J4.8 WIND ENERGY APPLICATIONS OF SYNTHETIC APERTURE RADAR

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1. INTRODUCTION

The wind is a natural, renewable energy resource, which offers potential solutions to the worldwide energy challenges we are facing today: the demand for energy is growing rapidly; we wish to eliminate our dependence on fossil fuel and incentives have been set up to reduce greenhouse gas emissions. Key research topics in wind energy include the design of wind turbines and blades, power grid connection, wind farm siting according to the wind resource, and evaluation of environmental impacts.

Recently, large-scale wind farms have been installed offshore. Ocean wind fields retrieved from synthetic aperture radar (SAR) images are useful for offshore wind energy applications. The high-resolution spatial information gained from a SAR cannot be obtained in any other way. A further advantage of SAR data, compared to other satellite products, is the coverage in near-shore areas where offshore wind farms are typically located. At Risø National Laboratory in Denmark, work is being carried out to quantify the impact of large offshore wind farms on the marine wind climate and to estimate wind resources from SAR. In this paper, we present objectives and results of these offshore wind energy studies.

2. SAR WIND RETRIEVAL

SAR wind retrievals are fundamental in our work. Wind speeds at 10 m can be retrieved from SAR images using geophysical model functions such as CMOD4 (Stoffelen and Anderson 1997) or CMOD5 (Hersbach 2003). Wind directions are required as model input. For wind energy purposes, offshore *in situ* measurements are often available e.g. (Hasager et al. 2004). Wind vectors may also be retrieved from wind aligned streaks in the SAR images through FFT (Lehner et al. 1998; Vachon and Dobson 1996), wavelet (Du et al. 2002; Fichaux and Ranchin 2002), or the local gradient method (Koch 2004; Horstmann et al. 2002).

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Alternative data sources include scatterometry (Monaldo et al. 2004), or atmospheric model predictions (Monaldo et al. 2001). Figure 1 shows a wind speed map retrieved from an Envisat ASAR image acquired in wide swath mode (WSM) over Denmark on 13 October 2004. The image conveniently covers the majority of Danish Seas. A software tool developed at The Johns Hopkins University Applied Physics Laboratory (JHU/APL) was used for the image processing (Monaldo, 2000). Wind vectors were obtained from the Navy Operational Global Atmospheric Prediction System (NOGAPS).

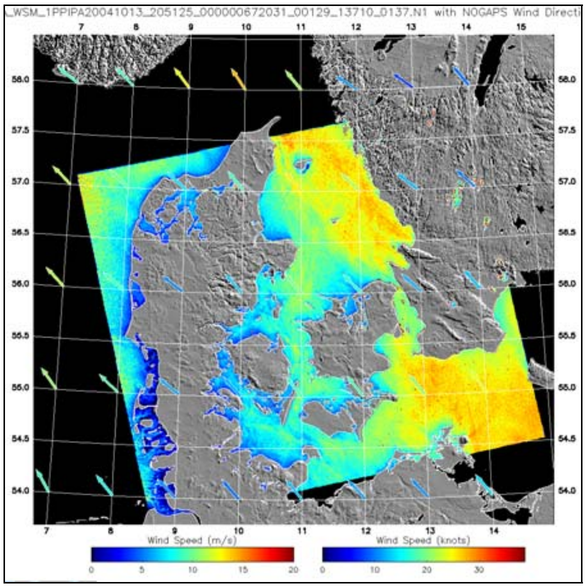

Figure 1. Wind speed map of the Danish Seas, 13 October 2004. Courtesy JHU/APL.

3. OFFSHORE WIND FARMING

The two largest offshore wind farms in the world are located at the Danish sites Horns Rev (7.8ºE, 55.5ºN) and Nysted (11.7ºE, 54.6ºN). The wind farm at Horns Rev became operational in late 2002 with 80 turbines and a total capacity 160 MW. The wind farm at Nysted became operational in mid-2003 with 72 turbines and a total capacity 166 MW. At both sites, the total turbine height is 110 m above mean sea level. When conditions are calm, individual wind turbines can be destinguished from satellite SAR-derived wind speed maps, as seen in Figure 2 for Horns Rev and Figure 3 for Nysted. Two new wind farm projects, Horns Rev II and Nysted II, are planned at the sites.

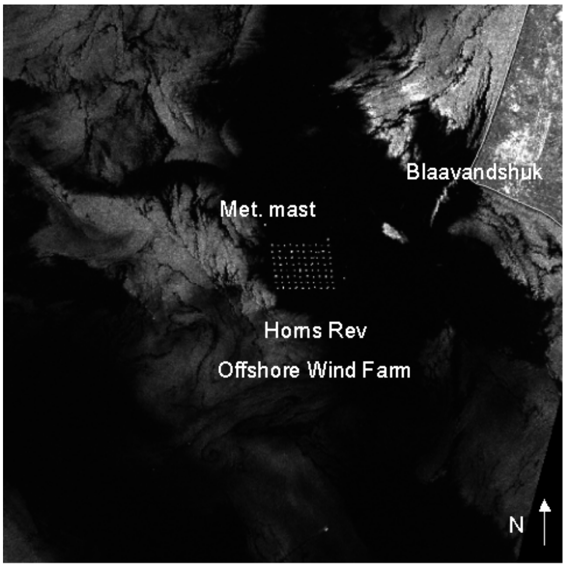

Figure 2. ERS-2 sub-image (50 km x 50 km) showing Horns Rev Offshore Wind Farm in the North Sea, Denmark under calm conditions. Bright areas offshore are not associated with the wind (Christiansen and Hasager 2005).

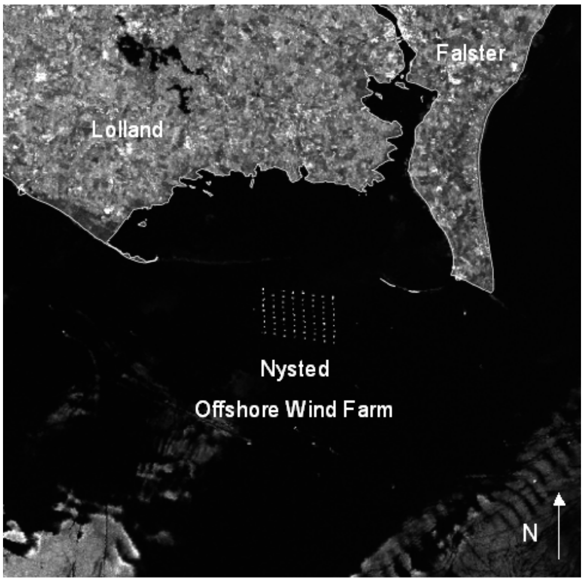

Figure 3. ERS-2 sub-image (50 km x 50 km) showing Nysted Offshore Wind Farm in the Baltic Sea, Denmark under calm conditions. Bright areas offshore are not associated with the wind (Christiansen and Hasager 2005).

4. WIND FARM WAKES

For siting of multiple nearby wind farms, the turbine wake effect must be considered. Wind wakes are regions of reduced mean wind speed and enhanced turbulence intensity downstream of wind turbines or other obstacles. Benefits of sharing maintenance costs and grid connections are counteracted by potential power loss and fatigue loads caused by turbulence, as wind farms are clustered. Figure 4 illustrates the wake phenomenon downstream of the wind farm at Horns Rev for a scene acquired by ERS-2 on 25 February 2003.

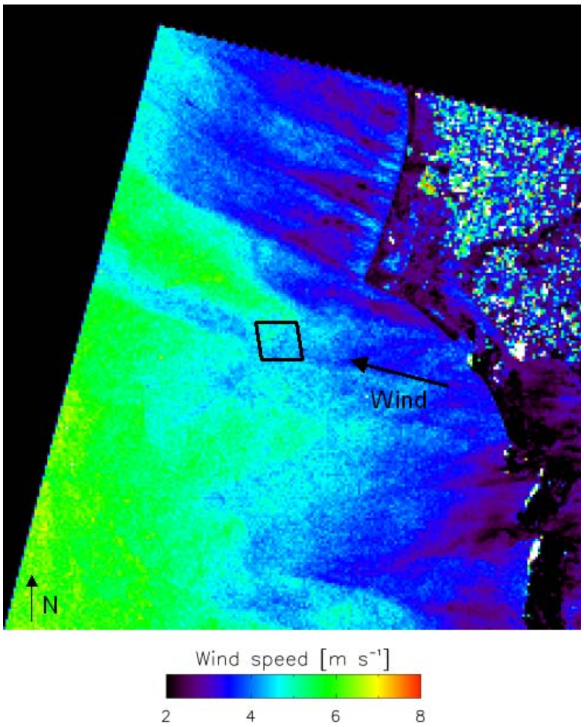

Figure 4. ERS-2 SAR-derived wind map (100 km x 100 km) showing the wake phenomenon downstream of Horns Rev offshore wind farm. 25 February 2003.

To quantify the wake effect, we have analyzed a series of airborne and spaceborne SAR images. For the first time, an airborne SAR was used for data acquisition over a wind farm during a campaign at Horns Rev on 12 October 2003. A nearly simultaneous overpass of the ERS-2 satellite ensured a broader coverage over the North Sea. Advantages of airborne SAR include a very high spatial resolution (~2 m in our case) and flexibility with respect to acquisition times, spatial coverage, radar frequency, and polarization. A limitation is the long acquisition time (here 2-4 minutes per track), which allows wind speed and direction to fluctuate within a single track. The major advantage of spaceborne SAR is the broad coverage of each snapshot and a high accuracy on the absolute calibration.

4.1. Wake analysis from airborne SAR

Airborne E-SAR data were acquired by the German Aerospace Center (DLR). Figure 5 shows the configuration of five flight tracks (A1-A5) downstream of the wind farm at Horns Rev with the swath width 3 km. Data were acquired in C-band with vertical polarization (C_{VV}) and later with horizontal polarization (C_{HH}). E-SAR data calibration and CMOD4 wind retrievals are described by Christiansen and Hasager (2005, manuscript submitted to *Wind Energy*).

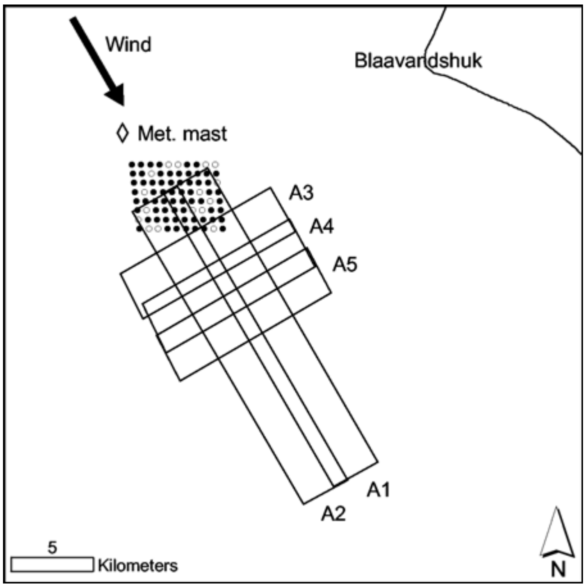

Figure 5. Configuration of E-SAR flight tracks downstream of the wind farm at Horns Rev. Wind turbines are indicated by dots (filled if running). Wind direction ~330º from the offshore meteorological mast.

Spatial averages of wind speed were obtained over the entire swath for each of the E-SAR tracks. Scattering from the wind turbines was masked out before averaging. Figure 6 shows the variation of wind speed for the wind-aligned tracks A1-A2 in C_{VV}.

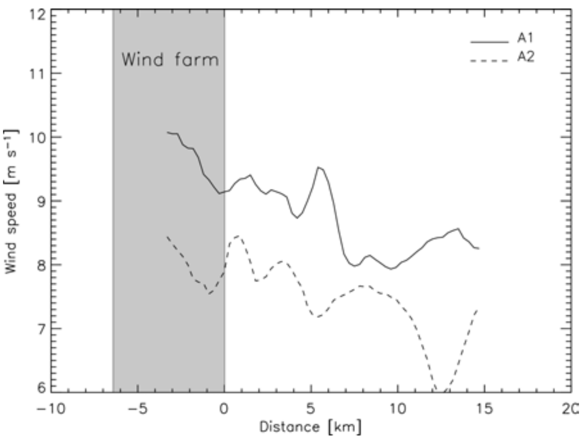

Figure 6. Wind speed variation for the wind-aligned E-SAR tracks A1-A2 (see Figure 5 for location).

Decreasing wind speeds with distance downstream of the wind farm were found and recovery to the free stream velocity was not observed. We believe, this was due to a general slow-down, as the wind approached land from the North Sea. Longitudinal variations of the wind are common in near-shore areas (Hasager et al. 2005).

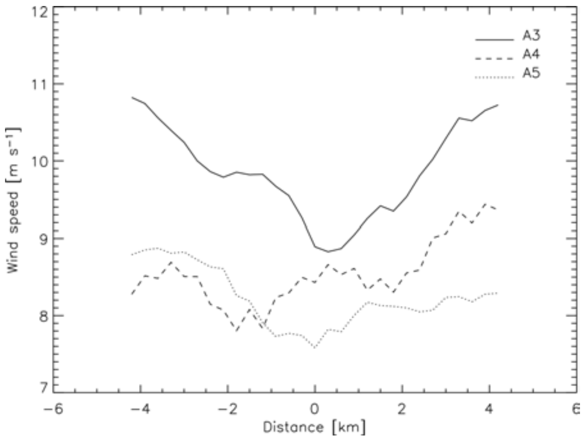

Figure 7. Wind speed variation for the crosswind E-SAR tracks A3-A5 (see Figure 5 for location). The distance 0 km is downstream of the wind farm center.

Figure 7 shows variations of wind speed for the crosswind tracks A3-A5 in C_{VV}. Wind speeds were reduced by up to 20% downstream of the wind turbine array (~0 km). Towards the ends of the tracks, wind speeds corresponded well to *in situ* measurements upstream of the wind farm (i.e. in the non-obstructed wind flow). E-SAR measurements in C_{HH} showed the same trends as the results presented here for C_{VV}.

4.2. Wake analysis from spaceborne SAR

Figure 8 shows a wind speed map retrieved with CMOD4 from the ERS-2 image of 12 October 2003. Winds were from the northwest and the highest wind speeds (~10 m s^{-1}) were found just north of Horns Rev. Spatial averages of wind speed were extracted from the ERS-2 SAR-derived wind map for transects corresponding to the airborne SAR tracks. The transects were denoted S1-S5 ('S'=spaceborne). Figure 9 shows wind speed variation for the transects S1-S2. The broad spatial coverage of the ERS-2 SAR image allowed us to extend the two tracks upstream of the wind farm to get measurements in the non-obstructed flow. An additional parallel reference transect (Ref.) was defined 8 km further offshore, also in the non-obstructed flow.

Wind speeds generally decreased over the wind farm at Horns Rev for the transects S1-S2. Further downstream, an increase of wind speed was found. For S1, the wind almost recovered to match the free stream velocity at the downstream distance 15 km.

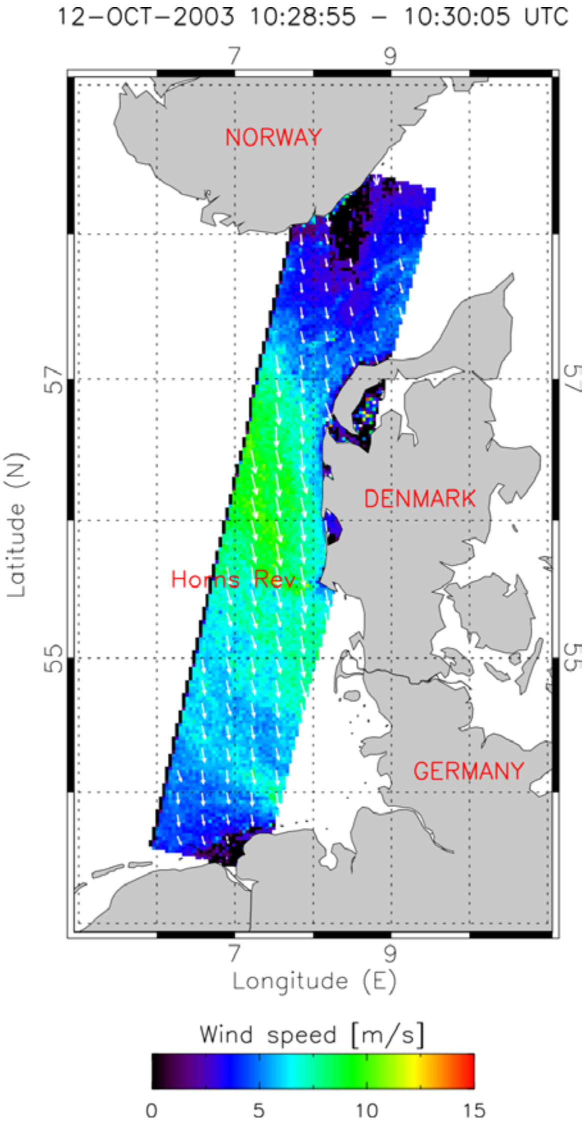

Figure 8. ERS-2 SAR-derived wind speed map over the North Sea. 12 October 2003.

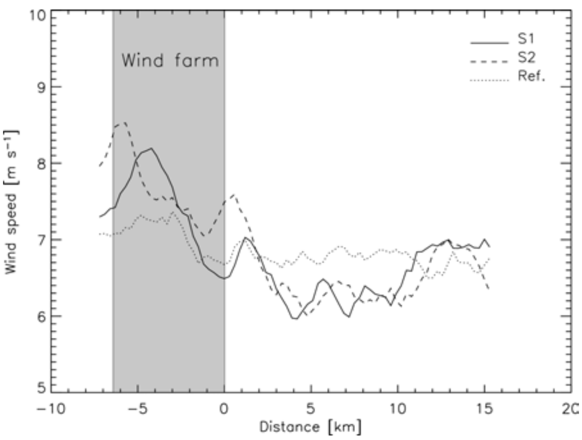

Figure 9. Wind speed variation for the wind-aligned ERS-2 SAR transects S1-S2 and for a parallel, non-obstructed reference transect.

Fluctuations over the wind farm were residual effects of turbine scattering. It is also possible that the reef, on which the wind farm is build, affected the radar measurements. Bathymetry effects are often found in near-shore areas (Alpers and Hennings 1984; Alpers et al. 2004). The non-obstructed reference transect showed a relatively constant wind speed of ~7 m s^{-1}. This shows that velocity deficits detected in transect S1-S2 were, indeed, caused by the wind farm.

5. WIND RESOURCES

Satellite SAR wind resource assessments provide useful information in the early planning phase of wind energy projects. Data are readily available in the archives, therefore a first estimate of the wind resource at a given site can be produced in a relatively short time. A limitation is that satellite SAR data are acquired at fixed times of the day. Diurnal variations in the wind climate are therefore not detected.

In order to estimate the wind resource at any given site, observations of wind speed and direction are needed. Conventionally, such observations are obtained from meteorological towers for a one-year period, preferably longer. Construction and maintenance of a meteorological mast offshore is costly, therefore remote sensing techniques are attractive alternative data sources. A further advantage is the gain of spatial information, whereas a meteorological mast provides measurements at one point in space. The high temporal resolution available from *in situ* measurements is not achievable with SAR but wind resource estimates can be produced if a sufficient number of scenes are available. The annual mean wind speed can be determined from 60-70 randomly selected samples with an accuracy of ±10% at the 90% confidence interval (Pryor et al. 2004). The accuracy on SAR-derived mean winds is lower since data acquisition is not random.

The Risø WEMSAR Tool (RWT) has been developed for retrieval of a probability density function from SAR-derived wind maps using footprint analysis (Nielsen et al. 2004). The function is described by its Weibull A (scale) and k (shape) parameters necessary for wind resource estimation with software packages such as the Wind Atlas Analysis and Application Program (WAsP) (Mortensen et al. 2002). Our results show good consistency between A and k values derived from high-resolution satellite SAR (ERS-2 and Envisat) and *in situ* measurements (Hasager et al. 2005).

In the following example, we illustrate how broader coverage wind resource estimates may be obtained from SAR. Figure 10 shows the outline of 25 Envisat scenes acquired in Wide Swath Mode (WSM) over Denmark.

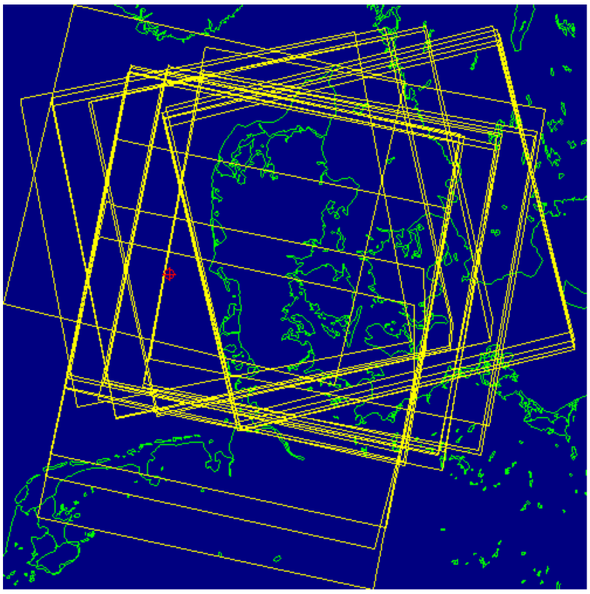

Figure 10. Location of 25 Envisat ASAR WSM wind maps retrieved for the Danish Seas.

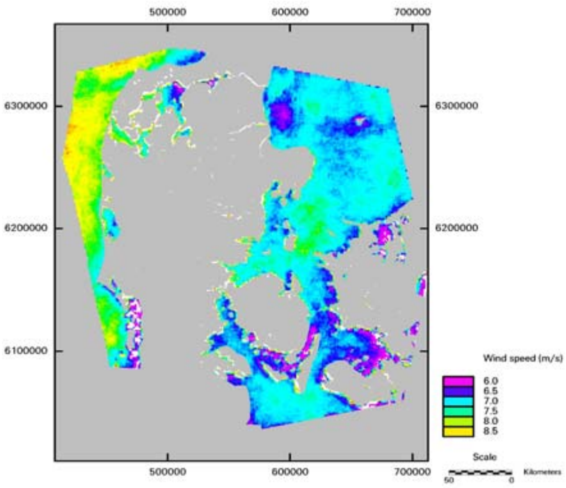

Figure 11. Mean wind speed offshore near Denmark from 20 Envisat ASAR WSM wind maps (UTM projection).

Figure 11 shows a map of mean wind speeds where sufficient coverage is available. The analysis was based on 20 SAR images and it shows that even from a relatively low number of SAR scenes, it is possible to identify spatial variations of the wind resource. For example, lee effects are seen in near-shore areas and around islands. Mean winds are generally higher in the North Sea compared to the more enclosed areas to the east. A detailed analysis of a longer series of images is in progress.

6. CONCLUSION

We have demonstrated that high-resolution SAR imaging is very useful for wind energy applications. Two examples were given:

1. Wind maps retrieved from airborne and spaceborne SAR were used to quantify the wake effect downstream of large offshore wind farms. Information on the magnitude and spatial extend of wind wakes is important for the siting of wind farms in clusters. Moreover, the information is needed in environmental impact studies.

2. Wind resource estimates were made from a series of Envisat ASAR scenes acquired in wide swath mode (WSM). Preliminary results are very promising and a detailed analysis of a longer data series is in progress. SAR wind resource assessments are very useful in the early planning of wind farms.

A number of challenges are related to wind mapping in near-shore areas where offshore wind farms are typically located. For example, acceleration/deceleration of wind speed is often observed, as are internal boundary layers affecting the vertical profiles of velocity. Oceanic parameters (e.g. bathymetry, internal waves and tidal currents) may affect SAR measurements directly. The major advantage of SAR measurements is the unique opportunity to obtain spatial information in near-shore areas. The spatial detail provided by high-resolution SAR images can not be gained from any other data source.

7. ACKNOWLEDGEMENTS

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