

# Satellite-based wind maps – Are they useful for siting of offshore wind farms?

**B. R. Furevik<sup>1</sup>, C. B. Hasager<sup>2</sup>, R. Barthelmie<sup>2</sup>, H. A. Espedal<sup>1</sup>, B. H. Jørgensen<sup>2</sup>, O. Rathmann<sup>2</sup>, S. Sandven<sup>1</sup>, G. Gaudiosi<sup>3</sup>, L. C. Christensen<sup>4</sup>, S. Pryor<sup>2</sup> and O. M. Johannessen<sup>1,5</sup>**

(1) Nansen Environmental and Remote Sensing Center, Edv. Griegsvei 3A, N-5059 Bergen, Norway. Phone: +47 5529 7288, fax: +47 5520 0050, [Birgitte.Furevik@nersc.no](mailto:Birgitte.Furevik@nersc.no)

(2) Risø National Laboratory, Frederiksborgvej 399, Postboks 49, DK-4000 Roskilde, Denmark, Phone: +45 4677 4677, Fax: +45 4677 5688, [charlotte.hasager@risoe.dk](mailto:charlotte.hasager@risoe.dk)

(3) ENEA, Divisione Fonti de Energia Rinnovabili, C. P. 2400-00100 Roma A. D., 00060 Roma, Italy, Phone: +39-06-30483994, Fax : +39-06-30486315, [gaetano.gaudiosi@casaccia.enea.it](mailto:gaetano.gaudiosi@casaccia.enea.it)

(4) NEG Micon, Wind & Site Departement, Alsvej 21, DK-8900 Randers, Denmark, Phone: +45 8710 5235, Fax: +45 8710 5004, [lcc@neg-micon.dk](mailto:lcc@neg-micon.dk)

(5) also at the Geophysical Institute, University of Bergen, Norway.

## Abstract

Offshore wind farms may soon contribute an important source of renewable energy. The energy production of a wind farm is closely connected to the wind climate and the local position, and the expected outcome is traditionally calculated based on least one year of accurate wind measurements. Satellite Synthetic Aperture Radar (SAR) wind mapping can be a useful tool in the process of selecting the optimal site for these measurements and may therefore increase the cost-effectiveness when planning wind farms, e.g. in feasibility studies. In the present study SAR, in situ and model output from three test sites have been analysed and a tool for effectively the retrieving wind from SAR images and utilising this in WAsP has been developed. Testing of the WEMSAR tool at Horns Rev in Denmark is ongoing.

## 1 - Introduction

In situ wind measurements are obtained from ground mounted instruments, such as cup- or sonic anemometers which usually provides time series of averaged 1 or 10 minutes intervals. In situ measurements do not resolve the spatial variations in the wind field and it may be difficult to estimate wind conditions at a nearby site. This problem is traditionally handled by using mathematical flow models called micrositing models such as the Wind Atlas analysis and application Program (WAsP<sup>1</sup>) developed at Risø National Laboratory, Denmark [1]. This model requires long-term wind statistics and an

---

<sup>1</sup> <http://www.wasp.dk/>

accurate time series of wind and air temperature during a whole year, in order to accurately estimate the wind energy potential in a given area. Since such measurements are expensive, it is important to choose the site best suited for the meteorological mast and the associated modelling. It is here we are proposing to use satellite Synthetic Aperture Radar (SAR) wind retrieval as a first step in a selection process where more detailed *in situ* observations are needed.

The SAR is an active sensor carried onboard several present satellites, i.e. the European satellites *ERS-2* and *Envisat* and the Canadian satellite *Radarsat-1*. The SAR antenna is sending pulses of microwave radiation (at C-band) to the right of the satellite track and records the amount of energy that is scattered back to the antenna. Over the sea, the backscattered energy is related to the amount of wind-generated capillary and short gravity waves on the sea surface. Therefore there exists a relationship between the wind speed and the normalised radar backscattering cross section over the sea. The objective is to utilise this relationship in a tool to effectively derive offshore wind maps from SAR images for use in offshore wind farm siting.

The SAR images used in this study are from the ERS-1 and ERS-2 satellites with a ground coverage of 100 km x 100 km. The images are absolutely calibrated in order to obtain values for the normalised radar cross section (NRCS). These values are translated into wind speed using a C-band model function and the local incidence angle and wind direction. The wind direction is derived from the direction of wind streaks on the sea surface originating from atmospheric roll vortices or Langmuir cells in the upper ocean.

A processing tool for the SAR data is being developed to run as an add-on to the WasP programme for wind farm siting developed at Risø National Laboratory. The tool is to be tested on the Danish west coast in the area of the new large offshore wind farm that will be ready for operation in November 2002.

## **2 - Method of approach**

Three sites were chosen for the study. These are the west coast of Norway, the west coast of Denmark and the Bonifacio strait between Corsica and Sardinia. We will describe the wind retrieval technique from satellite radar images, then give a brief description of the three sites and show comparisons between *in situ* data, model data and SAR data from the Norwegian and Italian sites. Finally the tool developed for using SAR data in wind resource estimation will be described.

The models used in the study are those for wind retrieval from SAR, an atmospheric non-hydrostatic model and a micrositing model (**Table 1**). The mesoscale model is the Karlsruhe atmospheric mesoscale model (KAMM) run at Risø National Laboratory, Denmark. This model is normally used for calculating the regional wind resource maps from global reanalysis data (eg. ECMWF, NCEP) [2]. In this project, model-runs for chosen days with SAR coverage are used for validation of the SAR retrieved wind as supplement to *in situ* data. The micrositing model, WasP, has been run in an untraditional way, i.e. on single cases, in order to provide detailed flow information in the coastal areas for spatial comparison with the SAR retrieved wind fields.

Table 1 – Overview of models used in the study.

MODEL	DESCRIPTION	INPUT	OUTPUT
CMOD-IFR2 CMOD4	Empirical relation to transfer the normalized radar backscatter cross-section (NRCS) values into wind speed.	Wind direction, antenna incidence angle, NRCS values.	Wind speed
Karlsruhe atmospheric mesoscale model (KAMM)	Three-dimensional non-hydrostatic atmospheric mesoscale model	Hindcast wind field, lateral boundary conditions	All wind components, pressure, temperature, humidity
Wind atlas analysis and application program (WAsP)	Micrositing model based on a mathematical flow model.	Wind measurements	Wind climate at a specific location

#### *Wind retrieval from SAR images*

In the incidence angle range of the SAR, the reflected amount of energy from the sea surface is proportional to the surface wind speed. The short gravity waves responsible for the backscatter of the radar signal are created instantly by the wind stress and are therefore good indicators of the sea surface wind speed. From a large number of collocations between scatterometer and buoy/model data empirical relations between the wind speed (normalized to 10m above the surface) and the NRCS have been established [3, 4]. These relations are known as C band models (CMOD) and their application and accuracy for SAR is reported in several papers [5-13].

The NRCS is obtained through calibration of the SAR precision images (PRI). The approach for calibrating ERS SAR PRI is described by Laur et al. [14] and ESA have made a package of routines available for their users for this purpose<sup>2</sup>. The SAR PRI has an initial pixel size of 12.5 m × 12.5 m. However, to obtain satisfactory statistical significance the images are reduced to a pixel size of 400 m × 400 m, still allowing detailed mapping of the wind [12]. The wind directions are estimated from FFT derived image spectra over a SAR scene [11,12]. This wind direction field is used as input to the CMOD algorithm to obtain the wind speed (**Table 1**).

#### *The Norwegian site*

The in situ data at the Norwegian site is obtained by the Norwegian Meteorological Institute (met.no) at the island of Hellisøy (Figure 1). The weather station on Hellisøy is situated on top of a 10 m high mast mounted in connection with a house, and is further surrounded by several other masts and buildings and a very rough terrain which all have impact on the wind climate. The anemometer measures wind at 33 m above sea level and records the average wind speed over ten minutes every hour. The speed-up effect caused by the terrain will vary for the different wind directions and may be considerable under certain conditions [15]. WAsP has been run on 7 days with SAR coverage but the

<sup>2</sup> <http://earth.esa.int/services/best/>

results are not fully analysed. At this site 53 SAR PRI scenes from two years have been analysed.

#### *The Danish site*

The in situ data for the Danish site is obtained from the offshore mast at the location of Horns Rev where a new large offshore wind farm is set into operation this winter. These data are of high quality and extensive analysis has taken place on the data from this site. The final validation of the tool is tested on the Danish site. The validation at the Danish site is discussed by Hasager et al [16] (this volume).

#### *The Italian site*

In situ data for the Italian site is obtained from a 10m high mast in La Maddalena shallow. 9 SAR PRI images have been analysed at this site.

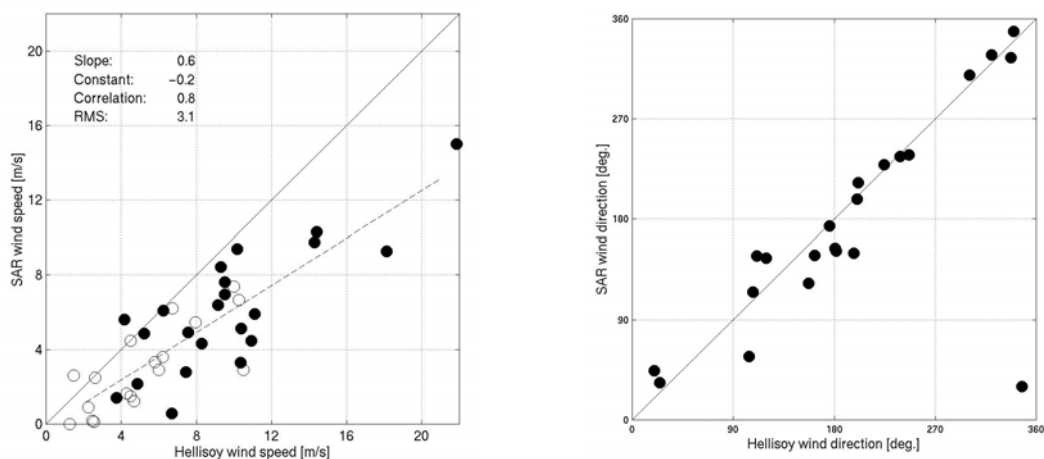
*Map will be inserted here with the location of the test sites.*

### 3 - Results

#### *Comparisons – absolute values*

The scatter plots for comparing wind speed and wind directions from the in situ observations with those obtained from SAR is shown in **Figure 1** for the Norwegian and the Italian sites. At the Norwegian site a discrepancy is seen between in situ observations and the SAR wind speeds, which is most pronounced for higher wind speeds. As this can be due to a speedup effect over the island, the reanalysis data from ECMWF from an offshore point outside Hellisøy was also used for comparison (middle row). In that comparison the high wind speeds observed in the in situ data are not found and the agreement is much better for the high wind speeds. Rms values for SAR wind speed compared to in situ data at Hellisøy of 3.1 m/s, to ECMWF data of 1.6 m/s and to in situ data at La Maddalena of 2.8 m/s was found.

In the cases where a wind direction was retrieved from the images, it generally agrees well to the measured wind directions (right column).



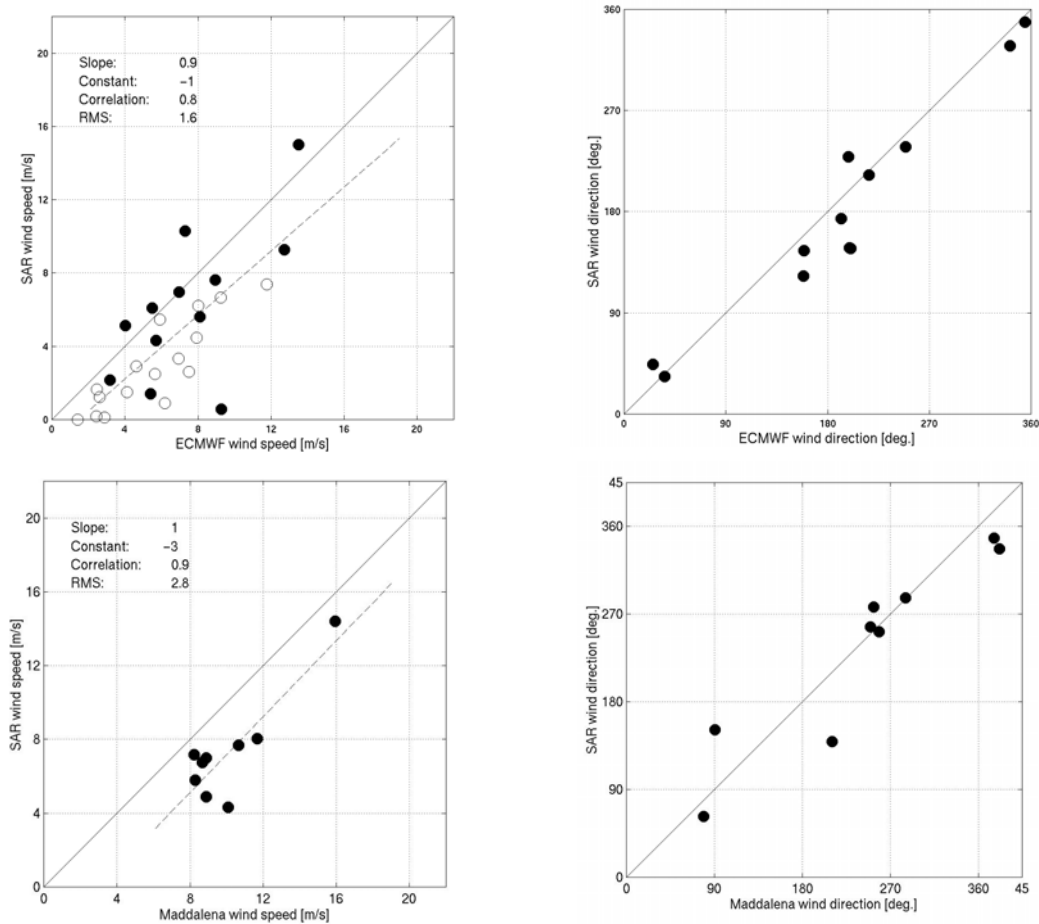


Figure 1 – Comparison of wind speed (left column) and wind direction (right column) retrieved from ERS SAR images and from in situ observations at Hellisøy, Norway (top – 40 data points), ECMWF reanalysis data offshore of Norway (middle – 28 data points) and in situ observations at La Maddalena, Italy (bottom – 9 data points). When possible, input wind direction was taken from SAR (Black dots). For the remaining cases, Hellisøy wind direction was used (white dots).

### *Comparisons – spatial features*

The analysis of the model data is still ongoing. However, in **Figure 2** an example comparison between WASP output and the SAR retrieved wind from February 14 1996. WASP is run using the wind speed and direction from Hellisøy weather mast at the time closest to the satellite passage. The model predicts 14m/s wind offshore while the SAR wind speed is lower at between 8-12 m/s. An increase in wind speed towards the coast is seen in the SAR wind field which may be due to the case not being stationary. From the time series in **Figure 2** it is seen that the wind is steadily increasing during that day. The KAMM model predicts 9-10 m/s offshore, which agree well with the SAR. All three captures a decrease in wind speed of 2-4 m/s in lee of Fedje (and Hellisøy) island.

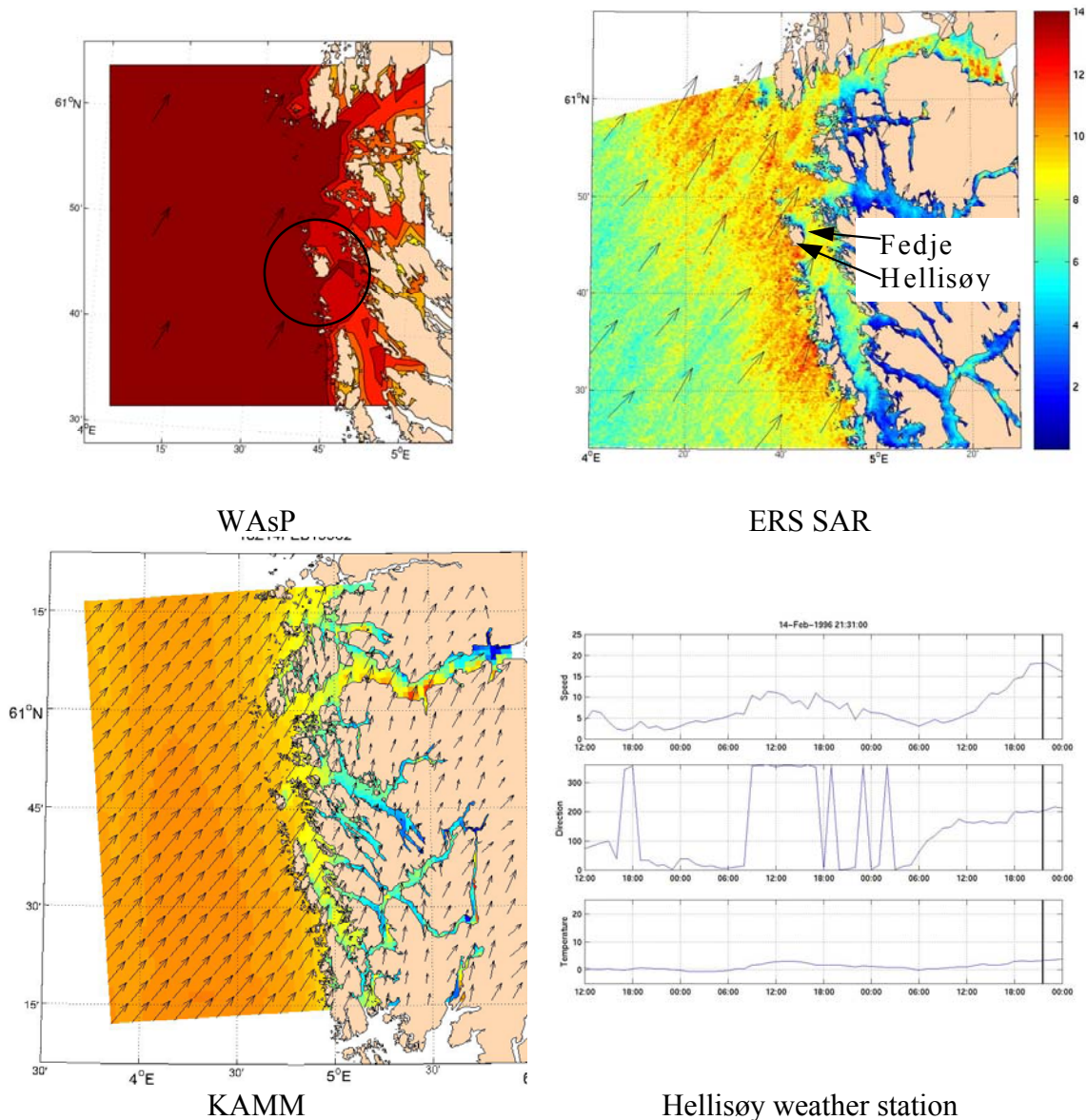


Figure 2 – Spatial comparison between model output from WAsP and KAMM and SAR retrieved wind field on February 14 1996 at the Norwegian site. The same colour scale is used for plots of model and SAR results. Below is shown the plots of wind speed, wind direction and temperature at Hellisøy weather station. The vertical bar indicates the time of the SAR passage. Please note that the WAsP results are only valid in a distance of about 5-10km from Hellisøy weather station.

### *The WEMSAR tool*

During a 3-year EC project a first version of a tool has been developed for effectively retrieving wind fields from ERS SAR images and integrating these data into the well known WAsP programme. So far the tool consists of two parts as sketched in **Figure 3**.

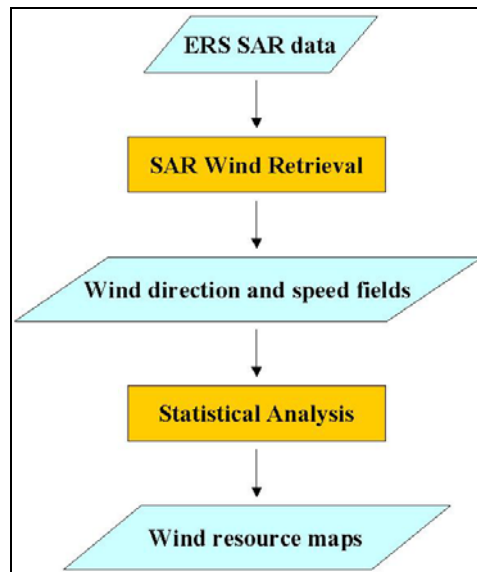


Figure 3: The WEMSAR tool consisting of a SAR wind retrieval part and a statistical part.

The first part of the tool is for wind retrieval from ERS SAR images. This module reads calibrated image files and the associated header files from ERS SAR toolbox. The images are reduced to approximately 1000x1000 pixels with a pixel size of 100 m by 100 m. The output is binary float files of wind speed and wind direction at a pixel size of 400 m by 400 m. These files are read into the second part of the tool, which is the statistical module. In this module all the satellite wind fields are treated together to provide input to WASP (*Charlotte could you please give me a sentence or two here?*)

The wind retrieval module is sketched in more detail in **Figure 4**. If the user inserts a wind direction from in situ observations one single wind direction is used over the whole 100 km by 100 km image. Otherwise the wind directions are calculated from image spectra in boxes of 12.5 km by 12.5 km over the image. The user have the possibility to remove erroneous vectors before the directions are interpolated to the whole field and the C-band models are called. After the validation phase only output from the one model with the best correlation with in situ observations at Horns Rev will be used in the tool.

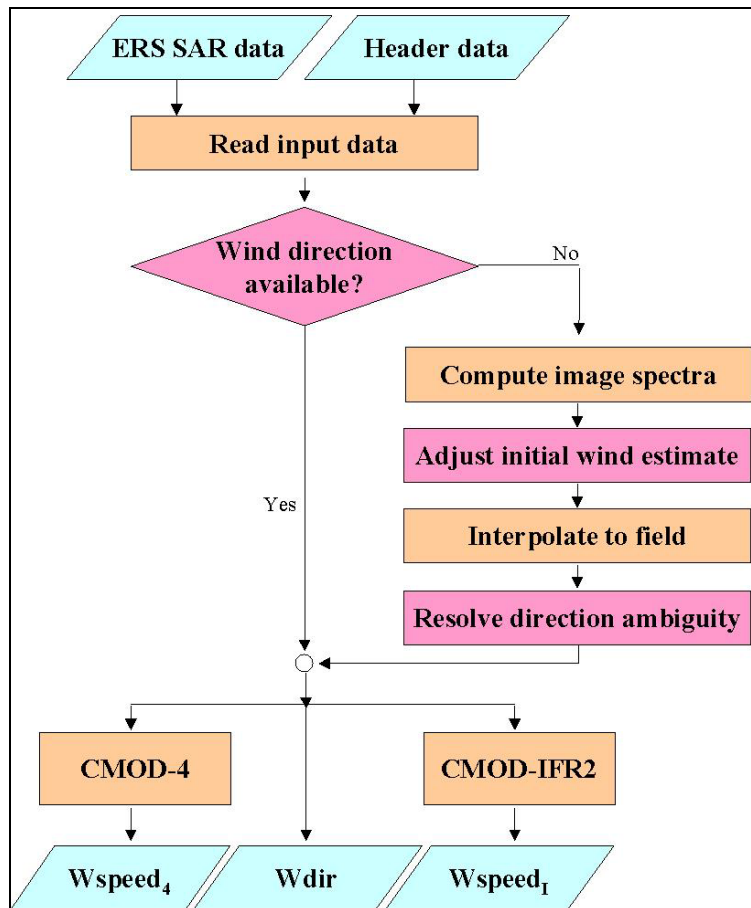


Figure 4 – The SAR wind retrieval module of the WEMSAR tool. Input is calibrated image files and output is files of wind speed from two models CMOD-4 and CMOD-IFR2 and wind direction. Pink boxes are where the user is asked to provide manual input.

#### 4 - Conclusions

The aim of the study is to utilise the advantages of remote sensing in finding the best locations for offshore wind farms with the highest possible energy output. Through analysis of 81 ERS SAR scenes from three different sites, KAMM and WAsP model runs and analysis of these data sources together a WEMSAR tool has been developed to give input to the WAsP programme for wind farm siting. This tool is presently being tested at Horns Rev using in situ data from an offshore mast and an additional 50 ERS SAR images.

#### Acknowledgements

The study has been carried out during the EC project Wind energy mapping using Synthetic Aperture Radar (WEMSAR), project number ERK6-CT99-00017. Data have been provided by European Space Agency, the Norwegian Meteorological Institute and ENEA, Italy. Funding from the Norwegian Research Council is acknowledged.



## References

- [1] Mortensen, N. G, D. N. Heathfield, L. Landberg, O. Rathmann, I. Troen, and E. L. Petersen (2000) Wind atlas analysis and application program: WAsP 7.0 Help facility, User's guide, Risø National Laboratory, Frederiksborgvej 399, Roskilde, Denmark, ISBN 87-5502667-2.
- [2] Frank, H., and L. Landberg (1997) Modelling the wind climate of Ireland, *Boundary-Layer Meteorology*, vol. 85, 359-378.
- [3] Quilfen, Y., B. Chapron, T. Elfouhaily, K. Katsaros and J. Tournadre (1998) Observation of tropical cyclones by high-resolution scatterometry, *Journal of Geophysical Research*, vol. 103, nr. C4.
- [4] Stoffelen, A., and D. Anderson (1997) Scatterometer data interpretation: Estimation and validation of the transfer function CMOD4, *Journal of Geophysical Research*, vol. 102, no. C3.
- [5] Scoon, A., I. S. Robinson and P. J. Meadows (1996) Demonstration of an improved calibration scheme for ERS-1 SAR imagery using a scatterometer wind model, *Int. J. Remote Sens.*, 17 (2), 413-418.
- [6] Vachon, P. W, and F. W Dobson (1996) Validation of wind vector retrieval from ERS-1 SAR images over the ocean, *The Global Atm. and Ocean Sys.*, 5, 177-187, 1996.
- [7] Fetterer, F., D. Gineris and C. C. Wackerman (1998) Validating a scatterometer wind algorithm for ERS-1 SAR, *IEEE transaction on Geoscience and Remote Sensing*, vol. 36, no. 2.
- [8] Korsbakken, E., J. A. Johannessen and O. M Johannessen (1998) Coastal wind field retrieval from ERS synthetic aperture radar images, *J. Geophys. Res.*, vol. 103, no. C4, April 15.
- [9] Furevik, B., and E. Korsbakken (2000) Comparison of derived wind speed from SAR and Scatterometer during the ERS tandem phase, *IEEE Trans., of Geosc. Rem. Sens.*, vol. 38, no. 2.
- [10] Horstmann, J., W. Koch, S. Lehner and R. Tonboe (2000) "Wind retrieval over the ocean using Synthetic Aperture Radar with C-band HH polarisation", *IEEE transactions on Geoscience and Remote sensing*, vol. 38, no. 5, 2122-2131.
- [11] Furevik, B. R., and H. A. Espedal (2002) Wind energy mapping using Synthetic Aperture Radar, *Canadian Journal of Remote Sensing*, Vol 28, no. 2, pp. 196-204.
- [12] Furevik, B., O. M. Johannessen and A. D. Sandvik (2002) SAR-retrieved wind in polar regions – comparison with in situ data and atmospheric model output, *IEEE Trans., of Geosc. Rem. Sens.*, Vol. 40, no. 8.
- [13] Thompson, D., F. Monaldo, R. C. Beal, N. S. Winstead, W. G. Pichel and P. Clemente-Colon (2001) Combined estimates improve high-resolution coastal wind mapping, *EOS, Transactions of the American Geophysical Union*, vol. 82, no. 41, October.
- [14] Laur, H., P. Bally, P. Meadows, P. J. Sanchez, B. Schaettler and E. Lopinto (1996) Derivation of the backscattering coefficient  $\sigma_0$  in ESA ERS SAR PRI products, *Doc. ES-TN-RS-PM-HL09*, issue 2, rev. 2, Eur. Space Res. Inst., Frascati, Italy, June 28.
- [15] Jackson, P. S., and Hunt, J. C. R. (1975). Turbulent wind flow over a low hill, *Quarterly Journal of the Royal Meteorological Society*, Vol. 101, pp. 929-955.
- [16] Hasager, C. B., B. R. Furevik, O. Rathmann and M. Nielsen (2003) Offshore wind resource estimation from satellite-based wind speed maps (these proceedings).