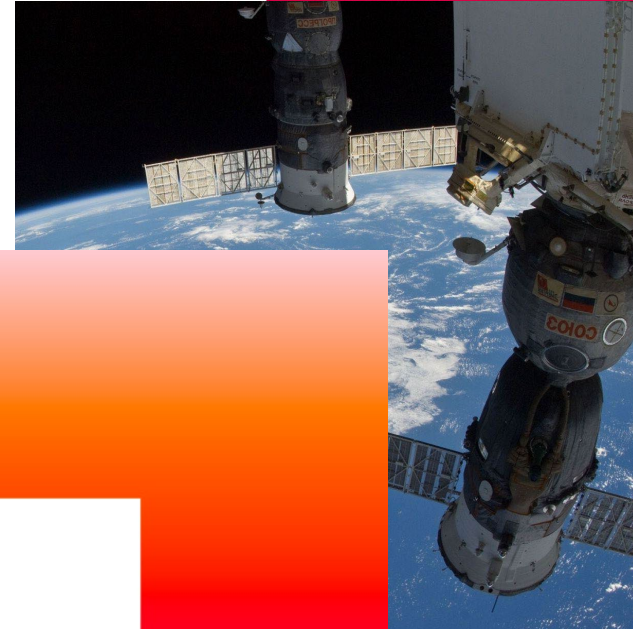


Reflection-Symmetry-Based Ship Detection with Sentinel-1 data for Maritime Surveillance

Environmental Crimes joint workshop
with ESA-JRC-UNODC

Simona Gargiulo

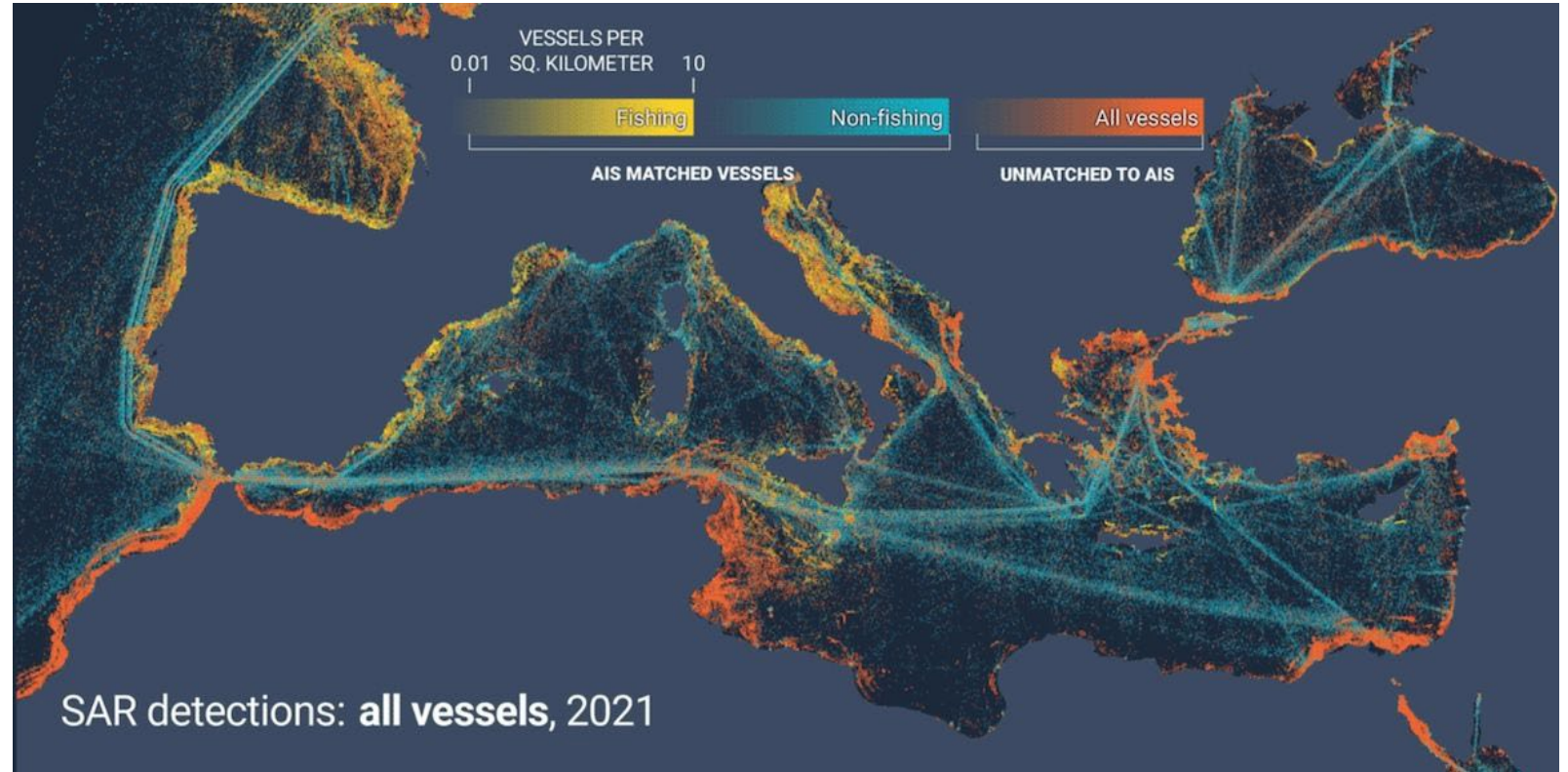
01/10/2026



SAR for the identification of «dark vessels»

Paolo, F.S., Kroodsmas, D., Raynor, J. *et al.* **Satellite mapping reveals extensive industrial activity at sea.** *Nature* **625**, 85–91 (2024).
<https://doi.org/10.1038/s41586-023-06825-8>

- About **90%** of the worldwide good traffic goes by ship: security and safety of maritime transportation is essential
- Marine traffic can be legal (transports, pleasure), or illegal (**drug trafficking, unreported and unregulated fishing, or illegal immigration**).
- AIS (Automatic identification System) used to identify and locate vessels by exchanging data with other nearby ships, AIS base stations, and satellites.
 - Not all vessels are required to have AIS on board (ex: fishing vessels > 65 ft in the US, > 49 ft in Europe)
 - Vessels involved in illegal activities turn off their AIS becoming invisible



- A study from Global Fishing Watch revealed that **75% of industrial fishing vessels are not publicly tracked**



SAR satellite

Reflection-symmetry principle

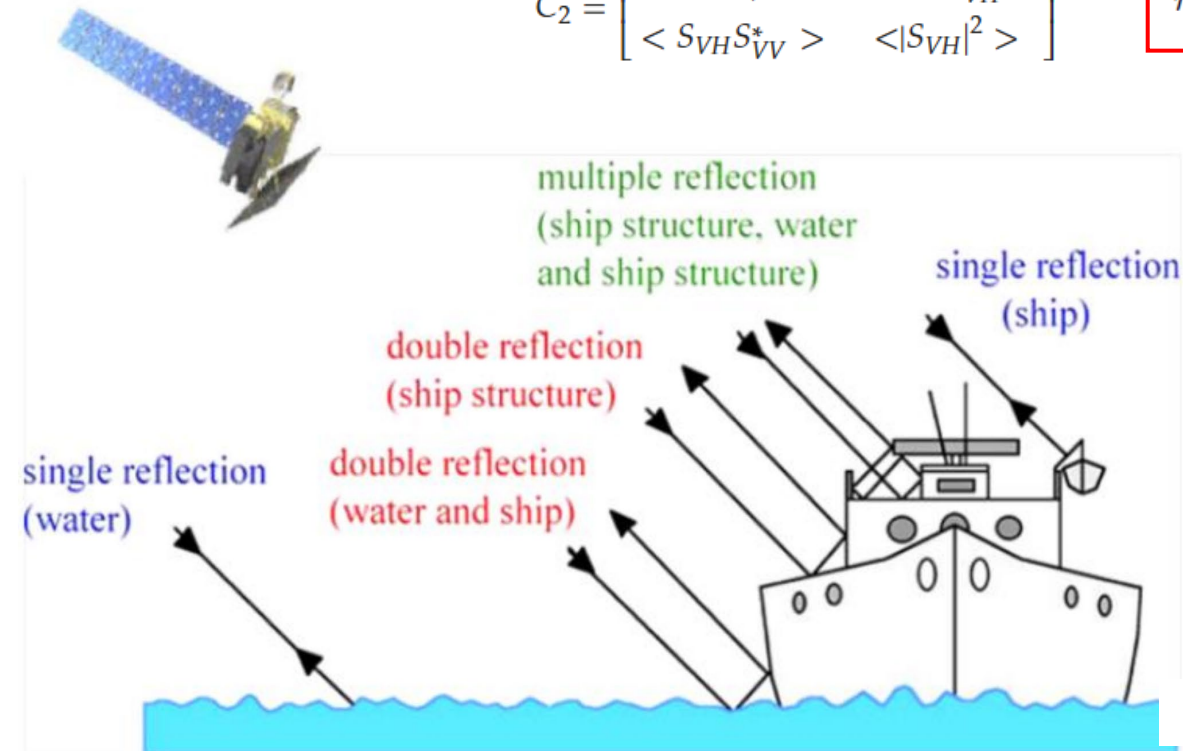
F. Nunziata, M. Migliaccio and C. E. Brown, "Reflection Symmetry for Polarimetric Observation of Man-Made Metallic Targets at Sea," in IEEE Journal of Oceanic Engineering, vol. 37, no. 3, pp. 384-394, July 2012, doi: 10.1109/JOE.2012.2198931.

- Most of vessel detection methods exploit **constant false alarm rate (CFAR) detector** on the radiometric info provided by **single-pol HH, VH, HV and VV**.
- By exploiting the polarimetric information of SAR data, better discrimination between sea and target can be achieved.
- The processor uses the **reflection-symmetry (RF) principle**

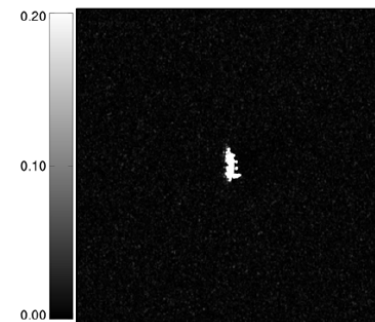
$$C_2 = \begin{bmatrix} \langle |S_{VV}|^2 \rangle & \langle S_{VV} S_{VH}^* \rangle \\ \langle S_{VH} S_{VV}^* \rangle & \langle |S_{VH}|^2 \rangle \end{bmatrix}$$

$$r = |\langle S_{xx} S_{xy}^* \rangle|$$

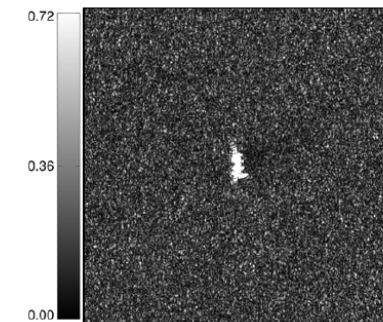
- $r \sim 0$ over the **sea surface**
- $r \neq 0$ for the **ship**



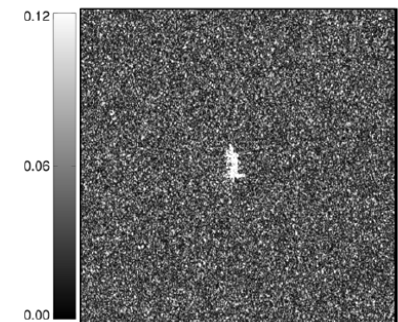
Under the reflection symmetry approach, **the target-to-clutter ratio is much more enhanced than using a single polarization.**
 – Helps **reducing false positives** and enhancing signal from **small vessels**.



(r)



sqrt(HH)



$\sqrt[3]{\text{HV}}$

Application domains

Illegal, Unreported and Unregulated Fishing

Marine Biodiversity Loss

Disruption of food chains and ecosystems

Economic impacts

- Up to \$36 billion annual loss to global fishing industry
- Unfair competition



Human rights violation

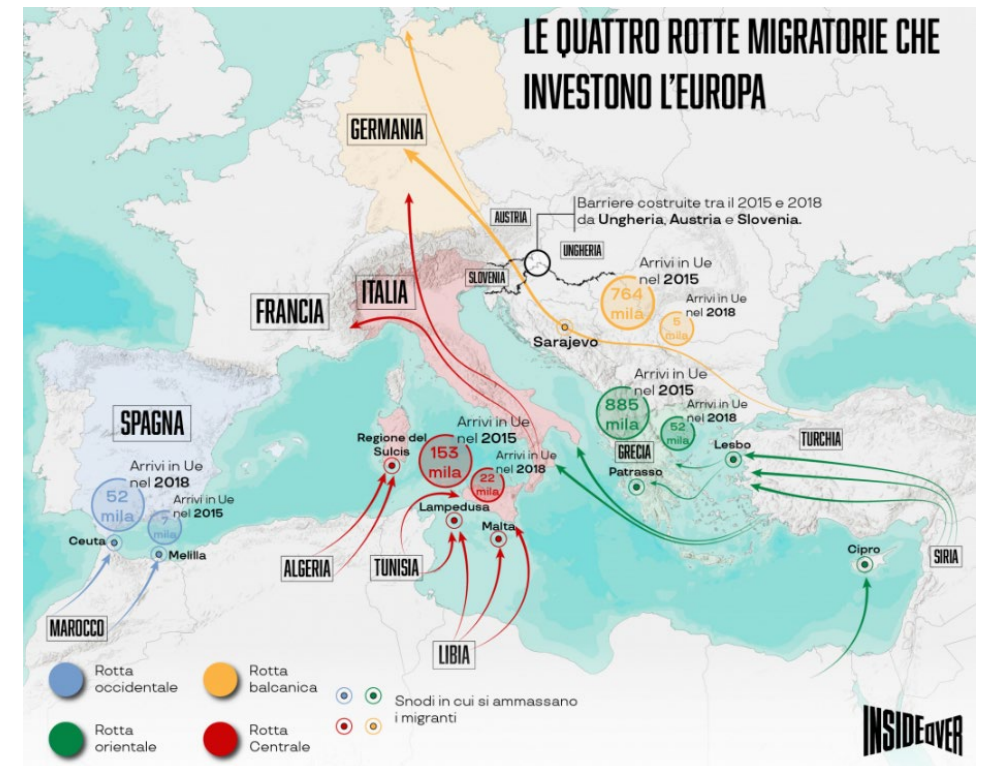
Use of forced labor, human trafficking

Food Insecurity

Especially in developing nations

Search and Rescue

- Support NGOs operating in the Mediterranean Sea in detecting vessels in distress in need of assistance.



Application domains

Illegal, Unreported and Unregulated Fishing

Search and Rescue

Marine
Biodiversity

Disruption of
chains and
ecosystems

**Goal: provide a scalable, repeatable
reflection-symmetry-based ship detection
pipeline using freely available SAR data
fully integrated in CGI Insula Platform**

Human rights
violation

Use of forced labor,
human trafficking

Food insecurity

Especially in
developing nations

Mediterranean Sea in
of assistance.

TE MIGRATORIE CHE
ROPA

il 2015 e 2018
a e Slovenia.

in Ue
2018

in Ue
2018

in Ue
2018

in Ue
2018

in Ue
2018

in Ue
2018

Rotta
occidentale

Rotta
balcanica

Rotta
orientale

Rotta
Centrale

Snodi in cui si ammassano
i migranti

INSIDE OVER

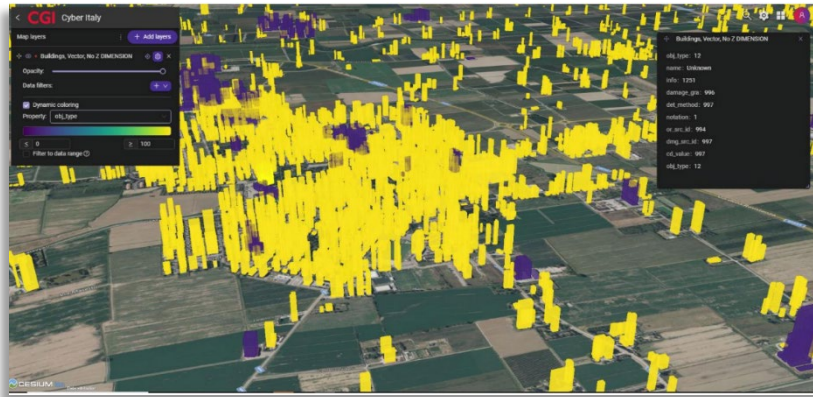
CGI Insula: Visualization, Analytics and Processing



Insula Perception



Find, explore, use data and services allowing users to perform advanced analytics.



Open Data

- Sentinel-1
- Sentinel-2
- Sentinel-3
- Sentinel-5P
- Landsat
- Envisat MERIS L1B
- SMOS

Commercial Data

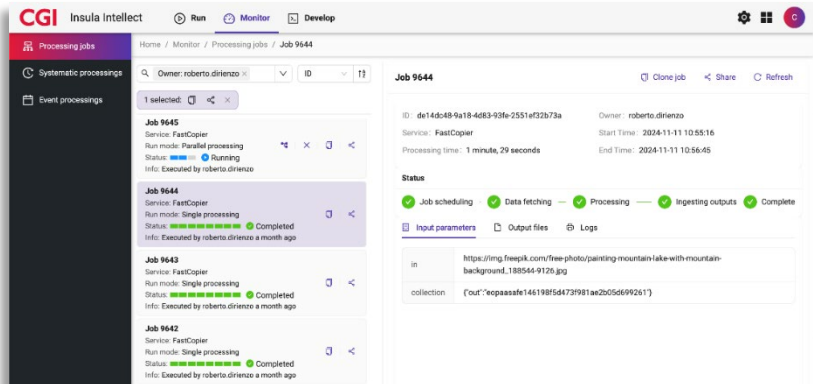
- SPOT 6 2023 over Italy

User uploaded and in-situ data

Insula Intellect



Combine data and service to transform raw information into actionable insights.



- Coding possible with



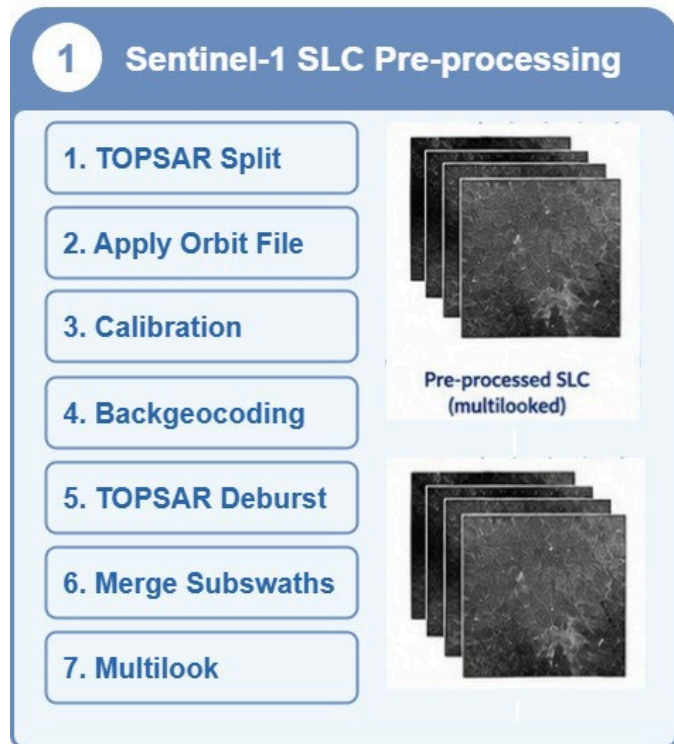
- Integrate new algorithms very easily
- Monitoring of the system to have a real-time supervision.
- Run **processing campaigns** with autoscaling to optimize large-scale processing.

Reflection-Symmetry (RF) ship detection pipeline

Sentinel-1 SLC IW VV, VH acquisitions: target acquisition and time series of the previous 6-month acquisitions with the exact same geometry used to remove static objects at sea (oil platforms, persistent infrastructures).

For each acquisition:

1. Run **Sentinel-1 SLC Pre-processing** and get multilooked output

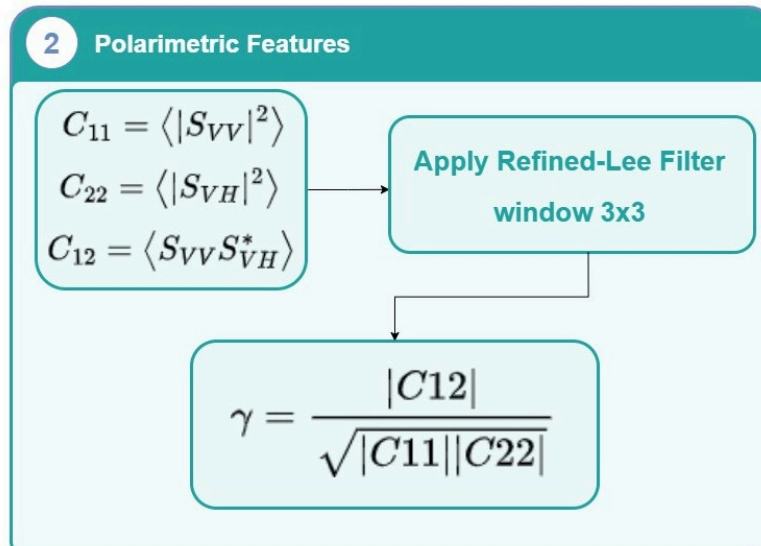


Reflection-Symmetry (RF) ship detection pipeline

Sentinel-1 SLC IW VV, VH acquisitions: target acquisition and **time series of the previous 6-month acquisitions** with the exact same geometry used to remove static objects at sea (oil platforms, persistent infrastructures).

For each acquisition:

1. Run **Sentinel-1 SLC Pre-processing** and get multilooked output
2. Compute **γ polarimetric feature**

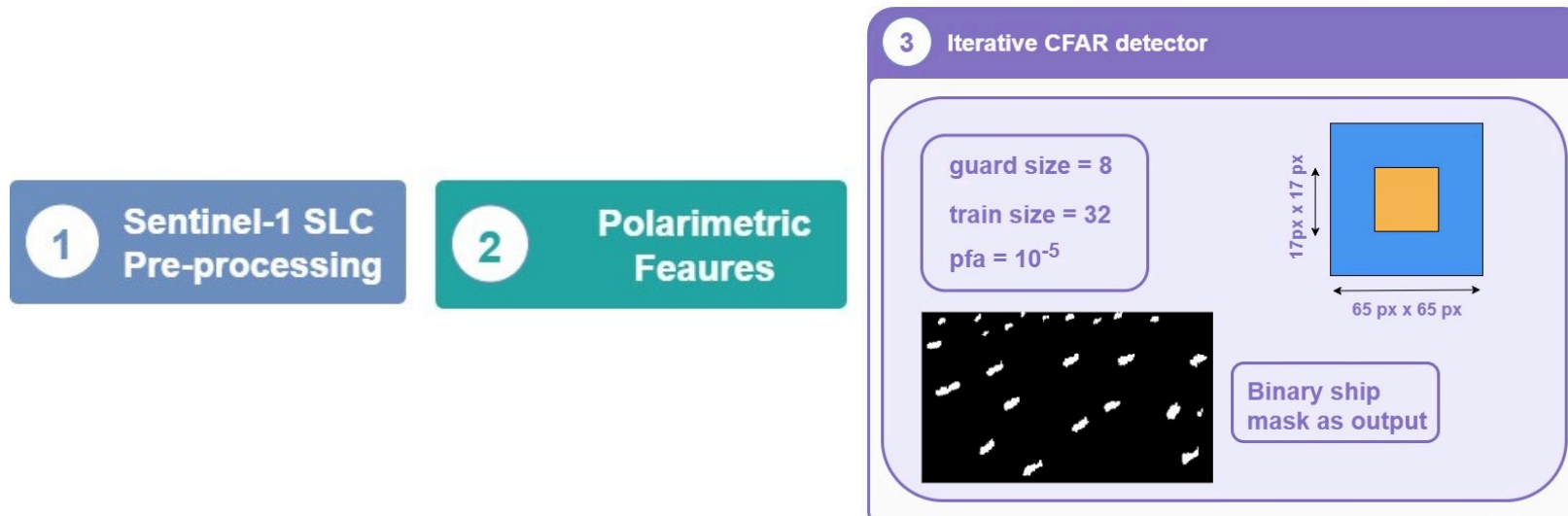


Reflection-Symmetry (RF) ship detection pipeline

Sentinel-1 SLC IW VV, VH acquisitions: target acquisition and **time series of the previous 6-month acquisitions** with the exact same geometry used to remove static objects at sea (oil platforms, persistent infrastructures).

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1. Run **Sentinel-1 SLC Pre-processing** and get multilooked output
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3. Run **Iterative CFAR detector** to get binary ship mask



Reflection-Symmetry (RF) ship detection pipeline

Sentinel-1 SLC IW VV, VH acquisitions: target acquisition and **time series of the previous 6-month acquisitions** with the exact same geometry used to remove static objects at sea (oil platforms, persistent infrastructures).

For each acquisition:

1. Run **Sentinel-1 SLC Pre-processing** and get multilooked output
2. Compute **γ polarimetric feature**
3. Run **Iterative CFAR detector** to get binary ship mask
4. Run **Terrain Correction** and apply **land-sea mask**



Reflection-Symmetry (RF) ship detection pipeline

Sentinel-1 SLC IW VV, VH acquisitions: target acquisition and time series of the previous 6-month acquisitions with the exact same geometry used to remove static objects at sea (oil platforms, persistent infrastructures).

For each acquisition:

1. Run **Sentinel-1 SLC Pre-processing** and get multilooked output
2. Compute **γ polarimetric feature**
3. Run **Iterative CFAR detector** to get binary ship mask
4. Run **Terrain Correction** and apply **land-sea mask**
5. Post-processing:
 - Remove detection if present in **at least 3** previous acquisition masks
 - Remove single pixels/very small objects
 - Shape-aware noise suppression
 - Bridge small gaps

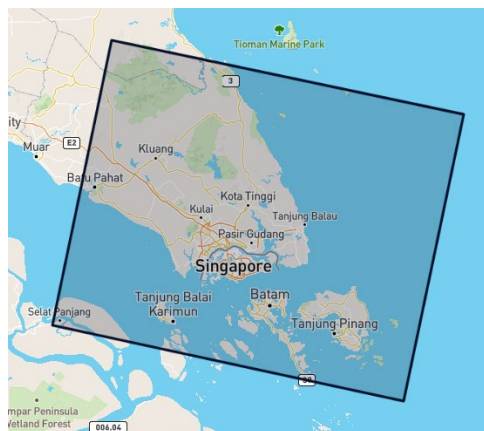


AOIs of the analysis and validation dataset

Paolo, F.S., Kroodsmas, D., Raynor, J. *et al.* **Satellite mapping reveals extensive industrial activity at sea.** *Nature* **625**, 85–91 (2024).
<https://doi.org/10.1038/s41586-023-06825-8>

Singapore Strait

11/01/2017 22:47:38



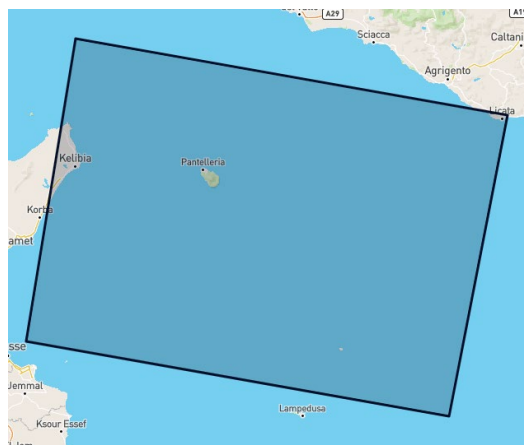
Gulf of Mexico

13/10/2017 00:01:38



Mediterranean Sea

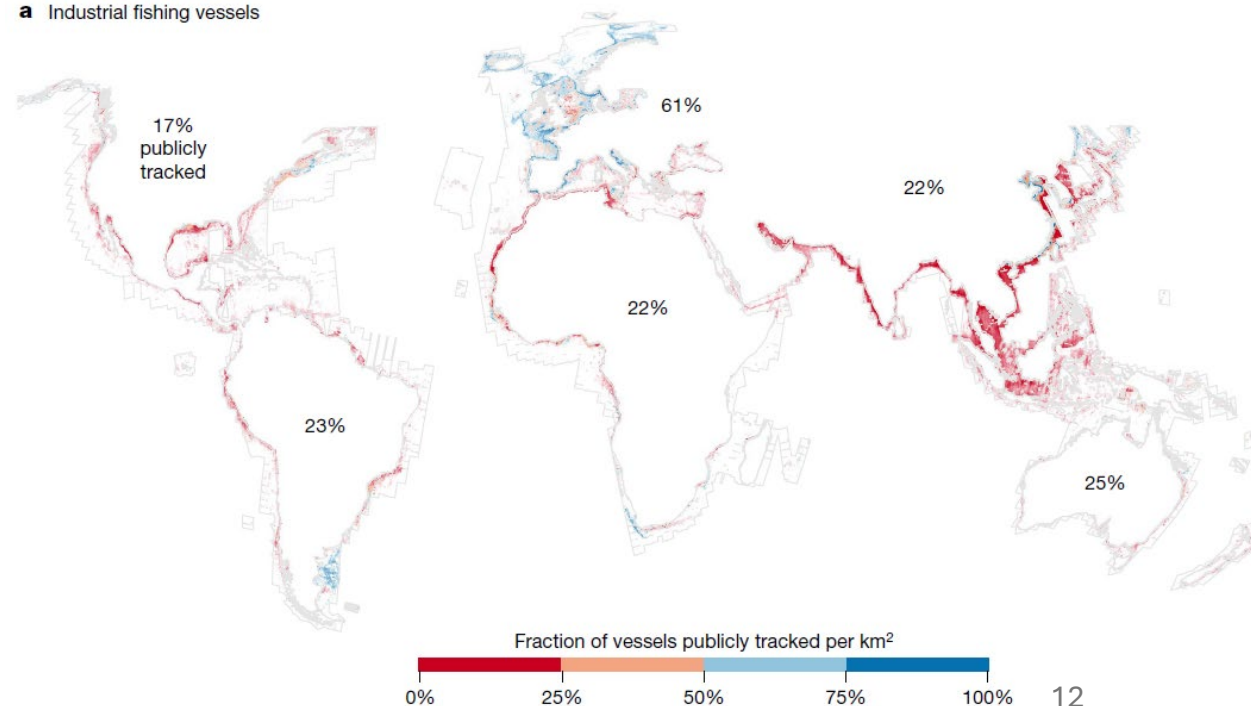
07/05/2018 05:13:07



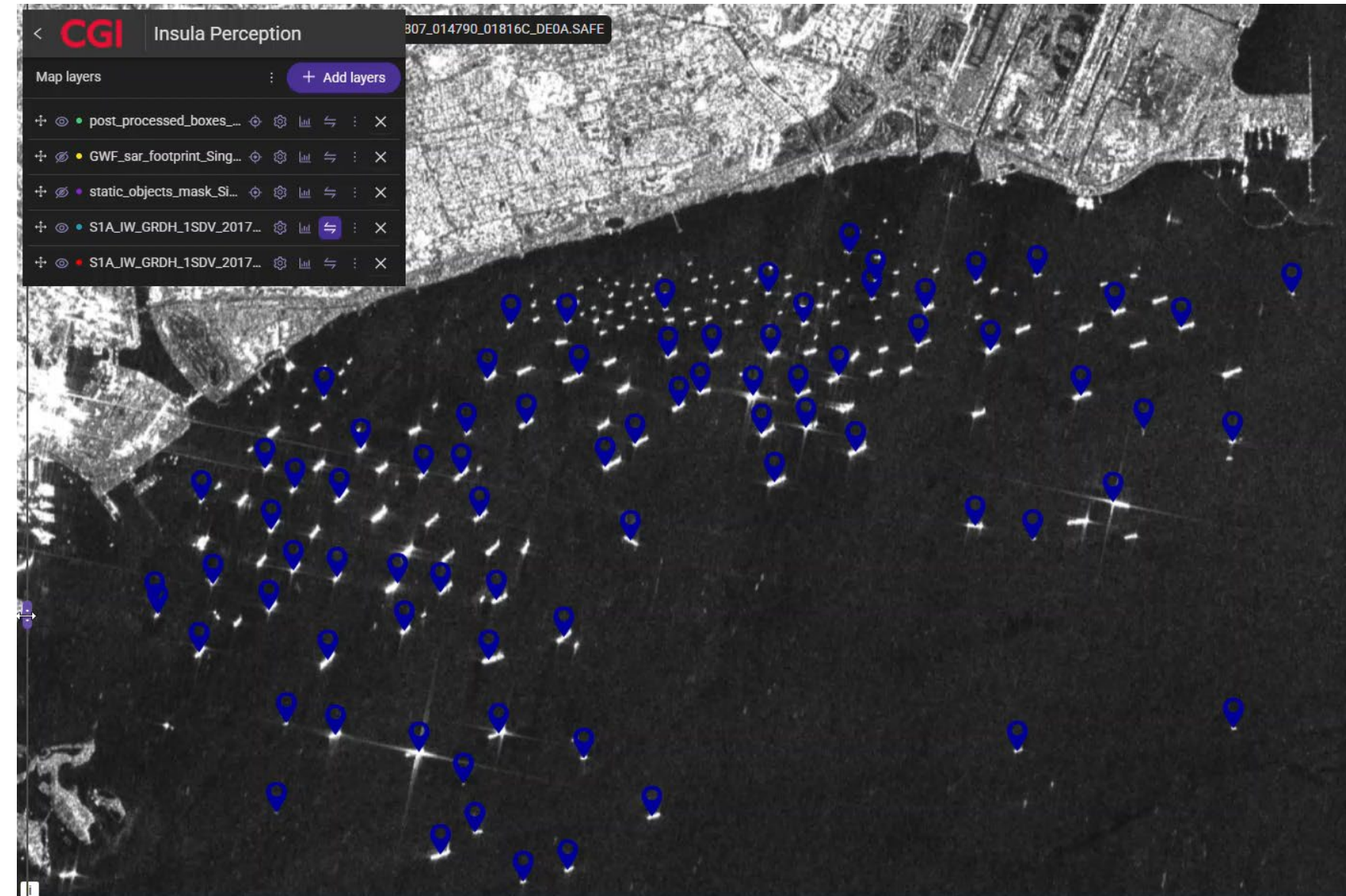
Global Fishing Watch dataset: Global map of industrial vessels detected from 2017 with a combination of **Sentinel-1 GRDH imagery, vessel AIS and deep learning models (*Nature*).**

- Wide range of vessels sizes (15-300m)

a Industrial fishing vessels



Preliminary results: Singapore Strait



 GFW detections

 RF detections

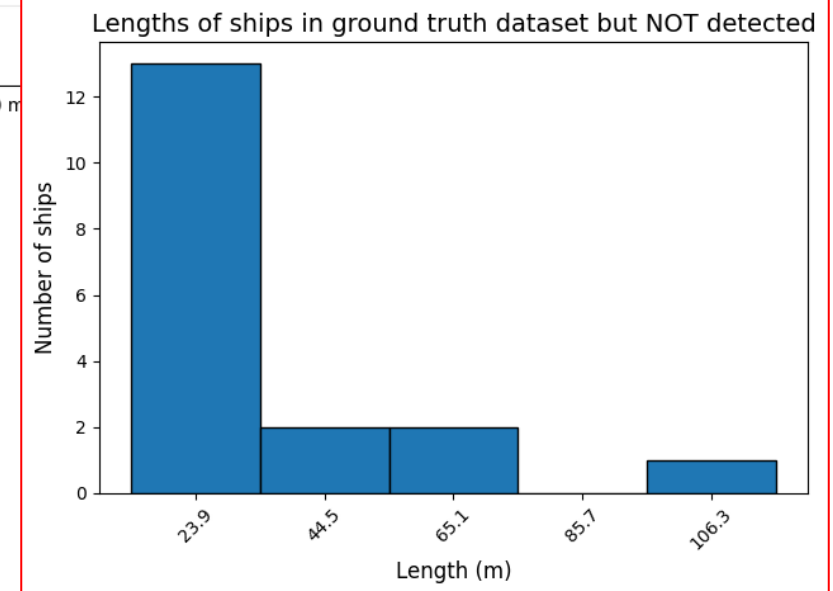
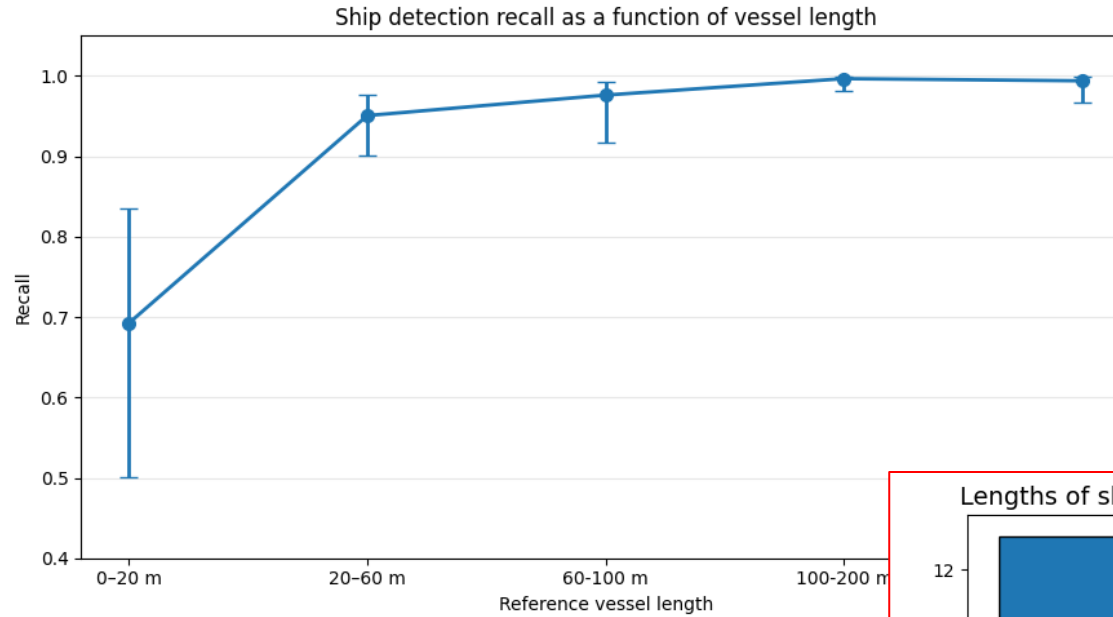
- Some **false positives** seem to be true ships not present in GFW dataset
- Some **ships** are removed due to the 1km shoreline buffer and the static objects mask

Preliminary results: Singapore Strait

	Singapore Strait
TP	697
FP	619
FN	19
precision	0.53
recall	0.97
F1 score	0.69
FOM	0.52



$$FOM = \frac{TP}{TP + FP + FN}$$



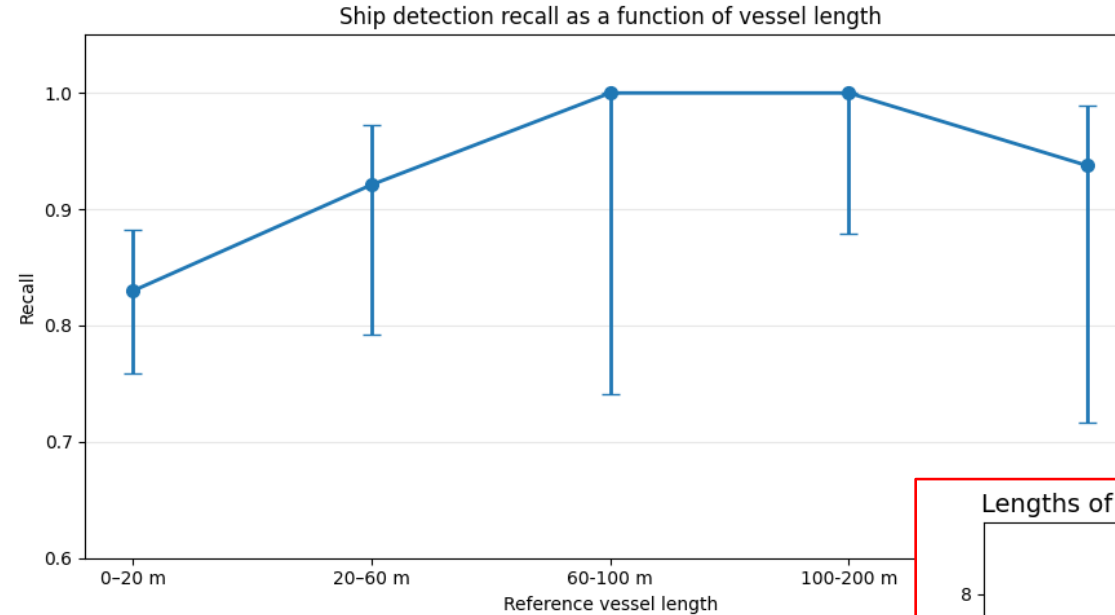
- Missed ships are typically <24m
- Most of them are fishing ships (wood/fiberglass)

Preliminary results: Mediterranean Sea

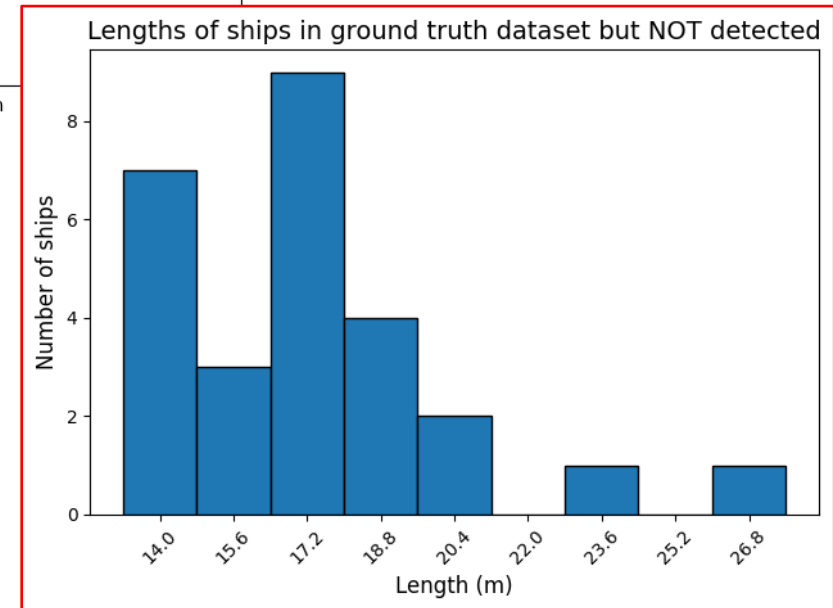
	Mediterranean Sea
TP	206
FP	52
FN	28
precision	0.80
recall	0.88
F1 score	0.84
FOM	0.72



$$FOM = \frac{TP}{TP + FP + FN}$$



- Missed ships are <20m.
- Most of them are fishing ships (wood/fiberglass)



Conclusions and way forward

Key takeaways

- The proposed reflection-symmetry-based pipeline shows **promising performance in detecting vessels across a wide range of sizes (15–300 m)**, in both coastal and open-ocean environments.
- **Most false negatives are associated with smaller vessels (<25 m)**, highlighting the challenge of detecting small targets in SAR imagery.

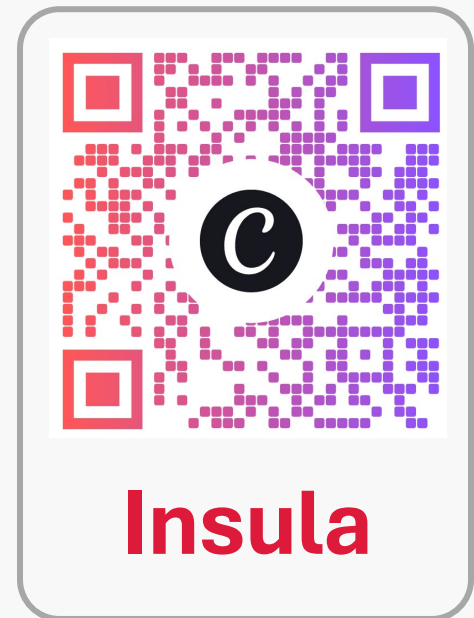
Next steps

- Extend the pipeline to NISAR dual-polarimetric **L-band SAR** data to investigate whether its higher spatial resolution improves the detection of **small vessels**.
- Match SAR detections with AIS records to identify **non-broadcasting (“dark”) vessels that may warrant further investigation**, including potentially illegal activities.
- **Final goal**: support scalable and repeatable maritime monitoring on the Insula Platform.

Thank you!

Simona Gargiulo

simona.gargiulo@cgi.com



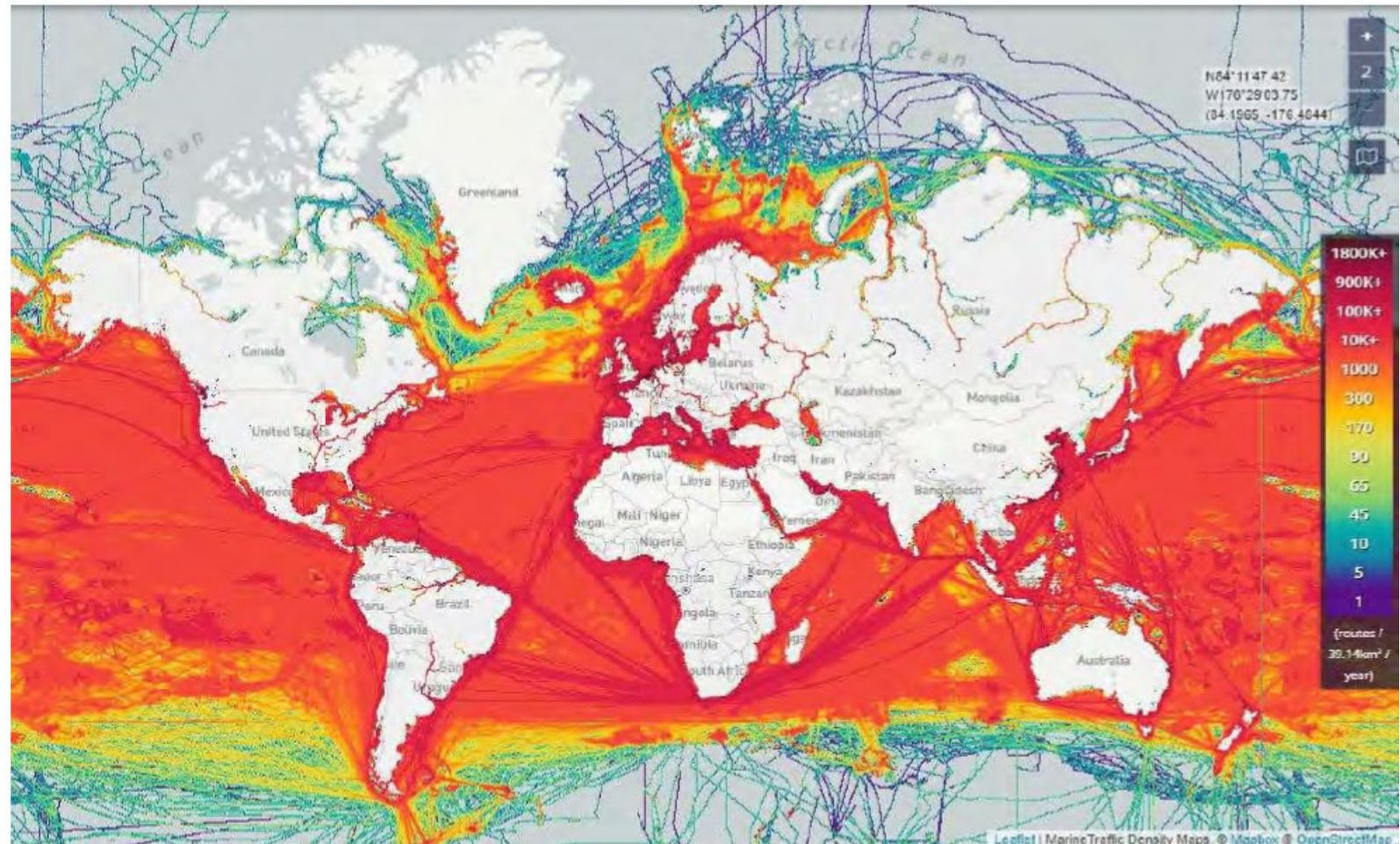


BACKUP

Automatic Identification System (AIS)

- Most of the ships are equipped with an AIS (Automatic identification System) designed to avoid collision and exchange info between ship-ship and ship-shore.
- Ships that must be equipped with AIS ([AIS transponders](#)):
 - All passenger ships
 - All ships > 300 gross tonnage on international voyages
 - Cargo ships > 500 gross tonnage not engaged on international voyage
 - EU flagged ships > 15m length
 - US commercial flagged fishing ships > 65 ft (19m) length

Worldwide ship density map based on AIS data in 2021



Illegal, Unreported and Unregulated fishing

- Marine wildlife makes up **80% of life** on Earth
- **Illegal operations in our oceans drain the world of up to \$36.4 billion worth of seafood every year**

Illegal Fishing

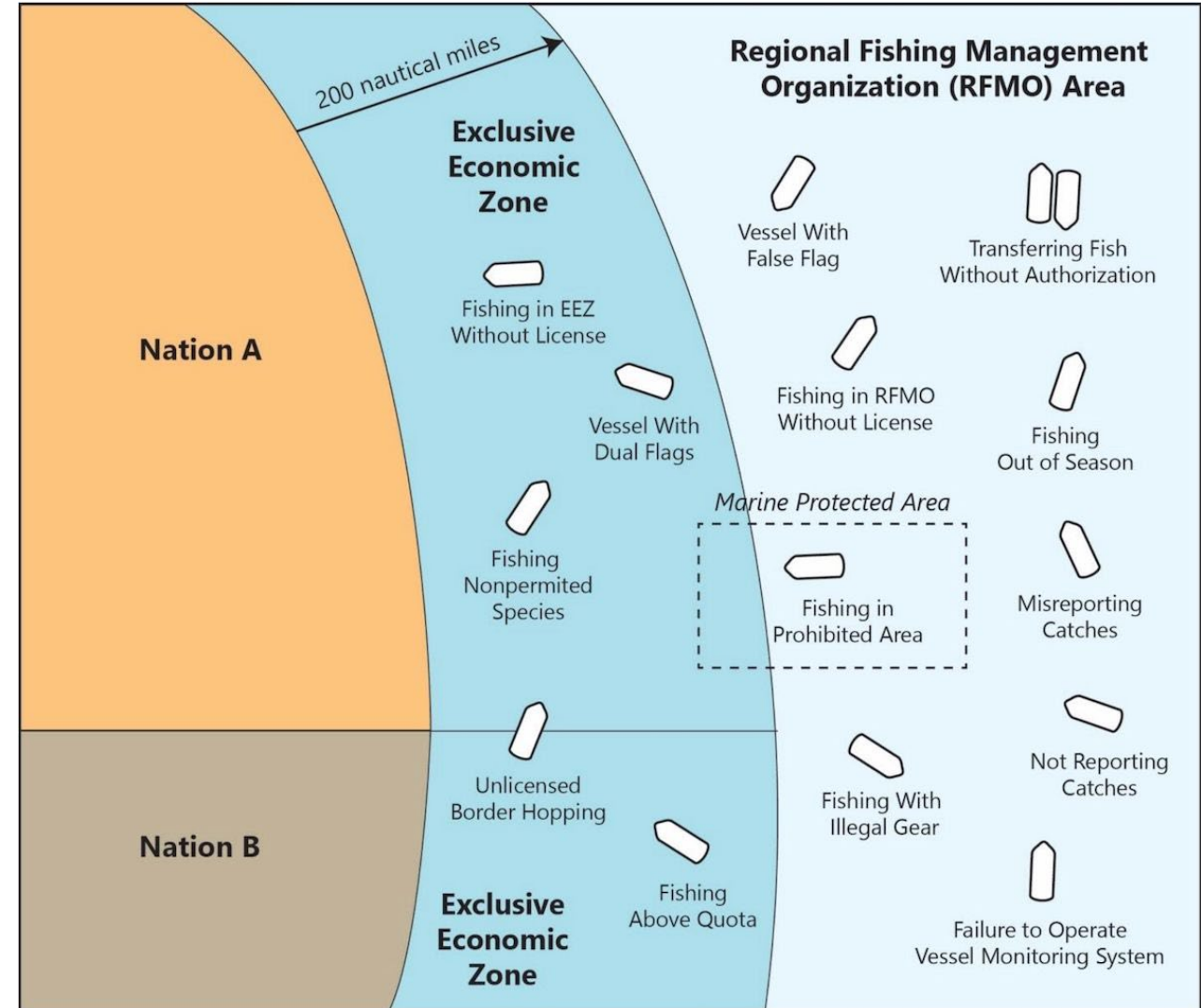
- Fishing without a valid license or permit
- Fishing in prohibited areas like marine reserves
- Catching prohibited species

Unreported Fishing

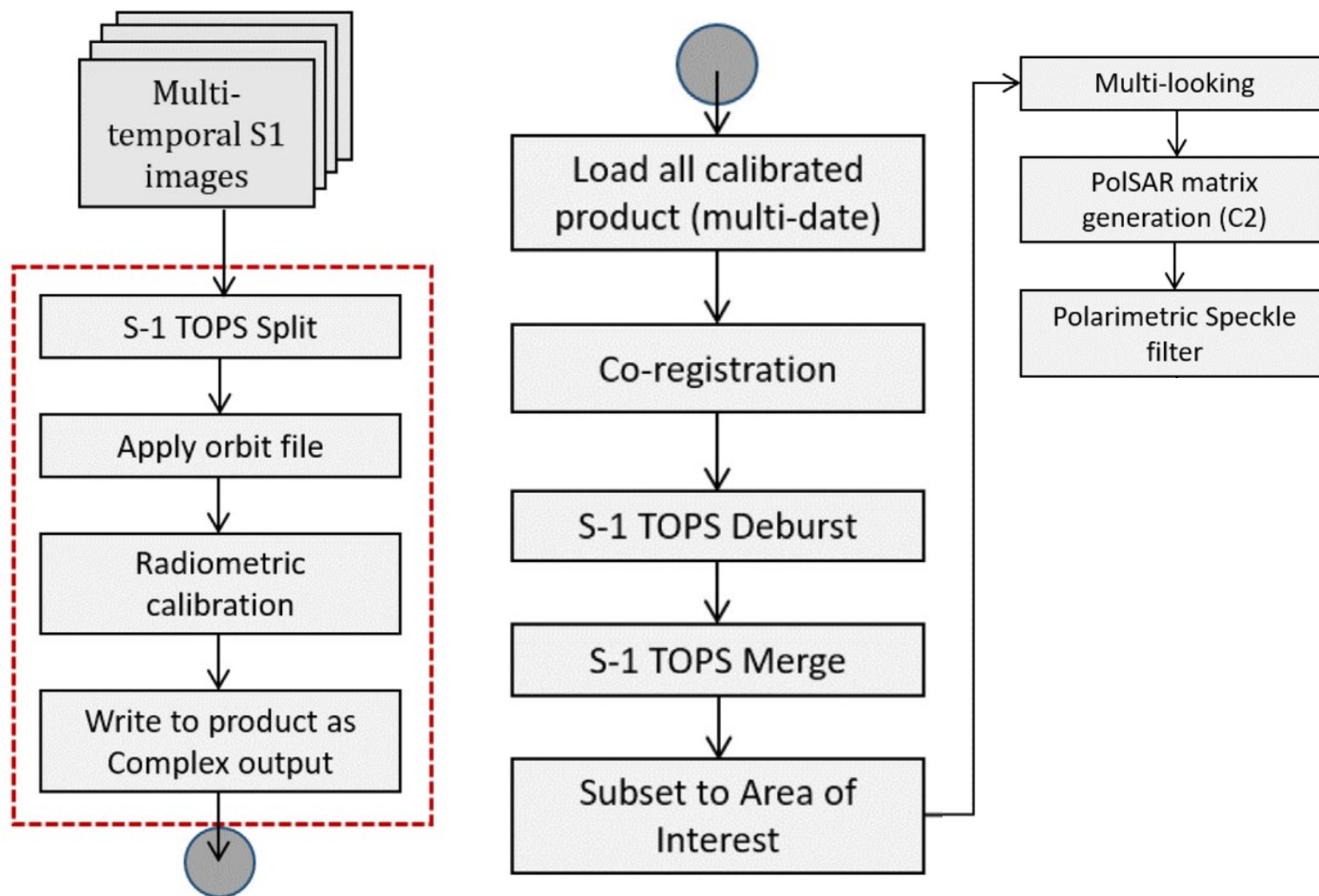
- Failing to report or misreporting catches to relevant national or regional authorities (to avoid quotas or controls)

Unregulated Fishing

- Fishing in areas with no applicable conservation or management measures
- Fishing in a manner inconsistent with responsible fishing practices



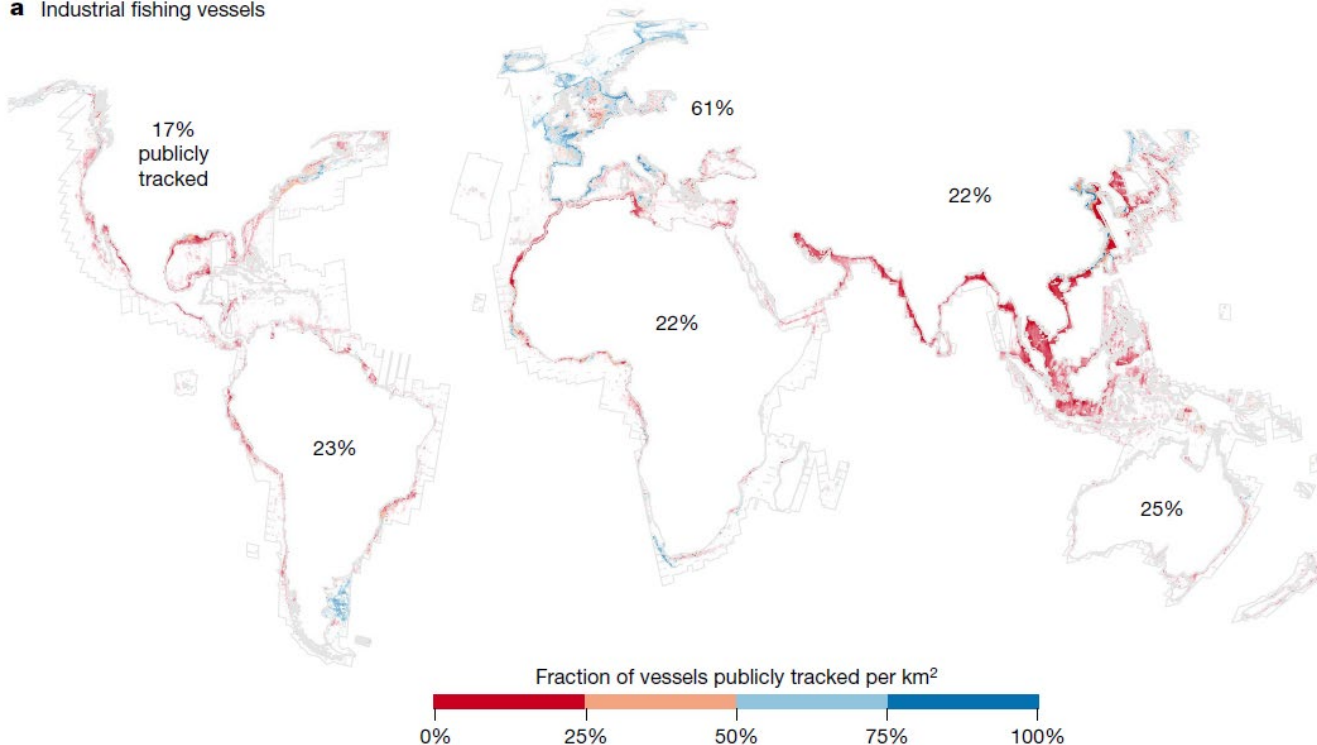
ESA SNAP S1 Preprocessing



Global Fishing Watch (GFW) dataset

Global map of industrial vessels detected from 2017 with a combination of **Sentinel-1 GRDH imagery**, vessel AIS and deep learning models.

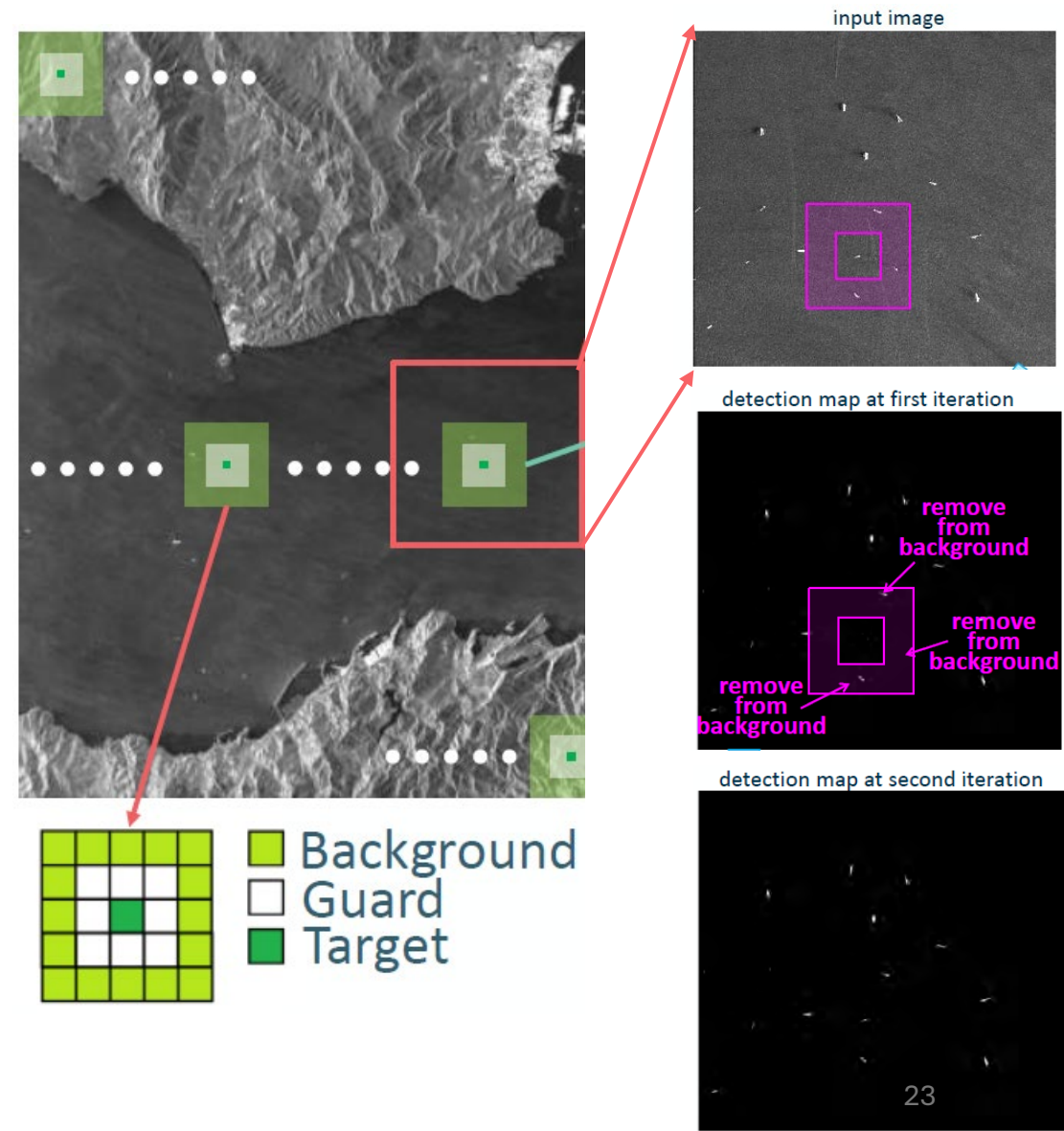
a Industrial fishing vessels



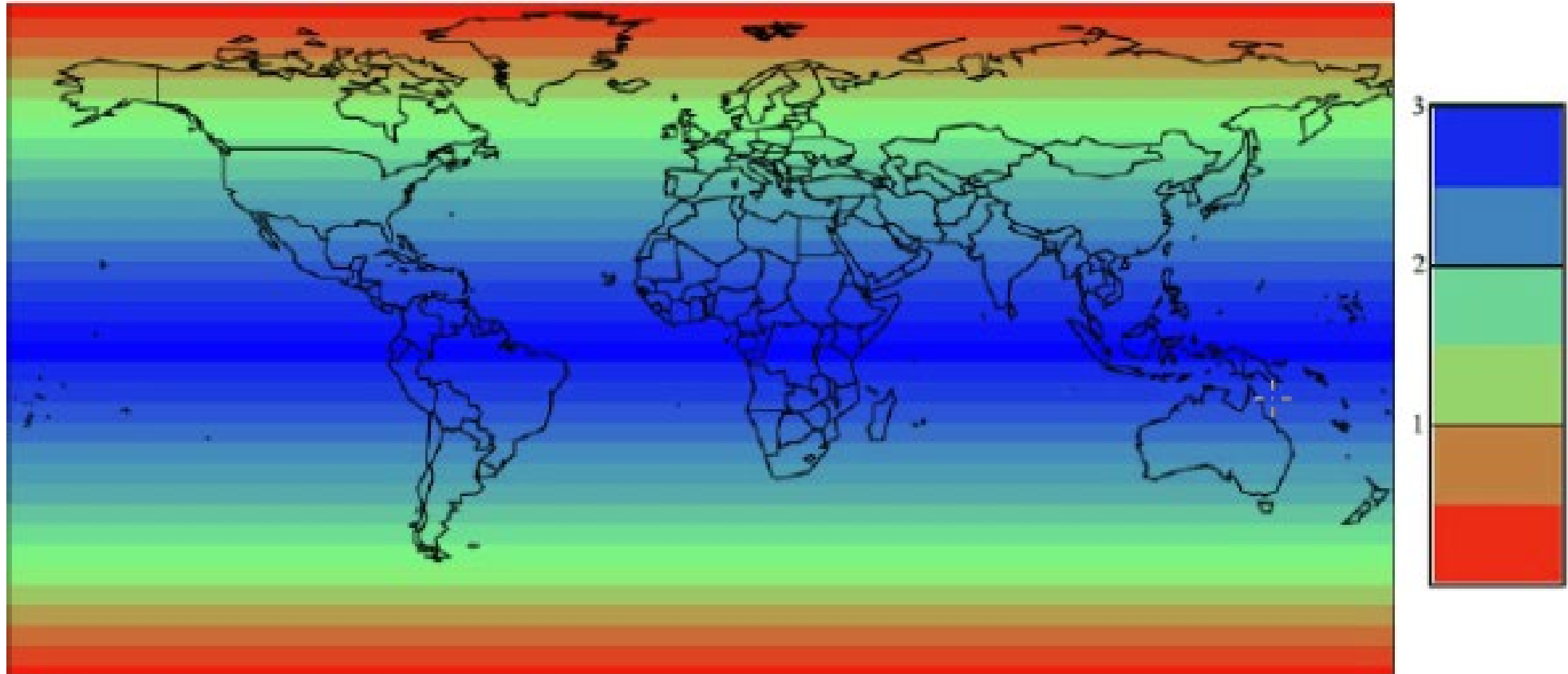
- **Constant False Alarm Rate (CFAR) algorithm** performed in a 'ring' composed of an **inner window** of **200 × 200 px** and an **outer window** of **600 × 600 px** on both **VH** and **VV** bands.
- **CNN to remove false positives**, taking both VH and VV bands in input, if the **probability of a pixel being a vessel is < 70%**.
- **1km buffer from shorelines and 500m buffer from image boundaries** to remove ambiguous coastlines, rocks, and potential noise artifacts.
- **Persistent objects** (such as offshore infrastructures) **removed** by running CFAR algorithm on **median composites** from SAR images within a **6-month time window**.
- Length of vessels estimated with a NN model
- Different categories of vessels identified by a combination of public vessel registries and a CNN:
 - Support
 - Carrier
 - Seismic vessel
 - Passenger
 - Cargo
 - Fishing
 - Bunker
 - Gear
 - Discrepancy

Differences between RF pipeline and GFW dataset

	RF Pipeline	GFW Dataset
Sentinel-1 imagery	SLC	GRDH
Resolution	~14m	20m
Discriminating feature	Normalized gamma	Single-pol VH, VV
Detector	Iterative CFAR with small guard and training windows	CFAR with large guard and training windows
False positives	Morphological operations	Deep learning model: probability of being a vessel < 70%



S1 Constellation Observation Scenario – S1A and S1B



- ✓ Two satellites in a 12 day orbit
- ✓ Repeat frequency: 6 days (important for coherence)
- ✓ Revisit frequency: (asc/desc & overlap): 3 days at the equator, <1 day at high latitudes (Europe ~ 2 days)

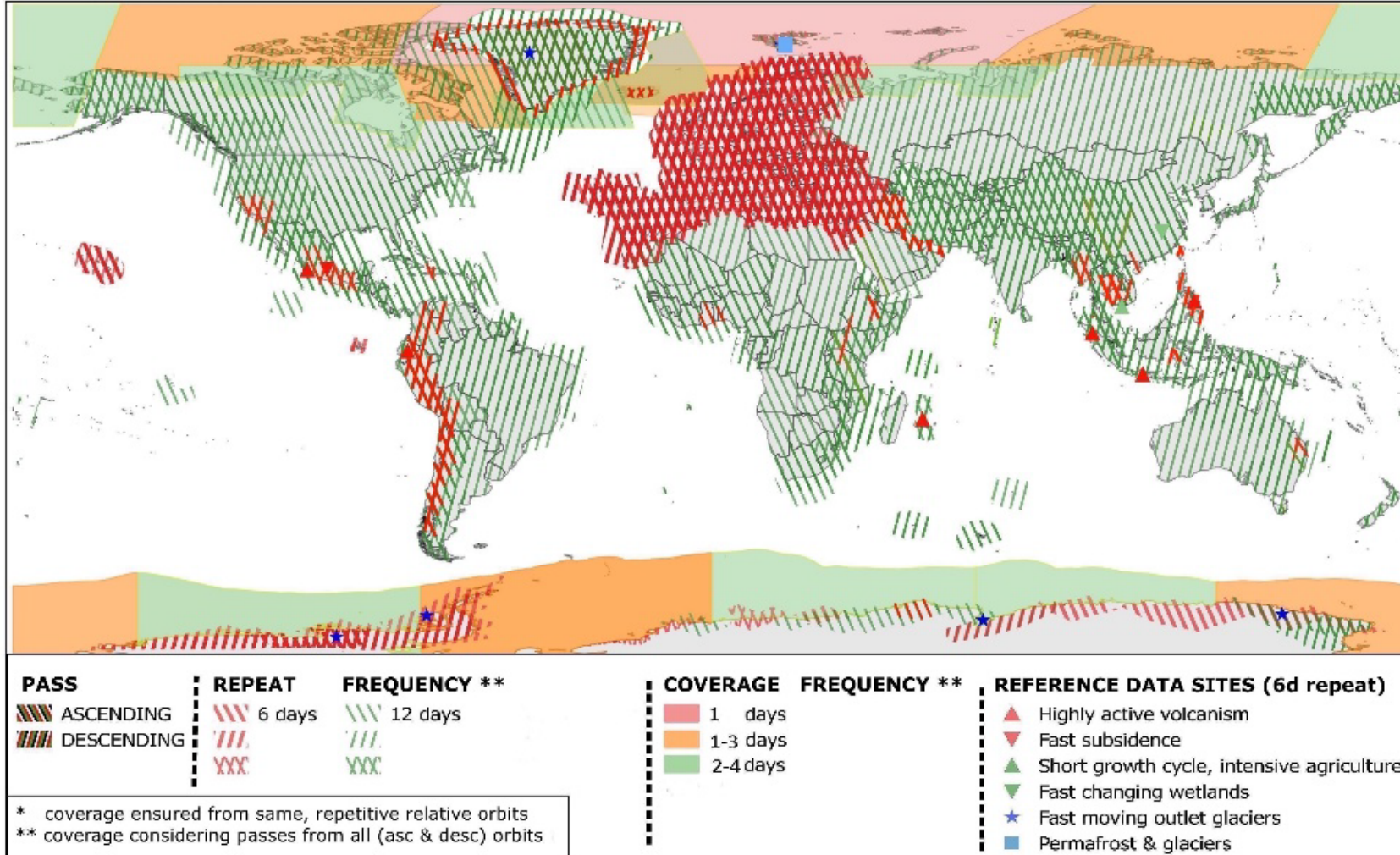
S1 Constellation Observation Scenario

Sentinel-1 Constellation Observation Scenario: Repeat & Coverage Frequency



validity start: 07/2025

Note: Seasonal campaigns not represented
Note: Wave mode systematically operated over open oceans not represented



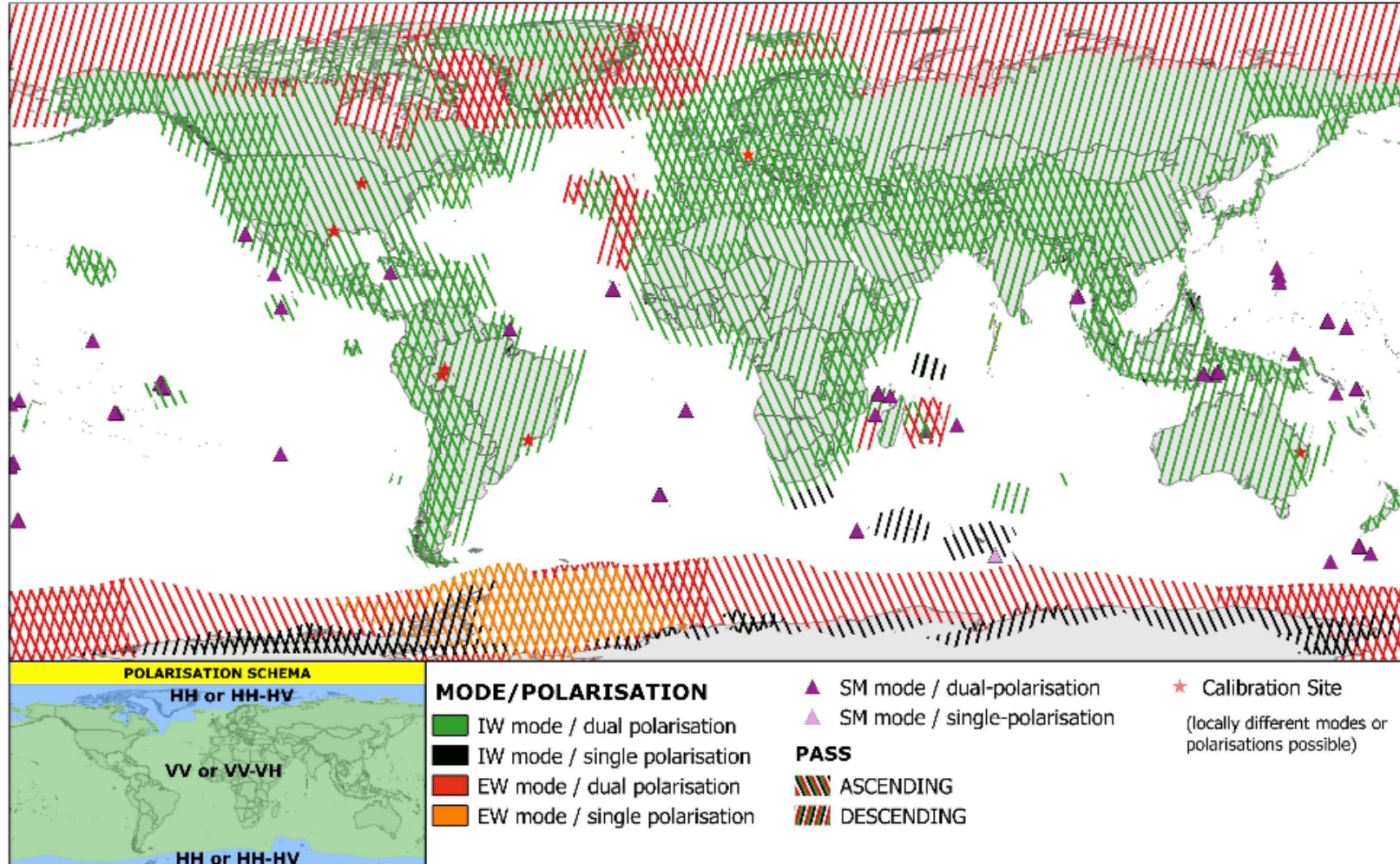
S1 Constellation Observation Scenario

Sentinel-1 Constellation Observation Scenario: Mode - Polarisation - Observation Geometry

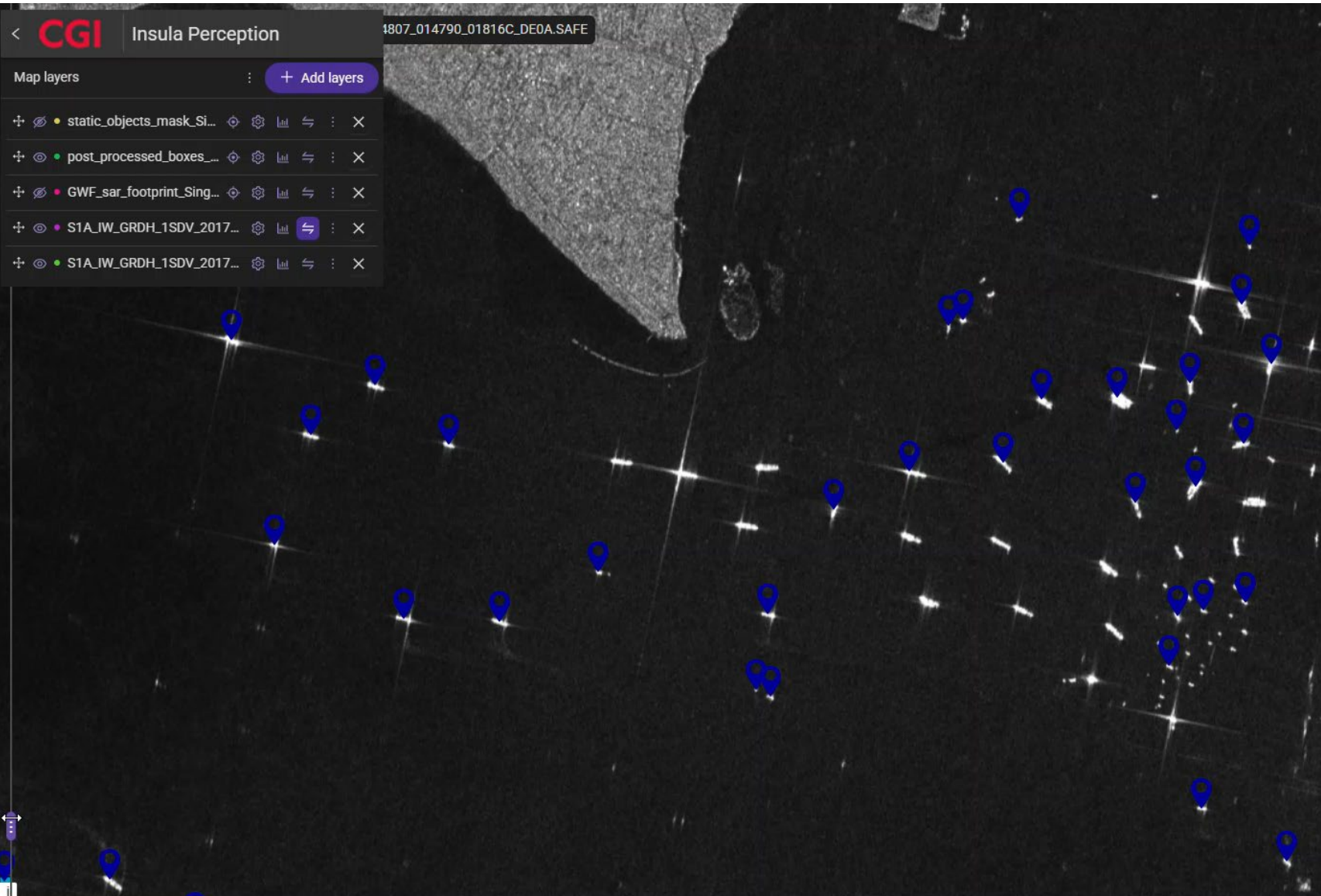


validity start: 07/2025

Note: Seasonal campaigns not represented
Note: Wave mode systematically operated over open oceans not represented



Preliminary results: Singapore Strait

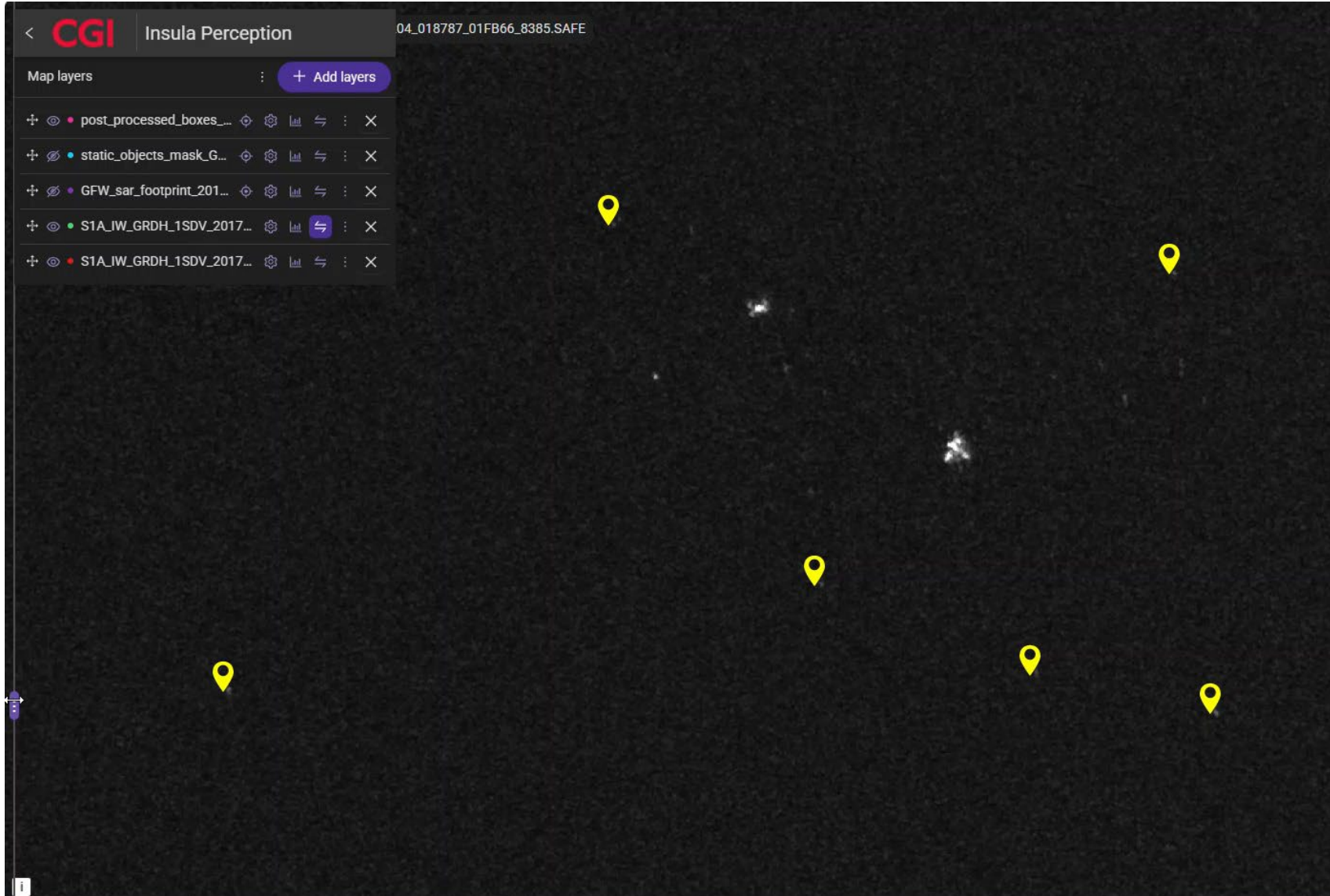


 GFW detections

 RF detections

- Some **large ships detected as two** different ships
- Some **real false positives** in RF pipeline detections

Ship detection over Gulf of Mexico

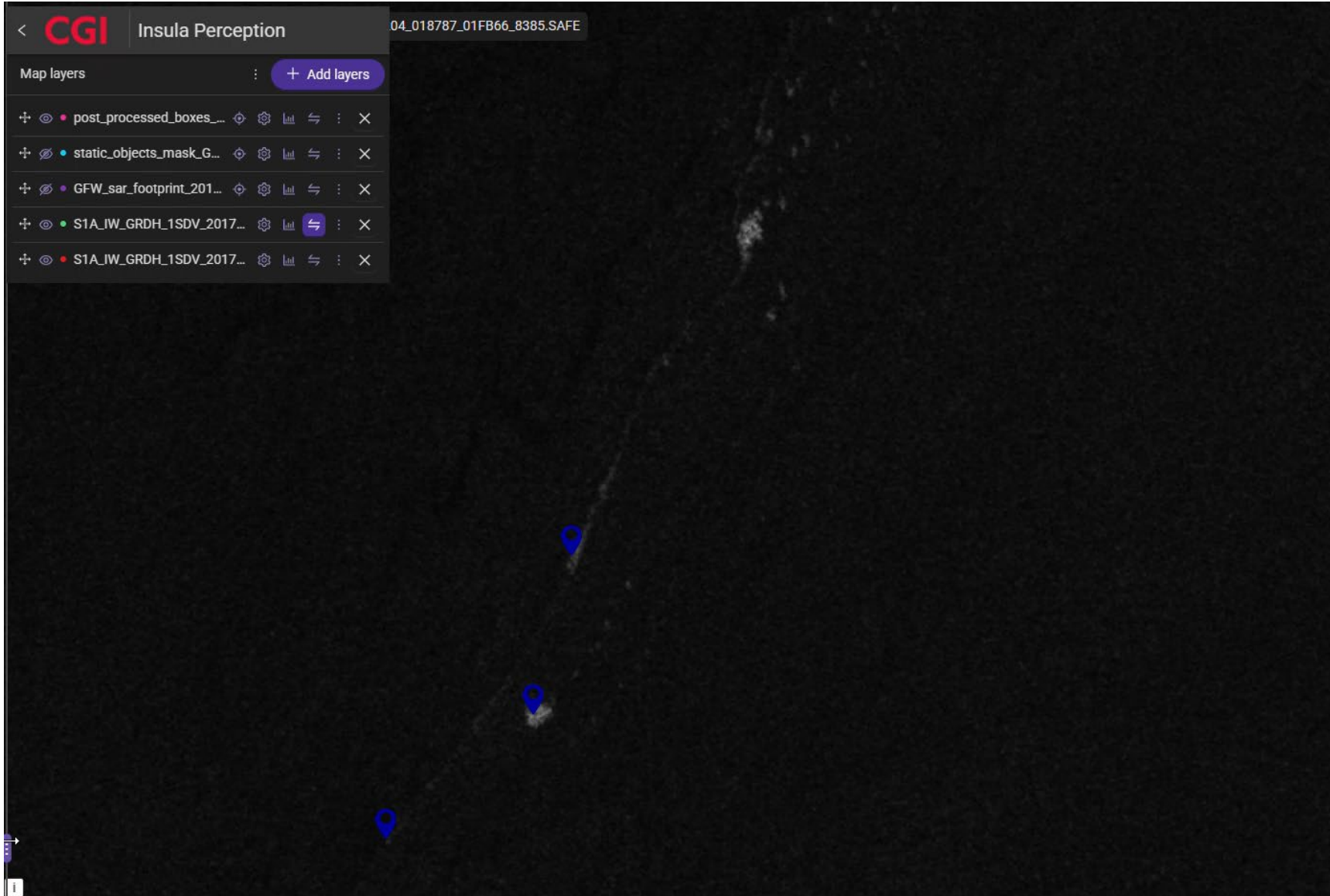


 GFW detections

 RF detections

- Some **real false negative** in RF pipeline detections in the case of ships $< 25\text{m}$

Ship detection over Gulf of Mexico



 GFW detections

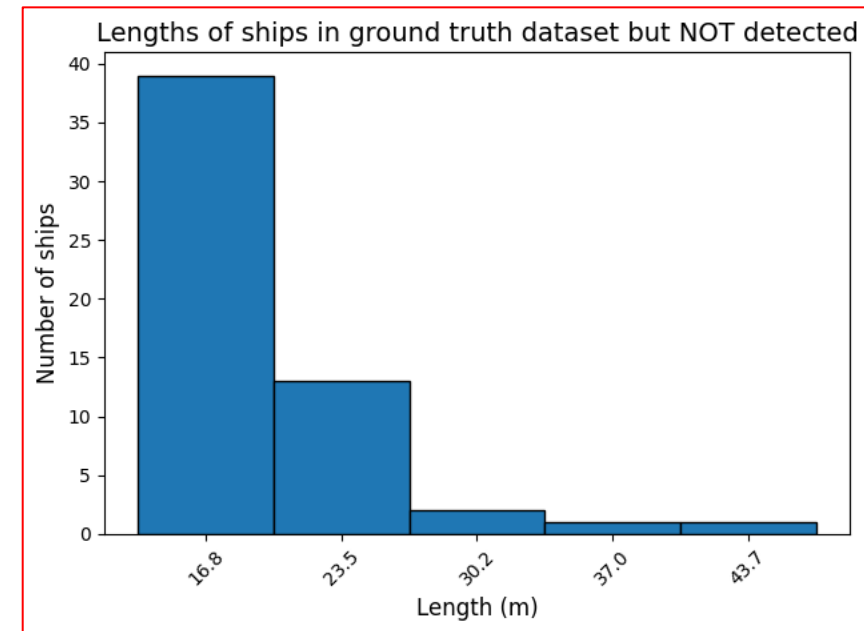
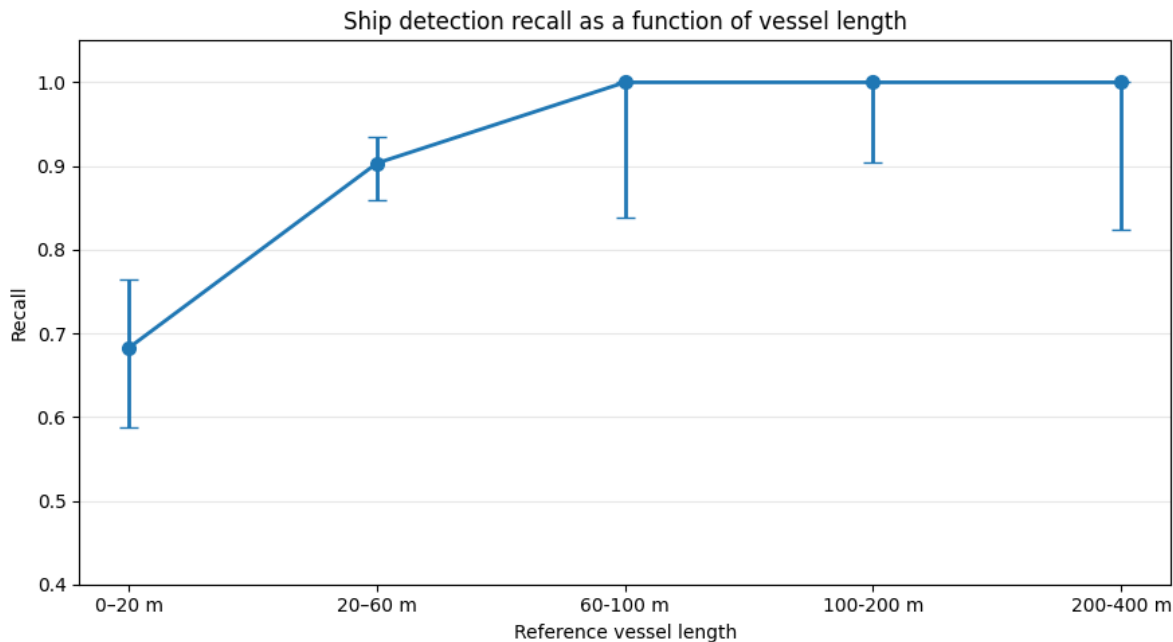
 RF detections

- Problems with **ship wakes?**
- Some **real false positives** in RF pipeline detections

Preliminary results: Gulf of Mexico

	Gulf of Mexico
precision	0.68
recall	0.87
F1 score	0.76
FOM	0.61

- Missed ships are < 45m long, most of them having a length <17m .
- They are fishing boats, so typically made of wood or fiberglass, which has a weaker signal with respect to metal.



Preliminary results: Mediterranean Sea



 **GFW detections**

 **RF detections**

- Real false negative
- False positive seems to be a true ship

Preliminary results: Mediterranean Sea

 GFW detections

 RF detections

- Some real false negatives