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Preliminary results of the NORCOWE Direct Covariance Flux System for Ship based measurements

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Abstract

To cover the increased demand of renewable energy the development of offshore wind turbines that can be placed in deep water has started. Model results from Sullivan et al. [2] indicate that the ocean has the ability to interact with the lower part of the Marine Atmospheric Boundary Layer (MABL). This leads to turbulent horizontal and vertical motions of the air that potentially reduces turbine lifetime and energy reliability. This paper gives a description of the Norwegian Center for Offshore Wind Energy (NORCOWE) direct covariance flux system. Consisting of a sonic anemometer, a state-of-the-art inertial measurement unit (IMU) and a data logger the system can easily be mounted on all floating platforms, e.g. ships or buoys and operates autonomously. This will in the future enable researchers to investigate turbulent motion and turbulent momentum transport processes in the MABL in more detail.

Keywords: Direct covariance flux method, Marine Atmospheric Boundary Layer, Motion correction, Turbulence

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1. Introduction

Offshore wind farms are at the moment predominantly located close to shore and in shallow water. These locations have the advantage that turbines can be mounted on solid jacket or monopole foundations that grant easy turbine access [1]. Due to the increased demand for sustainable energy, turbine manufacturers and wind farm operators have started to investigate the potential of floating wind turbines that can be moored in deep water. One challenge of such an enterprise is that little is known about the turbulent air-sea exchange processes under real offshore conditions. Running a Large Eddy Simulation (LES) Sullivan et al. [2] found indications that the underlying wave field might influence the overlying

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Marine Atmospheric Boundary Layer (MABL) up to turbine hub height [1]. The development of offshore wind farms in deep water requires better understanding of the turbulent air-sea exchange processes in the MABL. Up to today, most research measurement sites are located close to the shore line on small islets as these sides are cheap to operate and are easy accessible. For real offshore conditions only a few sporadic offshore measurement sites are available in shallow waters, e.g. the German FINO platforms or the US Air-Sea Interaction Tower at Martha's Vineyard [1]. In deep water, measurements of the turbulent air-sea fluxes require the use of ships or buoys as measurement platform. This has the disadvantage that flux measurements in deep water are mostly taken only during research cruises in a specific time window and that no continuous data sets are available. In the present paper, we present preliminary results from an offshore deployment of the Norwegian Center for Offshore Wind Energy (NORCOWE) direct covariance flux system.

2. Background

For deep water deployments, turbulent flux measurements have to be performed on non-stationary platforms, such as ships and buoys. Consequently, platform motion and flow distortion will contaminate the measurements and a motion correction is needed to determine the turbulent fluxes and corresponding air-sea exchange processes as accurate as possible. In general, four different methods can be used to obtain those data sets from floating platforms [3]:

- the profile method
- the bulk aerodynamic method
- the inertial dissipation method
- the direct covariance flux method.

The first three methods determine turbulent fluxes indirectly and give only an estimate of the momentum and heat fluxes at the sea surface [4]. Exact measurements of the turbulent air-sea fluxes can only be obtained by the direct covariance flux (DCF) method. The method is widely applied to flux measurements over land and is now used by many research groups for measurements from floating platforms due to cheaper and improved technical instrumentations. The principle for DCF measurements from floating platforms was for the first time described by Fujitani [5] and has since been adapted by many other research groups, i.e. Edson et al. [4], Miller et al. [6] and Brooks [7]. For investigation of momentum and heat fluxes the basic idea is that high frequency (20 Hz) wind measurements are sampled with a sonic anemometer in the floating platform frame of reference. An inertial measurement unit (IMU) is attached close to the flux instrumentation and record platform accelerations and the platforms attitude, i.e. roll, pitch and yaw angles for gyro stabilized systems and angular rates for strapped down systems. Following Edson et al. [4] the IMU output is used to transform the wind velocities from the platform frame to the earth frame by

$$\boldsymbol{U}_{true} = \boldsymbol{T}(\boldsymbol{U}_{obs} + \boldsymbol{\Omega}_{obs} \times \boldsymbol{R}) + \boldsymbol{V}_{mot} \tag{1}$$

where $\boldsymbol{U}_{true}$ is the desired wind velocity vector in the reference coordinate system, $\boldsymbol{U}_{obs}$ is the measured wind velocity vector in the platform frame of reference, $\boldsymbol{T}$ is the coordinate transformation matrix for a rotation of the platform frame coordinate system to earth frame coordinates, $\boldsymbol{\Omega}_{obs}$ is the angular velocity vector of the platforms reference frame, $\boldsymbol{R}$ is the position vector of the wind sensor with respect to the motion package (IMU), and $\boldsymbol{V}_{mot}$ is the translational velocity vector of the platform with respect to the fixed earth frame [1],[4]. In a strapped down system the integrated angular rates and accelerometer output is used to obtain the platform attitude angles which are needed for the transformation matrix $\boldsymbol{T}$. Furthermore, the accelerometer outputs are transformed into earth frame and integrated to obtain the wave induced motion of the sonic anemometer [4]. This translational velocity is then added to the transformed wind velocities recorded by the sonic anemometer to gain the true wind velocities relative to earth. If the platform is in motion during the measurements, i.e. steaming ship, the platforms velocity relative to earth has to be added to equation (1). Today, these velocities are generally provided by differential GPS. A complete description of the motion correction algorithm principle for DCF systems can be found in Edson et al. [4], Schulz et al. [7] and Miller et al. [6].

3. The NORCOWE Direct Covariance Flux System

The Norwegian Center for Offshore Wind Energy (NORCOWE) owns two state-of-the-art DFC systems. The systems were built in 2010 in cooperation of the air-sea interaction group of the University of Ireland, Galway and consists of the three main components, a sonic anemometer, an inertial measuring unit (IMU) and a data logger (figure 1).

3.1. Sonic anemometer

Wind measurements are taken with a Gill R3A-100 sonic anemometer with a sampling frequency up to 100 Hz. The sonic anemometer has three pairs of transducers that act as both transmitter and receiver. An ultrasound pulse is send between each pair and the travel time of the ultrasound pulse can be computed by

$$T_1 = \frac{L}{C+U} \; and \;\; T_2 = \frac{L}{C-U}, \tag{2}$$

where T_1 is the transit time of the forward ultrasound pulse, T_2 is the transit time of the backward ultrasound pulse, L is the distance between corresponding transducers, C is the speed of sound and U is the wind speed between the two transducers. Mathematical manipulation leads to the wind speed along one transducer pair axis

$$U = 0.5L\left(\frac{1}{T_1} - \frac{1}{T_2}\right). \tag{3}$$

The mathematical expression for the speed of sound can be found in a similar manner

$$C = 0.5L\left(\frac{1}{T_1} + \frac{1}{T_2}\right). \tag{4}$$

Combining equation *(3)* and *(4)* gives the sonic temperature

$$T_S = \frac{L^2}{1612}\left(\frac{1}{T_1} + \frac{1}{T_2}\right)^2 \tag{5}$$

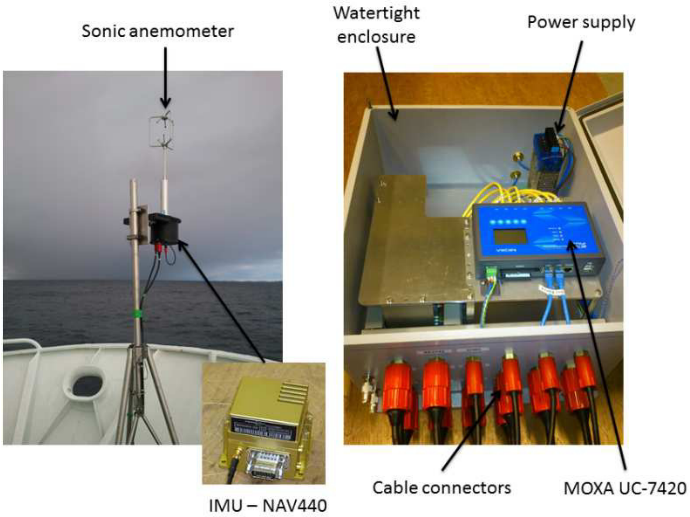

Figure 1: The NORCOWE direct covariance flux systems sensor head mounted on a tripod aboard R/V Håkon Mosby during a research cruise in November 2012. The IMU is mounted in a watertight housing directly below the anemometer (left panel). The power supply unit and the MOXA data logger are located in a watertight enclosure that can be mounted on any frame or on the floor below the sensor head (right panel).

that differs only slightly from the virtual temperature T_V. The sonic anemometer therefore provides us with all necessary information to directly compute heat and momentum fluxes. The anemometer also correct for crosswinds normal to the path of sound and high frequency measurements enable to measure the turbulent wind and temperature fluctuations. The wind velocity and temperature time series can be split into a mean component and turbulent fluctuation:

$$U = \bar{U} + u', \quad V = \bar{V} + v', \quad W = \bar{W} + w' \quad and \quad T = \bar{T} + T'. \tag{6}$$

The relevant fluxes of momentum (M) and heat (H) can then be determined directly from the corresponding co-variances as:

$$M_{xz} = -\bar{\rho}\overline{u'w'_s}, \quad M_{yz} = -\bar{\rho}\overline{v'w'_s} \quad and \quad H = \bar{\rho}C_p\overline{w'T'_s}. \tag{7}$$

3.2. Inertial Measuring Unit – NAV440

The inertial measurement unit (IMU) used in the system is a Crossbow NAV440 that is located in a watertight housing collinear below the sonic anemometer. The unit consists of three pairs of accelerometers and angular rate sensors that provide the user with three-axis accelerometer and angular rates measurements up to 100 Hz. An internal routine integrates the attitude and accelerometer sensor output to provide the user with roll, pitch and yaw angles in addition to the translational velocity fluctuations sensed by the accelerometers. Magnetometer and GPS aiding sensors are used with an extended Kalman filter to correct for sensor drift. Additionally, the GPS also provides position and GPS velocity data relative to the earth frame. Applying an internal coordinate transformation, the NAV440 provides the user with all necessary velocity information in the earth frame of reference needed for the correction of the sonic anemometer measurements. The attitude output data can directly be used in the transformation matrix $\boldsymbol{T}$ of equation *(1)* to yield the corrected wind velocity measurements

$$\boldsymbol{U}_{true} = \boldsymbol{T}(\boldsymbol{U}_{obs} + \boldsymbol{\Omega}_{obs} \times \boldsymbol{R}) + \boldsymbol{V}_{IMU} \tag{8}$$

where $\boldsymbol{V}_{\mathrm{IMU}}$ is the velocity obtained from the integrated accelerometers aided by the platforms GPS velocity over ground in earth frame.

3.3. Data logger

The data logging and control unit of the system is a MOXA UC-7420 industrial RISC-based LINUX computer. The unit has 8 serial ports and an interface for WLAN communication. One CompactFlash (CF) card slot and two USB2 ports are available for external storage of the recorded data from the instruments. An internal routine synchronize the anemometer and the IMU to UTC at each full hour and compresses data files to save disk space on the logger. A copy of all recorded data is send to an external filed PC by use of WLAN. Recording the data to both CF-card and an external field PC ensures that no data is lost if something happens to the instrumentation. This also provides a convenient possibility to check the data on the external field PC directly after recording, thus enabling us to make adjustments to the system during i.e. a field campaign.

The entire system is powered by either 230 V AC or 12 V DC. Both MOXA and the power supply unit are located in a watertight enclosure that is connected to the sonic anemometer and the IMU by two 6 m long cables. Depending on the research platform the enclosure can be attached to a mast or mounted on the floor. The sensor head consisting of the anemometer and the IMU can easily be attached to any kind of frame, i.e. ships railing, tripod or mast.

4. System performance

In this section we present first results describing the system performance during a recent research cruise outside Bergen, Norway, aboard R/V Håkon Mosby. The cruise took place between November 28th and November 30th where the system had its first offshore deployment. The system sensor head was mounted on a tripod directly at the vessels front bow and the sonic anemometers north spar and the IMU’s north side were pointing forward. The IMU’s coordinate system has been rotated prior to the following data analysis to coincide with the anemometers coordinate system. After the IMU coordinate rotation, the positive U-axis is pointing forward away from the vessels bow, the positive V-axis is pointing to the vessels port side and the positive W-axis is pointing upward for both instruments. If winds were blowing from the north and the vessel would have steamed directly northwards the sonic anemometer would have registered a negative U-component in the anemometer’s frame of reference and the IMU’s yaw angle would have shown a heading of 0º. Data have been recorded with a sampling frequency of 50 Hz during the entire cruise. Note that spikes in the IMU and anemometer data have been removed and the resultant missing data has been interpolated before the data analysis. An example for raw data of the attitude angles and the platforms velocity components in earth frame provided by the IMU is shown in figure 2 and figure 3.

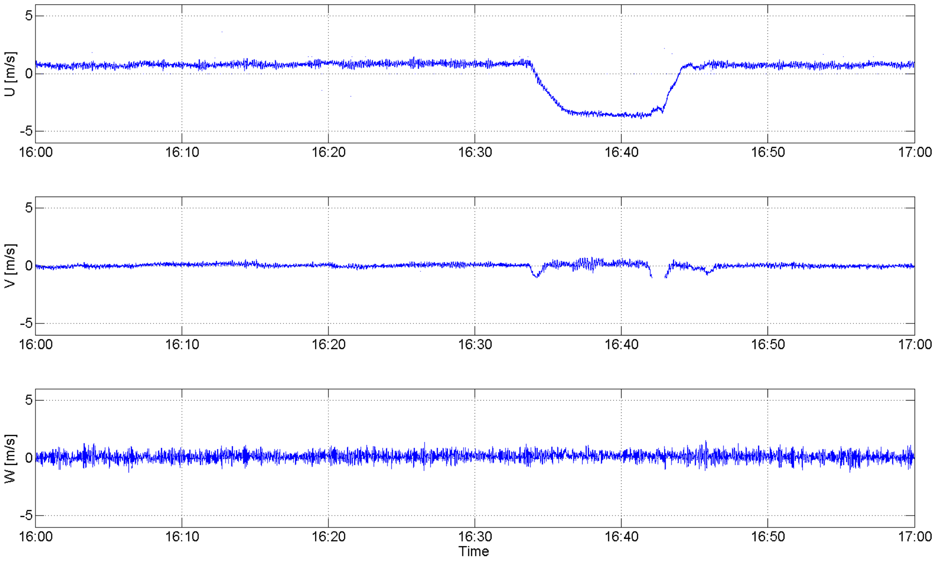

Figure 2: IMU output of corrected velocity components in earth frame. The IMU was mounted below the sonic anemometer at the front bow of R/V Håkon Mosby. Data have been recorded at November 29th 2012 during a research cruise outside Bergen, Norway.

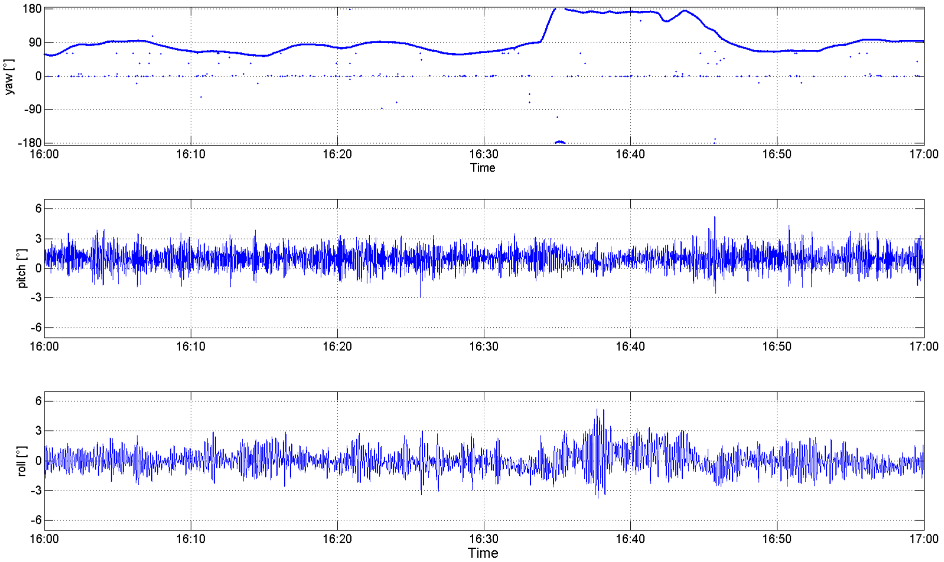

Figure 3: Attitude angles in earth frame computed from integrated IMU angular rate sensor output. The IMU was mounted below the sonic anemometer at the front bow of R/V Håkon Mosby. Data have been recorded at November 29th 2012 during a research cruise outside Bergen, Norway.

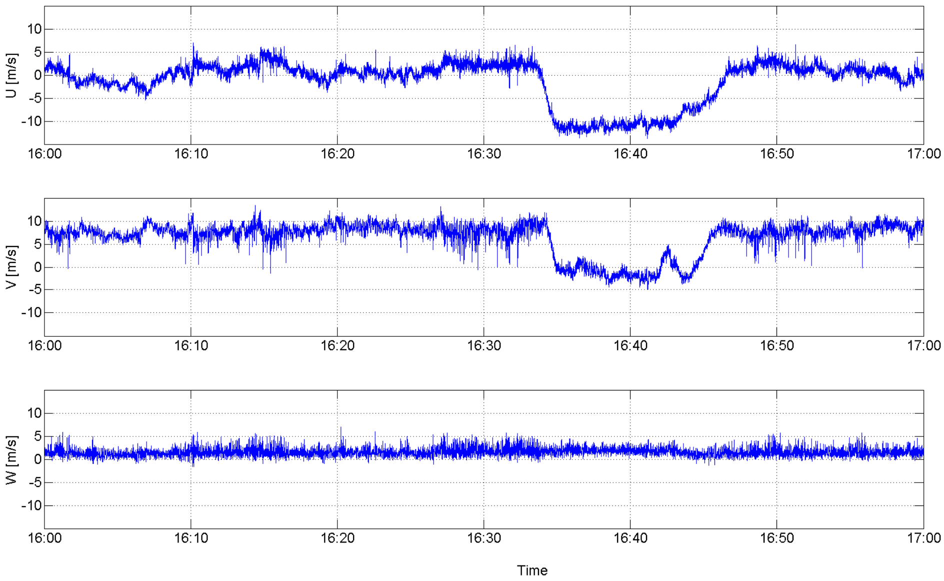

Figure 4: Uncorrected (in anemometer frame) wind components recorded by the sonic anemometer mounted at the front bow of R/V Håkon Mosby. Data have been recorded at November 29th 2012 during a research cruise outside Bergen, Norway.

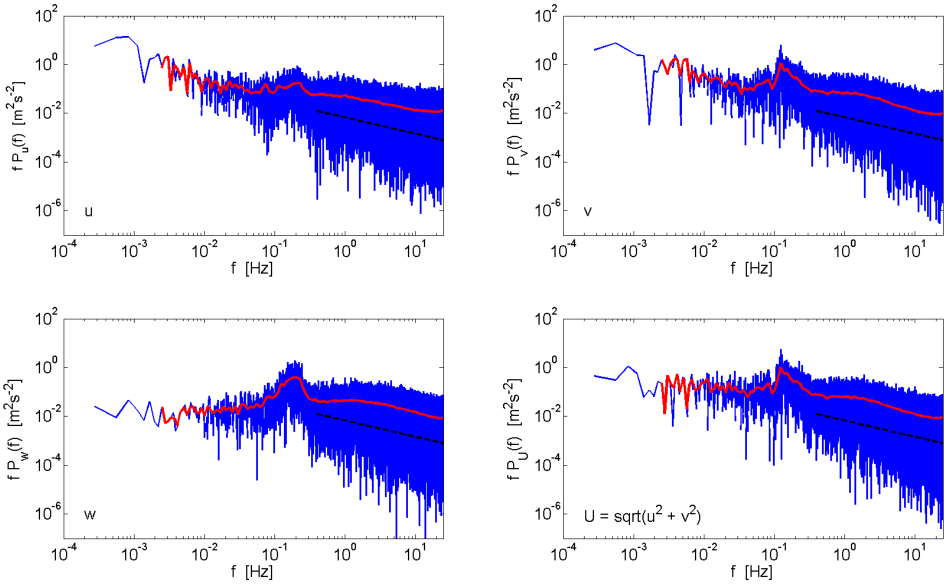

Figure 5: Power spectra of the uncorrected wind components recorded from the sonic anemometer mounted at the front bow of R/V Håkon Mosby. Upper panel: longitudinal (u) and lateral (v) velocity components relative to the vessel. Lower panel: vertical (w) velocity component and spectra of the horizontal wind vector (U). The dashed line indicates the theoretically expected -2/3 slope in the inertial subrange. Data have been recorded at November 29th 2012 during a research cruise outside Bergen, Norway.

Between 16:00 h and 16:35 h on November 29th the vessel was steaming in an approximately east-northeastward direction at low speed (≈ 1.5 knots) with southerly winds of 6 m/s to 10 m/s blowing almost perpendicular to the starboard side. The IMU recorded a northward velocity component of approximately 1 m/s and an eastward component close to zero in earth frame (figure 2). Even though the vessel had a north-northeastward heading that would imply a larger V-component the ship log shows that the vessel moved northwards. This indicates that the moderate southerly winds pushed the vessel northwards as it had only a very low eastward velocity. During this measurement period the uncorrected sonic velocity components (figure 4) show a positive wind between 6 m/s and 10 m/s for the lateral (v-velocity) component of the anemometer while the longitudinal (u-velocity) component varies between -5 m/s and 5 m/s depending on the ships heading relative to the southeasterly to southwesterly wind directions. Between 16:35 h and 16:45 h ship maneuvers were carried out as the vessel turned towards a southerly heading with a speed of ≈ 7 knots (figure 3). The IMU data in figure 2 clearly show the increase of the longitudinal velocity component from 1 m/s (northward velocity) to -3.5 m/s (southward velocity). At 16:42 h the vessel turns towards a southeasterly heading and the corresponding lateral velocity component changes accordingly. The vessels maneuver can also be clearly seen in uncorrected velocity components of the sonic anemometer in figure 4. The lateral velocity component decreases from 10 m/s to -1 m/s while the longitudinal component increases from 1 m/s to -10 m/s as the vessels changes from a easterly towards a southerly heading. Most of the vertical velocity components in figure 4 are positive and indicate upward blowing winds. Due to the sensor heads location directly above the front bow we suggest that flow distortion might have occurred, thus deflecting the vertical wind components as the wind hit the vessels bow. The raw power spectra of the wind velocity components recorded from the sonic anemometer are shown in figure 5 for completeness. The inertial subrange has been resolved by the 50 Hz measurements and wave induced motions of the ship can be seen by the peak between 0.1 Hz and 0.2 Hz. Enhanced turbulent kinetic energy due to flow distortion can be seen in the inertial subrange of the lateral and vertical velocity spectra where the spectrum is not closely following the theoretically -2/3 curve between 1Hz and 10 Hz.

5. Summary

The Norwegian Center for Offshore Wind Energy Covariance Flux System was built in 2010 and has since then undergone a series of laboratory and field tests. The first offshore deployment of the system took place in November 2012 during a research cruise outside Bergen, Norway. First results from this offshore deployment show that the system is able to provide the user with all necessary attitude and velocity information needed to correct measurements from the sonic anemometer for platform motion. The system only provides records of angular rates and accelerations if the IMU's GPS lock is poor or lost. In this case the motion correction has to be done "manually" by applying the motion correction procedure of Edson et al. [4]. The system is easy to transport and can be mounted on any kind of platform such as moored buoys in wind farms. Equipped with WLAN, recorded data can be sent directly to the researches office for a data analysis. Being state-of-the-art the system can easily be extended with i.e. differential GPS, open and close path LICOR's or radiation sensors.

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