Dual lidar: A cost-efficient and operational solution for offshore Wind Resource Assessments

Dominic Champneys

VAISALA

Introduction to dual lidar

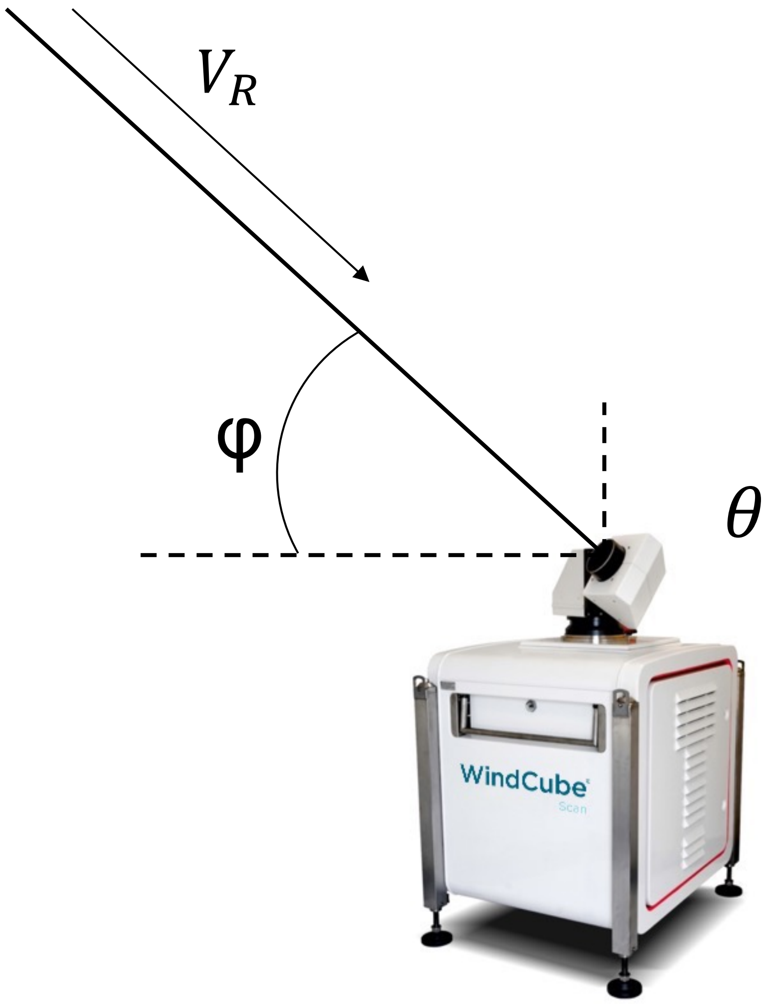
- A quasi-point measurement by pointing two scanning lidars at the same place
  - Can reconstruct the horizontal wind where the two beams intersect
- A series of these measurements (“virtual cups”) can be arranged in a horizontal profile to create a “virtual met mast”
  - One or more virtual met masts can be measured by a single pair of scanning lidars
- Lidars can be placed on the shore for easy installation and access
  - Suitable for many close-shore (10-15km) wind farm developments
  - Otherwise can be placed on offshore platforms

Why dual lidar for an offshore Wind Resource Assessment (WRA)?

- High flexibility to change between several measurement points
  - Can construct several “virtual met masts”
  - Easy to reconfigure to new locations
- Very cost-efficient for the offshore WRA application
  - Cheaper and easier to install than met masts
  - Good alternative to floating lidar solutions when lidars can be placed close enough
  - Can use scanning lidars in another campaign afterward, onshore or offshore
- Drastically reduced dependence on atmospheric homogeneity compared to single scanning lidar reconstruction
  - Results in reduced uncertainties and higher bankability

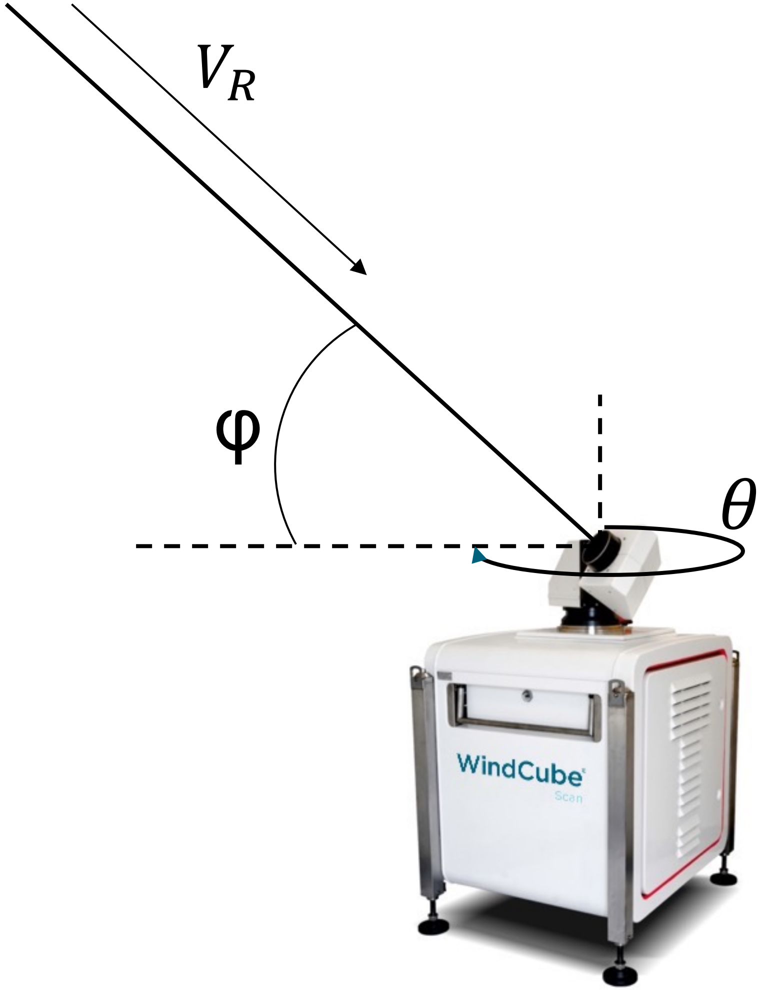
Dual lidar horizontal wind reconstruction

- If the measured radial velocity, V_R, of a single lidar can be expressed in terms of vector components as:
  - $V_R = u.cos\theta.cos\phi + v.sin\theta.cos\phi + w.sin\phi$
  - Where θ is the azimuth angle and ϕ is the elevation angle
- Then we can extend this to a dual lidar setup using the projection matrix **M**:
  - $\begin{bmatrix} V_{R_1} \\ V_{R_2} \end{bmatrix} = \boldsymbol{M}.\begin{bmatrix} u \\ v \\ w \end{bmatrix}$
  - $\boldsymbol{M} = \begin{bmatrix} cos\theta_1 cos\phi_1 & sin\theta_1 cos\phi_1 & sin\phi_1 \\ cos\theta_2 cos\phi_2 & sin\theta_2 cos\phi_2 & sin\phi_2 \end{bmatrix}$
- We can split the vertical wind component from the horizontal:
  - $\begin{bmatrix} V_{R_1} \\ V_{R_2} \end{bmatrix} = \mathbf{M}_{\text{reduced}}.\begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} sin\phi_1 \\ sin\phi_2 \end{bmatrix}.w$
  - $\boldsymbol{M}_{reduced} = \begin{bmatrix} cos\theta_1 cos\phi_1 & sin\theta_1 cos\phi_1 \\ cos\theta_2 cos\phi_2 & sin\theta_2 cos\phi_2 \end{bmatrix}$



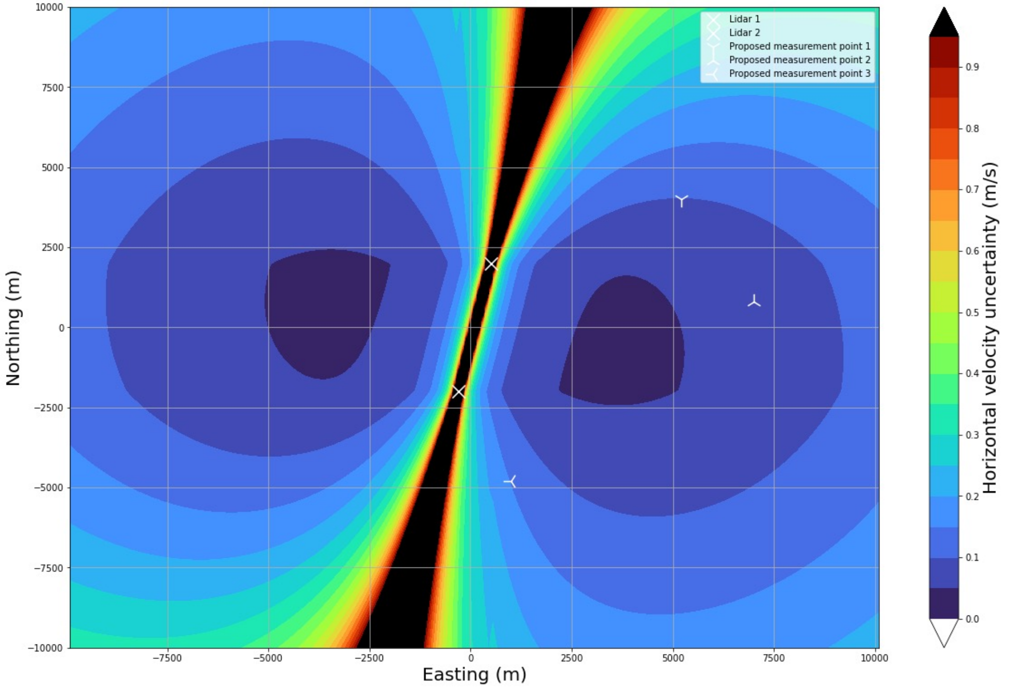
Dual lidar reconstruction accuracy

- To solve the reconstruction equation for u and v, we must assume that the term containing w vanishes to zero either because of vanishing vertical wind speed or elevation angle.
  - $\begin{bmatrix} \hat{u} \\ \hat{v} \end{bmatrix} = \boldsymbol{M}_{reduced}^{-1} \cdot \begin{bmatrix} V_{R_1} \\ V_{R_2} \end{bmatrix}$
  - The hat above the wind components indicates that they are biased by the assumption.
- Evaluating this assumption with respect to disregarding it leads to the equation for reconstruction bias as below:
  - $\delta \begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} \hat{u} \\ \hat{v} \end{bmatrix} - \begin{bmatrix} u \\ v \end{bmatrix}$
  - $\delta V_h = \frac{w}{\sin(\theta_2 - \theta_1)} (tan\phi_1 \sin(\theta_2 - WD) + tan\phi_2 \sin(\theta_1 - WD))$



Dual lidar error model

- Vaisala has developed a theoretical modelling tool that estimates the error of dual lidar measurements as a function of lidar, campaign, and atmospheric parameters.
- The two largest components of dual lidar measurement error are:
  - Reconstruction error
    - Bias introduced by the reconstruction equations
    - Minimized through proper lidar siting relative to the measurement point
  - Shear error
    - Uncertainty introduced by tiny variations in elevation angle causing the beam to measure a different part of the shear profile
    - Minimized through ensuring pointing accuracy

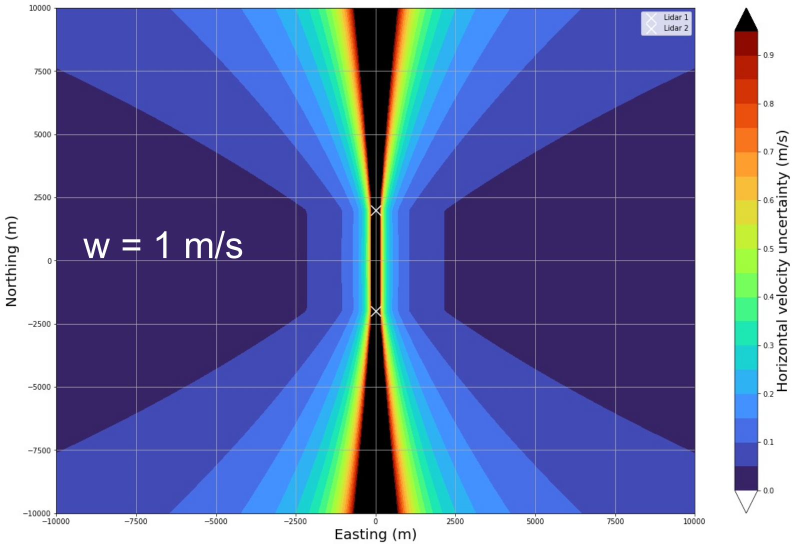


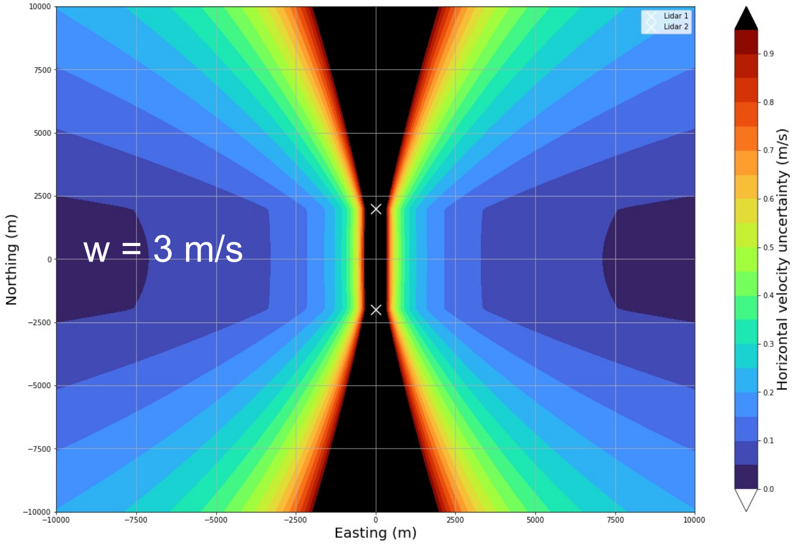
Restricted

Lidar positioning and campaign designs — Relative azimuth angles

- Bias scales with:
  - The inverse of the sine of the difference between the azimuths
  - The sine of the alignment of the azimuths with the wind direction
- In plain English:
  - You must keep the angle between the two beams a good amount from parallel – we recommend at least 30°-150°.
  - Bias is stronger when using high elevation angles – we recommend less than 10°.
  - Bias is also stronger when the wind is aligned with the lines of sight of the lidars.

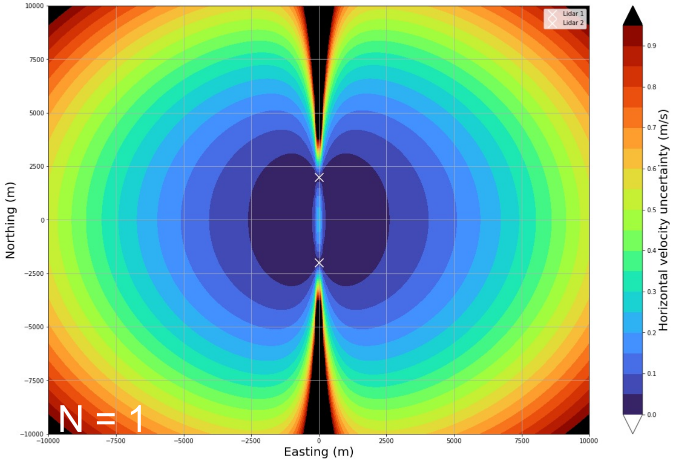
$$\delta V_h = \frac{w}{\sin(\theta_2 - \theta_1)}(tan\phi_1 \sin(\theta_2 - WD) + tan\phi_2 \sin(\theta_1 - WD))$$

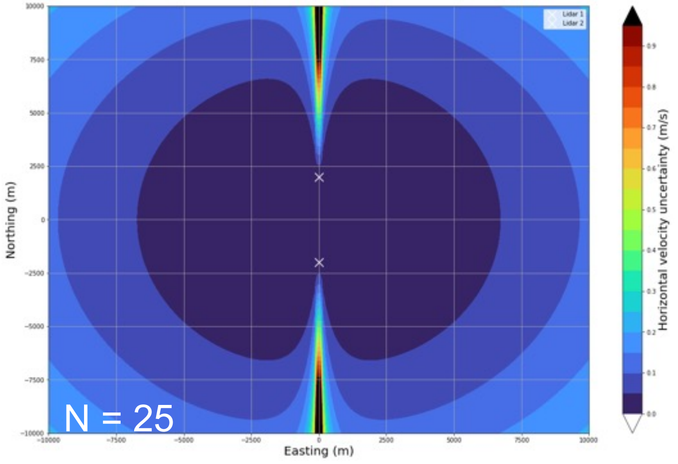




Lidar positioning and campaign designs — Elevation angles and range

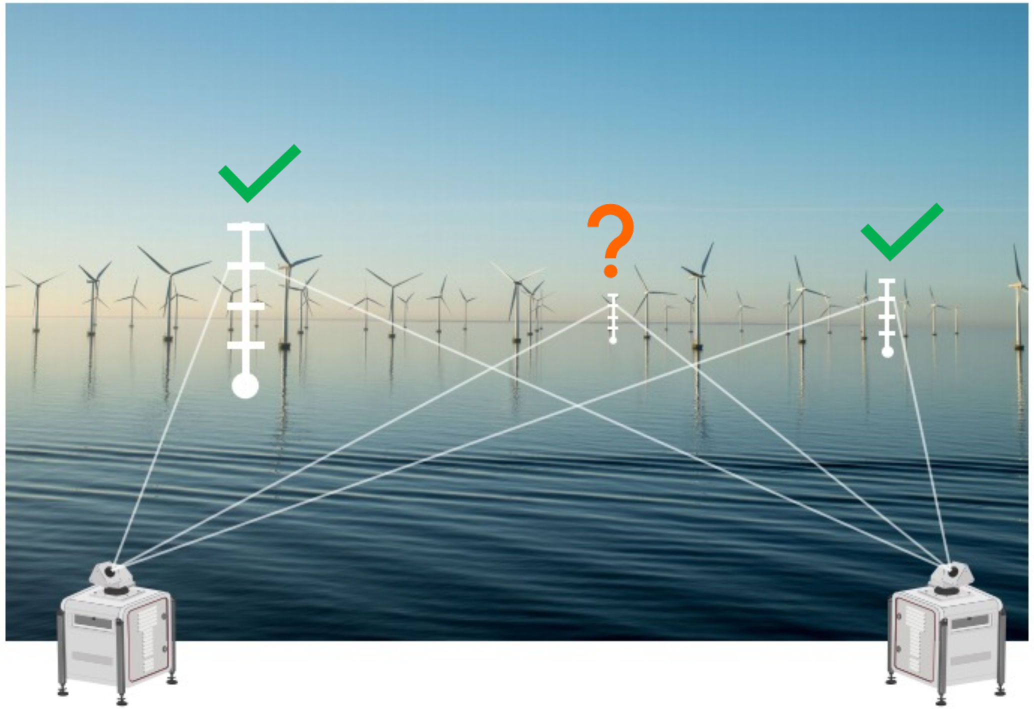
- At high ranges, small deviations in elevation angle can cause you to measure at a different point in the shear profile.
  - 0.1° deviation in azimuth at 10km range = ~17m!!
- As this is caused by random deviations in elevation angle, it is an uncertainty, not a bias.
  - Its effect can be reduced by averaging over 10 minutes.
  - If you want to measure at very long range, it is better to measure fewer points simultaneously and increase your number of samples within the averaging period.





Number of measurement points versus accumulation time

More points targeted → More time to scan all points → Less averaging time per point (for a given averaging period) → Less representative estimation of mean wind

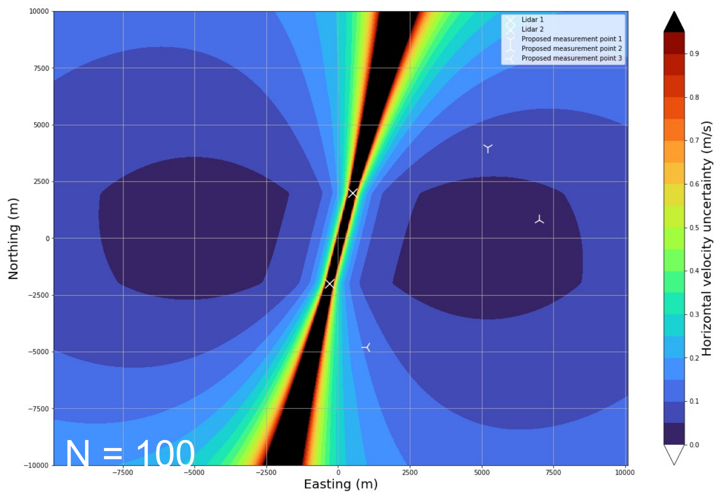


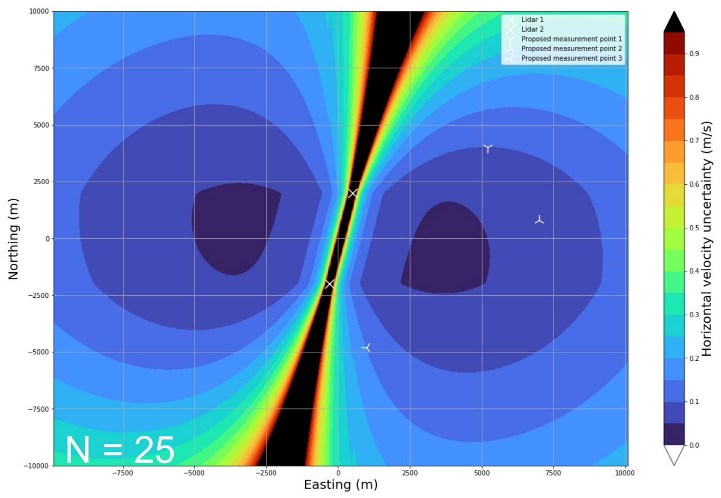
Restricted

VAISALA

Number of measurement points versus accumulation time

Scan configuration	Time taken for one complete scan	Number of samples per 10 minutes	TI uncertainty
1 virtual mast/2 virtual cups	~6s	~100	δTI
2 virtual mast/2 virtual cups	~15s	~40	δTI * 1.36
3 virtual mast/2 virtual cups	~24s	~25	δTI * 1.73





AMERICAN CLEAN POWER

VAISALA

Numerical error estimations for nominal conditions

- Nominal error is estimated, considering the site of a dual lidar validation campaign done by Carbon Trust in 2014 – Dublin Bay
- Parameters:
  - Vertical wind speed = 1.0 m/s
  - Wind direction = 0° (North)
  - Wind shear exponent = 0.11
  - One virtual mast with two measurement heights

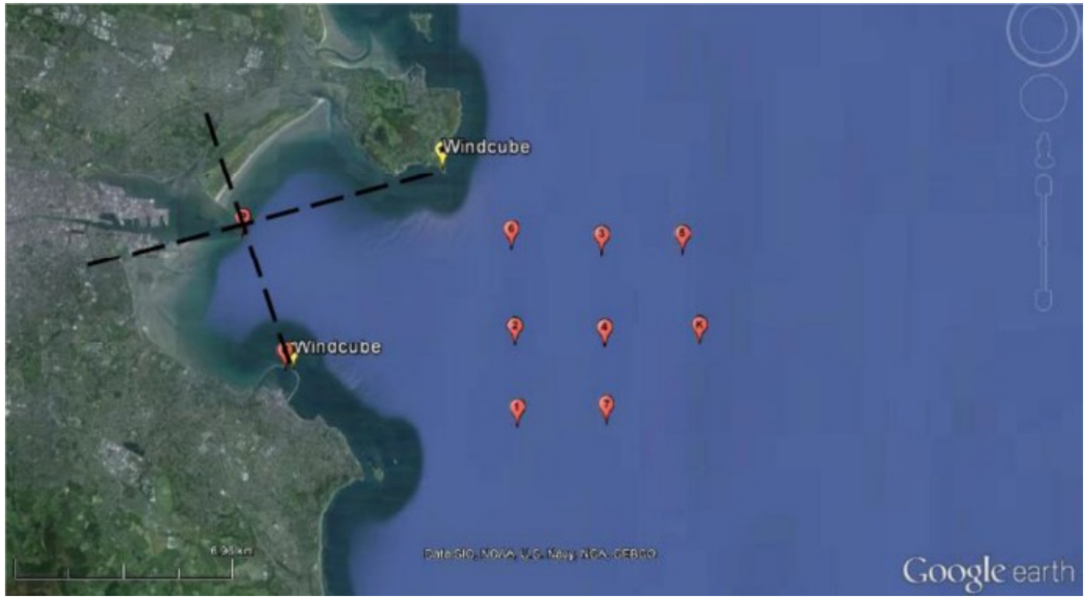
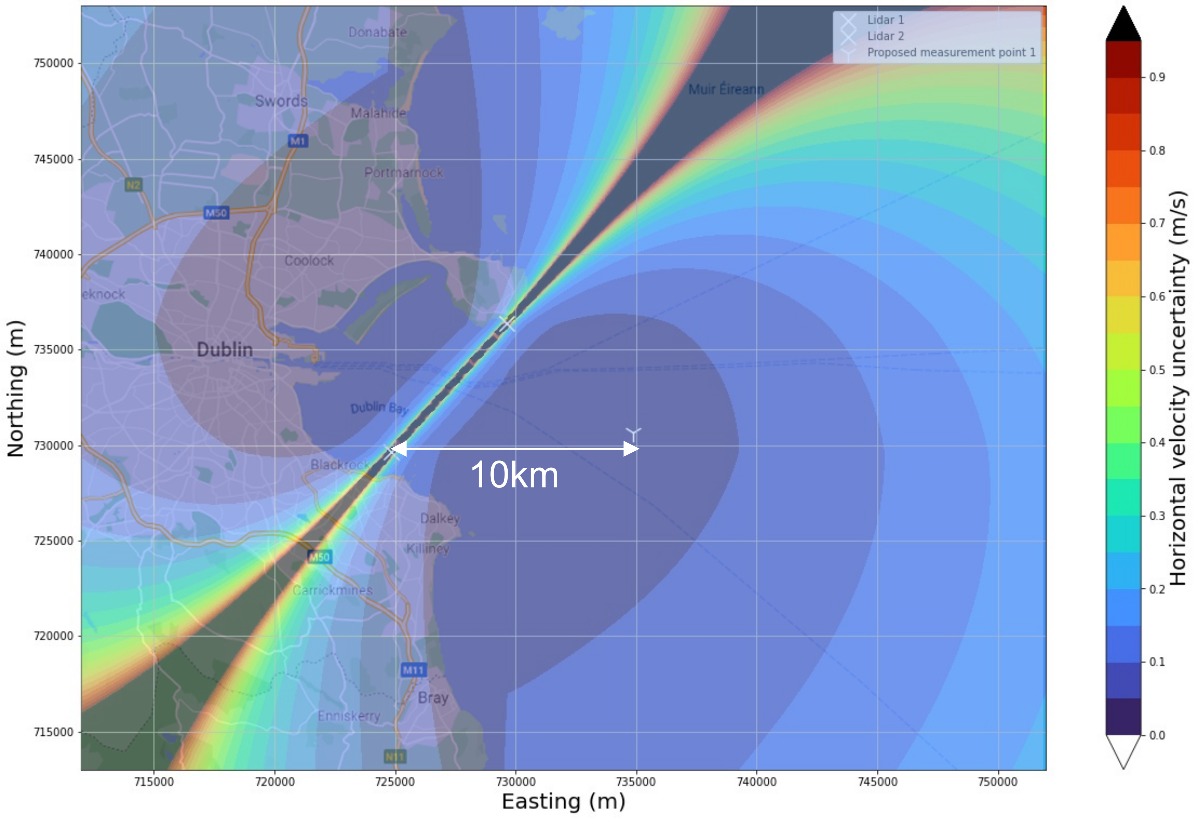


Image source: Cameron, L., Clerc, A., Feeney, S. and Stuart, P., 2014. *Remote Wind Measurements Offshore Using Scanning LiDAR Systems*.

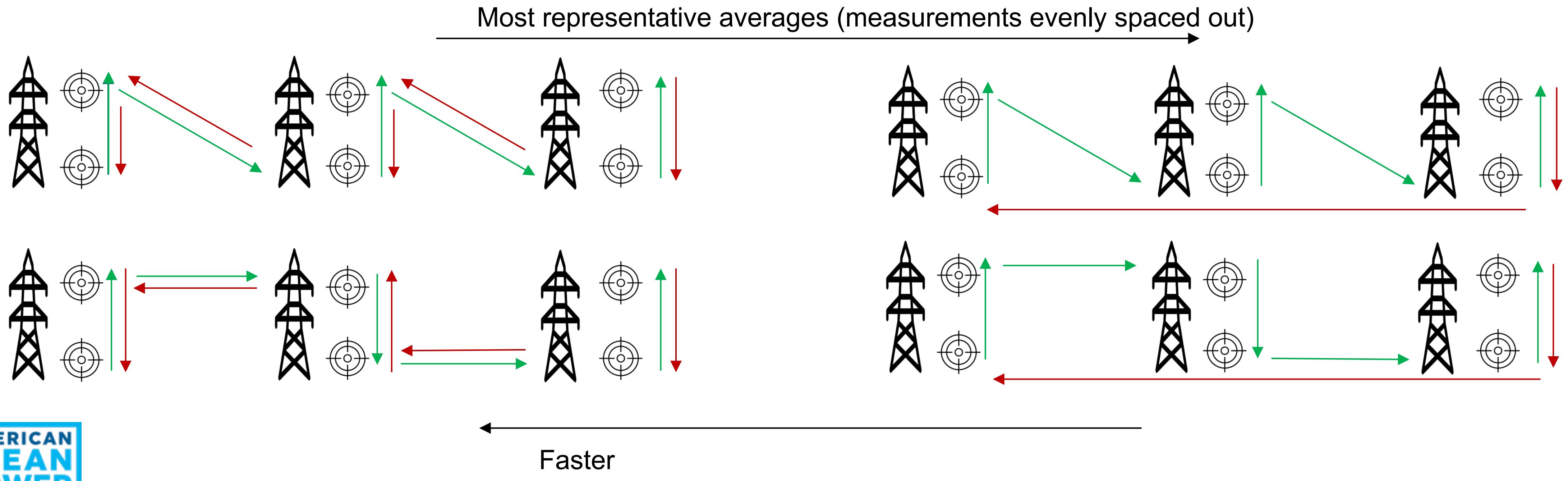
Numerical error estimations for nominal conditions

- Nominal error is estimated, considering the site of a previous dual lidar validation campaign by Carbon Trust — Dublin Bay
- Parameters:
  - Vertical wind speed = 1.0 m/s
  - Wind direction = 0° (North)
  - Wind shear exponent = 0.11
  - One virtual mast with two measurement heights
- Conclusion: errors < 0.1 m/s achievable with proper setup



Scan patterns

- When choosing a scan pattern for multiple virtual met masts, a trade off has to be made between:
  - The fastest pattern (more samples within the averaging period) and
  - The most evenly spaced out (most representative averages)
- From internal tests performed by Vaisala, very few samples can be gained per 10 minutes so representative averages should be prioritized.

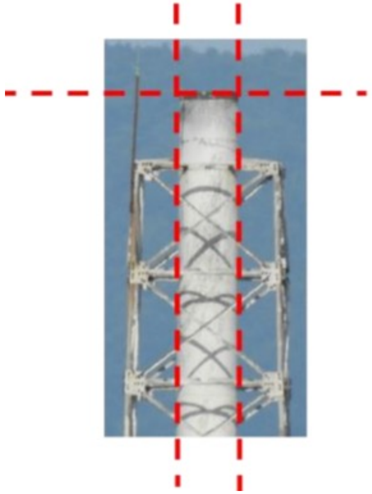


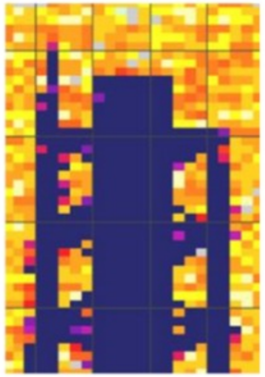
Practical installation guidelines

- Site selection and installation must be done with ensuring pointing accuracy as the highest priority.
  - Transportation recommendations should be followed.
  - The lidar should be installed on firm, flat, and rigid ground that will not change during the campaign (e.g., a concrete platform — not grass or mud).
  - Any constraints attached to the lidar should not be under tension.
- Normal installation procedures for WindCube® Scan must also be followed:
  - Plenty of free space available around the lidar to allow easy access.
    - 3x4m space for initial installation, 3x3m during operation
    - No obstruction to side doors and power converter
  - Reliable and stable internet connection and power supply to maximize technical availability.
  - No obstacles that could obstruct the view of the lidar.
- Vaisala field engineers are on hand to help.

Perfecting the pointing accuracy of WindCube Scan

- The levelling of the lidar can be fine-tuned by adjusting its feet, using the in-built inclinometer.
  - This can achieve an accuracy in pitch and roll of < ±0.1°.
- The levelling should be perfected through calibrating against a hard target, using the carrier-to-noise ratio (CNR) mapper within Vaisala's software.
  - Determine the reference hard target azimuth and elevation using a theodolite — better than Google Maps.
  - If no hard target is available, even a drone can be used.
  - Compare to the angles shown in the CNR mapper and apply offsets to your configuration as necessary.
  - It is possible to achieve an accuracy of < ±0.005°.



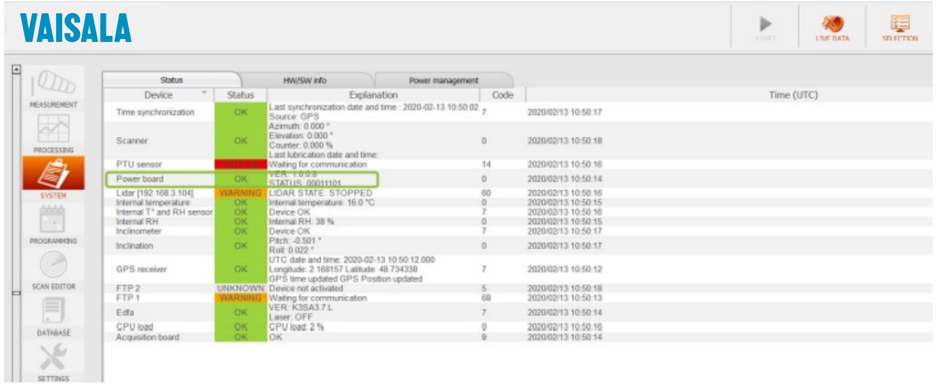


Network and data retrieval recommendations

- Data volumes can be high (GBs per lidar per day) and so considerations should be made toward an efficient "data pipeline."
  - Data should be regularly retrieved, using the API of WindCube Scan — recommended daily.
  - If transferring to Vaisala for reconstruction, data should be regularly uploaded to a pre-configured FTP server or other suitable file transfer service.
- The scans should be programmed according to timing from an NTP server so as to maintain synchronicity.
  - All lidars should have their clocks synchronized to the same NTP server.
  - Define a scanning pattern for each lidar using Windforge.
  - Use Windforge to request the launch of the scanning scenario at specific times.

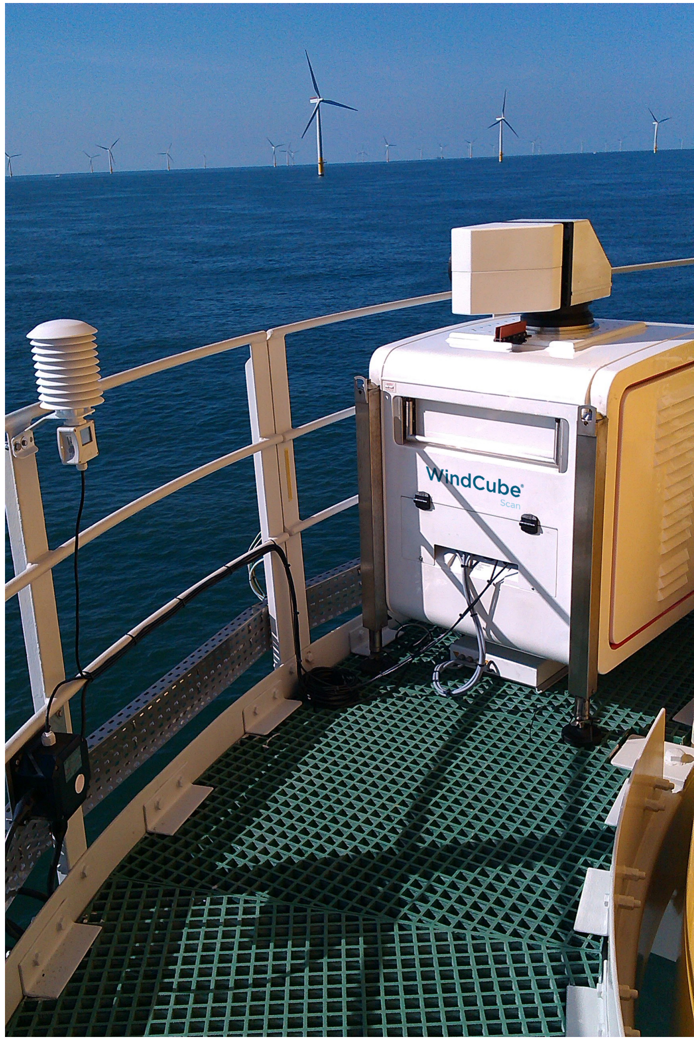
Monitoring and data processing

- If reprocessed by Vaisala, the data provided includes statistical quantities over a 10-minute averaging period of:
  - Radial wind speed
  - Horizontal wind speed
  - Wind direction
  - Turbulence intensity
  - Data availability
    - Combined and individual to each lidar
- Data monitoring during operation is important to maximize technical availability.
  - Monitoring and investigation of data availability
  - Regular checking lidar status and running of diagnostic procedures to ensure proper lidar functioning
  - Regular CNR mapping to ensure pointing accuracy is maintained
  - Also available as a service provided by Vaisala



Conclusions

- Dual lidar is robust, flexible, and cost-effective for offshore WRAs.
  - Commercial dual lidar projects with our customers are already underway.
  - Verification process against met mast is available.
- Attention must be paid to the siting, setup, and operation of a dual lidar campaign.
  - Uncertainties of less than < 0.1m/s can be achieved.
  - Particular care must be taken to ensure pointing accuracy and data availability is maximized.
  - Models of error are available.
- WindCube Scan is designed to be suitable for the dual lidar application.
  - Guidelines and support can be provided by Vaisala during your project.



VAISALA