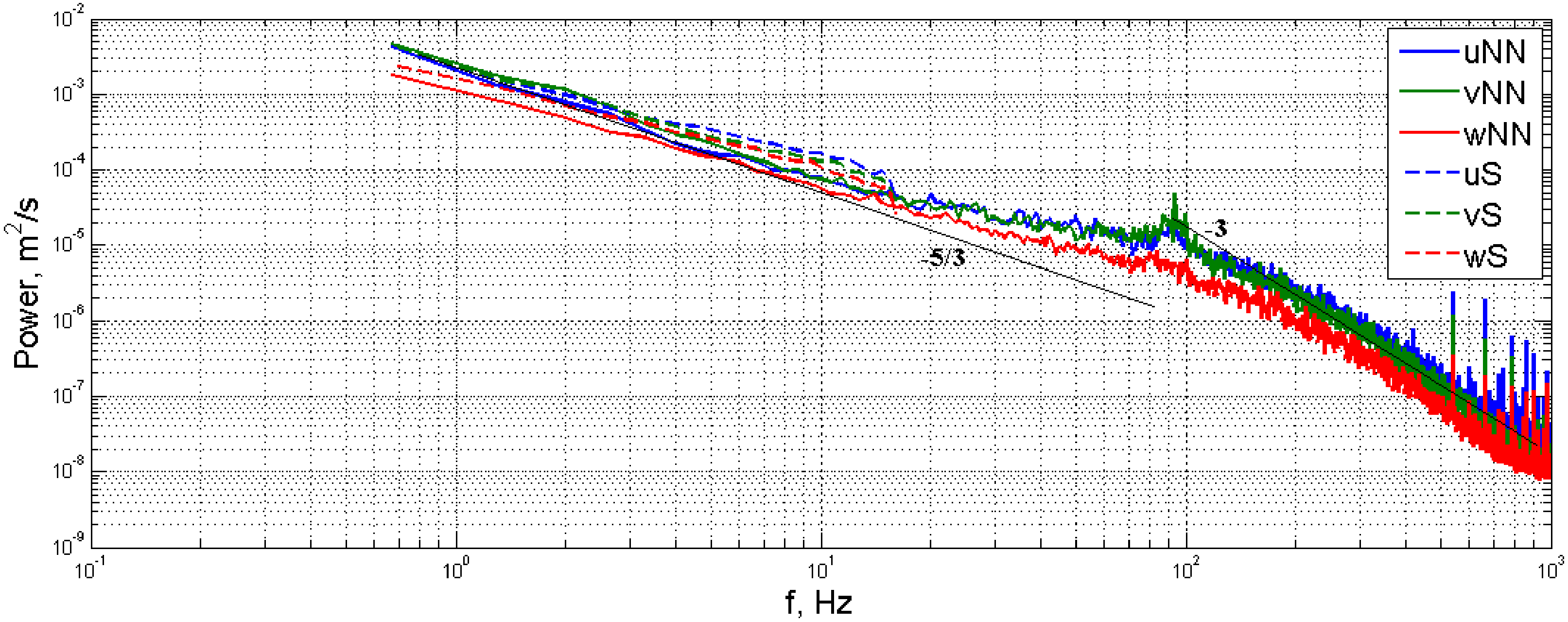




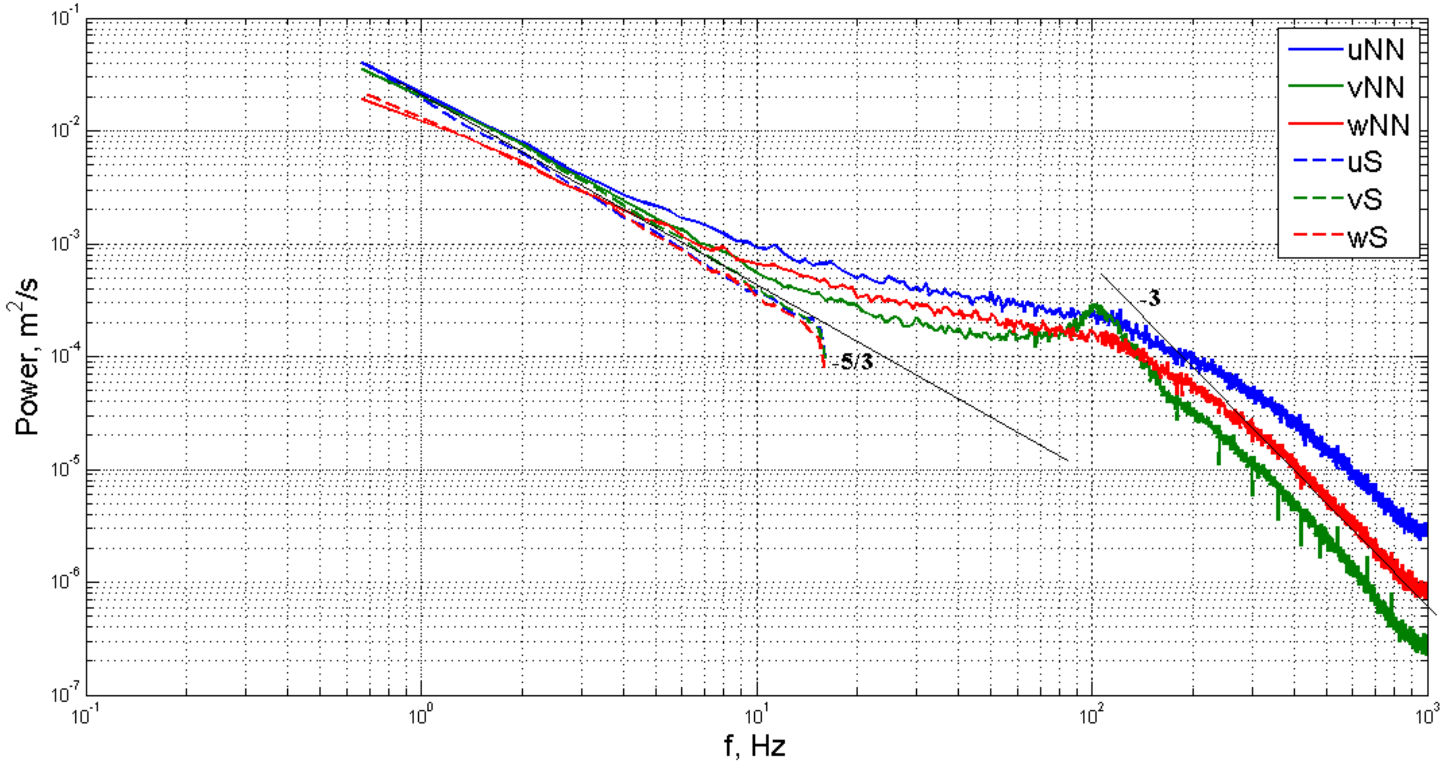
Sonic time series for the nocturnal time period at October 19 (9:30-11PM)



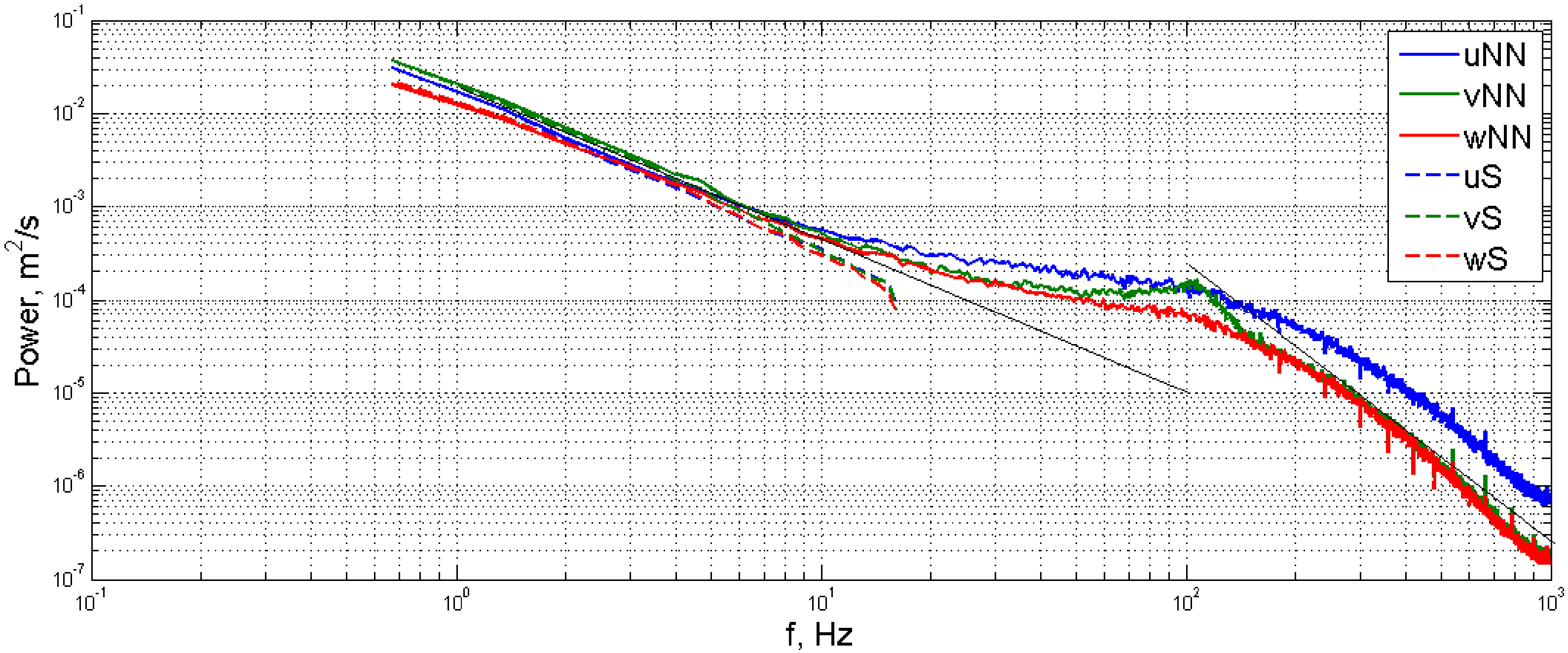
Spectra for Minutes 26-32



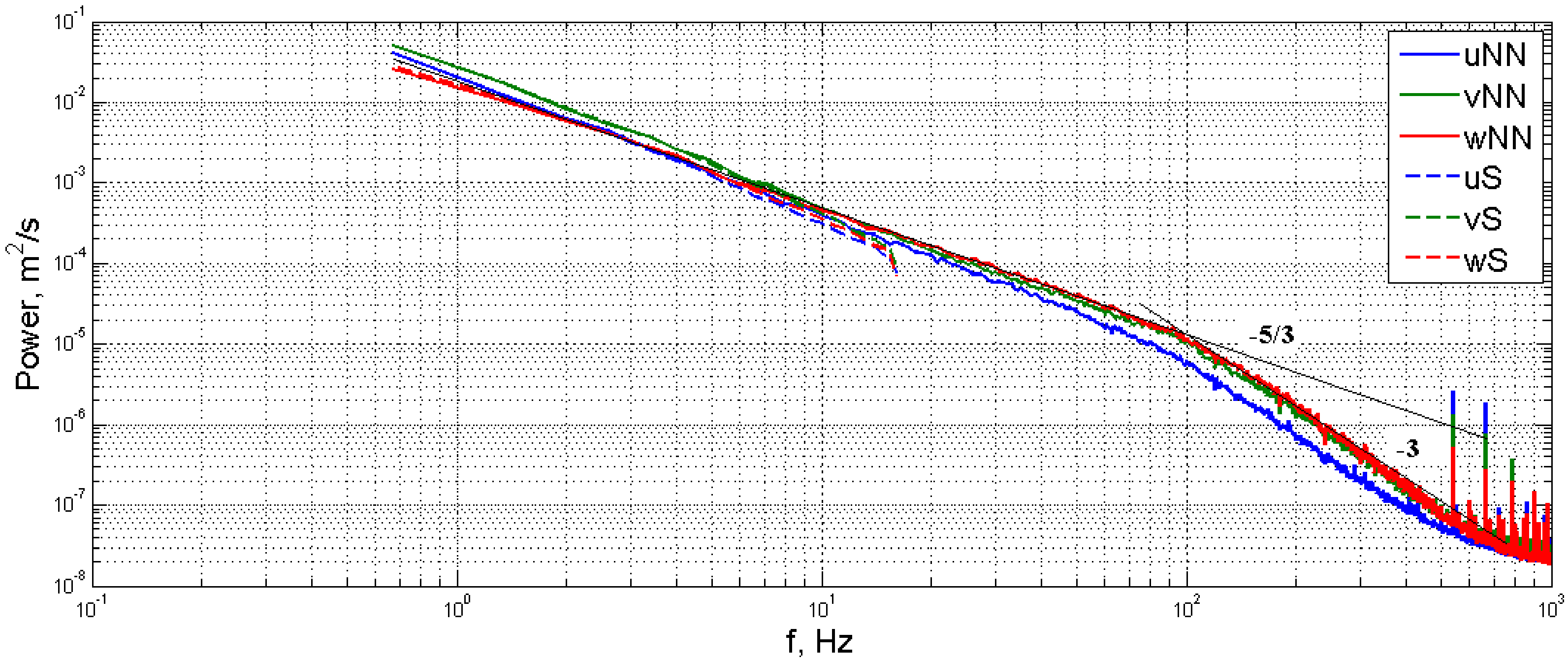
Spectra for Minutes 33-40



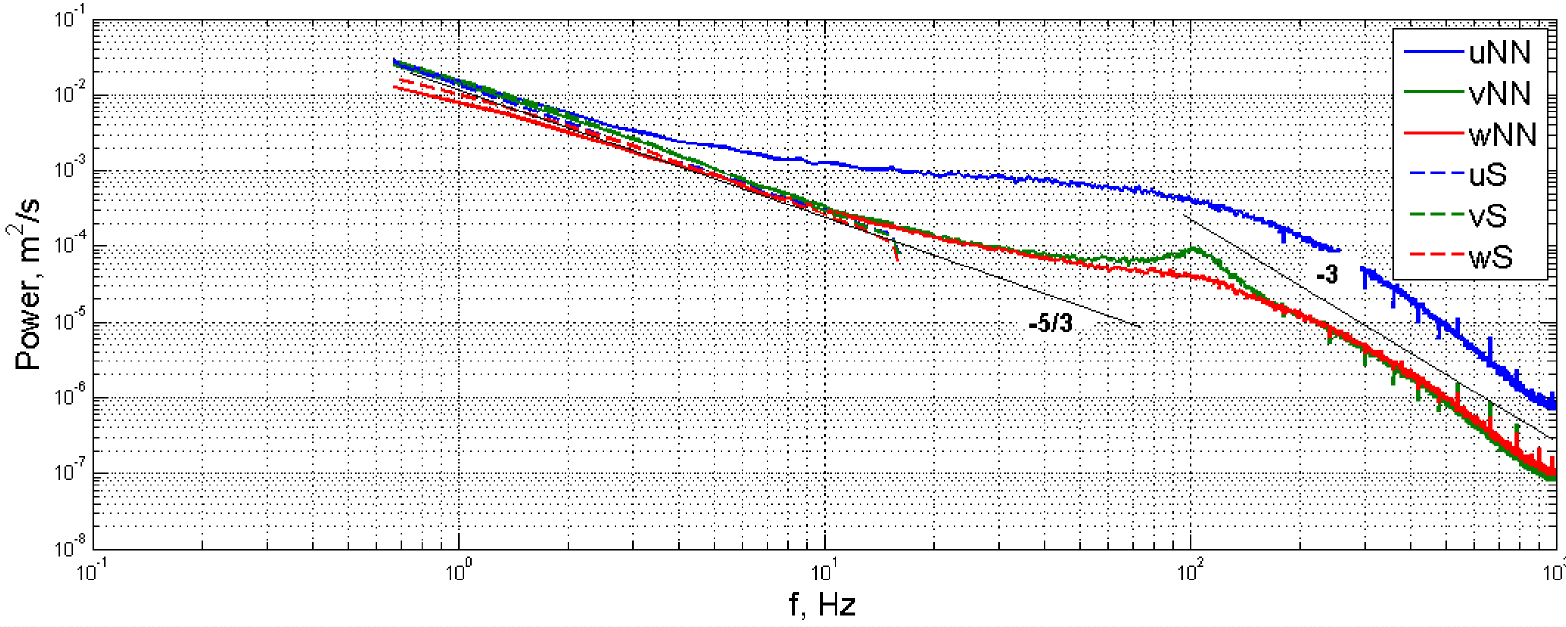
Spectra for Minutes 43-57



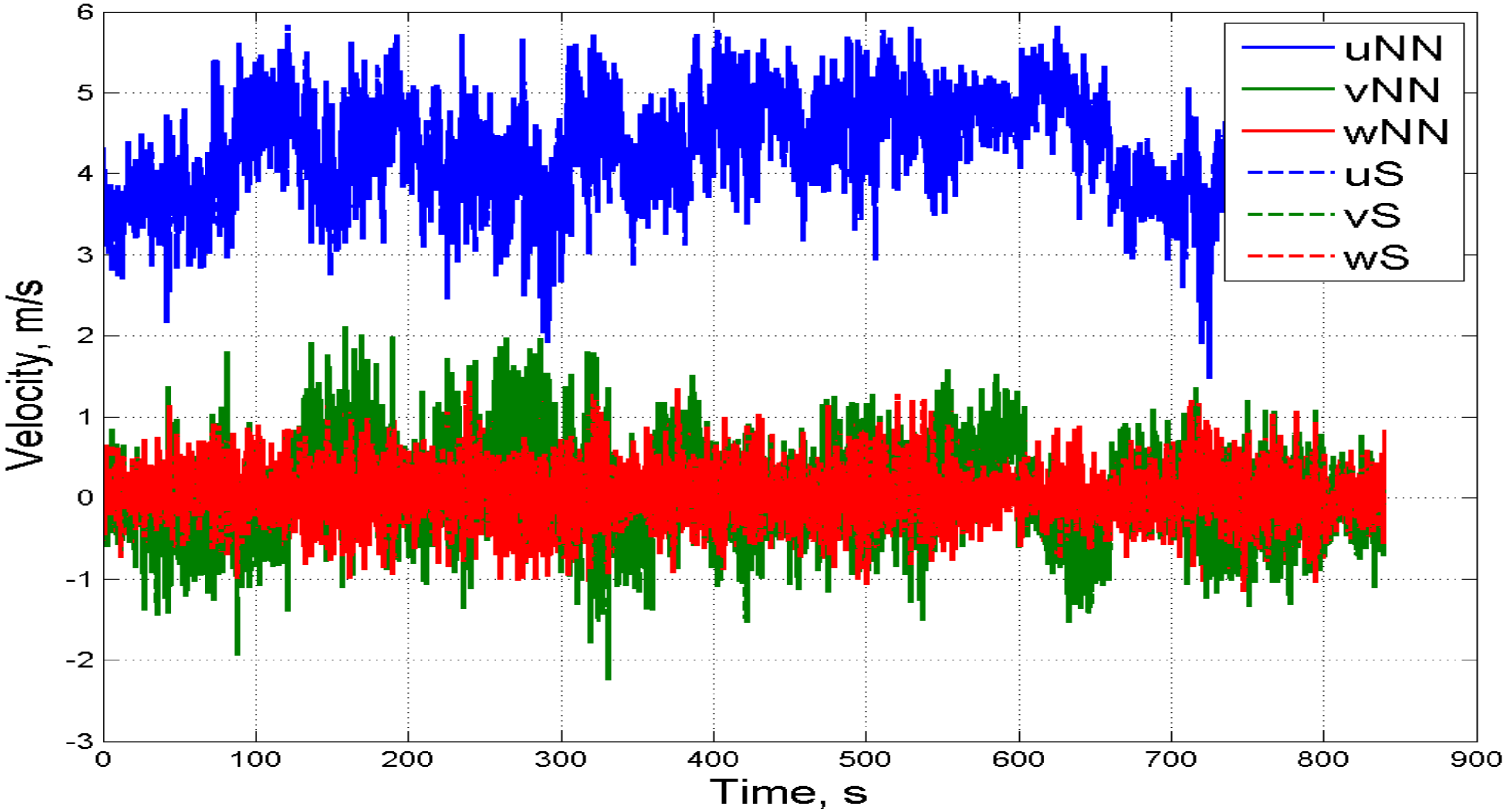
Spectra for Minutes 72-85



Spectra computed for the overlapping period of 30 min

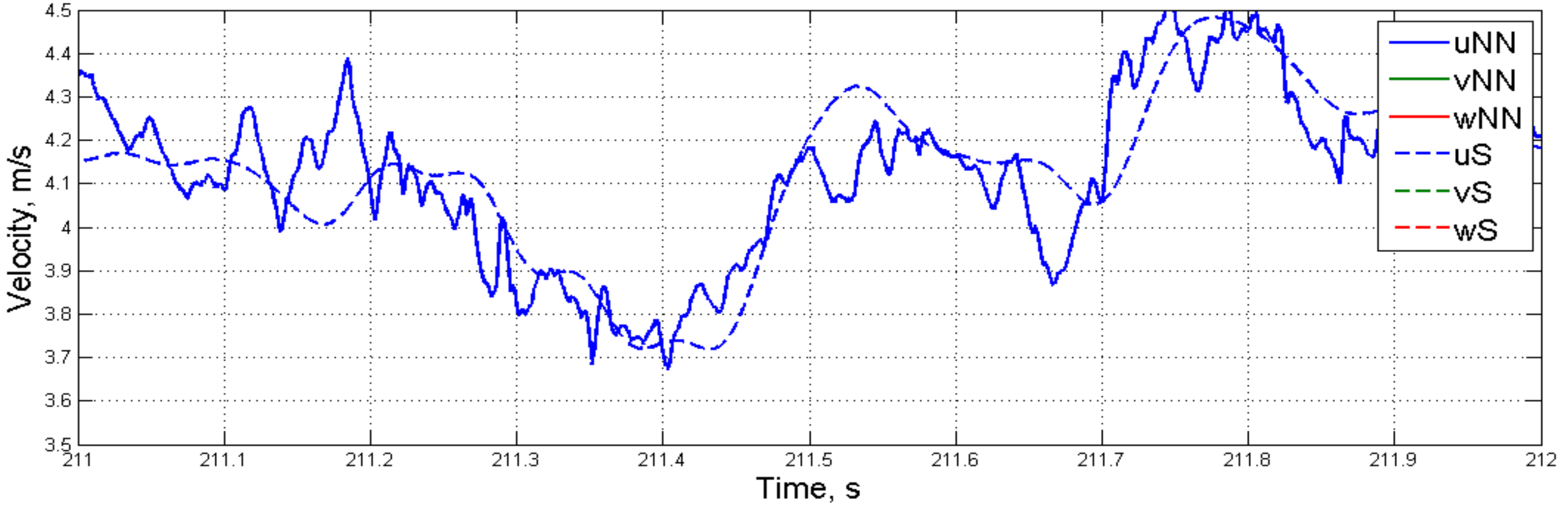


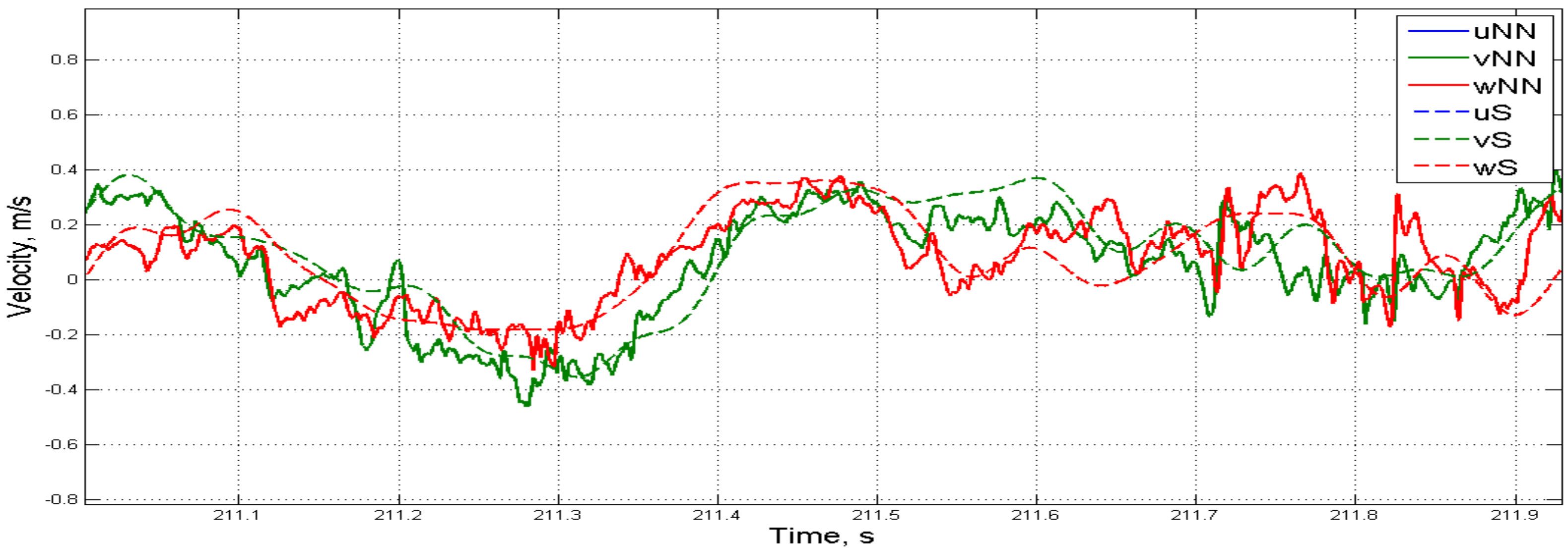
Time series



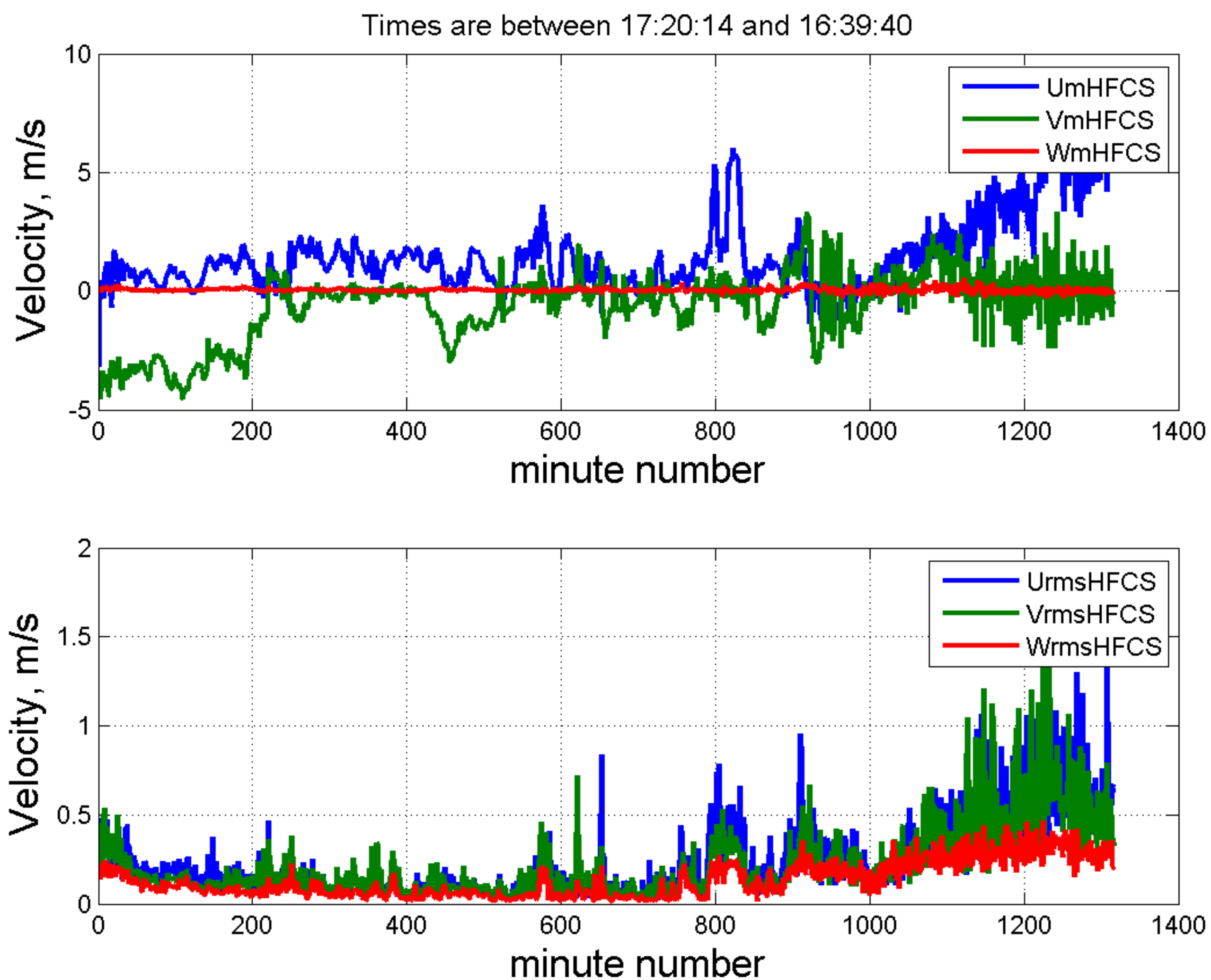
Velocity, m/s
Time, s
uNN
vNN
wNN
uS
vS
wS
6
5
4
3
2
1
0
-1
-2
-3
0
100
200
300
400
500
600
700
800
900

Time series (zoomed)





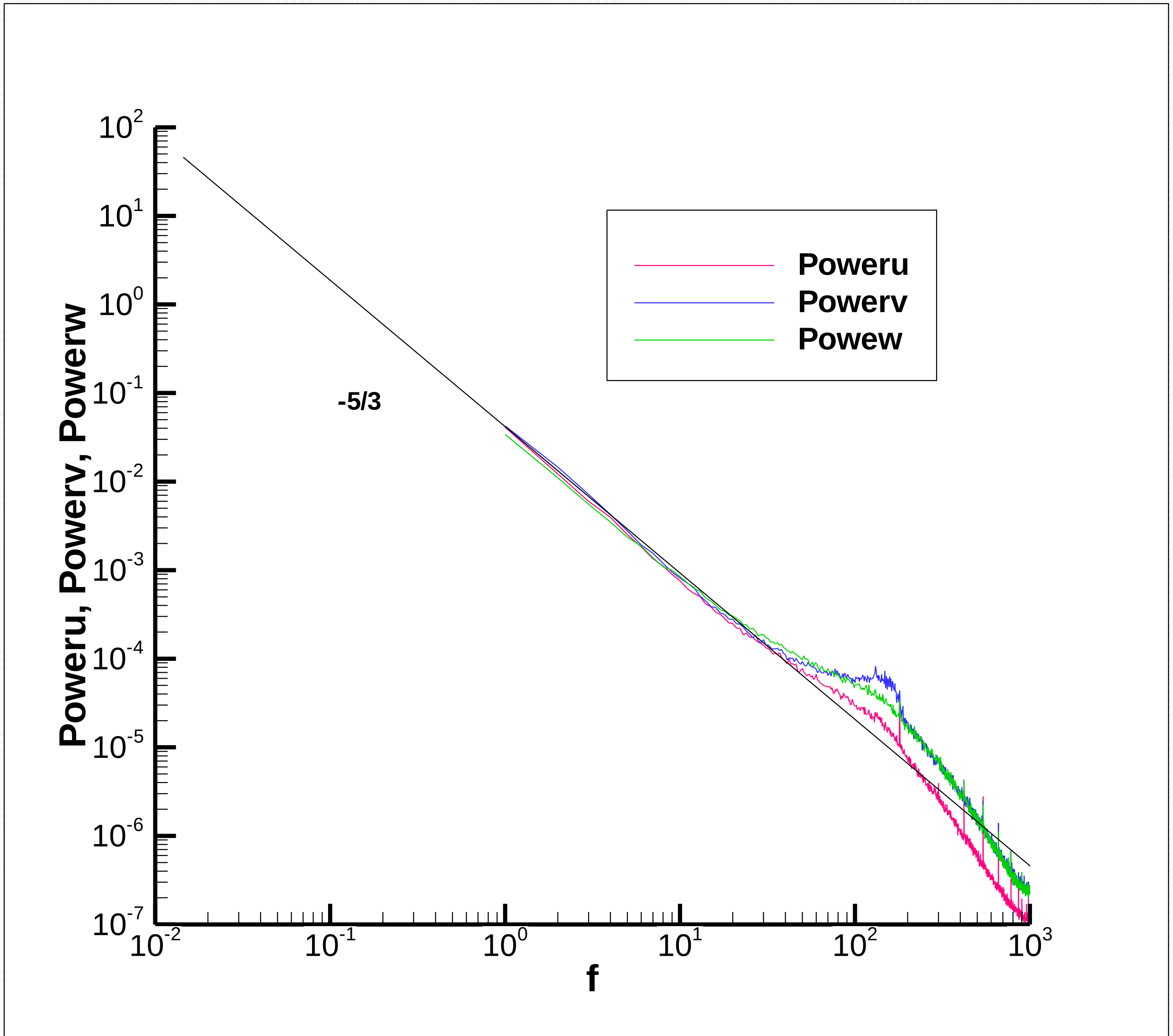
Sonic time series at October 9-10 (from 17:20 to 16:39)



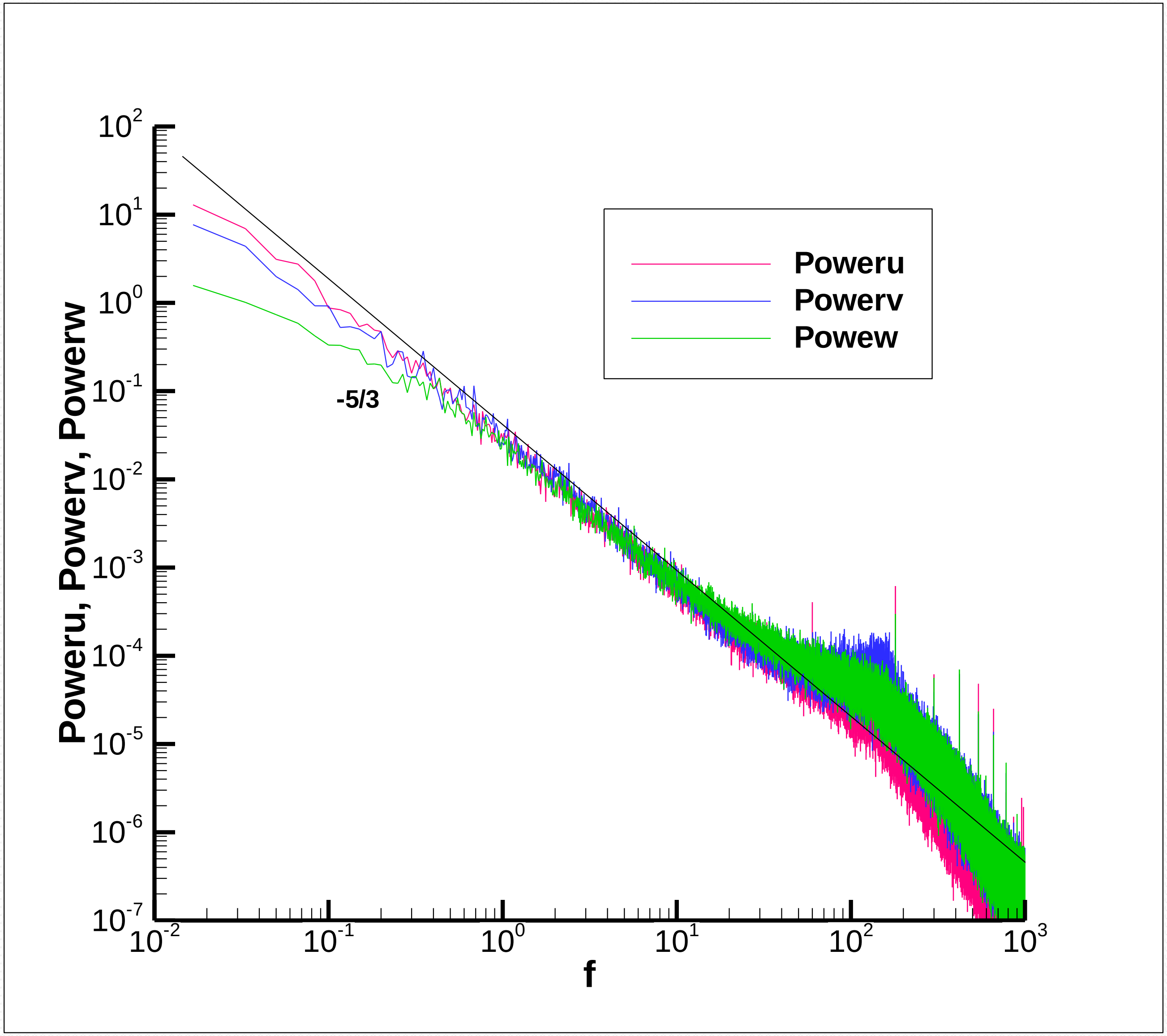
Results at 6m height October 10^{th}, afternoon 3PM

NofGoodMin,	avru,	avrv,	avrw
16	5.162	0.187	0.030
NofGoodMin,	**rmsu,**	**rmsv,**	**rmsw**
16	0.811	0.750	0.469
NofGoodMin,	**skwu,**	**disu,**	**disw**
16	0.377	0.046	0.032

Spectra at low frequency resolution
Great number of averaging



Spectra at high frequency resolution Low number of averaging



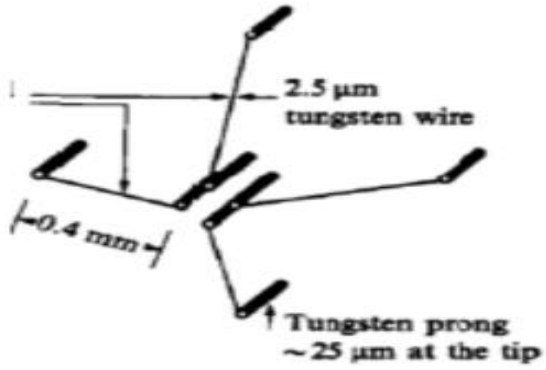
Conclusions

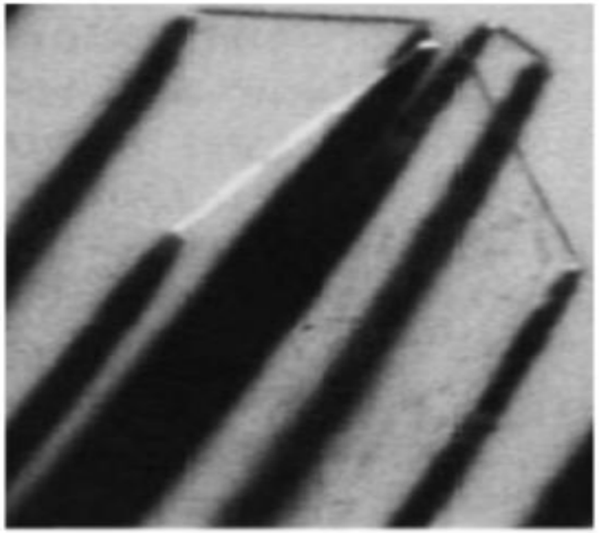
- Combo setup and Neural Network algorithm enable to obtain valuable information on the atmospheric flow especially during the transition events.
- Careful analysis is needed to select appropriate calibration datasets and time series for data processing
- The extrapolation of spectra based on Sonic data only can lead to a faulty conclusions as was indicated by velocity spectra obtained from combo measurements.
- There is indication that the use of four-sensor probes may be of advantage and can improve the signal-to-noise ratio due to redundant information.
- Further analysis of the spring data is in progress and hopefully will provide new perception

THANK YOU!
THE END

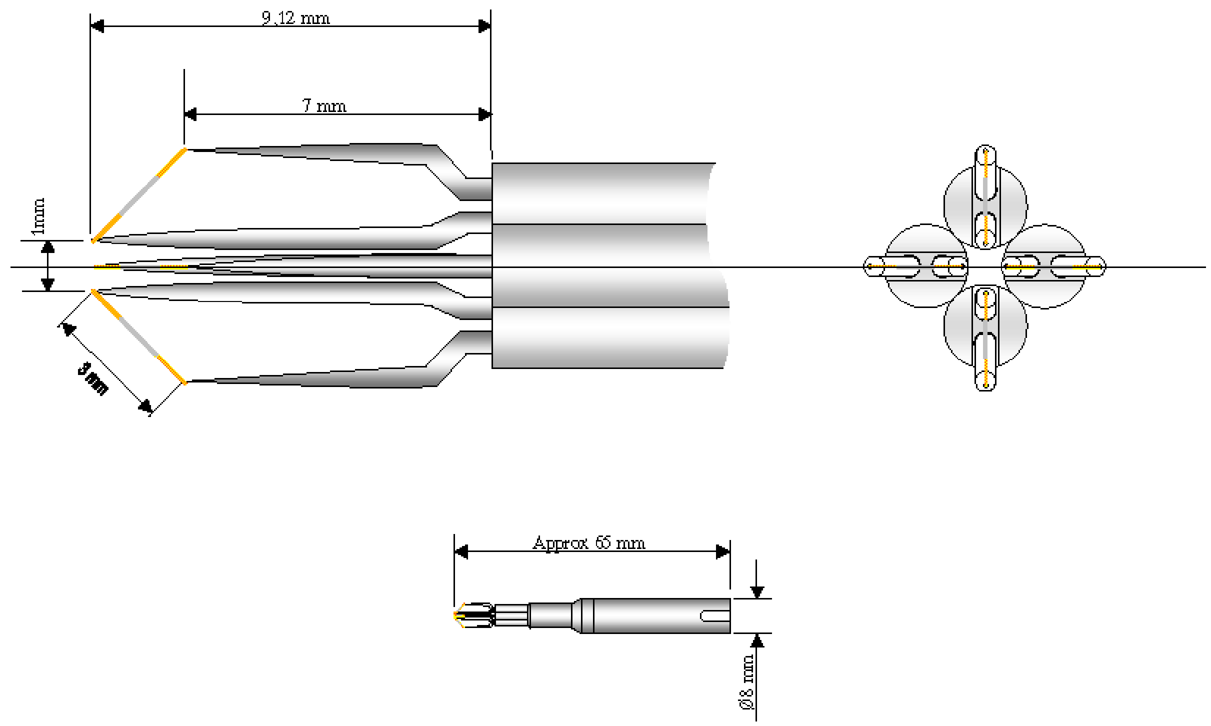
NEW HARDWARE DEVELOPMENTS

4-wire array home-made and used by Tsinober, Kit and Dracos (JFM, 1992)



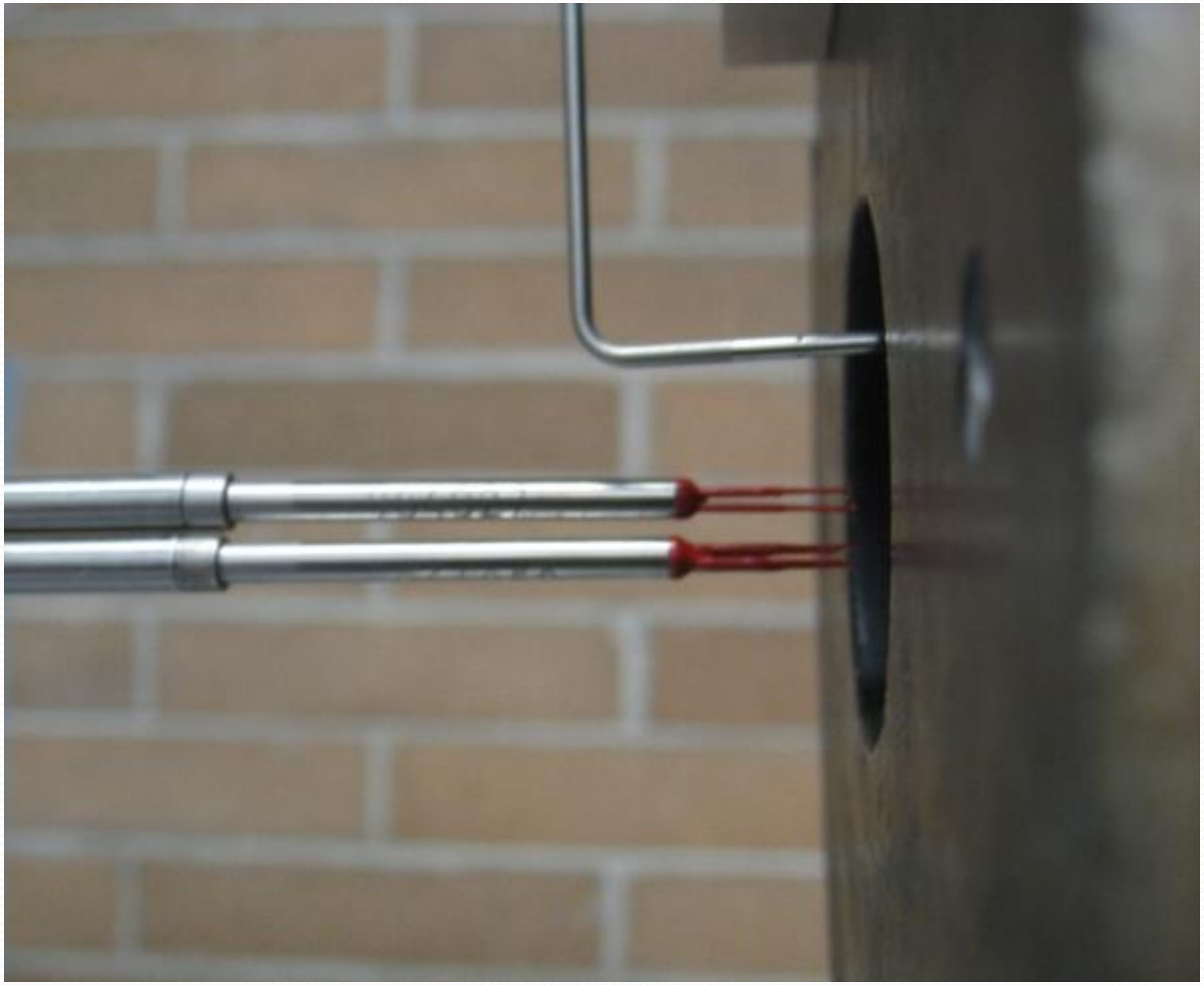


DANTEC Development of a new 3D-probe with 4 hot-film sensors.



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

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



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

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)**

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,

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

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

In the isotropic case (k=1):

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

Results – TI

- For TI (20%, 30%, 40%):

Turbulence Intensity

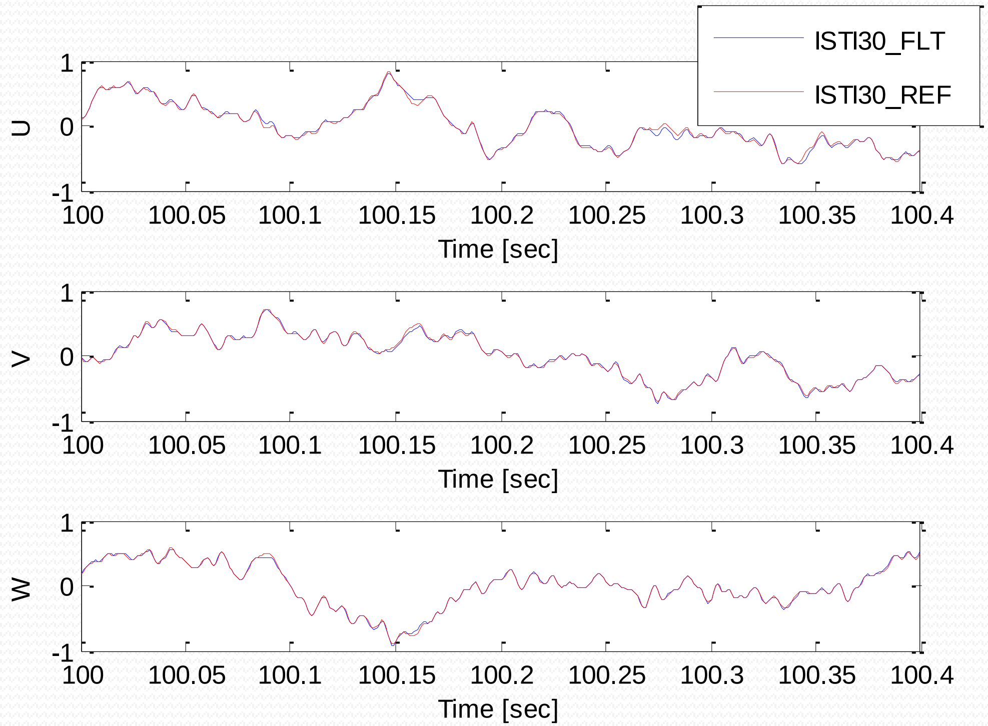
	TI 20%				TI 30%				TI 40%			
	Mean	STD	TI	δi	Mean	STD	TI	δi	Mean	STD	TI	δi
U (m/s)	2.97	0.57	20%	0.06	1.95	0.57	31%	0.1	1.41	0.58	42%	0.19
V (m/s)	0	0.43		0.05	-0.01	0.44		0.07	-0.02	0.43		0.15
W (m/s)	0	0.43		0.04	0	0.44		0.06	0.01	0.42		0.16

STD U	STD V	STD W
0.57	0.44	0.43

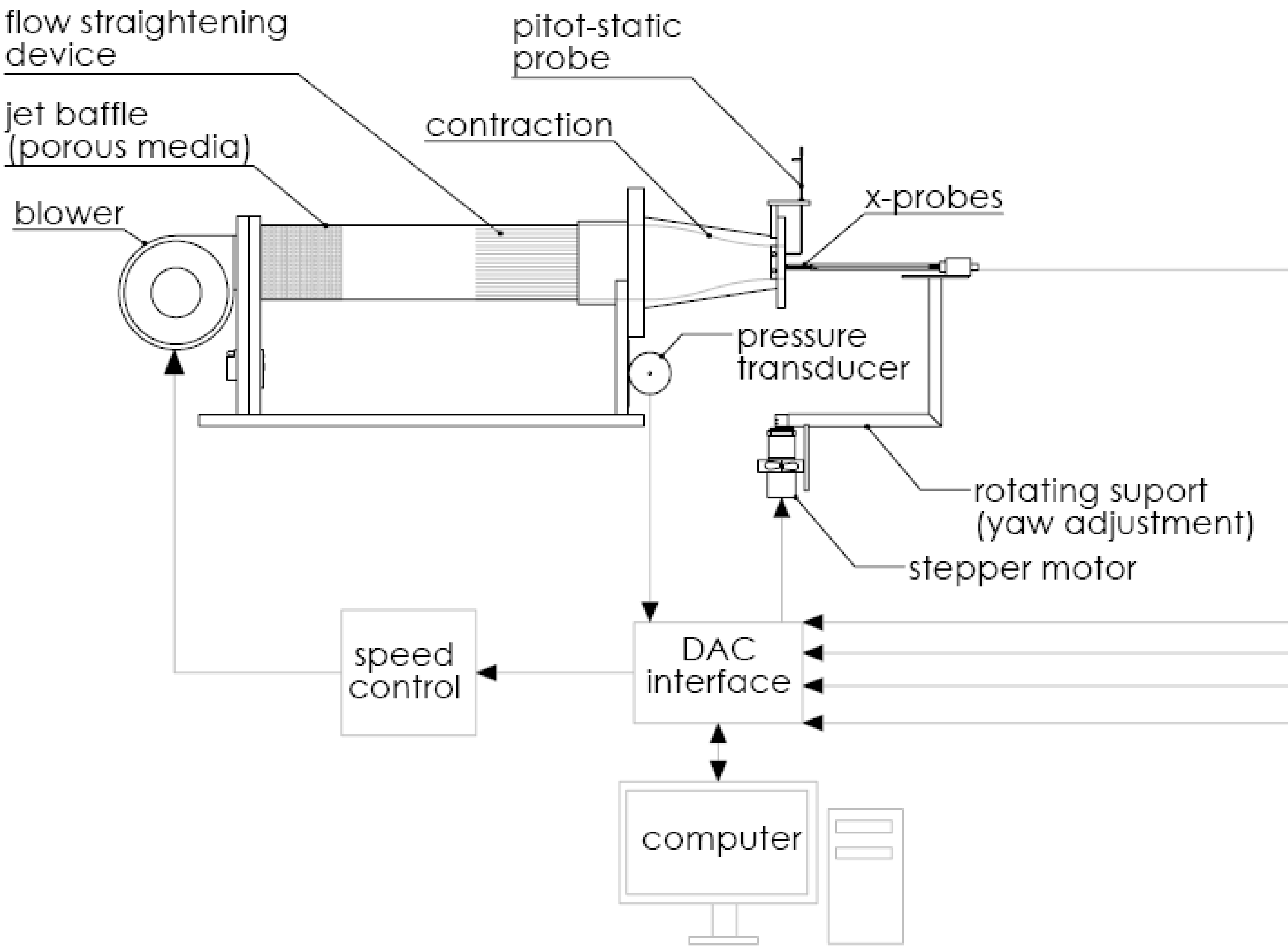
Results - Anisotropy

ISTI30	U (m/s)	V (m/s)	W (m/s)
Mean	1.92	0.00	0.00
RMS	0.51	0.51	0.49
TI	32%		
δi	0.19	0.12	0.10

LTII30	U (m/s)	V (m/s)	W (m/s)
Mean	1.95	-0.01	0.00
RMS	0.57	0.44	0.44
TI	31%		
δi	0.10	0.07	0.06



Jet Facility and traverse for probe yawing



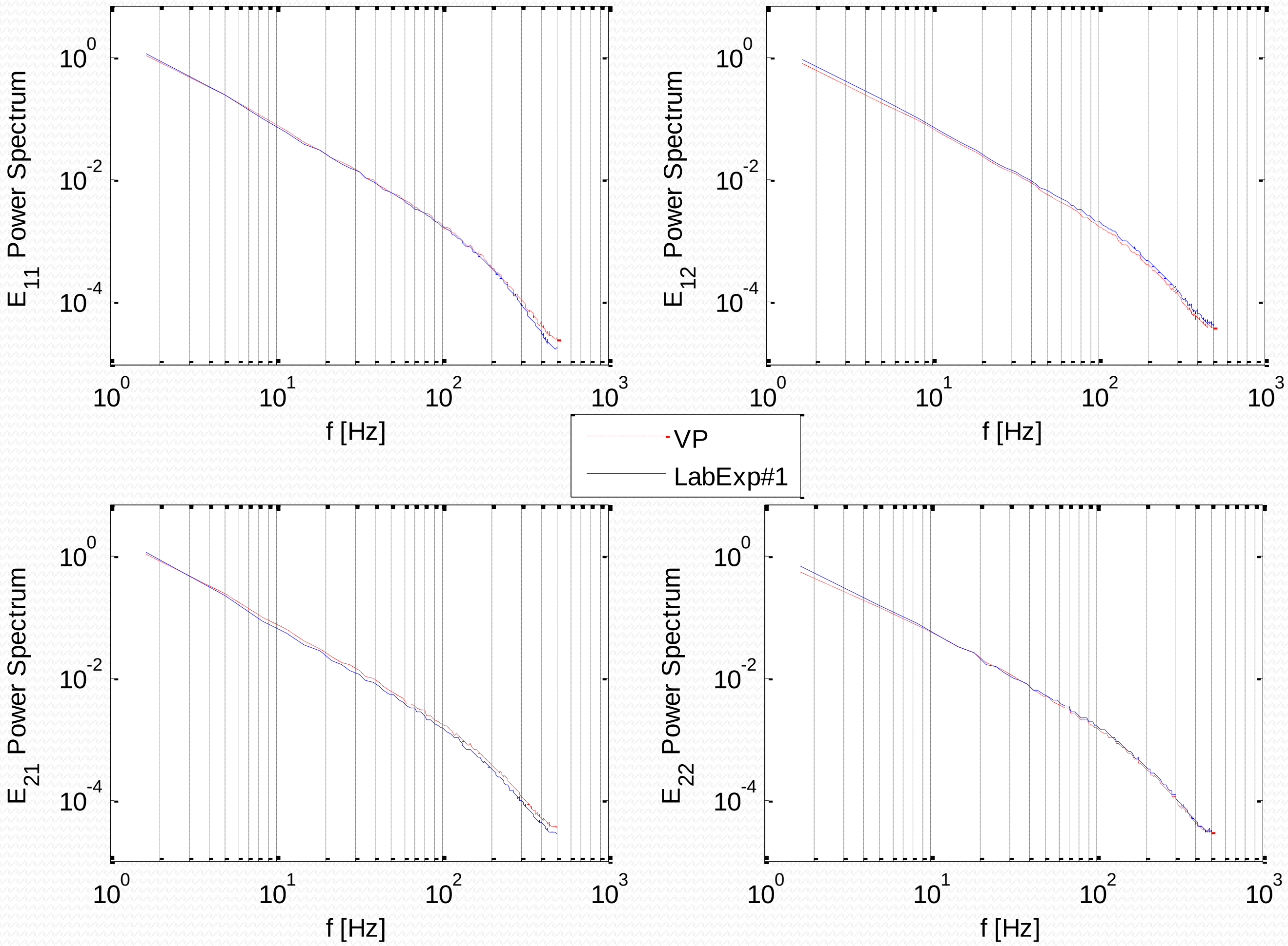
Questions Regarding HW Probe *in-situ* Calibration

- What are the TI bounds for Sonic calibration?
- What is the effect of the LPF on calibration set?
- What is the effect of anisotropy on the calibration?

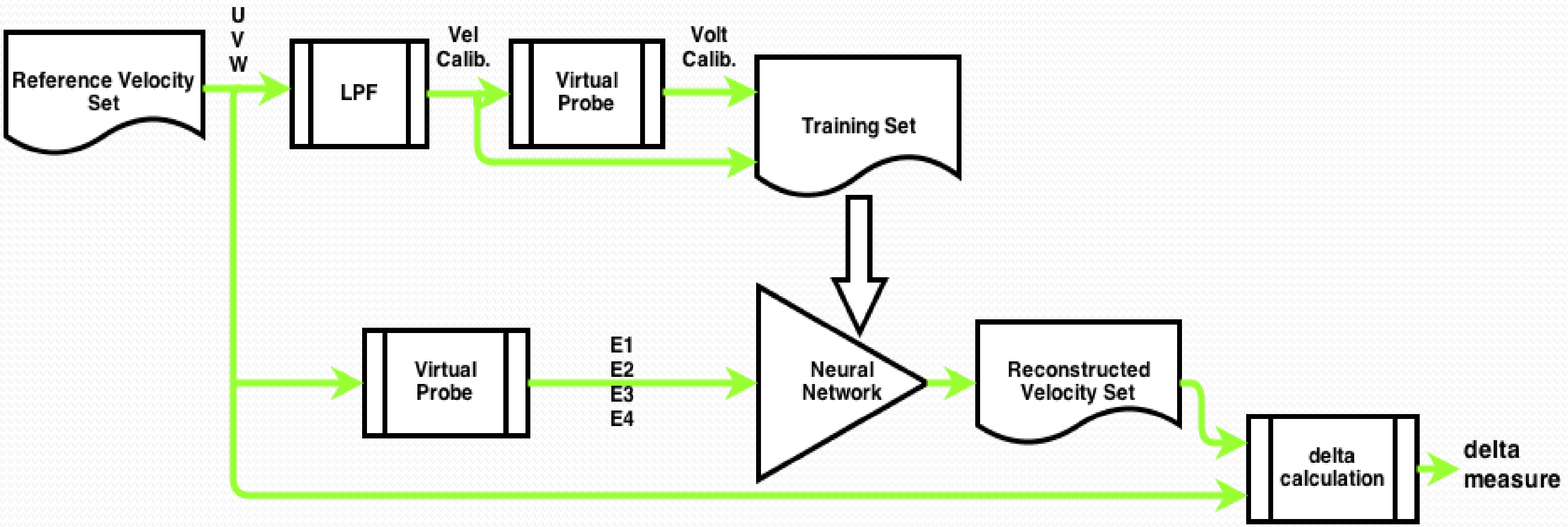
Turbulence Anisotropy Effect

- Real flows are anisotropic. What's the effect on calibration quality?
- Generate isotropic fields.
- Check calibration quality.

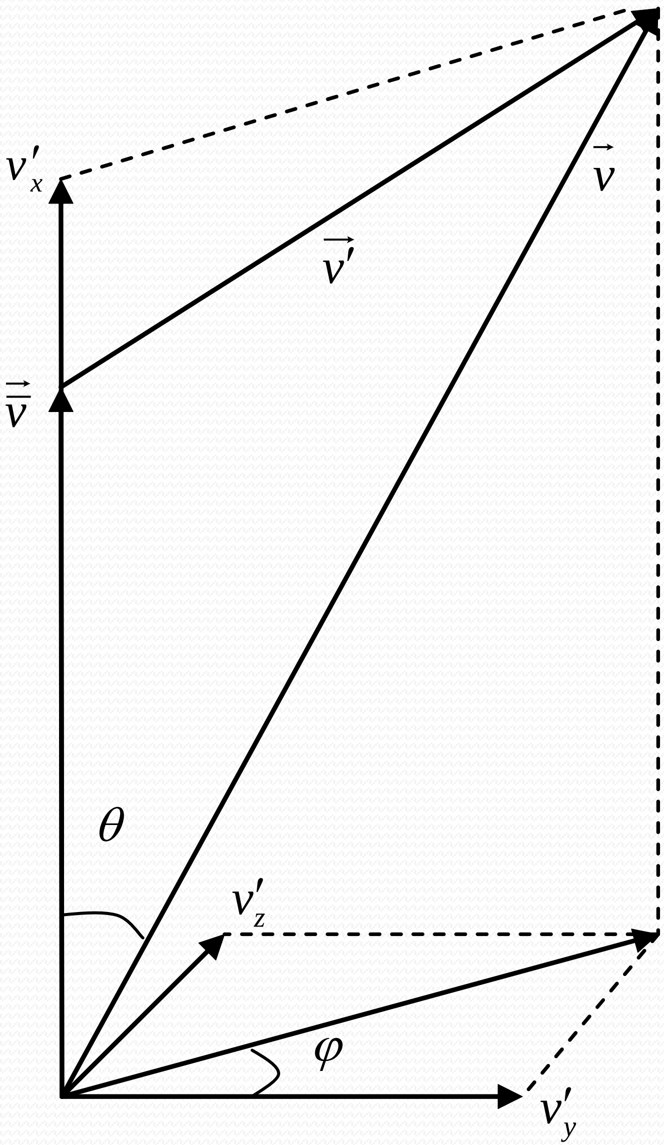
Virtual Probe contd. 3



LPF Contribution to Calibration Error



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.

Virtual Probe

- Use of calibration data-set previously measured (CBS dataset from Kit et al., 2010)
- Calculated the effective velocity for each wire.

$$U_{eff}^2 = U_n^2 + k^2 U_t^2$$

- Found best fit for King's law coefficients A, B and the power n.

$$E^2 = A + B \cdot U_{eff}^n$$

Virtual Probe contd. 2

	A	*B*	*n*
Wire 1	3.30	2.19	0.547
Wire 2	3.85	2.20	0.587
Wire 3	3.74	2.12	0.567
Wire 4	3.23	1.84	0.579

		Measured (CBS)				Calculated			
		e11	e12	e21	e22	e11	e12	e21	e22
Measured (CBS)	e11	1.000	0.504	0.748	0.690	**0.979**			
	e12	0.504	1.000	0.718	0.631		**0.975**		
	e21	0.748	0.718	1.000	0.609			**0.966**	
	e22	0.690	0.631	0.609	1.000				**0.962**

Results – LPF , TI

- For TI (20%, 30%, 40%):

No LPF of calibration voltage (ideal)

LTI20_VP	U (m/s)	V (m/s)	W (m/s)
Mean	3.00	0.00	0.00
RMS	0.57	0.44	0.43
TI	20%		
δ_i	0.02	0.03	0.02
LTI30_VP	U (m/s)	V (m/s)	W (m/s)
Mean	2.00	0.00	0.00
RMS	0.57	0.43	0.42
TI	29%		
δ_i	0.04	0.06	0.04
LTI40_VP	U (m/s)	V (m/s)	W (m/s)
Mean	1.52	-0.01	0.00
RMS	0.54	0.42	0.40
TI	37%		
δi	0.16	0.11	0.11

LPF of calibration voltage (real)

LTI20	U (m/s)	V (m/s)	W (m/s)
Mean	2.97	0.00	0.00
RMS	0.57	0.43	0.43
TI	20%		
δi	0.06	0.05	0.04
LTII30	U (m/s)	V (m/s)	W (m/s)
Mean	1.95	-0.01	0.00
RMS	0.57	0.44	0.44
TI	31%		
δi	0.10	0.07	0.06
LTI40	U (m/s)	V (m/s)	W (m/s)
Mean	1.41	-0.02	0.01
RMS	0.58	0.43	0.42
TI	42%		
δi	0.19	0.15	0.16

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
- Further development of the method: establishing of criteria for data quality.