SAR Image Quality Measures Relevant for Operational Ship and Oil Spill Detection

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Outline

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Introduction

In Europe, **oil spill detection** from satellite SAR has become operational with a service being provided at EU level by EMSA (image analysis carried out mostly by visual inspection).

For SAR based **ship detection**, automatic detection is still followed by final visual verification. Europe has recently seen a widespread build-up of nearly operational ship detection capabilities.

This increased (near-) operational use of SAR images for ship and oil spill detection is confronting service providers with several SAR image quality issues that impact on the **final product quality and reliability**.

A number of these issues yield an increase of the **false positives**, others introduce **“non-exploitable” areas** leading to potential false negatives in the detection process.

Introduction

Some SAR image particularities can cause serious problems with the service product, e.g. emissions, target azimuth ambiguities.

In such cases, the SAR image may be in accordance to specs, but the impact of some artifacts on the final product is still problematic.

In other cases, operationally delivered images are not in accordance to specs, e.g. processing errors or radiometric performance degradation.

Which SAR quality aspects are the most relevant for ship and oil spill detection?

How to measure image quality that could be used in practical situations?

Main Quality Indicators

Radiometric Quality

- Sensitivity ΔS
- Radiometric Resolution
- Radiometric Error, Accuracy and Stability
  - Residual Scalloping (Azimuth)
  - Radiometric Mismatch (Elevation)
- Polarimetric Image Quality

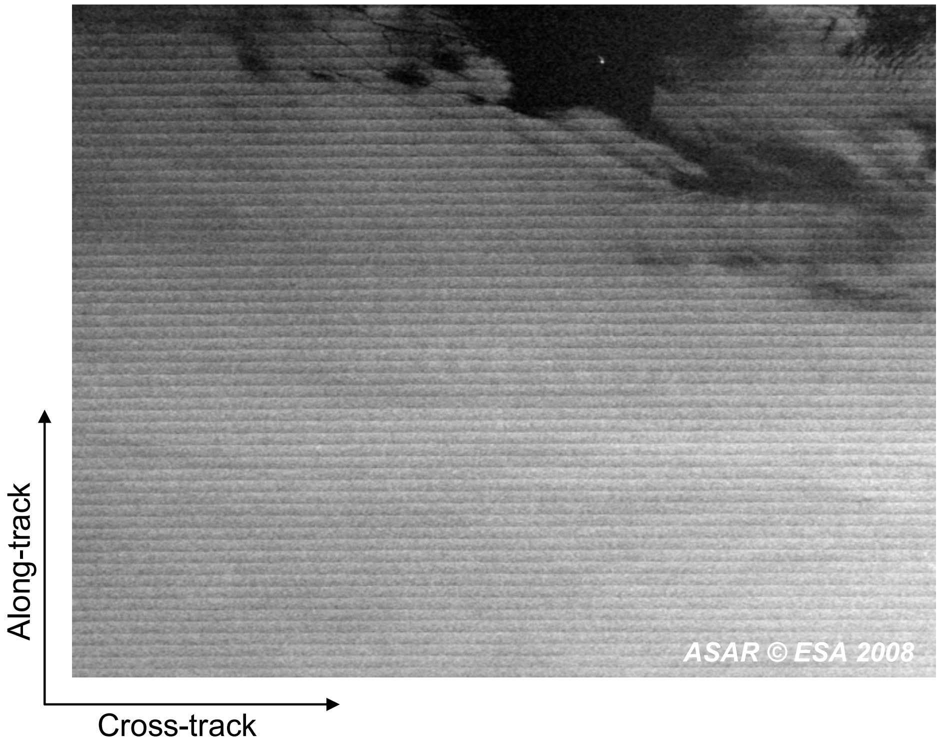
Geometric Quality Indicators

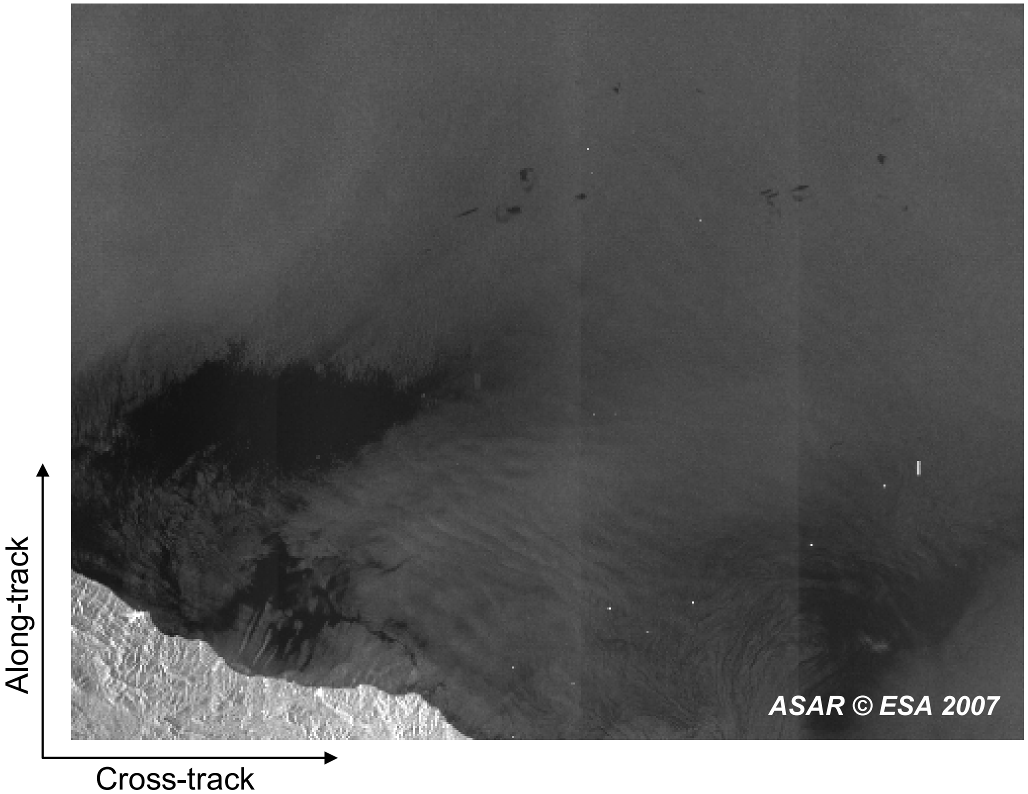
- Spatial Resolution
- Peak to Sidelobe Ratio & Integrated Sidelobe Ratio
- Target Related Ambiguities
- Geometric Localisation Accuracy

Data Integrity Indicators

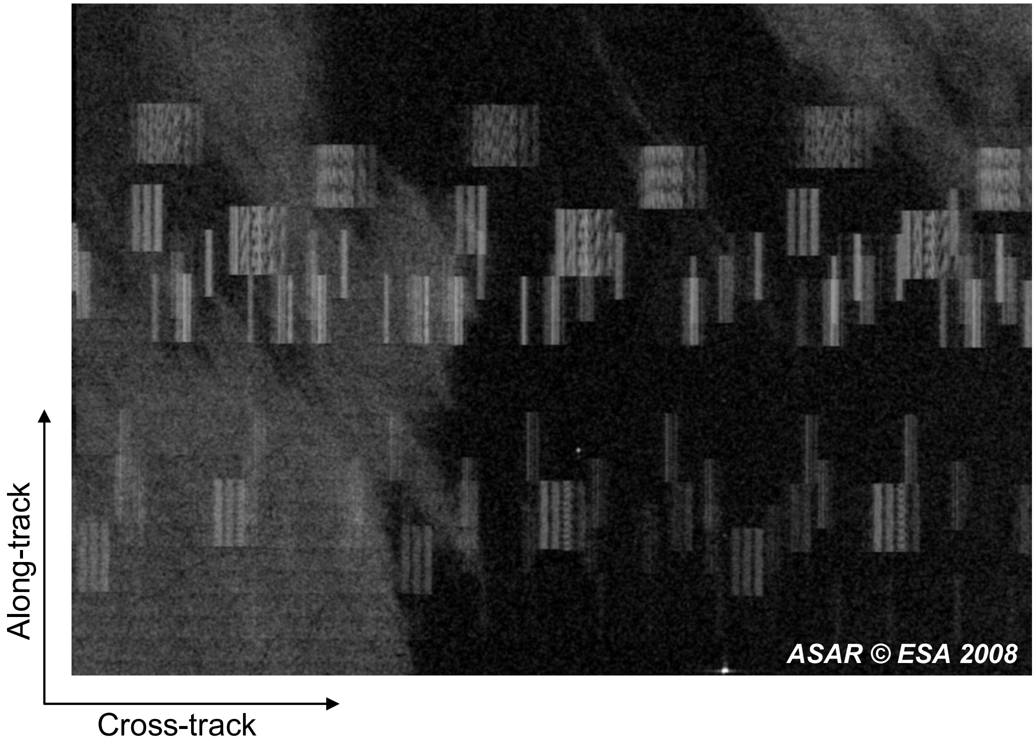
- Missing Data
- Artifacts

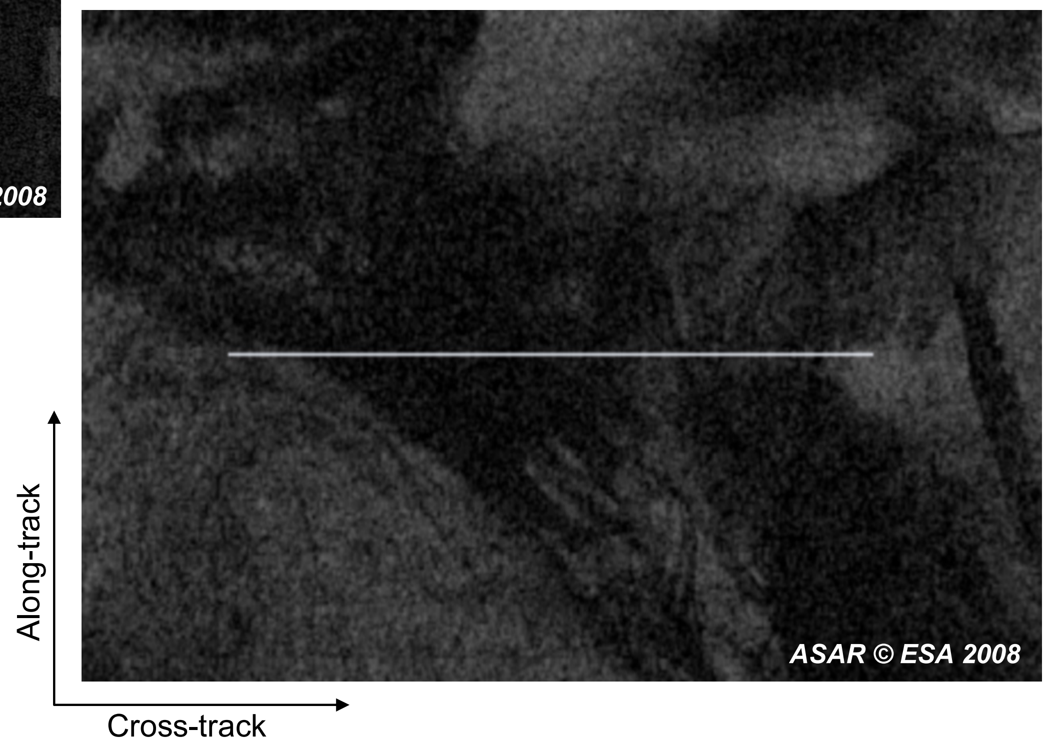
Scalloping & Inter-Beam Seams



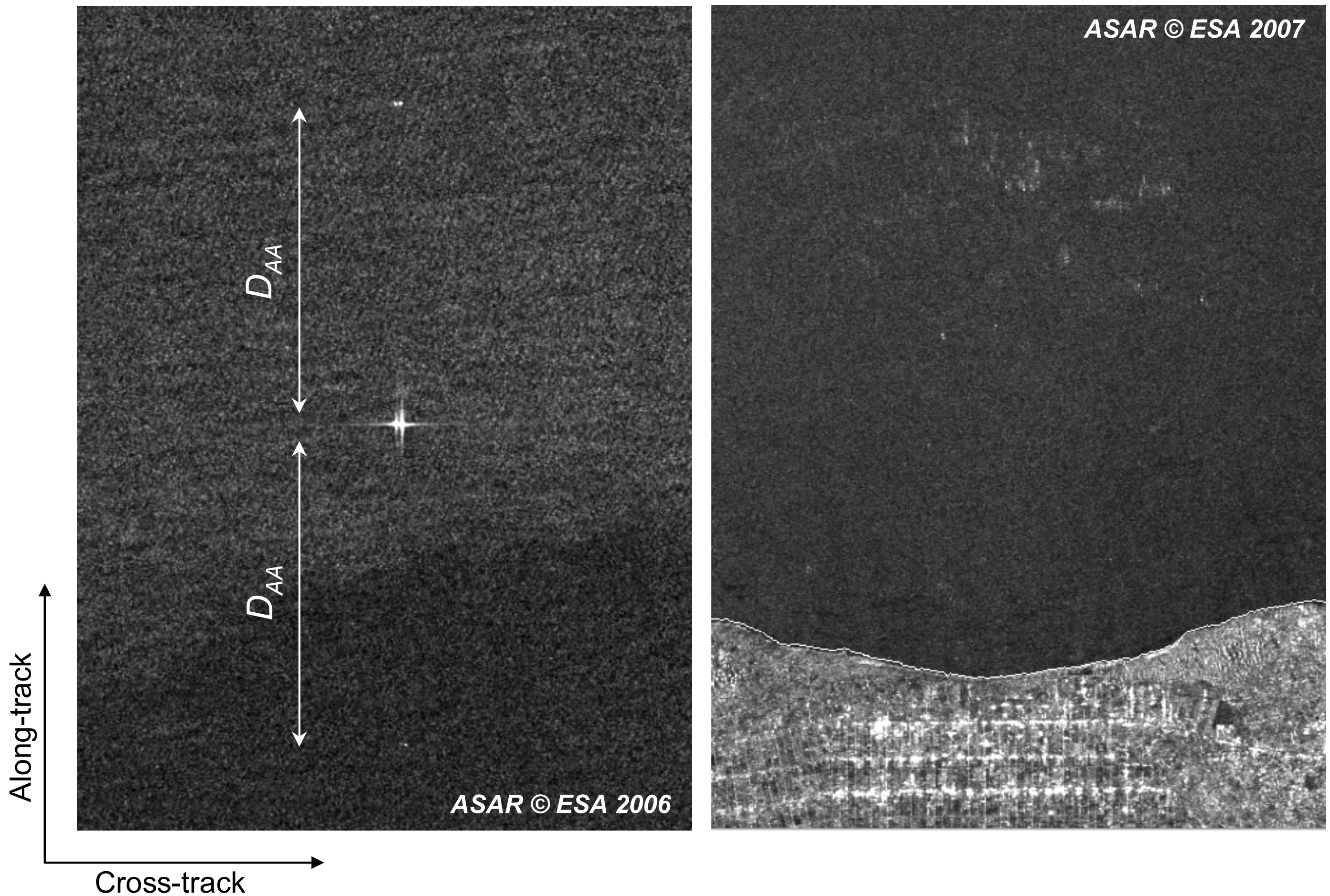


Artifacts


ASAR © ESA 2008
Along-track
Cross-track

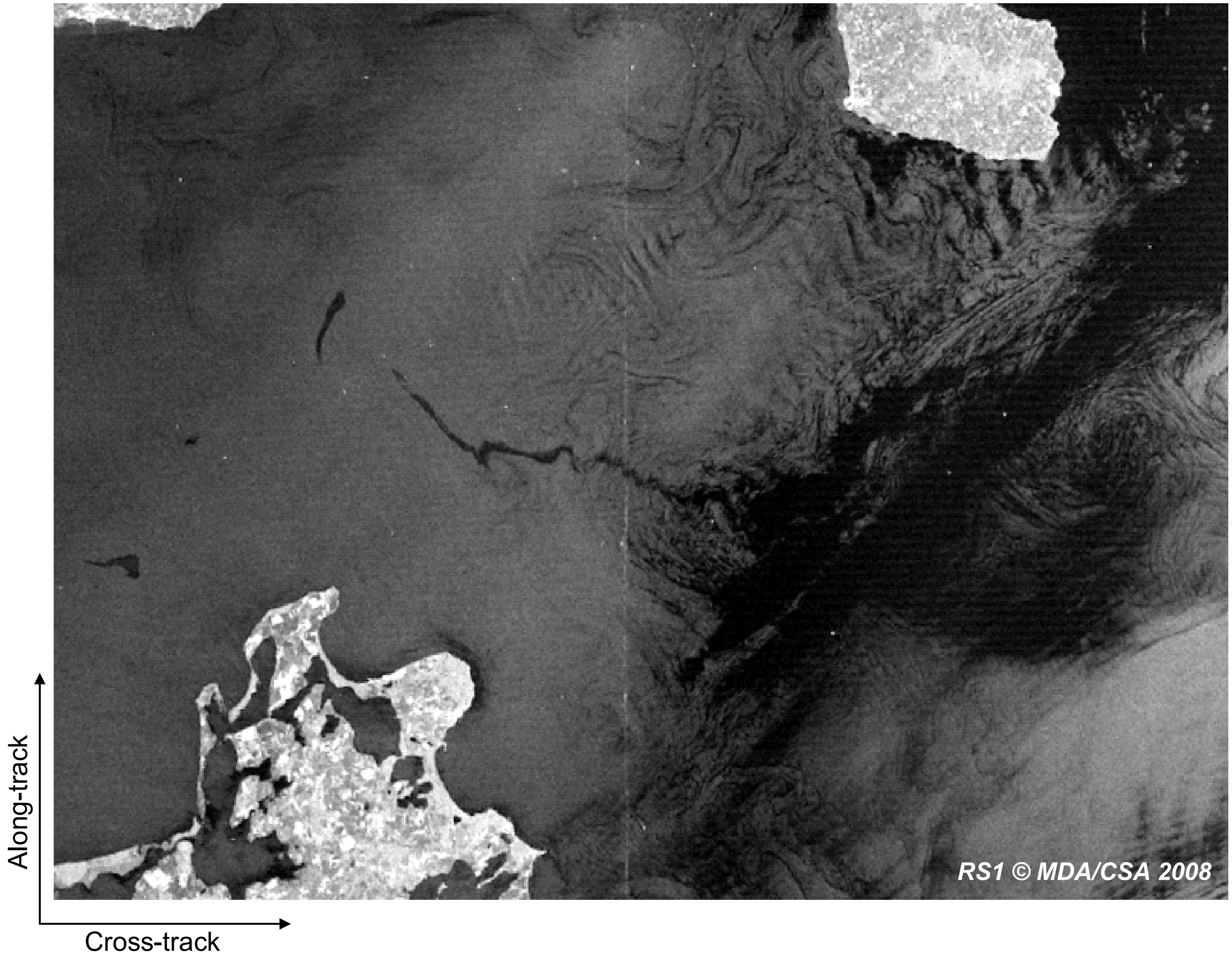

ASAR © ESA 2008
Along-track
Cross-track

Azimuth Ambiguities



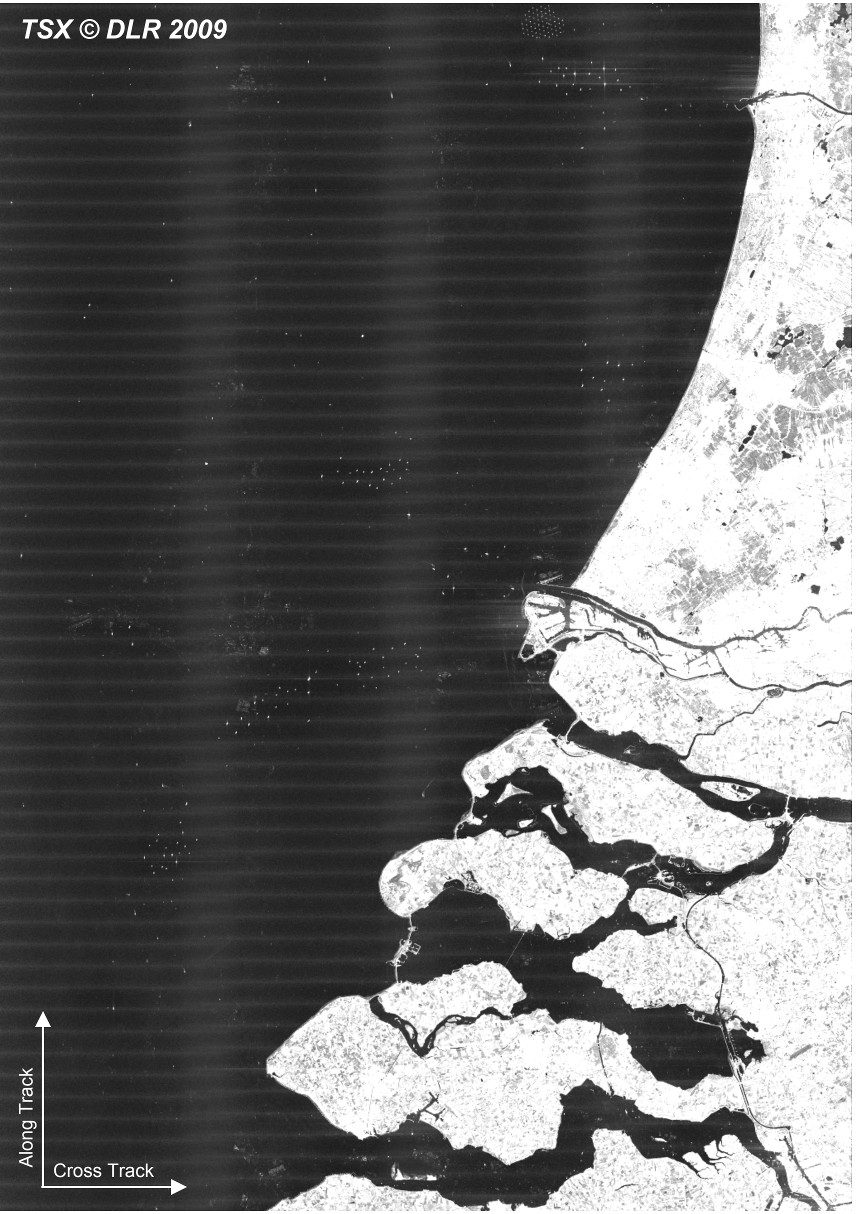
Range Artifacts

Nadir Ambiguities

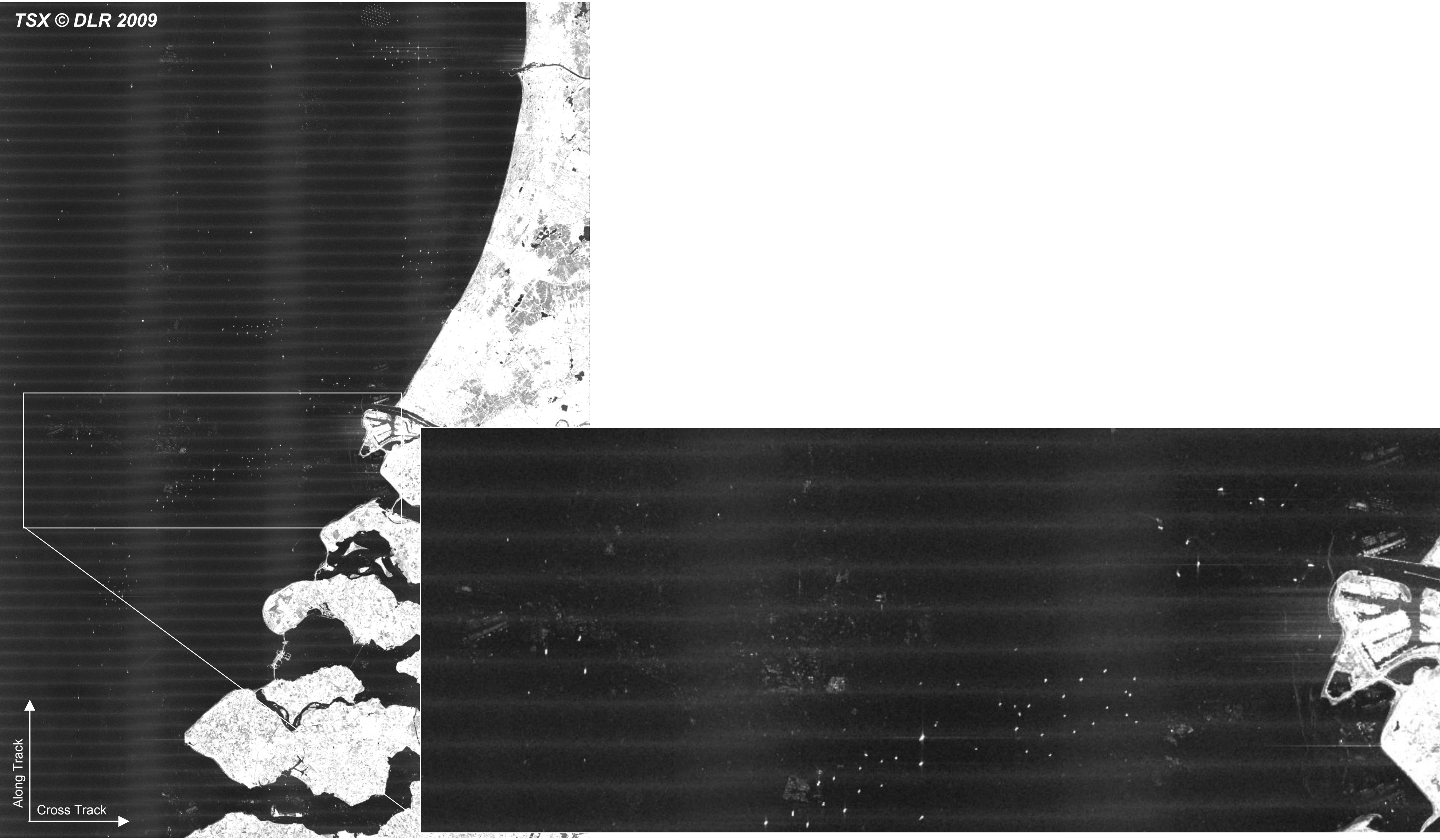


Nadir Ambiguities

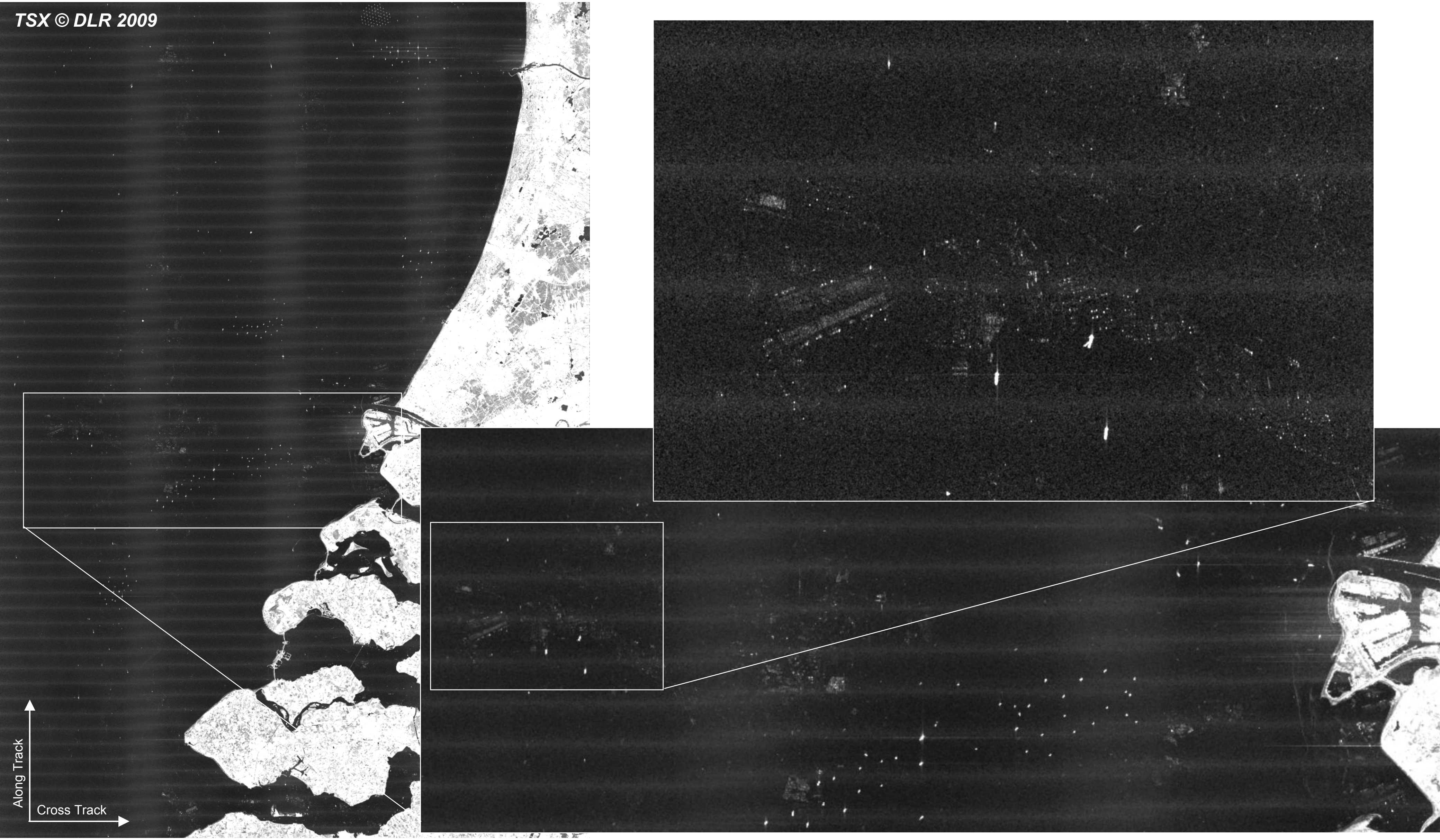
Range Ambiguities



Range Ambiguities



Range Ambiguities



Azimuth Ambiguities

Specs Compliance Vs Application Suitability

The derivation of a number of the quality indicators from magnitude detected products is dependent on the particular sensed scenario. If an indicator is not measurable from the image, it must be assumed compliant with the relevant specification.

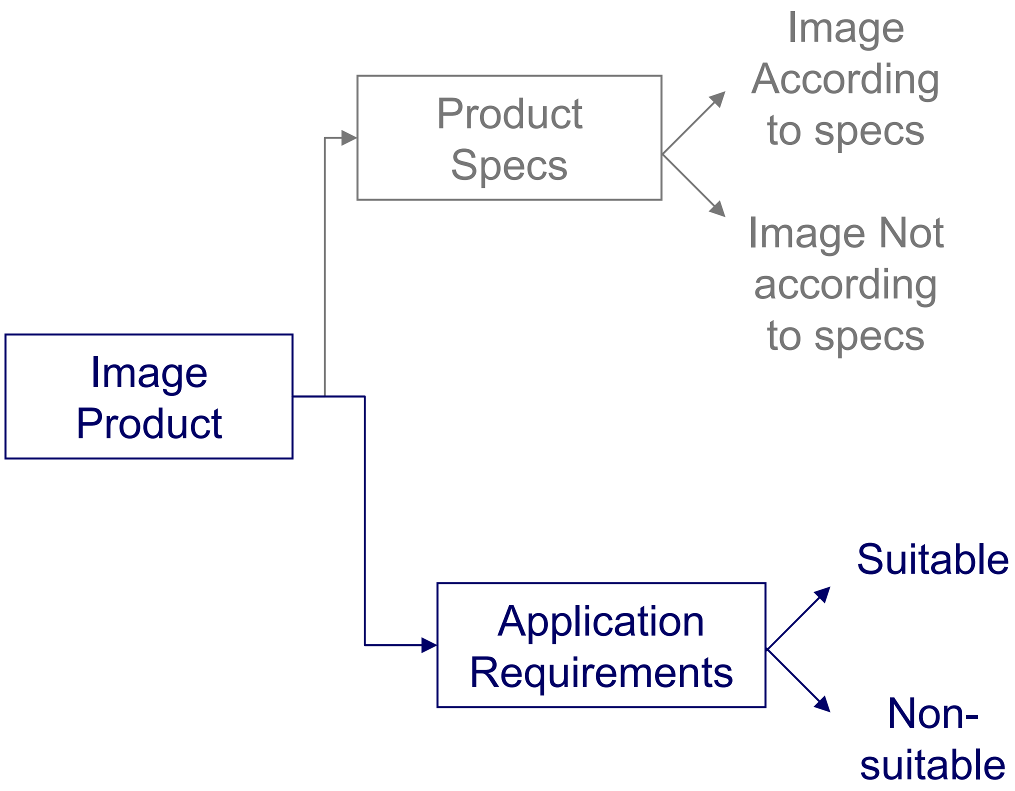
Some image derived quality indicators are ambiguously related to the corresponding **specifications**, e.g.:

- Azimuth ambiguity level cannot be measured with certainty on ship targets (due to target fading);
- Geometric indicators can be measured on calibration targets;
- Radiometric resolution can only be measured over homogeneous (feature–less) sea;

Often, only “positive sentence” wrt specs is possible with targets of opportunity (except geometric accuracy, missing data, radiometric error, scalloping, swath covered).

On the other hand, **application requirements** can be more consistently derived from the analysis of the maritime application.

Specs Compliance Vs Application Suitability



A single non-compliant parameter makes the *whole image* not compliant with specs. However, some of the measured indicators cannot be unambiguously evaluated (“positive sentence”).

The quality indicators are computed and combined into a single parameter. Such **combination** is strictly **dependent on the application.**

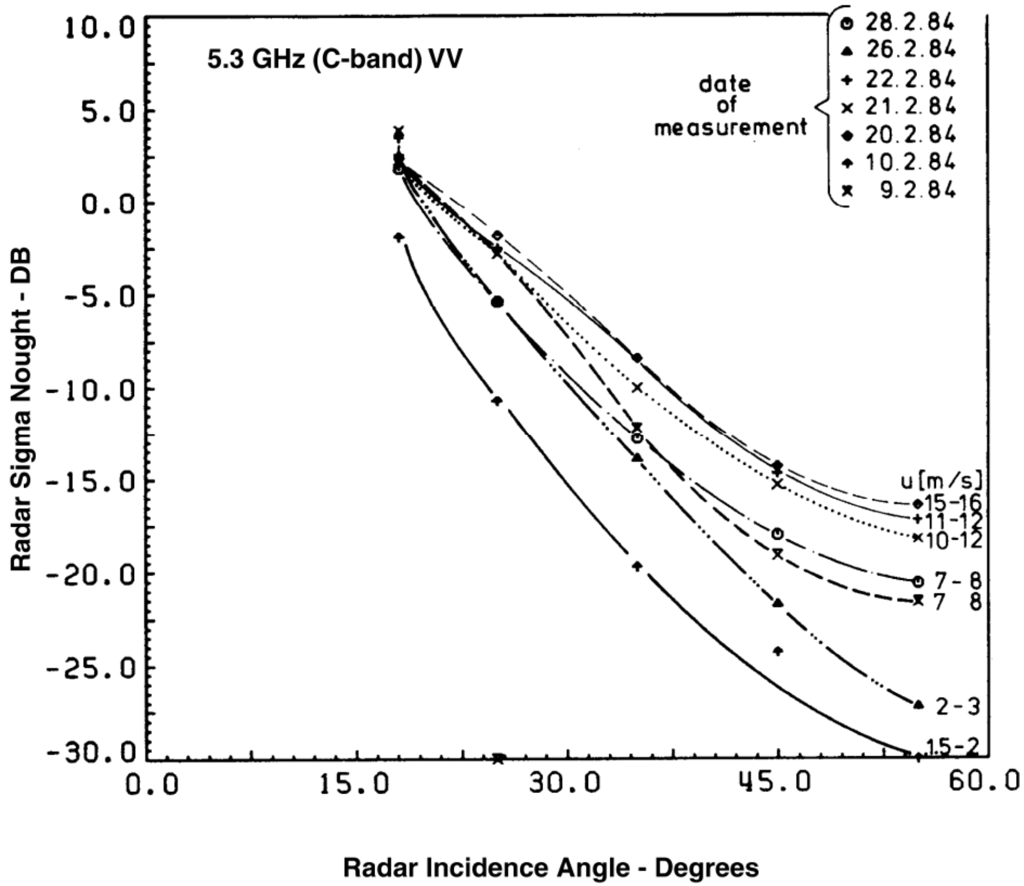
Some of the indicators have a **local** character (e.g. emissions, radiometric mismatch, ambiguities); others can be considered **global** (e.g. scalloping, sensitivity, radiometric resolution).

Oil Spill Detection Requirements

Oil Spill detection relevant parameters:

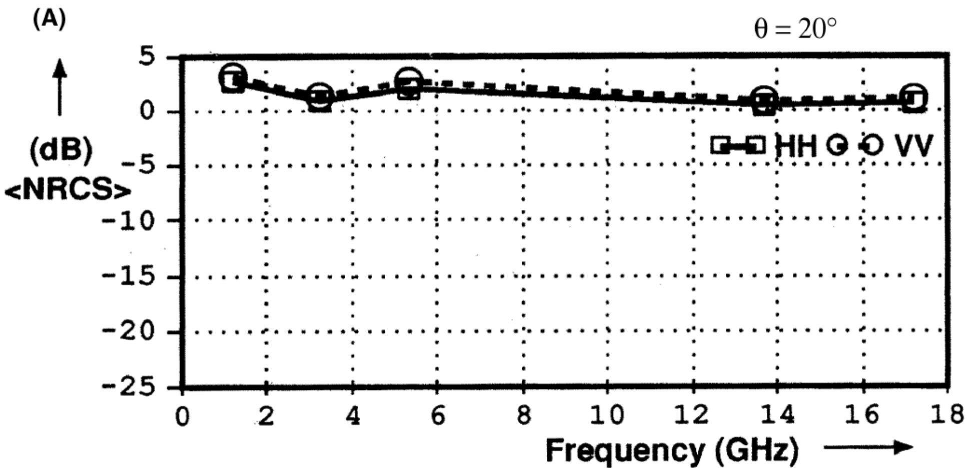
- **Minimum detectable dark feature contrast under variable wind speed conditions** (which primarily translates to radiometric resolution but is influenced by noise level, incidence angle, polarisation, ENL);
- **Instantaneous swath** (large swath is usually preferred for global routine monitoring);
- **Ability to describe geometric properties of the dark patch** (shape and area);
- **Ability to estimate the age of the spill** (shape derived)
- Revisit frequency (no repeat-pass interferometry over the sea, so not necessarily with the same beam);
- Tasking lead time (i.e., how fast can an acquisition be planned);
- Delay in delivering the results (detected spills positions at the end user after overpass);
- Ability to acquire imagery at any time of the day (and not just e.g. at dawn or dusk passes, because some activities at sea do not occur at those hours);
- Availability
- **Reliability** (primarily in the sense of reliability of detection, i.e. detection probability and false alarm rate);
- Accessibility

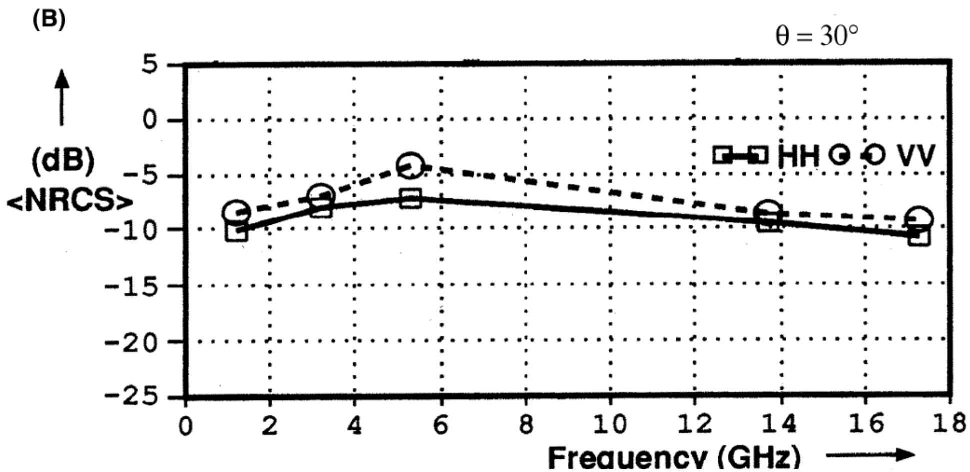
Oil Spill Detection Requirements



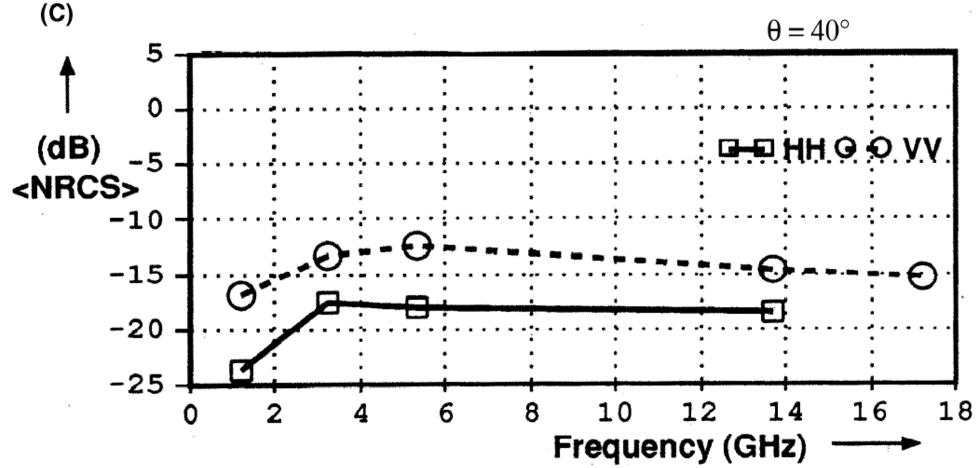
* Feindt, F.; Wismann, V.; Alpers, W.; Keller, W., "Airborne measurements of the ocean radar cross section at 5.3 GHz as a function of wind speed", Radio Science, vol. 21, issue 5, pp. 845-856

Oil Spill Detection Requirements





Average radar backscatter for wind speed of 10 ms^{-1}.

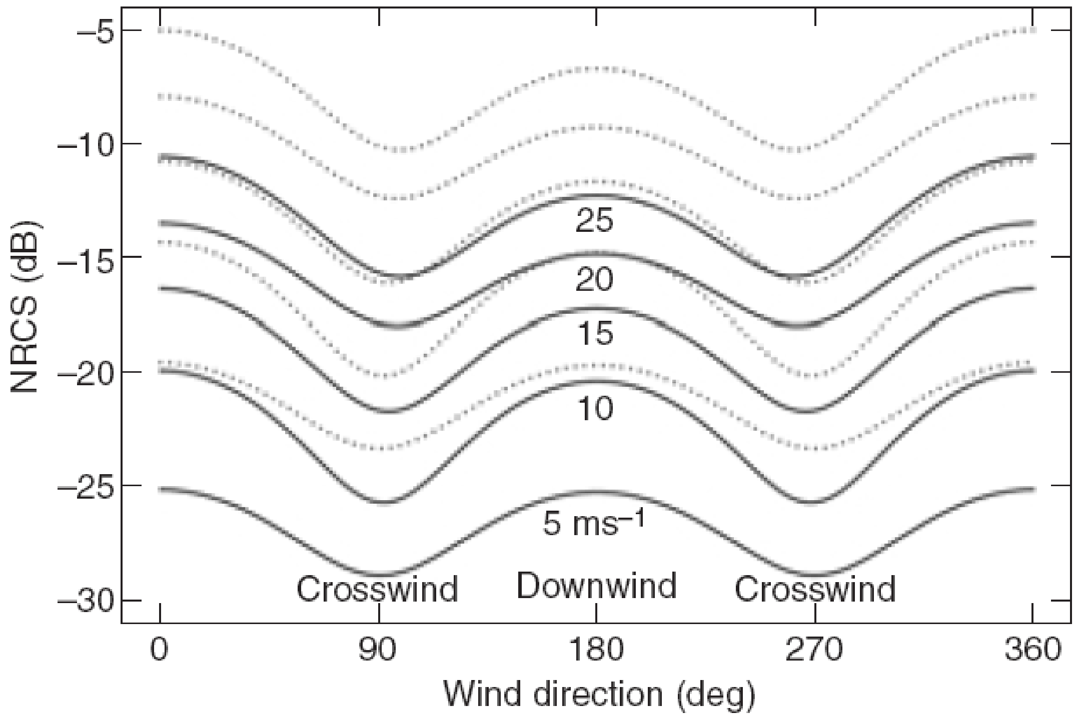


NRCS can be assumed almost constant from C- to X-band.

* Unal, C.M.H. Snoeij, P. Swart, P.J.F., "The polarization-dependent relation between radar backscatter from the ocean surface and surface wind vector at frequencies between 1 and18 GHz", IEEE GSRS,Jul 1991.

Oil Spill Detection Requirements

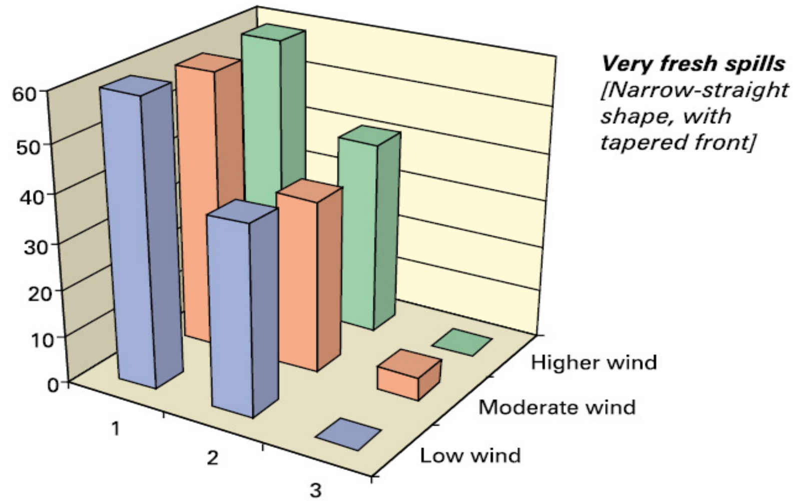
Wind speed between 5 and 25 ms^{-1} at fixed incidence angle of 45° using CMOD-IFR2 (VV, dotted) and empirical HH-VV relation (HH solid).



* Horstmann, J., Koch, W., Lehner, S., “Ocean wind fields retrieved from the advanced synthetic aperture radar aboard ENVISAT”, Ocean Dynamics, Vol 54, 2004

The worst NRCS case shows the necessity of **NES0 ≤ -28dB for HH and NES0 ≤ -23dB for VV**

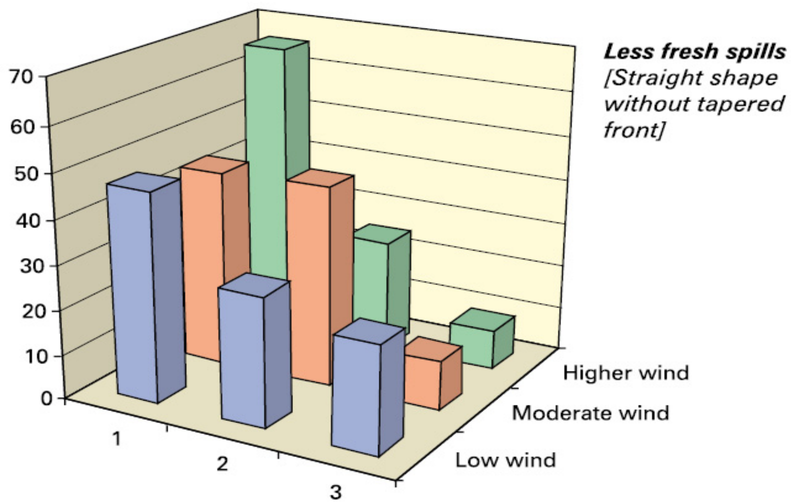
Oil Spill Detection Requirements

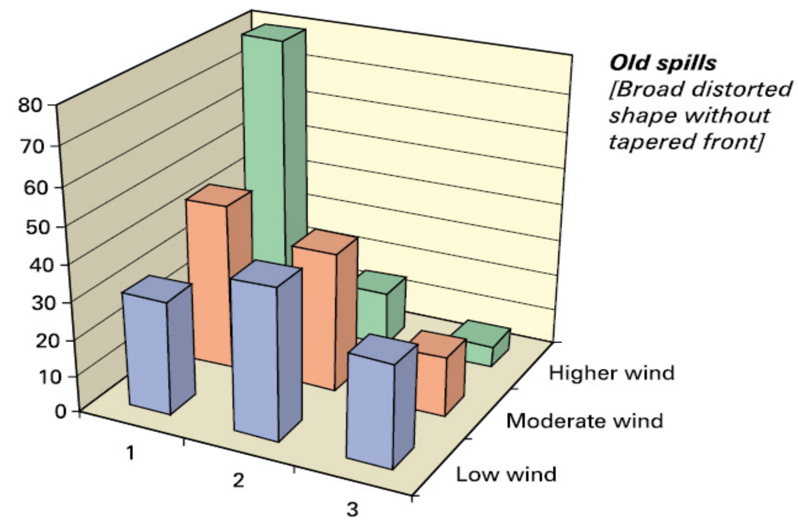


Histograms of radar backscattering contrast with respect to wind strength level and age of spills (from shape). The histograms are normalised along wind strength levels. The contrast levels are: 1 (<4dB), 2(4-6dB) and 3 (>6dB). The wind speed levels are Low (<4 ms-1), Moderate (4-5 ms-1) and Higher (above 5 ms-1)*

Low contrast (<4dB) spills represent the vast majority of the detections => requirement on detectable contrast (radiometric resolution). This analysis was conducted with ERS-2, with radiometric resolution ≤1.9 dB.

<u>Oil spill application requirement $\Gamma \leq 1.5$ dB</u>





* Pavlakis, P., Tarchi, D., and Sieber, A., “On the monitoring of illicit vessel discharges using spaceborne SAR remote sensing - a reconnaissance study in the Mediterranean sea”, Ann. Télécommun., 56, n. 11-12, pp. 700-718, 2001.

Oil Spill Detection Requirements

Spatial resolution requirements for oil spill detection can be set to distinguish small scale features (i.e. windrows) and therefore increase the classification level of the detections.

Minimum Resolution Requirements			Maximum Time During Which Useful Data Can Be Collected (hours)
Task	**Large Spill**	**Small Spill**	
Detect oil on water	6	2	1
Map oil on water	10	2	12
Map oil on land/shore	1	0.5	12
Tactical water cleanup	1	2	1
Tactical support land/shore	1	0.5	1
Thickness/volume	1	0.5	1
Legal and prosecution	3	1	6
General documentation	3	1	1
Long-range surveillance	10	2	1

*Fingas, M.F. and C.E. Brown, “Review of Oil Spill Remote Sensing”, in *Proceedings of Ecoinforma‘96, Global Networks for Environmental Information*, Environmental Research Institute of Michigan, Ann Arbor, Michigan, Vol. 10, pp. 465-470, 1996.

However, operational spills have been long detected using low resolution modes that privilege coverage requirements.

Oil Spill Detection Requirements

Features applied by various algorithms

#	Feature
1	Slick area (*A*)
2	Slick perimeter (*P*)
3	*P*/*A*
4	Slick complexity
5	Spreading (low for long thin slicks, high for circular shape)
6	Slick width
7	First invariant planar moment (Hu, 1962)
8	Dispersion of slick pixels from longitudinal axis
9	Object/dark area standard deviation
10	Background/outside dark area standard deviation
11	Max contrast (between object and background)
12	Mean contrast (between object and background)
13	Max border gradient
14	Mean border gradient
15	Gradient standard deviation
16	Local area contrast ratio
17	Power-to-mean ratio of the slick
18	Homogeneity of surroundings
19	Average NRCS inside dark area
20	Average NRCS in limited area outside dark area
21	Gradient of the NRCS across the dark area perimeter
22	Ratio #9 to #10
23	Ratio #19 to #9
24	Ratio #20 to #10
25	Ratio #23 to #24
26	Ratio #19 to #20
27	Distance to a point source
28	Number of detected spots in the scene
29	Number of neighbouring spots

Common algorithms are based on geometric and radiometric features.

However, it is common to pre-process the acquired image using de-speckling filters to increase the radiometric resolution.

Moreover, the use of properties related to oil texture implies that the radiometric quality presents higher impact on this application (wrt vessel detection).

*Camilla Brekke, Anne H. Solberg, "Oil spill detection by satellite remote sensing" Remote Sensing of Environment, Vol. 95, No. 1. (15 March 2005), pp. 1-13.

Vessel Detection Requirements

Vessel detection relevant parameters:

- **Minimum detectable vessel size** (which primarily translates to resolution but is influenced by noise level, incidence angle, polarisation, ENL);
- **Instantaneous swath** (given that SAR is good at detection but not at identification, it is typically used for searching, so the requirement is typically for a large swath);
- **Ability to estimate vessel size** (the difficulties here are caused by azimuth smearing due to vessel motions, distinction between ship and wake and high clutter background);
- **Ability to estimate vessel speed and course** (related to ability of wake detection and correct interpretation);
- **Ability to estimate vessel type** (primarily to be derived from vessel size, RCS and distribution of scattering centres);
- **Ability to estimate vessel activity** (e.g. the mere presence of a fishing ship may be legal, but actual fishing may not be);
- Revisit frequency (no repeat-pass interferometry over the sea, so not necessarily with the same beam);
- Tasking lead time (i.e., how fast can an acquisition be planned);
- Delay in delivering the results (detected vessel positions at the end user after overpass);
- Ability to acquire imagery at any time of the day (and not just e.g. at dawn or dusk passes, because some activities at sea do not occur at those hours);
- Availability
- **Reliability** (primarily in the sense of reliability of detection, i.e. detection probability and false alarm rate);
- Accessibility

Vessel Detection Requirements

Application area	Scenario	Min ship size to detect (m)	Swath (km)	S-1 mode
Fisheries control	Oceanic, industrial	35	400/600*	IW-EW
	Oceanic, artisanal	10	400/600*	(IW)
	Coastal, industrial	15	200/300*	IW
	Coastal, artisanal	8	200/300*	(IW)
Illegal immigra-tion	Long distance, large ship	50	200/300	IW
	Medium distance, small ship	15	200/300	IW
	Short distance, small boat	-	-	-
Smuggling	Heavy or bulky goods such as weapons, cars	50/20	200/300	IW
	Transferring goods from ship to shore	50/8	200/300	IW
	High-value small-volume goods like narcotics	-	-	-
Counter terrorism	Vessels intending to attack targets in the EU	50	200/300	IW
	Small IED vessels	-	-	-
Maritime safety	Act against vessels that do not obey traffic safety regulations	20	200/300	IW
	Estimate occurrence of infringements	20	100(1)	IW
	Support search & rescue operations	3	200/600	-
Maritime security	Verify LRIT reporting	50	400/600	IW-EW
	Provide protection against piracy	-	-	-
	Prepare for maritime security operations	15/4	100/300	SM-IW
	Critical infrastructure and valuable asset pro-tection	-	-	-
Natural resource protection	Be alerted to sea bottom exploration or exploi-tation activities	35	400/600	IW-EW
Intelligence	Recognising ships in ports	15/8	10	SM

*: swath may be smaller if tasking lead time is short (6-12 hrs).
(1): narrow instantaneous swath to be compensated by higher revisit.
-: very difficult for satellite, for reasons other than resolution or swath (mostly needing continuous monitoring).

Greidanus, H.; and Attema, E.; "Sentinel-1 Ship Monitoring Applications", Proceedings EUSAR 2008, 7th European Conference on Synthetic Aperture Radar, Friedrichshafen, May 2008.

Vessel Detection Requirements

The smallest vessel of interest could be RCS = 1 m^2. If observed with e.g. Radarsat-2 Ultra Fine (ρ = 3 m), the apparent NRCS is -10 dB. If observed by RS Fine (ρ = 8 m), the **apparent NRCS is -18 dB**. If observed by RS SN (ρ = 50 m), the apparent NRCS would be -33 dB, so completely clutter limited.

A small fishing vessel could have RCS = 10 m^2. If observed with RS Fine, the apparent NRCS is -8 dB.

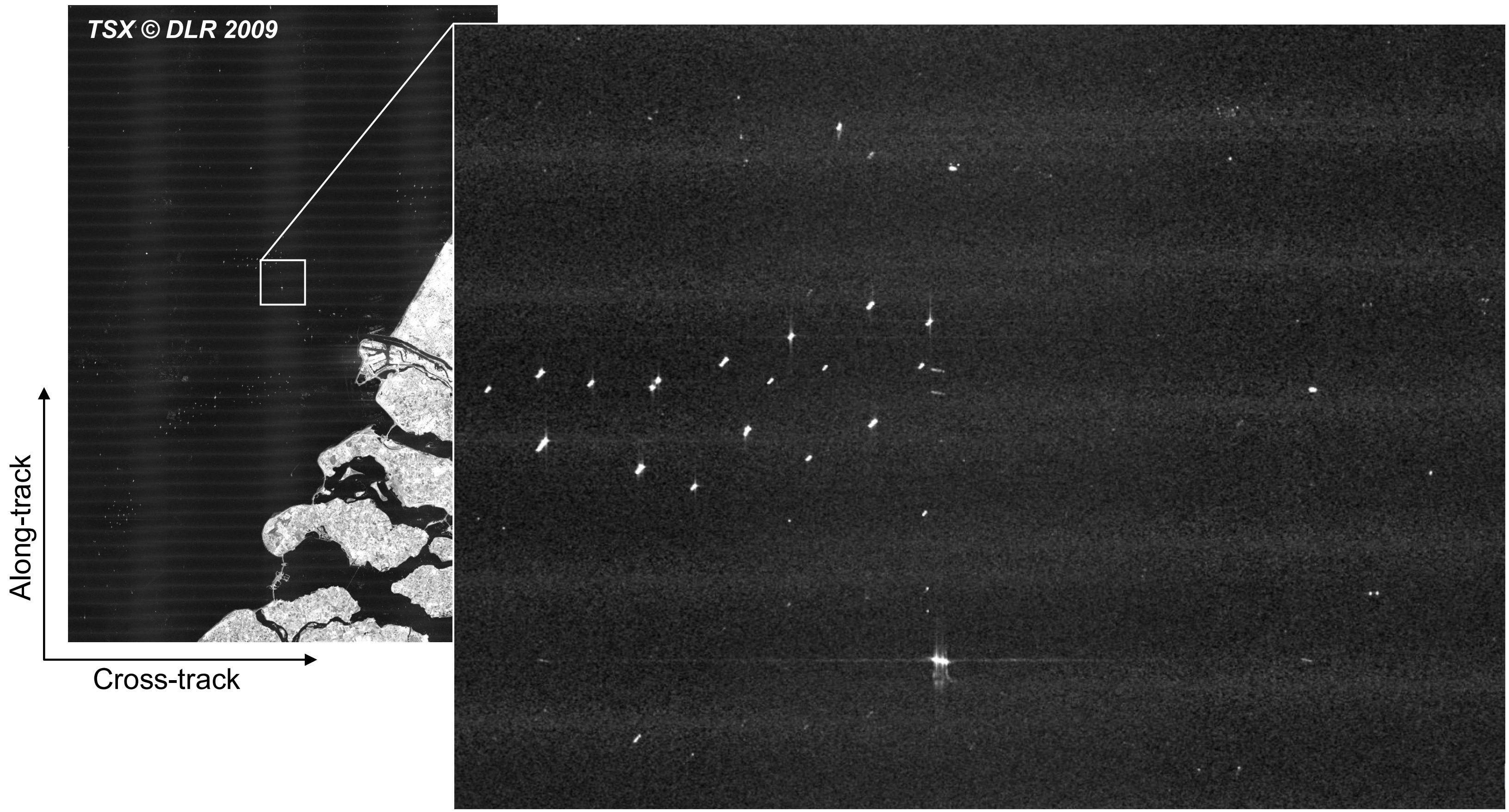
As a consequence, a **low limit for NESZ could be fixed at -20 dB** for ship detection. This would allow finding very small boats (5 m) in RS Fine images (50 x 50 km).

The upper limit above which it loses all relevance, can be set at -10 dB (which is anyway always obtained).

Vessel Detection Requirements

Some imperfections also derive within specs compliance and can be dealt with by vessel detection algorithms. Nevertheless such issues have severe consequences on image suitability. Examples are variable ENL and PRF values:

Variable PRF: this happens in ScanSAR modes to reduce range and azimuth ambiguities. Such PRF might be specified within the metadata to apply accurate azimuth target ambiguities filters.



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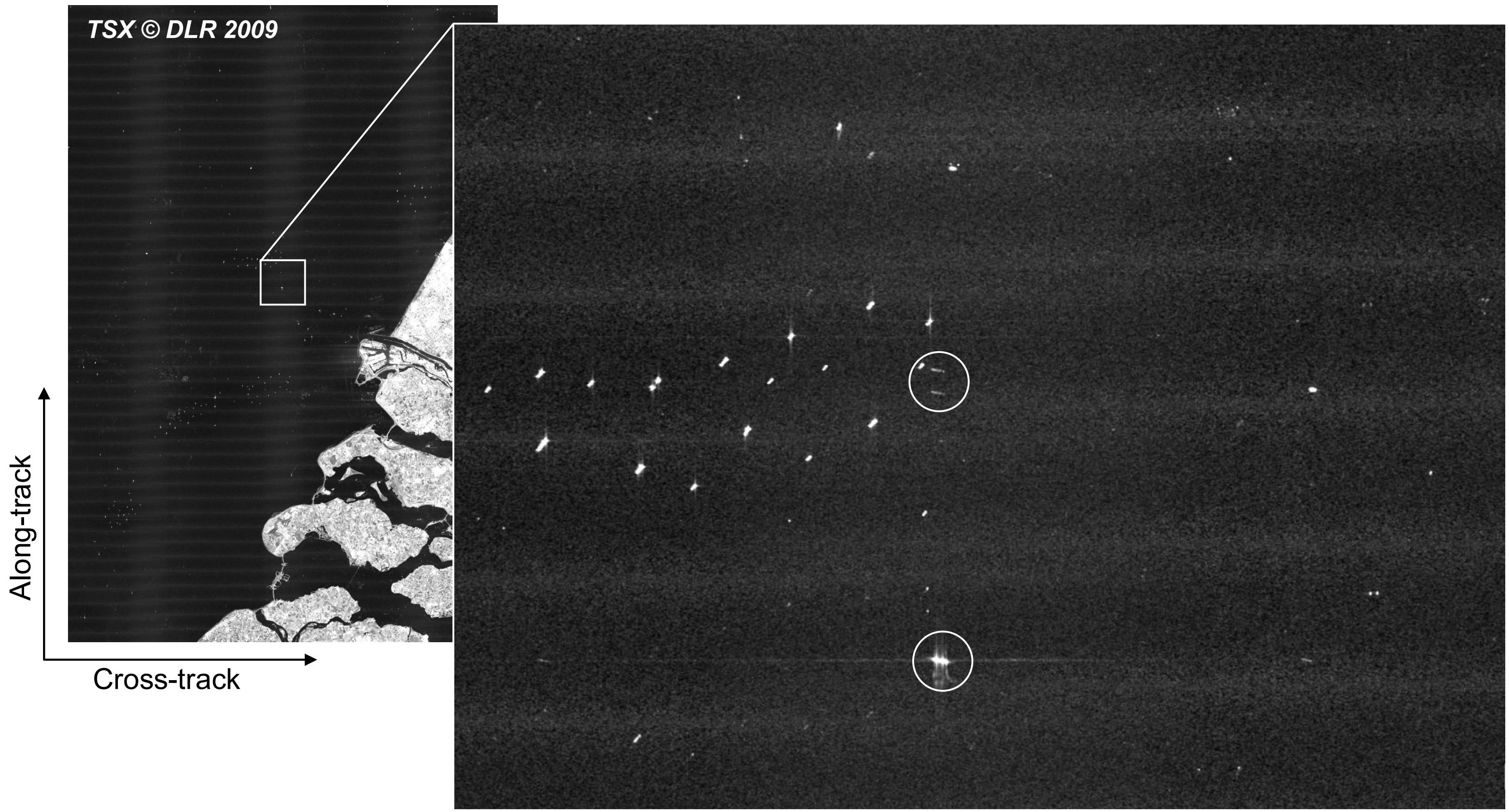

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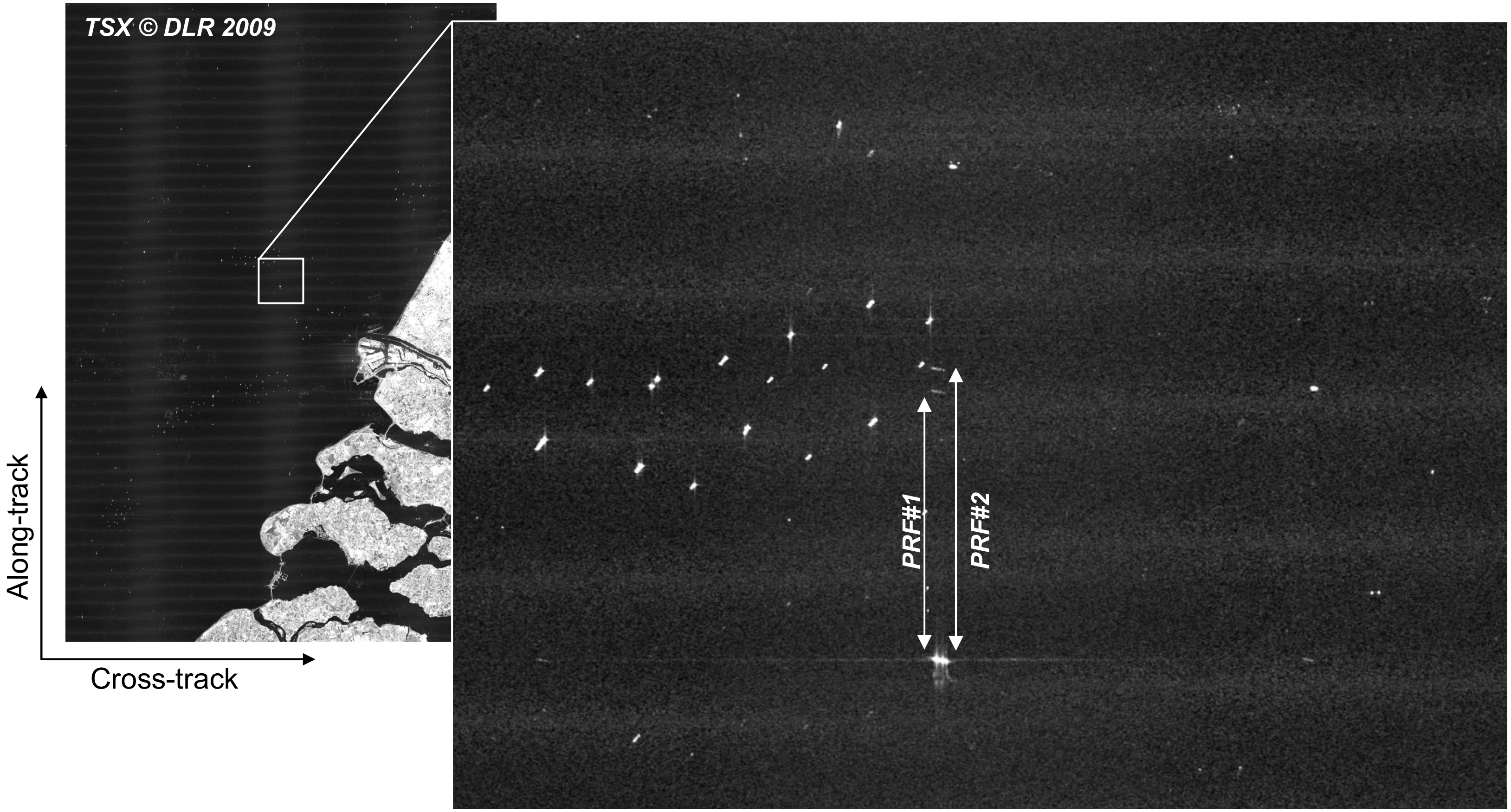

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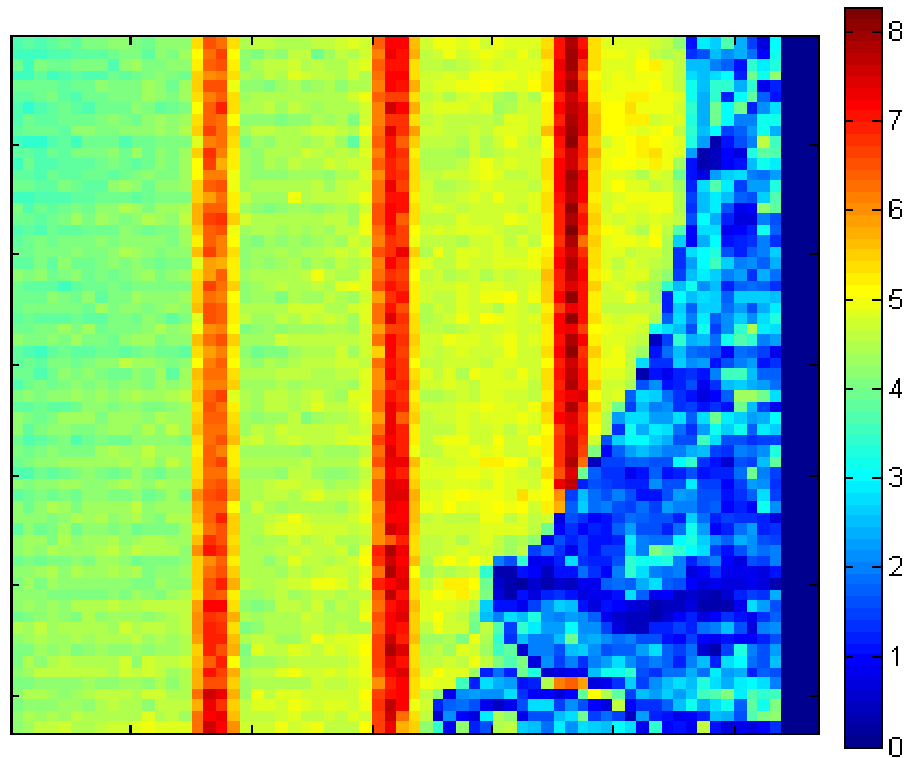
Variable ENL: it describes the system speckle noise level. ENL is a parameter that has to be set before automatic detection is run; its derivation form the image is often inaccurate, affecting the ship detection application output.



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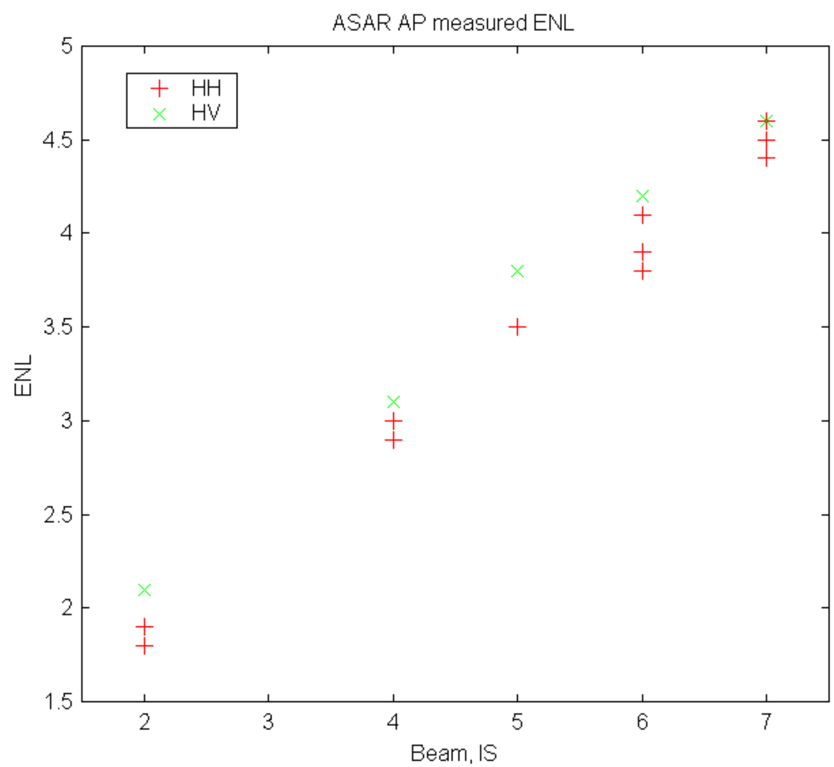
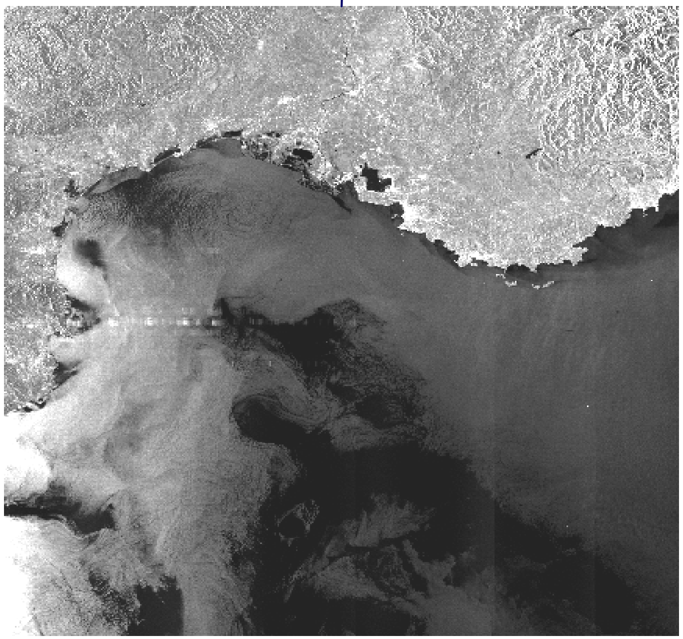
ENVISAT ASAR AP image data is specified as having ENL > 1.8. It was found, that AP images processed by the KSPT processor (used by KSAT) have an ENL of 2.2, and that AP images processed by the ASAR processor (in use at several other stations) have an ENL that depends on the beam. In the latter case, the shallower the beam (i.e., the higher the IS number), the higher the ENL.

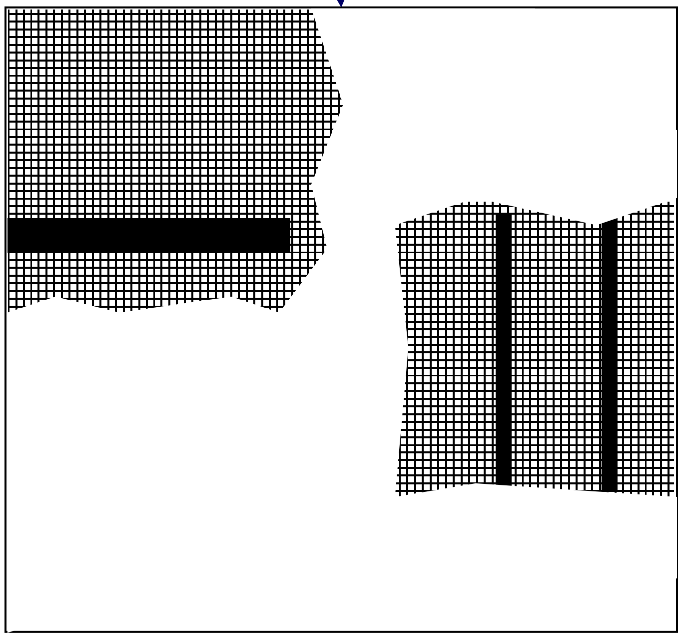


Local Indicators: Data Integrity Layer

- Radiometric Mismatch
- Target Ambiguities
- Missing Data
- Artifacts

Data Integrity Layer → *DI*
0 = data to be discarded
1 = data is usable

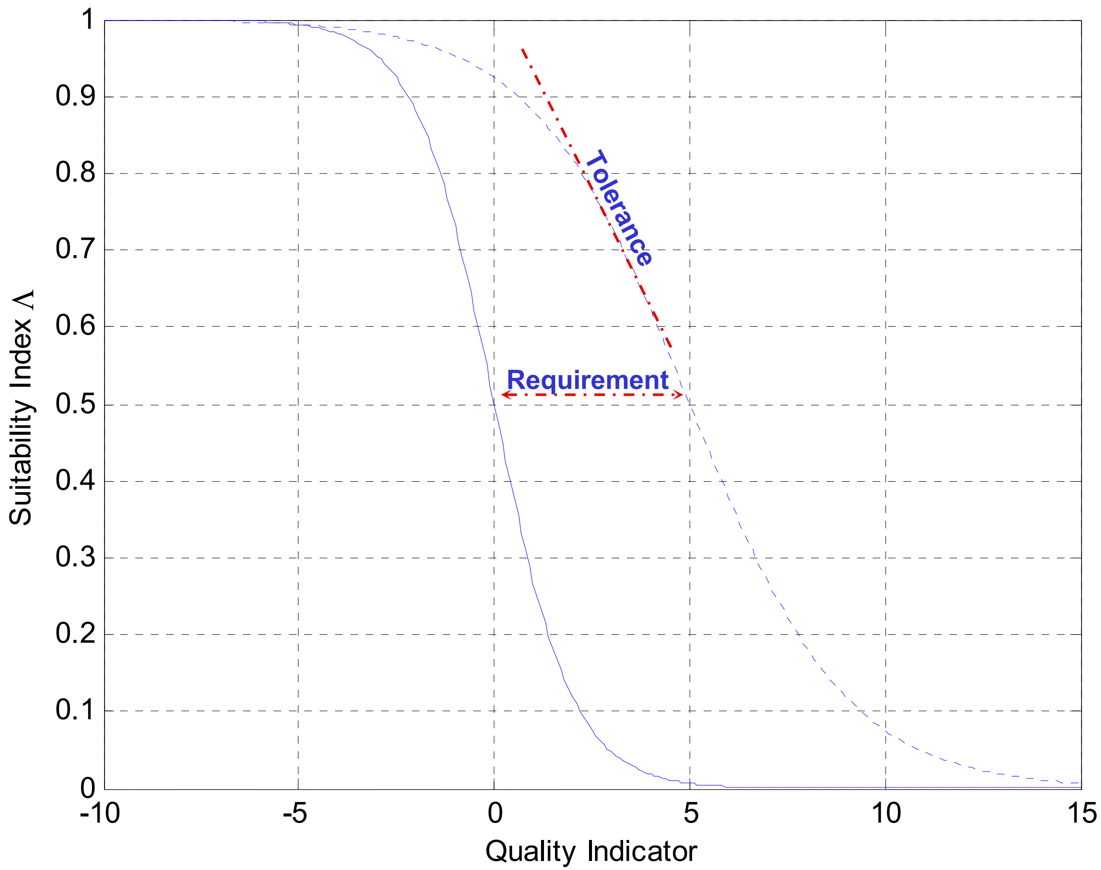




Global Indicators

Quality indicators (NES0, Γ, ρ, etc) are mapped onto indices of suitability (Λ_{NES0}, Λ_{Γ}, Λ_{ρ}, etc) related to the particular target application:

$$\Lambda_x = 1 - \frac{1}{\left[1 + \frac{(\text{Req-}\ x)}{\text{Tol}}\right]}$$



$x \rightarrow \Lambda_x$ in [0,1]
0 = reqs not met
0.5 = reqs met
1 = improvement wrt reqs

Global Indicators

Global indices are then established for radiometric (*R*) and geometric (*G*) quality indicators respectively:

$$R = \frac{1}{N_R}\left(\Lambda_{NES0} + \Lambda_{\Gamma} + \Lambda_{\delta\Gamma} + \Lambda_{\sigma_{sc}} + \Lambda_{\sigma_{em}} + \Lambda_{\sigma_{pol}}\right)$$

$$G = \frac{1}{N_G}\left(\Lambda_{\rho_r} + \Lambda_{\rho_a} + \Lambda_{\mathrm{PSLR}} + \Lambda_{\mathrm{ISLR}} + \Lambda_{\mathrm{TASR}} + \Lambda_{\Delta_{loc}}\right)$$

where ***NR*** and ***NG*** are the number of available radiometric and geometric indicators respectively. This is a consequence of the fact that some parameters are not always measurable, and some others are relevant only to specific radar modes. then fused into a single global quality value (*Q*)

$$Q = DI\frac{(R + G)}{2}$$

	Operational Oil Spill Detection		Vessel Detection		Wind Fields Analysis	Ocean Surface Wave Retrieval
	Req	Tol	Req	Tol		
$\Lambda_{NE\sigma0}$	-28 HH -23 VV	<-25 HH <-20 VV	-20 dB (HH)	< -10 dB		
Λ_{Γ}	1.5 dB	< 2 dB	1.5 dB	< 2 dB	Strict	
$\Lambda\varepsilon_{\delta\Gamma}$	2 dB	< 4 dB	10 dB	< 10 dB	Strict	
$\Lambda\varepsilon_{\delta sc}$	1 dB	< 2 dB	1 dB	< 2 dB	Strict	
$\Lambda\varepsilon_{\delta em}$	0.2 dB	< 1 dB	0.2 dB	< 1 dB	Strict	
$\Lambda\varepsilon_{\delta pol}$	-30 dB	< -25 dB	-30 dB	< -25 dB	Strict	
Λ_{pr}	150 m	< 200 m	See Prev Slides	10%		Strict
Λ_{pa}	150 m	< 200 m	See Prev Slides	10%		Strict
Λ_{PSLR}	-	< -20 dB	-	< -20 dB		Strict
Λ_{ISLR}	-	< -13 dB	-	< -13 dB		Strict
Λ_{TASR}	-	< -15 dB	-	< -15 dB		Strict
$\Lambda_{\Delta loc}$	100 m	< 150 m	20 m	< 30 m		
$\Lambda_{\Delta sw}$	150 km	>100 km	See Prev Slides	10 %		

Conclusions

Based on experience, the distinction between **specifications compliance** and **application suitability** has been introduced and discussed.

Global and Local quality indicators can be defined in order to evaluate the suitability of a SAR image to oil spill and ship detection applications.

A potential process to **quantitatively measure** such parameters has been introduced.

Work has to be carried out in **accurately specifying suitability requirements** and tolerance to effectively determine the application reliability output.

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