Monitoring MetOcean parameters from space - Implications for offshore safety and security

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Sea Surface Parameters from SAR

- Wind
- Sea State
- Oil
- Land-Water Line
- Currents

- Ships
- Bathymetry
- Wave breaking
- Wave groups
- Ice, Icebergs

Images showing various sea surface parameters.
1. Basic Research - Functions & Algorithms

- Fundamental research in SAR Imaging Mechanisms
- Finding interdependencies between SAR imaging and geophysical or oceanographic properties
- Develop (empirical) model functions to deduce sea surface properties from SAR

2. Software Development - Prototype & NRT Processor

- Robust implementation of developed algorithms and methods
- Performance optimisation for Near-Real-Time (NRT) capabilities
- Integration in operational data processing chain at antenna ground stations
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3. Processing, Databases and Scientific Exploitation
   - Contribution to improve forecasts, oceanographic and geophysical understanding
   - Analysis of extreme events
   - Possible applications for institutions and industry
Satellites: X-band SAR (synthetic aperture radar)

- TerraSAR-X and TanDEM-X launched in 2006 and 2010
- Active sensor: sunlight independence
- Signal penetrates the clouds

Sentinel 1A /1B
- ESA Satellite
- 703 km altitude
- Ground speed 8km/s, 14.5 orbits/day,
- Sensor: high frequency C-band SAR,
  wavelength 5.5mm, frequency 5.4GHz
- The repeat-cycle is 12 days, but the same region can be imaged with different incidence angles after 2 days.

- Active sensor: sunlight independence
- Signal penetrates the clouds
Satellites: X-band SAR (synthetic aperture radar)

TerraSAR-X and TanDEM-X launched in 2006 and 2010

- DLR/AIRBUS Cooperation
- 514 km altitude
- ground speed 7km/s, 15 orbits/day,
- sensor: high frequency **X-band SAR**, wavelength 31mm, frequency 9.6GHz
- The **repeat-cycle is 11 days**, but the same region can be imaged with different incidence angles after 2 days.
Satellites: X-band SAR (synthetic aperture radar)
TerraSAR-X

- **Wide ScanSAR:** 35m resolution
- **StripMap:** 3m resolution
- **TerraSAR-X and TanDEM-X** launched in 2006 and 2010

© Google Maps
SAR-Derived Wind Fields

Synthetic aperture radar is capable of providing wind information over the ocean by measuring the **roughness of the sea surface**.

Capillary waves traveling along the boundary layer of a fluid are dominated by the effects of surface tension. The source is the turbulent fluctuations of wind vector.

- **No wind** → smooth surface → no radar echo
- **Specular component** → slightly rough → strong radar echo
- **Very diffuse scattering** → very rough

**stronger wind** → **high surface roughness** → **stronger radar backscatter**
SAR Wind Algorithms

Geophysical Model Function (GMF):

\[ \sigma_0 = B_0(v, \theta)(1 + B_1(v, \theta)\cos \phi + B_2(v, \theta)\cos 2\phi) \]

- **v**: Wind Speed
- **\theta**: Incidence Angle
- **\phi**: Wind Direction

<table>
<thead>
<tr>
<th>Radar band</th>
<th>GMF</th>
<th>Spaceborne SAR Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-band (5.6GHz)</td>
<td>CMOD4, CMOD5/5N</td>
<td>ERS/SAR, ENVISAT/ASAR, RADARSAT-1/2</td>
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<tr>
<td>L-band (1.3GHz)</td>
<td>LMOD1/2</td>
<td>JERS-1, ALOS PALSAR-1/2</td>
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<tr>
<td>X-band (9.6GHz)</td>
<td>XMOD/XMOD2</td>
<td>TerraSAR-X/TanDEM-X, Cosmo-SkyMed</td>
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</table>
Operational NRT Wind Processor: SENTINEL-1 Wind Field (05.06. 2015)

Windparks:
- Built
- Under Construction
- Planned
Operational NRT Wind Processor: SENTINEL-1 Wind Field (05.06.2015)

Wind Shadows: Extend up to 80 km
Power Production: Cubic relation with wind speed

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Obviously:
Great Interest in high resolution + large coverage wind assessment

Windparks:
- Built
- Under Construction
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Open Questions:

• How accurate are GMFs designed for and validated with larger footprints to wind variations on 100m-500m scale?
• How accurately can small-scale SAR wind variations be extrapolated to greater heights?
XMOD2 Validation

<table>
<thead>
<tr>
<th>Colocations</th>
<th>Bias</th>
<th>RMSE</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>371 (training)</td>
<td>-0.32 m/s</td>
<td>1.47 m/s</td>
<td>16.0%</td>
</tr>
<tr>
<td>52 (validation)</td>
<td>-0.17 m/s</td>
<td>1.47 m/s</td>
<td>17.0%</td>
</tr>
</tbody>
</table>

Approach: Wind Fields From two Independent Methods
Joint Campaign with ForWind (Oldenburg)

On-Site LIDAR
Results in free flow
Comparison of spatial structures

- Offset in average wind measurement 1.1 m/s
- Spatial standard deviation comparable
Results in free flow
Comparison of spatial structures

- Spatial structures of lidar measurement well observable in TS-X measurement
Alpha Ventus Offshore Wind Park

TS-X Strimap (23.08.2012)

Wind Wakes
Turbine Signatures

Profile 2

Wind Speed along Profile

Wind Wake Signatures

Distance along Cross-Sectional Profile [km]

Cross-Sectional Mean Wind Speed
Sliding Average (500m)

Turbine Signatures

Distance Downstream of Wind Park [km]
TS-X StripMap (20150820); Riffgat Windpark vor Borkum
Windrichtung

Kármán Vortex Street
Example for large-scale phenomena:
Sentinel-1 IW of the German Bight Oct 27, 2016

Long and intense wind shadows lead to important questions:

Are there effects on the environment (onshore/offshore)?

How are wind shadows included in power yield predictions?

Are operators reimbursed for loss caused by wind shadows from other parks?
Example for large-scale phenomena: Sentinel-1 IW of the German Bight Oct 27, 2016

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SAR-Based Wind fields are a reliable complementary data source to study and measure wind variations on local and regional scale!
Ship Traffic near Riffgat Wind Park
(north of Borkum)
Ship traffic in the German Bight
Sea state important for situation awareness and operation planning!

Wave height can be 10-12m during storms

Helgoland today

Alpha Ventus: Offshore Windpark in der Nordsee
Sea State important for situation awareness and operation planning!
XWAVE empirical algorithm:
GMF principle and structure

\[ m = \frac{I(i, j) - \text{mean}}{\text{mean}} \]

\[ S = \text{FFT}(m) \]

\[ E = \int_{k=\min}^{k=\max} S(k, \theta) dk d\theta \]

signal intensity \( I \)

signal modulation \( m \)

image spectra \( S \)

filtering, \( L_{\text{min}}, L_{\text{max}} \)

Local Wind (XMOD)

XWAVE GMF function

Parameters: \( H_s, L_p, T_p \ldots \)

1D spectrum

frequency domain

buoy spectrum

integrated image spectrum

TS-X Stripmap

sub scene

wave number domain

2D image spectrum

50 m

100 m

50 m

1D spectrum

freq(\text{Hz})
waves: swell, windsea, short windsea in coastal areas

one peak, long waves

Two peaks (two wave systems)

Very short crest waves, current and bathymetry interaction

Hs 0.5-10m
PWL 100-500m

Hs 0.5-5m
PWL 80-200m

Hs 0.2-2.5m
PWL 20-80m

Errors in order up to 2m Hs possible based on classical scheme due to such waves interacting with bathymetry and tide currents.

Wave spectrum ~ image spectrum
TerraSAR-X X-band and Sentinel 1 C-Band SAR

Differences: resolution and bands

Sentinel-1 A/B IW 250km 10m pixel res.

\[ H_s \approx 1.5m \quad L_p \approx 80m \]

\[ H_s \approx 3.5m \quad L_p \approx 250m \]

TerraSAR-X StripMap 30km 1.2m pixel res.
Sea Surface by different Sensors

The same time and location

Sea state parameters estimation

SAR subscene

Image spectra

FFT

Transfer functions

empirical functions
using also local wind information

integration

Integrated parameters:

Wave height, mean period, etc.

GLCM (Grey Level Co-occurrence Matrix)

Entropy, Contrast, Dissimilarity, etc.,
Coastal applications: “contamination” impacts spectral analysis

Removing contaminations
- Sand banks
- Wave breaking
- Ships, Buoys, Wind farms
- Current fronts, ship wakes

GMF is applicable for “pure” sea state case only:
Pre-filtering of images is necessary for raster analysis

Without pre-filtering Integrated energy and $H_s$ can > 10 times overestimate real value

1. Before analysis
2. Function term
3. Results control
Sea State Processor for SENTINEL-1 and TerraSAR-X

Sea State Processor

- Step 1: TerraSAR-X/SENTINEL-1W image reading, calibrating
  - Sub-image(s) selection
  - Filtering outliers, e.g., ships
  - Filtering surface films, signatures, e.g., oil, ship wakes
  - Image structure analysis, GLCM parameters
  - Resampling, smoothing for SENTINEL-1W

- Step 3: XMOD-2, CMOD, local wind
  - Signal intensity $I$
  - Signal modulation $\sigma_w$
  - FFT, image spectra $I_S$
  - Integrated energy $E_{st}$, spectra parameters, noise level, etc.
  - Total of 24 parameters

- Step 4: Function XWAVE_C, SWAVE_S1, D-W
  - Control results
  - Results: total $H_s$, $I_p$, $T_r$

- Outputs: data files (lon, lat, values), graphs (gif, png), Google Earth (kmz), special points

Sea State Functions
- TerraSAR-X
- Sentinel-1

$H_s = a_1 \sqrt{B_1 E_{st}} \tan(\theta) + \sum_{i=1,n} a_i B_i$
Maritime situation awareness

NRT services: waves, wind ships

Raster: 6 km,
Subscenes: 2.5kmx2.5km
Sea State Processor for TerraSAR-X

Example: German Bight

TerraSAR-X acquisition 07.04.2015 05:51 UTC

Accuracy:
RMSE=0.24m for total wave height $H_s$ for coastal waters

Best delivery performance – 10min
Sea State Processor for Sentinel-1

Example: German Bight

TerraSAR-X acquisition 29.01.2016 17:16 UTC

Accuracy:
RMSE=0.80
for total wave height $H_s$ worldwide
Sea State Processor for Sentinel-1

Example: Arctic Sea, 05.01.2017  
Support of a research cruise

Processed in NRT and send to ship
Following a storm in the Black Sea

Total Significant Wave Height | Black Sea storm 20-23.04.2017 | SENTINEL-1 SAR C-band IW mode | processing mesh 6km x 6km

Maps showing significant wave height data over the Black Sea on different dates indicated.
Conclusions

• SAR-based met-ocean parameters are a reliable source to complement model predictions and buoy data
• Available in Near-Real-Time and for long-term analysis
• Important for offshore construction/maintenance operations planning
• Optimize power production estimates for offshore wind farms (including wind shadows and turbulent effects)