Using Sentinel-1 SAR satellites to map wind speed variation across offshore wind farm clusters

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Abstract. Offshore wind speed maps at 500m resolution are derived from freely available satellite Synthetic Aperture Radar (SAR) data. The method for processing many SAR images to derive wind speed maps is described in full. The results are tested against coincident offshore mast data. Example wind speed maps for the UK Thames Estuary offshore wind farm cluster are presented.

1. Introduction
This paper demonstrates how high resolution maps suitable for studying wind flow and wakes around offshore wind farms can be derived from open access satellite data. It presents an automatic method for processing Sentinel-1 Synthetic Aperture Radar (SAR) data [1] over many images that reduces the impact of the turbines’ own radar reflections and calculates wind speed values every five hundred metres across scenes of tens to hundreds of kilometres. The results are tested against coincident offshore mast data for 25 SAR scenes. The purpose is to develop and share a technique to make the large amount of routine, free and open access Sentinel-1 SAR data available to advance understanding of both wind flow around offshore wind farms and the impact of wind farms on the flow.

Synthetic Aperture Radar (SAR) is an active microwave radar instrument. That is it transmits and receives. It does not rely on illumination by daylight, and at the wavelengths used (of the order of centimetres) it isn’t impacted by cloud cover so it can operate at any time of day. The SAR beam interacts with the fine, centimetre scale surface roughness of water to affect the scattered return radar signal received by the SAR instrument. Wind speed across a water surface affects the degree of roughness and hence the received radar signal. This is the basis for measuring offshore wind speeds with SAR. Empirically derived Geophysical Model Functions (GMF) are used to relate the calibrated radar return to the wind speed at a height of 10m. GMFs usually relate the radar backscatter to wind speed and wind direction, so to find wind speed, wind direction data is a necessary input and this can be derived from image features or taken from other data.

A number of other features can also affect the radar return from the sea surface including surface currents, rain cells, oil spills and sometimes bathymetry in shallow water: SAR cannot make a direct measurement of wind speed at the sea surface and uncertainty arises in deriving the wind speed from the radar return. SAR, in common with other coherent radar instruments, features speckle noise which gives SAR images a grainy, salt and pepper look. This is because the signal returned from any smallest resolution cell will be a vector sum of the return from the scatterers in that cell and will thus vary from cell to cell randomly. In practice, this limits the resolution possible for wind speed results from a SAR
image, as some averaging across pixels must take place to reduce the random noise effect of speckle, leading to a trade-off between noise reduction and resolution.

Offshore wind speed retrieval from SAR is used in a wide range of fields from the study of mesoscale wind phenomena such as cyclones and atmospheric gravity waves, to wind energy [2-7]. A number of studies have specifically applied it to looking at external wakes from offshore wind farms [8-11]. These use a number of methods to assess the velocity deficit seen behind the wind farm: it is not straightforward to decide where to measure the reference, undisturbed wind speed as there are often underlying wind speed changes across SAR scenes, such as offshore and onshore wind speed gradients. Hasager et al [10] have developed a method to combine results from many SAR scenes to overcome this issue and this type of approach lends itself to the increased availability of SAR data arising from the Sentinel-1 mission.

The Sentinel-1 mission of two satellites, A and B, each carrying a SAR instrument is potentially significant for offshore wind studies because it provides free and open access SAR data. There is routine coverage especially over Europe. The data provided are recent and ongoing giving a good time overlap with many operating offshore wind farms. Previously SAR data have typically been expensive, or available in small amounts to academics, or available from older missions when far fewer offshore wind farms were operating. Sentinel-1A provides regularly available data following a calibration enhancement (https://sentinel.esa.int/documents/247904/2142675/Sentinel-1A_TOPS_Radiometric_Calibration_Refinement), from 25th November 2015. Sentinel-1B was launched later and has been providing regular data since late September 2016. The times at which data are available are limited. Across Europe the two satellites provide total coverage every 6 days. At any one location, images from both 1A and 1B will usually be taken at around the same time of day on the ascending satellite passes and at around the same time of day on the descending passes. (During an ascending pass a satellite passes over Europe approximately south to north, and on a descending pass approximately north to south.) So for example, images covering the Thames Estuary, UK are generally all at around 06:00 UT on descending passes or 17:40 UT on ascending passes.

There is also free software available to handle Sentinel data: the Sentinel Application Platform (SNAP). SNAP has a graphical user interface (GUI) and a command line interface. The command line interface in particular allows the automation of many tasks. The ability to derive wind fields from SAR data with a largely automated process allows the use of multiple scenes to provide climatological results about impacts of offshore wind farms on the wind flow under different conditions.

2. Methodology

2.1. Overview
The approach taken here has been to make as much use as possible of the tools made available with the Sentinel data and to extend these where necessary to produce results suitable for understanding wind fields around offshore wind farms at useful resolutions. In addition, the derivation of wind speeds should be as automated as possible, so that numbers of SAR scenes can be compared. In order to verify that meaningful wind speeds can result from this method, results are compared to coincident high quality, high time resolution mast data from the Met Mast Ijmuiden (MMIJ). The method for calculating wind speeds from SAR data is summarised in the flow chart in Figure 1.
2.2. Pre-processing and calibration
The Sentinel Application Platform (SNAP) provides the tools needed to calibrate Level 1 (L1) ground range detected (GRD) Sentinel-1 data products to get the Normalised Radar Cross Section (NRCS) values, known as Sigma0, which are then used to calculate the wind speed. The SNAP pre-processing steps used on the L1-GRD data are orbit correction, thermal noise removal, radiometric calibration (to calculate Sigma0), application of a land mask and multi-looking to smooth out speckle noise inherent in the radar data.

2.3. Masking bright objects
Wind turbines and ships are strong radar reflectors and so present as very bright objects in a SAR offshore scene. If they are not masked, they will distort the derived wind speed. The SNAP Ocean Object Detection tool is used to identify bright objects automatically. A minimum target size of 10m and a maximum target size of 470m were used. This is a tool primarily aimed at identifying shipping [12]. It produces an xml report which gives the location and estimated size of detected objects. SNAP doesn’t currently provide a method to create a mask from the Object Detection Tool results, except manually in the GUI. In order to be able to automate the data processing, Python code was written to parse the xml report; to create buffered point shapes at each object, and to use those to create a single, union shape file which could then be imported as a mask and used in subsequent processing. The Python modules Shapely and Fiona made this quite straight forward. It was decided to make the size of each buffered point the larger of 100m or the detected object size to be more certain of fully masking turbines.
2.4. Wind field estimation
SNAP also provides a wind field estimation tool. This uses a Fast Fourier Transform (FFT) method to determine wind direction from image features and then implements the geophysical model function CMOD5 [13] using these direction data. The FFT method was observed to fail at resolutions useful to this study, a known limitation of the method [14]. The default grid size in the SNAP wind field estimation tool is 20km by 20km, but the aim of this work was to be able to create wind speed maps at resolutions of 1km or less. As a result, CMOD5 was implemented in Python to allow the introduction of alternative wind direction information. The CMOD5 function relates Sigma0 from co-polarised (vertically polarised transmit and receive known as VV) C-band SAR data to wind speed, wind direction and SAR incidence angle. A look up table is created by using CMOD5 to calculate Sigma0 for a range of wind speeds, relative wind directions and incidence angles. This look up table can then be used to find the corresponding wind speed for a given Sigma0 measurement, relative wind direction and incidence angle. The relative wind direction is the wind direction relative to the satellite azimuth look angle.

A look up table of Sigma0 values derived from the CMOD5 geophysical model function (GMF) was created with a value for Sigma0 for all combinations of wind speeds from 1 to 60 ms\(^{-1}\) in 0.2 ms\(^{-1}\) bins, incidence angles from 20° to 46° in 0.2° bins, and relative wind directions from -180.0° to 180.0° in 2.5° bins.

2.5. Other inputs to CMOD5
The azimuth look angle of the SAR image is needed to find the relative wind direction. This has been calculated from the corner coordinates of each image. These are found in the .manifest meta data file that comes with each Sentinel-1 data file. The look direction is given by the bearing from the 1\(^{st}\) to the 2\(^{nd}\) or from the 4\(^{th}\) to the 3\(^{rd}\) corner coordinates. Python code made available by Jérôme Renard at https://gist.github.com/jeromer/2005586 was used to find a bearing between two points.

The remaining input data necessary for calculating wind speed is the wind direction. This study uses global reanalysis data MERRA2 [15] to provide wind direction. Global reanalysis data provide standardised meteorological and atmospheric data from forecast models run after the event. MERRA2 is available at time resolutions of up to one hour and spatial resolution of 0.5° latitude by 0.625° longitude. MERRA2 includes 1-hourly eastward and northward wind components at 2m, 10m and 50m in the 2d, 1-Hourly, Time-Averaged, Single-Level, Assimilation, Single-Level Diagnostics product (tavg1_2d_slv_Nx). As the CMOD5 GMF relates Sigma0 to winds at 10m, hourly MERRA2 10m wind components were used to give an input wind direction.

2.6. Applying CMOD5
The command line version of SNAP was used to carry out the following steps on level 1, ground-range-detected (GRD) Sentinel-1 data VV band:

1. Apply orbit corrections.
2. Remove thermal noise.
3. Radiometric calibration to give Sigma0.
4. Apply a land mask.
5. Import as a vector the shape file created as a result of object detection.
6. Apply this vector as a mask.
7. Reduce speckle noise by averaging Sigma0 over 500m squares by applying 50 by 50 multi-looking.
8. Export the results in netCDF4 format, selecting to save parameters Sigma0 and incidence angle.

The netCDF4 format is designed to support array-oriented scientific data. The netCDF4 results contain a grid of data with x, y coordinates and for each x, y point a value for the latitude, the longitude, the incidence angle and Sigma0. The relative wind direction is given by the local wind direction relative to north minus the satellite azimuth look angle relative to north. For each grid point
in the input data, the CMOD5 lookup table created earlier is used to look up the wind speed corresponding to Sigma0, the incidence angle and the relative wind direction.

2.7. Verifying the wind speed results
Although the approach of this work is to seek to understand the spatial variation, rather than to find absolute wind speeds, it is clearly necessary to verify that the wind speeds calculated are related to reality, or the variability may be spurious too.

High quality, very high time resolution mast data have been obtained from Met Mast Ijmuiden (MMIJ) for this purpose. MMIJ is a Dutch offshore mast located well offshore, between the Netherlands and the UK. The location is 52.84817° latitude, 3.43567° longitude. Wind speed and direction data are measured at three locations equally spaced around the mast at heights of 27m and 58m. Wind speed is measured on two sides of the mast and wind direction is measured at three equally spaced locations at 90m, which is the top of the mast. Air temperature data are available at heights 21m and 90m. Wind speed, wind direction and air temperature are all available at 4Hz time resolution. Sentinel-1 data are available from 25th November 2015 and MMIJ mast data is available until 11th March 2016. Coincident data from the mast and Sentinel-1A are available between November 2015 and March 2016 for 25 images.

The CMOD5 GMF relates the Sigma0 measured by the radar to the wind speed at a height of 10m. The mast wind speed data are processed to provide wind speeds at 10m for comparison. At 27m a ‘true’ wind direction is calculated as follows, in order to minimize mast shading effects. The directions around the mast are considered as six equal sectors, with a wind vane in the centre of every other sector. There are three measured wind directions: one will be the lowest value, one the highest and one in the middle. The middle value of the three measured wind directions is identified and the sector containing this wind direction is noted. One wind vane will be located in this sector, or in the sector directly opposite. This wind vane is disregarded as likely to be affected by mast shading, and the true wind direction measurement is taken to be the average of the values measured at the other two wind vanes. At 27m a ‘true’ wind speed is calculated by averaging the wind speed measurement from the two anemometers closest to the true wind speed direction at 27m. At 90m there are only two cup anemometers and this is at the top of the mast, so the wind speed is taken to be the average of the two measurements. The wind speed at 27m is adjusted to 10m using a Bulk Richardson method to determine stability conditions, which makes use of the mast air temperature data at 21m and 90m and the wind speed at 27m and 90m.

It is necessary to compare time series mast data at one location with SAR wind speeds located across a scene measured in a very short time period (less than half a minute). The 10m mast wind speeds are averaged over 10 minutes, for a time period centred on the mid-point of the SAR image time. The 10 minute average wind speed is chosen as it is a widely available standard in wind condition measurements. Assuming that the wind flow holds to Taylor’s frozen turbulence hypothesis, the spatial distance which should be compared to this time period is the distance crossed at the 10 minute average wind speed in 10 minutes. So for each SAR image, the SAR wind speeds are averaged across a footprint centred on the mast and with a diameter equal to the distance covered by the average mast wind speed in 10 minutes [11]. The SAR footprint average wind speed is compared to the mast 10 minute average wind speed.

3. Results and Discussion

3.1. Verifying the wind speed results at Met Mast Ijmuiden
The wind speed was derived from 25 SAR scenes coincident with data available from the MMIJ offshore mast. The wind speed at the mast was adjusted to a height of 10m, using air temperature data to account for atmospheric stability conditions. The mast 10m wind speeds were averaged over 10 minutes with the 10 minutes centred on the time of the SAR image. The distance covered by the 10 minute average wind speed measured by the mast in those 10 minutes was used as the diameter of a
footprint centred on the mast. The SAR derived wind speed was averaged for all points falling in this footprint. The results are shown in Table 1.

Table 1. Summary results of wind speeds at MMIJ

| SAR image start (YYYY-MM-DD HH:MM:SS) | SAR image end (HH:MM:SS) | MMIJ 10m wind speed, 10 minute average (ms⁻¹) | Footprint radius (m) | SAR 10m wind speed, footprint average (ms⁻¹) |
|----------------------------------------|--------------------------|------------------------------------------------|---------------------|---------------------------------------------|
| 2015-11-28 17:33:03                    | 17:33:25                 | 17.61                                          | 5283                | 19.17                                       |
| 2015-12-07 05:57:32                    | 05:58:01                 | 5.11                                           | 1532                | 4.74                                        |
| 2015-12-10 17:33:03                    | 17:33:24                 | 16.00                                          | 4800                | 16.20                                       |
| 2015-12-12 06:05:58                    | 06:06:23                 | 9.51                                           | 2854                | 10.88                                       |
| 2015-12-19 05:57:43                    | 05:58:12                 | 11.77                                          | 3530                | 8.81                                        |
| 2015-12-22 17:33:02                    | 17:33:24                 | 14.79                                          | 4437                | 15.50                                       |
| 2015-12-24 06:05:57                    | 06:06:22                 | 14.55                                          | 4364                | 12.89                                       |
| 2016-12-31 05:57:31                    | 05:58:00                 | 14.87                                          | 4460                | 15.42                                       |
| 2016-01-03 17:33:02                    | 17:33:23                 | 15.53                                          | 4658                | 17.17                                       |
| 2016-01-05 06:05:57                    | 06:06:22                 | 10.10                                          | 3029                | 9.32                                        |
| 2016-01-12 05:57:42                    | 05:58:11                 | 10.43                                          | 3130                | 12.19                                       |
| 2016-01-15 17:33:01                    | 17:33:23                 | 11.10                                          | 3330                | 11.24                                       |
| 2016-01-17 06:05:56                    | 06:06:21                 | 7.07                                           | 2121                | 7.82                                        |
| 2016-01-24 05:57:31                    | 05:58:00                 | 11.41                                          | 3422                | 9.37                                        |
| 2016-01-27 17:33:01                    | 17:33:22                 | 17.11                                          | 5134                | 16.19                                       |
| 2016-01-29 06:05:56                    | 06:06:21                 | 17.24                                          | 5173                | 14.73                                       |
| 2016-02-05 05:57:42                    | 05:58:11                 | 10.37                                          | 3112                | 11.10                                       |
| 2016-02-08 17:33:01                    | 17:33:22                 | 19.14                                          | 5743                | 21.27                                       |
| 2016-02-10 06:05:56                    | 06:06:21                 | 10.74                                          | 3223                | 12.28                                       |
| 2016-02-17 05:57:30                    | 05:57:59                 | 9.00                                           | 2701                | 8.77                                        |
| 2016-02-20 17:33:01                    | 17:33:22                 | 12.99                                          | 3896                | 13.78                                       |
| 2016-02-29 05:57:41                    | 05:58:10                 | 7.73                                           | 2319                | 7.66                                        |
| 2016-03-03 17:33:01                    | 17:33:22                 | 4.54                                           | 1361                | 6.70                                        |
| 2016-03-05 06:05:56                    | 06:06:21                 | 6.88                                           | 2064                | 7.93                                        |

The results of plotting the 10 minute average mast wind speed against the equivalent footprint averaged SAR wind speed for all available scenes is shown in Figure 2.

The plot shows a linear correlation, with a Pearson’s r value of 0.93 indicating a strong, linear correlation between the wind speed derived from the SAR images and the wind speed measured at the mast. The $r^2$ measure of 0.87 indicates that the amount of variance in wind speed derived from the SAR images that is explained by the wind speed measured at the mast is 87%.

As CMOD5 relates the calibrated radar signal of Sigma0 to wind speed and wind direction, it is reasonable to consider whether the use of spatially and temporally imprecise MERRA2 wind direction data is having a significant impact on the quality of results. In this case we have on site wind direction input data. This is explained by the wind speed measured at the mast is used and the SAR wind speed over an equivalent spatial footprint.

There is an improvement in the linear correlation, with Pearson’s r now equal to 0.96 and $r^2$ equal to 0.92. It is clear though that the difference between the SAR derived wind speed and the wind speed measured by the mast is not solely or even largely due to poor wind direction input data. This is a useful result as generally in applying this technique to studying wind fields around wind farms coincident mast measurements will not be available, but MERRA2 will be.
Figure 2. Comparison of mast and SAR wind speeds at MMIJ

Figure 3. Comparison of mast and SAR wind speeds at MMIJ with SAR input wind direction from the mast
3.2. Further work to test and improve the method
There is scope to try different wind direction data inputs with this method, for example by using the SNAP wind field estimation tool to calculate a wind direction on a larger grid. There is also scope to test the quality of the wind speed results for coarser and finer resolutions of calibrated Sigma0 input. The resolution of the calibrated radar signal depends on the level of multi-looking to reduce speckle noise, where increased multi-looking improves speckle noise but reduces spatial resolution. Further work to test this method against different wind direction inputs and for different levels of multi-looking would be useful to extend understanding of the limitations and accuracy available.

It would also be very desirable to test the method against longer time periods of offshore mast data and in different locations. The constraint here is the availability of such data in time periods that overlap Sentinel-1 operations.

3.3. Application to offshore wind farm clusters
The purpose of this work has been to provide wind field data for further investigation of the external wakes from offshore wind farms in clusters. We are interested in understanding the scale and likelihood of external wakes impacting on neighbours in clusters. As the industry expands, offshore wind farms are often located in clusters of several wind farms together in the same sea area. External wakes, that is wakes due to whole wind farms, may impact on other, nearby wind farms within a cluster. Better understanding of how often external wakes occur and with what extent and velocity deficit can inform decisions on the siting wind farms in relation to one another and may be expected to improve the accuracy of resource prediction.

Using the method described here the wind speed maps in figures 4 to 9 have been produced. They all show an area of the Thames Estuary with a number of wind farms, visible as arrays of darker pixels due to masking. London Array is approximately in the middle of each image. For each image the wind speed and wind direction at 10m for the nearest MERRA2 data point is given for context.

Figures 4 – 9 are provided as examples of the kind of wind field maps possible with this method. External wakes can be seen as darker regions downwind from wind farms in figures 5, 6, 8, and 9. In figure 4 the image is complicated by faster and slower regions of wind speed perpendicular to the wind direction due to gravity waves. In figure 7 gravity waves are the dominant feature to be seen. The wind field is also complicated by wind shadows downwind of land, as seen for example in figures 5 and 7. The complicated spatial nature of the wind speed requires careful consideration of reference wind speeds when quantifying velocity deficits behind wind farms.
Further work is planned to quantify the effect of variables such as ambient wind speed, coastal proximity and atmospheric conditions on the formation of external wakes at offshore wind farms, looking at many cases over a wide range of locations, seasons and wind conditions in order to separate out as best as possible the effects of the wind farms on the wind flow.

4. Conclusions
This paper sets out a method to derive 500m resolution wind speed maps from Sentinel-1 Synthetic Aperture Radar (SAR) data. The method is tested for accuracy against coincident offshore mast measurements for 25 SAR scenes and a strong correlation is found giving good confidence that the method is robust enough to quantify wind speed differences across offshore wind farms. It does this with free data, tools and software that are available to academia and industry alike.

The process is kept as automatic as possible to facilitate the study of external offshore wind farm wakes over as many scenes as possible. There is much opportunity still to refine and improve the process by trying different wind direction data sources and experimenting with the achievable resolution.

Examples of resulting wind speed maps in the Thames Estuary have been shown. It is anticipated that these wind speed maps will be used to quantify external wake extents and velocity deficits under various conditions.

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