Offshore wind farm flow measured by complementary remote sensing techniques: radar satellite TerraSAR-X and lidar windscanners

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Abstract. Scanning Doppler lidar systems offer continuous wind measurements with some kilometres of range and a spatial distribution of concurrent measurements down to some metres. The synthetic aperture radar (SAR) satellite TerraSAR-X is capable to cover offshore areas of hundreds of square kilometres and to obtain wind data spatially distributed with some tens of metres. Images can be taken up to twice a day when the satellite passes the measurement site. Simultaneous wind speed measurements with ground based scanning Doppler lidar and TerraSAR-X in the region of the offshore wind farm “alpha ventus” in the German North Sea were collected. A comparison of both systems in free stream conditions is performed by extrapolating the lidar data to the measurement height of the radar satellite assuming a logarithmic wind profile. In wake conditions the wake tracks obtained by lidar and TerraSAR-X are compared. In free stream conditions the comparison reveals a mean absolute wind velocity difference ≤ 0.4 m/s in two of the four considered cases and 1.1 m/s in one case. The fourth case shows a bad agreement due to a unusually low radar backscatter in the satellite’s measurement. In wake conditions the wind turbine wakes could be tracked in the lidar and the satellite data. The comparison for the considered case reveals similar wake tracks in principle, but no matching due to the time difference of the measurements and the lower spatial resolution of the radar measurements.

1. Introduction
Remote sensing technologies offer the opportunity to study atmospheric quantities like the wind velocity over large areas. Especially Doppler lidar has become an important tool for wind energy related research in the last years with application onshore [1, 2] and offshore [3, 4]. Ground-based lidar windscanners enable the measurement of vertical profiles or horizontal planar scans of the radial wind speed within a range of several kilometres. Typical lengths of sampling volumes in radial direction (range gates) are about 30 m. Dynamic flows can be resolved with a spatial distribution of range gates of some metres. Scan durations take seconds to minutes depending on the used settings. Investigations on wind turbine wakes using scanning lidars onshore [5, 6] and offshore [7] have been reported.
Another remote sensing technology to measure wind speeds is space-born synthetic aperture radar. The German synthetic aperture radar satellite TerraSAR-X (TS-X) scans the surface of the earth with image resolutions of down to one meter. Using the intensity of the backscattered signal from the sea surface the wind field at 10 m height is calculated using an empirical geophysical model function. The obtained wind fields can have resolutions as high as a few tens of meters. Results have already been validated against buoys equipped with anemometers at low measurement heights and the results of the German Weather Service (DWD) atmospheric model and have proven an accuracy of 1.5 m/s [8]. Wakes of offshore wind farms have already been investigated using SAR satellites [9, 10].

To our knowledge ground based lidar and radar satellite have been validated only against single point measurements or weather models, a direct comparison of the methods against each other has not been performed so far.

The contribution presents the comparison of concurrent measurements of the wind field in and around the offshore wind farm "alpha ventus" in the German North Sea taken with TerraSAR-X and a lidar system. The analysis is done separately for areas with undisturbed flow and those influenced by wakes. To obtain comparable data, the lidar measurements are extrapolated to the 10 m height level of the TS-X wind speed, using a logarithmic wind profile. Both data sets are interpolated to a reference grid for comparison.

2. Methods

2.1. Lidar measurements

Three scanning long range Doppler lidar systems of type Leosphere Windcube200S were operated in the offshore wind farm "alpha ventus" in the German North Sea. One lidar was located on the wind farm’s sub station, two were positioned on the nearby research platform and meteorological mast "Fino1". The layout of the wind farm is shown in Figure 1. The lidar systems are described in [6].

All lidar systems were operated in the so-called PPI (plan position indicator) mode, scanning a wide azimuth range using a small fixed elevation angle $<1^\circ$ leading to increasing measurement heights with distance. The scanning speed was set to $1^\circ$/s with an averaging time of 1 s. All systems scanned the whole azimuthal range excluding some sectors with blocked sight. Each lidar recorded 198 range gates equally spaced from 100 m to 6000 m range. The pulse length of the lidar systems was set to 400 ns corresponding to a probed length of approx. 75 m.

The filtered line of sight wind (LoS) speeds of one lidar PPI scan are plotted in Figure 2, the distribution of the LiDAR measurement points over height are shown in Figure 4. For the
comparison with TS-X in free stream conditions data from the lidar located on the sub station of the wind farm is considered.

2.2. Radar satellite TerraSAR-X measurements
The X-band synthetic aperture radar (SAR) satellite TerraSAR-X sends radar pulses to the earth’s surface. From the ocean, the radar pulse is returned to the sensor mainly by Bragg-Scattering from capillary waves in the centimetre scale. These small scale waves are directly related to the wind flow and therefore it is possible to relate the radar back scatter and the 10 m surface wind empirically via geophysical model functions (GMF). However, the GMF coefficients need to be tuned for every satellite, which is an extensive and cumbersome process and which demands a large and representative dataset. The empirical wind algorithm for TS-X is called XMOD2 and it has been successfully validated against buoy measurements [8]. An example of a wind field calculated from a TS-X image at "alpha ventus" is shown in Figure 3. For the measurement campaign radar images were taken simultaneously to the lidar measurements on four different dates in January 2014. As TS-X operates on a dawn/dusk orbit, measurements were done around 6:00 (UTC) for three dates and 17:30 (UTC) for one date, respectively. From the radar images, wind fields with a spatial resolution of 60 m have been calculated using the XMOD2 algorithm.

![Figure 2. Line of sight wind speeds scanned by one long range lidar located on the sub station in "alpha ventus".](image1)

![Figure 3. Image of the 10 m wind field in the "alpha ventus" region calculated with XMOD2 from an image of the radar satellite TerraSAR-X.](image2)

2.3. Data analysis
To compare both measurement systems the data has to be preprocessed. Particularly a calculation of absolute horizontal wind speeds from the lidar data and an extrapolation to the 10 m height of the TS-X data is performed. Before the comparison a linear interpolation of both data sets to a standard grid is done. All lidar data is filtered for bad CNR (carrier to noise ratio) values and a maximum time lag to the measurement of TS-X of 120 s first. Some corrupt data points e.g. at the location of hard targets are removed by hand. Furthermore the field is divided to be in free stream or to be affected by the wind farm wake dependant on the wind direction.

For the data analysis, the atmospheric conditions around the wind farm "alpha ventus" are
needed. Since the meteorological mast "Fino1" was in the wake of the wind farm in all situations considered here, the parameter for the assumed logarithmic atmospheric boundary layer \( z_0 \) (c.f. Equation 2), the ambient wind direction and wind speed were taken from the operational analysis data from the COSMO-DE numerical weather prediction model. COSMO-DE uses a time step of one hour and a spatial resolution of 2.8 km [11], so just one grid point located in the wind farm region is considered.

To calculate the absolute horizontal wind from the lidar’s line of sight measurement, all measured LoS wind speeds are transformed to the mean horizontal wind direction obtained from COSMO-DE using

\[
v = v_{\text{LoS}} / \cos \alpha
\]  

with \( \alpha \) being the angle between the LoS direction and the wind direction. The error of this method increases with the angle \( \alpha \) and therefore sectors with \( |\alpha| > 40^\circ \) are not used in the further analysis. A correction for the small elevation angle is not performed. Next all measured lidar data is transferred to a planar polar grid with centre at the lidar’s position and a resolution of 60 m in radial and 1° in azimuthal direction. In each grid point the average height of the measured range gates and the corresponding average horizontal wind speed \( v \) are calculated.

Then all wind speeds are extrapolated to the height \( z = 10 \) m using the logarithmic wind profile for neutral conditions

\[
v(z) = v_m \frac{\ln z / z_0}{\ln z_m / z_0}
\]

with height \( z \), the measurement height \( z_m \), the wind speed in measurement height \( v_m \) and the surface roughness \( z_0 \). Offshore, the surface roughness is dependent on the swell. Typical values range from \( z_0 = 1 \cdot 10^{-5} \) m to \( z_0 = 1 \cdot 10^{-3} \) m [12].

The model used in Equation 2 is valid for a neutral stratification of the atmosphere. Due to a lack of dependable data neither of the actual stratification nor the predominant wind profile, it was chosen for all considered cases. To compare this assumption against measured data Figure 4 illustrates suitable lidar data available for heights from approx. 30 m to 90 m obtained from lidar and TS-X for free stream conditions on the 19.01 and 22.01. Lidar values are grouped in bins with 5 m height and for each bin mean value and standard deviation are calculated. The neutral logarithmic profile (c.f. Equation 2) is plotted using the bin average at 57.5 m height as reference.

The high variation in wind speed of the lidar data is supposed to result mainly from the spatially distributed measurements in the variable flow field. The spreading is increased by the error occurring from the transformation of the LoS measurement to the absolute wind speed \( v \) according to Equation 1 which increases with \( \alpha \).

Of course the used model could just be a first approximation. Nevertheless, in this case a check of the used logarithmic model is not possible since no data in the most critical heights regarding wind shear was available. In future applications the predominant wind profile should be measured directly especially at lower heights.

For comparing wind speeds of lidar and TerraSAR-X in free stream conditions, the spatial average and standard deviation of the extrapolated wind speeds of each system on the standard grid are calculated. Additionally the mean difference of lidar and TS-X wind speeds is determined. Furthermore lidar and radar satellite are compared to the meso scale weather model COSMO-DE.

In wake conditions the comparison has to be performed differently. The logarithmic wind profile used to transfer the wind speeds of the lidar to the height of the TS-X values does not hold valid in wake conditions. So a comparison of wind speeds is not meaningful. Therefore the analysis is limited to the comparison of wake positions. For that purpose lidar and TS-X data are interpolated to a Cartesian grid covering the wake area downstream of the turbine. The
maximum deficit of the wake is searched in several distances down stream fitting Gaussians to lines perpendicular to the wake.

3. Results and discussion

3.1. Free stream

Figure 5 illustrates the absolute horizontal wind speed in 10 m height on the standard grid obtained from lidar and radar satellite. It can be directly seen, that the mean wind speed calculated from the lidar measurement (6.4 m/s) is about 1.1 m/s higher than the one from TS-X (5.3 m/s). This is assumed to result mainly from the extrapolation of the lidar measurements to 10 m height, since no information on the predominant wind profile was available. The standard deviations of lidar and TS-X compare well with 0.39 m/s and 0.36 m/s respectively. Aside the speed difference most of the structures in the flow can be found to be very similar in both plots. The TS-X wind field looks a little bit smoother than the one from the lidar due to the lower spatial resolution of the original data being interpolated on the standard grid. These promising results benefit from the low time difference in the regarded case of ≤ 30 s.

Figure 6 summarizes the results found in four different concurrent measurements from the lidar system located on the sub station in "alpha ventus" and TS-X. On the 16.01. and 19.01. a very good agreement of less than 0.5 m/s mean difference between lidar and TS-X is found. The difference obtained on the 22.01. is still on a very good level of approximately 1.1 m/s. On the 17.01. the mean difference reaches a value of almost 4 m/s. The mean difference between lidar and TS-X is positive in all cases, meaning that the lidar measures higher averaged wind speeds in all cases.

The comparison of the mean lidar wind speed to the meso scale weather model COSMO-DE reveals negative values in all four cases, meaning higher wind speeds obtained by COSMO-DE than with the lidar. Differences are about 1.5 to 1.8 m/s, on the 19.01. the difference is lower than 0.5 m/s. Reasons for the deviations are seen in the time lag between lidar and COSMO-DE and in the assumption of a logarithmic wind profile in all cases.
Figure 5. Absolute wind fields in 10 m height upstream of "alpha ventus" with south eastern wind conditions on the standard grid measured on the 22.01.2014. The time difference between lidar and radar measurement was \( \leq 30 \) s. **Left:** Lidar-LoS measurements are transformed back to the absolute wind speed in the ambient wind direction taken from the meso scale weather model COSMO-DE and extrapolated to 10 m height using a logarithmic wind profile. **Right:** TerraSAR-X wind speeds. The wind direction passed to the algorithm XMOD2 is taken from the meso scale weather model COSMO-DE.

A big deviation between lidar and TS-X and between TS-X and COSMO-DE on the 17.01. is observed, while lidar and COSMO-DE compare well. This seems to originate from an unusually low radar backscatter, which results in a lower derived wind speed. The reasons for the low backscatter level might be related to the ambient atmospheric conditions, but need to be further investigated in detail.

The remaining offset between lidar and TS-X can result from the transformation of the measured lidar data to the height of the TS-X measurement. The used logarithmic wind profile works in neutral conditions but introduces an error in stable or unstable stratification of the atmosphere. As a future application long range scanning lidar data measured on 10 m height or alternatively with the knowledge of the prevailing wind profile could serve to further optimize the geophysical model used to calculate the 10 m wind from the TS-X radar backscatter and to reduce the systematic error of the SAR measurement.

3.2. Wake

The comparison of wake tracks observed with lidar and TS-X is presented in Figure 7. The magnitude of the horizontal wind speed of the lidar is shown together with the wake tracks calculated from the lidar data and the corresponding TS-X data. Measurement times of both data sets on 22.01.2014 differ [90 \( \pm \) 4] s from each other. The height of the lidar's measurement points reduces from 40 m at 4 \( D \) to 28 m at 16 \( D \). The wake of turbine AV12 measured by the lidar can be nicely seen with a speed deficit of up to 60\% at 4 \( D \) to 7 \( D \) and a recovery to a deficit of approximately 25\% in 9.5 \( D \). At approximately 10 \( D \) the wake partly hits turbine AV08 and merges with the new wake. The wake tracks of lidar and TS-X deviate from each other up to 2 \( D \) but lay in the same region in principle. With the resolution of 60 m in the horizontal plane TS-X resolves just about two data points per rotor diameter \( D \) at the regarded turbines \((D_A = 116 \text{ m} \text{ and } D_S = 126 \text{ m})\). However, TS-X can yield wind fields of higher spatial resolution, but with drawbacks in the wind speed accuracy. So the localization of the wake tracks is limited
by the spatial resolution of the chosen dataset. Another reason for the differences is the time lag between lidar measurement and TS-X image of about 90 s. Furthermore the fundamental differences in the measurement methods have to be considered. While the lidar measures one component of the actual wind speed in a specific location, TS-X uses a tuned model function to calculate a wind speed from the capillary wave induced backscattered intensity on the sea surface. This makes the radar image prone for other influences on the sea surface like strong rain, oil spills, etc. While TS-X takes an image in about 1 s, a scan of the lidar takes up to some minutes depending on the area coverage. So there are considerable differences in the location, the duration and time difference and the principle itself of the measurements. Regarding this, the results obtained are quite promising.

4. Conclusions
In free stream conditions a comparison of wind speeds between lidar and radar satellite is performed. Good agreement in the difference of the mean wind speed of both systems in the
magnitude of less than 0.5 m/s is observed for two of the regarded four cases. This remaining offset of higher lidar wind speeds could be related to the assumption of the neutral stratification of the atmosphere for extrapolation. With information about the real wind profile obtained from meteorological measurements or from a lidar profiler another model can be used to transform the lidar wind speed to the level of the TS-X wind field in future campaigns. The comparison of the variability of the wind field characterized by the standard deviation reveals a good agreement. A parallel view of the wind fields of lidar and TS-X shows similarity of most flow structures. The comparison of wake tracks revealed low spatial agreement, but looked similar in principle. Due to the lower resolution of the TS-X wind field and the possibility to cover large areas, this method appears to be better suited to study the wake of whole offshore wind farms on a bigger scale. Future measurement campaigns will be used to compare the wake of a whole offshore wind farm measured with lidars to the ones calculated from TS-X data.

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