Turbulence measurement by using vertical lidar and its validation at an offshore Met Mast

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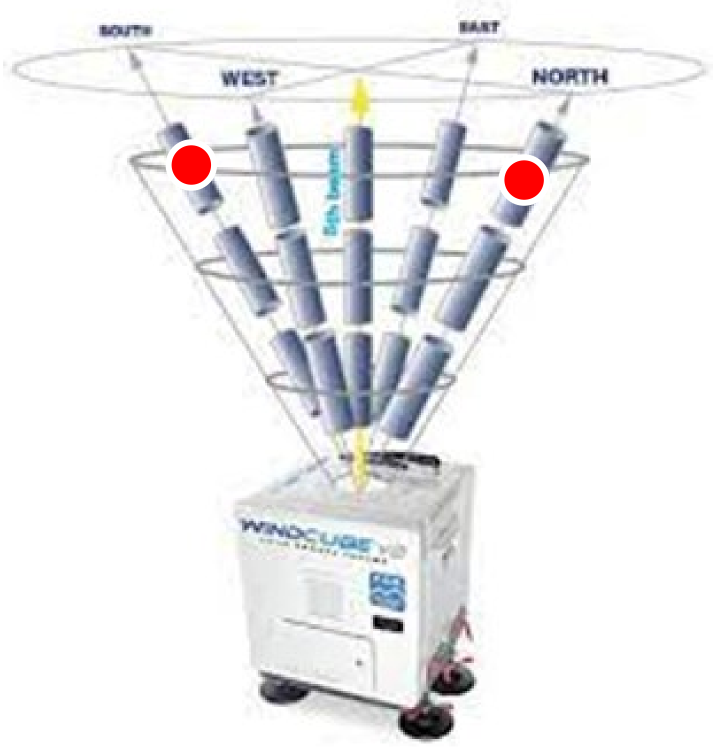
Background

- Wind measurement at hub height is needed for wind farm design.
- Recently, doppler lidars have been widely used to reduce the cost of the met mast.
- Lidar measured mean wind speeds show good agreement with cup anemometers.
- Turbulence measurement is still facing challenges.

This study focuses on the pulsed fixed vertical lidar

Error in lidar measured turbulence

Sathe et al. (2010) mentioned that there are two sources of the error.

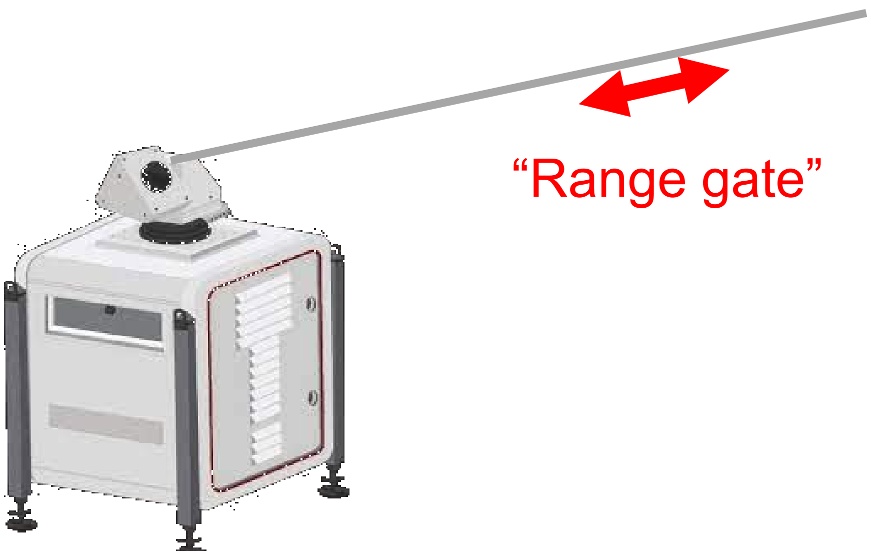


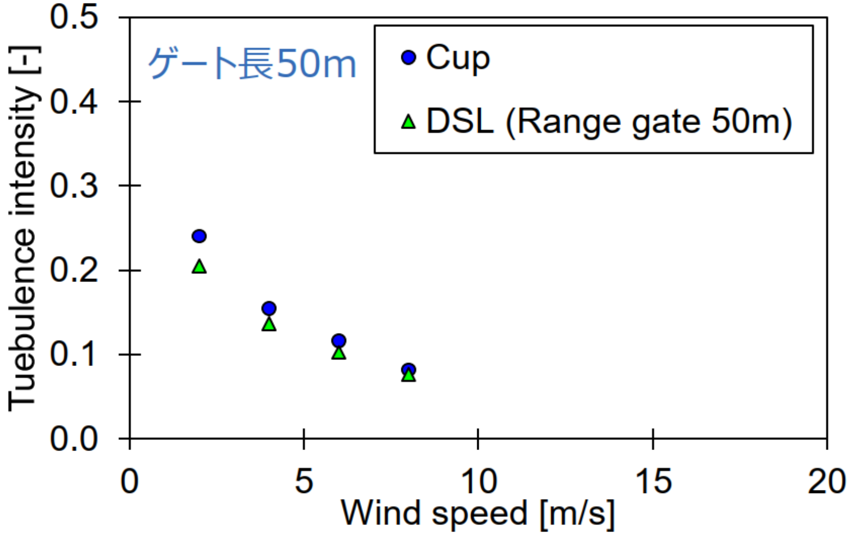
The first source is the spatial separation in the conical section.

Sathe et al. (2010) pointed out that covariance of the fluctuating wind components affects the lidar measured turbulence. However, no correction method was proposed.

Error caused by the spatial separation in LoS

The second source of the error is the spatial separation of the data point along the Line of Sight (LoS).





Tanemoto et al., (2022)

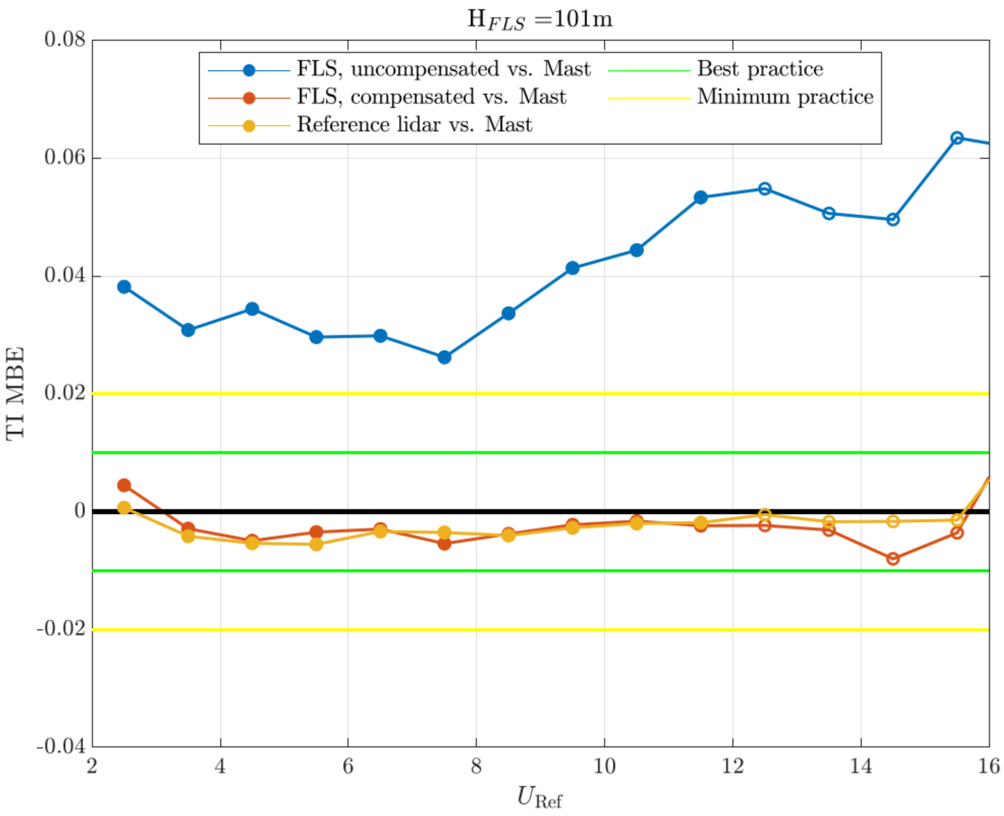
Tanemoto et al. (2020) proposed the correctio method for similar error in dual scanning lidar measurement.

Correction method for vertical lidar is needed.

Validation problem

Kelberlau et al. (2023) compared the standard deviation of wind speed measured by fixed lidar and reference Met Mast based on 1.5 months of measurement campaign in summer.

However, the seasonal variation of the error needs to be investigated and validation by using one year is needed.



Objective

- Investigate the effect of spatial separation in conical section on the standard deviation of the lidar measured horizontal wind speed, and propose a method to solve this problem.
- Propose a correction method for the error caused by the spatial separation in LoS
- Validate the proposed method by using one year of offshore met mast measurement data and investigate the seasonal variation

Lidar measured horizontal wind speed

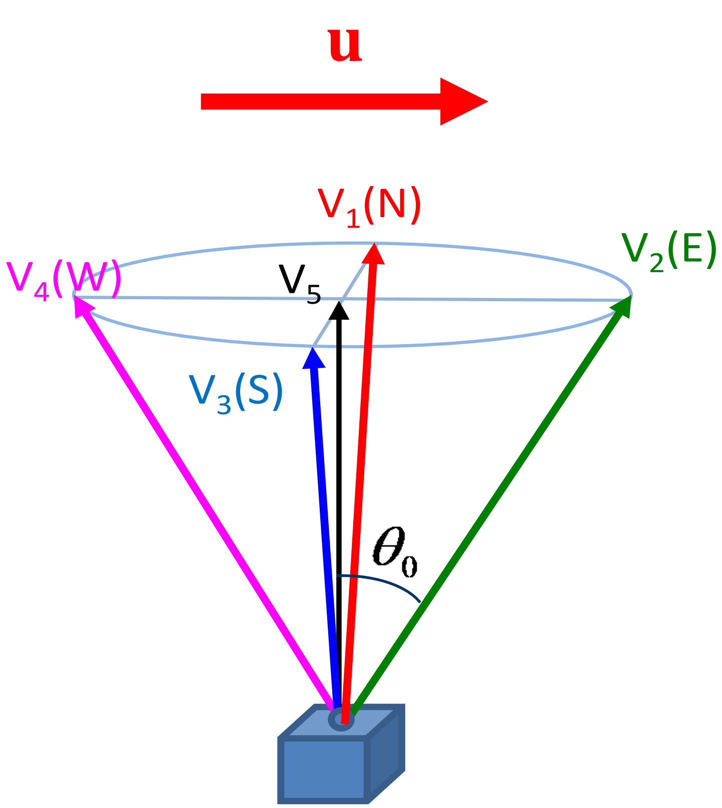
Assume mean wind direction is westerly.

Lidar measured wind speed

$$|\mathbf{u}_{\mathrm{Lidar}}(i)| = \frac{V_{\mathrm{LOS},E}(i-2,2) - V_{\mathrm{LOS},W}(i,4)}{2\sin\theta_0}$$

$$V_{\mathrm{LOS},E}(i,2) = u_2 \sin\theta_0 + w_2 \cos\theta_0$$

$$V_{\mathrm{LOS},W}(i,4) = -u_4 \sin\theta_0 + w_4 \cos\theta_0$$



$$|\mathbf{u}_{\mathrm{Lidar}}(i)| = \frac{1}{2}[(\overline{u_2} + \overline{u_4}) + (u'_2 + u'_4)] + \frac{\cos\theta_0}{2\sin\theta_0}[(\overline{w_2} - \overline{w_4}) + (w'_2 - w'_4)]$$

The variance of lidar measured horizontal wind speed

$$|\mathbf{u}_{\text{Lidar}}(i)| = \frac{1}{2}[(\overline{u_2} + \overline{u_4}) + (u'_2 + u'_4)] + \frac{\cos\theta_0}{2\sin\theta_0}[(\overline{w_2} - \overline{w_4}) + (w'_2 - w'_4)]$$

Assumption: $\overline{u_2} = \overline{u_4} = \bar{u}$ and $\overline{w_2} = \overline{w_4} = \bar{w}$

$$|\mathbf{u}_{\text{Lidar}}(i)| = \bar{u} + \frac{1}{2}(u'_2 + u'_4) + \frac{\cos\theta_0}{2\sin\theta_0}(w'_2 - w'_4)$$

$$\sigma^2_{\text{Lidar}} = \frac{1}{2}\sigma_u^2 + \frac{1}{2}\rho_{uu}\sigma_u^2 + \frac{\cos^2\theta_0}{2\sin^2\theta_0}(1-\rho_{ww})\sigma_w^2 + \frac{\cos\theta_0}{2\sin\theta_0}\left(\overline{u'_2w'_2} - \overline{u'_2w'_4} + \overline{u'_4w'_2} - \overline{u'_4w'_4}\right)$$

$$\rho_{uu} = \overline{u'_2u'_4}, \rho_{ww} = \overline{w'_2w'_4}$$

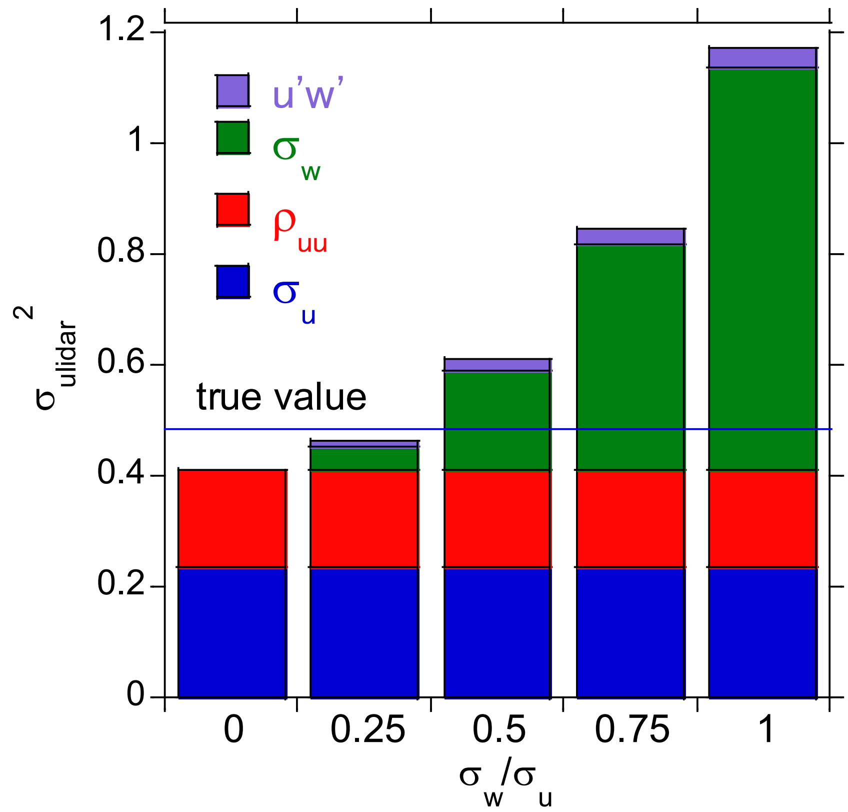
Note: if $\rho_{uu} = \rho_{ww} = 1$, then $\sigma^2_{\text{Lidar}} = \sigma^2_u$

The lidar measured variance for different vertical turbulence

$$\sigma^2_{\mathrm{Lidar}} = \frac{1}{2}\sigma_u^2 + \frac{1}{2}\rho_{uu}\sigma_u^2 + \frac{\cos^2\theta_0}{2\sin^2\theta_0}(1-\rho_{ww})\sigma_w^2 + \frac{\cos\theta_0}{2\sin\theta_0}\left(\overline{u'_2w'_2} - \overline{u'_2w'_4} + \overline{u'_4w'_2} - \overline{u'_4w'_4}\right)$$

The magnitude was evaluated by using synthetic turbulent wind field (Ishihara et al., 2008).

- $\theta_0 = 28°$, z=80m (a.g.l.)
- Mean wind speed 8m/s
- Von Karman spectrum
- Coherence and length scale: IEC61400-1
- $I_2 = 0.8 I_1$
- I_3 =0, 0.25I_1, 0.5I_1, 0.75I_1, 1.0I_1

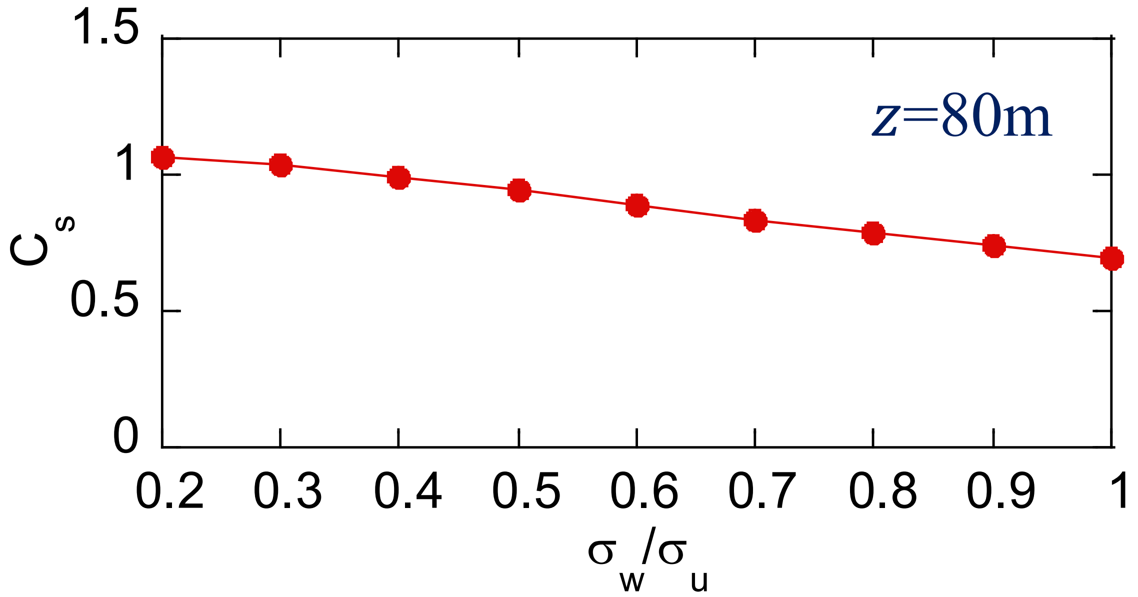


Turbulence measurement is affected by vertical turbulence

Correction of the effect of spatial separation

A correction factor C_s as function of σ_w/σ_u and height (z) is calculated from synthetic turbulent wind field.

$$C_s\left(\frac{\sigma_w}{\sigma_u}, z\right) = \frac{\hat{\sigma}_u(\sigma_w/\sigma_u)}{\hat{\sigma}_{uLidar}(\sigma_w/\sigma_u)}$$



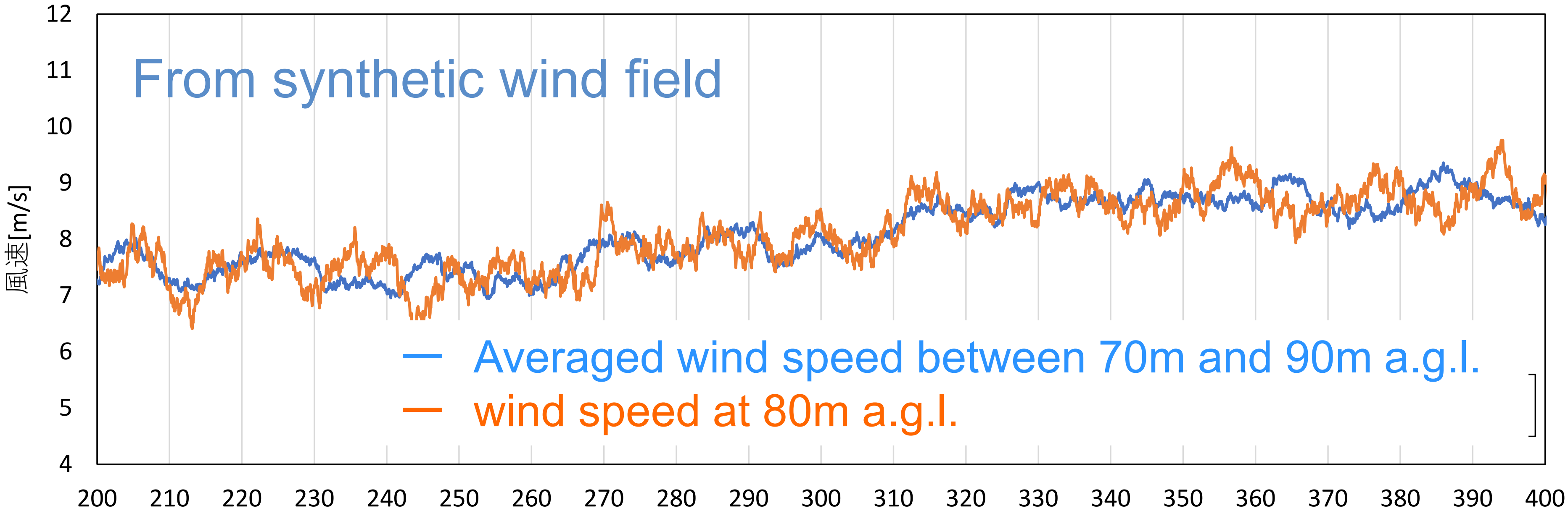
By using this correction factor, the first error can be improved.

The effect of spatial separation along LoS

The lidar measured (LoS) wind speed is averaged over “gate range”.

- 20m for typical pulsed lidar

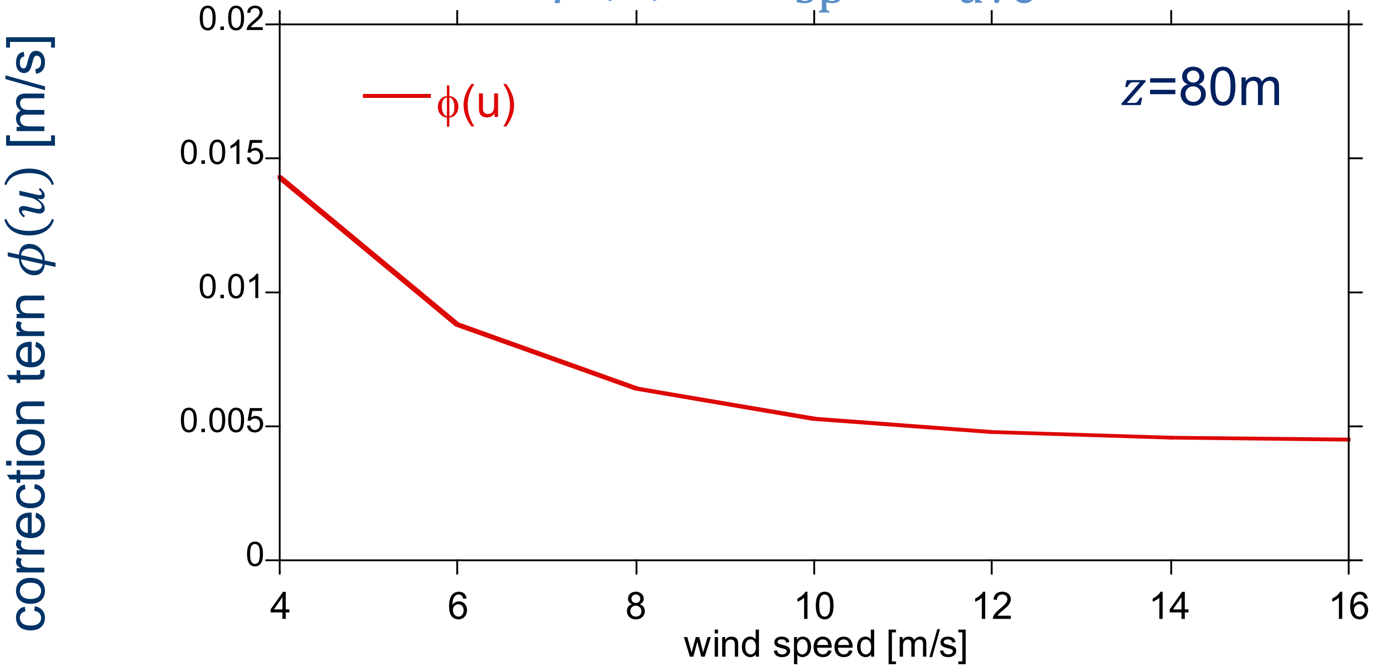
Results in the underestimation of turbulence



Correction of the effect of spatial separation in LoS

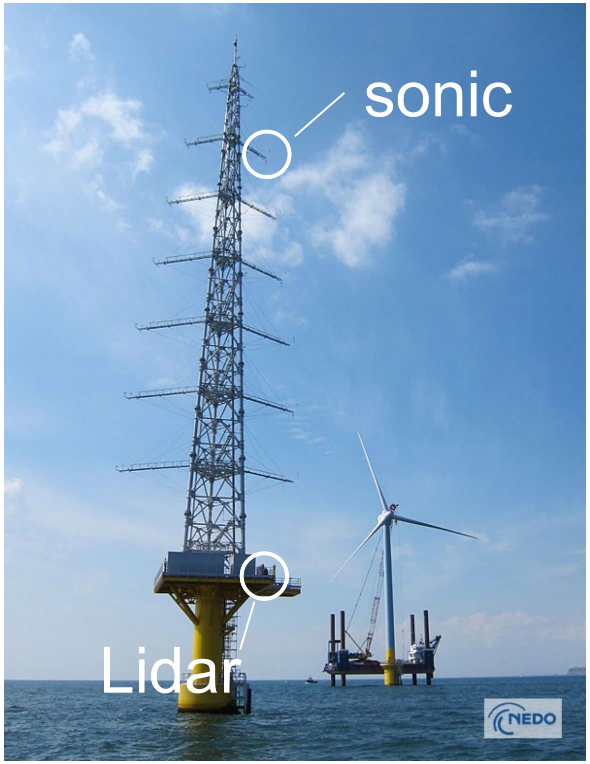
A correction term ϕ as function of mean wind speed (u) and height (z) is calculated from synthetic turbulent wind field.

$$\phi(u) = \sigma_{\text{sp}} - \sigma_{\text{ave}}$$



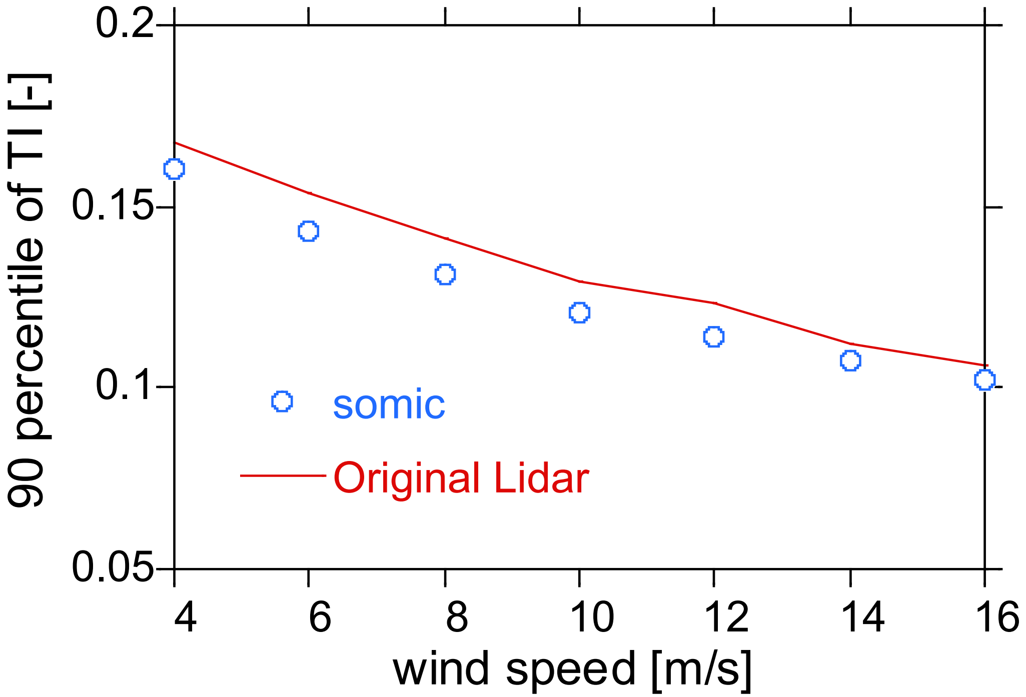
By using this correction term, the second error can be improved.

Validation of the proposed method



Measurement data at Choshi offshore met mast was used for validation

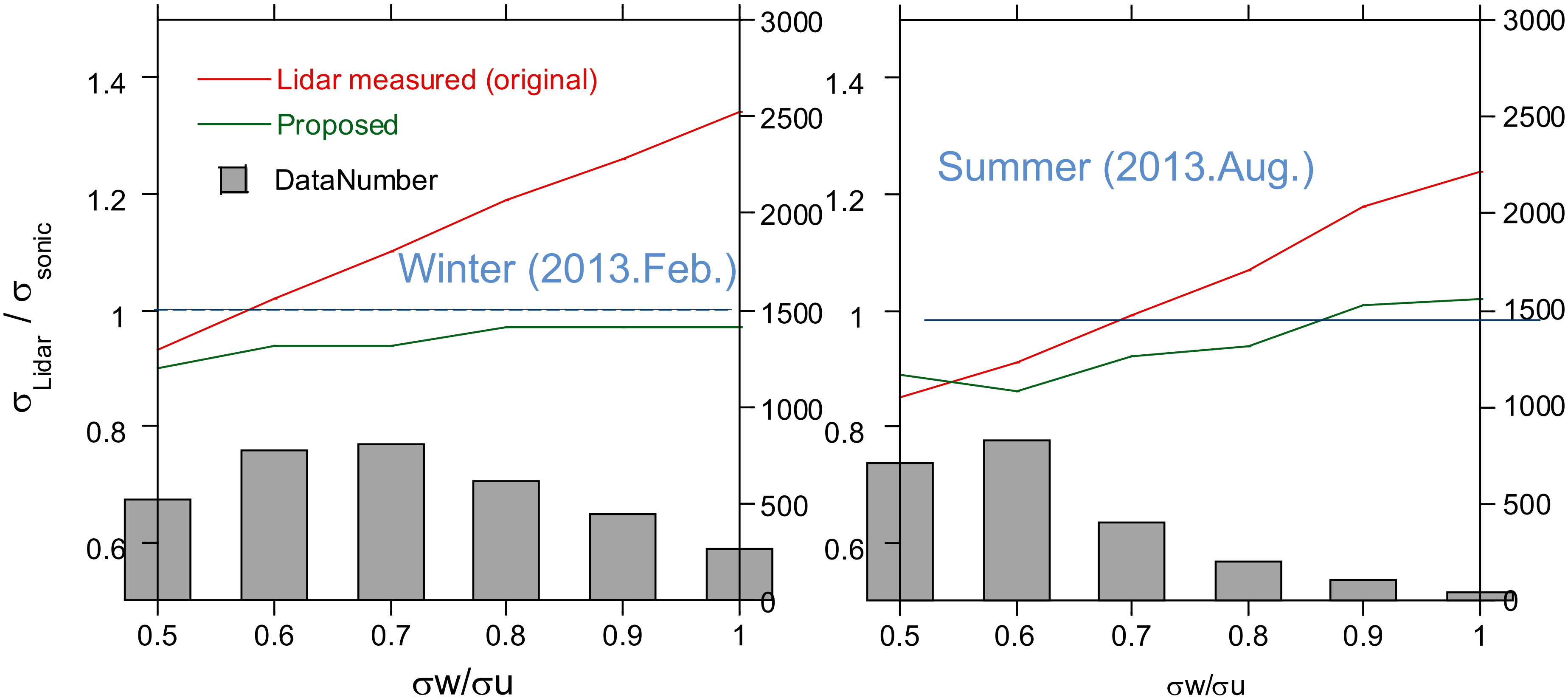
- Sonic anemometer at 80m a.s.l.
- Lidar on the platform



Lidar measured turbulence intensity is overestimated

The seasonal effect

The ratio of lidar measured σ_u and sonic anemometer measurement are bin averaged as function of σ_W/σ_u.

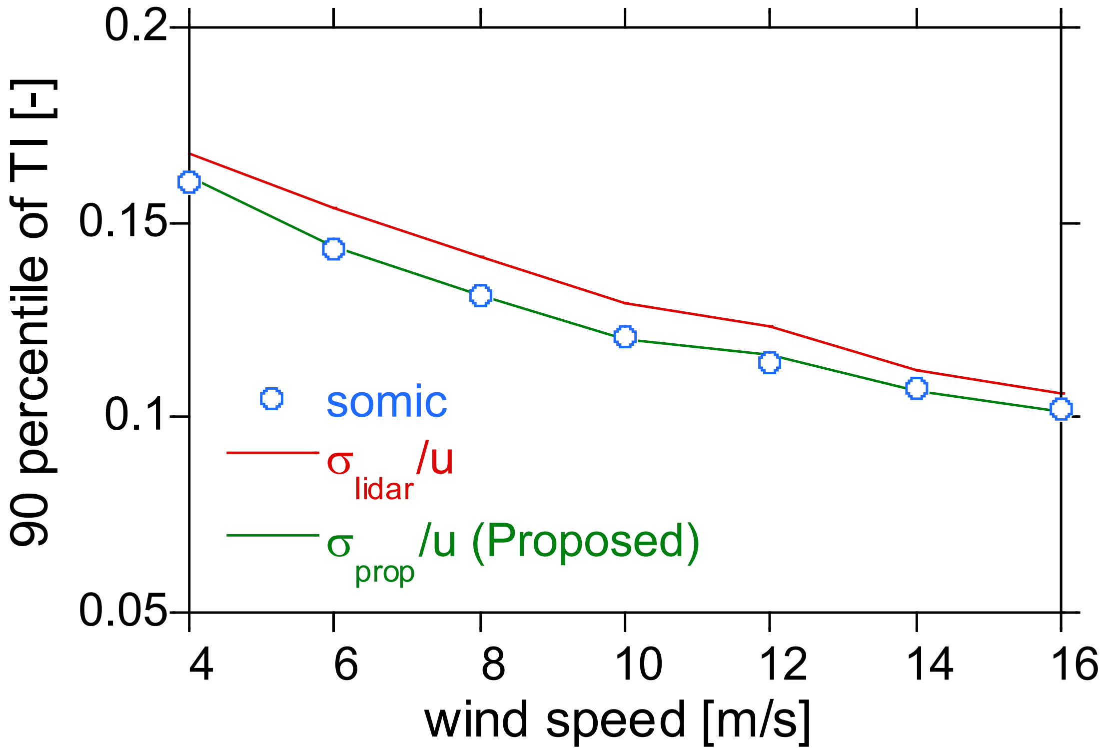


In summer, the overestimation and underestimation can be cancelled each other for higher occurrence rate of lower σ_W/σ_u , but not in winter.

Proposed method application

Correction of the effect of separation in LoS (Range gate) and spatial separation in the conical scan.

$$\sigma_{\text{prop}} = C_s\left(\frac{\sigma_u}{\sigma_w}, z\right)\sigma_{\text{lidar}} + \phi(u, z)$$



Corrected lidar measured turbulence intensity shows good agreement with the sonic anemometer, while without correction, lidar measured TI are overestimated.

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Conclusion

- The main source of the error from the spatial separation in the conical section, is the vertical component of the turbulence. A correction factor is proposed for this problem.

- A correction term is proposed to consider the effect of the separation in LoS in lidar measurement.

- Proposed correction factor and term are applied to the lidar measurement at Choshi met masts. After applying the proposed method, the measured 90 percentile of the turbulence intensity by using the vertical lidar shows good agreement with that measured by sonic anemometer.