END-TO-END VESSEL SEGMENTATION FROM RAW SAR SIGNALS: A PRELIMINARY STUDY

EDHPC conference – October 16th, 2025

Author: **Alessio Auddino**

Co-authors: **Roberto Del Prete (ESRIN), Federica Biancucci (TASI), Edoardo Montecchiani (TASI), Oreste Trematerra (TASI), Gabriele Meoni (ESRIN), Nicolas Longépé (ESRIN)**

TABLE OF CONTENTS

SAR: PROS AND CONS

/// **SAR** (Synthetic Aperture Radar) is an imaging radar in C-band used for Earth Observation (EO) applications where electromagnetic waves are transmitted and backscattered echoes are recorded and combined to reconstruct the scene as in virtual aperture.

/// *PROS*

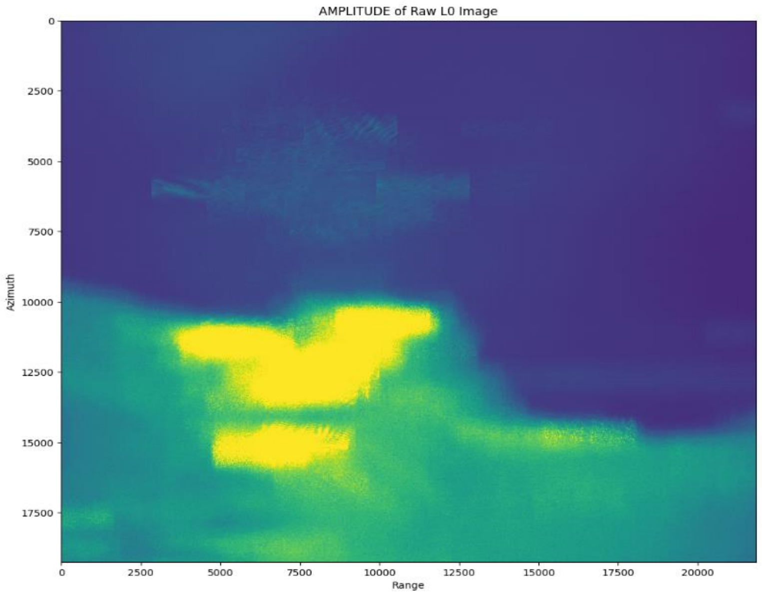
- Works under any weather and light conditions
- Easy to acquire
- Constantly updated through web portals

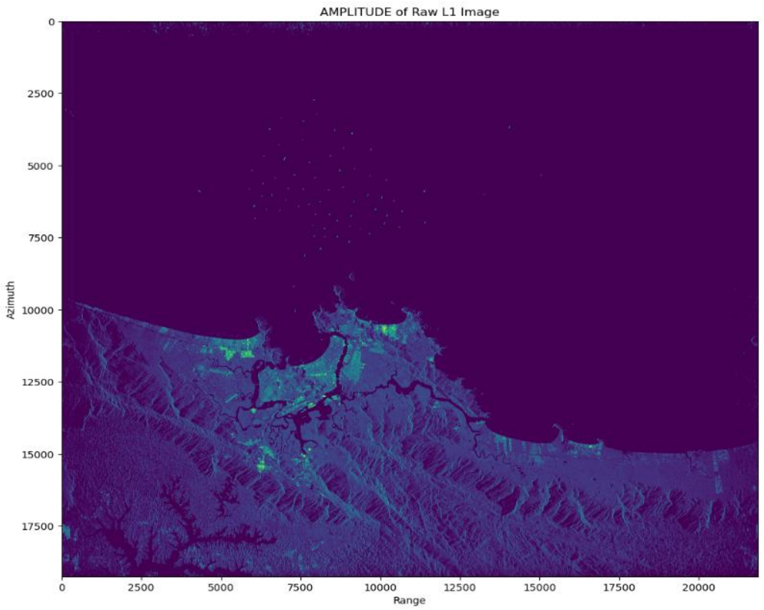
/// *CONS*

- Highly-dimensional complex data stored on-board
- Processing and transmission of observed data is expensive

/// *Raw SAR data can be processed at many levels*

- L0 products (aka decompressed)
- L1 products (aka focused)

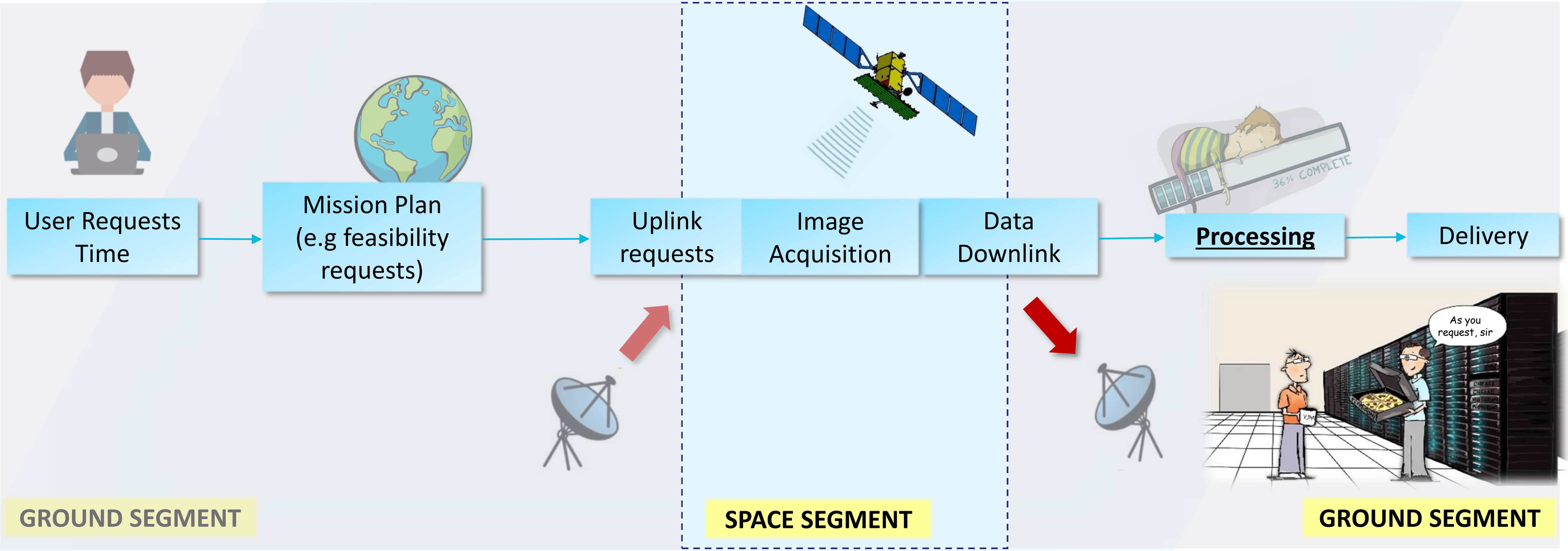




EO AND STATE OF THE ART ANALYSIS

EO – Legacy Approach

End-to-end time from user requests to data delivery is composed by the different steps:



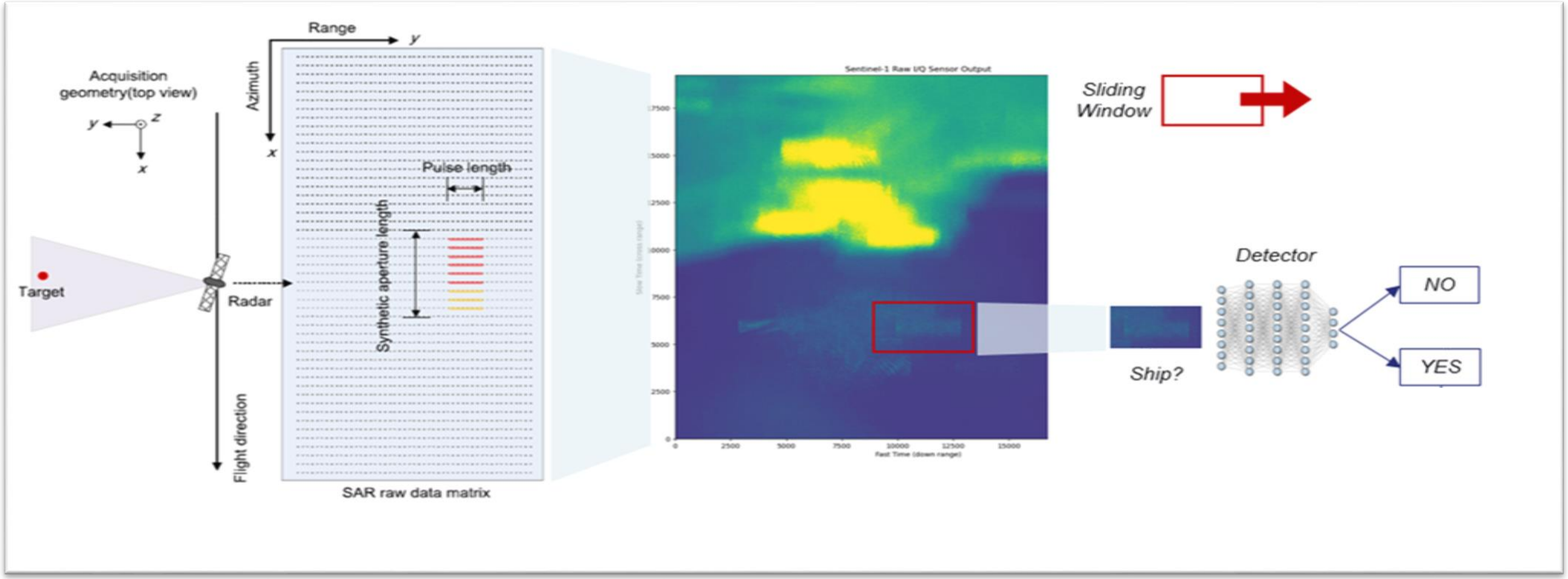
Date: 13/10/2025
Ref:
Template: 83230347-DOC-TAS-EN-006

SHIP DETECTION FOR MARITIME SURVEILLANCE

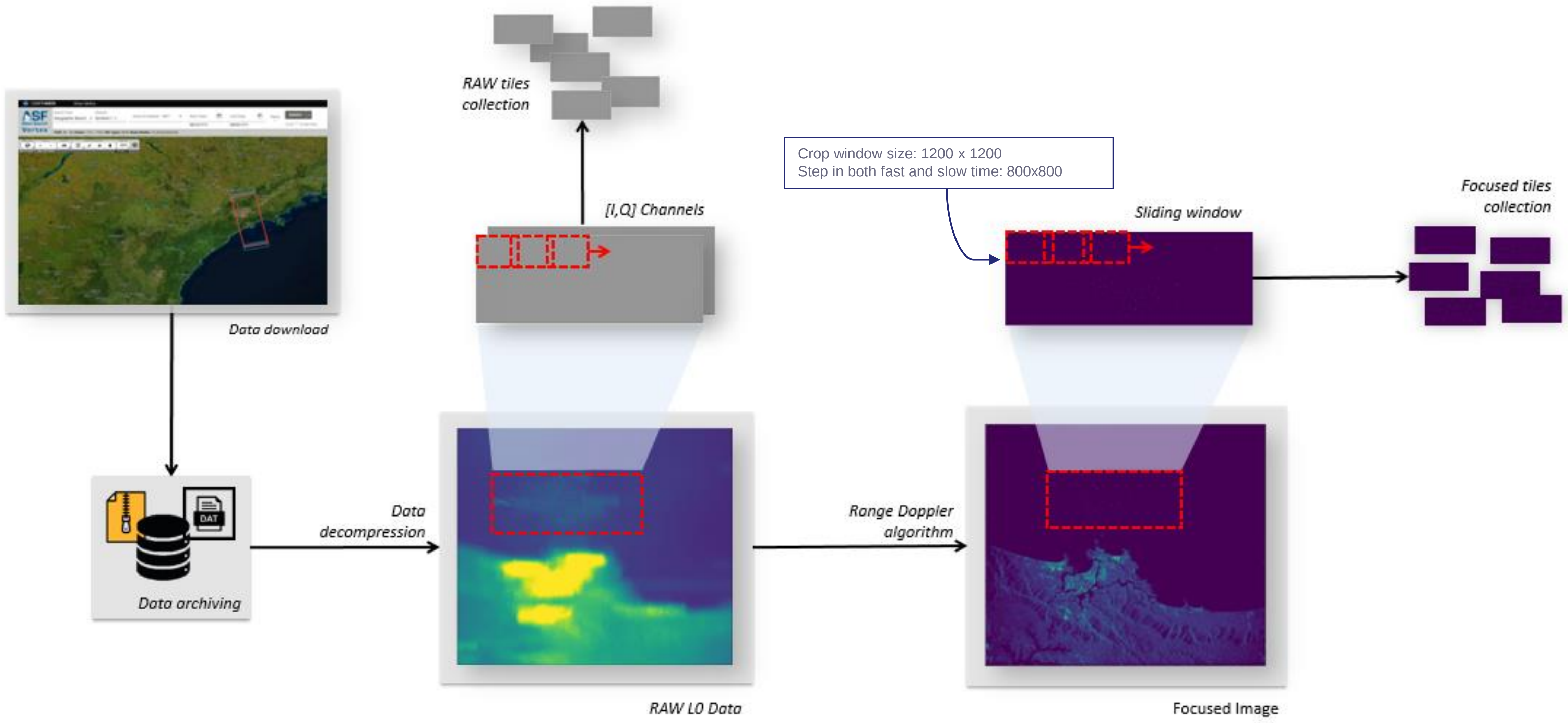
- *Enhancing AI algorithms and NNs to optimize the process ON BOARD!*

/// Use case:

- Detect and localize vessels from decompressed image in (almost) real time
- Exploit deep learning with sar technology in the context of Sentinel-1 mission



DATA HANDLING: TILE EXTRACTION & PROCESSING

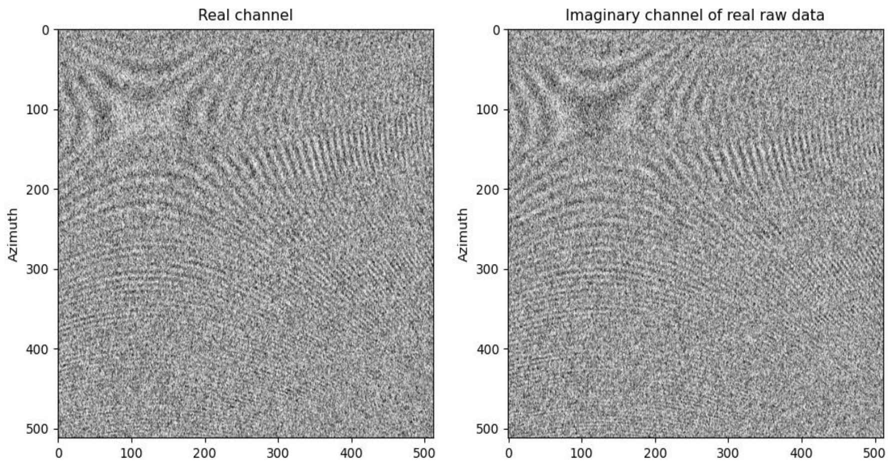


Date: 13/10/2025
Ref:
Template: 83230347-DOC-TAS-EN-006

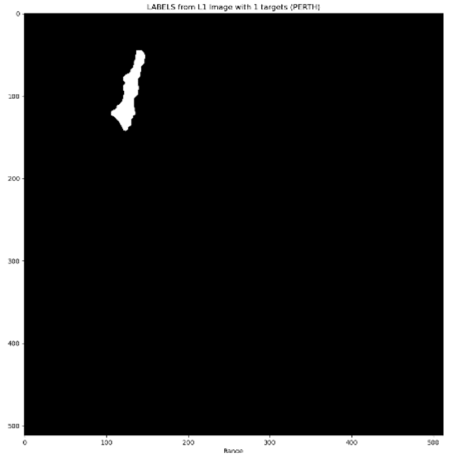
DATA HANDLING: OVERVIEW ON PRE-PROCESSING

/// Finally, we have created input images and ground truth masks as follows:

- on decompressed image (2D inputs): channel split (I,Q) -> crop with sliding window



- on focused image (ground truth): CFAR -> thresholding -> …



Date: 13/10/2025
Ref:
Template: 83230347-DOC-TAS-EN-006

DATA HANDLING: MORPHOLOGICAL OPERATIONS

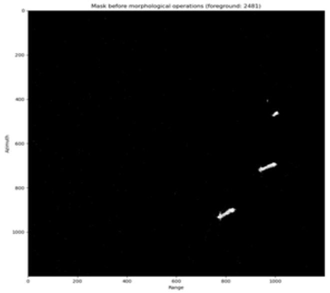
/// One major problem: CLASS IMBALANCE!

- The number of foregrounds is way much lower than the background, thus the model will struggle to recognize groups of pixels as target in the scene!

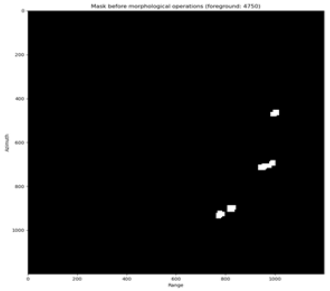
/// Morphological operations:

- **EROSION**: reduces size of targets in the binary image by removing pixels from the boundaries of the object.
- **DILATION**: increases size of targets in the binary image by adding pixels to the boundaries of the object.
- **OPENING**: combines erosion and dilation, is used to remove small portions from the image and fill small gaps in the objects.
- **CLOSING**: combines erosion and dilation, is used to remove small holes and connect small gaps between objects.

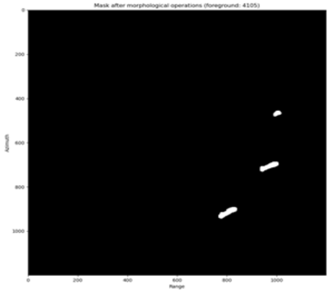
PREPROCESSED
(thresholding with 0.045)
=> **2481** foreground



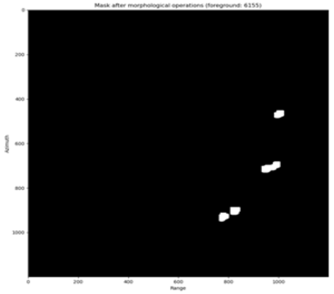
PREPROCESSED
(fill 10x10 area of any point passing CFAR)
=> **4750** foreground



POSTPROCESSED
(closing 6x6 -> opening 10x10 -> dilation 6x6)
=> **4105** foreground



POSTPROCESSED
(opening 10x10 -> closing 6x6 -> dilation 10x10)
=> **6155** foreground



/// The following operations are applied:

- **DILATION 6x6 -> CLOSING 10x10 -> EROSION 4x4** in preprocessing (dataset creation)
- **EROSION 4x4 -> OPENING 6x6 -> CLOSING 10x10 -> DILATION 3x3** in postprocessing (reduce outliers prediction)

DATA HANDLING: DATA AUGMENTATION

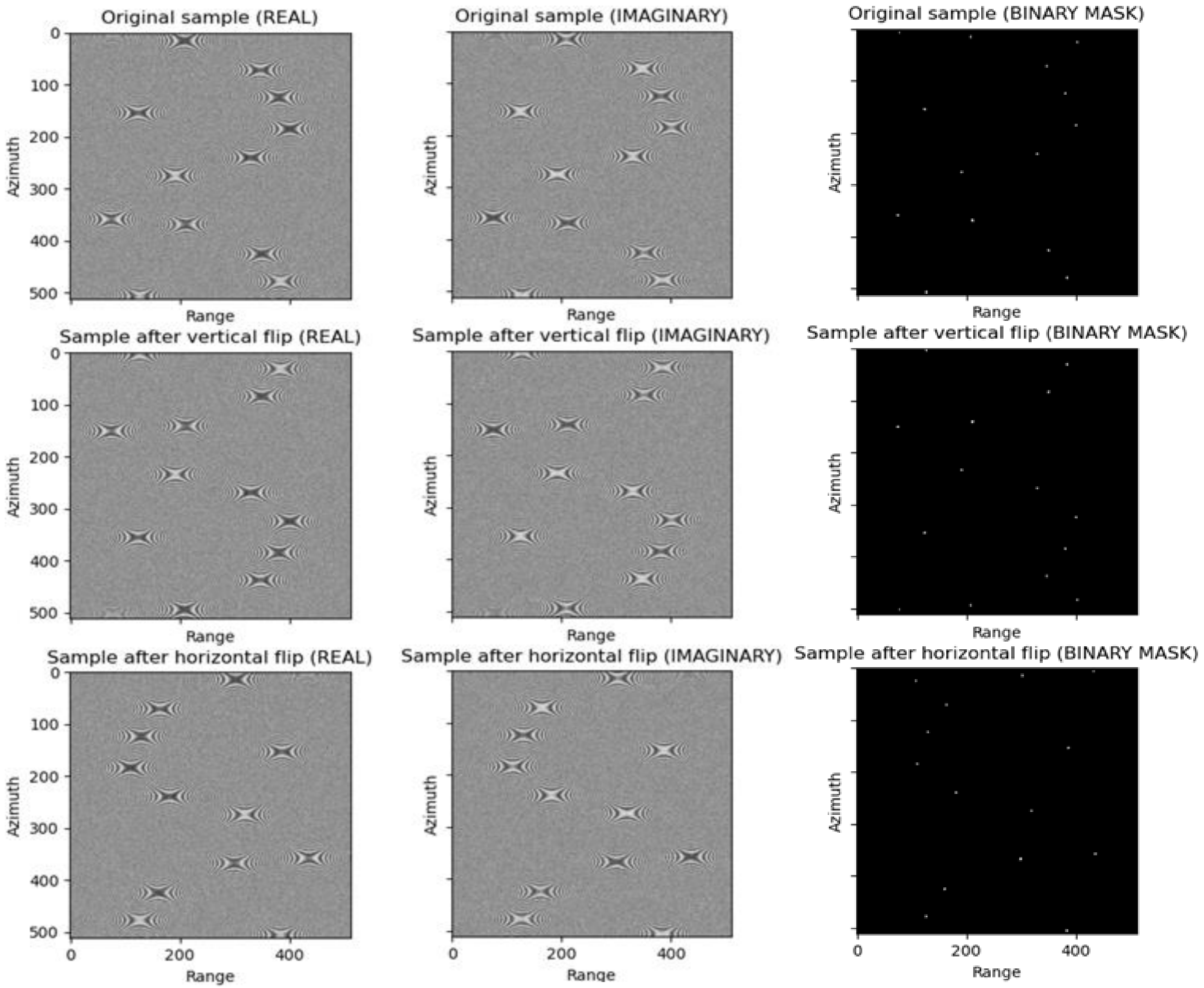
/// We apply the following transforms:

- **Per-channel normalization**
- **Vertical flipping**
- **Horizontal flipping**
- **Resize at (512, 512)**

/// Original samples are kept along with the transformed ones!

/// Final dataset size is tripled

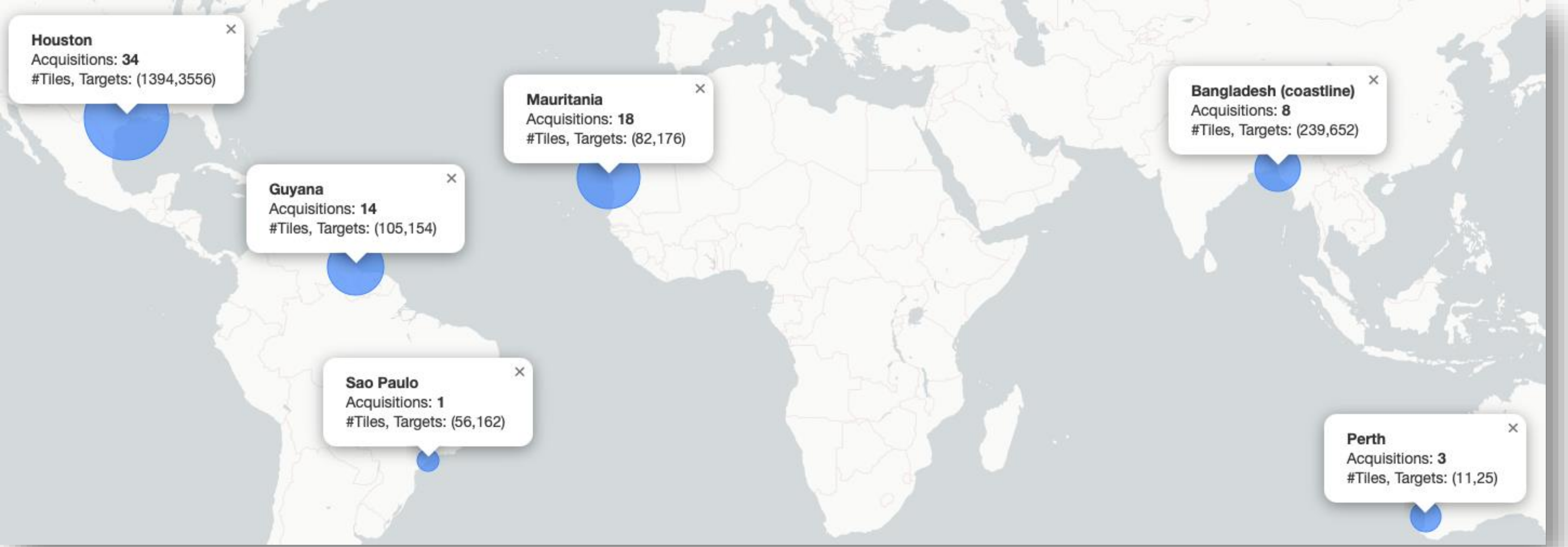
- **From 1648 to <u>4944</u> samples**



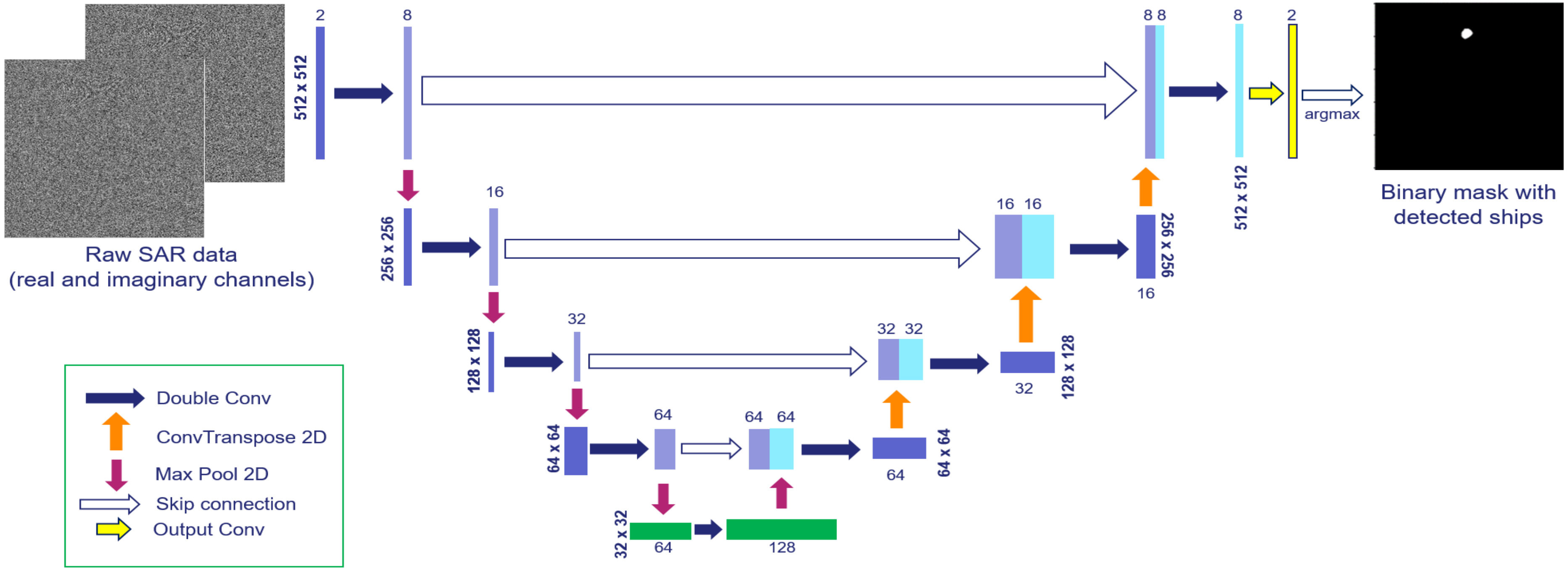
DL MODEL: DATASET CONSTRUCTION

Acquisitions are downloaded from [ASF Data Search DAAC web portal]

- **68** coastline acquisitions with different polarization and world-wide coverage
  - 34 over Houston (HH,S3), 14 over Guyana (VV,S3), 18 over Mauritania (VV,S3), 3 over Perth (HH,S5), 1 over San Paolo (HH,S3)
- Extracted tiles: **1648**, where:
  - 1394 from Houston (used for training), 105 from Guyana, 82 from Mauritania, 56 from San Paolo, 11 from Perth
- Splitting after augmentation: **4182** for testing, **384** for validation, **126** for testing
- 239 tiles from 8 acquisitions above Bangladesh coastline are used to validate the model on the edge



DL MODEL: ARCHITECTURE & HYPERPARAMETERS



- /// **LOSS FUNCTION**: focal loss, α = proportion of foreground, γ = 2
- /// **OPTIMIZER**: **AdamW** with different configurations of learning rate and weight decay
  - Learning rates: $5e^{-4}, 1e^{-4}, 5e^{-5}, 1e^{-5}$
  - Weight decays: $0, 5e^{-4}, 1e^{-4}, 4e^{-5}$
  - Batch sizes: 4, 8, 16, 32
- /// Model hyperparameters must be optimized to learn effectively from real imagery!
  - Dropout lowered to 0.1
  - Adjust internal parameters (padding, kernel sizes)
  - Training phase lasting for 50 epochs

DL MODEL: METRICS

/// Weighted F1 score not precise -> *RELAXED F1 SCORE!*

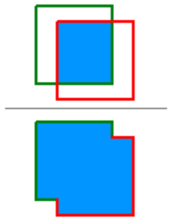
$$F1_{rel} = \frac{2TP}{2TP+FP+FN}$$

Starting from ground truth, we compute structures and their center of mass. If a center of mass lies inside a blob in the prediction, it is considered as TP, otherwise it is considered as a TN. If some labels are not mapped in the prediction, consider them as FN.

/// Additional performance metrics: *IoU SCORE & DICE SCORE*

IoU score

$$IOU = \frac{\text{area of overlap}}{\text{area of union}} =$$



Dice score

$$DSC = 2\frac{A \cap B}{A + B}$$

DL MODEL: QUANTITATIVE RESULTS (1)

- Top 5 model configs with **depth 4**
- We consider the **relaxed F1 score** as main value!

Learning rate	Weight Decay	Batch size	Balanced Accuracy	Relaxed F1	Dice score	IoU score
$1e^{-4}$	0	8	.8852	**.7502**	.3138	.4558
$5e^{-4}$	$5e^{-4}$	8	.8836	.7370	.3314	.4726
$5e^{-4}$	$5e^{-4}$	4	.8691	.7360	.3361	.4798
$1e^{-4}$	0	32	.8619	.7328	.3670	.5074
$5e^{-4}$	$4e^{-5}$	16	.8756	.7244	.3451	.4874

Date: 13/10/2025
Ref:
Template: 83230347-DOC-TAS-EN-006

DL MODEL: QUANTITATIVE RESULTS (2)

- Top 5 model configs with **depth 5**
- We consider the **relaxed F1 score** as main value!

Learning rate	Weight decay	Batch size	Balanced Accuracy	Relaxed F1	Dice score	IoU score
$5e^{-4}$	$5e^{-4}$	32	.8721	**.7280**	.3746	.5172
$5e^{-5}$	$1e^{-4}$	4	.8411	.7212	.3692	.5110
$1e^{-4}$	$4e^{-5}$	16	.8783	.7134	.3344	.4757
$5e^{-4}$	$5e^{-4}$	8	.8843	.7039	.3226	.4661
$1e^{-4}$	$4e^{-5}$	16	.8399	.6916	.3396	.4786

Date: 13/10/2025
Ref:
Template: 83230347-DOC-TAS-EN-006

DL MODEL: QUANTITATIVE RESULTS (3)

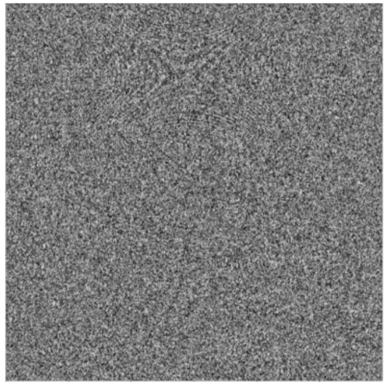
- Top 5 model configs with **depth 6**
- We consider the **relaxed F1 score** as main value!

Learning rate	Weight Decay	Batch size	Balanced Accuracy	Relaxed F1	Dice score	IoU score
$1e^{-4}$	0	8	.8349	**.7258**	.3889	.5271
$5e^{-4}$	$4e^{-5}$	4	.8911	.6894	.3164	.4582
$1e^{-4}$	$1e^{-4}$	4	.8677	.6888	.3579	.5019
$1e^{-4}$	$5e^{-4}$	8	.8683	.6844	.3197	.4621
$5e^{-5}$	$4e^{-5}$	4	.8753	.6798	.3245	.4654

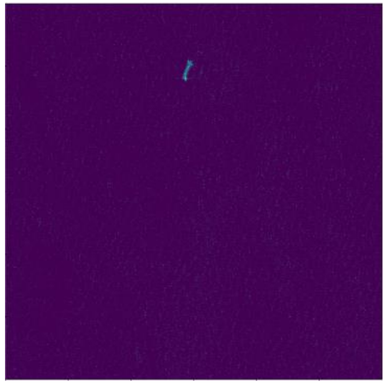
Date: 13/10/2025
Ref:
Template: 83230347-DOC-TAS-EN-006

DL MODEL: QUALITATIVE RESULTS

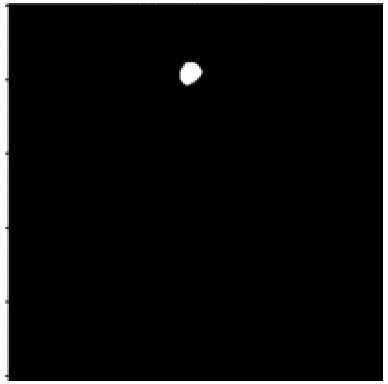
SINGLE TARGET SCENARIO



Decompressed input tile (real channel)

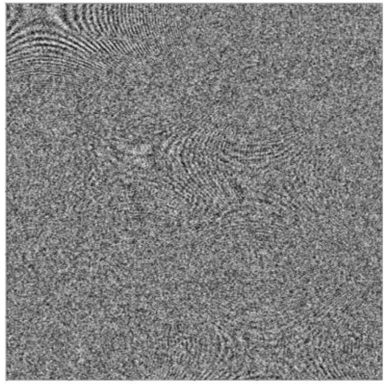


Focused patch (ground truth)

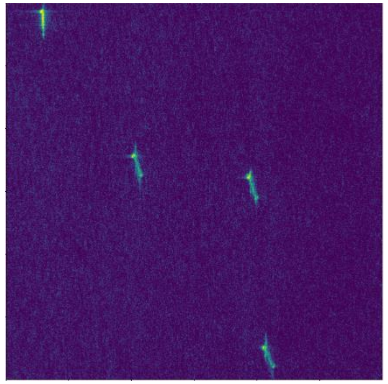


Model output (prediction)

MULTIPLE TARGET SCENARIO



Decompressed input tile (real channel)



Focused patch (ground truth)

Model output (prediction)

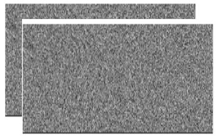
RECAP OF END-TO-END PIPELINE

SPACE SEGMENT

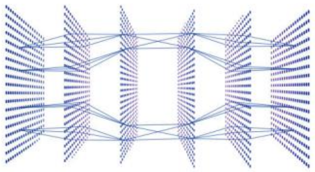
User Requests → Mission Plan (e.g feasibility requests) → Uplink requests → Image Acquisition & **NN inference + Processing** → Data Downlink → Delivery

GROUND SEGMENT

GROUND SEGMENT

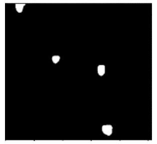


Input tiles



Ships?

NO-YES

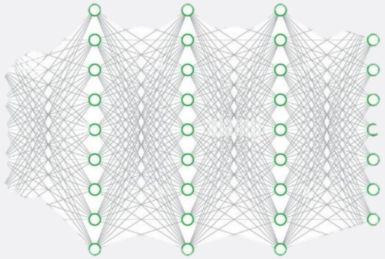


Binary Mask

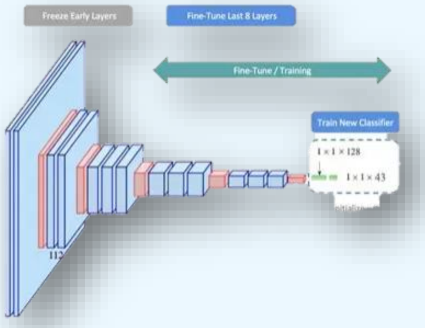
Inference time after quantization:
1.3 seconds on average!

CONCLUSIONS & FUTURE WORKS

Extend data augmentation and increase model complexity



Finetune model by integrating synthetic and real imagery



Deploy checkpoint to test on board processor units (Unibap, Versal)

Georeference vessels position with AIS data

Date: 13/10/2025
Ref:
Template: 83230347-DOC-TAS-EN-006

THANK YOU FOR YOUR ATTENTION