Offshore wind resources quantified from satellite SAR: methodology and technical aspects

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ABSTRACT *For the planning of offshore wind farms, the offshore wind resource is a key parameter. Satellite SAR-based wind speed mapping may be used for estimating the wind resource either in feasibility studies or in combination with meteorological mast observations to investigate spatial patterns along coastlines. The wind power potential is proportional to the third power of wind speed and therefore the demand on accuracy on wind speed mapping is very high. The current study investigates the technical aspects of quantitative wind speed mapping relating to the precision in ERS SAR as well as the accuracy in C-band algorithms used for wind speed mapping including the error estimation due to uncertainty on wind directions. Wind direction may be found from SAR streaks or taken from other sources e.g. meteorological observations. Comparison to in-situ offshore mast observations is done by footprint analysis, a method that effectively integrates the upwind source area to a wind sensor at a given height above sea level. Finally, the biases inherent in current satellite-based wind speed maps are discussed in relation to wind resource calculation, i.e. wind statistics (1st to 4th moment).*

1 INTRODUCTION

The offshore wind resource is one of the renewable energy sources that have attracted an increasing commercial interest during the last decade. The first offshore wind farm to be installed was the Vindeby wind farm in Denmark in 1991. Since then a number of offshore wind farms e.g. Tunø Knob and Middelgrunden (DK) and Bockstigen, Utgrunden and Stengrund (S) have started operation. Currently the largest offshore wind farm is under construction at Horns Rev (DK) and several more are underway e.g. Rødsand and Samsø (DK) and some in England, Ireland, Germany and the Netherlands.

Prior to investment in an offshore wind farm, it is a necessity to calculate the potential wind power output. The cost of installation and operation is very high and the investment should be balanced by the profitability of the wind farm with respect to electricity generation. The wind power potential is proportional to the cube of the mean wind speed. Hence in the early phase of an offshore wind farm project, there is a strong need for an accurate mapping of the local and regional wind climate.

The classical method of calculation of the wind resource is based on meteorological time-series of at least one years duration. It is costly to collect such data.

Therefore satellite SAR-derived wind speed and wind direction observations may become an attractive alternative or additional source of observations for offshore wind resource calculation. The SAR C-band observations are available from ERS-1 and –2 SAR, ENVISAT ASAR and RADARSAT. The historical archives contain large numbers of scenes for most of the globe. It is clear however that with a relatively low sampling rate e.g. 3 per month, the total number of scenes for a specific location may be rather limited. For ENVISAT ASAR it will be necessary to pre-order the scenes in advance. The SAR scenes have to be calibrated. Then a CMOD algorithm has to be applied to the scene e.g. CMOD4 (Stoffelen and Anderson, 1993) or CMOD-IFR2 (Quilfen et al., 1998) to derive the wind speed. Prior to applying the CMOD models, the wind direction has to be known e.g. from SAR wind streak analysis (Furevik et al., 2002) or in-situ observations (Hasager et al., 2002a).

Statistics of the wind speed and wind direction from the SAR imagery may then be used in a wind resource calculation tool, i.e. a software that translates the 10 m wind speed to the typical hub-height of wind turbines and include the actual coastal terrain effects. Even very modest coastal topography may have a significant impact on the calculated potential wind power (Hasager et al., 2002b).

A typical met-observation time-series consists of hourly mean values from one (or more) years, i.e. 8760 observations on wind speed and wind direction per year. For SAR-based wind resource estimation the number of samples will be much less, dependent on available SAR scenes as well as the economy (price per scene). It has been tested how much error may be expected from a very reduced set of observations (Barthelmie and Pryor, 2002; Pryor et al., 2002). The findings support the applicability of using SAR scenes in offshore wind resource estimation, however with a significantly lower accuracy and confidence level as compared to classical meteorological observations. It is shown that approx. 60-70 SAR wind speed maps should be collected for obtaining reliable statistics of the mean wind speed (eg. 10% significance at 90% confidence level) assuming no error in the SAR wind speed maps (Pryor et al., 2002). An advantage of the SAR-derived wind speed maps is that spatial patterns are directly mapped rather than modelled.

2 ON SAR-DERIVED WIND SPEED MAPPING

In the current study only ERS-2 SAR scenes are analysed. These are C-band VV polarized data.

2.1 Calibration

The SAR imagery has to be in precision image mode (PRI). It is then possible by use of the ESA SAR tool box(http://earth.esa.int/stbx/documentation/manual/stbx_v-5_5.html) to calibrate the images.

2.2 CMOD wind speed retrieval

The CMOD models can be applied to the calibrated SAR scenes. The CMOD models originate from scatterometer data, buoy data and ECMWF (European Center of Medium-Range Weather Forecasting). The CMOD4 is based on correlation analysis between ERS AMI-SCAT and ECMWF ocean wind speeds (Stoffelen and Anderson, 1993) and the CMOD-IFR2 is based on NOAA buoy data (Quilfen et al., 1998). The functions for scatterometer are adjusted for wind speed in the interval 1-28ms^{-1} with a precision of ±2ms^{-1} and for wind directions ±20º. Outside the wind-speed interval the functions are modelled by extrapolation. The model functions are defined for wind speeds between 0-60 ms^{-1} and for incidence angles between 16-60º. For the ERS SAR the incidence angle interval is very narrow from 21-26º.

The SAR wind speeds are valid for 10 m above sea level.

The relationship between the measured backscatter in each resolution cell and wind speed is given in eq. 1.

$$\sigma^0 = B_0(1 + B_1\cos(\phi) + B_2\cos(2\phi)). \qquad (1)$$

Here Φ^0 (dB) is the normalised radar cross section (backscatter coefficient) in each resolution cell. It is dependent upon the relative wind direction, *N*, (*N* = 0º for a wind blowing against the radar), the local radar beam incidence angle, ∀, of the illuminated area and the wind speed, *U*. The coefficients B_0, B_1, B_2 depend on ∀ and *U* (Quilfen et al., 1998).

From eq.1 it is clear that the geometry between the local radar incidence angle and wind direction is of importance. The relationship is graphed in Figure 1 for the CMOD-IFR2 algorithm. It is clear that uncertainty on the relative wind direction gives a large effect especially for high wind speed.

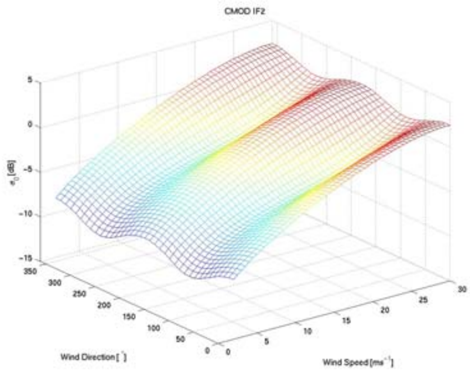

Figure 1. The dependence between backscatter coefficient, wind speed and relative wind direction for the CMOD-IFR2 algorithm.

For a relative wind direction of 0º and an incidence angle of 23º, the relationship between wind speed and backscatter coefficient is shown in figure 2 for the CMOD4 and CMOD-IFR2 models. In the current study the CMOD-IFR2 is used as this model gave the best results when comparing research ship met-observations to SAR-derived ocean wind speeds (Furevik et al., 2002).

Obviously the absolute precision in the SAR imagery is of importance. The radiometric accuracy of ERS-1 and –2 SAR's is within ±0.4dB (Attema et al., 2000) that translates to approximately ±0.7ms^{-1}. For very high wind speeds with around 0 dB, the error may be larger dependent on the calibration procedure (Horstmann et al., 2000).

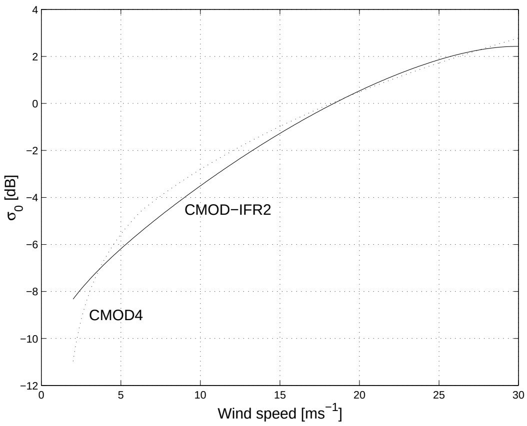

Figure 2 The model functions of the CMOD4 and CMOD-IFR2 are shown for a relative wind direction of 0º and an incidence angle of 23º.

3 THE STUDY SITE

The study site is Horns Rev in the North Sea where the worlds largest offshore wind farm is under construction in the summer of 2002. The wind farm (http://www.hornsrev.dk/) belongs to ELSAM and the collection of meteorological observations is performed by Tech-wise(Neckelmann and Petersen, 2000). The in-situ observations are from a tall meteorological mast located 14 km offshore from the coast, see figure 3. The observations studied are from the period May 1999 to June 2000, i.e. collected prior to the installation phase of the wind farm.

4 ANALYSIS RESULTS

4.1 On SAR wind fields

A total of 16 ERS-2 SAR scenes are analysed with respect to wind speed and wind direction accuracy. The mean wind speed in the SAR wind speed maps are calculated for a simple ellipse-shaped area upwind of the mast and compared case by case to the in-situ observations, see an ellipse in figure 3. The size of the ellipse is a function of height (here 10m) and the ellipse is located in the upwind direction of the mast. It is a simple footprint area-averaging method where all pixels in the footprint are weighted equally.

It is found that the linear regression result is y = 1.038x – 1.785 with $r^2 = 0.882$ on SAR wind speed and in-situ wind speed for wind direction taken a priori from the in-situ observations and used in the CMOD-IFR2. This result is for the 10 m wind speed.

Intercomparison of in-situ wind directions and SAR streak directions derived from 2D-FFT functions shows a linear regression of y=1.11x-31.57 with r^2=0.95. The accuracy on wind speed and wind direction compares to other studies e.g. (Vachon and Dobson, 1996).

The wind direction is relatively well defined from the wind streaks, however using the wind streak directions in the CMOD-IFR2 algorithm seem to introduce more uncertainty in the wind speed retrieval. This is found from the linear regression y = 1.102x – 2.126 with r^2 = 0.768 for a set of SAR wind speed maps calculated from a priori wind direction from the streaks and compared to in-situ wind speed (Hasager et al., 2002a).

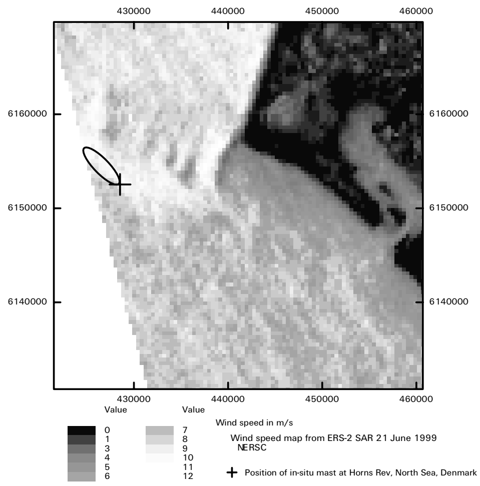

Figure 3 Wind speed map from Horns Rev in the North Sea calculated by the CMOD-IFR2 model based on an ERS-2 SAR satellite scene. In-situ wind speed at 10 m is 10.1ms^{-1} and wind direction 313.9º.

4.2 On offshore wind statistics and sampling

In a study based on offshore in-situ meteorological data from two Danish sites, Horns Rev as mentioned above, and the Vindeby site, an analysis is undertaken to answer the question: ‘Can satellite sampling of offshore wind speeds realistically represent wind speed distributions?’ At both sites tall met-mast with long-term high-quality time-series are available. The investigation deals with the statistical properties of the wind speed distributions. In order for wind resources to be calculated either the 1st to 4th moments of the probability distribution or the Weibull shape and scale parameters are needed.

Based on the data analysis and assuming an uncertainty of ±10% at a confidence level of 90% is acceptable then of the order of 60-70 randomly selected samples (SAR images) are required to characterize the mean wind speed and Weibull c parameter, while of the order of 150 images are required to obtain a variance estimate, and nearly 2000 are needed to obtain an energy density (or Weibull k) estimate. This finding is based on perfect accuracy of the image wind speed retrieval, a criteria that cannot be fulfilled. Furthermore the SAR scenes cannot be selected randomly in time as the satellite orbital parameters place a limit on availability in time. For the given cases (Horns Rev and Vindeby) the daily variations in mean wind speed was reasonably well-represented from the local recording times of the ERS-2 SAR (around 10.30 and 21.30 UTC) (Barthelmie and Pryor, 2002; Pryor et al., 2002).

An important finding of this research is that conditional sampling of in situ observations to replicate data that may currently be derived using SAR is that biases inherent in the SAR sampling methodology (importantly truncation of low and high wind speeds) lead to substantial over-estimation of the energy density. In the case of the Vindeby wind farm this over-estimation is of the order of 10 % relative to a 10 year time series, and hence is of sufficient magnitude to significantly impact feasibility studies.

The above-mentioned statistical limits at uncertainty bound and confidence level are shown as a cautionary note and the confidence levels use are chosen as an example, rather than a strict guideline. In feasibility studies the goal for predicting the offshore wind resource may be site specific, hence the SAR wind speed maps may offer valuable information content in certain cases.

5 DISCUSSION

The accuracy needed for feasibility studies on wind resource mapping may be obtained from ERS-2 SAR wind speed maps. In order to reduce the uncertainty in the estimation of the mean wind speed to an acceptable level, a large number e.g. 60-70 scenes will have to be used. This is possible in some parts of the world as the SAR scenes are stored in archives from the ESA satellites ERS-1 and ERS-2 SAR as well as the Canadian Radarsat satellite. Currently ERS-2 SAR, ENVISAT ASAR and RADARSAT are collecting SAR observations and these may be pre-ordered for a site of interest. The cost of SAR scenes for commercial purposes may however limit the use (e.g. 1200 Euro per ERS SAR scene). The cost should however be compared to the expenses necessary to obtain wind speed measurements and the time involved. In remote areas wind speed observations may not be readily available from airports, met-offices and the like. Hence it may be necessary to operate a met-mast at the site. Such operation involves a planning phase (e.g. legislation to erect the mast), logistical consideration and technical work. The met-observation collection phase itself is minimum one year to obtain a climatological record.

The advantages of SAR wind speed maps are that they are readily available and only image processing is necessary (office work). Furthermore SAR wind speed maps may directly indicate local wind phenomenon that atmospheric models may not necessarily capture accurately. This spatial information could be useful for exact geo-positioning of a proposed offshore wind farm.

The disadvantages of SAR wind speed maps are that the accuracy is far less accurate than high-quality wind speed observation (e.g. less than 1 % error on the in-situ wind speed observations from cup anemometers at Horns Rev) and that the number of samples may be rather limited due to cost.

A prototype tool for wind resource calculation based on SAR wind speed maps is under development. It is based on a footprint methodology of area-averaging the SAR wind speeds and classical methods in wind resource estimation extrapolating from the 10m level to hub-height (60-80m) of modern offshore wind turbines. So far a full validation on the SAR wind speed map methodology for offshore wind resource mapping has not been possible due to the limited number of satellite scenes but work is ongoing to achieve this.

6 CONCLUSION

The accuracy on SAR-derived wind speed maps is by careful processing less than the ±2ms^{-1} and the accuracy on wind direction retrieval around ±20º. The number of satellite scenes (samples) that would give an estimation of the mean wind speed within ±10% of the true value at the 90% confidence level (assuming no error in the SAR wind speed maps) is around 60-70 scenes.

The uncertainty in other parameter estimates is larger and hence caution must be used in use of SAR for offshore wind resource feasibility studies. Nevertheless many technical issues have been resolved with respect to the accuracy of wind speeds from analysis of individual scenes and the future may yield important advances with respect to asymmetric errors associated with SAR wind speed retrievals.

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REFERENCE LIST

Attema, E., Desnos, Y.-L., and Duchossiois, G.: 2000, 'Synthetic Aperture Radar in Europe: ERS, Envisat, and Beyond', *John Hopkins APL Technical Digest,* **21**, 155-169

Barthelmie, R. J. and Pryor, S. C.: 2002, 'Can Satellite Sampling of Offshore Wind Speeds Realistically Represent Wind Speed Distributions?', *Journal of Applied Meteorology* (accepted)

Furevik, B., Johannessen, O., and Sandvik, A. D.: 2002, 'SAR-Retrieved Wind in Polar Regions - Comparison With in Situ Data and Atmospheric Model Output', *IEEE Transactions on Geoscience and Remote Sensing* **40**, (to appear August)

Hasager, C. B., Dellwik, E., Nielsen, M., and Furevik, B.: 2002a, 'Validation of ERS-2 SAR Offshore Wind-Speed Maps in the North Sea', *International Journal of Remote Sensing* (submitted)

Hasager, C. B., Frank, H. P., and Furevik, B. R.: 2002b, 'On Offshore Wind Energy Mapping Using Satellite SAR', *Canadian Journal of Remote Sensing,* **28**, 80-89

Horstmann, J., Lehner, S., Koch, W., and Tonboe, R.: 2000, 'Computation of Wind Vectors Over the Ocean Using Spaceborne Syntheric Aperture Radar', *John Hopkins APL Technical Digest,* **21**, 100-107

Neckelmann, S. and Petersen, J.: 2000, 'Evaluation of the Stand-Alone Wind and Wave Measurement Systems for Horns REv 150KW Offshore Wind Farm in Denmark In: *Proceedings of OWEMES offshore wind energy in Mediterranean and other European Seas*, 13-15 April 2000, Sircusa, Sicily, Italy. ATENA/ENEA, Rome.

Pryor, S. C., Barthelmie, R. J., and Hasager, C. B.: 2002, 'Can Satellite Sampling of Offshore Wind Speeds Represent Wind Speed Distributions?', *In: Proceedings Global Windpower Conference and Exhibition*, Paris (FR), 2-5 Apr 2002. (European Wind Energy Association, Brussels) CD-ROM, p.5

Quilfen, Y., Chapron, B., Elfouhaily, T., Katsaros, K., Tournadre, J., and Chapron, B.: 1998, 'Observation of Tropical Cyclones by High-Resolution Scatterometry', *Journal of Geophysical Research,* **103**, 7767-7786

Stoffelen, A. and Anderson, D. L. T.: 1993, 'Wind Retrieval and ERS-1 Scatterometer Radar Backscatter Measurements', *Advance Space Research*, **13**, 53-60

Vachon, P. W. and Dobson, F. W.: 1996, 'Validation of Wind Vector Retrieval From ERS-1 SAR Images Over the Ocean', *Global Atmosphere and Ocean System,* **5**, 177-187