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Abstract:

The knowledge of wind resource is essential to the sitting of a wind farm. This is crucial especially in coastal areas where installation of windmills is more costly than onshore. More accurate estimation of the resource is necessary to preserve the confidence of investors and reduce the cost of production.

Nowadays, the resource is evaluated by interpolation of discrete measurements but offshore measurements are rare and very costly (750,000 euros for an offshore mast) [1]. In addition, coastal wind distribution is characterised by large spatial variations, which are not represented by local measurements [1].

Several studies demonstrated the potentials of using satellite images to map the wind field at sea surface. However, [3] and [4] show the limitations of the use of only one source of data. These limitations are caused by either low spatial resolution of data or localisation far away from coast or too low numbers of measurements for a given site.

One solution is to merge all available data to get a more accurate estimation of wind resource [4]. Satellite data have different spatial resolutions, localisations and temporal sampling. These differences impose constraints to the fusion method. In order to work out a data fusion method and evaluate it, it is necessary to study these constraints and their impacts.

This paper gives an overview of various available offshore wind data. They are obtained by an appropriate processing of observations of the sea surface performed by spaceborne radars. We study the characteristics of the various data sets, namely, spatial and temporal coverage, spatial and temporal sampling, data support and accuracy. Finally, we discuss the design of a fusion algorithm.

1. Introduction

Wind energy investors need reliable wind resource maps before deciding the sitting of a wind park. This need is increased offshore where installation costs are greater than onshore. An error of a few percent in wind resource evaluation may hardly affect the benefits of an offshore wind park. Thus, improving wind resource assessment accuracy is crucial to reduce financial risks associated to the installation of offshore wind farms.

Usually, for evaluating the resource of a site, a meteorological mast is installed on the prospected site for one year. The measurements taken by this mast are compared to data undertaken by a nearby meteorological station for the same period. The correlation between the two data sets is then used to transpose the long-term data acquired on the station to the prospected site. This method is very costly offshore [1]. In addition, mast measurements are punctual and could not represent spatial variability of wind. Another inconvenient of this method is that few long-term meteorological measurements are available offshore.

Remotely sensed data could be an accurate and economic way to access wind data. Indeed, several studies showed the capability of some spaceborne instruments to measure wind. In the literature, some instruments have been proposed for wind resource assessment: radar altimeters, scatterometers and synthetic aperture radars (SAR). They can acquire measurements by all time and by all weathers. These instruments have, however, different spatial resolutions and different temporal coverages. These differences induced a different use of data acquired by these instruments. Thought remotely sensed data showed their usefulness for wind farms sitting, the use of each data source separately could not permit to assess wind resource at a kilometer-scale. The solution to this problem is to merge available data. This operation is called data fusion.

The data fusion process has to take in account data specificities. So, it is necessary to study constraints imposed by the data heterogeneity to design an efficient data fusion algorithm.

In this paper, we give an overview the most important spatial and temporal characteristics of satellite based wind measurements. Then, we present the constraints imposed by the different characteristics on the design of a fusion algorithm. A statistical fusion algorithm was proposed by [1]. We discuss the feasibility of such an algorithm and in which extent it respects the constraints introduced by the data heterogeneity.

2. Offshore wind data from spaceborne radars

Radars are active sensors. They send an electromagnetic wave and receive the backscatter. This backscatter depends on surface roughness. In the case of sea surface, the roughness is related to the presence of waves. The radar response from sea surface depends on waves instantaneously generated by wind and consequently on wind speed [5]. Thus, by an appropriate processing of satellite data, we can extract wind measurements. Though radars have the same principle of work, they have different imaging mechanisms depending on the most important parameters for the mission: spatial resolution, repetitiveness, … Previous studies highlighted the contribution of the different kind of instruments: altimeters, scatterometers and synthetic aperture radars. In this section, we present the spatial and temporal characteristics of the different spaceborne instruments launched in the last decade. In addition, we give an overview of the reported errors and the different algorithms used to compute wind speed from raw satellite data. Some conclusions on the potential of these instruments for wind resource assessment are proposed.

2.1. Altimeters

Radar altimeters were originally designed for the measurement of ocean surface height. The ability to assess wind speed using these instruments was shown by [6]. A summary of the different spaceborne altimeters is given in Table 1. The low swath width combined to the given repeat cycles induces low spatial and temporal coverage of wind speed. [1] reported that ERS-1, for example, covers earth surface on 35 days with a spatial resolution of 7 km on latitude and 80 km on longitude. In addition to the lack of information on direction, the temporal and spatial resolutions of radar altimeters are limitations to the use of this data to wind resource assessment.

Satellite	Swath width (km)	Repeat cycle (days)
Geosat	1.7	17
ERS–1	1.7	35
Topex/Poseidon	2.2	10
ERS–2	1.7	35
Geosat follow-on	2	17
Jason–1	2.2	10
ENVISAT	1.7	35

Table 1 Altimeters summary [7].

2.2. Scatterometers

Since 1991, there has continuously been a scatterometer observing the Earth. A summary of the instruments launched since then and their characteristics is given in Table 2. An important characteristic of these instruments is their revisit period, *i.e.* the period between two successive measurements at the same point. The revisit period depends on the repeat cycle of the satellite, *i.e.* the period between two successive identical orbits, and the swath width, *i.e.* the total width of the area covered by the sensor on the ground. The revisit period depends also on the latitude. Measurements are more frequent for high latitudes than at equator. Thanks to a large swath width, measurements repetitiveness is more frequent than the repeat cycle of the satellite. In fact, during a single repeat cycle, a point is included in satellite's swath more than one time.

Satellite	Swath width (km)	Resolution (km)	Repeat cycle (days)	Temporal Coverage
ERS–1	500	50	35	August 1991 - June 1996
ERS–2	500	50	35	March 1996 - January 2001
ADEOS	2*600	25/50	41	September 1996 - June 1997
QuikSCAT	1800	50	4	July 1999 - now
ADEOS–2	1800	50	4	April 2003 - October 2003

Table 2: Wind scatterometers summary[7],[8],[9],[10],[11].

Quikscat has a repeat cycle of 4 days. During this period it covers 57 orbits. This implies that at equator, where earth circumference is 40,000 kilometres, the distance inter-track is of 700 km. The swath width of 1800 km covers 2 orbits. Thus, during its repeat cycle 4 measurements are taken at each point at the equator. The sampling period of this instrument is of approximately one day. We have done this computation for the different instruments and represented the theoretical sampling period on Figure 1. Although this computation is approximate, it gives an indication on the sampling period.

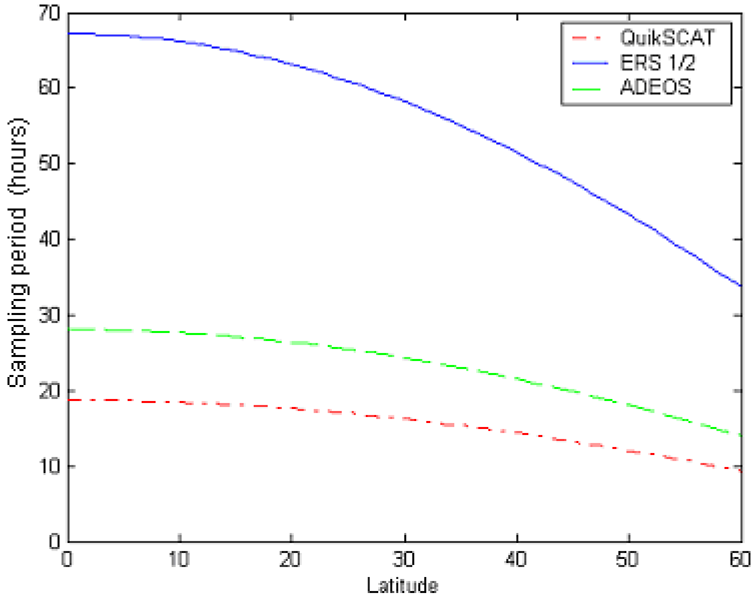

Figure 1 Indicative sampling period of different scatterometers in function of the latitude.

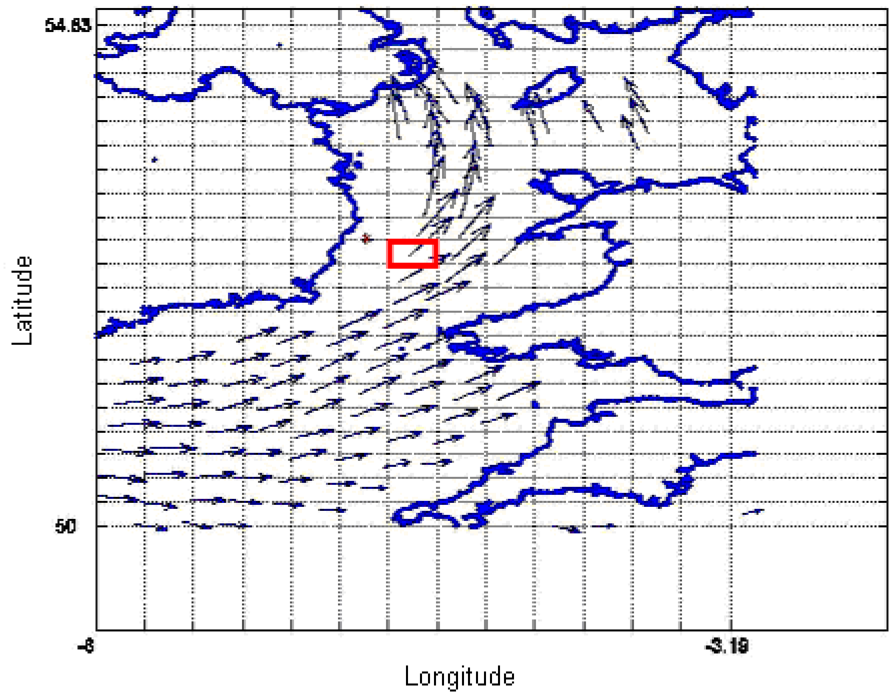

Figure 2 Wind measurements taken by Quikscat on 20/09/1999. Arklow Bank wind farm location is indicated by the red point.

The spatial resolution of scatterometers wind measurements is between 25 and 50 km. Due to noise introduced by land, scatterometer measurements are located at least 25 km of the coast.

For retrieving wind speed and direction from satellite raw measurements, empirical models are used. These models provide 10-meter height wind speed and direction. For instruments working on Ku band such as NSCAT onboard ADEOS and SeaWinds on Quikscat, the reported error is of 2 m/s for wind speed and 20° for wind direction. For instruments working on C band, i.e. ERS1/2, algorithms used are CMOD4 [12], CMOD5 [13], CMOD-ifr2. The performance of these algorithms is similar and the reported error goes from 1.2 to 1.6 m/s for wind speed and 14° to 24° for wind direction.

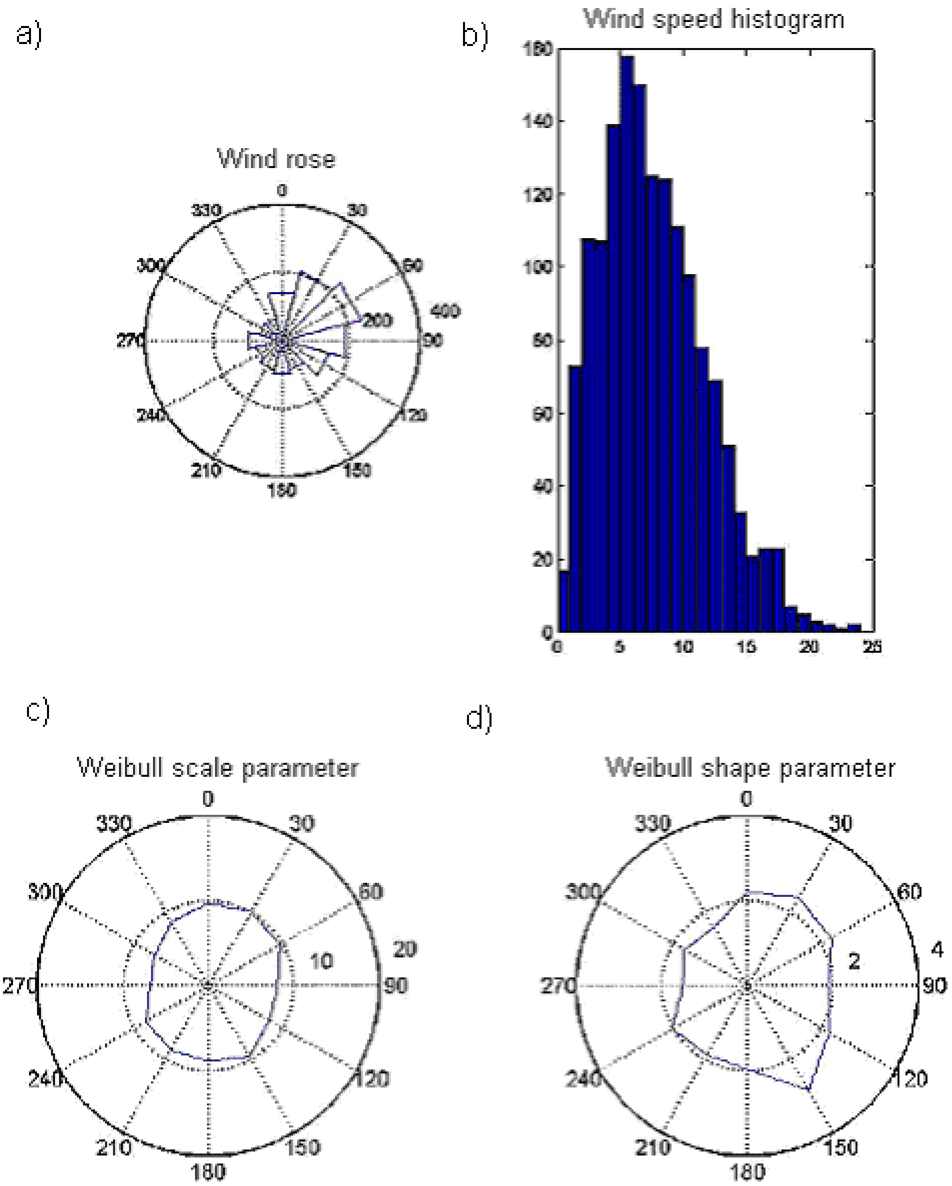

Figure 3 Wind statistics using data acquired by Quikscat between 1999 and 2001: a) Wind rose showing the number of measurements in each direction sector b) Wind speed histogram with speed bins of 1 m/s c) Weibull scale parameter computed for each direction sector d) Weibull shape parameter computed for each direction sector.

These models provide a backscattering coefficient from given wind speed, wind direction and incidence angle. To obtain wind vector, these models have to be inverted. As the incidence angle and backscattering coefficient are known, at least two measurements at different incidence angles are needed to assess jointly wind speed and direction. Scatterometers have several antennas and thus they can take measurements at different incidence angles. This makes scatterometers able to assess both wind speed and direction.

Using wind measurements acquired by Quihscat from 1999 to 2001, we established wind statistics over an area near Arklow Bank wind park and we computed Weibull parameters. An example of wind vector instantaneous measurement is given <u>Figure 2</u>. This map exhibits interesting patterns at a regional scale. The cell size of the measurements is of 25 by 25 km. We focused on the highlighted cell and established wind rose for this area. In addition, we computed Weibull parameters by direction. These parameters are reported on Figure 3. The number of measurements for the most frequent direction exceeds 200 which is greater than the minimum number of samples needed to fit Weibull parameters with 10% accuracy and 90% confidence as proposed by [14].

2.3. Synthetic aperture radar

SAR combines the measurement of a backscattering coefficient, such as a scatterometer does, with a frequency analysis. This analysis enables SAR to have a high spatial resolution. A summary of spaceborne SAR is given in Table 3. The typical spatial resolution of a SAR image is a few tens of meters. However, this high spatial resolution is associated to a low temporal sampling. This is due to the low swath width of these instruments. Doing the same computation than for scatterometers, we find that the sampling period of all the instruments is greater than 150 hours.

Previous studies have shown the possibility of adapting CMOD to wind speed retrieval from SAR images [15]. In contrast with scatterometers and due to operational constraints, there is only one antenna on these sensors. This makes impossible to assess jointly wind speed and direction. One of these parameters has to be known a priori. Wind direction can be retrieved using wind related features present on SAR images [16]. A method based on a multi-resolution analysis of SAR images was proposed by [1]. Using a Fourrier transform, this method extracts structures representing wind direction. This direction is then used as an input to the CMOD model for speed computation. However, this method doesn’t work when the wind has a strong azimuth component. The use of wind direction provided by meteorological models has also been proposed [17].

Satellite	Swath width (km)	Resolution (m)	Repeat cycle (days)
ERS–1	100	30	35
JERS–1	75	18	44
ERS–2	100	30	35
RADARSAT	100-170	10	24
ENVISAT	100	30	35

Table 3: SAR summary [7],[9] ,[18] ,[19] ,[20].

2.4. Conclusions on available data

Wind measurements acquired by altimeters have a low spatial resolution and a great temporal sampling period. These characteristics are less in agreement with wind resource assessment needs than both scatterometers and SAR. The contribution of altimeters to a data fusion process will be limited. Thus, we focus on scatterometers and SAR data for wind resource assessment.

The measurements taken by scatterometers and SAR are instantaneous. The usual meteorological data used for wind resource assessment consists of hourly wind speed series. These speeds are averaged over 10 minutes. Although meteorological and spaceborne measurements are, apparently, of different natures several studies shown that spaceborne measurements could be used for wind resource assessment. In fact, the spatial averaging of satellite data could be seen as equivalent to the temporal averaging of *in situ* data.

For the assessment of wind statistics at least 250 images are needed [14]. Scatterometer temporal coverage fulfils this requirement. Thus, scatterometer measurements of wind enable the establishment of wind statistics but at low spatial resolution and far of the coastal area. The information on spatial variability given by SAR images is very useful to wind energy investors. However, the current temporal sampling and coverage of SAR is not sufficient to assess reliable wind statistics based only SAR. In addition, the cost of SAR images could be an obstacle for methods based only on this data source. The solution, as proposed by [4], is to merge data issued from scattrerometers and from SAR. In this data fusion algorithm, the local variations would be introduced by SAR images while the regional wind climate is assessed by scatterometer data.

Before the design of this algorithm we have to study the constraints imposed by data heterogeneity (temporal coverage, temporal sampling, spatial coverage, spatial resolution) on the data fusion. The differences between data issued from scatterometers and SAR will induce preliminary processing. In the next section, we focus on these different constraints and present the different operators that have to be defined for data fusion.

3. Data fusion algorithm characteristics

Data fusion is a formal framework in which are expressed means and tools for the alliance of data originating from different sources. It aims at obtaining information of greater quality; the exact definition of 'greater quality' will depend upon the application [21]. In our case, greater quality means improving the temporal coverage of SAR and spatial resolution of scatterometers to establish accurate wind statistics at high resolution. The temporal resolution in the data fusion algorithm will be ensured by scatterometer data while spatial information is given by SAR images. However, differences in the data acquired by SAR and scatterometers induce preliminary processing. The aim of this processing is to put the two different data sets in the same space in which they can be merged.

3.1. Data alignment

Data alignment consists on defining a common representation space for data issued from different sensors. In our case, measurements of SAR and scatterometers are of same type. However, the incapability of scatterometers to make measurements near the coast (up to 25 km offshore) leads to the definition of a propagation function.

3.2. Spatial high resolution synthesis

Due to the low number of available SAR images, they should be used as images of typical behaviour of wind field over the interest area. This data set will be a set of wind patterns to be used to determine local scale wind variations. This implies that scatterometer wind measurements have to be classified in different categories. For the synthesis of high resolution we need to establish an association rule between the two data sets. This will enable to associate a local variation pattern to each scatterometer measurement.

4. Analysis of a probabilistic approach

[1] proposed a probabilistic algorithm for combining data from scatterometers and SAR. Wind statistics based on scatterometer data are established far of the coast where data is available. For each wind direction sector $Theta_i$ we have the probability P($Theta_i$) of appearance of wind in this sector. For the transfer of this data to interest area, probabilities of direction change probabilities are used. These probabilities P($Theta_j$/ $Theta_i$) represent the probability that wind blowing in wind sector $Theta_i$ far of the coast blows in sector $Theta_j$ near coastal area. Functions relating wind speeds are associated to these probabilities of wind rotation.

For the spatial high resolution synthesis, [1] proposed to classify wind situations for each wind direction accordingly to the behaviour of the turbulent component of the wind. In fact, wind is decomposed into a mean component, representing the wind at low spatial resolution, and a turbulent component characteristic of the local scale. The knowledge of the probability of apparition of each wind turbulent pattern could enable the assessment of wind statistics at high spatial resolution.

This method respects the constraints defined on the previous section. However, due to the great number of probabilities needed, it could not used in a practical a case.

5. Conclusion

In this paper, we presented different scatterometer and SAR data characteristics. These data are of great interest to wind resource assessment at a kilometre-scale. However, any of these data sources could, alone, provide accurate wind statistics at the requested scale. Data fusion is a promising framework for mapping offshore wind resource. It will improve the accuracy of wind resource assessment by combining the high spatial resolution of SAR images and the good temporal repetitiveness of scatterometers measurements. The data fusion algorithm has to take in account the differences between the two data sets. These differences are in temporal coverage, temporal sampling, spatial coverage and spatial resolution. Data heterogeneity induces some preliminary processing for data alignment. This data alignment will define a common representation space in which the two data sets become compatible. The most important operation in this stage is the propagation of scatterometers measurements located far of the coast to interest area. Once data aligned, for assessing high resolution we have to establish an association operator. This operator will guarantee a good use of the data at high resolution and avoid a misuse of data. More have to be done to establish these operators and thus build an efficient data fusion algorithm.

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