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Floating offshore wind measurement system by using LIDAR and its verification

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Introduction

The use of floating LIDAR will be an important technology to reduce the cost of offshore wind measurement. Floater motion due to wave force may result in the error of measured wind speed and floater motion compensation is necessary.

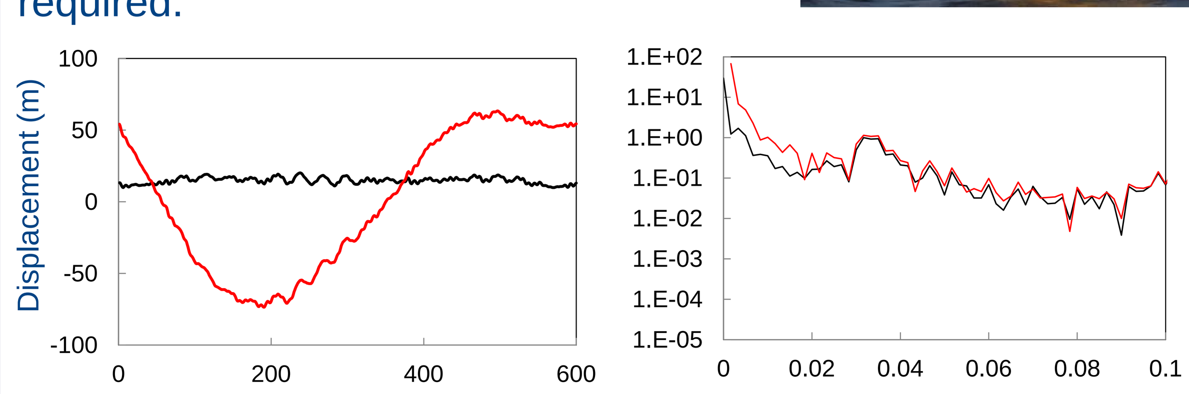
Several studies have been carried out focusing on floater motion compensation[1)2)]. However, the detailed algorithm for motion compensation is not described. The most simple motion compensation algorithm is simply to perform coordinate transformation. Fujitani[3)] applied coordinate transformation for sonic anemometer on ship. But due to the difference in the mechanism of wind speed measurement between sonic anemometer and lidar, the coordinate transformation may not be used.

Another problem is that there is no validated method for the measurement of the motion of the floater. Typically gyro and accelerometer are used to measure the floater motion. But numerical integral may introduce additional error. On the other hand, GPS can give the position of the floater directly, but the accuracy easily changes depending on satellite conditions.

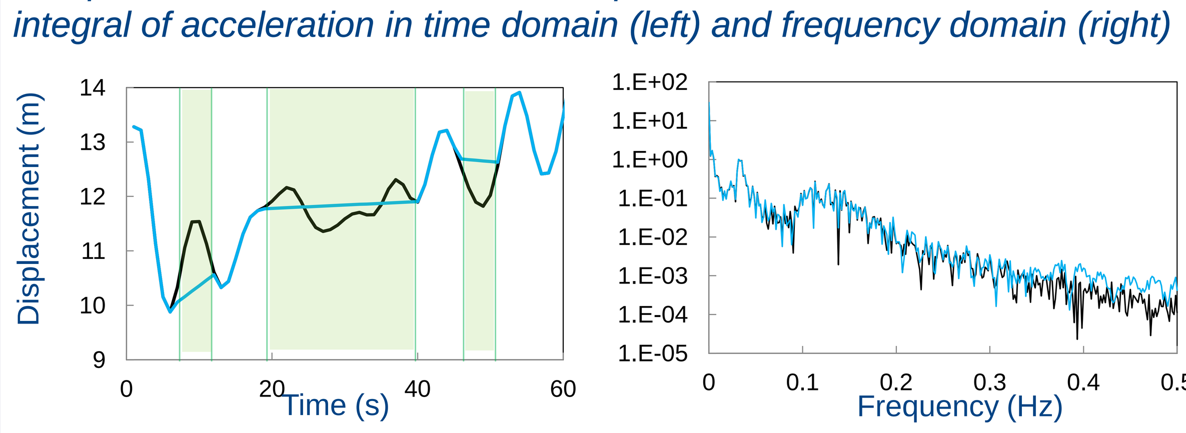
In this study, first, a method to measure the motion of the floater is established, and then, different motion compensation algorithms are applied and their applicability is investigated.

Floater motion measurement

The substation of Fukushima FORWARD project[4)] is equipped with RTK-GPS sensor, accelerometer and gyro in order to measure the floater motion in addition to the Lidar. Theoretically, one GPS sensor and gyro can be used to identify the six degree of freedom motion of the floater. However, sometimes the GPS measurement in RTK mode is not available and interpolation of GPS measurement is required.

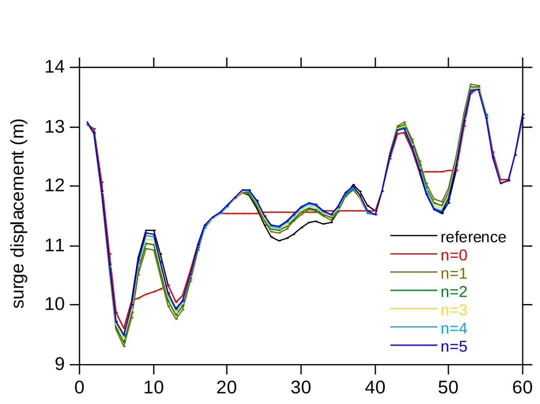


Comparison of reference data and displacement obtained from numerical integral of acceleration in time domain (left) and frequency domain (right)

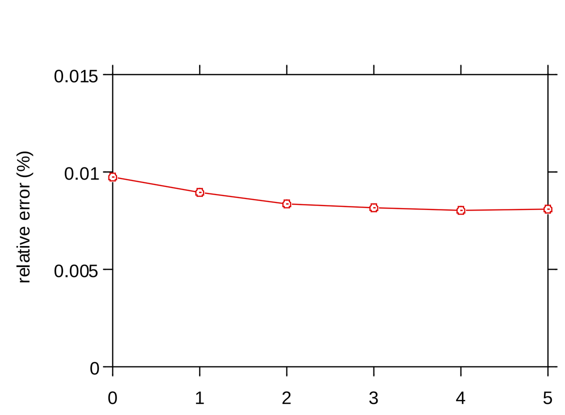


Comparison of reference data and GPS data with missing value in time domain (left) and frequency domain (right)

- Integration of acceleration shows good agreement with the reference data for high frequency.
- GPS data with missing value shows good agreement with the reference data for low frequency.



Displacement calculated by proposed method



Relative RMSE of the estimate for different number of iterations

GPS data with missing values and the displacement obtained by integrating acceleration are combined in frequency domain. GPS data with missing value is updated based on the error of the missing intervals and same procedure is performed.

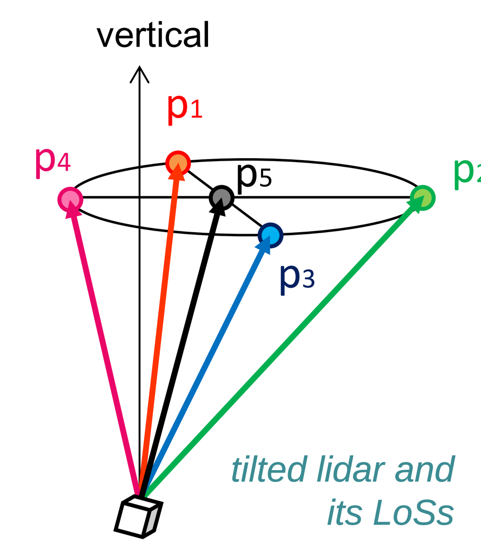
$$s(f) = g(f)s_{GPS}(f) + (1 - g(f))s_{acc}(x)$$

$$g(f) = \begin{cases} 1 & (f \le f_a) \\ \frac{1}{f_a - f_b}(x - f_b) & (f_a < f \le f_b) \\ 0 & (f_b < f) \end{cases}$$

Motion compensation of LIDAR

■ Correction of tilting

1) Horizontal wind speed component in p_2-p_4 plane ($|\mathbf{u}_{2,4}|$) and p_1-p_3 plane ($|\mathbf{u}_{1,3}|$) at the target height is calculated respectively.
2) Horizontal wind speed component ($|\mathbf{u}|$) and direction ($\mathbf{u}/|\mathbf{u}|$) at the target height is calculated.
3) Vertical wind speed component (w) is calculated.



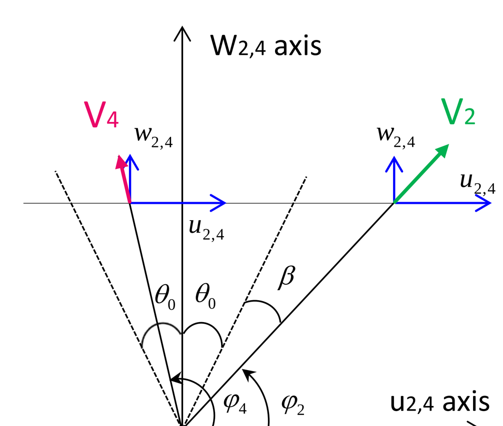
Horizontal wind speed component in p_2-p_4 and p_1-p_3 plane

Define the angle between LoS and horizontal ground (φ_i) as:

$$\varphi_2 = 90° - \theta_0 - \beta$$
$$\varphi_4 = 90° + \theta_0 - \beta$$

where, β is the pitch angle of the lidar.

The wind speed component in LoS (V_2, V_4) can be written as



wind speed component in p_2-p_4 plane

$$V_2 = |\mathbf{u}_{2,4}|\cos(\varphi_2) + |\mathbf{w}_{2,4}|\sin(\varphi_2)$$
$$V_4 = |\mathbf{u}_{2,4}|\cos(\varphi_4) + |\mathbf{w}_{2,4}|\sin(\varphi_4)$$

where, $\mathbf{w}_{2,4}$ is the component of the wind speed in in p_2-p_4 plane and perpendicular to $\mathbf{u}_{2,4}$.

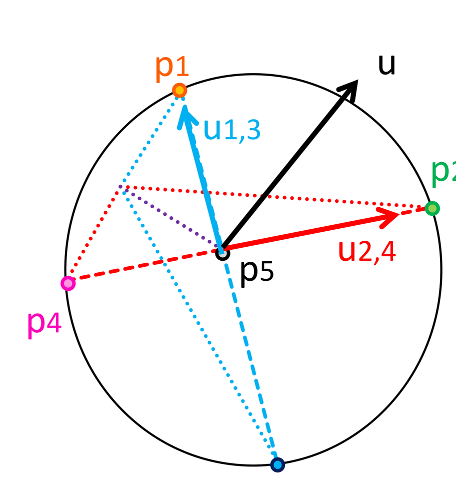
By solving this equation, $|\mathbf{u}_{2,4}|$ and $|\mathbf{w}_{2,4}|$ can be calculated. $|\mathbf{u}_{1,3}|$ can also be calculated in the same way.

Horizontal wind speed and direction

Let the direction of $\mathbf{u}_{2,4}$ and $\mathbf{u}_{2,4}$, $\hat{\mathbf{u}}_{2,4}$ and $\hat{\mathbf{u}}_{1,3}$ respectively. They can be written as:

$$\hat{\mathbf{u}}_{2,4} = \frac{\mathbf{u}_{2,4}}{|\mathbf{u}_{2,4}|} = \frac{\mathbf{p}_2 - \mathbf{p}_4}{|\mathbf{p}_2 - \mathbf{p}_4|},$$

$$\hat{\mathbf{u}}_{1,3} = \frac{\mathbf{u}_{1,3}}{|\mathbf{u}_{1,3}|} = \frac{\mathbf{p}_1 - \mathbf{p}_3}{|\mathbf{p}_1 - \mathbf{p}_3|}$$



wind speed component in horizontal plane at the target height

The horizontal wind direction $\mathbf{u}/|\mathbf{u}|$ and speed $|\mathbf{u}|$ can be calculated as:

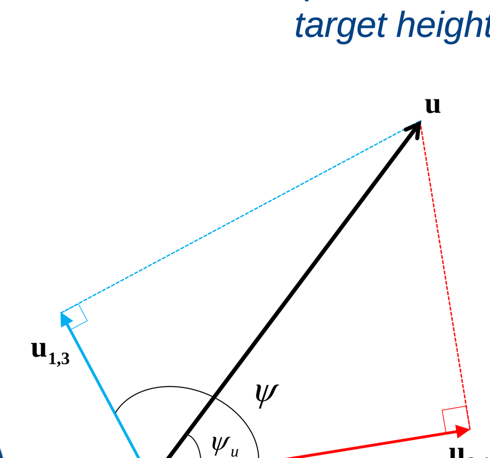
$$\frac{\mathbf{u}}{|\mathbf{u}|} = \begin{pmatrix} \cos\psi_u & -\sin\psi_u & 0 \\ \sin\psi_u & \cos\psi_u & 0 \\ 0 & 0 & 1 \end{pmatrix} \mathbf{u}_{2,4}$$

$$\mathbf{u} = \frac{|\mathbf{u}_{2,4}|}{\cos\psi_u}$$

where

$$\psi_u = \arctan\left(\frac{|\mathbf{u}_{1,3}| - |\mathbf{u}_{2,4}|\cos\psi}{|\mathbf{u}_{2,4}|\sin\psi}\right)$$

$$\psi = \arccos(\hat{\mathbf{u}}_{2,4} \cdot \hat{\mathbf{u}}_{1,3})$$



horizontal wind speed and direction at the target height

Vertical wind speed

Vertical wind speed can be calculated as the average of vertical wind speed calculated from each LoS speeds by the equation as follows.

$$w = \frac{V_i - u_x\hat{p}_{ix} - u_y\hat{p}_{iy}}{\hat{p}_{iz}}$$

where

$$(u_x, u_y) = \mathbf{u}\,, (\hat{p}_{ix}, \hat{p}_{iy}, \hat{p}_{iz}) = \hat{\mathbf{p}}_i = \frac{\mathbf{p}_i}{|\mathbf{p}_i|}$$

■ Correction of translational motion

The horizontal wind speed $\mathbf{u}_{\mathrm{true}}$ can be obtained by subtracting the translational velocity of the lidat $\mathbf{u}_{\mathrm{t}}$ from the horizontal wind speed after tilting correction $\mathbf{u}$. [3]

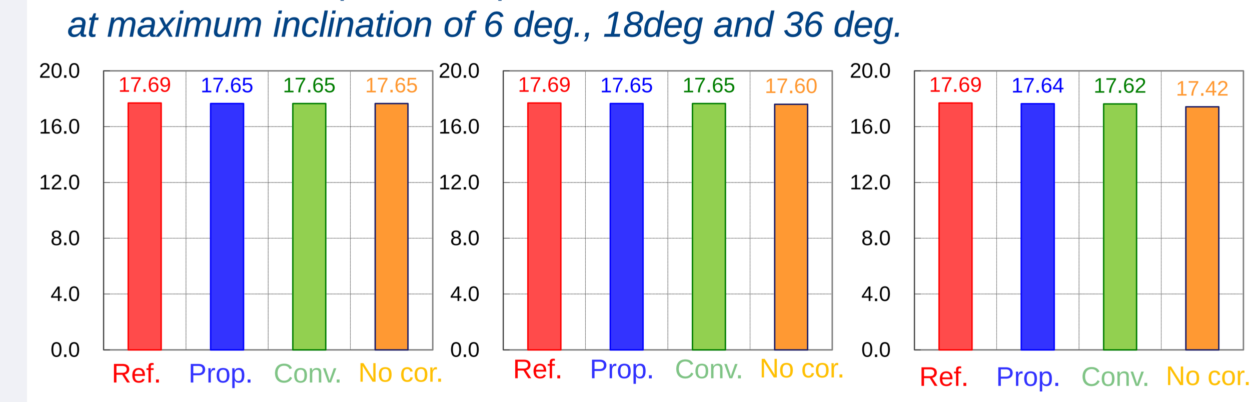
$$\mathbf{u}_{\mathrm{true}} = \mathbf{u} - \mathbf{u}_{\mathrm{t}}$$

Verification

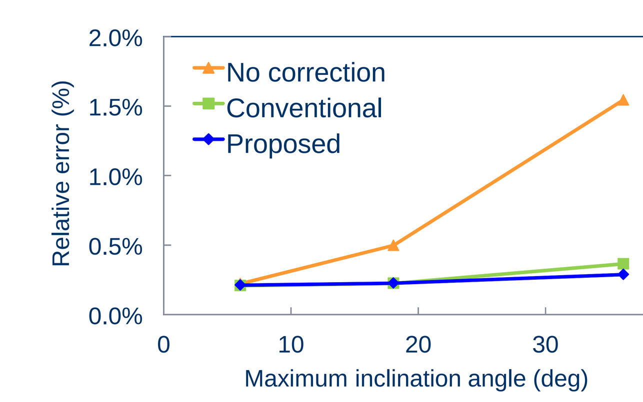
Proposed correction method was verified by numerical simulation.

- Three different synthetic floater motion data were generated.
- The maximum pitch and roll angle of the motion data are 5, 15 and 30 degree.
- 10 minutes average wind speed in three component are verified.

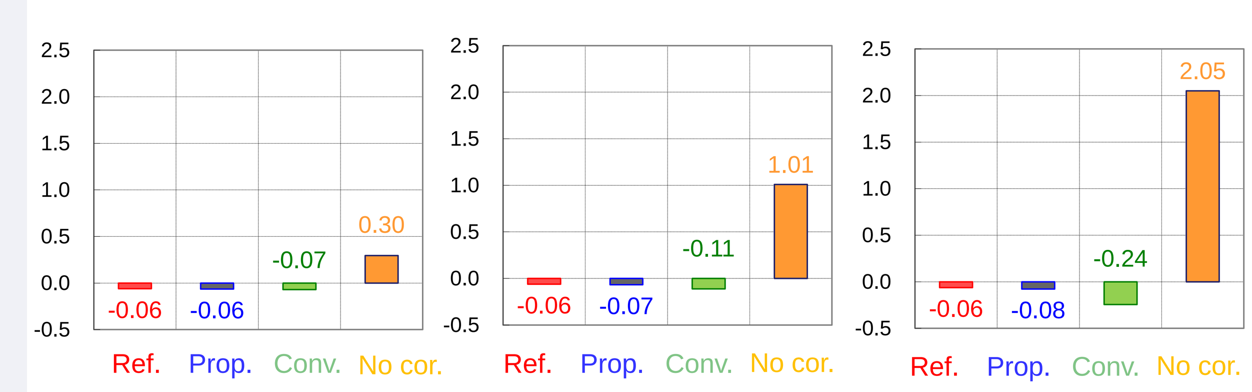
Horizontal wind speed component at maximum inclination of 6 deg., 18deg and 36 deg.



- The estimation error by conventional method increase when inclination becomes large while proposed method can measure wind speed regardless of the inclination angle



Vertical wind speed component at maximum inclination of 6 deg., 18deg and 36 deg.



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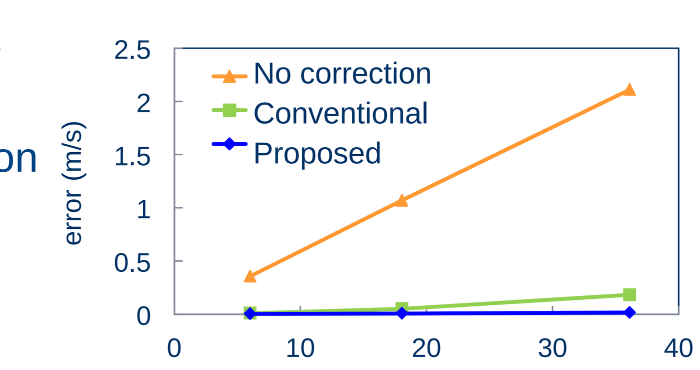

Conclusion

In this study, a method to measure the floater motion and a motion compensation method for Lidar are proposed and verified. Following results were obtained.

1) Proposed method can measure the six degree of freedom floater motion even when some of the RTK-GPS data are missing.
2) Proposed motion compensation method for lidar can predict the wind speed regardless of the maximum pitch angle. When maximum pitch is 36degree, the error in horizontal wind speed becomes 1.5% without motion compensation., but can be reduced to 0.3% by using motion compensation.

Acknowledgement

This study was carried out as a part of Fukushima FORWARD project funded by Ministry of Economy, Trade and Industry (METI), Japan.

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