Offshore wind resource mapping in Europe from satellites

Charlotte Bay Hasager

Seminar at University of Auckland,
Dept. of Physics
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DTU Wind Energy
Department of Wind Energy
Content

- DTU Wind Energy
- Offshore wind turbines
- New European Wind Atlas
- Satellite remote sensing on surface ocean winds
- Offshore wind resource estimation
- Selected results
- Offshore wind farm wake examples
- Summary
DTU Wind Energy

> 240 staff members
Including 150 academic staff members and 50 PhD students

http://www.vindenergi.dtu.dk
International wind turbine standards - IEC

a) Safety & functional requirements
b) Test methods
c) Certification procedures
d) Interfaces & Component

IEC TC88: IEC 61400 series:
IEC 61400-1 Design requirements
IEC 61400-2 Small wind turbines
IEC 61400-3 Design requirements for offshore wind turbines
IEC 61400-4 Gears for wind turbines
IEC 61400-(5) Wind Turbine Rotor Blades
IEC 61400-11, Acoustic noise measurement techniques
IEC 61400-12-1 Power performance measurements
IEC 61400-13 Measurement of mechanical loads
IEC 61400-14 Declaration of sound power level and tonality
IEC 61400-21 Measurement of power quality characteristics
IEC 61400-22 Conformity Testing and Certification of wind turbines
IEC 61400-23 TR Full scale structural blade testing
IEC 61400-24 TR Lightning protection
IEC 61400-25-(1-6) Communication
IEC 61400-26 TS Availability
IEC 61400-27 Electrical simulation models for wind power generation
Wind Energy – Test and measurements

Høvsøre
2002

Østerild
2012
6 MW
Vestas 8 MW at Østerild 2015

Vestas Wind Systems A/S
V164-8,0 MW
Rotor diameter 164 m
Hub height 140 m
Tip height 222 m

Tip → 222 m

180m
Height, The Gherkin.
Vestas 8 MW
New European Wind Atlas (NEWA)

DTU Wind Energy coordinator: Prof. Jakob Mann

Eight participating countries

Most of Europe will be covered including offshore

Project period: 1 March 2015 to 1 March 2020 (5 years)
New European Wind Atlas (NEWA)

Wind resource assessment and extreme wind

Downscaling model chain

- **Global**
- **Regional**
- **Local**

**Mesoscale modeling**
KAMM, WRF etc.

**Microscale modeling**
(WAsP, WAsP engineering, CFD, etc) + observation
Level of detail for satellite wind products

SSM/I

QuikScat

Envisat ASAR
## Ocean wind fields from satellites

<table>
<thead>
<tr>
<th>Retrieved parameters</th>
<th>Radiometer</th>
<th>Scatterometer</th>
<th>Synthetic Aperture Radar (SAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wind speed</td>
<td>Wind speed and direction</td>
<td>Wind speed</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>0.25° lat/lon</td>
<td>0.25° lat/lon</td>
<td>500 m</td>
</tr>
<tr>
<td>Spatial coverage</td>
<td>Global</td>
<td>Global</td>
<td>Selected areas</td>
</tr>
<tr>
<td>Coastal mask</td>
<td>Cover open oceans only</td>
<td>Up to 70 km from coastline</td>
<td>None</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>4-6 times per day</td>
<td>Twice daily</td>
<td>Variable – less than one per day</td>
</tr>
<tr>
<td>Temporal coverage</td>
<td>Systematically since 1987</td>
<td>Systematically since 1991</td>
<td>ScanSAR since 1995</td>
</tr>
<tr>
<td>Rain sensitivity</td>
<td>High (rain flags)</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
SAR image coverage

Images frames over a given site have different spatial coverage and orientation
SAR wind retrieval

Original brightness image

Wind speed map
From wind to radar backscatter

Bragg / resonance scattering:

$$\lambda_{Bragg} = \frac{\lambda_{radar}}{2 \sin \theta}$$

$$\theta = \text{incidence angle (15-70°)}$$
$$\lambda = \text{wave length}$$

Bragg waves ride on longer-period waves
Random variation occurs (speckle) → Pixel averaging is necessary
Empirical geophysical model functions (GMF):

\[ NRCS = U^{\gamma(\theta)} A(\theta) \left[ 1 + B(\theta,U) \cos \phi + C(\theta,U) \cos 2\phi \right] \]

- \( NRCS \) = radar backscatter [dB]
- \( \theta \) = incidence angle [degrees]
- \( U \) = wind speed at 10 m [m/s]
- \( \Phi \) = relative wind direction [degrees]

Model functions apply to open oceans and neutral atmospheric stability.
The nominal accuracy on wind speed is +/- 2 m/s.
Geophysical model functions

Developed for hurricane wind retrieval
APL/NOAA SAR Wind Retrieval Software

• Developed by the Johns Hopins University, Applied Physics Laboratory (JHU/APL), USA (http://fermi.jhuapl.edu/)

• Implemented at DTU, NOAA, the Alaska SAR Facility, ...

• Performs SAR wind mapping in near-real-time (when satellite data is available)

• Default wind directions from the Navy Operational Global Atmospheric Prediction System (NOGAPS):

  - Spatial resolution: 1° latitude/longitude
  - Temporal resolution: 6 hours
SAR showing meso-scale wind phenomena

Strait of Gibraltar

The Azores
Case-by-case comparison SAR and model: Iceland

10 Jan 2011 (SAR)

10 Jan 2011 (Harmonie)

10 Sep 2011 (SAR)

10 Sep 2011 (Harmonie)

Courtesy: Nikolai Nawri, Icelandic Meteorological Office
Case-by-case comparison SAR and model: Denmark

Satellite wind map

KAMM model

m/s

0 5 10 15 20

54 54.50 55

54 54.50 55

10.50 11 11.50 12 12.50 13

10.50 11 11.50 12 12.50 13
NORSEWInD: SAR data
Comparison of SAR and mast winds at 10 m

Horns Rev M2

$R^2 = 0.88$
RMSE = 1.26
$y = 0.98x - 0.14$
N = 149

Egmond aan Zee

$R^2 = 0.81$
RMSE = 1.47
$y = 0.91x + 0.42$
N = 197
Archived SAR scenes over Europe (~15,000)
Wind resource mapping from SAR
Hasager et al. 2014
Rem Sens. Env.
Baltic Sea existing and planned offshore wind farms

Synergetic use of satellite wind products

Mean wind speed map from Envisat ASAR, QuikScat, and ASCAT

Wind rose from the mast
Horns Rev M2

Wind rose from the merged satellite data set

Hasager et al. 2014, Rem Sens. Env.
The SAR data archive at DTU Wind Energy

- Our data archive is based on ENVISAT ASAR 2002-12
  - freely available from ESA

- Continuation of the data supply is secured with the Sentinel-1 mission (2014 -> )

- Sentinel-1 sets new requirements for data processing
  - much more data, rolling archive (no permanent storage)
Processing chain for SAR wind atlas

- SAR data download
- ESA archives

- Ancillary data download
- Model wind direction, land mask, ice mask

- SAR wind retrieval
- APL/NOAA SAR Wind Retrieval System

- Wind field data base
- Virtual server

- Wind resources
- S-WAsP tool
Wind farm wake
Offshore wind farm status: Source C4Offshore
Offshore wind farm status: Source C4Offshore
Horns Rev 1

DTU Wind Energy, Technical University of Denmark
Horns Rev 1 offshore wake photo study case

The special atmospheric conditions are characterized by a layer of cold humid supersaturated air that re-condensates to fog in the wake of the turbines. The process is fed by humid warm air up-drafted from below and adiabatic cooled air down-drafted from above by the counter-rotating swirl generated by the rotors.

The large-scale structure of the fog has an imprint of rotational spiraling bands similar to wake flow characteristics deduced from CFD DES modeling.

Wind speed near cut-in.

Horns Rev 1

Detached eddy simulation results showing vertical velocity
Wind farm wake analysis

Wind field from ERS-2 SAR, Horns Rev, Denmark
Wakes in the EERA-DTOC project (2012-15)

Wake
85x8 km

Courtesy CLS, France
Wakes in the EERA-DTOC project (2012-15)

15-AUG-2012 05:49:27.4 (UTC)

Courtesy CLS, France
Example from Radarsat-2 2013/04/30
- radar backscatter

Courtesy CLS, France
Example from Radarsat-2 2013/04/30
- wind speed

Courtesy CLS, France
Summary of SAR advantages and limitations

Advantages:

A high spatial resolution (sufficient to reveal meso-scale wind phenomena)

Coastal seas are covered (very important for wind energy applications)

Limitations:

Wind retrievals are valid for the height 10 m

A limited number of samples for statistical analyses
Acknowledgements

**Satellite data:**
The European Space Agency (ESA)
EUMETSAT Ocean and Sea Ice Satellite Application Facility
Remote Sensing Systems (RSS)

**SAR wind field retrieval:**
Collecte Localisation Satellites (CLS)
The Johns Hopkins University, Applied Physics Laboratory (JHU/APL)

**Mast observations:**
All mast data accessed through the NORSEWInd project. Horns Rev: DONG energy and Vattenfall, Egmond an Zee: NoordZeewind.

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