

The Bolund Experiment

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in cooperation with Vestas

Risø DTU, Roskilde, Denmark

December 3-4, 2009 – Bolund Workshop, Risø DTU, Denmark

Approvals needed for the Bolund experiment

- Landowners' approval (Karen, Christian and Benny)
- Fredningsnævnet
- Building approval (Byggesagsgodkendelse, Roskilde Kommune)
- Environmental Center Roskilde
- Neighbor hearing (two complaints filed)
- Meeting with the neighbors (a very peaceful meeting with some understanding)
- Danish Maritime Safety Administration (Farvandsdirektoratet in Thisted)

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Normal processing time 1/2 year - Bolund $\sim$ 3 months

Previous experiments

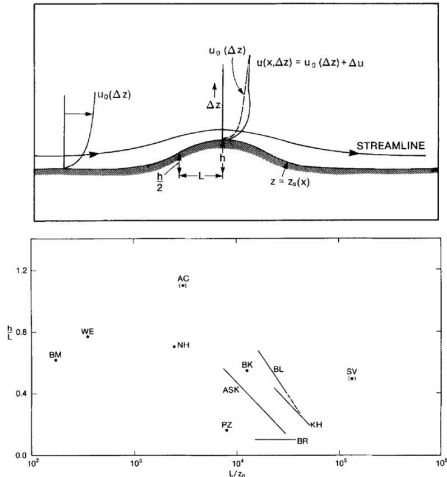


Fig. 3 Diagram and scatter plot of field studies of boundary-layer flow over low hills. See Table I for additional

TABLE I
Field studies of boundary-layer flow over low hills

Code	Hill	Reference	Experiment details	
			Mean flow data	Turbulence instrumentation
BK	Brent Knoll	Mason and Sykes (1979b)	2 m wind speed at about 20 sites.	None
PZ	Pontargues Hill	Sacré (1979)	3 25 m masts.	Gill UVW anemometers at 10, 15, 20, and 25 m levels on three masts.
BM	Black Mountain	Bradley (1980)	Cup anemometers at 9 levels up to 124 m on hilltop tower and 7 levels to 25 m on upwind reference tower.	Gill UVW and Sonic anemometers at various levels.
AC	Adna Craig	Jenkins et al. (1981)	4 m wind speed at 12 sites plus aircraft data.	Tethered balloon-borne measurements.
KH	Kettles Hill*	Taylor et al. (1983b)	3, 6, and 10 m wind speed on 8 3-m posts and 10 10-m towers. Direction at 10 m levels only.	10 Gill UVW anemometers at 10 m along hill axis + 10 m Sonic at hilltop. (Turbulence data not yet published.)
KH	Kettles Hill	Mickle et al. (1984)	2.5, 5, and 10 m wind speed on 4 10-m posts plus TALA kite profiles at hilltop and reference sites.	None
WE	Worms Embankment	Hauf and Neumann-Hauf (1982)	Two 18 m masts upstream of embankment with 6 cup anemometers on each.	One 3-component Sonic anemometer on boom or small mast above embankment.
BR	Bungendore Ridge	Bradley (1983)	3 27 m towers with cup anemometers.	2 Sonic and 4 Gill UVW anemometers at 2.2, 4, and 8 m levels on 2 towers.
SV	Sirhowy Valley	Mason and King (1984)	8 m wind speed at 12 sites.	One Sonic anemometer at 16 m in valley and hot film up to 16 m on summit. Tethered balloons and aircraft measurements.
BL	Blushaval	Mason and King (1985)	11 8 m towers with 2 component propeller anemometers + cup anemometer profile to 16 m at upwind reference site and TALA kite profiles.	Hot film and Gill propeller anemometers on 16 m towers at reference and summit sites.
ASK	Askervein*	Taylor and Trueman (1983)	35 10 m posts plus profile to 50 m at hilltop (HT) and upwind reference site (RS).	6 Sonic anemometers (2 at RS, 4 at HT) on 50 m towers plus Gill UVW anemometers at 10 m (RS and HT). Cup anemometer vanes also available from 50 m towers.
ASK	Askervein*	Taylor and Trueman (1985)	As above plus TALA kite profiles to ~150 m at HT and RS.	As above, plus Gill UVW anemometers on 50 m towers, on 30 m tower just upwind of hill, on 17 m tower at second hilltop location and on 13 10 m towers at other locations.
NH	Nylund Hill	Mason (1986)	Hilltop and upwind measurements to 16 m in 2 lines of 8 m towers down hill sides (10 sites).	Hot film, Sonic, and Gill propeller anemometers on 16 m towers at hilltop and upwind reference sites.

Previous experiments

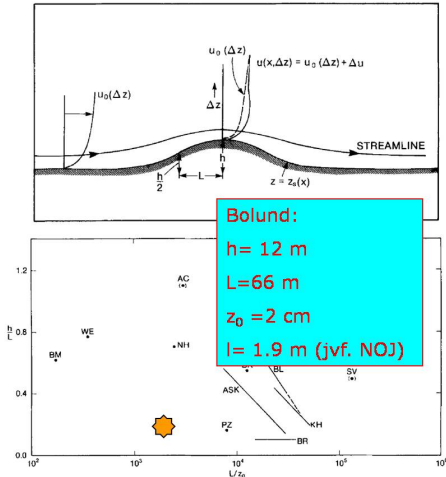


Fig. 3. Parameter space diagram. Field studies of boundary-layer flow over hills. See Table I for additional

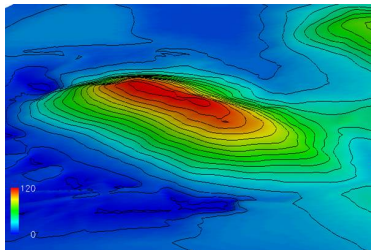
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Bolund vs. Askervein

Askervein Experiment 1983

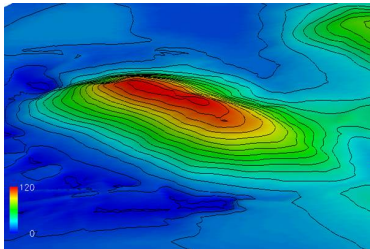
- Well-defined inflow conditions.
- Uniform Roughness.
- Low hill / simple terrain.
- “Linear”.



Bolund vs. Askervein

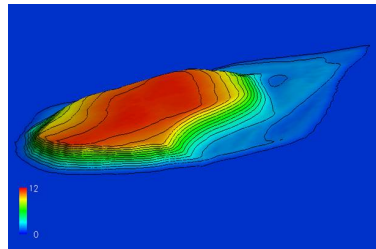
Askervein Experiment 1983

- Well-defined inflow conditions.
- Uniform Roughness.
- Low hill / simple terrain.
- “Linear”.



Bolund Experiment 2008

- Well-defined inflow conditions.
- Roughness change.
- Steep Escarpment.
- “Complex”.



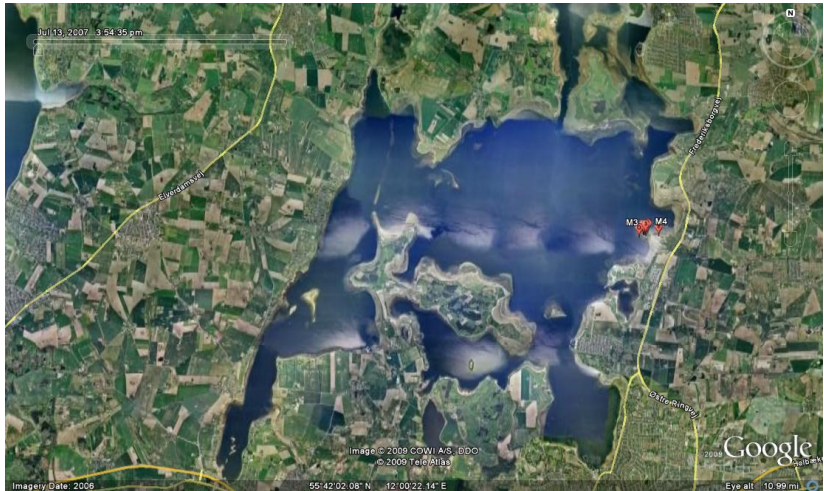
The Bolund peninsula

Map width: 50 km



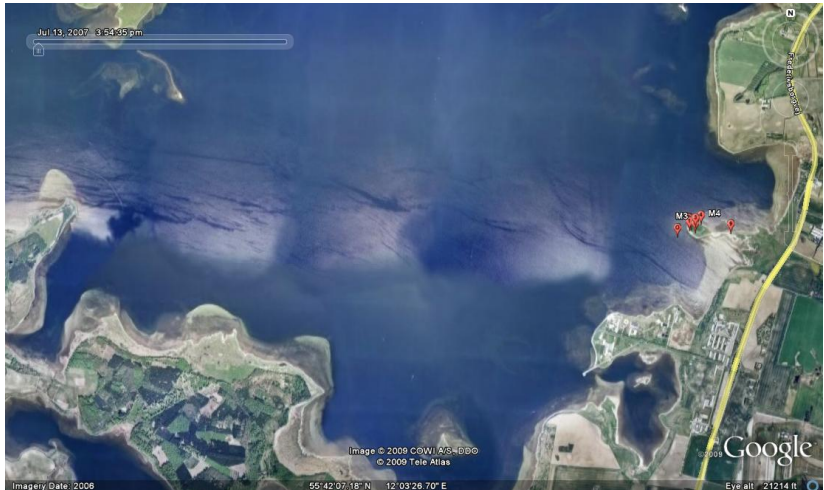
The Bolund peninsula

Map width: 20 km



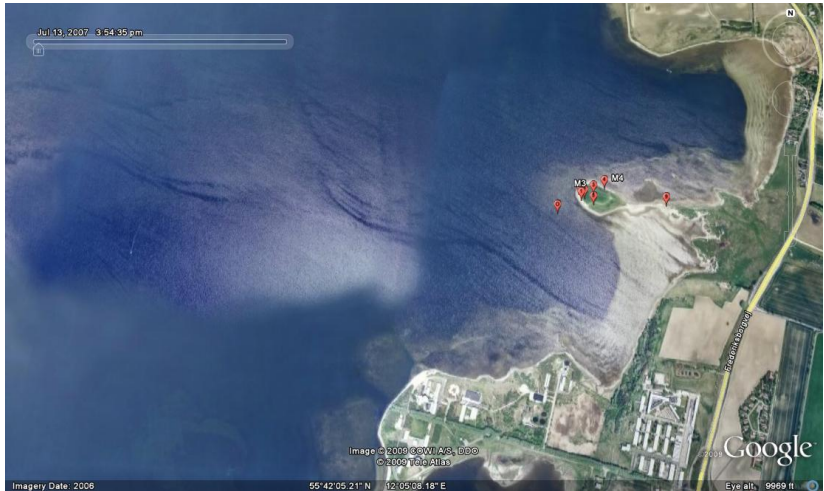
The Bolund peninsula

Map width: 7 km



The Bolund peninsula

Map width: 3.5 km



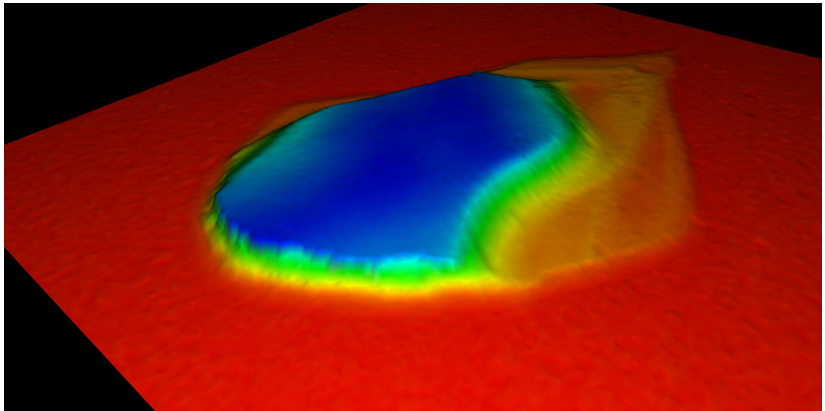
The Bolund peninsula

Map width: 1 km



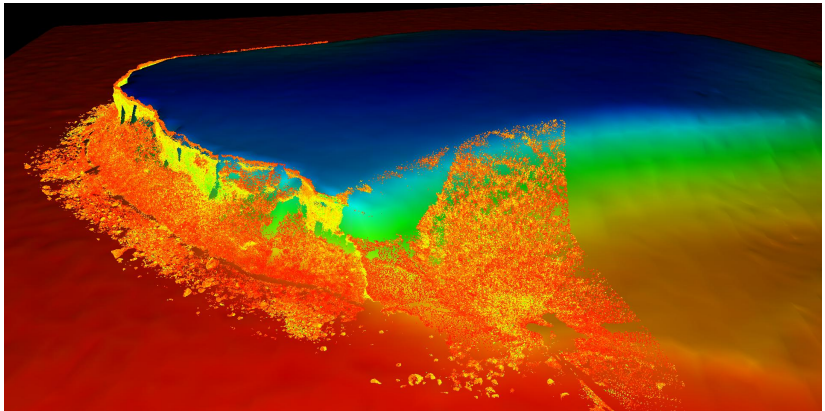
Height scanning with laser

Optech Airborne Laser Terrain Mapper: ≈ 2 m resolution



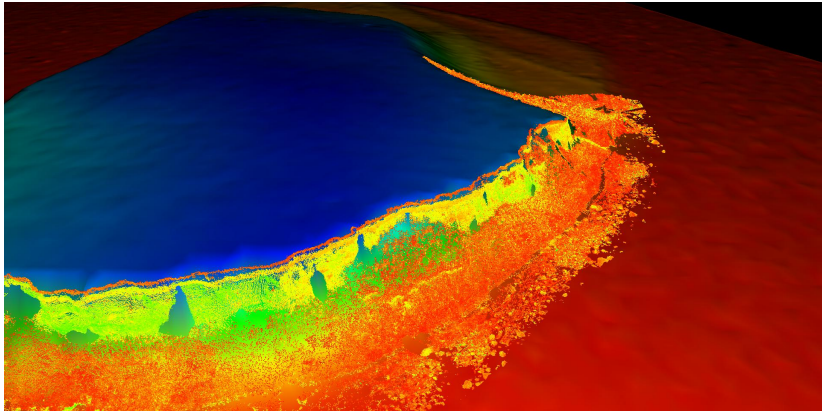
Height scanning with laser

Cliff to steep: additional < 0.1 m resolution scanning applied



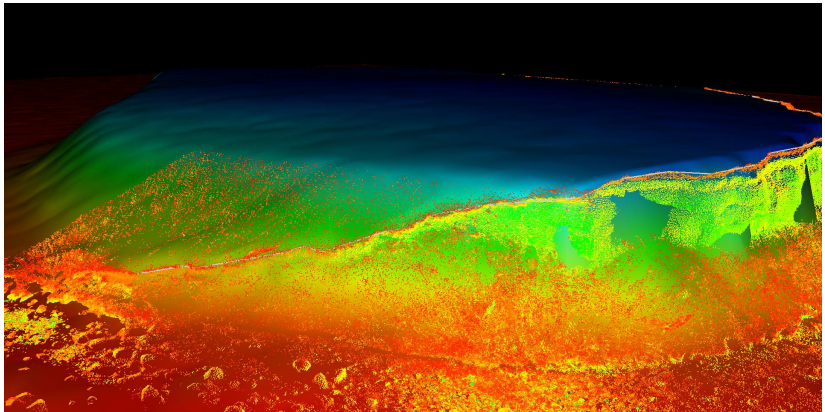
Height scanning with laser

Cliff to steep: additional < 0.1 m resolution scanning applied

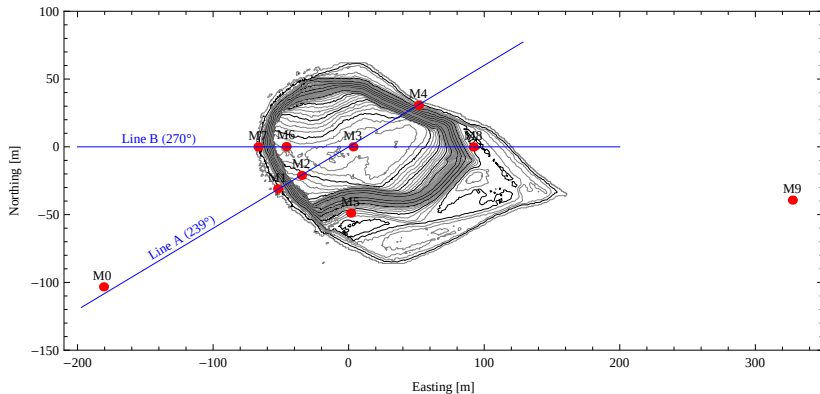


Height scanning with laser

Cliff to steep: additional < 0.1 m resolution scanning applied



Masts



Erection of masts



Instrumentation

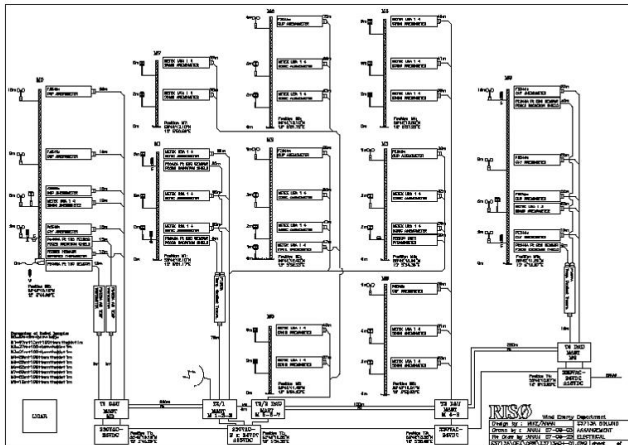
- 23 Metek USA-1 Basic sonics – off-line flow correction
- 12 Risø cup anemometers (WindSensor P2546)
- 2 ZephIR lidars + one scanning lidar
- Temperature and temperature difference
- No pressure and no humidity



Sonic Configuration

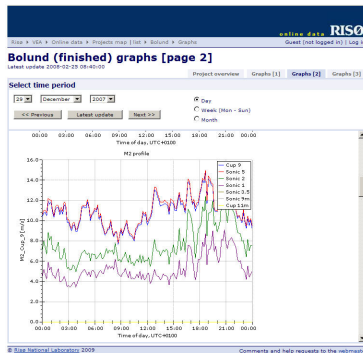
Mast. ID	2m	5m	9m	15m	Lidar
M0	C	C,S	C	C	-
M1	S	S	S	-	-
M2	S	S	C,S	-	L
M3	S	S	C,S	-	-
M4	S	S	S	-	-
M5	S	S	-	-	-
M6	S	S	C	-	-
M7	S	S	-	-	-
M8	S	S	C	-	-
M9	C	C,S	C	C	L

Technical Diagram

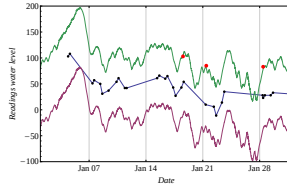
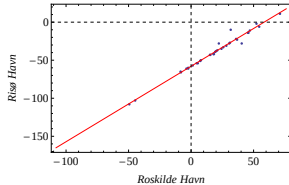


Database and Rodeo

- Central Acquisition of all Meteorological Data (20 Hz)
- Direct Data Transfer to Risø via RadioLink
- Database Storage MySQL (20 Hz and 10 min averages)
- Online Data Display



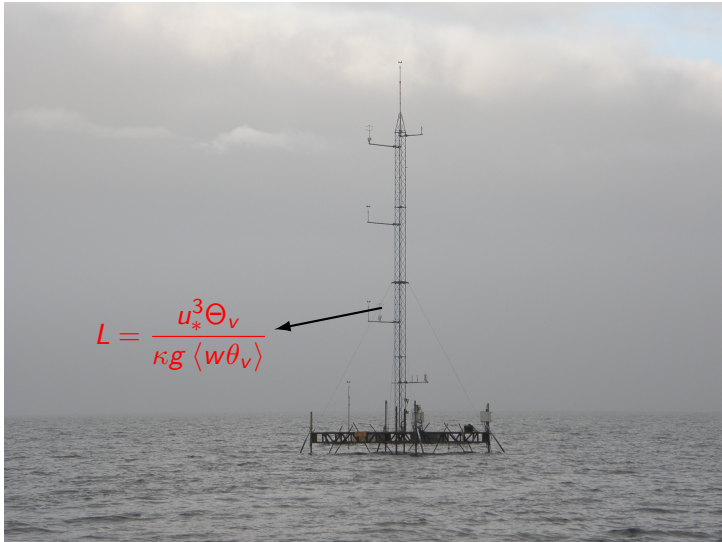
Water level in Roskilde Fjord



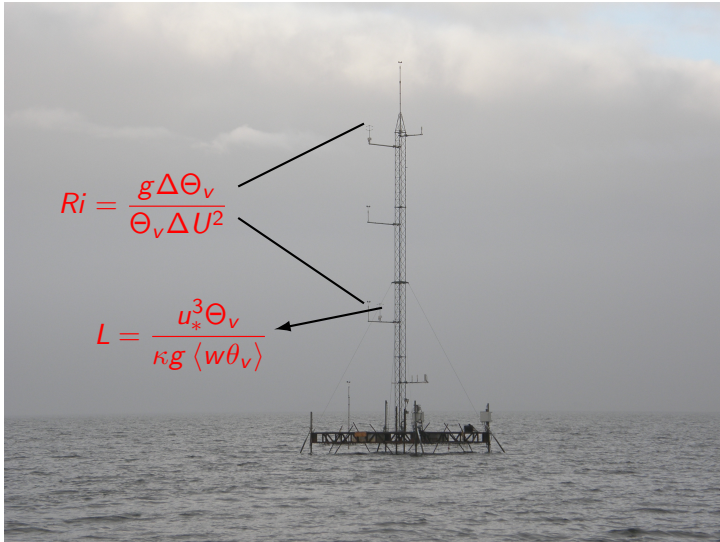
The upstream mast M0: Atmospheric stability



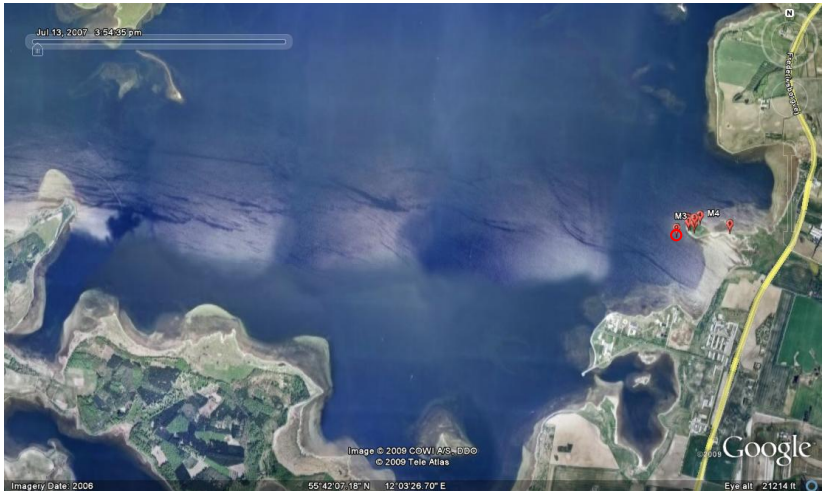
The upstream mast M0: Atmospheric stability



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Fetch



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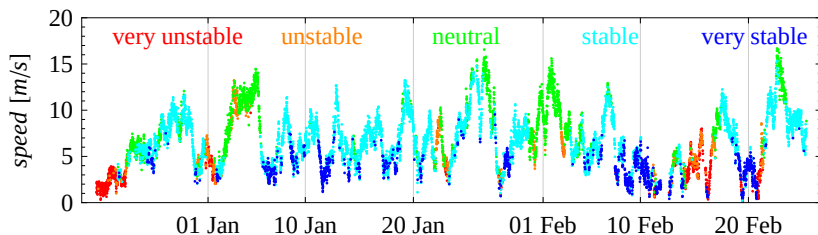
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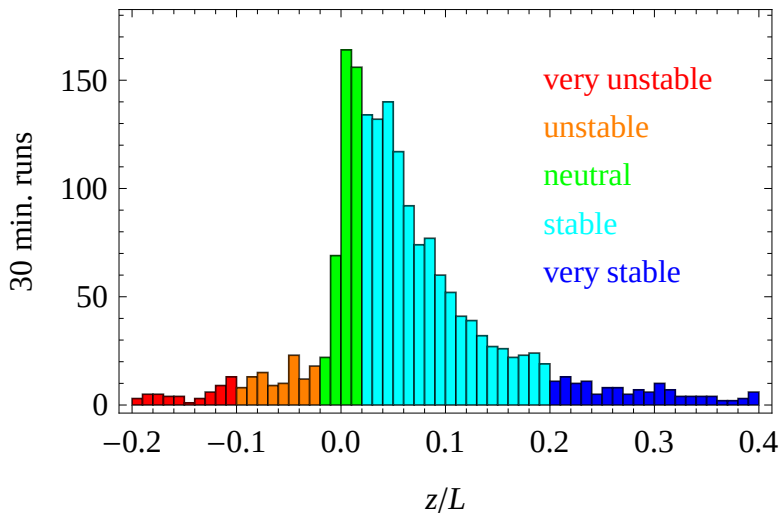
Fetch



Measurement period and stability

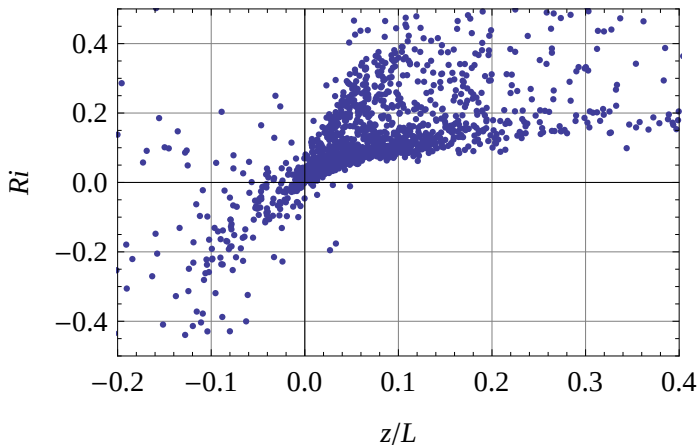


Stability in terms of the Monin-Obukhov stability parameter z/L



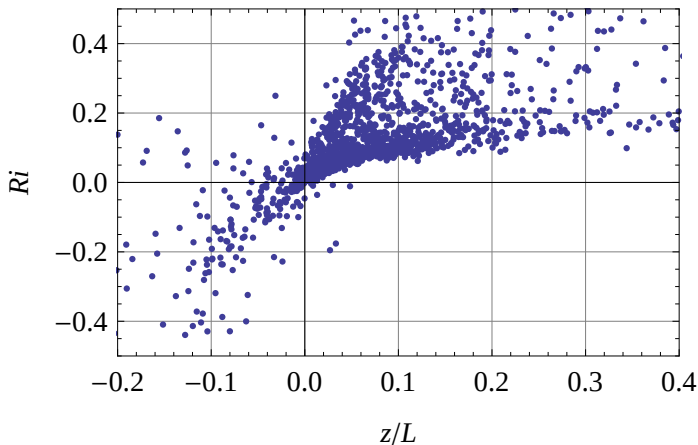
Atmospheric stability: z/L versus Ri

$180^\circ < \theta < 360^\circ$ and $U_5 > 0$ m/s



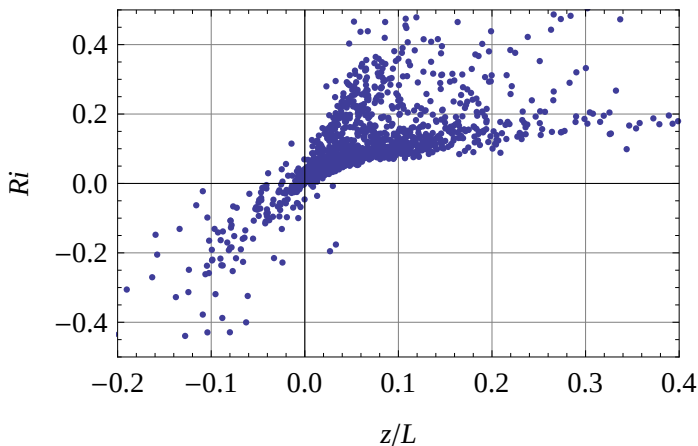
Atmospheric stability: z/L versus Ri

$180^\circ < \theta < 360^\circ$ and $U_5 > 2$ m/s



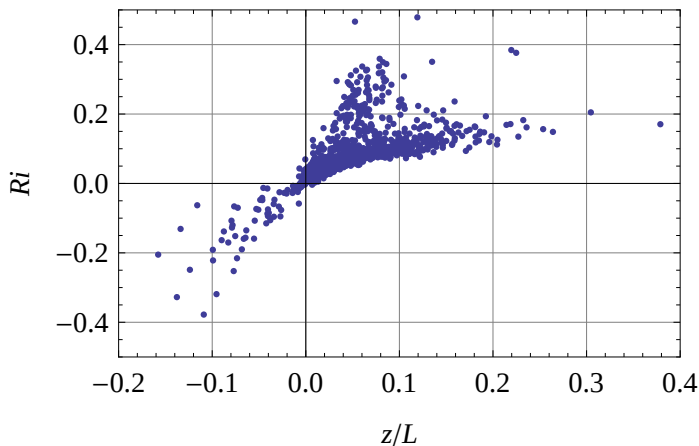
Atmospheric stability: z/L versus Ri

$180^\circ < \theta < 360^\circ$ and $U_5 > 4$ m/s



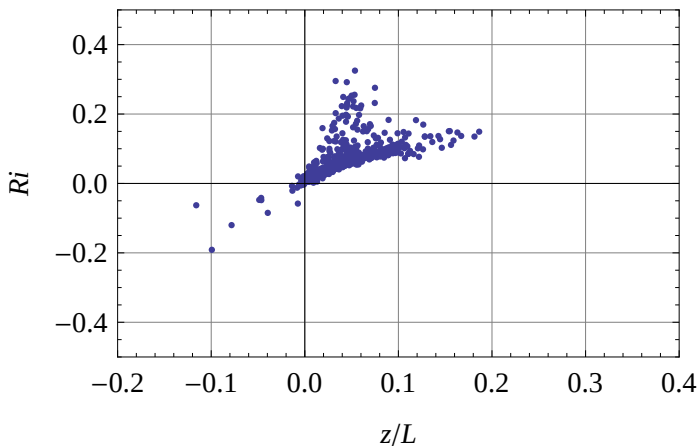
Atmospheric stability: z/L versus Ri

$180^\circ < \theta < 360^\circ$ and $U_5 > 6$ m/s



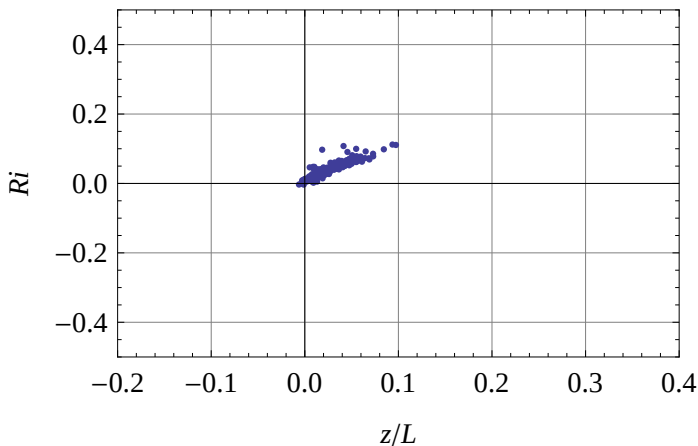
Atmospheric stability: z/L versus Ri

$180^\circ < \theta < 360^\circ$ and $U_5 > 8$ m/s



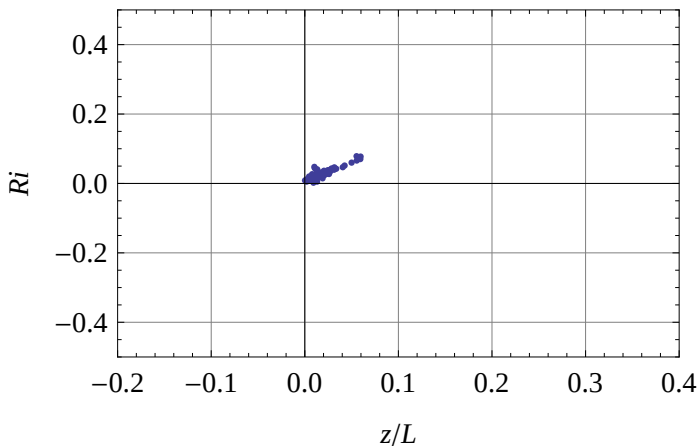
Atmospheric stability: z/L versus Ri

$180^\circ < \theta < 360^\circ$ and $U_5 > 10$ m/s



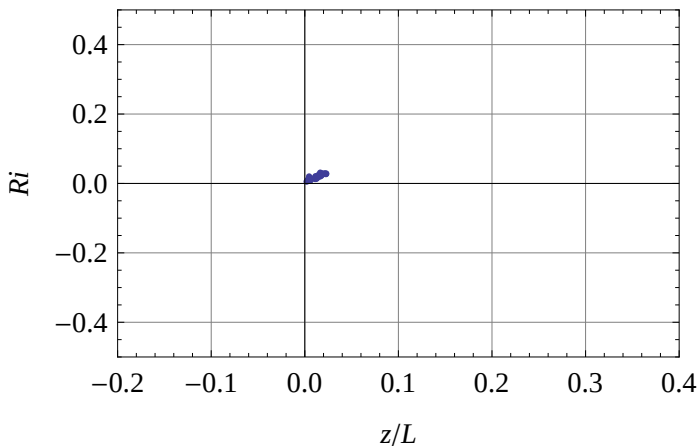
Atmospheric stability: z/L versus Ri

$180^\circ < \theta < 360^\circ$ and $U_5 > 12$ m/s



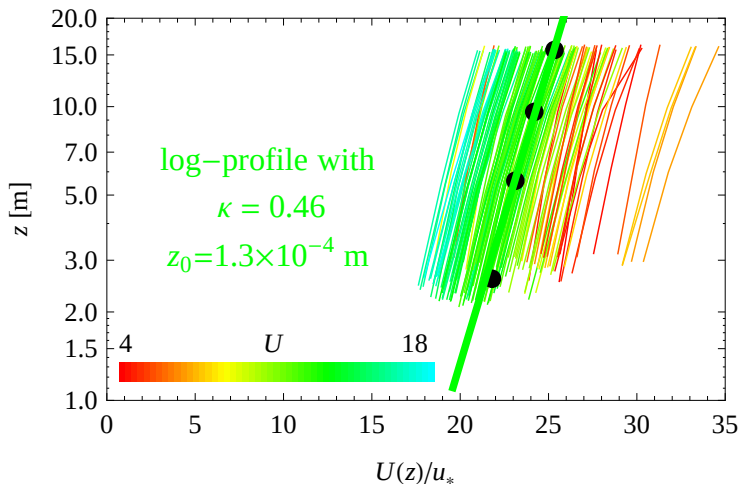
Atmospheric stability: z/L versus Ri

$180^\circ < \theta < 360^\circ$ and $U_5 > 14$ m/s



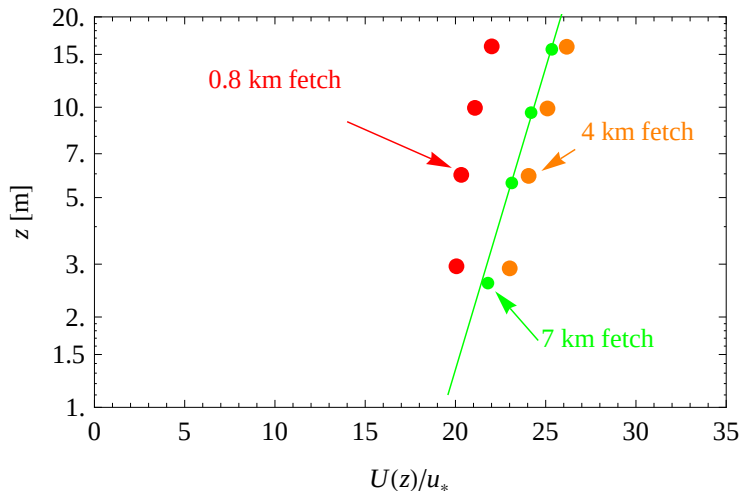
Neutral upwind profile

$-0.02 < z/L < 0.02$ and $260^\circ < \theta < 300^\circ$ (long fetch)



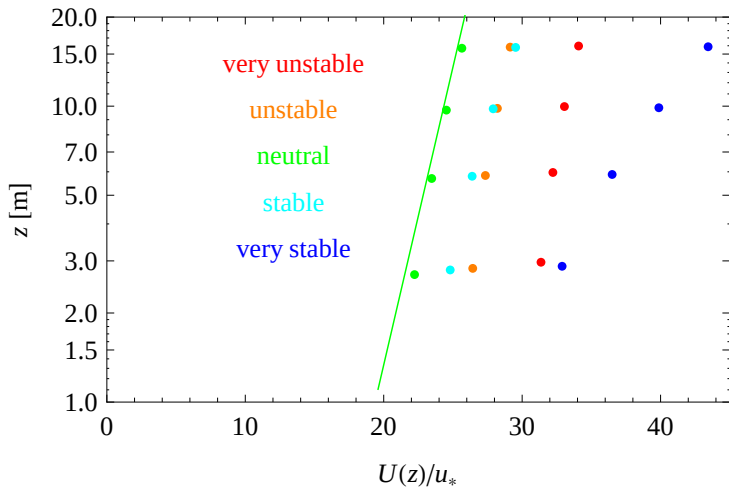
The upstream conditions

Is the flow “undisturbed”? ($-0.02 < z/L < 0.02$)



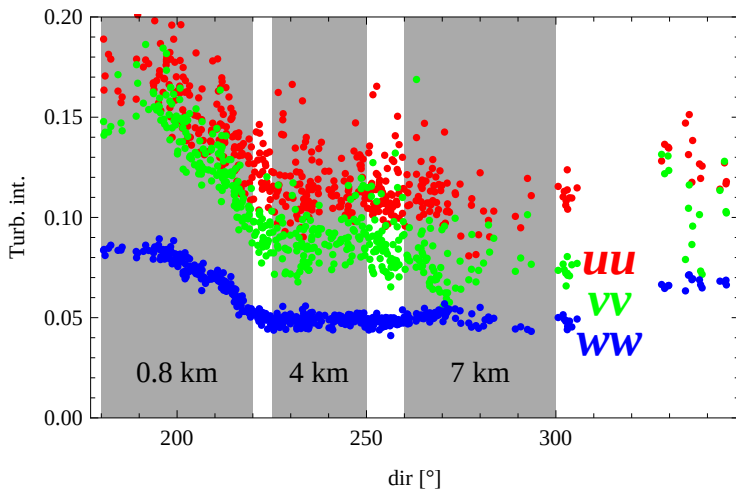
The upstream conditions

Stability changes the wind gradient $\partial U / \partial z$ slightly



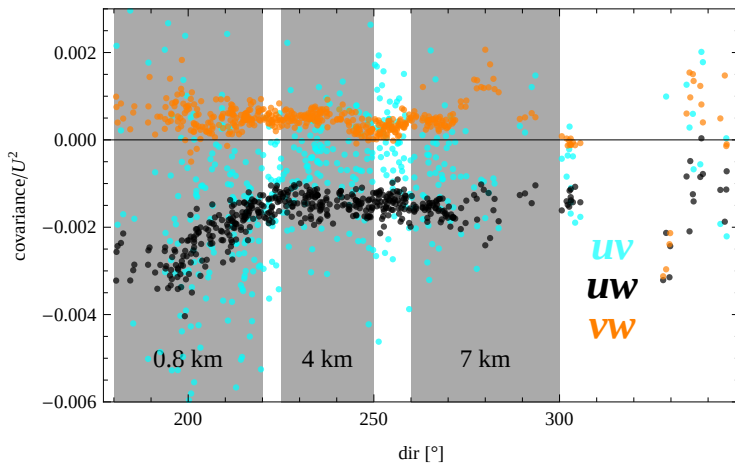
Upstream turbulence

$$8 \text{ m/s} < U_5 < 10 \text{ m/s}$$



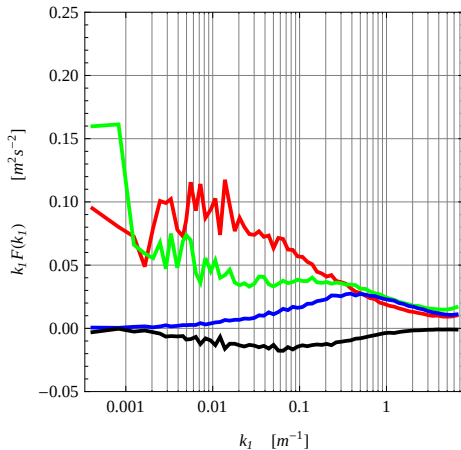
Upstream covariances

$$8 \text{ m/s} < U_5 < 10 \text{ m/s}$$



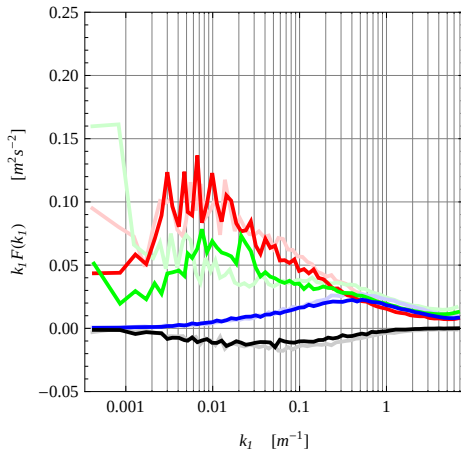
Upstream spectra

Along wind, u , transverse v , vertical w , co-spectrum uw



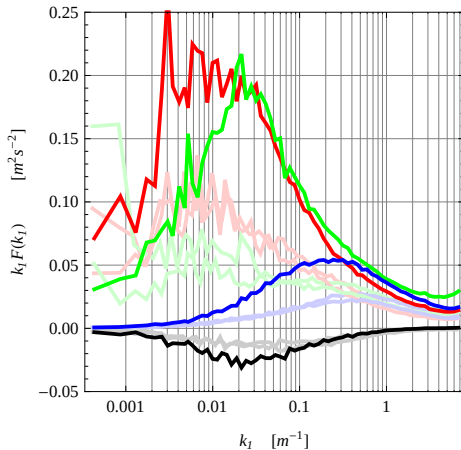
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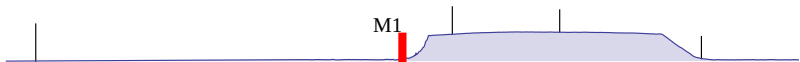
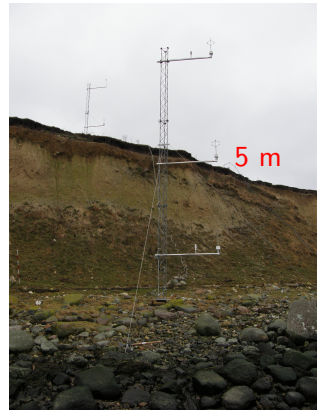
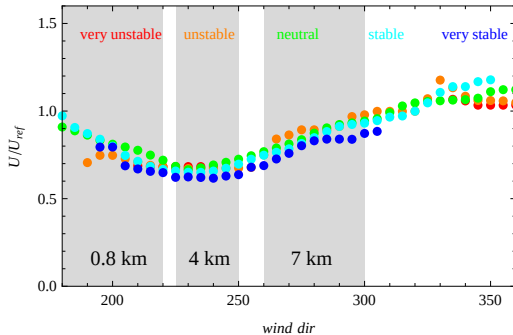


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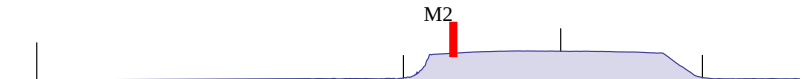
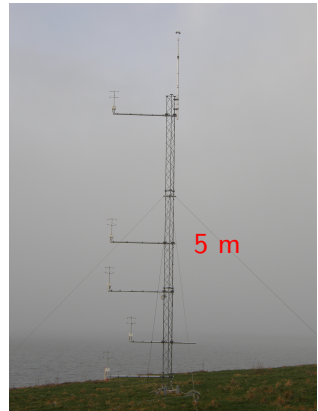
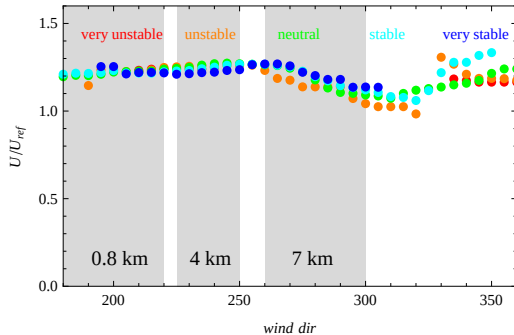
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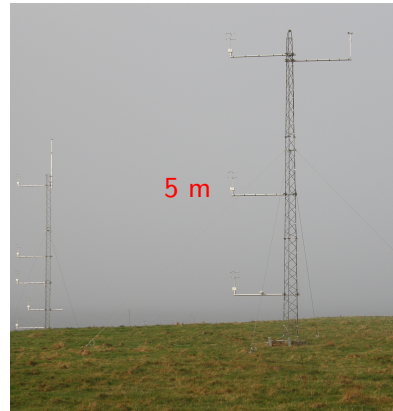
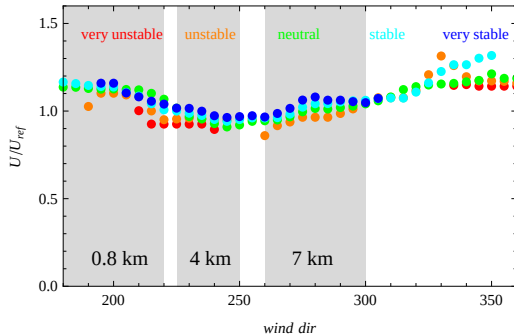
Speed at line A (5 m above terrain)



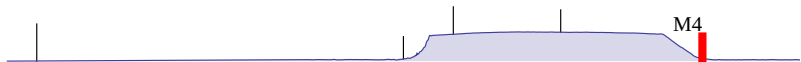
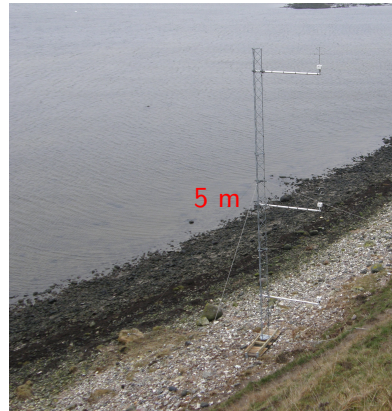
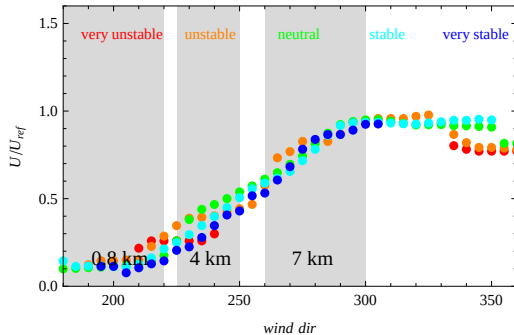
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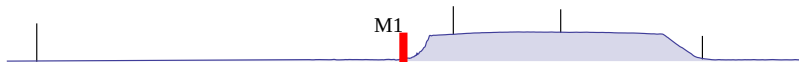
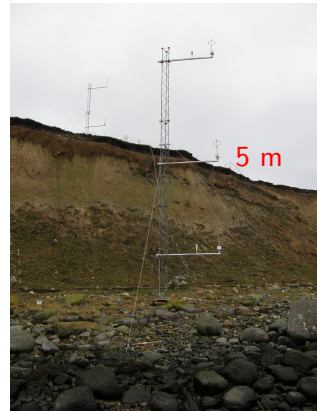
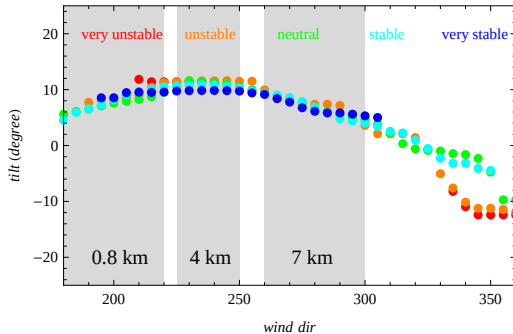
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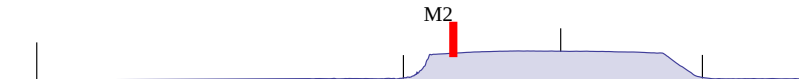
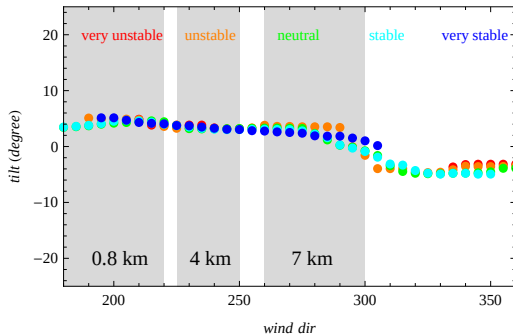
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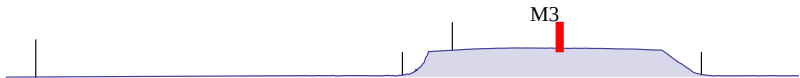
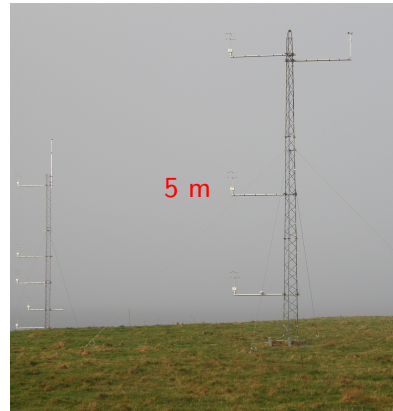
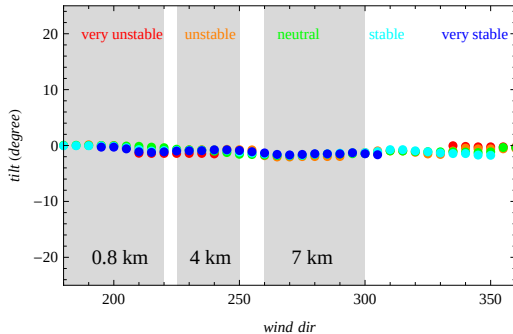
Tilt at line A (5 m above terrain)



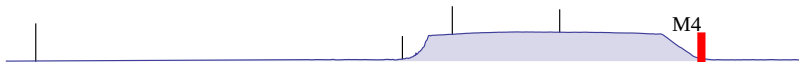
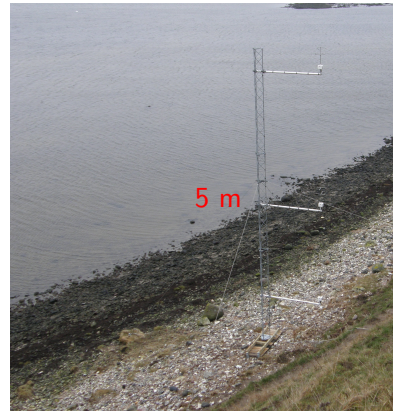
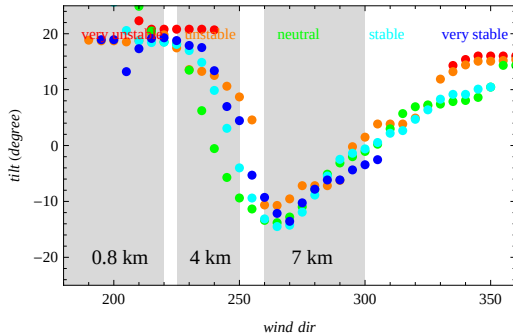
Tilt at line A (5 m above terrain)



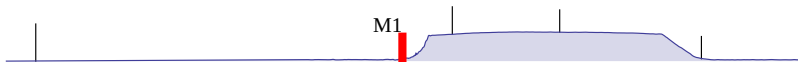
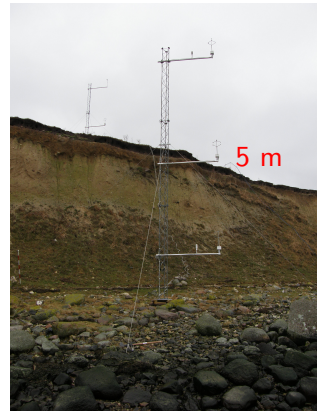
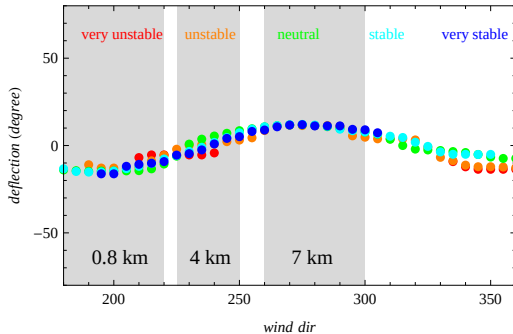
Tilt at line A (5 m above terrain)



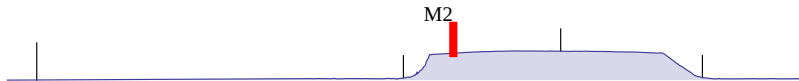
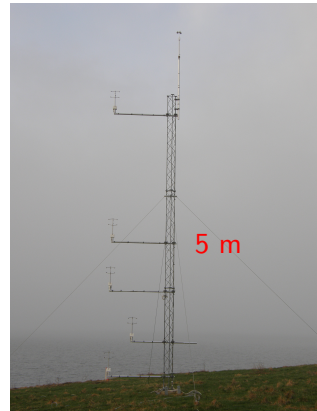
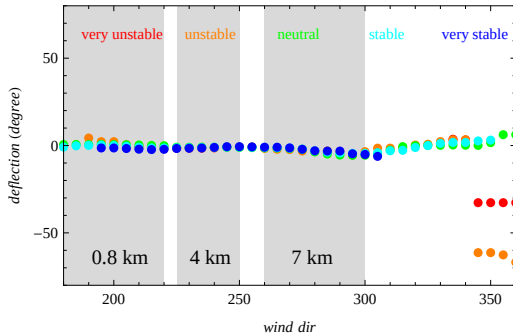
Tilt at line A (5 m above terrain)



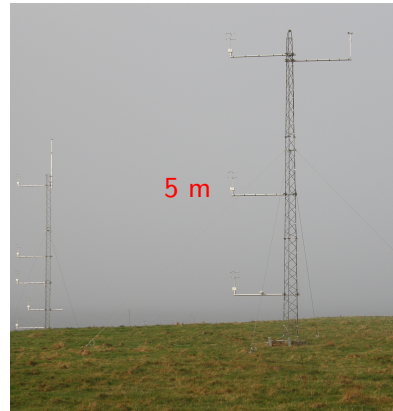
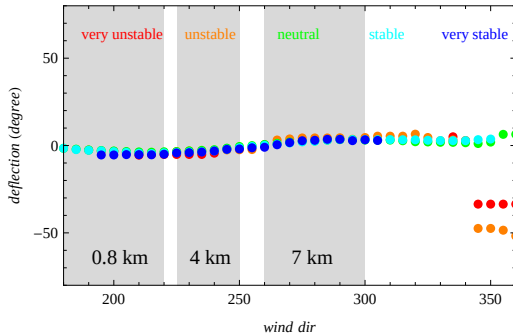
Deflection at line A (5 m above terrain)



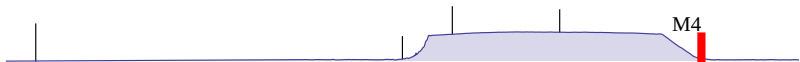
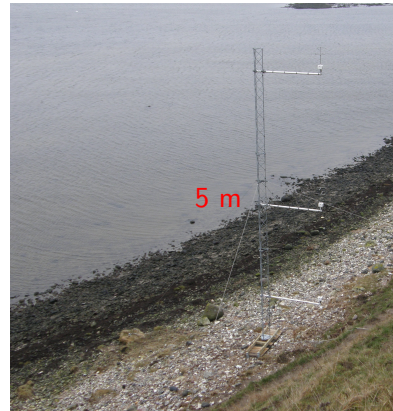
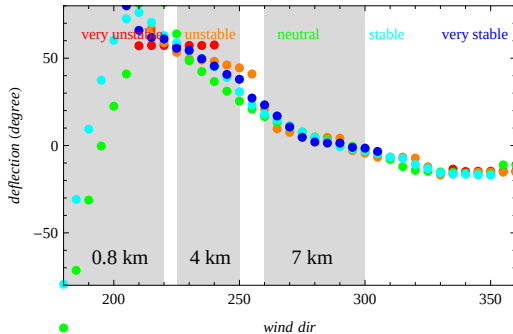
Deflection at line A (5 m above terrain)



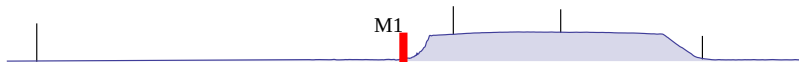
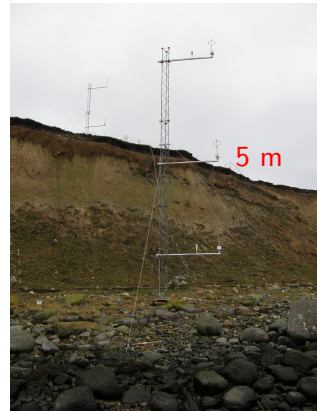
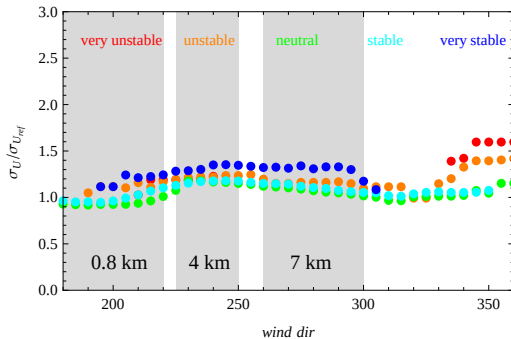
Deflection at line A (5 m above terrain)



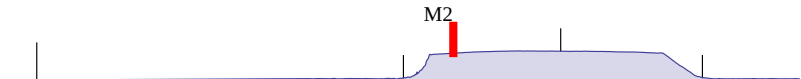
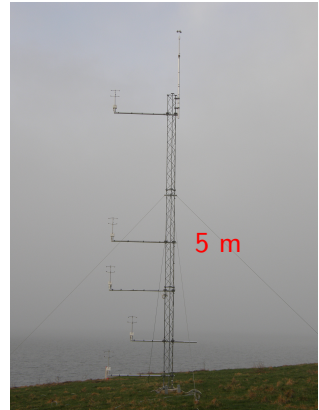
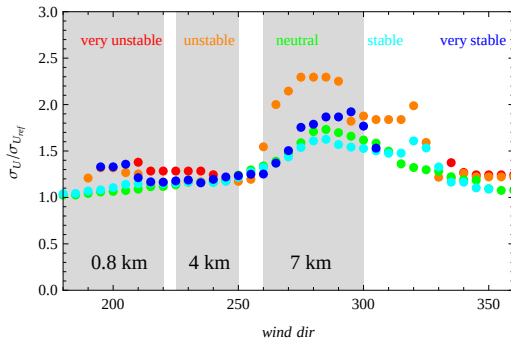
Deflection at line A (5 m above terrain)



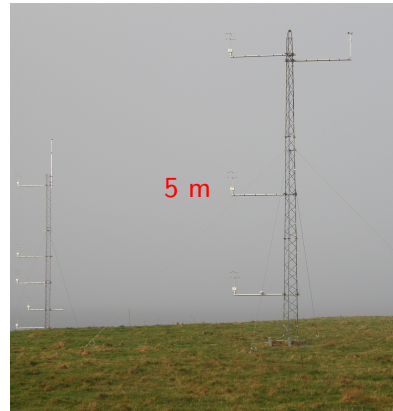
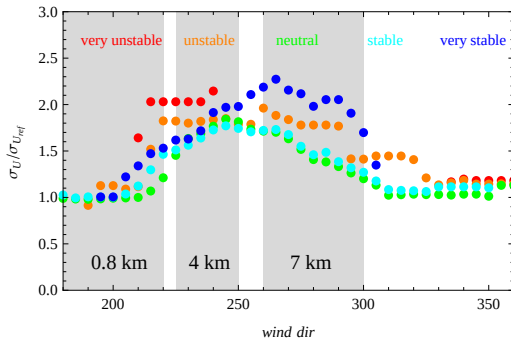
Turbulence intensity at line A (5 m above terrain)



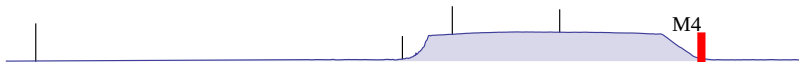
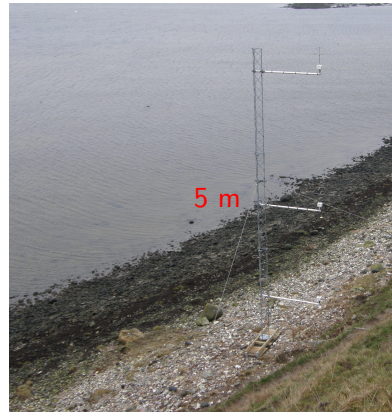
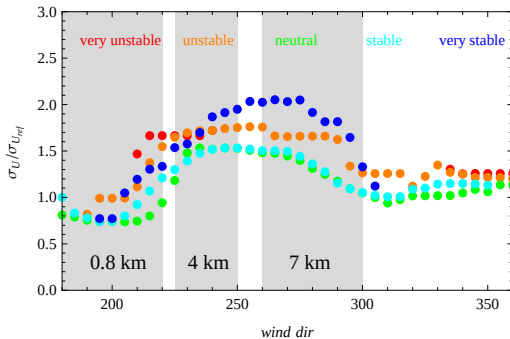
Turbulence intensity at line A (5 m above terrain)



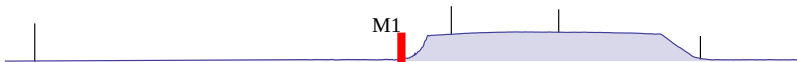
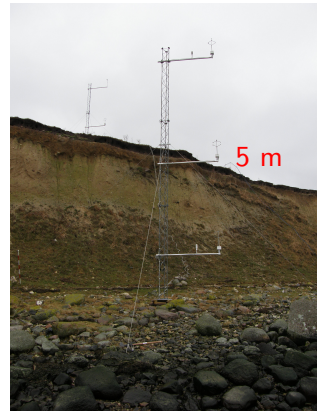
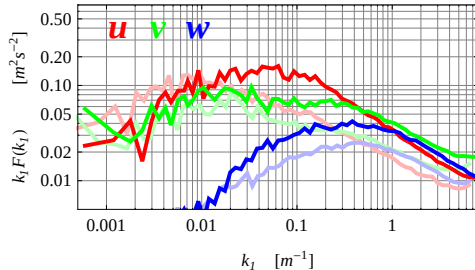
Turbulence intensity at line A (5 m above terrain)



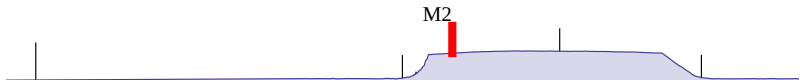
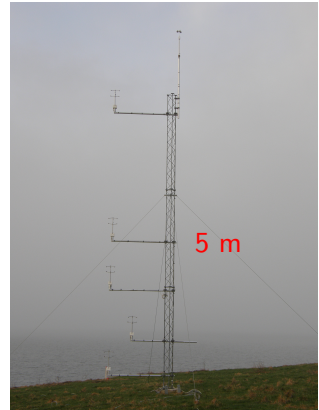
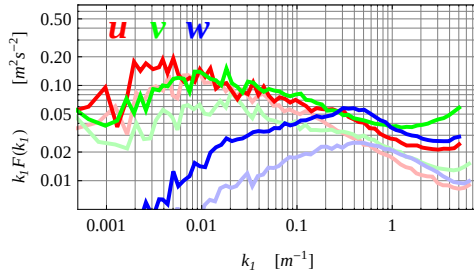
Turbulence intensity at line A (5 m above terrain)



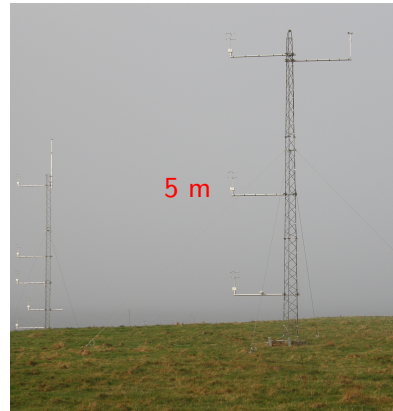
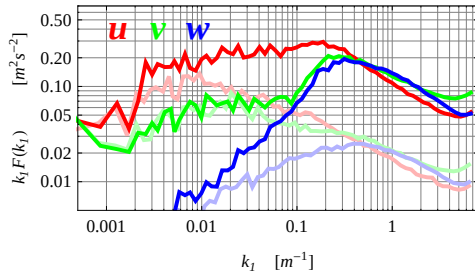
Turbulence spectra at line A (5 m above terrain)



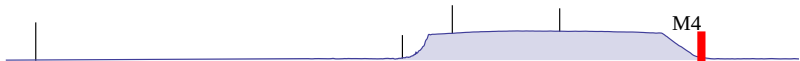
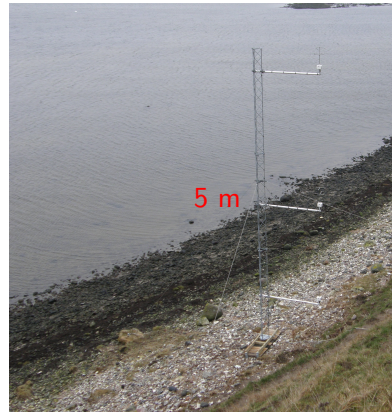
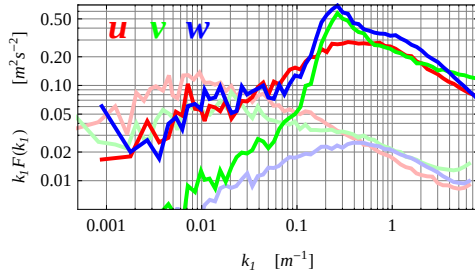
Turbulence spectra at line A (5 m above terrain)



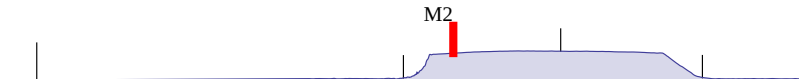
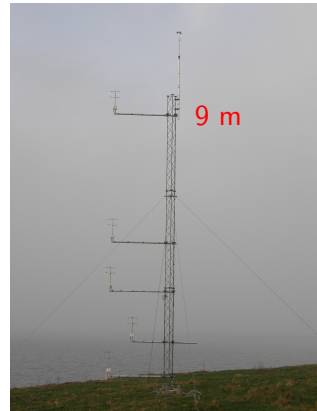
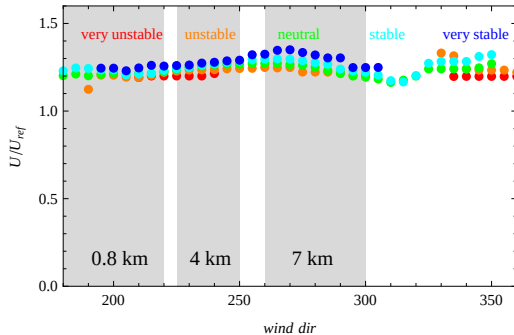
Turbulence spectra at line A (5 m above terrain)



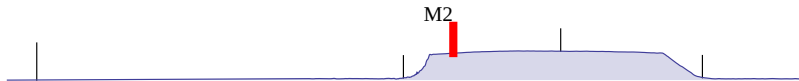
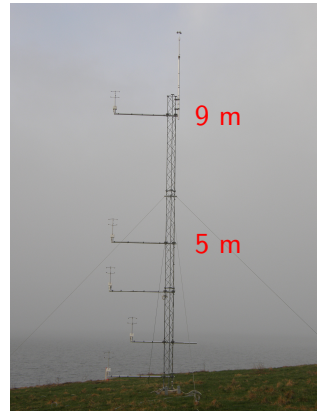
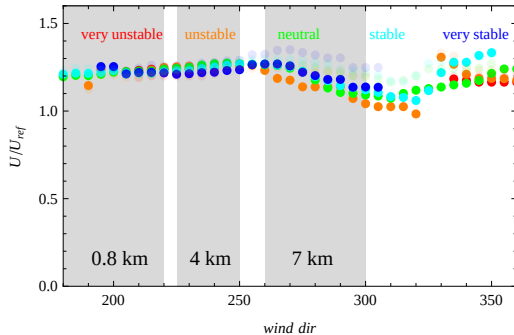
Turbulence spectra at line A (5 m above terrain)



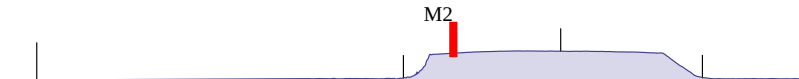
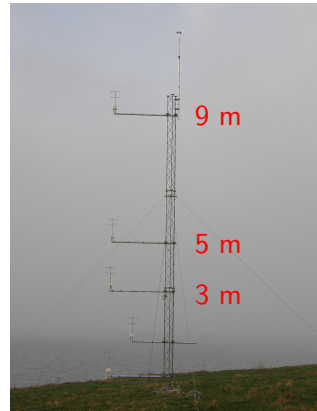
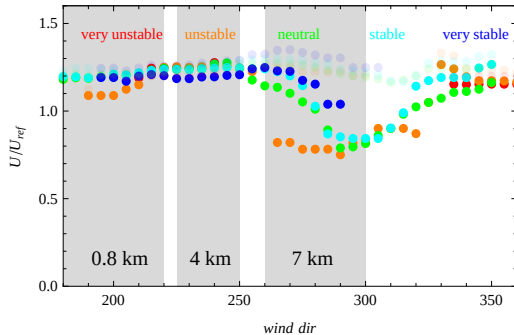
Speed at M2



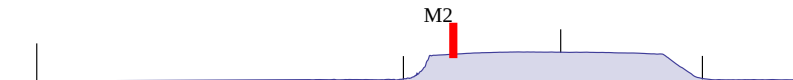
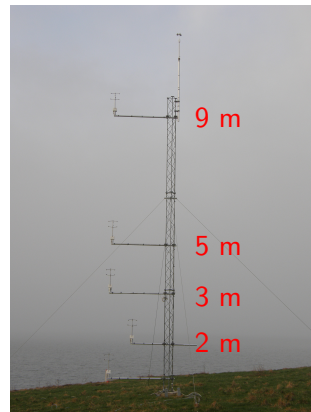
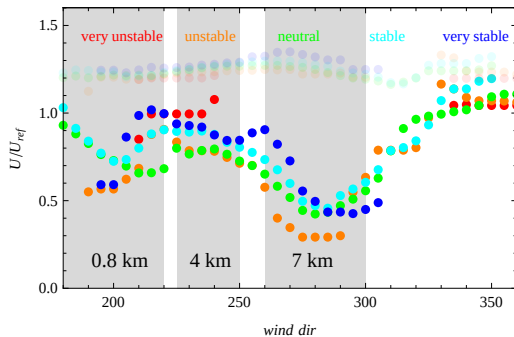
Speed at M2



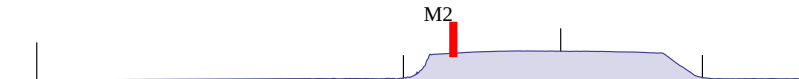
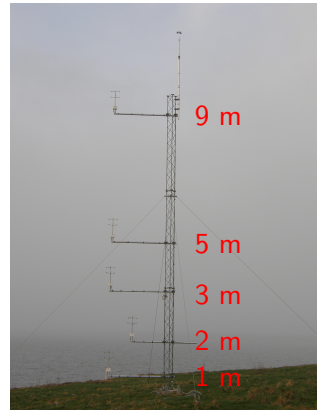
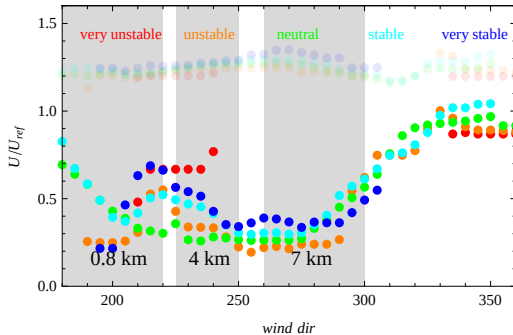
Speed at M2



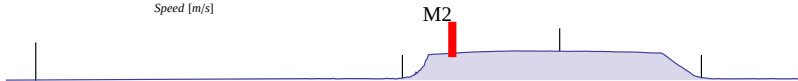
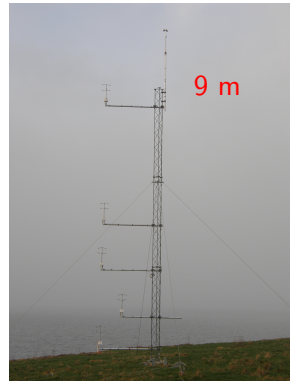
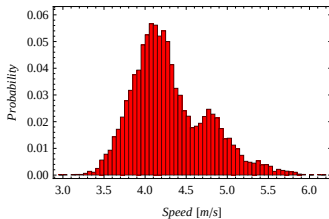
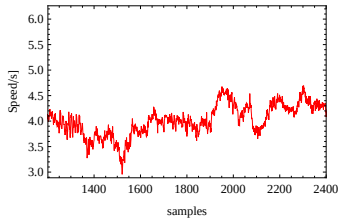
Speed at M2



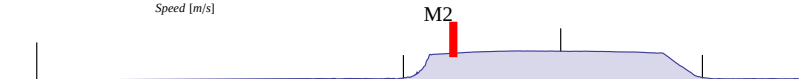
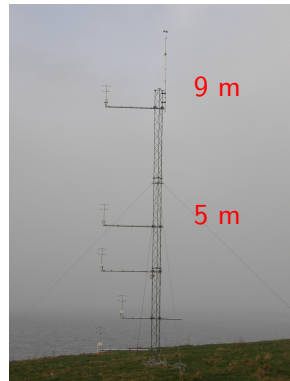
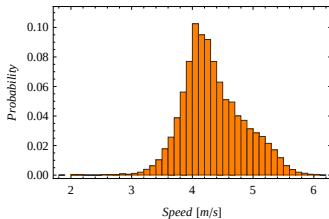
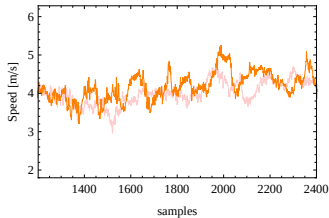
Speed at M2



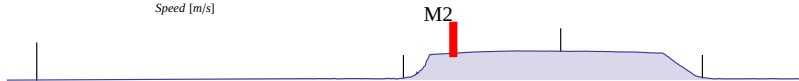
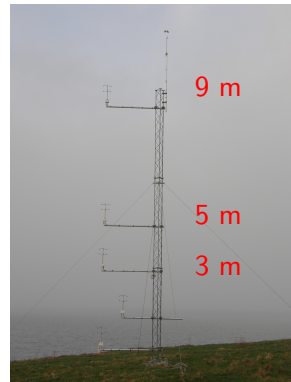
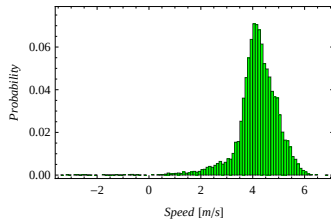
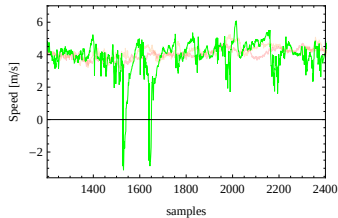
Time Series at M2



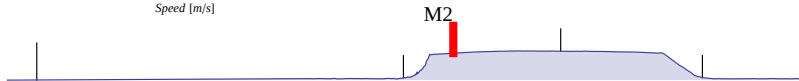
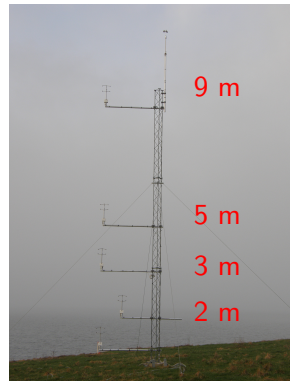
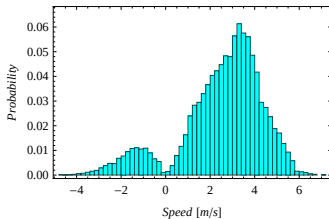
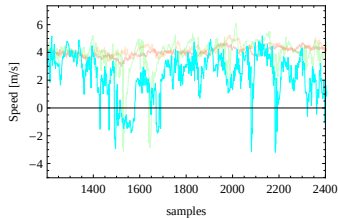
Time Series at M2



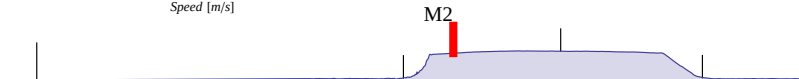
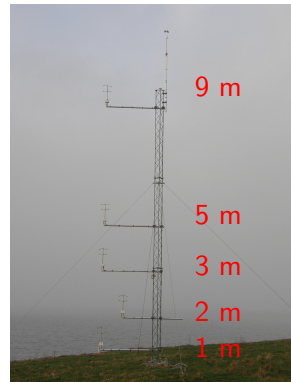
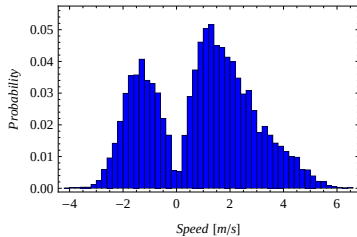
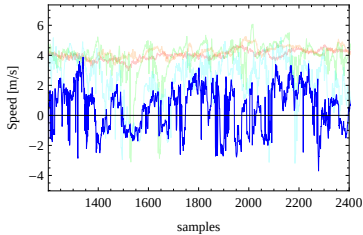
Time Series at M2



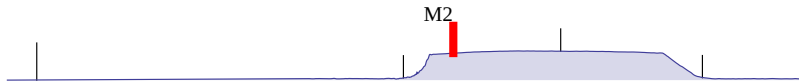
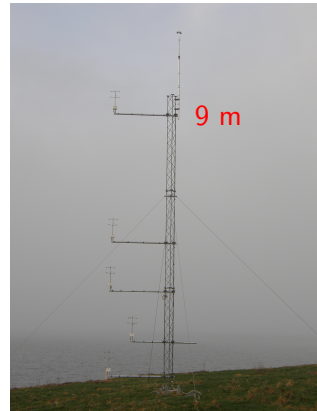
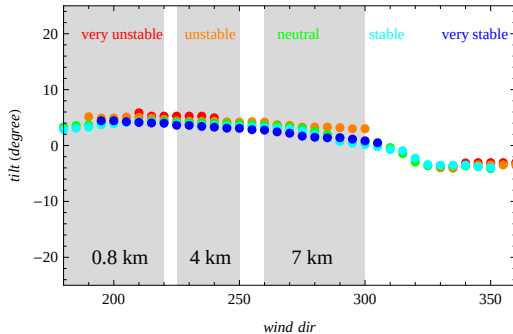
Time Series at M2



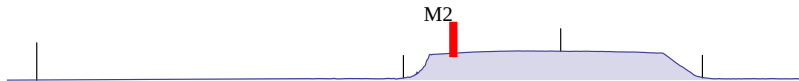
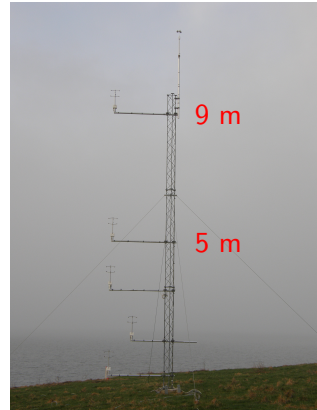
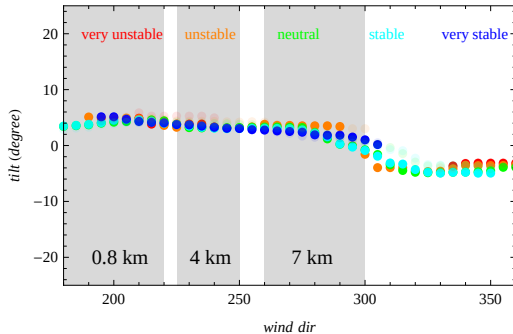
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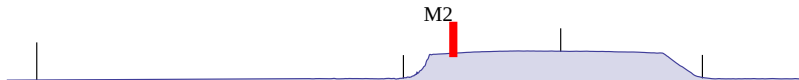
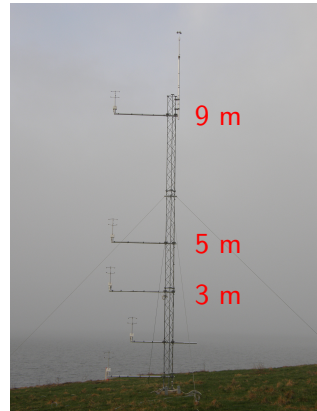
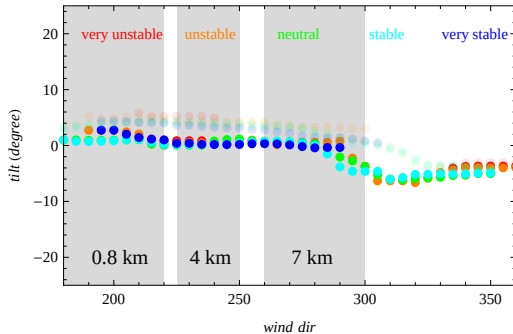
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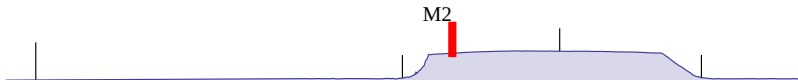
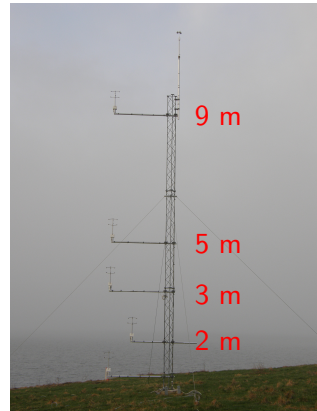
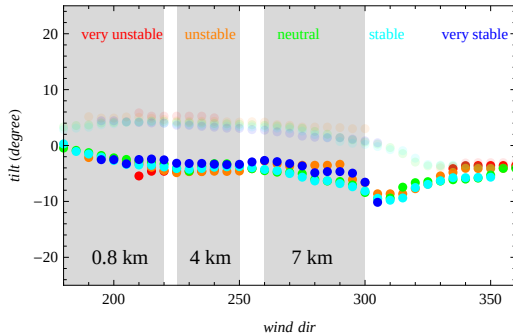
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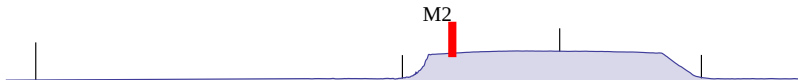
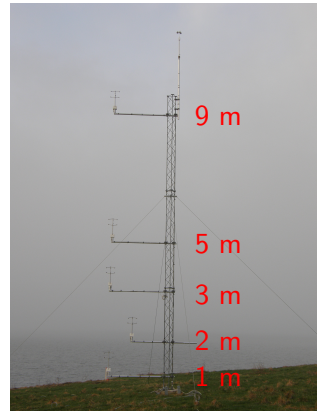
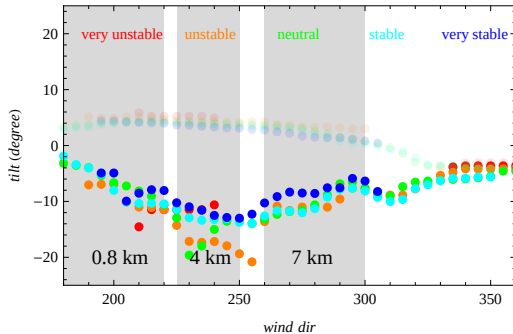
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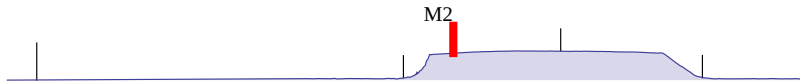
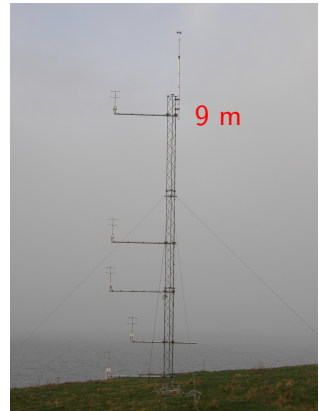
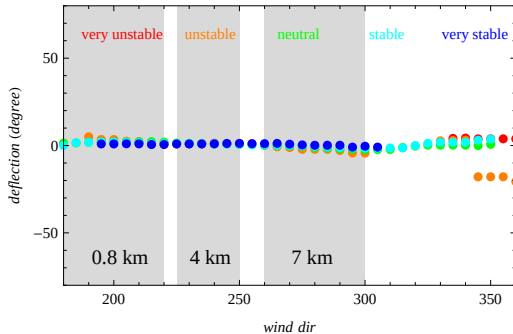
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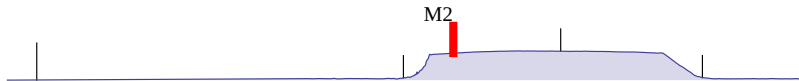
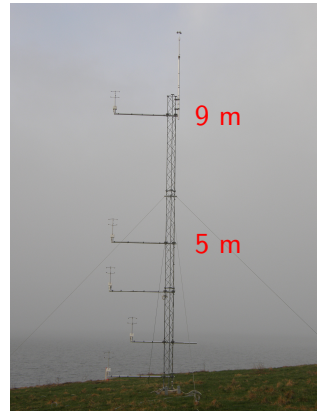
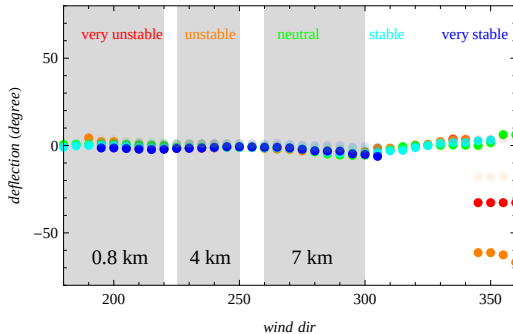
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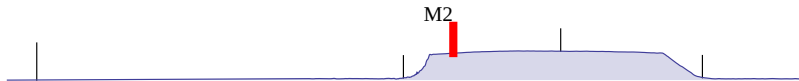
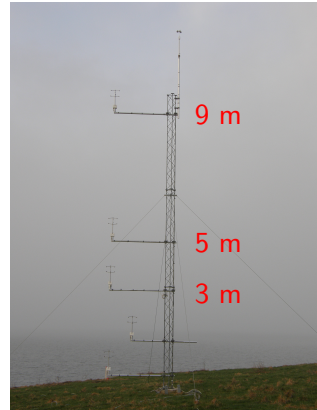
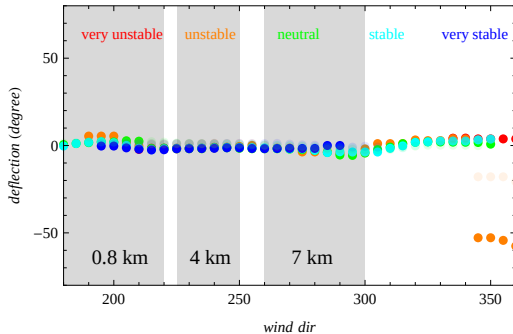
Deflection at M2



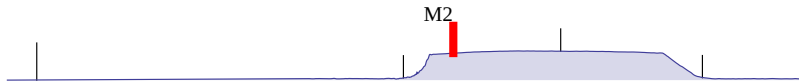
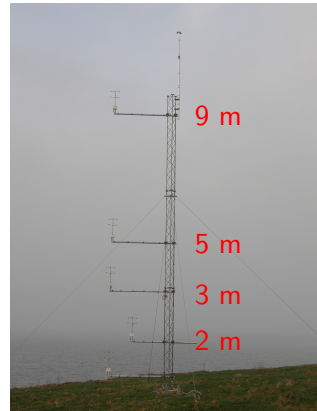
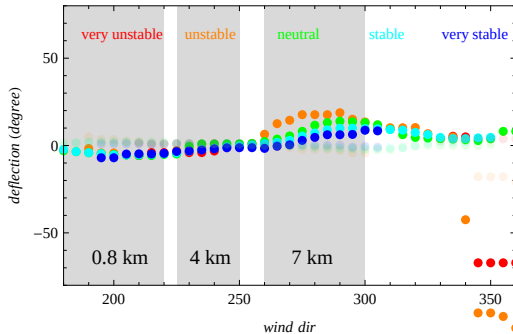
Deflection at M2



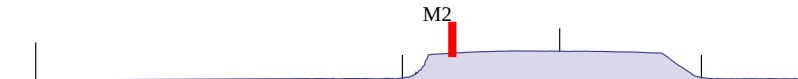
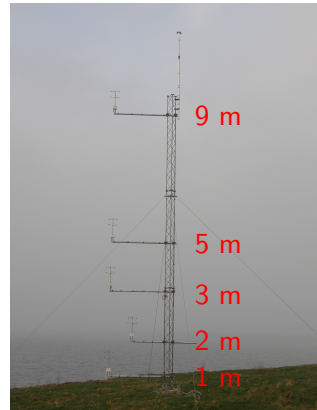
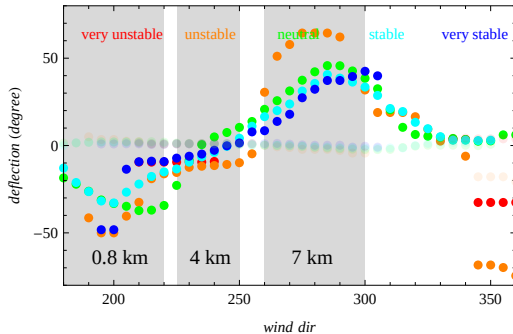
Deflection at M2



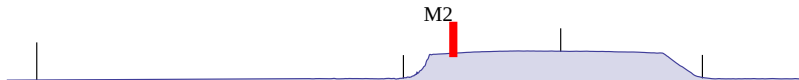
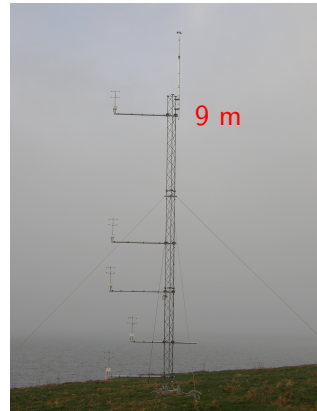
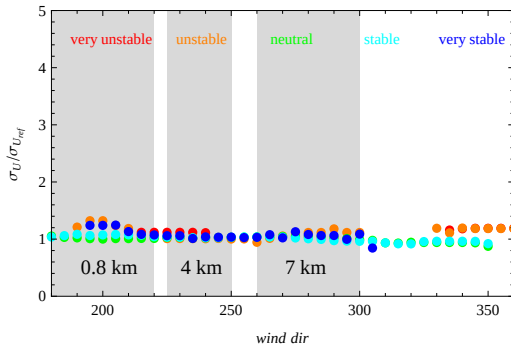
Deflection at M2



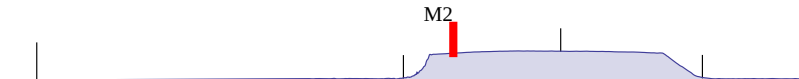
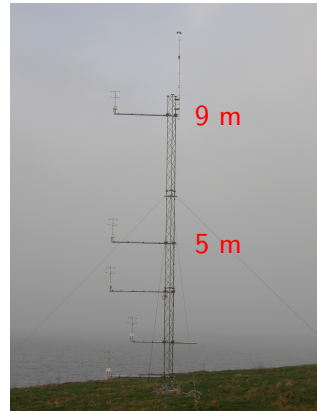
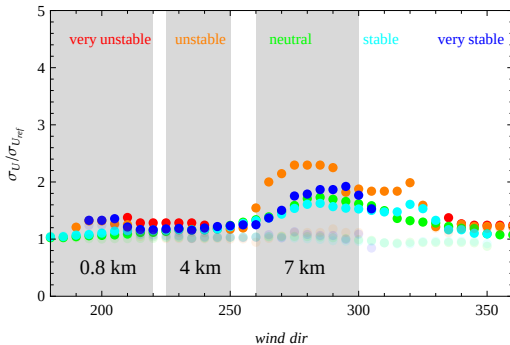
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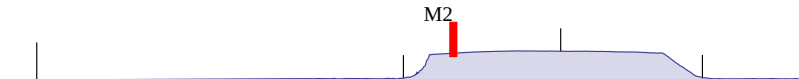
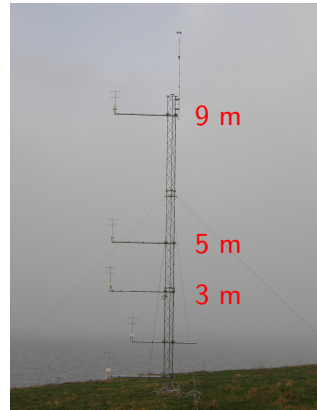
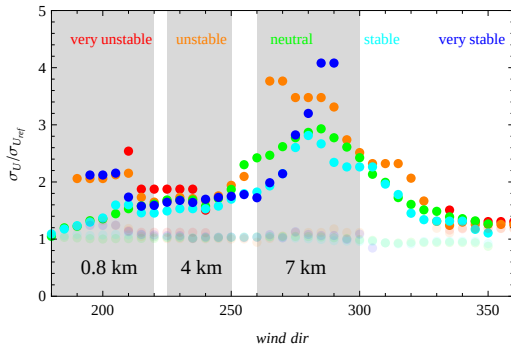
Turbulence intensity at M2



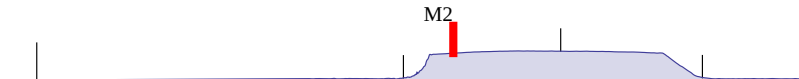
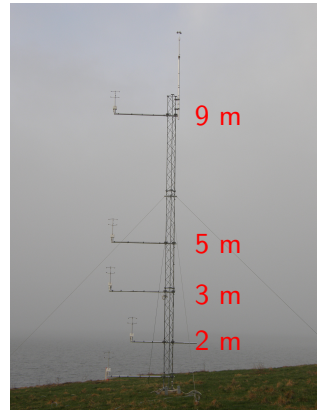
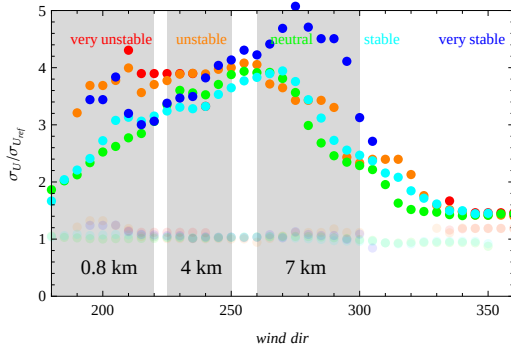
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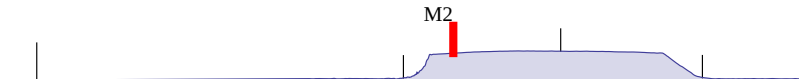
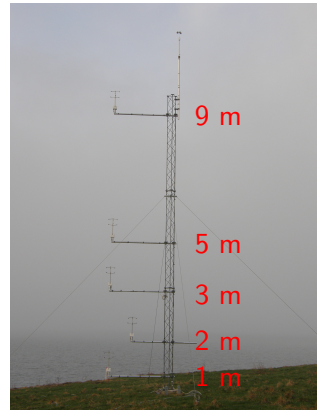
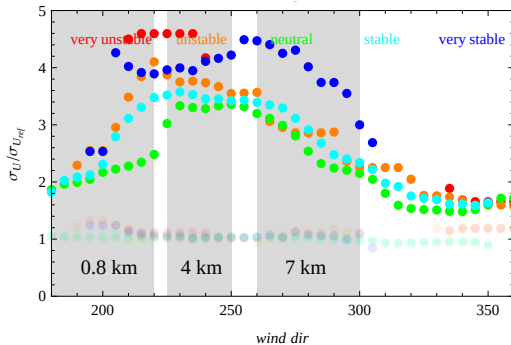
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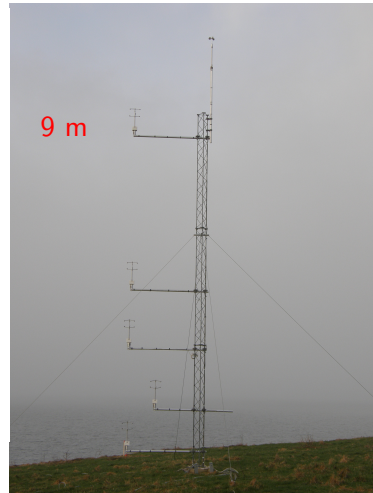
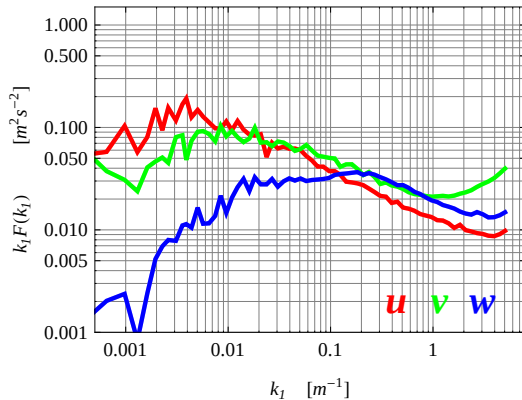
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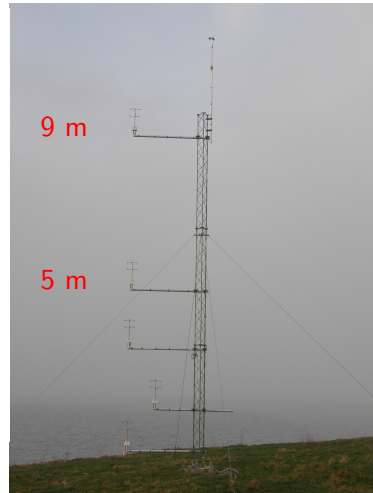
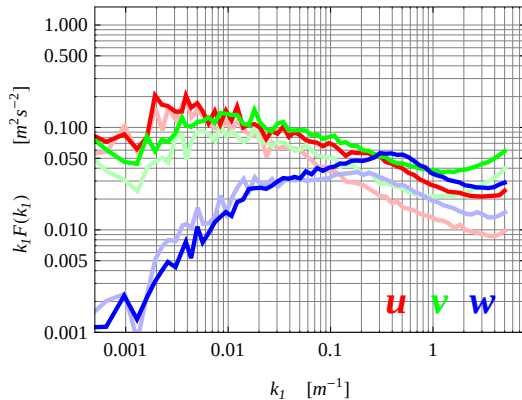
Turbulence spectra at Mast 2 (239 degrees)



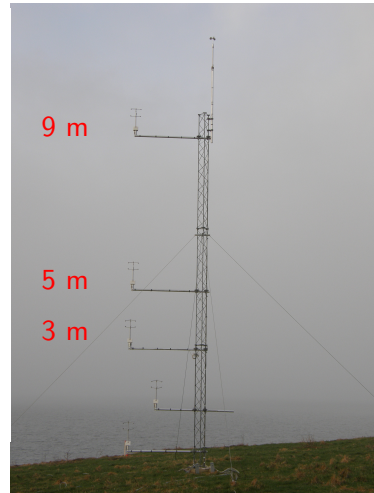
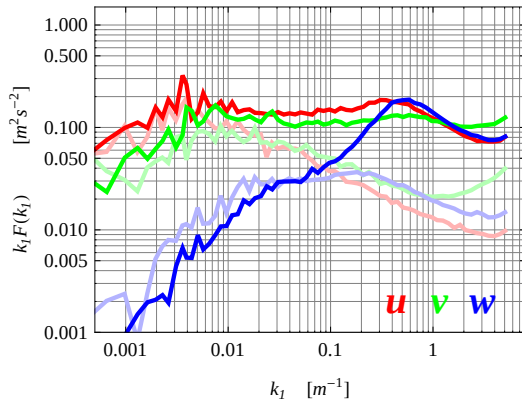
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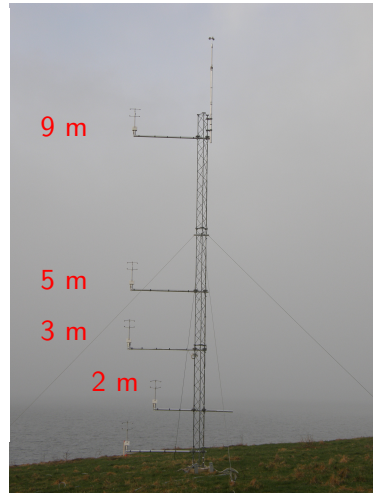
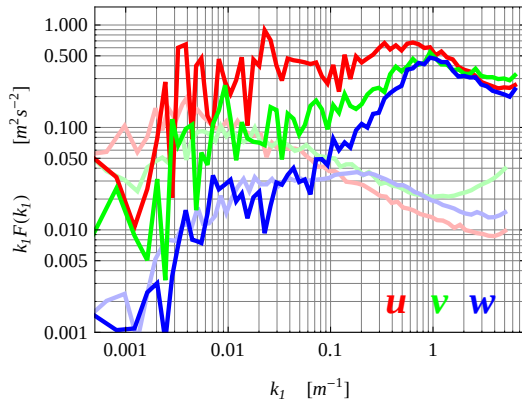
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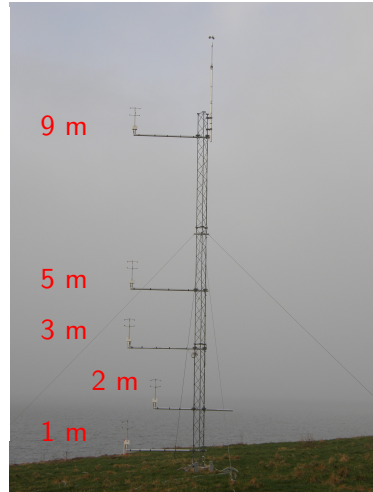
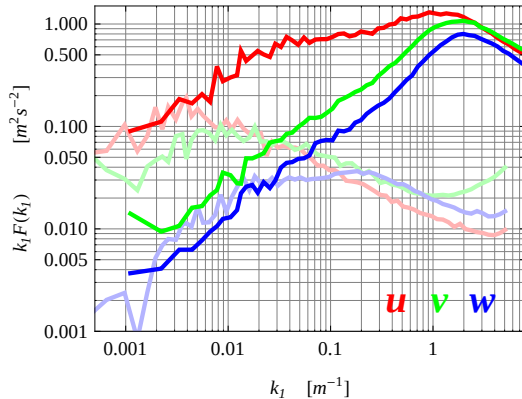
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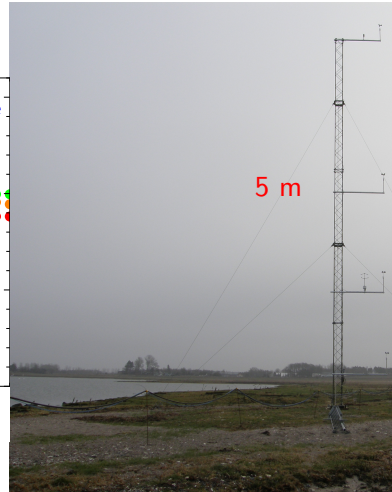
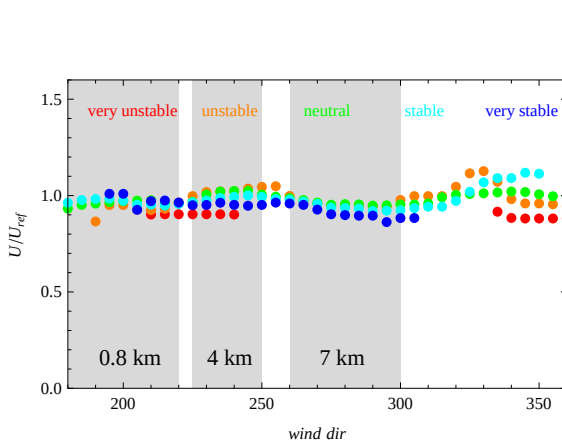
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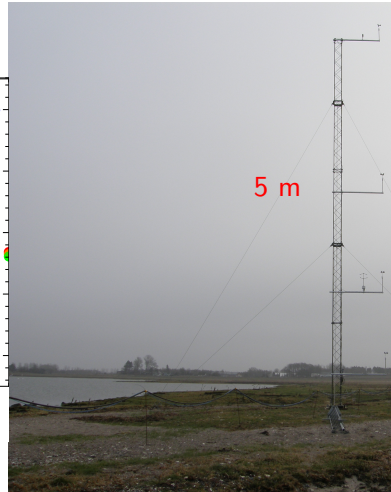
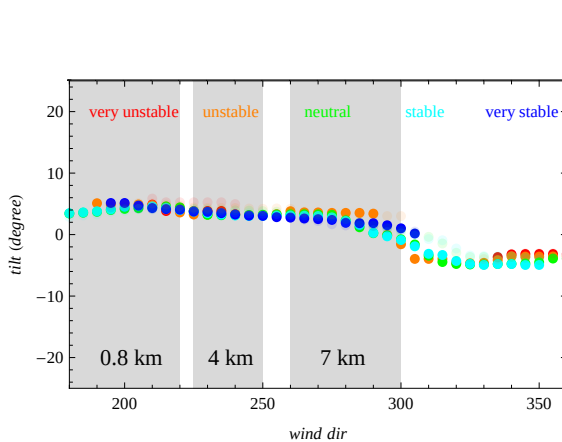
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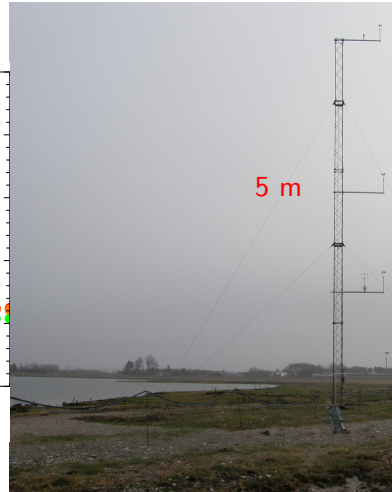
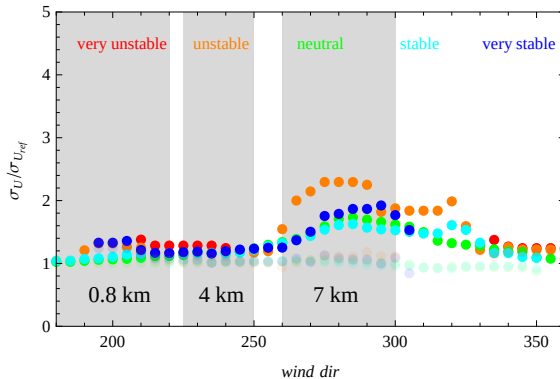
The downstream direction at Mast 9



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- Should we do it over again: Only measurements along one line, but more heavily instrumented