Below the clouds:

Taming a weather-related measurement error of floating LiDAR systems.

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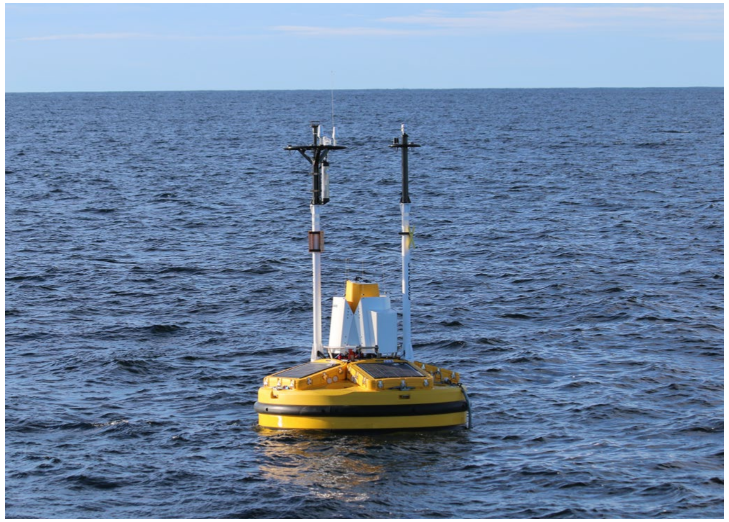
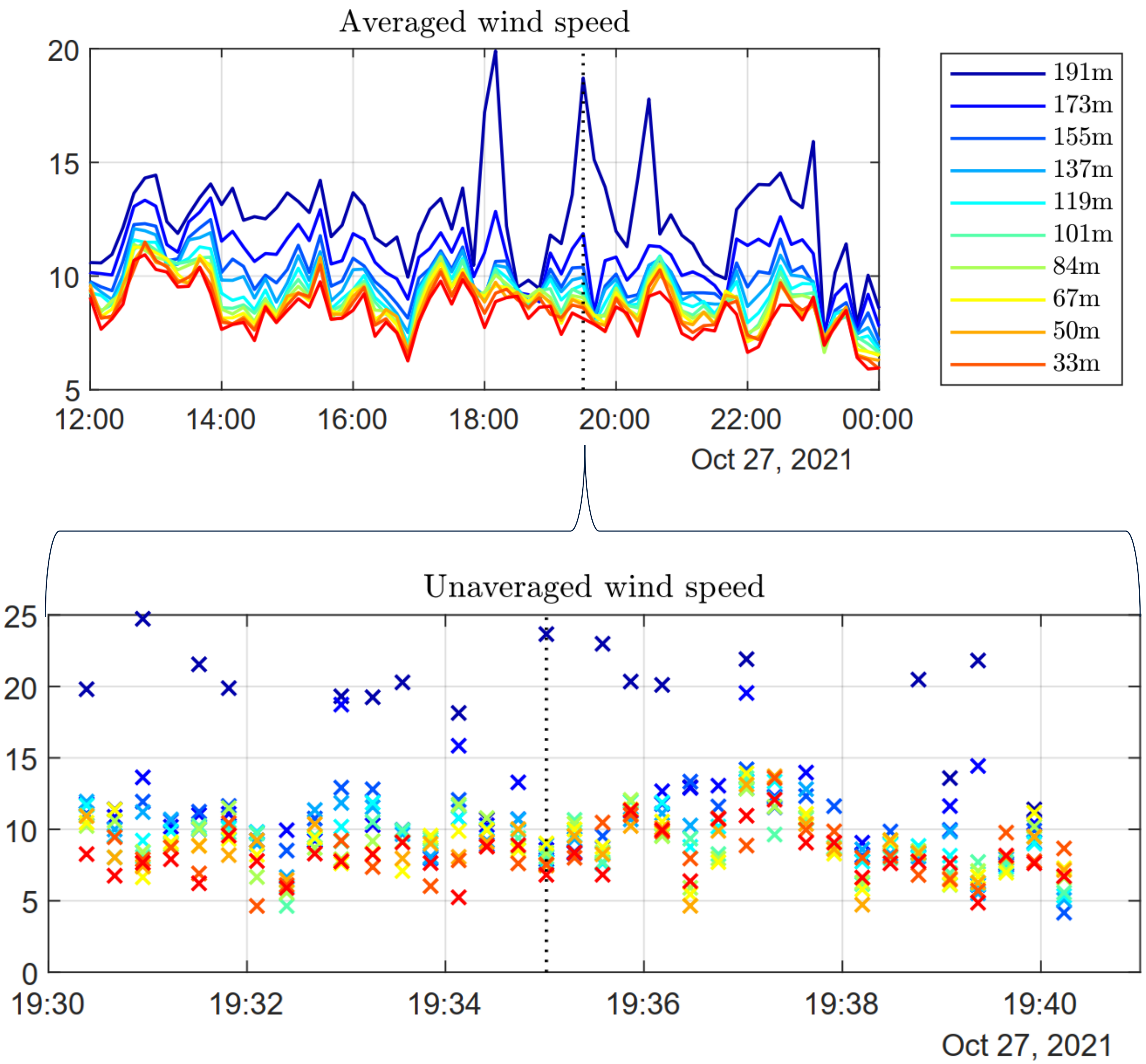
EERA DeepWind '24, 17.01.2024

SEAWATCH Wind LiDAR Buoy



- 100 units built
- 120+ successful independent third-party assessed sea trials
- Highest commercial maturity rating (Stage 3)
- Best-practice data accuracy up to 250m

Measurement error



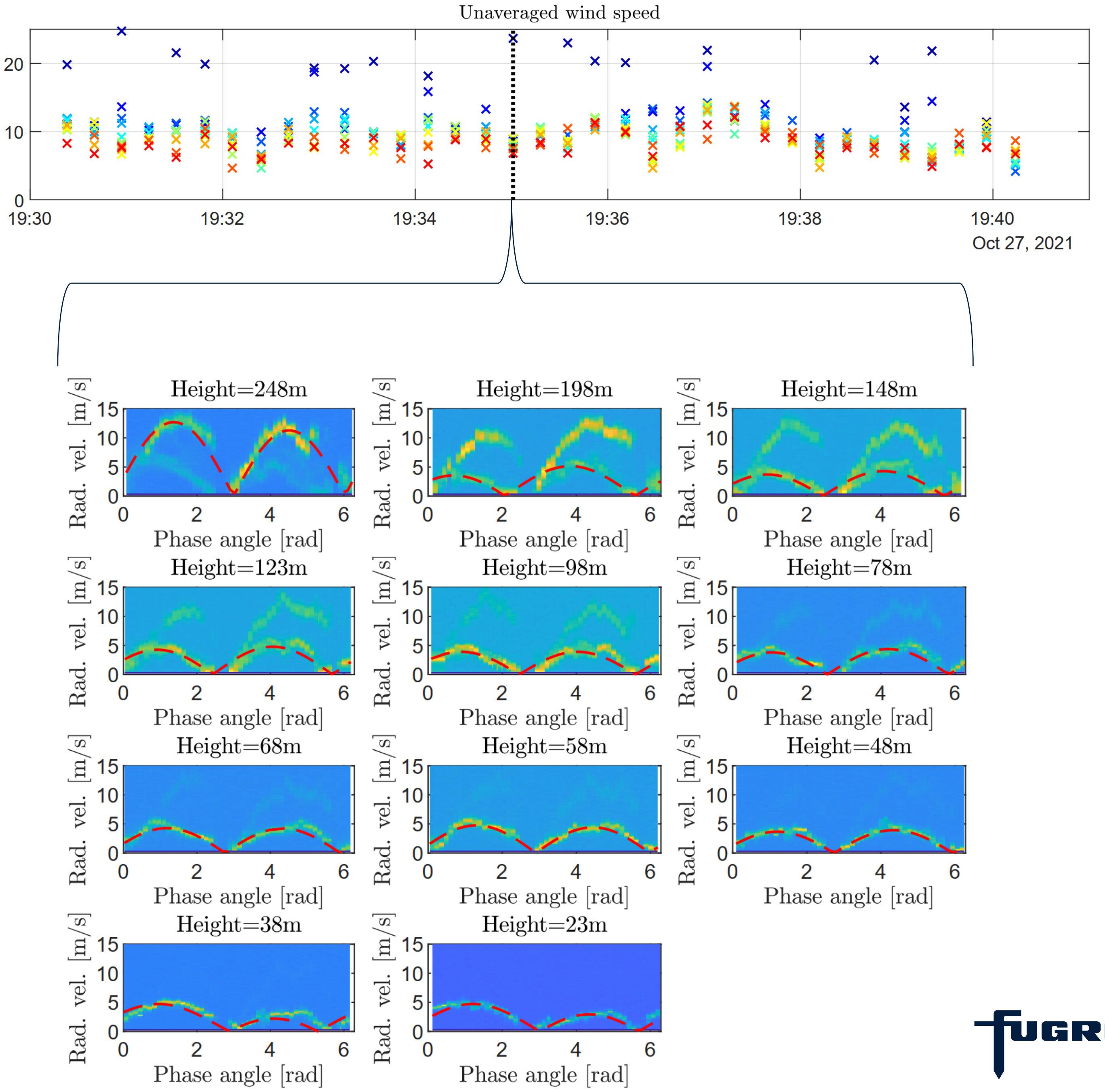
Unfiltered lidar data

Example time series with too high wind speed at highest measurement elevations

Measurement error

LiDAR **Doppler spectra** of the same wind vectors

- Rayleigh length increases with measurement height.
- High aerosol density above focus height appears like low aerosol density at focus height.
- Cloud speed well above the measurement elevation can dominate Doppler spectra.



FUGRO

Measurement error

Summary:

1. Low optical **focus precision** at high elevations
2. **Strong backscatter** from above measurement elevation (clouds)
3. **Cloud detection and removal** identifies cloud signature in Doppler spectra
4. **Buoy motion** disturbs this detection and removal
5. **Cloud speed** might be measured instead of wind at measurement elevation

Cloud detection and removal procedure:

- Speed of clouds far up measured by defocused LiDAR beam
- Cloud signature is removed from Doppler spectra at measurement height
- But: **Under influence of motion, cloud signature might not be found in Doppler spectra from measurement heights**

➢ Large measurement error if…

1. Atmospheric wind shear and veer are high and…
2. Cloud layer is far above the intended measurement height.

	Weak wind shear	**Strong wind shear**
Clouds close	*Small impact*	*Small impact*
Clouds far	*Small impact*	***High impact***

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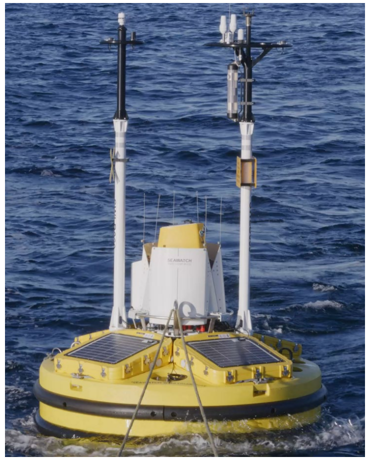
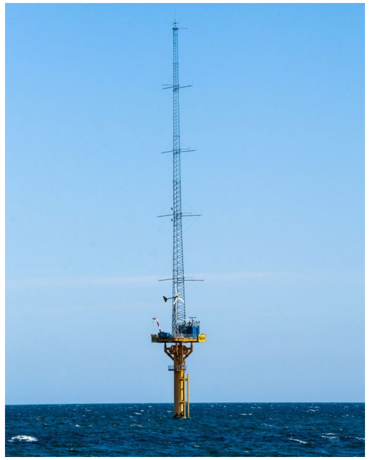
Offshore trial setup

National Offshore Anemometry Hub at Blyth, UK



Credit: ZX Lidars



Credit: ORE Catapult

Floating Lidar System

- SEAWATCH Wind Lidar Buoy
- 11 Elevations up to 193m

Fixed Reference Lidar

- ZX 300 on transition piece
- 11 Elevations up to 193m

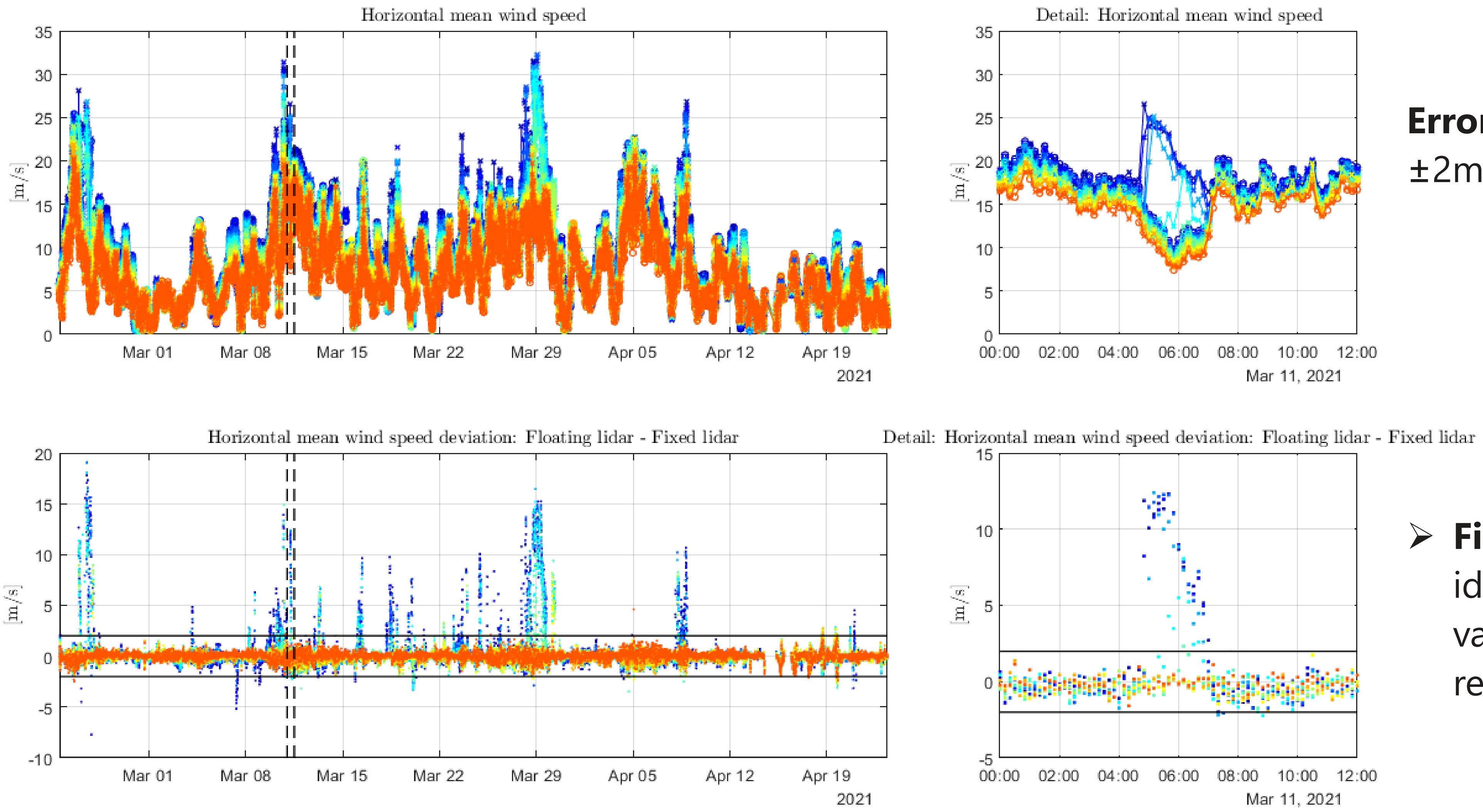
Meteorological Mast

- Cup anemometers
- 5 Elevations up to 103m

Effects of motion at all elevations

Mast not high enough for meaningful comparison

Measurement results



Error definition:
±2m/s deviation

- **Filter needed** that identifies erroneous values without need for reference data

Tested filters

1. **Relative spread** of mean wind speed profile exceeds threshold
   - $\frac{\sigma(U_h)}{\overline{U_h}} > 0.2; \qquad U_h = U_1 \dots U_H$
   - ➢ Filter entire profile

2. **Linear shear** gradient exceeded
   - $\frac{\Delta U_h}{\Delta h} > 0.125 \frac{\mathrm{m}}{\mathrm{sm}}$
   - ➢ Filter 10-min values above exceedance

3. **Power- and linear-law** fail
   - Speed at higher height exceeds complex prediction based on lower heights
   - ➢ Filter 10-min values above exceedance

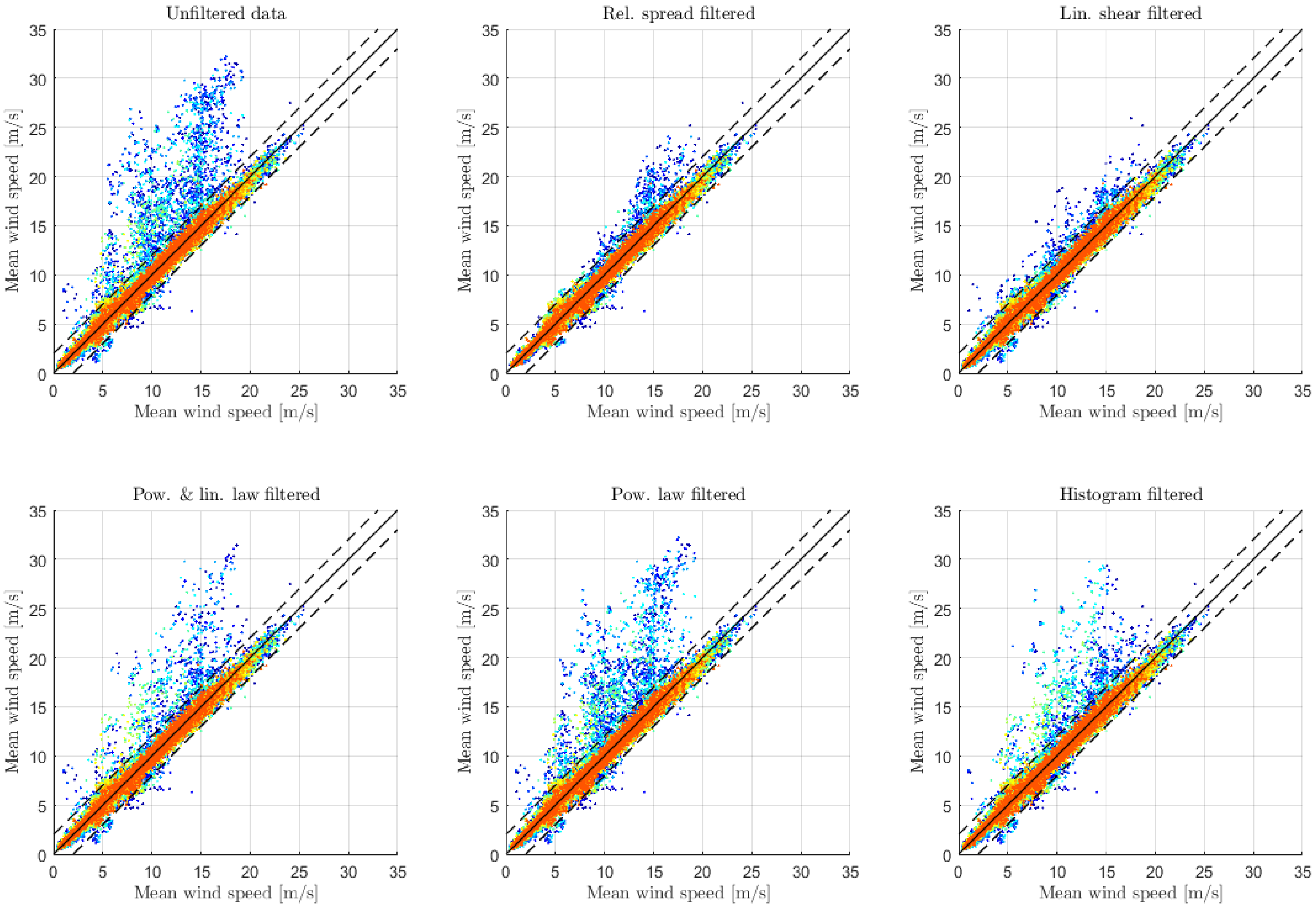
4. **Power-law** fit (Reference)
   - $\frac{U_{meas} - U_{pred}}{U_{pred}} > 1.08$
   - ➢ Filter 10-min values > 20m/s and above 150m

(Filters 1–4: 10-min averaged wind data)

5. ***Histogram** analysis of unaveraged wind data*

These filters are either described in literature, suggested by lidar OEM, used by third-party assessor, or developed by Fugro

Scatter plots



Linear regression results reward strict filtering that reduces data availability

Filter performance

1. Sensitivity:

   Ratio of all bad values filtered successfully

   E.g., 90% means 90% of bad values were removed by filter

2. Specificity:

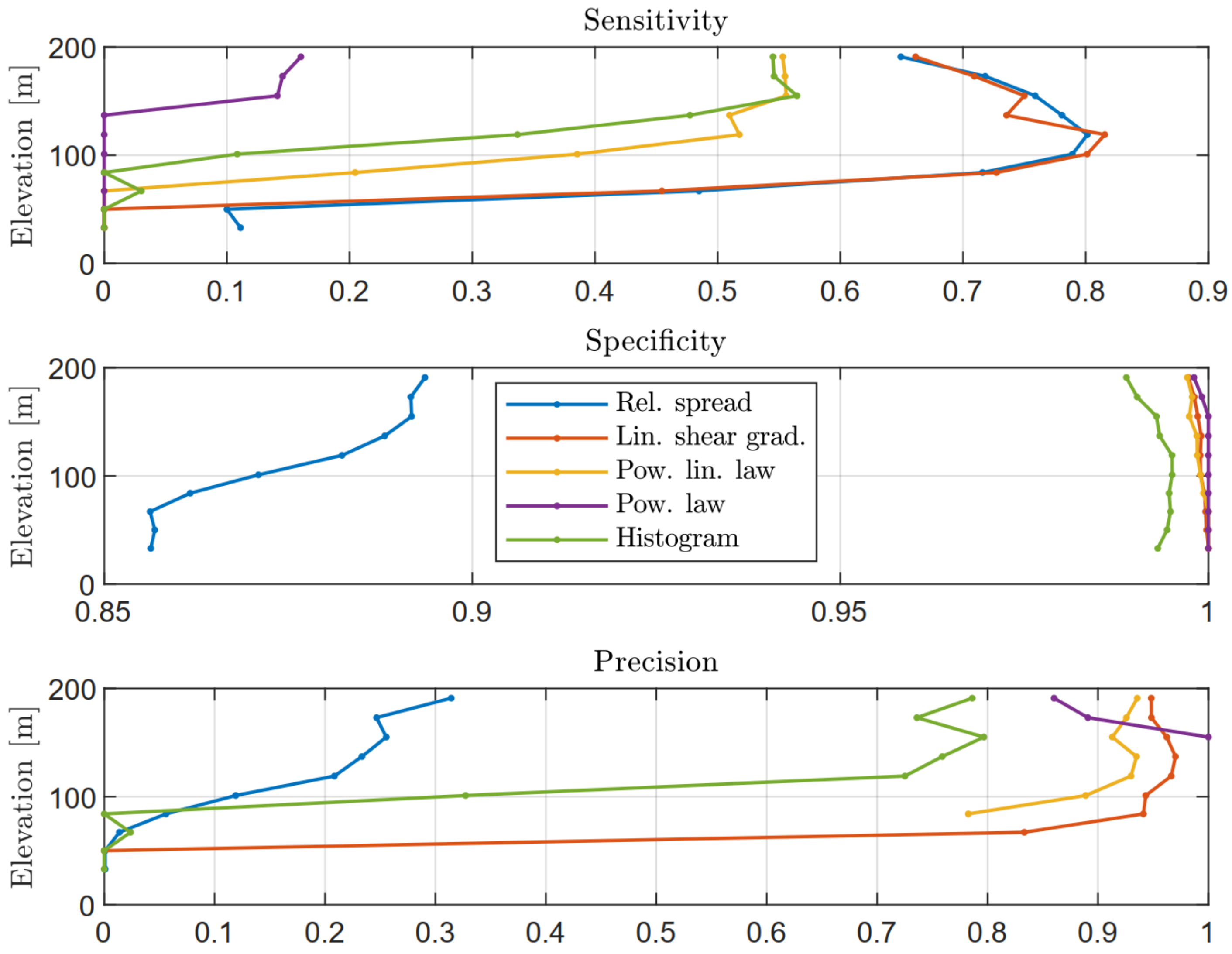
   Ratio of all good values remaining after filtering

   E.g., 90% means 10% of all good data is filtered falsely

3. Precision:

   Correctly filtered of all filtered values

   E.g., 90% means only every 10th filtered value is a false positive

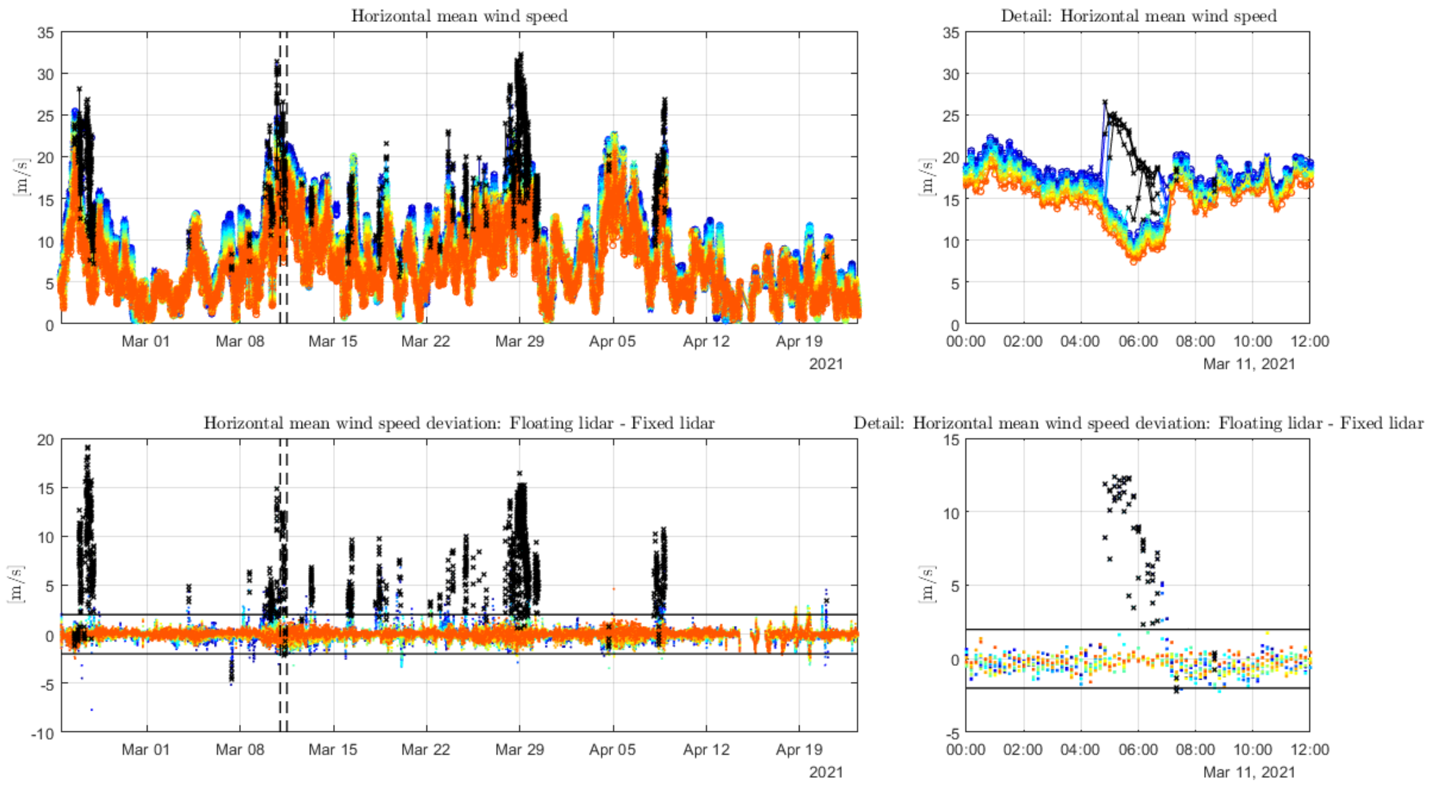


Linear shear gradient filter

Description:

For each 10-minute interval calculate the linear shear gradient between measurements at neighboring elevations (lowest and second lowest, second lowest and third lowest…).

If the linear shear gradient at one elevation exceeds 0.125 m/s per meter elevation, then filter horizontal mean wind speeds at this elevation and all elevations above.



This filter shows best performance of all tested filters

Conclusions

- Floating continuous-wave profiling wind lidar can measure wrong mean wind speeds if
  - Wind shear is significant above the measurement elevation
  - Clouds are present above the measurement elevation

- Excessive linear shear gradients (i.e., >1.25 m/s per m) are a well-suited indicator for detecting these events

- Manual expert assessment will further improve filtering results

ZX Lidars has just proposed a new filter. Not yet tested.

Linear shear gradient filter realization (MATLAB)

```
% WS_FLS10:     Matrix of 10min wind speeds [m/s] as measured by the floating lidar, rows: 10-min intervals, columns: measurement elevations in descending order (invalid values=NaN)
% FLS_heights:  Vector of measurement elevations [m] in descending order

k=0.125;                                  % Linear shear gradient threshold for filtering

WS_FLS10_interp=fillmissing(flip(WS_FLS10,2),'linear', 2,'SamplePoints',flip(FLS_heights),'EndValues','none’);
                                          % Interpolate invalid wind speed values between values at the lowest and highest elevation; ascending order (Interpolated
                                          % values will only be used for the filter, not for the actual dataset)

shear=diff(WS_FLS10_interp,1,2);          % Linear wind shear [m/s] between adjacent measurement elevations
grad=diff(flip(FLS_heights));             % Vertical gradient [m] between adjacent measurement elevations
shear_grad=shear./grad;                   % Linear wind shear gradient [(m/s)/m] between adjacent measurement elevations
shear_filter=abs(shear_grad)>k;           % Set filter flag if linear wind shear gradient exceeds k

[rc(:,1), rc(:,2)]=find(shear_filter==1);
for i=1:length(rc)
        shear_filter(rc(i,1),rc(i,2):end)=true;     % Set filter flag for values vertically above already flagged values
end

shear_filter=flip([false(length(shear_filter),1), shear_filter],2);   % Do not set flag for values from lowest elevation (since they don’t have a shear gradient) and flip back into descending order
shear_filtered=WS_FLS10;                  % Copy WS_FLS10 values to new matrix shear_filtered
shear_filtered(shear_filter==true)=NaN;   % Set all flagged values to NaN
```

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