ABSTRACT
Offshore wind farms are a growing business worldwide. The energy output of a wind farm can be predicted by knowing the local wind climate. Usually, the wind climatology is based on at least one year of accurate wind measurements. Before such data are available at a site, satellite-based wind mapping can be a helpful tool in giving the first estimates of the wind conditions. In the Wind Energy Mapping using Synthetic Aperture Radar (WEMSAR) project wind fields from SAR, in situ measurements and model output from three test-sites have been analysed. Subsequently, a tool for retrieving wind maps from SAR images and utilising them in the Wind Atlas analysis and application Programme (WAsP) has been developed.

1 - INTRODUCTION

Usually the prediction of the energy production of a wind farm is based on a combination of historical data from the region and one year of accurate in situ measurements from a mast on the specific site. Measurements are carried out in three different heights with the aim of predicting the mean wind speed within ±5 %. The wind conditions at a nearby location at a certain hub height is traditionally estimated by using micrositing models such as the Wind Atlas analysis and application Programme (WAsP) developed at Risø National Laboratory, Denmark [1]. In some areas of the world where no observations are available, satellite Synthetic Aperture Radar (SAR) and other remote sensing wind measurements can aid in giving the first estimate of the 10 m wind conditions at a site.

The previous work done on the topic reveals a few different approaches. The first approach using 1-5 SAR images from a site [2] is not useful for estimating the wind climate. But choosing the images during periods of typical local wind conditions it can be a quick way to get an idea of some wind phenomena in the area, in particular when the coast is mountainous and thus local wind is more unpredictable and spatially inhomogeneous.

The other extreme is to aim at ordering and analysing enough SAR scenes from the site of interest so as to represent a time series. This approach is necessary in trying to estimate the Weibull parameters of the wind speed distribution from the data. These parameters can then be input to the WAsP programme [3]; [4]. According to [5] and [6] 60-70 SAR scenes are needed to give a reliable estimate of the mean wind speed and the Weibull scale parameter, while about 250 scenes are needed in order to fit the Weibull parameters. With the present cost and coverage of SAR data, it would be optimistic to believe we could acquire this much data over any coastal site on the Earth. In addition, the SAR wind vectors are of limited accuracy and the acquisition not random. The accuracy of the data is generally agreed to be around 2 m/s in speed and 2-20 degrees in wind direction [7]. The acquisition of satellite SAR scenes is dependent on the needs of the SAR community and may therefore be strongly biased from the purpose of the original order (interest in wind, oil slick, natural film, current shear etc.). Additional bias occurs due to the satellites passing the site at the same time of the day.

A compromise of the two approaches is to utilise for instance scatterometer winds to give the temporal coverage while ordering as many SAR scenes as possible for the spatial variability [8]. The main limitation of the scatterometer data is, of course, the coarse resolution and the lack of wind vectors near the coast. The area of interest for wind farm projects is related to the water depth that should not exceed 20-30 m. Using micrositing models such as WAsP to move the offshore scatterometer observations closer to the coast may solve this problem.

2 - APPROACH

The second approach is used in the WEMSAR project. SAR PRI (SAR precision image) products from the ERS-1 and ERS-2 satellites are calibrated2 to obtain the normalised radar cross section (NRCS) [9]. The images are averaged down to a pixel size of 400 m x 400 m in

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1 http://www.wasp.dk/

2 using software from http://earth.esa.int/services/best/
order to reduce noise, while still allowing detailed mapping of the wind. The wind directions are estimated from the peaks in the FFT-derived image spectra in areas of 12.5 km x 12.5 km over the SAR scene as described in [2] and [10]. This wind direction field is interpolated to the whole image and used as input to the CMOD-IFR2 algorithm [11] to obtain the wind speed at 10 m above sea level.

In addition to SAR wind maps, results are shown from Karlsruhe Atmospheric Mesoscale Model (KAMM2), a non-hydrostatic atmospheric model forced with NCEP/NCAR data. Output from the model runs has been compared to SAR wind maps and the Wind Atlas analysis and application Programme (WAsP) has been used to correct the wind speed observations from the mast at 33 m above sea level (a.s.l) down to 10 m a.s.l to be easier comparable to the wind estimates from SAR data. WAsP is a siting tool for the wind farm industry based on a mathematical flow model. WAsP and KAMM2 have been run on 7 of the 49 days with SAR coverage at the Norwegian west coast [12], [13].

3 - RESULTS
The in situ data at the Norwegian west coast are obtained by the Norwegian Meteorological Institute (met.no) at the island Hellisøy. The weather station on Hellisøy is situated on top of a 10 m high mast mounted beside a house, and surrounded by several other masts and buildings. Such obstacles, the topography and the very rough terrain affect the wind climate. The anemometer is situated 33 m above sea level and records the average wind speed over ten minutes every hour. The speed-up effect caused by the terrain varies for the different wind directions and may be considerable under certain conditions [14].

Previously a comparison between offshore SAR wind speed and the mast observations was made [2]. In this paper, WAsP was used to calculate the wind speed down from the mast level (33 m a.s.l.) to the level of the SAR wind speed estimations at 10 m a.s.l. by correcting for topography and roughness. The WAsP results are valid until about 10 km from the mast at Hellisøy. SAR wind speeds are compared with the model results of KAMM2 and WAsP within an area of 5.5 km x 5.5 km offshore from Hellisøy/Fedje (Fig. 3 ii)).

The comparison for the 7 cases of model runs and SAR coverage is shown in Fig. 1. For only one situation the SAR retrieved wind speed (12.3 m/s) does not agree with either WAsP or KAMM2 wind speeds (9.0 m/s and 5.8 m/s respectively). For the rest of the cases SAR wind speed agrees within ±2 m/s with at least one of the models. The wind directions used in the CMOD-IFR2 are from SAR in 5 of the 7 cases from Fig. 1, these are presented against KAMM2 directions and in situ/WAsP directions in Fig. 2.

Fig. 1: Wind speed from SAR using CMOD-IFR2 plotted against model wind speed from WAsP * and KAMM2 ° over the area outside the Norwegian west coast shown in Figure 2 (Previously published in Wind Engineering, vol. 27, issue 5 (2003) by Multi-Science Publishers, UK) [3].

The two cases where SAR significantly underestimates the wind speed compared to WAsP are related to unstationary weather conditions, since the wind speed is changing at the time of the SAR acquisition. As southern Norway lies in the zone of the westerlies, unstationary wind conditions are the rule rather than the exception due to the frequently incoming atmospheric lows.

Fig. 2: Wind directions from SAR for 5 cases compared to KAMM2 and in situ directions outside Hellisøy.

Fig. 3 shows a comparison between WAsP output and the SAR retrieved wind from February 14 1996 at 21:35 UTC during on-shore wind conditions. The SAR wind speed steadily increases towards the coast from 6 m/s offshore to 10 m/s near to the coast. Clear linear features in the SAR image (Fig. 3 i)) indicate a southwesterly wind direction. At 2100 UTC, the anemometer at 33 m asl on Hellisøy recorded southwesterly wind 18.1 m/s 199°. From the time
series of anemometer data shown in Fig. 3, note that wind speed was steadily increasing during the day and decreasing after satellite passage which may be the reason for this variable SAR wind field. A profile through the three data sets (SAR, WAsP and KAMM2) in the along wind direction from the coast across Fedje to the sea is indicated in all three plots and shown in Fig. 3 (iv). Based on the 18.1 m/s recording at Hellisøy, WAsP predicts an offshore wind speed of 14.5 m/s. KAMM2 and CMOD-IFR2 agree on a somewhat lower wind of 10 m/s offshore. Leeward of Fedje all three capture a drop of 1-2 m/s in wind speed.

Fig. 3: (i) ERS SAR wind field over the Norwegian west coast, February 14 1996. (ii) SAR retrieved wind speeds (interpolated to the WAsP grid) with the box for comparison in Figure 1 and profile line indicated. (iii) Model output from WAsP at 10 m a.s.l. with box for comparison in Figure 1 and profile line indicated (v) Model output from
KAMM2 with WAsP area, box for comparison in Figure 1 and profile line indicated. (iv) Profiles along the line oriented from land across the island Fedje and to the open sea in the SAR wind speed map. WAsP and KAMM2 output from the same hour. * is the observation at Hellisøy. (vi) Plots of wind speed, wind direction and temperature at the Hellisøy weather station. The vertical bar indicates the time of the SAR passage. All wind speeds are in m/s, please note that the WAsP results are only valid out to a distance of about 10 km from the Hellisøy weather station. (Previously published in Wind Engineering, vol. 27, issue 5 (2003) by Multi-Science Publishers, UK) [3].

At the Norwegian west coast 49 ERS SAR images were analysed. This is not quite enough for a definitive statistical analysis. In particular, the scenes obtained contain a fairly large number of low wind situations. However, in order to collect the information all the available wind maps have been geocoded to the same grid and averaged. The resulting mean wind speed map is seen in Fig. 4 i) and the SAR wind speed data in an area offshore from Hellisøy shown in histogram in Fig. 4 iii). The corresponding histogram for the same days but using data from Hellisøy weather mast is also shown. The number of scenes used for the mean wind map is shown in Fig. 4 ii) and the Weibull distribution and histogram based on two years of data from the weather station is shown as a reference (Fig. 4 iv)).

The probability density function of the wind speed \( U \) for the Weibull distribution is given by

\[
    f(U) = \frac{k}{A} \left( \frac{U}{A} \right)^{k-1} \exp\left\{ -\left( \frac{U}{k} \right)^k \right\}
\]

where \( A \) is called the scale parameter and \( k \) is the shape parameter. The shape parameter \( k \) is expected to lie at a value around 2.

The mean wind speed map (Fig. 4 i)) suffers from too few scenes and the line pattern of the coverage map clearly shows. But within the area covered by the largest number of scenes (40) the map starts to give some information of the relative wind distribution (even if the mean wind speed is too low). The SAR wind speed histogram clearly shows that more SAR data are needed to be able to estimate the wind statistics with SAR.

During the WEMSAR project, a first version of a tool has been developed for retrieving wind fields from ERS SAR images and integrating these data into the WAsP programme [15]. The tool consists of the two parts; wind retrieval and statistical analysis. The first part of the tool is the wind retrieval from ERS SAR images. This module reads calibrated image files and the associated header files, retrieving wind speed and wind direction, which are then read by the statistical module. In this module all the satellite wind fields are treated together to provide input to WAsP.

The WEMSAR statistical module has been developed as add-on software to the WAsP programme [4]. The basic functionality is to area-average the relevant footprint area of the SAR wind map into a wind speed and wind direction and use it for calculating observed climatology from the series of wind maps. The relatively low sample number might compromise the accuracy of the statistical model for the wind speed distribution. Therefore the RWT program first fit a Weibull distribution to the entire dataset independent of wind direction and applies the shape parameter of this for all directions. The Weibull scale parameters representative for different wind direction sectors is determined by individual average wind speeds. The observed wind climate file, needed as input to the WAsP program, is generated from the estimated Weibull distributions. A selection of Weibull fitting methods were implemented, and tested by wind speed measurements from buoys. The error of using few measurements was evaluated by comparison of fits to random selections and a fit to the long-term data set. A theory for the error was derived and found in agreement with this analysis [6]. The accuracy depends on sample size and Weibull shape parameter, and it is comparable for most of the evaluated methods. The Weibull scale parameters quoted herein are estimated by the maximum likelihood method [16].

4 - CONCLUSIONS

The aim of the study is to utilise the advantages of remote sensing in offshore wind resource assessment. Wind fields from the Norwegian coastal zone calculated from the KAMM2 mesoscale model and the WAsP wind farm siting program was compared to SAR wind maps. The comparison of spatial features shows a fair agreement for the example shown, and all three methods (SAR, WAsP and KAMM2) capture a decrease in wind speed of 1-2 m/s in the lee of Fedje and Hellisøy islands.

\[a=A-k\quad \text{and} \quad b=k\]
Comparing SAR surface wind speeds with wind speed from WASP runs based on the Hellisøy observations normalised to 10 m a.s.l. was in fairly good agreement i.e to within ±2 m/s for four cases. The reason for the disagreement (SAR underestimating in two cases and overestimating in one case) for the last three cases seems to be due to un-stationary weather situations or oceanic influence on the images. On the other hand, in two of these cases the SAR wind speeds estimates agree well with the KAMM2 wind speeds. This may indicate that WASP runs may not deal with special conditions over the ocean (with respect to atmospheric boundary layer, sea surface roughness) as well as an atmospheric model. The fact that the SAR winds agree with one model or the other in six of the seven cases suggests that the surface measurements carried out using the SAR may add useful information. At present, the strength of SAR wind maps lies in the added spatial information, as the relative accuracy within each image is good. Comparing SAR wind speed with measurements from an offshore mast about 13 km from the coast (not shown) gives a good agreement, which also is encouraging for the future work [17].

A prototype software, the so-called WEMSAR Tool, has been developed for utilising SAR retrieved wind measurements in WASP. The major advantage of the software is that it can handle a large number of SAR scenes to give the first wind estimations in offshore areas where no suitable in-situ wind observations are available. Although SAR has not yet made a difference in the decision process of wind farm projects, the potential will be greatly improved when including Radarsat and Envisat data and combining with high temporal resolution scatterometer data.

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**References**


