# Highlights from the WINTWEX-W campaign

*Joachim Reuder, University of Bergen; Valerie Kumer, University of Bergen; Benny Svardal, CMR and Jan Willem Wagenaar, ECN*

**Purpose**

A joint measurement campaign between NORCOWE and the Energy Center of the Netherlands (ECN) was performed in the period October 2013 until November 2014 at the ECN test site Wieringermeer in the Netherlands. The main purpose of this campaign was the characterization of the structure and dynamics of single turbine wakes by the extensive use of static and scanning wind lidar systems. A particular focus was set on the investigation of the effect of atmospheric stability on the strength and extension of the wake downstream the turbine. The experiences related to the long term deployment of lidar systems, the setup of data communication links and the development and test of measurement strategies and appropriate scanning patterns, constitute an important intermediate step in the NORCOWE project towards future offshore measurement campaigns.

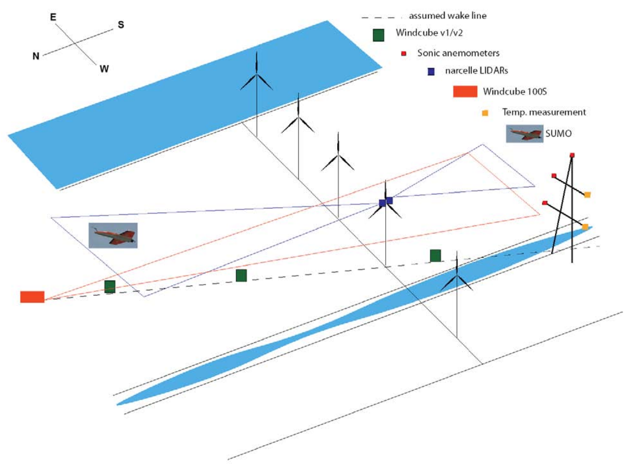


*Figure 1: Schematics of the instrumental setup during the WINTWEX-W campaign*

## Measurement setup

The campaign was mainly based on the extensive use of static and scanning wind lidar technology and the instrumental setup is sketched in Figure 1. In addition to the ECN meteorological 110 m mast, equipped with cup and sonic anemometers, one scanning lidar (Leosphere 100S), four static lidars (Leosphere Windcubes v1 and v2) as well as a downstream looking nacelle lidar (ZephIR 300) were deployed in the period November 2013 until May 2014. The main aim of the campaign was the qualitative and quantitative description of single full-scale wind turbine wake structure, propagation and persistency under various atmospheric conditions. The scanning wind lidar system (Leosphere WindCube100S) was located ca. 12 rotor diameters downstream of one of the wind turbines in the main wind direction. It was repeating a predefined scan pattern every minute, that consisted of a 60° azimuth sector at three different elevations (2.4°, 4.7°, and 7.1°, corresponding to nacelle height and bottom and top tip height close to the turbines) and three vertical cross-sections at a fixed azimuth angle of 228°. Additional static Windcubes v1 measured wind profiles every second at 2 and 4 rotor diameter downstream distances. Two other static WindCube lidars, a forward-looking nacelle LiDAR (Avent) and three


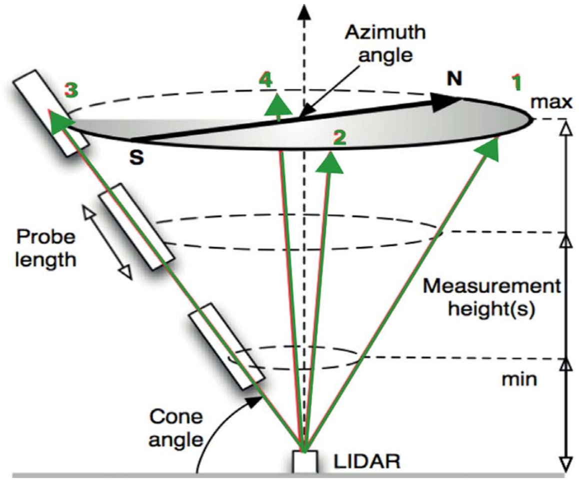


*Figure 2: Measurement principle of static Doppler LiDAR (Windcube v1) Courtesy Valerie Kumer*



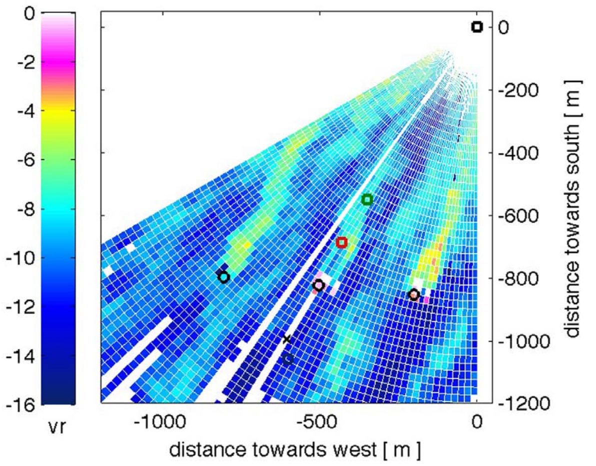


***Figure 3: 60° PPI scan with 4.7° elevation angle cutting through hub hight of the research turbines. Colors show the radial wind speeds measured by the device while circles, squares and a cross indicate the position of the research turbines, the WindCubes and the metmast respectively. Courtesy Valerie Kumer.***

sonic anemometers on the 110 m mast were placed upstream for a detailed characterization of the flow field approaching the wind turbines.

The comprehensive data set collected during the campaign is, at the moment, analyzed by the NORCOWE partners UiB and CMR and by our colleagues from ECN. In addition to the modellers in NORCOWE, several international research groups from outside the consortium have already indicated an interest in using the data for model validation purposes. A few results of the campaign are highlighted in the following sections.

**4D wake mapping with a scanning LIDAR**

An analysis of first horizontal scans of the scanning WindCube 100s shows that we could catch some of the meandering motion of the research turbine wakes, which is induced by adapting the yaw of the turbine to the upstream main wind direction. The wakes extended beyond 10 rotor diameter downstream distances, leaving the intended layout of the measurement campaign. On top of the research turbine wakes we could also catch wakes from the 2 kilometre upstream prototype turbines. Therefore, the wake deficit of the research turbines is varying between 4 and 8 m/s, dependent on whether the wakes are interacting or not (figure 3).

**Measurement of wake effects by the SUMO RPAS**

During the last years NORCOWE has started to include remotely piloted aircraft systems (RPAS) in its portfolio of instrumentation for the investigation of wake effects.
The SUMO system (Small Unmanned Meteorological Observer), a fixed wing aircraft with a length and wingspan of about 80 cm and a total take-off weight of below 700 g, was developed and is owned and operated by GFI/UiB.
In the afternoon of May 10, 2014 the system performed several flights around the wind turbines at the test site in rather strong winds of 15 m/s as 10 minute average and slightly above 20 m/s in gusts. The wind direction was from the Southwest.

Figure 4 shows the results gained during the five flights performed. Presented is the East-West component of the horizontal wind speed (u) for flight legs ca. 1 rotor diameter downstream of the turbine row (position B, upper panel), compared to those for the flight legs upstream (position D; lower panel). The grey curves indicate the individual legs (13 for B and 4 for D) and the blue and orange lines represent the corresponding average values. The upstream background wind level in the u component is around 10 m/s (leg D, bottom panel). One rotor diameter behind the turbines the energy extracted by two of the turbines is documented by a clear reduction in wind speed reaching a maximum of around 3 m/s. The wind speed reduction of each of the turbines about 1 rotor diameter downstream covers a distance of about 150-200 m (one tick on the x-axis corresponds to 100 m).

The SUMO operations during the WINTWEX-W campaign have proven the capability of small and lightweight RPAS to measure wake effects in the vicinity of wind turbines. NORCOWE will continue to intensify the use of such small unmanned atmospheric measurement platforms, in particular for the detailed investigation of wake effects.

**The effect of atmospheric stability on wakes**

Averaging the profiles collected by the WindCubes v1 over a three months period (from November until January) shows similar results as the WindCube 100s with wind speed deficits varying between 4 and 6 m/s. Distinguishing the results between different stability classes reveals that wake deficits and turbulence intensities are strongest during stable atmospheric conditions. As we saw earlier the research turbines

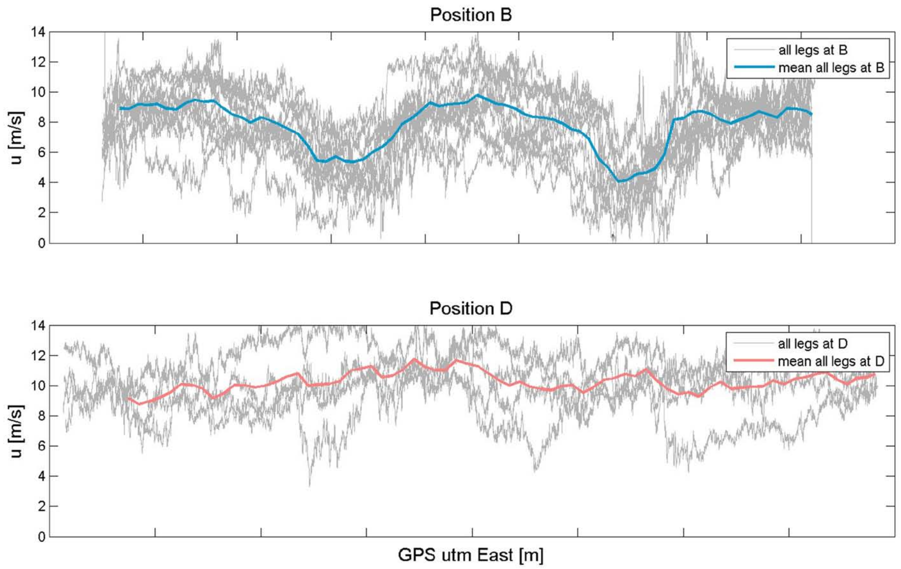


*Figure 4: East-west wind component (u) for flight legs ca. 1 rotor diameter downstream of two of the five turbines at the ECN test site (position B; upper panel), and for flight legs upstream (position D; lower panel). The grey curves indicate the individual legs of the corresponding SUMO flights (13 for B and 4 for D), the blue and orange curve the corresponding averages.*
*Courtesy Line Båserud and Joachim Reuder.*

**Nacelle Lidar wake measurements**

Parallel to the ground Lidar measurements, a ZephIR 300 Lidar with conical scan pattern was installed on the turbine nacelle from November 2013 until November 2014, in order to characterize the wake flow. These measurements are being compared with data from the met mast, ground lidars, and an Avent WindIRIS nacelle Lidar mounted in single-beam rear view mode on the same turbine for part of the project period. First results from the nacelle measurements will be presented at the EWEA Offshore Wind 2015 conference in Copenhagen.

do not face undisturbed upstream flows but are influence by rather far upstream turbines. Therefore, the power output of the research turbine number 6 is altered during stable conditions. Wakes are trapped in a stable atmospheric layer and cannot mix easily with the ambient air as vertical motions are suppressed.





The opposite is happening during unstable conditions, when vertical motions are accelerated, leading to a vertically expanding wake, which recovers almost to upstream conditions at 4 rotor diameters downstream.

During traditionally modeled neutral conditions, wind resources are highest and turbulence intensities are lowest. However, this leads only to an above average power output for wind speeds below 10 m/s, as for higher wind speeds strong vertical wind shear may be an issue.

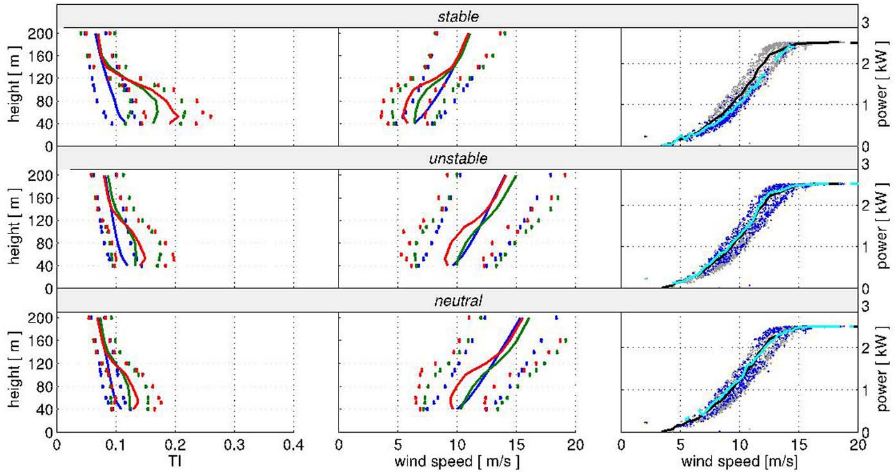


*Figure 5: Profiles of turbulence intensity (TI, left), wind speed (center) and actual power curve for different stability regimes. The solid lines represent the average, the dots in the left and center row indicate the standard deviation. The colors in the left and central panel correspond to the position of the lidar wind profilers (blue : upstream, red : 1.7 D downstream ; green : 3.5 D downstream), while in the right panel grey and black indicates data from the three months period and blue colors show stability dependent data. Courtesy Valerie Kumer.*