EARS4WindEnergy

Ensemble-based Approach utilizing a Refined SODAR
for Wind Energy Applications

Next level wind integration by listening to the wind

– Windintegration Workshop 2023 –

Kgs. Lyngby, 26. Sep. 2023

AQSystem Remote sensing technique

DTU

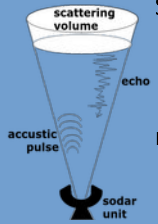
UPPSALA UNIVERSITET

WEPROG

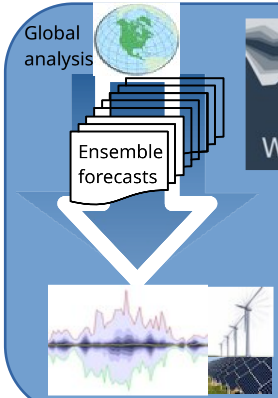
Project Consortium

www.aqsystem.se

AQSystem
Remote sensing technique



started in 1989 to produce SODARs to monitor wind and turbulence for the wind energy market. Today the AQ510 is a robust self-sufficient life-cycle instrument for all climate conditions...



WEPROG

..started in 2003 to generate ensemble weather and energy forecasts for the energy market.

Today, the 75 ensemble member MSEPS system is run world-wide to serve efficient renewables integration and to assist in "dealing with uncertainties"..

UPPSALA UNIVERSITET

Uppsala University has long experience working with wind power as well as observations and analysis of measurements in the atmospheric boundary layer.

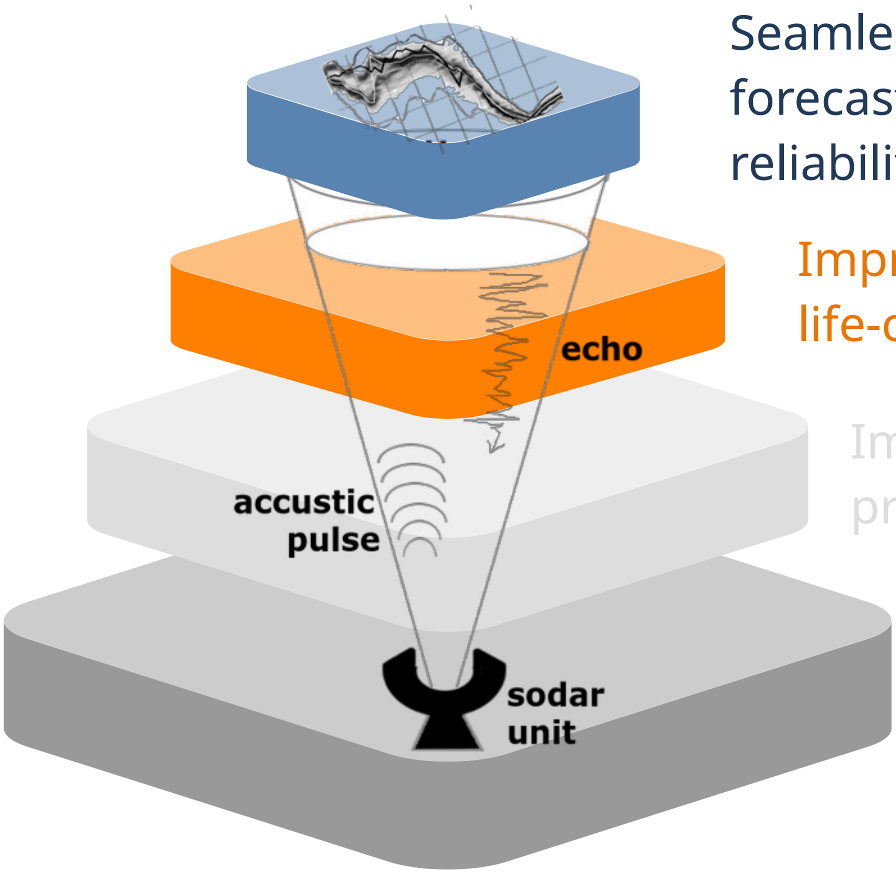
Risø Campus & Test facilities

DTU

Project Overview

WP1	• Project Management • Meetings and Dissemination
WP2	• SODAR Technology Advancement • Signal Processing
WP3	• Ensemble Forecasting Advancement with SODAR Data assimilation • Use of multiphysics ensemble to develop an optimal gap-filling method
WP4	• Special In-situ Windscanner Experiments • Demonstration of technical advances at 4 different locations in Europe

Project Goals



Seamless hybrid products for SODAR and ensemble forecast data for improved measurement data reliability & forecasting processes

Improved signal processing of SODAR to qualify as life-cycle instrument for wind farms

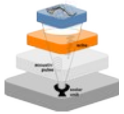
Improved Ensemble Forecasts, assimilation, presentation & accessibility of large data volumes

Improved experimental procedures and processes for efficient product development

How we want to achieve the project goals

1) The remote sensing technique has a long history of problems measuring turbulence

2) Grid balancing will require more accurate forecasting i the future with higher shares of renewables



We want to tackle the **first problem** with a <u>new signal processing routine</u>

We want to tackle the **second problem** with <u>combining a multiphysics ensemble with sodar measurments</u>

Reasons why we think we will be successful are:

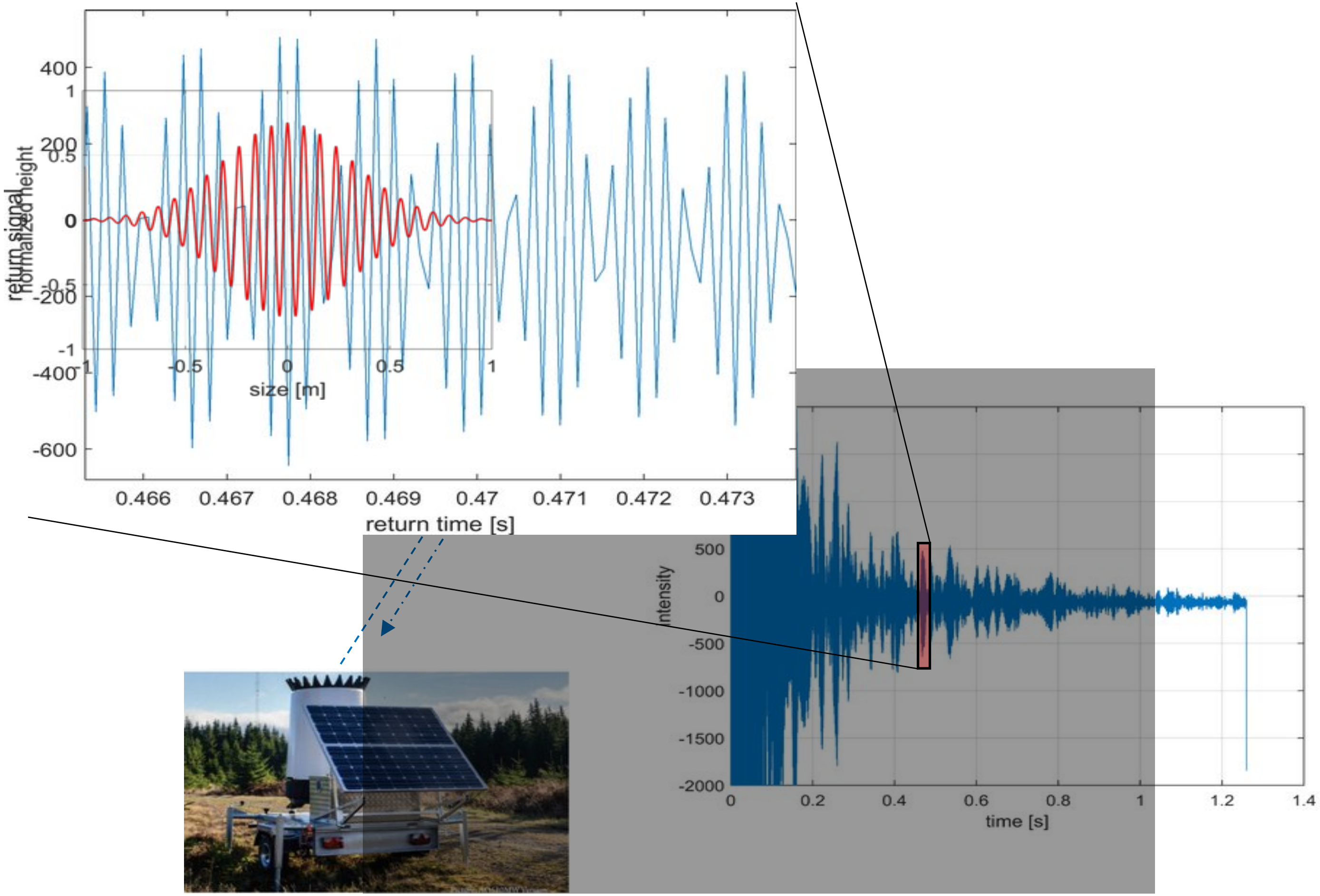
- Sound is much slower than light, this enables much more freedom when dispatching, recording and analysing the echo signal.
- NWP becomes much better when combined with in situ data (phase shift correction, etc)
- Remote sensing is problematic in some specific weather conditions - NWP is problematic in some specific weather conditions. <u>It is thus highly likely that some NWP physics are better than others to fill in missing observations</u>.

Ongoing work: WP2 - Signal Processing

Instead of using a plane wave to find the Doppler shift in a window of the echo; use a wavelet

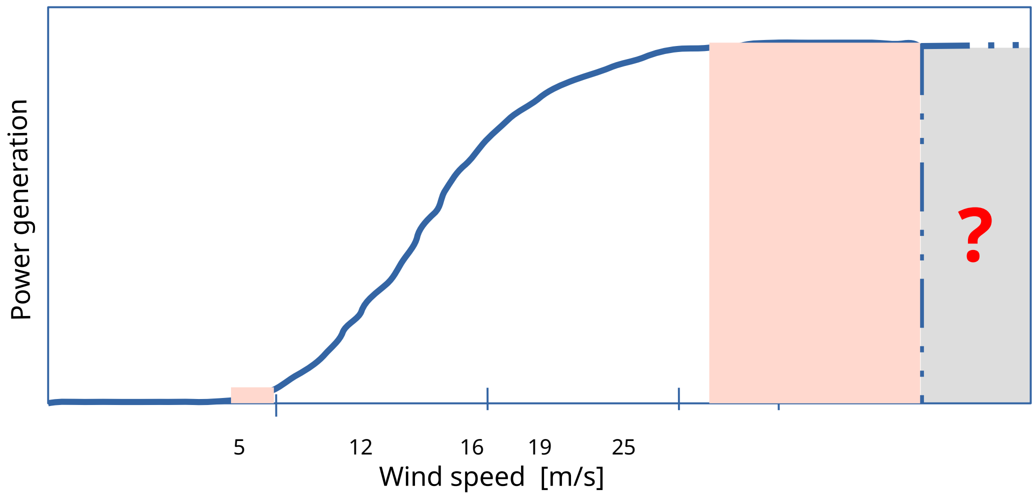
- The particular wavelet has minimal uncertainty in detecting *frequency shift* and *time localization*

- The algorithm is tailored to remote sensing specific needs



Ongoing work: WP3 - Blending of MSEPS ensemble forecasts and SODAR data

Met measurements are important when dealing with:



- cut-in and cut-off uncertainty (high-speed shut down)
- dispatch
- computing current turbine availability
- situational awareness in the control room
- measurements fill the gap of time resolution difference in meteorology and power industry
- solves background error issues (e.g. turbine failure, non-reported maintenance, phase error in weather forecast ..)

Ongoing work: WP4 - in-situ experiments

Site 1: Risø Campus, Roskilde,
Denmark

Site 2: Østerild – DTU Test center
Northwest Jutland, Denmark

Site 3: Moholm, Sweden

In planning:

Site 4: Stötten (WINSENT Testsite),
Southwest Germany

Site 5: Meentycat, Co. Donegal,
Northwest Ireland

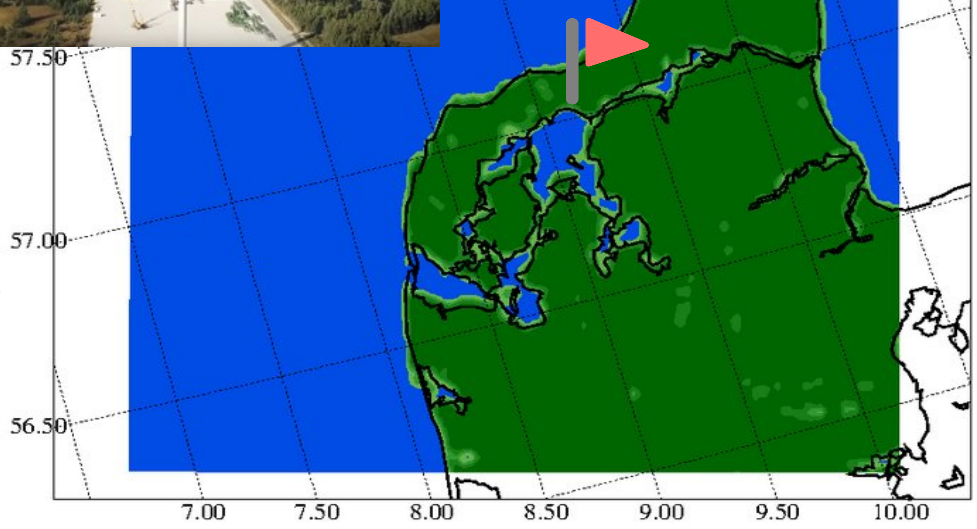
Ongoing Work: WP3 - NWP experiments

13 HighRes Experiments at DTU Testsite Østerild

Period: 3rd June 2022 - 28th June 2022

Mast Data (applied): Wind speed
Anemometer at 40m, 50m, 100m, 140m, 178m

SODAR: Wind Speed at 40m,70m, 100m, 178m



Purpose of Experiments with 5 MSEPS members:
What is the most effective resolution for the NWP models

Test:

1) At which time scales can measurements be resolved adequately
2) Apply different vertical diffusion schemes to verify how much
3) (wind) variability can be generated in the NWP model space
4) investigate the sensitivity of the optimal number of vertical levels for most realistic variability

Ongoing work: WP3 – 13 NWP experiments

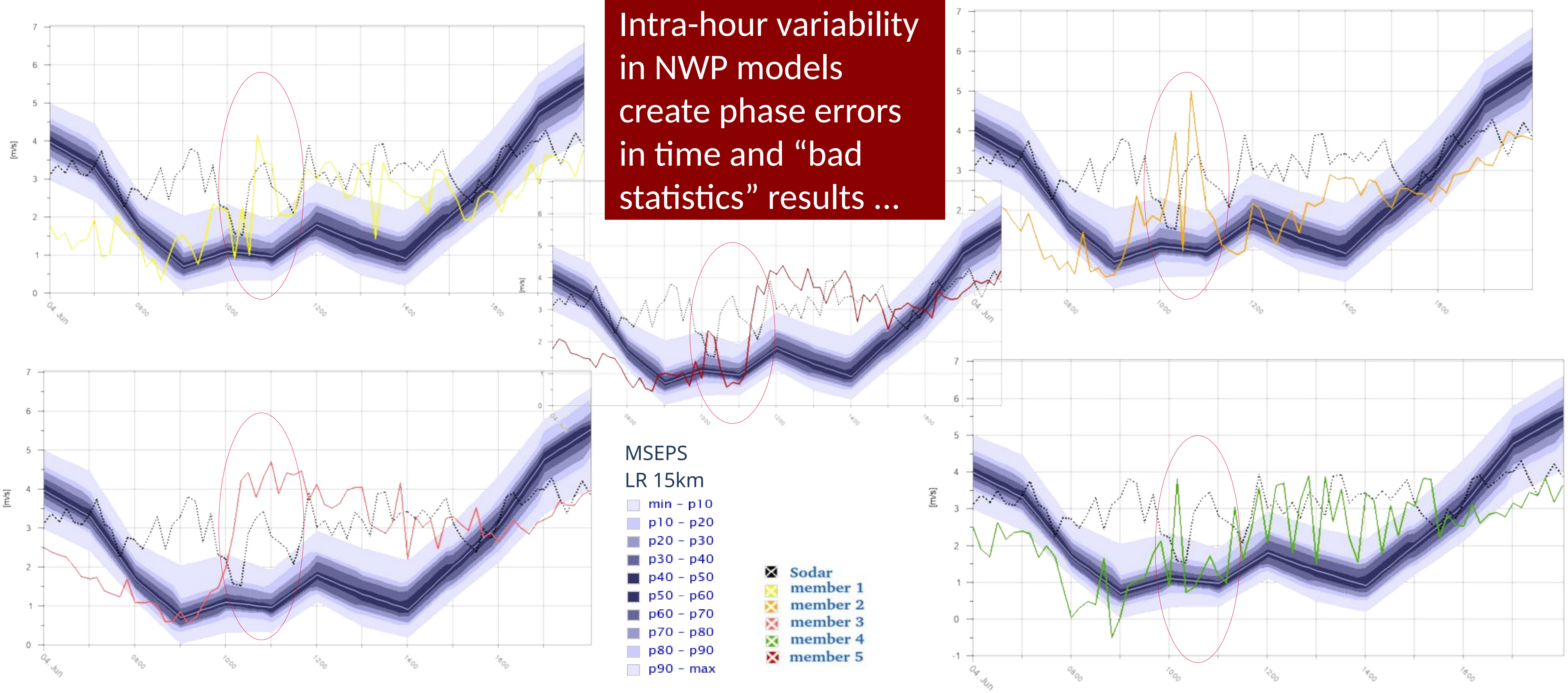
Description and Details of the setup of the experiments

SETUP	horiz. resolution	vertical model levels	other Change	Description
Exp01	1.4km	72 level		layer distribution starting in 28m
Exp02	1.4km	60 level		clarify impact of vertical layers
Exp03	1.4km	60 level		clarify if pure 1.4km is better than 2.5km with 4dinc analysis incrementation
Exp04	1.4km	60 level	Time-stepping	clarify if physics every time step improve with 4dinc analysis incrementation
Exp05	1.4km	60 level	new schemes	clarify if other diffusion schemes perform better than opr-versions
Exp06	5.0km	60 level		clarify impact of resolution at same vertical layer distribution
Exp07	5.0km	60 level	analysis incr.	clarify impact of different analysis increment strategy (4dinc)
Exp08	5.0km	72 level	analysis incr.	clarify layer distribution with 4dinc analsyis incrementation
Exp09	5.0km	48 level	climate file resolution	impact of using 15km climate file in 5km rsolution model setup (in case of lack of highres climate data)
Exp10	5.0km	40 level		use best 5 diffusion schemes and combine with condensation schemes
Exp11	5.0km	60 level		clarify if 60 levels is better than 48 in 5km 4dinc exp
Exp12	2.5km	60 level		clarify if 2.5km resolution is better than pure 5km 4dinc
Exp13	2.5km	60 level	climate file resolution	clarify if cl1.4km is better than cl5km in 2.5km res 4dinc

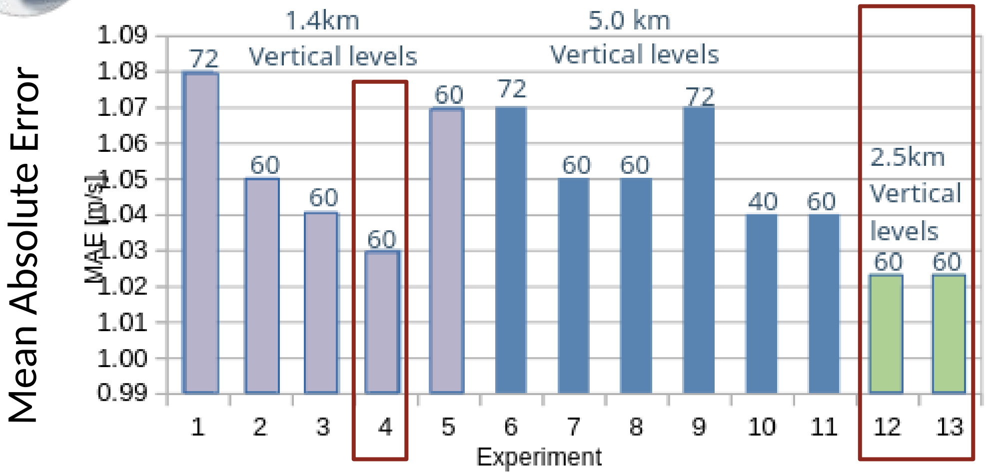
First Results: WP3 - NWP experiments to fit measurements

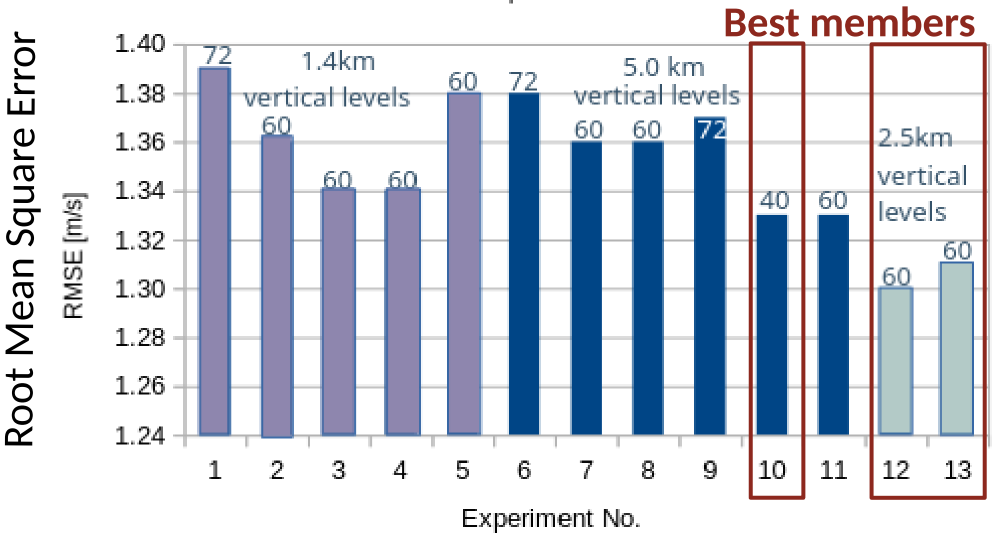
Example Plots of 5 MSEPS V-diff-members + Measurements
– 1.4km MSEPS level 69 (100m) in 10min time resolution–

Intra-hour variability in NWP models create phase errors in time and “bad statistics” results …



First Results: WP3 – Summary statistics of NWP experiments





	MAE [m/s]		Selected MEMBERS				
Experiment	best	mean	1	2	3	4	5
1	1.08	1.08	1.11	1.14	1.13	1.11	1.09
2	1.05	1.07	1.08	1.05	1.11	1.09	1.09
3	1.04	1.04	1.07	1.04	1.09	1.04	1.05
4	1.03	1.03	1.07	1.05	1.09	1.03	1.05
5	1.07	1.07	1.09	1.05	1.10	1.09	1.10
6	1.07	1.08	1.09	1.07	1.16	1.11	1.10
7	1.05	1.06	1.07	1.05	1.13	1.09	1.08
8	1.05	1.05	1.08	1.06	1.10	1.10	1.07
9	1.07	1.08	1.10	1.07	1.12	1.11	1.10
10	1.04	1.04	1.09	1.05	1.08	1.06	1.05
11	1.04	1.04	1.06	1.05	1.09	1.08	1.04
12	1.02	1.02	1.07	1.04	1.15	1.05	1.02
13	1.02	1.02	1.09	1.05	1.09	1.05	1.03

	RMSE [m/s]		Selected MEMBERS				
Experiment	best	mean	1	2	3	4	5
1	1.39	1.39	1.43	1.46	1.45	1.43	1.41
2	1.36	1.38	1.40	1.36	1.45	1.41	1.41
3	1.34	1.34	1.38	1.36	1.42	1.36	1.35
4	1.34	1.34	1.38	1.36	1.43	1.35	1.36
5	1.38	1.38	1.42	1.36	1.44	1.41	1.42
6	1.38	1.40	1.42	1.38	1.51	1.43	1.43
7	1.36	1.37	1.39	1.36	1.46	1.39	1.40
8	1.36	1.36	1.38	1.37	1.42	1.41	1.39
9	1.37	1.38	1.41	1.37	1.43	1.42	1.40
10	1.33	1.33	1.42	1.36	1.40	1.37	1.33
11	1.33	1.33	1.40	1.36	1.41	1.39	1.33
12	1.30	1.30	1.40	1.34	1.49	1.36	1.30
13	1.31	1.31	1.42	1.35	1.41	1.37	1.31

NOTE: Only 50% if the “best forecasts” are from the mean of the members

First Results: WP3 – Summary statistics of NWP experiments

RESULTS	Resolution	MAE Ranking	RMSE Ranking	Description of results
Exp01	1.4km	13	13	similar variability as in measurements, but out of phase
Exp02	1.4km	7	7	Normal variability and the result improved
Exp03	1.4km	4	5	Resolution creates too high phase errors
Exp04	1.4km	3	6	very small improvement but not on all members
Exp05	1.4km	10	11	One diffusion scheme is superior in 1.4km
Exp06	5km	11	12	1.4km score marginally better than 5km
Exp07	5km	8	8	4d-analysis incremenation improves
Exp08	5km	9	9	72 level is better than 60 level
Exp09	5km	12	10	significantly simplified, the result is comparable to Exp01-02
Exp10	5km	5	3	different condensation schemes are important
Exp11	5km	6	4	best single member performance so far for the KF
Exp12	2.5km	1	1	best score with KainFritsch condensation and good mean
Exp13	2.5km	2	2	no sensitivity to finer climate data

Rank	MAE [m/s]		RMSE [m/s]	
	Exp	Best	Exp	Best
1	12	1.02	12	1.30
2	13	1.02	13	1.31
3	4	1.03	10	1.33
4	3	1.04	11	1.33
5	10	1.04	3	1.34
6	11	1.04	4	1.34
7	2	1.05	2	1.36
8	7	1.05	7	1.36
9	8	1.05	8	1.36
10	5	1.07	9	1.37
11	6	1.07	5	1.38
12	9	1.07	6	1.38
13	1	1.08	1	1.39

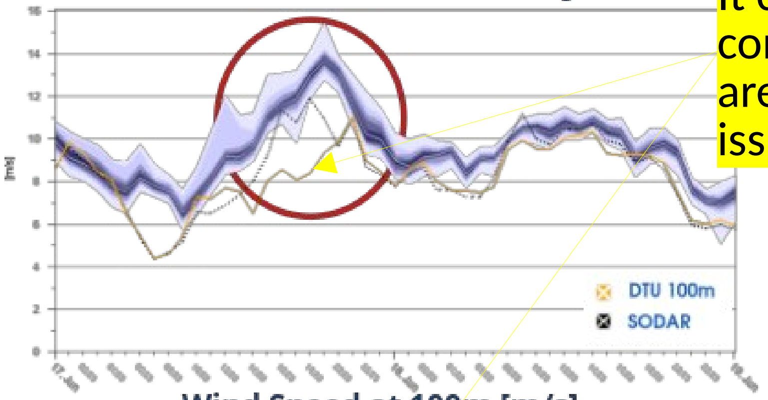
- Higher resolution does not perform better statistically
- Error difference from best to worst is not significant…
- High-resolution forecast shows similar variability as SODAR data, but is not in phase with measurements
- Knowing the effective best resolution + use of physical uncertainty is a useful combination for improved forecasting & gap filling

First Results: WP3 - NWP fit to measurements

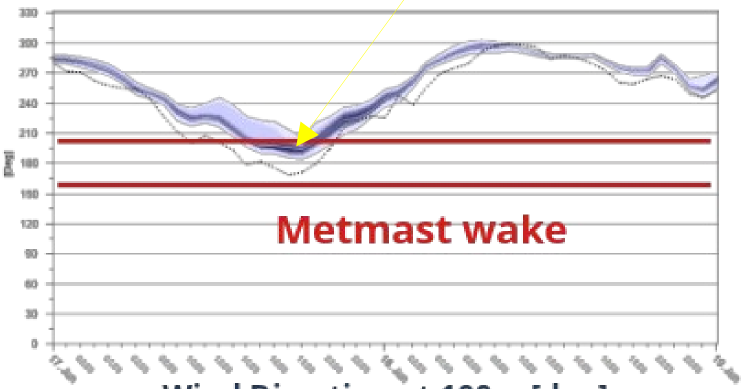
Type: discrepancy to met mast cup can be confusing..

Example Plots of MSEPS + Measurements – level 31 (100m) – 17. juni

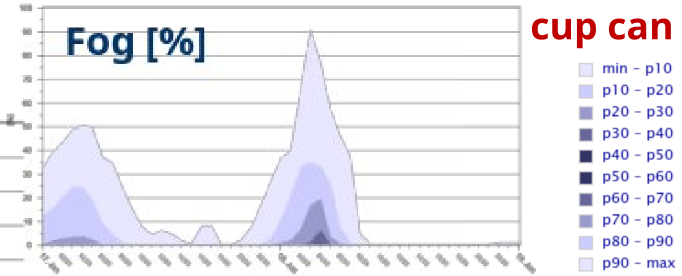
It can be confusing, if there are instrument issues…

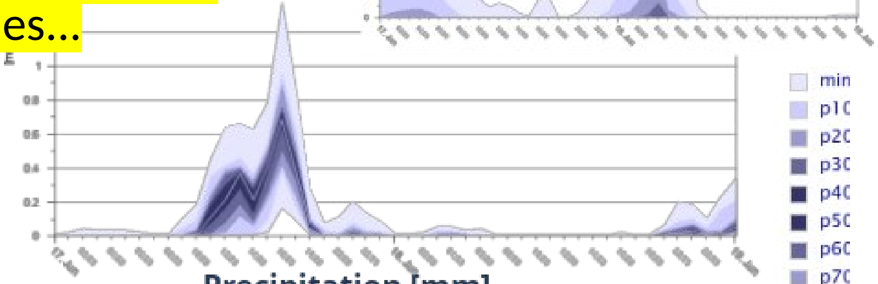


Wind Speed at 100m [m/s]

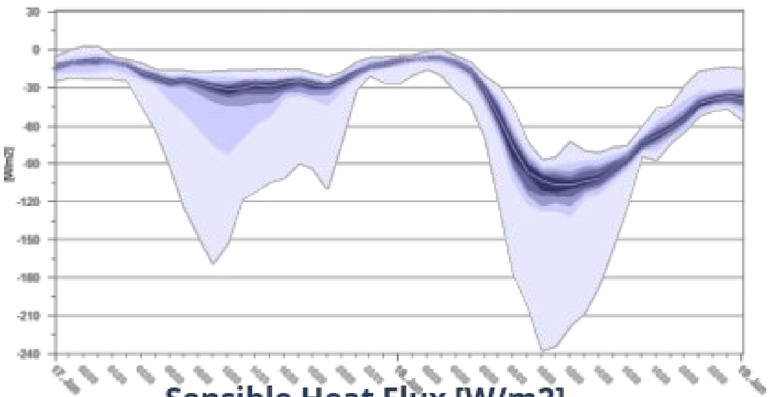


Wind Direction at 100m [deg]

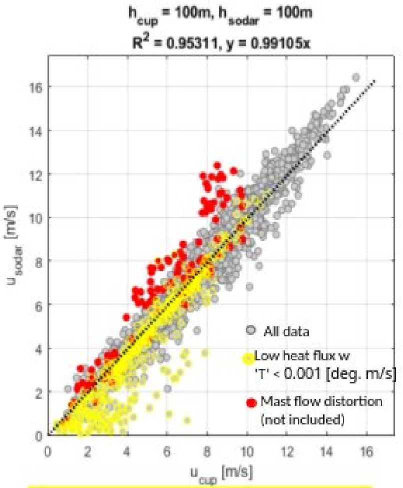




Precipitation [mm]



Sensible Heat Flux [W/m2]



Measurement analysis with cup & sodar shows mast flow distortion and possible sensitivity to low heat flux…

First Results: WP3 - NWP to fit measurements

Place: AQ System Teststation Fimmerstad – Moholm Sweden
Period: 21st March 2022 - 13th June 2023

<u>SODAR Data</u>
Wind Speed at 40m, 100m, 170m, 200m
Wind Direction at 100m
Temperature
Humidity

<u>Met Mast Data:</u>
Wind Speed from FMTC_2 Tiess cup 4335 at 100.9m

<u>MSEPS Data:</u>
Wind Speeds at level 32, 31 and 30 (approx. 35m, 100m, 170m)
Wind Direction at 100m
Temperature at 2m
Rel. Humidity at 2m

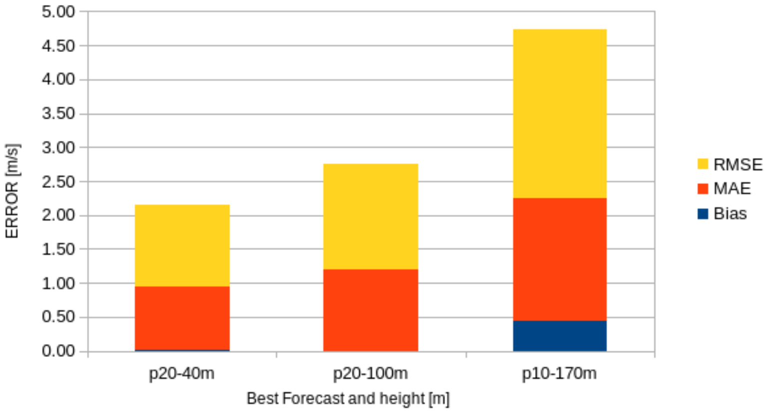
First Results: WP3 - NWP to fit measurements

Validation period: 22. March 2022 – 13. June 2023

Result › Location: AQ_MoholmSE › Forecast Variable: Wind Speed at 40m					
Curve	**Mean**	**Bias**	**MAE**	**RMSE**	**STDV**
min	*3.88*	*-0.71*	*1.12*	*1.46*	*1.27*
p10	*4.37*	*-0.22*	*0.94*	*1.23*	*1.21*
p20	*4.62*	*0.02*	*0.93*	*1.20*	*1.20*
p30	*4.81*	*0.22*	*0.95*	*1.23*	*1.21*
p40	*4.99*	*0.39*	*1.00*	*1.28*	*1.22*
p50	*5.16*	*0.56*	*1.06*	*1.35*	*1.23*
p60	*5.32*	*0.73*	*1.14*	*1.44*	*1.25*
p70	*5.51*	*0.91*	*1.24*	*1.56*	*1.27*
p80	*5.71*	*1.12*	*1.37*	*1.72*	*1.31*
p90	*6.01*	*1.41*	*1.59*	*1.98*	*1.38*
max	*6.56*	*1.97*	*2.05*	*2.47*	*1.49*
SODAR	*4.60*	*0.00*	*0.00*	*0.00*	*0.00*
mean	*5.17*	*0.58*	*1.06*	*1.36*	*1.23*
median	*5.19*	*0.60*	*1.08*	*1.38*	*1.24*

Result › Location: AQ_MoholmSE › Forecast Variable: Wind Speed at 100m					
Curve	**Mean**	**Bias**	**MAE**	**RMSE**	**STDV**
min	*5.20*	*-0.80*	*1.41*	*1.82*	*1.64*
p10	*5.75*	*-0.25*	*1.23*	*1.59*	*1.57*
p20	*6.00*	*0.00*	*1.20*	*1.56*	*1.56*
p30	*6.20*	*0.20*	*1.20*	*1.56*	*1.55*
p40	*6.37*	*0.37*	*1.22*	*1.59*	*1.55*
p50	*6.55*	*0.55*	*1.26*	*1.64*	*1.54*
p60	*6.72*	*0.72*	*1.32*	*1.71*	*1.55*
p70	*6.91*	*0.91*	*1.40*	*1.80*	*1.55*
p80	*7.13*	*1.13*	*1.52*	*1.93*	*1.56*
p90	*7.44*	*1.44*	*1.72*	*2.15*	*1.60*
max	*8.06*	*2.06*	*2.20*	*2.66*	*1.68*
SODAR	*6.00*	*0.00*	*0.00*	*0.00*	*0.00*
mean	*6.57*	*0.57*	*1.27*	*1.64*	*1.54*
median	*6.60*	*0.60*	*1.28*	*1.65*	*1.54*

Result › Location: AQ_MoholmSE › Forecast Variable: Wind Speed at 170m					
Curve	**Mean**	**Bias**	**MAE**	**RMSE**	**STDV**
min	*6.25*	*-0.20*	*1.91*	*2.52*	*2.52*
p10	*6.87*	*0.43*	*1.82*	*2.49*	*2.46*
p20	*7.19*	*0.74*	*1.85*	*2.56*	*2.45*
p30	*7.43*	*0.98*	*1.90*	*2.64*	*2.45*
p40	*7.63*	*1.18*	*1.96*	*2.72*	*2.45*
p50	*7.82*	*1.38*	*2.03*	*2.81*	*2.45*
p60	*8.02*	*1.58*	*2.12*	*2.91*	*2.45*
p70	*8.26*	*1.82*	*2.25*	*3.06*	*2.46*
p80	*8.54*	*2.10*	*2.43*	*3.25*	*2.48*
p90	*8.93*	*2.48*	*2.71*	*3.54*	*2.52*
max	*9.71*	*3.26*	*3.37*	*4.19*	*2.62*
SODAR	*6.44*	*0.00*	*0.00*	*0.00*	*0.00*
mean	*7.86*	*1.42*	*2.04*	*2.82*	*2.44*
median	*7.90*	*1.45*	*2.06*	*2.84*	*2.44*



Long-term statistics reveals that...

NWP has very little BIAS up to 100m

Some skewness in the ensemble (P20 best...)

Some error growth with height ...

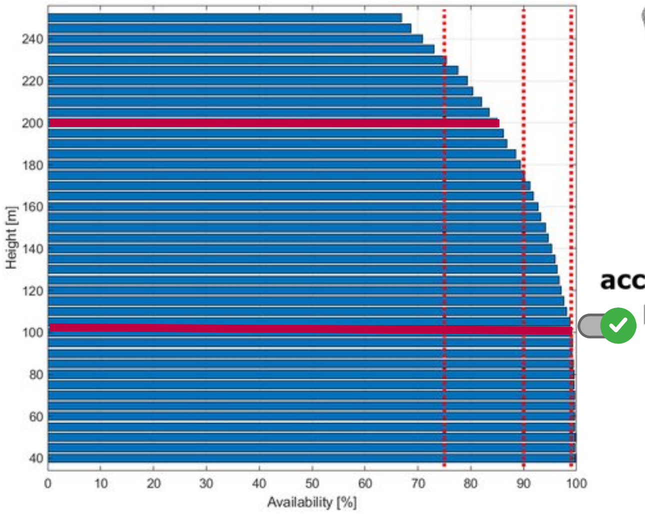
Ongoing work: Instrument analysis

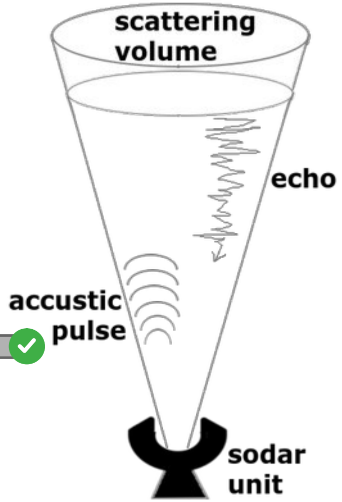
Remote sensing device’s volume based measurement with height is of advatage

Availability of ”trustworthy” data from remote sensing devices deteriorate with height…

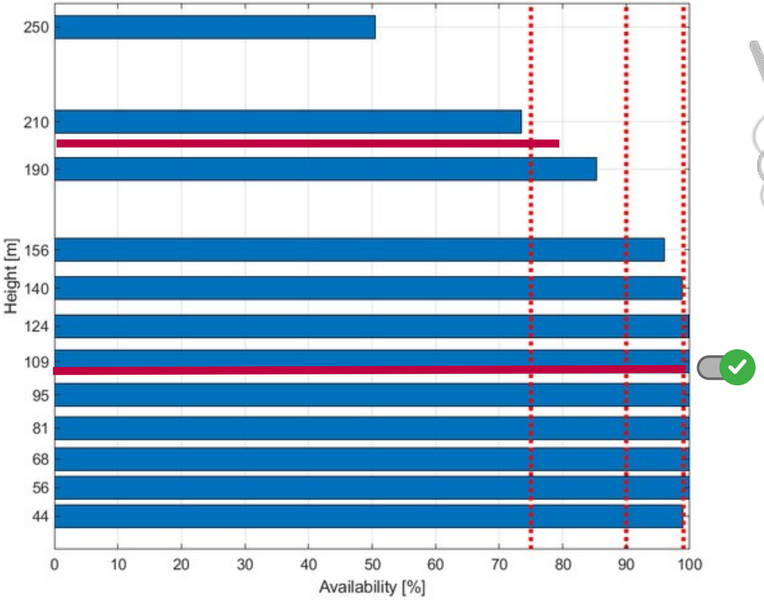
---> The aim of signal processing research is to enhance availability in the higher levels

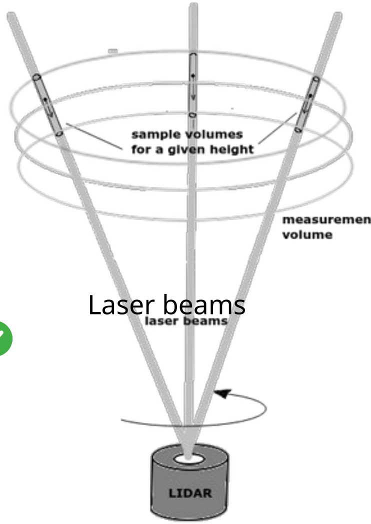
AQ510 SODAR





LIDAR





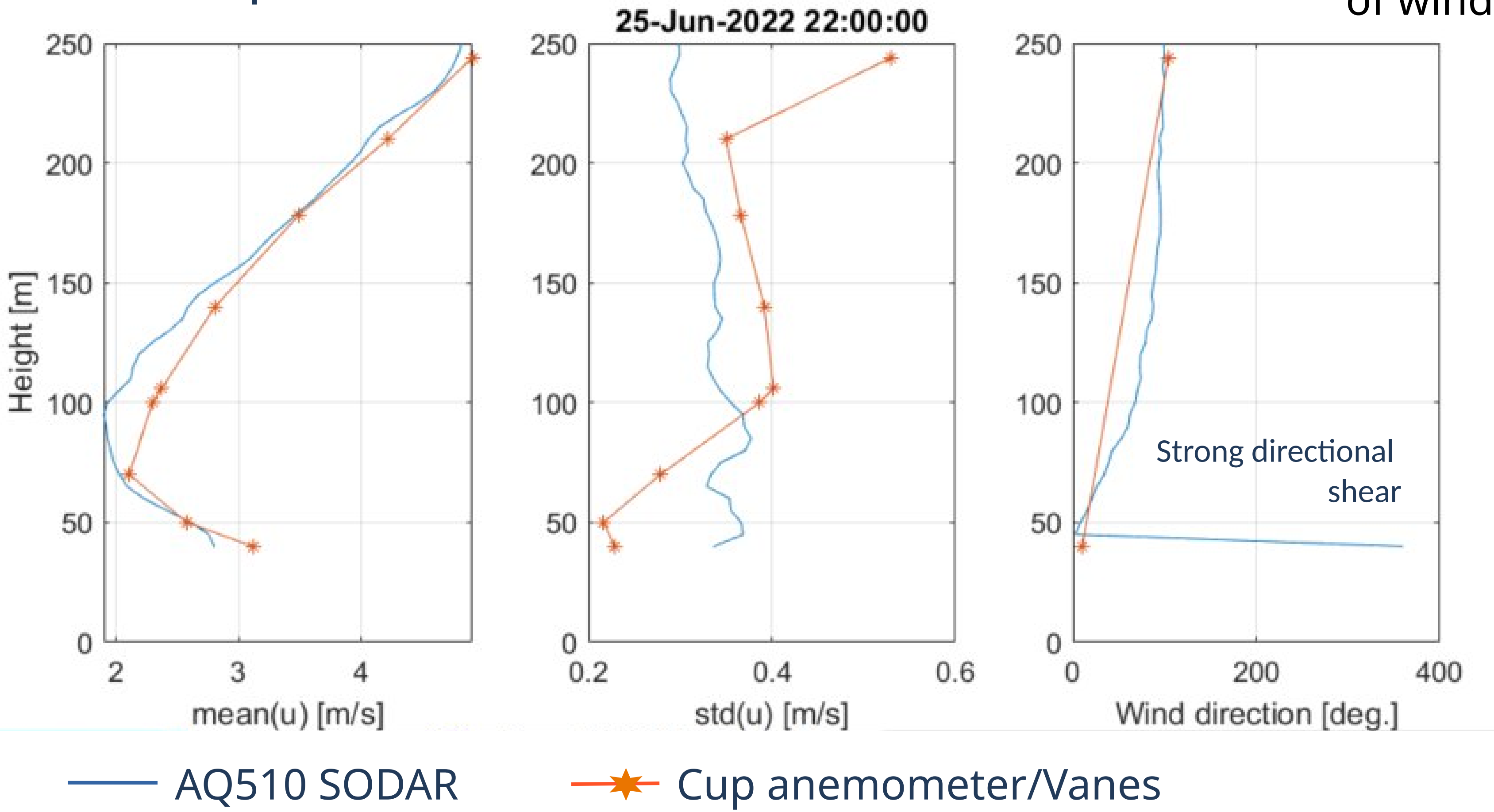
SODAR measure in more height levels

Lidar measures typically in less heights for robustness of signals

Ongoing work: instrument analysis

Østerild Test site at 100m agl.
SODAR placed 350m from mast

Good general fit of wind profile



First Results: WP2 - Wavelet implementation

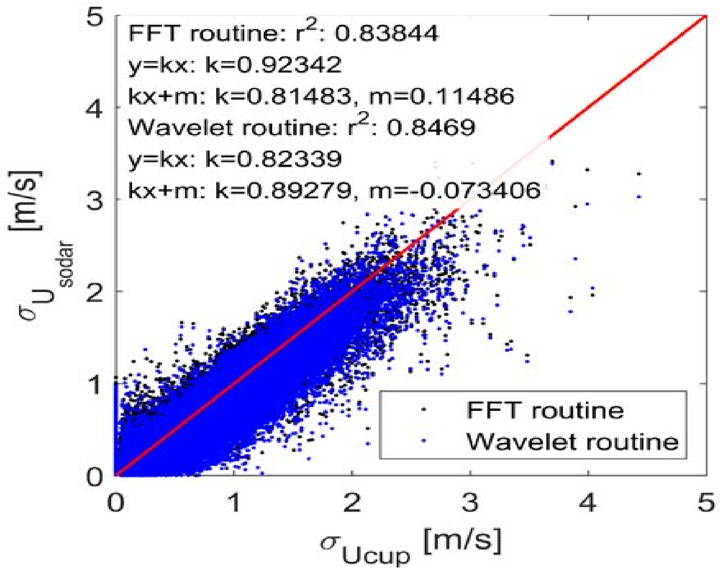
Change of the signal processing algorithm of the SODAR from a FFT routine to a wavelet type of routine.

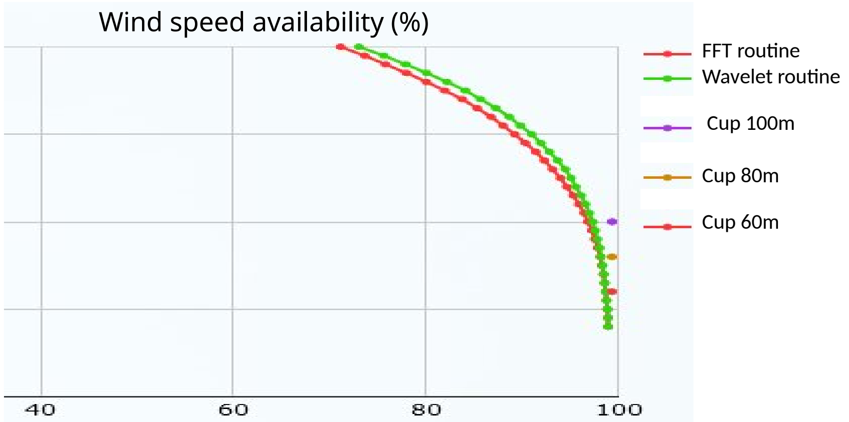
Aims:

- Decrease measurement volume to improve turbulence estimate
- Filter out noise more effectively, thus increasing availability

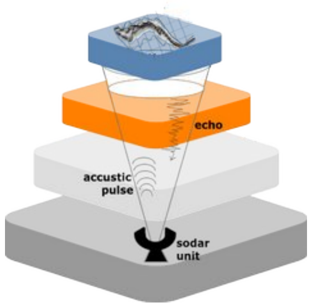
Status:

First results are encouraging that a substantial improvement can be achieved and that we are on the right track…





Summary & Lessons Learned



Remote Sensing with the SODAR technology is promising

- AQ SODAR shows good average performance in comparison to cups at met masts
- AQ SODAR has the potential as life-cycle instrument for wind farms (design robustness)

Volume based remote sensing fits well to 3D weather prediction models

- SODAR is well-suited as independent wind measurement for data assimilation
- Physics-based ensemble predictions can be used to quality check data & identify issues in signal processing

Thank you for you attention

Questions …

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