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Sensor movement correction for direct turbulence measurements in the marine atmospheric boundary layer

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Abstract

Understanding of the turbulent exchange processes between the ocean and the overlying atmosphere is essential for wind shear and turbulence structure of the Marine Atmospheric Boundary Layer (MABL). This is highly relevant for the development of offshore wind projects with respect to the expected power output and acceptable structural loads and fatigue of turbines. This paper presents preliminary results from a recent field experiment off the coast of Martha's Vineyard, Massachusetts. Turbulent fluxes have been measured from both a discus buoy and the Air Sea Interaction Tower (ASIT). Using the correction algorithm of Edson et al. (1998) the buoy data are corrected and compared with the ASIT measurements. The comparison shows that the corrected fluxes measured from the mooring are in good agreement with measured fluxes from the tower and that the direct covariance flux method is applicable for offshore turbulent flux measurements.

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

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1. Introduction

In recent years the development of deep water offshore wind farms has begun. Until today, offshore wind turbines are placed in relatively shallow water with a jacket or monopile foundation. With the introduction of new technologies and the need for more sustainable energy wind farms will be placed further offshore in the next years. One of the main challenges in offshore wind energy is to gather a better understanding of the turbulent interaction processes in the Marine Atmospheric Boundary Layer. Model results from Sullivan et al. (2008) [1] indicate that ocean surface waves clearly influence the lower part of the MABL up to altitudes relevant for offshore wind turbines. Direct turbulence measurements will distinctly improve the understanding of the turbulent momentum transfer in the lower atmosphere and the corresponding exchange processes with the sea surface. This is of outermost importance for offshore wind

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with respect to tolerable structural turbine loads and fatigue. Offshore turbulence measurement remain expensive and only a few continuous air-sea interaction data sets (table 1) are available, e.g. the German FINO platforms. The direct covariance flux method is the only direct method for the determination of turbulent fluxes ([2], [3], [4]). The method is widely used over land but corrections for platform motion and flow distortion need to be applied when it is used from moving platforms. Direct covariance flux measurements from offshore towers in shallow waters need no motion correction but flow distortion from the tower structure is likely to be introduced in the data set. Turbulence measurements in deep water can be taken from ships and buoys. The former method has the advantage of a continuous power supply for the instruments but ships need to be on a steady course turned into the mean wind direction during the measurement period and flow distortions from the ship's bow might influence the measurements (e.g. Edson et al., 1998 [5]). In recent years buoys became more popular for investigation of the turbulent air-sea interactions. Reduced flow distortion make buoys to an ideal platform for direct covariance flux measurements. The covariance flux sensors are mounted on a small tower a few meters above the water line and the sensors are turned into the upwind direction by the buoys vane [6]. Generally, data gathered from ships and buoys are contaminated by platform motions that have to be removed before the measurements are transformed into a reference coordinate system.

Table 1. Overview of scientific meteorological towers close to the coast line equipped with direct covariance flux sensors. Note that the research at Meetpost Noordwijk platform ended January 1, 2004.

Tower name	Location	Nation
FINO	North Sea \ Baltic Sea	Germany
ASIT	Martha's Vineyard, MA – North Atlantic	USA
FLIP	Floating Platform, CA – North Pacific	USA
Östergarnsholm	Östergarnsholm – Baltic Sea	Sweden
Skipheia	Frøya – Norwegian Sea	Norway
M2	Horns Rev – North Sea	Denmark
Meetpost Noordwijk platform	North Sea	Netherlands

2. Background

2.1. Theory

The motion correction algorithm applied in the present study follows Edson et al. (1998) [5] and is originally based on Fujitani (1981) [7]. The true velocity of a moving platform can be estimated by their equation (4)

$$\boldsymbol{V}_{true} = \boldsymbol{T}\boldsymbol{V}_{obs} + \boldsymbol{\Omega} \times \boldsymbol{T}\boldsymbol{M} + \boldsymbol{V}_{CM} \qquad (1)$$

where $\mathbf{V}_{\mathrm{true}}$ is the desired wind velocity vector in the reference coordinate system, $\mathbf{V}_{\mathrm{obs}}$ is the measured wind velocity vector in the platform frame of reference, $\mathbf{T}$ is the coordinate rotation matrix for a rotation of the platform frame coordinate system to the reference coordinates, $\mathbf{\Omega}$ is the angular velocity vector of the platform coordinate system, $\mathbf{M}$ is the position vector of the wind sensor with respect to the center of gravity, and $\mathbf{V}_{\mathrm{CM}}$ is the translational velocity vector at the center of motion of the platform with respect to a fixed coordinate system [5]. By applying a digital filtering approach based on complimentary filtering, the true wind velocity in Earth frame measured from the moving platform can be estimated by

$$\boldsymbol{U}_{true}^{earth} = \boldsymbol{T}(\boldsymbol{U}_{obs} + \boldsymbol{\Omega}_{obs} \times \boldsymbol{R}) + \boldsymbol{V}_{hp} + Lp[\boldsymbol{V}_{GPS}] \tag{2}$$

where $\mathbf{V}_{\mathrm{hp}}$ are the high pass filtered platform velocities and $\mathbf{V}_{\mathrm{GPS}}$ is the platform velocity relative to earth and Lp represents a low-pass filter operator [5]. The last term in equation (2) is only required for ship based measurements to filter out the low frequency velocity components added by ship maneuvers. A detailed description of the motion correction algorithm applied in the present study can be found in Edson et al. (1998) [5].

2.2. Campaign

In spring 2010 a discus buoy has been moored in approximately 600 meters distance from the Air Sea Interaction Tower (ASIT) at Martha's Vineyard Coastal Observatory (MVCO), Massachusetts. The ASIT is located 3.2 km off Martha's Vineyards south beach in a water depth of 15 m [8]. Both tower and buoy have been equipped with a DCFM system and measurements of the turbulent air-sea fluxes at low wind speeds have been performed between April 13 and June 29, 2010 (day 103 – 180). The main instrument of the DCFM system was a Gill R3 sonic anemometer with an operation height of 4 m above mean sea level on both the buoy and tower. An Inertial Measurement Unit (IMU) with accelerometers has been attached to the buoy to keep track of the platforms attitude, i.e. pitch, roll, yaw and translational velocities. The accelerometer output is used in post processing to correct the measured wind speeds at the buoy that have been contaminated by platform motions. Measurements from the ASIT do not need any motion correction but need to be limited to predefined wind directions to avoid flow distortion induced from the mast itself. In the present paper the buoy data are post processed by the correction algorithm of Edson et al. (1998) [5] and compared with the measurements from the ASIT.

3. Preliminary results

The data from the sonic anemometer at the buoy and ASIT were used to compute the turbulent momentum fluxes by means of the direct covariance (DC) and the bulk aerodynamic method. Before the computation of the covariances the measured and corrected velocities at the buoy and ASIT (uncorrected) have been rotated into the mean wind direction and the friction velocity is computed for the along wind direction by

$$u_* = \sqrt[4]{(u'w')^2} \ . \tag{3}$$

Due to the rotation of the measured velocities into the mean wind the vertical momentum flux in the cross wind direction is negligible in the latter equation. The bulk friction velocity can be used as a measure of the DC flux estimates [5] and is computed by

$$u_{*\,BULK} = U_r \sqrt{\frac{C_{drag}}{1000}} \tag{4}$$

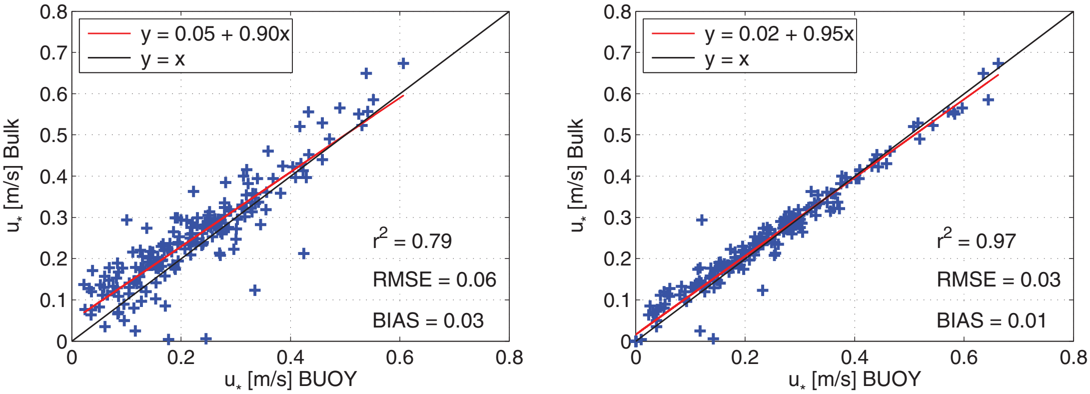

Figure 1: Uncorrected (left) and corrected (right) friction velocity estimates from the buoy computed from equation (3) versus friction velocity computed by the bulk method (equation 4). The fluxes are shown for a 10 day period (days 120 - 129) and represent averages over 20 minutes. In addition to the $y = x$ line (black) a linear regression line (red, $u_{*\,BULK}$ regressed on $u_{*\,BOUY}$) has been fitted to the data. Correlation of determination, root mean square error and bias for the uncorrected (left) and corrected (right) data is given in the respective panels.

where U_r is the wind speed at the reference height, C_{drag} is the dimensionless drag coefficient computed by

$$C_{drag} = \left(\frac{\kappa}{ln\frac{z_r}{z_0}}\right)^2 1000 \qquad (5)$$

κ is the von Karman constant, z_r is the reference height and z_0 is the roughness parameter computed based on the algorithm described in Fairall et al. (1996) [9]. In the present paper flux comparisons have been

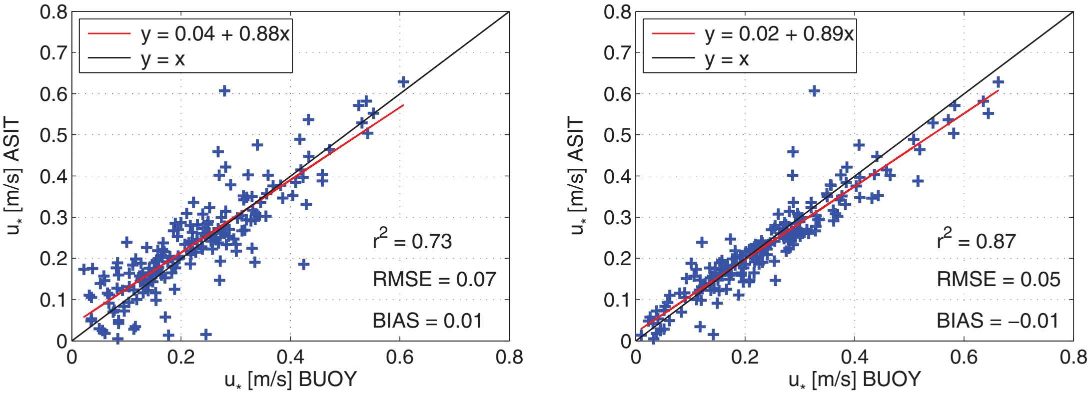

Figure 2: Uncorrected (left) and corrected (right) friction velocity estimates from the buoy versus ASIT. The fluxes are computed from equation (3) for a 10 day period (days 120 – 129) and represent averages over 20 minutes. In addition to the $y = x$ line (black) a linear regression line (red, $u_{*\,BULK}$ regressed on $u_{*\,BOUY}$) has been fitted to the data. Correlation of determination, root mean square error and bias for the uncorrected (left) and corrected (right) data is given in the respective panels.

performed for a ten day period starting at April 30 (day 120) with a predominant southwest wind direction where the wind is blowing from open sea towards the ASIT. To avoid flow distortion from the mast the analysis of the ASIT data is limited to the wind sector 135° - 315°. Figure 1 shows the comparison of the estimated friction velocities computed by the direct covariance flux method versus the friction velocities obtained by the bulk method. In the left panel, $u_{*\,\mathrm{BUOY}}$ is underestimated and the flux estimates have a broad scatter for the uncorrected buoy data. The scatter decreases after applying the motion correction algorithm of Edson et al. (1998) and the estimated DC friction velocities are in good agreement with $u_{*\,\mathrm{BULK}}$ in the right panel. For the corrected buoy data (the right panel of figure1) the steepness of the regression line increased and the linear regression of $u_{*\,BULK}$ on $u_{*\,BOUY}$ explain 79% and 97% of the total sample variance for the uncorrected and corrected buoy data. A comparison of the uncorrected and corrected friction velocities estimates between the buoy and ASIT for the same period is shown in figure 2. Without motion correction the flux estimates of the buoy are underestimated compared to the tower while they are in fairly good agreement after the correction. Note that the motion correction algorithm tends to slightly overestimate the buoy fluxes compared to the fluxes measured at the ASIT, though the correlation between $u_{*\,ASIT}$ and $u_{*\,BOUY}$ has increased and more of the sample variance is explained by the data after the correction. A similar result was found by comparing the direct vertical momentum flux estimates in the along wind direction ($\mathrm{u'w'}$) of the buoy versus ASIT (not shown). The time series of the measured and corrected buoy and ASIT flux estimates and the corresponding mean wind speeds are shown in figure 3. As expected, low wind speeds result in low vertical momentum fluxes while the momentum exchange increases with higher wind speeds. Generally, Edson et al. (1998) [5] uses a complementary filtering approach to correct flux measurements that were taken from ships. The yaw, roll and pitch angles are found by complementary filtering and are used in computing the platform velocities. To remove unwanted drift a high-pass filter is applied before and after the integration of the accelerometers. The translational velocity of the ship is measured by GPS or current meter and a low-pass filter is applied before these components are added to the integrated and high-pass filtered accelerometers. In this approach the cut-off frequency of the low pass filter is chosen to compliment the high-pass filter [5]. Finally, the translational platform velocities are added to the measured wind velocities that have been rotated into the reference coordinate system after adding the angular velocities. The correction procedure can be simplified for covariance flux systems mounted on moored buoys. These platforms do not have large translational velocities or perform manoeuvers, thus low frequency translational platform

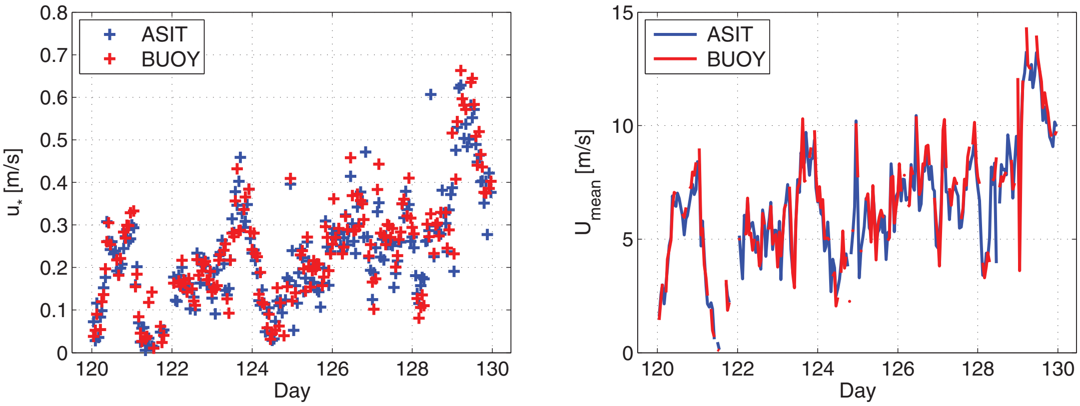

Figure 3: Left: Corrected friction velocity estimates from the ASIT (blue) and buoy (red) between days 120 – 129. Right: The same as in the left panel, but for measured wind speeds.

movements can be neglected. In the present study, the yaw, roll and pitch angles are found by complementary filtering of the angular rates with a predefined time constant. Instead of using the same time constant in high-pass filtering the platform accelerations, the high-pass filter for the accelerometers has been modified to use a different cut-off frequency. The main objective in the present study is to fine tune the motion correction algorithm by finding the appropriate time constant values for the two filters. This will contribute to increased accuracy of offshore direct turbulence flux measurements from moving platforms.

4. Summary and outlook

In the present study direct covariance flux measurements from a moored discus buoy and a tower have been compared. After correction for platform motions DC flux estimates from the buoy are found to agree fairly well with measurements obtained by means of the bulk method (e.g. Fairall et al., 1996 [5]) and DC flux measurements from the ASIT. These results indicate that direct covariance flux measurements can be performed from moored buoys when contamination due to platform motion is taken into account. Wind speeds in the present study do not exceed 15 m/s but a study involving a similar buoy system gives evidence that the system is working for wind speeds up to 25 m/s [10]. Due to their size buoys are subject to distinctly reduced flow distortion compared to ships and offshore towers, illustrated in figure 4. It shows a power spectrum from a 20 minute horizontal U-velocity record at the buoy and ASIT starting at 23:00h UTC on May 10 (day 130) with a predominant eastward wind direction. In this case, the wind hits the ASIT legs before it is recorded at the sonic anemometer. The induced flow distortion can be as seen enhanced turbulent kinetic energy towards higher frequencies in the left panel where the energy spectrum no longer follows the theoretically expected -5/3 slope in the inertial subrange. The blue line in the right panel shows how the turbulence measurements at the buoy are contaminated by the platforms attitude, indicated by the two peaks in the inertial subrange at around 0.2 Hz and 0.5 Hz. These distortions are filtered out by the motion correction algorithm and, in comparison to the ASIT, no flow distortion is present (red line). Note that the power spectra of the corrected wind speeds is not simply approximated by a straight line below the two peaks but still retains atmospheric motions induced by the wave field in the same frequency range. Other advantage of moored buoys are that they can be used in shallow and

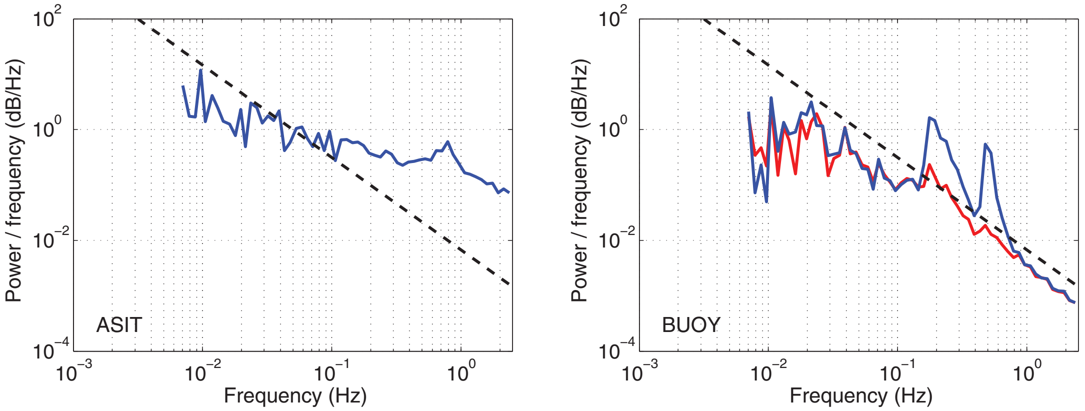

Figure 4: The measured (blue) and corrected (red) horizontal U-velocity power spectra from the ASIT (left) and the buoy (right). The measurements were taken simultaneously in a 20 minute period starting at 23:00h UTC on May 10 (day 130) with an eastward wind. The left panel shows ASIT measurements contaminated by flow distortion from the tower legs. The dashed line indicates the -5/3 slope theoretically expected for the inertial subrange.

intermediate waters (up to 400 m), are easy to maintain and can be redeployed several times. The weakness of the buoy approach still remains the power supply due limited battery lifetime [11] although modern buoys are equipped with additional solar panels. Despite this weakness the development of low energy turbulence sensors and inertial measuring units and decreasing costs will make flux measurements from buoys more attractive in the future. The results in the present study will with no doubt contribute to the further development of autonomous direct covariance flux systems that can be deployed anywhere at sea, especially inside offshore wind farms due to the small size of buoys. The experience and results of this study will be used and applied for the development and deployment of two own turbulent flux buoys.

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