Coherent structures in wind measured at a large separation distance

Hálfdán Ágústsson, Knut Harstveit
and Tuuli Pilvi Miinalainen

Kjeller Vindteknikk AS

halfdan.agustsson@vindteknikk.no

Experience from 'extreme' bridges

- The Norwegian Public Roads Administration shall bridge the remaining ferry crossings along road E39:
  - Fjord widths 2-7.5 km
  - Fjord depths 300-1300 m
  - High and variable wind, wave and current loads


Concept bridge across Bjørnafjorden (5km)

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Statens vegvesen
Norwegian Public Roads Administration

Design loads and climatic conditions

- Very high resolution (500 m) meso-scale atmospheric simulations
  - → Estimating wind climate and extreme winds
  - → Input to high-res. wave (ROMS) and current (SWAN) models

- High frequency measurements of wind at several levels in tall meteorological masts:
  - → Verification of simulated winds
  - → **Assessment of design loads and climatic conditons**

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Measurements masts - overview

Site	Fjord	Mast height	Mast type	Data start
Julbø	Julsundet	50 m	Guyed pipe mast	07.02.2014
Midsund	Julsundet	50 m	Guyed pipe mast	06.02.2014
Nautneset	Julsundet	68 m	Lattice tower	07.07.2016
Halsaneset	Halsafjorden	50 m	Guyed pipe mast	26.02.2014
Åkvik	Halsafjorden	50 m	Guyed lattice mast	06.03.2015
Kvitneset	Sulafjorden	96 m	Guyed lattice mast	24.11.2016
Trælboneset	Sulafjorden	78 m	Guyed lattice mast	Spring 2017
Langeneset	Sulafjorden	98 m	Lattice tower	Spring 2017
Kårsteinen	Sulafjorden	62 m	Lattice tower	Spring 2017
Rjåneset	Vardalsfjorden	72 m	Guyed lattice mast	Spring 2017
Synnøytangen	Bjørnafjorden	50 m	Guyed pipe mast	23.02.2015
Svarvehelleholmen	Bjørnafjorden	50 m	Guyed pipe mast	18.03.2015
Ospøya 1	Bjørnafjorden	50 m	Guyed pipe mast	03.12.2015
Ospøya 2	Bjørnafjorden	50 m	Guyed pipe mast	17.12.2015
Landrøypynten	Langenuen	50 m	Guyed pipe mast	06.03.2015
Nesøya	Langenuen	50 m	Guyed pipe mast	24.02.2015

Data coverage: 98- 99%

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Measurement sites in Bjørnafjorden

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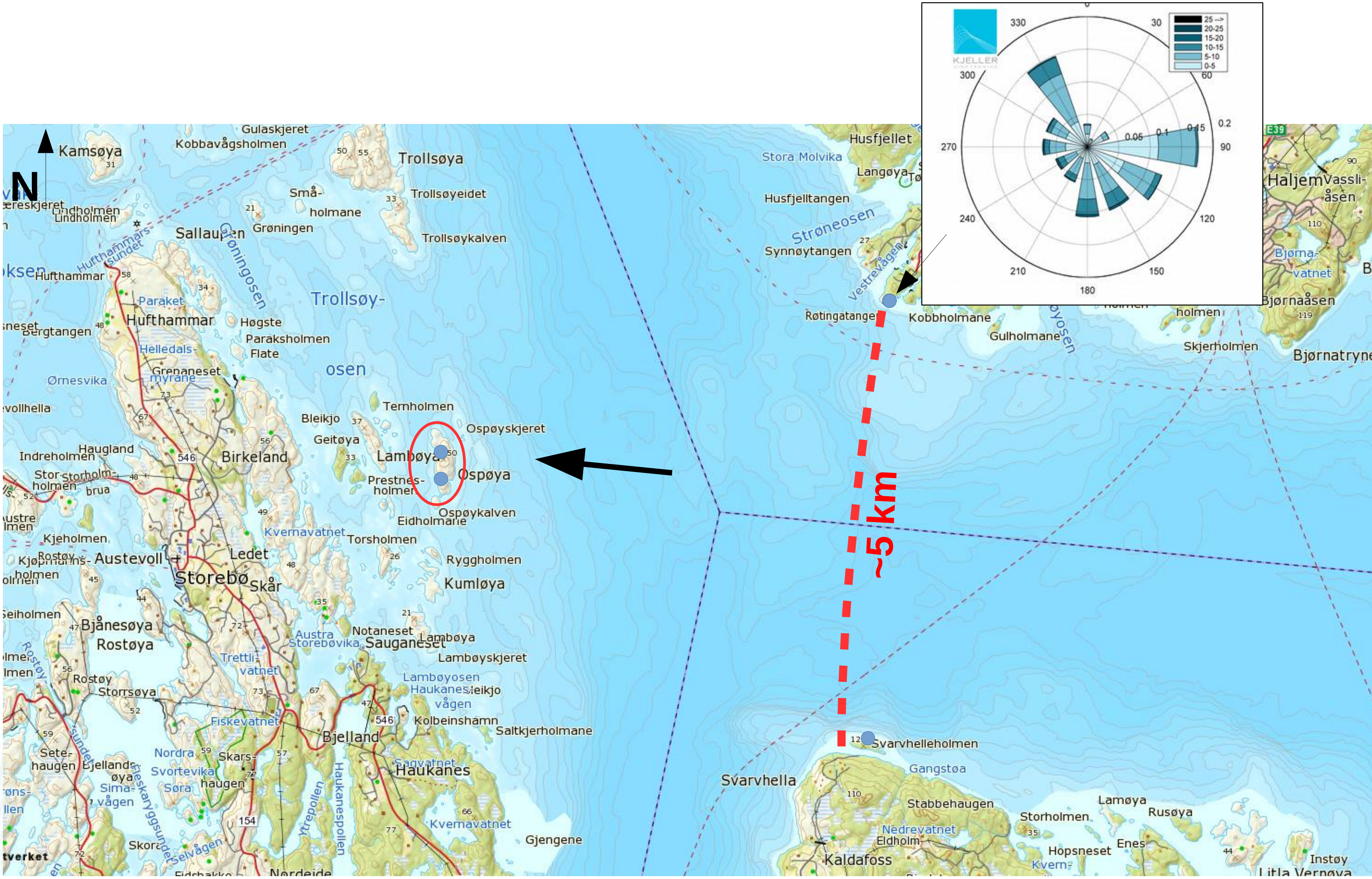
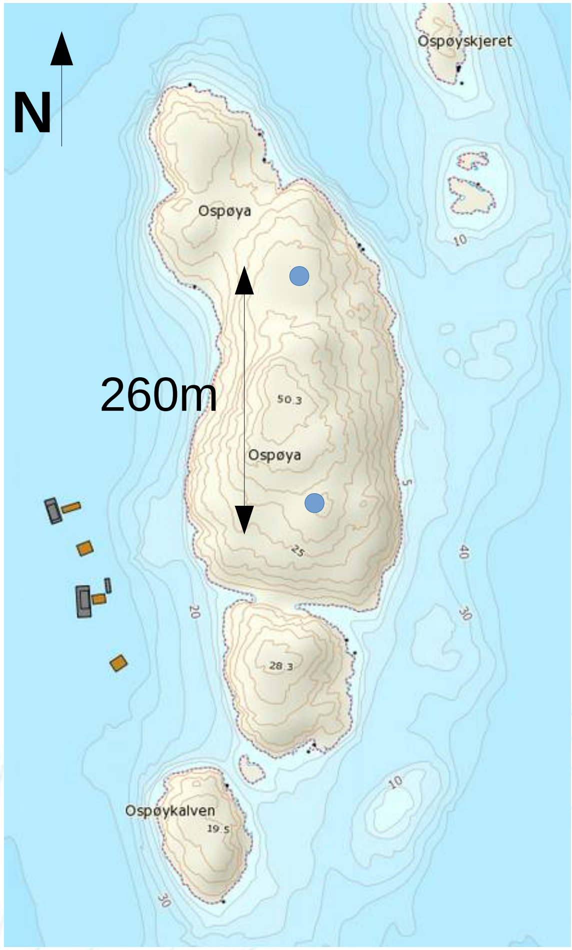
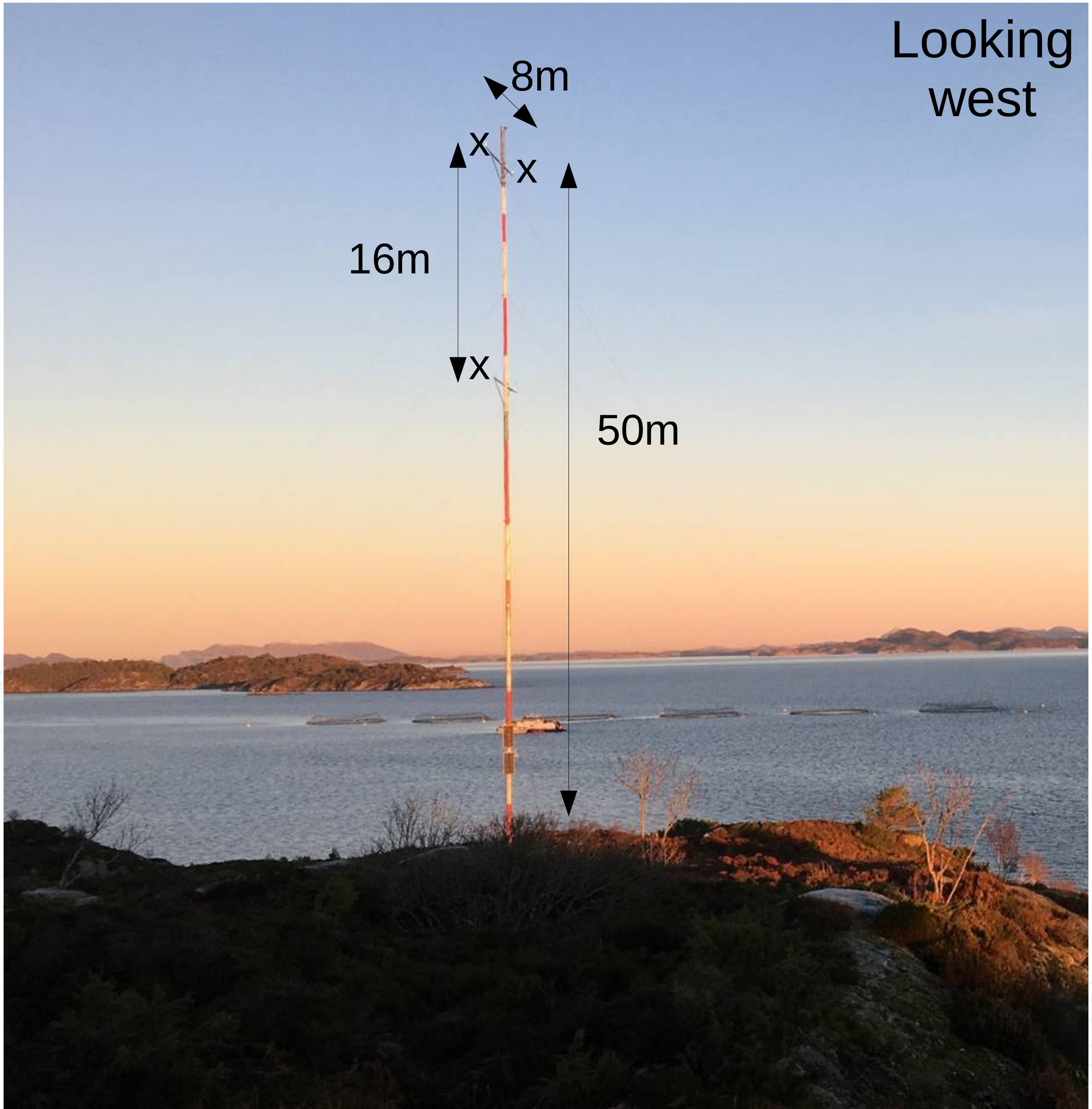
Measurements at Ospøya in Bjornafjørden



Measurements at Ospøya





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Wind measurements

1. Made by group of engineers/technicians at KVT
2. Installed 10 50 m high masts in 2014 - 2015
3. Installed/planned 5 80 - 100 m high masts, for start in 2016 - 2017
4. 3 sensors in each mast, at 2 or 3 levels
5. Data sampling frequency: 10 Hz
6. Wind components: u, v, w
7. Transfer to Kjeller Vindteknikk every hour
8. Driven by batteries with solar cell charging
   Battery voltages is monitored on daily basis
9. Data availability 95 % - 99 %
10. All raw data also stored for inspection and for spectral and coherence analysis
11. Data are filtered for spike and error removals
12. Twice a year: Reports written including long term statistics and extreme value analysis

Gill WindMaster Pro 3-Axis Anemometer

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Systematic analysis of coherence and spectra

- All analysis done using python, scipy, numpy, pandas, stats…
- Approximately 1 year of 10 Hz data from 4 synchronized anemometers
- Turbulence spectra, autocorrelation and integral length scales analysed for each 20 minute period
- Coherence analyzed for each:
  - 20 minute period at short distances (8 and 16 m)
  - 60 minute period at long distances (~260 m)
- Data is filtered, detrended and tapered using a Hann-window
- Main wind direction (U) is rotated along the flow
- Spectra based on a periodogram-method with Tukey-windowing, results scaled with frequency and std. dev. of wind.
- Coherence based on cross spectral density and power spectral densities based on Welch's method, with 4 segments and 50% overlap within segments, results scaled with f and σ^2

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Methodology for analysis of coherence and spectra

- Reference curves for spectra and coherence are based on handbooks H185 and H400, used in the design of bridges.
- Large sets of calculated spectra and coherences are fitted to the models (Davenport) prescribed in the handbooks, for given wind directions and wind speeds U>10 m/s.

The computed turbulence spectras and coherences for measured data were compared to Statens vegvesens guideline book values, referred as “H185”. The handbook value for scaled turbulence spectra is computed by

$$\frac{fS_i}{\sigma^2}=\frac{A_i f_i^{'}}{\left(1+1.5A_i f_i^{'}\right)^{\frac{5}{3}}} \quad ,$$

$$f_i^{'}=\frac{f\,L_u(z)}{U(z)} \quad ,$$

and $U(z)$ is the mean wind speed. The coefficients for different wind components are $A_u=6.8$, $A_v=9.4$ and $A_w=9.4$. Moreover, the length scale $L_u(z)$ for guideline reference is computed by

$$L_i(z)=c*100*(0.1*z)^{0.3},$$

Where one has coefficients $c_i=[1,\frac{1}{4},\frac{1}{12}]$ for u,v and w components.

Coherence series by hand book are computed with Davenport-model,

$$Coh_{185}=\exp\left(-C_{ij}\frac{f\,\Delta s}{U(z)}\right) \quad ,$$

where $C_{ij}=[10,6.5,3]$ and Δs is the distance between sensors.

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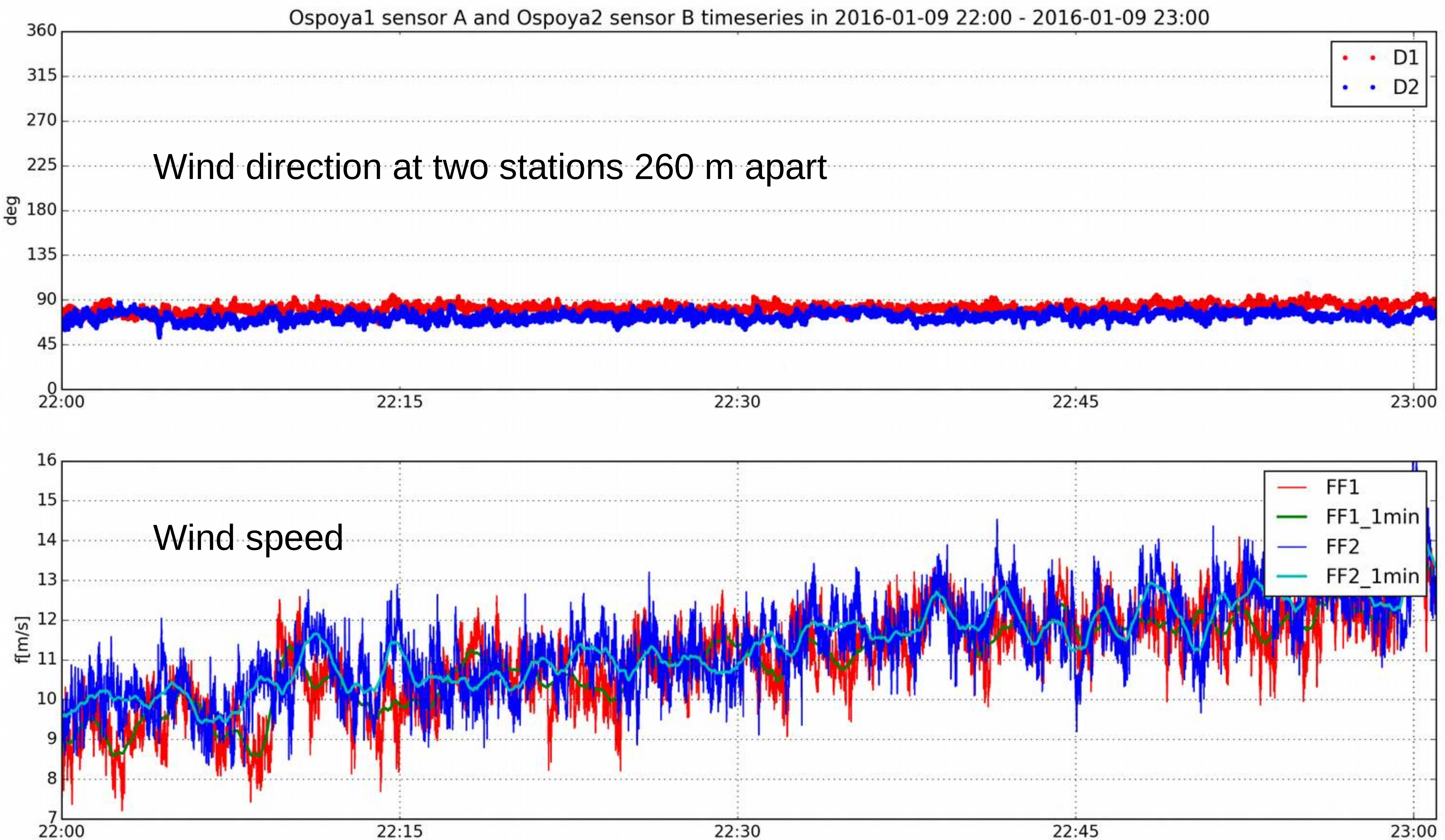
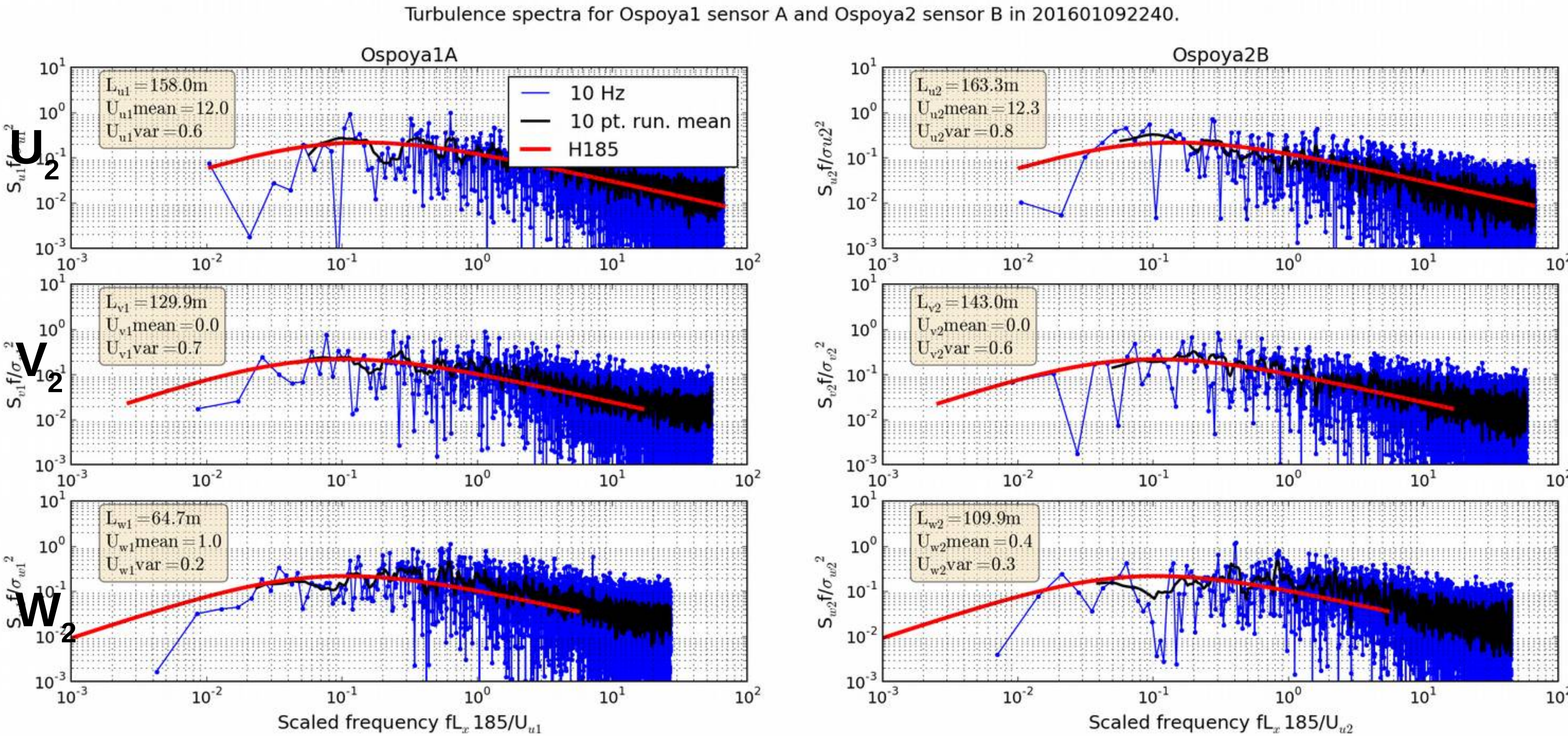
Example wind series during an easterly event
50 m agl, 22-23 UTC, 9. January 2016



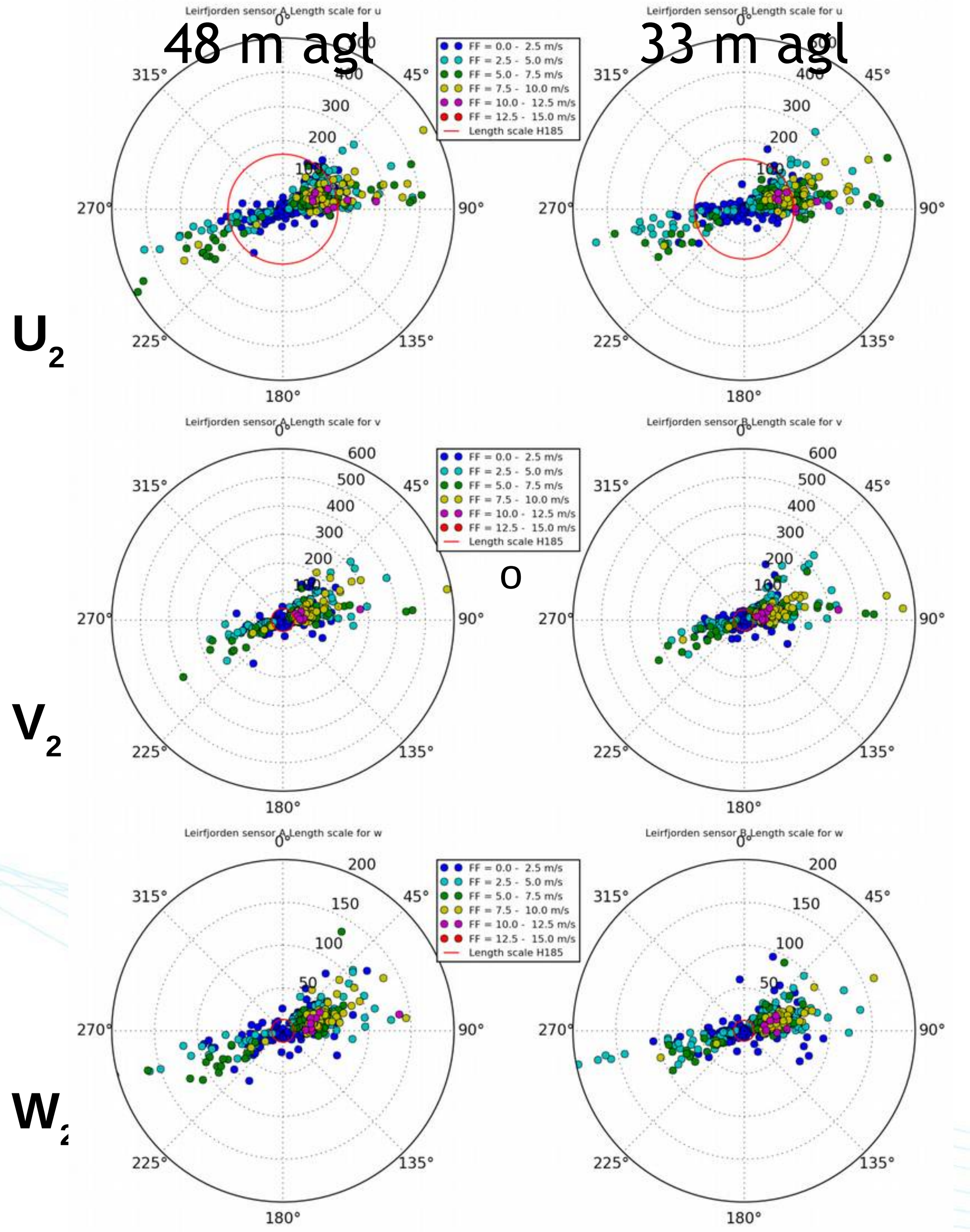
Example turbulence spectra (easterly wind)
50 m agl, 20 minutes at 22 UTC, 9. January 2016

Ospøya 1 (north) ← 260 m → **Ospøya 2 (south)**

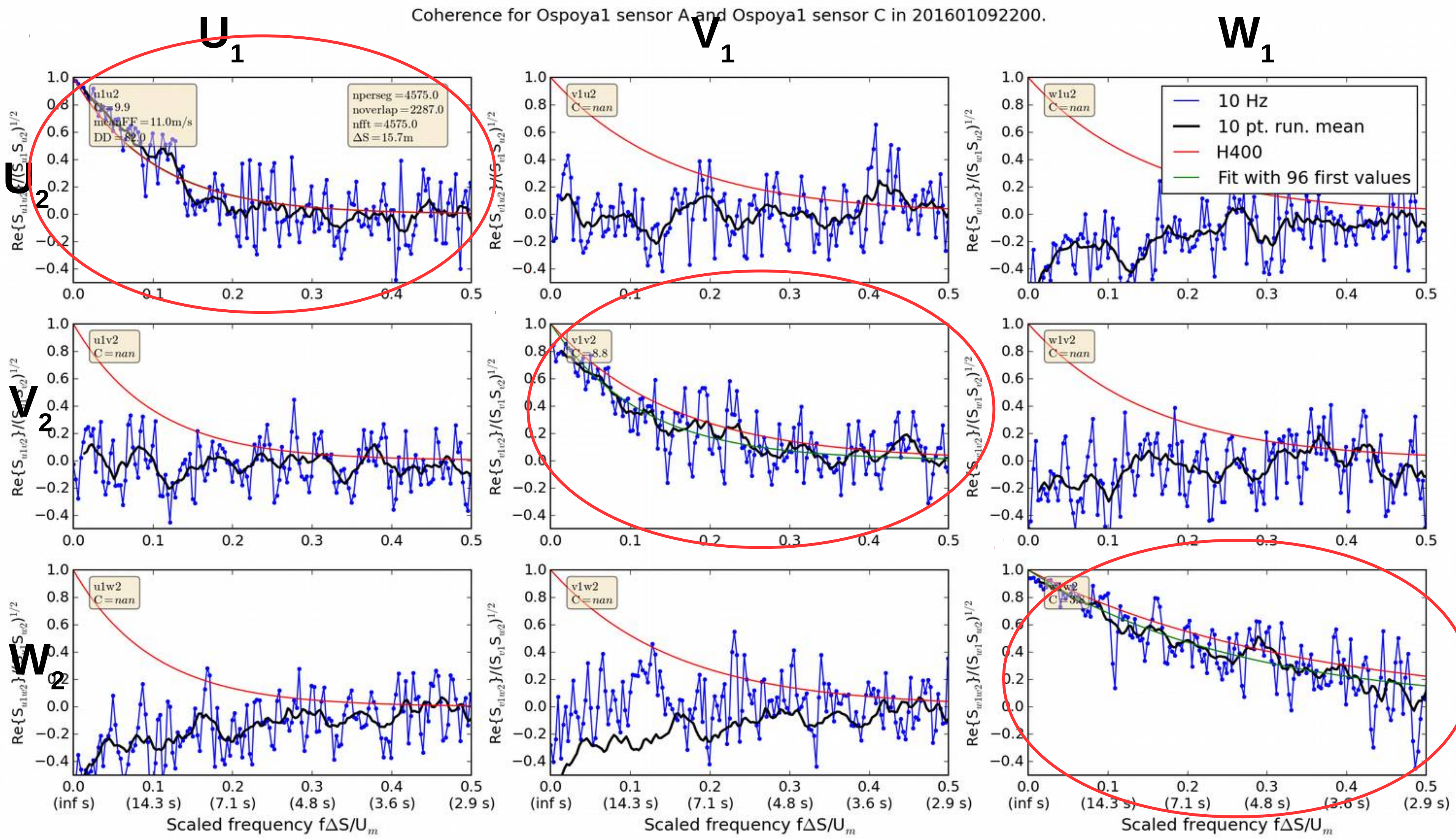


Integral length scales

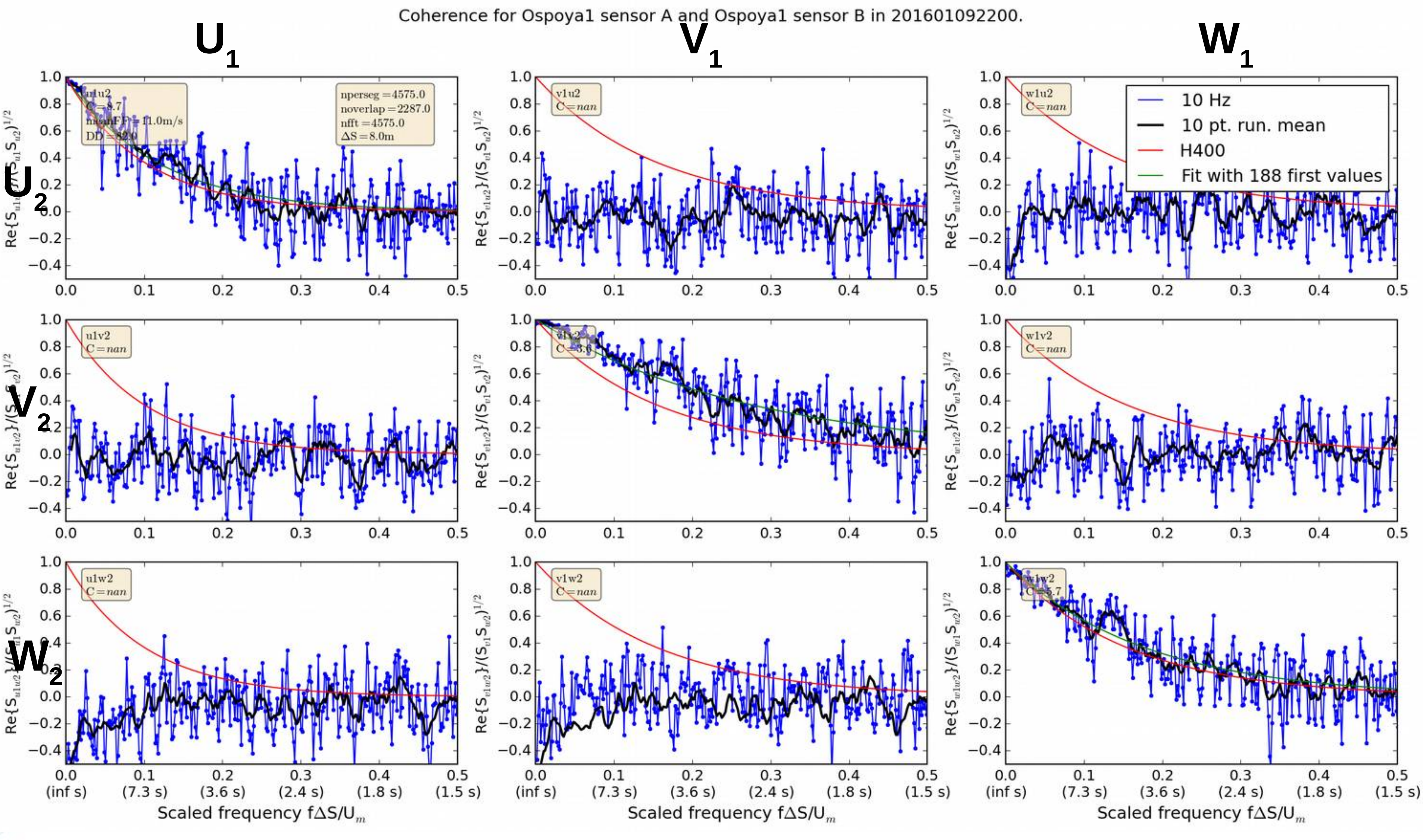
Systematic analysis based on 20 minute periods (shown for another station than Ospøya)



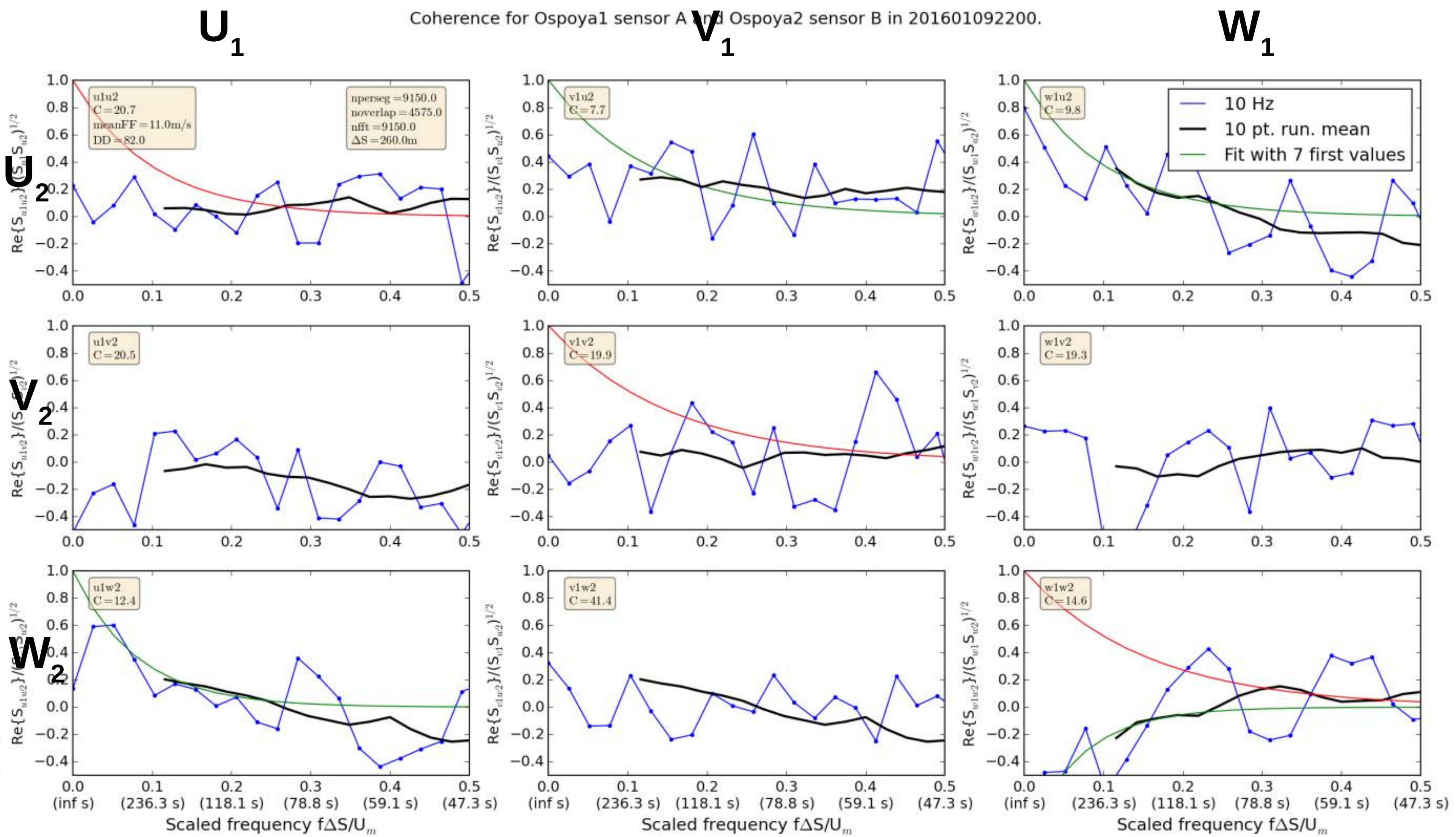
Vertical coherence at Ospøya at 16 m (easterly wind) 33-50 m agl, 20 minutes at 22 UTC, 9. January 2016



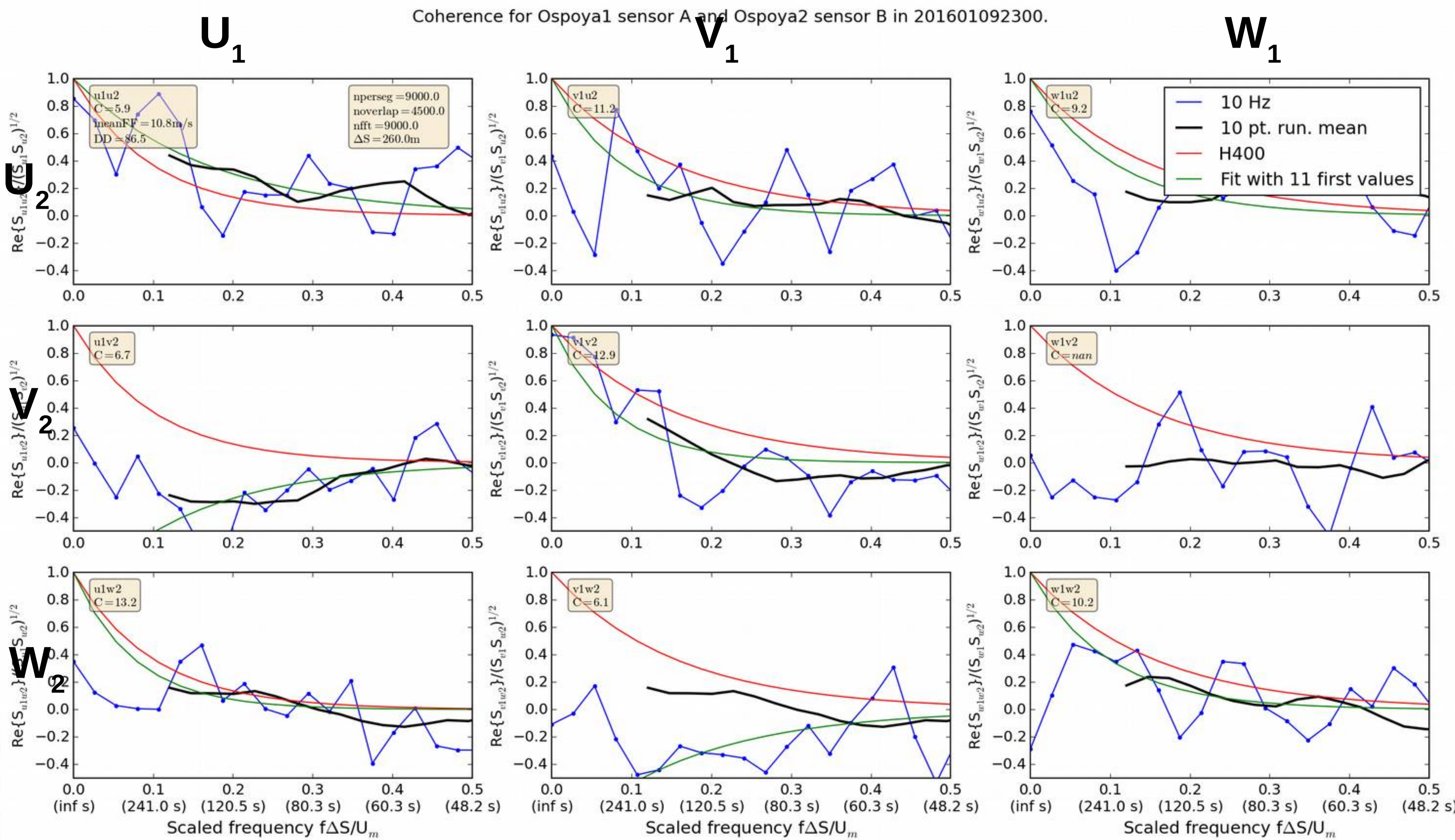
Horizontal coherence at Ospøya at 8 m (easterly wind) 50 m agl, 20 minutes at 22 UTC, 9. January 2016



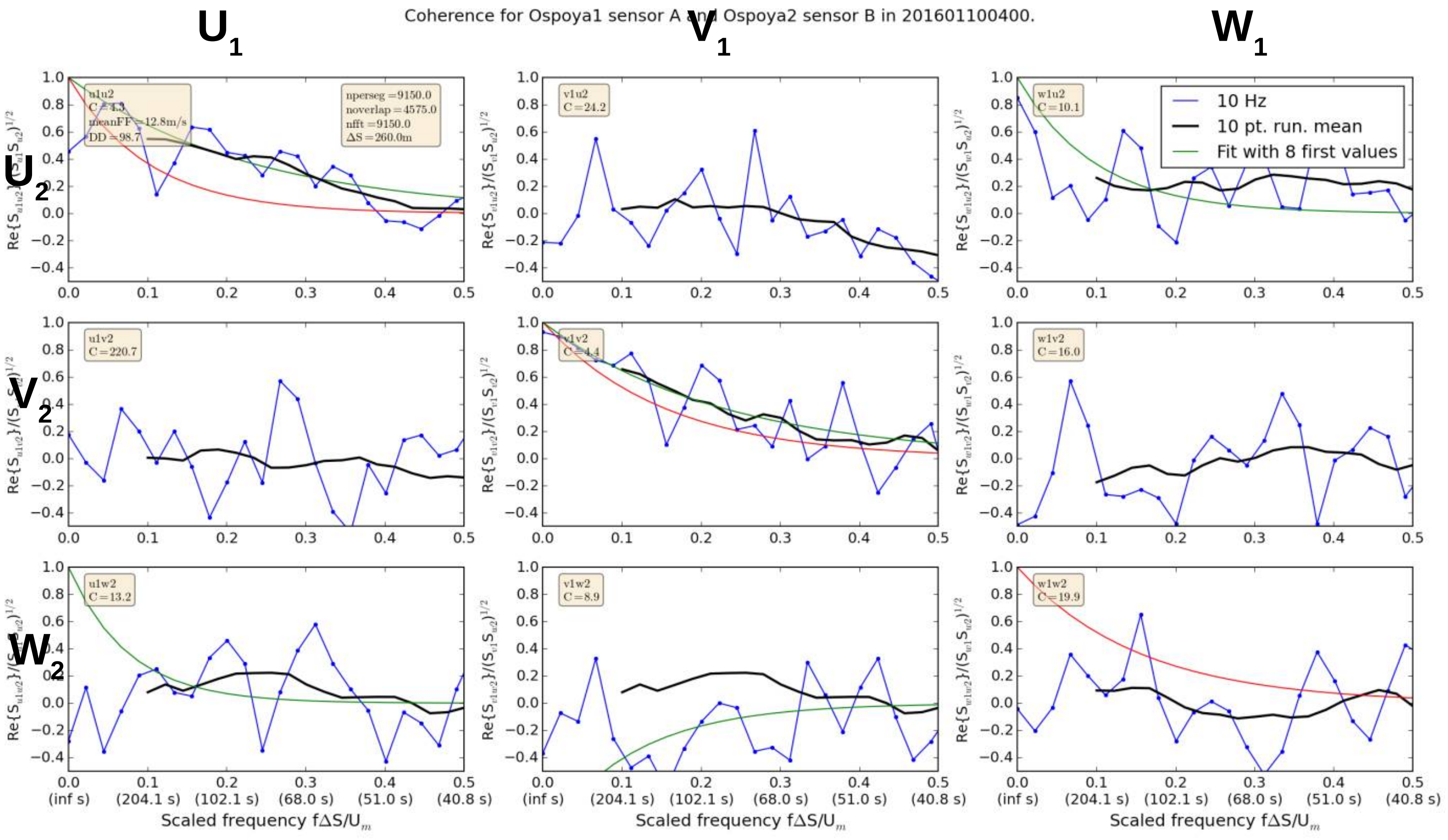
Horizontal coherence at Ospøya at 260 m (easterly wind)
50 m agl, 60 minutes at 22 UTC, 9. January 2016



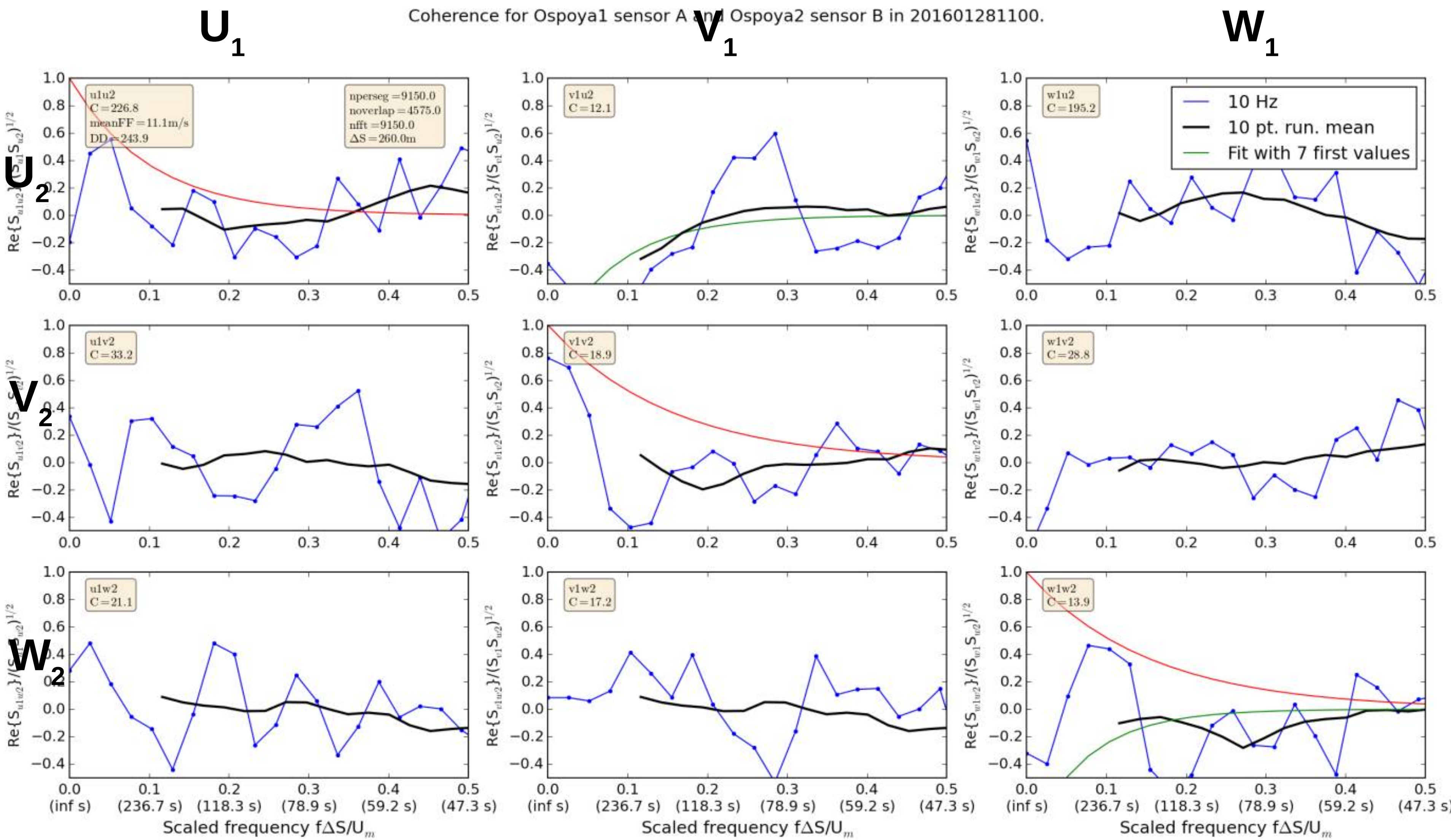
Horizontal coherence at Ospøya at 260 m (easterly wind)
50 m agl, 60 minutes at 23 UTC, 9. January 2016



Horizontal coherence at Ospøya at 260 m (easterly wind)
50 m agl, 60 minutes at 4 UTC, 10. January 2016



Horizontal coherence at Ospøya at 260 m (westerly wind) 50 m agl, 60 minutes at 11 UTC, 28. January 2016



Ospøya horizontal coherens over 260 m distance

From the H400 handbook

Kospektra $S_{i_1 i_2}$ på normalisert form for separasjon normalt på hovedstrømsretningen, horisontalt (y) eller vertikalt (z), er gitt ved:

$$\frac{\mathrm{Re}\,[S_{i_1 i_2}(n,\Delta s_j)]}{\sqrt{S_{i_1}(n)\cdot S_{i_2}(n)}} = \exp\left(-C_{ij}\frac{n\Delta s_j}{V_m(z)}\right) \qquad (5.6)$$

hvor Δs_j er horisontal- eller vertikalavstanden mellom betraktete punkter, og:

$i_1, i_2 = u, v, w$

$j \quad = y, z$

$C_{uy} = C_{uz} = 10{,}0$, C_{vy} , $= C_{vz} = C_{wy} = 6{,}5$, $C_{wz} = 3{,}0$

For horizontal coherence from east and west, Cuy=10, Cvy=6.5 and Cwy=6.5 ifølge håndboken (Davenport model). Here named Cuu, Cvv and Cww in order to not mix up with Cij, i≠j

Coherence is calculated for all 1 hour periods measured, with wind speed > 10 m/s and easterly/westerly flow, and model fitted to the data

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Calculation of coefficients with Davenports cospectra with percentiles of optimized Cij

						Obs.	Handbook
				P=0.05	P=0.1	P=0.5	H400
U	Cuu	Ø	EXP(-cij*DS*f/Vm)	4.3	5.0	8.7	10
		Ø	-EXP(-cij*DS*f/Vm)	16.3	16.6	42.3	10
		V	EXP(-cij*DS*f/Vm)	10.3	11.1	14.7	10
		V	-EXP(-cij*DS*f/Vm)	11.5	12.2	37.2	10
V	Cvv	Ø	EXP(-cij*DS*f/Vm)	4.4	5.1	9.8	6.5
		Ø	-EXP(-cij*DS*f/Vm)	10.3	10.9	15.9	6.5
		V	EXP(-cij*DS*f/Vm)	8.5	8.8	14.7	6.5
		V	-EXP(-cij*DS*f/Vm)	10.2	12.7	197.0	6.5
W	Cww	Ø	EXP(-cij*DS*f/Vm)	6.4	7.8	14.1	6.5
		Ø	-EXP(-cij*DS*f/Vm)	12.4	13.0	21.6	6.5
		V	EXP(-cij*DS*f/Vm)	8.2	8.4	13.2	6.5
		V	-EXP(-cij*DS*f/Vm)	10.1	11.9	20.6	6.5

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Calculation of coefficients with Davenports cospectra with percentiles of optimized Cij. Effect of lag at one station.

P=0.1	-6s	-3s	0s	1s	3s	6s	9s
ALLE Cij,i=j fra Ø							
EXP(-cij*DS*f/Vm)	5.8	5.9	6.0	5.8	6.0	6.0	6.5
-EXP(-cij*DS*f/Vm)	12.0	12.6	13.5	12.7	17.5	17.5	15.0
ALLE Cij,i=j fra V							
EXP(-cij*DS*f/Vm)	9.4	9.4	9.4	8.4	6.1	6.3	9.1
-EXP(-cij*DS*f/Vm)	13.8	13.2	12.2	11.8	10.1	12.0	10.8
P=0.5	-6s	-3s	0s	1s	3s	6s	9s
ALLE Cij,i=j fra Ø							
EXP(-cij*DS*f/Vm)	11.0	11.0	10.9	10.8	10.0	10.0	11.1
-EXP(-cij*DS*f/Vm)	21.0	19.9	26.6	22.7	69.3	69.3	20.6
ALLE Cij,i=j fra V							
EXP(-cij*DS*f/Vm)	14.6	14.4	14.2	13.8	11.3	9.8	14.6
-EXP(-cij*DS*f/Vm)	82.8	77.1	84.9	83.3	52.6	108.3	81.1

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Main conclusions and summary

- Present systematic analysis of coherence (and spectra) from a unique measurement site in an open fjord
- 1) The coherence is higher (lower persentiles of Cij) for easterly than for westerly wind
- 2) For easterly wind, no differences in the 0.05, 0.1, and 0.5 percentiles of Cij are seen using -6 sec, -3 sec, 0 sec 1 sec, 3 sec or 6 sec as time lag on Ospøya 1 resp Ospøya 2
- 3) For westerly wind, we find that the coherence are gradually improving from 0 to 6 sec lag.
  - possibly due to the islands west of Ospøya. Wind along 250 - 260 degrees is typically slowd down for one of the stations but not the other.
- The Davenport model is rarely good at large separation distances. Other models are being tested, e.g. Krenk, and analysis methods are being scrutinized.

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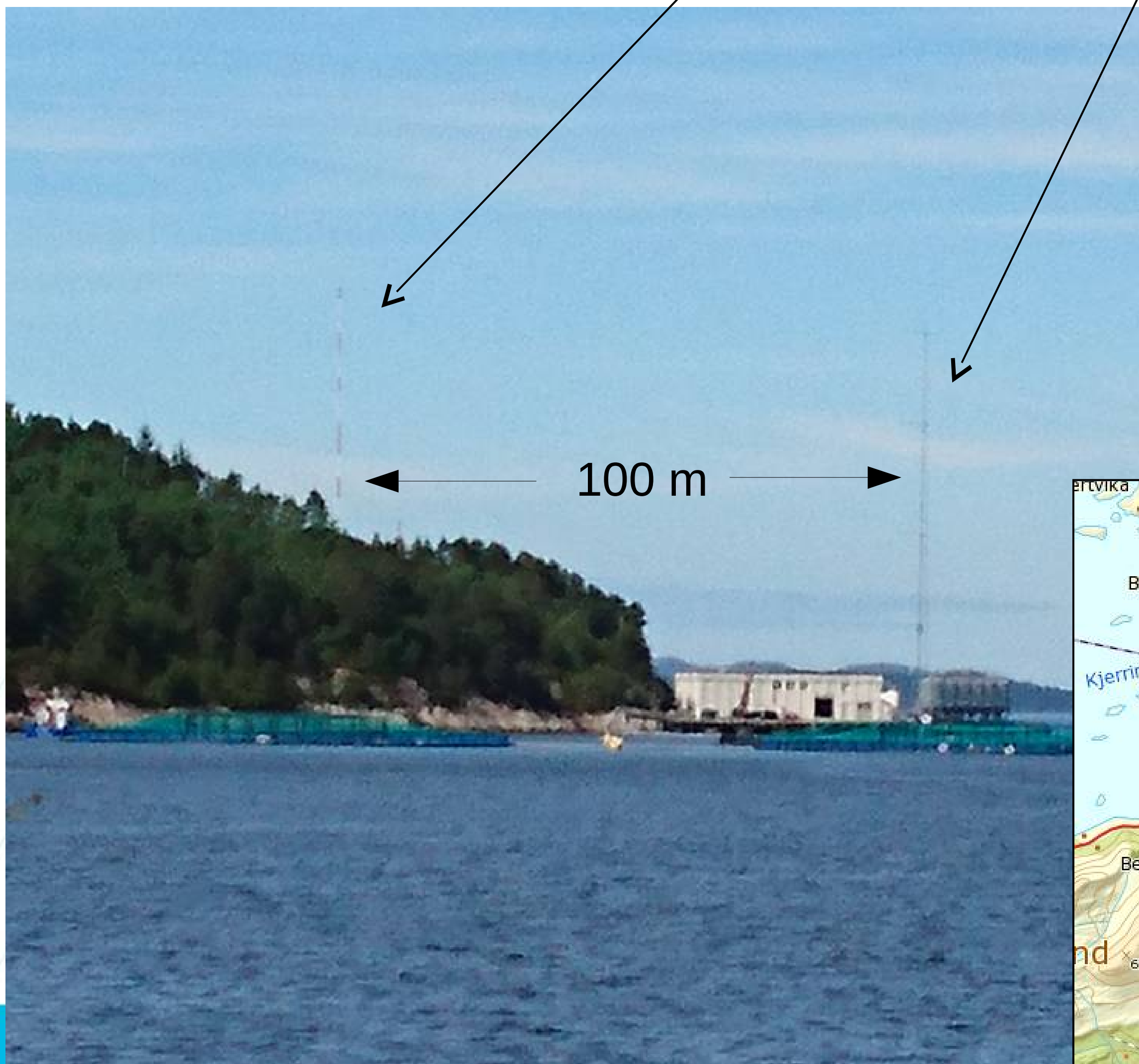
Measure masts: Midsund and Nautneset



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