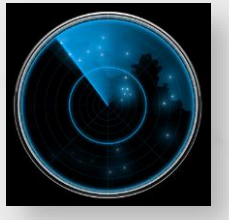




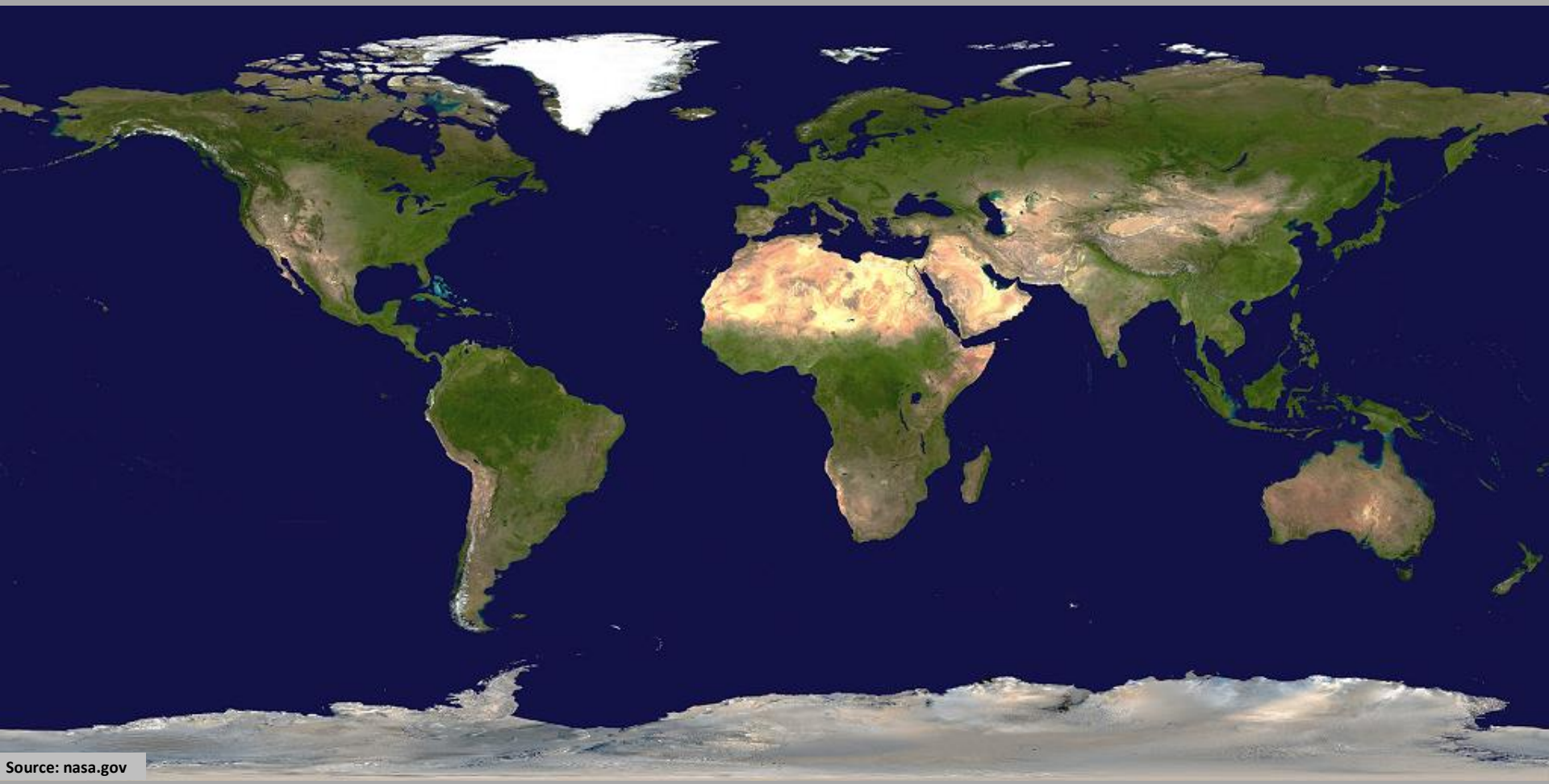

Fusion of AIS and Radar Data for Maritime Surveillance

Fábio Manzoni Vieira[1], François Vincent[2], Jean-Yves Tourneret[2], David Bonacci[1], Marc Spigai[3], Marie Ansart[3] and Jacques Richard[3]

[1]TéSA Laboratory, Toulouse, France
[2]University of Toulouse, France
[3]Thales Alenia Space, Toulouse, France

Why Maritime Surveillance?

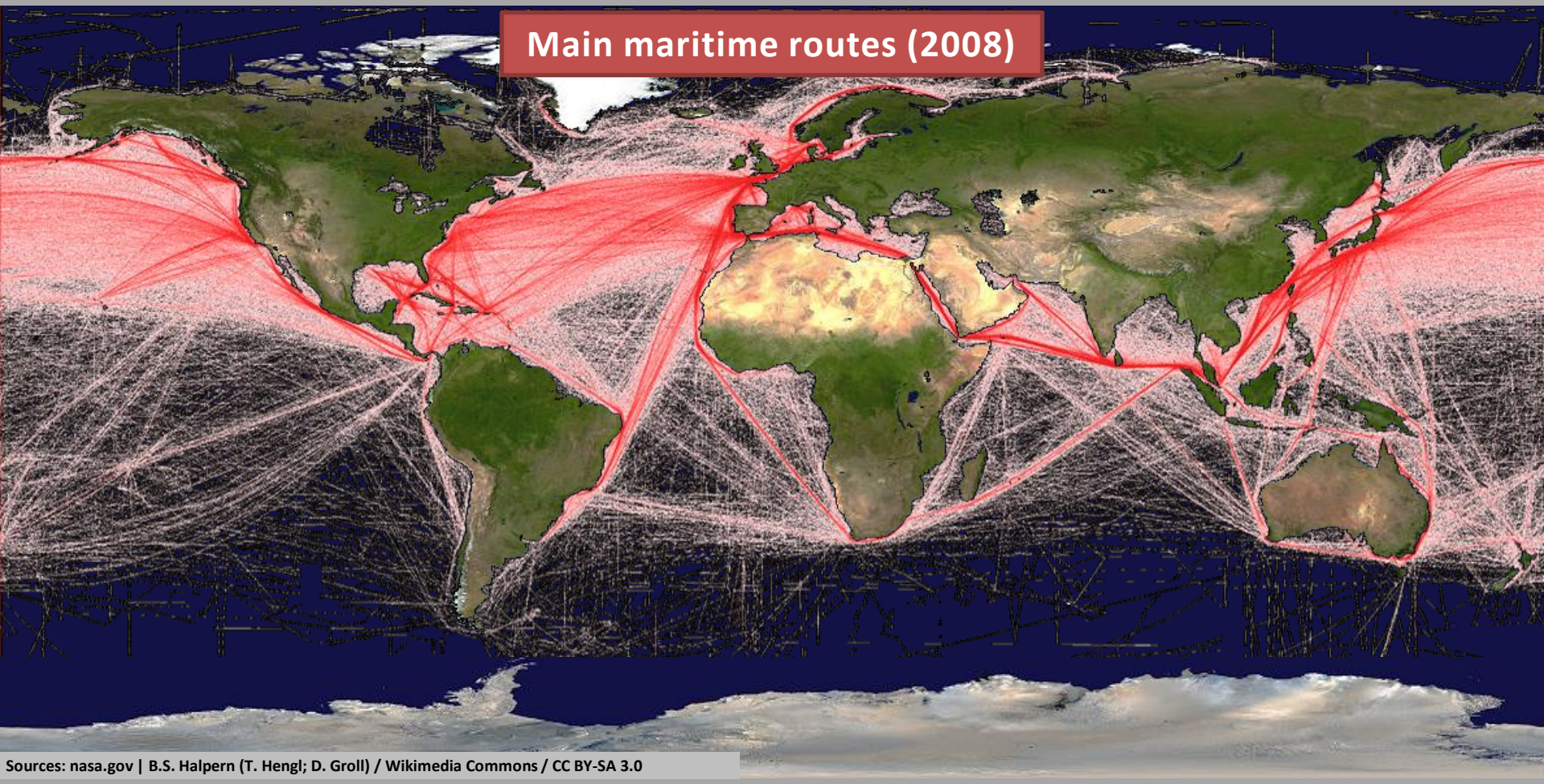
- **Oceans cover 3/4 of the Earth surface**



Source: nasa.gov

Why Maritime Surveillance?

- **Oceans cover 3/4 of the Earth surface**
- **About 90% of the world trade is transported by maritime routes**

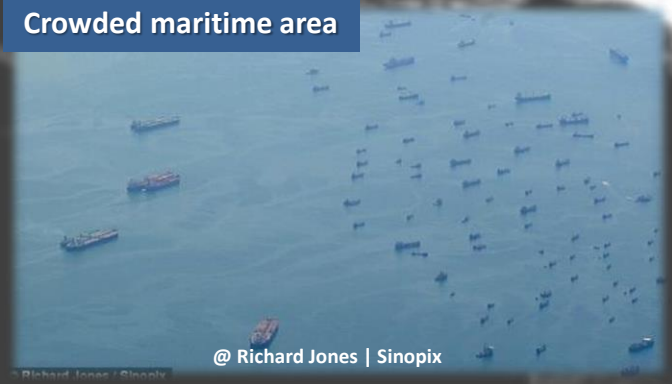


Sources: nasa.gov | B.S. Halpern (T. Hengl; D. Groll) / Wikimedia Commons / CC BY-SA 3.0

Why Maritime Surveillance?

- **Oceans cover 3/4 of the Earth surface**
- **About 90% of the world trade is transported by maritime routes**
- **Potentially dangerous environment with limited infrastructure**

Crowded maritime area



@ Richard Jones | Sinopix

Incident

Source: gcaptain.com

Shipwreck

Source: today24news.com

Security, safety of navigation, state law enforcement …

Piracy

Photo: EU

Illegal fishing

@ Lim Tae Hoon | Greenpeace

Cargo transshipment

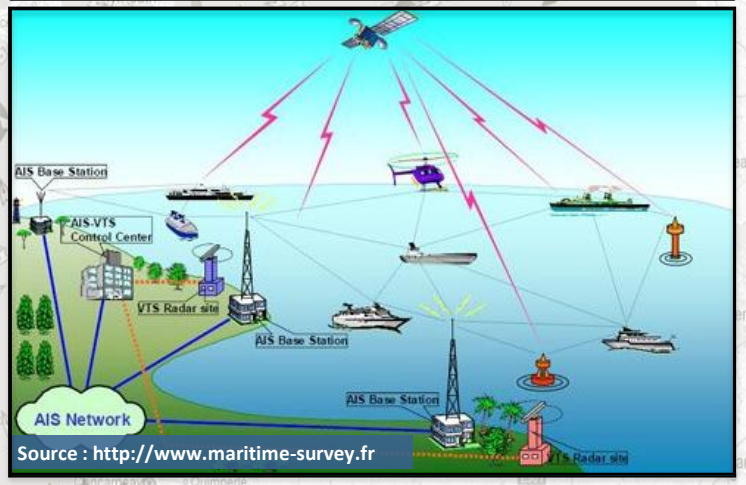
Source: maritime-executive.com | Greenpeace

Ship detection with cooperative and non-cooperative systems

Automatic Identification System (AIS)

- Telecommunication equipment
- Limited to cooperative vessels
- Ship information is encoded in AIS binary messages (id, position, heading, speed, size …)

AIS infrastructure concept



Cooperative system

Synthetic Aperture Radar (SAR)

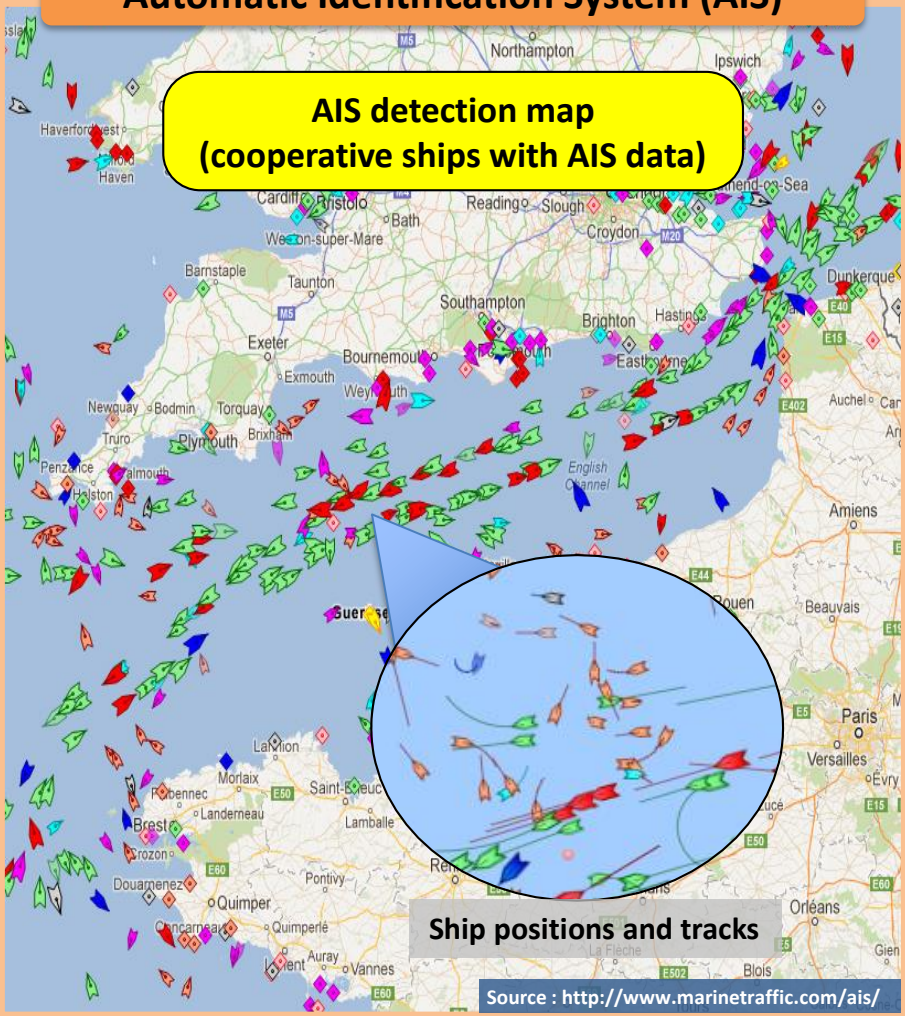
- Radar sensor
- Visible targets (cooperative or not)
- Information is limited to features extracted from radar data (e.g., ship size, heading, vessel type …)

SAR over satellite concept

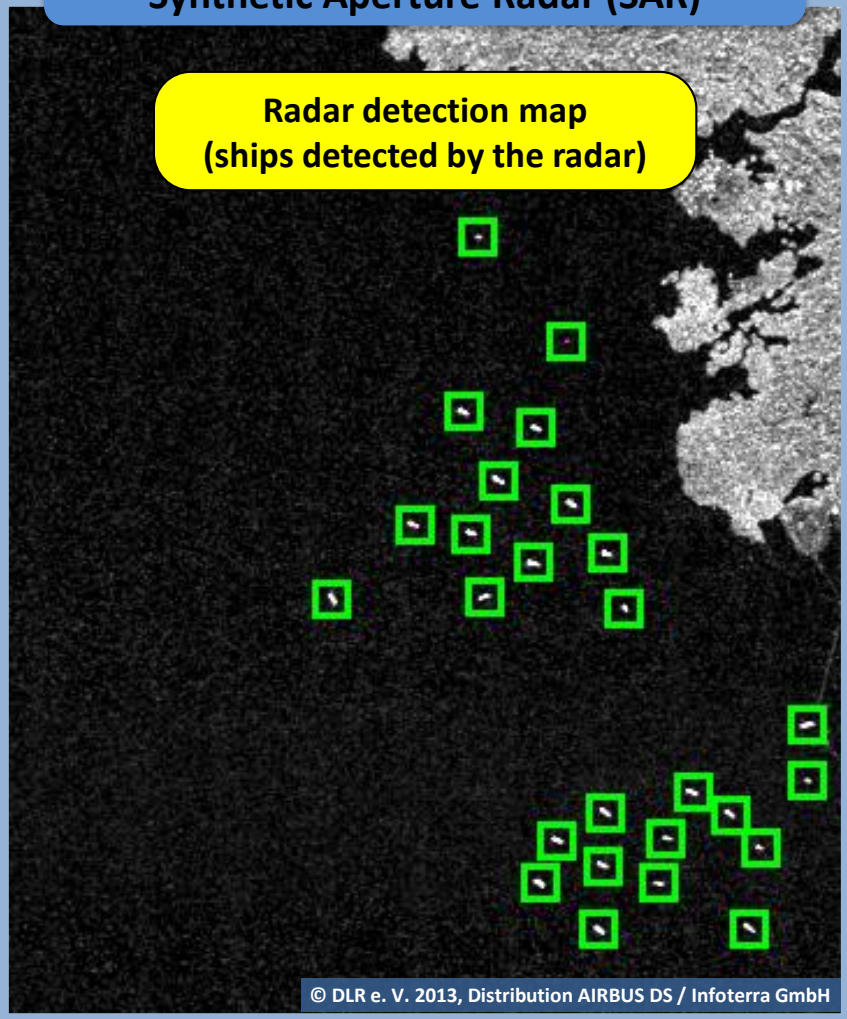
Non-cooperative system

Ship detection with cooperative and non-cooperative systems

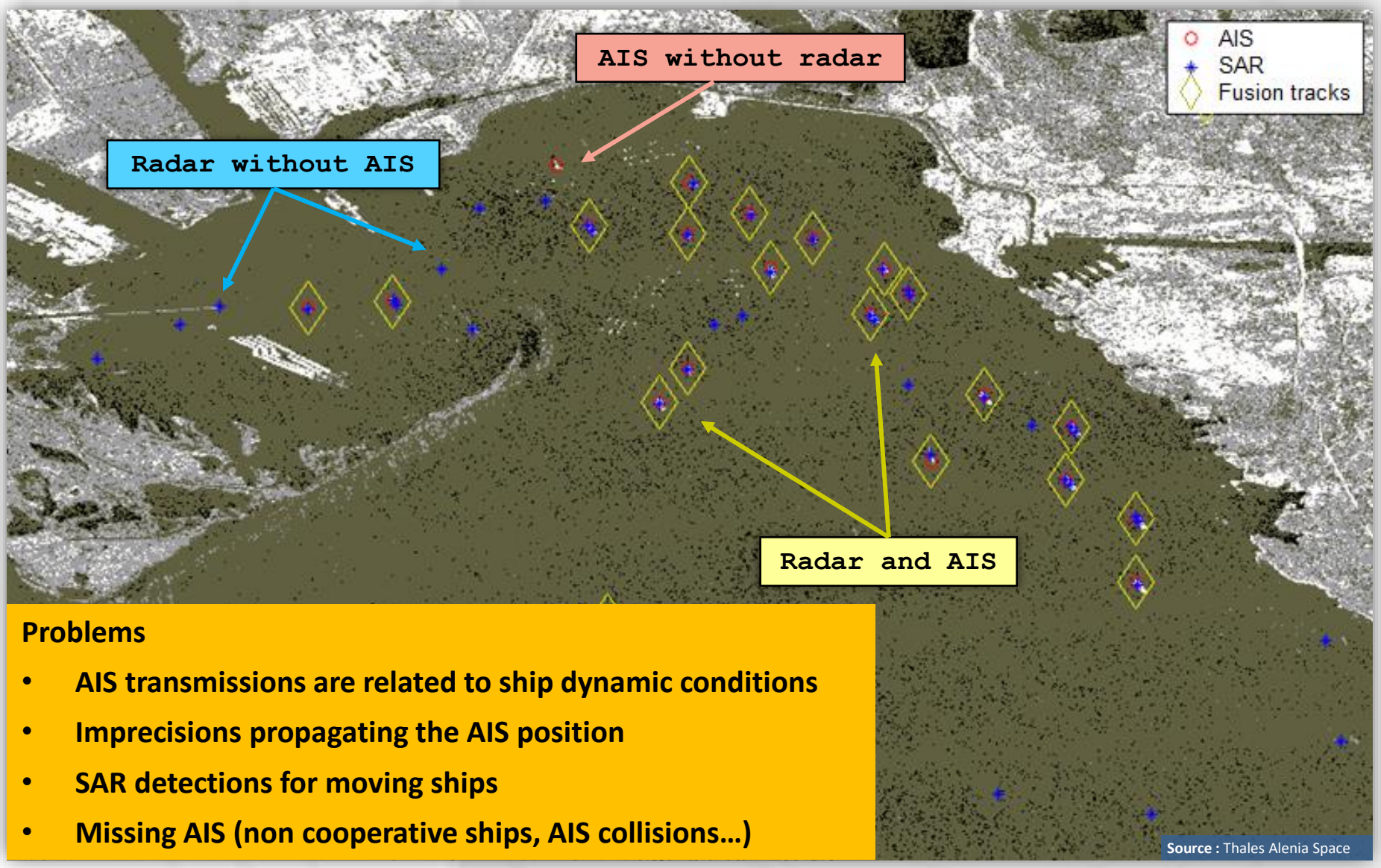
Automatic Identification System (AIS)



Synthetic Aperture Radar (SAR)



How to associate AIS and Radar data?



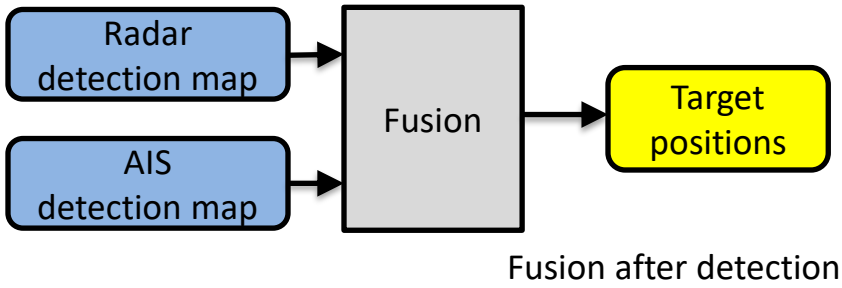
Problems

- **AIS transmissions are related to ship dynamic conditions**
- **Imprecisions propagating the AIS position**
- **SAR detections for moving ships**
- **Missing AIS (non cooperative ships, AIS collisions…)**

- **AIS and Radar processed data (classical fusion)**

Fusion of SAR and AIS detection maps

Classical fusion



Fusion after detection

M. Guerriero, et al , "Radar/AIS data fusion and SAR tasking for Maritime Surveillance," in Proc. Fusion 2008.

- AIS, Radar, anomaly detector

R.-M. Pelich, "Ship detection and characterization from SAR imagery linked with cooperative vessel tracking data," PhD Thesis, 2015.

- SAR detection for high prob. AIS positions
- SAR target classification using AIS

R. Grasso et al, "Performance Assessment of a Mathematical Morphology Ship Detection Algorithm for SAR Images through Comparison with AIS Data," in Proc. ISDA'2009.

- AIS-SAR association
- Ship detection, AIS validation as ground truth

Thesis contribution

- Improve ship detection using AIS and radar **raw** signals
- Outperform ship detection in difficult surveillance scenarios

Cargo transshipment

Source: maritime-executive.com | Greenpeace

Piracy

Small ship near a bigger one

Photo: EU

Detection of ships that are close distance

Source : Sea Shepherd

Crowded maritime area

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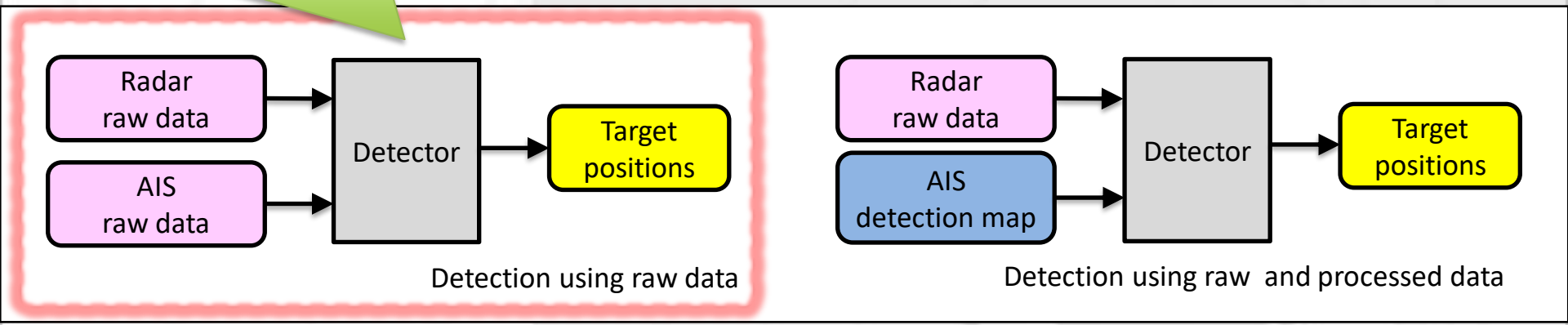
Chapter 2
Raw radar and raw AIS data

- **AIS and Radar processed data (classical fusion)**
- **AIS and Radar raw data**

Fusion before detection

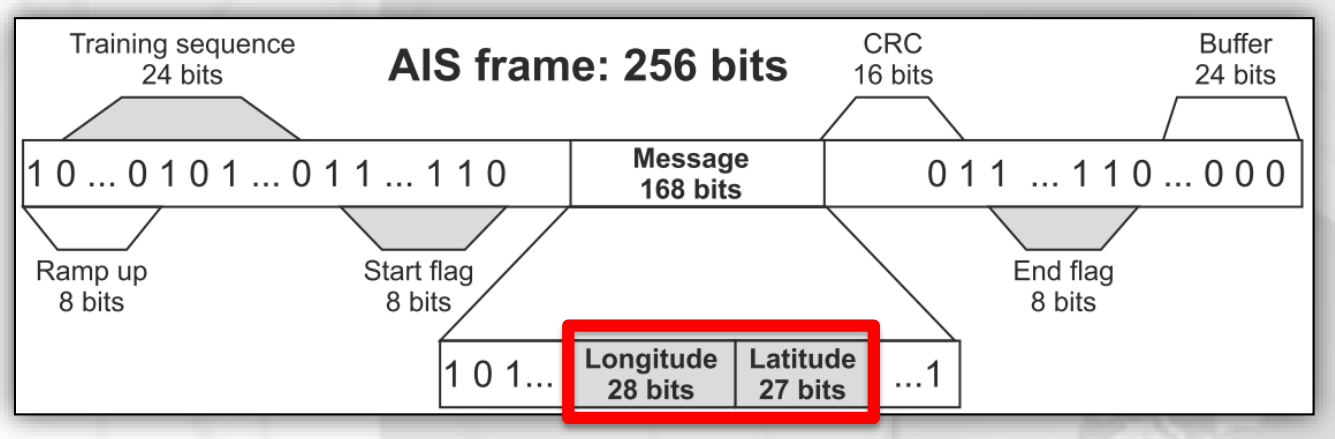
F. M. Vieira *et al.*, "Ship detection using SAR and AIS raw data for maritime surveillance," in Proc. *EUSIPCO'2016.*



- **Improved detection performance**

Automatic Identification System (AIS)

- **Maritime VHF radio**
- **Automatically broadcasts ship information (identification, size, position, heading, speed …)**
- **AIS is mandatory (IMO/SOLAS requirements) with some exceptions**



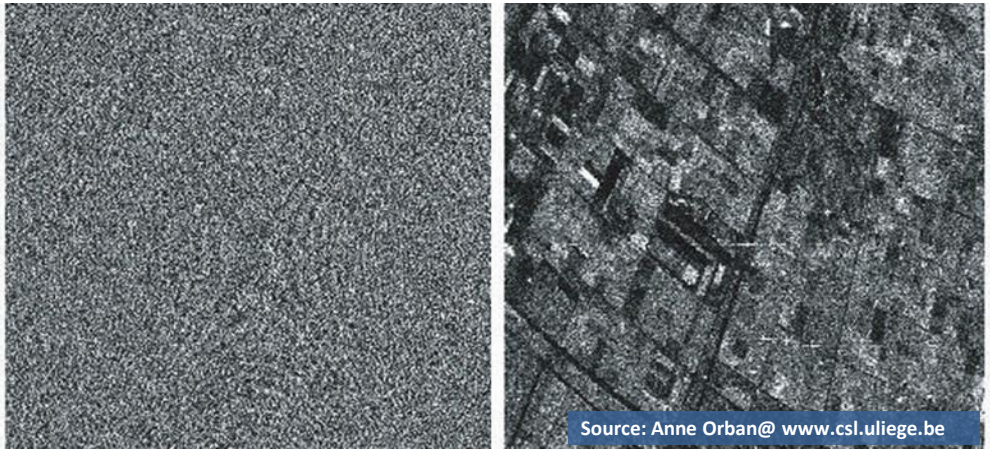
Ship position θ

AIS is required for all passenger ships and cargo ships of 300 gross tonnage and upwards

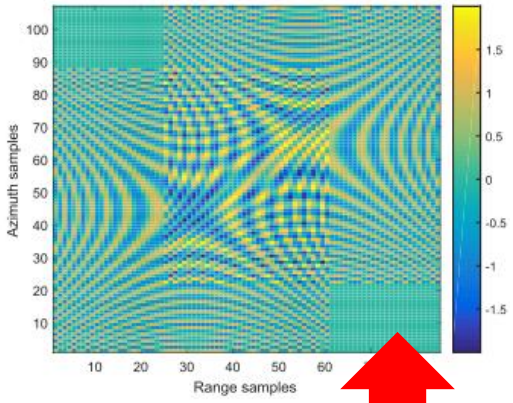
AIS specifications (class A)
GMSK modulation
SOTDMA access scheme
AIS1 (Ch. A) : 161.975MHz
AIS2 (Ch. B) : 162.025MHz
25kHz channels
2250 time slots per minute
9.6 kbps transmission rate

Synthetic Aperture Radar (SAR)

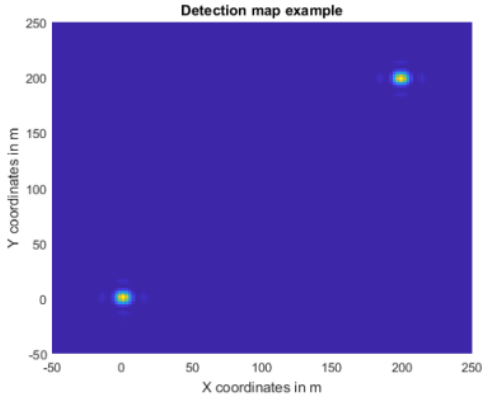
Difference between raw (left) and processed (right) SAR data



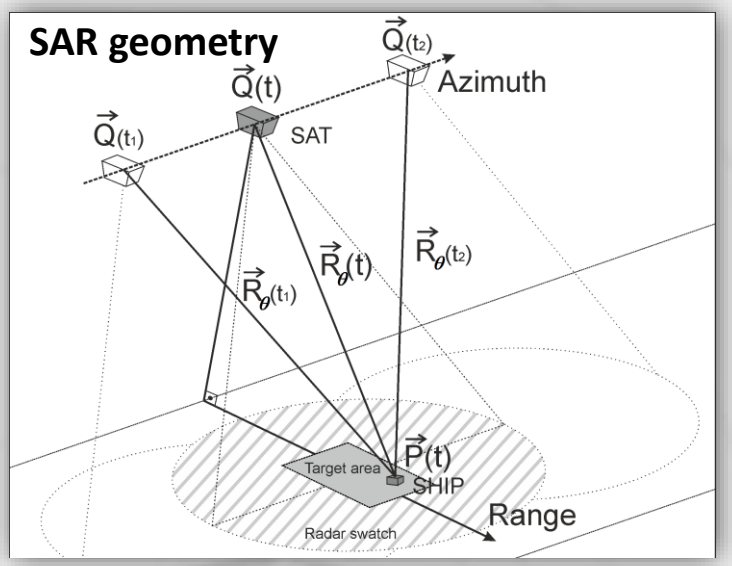
Point target radar raw signal (y_{rad})



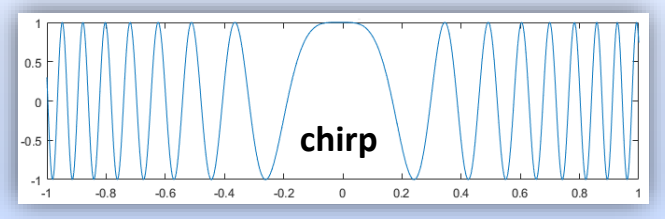
Radar detection map (before thresholding)



Radar raw signal



LFM signal (chirp): $\psi(t) = 1_T(t)e^{j\gamma t^2}$



Transmitted signal (Np pulses)

$$s(t) = \sum_{h=1}^{N_P} \psi(t - hT_i)e^{j2\pi f_0 t}$$

Raw signal for a target at θ

$$Ar(t) = As(t - \tau_\theta(t))$$

(delay) $\tau_\theta(t) = 2\|R_\theta(t)\|/c$

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Models considering raw data

Measurement vectors

$$\boldsymbol{y}_{\text{AIS}} = \beta \boldsymbol{b}(\boldsymbol{\theta}) + \boldsymbol{n}_{\text{AIS}}$$
$$\boldsymbol{y}_{\text{rad}} = \alpha \boldsymbol{a}(\boldsymbol{\theta}) + \boldsymbol{n}_{\text{rad}}$$

α, β : unknown complex signal amplitudes

Signal vectors

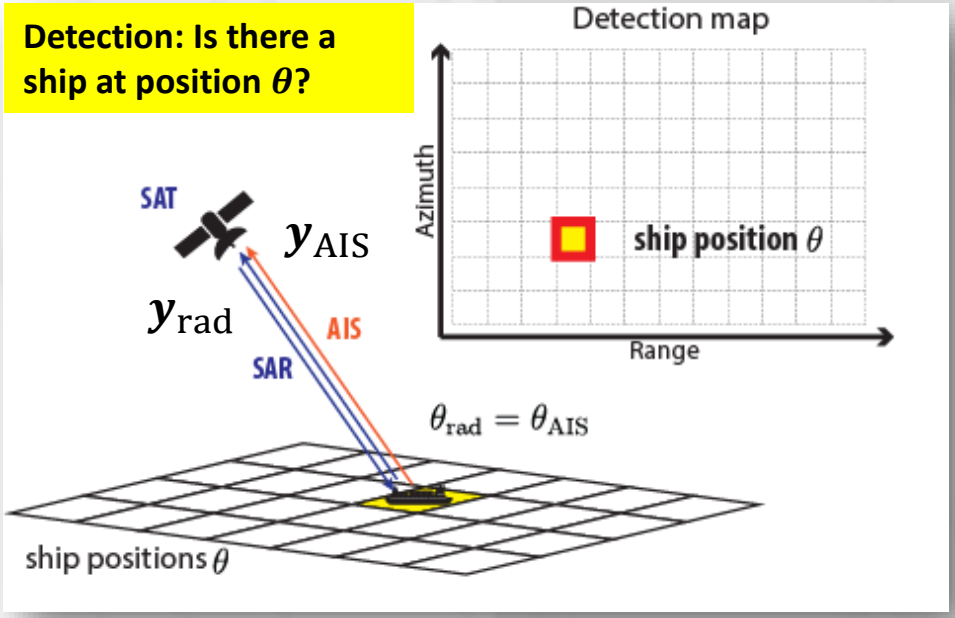
$\boldsymbol{b}(\boldsymbol{\theta})$ = AIS signal vector for a ship at $\boldsymbol{\theta}$

$$\boldsymbol{a}(\boldsymbol{\theta}) = (r(t_1), ..., r(t_{N_{\text{rad}}}))^T$$

$(t_1, ..., t_{N_{\text{rad}}})$: radar sampling times

$r(t)$: radar signal sample for a ship at $\boldsymbol{\theta}$

Detection: Is there a ship at position $\boldsymbol{\theta}$?



Noise vectors

$$\boldsymbol{n}_{\text{AIS}} \sim \mathcal{CN}\left(0, \sigma^2_{\text{AIS}} \boldsymbol{I}_{N_{\text{AIS}}}\right)$$
$$\boldsymbol{n}_{\text{rad}} \sim \mathcal{CN}\left(0, \sigma^2_{\text{rad}} \boldsymbol{I}_{N_{\text{rad}}}\right)$$

Detector for raw AIS and Radar data

Detector considering raw AIS and radar signals

(known noise power case)

Radar	Joint AIS/Radar

Binary hypothesis test

$$\begin{cases} H_0 : \alpha = 0, \text{(absence of ship)} \\ H_1 : \alpha \neq 0, \text{(presence of ship)} \end{cases}$$

$$\begin{cases} H_0 : \alpha = \beta = 0, \text{(absence of ship)} \\ H_1 : \alpha \neq 0, \beta \neq 0, \text{(presence of ship)} \end{cases}$$

Generalized likelihood ratio test (GLRT)

$$\frac{p(\boldsymbol{y}_{\text{rad}}|\hat{\alpha}, \boldsymbol{\theta}, H_1)}{p(\boldsymbol{y}_{\text{rad}}|\alpha = 0, \boldsymbol{\theta}, H_0)}$$

$$\frac{p(\boldsymbol{y}_{\text{AIS}}, \boldsymbol{y}_{\text{rad}}|\hat{\alpha}, \hat{\beta}, \boldsymbol{\theta}, H_1)}{p(\boldsymbol{y}_{\text{AIS}}, \boldsymbol{y}_{\text{rad}}|\alpha = 0, \beta = 0, \boldsymbol{\theta}, H_0)}$$

Detectors

$$T_{\text{rad}} = \frac{\boldsymbol{y}_{\text{rad}}^H \boldsymbol{P}_a(\boldsymbol{\theta}) \boldsymbol{y}_{\text{rad}}}{\sigma_{\text{rad}}^2} \underset{H_0}{\overset{H_1}{\gtrless}} \eta_{\text{rad}}$$

$$T_{\text{f}} = \frac{\boldsymbol{y}_{\text{AIS}}^H \boldsymbol{P}_b(\boldsymbol{\theta}) \boldsymbol{y}_{\text{AIS}}}{\sigma_{\text{AIS}}^2} + \frac{\boldsymbol{y}_{\text{rad}}^H \boldsymbol{P}_a(\boldsymbol{\theta}) \boldsymbol{y}_{\text{rad}}}{\sigma_{\text{rad}}^2} \underset{H_0}{\overset{H_1}{\gtrless}} \eta_f$$

Theoretical distributions

$$T_{\text{rad}} \sim \begin{cases} \frac{1}{2}\chi_2^2(0) & \text{under } H_0 \\ \frac{1}{2}\chi_2^2(\lambda_{\text{rad}}) & \text{under } H_1 \end{cases}$$

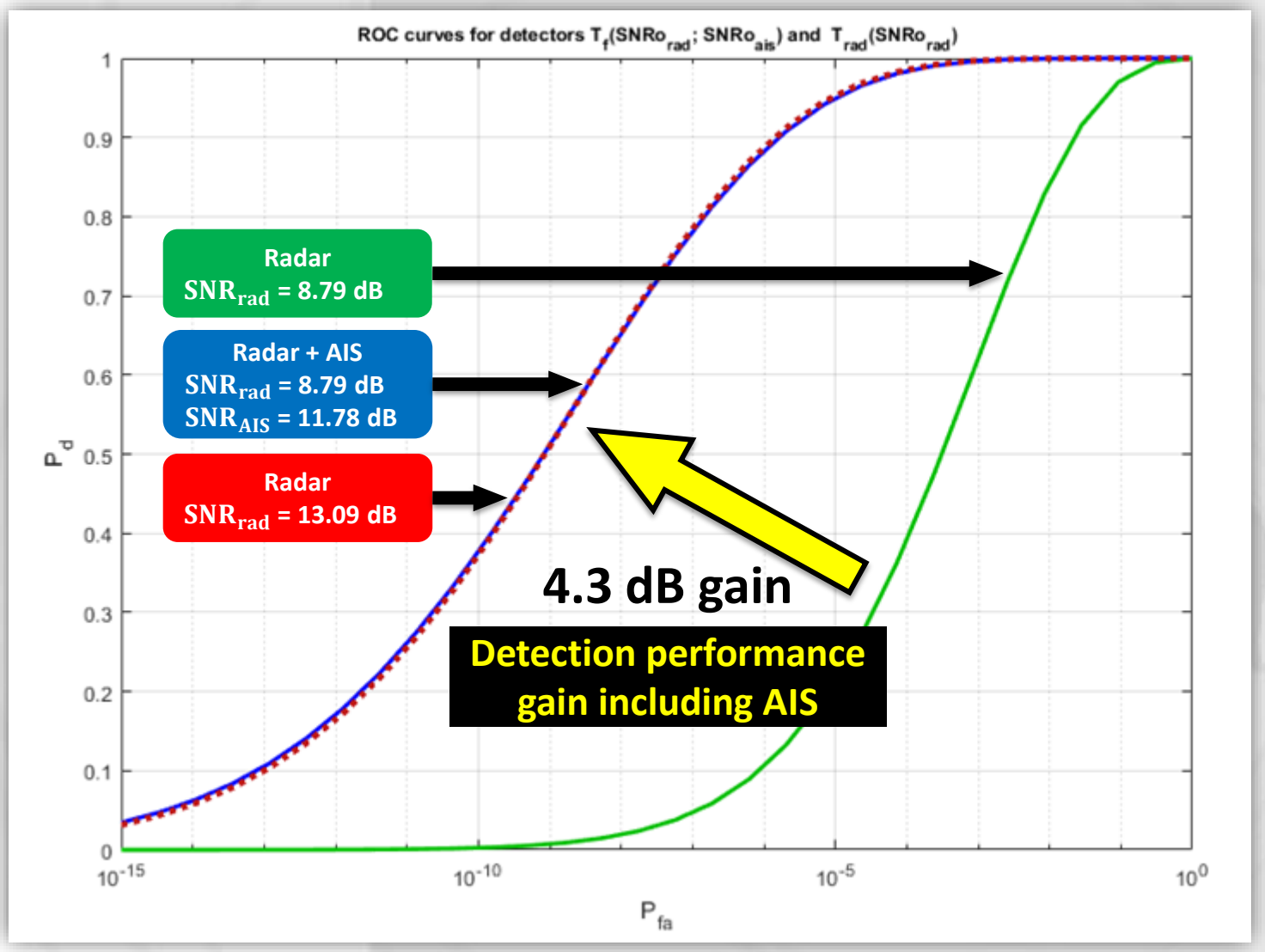
$$T_{\text{f}} \sim \begin{cases} \frac{1}{2}\chi_4^2(0) & \text{under } H_0 \\ \frac{1}{2}\chi_4^2(\lambda_{\text{AIS}} + \lambda_{\text{rad}}) & \text{under } H_1 \end{cases}$$

$$\lambda_{\text{AIS}} = 2\beta^2 \|\boldsymbol{b}(\boldsymbol{\theta})\|^2 / \sigma_{\text{AIS}}^2 = 2N_{\text{rad}}\,\text{SNR}_{\text{rad}} = 2\,\text{SNRo}_{\text{rad}}$$

$$\lambda_{\text{rad}} = 2\alpha^2 \|\boldsymbol{a}(\boldsymbol{\theta})\|^2 / \sigma_{\text{rad}}^2 = 2N_{\text{AIS}}\,\text{SNR}_{\text{AIS}} = 2\,\text{SNRo}_{\text{AIS}}$$

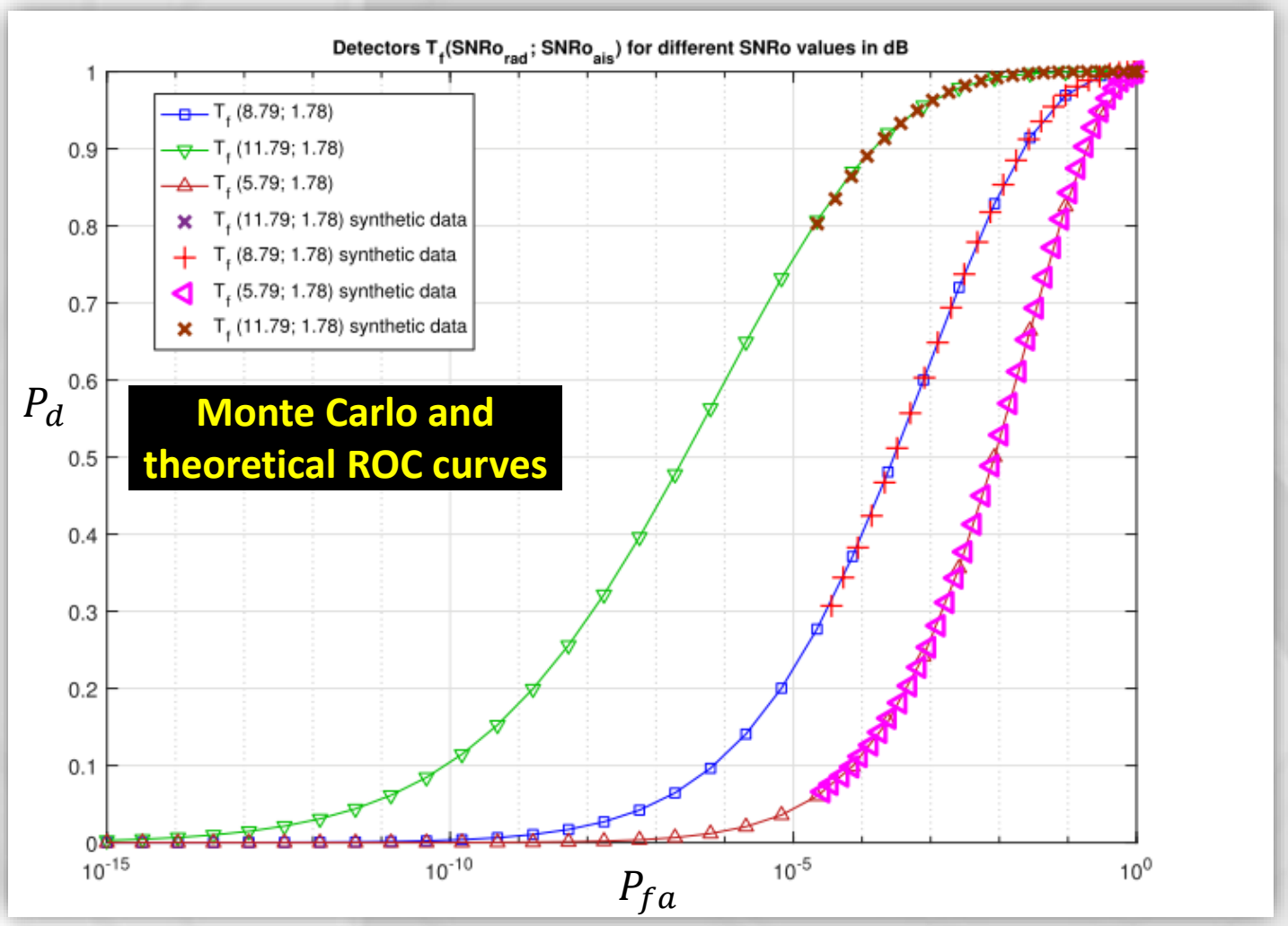
Detector for raw AIS and data

Theoretical ROC curves comparing the proposed and classical radar detectors



Detector for raw AIS and Radar data

Theoretical and simulated ROC curves for different SNR levels using the proposed detector



Limitation

Important assumptions

- AIS and radar signals come from the same target position
- Target is cooperative
- Many parameters have to be estimated in the AIS signal model

Computational intensive for real-time implementation

Alternative

Use AIS processed data

- Advantage: Do not require a model for AIS raw signals
- Drawback: Performance is sub-optimal

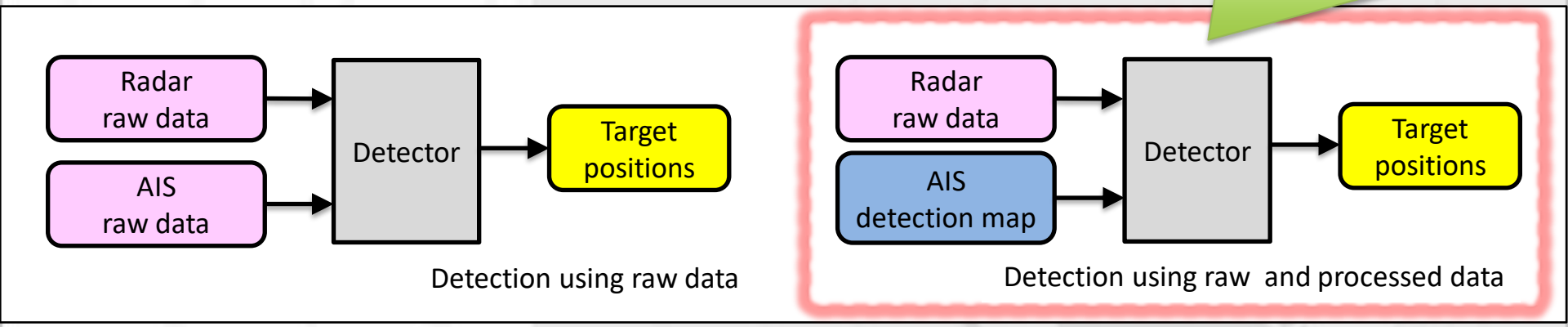
Chapter 3
Raw radar and processed AIS data

How to associate AIS and Radar?

- **AIS and Radar processed data (classical fusion)**
- **AIS and Radar raw data**
- **Processed AIS and raw Radar data (AIS detection map + raw Radar data)**

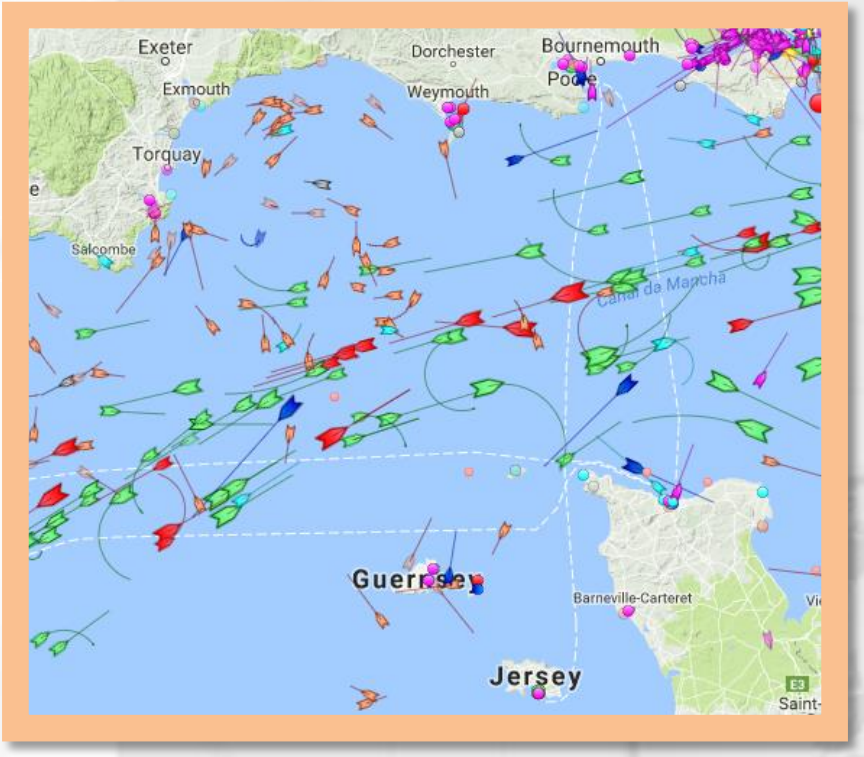
Fusion before Detection

F. M. Vieira *et al.*, "Improving synthetic aperture radar detection using the automatic identification system," In Proc. *IRS'2017*.



- **Classification of surveillance scenarios**
- **Detection in difficult scenarios**

AIS detection map (list of ship positions)



$$\text{Positions} = \theta_{\text{AIS}}$$

Interpolation errors are **lower** than the radar resolution (negligeable)

Problem statement

Idea: Some ship positions are provided by the AIS list

Radar measurement

$$\boldsymbol{y}_{\mathrm{rad}} = \boldsymbol{A}\left(\theta_{\mathrm{AIS}}\right)\boldsymbol{\alpha} + \beta\boldsymbol{a}\left(\boldsymbol{\theta}\right) + \boldsymbol{n}_{\mathrm{rad}}$$

Radar signal model

$$\boldsymbol{a}(\boldsymbol{\theta}) = \left(r(t_1), \ldots, r(t_{N_{\mathrm{rad}}})\right)^T$$

β : unknown complex signal amplitude

Noise vector

$$\boldsymbol{n}_{\mathrm{rad}} \sim \mathcal{CN}\left(0, \sigma_{\mathrm{rad}}^2 \boldsymbol{I}_{\boldsymbol{N}_{\mathrm{rad}}}\right)$$

This model assumes that the AIS list is valid (no detection error)

With detection errors, there are four hypotheses

H_0: No ship

H_1: Radar with AIS (cooperative ship)

H_2: Radar without AIS (non-cooperative ship)

H_3: AIS without radar (AIS bias, small ship with AIS*, false AIS…)

*AIS parameters may help separate H_3 (e.g., weak radar signature for a big ship)

How to handle errors (in the AIS detection list)?

Two-step procedure to discriminate targets

1. Confirmation of the AIS list (test exclusively $\boldsymbol{\theta}_{\mathrm{AIS}}$).
2. Detection of unknown ships (all $\boldsymbol{\theta} \neq \boldsymbol{\theta}_{\mathrm{AIS}}$).

Validation of AIS list

STEP 1: Test whether α_i is zero or not. **Decide between hypotheses $\boldsymbol{H_1}$ and $\boldsymbol{H_3}$**

$$\boldsymbol{y}_{\mathrm{rad}} = \boldsymbol{A}_{\sim i}\left(\boldsymbol{\theta}_{\mathrm{AIS}\sim i}\right)\boldsymbol{\alpha}_{\sim i} + \alpha_i \boldsymbol{a}\left(\boldsymbol{\theta}_i\right) + n_{\mathrm{rad}} \qquad \boldsymbol{\theta} \in \boldsymbol{\theta}_{\mathrm{AIS}}$$

The AIS list is validated

Detection of non-cooperative ships

STEP 2: Test for unknown ships. **Decide between hypotheses $\boldsymbol{H_2}$ and $\boldsymbol{H_0}$**

$$\boldsymbol{y}_{\mathrm{rad}} = \boldsymbol{A}\left(\boldsymbol{\theta}_{\mathrm{AIS}_{\mathrm{conf}}}\right)\boldsymbol{\alpha}_{\mathrm{conf}} + \beta \boldsymbol{a}\left(\boldsymbol{\theta}\right) + \boldsymbol{n}_{\mathrm{rad}} \qquad \boldsymbol{\theta} \notin \boldsymbol{\theta}_{\mathrm{AIS}}$$

The detector looks for new ships

Proposed Detector

Radar detector
(unknown noise power)

$$T_c = \frac{\boldsymbol{y}^H \boldsymbol{P_a}(\boldsymbol{\theta})\boldsymbol{y}}{\boldsymbol{y}^H \boldsymbol{P_a}^{\perp}(\boldsymbol{\theta})\boldsymbol{y}} \underset{H_0}{\overset{H_1}{\gtrless}} \eta_c$$

$$T_c \sim \begin{cases} \frac{1}{2}F_{2,2(n-1)}(0) & \text{under } H_0 \\ \frac{1}{2}F_{2,2(n-1)}(\lambda_c) & \text{under } H_1 \end{cases}$$

Radar detector using the AIS list

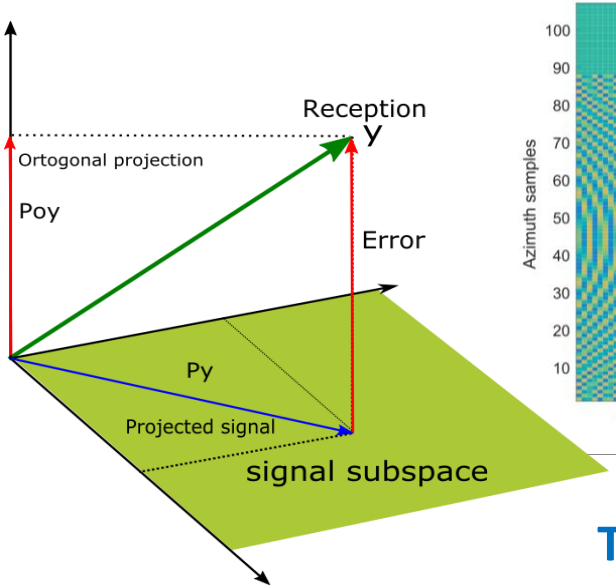
$$T_p = \frac{\|\acute{\boldsymbol{a}}^H \acute{\boldsymbol{y}}\|^2}{\|\acute{\boldsymbol{a}}\|^2 \|\acute{\boldsymbol{y}}\|^2} \underset{H_0}{\overset{H_1}{\gtrless}} \eta_p$$

$$\acute{\boldsymbol{a}} = \boldsymbol{P}_{\boldsymbol{A}}^{\perp}(\boldsymbol{\theta}_{\mathrm{AIS}})\boldsymbol{a}(\boldsymbol{\theta})$$
$$\acute{\boldsymbol{y}} = \boldsymbol{P}_{\boldsymbol{A}}^{\perp}(\boldsymbol{\theta}_{\mathrm{AIS}})\boldsymbol{y}(\boldsymbol{\theta})$$

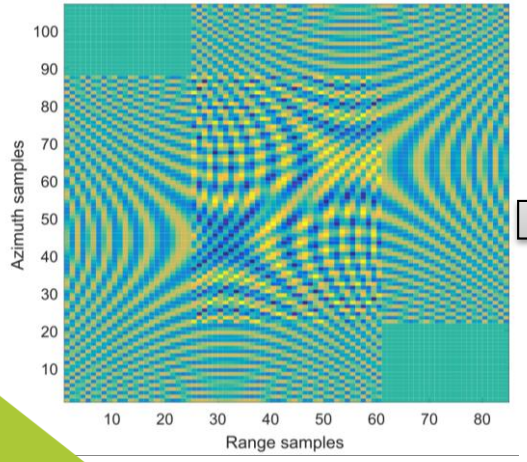
$$T_p \sim \begin{cases} \frac{1}{2}F_{2,2(n-k-1)}(0) & \text{under } H_0 \\ \frac{1}{2}F_{2,2(n-k-1)}(\lambda_p) & \text{under } H_1 \end{cases}$$

$$n = N_{\mathrm{rad}}, \mathrm{k} = \mathrm{N_{AIS}}$$
$$\lambda_p = \lambda_c = 2\mathrm{SNRo_{rad}}$$
(for AIS error < radar resolution)

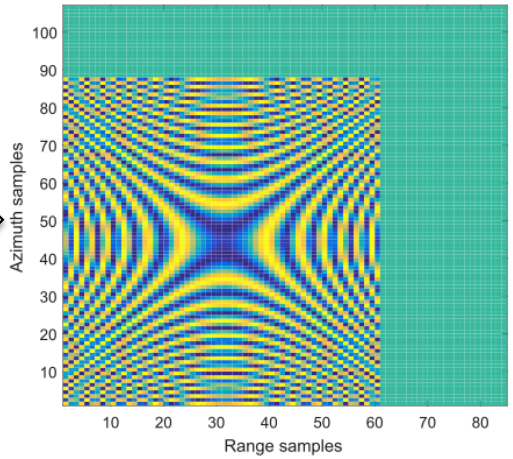
Orthogonal projection principle



$\boldsymbol{y}$



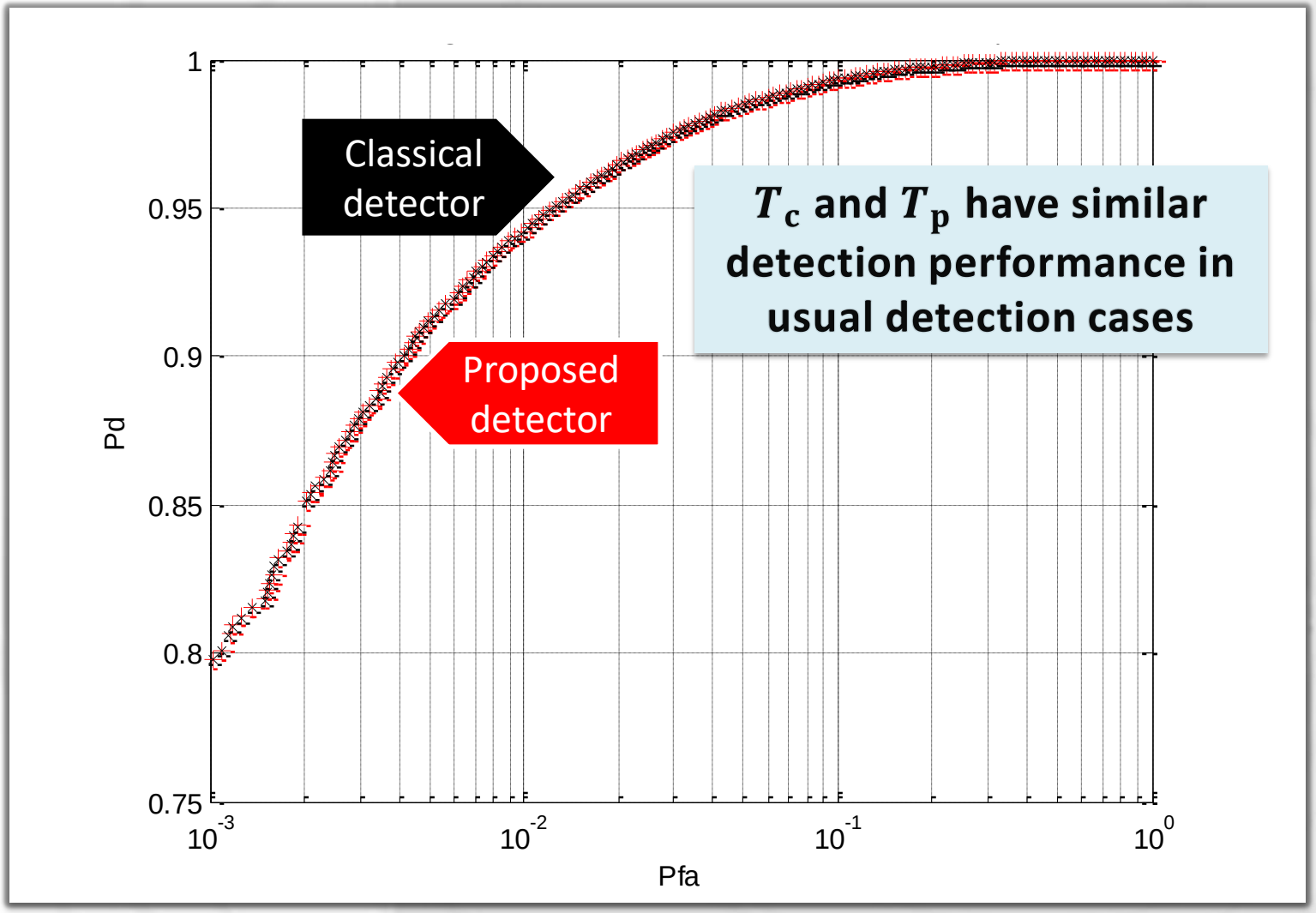
$\acute{\boldsymbol{y}}$



The raw radar signal is cleared from known ships

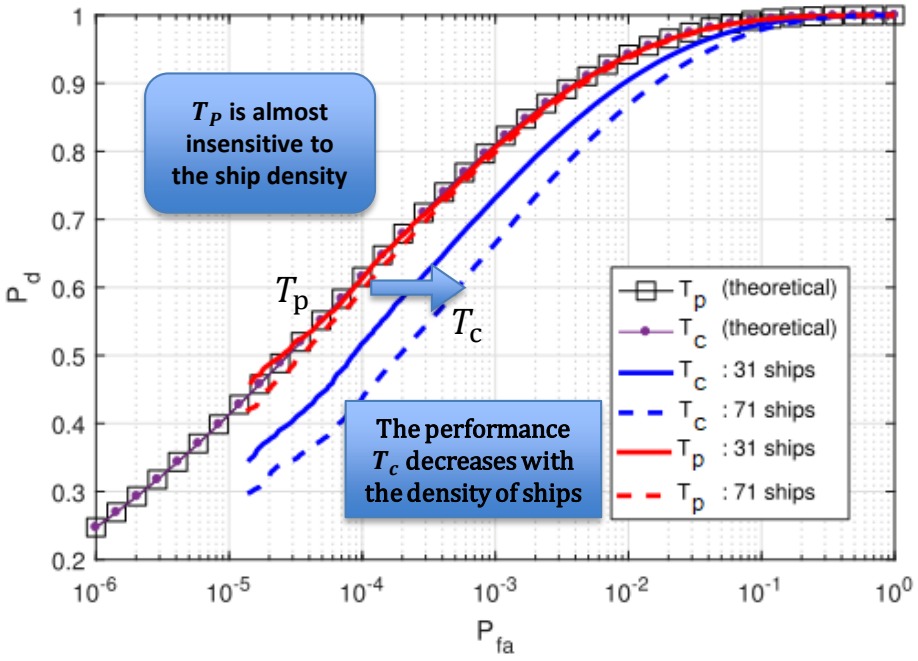
Removes the radar signatures of known ships (those at the AIS positions) from the measurement $\boldsymbol{y}$.

Detection performance in usual detection cases

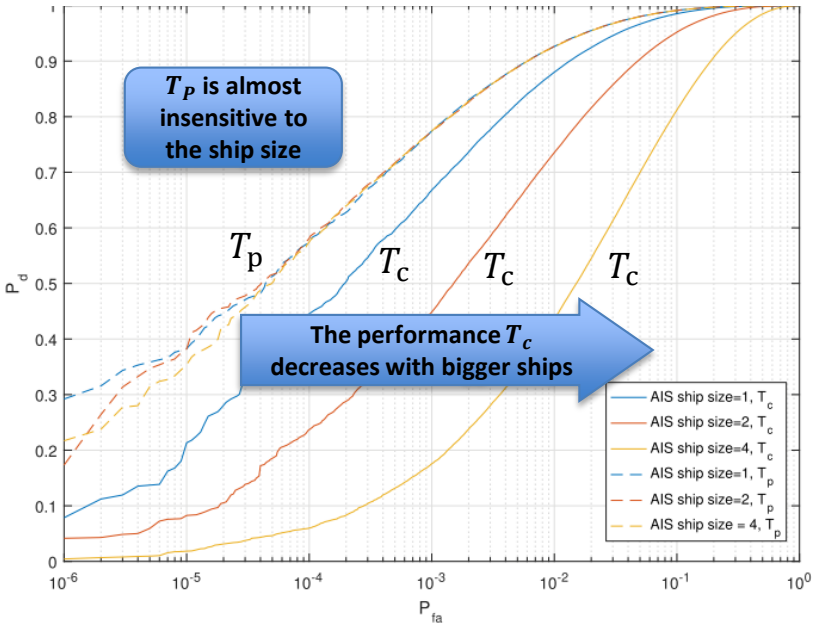


Detection performance in particular scenarios is improved

High ship density (cooperative ships)

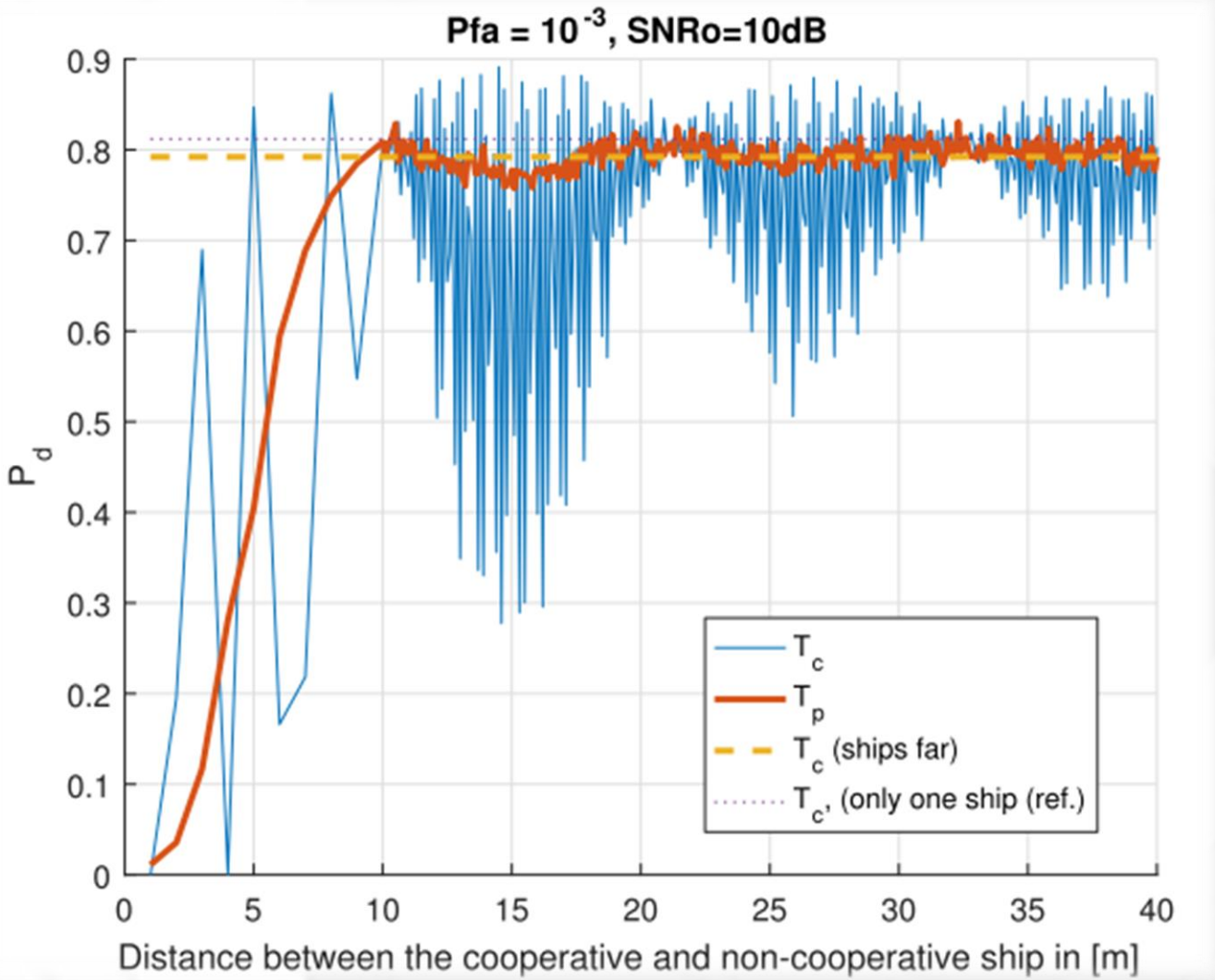


A non-cooperative small ship near a cooperative ship with different sizes



Performance comparison between detectors

Detection performance in particular scenarios

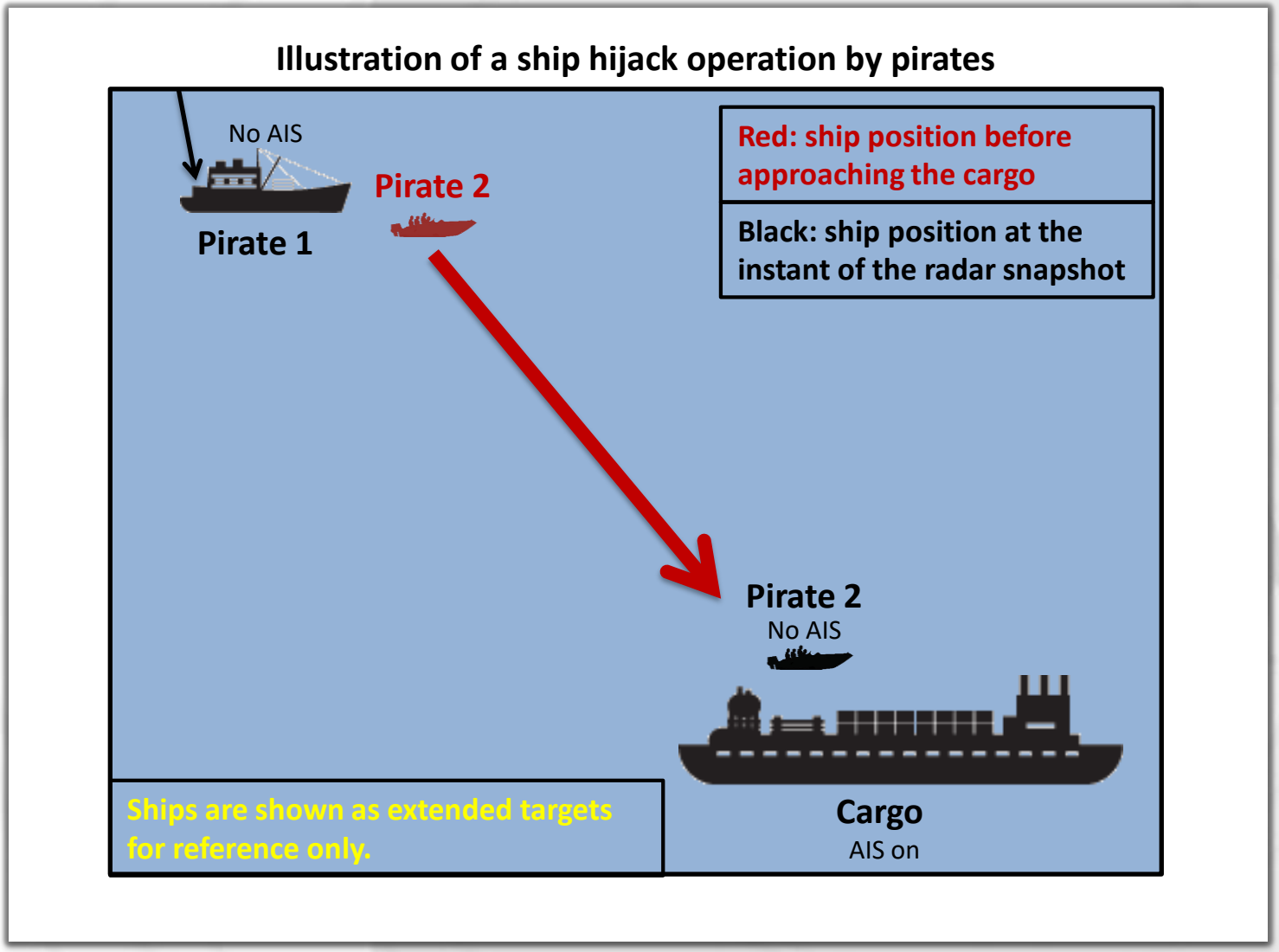


Chapter 4
Maritime surveillance scenarios and the proposed detector

Simulation of surveillance scenarios

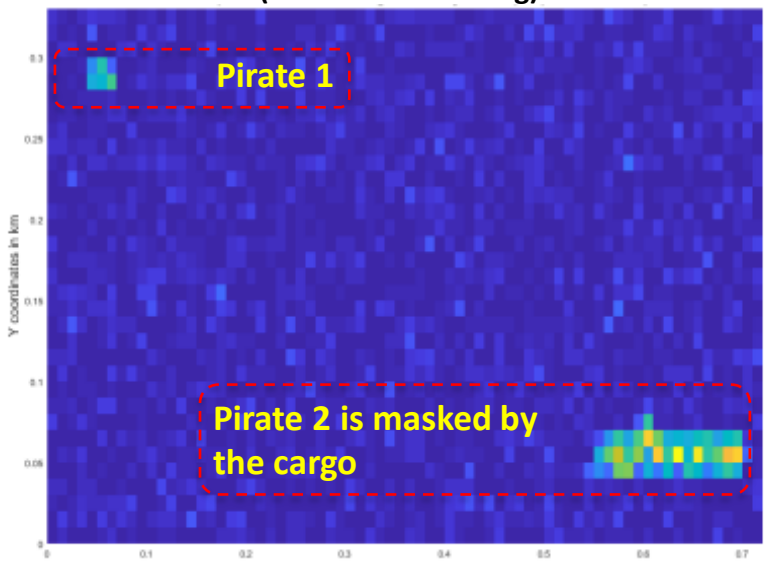
- **Piracy: ship hijack case**
- **Cargo transshipment**
- **Dense ship traffic scenario**

Piracy: Ship hijack

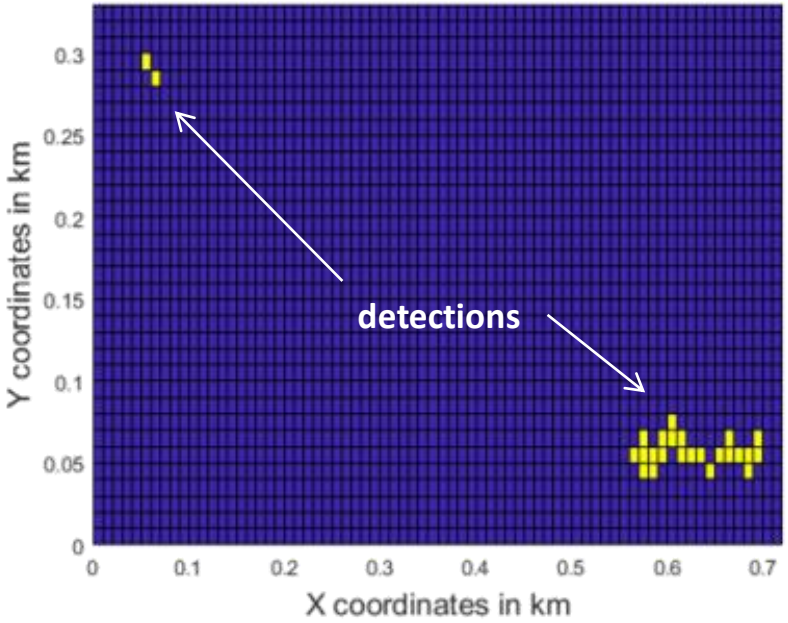


Classical radar detector

(before thresholding)

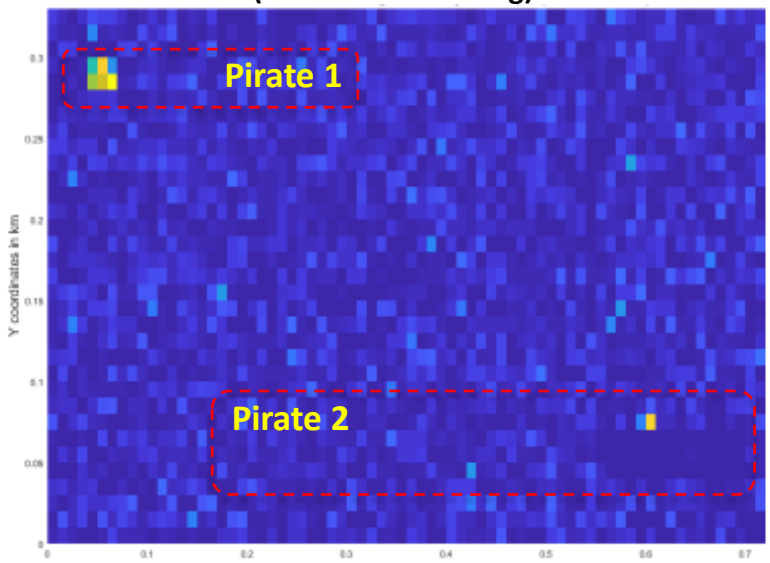


(after thresholding)

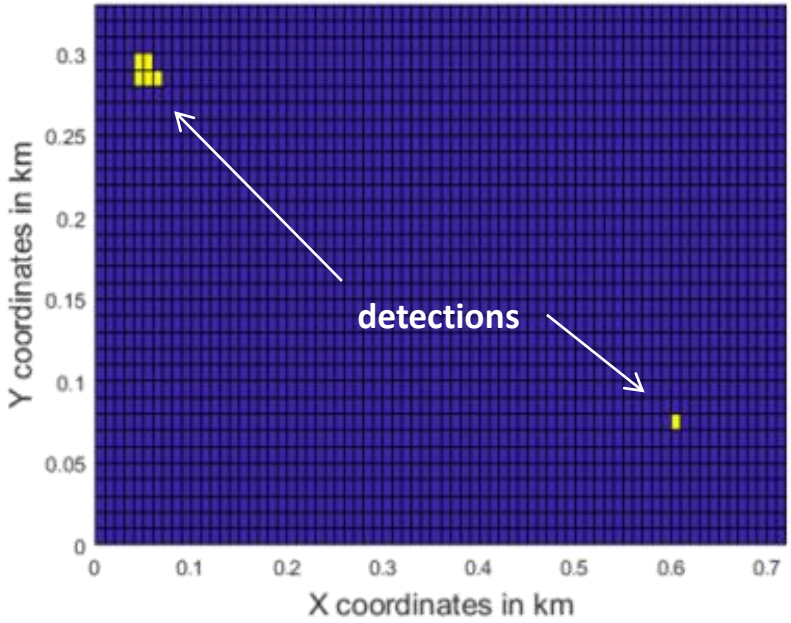


Proposed detector

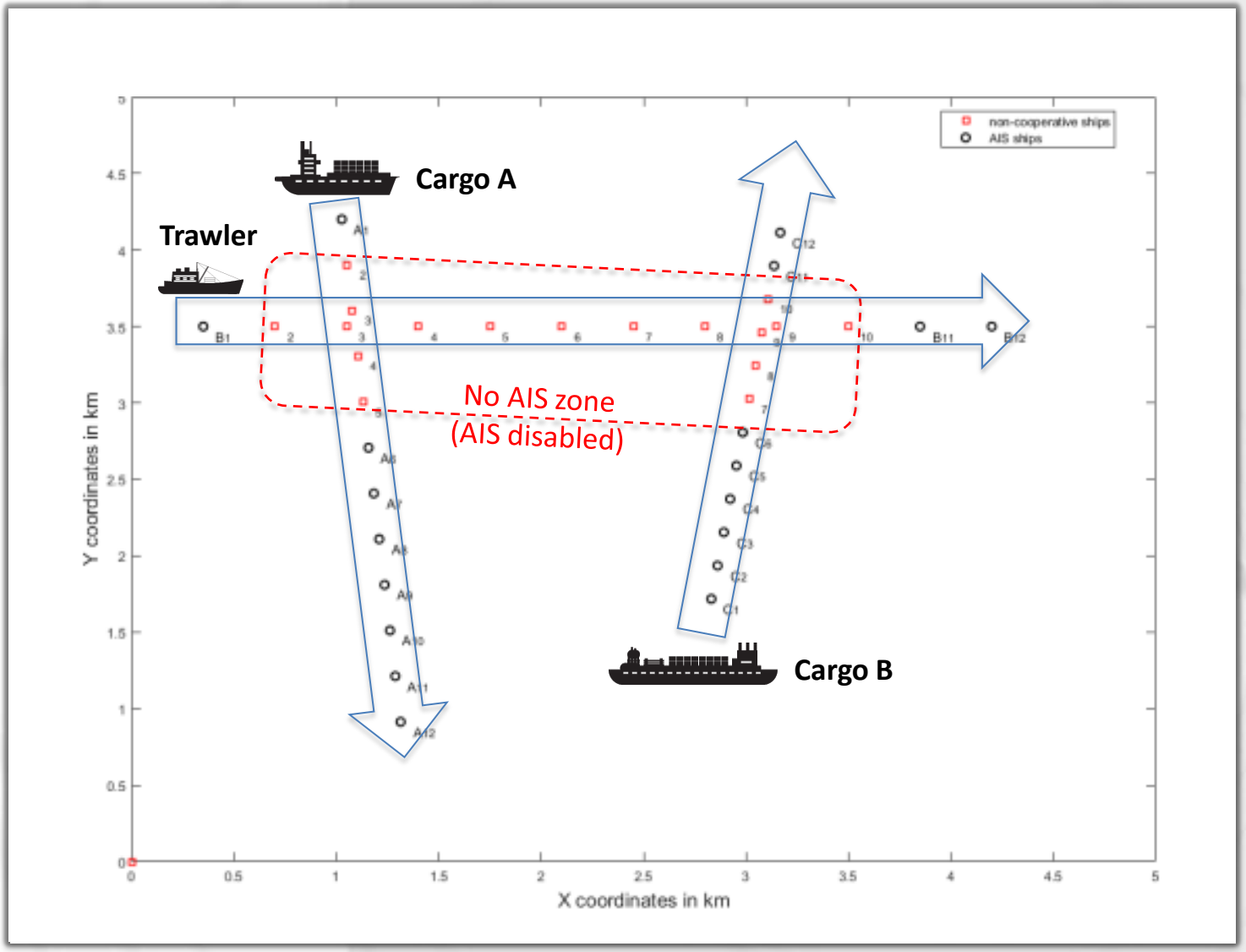
(before thresholding)



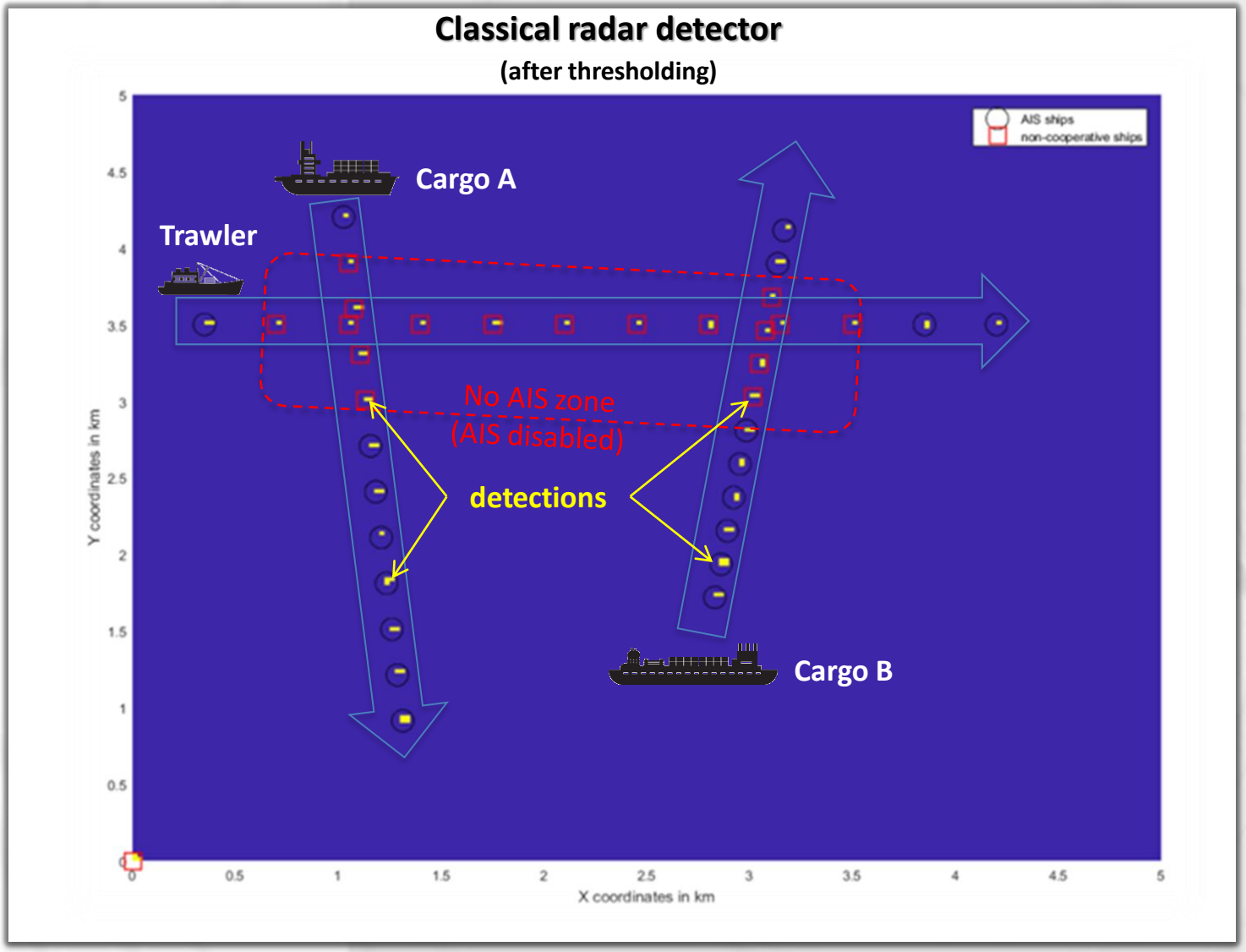
(after thresholding)



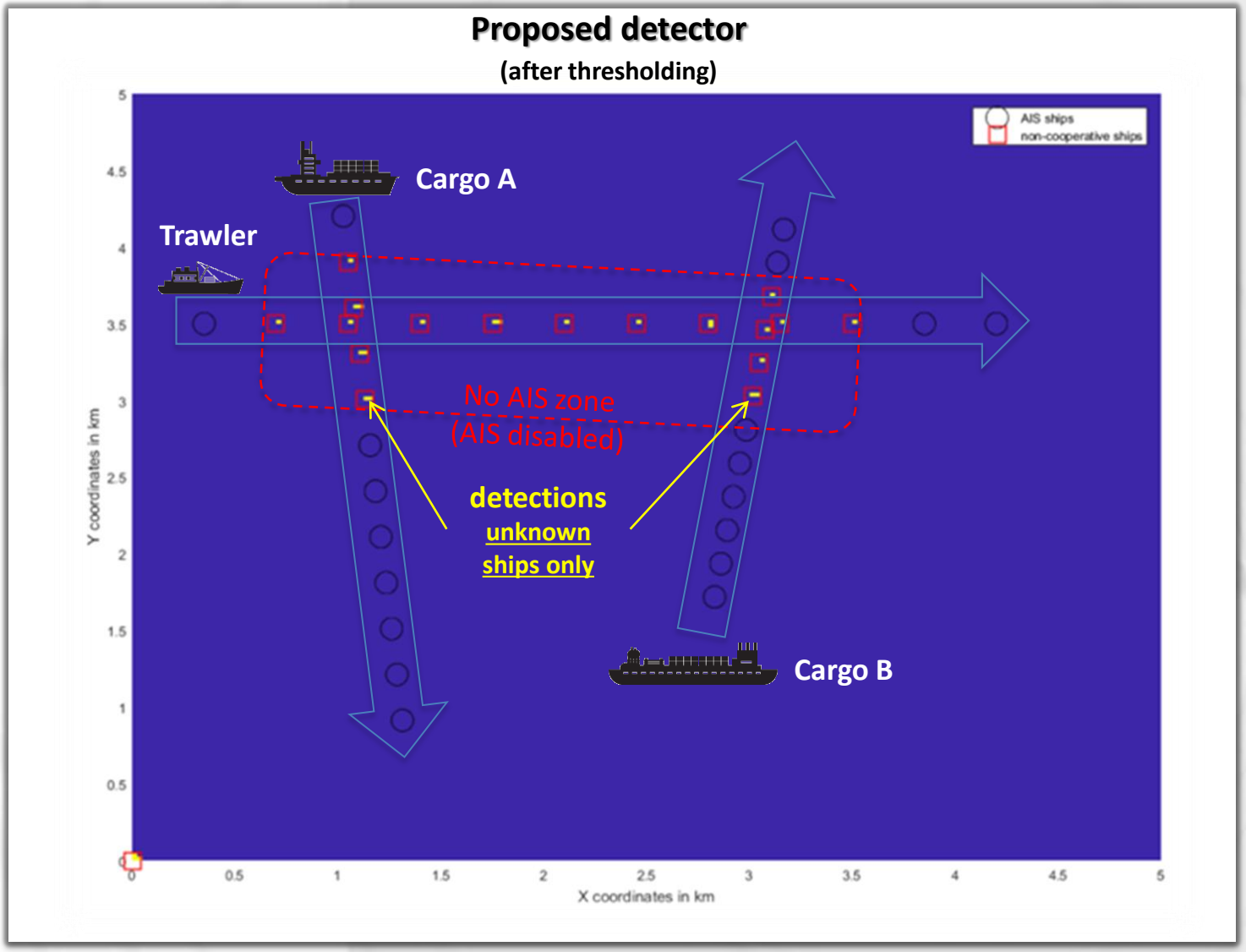
Cargo transshipment



Cargo transshipment

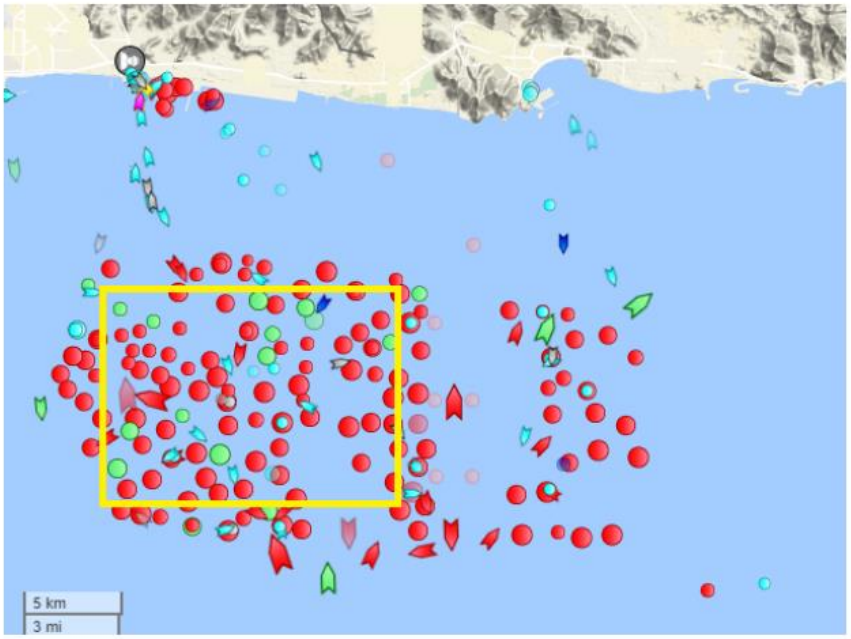


Cargo transshipment

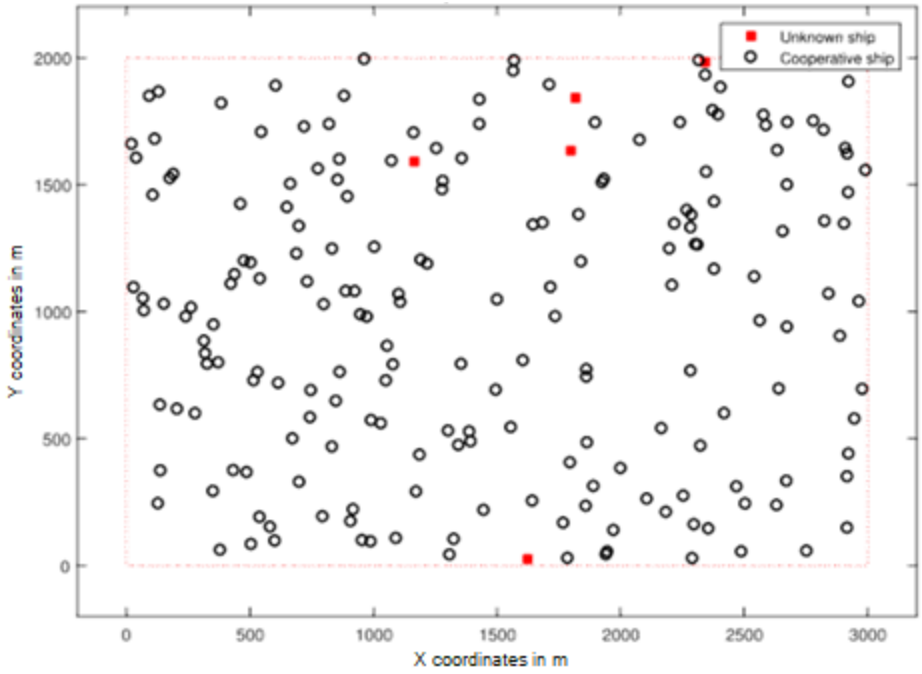


Dense ship traffic with cooperative ships

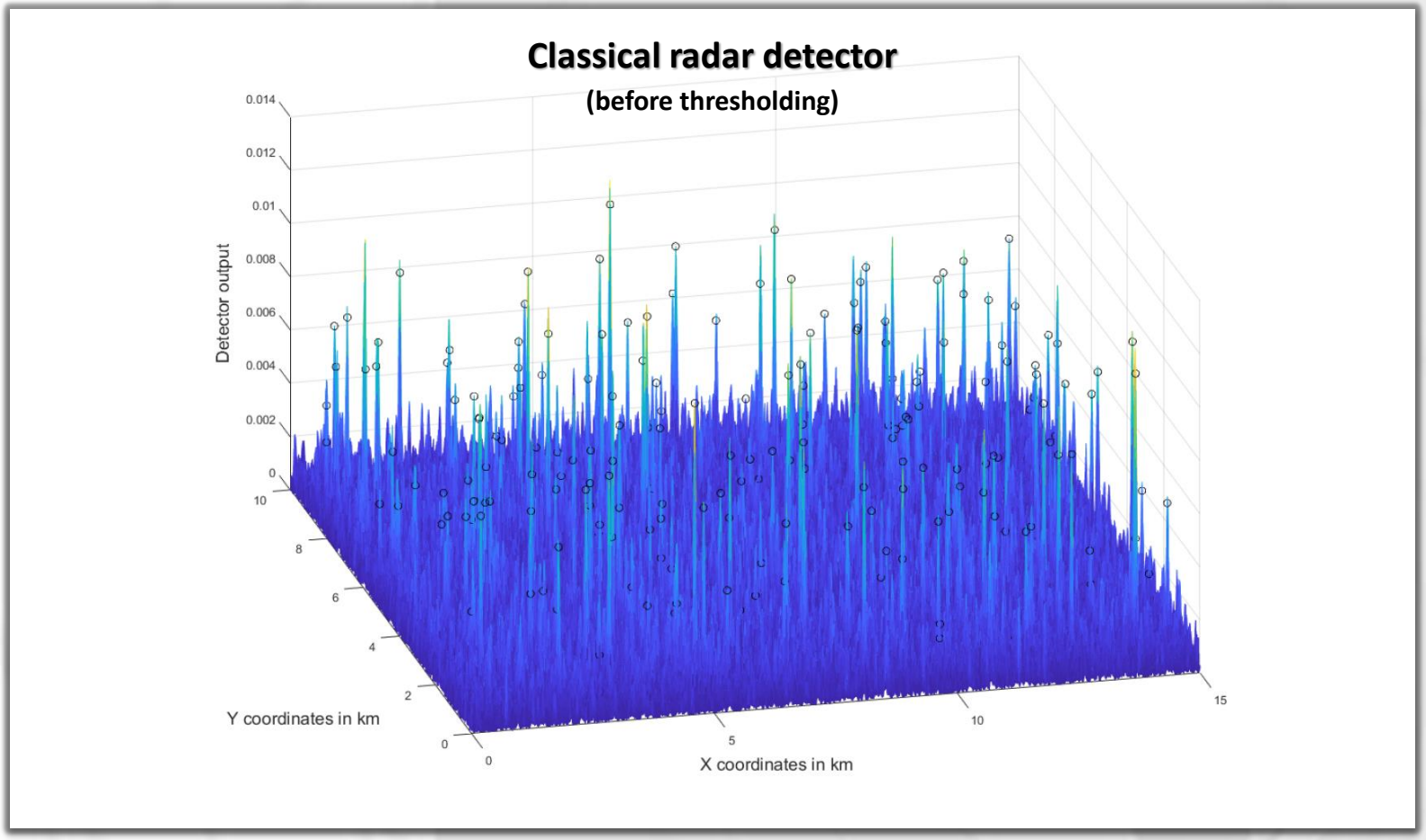
Ship traffic in a crowded region



Example of dense ship traffic

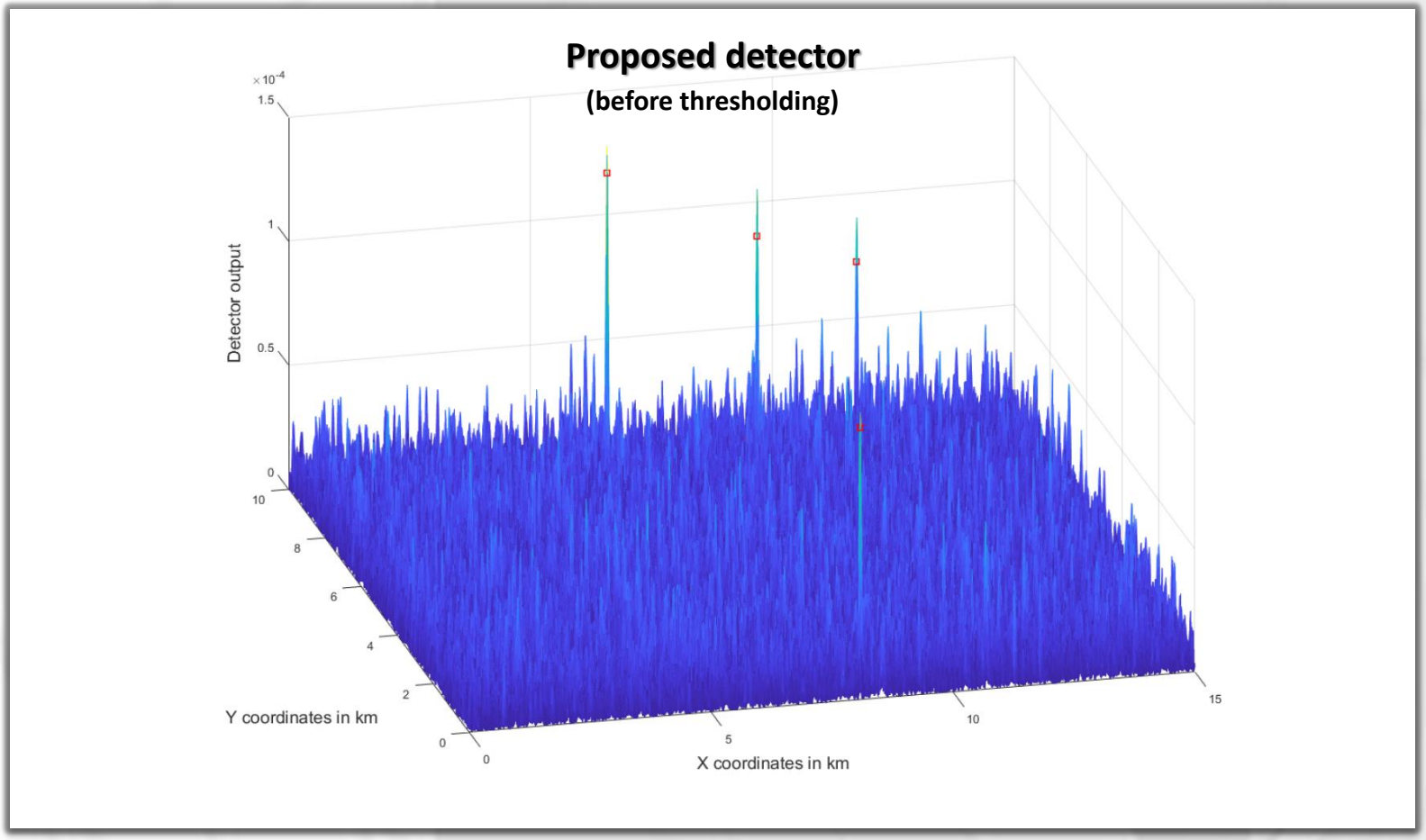


Dense ship traffic with cooperative ships



Detection map with all ships

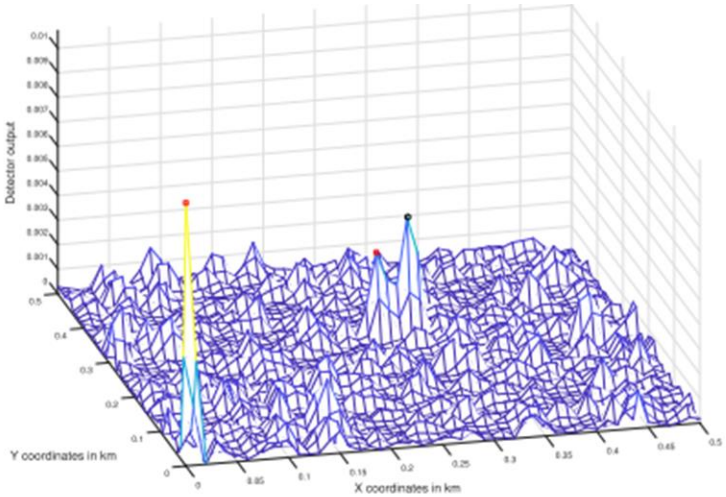
Dense ship traffic with cooperative ships



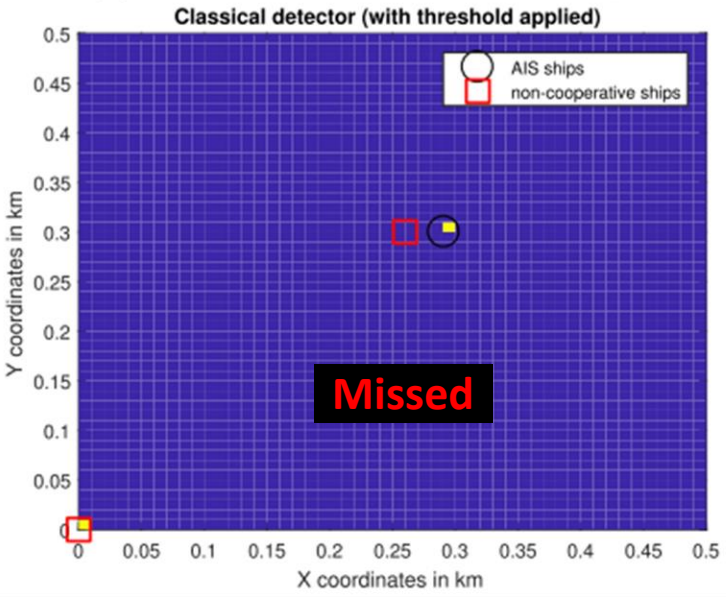
Detection map with the unknown ships

Two ships at close distance

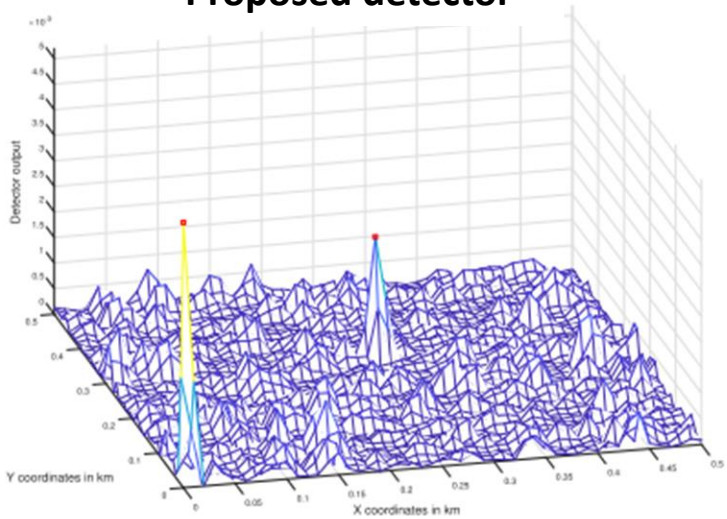
Classical radar detector



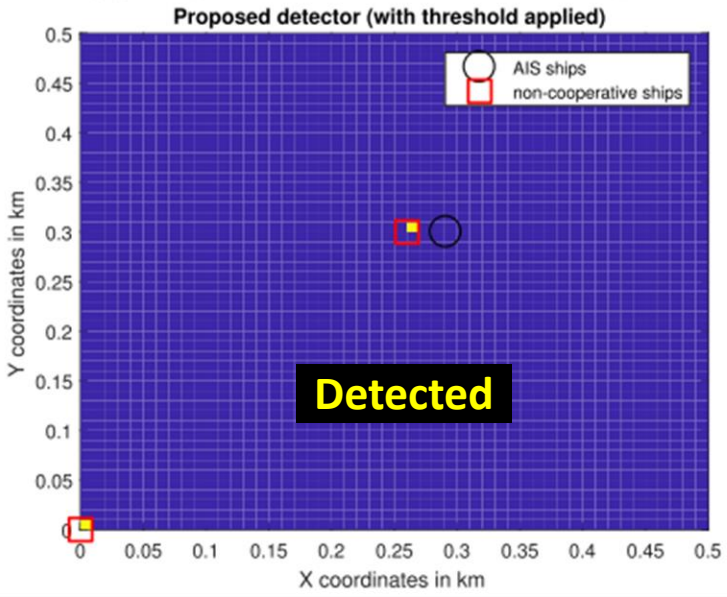
(a) Classical detector : Detection map.



Proposed detector

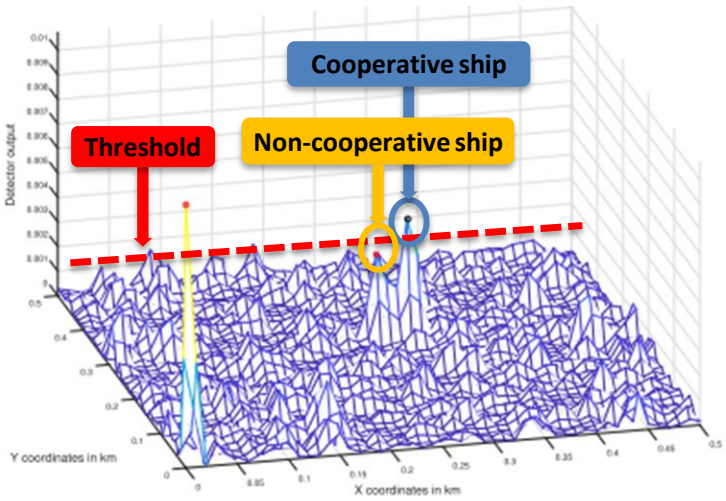


(b) Proposed detector : Detection map.

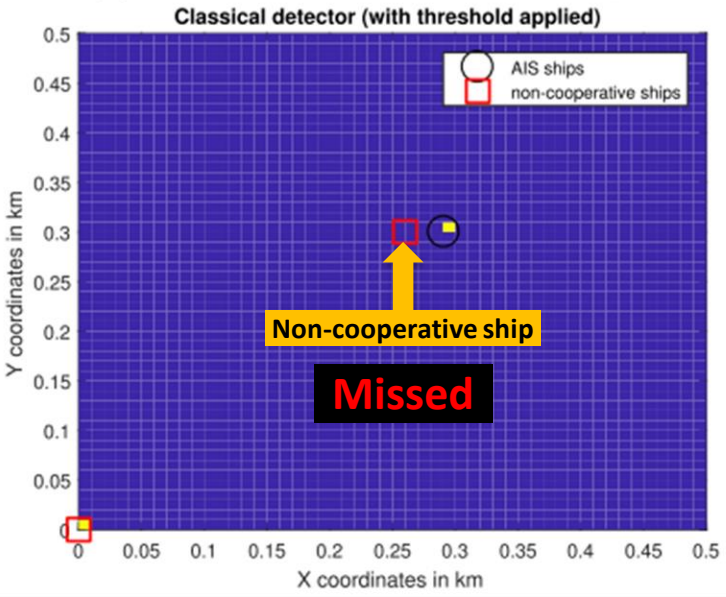


Two ships at close distance

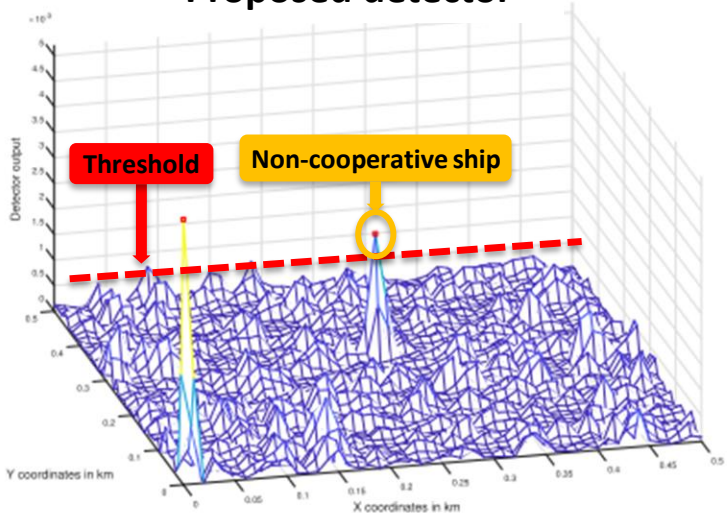
Classical radar detector



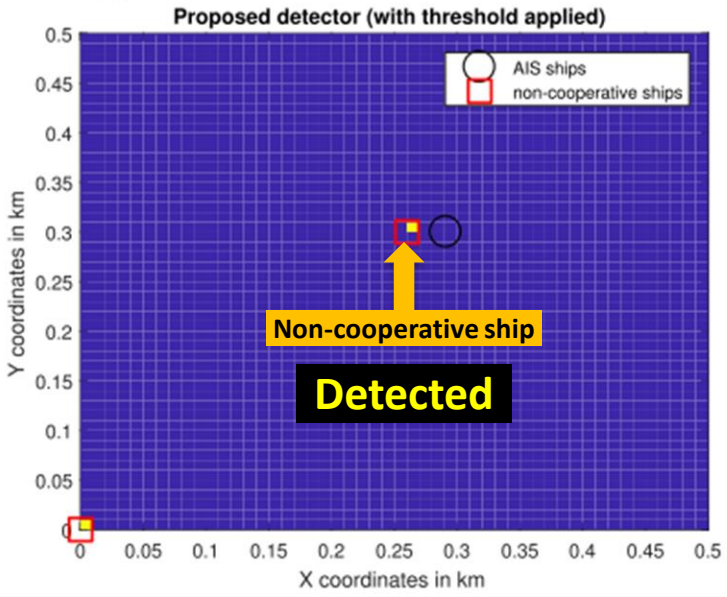
(a) Classical detector : Detection map.



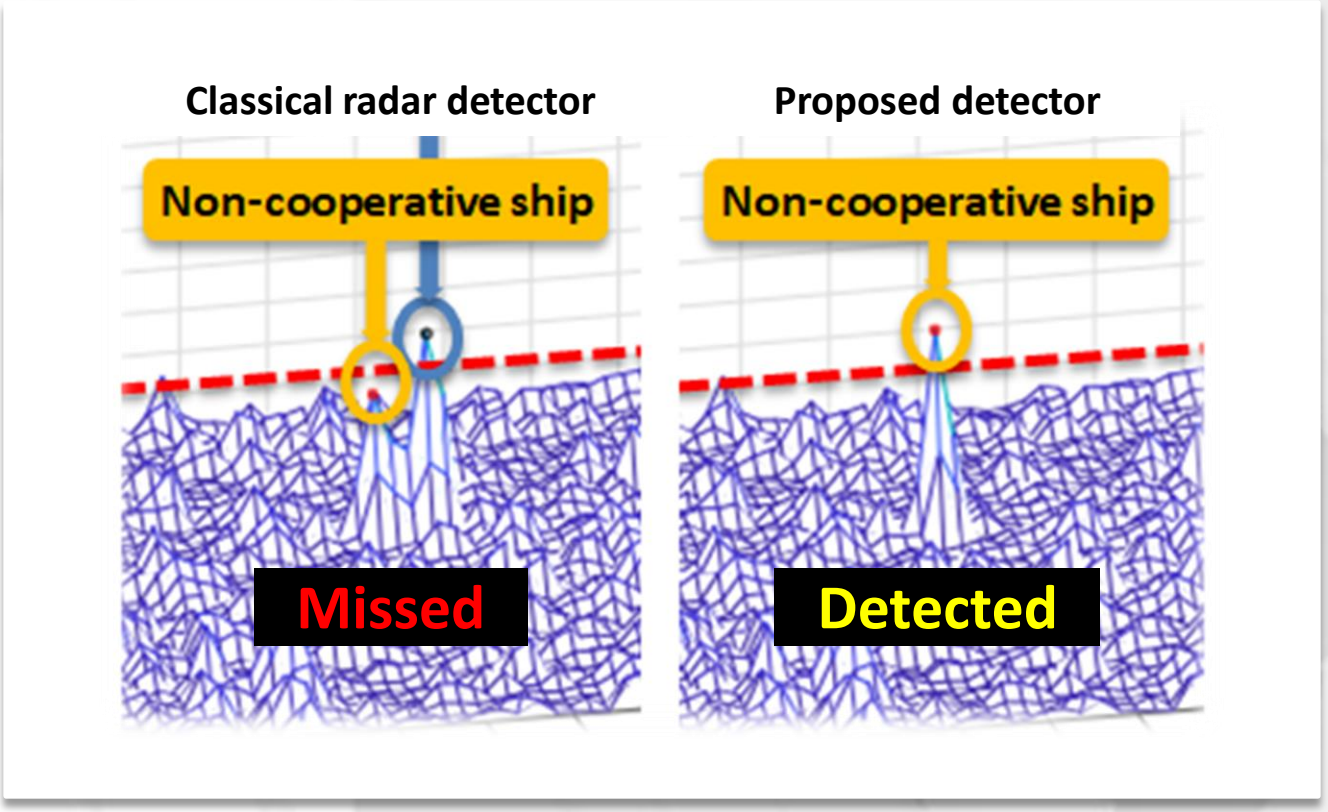
Proposed detector



(b) Proposed detector : Detection map.

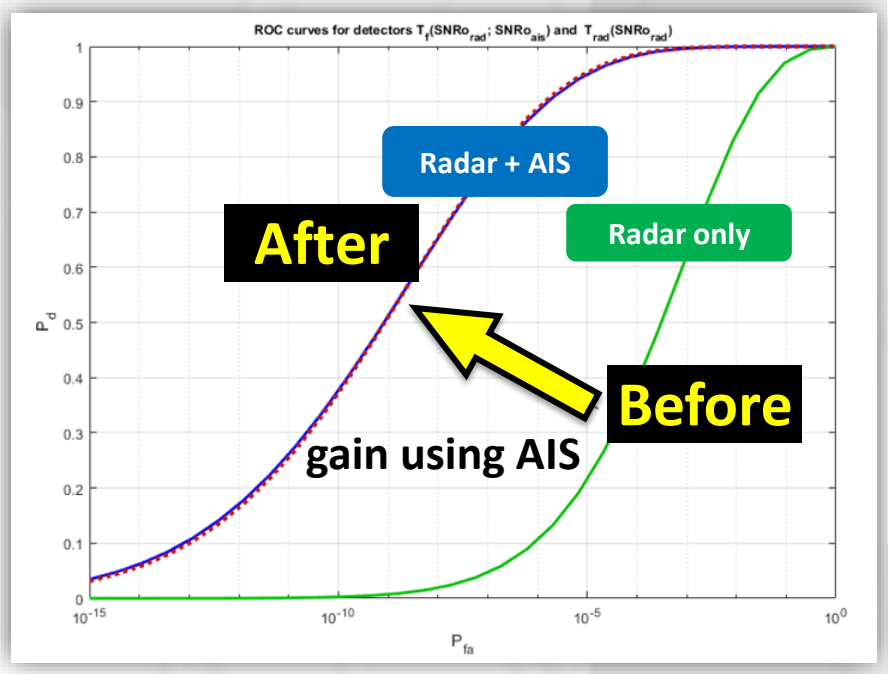


Two ships at close distance

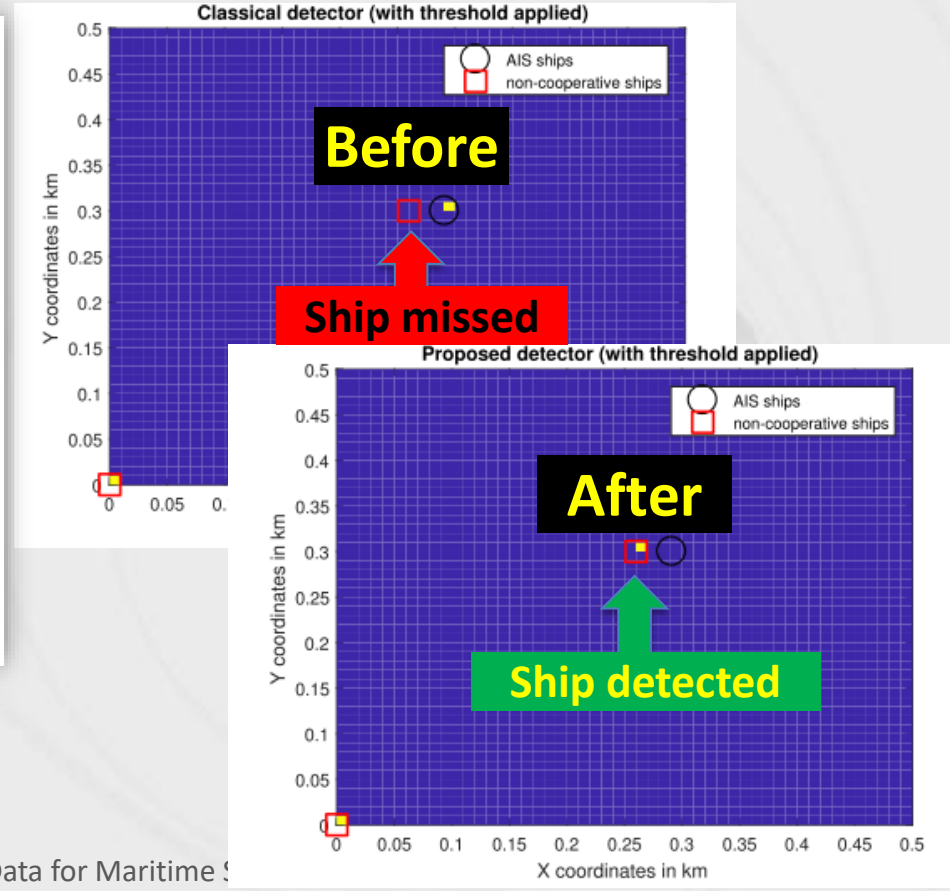


- State-of-the-art: Fusion of detection maps
- We proposed to explore raw AIS and Radar signals to improve ship detection in particular scenarios: *dense ship traffic, Cargo transshipment, ship hijack.*

Chapter 2: raw AIS + raw radar

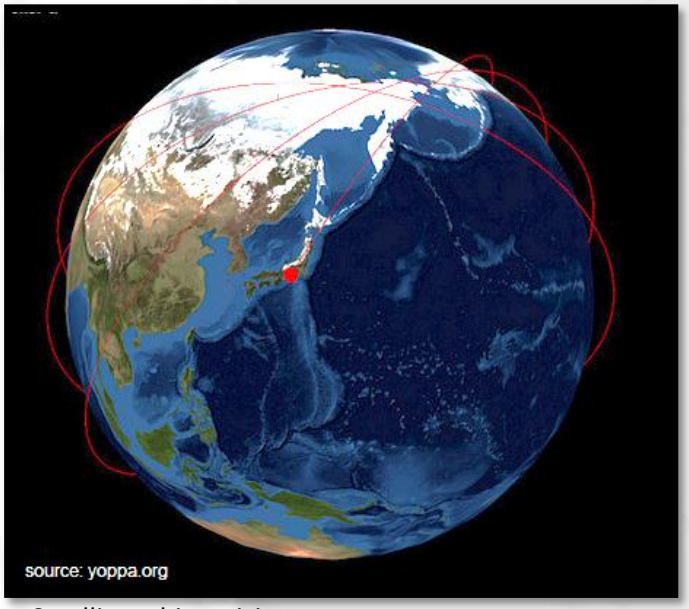


Chapter 3: raw radar + AIS detection map

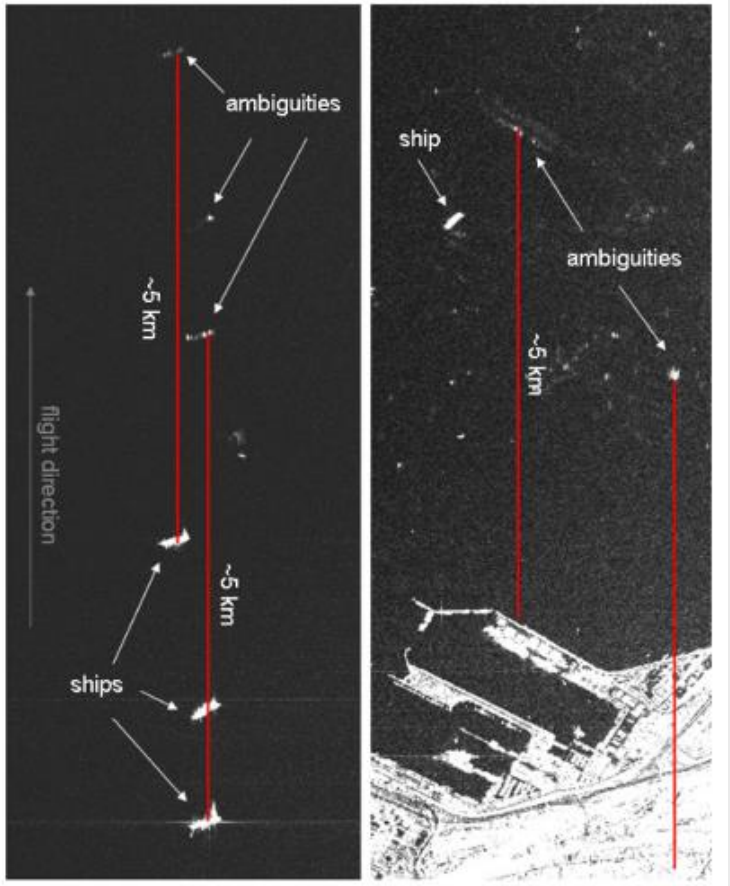


Futher work

- Explore ship tracking information (satellite revisit)
- Consider different detectors models and methods (e.g., Bayesian approach, exploit sparsity)
- Deal with extended targets
- Other radar problems (e.g., radar ambiguities)



Satellite orbit revisit



Radar azimuth ambiguities. Source: S. Brusch, *et al*, "Ship Surveillance with TerraSAR-X," *Int Trans. IGARSS'2011*.

Thank you