Use of SAR wind measurement techniques to support offshore wind farming

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INTRODUCTION

Active microwave radar satellites transmit and receive radar signals with wavelengths in the range of centimeters to one meter thus measuring the roughness of the sea surface, which enables the retrieval of wind and ocean wave fields. Synthetic Aperture Radars (SAR) are capable of imaging synoptic wind fields with a coverage of up to 500 km x 500 km and a resolution of down to 100 m. As the radar signals penetrate clouds these sensors have all weather capability [1] and can acquire data as well during nighttime. Therefore, they are especially suited for sea surface observations in coastal regions and in severe weather conditions [2].

Since the launch of the European remote sensing satellites ERS-1 and ERS-2, the Canadian satellite RADARSAT-1 and the European environmental satellite ENVISAT, satellites have been acquiring SAR images over the oceans on a continuous basis since 1991. Their high resolution and large spatial coverage make them a valuable tool for measuring wind fields especially in coastal areas and for comparisons of wind fields around wind park sites. The derived information can support offshore wind farming in optimal siting and optimal design and help to estimate their effects on the environment.

OFFSHORE WIND FARMING IN EUROPE

In Europe offshore wind farming is developing rapidly. During the past 10 years several wind parks all over Europe have been constructed. Within the last few years a fast development of wind energy production has taken place in Europe with more than 23000 MW installed by the end of the year 2002 and nearly 32000 MW worldwide. Wind energy is about to replace hydropower as the most important commercial source of clean, renewable energy. Up to now about 280 MW offshore power is installed all in the North and Baltic Sea. In near future many wind farms with over 100 single wind turbines with an output of more than 5000 MW covering areas of more than 200 km^2 are planned and already under construction.
For example, the first planned and approved German offshore wind park Borkum West will have more than 200 wind turbines with a total power yield of up to 1000 MW and will cover an area of nearly 200 km^2. The largest wind park that is already in operation is Horns Rev (Fig. 1), which is situated in the North Sea at the west coast of Denmark. Fig. 2 shows a cut-out of a SAR image of the wind park Horns Rev. Today, 80 wind energy converters are running at this offshore site, that can be seen in the SAR image.

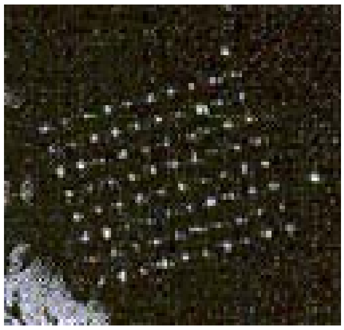
 

Fig. 1 and Fig. 2. Horns Rev wind park from air and from space (ERS SAR image mode scene, 9 x 9 km zoom)

Several mainly ecological short- and long-term effects of these parks on the environment are under investigation. One important parameter that can be observed with space borne SAR is the high-resolution wind field in the vicinity of the wind farms. SAR enables to investigate changes of the wind field due to the wind turbines, e.g. turbulent wakes and blockage effects in front of the wind farm.

INVESTIGATED SAR DATA

Since the launch of the European remote sensing satellites ERS-1 and ERS-2 in 1991 and 1995, synthetic aperture radar (SAR) images have been acquired over the oceans on a continuous basis. The ERS SAR operates at C-band with vertical (VV) polarization in transmit and receive. The resolution is about 30 m in range (across flight direction) and 10 m in azimuth (along flight direction).

The European remote sensing satellites ERS-1, ERS-2, and ENVISAT as well as the Canadian satellite RADARSAT-1 are positioned in a near-circular, polar and sun-synchronous orbit at an altitude of ~790 km. ERS provides in the image mode calibrated high-resolution images of the earth's surface in a range of incidence angles, between 20° and 26° perpendicular to the flight direction, corresponding to a coverage of 100 km x 100 km.

In ScanSAR wide swath mode RADARSAT-1 and ENVISAT ASAR Scan SAR mode provides an additional wide swath mode with incidence angles between 15^o and 50^o covering thus a swath width of up to 500 km. This mode gives the opportunity to get a synoptic overview of large areas, e.g. nearly the entire North Sea. The alternative image mode shows higher resolution and guarantees the continuity of the standards of the ERS SAR data. That way, comparisons with historic scenes are possible and statistics over more than 10 years of wind field data can be undertaken. The revisit time of the ERS satellites was about 11 days caused by the area coverage of 100 to 100 km. With ENVISAT the revisit time in the wide swath mode (500 to 500 km) is reduced to 3 days. The availability is depending on existing acquisition requests.

SAR WIND MEASUREMENT

SAR wind field retrieval is a two-step process. In the first step wind directions are retrieved, which are a necessary input into the second step to retrieve wind speeds from the intensity values. Wind directions are retrieved from wind-induced phenomena aligned in wind direction, which are visible in most investigated SAR images. Their imaging by SAR is caused by phenomena such as boundary layer rolls, Langmuir cells and wind shadowing. The orientation of these streak-like features is approximately in direction of the mean surface wind. The method used hereafter, defines the wind direction as normal to the local gradients derived from smoothed amplitude images. Therefore the SAR images are smoothed and reduced to an appropriate pixel size, e.g., 100 m, 200 m, and 400 m. From these pixels the local directions, defined by the normal to the local gradient is computed leaving a 180^o ambiguity [3]. From the resulting directions the most frequent and most probable local direction is selected using additional assumptions about the wind flux pattern. The 180^o ambiguity can be removed if wind shadowing is present, which is often visible in the lee of coastlines and large objects such as offshore structures.

For retrieving wind speeds from SAR data a model function relating the NRCS of the ocean surface σ_0 to the local near-surface wind speed u, wind direction versus antenna look direction Φ and incidence angle θ,

$$\sigma_0^{pol} = a(\theta)u^{\gamma(\theta)}[1 + b(\theta)\cos\Phi + c(\theta)2\cos\Phi] \qquad (1)$$

is applied. Here *a*, *b*, *c* and γ are coefficients that in general depend on radar frequency and polarization *pol*. These coefficients were determined empirically in the case of the model functions CMOD4 by evaluation of scatterometer data of the European satellite ERS-1 and wind fields from the ECMWF [4]. CMOD4 has been applied successfully for wind speed retrieval from C-band VV polarized ERS-1 and ERS-2 SAR images [5], [6], [7] in which the accuracy of the algorithm was shown to be about 1 ms^{-1} in wind speed and about 22° in wind direction. The CMOD4 was extended to HH-polarization (Horstmann *et al.*, 2000b), which enables to extract wind fields also from HH-polarized SAR imagery as acquired by RADARSAT-1 and by choice can also be acquired by ENVISAT.

SUPPORT FOR OFFSHORE WIND FARMING

The short- and long-term effects of these offshore wind parks on the environment are not yet well understood. One important parameter that can be observed with space borne SAR is the high-resolution wind field in the vicinity of the wind parks. The SAR enables to investigate changes of the high-resolution wind field due to the wind turbines, e.g. turbulent wakes, as well as ocean surface wave fields.

In the near future the first approved German wind park "Borkum West" will be built about 35 km north of Borkum island. In a first step 12 turbines of the 3,5 to 5 MW class will be erected. At this site the research platform Forschungsplattformen in Nord- und Ostsee (FINO-I) was installed for logging numerous different parameters like wind speed and wind directions at different heights. Time series in different frequency scales are logged that support SAR wind measurements and turbulence investigations. This enables small-scale analysis of possible effects on the local wind field like turbulent wakes or wind shadowing [8]. But also data about air pressure, air temperature, humidity or e.g. rainfall is taken at this station to improve weather forecast that can be used for validating short-term forecasts by SAR.

The research platform FINO-I at Borkum West is comparable to the platform at Horns Rev logging data since 1999.

During the planning stage of wind farms SAR retrieved wind fields will help to solve the following issues

- Optimal siting of the wind farm as a whole
- Optimal positioning of wind turbines within the wind farm

For the first point it is helpful to have a long record of historic data, which provide information on the wind and wave parameters relevant for wind farms. Up to now ERS data are available since 1991. Relevant geophysical parameters are

- Mean wind speed and direction – it is clear that a certain minimum of average wind speed is required for economic operation of the wind farm
- Wind variability
- Turbulences induced by the wind turbines and the whole wind park

Using satellite borne SAR data will offer following opportunities:

- Get synoptic overviews of the wind field.
- Use the possibilities of in situ measurement to improve the wind field algorithms.
- Improve mesoscale models used for short term power forecast.
- Increase the awareness of wind farmers to use remote sensing data in their planning.
- Estimate the effects offshore wind farms have on the environment.

For the offshore wind farming special high resolution regional operational forecasting of metocean conditions is needed [9]. Additionally, large wind farms will themselves influence the wind field and related parameters, something which has to be incorporated into the operational models.

Strategic siting requires detailed knowledge on the impact of turbines [10] on the local wind field to

- Optimise the output
- Minimise the impact on environmental conditions

While many studies are on the way, concerned either with improving the technology of wind turbines, e.g., constructing larger and more powerful ones for offshore use, or with environmental issues like the effect on birds and fishery, no joint studies have been undertaken on how this new technology can be assisted by operational forecasting. Similar experience exists in respect to offshore oil industry. Another research aspect is to investigate how these large wind farms alter the wind field and the related processes themselves. With SAR wind measurement high-resolution wind fields can be derived that gives the opportunity to look into wind parks to investigate small-scale features like turbulences or shadowing effects. In Fig. 3 two wind speed profiles at the wind farm Horns Rev are shown.

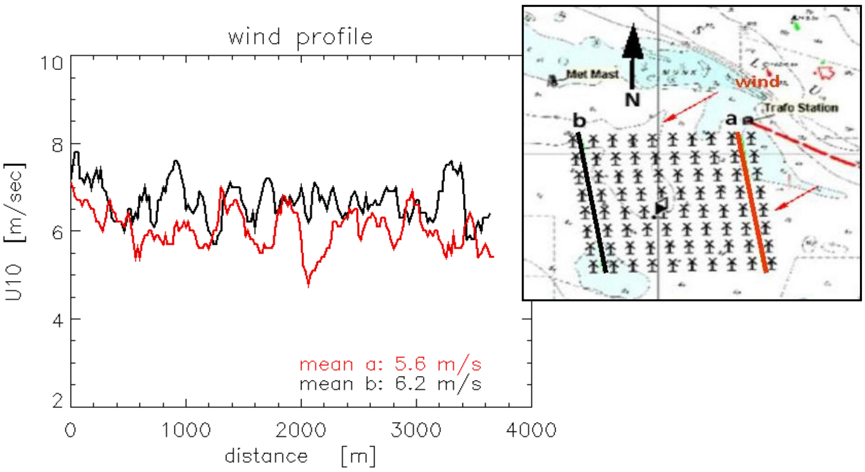


Figure 3: Plot of the SAR derived wind profile at the wind park Horns Rev. Red line shows first line of the wind park and the black line the last row

The red line represents the wind speed behind the first row of turbines of the wind park and the black line the last one seen from wind direction. The values are smoothed to 300 m resolution to reduce the influence of speckle of SAR images. The higher wind speed behind the turbines is due to turbulences that increase the near surface wind velocity. This example shows the possibilities given by the high-resolution SAR wind fields.

COMPARISON OF WIND PARK SITES

Basis for this comparison are 32 ERS SAR scenes of the North Sea showing the area of both wind farms. In 4 cases the wind park sites are on consecutive scenes, Therefore, the data set shows only 28 single dates of observation. The SAR scenes (like the example in Fig. 4 with imprinted wind field) that were analysed in this comparison represent one year of data in this area, which are available at the European Space Agency. The two offshore wind farms investigated are located in the German Bight of the North Sea about 60 km apart. An overview is given in Fig. 4 where the locations are indicated on an ERS SAR image mode scene.

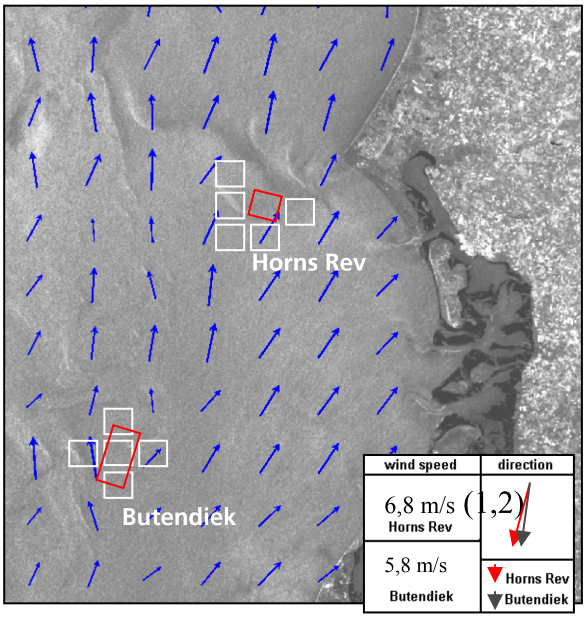


Fig. 4. Wind field derived from an ERS SAR scene of 100 by 100 km size with indicated areas used for wind measurements (white boxes) and the location of the wind park sites (red boxes).

The Danish wind farm investigated is Horns Rev, 15 km off the Danish west coast near Blavands Huk. The wind farm was built in 2002 and the turbines are in operation since October 2002. It is the first wind farm of this size in the world. There are 80 single 2 MW wind turbines installed with 70 m hub height and rotor diameters of over 80 m, resulting in an overall height of 110 m. The turbines are arranged as a rectangle with 8 × 10 piles. The separation distance is 560 m between the rows and therefore the site covers a region of about 20 km^2. The cut-in wind speed is 4 ms^{-1} and the cut-out wind speed is reached at 25 ms^{-1} with full power output from 13 ms^{-1} and above.

The second wind farm investigated, Butendiek, is approved and in planning stage. This wind farm will be located 35 km off the German island Sylt. It consists of 80 single wind turbines of the 5 MW class. The hub height will be in 80 meters and the rotor diameter 90 meters.
The following SAR data are used to investigate the difference in wind climate between the two sites, which are about 60 km apart. The varying distance to the coast and the different exposure in the North Sea is affecting the wind direction and the wind speed and thus the energy yield of the two farms.

Local wind speed is the key parameter for estimating the generating power of a wind farm. The power output is in a first approximation proportional to the cube of wind speed. For an idealized wind turbine with blade diameter D the power yield is given by

$$power = \frac{\pi}{8} \rho \cdot D^2 \cdot U^3 \qquad (2)$$

where U is the wind speed at hub height and ρ is the air density (≈ 1 kg m^{-3}). In practice wind converters are limited to a certain range of wind speeds. Typically, wind turbines are operating at wind speeds between 4 and 25 ms^{-1} (see also Fig. 6, output of a 2 MW class turbine). The maximum energy output is reached with wind speeds of more than 13 ms^{-1}. When the wind speed reaches 25 ms^{-1} and above the wind converters have to be switched off, because of possible damages.
Therefore, special interest is given to the increasing part of the power curve between 4 and 13 ms^{-1}. Even small uncertainties in wind speed result in big differences in the estimated energy output.

Wind direction analysis

Both wind farms are situated in the North Sea where normally winds from West and Southwest are dominating. In the SAR data set southern and eastern directions are more prevalent than directions from North and West. The difference in the distribution of the wind directions can be due to the fact that 18 scenes were acquired during the winter half year and only 14 scenes during the summer half year. In the winter season directions from the East are more frequent than in the summer season. To get a more realistic distribution longer time series have to be analysed.
The wind directions of the two sites are compared in Fig. 6. Normally, at Horns Rev the most frequent wind directions are from Southwest to Northwest.

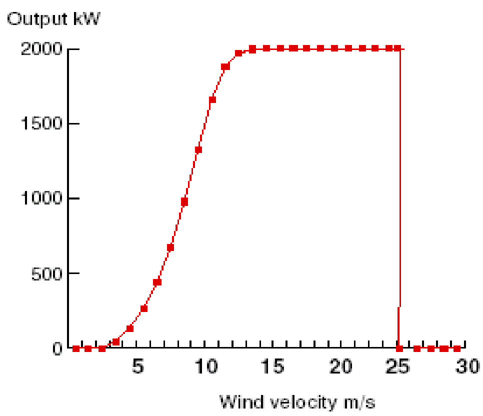


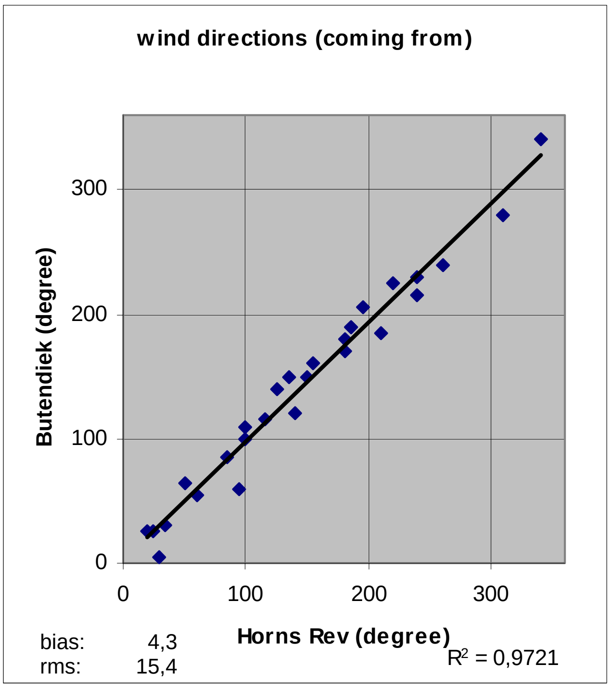
Fig. 5. Energy output of a 2 MW wind turbine for wind speeds from 0 to 30 ms^{-1} (courtesy of ELSAM).

The comparison of the wind directions shows no significant change between the two sites. A small adaptation of North and East winds to the coastline around Horns Rev can be observed. This effect is not present at Butendiek because of the long distance to the shore.

Wind speed analysis

In a first step the local wind field for the SAR images were determined deriving the wind direction and the wind speed for the whole scene with a resolution of 10 km. Afterwards, the areas of the wind farms were cut out from the resulting data. Five areas each of about 5 x 5 km around the wind farms were taken to reduce the effects of non-wind induced features. This is the reason for the varying positioning of the white boxes in Fig. 4. At Horns Rev the wind turbines themselves affect the derivation by their bright return and therefore the measurement areas are put around the site. The second cause affecting this formation is the effect of the tidal current flowing over the shallow area at Blavands Huk, causing strong variations in currents, which can be seen in Fig. 4.
The wind farm Butendiek is in planning stage and therefore no reflectance of piles affects the backscatter yet. Additionally the site shows no current features that influence the derivation of wind fields.

The mean wind speed at the two locations was derived and compared for all 28 scenes. The wind speed derived for each wind farm was taken to be the mean of 5 measurement areas around the respective offshore site.
The results are plotted in Figure 7. One can see that the wind speed measurements at the two sites are the same to measurement accuracy for the 28 wind field situations imaged by the SAR. At medium wind speeds from 4.5 to 8 ms^{-1} the wind speed at Butendiek is slightly higher than the corresponding values of Horns Rev. Below a wind speed of 4.5 ms^{-1} and above 8 ms^{-1} the behaviour is opposite.
At Horns Rev the mean wind speed for the scenes investigated is 5.5 ms^{-1} and at Butendiek it is 5.6 ms^{-1}, a difference of 2 %.
Therefore to SAR measurement accuracy and assuming that the data set investigated is representative the wind speed distributions at the two sites show no significant difference.



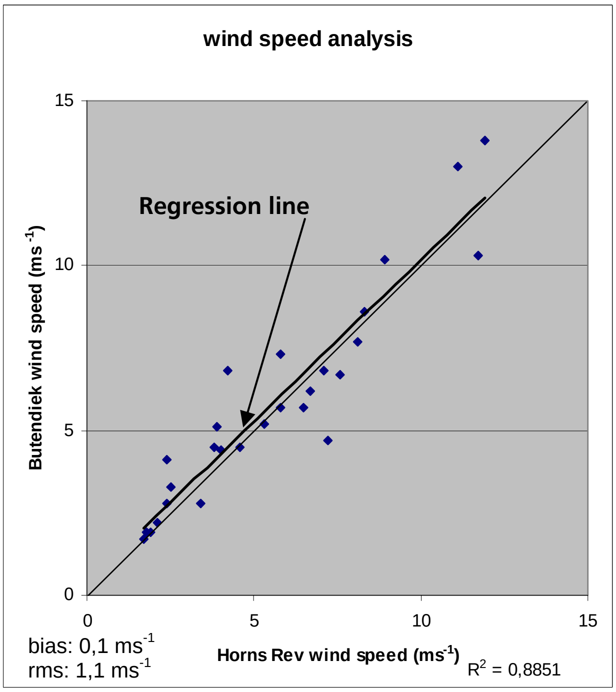


Fig. 6. Mean wind directions occurring in the 28 analysed SAR
Fig. 7. Wind speed U_{10} at Horns Rev versus wind speed at Butendiek

CONCLUSAIONS AND OUTLOOK

Using SAR derived wind fields the spatial variability of wind fields between two offshore wind farm locations in the German Bight of the North Sea was investigated.

The comparison of 28 SAR scenes representing different wind field situations from the year 2002 shows slightly increasing wind speeds between the wind farms Horns Rev and Butendiek. The difference of the mean wind speed between the two sites amounts 0.1 ms^{-1} or 2% higher wind speeds at Butendiek. The rms error of 1.1 ms^{-1} is about the measurement accuracy. Bias in wind direction is 4.3 degrees and a rms error of 15.4 degrees. The applied methodology is well suited to determine the size of the area of validity of *in situ* wind velocity statistics like taken at the mast in Horns Rev.

To verify this result a larger data set of more than 28 SAR images of one complete year will be analysed together with results of an atmospheric numerical model. ERS image mode data are taken since 1991 on a continuous basis, which makes it possible to carry out a long time statistic using this method.

The comparison of the local wind field and the weather situation showed good agreements, additional features like spatial wind variability can be observed in the SAR images.

For future applications ENVISAT data are available in the same format. An additional wide swath mode with up to 400 km swath width and 150 m spatial resolution extends the application of this tool to an area covering nearly the whole North Sea in one scene. This gives new opportunities to compare more offshore wind farm sites and validate the results with *in situ* stations located in the images yielding a synoptic overview of nearly the whole North Sea. Furthermore, due to the larger area covered the repetition rate of the acquisitions is increased to nearly daily measurements.

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