Development of an uncertainty model for ship-based lidar measurements

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Introduction and Motivation

Offshore wind characterization

- Offshore sites offer advantageous wind resources compared to onshore:
  - Higher mean wind speeds
  - More stationary
- Scarce offshore measurements → ship-based lidar technology
  - Reduction of cost and complexity of offshore meas. campaigns
  - Characterization of winds along vast regions
  - Not limited to shallow waters

Introduction and Motivation

Ship-based lidar technology

- Lack of reference data to compare with. Two main questions arise:
  - How accurate are these measurements?
  - What is the best configuration for ship-based lidars?

- These questions are addressed in this study by developing an analytical uncertainty model (error propagation method [1]):
  - Not requires comparable/reference data
  - Allow the consideration and combination of the relevant parameters

Materials and Methods

Methodology summary

Setting the equations

Derivation the equations for retrieving wind speed from pulsed Doppler lidar measurements

Introduction of motion effects in the model

Consideration of **ship rotation, translation and tilting** effect in the radial velocity

Derivation of radial velocity uncertainty

Application of **error propagation methodology** to obtain radial velocity uncertainty

Derivation of horizontal wind speed uncertainty

Reconstruction of horizontal wind speed using a **DBS** algorithm and use **error propagation** to obtain horizontal wind speed uncertainty

Materials and Methods

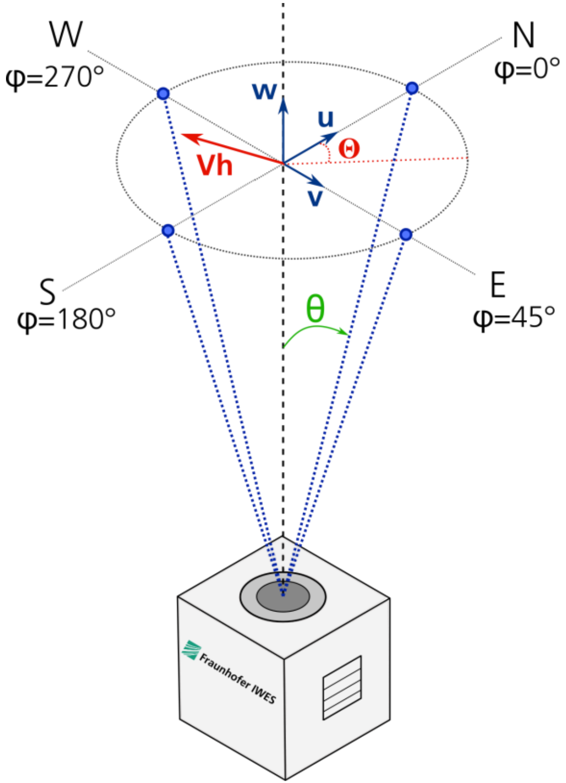
From lidar measurements to wind speed

- The calculation of the radial wind speed calculated as:

$$v_{radial} = \vec{r} \cdot \vec{u}_{wind} = \begin{pmatrix} \sin(\theta)\cos(\varphi) \\ \sin(\theta)\sin(\varphi) \\ \cos(\theta) \end{pmatrix} \cdot \begin{pmatrix} u \\ v \\ w \end{pmatrix}$$

$$u = V_h \cos(\Theta) \qquad v = V_h \sin(\Theta)$$

- With:
  - V_h as the horizontal **wind speed**
  - Θ as the **wind direction** (from which the wind originates)



Materials and Methods

Consideration of the ship motions

- The retrieved radial velocity is affected by the tilting, rotation and translation of the ship:

$$v_{radial}^{meas} = \underbrace{R_{rot} \cdot \vec{r} \cdot \vec{u}_{wind}}_{\text{Wind contribution}} + \underbrace{R_{rot} \cdot \vec{r} \cdot \vec{u}_{ship}}_{\text{Ship translation contribution}}$$

$$\bar{u}_{ship} = \begin{pmatrix} sog^{1} * \cos(cog^{2}) \\ sog * \sin(cog) \\ heave \end{pmatrix}$$

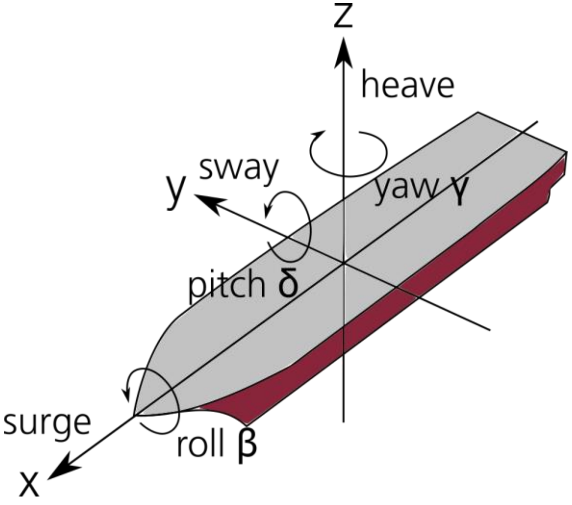


Figure: ship's 6 degrees of freedom

[1] Speed over ground
[2] Course over ground

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Materials and Methods

Radial velocity uncertainty

- For simplification, a separation of the tilting and rotation motions has been done:
  - Consideration of ship rotation → $R_{rot} = R_{yaw}$
  - Consideration of ship tilting → $R_{rot} = R_{roll} R_{pitch}$
- Applying the law of the uncertainty propagation for each case, we obtain the radial velocities uncertainties:

$$U^2_{v^{meas}_{radial}} = \left(U_\gamma \frac{\partial v^{meas}_{radial}}{\partial \gamma}\right)^2 + \left(U_{cog} \frac{\partial v^{meas}_{radial}}{\partial cog}\right)^2 + \left(U_{sog} \frac{\partial v^{meas}_{radial}}{\partial sog}\right)^2$$

$$U^2_{v^{meas}_{radial}} = \left(U_\beta \frac{\partial v_{los,i}}{\partial \beta}\right)^2 + \left(U_\delta \frac{\partial v_{los,i}}{\partial \delta}\right)^2 + \left(U_{cog} \frac{\partial v_{los,i}}{\partial cog}\right)^2 + \left(U_{sog} \frac{\partial v_{los,i}}{\partial sog}\right)^2$$

Materials and Methods

Horizontal wind speed uncertainty

- Using a DBS algorithm, the horizontal wind speed components measured by the lidars can be calculated as:

$$u_{meas} = \frac{v_{los,N}^{meas} - v_{los,S}^{meas}}{2\sin(\theta)} \qquad v_{meas} = \frac{v_{los,E}^{meas} - v_{los,W}^{meas}}{2\sin(\theta)}$$

- And by considering the ship motions effects: $\bar{u}_{wind} = R_{rot} \cdot \bar{u}_{meas} + \bar{u}_{ship}$
- The horizontal wind speed will be then: $V_h = \sqrt{u_{wind}^2 + v_{wind}^2}$
- Applying the error propagation:

$$U_{V_h}^2 = \sum_{i=0}^{n} \left(U_{v_{radial,i}^{meas}} \frac{\partial V_h}{\partial v_{radial,i}^{meas}} \right)^2$$

Where n is the number of lidar beams

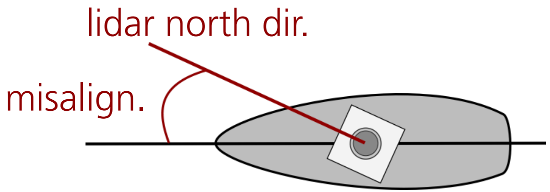
Materials and Methods

Model assumptions

- Vertical wind speed component is small, so it is omitted in the model derivation
- Time scales of motion and orientation changes are longer than the reference time scale
- No shear impact considered

Results

Effect of lidar north misalignment



Parameterization	
V_h	5 m/s
Θ	[0°-360°]
sog	2 m/s
cog	[0°-360°]
γ	[0°-360°]
θ	28°

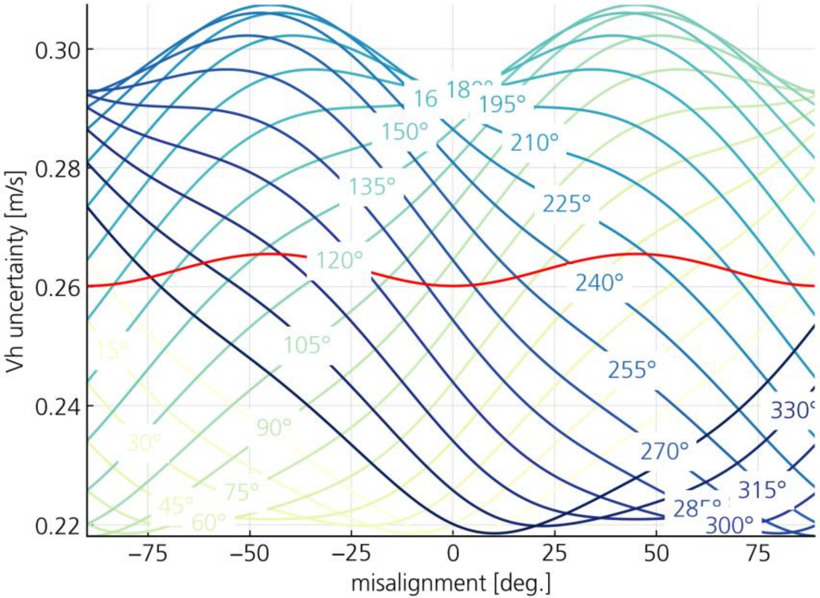


Figure: V_h uncertainty for several cog angles. Red line indicates the overall average uncertainty for all cog angles

- Minimum uncertainty with no misalignment or an offset of ± 90°
- Maximum uncertainty at ± 45°
- The overall average uncertainty (red line) is the same for $\theta = [0° - 90°]$

Results

Effect of velocity ratio

$$velocity\ ratio = \frac{sog}{V_h}$$

Parameterization

V_h	0-15 m/s	cog	0°
Θ	[0°-360°]	γ	0°
sog	0-15 m/s	θ	28°

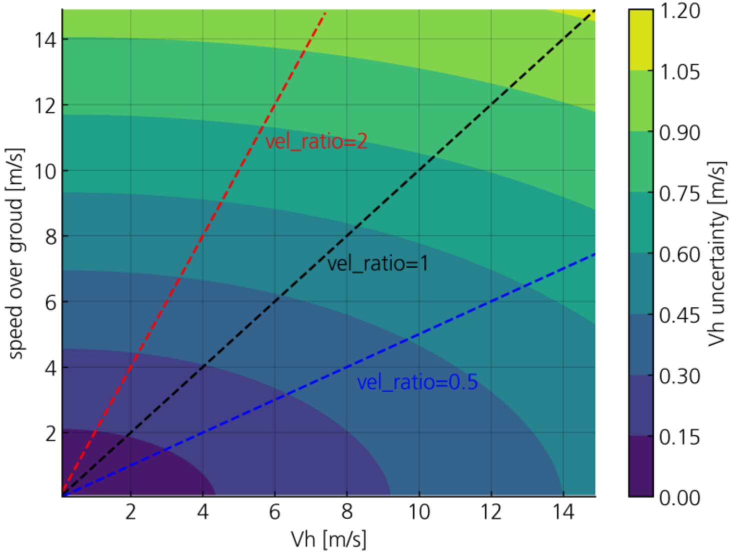


Figure: V_h uncertainty different values of sog and V_h. Red, black and blue lines indicate vel. ratios of 2, 1 and 0.5 respectively

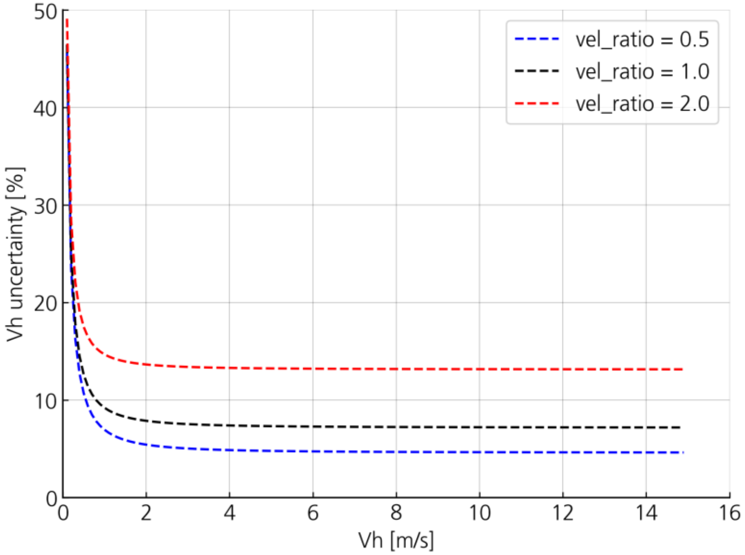


Figure: V_h relative uncertainty for three different vel. ratios

Results

Effect of pitch and roll

Parameterization			
V_h	5 m/s	cog	0°
Θ	[0° - 360°]	pitch, roll	[-10° - 10°]
sog	2 m/s	θ	28°

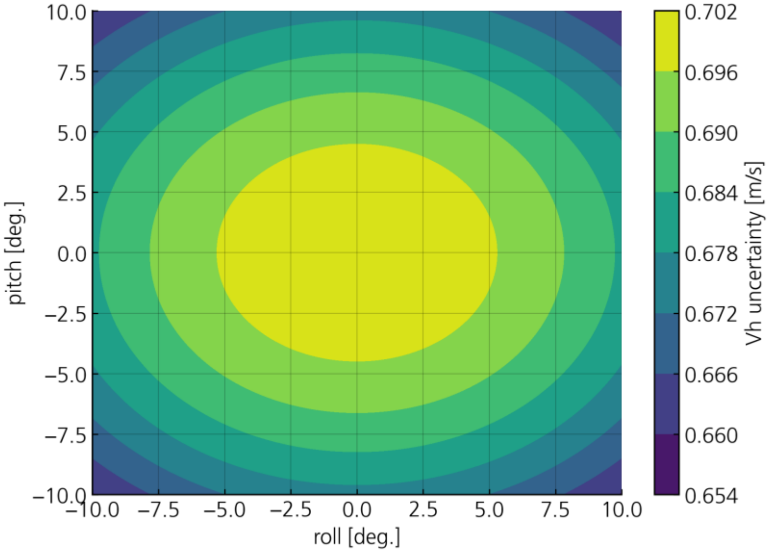


Figure: V_h uncertainty for different pitch and roll values

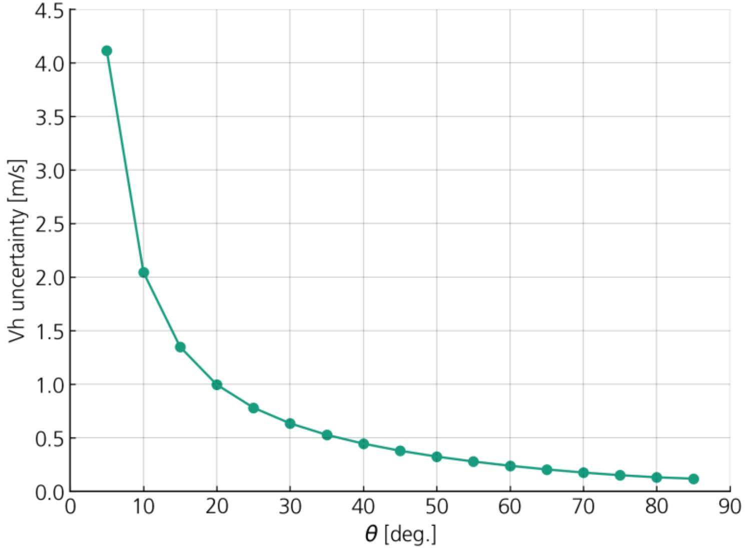


Figure: V_h uncertainty for different cone angles

Conclusions

- The effect of lidar north misalignment is small, but maximum when the offset is ± 45°
    - Increasing the number of lidar beams could help to minimize this effect
- Uncertainty is very high for low horizontal wind speed values
- Increasing the ship velocity with regards to the wind speed considerably increases the uncertainty of the measurements
- Tilting effects slightly affect the wind speed uncertainty. However, smaller pitch and roll values show higher uncertainty levels

Conclusions

- The effect of lidar north misalignment is small, but maximum when the offset is ± 45°
  - Increasing the number of lidar beams could help to minimize this effect
- Uncertainty is very high for low horizontal wind speed values
- Increasing the ship velocity with regards to the wind speed considerably increases the uncertainty of the measurements
- Tilting effects slightly affect the wind speed uncertainty. However, smaller pitch and roll values show higher uncertainty levels
- Further work:
  - Consideration of different lidar technologies and correction methods
  - Include other potentially relevant parameters: heave, shear…
  - Validation of model with real observational data

References

- [1] Joint Committee for Guides in Metrology: Evaluation of measurement data — Guide to the expression of uncertainty in measurement

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Thank you for your attention!

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