A new motion compensation algorithm of floating lidar system for the assessment of turbulence intensity

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Abstract. In this study, a new motion compensation algorithm was proposed and verified by using numerical simulation. Compensated horizontal mean wind speed by using conventional method shows good agreement with reference wind speed regardless of the motion of the floater. However, turbulence intensity is always overestimated. The overestimation is more significant when the maximum pitch angle of the floater motion is larger. When proposed method is used, the overestimation of the turbulent intensity is improved and estimated turbulent intensity shows better agreement with reference value. There still remains underestimation of the turbulence intensity with the bias of -1.1%. This is probably caused by the low sampling frequency in LIDAR measurement and further research is needed to model the high frequency component of the wind speed for LIDAR measurement.

1. Introduction

For the efficient assessment of offshore wind climate, floating LIDAR has been used. The floating LIDAR experiences the motion induced mainly by wave and compensation is needed. There are two approaches to compensate the floater motion, mechanical compensation [1] and software-based compensation [2][3][4]. Tiana-Alsia et al.[1] proposed a mechanical compensation system and measured mean wind speed better than non-compensated case. The other approach, software based compensation has an advantage that it does not require any additional hardware to compensate the floater motion except for the floater motion measurement system. Schlipf et al.[2] proposed a new wind field reconstruction algorithm from LIDAR and applied the algorithm to floating LIDAR and estimate the mean wind speed and turbulence intensity and showed that estimated mean wind speed and turbulence intensity by using proposed method showed good agreement with the fixe LIDAR measurement results. Wolken-Möhlmann and Lange [3] apply a compensation algorithm to a simulated synthetic three dimensional wind field and showed that the algorithm works to measure mean wind speed. Yamaguchi and Ishihara [4] also proposed a motion compensation algorithm and verified the algorithm for different floater motion. However, they did not verify the estimation accuracy of turbulence intensity. As the sampling frequency of the LIDAR is typically much lower than sonic anemometer, large uncertainty on the measurement of turbulence intensity is expected. In this study, first, the estimation accuracy of turbulence intensity by using conventional motion compensation method was investigated, and the effect of turbulence intensity and the floater motion on the estimation error is investigated. Then, a new motion compensation algorithm is proposed for the assessment of turbulent intensity and verified by using numerical simulation.

2. Generation of three dimensional synthetic wind field and calculation of LoS-speed under floater motion

In this study, first, three dimensional synthetic turbulent wind fields were generated by using the method described in [5]. In this method, first, time-varying three dimensional turbulent wind components are generated in y-z plane (i.e., the plane perpendicular to the mean wind direction) by considering turbulence spectrum and spatial correlations of turbulent wind component. The turbulence spectrum are assumed to follow standard Kaimal spectrum and the spatial correlations to follow exponential decay model as specified in IEC61400-1 [6]. The ratios of turbulence intensity between wind direction, cross wind direction and vertical direction are also assumed to follow the value specified in IEC61400-1[6]. Note that generated three dimensional turbulent wind field $\widetilde{\mathbf{u}}'(y,z,t) = \left(\widetilde{u}'(y,z,t), \widetilde{v}'(y,z,t), \widetilde{w}'(y,z,t)\right)$ is normalized so that the mean wind speed $\overline{\widetilde{\mathbf{u}}'(y,z,t)}$ is 0 and the standard deviation of the wind speed in longitudinal direction ($\sigma_{\widetilde{u}}$) is 1. Then, considering the mean wind speed and turbulence intensity, the dimensional turbulent wind field in y-z plane $\widehat{\mathbf{u}}(y,z,t)$, is calculated from non-dimensional turbulent wind field $\widetilde{\mathbf{u}}'(y,z,t)$ by equation (1)

$$\widehat{\mathbf{u}}(y,z,t) = \sigma_u \times \widetilde{\mathbf{u}}'(y,z,t) + \bar{u}(z) \tag{1}$$

Here, σ_u is the actual turbulence intensity in longitudinal direction and $\bar{u}(z)$ is the mean wind speed as a function of height. In this study, a power law with the exponent of 0.1 is assumed for the vertical profile of wind speed. The turbulence intensities were varied from 8% to 15%. Lastly, this time varying wind field in y-z plane $\widehat{\mathbf{u}}(y,z,t)$ is extended to the wind field in x-y-z space $\mathbf{u}(x,y,z,t) = \mathbf{u}(\mathbf{x},t)$ by assuming Taylor's frozen turbulent hypothesis as shown in equation (2).

$$\mathbf{u}(\mathbf{x},t) = \widehat{\mathbf{u}}\left(y,z,t - \frac{x}{\overline{u(z)}}\right) \tag{2}$$

A pulsed LIDAR is chosen as an example in this study. A pulsed LIDAR emits the laser beam in four directions (in recent models, five directions including vertical), and measures the wind speed component in line of sight (LoS), which is called LoS speed. This process takes about one second. Then, horizontal and vertical wind speed is estimated assuming that wind field does not change during one cycle (four to five seconds) and horizontally uniform.

In this study, the LoS speed of the pulsed LIDAR was calculated in the three dimensional wind field mentioned above considering the motion of the LIDAR. The LoS speed of the LIDAR at ith level at time t can be calculated by using equation (3).

$$V_{LOS}(i,t) = \left(\mathbf{u}[\mathbf{l}_i(t),t] - \frac{\mathrm{d}}{\mathrm{d}t}\widehat{\boldsymbol{\xi}}[\mathbf{l}_i(t),t]\right) \cdot \frac{\mathbf{l}_i(t)}{|\mathbf{l}_i(t)|} \tag{3}$$

Here, $\mathbf{l}_i(t)$ is the position vector at which the LoS is measured at level i and time t, and $\widehat{\boldsymbol{\xi}}[\mathbf{l}_i(t),t]$ is the displacement of the LoS measurement point due to the floater motion and can be calculated in equation (4).

$$\widehat{\boldsymbol{\xi}}[\mathbf{l}_i(t),t] = \begin{pmatrix} \xi_x \\ \xi_y \\ \xi_z \end{pmatrix} + \mathbf{R}(\theta_x,\theta_y,\theta_z)(\mathbf{l}_i(t) - \mathbf{g}) \tag{4}$$

Here, ξ_x, ξ_y, ξ_z, θ_x, θ_y and θ_z are the surge, sway, heave, roll, pitch and yaw component of the floater motion, respectively. $\mathbf{R}(\theta_x,\theta_y,\theta_z)$ is the rotation matrix and $\mathbf{g}$ is the position vector of the centre of gravity of the floater.

The floater motion is derived from the motion of the Fukushima offshore substation floater [7]. Because the floater motion is mainly excited by wave force, the frequency of the floater motion has a peak around peak wave period (5s to 8s). With same phase information, four different amplitudes were tested by setting the maximum pitch angle as 5 degree, 10 degree, 15 degree and 20 degree. Figure 1 shows the example of the floater motion used in this study.
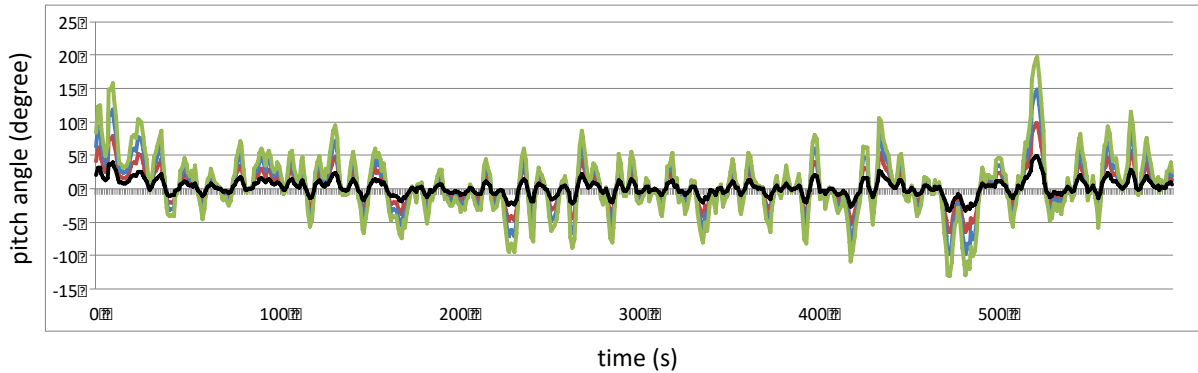

Figure 1 example of the pitch motion of the floater used in this study

3. Estimation accuracy of turbulence intensity by using conventional motion compensation algorithm

The points where LoS speed is measured in a typical pulsed LIDAR system are shown in figure 2. The LoS speed is measured along four LoSs (i.e., east, north, west and south) with the constant angle θ_0 between LoS and vertical ($\mathbf{l}_i^E$, $\mathbf{l}_i^N$, $\mathbf{l}_i^W$ and $\mathbf{l}_i^S$ in Figure 2). In latest model, the LoS speed is also measured along vertical axis ($\mathbf{l}_i^C$ in Figure 2). It takes about one second to measure one LoS speed. Table 1 shows an example of LoS measurement. When LoS speed at $\mathbf{l}_i^E$ is measured at $t = 1$, LoS at $\mathbf{l}_i^N$ is measured at $t = 2$, etc.
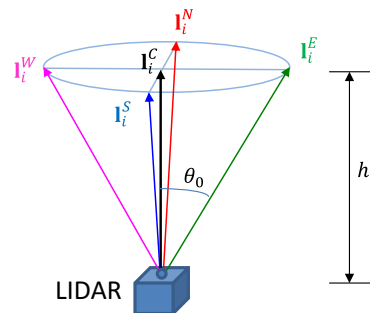

Figure 2 Typical pulsed LIDAR with its laser emission direction

Table 1 Example of LoS measurement (+: measured; -: not measured)

t	$\mathbf{l}_i^N$	$\mathbf{l}_i^W$	$\mathbf{l}_i^S$	$\mathbf{l}_i^E$	$\mathbf{l}_i^C$
1	+	-	-	-	-
2	-	+	-	-	-
3		-	+	-	-
4	-	-	-	+	-
5	-	-	-	-	+
6	+	-	-	-	-

The wind velocity can be estimated assuming that wind field is horizontally uniform and temporary steady for five seconds, thus the horizontal wind speed at h_i and $t = 3$ can be calculated by solving following equations.

$$u_i|_{t=3} = \frac{\left(V_{LOS}(i,2) - V_{LOS}(i,4)\right)}{2\sin\theta_0} \tag{3}$$

$$v_i|_{t=3} = \frac{\left(V_{LOS}(i,1) - V_{LOS}(i,3)\right)}{2\sin\theta_0} \tag{3}$$

Here, $u_i|_{t=3}$ and $v_i|_{t=3}$ are the east-west component and the north-south component of the horizontal wind velocity at h_i and $t = 3$, respectively, and $V_{LOS}(i,t)$ is the measured LoS speed at h_i and t.

When the LIDAR is on a floater and in motion, these equations has to be modified. Yamaguchi and Ishihara (2015)[3] proposed an algorithm to compensate the floater motion. This method consists of following four steps.

1) Interpolation of measured LoS speed to the target height.
    When the floater experience pitch motion (i.e., rotation along y axis), $\mathbf{l}_i^E$ and $\mathbf{l}_i^W$ moves to $\mathbf{l'}_i^E$ and $\mathbf{l'}_i^W$, respectively as shown in figure 3. The height of $\mathbf{l'}_i^E$ and $\mathbf{l'}_i^W$ are not h_i any more. To estimate the horizontal wind speed at h_i, the LoS are interpolated at $\boldsymbol{\lambda}_i^E$ and $\boldsymbol{\lambda}_i^W$ where the height is h_i. In the case of Figure 3, $\boldsymbol{\lambda}_i^E$ is interpolated from $\mathbf{l}_i^E$ and $\mathbf{l}_{i+1}^E$.
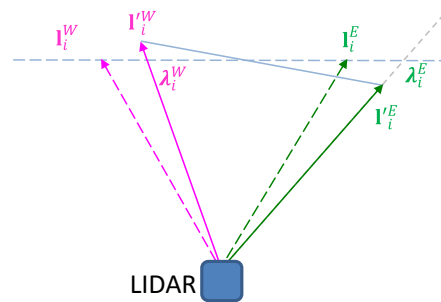

Figure 3 Interpolation of measured LoS wind speed to the target height

2) Estimation of horizontal wind speed in $\mathbf{o} - \boldsymbol{\lambda}_i^E - \boldsymbol{\lambda}_i^W$ plane and $\mathbf{o} - \boldsymbol{\lambda}_i^N - \boldsymbol{\lambda}_i^S$ plane.
    Once, the LoS wind speed at $\boldsymbol{\lambda}_i^E$ and $\boldsymbol{\lambda}_i^W$ are obtained, the horizontal wind speed in $\mathbf{o} - \boldsymbol{\lambda}_i^E - \boldsymbol{\lambda}_i^W$ plane can be calculated easily. It is noted that in this algorithm, when horizontal wind speed in $\mathbf{o} - \boldsymbol{\lambda}_i^E - \boldsymbol{\lambda}_i^W$ plane is estimated, as shown in Figure 4, the whole the LIDAR measurement system is "frozen" and the pitch angle θ_y at $t = 3$ is used together with the measured LoS speed at $\boldsymbol{\lambda}_i^E$ at $t = 4$ ($V_{LoS}(i,4)$) and at $\boldsymbol{\lambda}_i^W$ at $t = 2$ ($V_{LoS}(i,2)$). In other world, the horizontal wind speed in $\mathbf{o} - \boldsymbol{\lambda}_i^E - \boldsymbol{\lambda}_i^W$ at $t = 3$ is estimated.
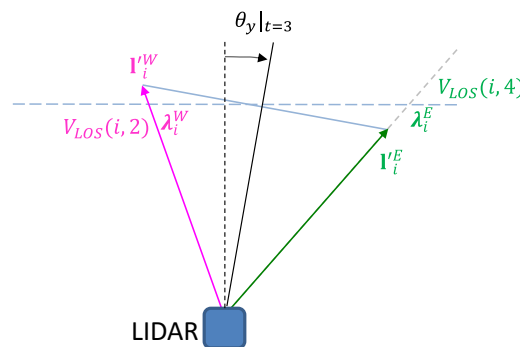
Figure 4 Estimation of horizontal wind speed in $\mathbf{o} - \boldsymbol{\lambda}_i^E - \boldsymbol{\lambda}_i^W$ plane (conventional algorithm)

3) Estimation of horizontal wind velocity.

From the horizontal wind speed in $\mathbf{o} - \lambda_i^E - \lambda_i^W$ plane and $\mathbf{o} - \lambda_i^N - \lambda_i^S$ plane, the horizontal wind velocity is calculated.

4) Correction of wind speed considering LIDAR speed.
The wind velocity obtained above only includes the effect of the floater inclination but the error related to the floater movement (floater speed) is not included. The floater speed is added to the obtained wind speed above to estimate the true wind speed.

Table 2 summarises the data used in this algorithm to estimate the wind velocity at conventional algorithm at $t = 3$. In this algorithm, LoS-speed measured at $t = 1, 2, 3$ and 4 are used. However, during these four seconds, it is assumed that the LIDAR inclination angle does not change and LIDAR motion velocity is constant. This assumption has an advantage that the algorithm is simple and the numerical verification shows that it can estimate the horizontal mean wind speed with the error of less than 1% even under large floater motion, where if no correction is applied, the estimation error of horizontal wind speed reaches 1.5% [2].

Table 2 Summery of the data used in conventional algorithm at $t = 3$ (x: measured and used, +: measured but not used, -: not measured)

t	$\mathbf{l}_i^N$	$\mathbf{l}_i^W$	$\mathbf{l}_i^S$	$\mathbf{l}_i^E$	$\mathbf{l}_i^C$	LIDAR angle	LIDAR velocity
1	x	-	-	-	-	+	+
2	-	X	-	-	-	+	+
3	-	-	x	-	-	x	x
4	-	-	-	x	-	+	+
5	-	-	-	-	+	+	+
6	+	-	-	-	-	+	+

However, this method includes large errors in the measurement of turbulence intensity. Figure 5 shows the estimated turbulence intensity for different maximum pitch angle and reference value. It is shown that the estimation error of the conventional algorithm becomes higher as the maximum pitch angle increases. Figure 7 shows the estimated and reference time series of wind speed. The estimated wind speed by conventional method shows unrealistically larger amplitude of fluctuation compared to the reference value, which causes the overestimation of the turbulence intensity. This is caused by the assumption that LIDAR angle and LIDAR motion velocity stays constant during four seconds, which in reality is not correct.
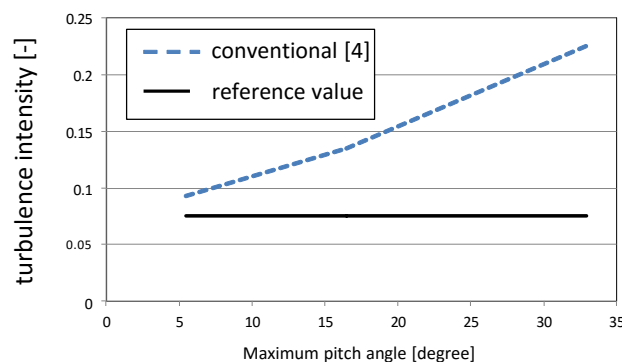

Figure 5 The estimated turbulence intensity for different maximum pitch angle [3]

4. A new motion compensation method for floating lidar

A new motion compensation algorithm is proposed in this study to solve the problem of the conventional method. Following three steps summarizes the new algorithm.
1) Interpolation of measured LoS to the target height.

This step is exactly same as the conventional algorithm mentioned in the previous section.

2) Estimation of horizontal wind speed in in $\mathbf{o} - \lambda_i^E - \lambda_i^W$ plane and $\mathbf{o} - \lambda_i^N - \lambda_i^S$ plane considering the floater motion velocity.

In this algorithm, the pitch angles of the floater at the time of measurement of LoS are used. Figure 5 shows the estimation of horizontal wins speed in $\mathbf{o} - \lambda_i^E - \lambda_i^W$ plane in the proposed algorithm. The LoS speed, $V_{LoS(i,4)}$ at λ_i^E under pitchangle θ_y at $t = 4$ (Figure 6(a)) and $V_{LoS(i,2)}$ at λ_i^W under pitchangle θ_y at $t = 2$ (Figure 6(b)) are combined as shown in Figure 6(c) and horizontal wind speed in $\mathbf{o} - \lambda_i^E - \lambda_i^W$ is estimated. When horizontal wind speed in $\mathbf{o} - \lambda_i^E - \lambda_i^W$ is estimated, the floater motion speed is considered at each time of the LoS speed measurement.
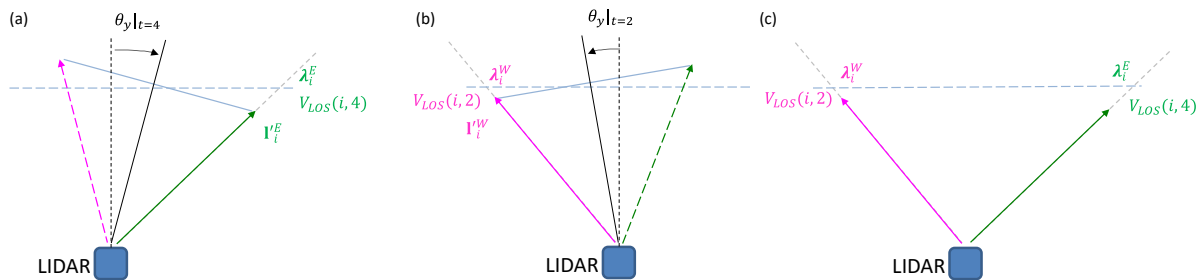

Figure 6 Estimation of horizontal wind speed in $\mathbf{o} - \lambda_i^E - \lambda_i^W$ plane (proposed algorithm)
(a) LoS speed at t =4, (b) at t =2, (c) the plane where horizontal speed is estimated

3) Estimation of horizontal velocity.
The estimation of the horizontal velocity is carried out in similar way as the conventional method.

Table 3 summarizes the data used for the proposed algorithm. Compared to the conventional algorithm (Table 2), the LIDAR inclination angle and motion velocity for all the time steps are used, which makes the estimation more realistic.

Table 3 Summery of the data used in the proposed algorithm at $t = 3$ (x: measured and used, +: measured but not used, -: not measured)

t	$\mathbf{l}_i^N$	$\mathbf{l}_i^W$	$\mathbf{l}_i^S$	$\mathbf{l}_i^E$	$\mathbf{l}_i^C$	LIDAR angle	LIDAR velocity
1	x	-	-	-	-	x	x
2	-	x	-	-	-	x	x
3	-	-	x	-	-	x	x
4	-	-	-	x	-	x	x
5	-	-	-	-	+	+	+
6	+	-	-	-	-	+	+

5. Results and discussion

By using the conventional and proposed method, horizontal wind speed is estimated for every second and compared by changing maximum floater inclination angle and turbulence intensity. Figure 7 shows an example of the time history of calculated wind speed and reference wind speed. It is clear that mean wind speed shows good agreement with the reference value, for both method, but the fluctuating component differs considerably. The conventional method sometimes overestimates the instantaneous wind speed and sometimes underestimates. This causes overestimation of the turbulence intensity.
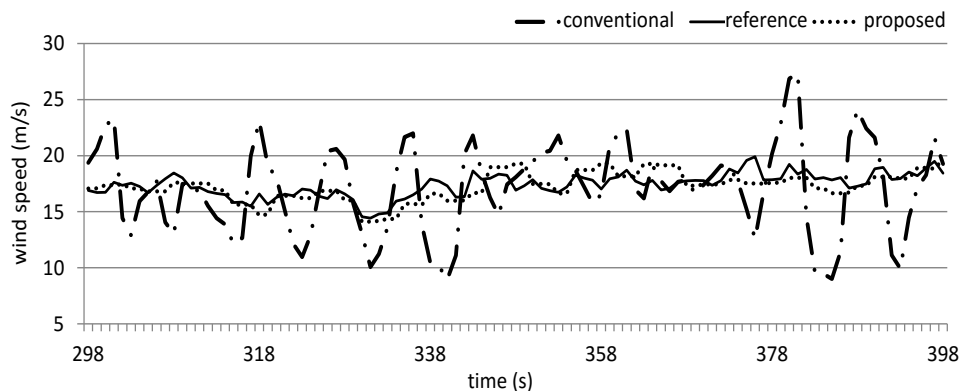
Figure 7 time history of instantaneous wind speed

Figure 8 shows the comparison of mean wind speed and turbulent intensity for conventional and proposed motion compensation method. Little difference can be seen between conventional and proposed methods for the estimation of mean wind speed. However, measured turbulent intensity by using conventional method and proposed method differs considerably. Especially when the maximum angle of floater motion is larger, calculated turbulent intensity tend to be larger, which causes large error in the measurement of turbulent intensity. When proposed method is used, estimated turbulence intensity shows relatively better agreement with reference value, regardless of the maximum inclination angle. However, still, there exists a bias of -1.1% on the estimation of the turbulence intensity.

This bias is probably caused by the limitation in the temporal resolution in LIDAR measurement. As it takes a few second to estimate the horizontal wind speed, turbulence related to smaller eddy than this time scale cannot be captured. Further research is needed for the modelling of this high frequency component of the wind speed for the measurement of turbulence intensity by using Doppler LIDAR.

6. Conclusion
In this study, a new motion compensation algorithm was proposed and verified by using numerical simulation for mean wind speed and turbulence intensity. Following results were obtained.

1. Compensated horizontal mean wind speed by using conventional method shows good agreement with reference wind speed regardless of the motion of the floater. However, turbulence intensity is always overestimated. The overestimation is more significant when the maximum pitch angle of the floater motion is larger. This is due to overestimation and underestimation of the instantaneous wind speed.
2. When proposed method is used, the overestimation of the turbulent intensity is improved and estimated turbulent intensity shows better agreement with reference value. There still remains underestimation of the turbulence intensity with the bias of -1.1%. This is probably caused by the low sampling frequency in LIDAR measurement and further research is needed to model the high frequency component of the wind speed for LIDAR measurement.
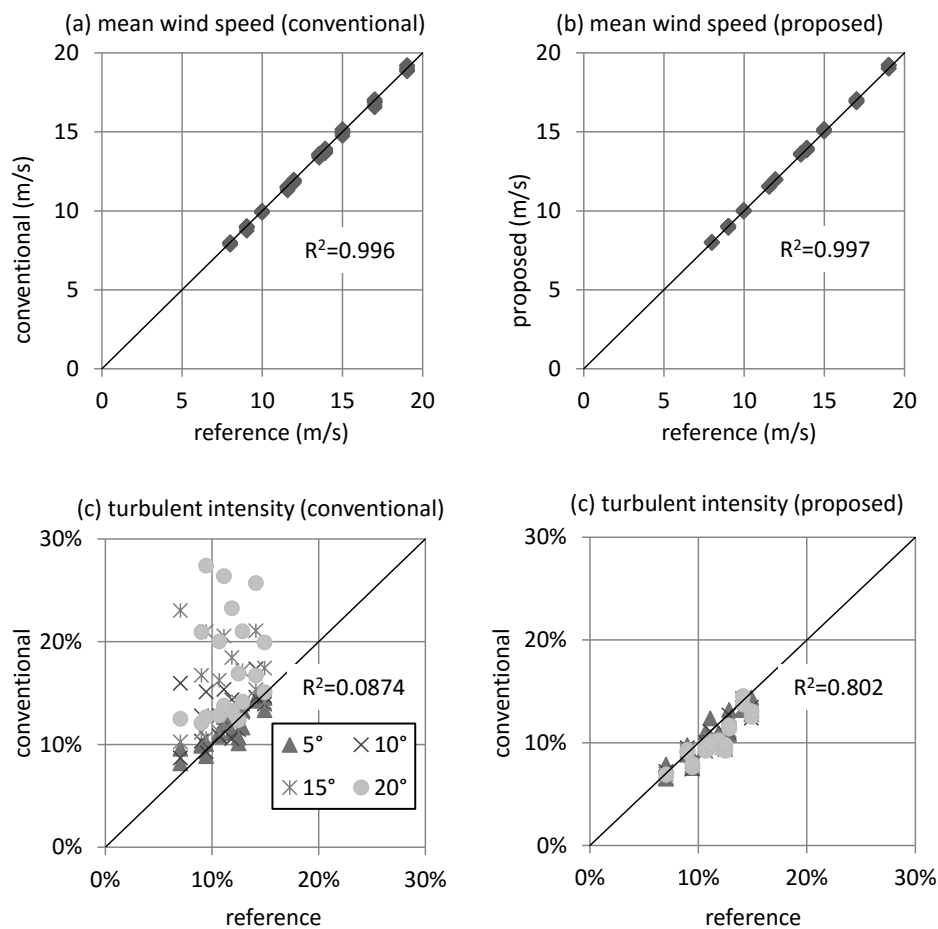
Figure 8 comparison of mean wind speed and turbulent intensity

7. References

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