SHIP WAKE DETECTABILITY IN TERRASAR-X IMAGERY – SUMMARY AND APPLICATIONS FOR WAKE DETECTION

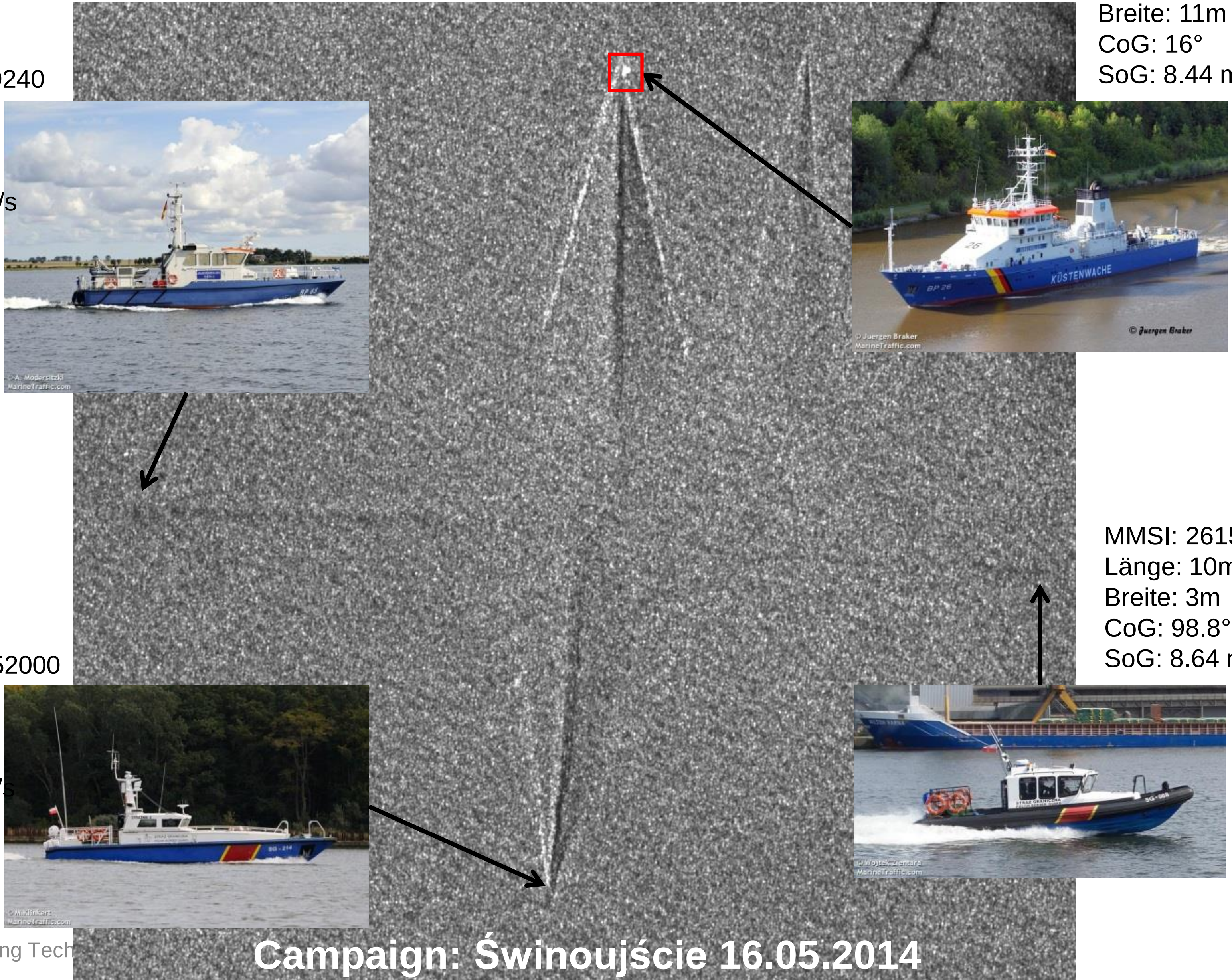
TerraSAR-X / TanDEM-X Science Team Meeting 2023

Björn Tings, DLR – Remote Sensing Technology Institute, 19.10.2023

Detectability of wakes

MMSI: 211404810
Länge: 66m
Breite: 11m
CoG: 16°
SoG: 8.44 m/s

MMSI: 211179240
Länge: 22m
Breite: 6m
CoG: 284.3°
SoG: 10.24 m/s

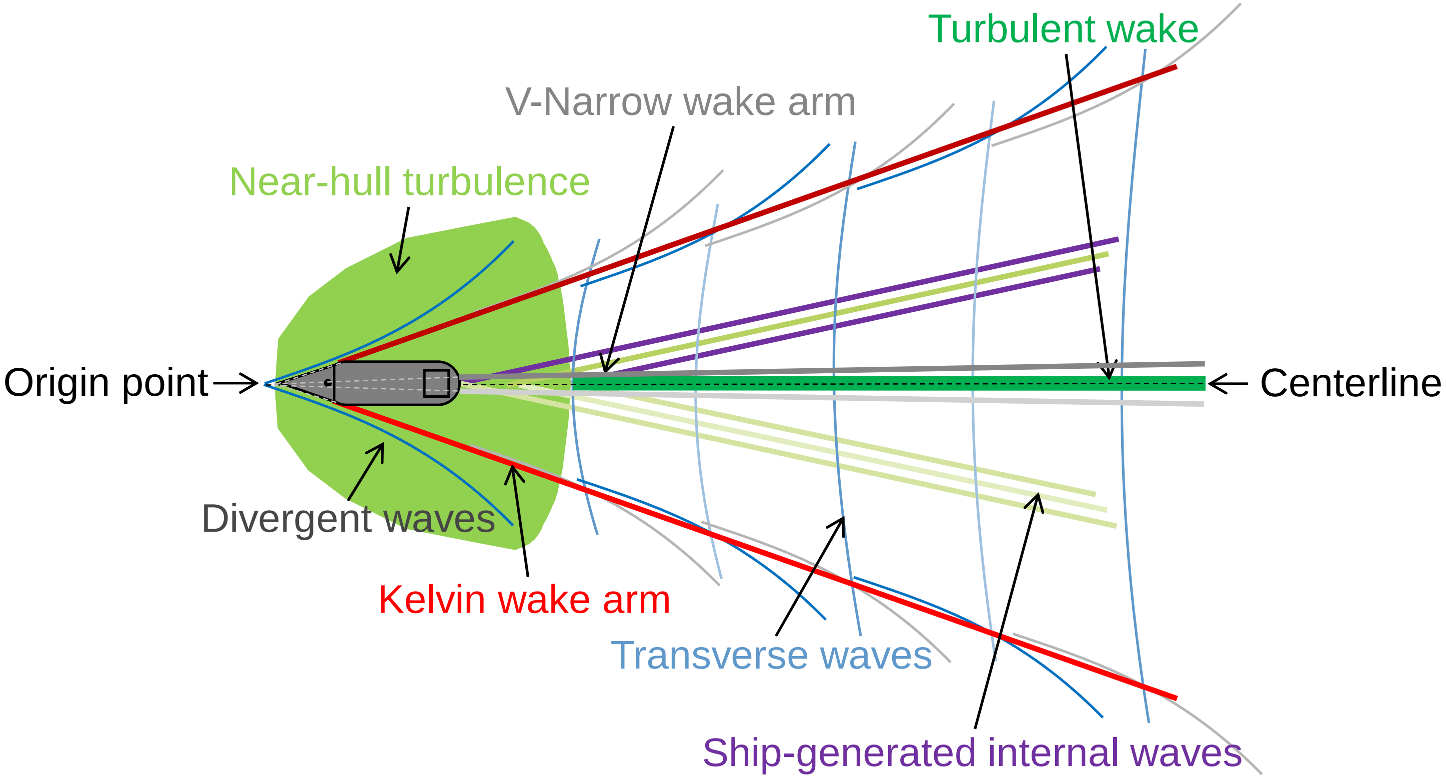


MMSI: 261520000
Länge: 10m
Breite: 3m
CoG: 98.8°
SoG: 8.64 m/s

MMSI: 261352000
Länge: 16m
Breite: 4m
CoG: 194.8°
SoG: 9.04 m/s

Campaign: Świnoujście 16.05.2014

Wake components in SAR



Wake detectability modelling
Wake component dataset

- ~3000 TerraSAR-X wake samples in the dataset
- Vessel information retrieved from AIS
- Wake components manually retraced

- Proportion of main wake components in the used dataset:

Wake component	Proportion (rounded to integer)
Near-hull turbulence (nt)	59%
Turbulent wake (tw)	61%
Kelvin wake arm (kw)	21%
V-narrow wake arm (vw)	27%

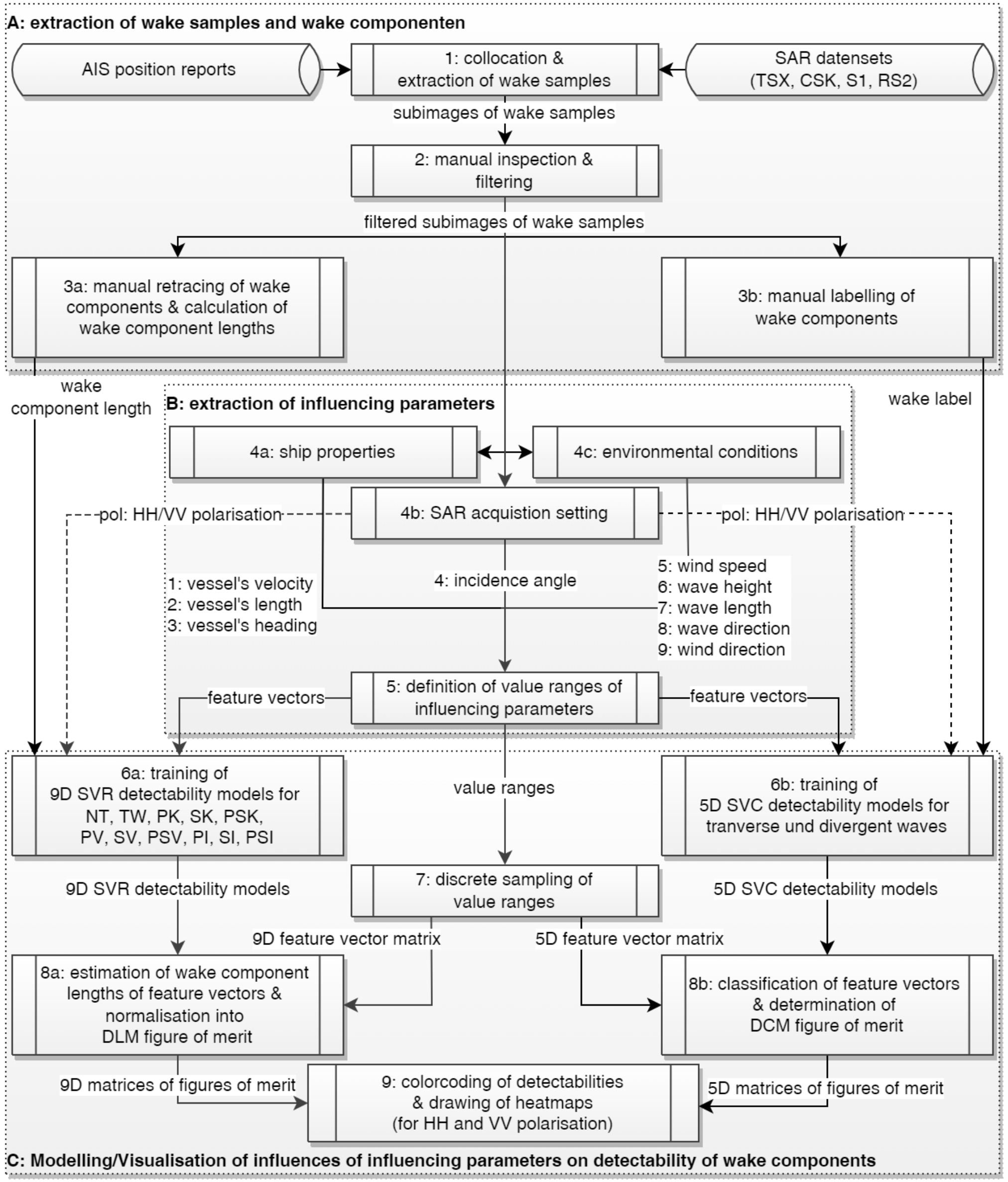
Wake detectability modelling
Influencing parameters

- Nine Influencing parameters affecting the detectability:

Symbol with index x_i	**Influencing Parameter Name**	**Description**
x_1	AIS-Vessel-Velocity	Velocity of the vessel derived from AIS messages interpolated to the image acquisition time
x_2	SAR-Wind-Speed	Wind speed estimated from the SAR background around the vessel using the CMOD-5h or XMOD-2 geophysical model function
x_3	Incidence-Angle	Incidence angle of the radar cropped full performance value range
x_4	AIS-Length	Length of the corresponding vessel based on AIS information
x_5	AIS-CoG	The course over ground based on AIS information relative to the radar looking direction (0° means parallel to range and 90° mean parallel to Azimuth).
x_6	SAR-Significant-Wave-Height	Significant wave height estimated from the SAR background around the vessel using the SAR-SeaStaR algorithm
x_7	SAR-Significant-Wave-Length	Wave length estimated from the SAR background around the vessel using the SAR-SeaStaR algorithm
x_8	AIS-CoG-SAR-Wave-Direction	Absolute angular difference between AIS-CoG and wave direction estimated from the SAR background around the vessel using the SAR-SeaStaR algorithm
x_9	AIS-CoG-WRF-Wind-Direction	Absolute angular difference between AIS-CoG and wind direction estimated by the Weather Research and Forecasting Model (WRF) nearby the vessel.

Wake detectability modelling
Procedure for analysis of detectability

- Localizing moving vessels by AIS data collocated with SAR images
- Filtering of SAR-artifacts not related to ship movements
- Manual inspection
- Extracting influencing parameters
- Modelling of detectability
- Estimation of uncertainty
- Plotting and Interpretation



A: extraction of wake samples and wake componenten

AIS position reports

1: collocation & extraction of wake samples

SAR datensets (TSX, CSK, S1, RS2)

subimages of wake samples

2: manual inspection & filtering

filtered subimages of wake samples

3a: manual retracing of wake components & calculation of wake component lengths

3b: manual labelling of wake components

wake component length

wake label

B: extraction of influencing parameters

4a: ship properties

4c: environmental conditions

4b: SAR acquistion setting

pol: HH/VV polarisation

pol: HH/VV polarisation

1: vessel's velocity
2: vessel's length
3: vessel's heading

4: incidence angle

5: wind speed
6: wave height
7: wave length
8: wave direction
9: wind direction

5: definition of value ranges of influencing parameters

feature vectors

feature vectors

value ranges

6a: training of 9D SVR detectability models for NT, TW, PK, SK, PSK, PV, SV, PSV, PI, SI, PSI

6b: training of 5D SVC detectability models for tranverse und divergent waves

9D SVR detectability models

7: discrete sampling of value ranges

5D SVC detectability models

9D feature vector matrix

5D feature vector matrix

8a: estimation of wake component lengths of feature vectors & normalisation into DLM figure of merit

8b: classification of feature vectors & determination of DCM figure of merit

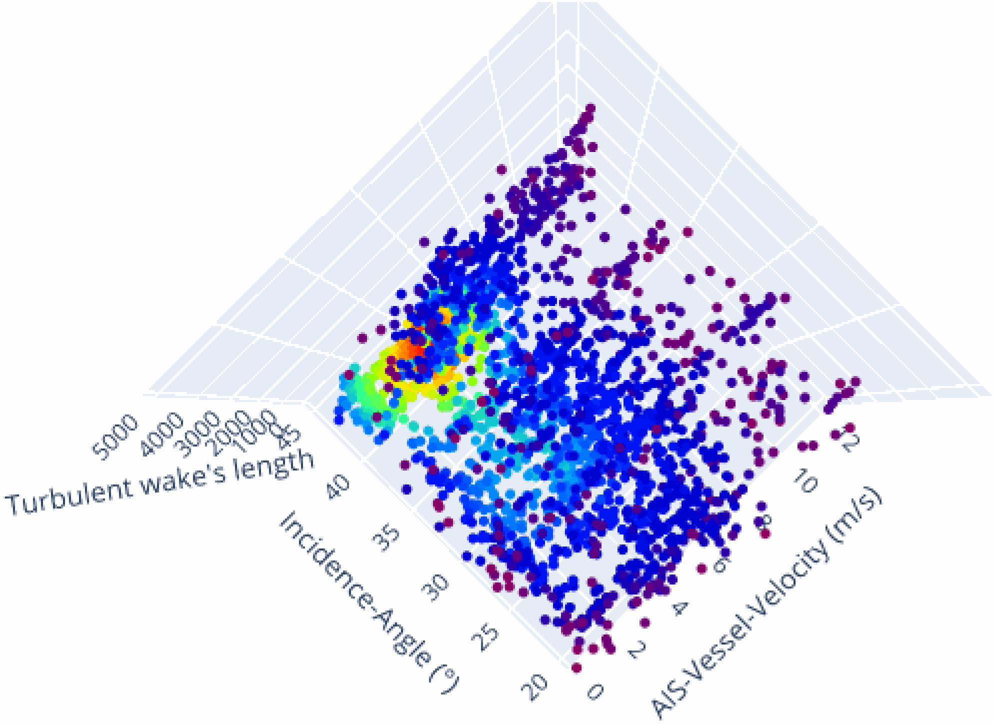
9D matrices of figures of merit

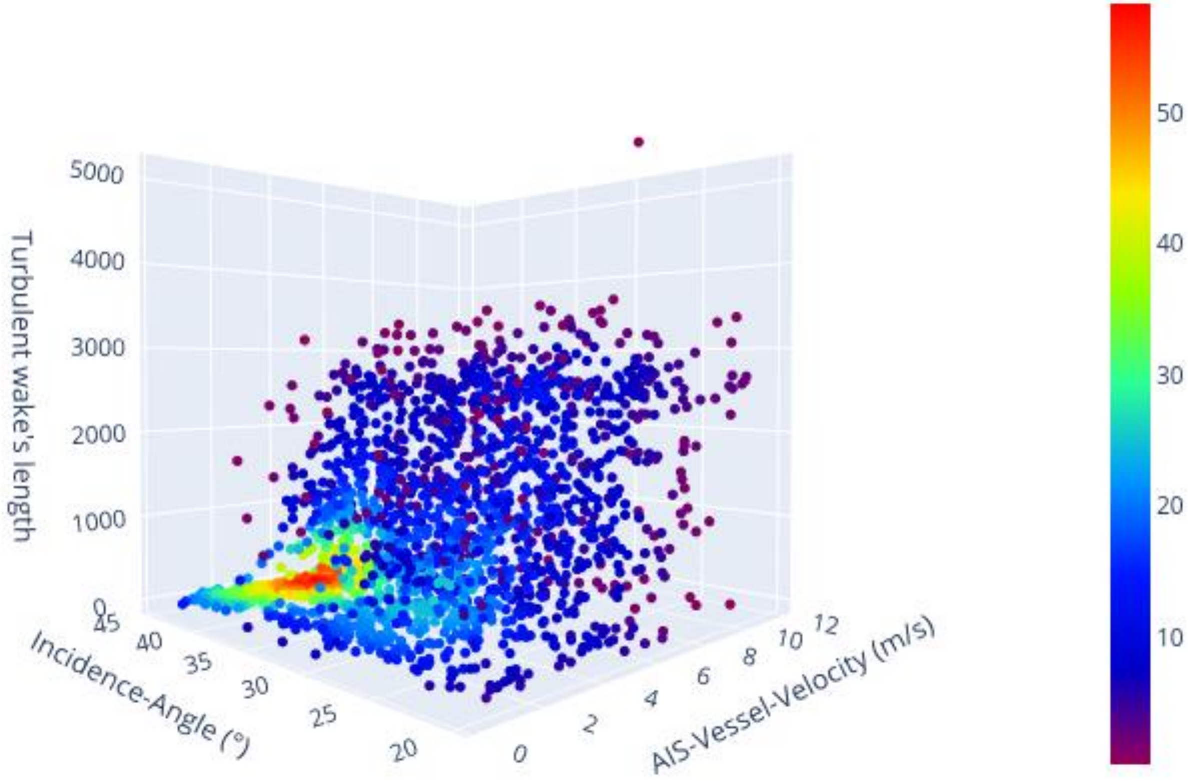
9: colorcoding of detectabilities & drawing of heatmaps (for HH and VV polarisation)

5D matrices of figures of merit

C: Modelling/Visualisation of influences of influencing parameters on detectability of wake components

Wake detectability modelling
Visualization of feature space





Wake detectability modelling
Modelling the wake component detectability

- Wake component length l_w is used as indicator for wake component detectability
- Training a Support Vector Regression model f_w for mapping wake component length l_w to the influencing parameters x_i:

$l_w = f_w(X^{9D})$, with $X^{9D} = \{x_1; x_2; x_3; x_4; x_5; x_6; x_7; x_8; x_9\}$ and w denotes wake component

- Detectable Length Metric (DLM, figure of merit for detectability) is calculated by normalizing l_w linearly between a minimum and maximum boundary:

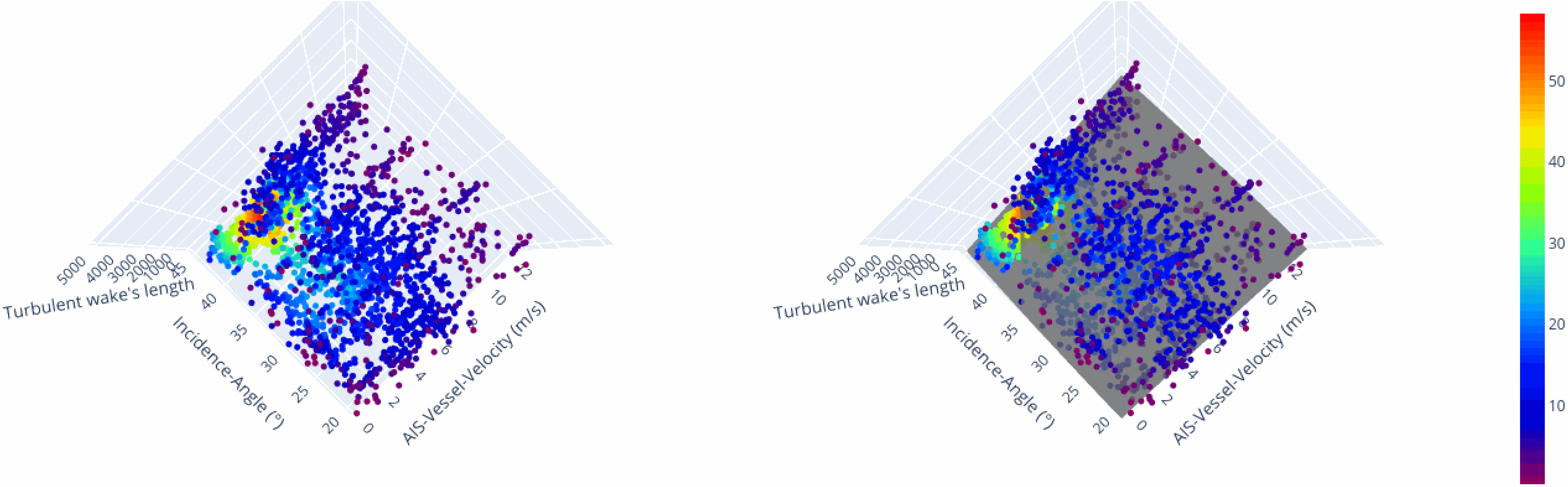
$$DLM_w = g_w(l_w) = \frac{l_w - l_w^{min}}{\left|l_w^{max} - l_w^{min}\right|},$$

hyperparameter settings are:

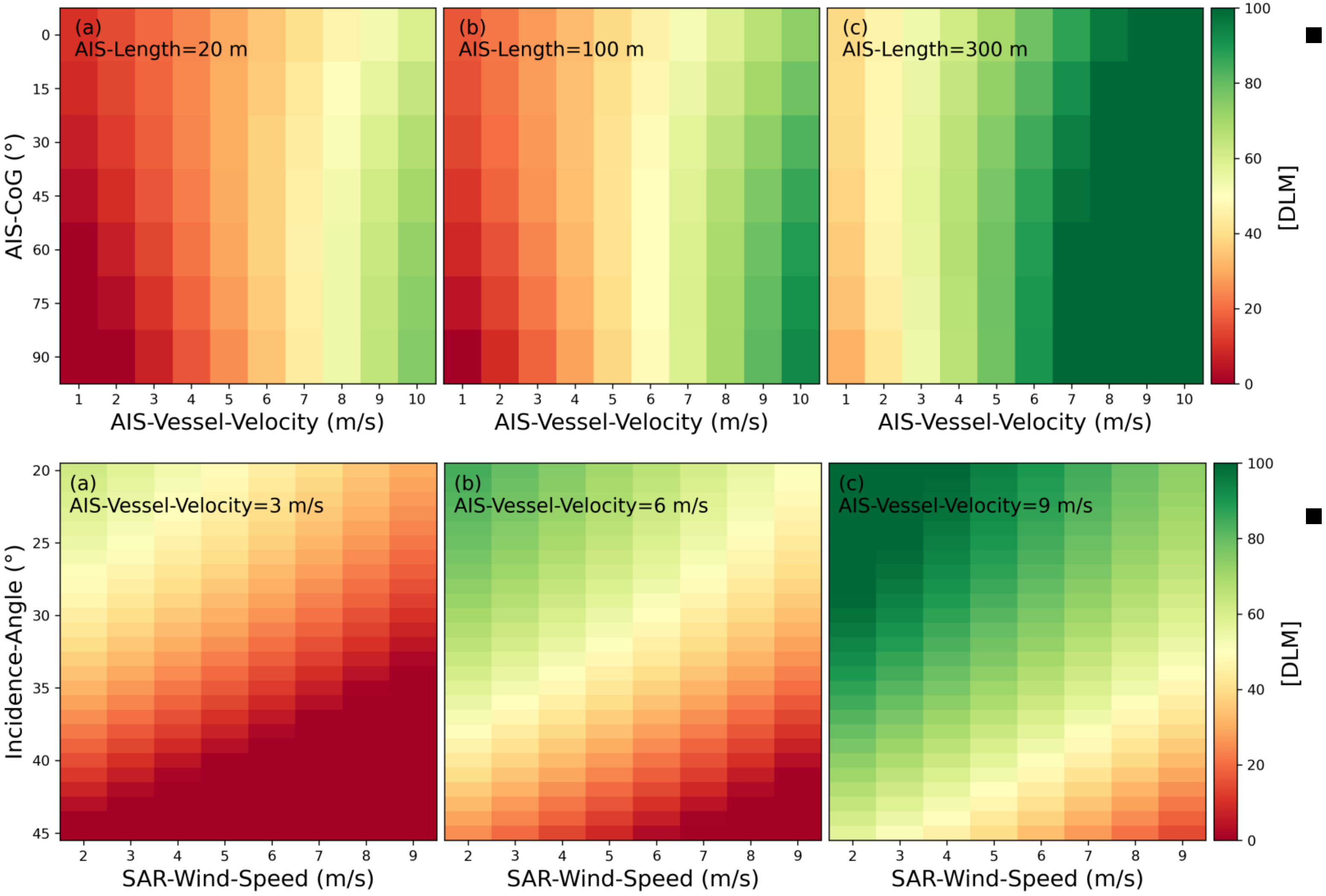
hyperparameter name	value
Kernel type	polynomial
Kernel degree d	2
error tolerance ε	0,001
error weighting C	1,0
gradient γ	0,0
offset β	0

Wake detectability modelling
Visualization of feature space with detectability model

- Gray hyperplane represents the detectability model



Applications of wake detectability models
Dissection of 9D non-linear model for turbulent wakes



- View into the models provide insight on dependency between influencing parameters and detectability of wake components (here turbulent wakes)
- The vertical axis is labelled with [DLM] due to figure of merit for detectability being **D**etectable **L**ength **M**etric

Applications of wake detectability models
Characteristics of influences

Influencing parameter	**Summary on characteristics of influences on detectability of wake components** **"↑": Wake components better detectable** **"≈": Detectability of wake components hardly influenced** **„n.a.": No statement available in scientific publication**			
	Near hull turbulences[±]	**Turbulent wakes**	**Kelvin wake arms**	**V-narrow wake**
Vessel's velocity	↑ for faster ships [n]	↑ for faster ships [n]	↑ for faster ships [b]	↑ for faster ships [b]
Vessel's length	↑ for larger ships [n]	↑ for larger ships [n]	↑ for larger ships [b]	↑ for larger ships [n]
Vessel's course over ground	↑ for CoGs parallel to range direction, when vessel's velocities are at most moderate [n]	≈	↑ for CoGs parallel to Azimuth direction [b]	↑ for CoGs parallel to Azimuth direction [b]
Incidence angle	↑ for larger incidence angles, when vessel's velocities are at least moderate [n]	↑ for smaller incidence angles [b]	↑ for smaller incidence angles [b]	↑ for smaller incidence angles [b]
Wind speed	↑ for lower wind speeds [n]	↑ for lower wind speeds [b]	↑ for lower wind speeds [b]	↑ for lower wind speeds [b]
Sea state's wave height	≈ [n]	≈ [t]	≈ [t]	≈ [t]
Sea state's wave length	↑ for higher wave lengths, when wind speeds are at least moderate [n]	↑ for lower wave lengths, when wind speeds are at least moderate [n]	≈ [n]	≈ [n]
Sea state's wave direction	≈ [n]	↑ for wave directions parallel to CoG, when wave lengths correspond to swell waves [n]	↑ for wave directions parallel to CoG [n]	≈ [n]
Wind direction	≈ [n]	↑ for wind directions perpendicular to CoG [n]	≈	↑ for wind directions perpendicular to CoG [n]

Applications of wake detectability models
Tuning of wake detectors

- Wake detector based on YOLOv4:

Precision	Recall	True-Negative-Rate	Accuracy	F1-Wert
0,759	0,506	0,000	0,373	0,607

- YOLOv4 wake detector with static threshold for filtering of false alarms:

Precision	Recall	True-Negative-Rate	Accuracy	F1-Wert
0,742	0,264	0,429	0,247	0,390

- YOLOv4 wake detector with dynamic threshold for filtering of false alarms (based on $l_{wX} = f_w\left(x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{pol}\right)$):

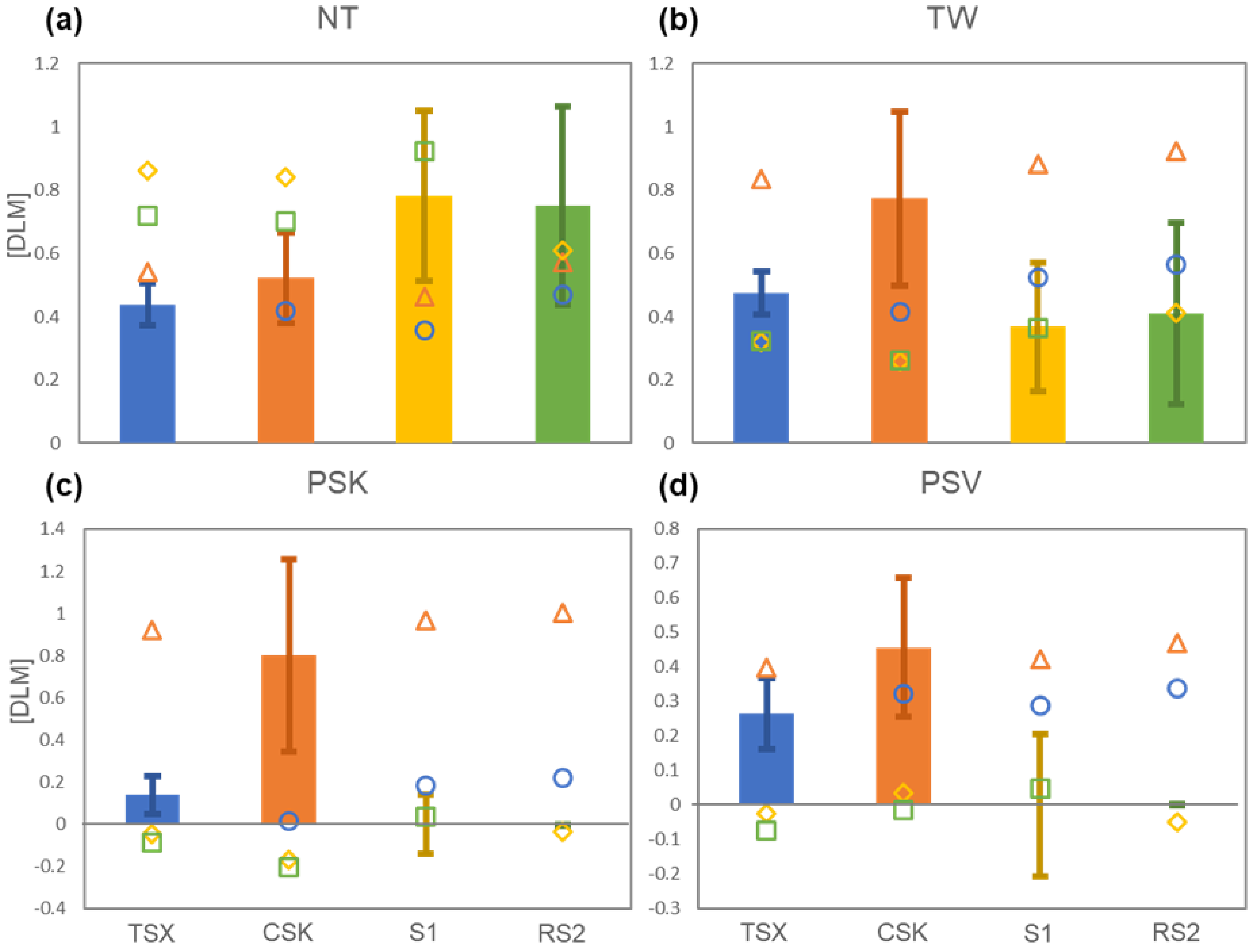
Precision	Recall	True-Negative-Rate	Accuracy	F1-Wert
0,824	0,483	0,357	0,399	0,609

Applications of wake detectability models
Estimation of vessel’s velocity

- Inversion of $f_w(X^{9D})$ with respect to vessel’s velocity x_1:
  $f_w^{x_1^{-1}}\left(l'_w, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{pol}\right) = x_1$
  where $l'_w = DLM_w\left|l_w^{max} - l_w^{min}\right| + l_w^{min}$
- Method estimates vessel’s velocity required as a minimum so that the respective wake component appears at least with length l'_w in a SAR image

	Near-hull turbulences	**Turbulentwakes**	**Kelvin wake arms**	**V-narrow wakes**	**Highest confidence value**
RMSE (m/s)	4,60	2,45	1,17	4,86	2,71

Applications of wake detectability models
Wake detectability comparison between sensors



- In case the bars are not visible in the plots, this means $\overline{DLM_{w,s}} = 0$.
- Detectability difference $\overline{\Delta \widehat{DLM}_{w,s_1,s_2}}$ are indicated by colored symbols
- Uncertainties $\overline{RMSE_{w,s}}$ are visualized for each sensor by error bar.

➢ X-Band better for detection of Kelvin wake arm and V-narrow wakes

Summary & Conclusion

- Detectability of ship wakes is influenced by ship properties, image acquisition settings and environmental conditions (influencing parameters)
- Characteristics of influences are reproduced by detectability models

➢ Determined characteristics are in good agreement with literature

- Ability of SAR missions to detect ship wakes can be compared

➢ X-Band is better suited for detection of Kelvin wake arms and V-narrow wakes than C-Band

➢ Precision of wake detectors can be improved by dynamic thresholds

➢ New method for estimation of vessel’s velocity by model inversion suggested, performance can keep up with state-of-the-art methods

References

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- B. Tings, "Non-Linear Modeling of Detectability of Ship Wake Components in Dependency to Influencing Parameters Using Spaceborne X-Band SAR", *Remote Sensing*, 2021, 165
- B. Tings, A. Pleskachevsky, S. Wiehle, "Comparison of detectability of ship wake components between C-Band and X-Band synthetic aperture radar sensors operating under different slant ranges", *ISPRS Journal of Photogrammetry and Remote Sensing*, 2023, 306-324

About

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Thank you!

Questions? Critics?