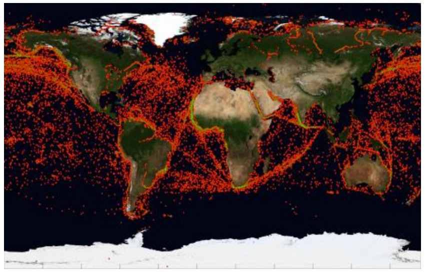
# High-Resolution Sea State from SAR images: Traditional vs. Novel Approaches

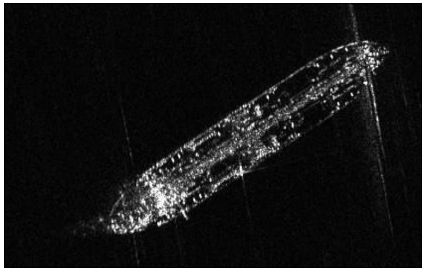
Dr. Sven Jacobsen, Dr. Andrey Pleskachevsky

DLR Maritime Safety and Security Lab, Bremen

## Maritime Safety and Security Lab, Bremen

- Fundamental science, development of new methods and algorithms
- Development of operational software processors to generate value added maritime data and information products



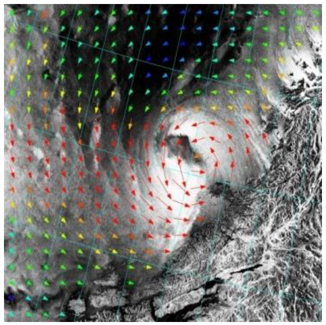


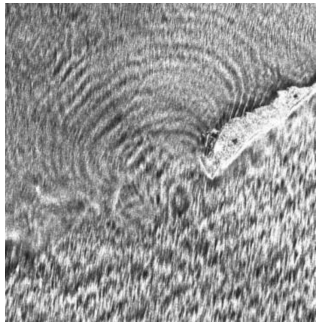
## Maritime Safety and Security Lab, Neustrelitz

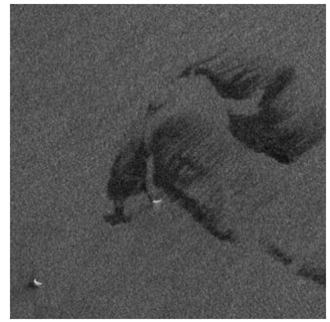
- Satellite-based near-real-time (NRT) services
- Systems for the improvement of maritime traffic safety and integrity

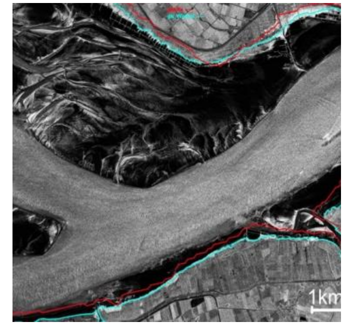



# Introduction: Sea Surface Parameters from SAR

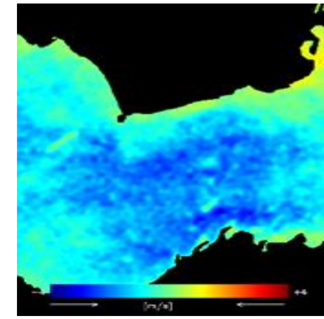

Wind

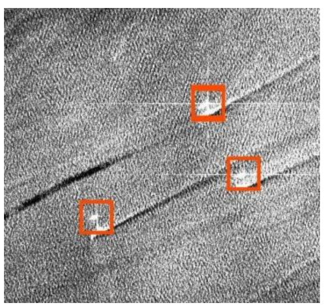

Sea State

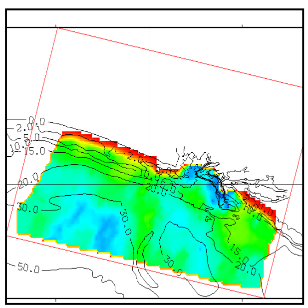

Oil



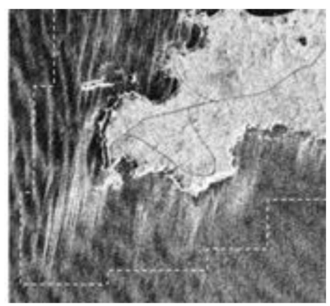
Land-Water Line

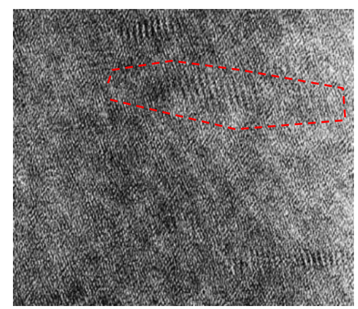

currents

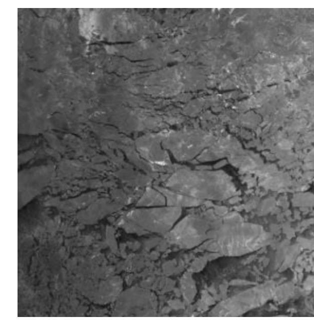

Ships



Bathymetry


Wave breaking


Wave groups


ice, Icbergs



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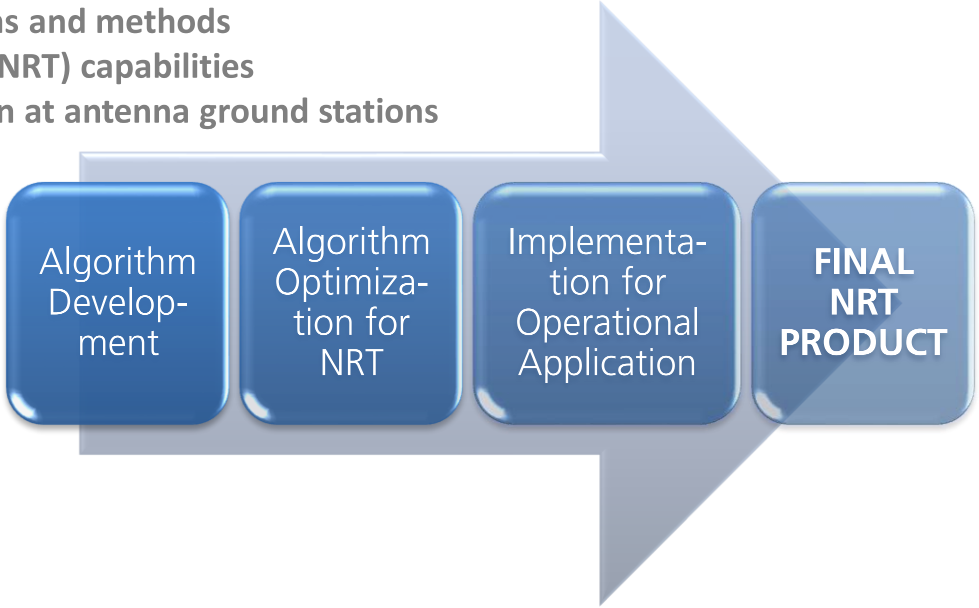
# Introduction: SAR oceanography research and development

## 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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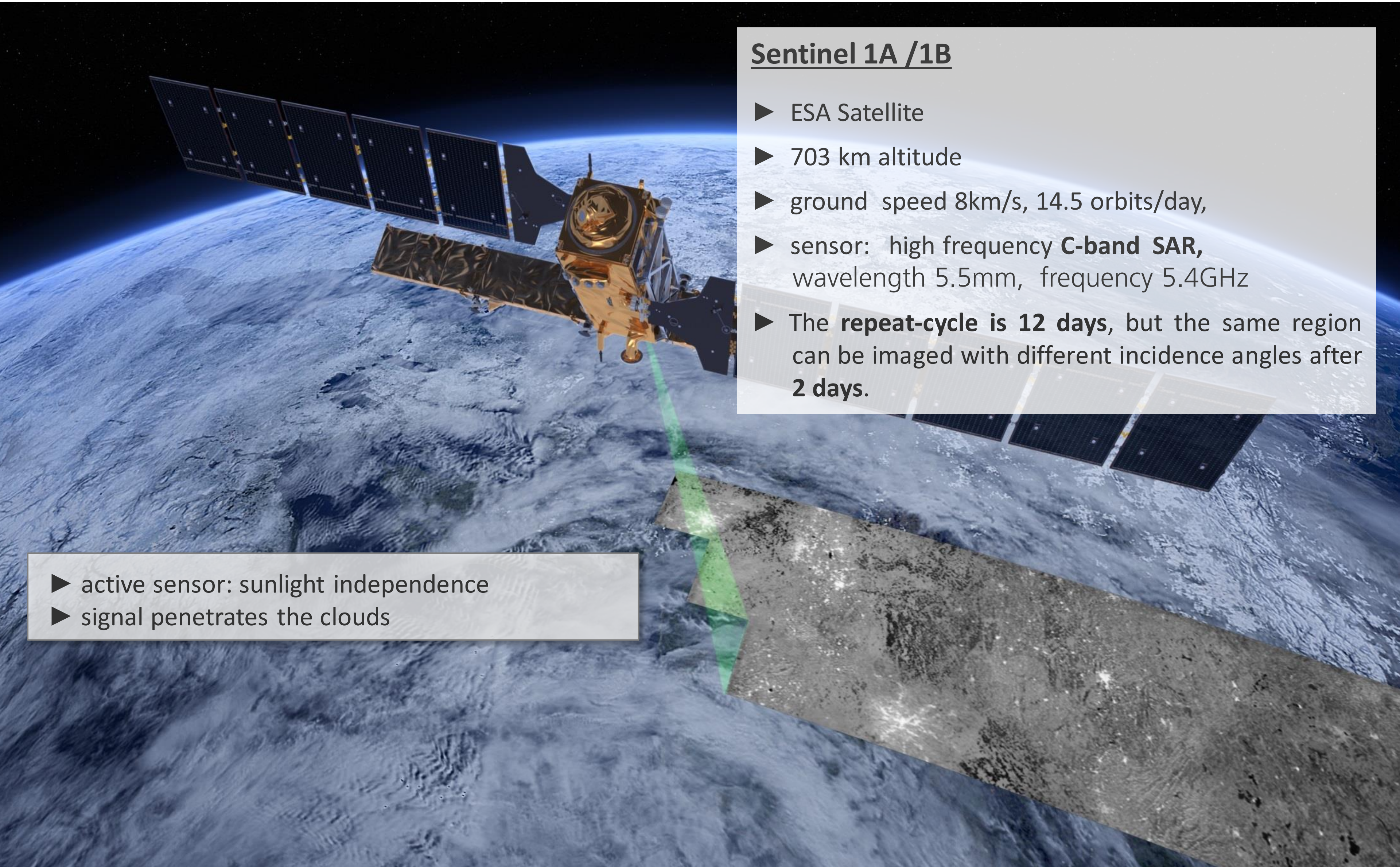
## 3. Processing, Databases and Scientific Exploitation

- 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)

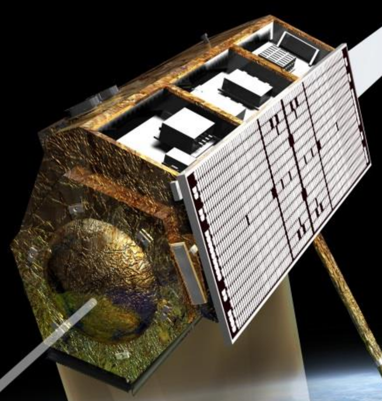


**Sentinel 1A /1B**

- 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)

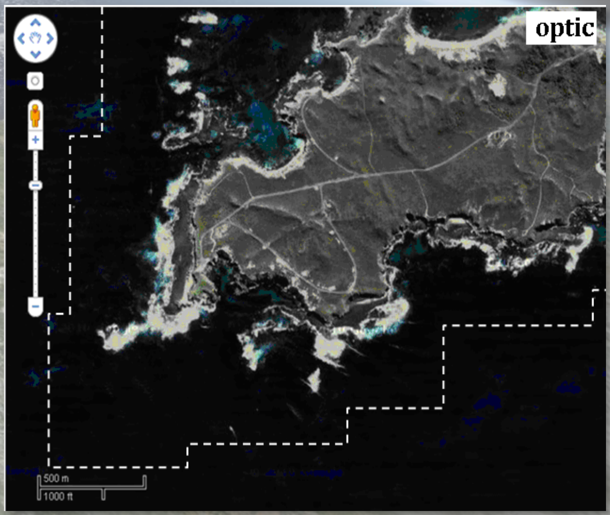


## TerraSAR-X / TanDEM-X

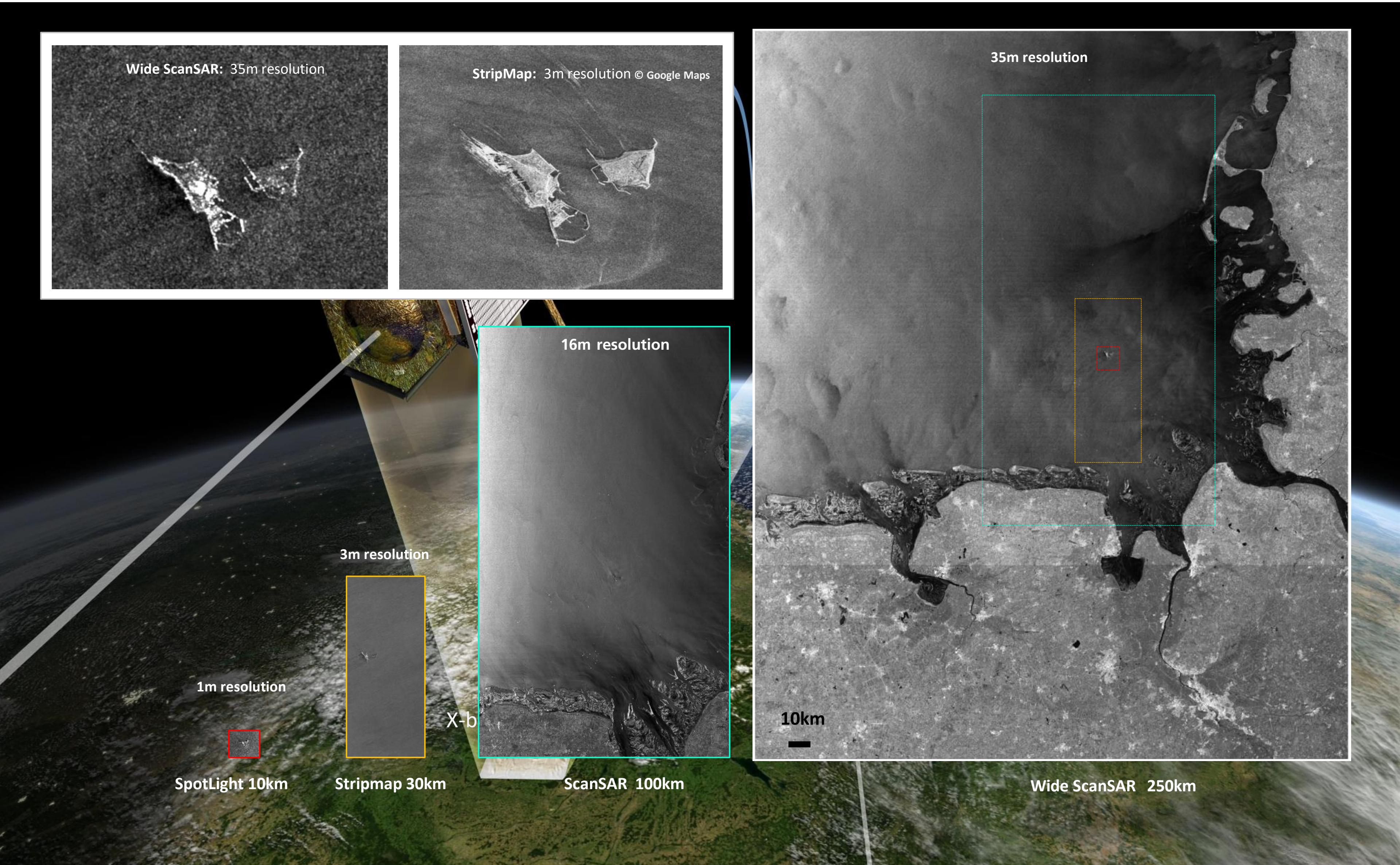
- DLR/AIRBUS Cooperation
- 514 km altitude
- ground speed 7km/s, 15 orbits/day,
- sensor: high frequency **X-band SAR,** wavelength 31mm, frequency 9,6GHz
- The **repeat-cycle is 11 days**, but the same region can be imaged with different incidence angles after **2 days**.

SAR


OPTICAL

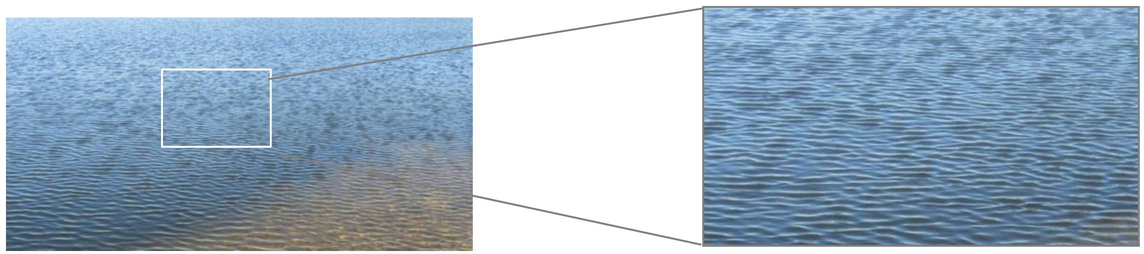


# Satellites: X-band SAR (synthetic aperture radar) TerraSAR-X

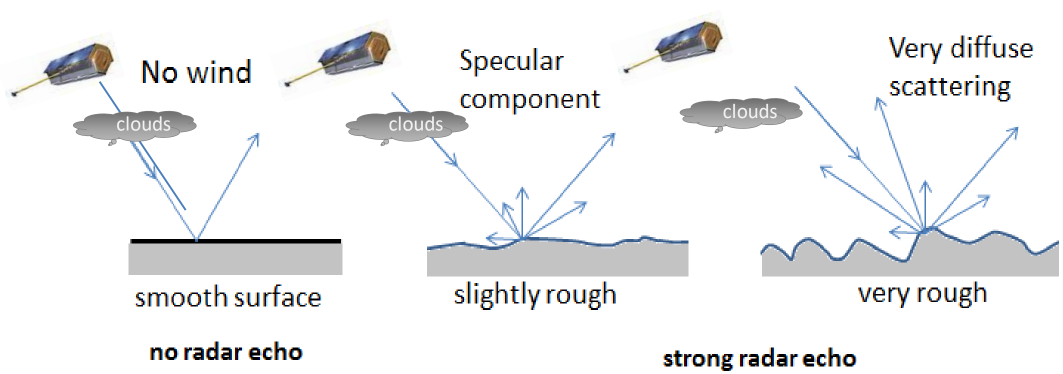


# SAR-Derived Wind Fields

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

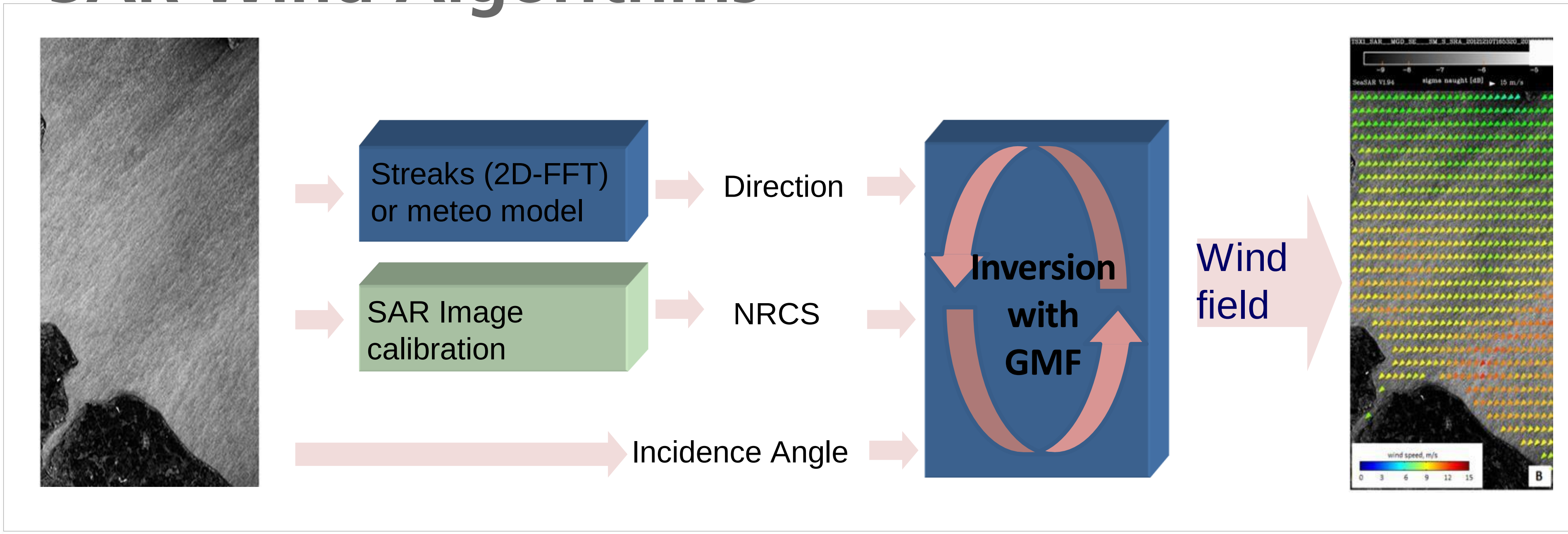


**Capillary waves** traveling along the boundary layer of a fluid are dominated by the effects of surface tension. The source is the turbulent fluctuations of wind vector.




stronger wind → high surface roughness → stronger radar backscatter

# SAR Wind Algorithms




Geophysical Model Function (GMF):

$$\sigma_0 = B_0(v,\theta)\left(1 + B_1(v,\theta)\cos\phi + B_2(v,\theta)\cos 2\phi\right)$$

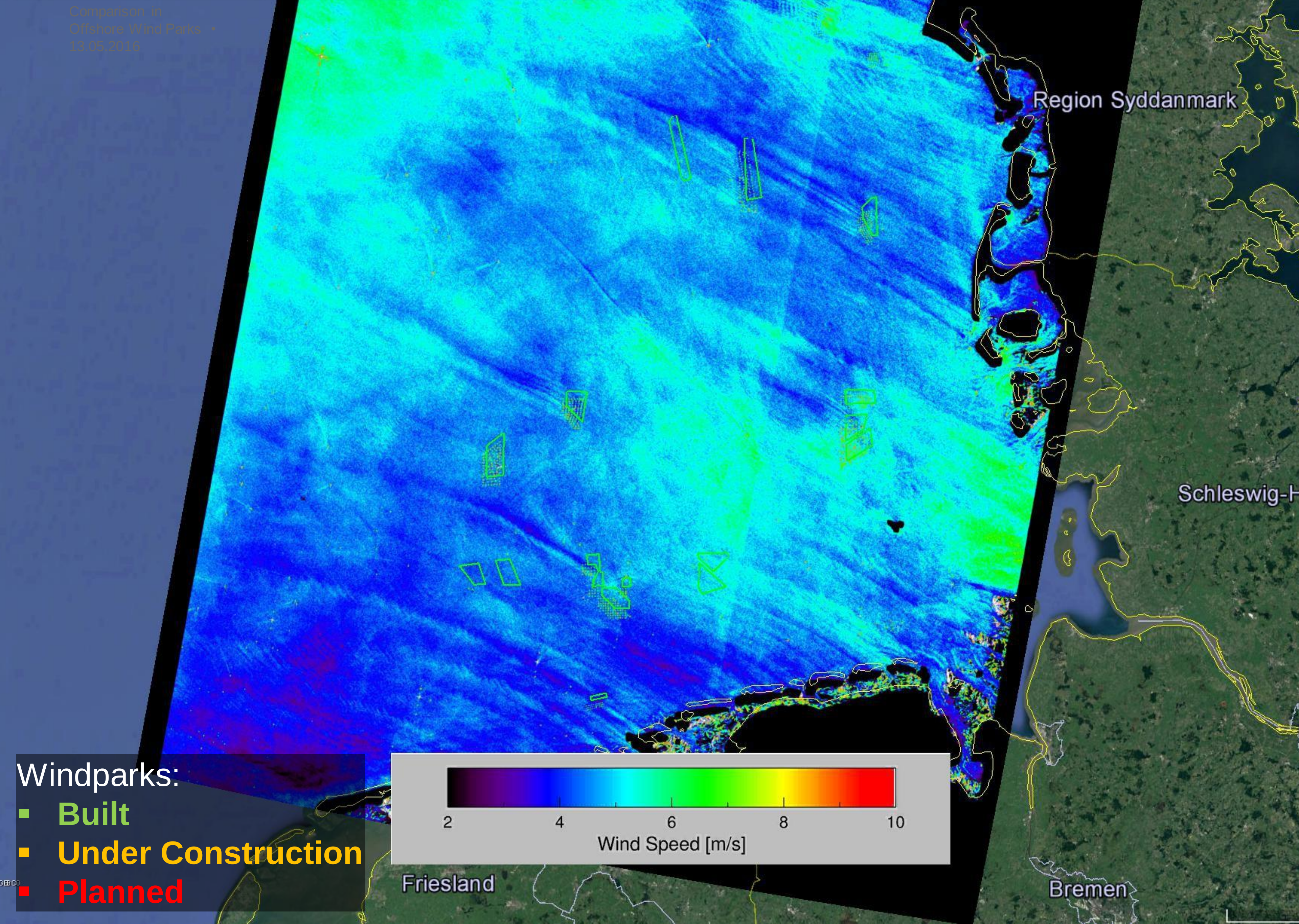
$v$: Wind Speed

$\theta$: Incidence Angle

$\varphi$: Wind Direction

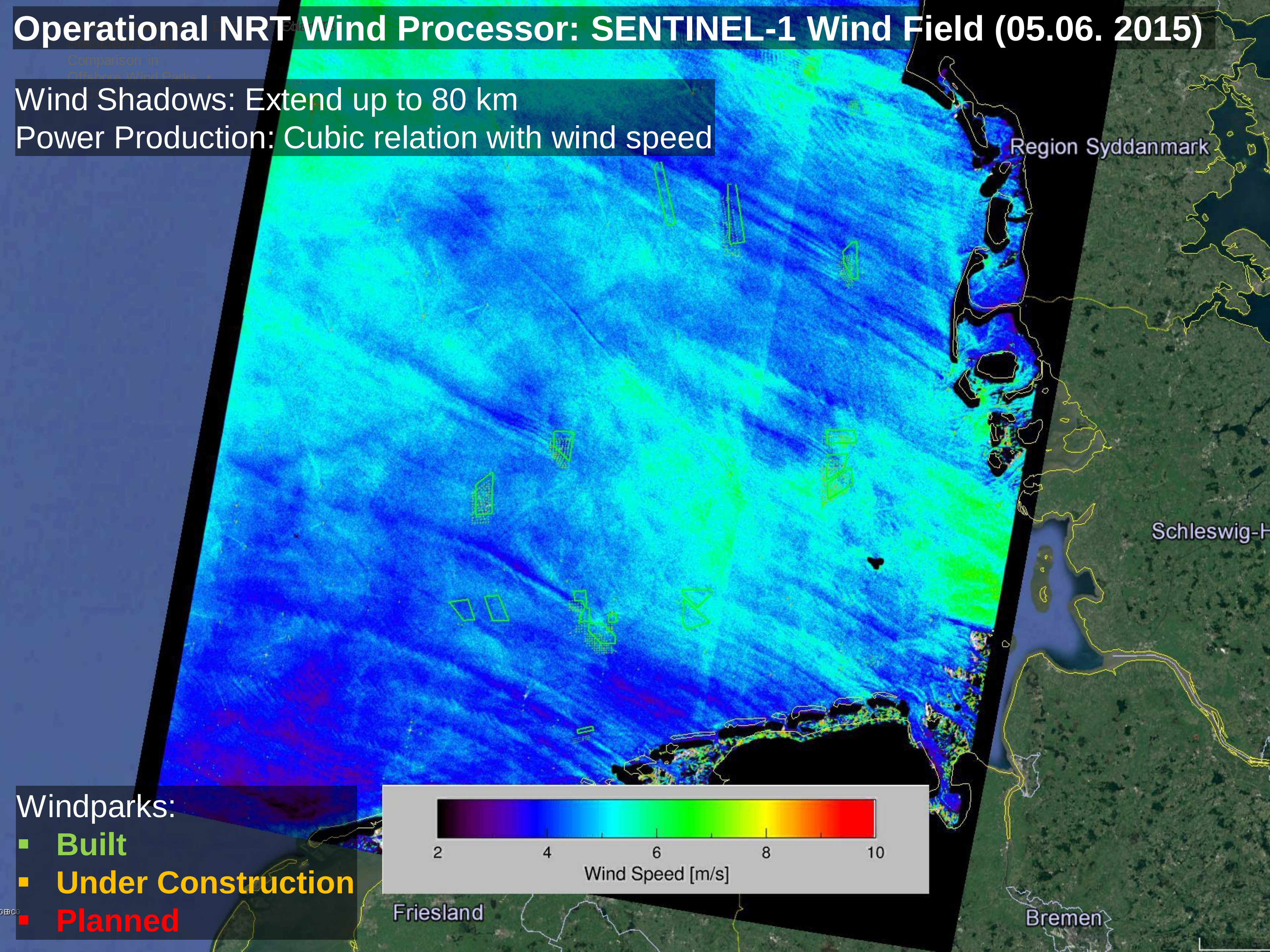
| Radar band | GMF | Spaceborne SAR Sensors |
|---|---|---|
| C-band (5.6GHz) | CMOD4,CMOD5/5N | ERS/SAR,ENVISAT/ASAR, RADARSAT-1/2 |
| L-band (1.3GHz) | LMOD1/2 | JERS-1, ALOS PALSAR-1/2 |
| X-band (9.6GHz) | **XMOD/XMOD2** | TerraSAR-X/TanDEM-X, Cosmo-SkyMed |

# Operational NRT Wind Processor: SENTINEL-1 Wind Field (05.06. 2015)



# 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




Windparks:
- Built
- Under Construction
- Planned

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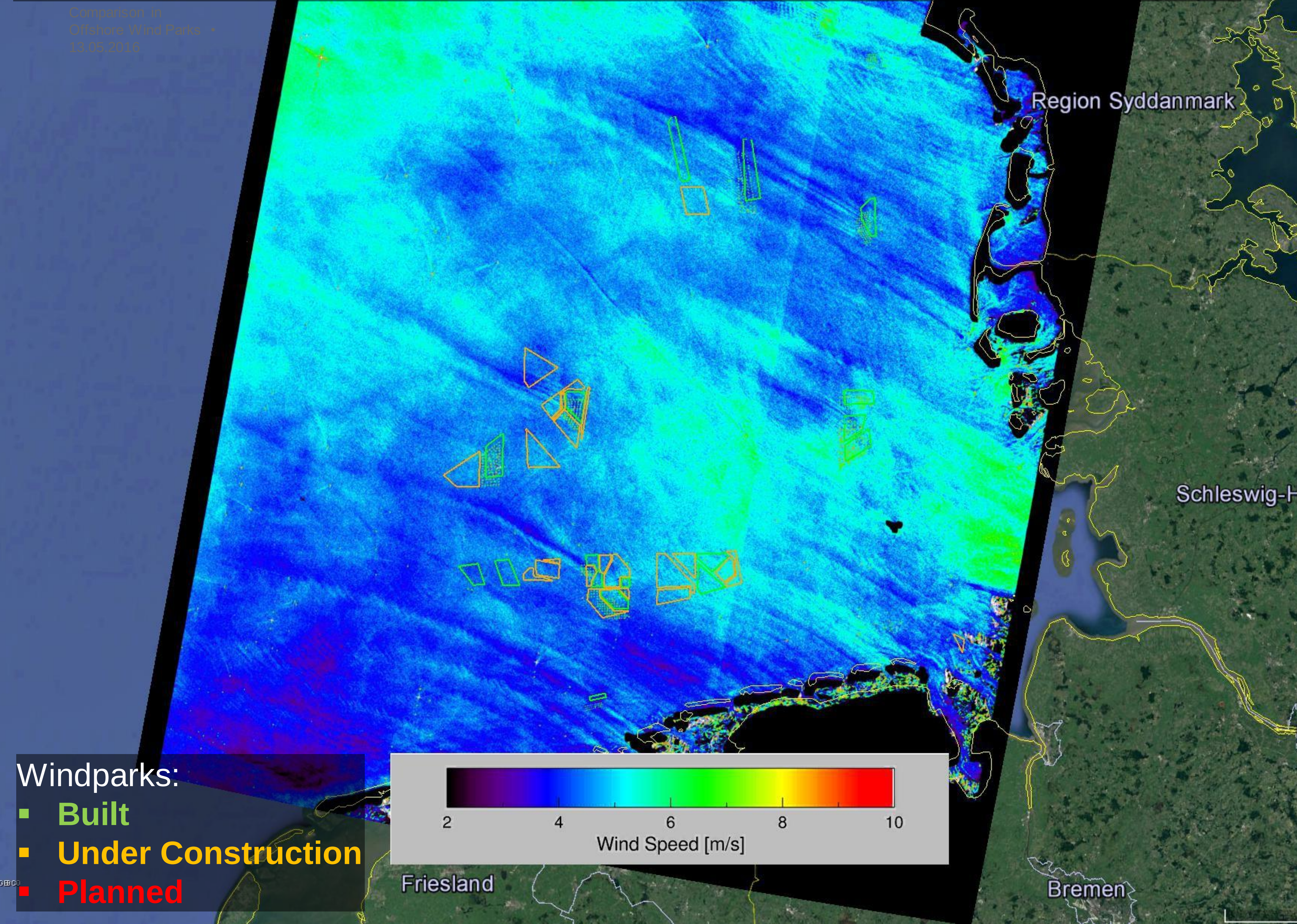

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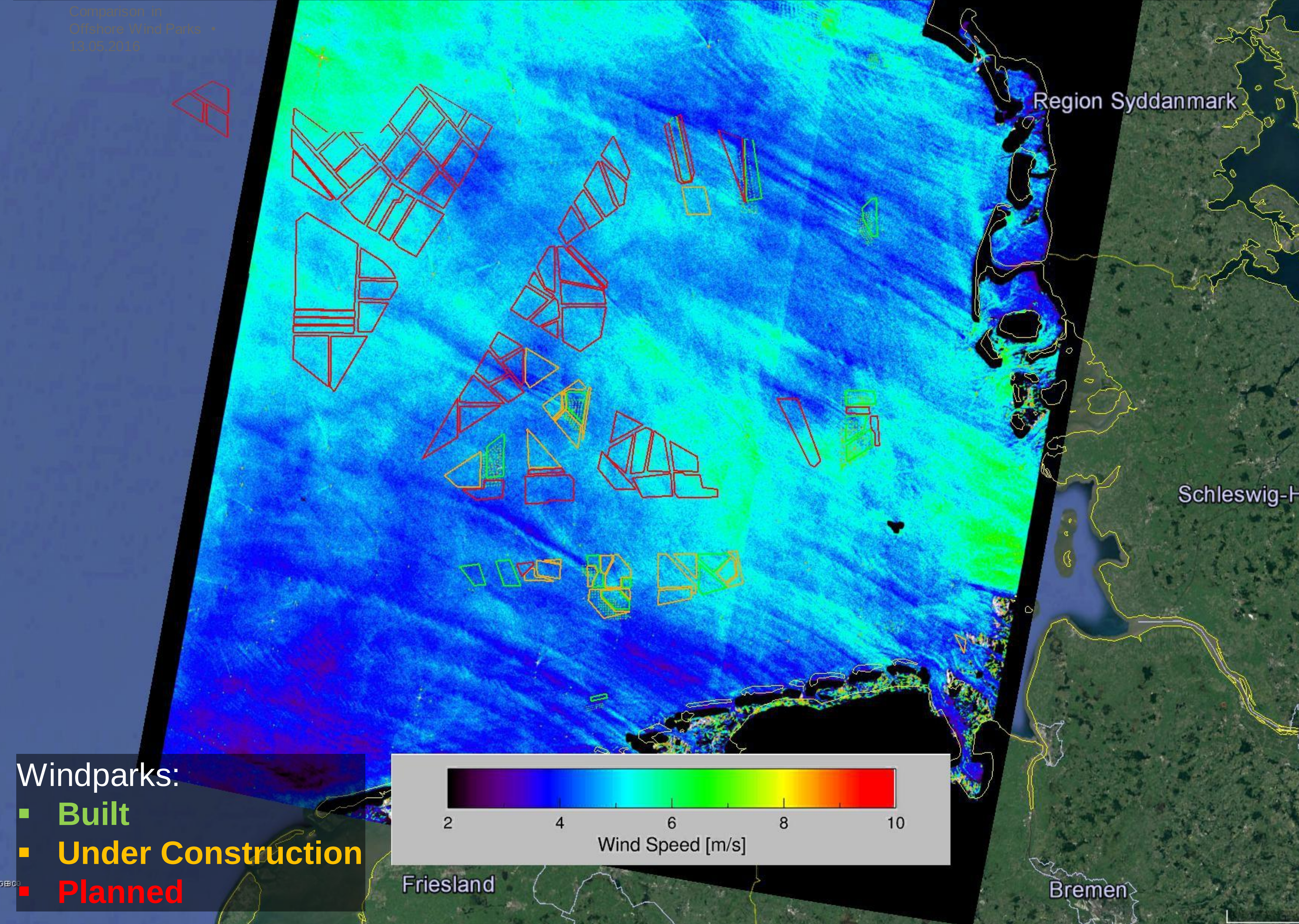

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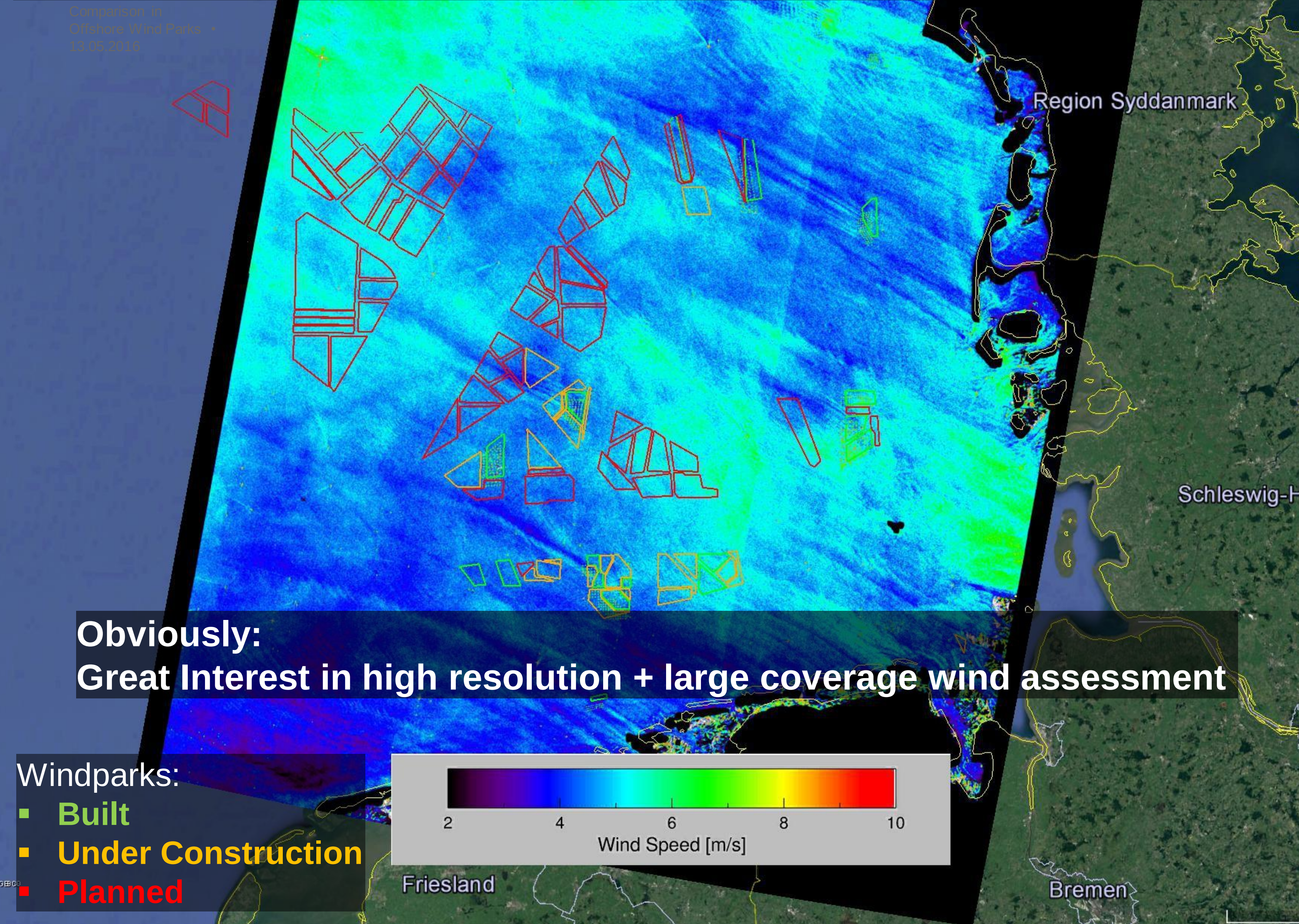
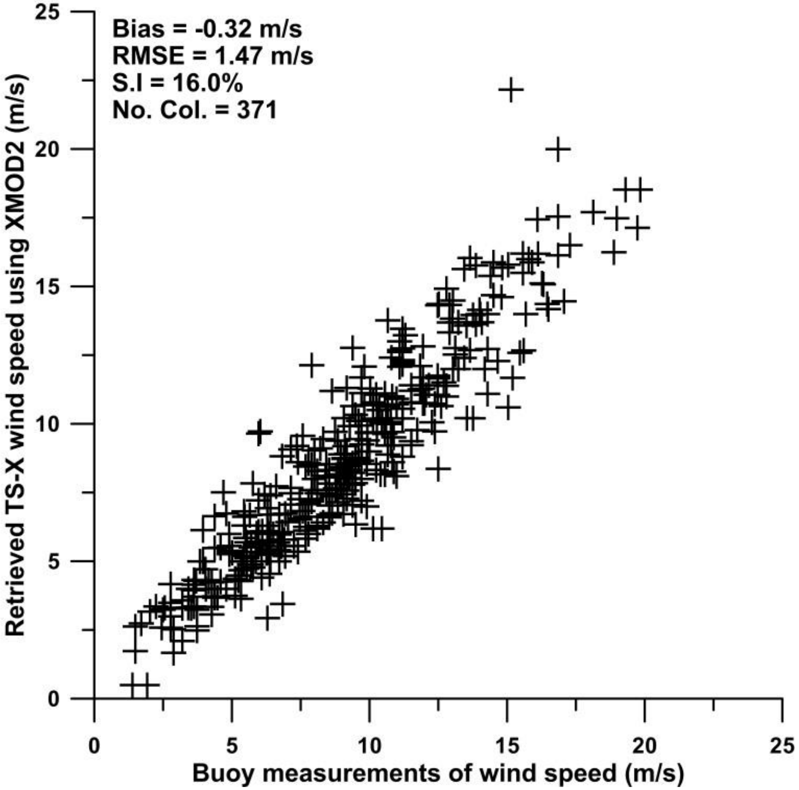
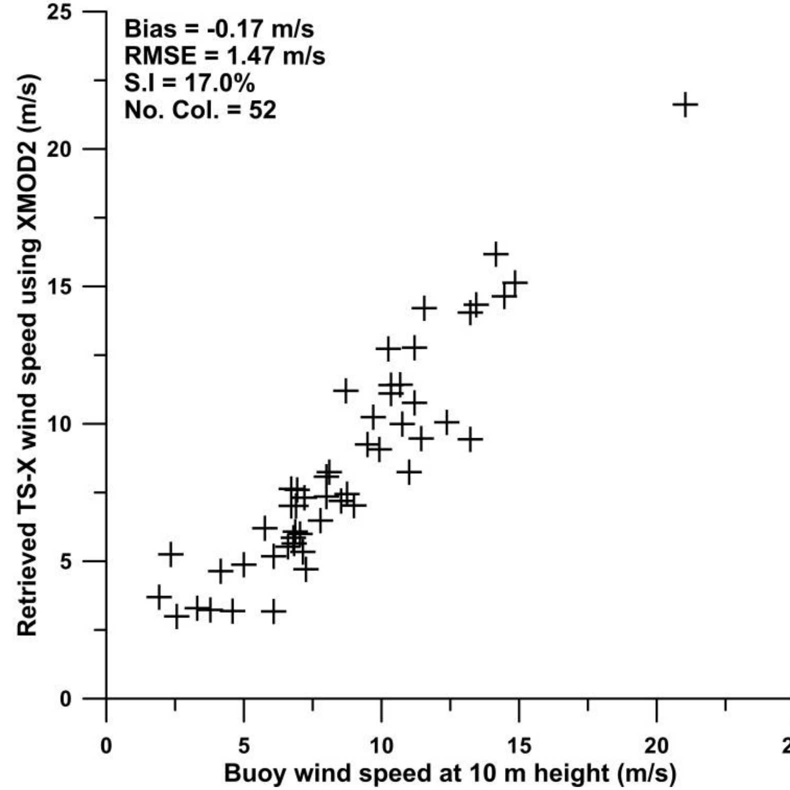



**Obviously:**
**Great Interest in high resolution + large coverage wind assessment**

Windparks:
- **Built**
- **Under Construction**
- **Planned**

# XMOD2 Validation




| Colocations | Bias | RMSE | SI |
|---|---|---|---|
| 371 (training) | -0.32 m/s | 1.47 m/s | 16.0% |
| *52 (validation)* | *-0.17 m/s* | *1.47 m/s* | *17.0%* |

X.-M. Li and S. Lehner, "Algorithm for Sea Surface Wind Retrieval From TerraSAR-X and TanDEM-X Data," *IEEE Transactions on Geoscience and Remote Sensing*, vol. Early Access Online, 2013.

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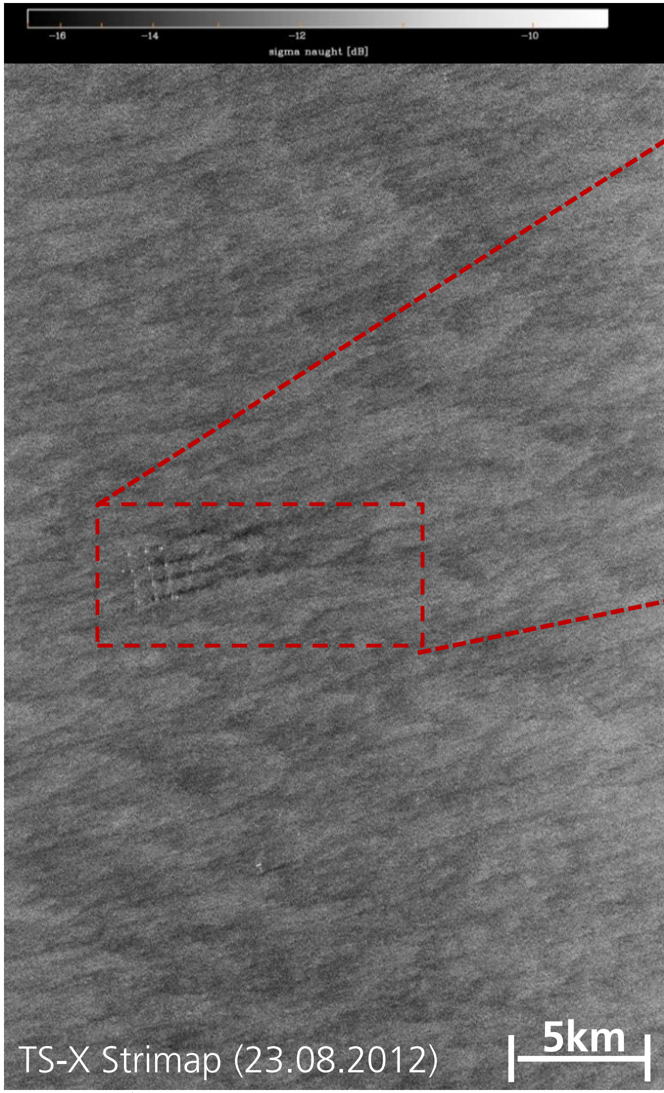
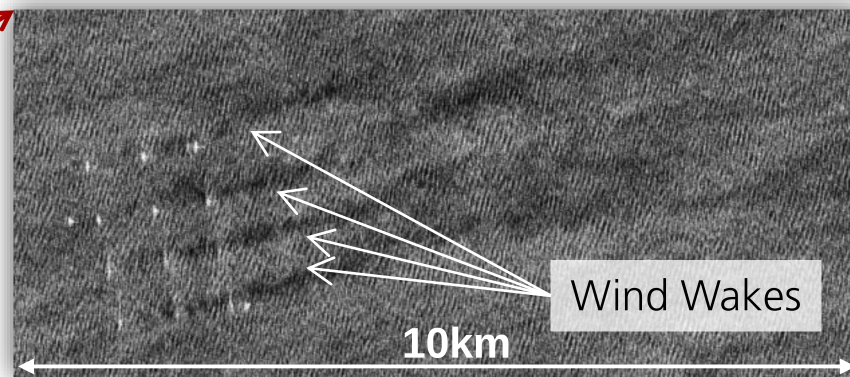
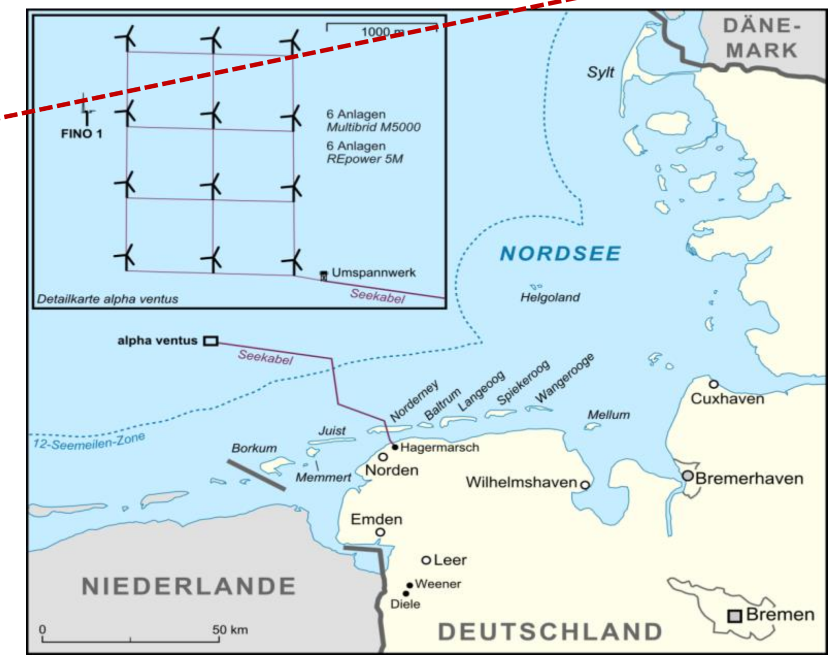
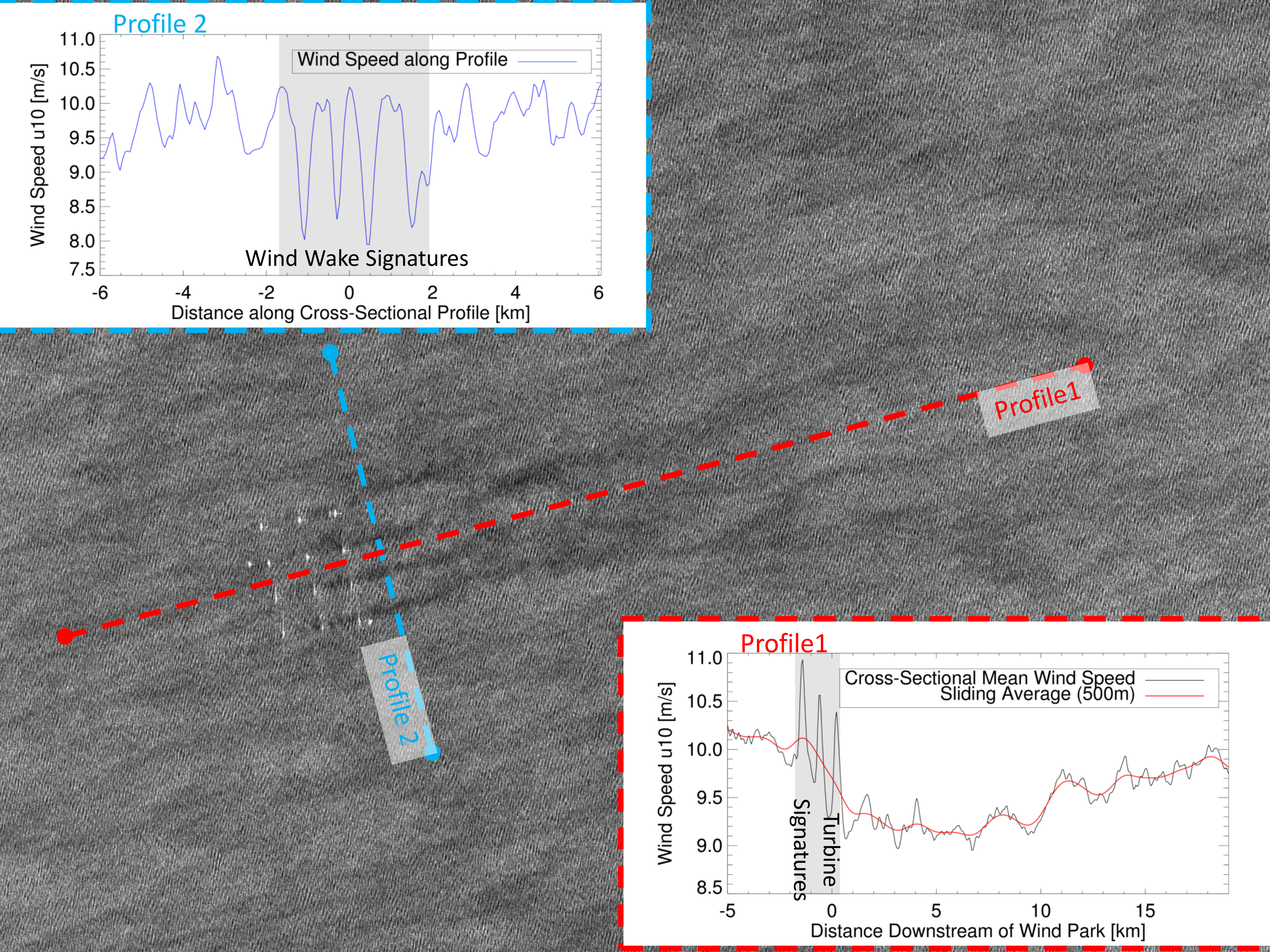
# Alpha Ventus Offshore Wind Park





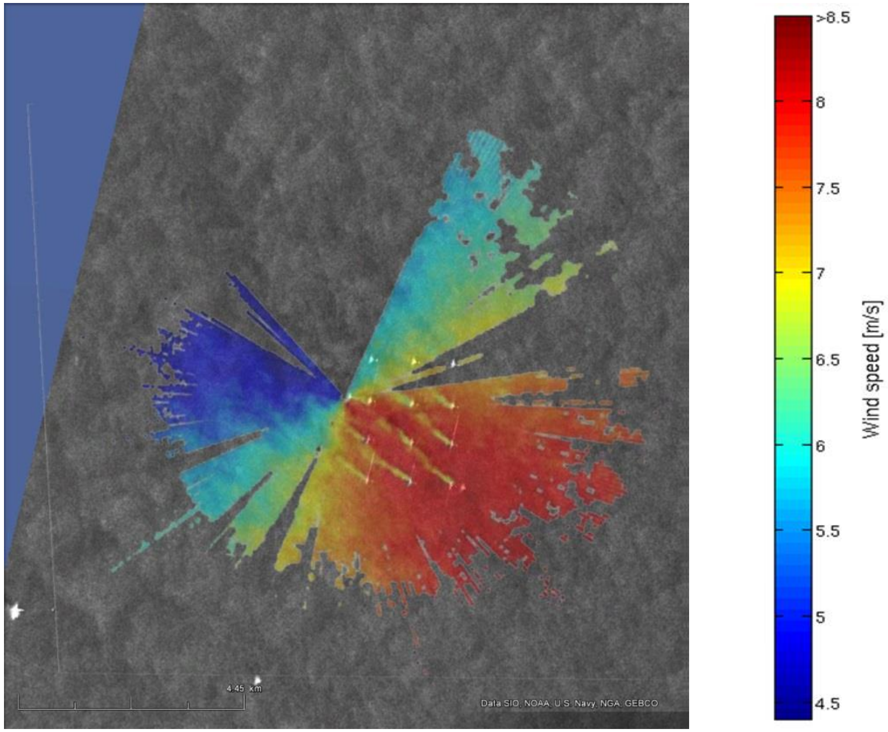
Profile 2
Wind Speed along Profile
Wind Wake Signatures
Wind Speed u10 [m/s]
Distance along Cross-Sectional Profile [km]
Profile1
Profile 2
Profile1
Cross-Sectional Mean Wind Speed
Sliding Average (500m)
Turbine Signatures
Wind Speed u10 [m/s]
Distance Downstream of Wind Park [km]

# 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 ?

# Approach: Wind Fields From two Independent Methods



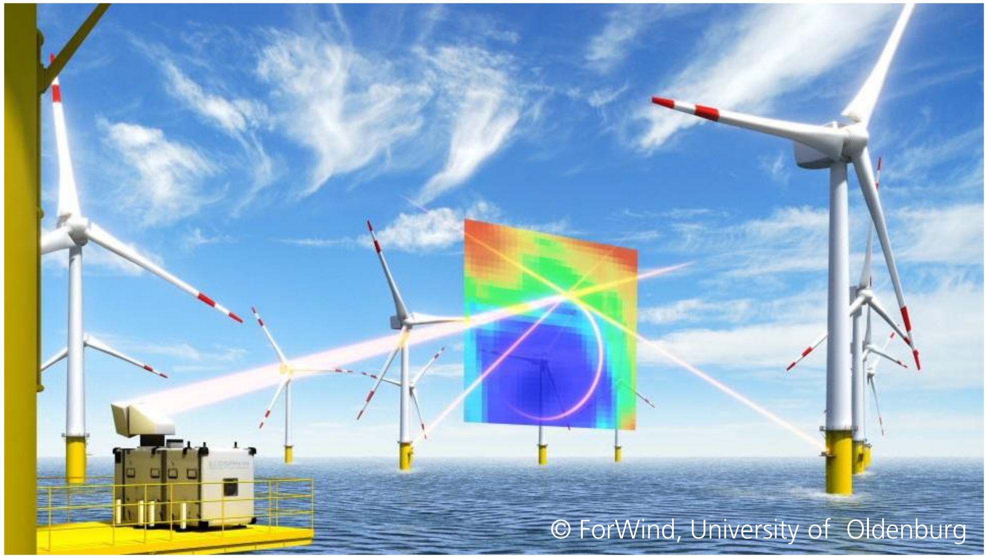



*Alpha Ventus Offshore Wind Park*

# Joint Campaign with ForWind (Oldenburg)

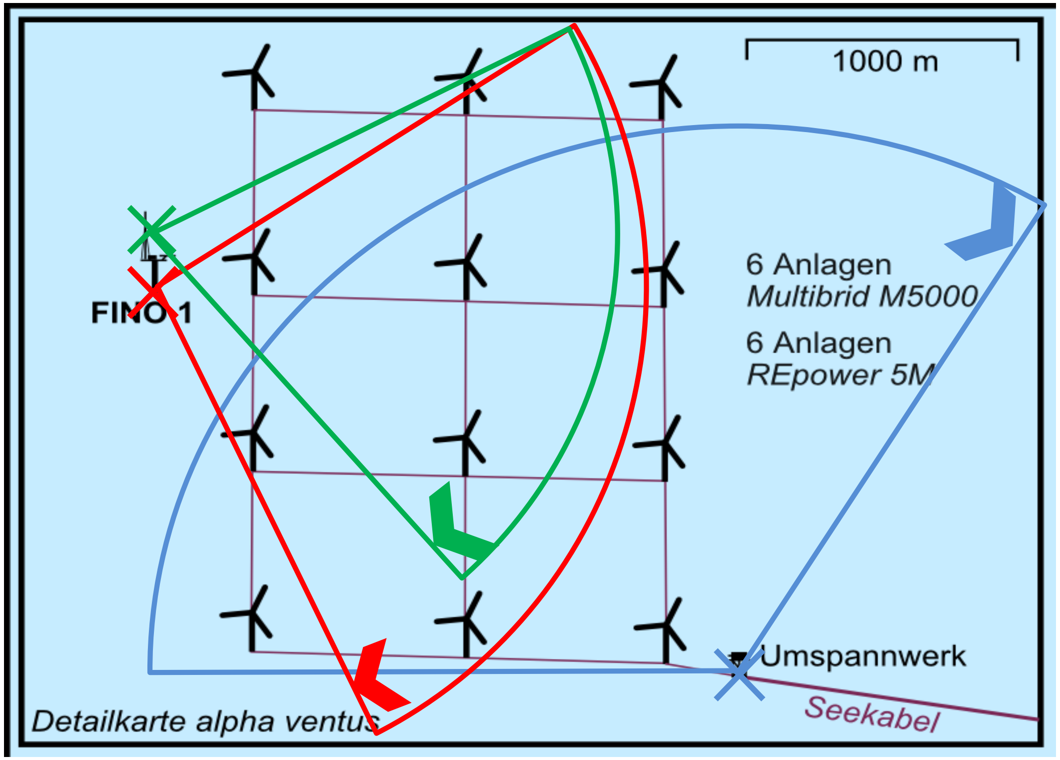
## On-Site LIDAR

- Pulsed long range Lidar installed in **Alpha Ventus Wind Park**
- Cooperation with *ForWind (University of Oldenburg, Germany)*
- System: Windcube
- Master Thesis of Julian Hieronimus

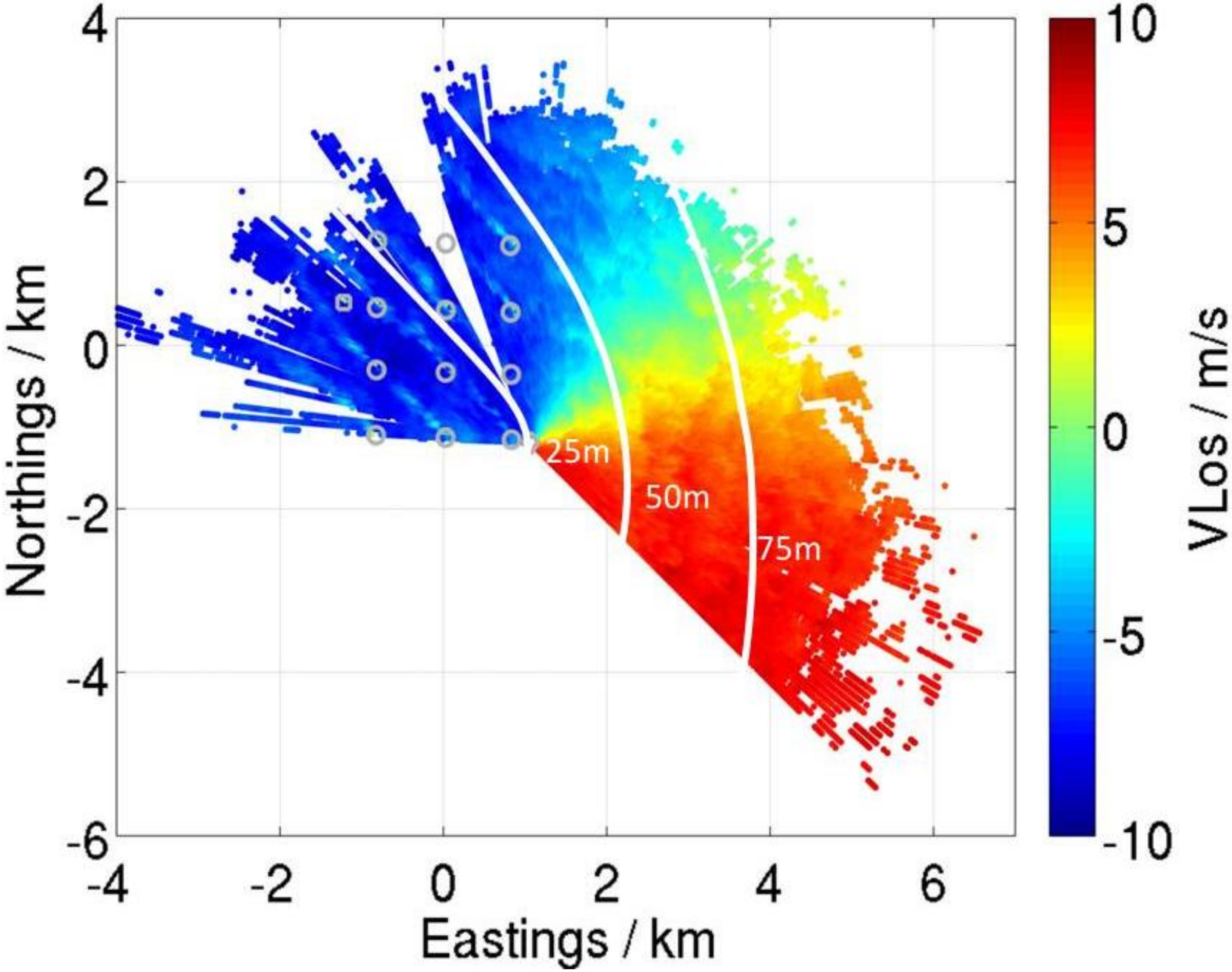
# Experimental Set-Up

- TS-X wind field measurements measurements on 4 different dates in January 2014
- Satellite wind field resolution ca. 60x60m
- Simultaneously LiDAR PPI scans (approx. 4min per scan)
- Additional data from COSMO-DE weather model from German Weather Service (DWD)




***Positions of LiDAR systems in alpha Ventus***
***[Map: www.commons.wikimedia.org]***

# LiDAR raw data: Line-of-Sight Velocities

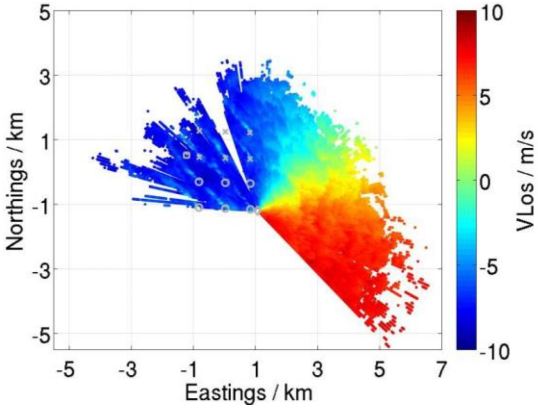


# Wind measurements in free flow & LiDAR post processing

LoS -> absolute horizontal wind speed

Filtering for free flow sectors

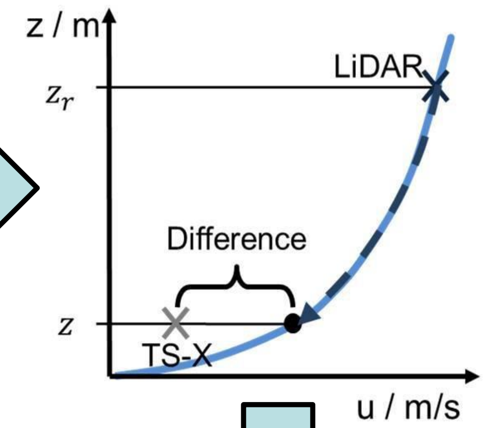
Extrapolation to 10 m height on standard grid



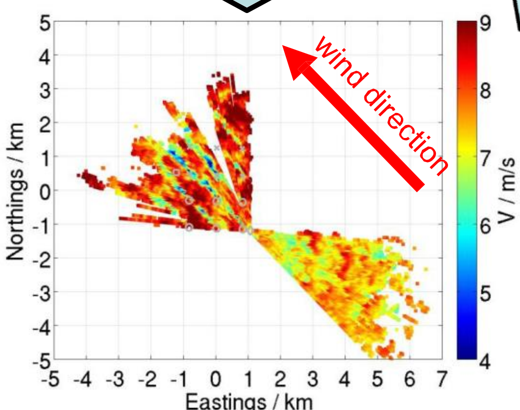

meso-scale weather model COSMO-DE:

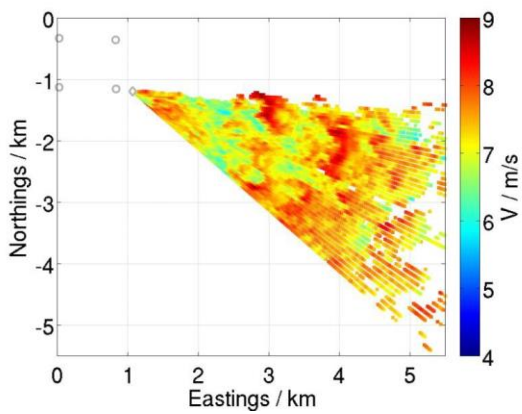
- wind direction
- roughness parameter $z_0$

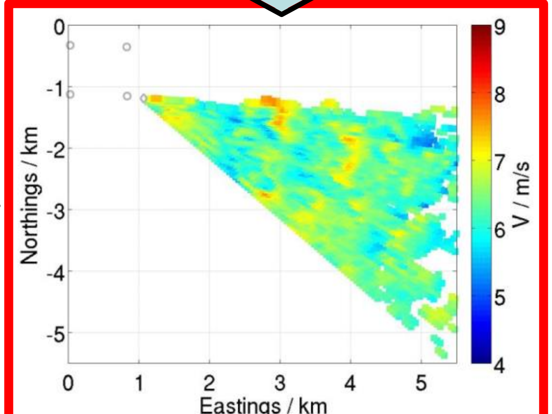
$z_0$




wind direction

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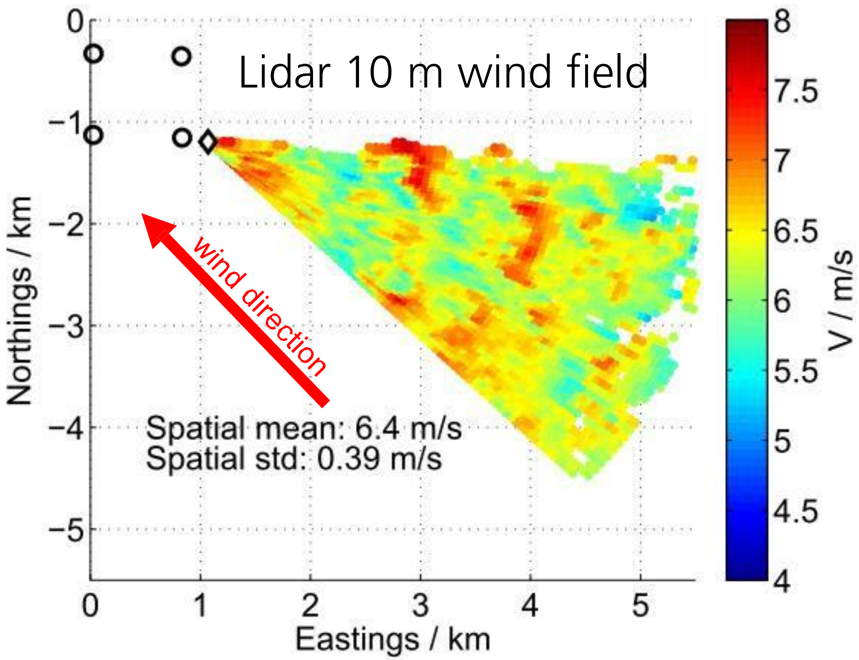
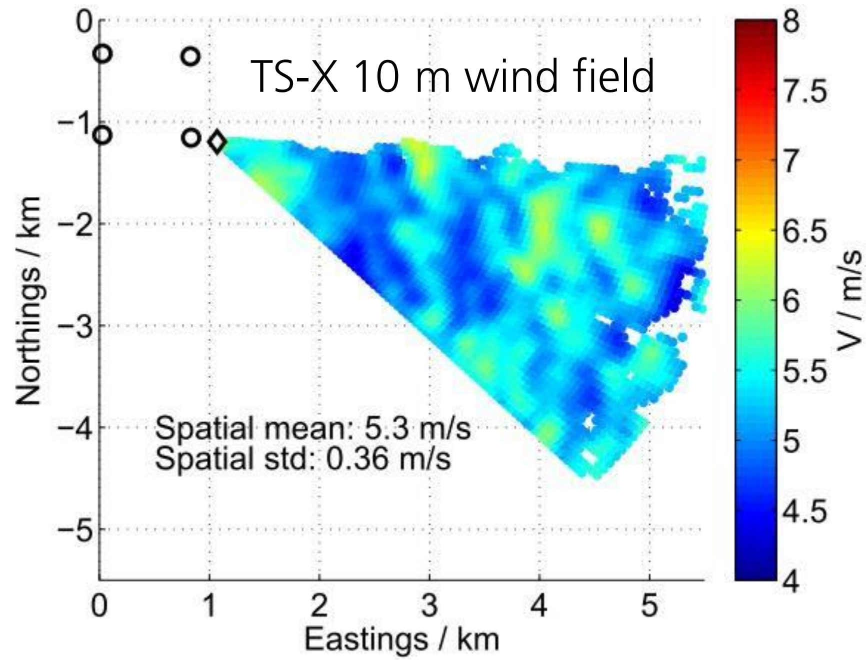
# Results in free flow
## Comparison of spatial structures

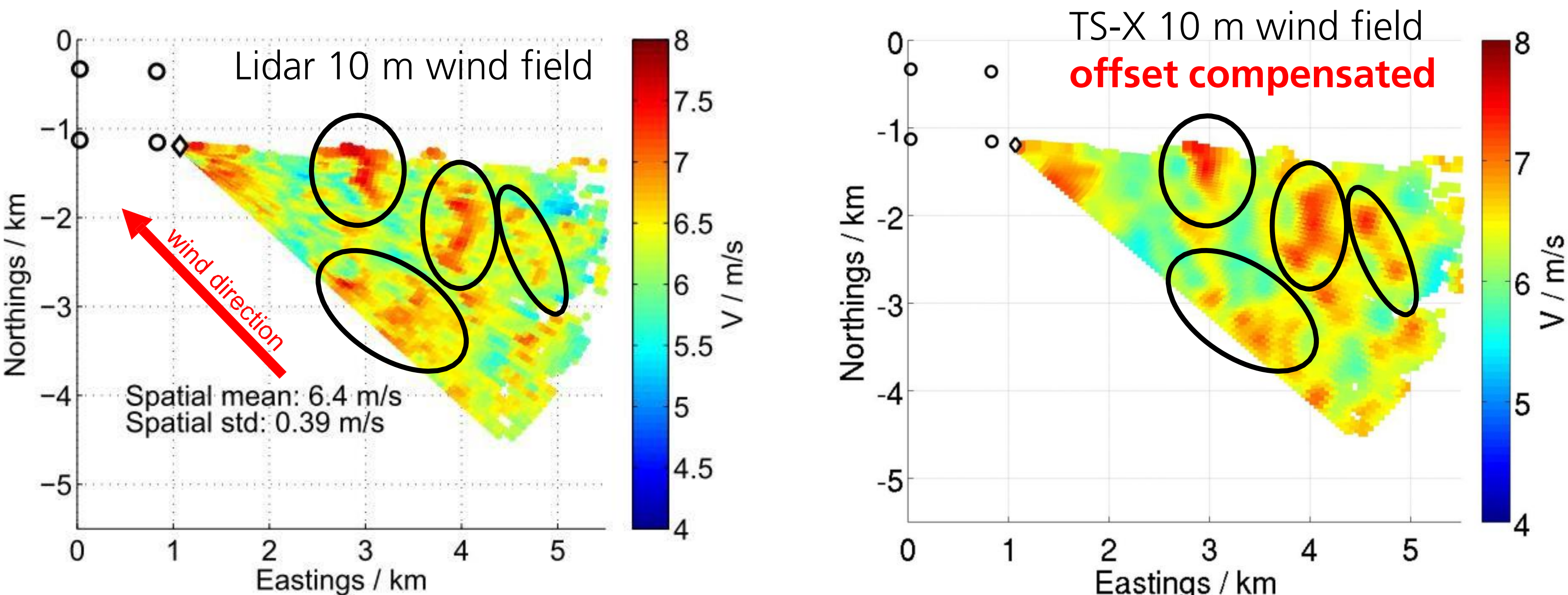
- Offset in average wind measurement 1.1 m/s
- Spatial standard deviation comparable



# Results in free flow
## Comparison of spatial structures

- Spatial structures of lidar measurement well observable in TS-X measurement



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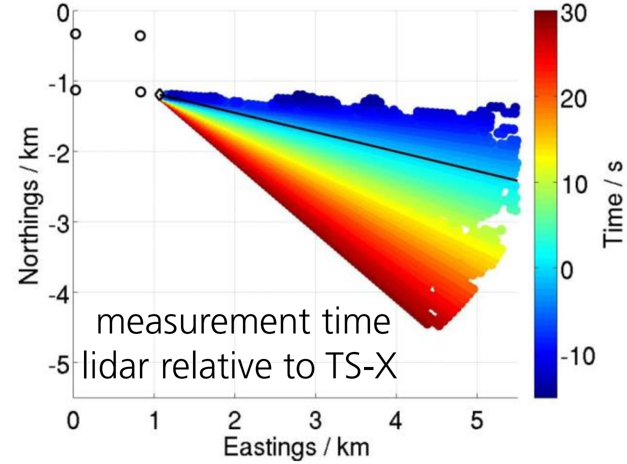


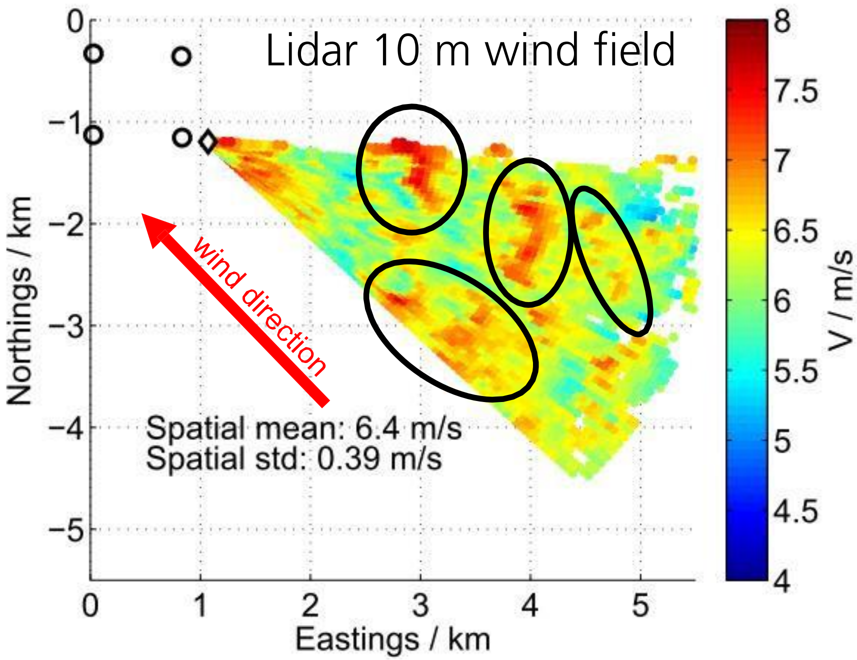


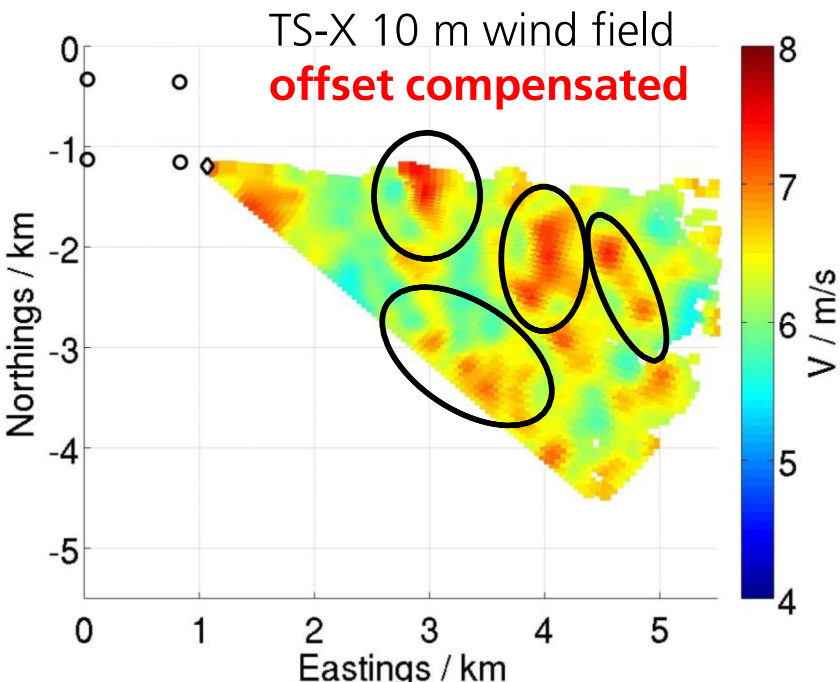




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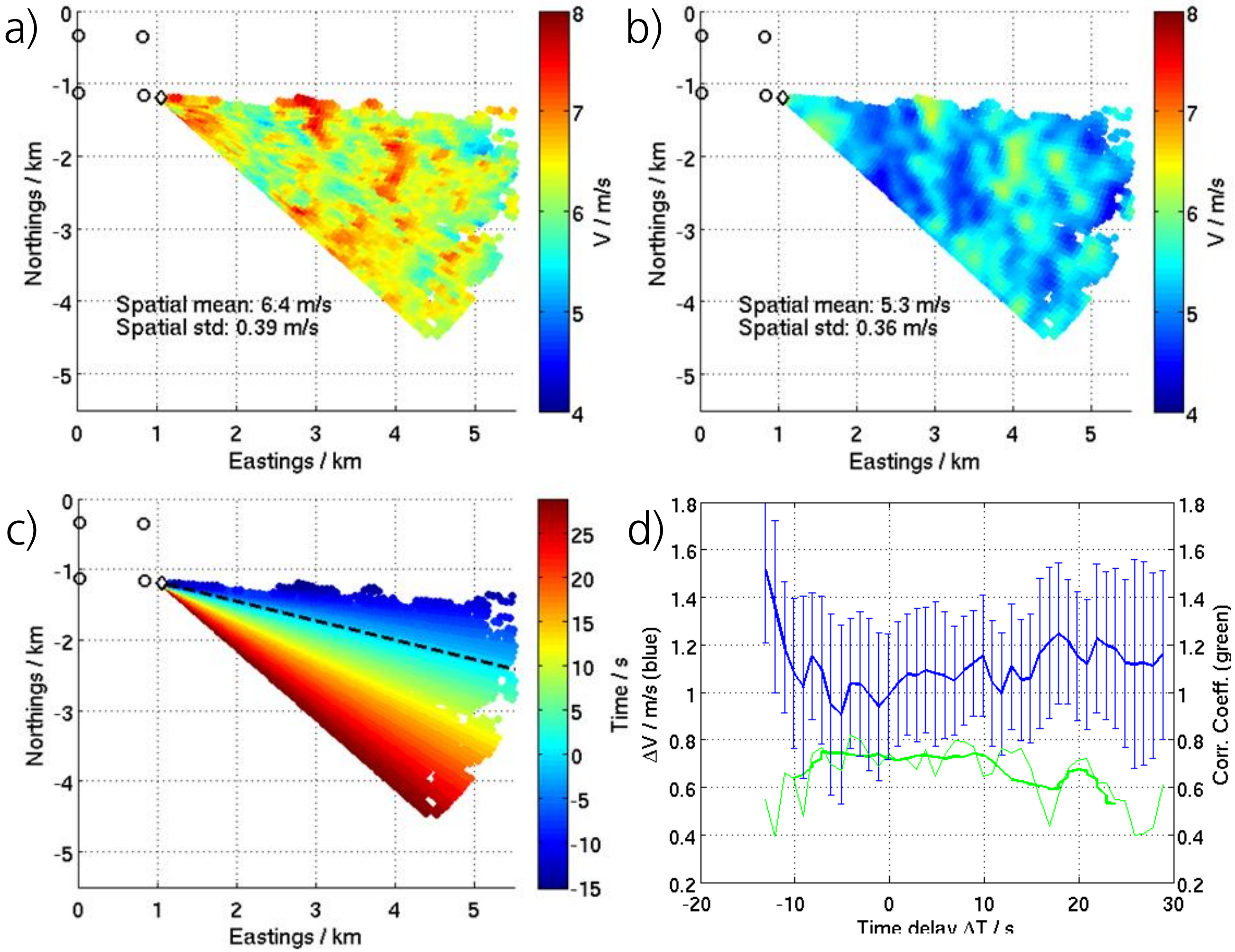
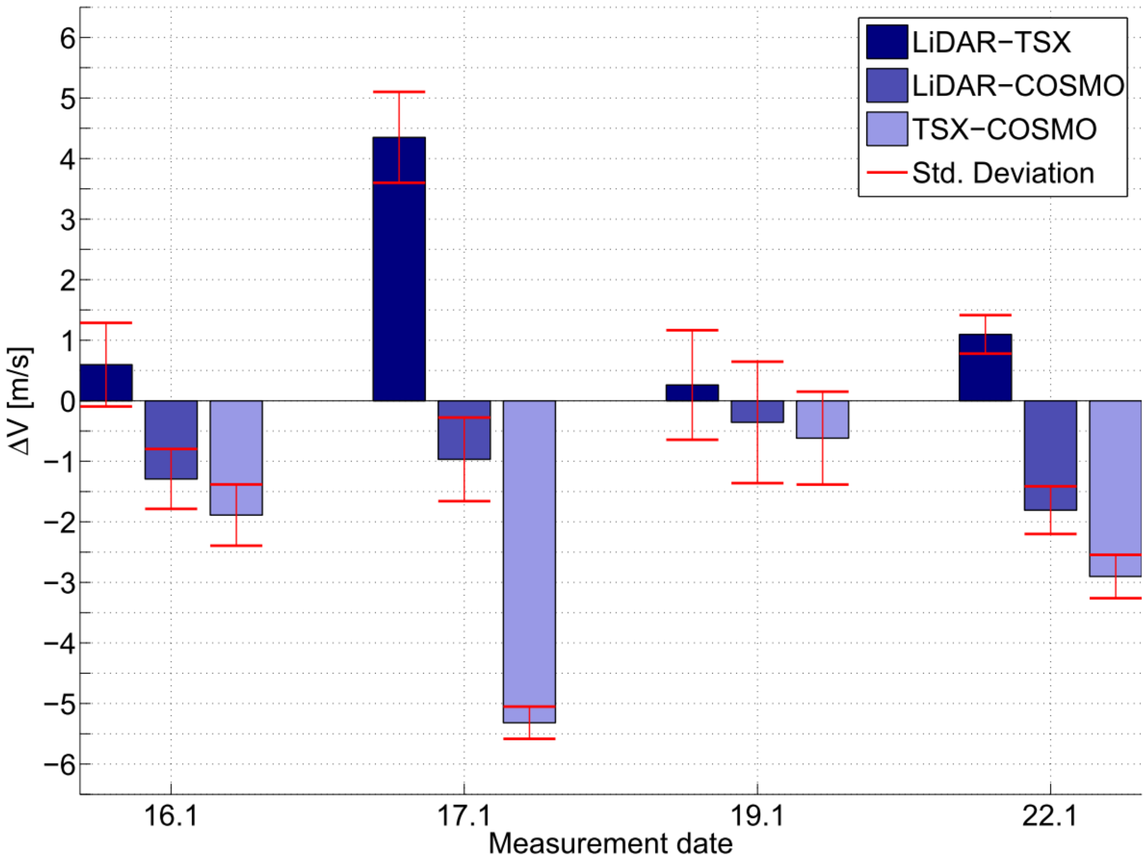


# Results in free flow
# Statistical comparison

- TS-X and lidar compare well in average on three days
- TS-X wind estimate much to low due to very low radar backscatter on one day
- Meteorological reason?




| Date | 16.01. | 17.01. | 19.01. | 22.01. |
|---|---|---|---|---|
| Wind Direction COSMO-DE (coming from) | 174.3° | 174.5° | 125.3° | 134.8° |
| Mean wind speed COSMO-DE | 10.3 m/s | 10.8 m/s | 12.9 m/s | 8.2 m/s |
| Mean Wind Speed LiDAR | 8.8 m/s | 10.0 m/s | 12.5 m/s | 6.4 m/s |
| Mean Wind Speed TSX | 8.4 m/s | 6.1 m/s | 12.2 m/s | 5.2 m/s |

# Data for mismatch occasion (Jan 17)

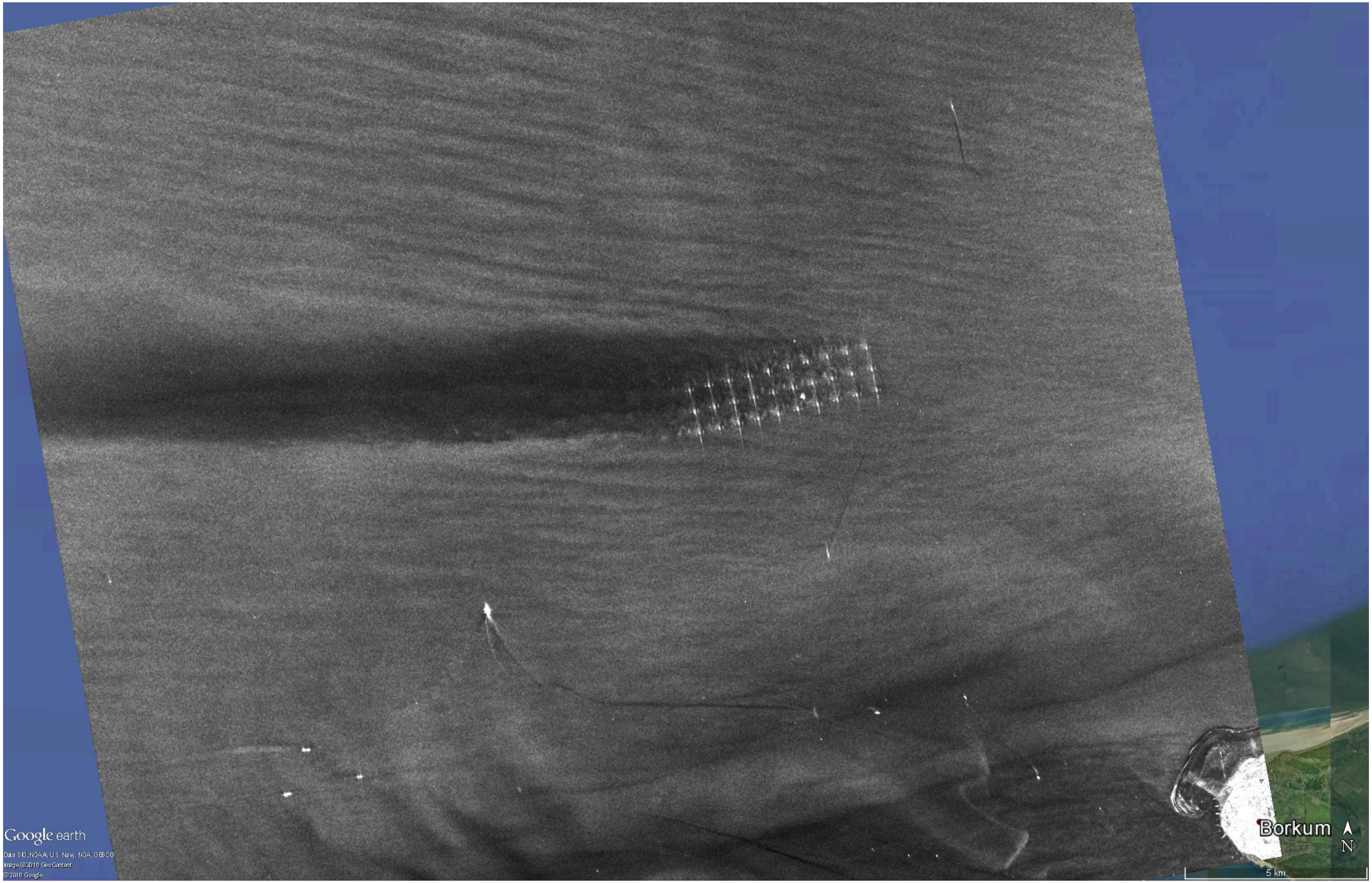
| Date | 17.01. |
|---|---|
| Wind Direction COSMO-DE (coming from) | 174.5° |
| Mean wind speed COSMO-DE | 10.8 m/s |
| Mean Wind Speed LiDAR | 10.0 m/s |
| Mean Wind Speed TSX | 6.1 m/s |

Puzzle Pieces:

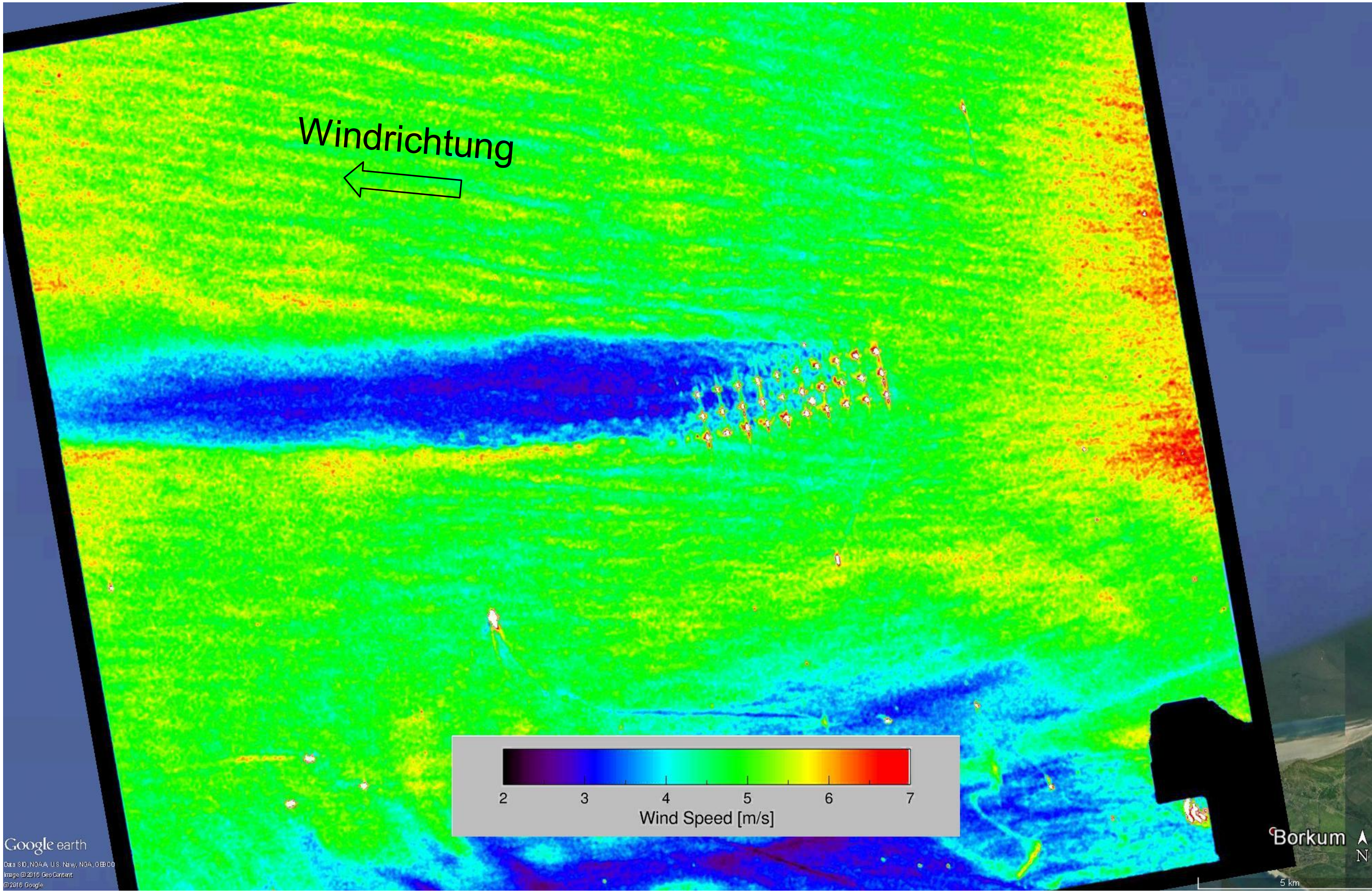
- Comparatively Smooth surface
- No wind sea from south (30 km fetch)
- Wake cross-sectional winds increased

➢ Exceptional meteorological conditions
➢ More investigation needed!

# TS-X StripMap (20150820); Riffgat Wind Park near Borkum




# TS-X StripMap (20150820); Riffgat Windpark vor Borkum

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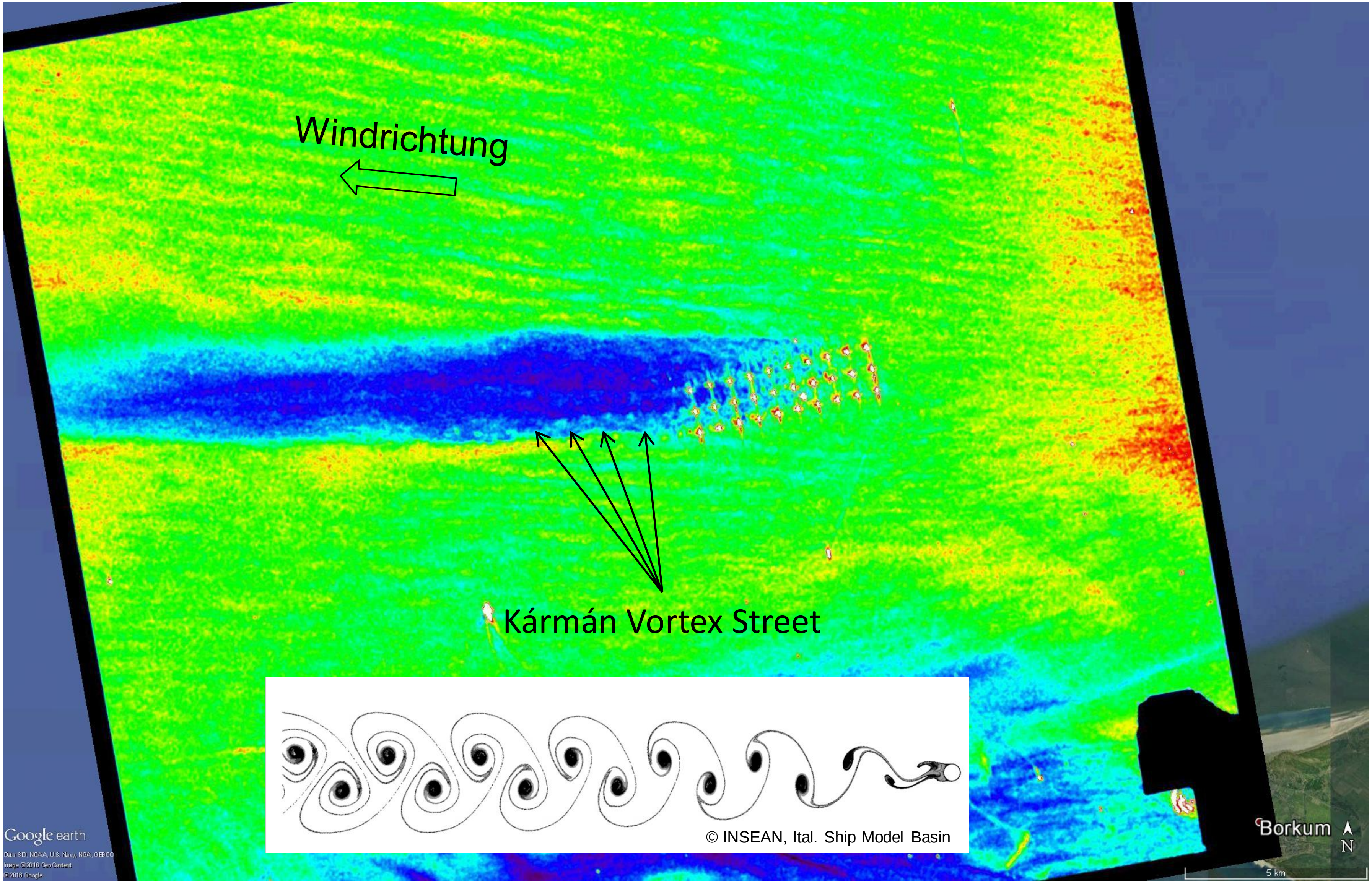
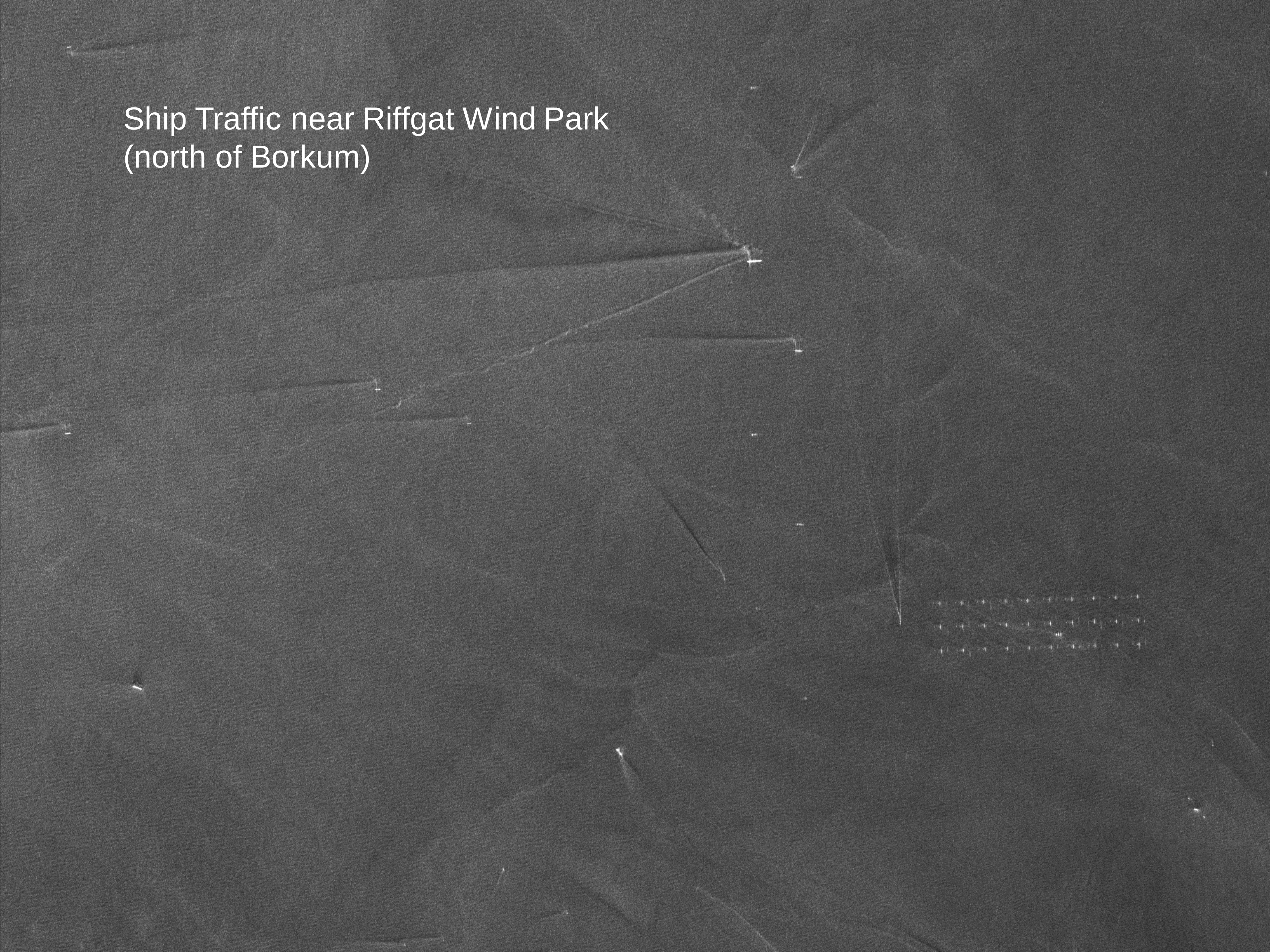


# Conclusions (Wind)

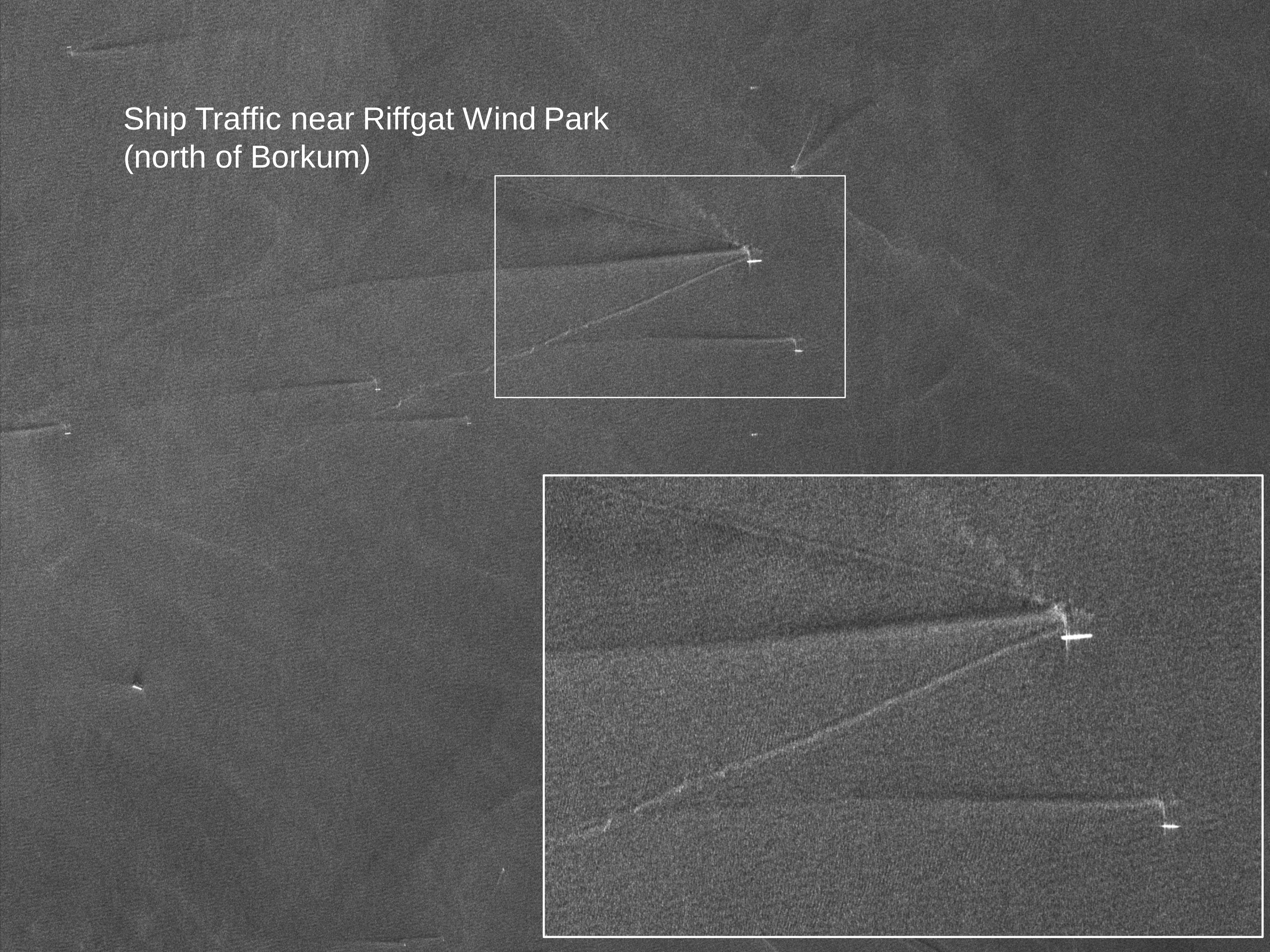
- Small scale wind variations agree well in LiDAR and SAR
- Relative wind variations translate best between methods
- High correlation LiDAR-SAR at turbine height
- Mismatch in special meteorological conditions
- Very important for offshore wind industry in Germany

# Todo

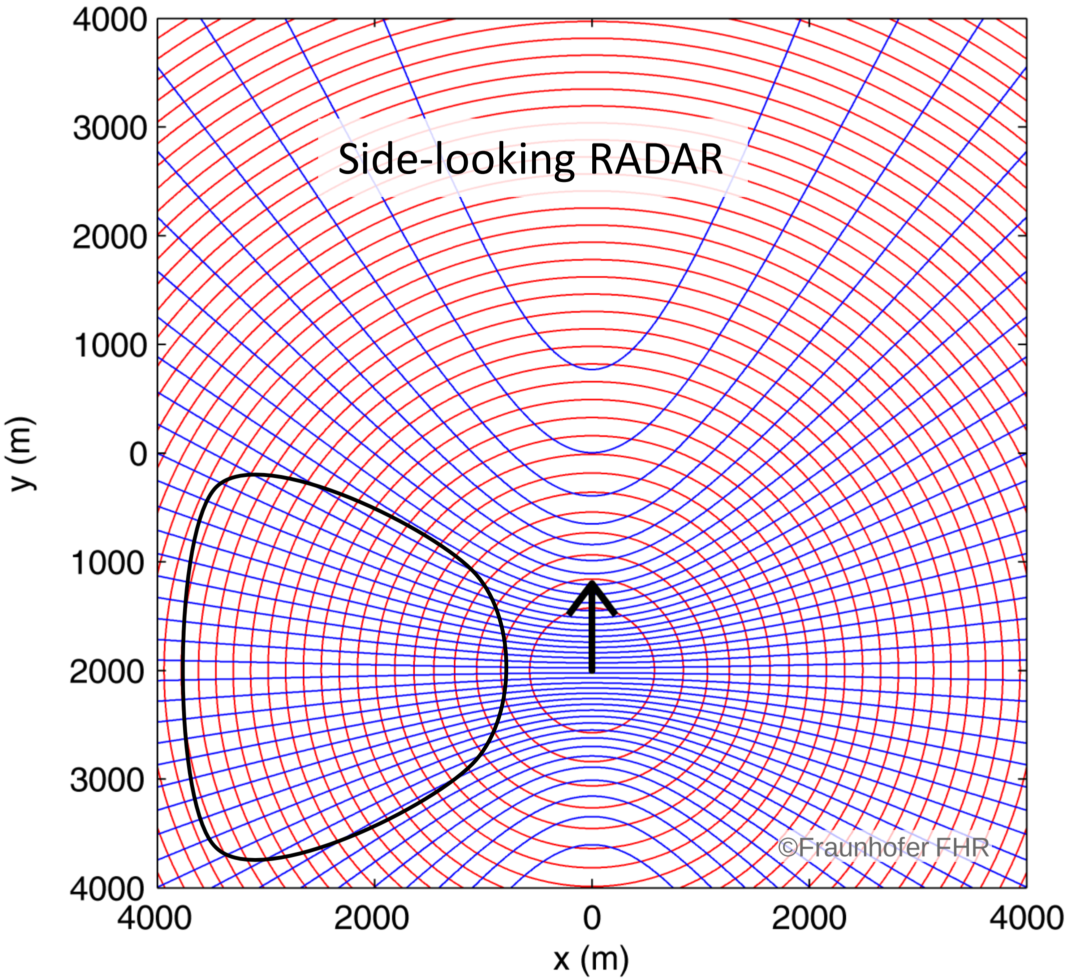
- Investigate turbine wake structures with LiDAR – SAR combination
- Which vertical wind profiles in wake?
- More statistics needed to correlate accuracy with ambient weather conditions.


Ship Traffic near Riffgat Wind Park
(north of Borkum)

# Ship Traffic near Riffgat Wind Park
# (north of Borkum)



# SAR Image Generation: Focussing



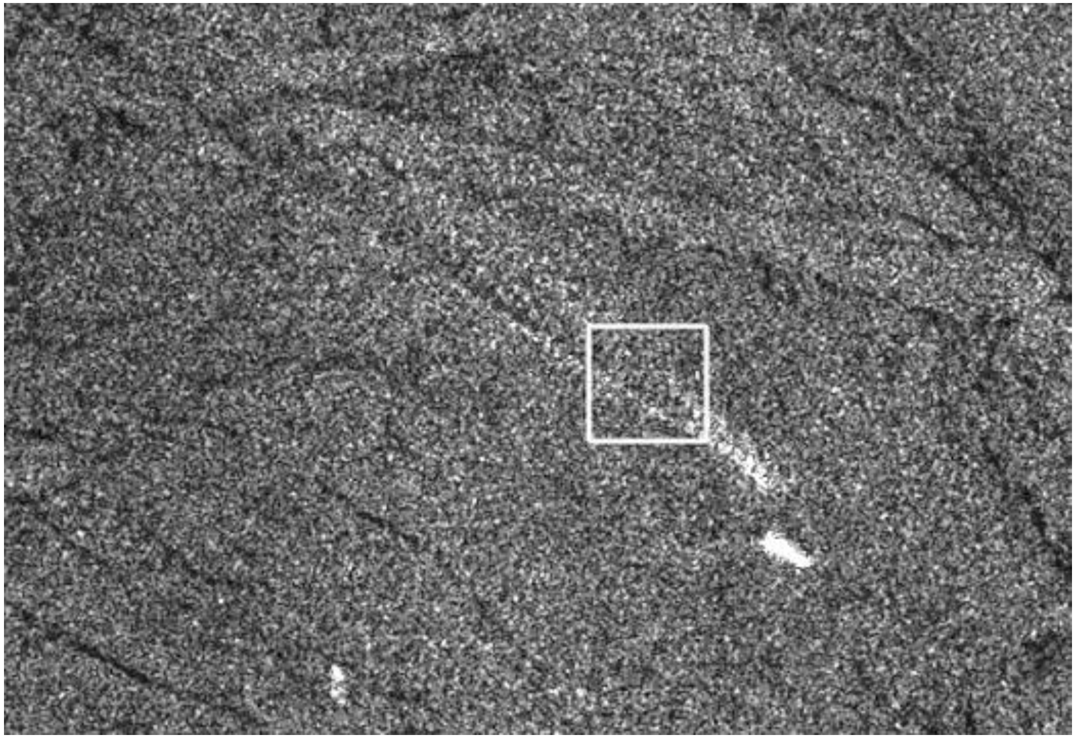

Iso-range and iso-Doppler contours (Monostatic case)

- No Lens
- Focussing with range (delay) and Doppler (frequency) information
- Assumption: Doppler Shift from sensor movement

➢ Moving targets?

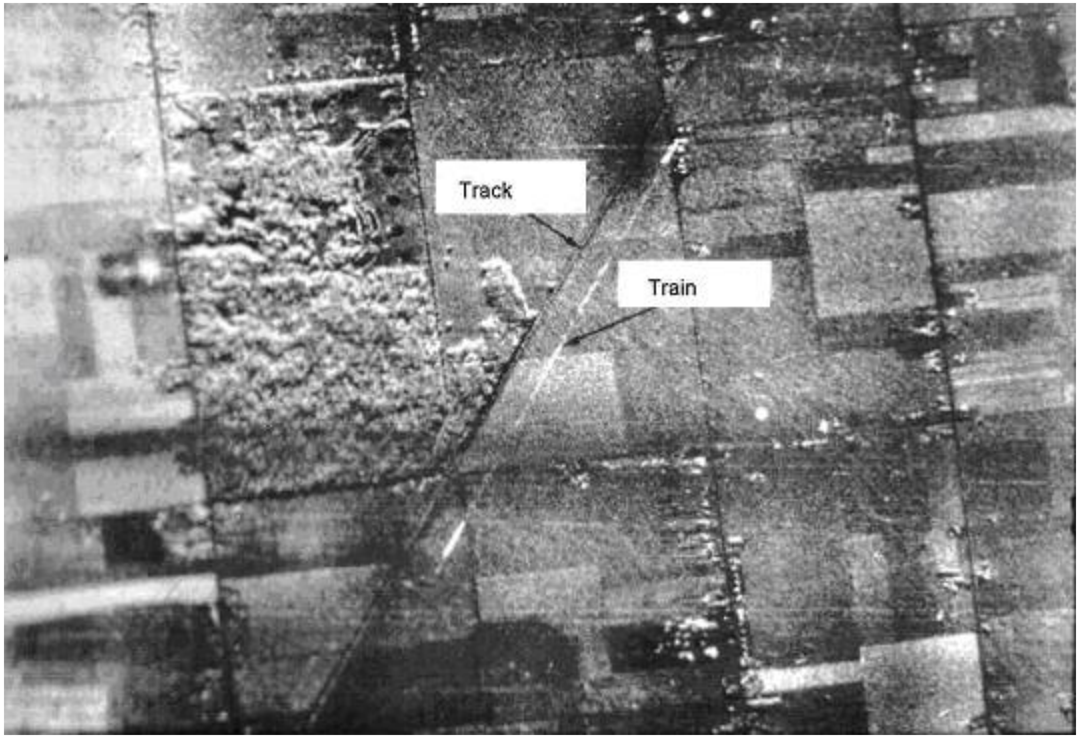
# SAR Imaging of Moving Objects

Misplacement of moving objects



# SAR Imaging of Moving Objects

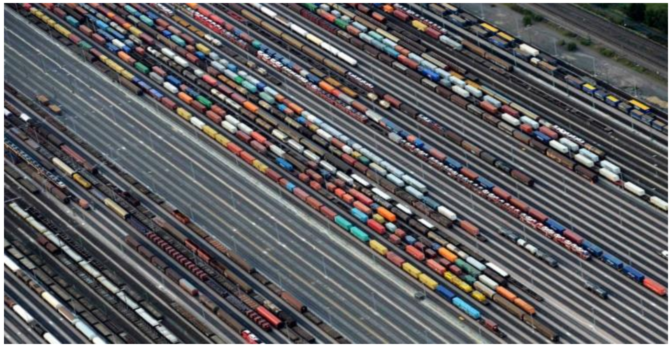
So-called:
„Train off the Tracks“ Effect



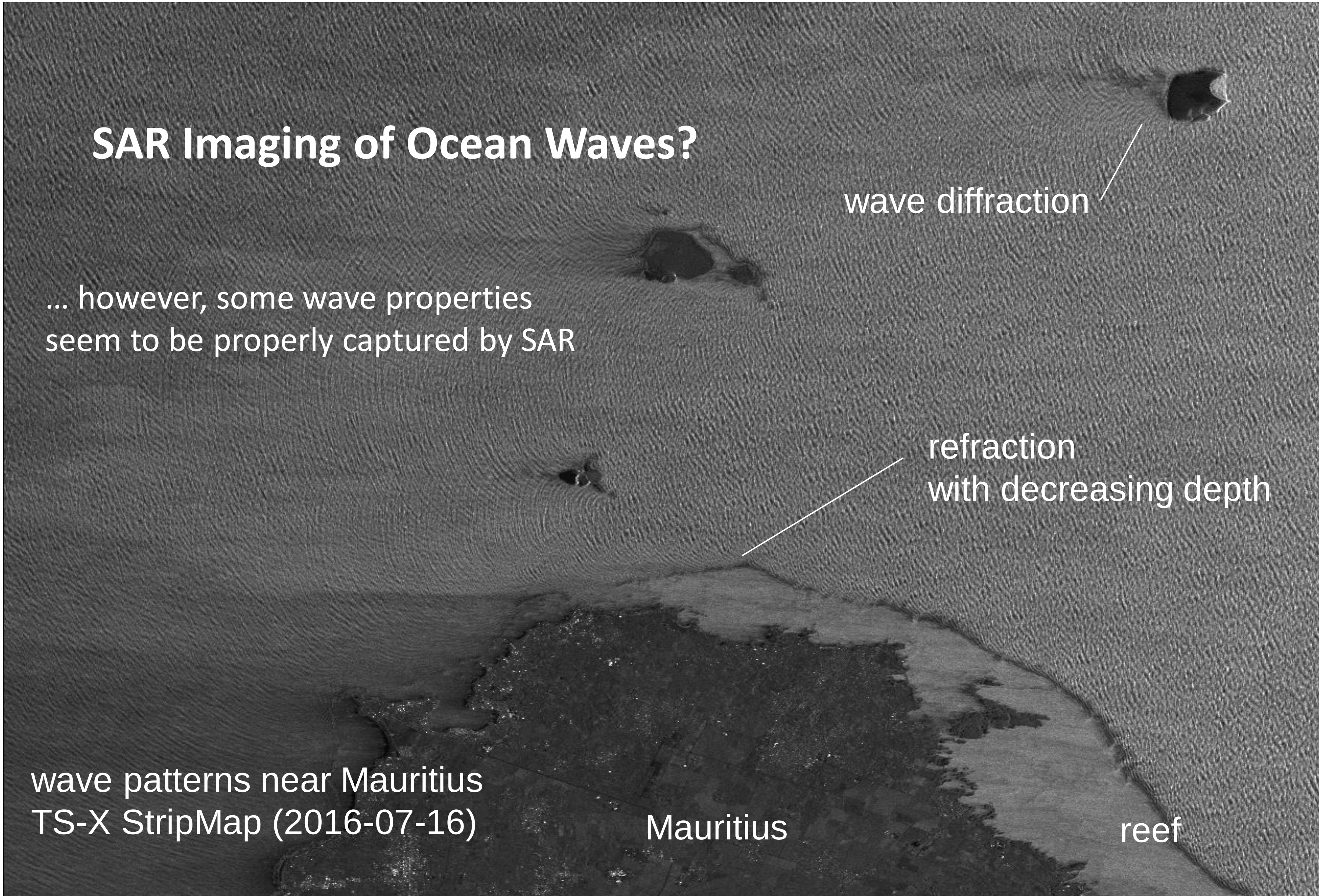
# SAR Imaging of a Moving Surface?

Imaging of moving sea surface?

Well, more like capturing a moving train yard!

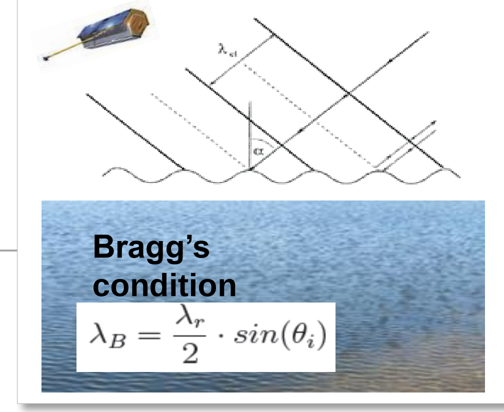


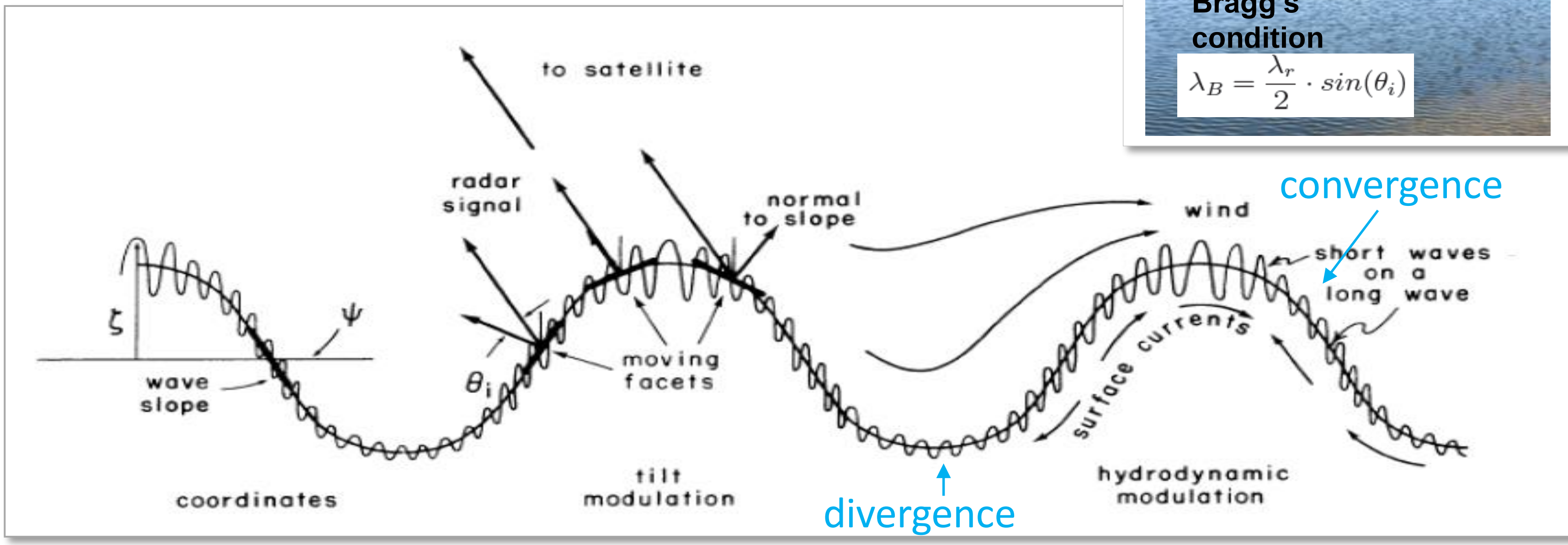
# SAR Imaging of Ocean Waves?




DLR

# Wave Imaging by Spaceborne SAR




Classical schema for long swell waves imaging (moderate wind)[Jackson and Apel 2005].

**Contributions to sea surface imaging: Modulation of NRCS by**

1. Wave surface facette tilt => Bragg condition is changed by modulation of the local incidence angle, resulting in backscatter modulation: **Tilt Modulation**
2. Modulation of wavelength and amplitude of capillary waves due to wave orbital motion, resulting also in backscatter modulation: **Hydrodynamic Modulation**
3. Doppler component by LOS orbital motion component and of moving wave facets, leads to azimuthal displacement: **Velocity Bunching**

DLR

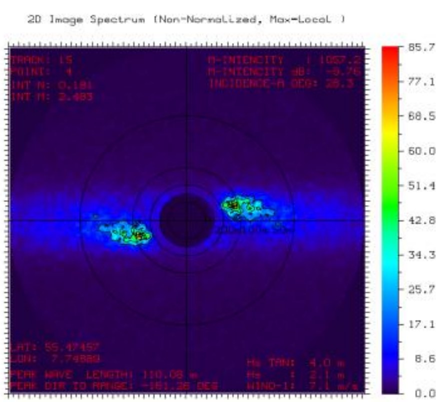
# Wave Imaging by Spaceborne SAR

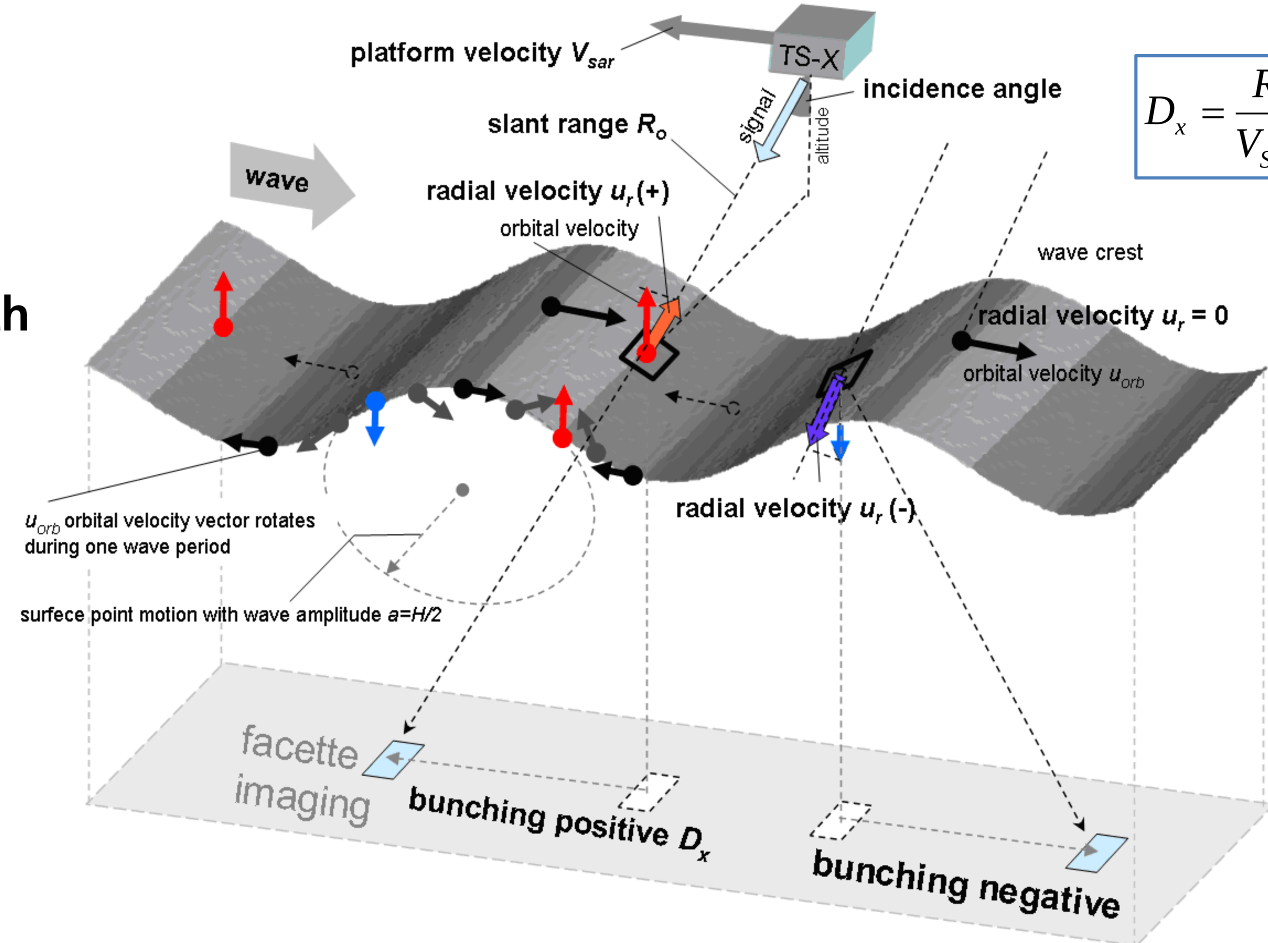
- SAR not designed for moving targets (Doppler shift used for location finding)
- Seastate derivation non-trivial (moving targets, **non-linear imaging**)

„Smearing“ of image

⇒ **cut-off wavelength**

$$D_x = \frac{R_o}{V_{SAR}} u_r$$



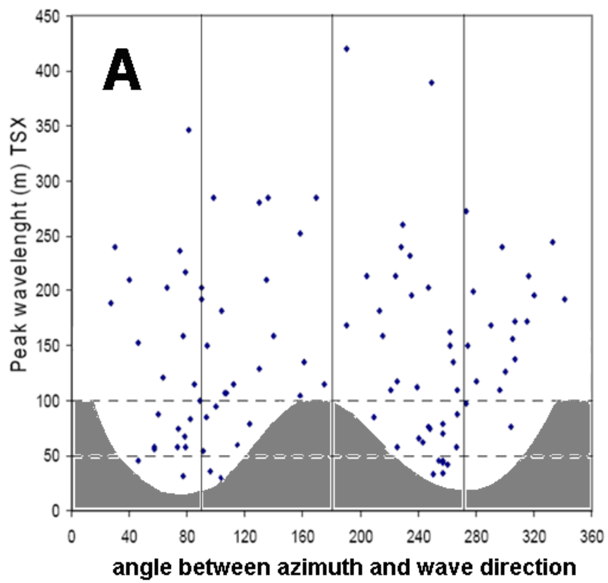

# Wave Imaging by Spaceborne SAR

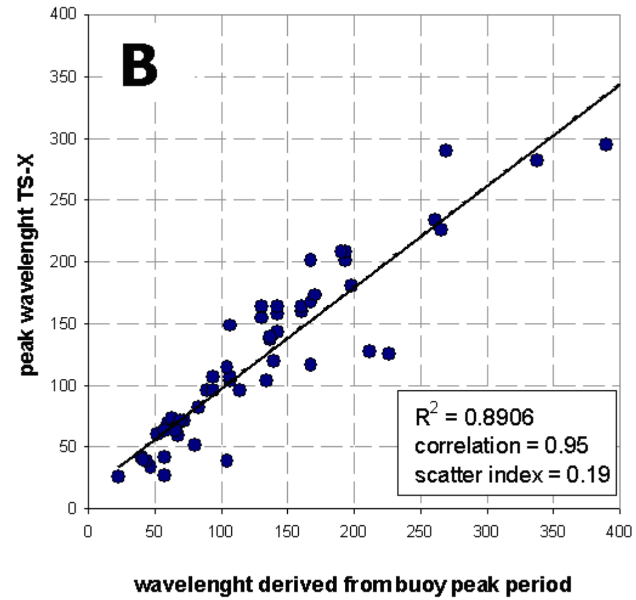
- Wave spectrum derivation cumbersome **=> Inverse calculation of imaging mechanism**
- Different Methods / Algorithms available (most of them C-Band: ERS, ENVISAT)

<u>TerraSAR-X</u>

- Low orbit (500km)
- Minor non-linear effects => Wave lenghts as short as 30m can be identified without running into azymuthal cut-off
- High resolution (up to 1m

TS-X characteristics favor analysis of coastal wave fields

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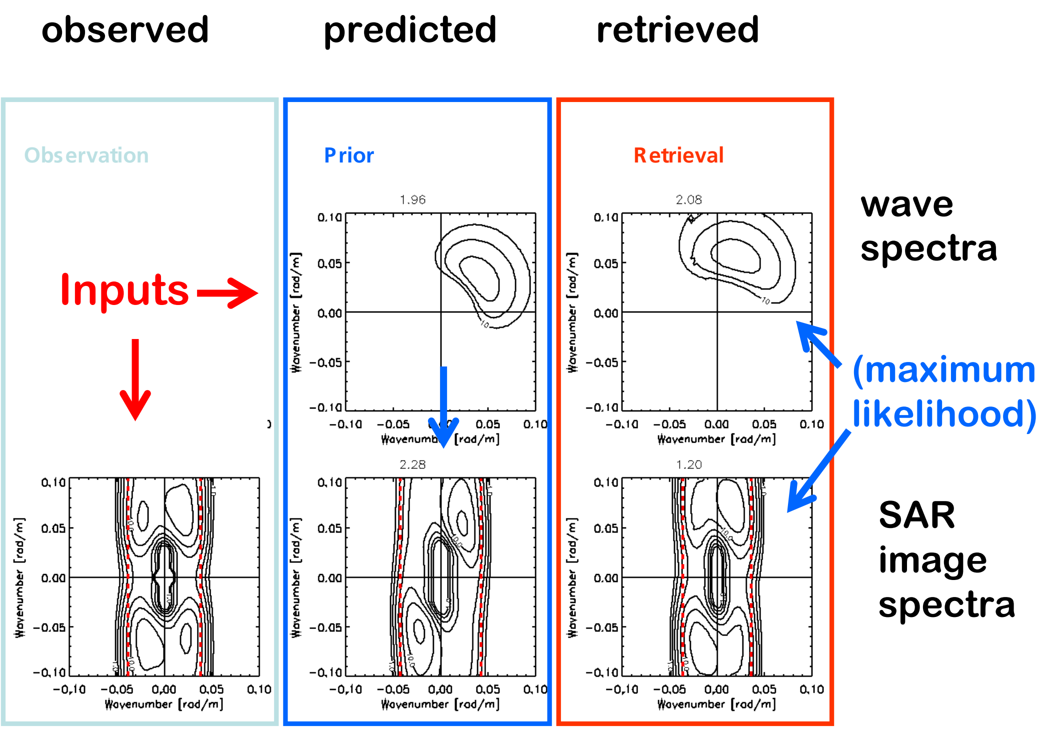
# SAR Ocean wave inversions - First generation

The original inversion method of Hasselmann and Hasselmann [1991] is based on a maximum likelihood matching of the first guess (prior) information available from a wave model and the data provided by the SAR wave image spectrum. From the first-guess wave spectrum, the forward transform is applied to first compute the associated SAR wave image spectrum. This will generally differ from the observed SAR wave image spectrum. One then constructs a maximum likelihood resultant wave spectrum and an associated SAR wave image spectrum by linearly combining the two (in general inconsistent) sets of information.



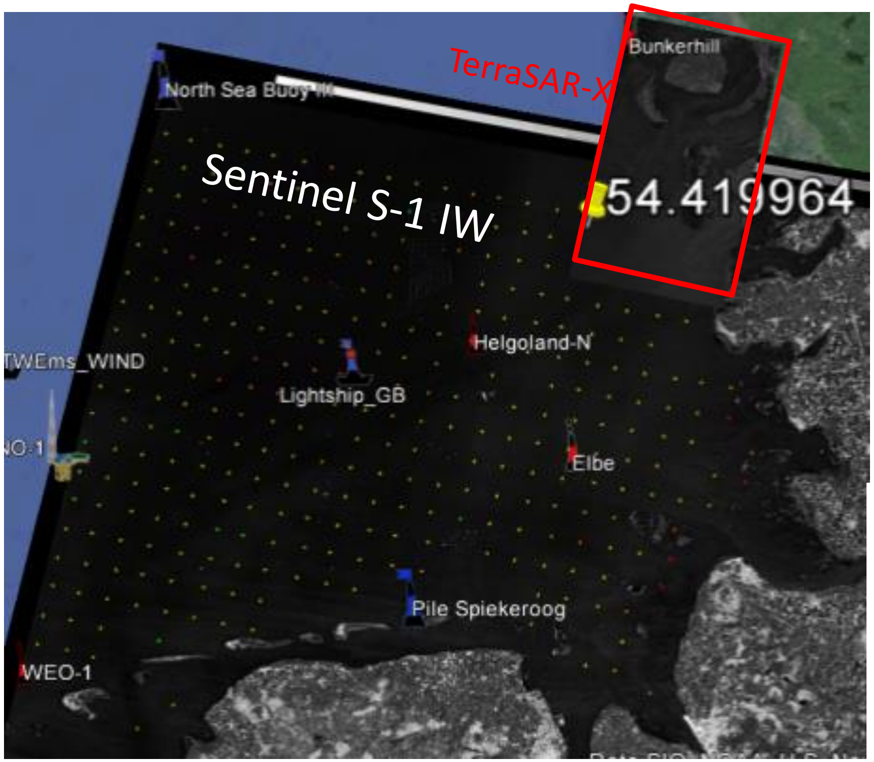

Contour plots of observed and computed 2d wavenumber spectra
(Courtesy by Klaus Hasselmann)

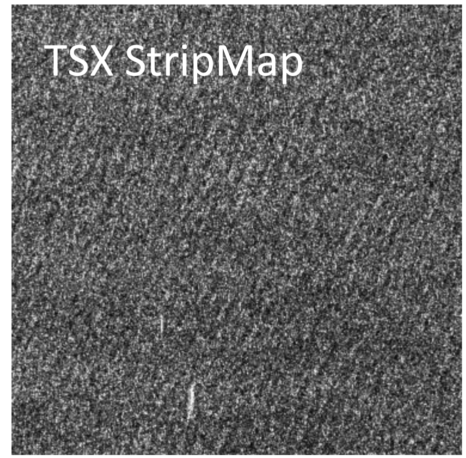
# Sea surface imaging by different sensors

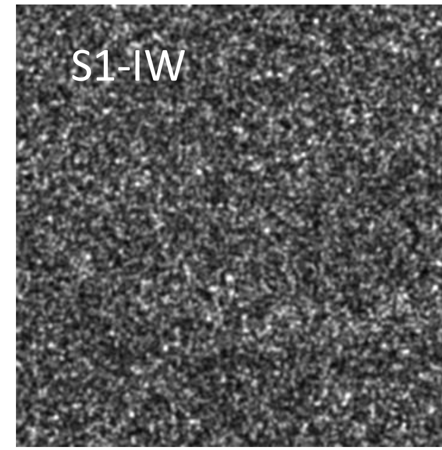
**SENTINEL S-1 IW VV 10m Pixel, C-band**

**TerraSAR-X StripMap VV 1.25m Pixel, X-band**

Subscenes – the same location

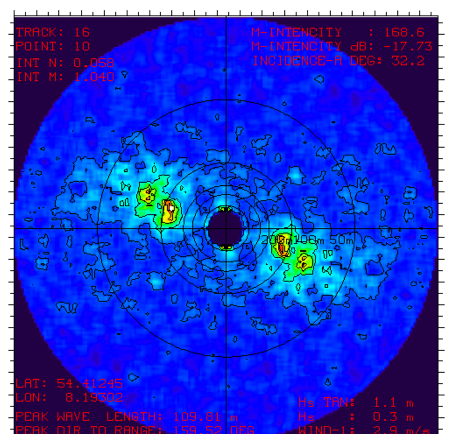


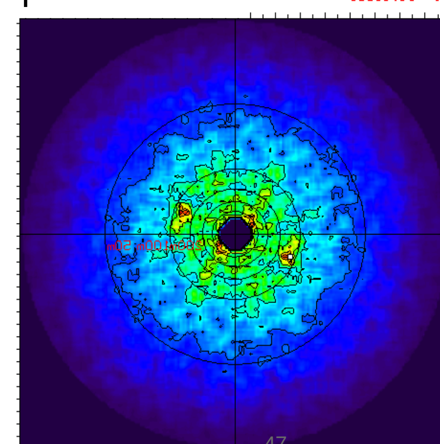




2D Image Spectrum (Non-Normalized,

Image Spectra



2015-06-12 05:41 S1

2015-06-12 05:51 TSX



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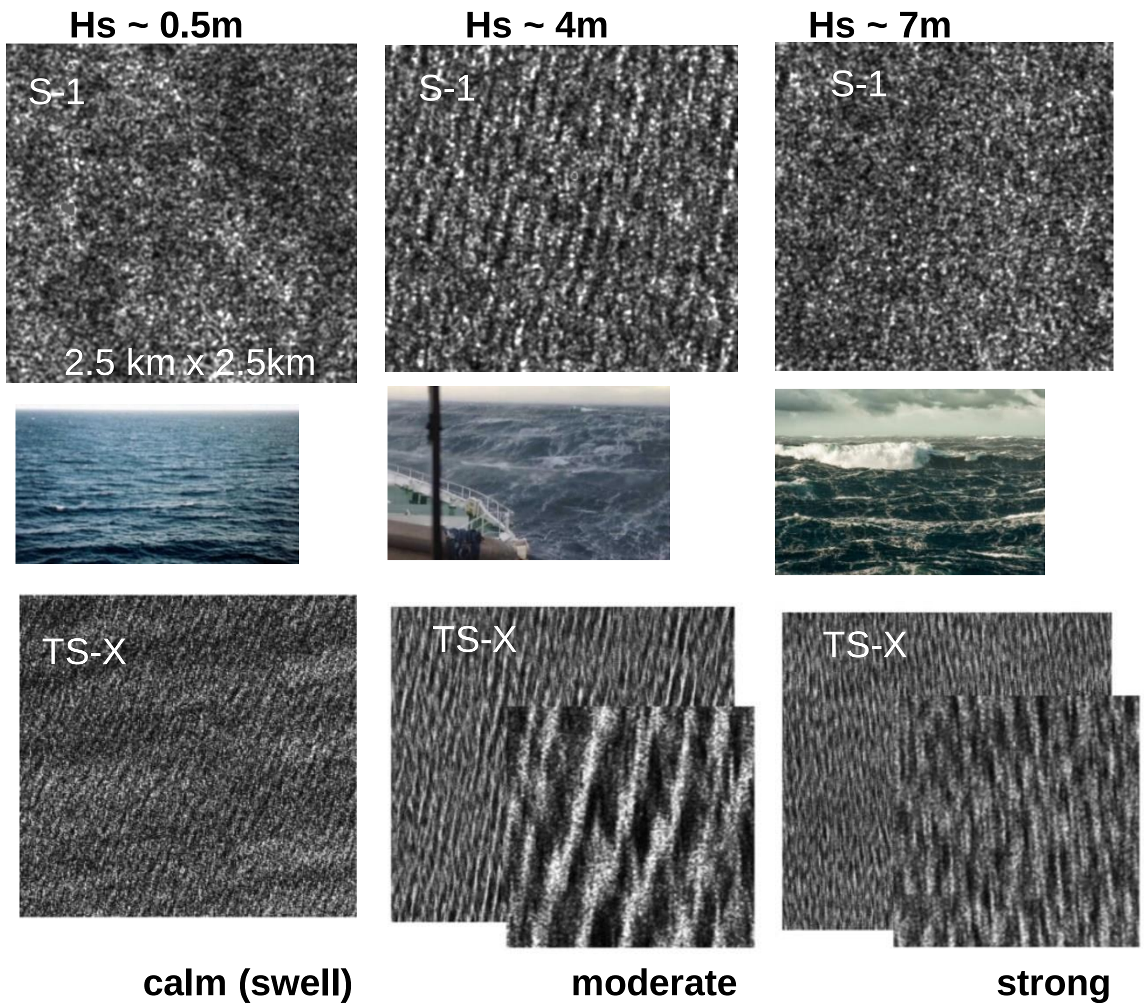
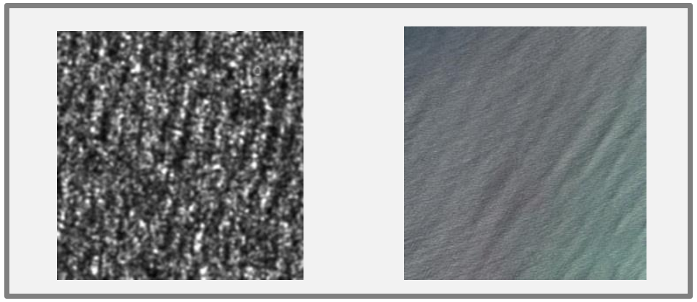
# Sea surface imaging by different sensors



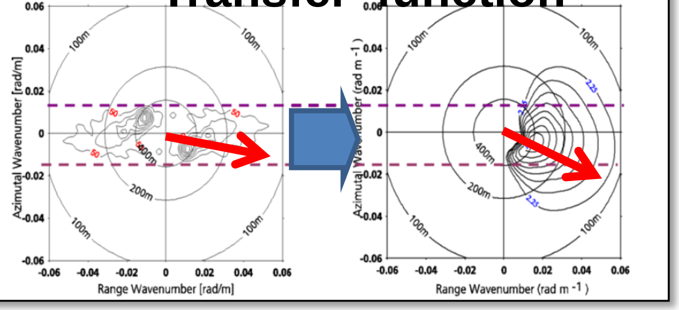

**SENTINEL S-1 IW VV 10m Pixel, C-band**

**TerraSAR-X StripMap VV 1.25m Pixel, X-band**

# SAR Ocean wave inversions - Two paradigms



Transfer function




SAR scene

SAR sub-scene

filtering

1. Wave spectrum reconstruction (transfer functions)

2. Empirical methods (usually linear regression)

Parameters

**Ground truth:**
- Hindcast models
- Measurements

# SAR Ocean wave inversions - Two paradigms

**Spetrum-inversion** using image spectra transformation

+ resulting wave spectrum can be directly used for assimilations into a forecast model
- Applicable only for scenes with well imaged swell (~80% in open ocean, ~20% in coastal areas)
- Takes relatively long time for iterations

**Empirical**

+ Applicable in 99% of all cases
+ Rapid calculations
- Full wave spectrum is not available

using linear regression (empiric 2- generation)

+ Analytical solution, tuning takes only time for singular vector decomposition (order of minutes)
+ resulting model: set of coefficients takes practically no space and can be read and applied quickly
+ Solution is stable already by ~20.000 training collocations.
+ Extension of training data set > linear increasing the time for coefficients estimation
- Accuracy is relatively high, but local results can not be improved – method "ignores outliers"

using machine learning (3- generation)

+ Accuracy can be significantly improved (~20% in comparison to linear regression)
+ Accuracy for local effects can be improved – method does not "ignore outliers"
- Larger data set needed - solution is stable by > ~200.000 training collocations
- Training time can take months, the resulting model can be ~GB and takes minutes to be read an applied

**Combinations**

e.g. DLR: Support Vector Machine (SVM)

DLR

# SAR Ocean wave inversions - Empirical Approach

## Linear regression method: CWAVE approach

**Analytical solution:** quadratic minimization using SVD (singular value decomposition) – optimal solution for a linear system

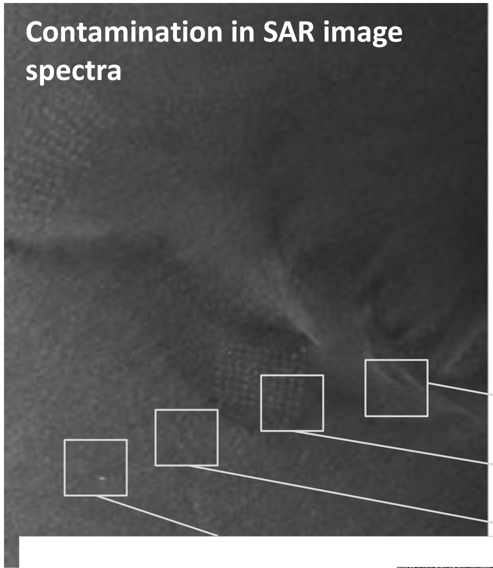
**Function:** linear regression

$$P_i = \sum_{n=0}^{N} A_n S_n + C$$

$P_i$ – sea state parameter to be estimated (wave height, periods, etc.)
$A_n$ – coefficient set (for each feature) to be tuned for the parameter
$S_n$ – SAR features estimated from SAR image (e.g. variance)

- **group 1** - Statistics: variance, skewness, kurtosis, etc.
- **group 2** – Geophysical: wind
- **group 3** – FFT > image spectrum, image spectrum energies
- **group 4** – GLCM: grey level co-occurrance Matrix
- **group 5** – Products of image spectrum with orthonormal functions

# Coastal applications: “contamination” impacts spectral analysis



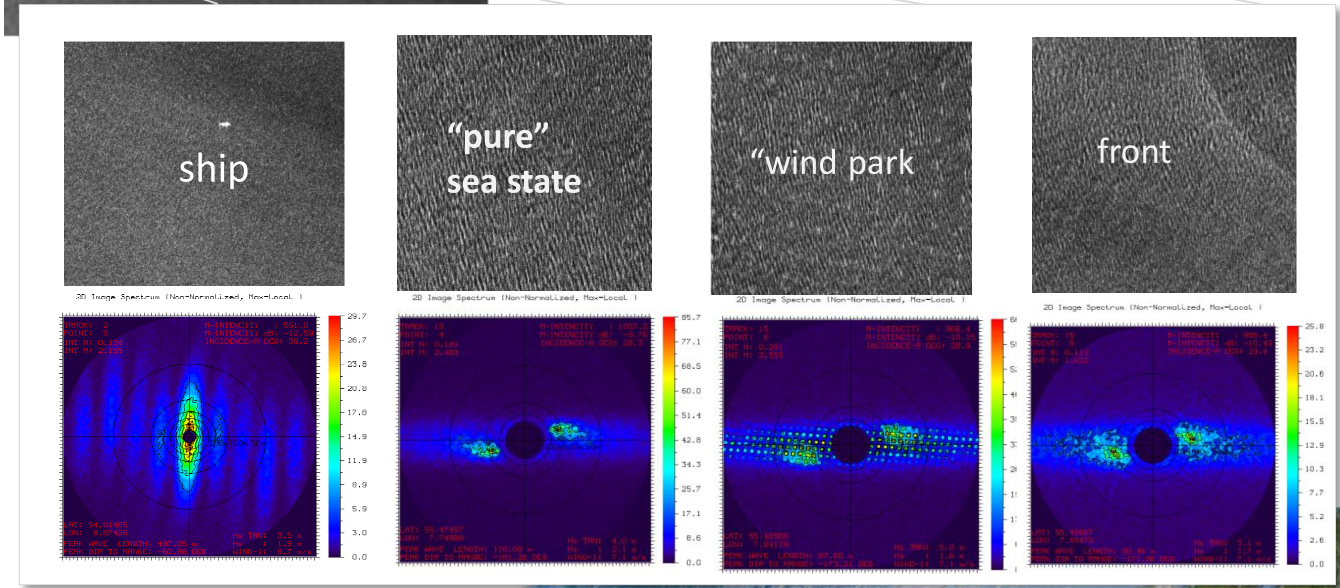

**Removing contaminations**

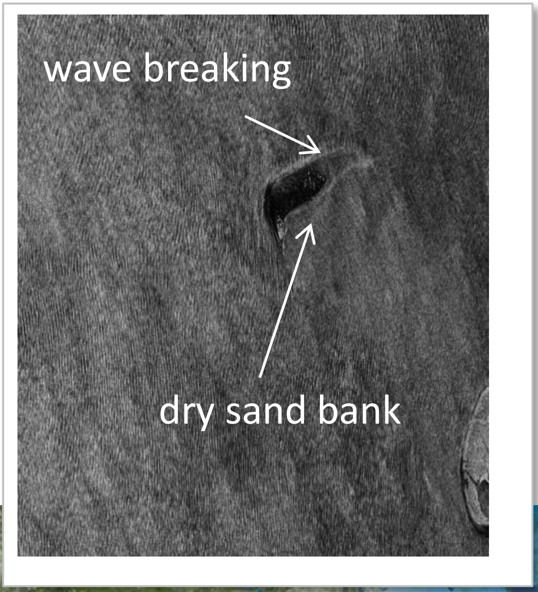
- Sand banks
- Wave breaking
- Ships, Buoys, Wind farms
- Current fronts, ship wakes

1. Before analysis
2. Function term
3. Results control

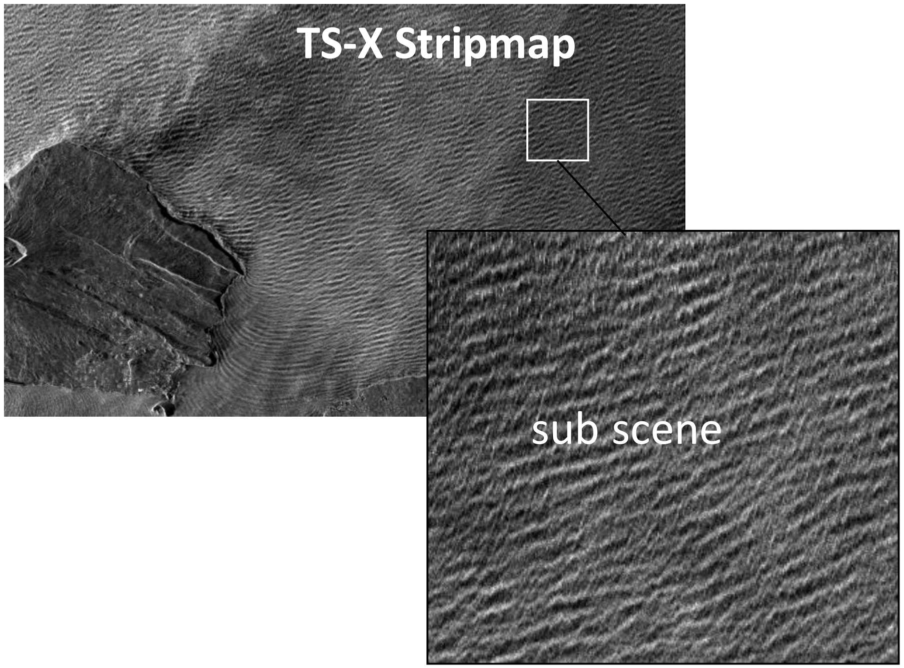
**GMF is applicable for “pure” sea state case only:**
**Pre-filtering of images is necessary for raster analysis**

Without pre-filtering Integrated energy and *Hs* can > 10 times overestimate real value



# XWAVE empirical algorithm: GMF principle and structure




$$m = \frac{I(i,j) - mean}{mean}$$

$$S = FFT(m)$$

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

signal intensity $I$

signal modulation $m$

image spectra $S$

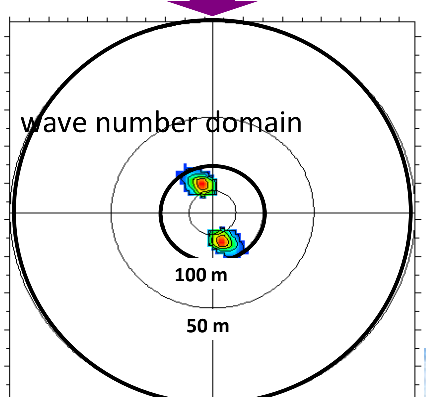
filtering, $L_{min}$, $L_{max}$

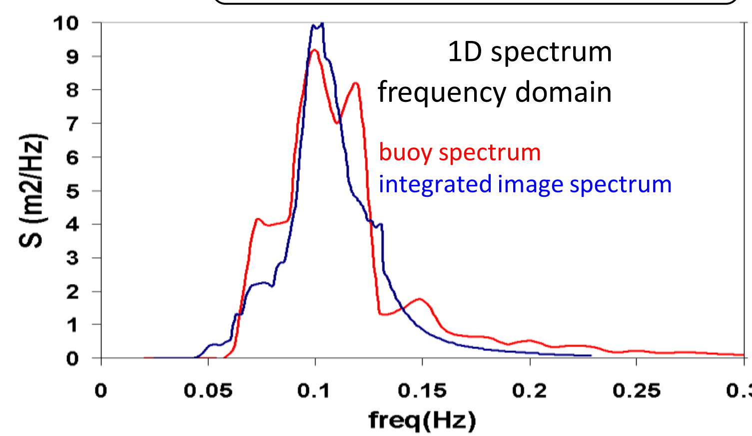
Local Wind (XMOD)

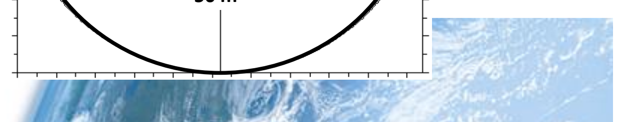
**XWAVE GMF function**

Parameters: $H_s$, $L_p$, $T_p$...

2D image spectrum



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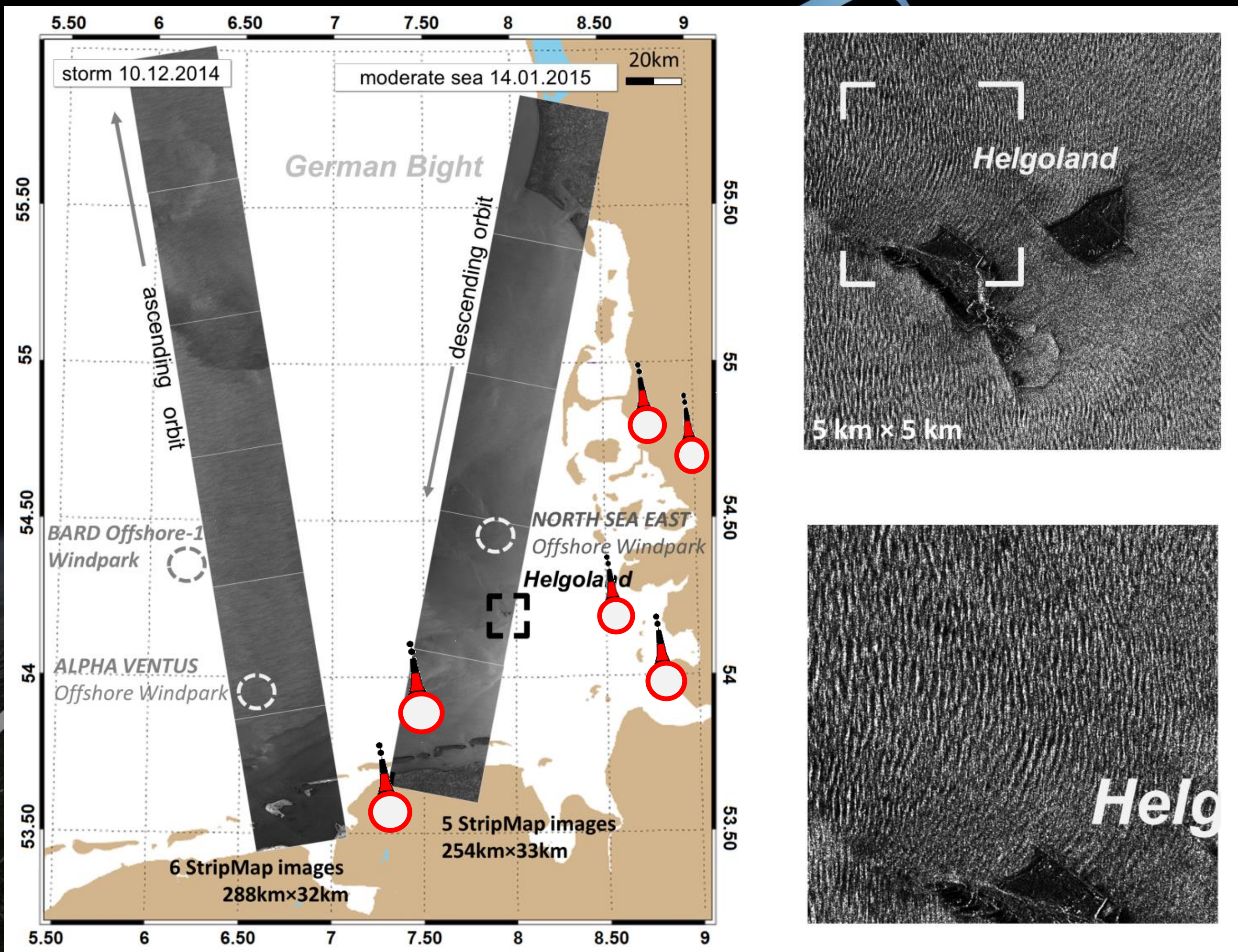
# Data for coastal function

Two typical TerraSAR-X overflights in German Bight




**Tuning**

**Step 1:** spatial, using model data to get "*idealized function*"

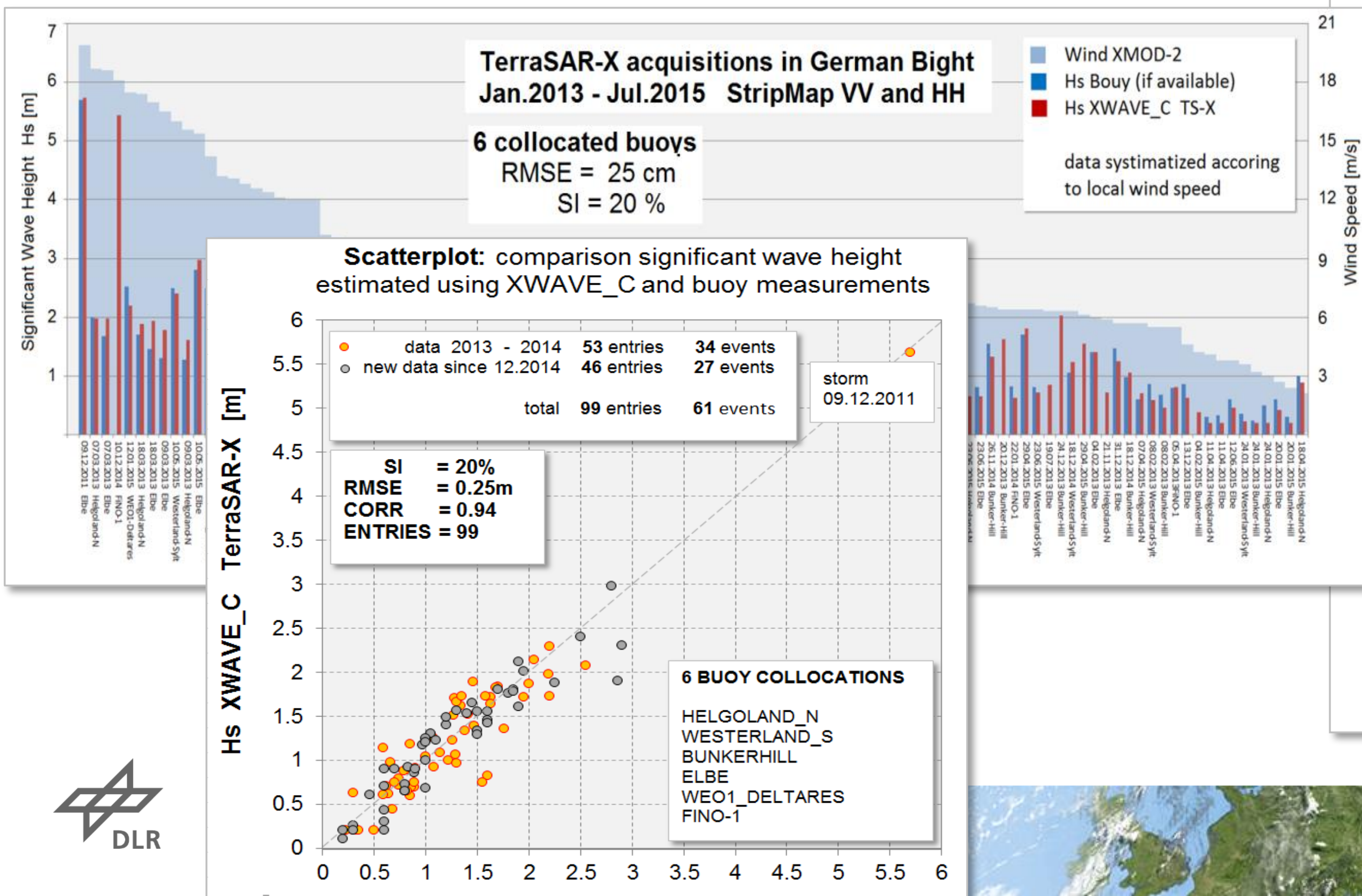
**Step 2:** collocated, buoy data to improve function coefficients

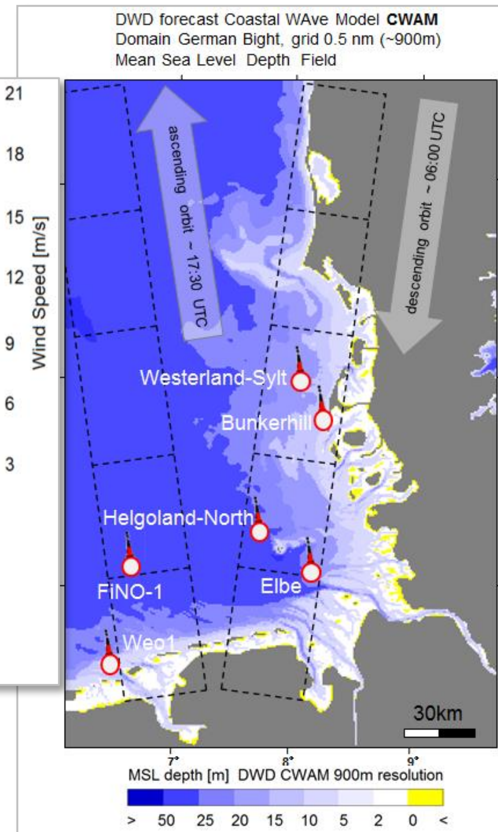
# Sea State processor (buoy comparisons): TerraSAR-X in DWD model domain results

**All TerraSAR-X collected acquisitions 01.2013-06.2015** over the German Bight.
Shown are the buoy locations
- 59 scenes, 196 images, 107 collocations, 81 comparison pairs with buoy measurements
- RMSE=25cm and SI=20%

sorted by local wind

6 Buoys in DWD model domain „German Bight“




# Latest S1 - Sea State Processor

1. **Satellites/modes:** S1-IW, S1-WV, S1-EW, TS-X SM(SL) - Tuning/Validation

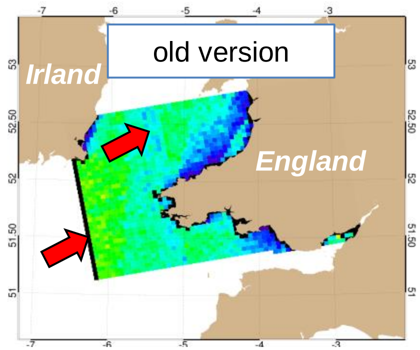
2. **Improvements:**
> Additional 7 parameters: wave periods, swell/windsea wave height
> **S1-IW** accuracy improved (SWH total RMSE=0.62 m against 0.95 m previous version)
> **S1-EW** added
> **TS-X SM** retuned/added

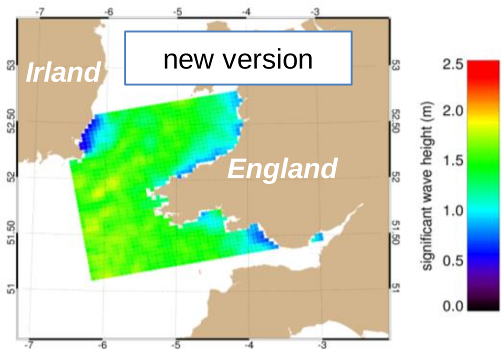
> Improved outlier filtering
> Smooth output fields due to SAR feature interpolation form 9 neighbor subscenes.
> Borders (black streaks) corrected.
> new KEY (FLAG) for results
> Parallelized processing for all modes
> New FFT > 30% processing acceleration

> Settings and configuration from xml-files.
> Special point's collocation can be defined by distance given from setting file.

**> S1 WV: For *ESA CCI Seastate* Project reprocessing whole S1-WV archive (since 2014-10)**
**(1 month ~ 1800 products each 4-15 GB)**

S1 IW 2018-11-02 18:05 UTC



# Sea State Processor Accuracy

**Sea State Processor = (filtering + feature's extraction + model functions + control results) > SAINT**

Products processed, output and RMSE for all sea state conditions all parameters

**Comparison with CMEMS Model data**

| Sea State Parameter | Description | S1 WV | S1 IW | S1 EW | TS-X SM / SL |
|---|---|---|---|---|---|
| | **Products used >** | SLC | GRDH | GRDM | MGD RE/SE |
| | **Kind output >** | Along track (imagettes 20km×20km each 100 km) | Sea state fields (raster) | Sea state fields (raster) | Sea state fields (raster) |
| **SWH (m)** | **Total significant wave height** | **0.35** | **0.62** | **0.64** | **0.36** |
| **$T_{m0}$ (s)** | Mean wave period | 0.62 | 0.96 | 0.86 | 0.72 |
| **$T_{m1}$ (s)** | First moment period | 0.52 | 0.97 | 0.85 | 0.59 |
| **$T_{m2}$ (s)** | Second moment period | 0.45 | 0.82 | 0.86 | 0.51 |
| | | | | | |
| **SW1 (m)** | Dominant swell wave height | 0.46 | 0.68 | 0.63 | 0.33 |
| **SW2 (m)** | Secondary swell wave height | 0.35 | 0.38 | 0.44 | 0.27 |
| **SWW (m)** | Windsea wave height | 0.41 | 0.77 | 0.66 | 0.37 |
| **$T_{mw}$ (s)** | Windsea wave period | 0.62 | 0.97 | 0.95 | 0.71 |

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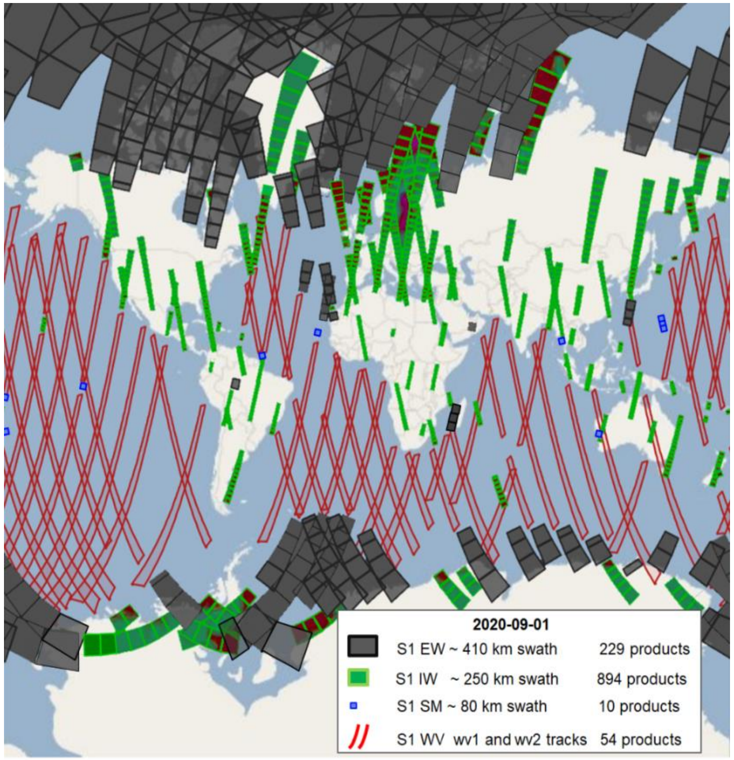
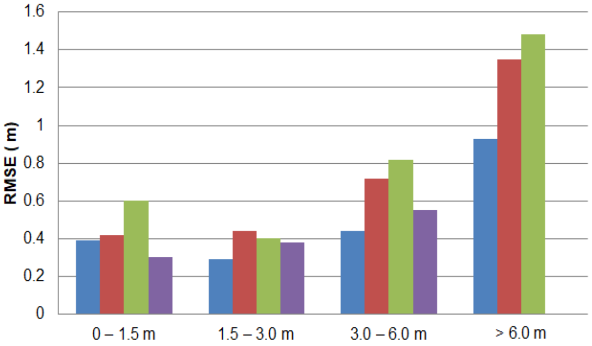
# New Sea State Processor:
# Wave height accuracy distribution

**Sentinel-1 acquisitions during one day**




**Wave height SWH RMSE (m) distribution for different sea state conditions**




S1 WV ~ 4 m/pixel -ocean
S1 IW 10 m/pixel -coast
S1 EW 40 m/pixel -ocean

TS-X SM 2.5-4.5 m/pixel -coast

| | SWH RMSE for sea state categories | | | |
|---|---|---|---|---|
| | 0 – 1.5 m | 1.5 – 3.0 m | 3.0 – 6.0 m | > 6.0 m |
| **S1 WV** | 0.39 (11%) | 0.29 (61%) | 0.44 (24%) | 0.93 (2%) |
| **S1 IW** | 0.42 (27%) | 0.44 (36%) | 0.72 (29%) | 1.35 (7%) |
| **S1 EW** | 0.60 (10%) | 0.40 (54%) | 0.82 (32%) | 1.48 (4%) |
| **TS-X SM** | 0.30 (60%) | 0.38 (33%) | 0.55 (6%) | - (0 %) |

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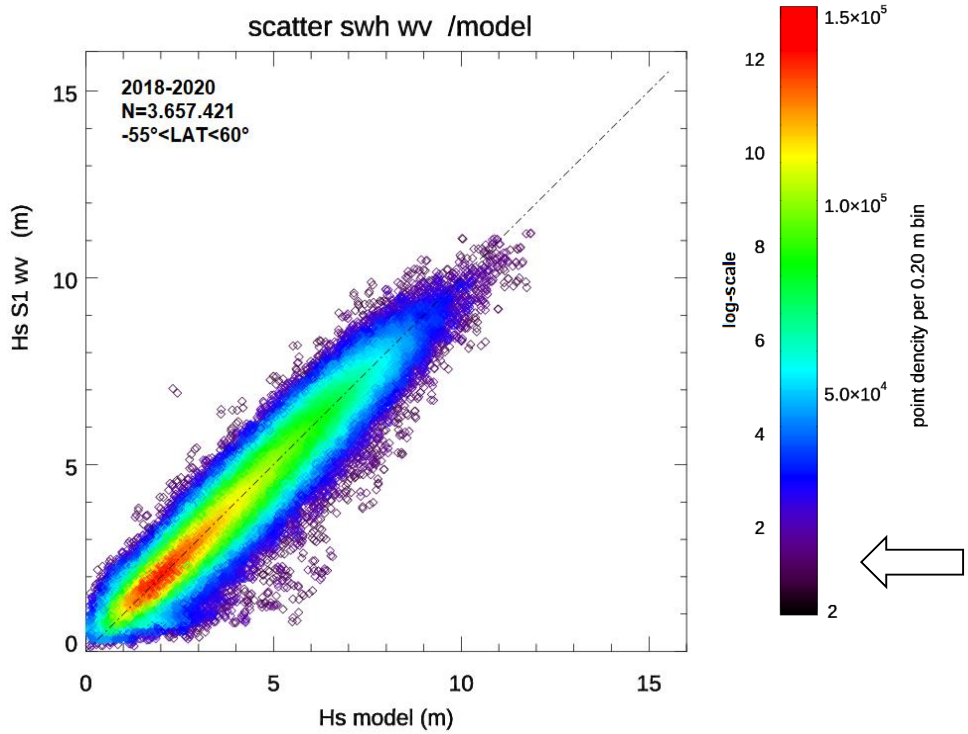
# New Sea State Processor: Wave height validation with CMEMS for S1 Wave Mode (wv)

**SAR Sentinel-1 Wave Mode**
**2018-2020 Validation with CMEMS**

**3.5 Mio collocations, complete archive 2018-2020**
RMSE wv1=0.245 m
RMSE wv2=0.273 m

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# New Sea State Processor: Wave height validation (independent/ 3rd party)

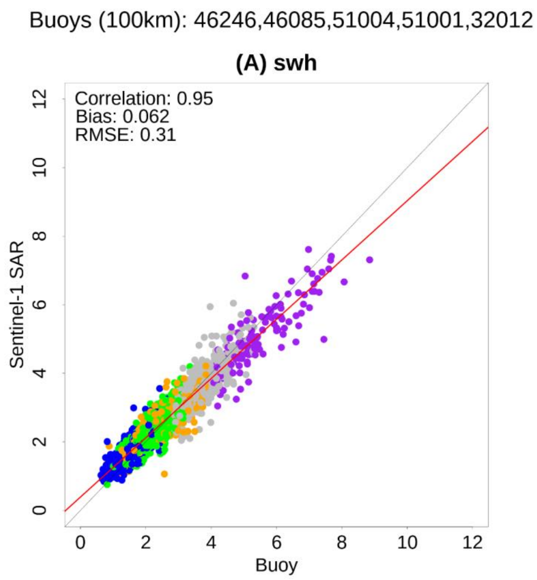


Figure 12 : Scatter plot of Sentinel-1 SAR observations of Hs at NDBC wave buoy stations in the North Pacific.

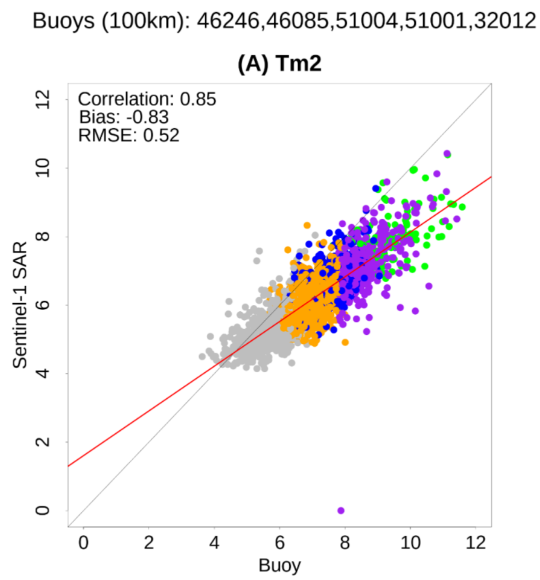


Figure 14 : Scatter plot of Sentinel-1 SAR observations of Tm2 at NDBC wave buoy stations in the North Pacific.

CCI Sea State Product Validation and Intercomparison Report (PVIR)

Author: Ben Timmermans ben.timmermans@gmail.com
National Oceanography Centre, UK, Marine Physics and Ocean Climate

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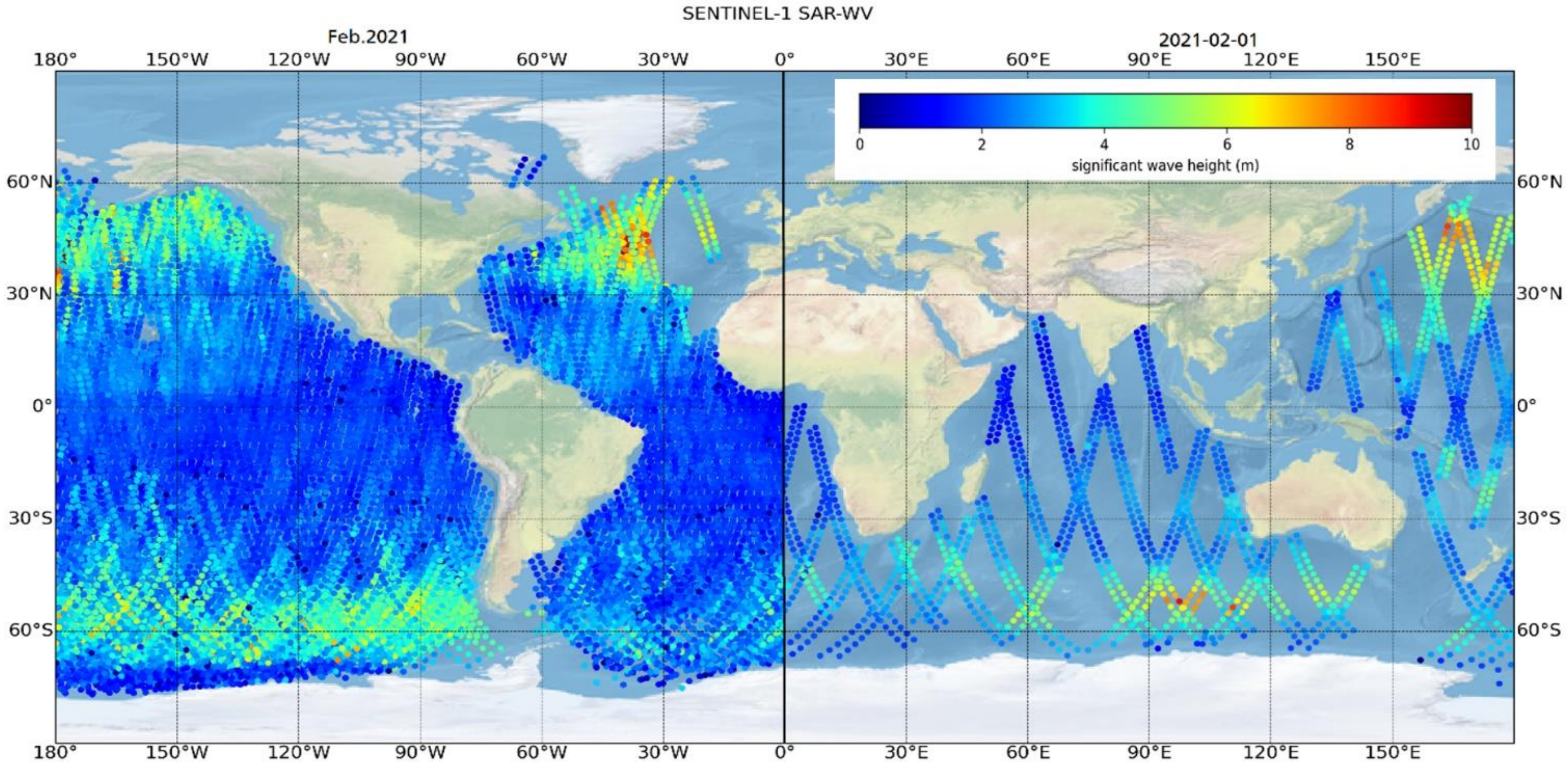
# New Sea State Processor:
# Wave height example for global processing




Examle of Sentinel-1 Wave Mode WV archive processing. On the right half of the globe only one-day acquisitions are displayed, on the left half all data acquired during February 2021

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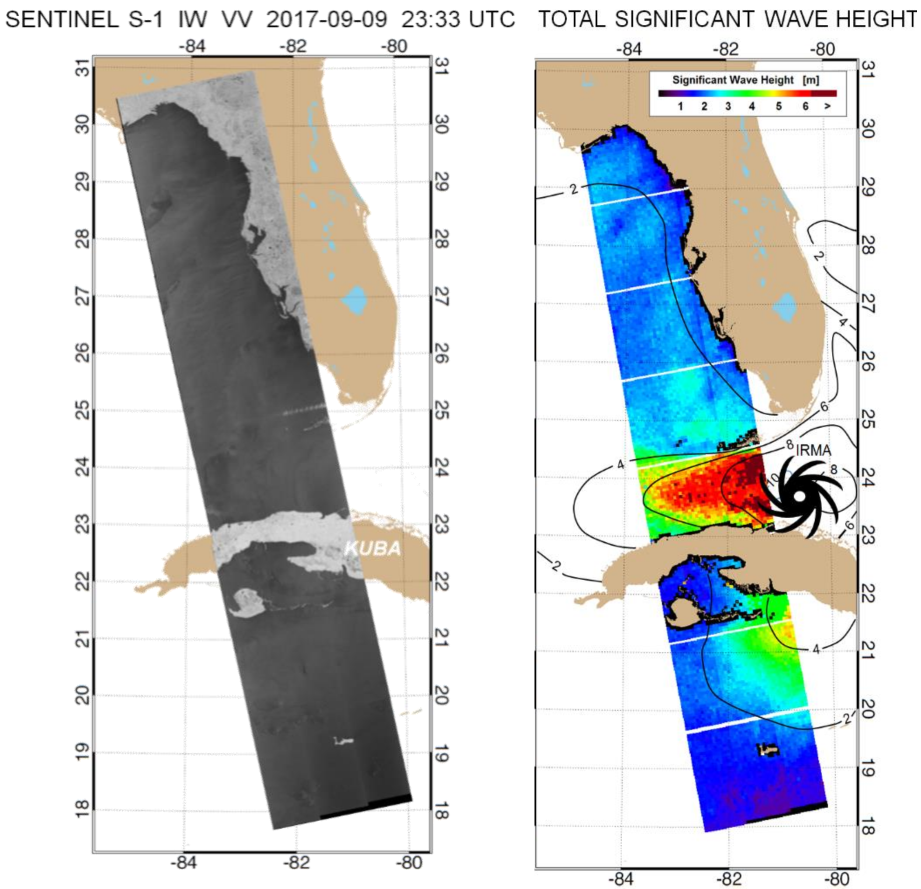
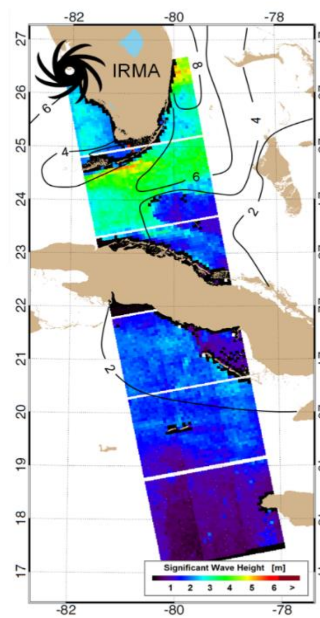
# Examples for Sea State Measurements

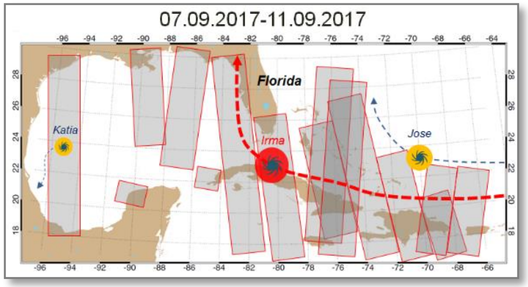
## Hurricane „Irma“ 2017 (S-1 IW), Florida coast

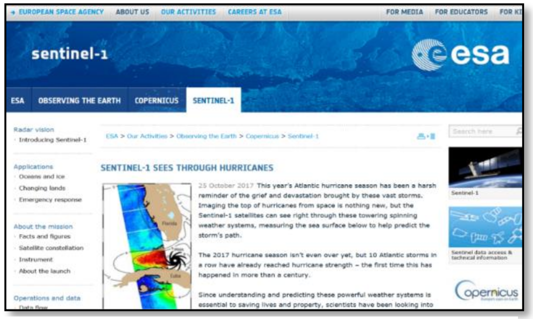



new techniques and algorithms allow observation and validation of forecast models worldwide

2017-09-10 23:25 UTC




**ESA news:**
**Sentinel-1 sees through hurricanes**

“… information about the sea state can help to assess how destructive a hurricane is and can predict its path respectively time and location on which it will make landfall ….”

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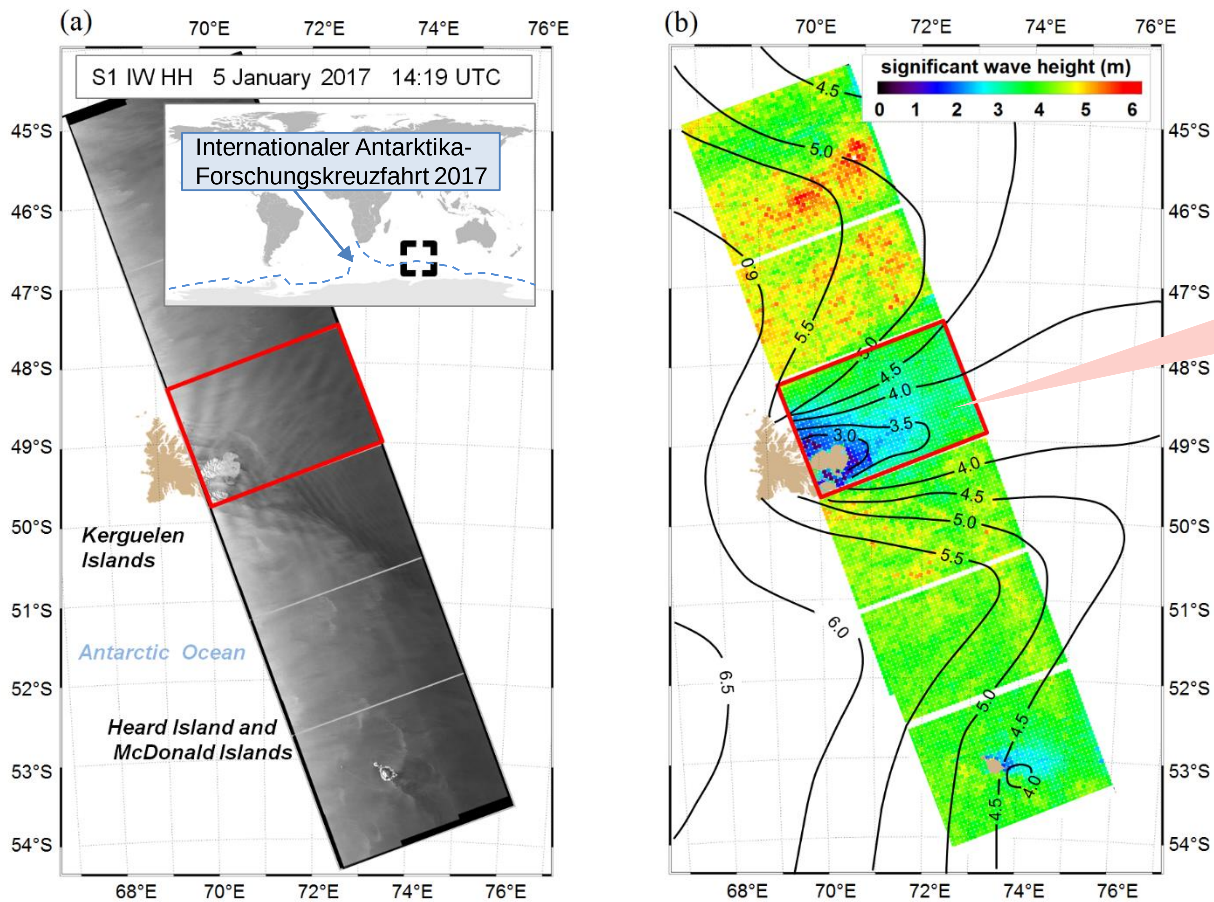
# Examples for Sea State Measurements

## Arctic Sea, S1 IW, route optimization support




**Arctic Sea, 05.01.2017**
route optimization

Procced in NRT,
Sent to
Research vessel
“Akademik Treshnikov”

# Examples for Sea State Measurements

## Black Sea, fast moved storm

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

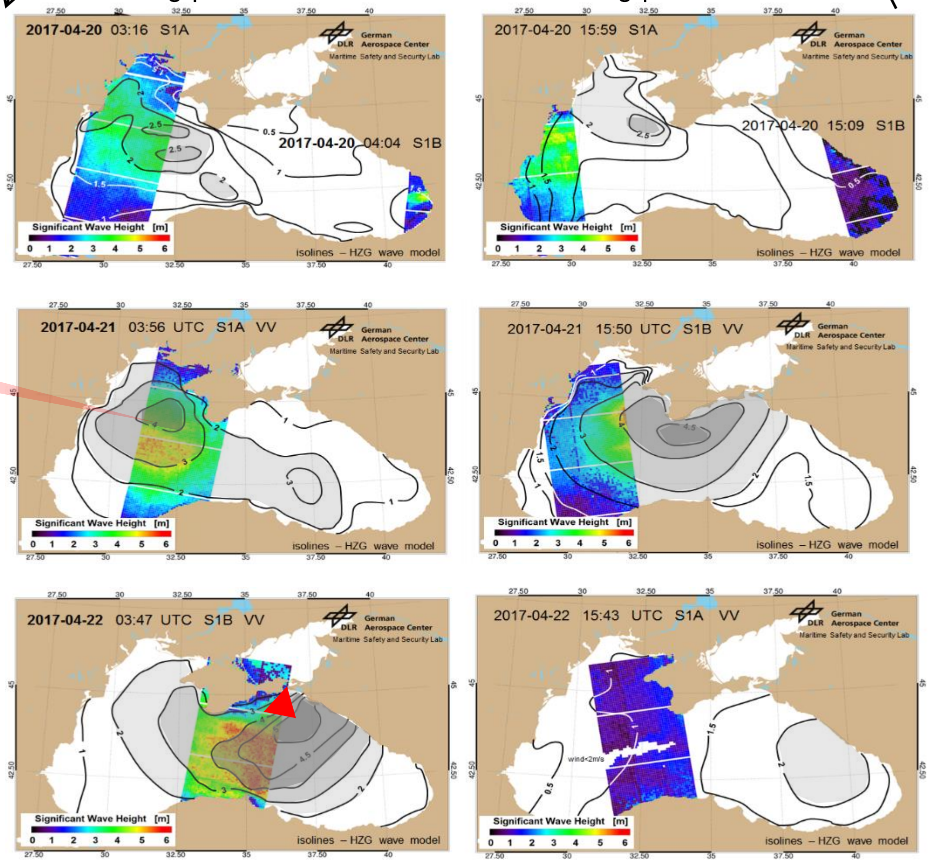
descending path ~03:00 UTC ascending path ~16:00 UTC

2017-04-20

Sturm Peak Modell
~90 km northerly

2017-04-21

2017-04-22

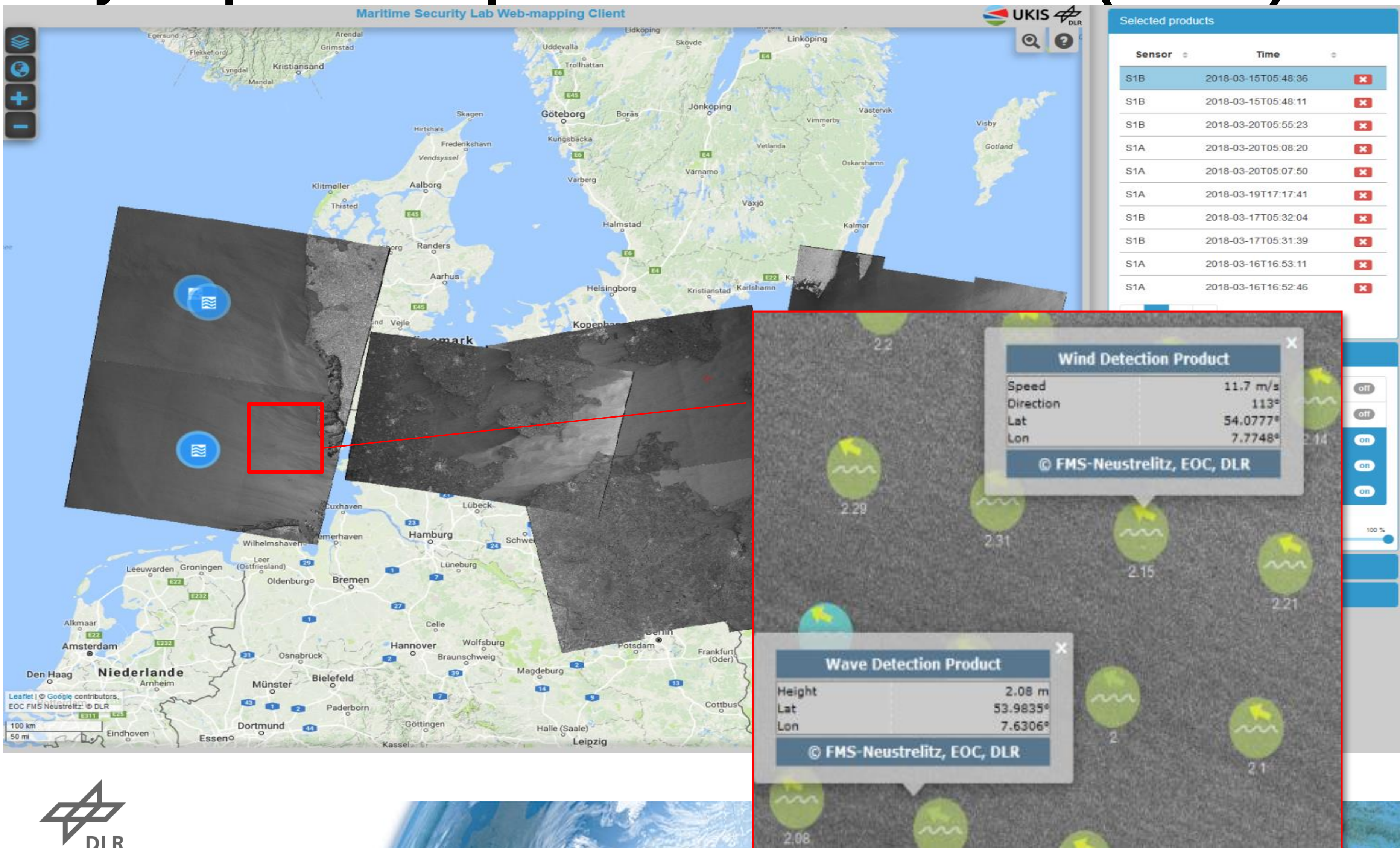



114-m long cargo vessel with 12 crew sinks

Raging Black Sea storm
splits cargo ship in half

# Examples for Sea State Measurements

## Daily acquisitions processed NRT online (S1-IW)



# I want to thank …

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