RWT TOOL: OFFSHORE WIND ENERGY MAPPING FROM SAR

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ABSTRACT

Demonstration of software RWT (Risoe Wemsar Tool) developed by Risoe National Laboratory, Dept. of Wind Energy for assessment of offshore wind resource maps based on satellite Synthetic Aperture Radar (SAR) observations is given. The software runs on pc in Windows and is compatible with WAsP (Wind Atlas Analysis and Applications Programme). WAsP is the de facto standard software in wind resource mapping used in more than 90 countries by more than 1300 users worldwide. Calculation on wind power production typically is based on meteorological data input to WAsP. RWT provides an alternative method for wind data input in offshore regions based on satellite SAR wind field observations. Wind statistics related to spatial variations (e.g. noise level, physical representation) and temporal variations (e.g. number of samples, cut-off range) are included. Error estimation on wind resource parameters (e.g. Weibull distribution parameters) is provided through RWT. Work to include scatterometer wind fields for wind resource estimation in RWT is ongoing. RWT is part of the EO-WINDFARM service in development in the EOMD project EO-WINDFARM (17736/03/I-IW).

1. INTRODUCTION

Wind energy offshore has gained much interest during the last decade. The adventure started in 1991 when the first offshore wind farm was constructed at Vindeby in Denmark. At the time it was known that the wind energy potential is much higher offshore than on land, but the investment cost is also much higher. The cost-benefit for offshore wind power was largely unknown.

Recent history shows a successful development of a number of offshore wind farms in Denmark: Middelgrunden near Copenhagen, Horns Rev in the North Sea and Nysted in the Baltic Sea. New development plans near Horns Rev and Nysted are ongoing. Offshore wind farms are in development or constructed also in Germany, Ireland, Sweden and UK. In several more countries investigation of the offshore wind power potential is intense.

Offshore wind observations are sparse, indeed. The high cost on the installation and maintenance of offshore meteorological masts also limits the number of observations that will be collected in the near future.

This situation makes it an ideal time for introduction of alternative ocean wind observations to the community dealing with offshore wind resources.

The Earth Observation Market Development (EOMD) project funded by the European Space Agency (ESA) called EO-windfarm (http://www.eo_windfarm.org) is aiming to enhance the use of satellite observations in wind farm development and management. The project deals with both land- and sea-based wind farms.

The present paper presents software developed to produce offshore wind maps and wind statistics with the highest possible spatial detail using images from satellites.

2. SATELLITE IMAGES

Offshore wind mapping can be obtained from satellite SAR. These images offer the highest spatial detail (~500 m by 500 m grid cells) and are observed within the offshore ‘wind-farming’ zone (~5 to 30 km offshore). New images are continuously received from three orbiting satellites: ERS, Radarsat and Envisat. For wind engineers with a fast-moving business, the SAR image archive may be of great value. The historical record dates back to year 1991 and archived SAR images can be order and received in about a week. The commercial cost is currently 400 euro per ERS SAR PRI and Envisat ASAR PRI scene. One ERS scene covers 100 km by 100 km. Envisat images can be ordered in similar size but also at 405 km by 405 km (however then the spatial detail in the wind map will be around 2.5 km by 2.5 km grid cells).

2.1 Wind retrieval from SAR

Wind mapping from imaging SAR is described in the scientific literature (e.g. [1,2,3]).

Firstly, wind direction is found using a detection algorithm ([4,5]) to quantify the alignment of linear

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features called streaks. The streaks are visible in most SAR images. The higher the wind speed, the better the alignment is determined in general. The streaks only reveal the alignment, not the direction vector. This has to be assessed from an external source of information such as a weather map, a nearby (coastal) mast, or in some cases for offshore flow conditions, lee-effects are visible near the coastline.

Secondly, wind speed is determined in SAR images using the *a priori* wind direction (from the streak analysis) as input to a wind retrieval algorithm ([6]). The uncertainty on wind direction is ±20º and for wind speed ± 1.3 ms^{-1} ([3]). Similar values are reported elsewhere. Satellite wind vectors are valid for 10 m above sea level.

2.2 The physical interpretation

The instantaneous wind speed is causing capillary- and short gravity waves to develop at the ocean surface within ~1 second. The small waves are riding on top of longer waves, e.g. 1 m waves that are a result of several hours of strong wind, and on top of very long waves (swell) of several hundred meters wavelength. The shortest waves have a wavelength of the order of 5 cm. This is similar to the C-band radar signals (5.3 cm wavelength) emitted and received from the SAR instruments. The C-band electromagnetic radiation is backscattered from the sea surface as a function of the number of short waves and their direction relative to the look angle.

The highest response is found for head wind (i.e. the short waves are orthogonal to the look direction) and the lowest response is found for parallel alignment. Therefore the relative angle between wind direction and look angle has to be known *a priori*.

The higher the wind speed, the higher is the backscattered signal (and the brighter the image). For winds less than 2 ms^{-1} the algorithm is not valid. In such cases the image can be black (as the surface then acts as a mirror). The new algorithm (CMOD5, Stoffelen 2004, same issue) is valid to 35 ms^{-1}, whereas CMOD4 [6] is only valid to 24 ms^{-1}.

Possible errors in wind speed retrieval from SAR images are related to condition affecting the sea surface. Oil slicks and algal blooms can hinder the development of short waves. Hence wind speed will be underestimated in such cases. Heavy rain can also disturb the sea surface and rain cells can be seen as areas with too low wind speed. Finally should be mentioned that ocean currents (e.g. tidal currents) and flow over shallow areas can cause development of extra short waves. These phenomena will show up as areas of too high wind speed in the wind maps. Satellite SARs have all-weather capabilities mapping day and night, and through cloud and precipitation.

3. SOFTWARE

Software for practical application using satellite SAR for offshore wind mapping is developed. The software is aimed for wind engineers. The development was initiated during the WEMSAR project funded by the European Commission (years 2000-2003). The software is in two parts. One developed at the Nansen Environmental and Remote Sensing Centre (NERSC) in Norway (Wemsartool), the other at Risoe National Laboratory in Denmark (RWT). In addition the free-ware BEST from ESA is necessary. Fig.1 shows a sketch of the work-line.

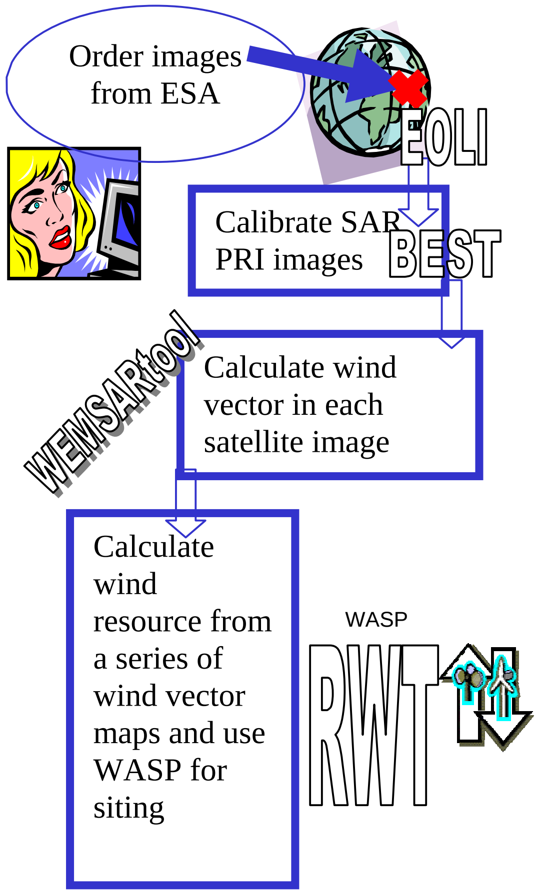

Fig. 1 Software for mapping offshore wind resources based on satellite SAR images.

The first step is to search for available satellite images in the ESA archive using EOLI (http://pooh.esrin.esa.it/services/catalogues.html) for an area of interest. Just insert latitude and longitude and a search radius in degrees. Select either ERS-1/-2 SAR PRI level 1 images, or Envisat ASAR

PRI level 1 images. The available images can be screened through the quicklook browse facility. An order can be placed and the scenes will be delivered on CD-rom.

The second step is to calibrate each satellite image. The BEST software (http://earth.esa.int/services/best/) is easily installed and run, either in command-line or interactive screen.

The third step is to compute the wind direction and then wind speed using the Wemsartool ([1]) for each satellite image. It is based on two-dimensional Fast Fourier transform to assess the wind direction [5] and CMOD4 [6]to calculated the wind speed. A user-guide describes the method.

Finally, a series of wind speed and wind direction maps (from Wemsartool) is input to RWT (Risoe Wemsar Tool). RWT allows wind resource statistics to be calculated as maps. The wind statistics can be exported to wind siting software such as the Wind Atlas and (WASP) program [7], http://www.wasp.dk.

WASP contains information on most wind turbine types, power curves and thrust coefficients. WASP is used to calculated the predicted annual wind energy yield for a given wind farm outlay. In case the prospected wind farm is located offshore near the coastline, the effect of topography and land roughness also has to be included to WASP in order to obtain an accurate power prediction. The modest topography of the island Sprogoe in Denmark is quantified as an example in [8].

4. RWT

RWT is a pc-based software. RWT is developed such that the wind statistical output from the satellite SAR images is similar to the wind statistics usually obtained from a time-series collected at a meteorological mast. This is not trivial, as the satellite wind maps contain spatial information for a snapshot period (few seconds) whereas a meteorological time-series contains time-series information for a specific geographical point (x, y, z coordinates). The wind data must be specified as a histogram of wind speed and direction.

Satellite wind maps are valid for 10 m above sea level. Hence the wind data will have to be extrapolated to hub-height. Modern turbines are 60 to 100 m tall with blades of 70 to 90 m. The tip of blades can reach 190 m above sea level. RWT is not used to extrapolate 10 m winds to hub-height (or beyond). WASP is adequate for this task.

RWT is taking care of three issues

- area-averaging (footprint)
- noise reduction in satellite-based wind maps
- Weibull fitting to a limited data set

Observations at e.g. 50 m height are not related to the surface conditions at the foot of the mast, but only to the upwind conditions within the source area. The theoretical framework is well established in boundary layer modelling, and is typically referred to as flux footprint [9]. The simple footprint method described in [3] is used here. In more advanced footprint models accurate information on thermal stratification of the air mass is needed.

Applying a footprint averaging method instead of a box-area average in the vicinity of a point of interest is superior from a physical point of view. In RWT the footprint is directed to the upwind area in regard to the point of interest (i.e. in every grid cell in the domain) in each wind speed map using information from the wind direction map. A spectral filter is applied in order to achieve fast computation.

Furthermore, the applied footprint averaging reduces random and small-scale noise in the wind speed grid cells prior to further analysis. Noise due to speckle is found in the wind maps at a 400 m by 400 m resolution. The filtering also reduces limited noise from atmospheric and oceanic features.

However in case of large areas with atmospheric or oceanic noise (visual inspection is needed!), it is recommended to deselect these regions drawing a polygon to exclude them from further analysis. Likewise it is a must to exclude all land surfaces (winds cannot be retrieved from SAR over land!). To ease land-sea detection in the wind map, a coastline can be shown in RWT.

After applying the spectral filtering and the flux footprint algorithm, the wind data from SAR consists of a short time series of wind speed and wind direction representative for every point in the map. In principle, further analysis could be made with the WAsP Observed Wind Climate wizard (OWC) but the RWT program offers an alternative method dedicated to sparse data sets.

The limited amount of data (images) is a statistical problem. The number of scenes needed to determine the Weibull parameters with 10% accuracy and 90% confidence is approximately 75 and 175 for the scale parameter A and shape parameter k, respectively, depending on the shape parameter k and the fitting method [10,11]. More data are needed when better accuracy is sought.

The Weibull parameters usually are estimated per wind direction sector (e.g. 12 bins) but due to the limited data set, the shape parameter of the distribution of all satellite observations is used for all sectors, and only the Weibull scale parameter is estimated in each bin.

The few number of samples also puts special emphasis on the function for fitting the Weibull distribution to the data. The maximum likelihood method is recommended for the following reasons

- enhanced fitting distributions to censored data [12]
- direct estimation of uncertainties.

Satellite wind maps are censored data as wind speeds less 2 ms^{-1} or above 24 ms^{-1}, are outside the validity range of CMOD4. (CMOD5 above 35 ms^{-1}, Stoffelen, 2004, same issue).

The frequencies of wind directions currently can be estimated either by simple bin counting, or by resampling local frequencies evaluated by the angles between observed wind directions in RWT. Both methods are insufficient in sparse data sets, and we plan to improve the performance including the measure-correlate-predict technique.
Wind climate statistics based on satellite observations may be biased due to diurnal wind variations. Satellite SARs only observe twice per day (late morning and early evening) as a function of their polar orbits. Diurnal wind variation in coastal regions are known, e.g. land and sea breezes systems. These are prevalent in weak synoptic flow conditions, but not dominating in strong wind climates. Care should be taken, however, in all cases.

5. EXAMPLES: Horns Rev wind farm

A series of 85 ERS-2 SAR satellite images from Horns Rev in the North Sea, Denmark is analysed with the software described in section 3 and 4. The images are collected since May 1999. The map of mean wind speed from RWT is shown in Fig. 2.

Comparison of wind speed at the mast and footprint-averaged values from a subset of 56 images (all collected prior to installation of the wind farm) shows CMOD4 to be biased around 0.3 ms^{-1} with a standard error of 1.3 ms^{-1} ([3]).

The wind farm (http://www.hornsrev.dk) was constructed from November 2001 and started operation December 2002. The wind climate measured at Horns Rev shows that at 10 m above sea level Weibull A is 7.34 ms^{-1} and Weibull k 2.3 [13]. The values are found from extrapolation of a 3.5-year 10-minute data series (183.960 samples) collected at four heights.

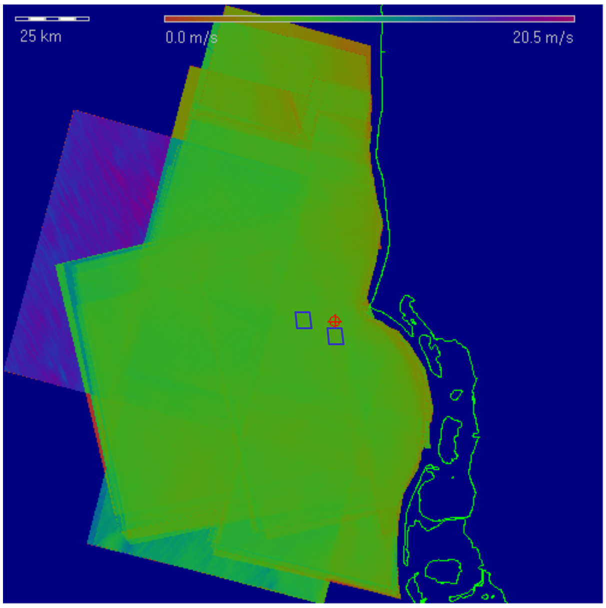

Fig. 2 Mean wind speed from 85 ERS-2 SAR satellite images near Horns Rev in the North Sea. Meteorological mast at red crosshair. Trapezoids with current (eastern) and prospected wind farm (western)

The satellite images show a mean wind speed of 6.17 (0.52) ms^{-1}, Weibull A 6.92 (0.59) ms^{-1} and Weibull k 1.73 (0.19) at the centre of the current wind farm. The uncertainty estimate is given in (). The uncertainty only is related to the low number of samples and does not include errors within each SAR wind map. All values are for 10 m above sea level based on 51 images collected prior to construction of the wind farm.

At the centre of the prospected wind farm, the mean wind speed is 6.50 (0.48) ms^{-1}, Weibull A 7.33 (0.55) ms^{-1} and Weibull k 1.98 (0.20). It is found that the mean wind speed at the prospected site is 5.3% higher than at the wind farm. The distance between the two points is 11 km. Some uncertainty is related to the finding as not all images cover the two sites ([14], same issue).

The absolute accuracy for estimation of wind resources from a few (e.g. 50) satellite images is poor, whereas the relative uncertainty between the two sites is believed to fair. The general decrease in wind speed from offshore to inland (e.g. 8.1 ms^{-1} to 4.5 ms^{-1}) can be estimated from a geostrophic flow model assumption. The result compares well to the SAR winds.

The data set has been divided into cases of onshore and offshore wind condition. The result shows that for onshore flow the satellite-based wind speed data are very close to observed wind speed at the mast whereas for offshore flow the satellite wind maps have a negative bias. It is most likely related to internal marine boundary layer development and decoupling between the near-surface winds, e.g. less than 5 m above sea level, and observed winds at the mast. Further investigation is ongoing in search for a correction method for the negative bias for offshore flow.

5.1 Wake effects

The mean wind speed is reduced behind a wind farm and the turbulence intensity increased. The reduction in wind speed has been investigated in the satellite images collected after the wind farm started operation. In calm conditions the outlay of the wind farm is very clear whereas in windy conditions the single turbines are less visible. The reduction in mean wind speed from the free-stream value is on average ~1 ms^{-1}. It is found to occur on average ~5 km downwind of the last row of turbines. The recovery of the wind further downstream is rather slow and it occurs considerably further downwind of the last row of turbines. The spatial dimension and absolute magnitude in the wake quantified from satellite SAR have successfully been compared to results from a state-of-the-art wake model [15]. The satellite-based mapping of the wake of the Horns Rev wind farm strongly indicates that the two wind farms will 'steal' wind energy from each other in certain wind direction. The shortest distance between the wind farms will be ~5 km.

6. DISCUSSION

Using satellite SAR wind maps for offshore wind resource assessment is not possible as a stand-alone technique. The major limitation is the limited number of satellite images for a specific site. It can be around 400 images from ERS alone. These images could be combined with Radarsat and Envisat images. For Radarsat the wide-swath mode has often been used, hence some parts of the world may be covered frequently. The spatial resolution of wide-swath images would decrease the spatial details to a few km grid cells instead of ~ 500 m by 500 m grid cells.

Advantages of high-resolution mapping are demonstrated from the examples at Horns Rev. The absolute accuracy is very low, yet the relative accuracy for geo-spatial comparison is thought to be fair. Only one mast is available for the (true) spatial verification and therefore this validation is combined with classical model estimates. Results from the satellite-based wake study compare well to model results. In general, the satellite-based SAR wind mapping technique provides new insight to the offshore near-coastal wind climate.

6. OUTLOOK

Major limitations for practical use of high-resolution satellite SAR are the revisit time (~3 images per month), and the cost. To circumvent the first issue, Radarsat and Envisat ASAR wide-swath mode images would be attractive. Their revisit time is shorter and the area mapped is larger.

Alternatively, Quikscat and Midori-2 (http://podaac-www.jpl.nasa.gov/seawinds) scatterometer wind vector maps are of interest. The wind maps are freely available with global coverage twice per day since July 1999 (~3600 samples). Basic research [14] and development for the EOMD project is in progress.

A major limitation of Quikscat observations, however, is that the grid cells are 25 km by 25 km and there is a coastal zone void of data (~100 km). A new wind vector mapping grid resolution at 12.5 km by 12.5 km is in progress (pers. com. Paul Chang). But in all circumstances, there is a need to use the ocean wind climate (as Observed Wind Climate) from scatterometer and to extrapolate this towards the coastline. The optimal way of doing so is through WASP using topography and land roughness information.

Topographical effects are, as stated previously[8], important for mapping the offshore wind climate within the zone of major interest for wind farming. The digital elevation map (DEM) in raster file-format from the Shuttle Radar Topography Mission (SRTM) (http://www2.jpl.nasa.gov/srtm/) has been investigated. The accuracy for a mountainous area in Spain and a modest relief in Denmark shows very promising results. A software routine is developed in the EO-windfarm project to facilitate practical use of SRTM data in WASP.

Another development in the project is a new raster to vector conversion routine. Digital roughness maps obtained from optical satellite images classified into a number of land cover types can be used. Relevant roughness numbers are assigned to the classes [16]. In case the roughness can be mapped directly from SAR into a digital raster-based format such maps can also be used. Otherwise classic optical classification analysis has to be performed as in previous work related to surface flux studies [17,18]. The new conversion routine developed in the EO-windfarm project allows easy use in WASP.

7. CONCLUSION

RWT is useful for mapping spatial wind climate variations in the coastal zone. Offshore wind resource assessment cannot be based on satellite SAR images alone, however. The absolute accuracy is too low. The advantage of satellite SAR wind climate maps is their high spatial detail that is unsurpassed by other wind observing techniques.

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