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Article

# Ship identification and characterization in Sentinel-1 SAR images with multi-task deep learning

Clément Dechesne <sup>1</sup>, Sébastien Lefèvre <sup>2</sup>, Rodolphe Vadaine <sup>3</sup>, Guillaume Hajduch <sup>3</sup>, Ronan Fablet <sup>1</sup>

<sup>1</sup> IMT Atlantique – Lab-STICC, UMR CNRS 6285, Brest, FR

<sup>2</sup> Univ. Bretagne Sud – IRISA, UMR CNRS 6074, Vannes, FR

<sup>3</sup> Collecte Localisation Satellites, Brest, FR

\* Correspondence: sebastien.lefevre@irisa.fr

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**Abstract:** The monitoring and surveillance of maritime activities are critical issues in both military and civilian fields, including among others fisheries monitoring, maritime traffic surveillance, coastal and at-sea safety operations, tactical situations. In operational contexts, ship detection and identification is traditionally performed by a human observer who identifies all kinds of ships from a visual analysis of remotely-sensed images. Such a task is very time consuming and cannot be conducted at a very large scale, while Sentinel-1 SAR data now provide a regular and worldwide coverage. Meanwhile, with the emergence of GPUs, deep learning methods are now established as state-of-the-art solutions for computer vision, replacing human intervention in many contexts. They have been shown to be adapted for ship detection, most often with very high resolution SAR or optical imagery. In this paper, we go one step further and investigate a deep neural network for the joint classification and characterization of ships from SAR Sentinel-1 data. We benefit from the synergies between AIS (Automatic Identification System) and Sentinel-1 data to build significant training datasets. We design a multi-task neural network architecture composed of one joint convolutional network connected to three task-specific networks, namely for ship detection, classification and length estimation. The experimental assessment showed our network provides promising results, with accurate classification and length performance (classification overall accuracy: 97.25%, mean length error: 4.65 m  $\pm$  8.55 m).

**Keywords:** Deep neural network, Sentinel-1 SAR images, Ship identification, Ship characterization, Multi-task learning

## 1. Introduction

Deep learning is considered as one of the major breakthrough related to big data and computer vision [1]. It has become very popular and successful in many fields including remote sensing [2]. Deep learning is a paradigm for representation learning and is based on multiple levels of information. When applied on visual data such as images, it is usually achieved by means of convolutional neural networks. These networks consist of multiple layers (such as convolution, pooling, fully connected and normalization layers) aiming to transform original data (raw input) into higher-level semantic representation. With the composition of enough such elementary operations, very complex functions can be learned. For classification tasks, higher-level representation layers amplify aspects of the input that are important for discrimination and discard irrelevant variations. For humans, it is simple through visual inspection to know what objects are in an image, where they are, and how they interact in a very fast and accurate way, allowing to perform complex tasks. Fast and accurate algorithms for object detection are thus sought to allow computers to perform such tasks, at a much larger scale than

32 humans can achieve.

33

34 Ship detection and classification have been extensively addressed with traditional pattern recognition  
35 techniques for optical images. *Zhu et al.*[3] and *Antelo et al.*[4] extracted handcrafted features from  
36 images such as shapes, textures and physical properties, while *Chen et al.*[5] and *Wang et al.*[6]  
37 exploited Dynamic Bayesian Networks to classify different kinds of ships. Such extracted features are  
38 known for their lack of robustness that can raise challenges in practical applications (e.g. they may  
39 lead to poor performances when the images are corrupted by blur, distortion, or illumination which  
40 are common artifacts in remote sensing). Furthermore, they cannot overcome the issues raised by big  
41 data such as image variabilities (i.e. ships of same type may have different shape, color, size, etc.) and  
42 data volume. Recently, following the emergence of deep learning, an autoencoder-based deep neural  
43 network combined with extreme learning machine was proposed [7] and outperformed some other  
44 methods using SPOT-5 spaceborne optical images for ship detection.

45

46 Compared with optical remote sensing, satellite SAR imaging appears more suited for maritime  
47 traffic surveillance in operational contexts as it is not critically affected by weather conditions  
48 and day-night cycles. In this context, open-source Sentinel-1 SAR data are particularly appealing.  
49 Almost all coastal zones and shipping routes are covered by Interferometric Wide Swath Mode  
50 (IW), while the Extra-Wide Swath Mode (EW) acquires data over open oceans, providing a global  
51 coverage for sea-oriented applications. Such images, combined with the Automatic Identification  
52 System (AIS), represent a large amount of data that can be employed for training deep learning  
53 models [8]. AIS provides meaningful and relevant information about ships (such as position, type,  
54 length, rate of turn, speed over ground, etc.). The combination of these two data sources could  
55 leverage new applications to the detection and estimation of ship parameters from SAR images,  
56 which remains a very challenging task. Indeed, detecting inshore and offshore ships is critical  
57 in both military and civilian fields (e.g. for monitoring of fisheries, management of maritime  
58 traffics, safety of coast and sea, etc). In operational contexts, the approaches used so far still rely  
59 on manual visual interpretations that are time-consuming, possibly error-prone, and definitely  
60 irrelevant to scale up to the available data streams. On the contrary, the availability of satellite data  
61 such as Sentinel-1 SAR makes possible the exploration of efficient and accurate learning-based schemes.

62

63 One may however consider with care AIS data as they involve specific features. AIS is mandatory for  
64 large vessels (e.g., >500GT, passenger vessels). As such, it provides representative vessel datasets  
65 for international maritime traffic, but may not cover some maritime activities (e.g., small fishing  
66 vessels). Though not authorized, ships can easily turn off their AIS and/or spoof their identity. While  
67 AIS tracking strategies [9] may be considered to address missing track segments, the evaluation of  
68 spoofing behaviour is a complex task. *Iphar et al.* [10] evaluate that amongst ships with AIS, about 6%  
69 have no specified type, 3% are only described as "vessels". Besides, respectively 47% and 18% of the  
70 vessels may involve uncertain length and beam data. These points should be considered with care in  
71 the analysis of AIS datasets, especially when considering learning strategies as addressed in this work.

72

73 Among existing methods for ship detection in SAR images, Constant False Alarm Rate (CFAR)-based  
74 methods have been widely used [11,12]. The advantage of such methods is their reliability and high  
75 efficiency. Using AIS information along with SAR images significantly improves ship detection  
76 performance [13]. As the choice of features has an impact on the performance of discrimination,  
77 deep neural networks have recently taken the lead thanks to their ability to extract (or learn)  
78 features that are richer than hand-crafted (or expert) features. In [14], a framework named Sea-Land  
79 Segmentation-based Convolutional Neural Network (SLS-CNN) was proposed for ship detection,  
80 combined with the use of saliency computation. A modified Faster R-CNN based on CFAR algorithm  
81 for SAR ship detection was proposed in [15] with good detection performance. In [16], texture features

82 extracted from SAR images are fed into artificial neural networks (TF-ANN) to discriminate ship pixels  
83 from sea ones. *Schwegmann et al.* [17] employed highway network for ship detection in SAR images and  
84 achieved good results, especially in reducing the false detection rate. These state-of-the-art approaches  
85 focused on ship detection in SAR images. In this paper, we aim to go beyond ship detection and  
86 investigate higher-level tasks, namely the identification of ship types (a.k.a. classification) and their  
87 length estimation, which to our knowledge remain poorly addressed using learning-based frameworks.

88  
89 The problem of ship length estimation from SAR images has been briefly discussed in [18,19]. In [18],  
90 the best shape of a ship is extracted from a SAR image using inertia tensors. The estimated shape  
91 allows to obtain the ship length. However, the absence of ground truth does not allow to validate  
92 the accuracy of this method. In [19], a three-step method is proposed in order to extract a rectangle  
93 that will be the reference model for ship length estimation. The method produces good results (mean  
94 absolute error:  $30\text{ m} \pm 36.6\text{ m}$ ). However, the results are presented on a limited dataset (only 127 ships)  
95 and their generalization may be questioned.

96  
97 In this paper, we propose a method based on deep learning for ship identification and characterization  
98 with the synergetical use of Sentinel-1 SAR images and AIS data.

## 99 2. Material and Methods

100 The proposed framework combines the creation of a reference groundtruthed dataset using AIS-SAR  
101 synergies and the design of a multi-task deep learning model. In this section, we first introduce the  
102 proposed multi-task neural network architecture, which jointly addresses ship detection, classification  
103 and length estimation. Second, we describe the training framework in terms of the considered training  
104 losses and of the implemented optimization scheme. Third, we detail the creation of the considered  
105 reference datasets, including how we tackled data augmentation and class imbalance issues, which  
106 have been shown to be critical for the learning process.

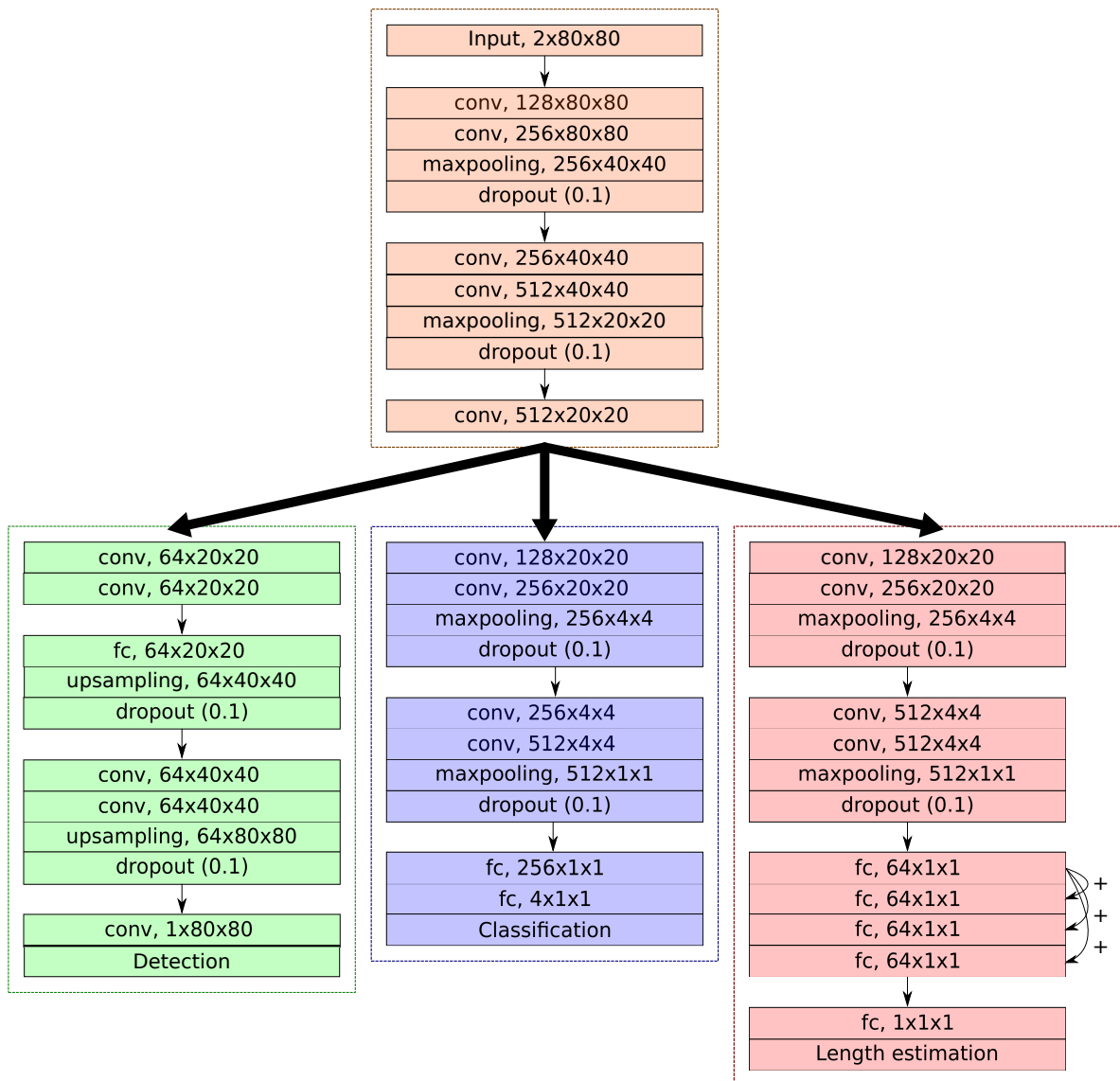
### 107 2.1. Proposed framework

108 The proposed multi-task framework is based on two stages, with a first common part and then  
109 three task-oriented branches for ship detection, classification and length estimation, respectively (see  
110 Figure 1). The first part is a convolutional network made of 5 layers. It is followed by the task-oriented  
111 branches. All these branches are made of convolutional layers followed by fully connected layers (the  
112 number of which depends on the complexity of the task). For the detection task, the output consists in  
113 a pixel-wise probability map of the presence of ships. It only requires 1 fully-connected layer after the 4  
114 convolutional layers. For the classification task, we consider 4 or 5 ship classes (Cargo, Tanker, Fishing,  
115 Passenger, and optionally Tug). The branch also requires 4 convolutional layers and 2 fully connected  
116 layers. The last task is related to the length estimation. This branch is composed of 4 convolutional  
117 layers and 5 fully-connected layers.

118 This architecture is inspired from state-of-the-art architectures [20–22]. The number of layers has been  
119 chosen to be similar to the first layers of the VGG network [22]. All the activations of the convolutional  
120 layers and fully-connected layers are ReLu [23]. Other activation functions are employed for the output  
121 layers: a sigmoid for the detection, a softmax activation for the classification, and a linear activation is  
122 employed for the length estimation, further details are presented in Section 2.2. We may emphasize  
123 that our model includes a detection component. Though this is not a targeted operational objective in  
124 our context, it was shown to improve the performance for the other tasks (See Table 7).

### 125 2.2. Training procedure

126 We describe below the considered training strategy, especially the training losses considered for each  
127 task-specific component. The proposed end-to-end learning scheme combines task-specific training  
128 losses as follows:



**Figure 1.** Proposed multi-task architecture for ship detection, classification (4 classes) and length estimation from a Sentinel-1 SAR image.

- **Detection loss:** the detection output is a ship presence probability. We employ a binary cross-entropy loss, which is defined by:

$$L_{det} = -\frac{1}{N} \sum_{n=1}^N \sum_{k \in I} (y_k \log(p(k)) + (1 - y_k) \log(1 - p(k))), \quad (1)$$

129 where  $N$  is the number of samples,  $k$  is a pixel of the output detection image  $I$ ,  $y_k$  is the ground  
 130 truth of ship presence (0 or 1), and  $p(k)$  is the predicted probability of ship presence. It is a usual  
 131 loss function for binary classification tasks [24].

- **Classification loss:** The output for the last classification layer is the probability that the input image corresponds to one of the considered ship types. We use here the categorical cross-entropy loss:

$$L_{class} = -\frac{1}{N} \sum_{n=1}^N \sum_{c=1}^{n_c} (y_{o,c} \log(p_{o,c})), \quad (2)$$

132 where  $N$  is the number of samples,  $n_c$  is the number of classes (here,  $n_c = 4$  or  $n_c = 5$ ),  $y_{o,c}$  is a  
 133 binary indicator (0 or 1) if class label  $c$  is the correct classification for observation  $o$  and  $p_{o,c}$  is the  
 134 predicted probability for the observation  $o$  to belong to class  $c$ . It is a widely-used loss function  
 135 for multiclass classification tasks [25,26].

- **Length estimation loss:** in the length estimation network, the 4 fully-connected layers of shape  $(64 \times 1 \times 1)$  are connected to each other (see Figure 1). The idea is to propagate the difference between the first layer and the current layer and is related to residual learning [27]. We use here the mean squared error defined as

$$L_{length} = \frac{1}{N} \sum_{n=1}^N (l_{pred} - l_{true})^2, \quad (3)$$

136 where  $N$  is the number of samples,  $l_{pred}$  is the predicted length and  $l_{true}$  is the true length.

Overall, we define the loss function of the whole network as

$$L = L_{det} + L_{class} + L_{length}. \quad (4)$$

137 Each specific loss employed to design the loss of the whole network could have been weighted.  
 138 Nevertheless, we have observed no significant effect of such a weighting scheme. Thus we decided  
 139 to rely on a simple combination through adding the different task-dedicated losses, giving the same  
 140 importance to each task. Our network is trained end-to-end using RMSProp optimizer [28]. The  
 141 weights of the network are updated by using a learning rate of 1e-4 and a learning rate decay over  
 142 each update of 1e-6 over the 500 iterations. Such parameterization has shown good results for our  
 143 characterization tasks.

### 144 2.3. Creation of reference datasets

145 With a view to implementing deep learning strategies, we first address the creation of reference datasets  
 146 from the synergy between AIS data and Sentinel-1 SAR data. AIS transceiver sends data every 2 to 10  
 147 seconds. These data mainly consist in a positional accuracy (up to 0.0001 minutes precision), and the  
 148 course over ground (relative to true north to 0.1°). For a given SAR image, one can interpolate AIS  
 149 data from the associated acquisition time. Thus it is possible to know the precise location of the ships  
 150 in the SAR image and the related information (in our case, length and type). The footprint of the ship  
 151 is obtained by thresholding the SAR image in the area where it is located (the brightest pixel of the  
 152 image). Since the database is very unbalanced in terms of class distribution, a strategy is also proposed  
 153 in order to enlarge the training set with translations and rotations, which is a standard procedure for  
 154 database enlargement (a.k.a. data augmentation). Concurrently to our work, a similar database has  
 155 been proposed in [29]. We also evaluate our framework with this dataset (see Section 3.5).

156 In our experiments, we consider a dataset composed of 18,894 raw SAR images of size  $400 \times 400$  pixels  
157 with a 10 m resolution. The polarization of the images are either HH (proportion of horizontally  
158 transmitted waves which return horizontally) or VV (proportion of vertically transmitted waves which  
159 return vertically). Polarization has a significant effect on SAR backscatter. However, our goal is to  
160 allow us to process any Sentinel-1 SAR images. We thus consider any HH and VV polarized image  
161 without prior information on the type of polarization. Each image is accompanied with the incidence  
162 angle since it impacts the backscatter intensity of the signal. For the proposed architecture, the input  
163 is a 2-band image (backscatter intensity and incidence angle). Thus we did not use any pre-trained  
164 network since we assume that they can not handle such input data. We rely on Automatic Identification  
165 System (AIS) to extract images that contain a ship in their center. AIS also provides us with information  
166 about the ship type and length. As stated before, AIS may have been corrupted (e.g. with spoofing),  
167 when creating the database, we only consider ships that responds to the two following criteria; (i)  
168 their type is clearly defined (i.e. they belongs to the retained classes), (ii) their length is greater than  
169 0 and smaller than 400 meters (the largest ship in the world). Besides, the SAR images we selected  
170 were acquired over European waters, where we expect AIS data to be of higher-quality compared with  
171 other maritime areas.  
172 The dataset is strongly imbalanced, amongst the 5 classes (*Tanker*, *Cargo*, *Fishing*, *Passenger* and *Tug*),  
173 the *Cargo* is the most represented (10,196 instances), while the *Tug* is the less represented (only 444  
174 instances). The class distribution is detailed in Figure 2 and Table 1. The length distribution shows that  
175 *Tanker*, *Cargo*, and *Passenger* ships have similar length distributions. *Fishing* ships have relatively small  
176 lengths, while *Tug* ship length are intermediate.

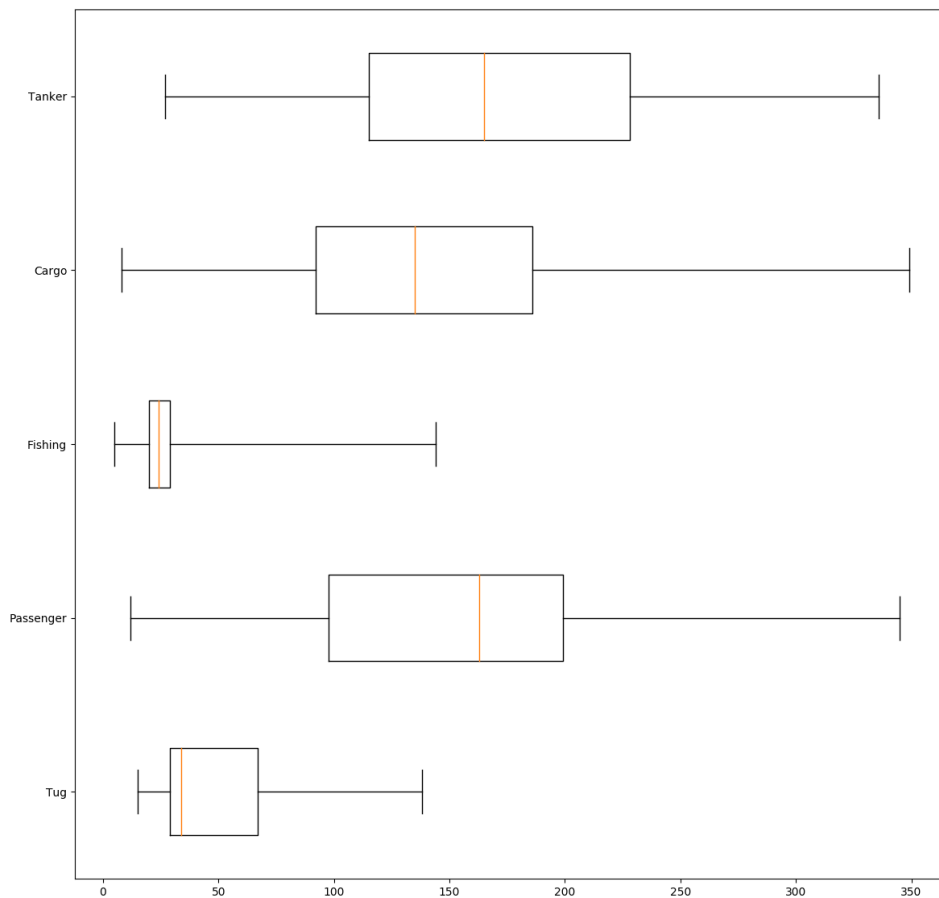


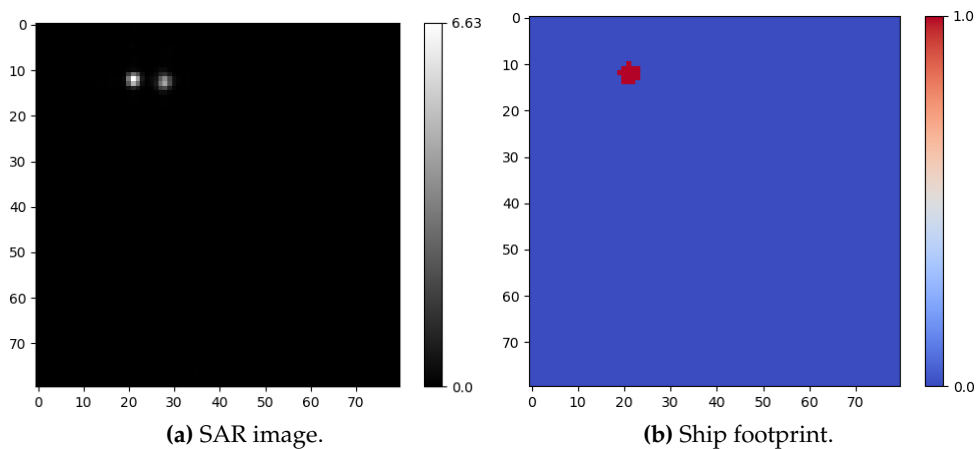
Figure 2. Boxplot of length distribution for each class in our dataset. Length data are given in meters.



	Tanker	Cargo	Fishing	Passenger	Tug
Number of samples	4737	10196	2664	1071	444
Length mean (m)	168.4	146.5	26.6	153.5	47.3
Length standard deviation (m)	64.6	60.8	12.2	68.9	26.0
Number of augmented samples (4 classes)	263	0	2336	3929	-
Number of augmented samples (5 classes)	0	0	1336	2929	3556

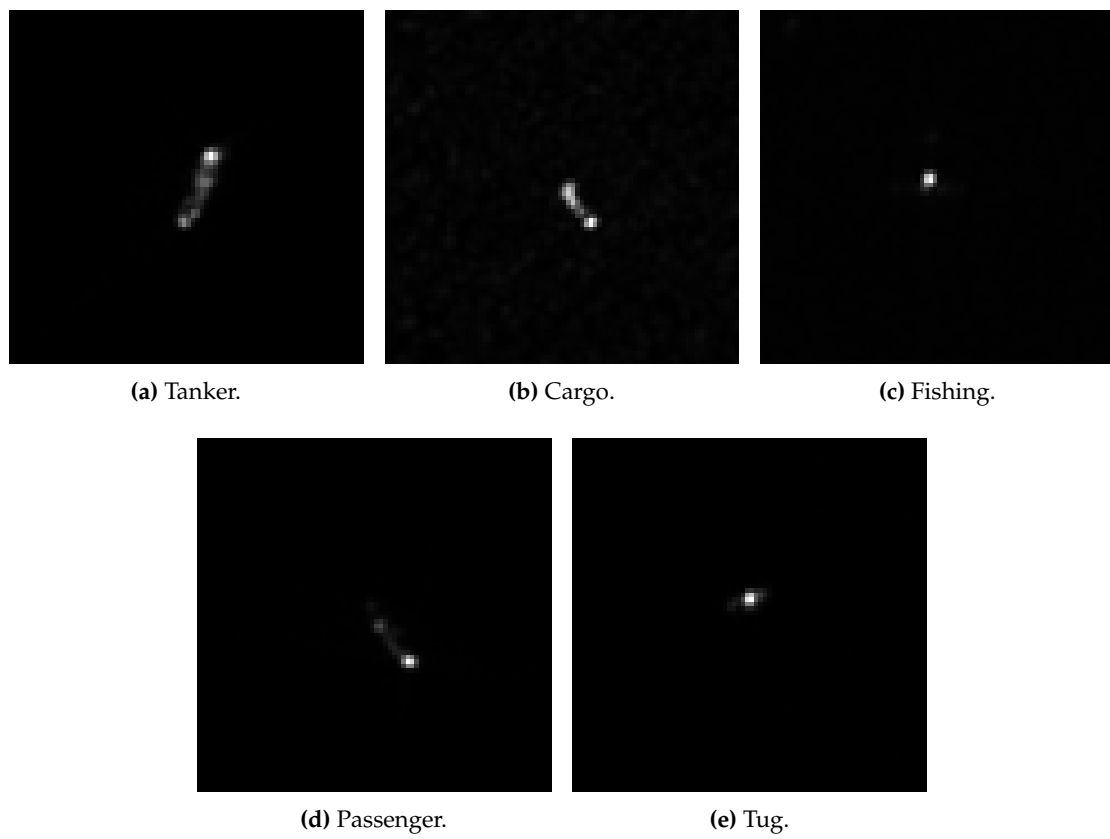
**Table 1.** Length distribution and number of samples for each class in our dataset.

177 To account for class imbalance [30], we apply data augmentation with translations and rotations.  
 178 We first perform a rotation of a random angle centered on the brightest pixel of the SAR image (the  
 179 center of the ship), and then perform a random translation. The same transformation is applied  
 180 to the incidence angle image. The images employed to train the networks are of size  $80 \times 80$  pixels.  
 181 They contain ships (not necessarily in their center, see Figure 4). The ship footprint groundtruth is  
 182 generated by thresholding the SAR image since we precisely know the location of the ship (i.e. it is the  
 183 brightest pixel of the SAR image, see Figure 3). The obtained footprint is not perfect (see Figure 3b) but  
 184 was shown to be sufficient to train the network. Let us note that a CFAR approach could have been  
 185 employed in order to extract more precisely the ship footprint [11]. But since our goal is not to detect  
 186 ships, a coarse ship footprint is sufficient. We considered 2 configurations for the databases; a 4-classes  
 187 database, employed to compare our baseline to other state-of-the-art approaches (namely MLP and  
 188 R-CNN), and 5-classes database in order to evaluate how our network responds with more classes.  
 189 Each database is composed of 20,000 images of  $80 \times 80$  pixels, with the same amount of samples per  
 190 class (5,000 per class for the 4-classes database, and 4,000 per class for the 5-classes database). The  
 191 networks are trained with 16,000 images and the remaining 4,000 are used for validation. Throughout  
 192 the data augmentation process, we ensure that images can be seen either in the training or validation  
 193 set, but not in both. Ships with no AIS signal are not considered in our dataset (neither to train or  
 194 evaluate our model), since our strategy to build the dataset relies on matching AIS signal with SAR  
 195 imagery. However, once a model has been trained, it can perform in an operational settings to detect  
 196 ships with no AIS (it is indeed one of our long-term goals).



**Figure 3.** Example of SAR image (with backscatter intensity) and associated ship footprint (best viewed in color).





**Figure 4.** Examples of SAR image (with backscatter intensity) for each ship type of the collected database.

### 197 3. Results

198 We run all numerical experiments on a PC with a NVIDIA GTX 1080 Ti, an Intel Xeon W-2145 CPU  
 199 3.70GHz and 64GB RAM (with a Keras [31] implementation). We evaluate the proposed framework  
 200 with respect to other popular deep learning-based solutions. We first consider a Multi-Layer  
 201 Perceptron (MLP) [32] with only one hidden layer with 128 hidden units. The MLP is the most  
 202 simple network that can be proposed for the desired task and can be a good basis in order to evaluate  
 203 the performance of our network. We also designed a R-CNN (Regions with CNN features) [33]  
 204 network in order to extract ship bounding boxes along with classification. Even if the R-CNN-based  
 205 bounding boxes do not allow to precisely measure the ship length, they can provide a good basis for  
 206 its estimation. R-CNN is a state-of-the-art algorithm for object detection and classification [33]. Thus  
 207 it is worth being compared with our proposed model. The R-CNN has a very simple architecture  
 208 presented in Figure 5. The networks are trained using 16,000 images from the augmented dataset and  
 209 the remaining 4,000 images are used for validation.

210  
 211 The evaluation of the models is performed using several metrics. The classification task is assessed  
 212 through the confusion matrix, giving, for each class and overall, several metrics. The Intersection over  
 213 Union (IoU or Jaccard index) [34] measures similarity between finite sample sets, and is defined as  
 214 the size of the intersection divided by the size of the union of the sample sets. It has been designed  
 215 for the evaluation of object detection. The F-score is the harmonic mean of precision and recall, it  
 216 reaches its best value at 1 and worst at 0. The Kappa coefficient [35] ( $\kappa$ ) is generated from a statistical  
 217 test to evaluate the accuracy of a classification. Kappa essentially evaluates how well the classification  
 218 performs as compared to just randomly assigning values (i.e. did the classification do better than  
 219 randomness?) The Kappa coefficient can range from -1 to 1. A value of 0 (respectively -1 or 1) indicates  
 220 that the classification is no better (respectively worse or better) than a random classification.

221 For the length estimation task, the mean error (and its standard deviation) are employed. For a ship  
 222  $k$ , the length error is defined as  $e_k = l_{k,pred} - l_{k,true}$ , where  $l_{k,pred}$  is the predicted length and  $l_{k,true}$  is  
 223 the actual length. The mean error  $m_{err\_length}$  (respectively the standard deviation  $stdev_{err\_length}$ ), is the  
 224 mean (respectively the standard deviation) of all the  $e_k$ . We further refer mean error to  $m_{err\_length} \pm$   
 225  $stdev_{err\_length}$ .

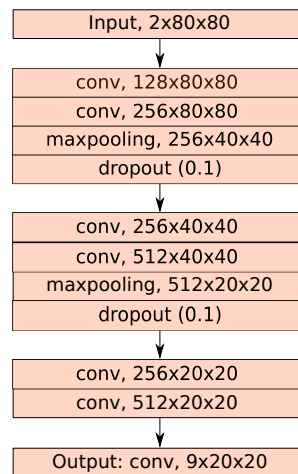


Figure 5. R-CNN architecture considered for ship classification.

#### 226 3.1. MLP model

227 For a  $80 \times 80$  image, the MLP runs at 2,000 frames per second. The whole training takes about one  
 228 hour. The testing takes less than a minute. It produces very poor results. Indeed, the overall accuracy

229 for classification is **25%**, which means that the classifier assigns the same class to all the images (see  
 230 Table 2). The length estimation is also rather inaccurate, the ship length being underestimated with a  
 231 very large standard deviation (mean error:  $-7.5 \text{ m} \pm 128 \text{ m}$ ).

Confusion matrix					
Ground Truth \ Prediction	Tanker	Cargo	Fishing	Passenger	Precision
Tanker	1000	0	0	0	100.0
Cargo	1000	0	0	0	0.0
Fishing	1000	0	0	0	0
Passenger	1000	0	0	0	0.0
Recall	25.0	-	-	-	

Accuracy metrics					
Label	Tanker	Cargo	Fishing	Passenger	Overall
IoU	25.0	0.0	0.0	0.0	6.25
F-Score	40.0	-	-	-	10.00
Accuracy	25.0	75.0	75.0	75.0	25.00
$\kappa$	0.0	0.0	0.0	0.0	0.25

**Table 2.** Confusion matrix and accuracy metrics for the MLP with 4 classes.

### 232 3.2. R-CNN model

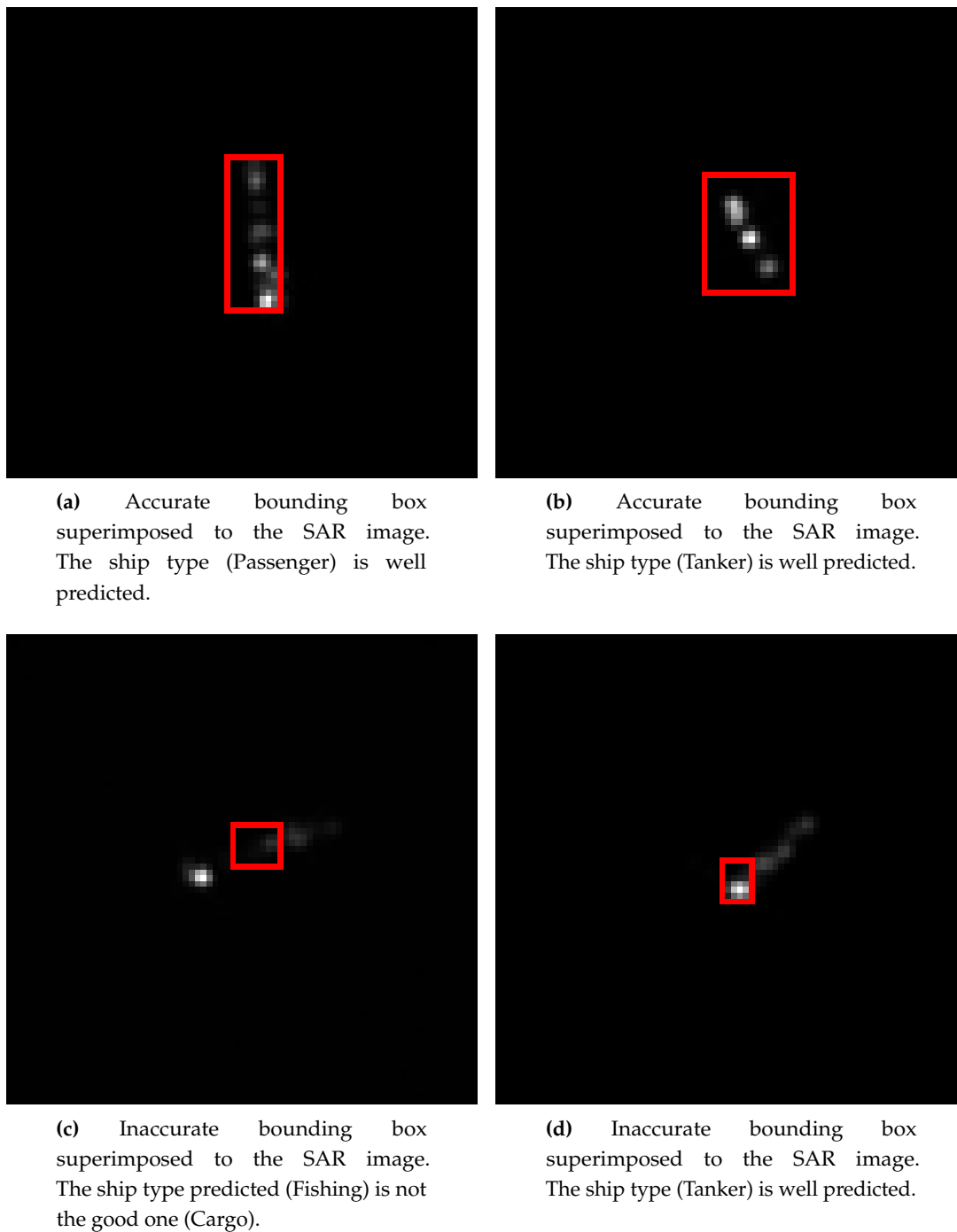
233 For a  $80 \times 80$  image, the R-CNN runs at 333 frames per second. The whole training takes about 6.5  
 234 hours and the testing about a minute. It produces better results than the MLP. The network estimates  
 235 the 4 corners of the bounding box. As the groundtruth for bounding boxes is obtained from the ship  
 236 footprint extracted by thresholding the SAR image, it might not be well-defined (see Figure 6c and 6d).  
 237 In Figure 6c, the bounding box is well centered on the ship, but has a wrong size. In Figure 6d, the  
 238 bounding box is also not well-sized, and accounts for the brightest part of the ship. We recall that the  
 239 detection task is not our main objective, but rather regarded as a means to better constrain the training  
 240 of the models. The R-CNN have a classification overall accuracy of **89.29%**. Several other metrics are  
 241 presented in Table 3.

242

Confusion matrix					
Ground Truth \ Prediction	Tanker	Cargo	Fishing	Passenger	Precision
Tanker	845	97	3	33	86.40
Cargo	98	787	24	77	79.82
Fishing	2	9	891	51	93.49
Passenger	8	15	1	961	97.56
Recall	88.67	86.67	96.95	85.65	

Accuracy metrics					
Label	Tanker	Cargo	Fishing	Passenger	Overall
IoU	77.81	71.09	90.83	83.86	80.90
F-Score	87.52	83.10	95.19	91.22	89.26
Accuracy	93.82	91.80	97.69	95.26	89.29
$\kappa$	0.83	0.78	0.94	0.88	0.88

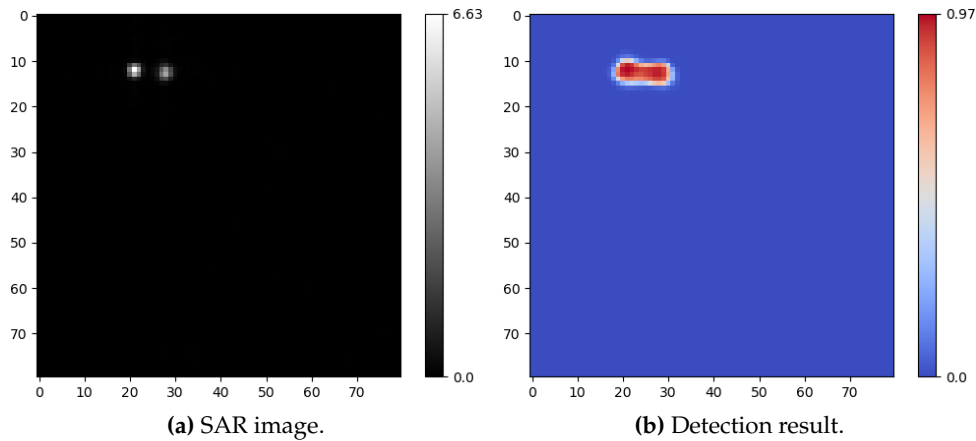
**Table 3.** Confusion matrix and accuracy metrics for the R-CNN with 4 classes.



**Figure 6.** Illustration of detection and classification performance of the evaluated R-CNN model: each subpanel depicts a SAR image with superimposed the detected bounding box.

### 243 3.3. Our network

244 For a  $80 \times 80$  image, our method can run at 250 frames per second. The whole training takes about  
 245 9 hours and the testing about a minute. With an overall accuracy and a mean F-score of **97.2%**, the  
 246 proposed multi-task architecture significantly outperforms the benchmarked MLP and R-CNN models.  
 247 We report in Table 4 the confusion matrix and additional accuracy metrics. Interestingly, classification  
 248 performances are relatively homogeneous across ship types (mean accuracy above 92% for all classes).  
 249 Tankers involve the greater misclassification rate with some confusion with cargo.  
 250 Regarding length estimation performance, our framework achieves very promising results. The length  
 251 is slightly over-estimated (mean error: **4.65 m  $\pm$  8.55 m**), which is very good regarding the spatial  
 252 resolution of the Sentinel-1 SAR data (10m/pixel). To our knowledge, this is the first demonstration  
 253 that reasonably-accurate ship length estimates can be derived from SAR images using learning-based  
 254 schemes, whereas previous attempts using model-driven approaches led to much poorer performance.  
 255 Overall, the results of the classification and length estimation tasks for all the tested architectures are  
 256 summarized in Table 6.



**Figure 7.** Example of detection output for the considered multi-task architecture: left, SAR image (with backscatter intensity) used as input; right, output of the detection module of the considered architecture.

Confusion matrix					
Prediction \ Ground Truth	Tanker	Cargo	Fishing	Passenger	Precision(%)
Tanker	985	11	0	4	98.5
Cargo	65	907	12	16	90.7
Fishing	0	2	998	0	99.8
Passenger	0	0	0	1000	100.0
Recall(%)	93.81	98.59	98.81	98.04	

Accuracy metrics					
Label	Tanker	Cargo	Fishing	Passenger	Overall
IoU(%)	92.49	89.54	98.62	98.04	94.67
F-Score(%)	96.10	94.48	99.30	99.01	97.22
Accuracy(%)	98.00	97.35	99.65	99.50	97.25
$\kappa$	0.95	0.93	0.99	0.99	0.97

**Table 4.** Confusion matrix and accuracy metrics for the proposed network with 4 classes.

257 We also train our model with 5 classes, and it confirms that our framework performs well. The length  
 258 is slightly over-estimated (mean error: **1.93 m  $\pm$  8.8 m**) and the classification is also very good (see

259 Table 5). Here, we still report some light confusion for Tanker and Cargo classes. The accuracy metrics  
 260 are slightly worse than the 4-class model but still report an overall accuracy and a mean F-score of  
 261 **97.4%**.

Confusion matrix						
Prediction \ Ground Truth	Tanker	Cargo	Fishing	Passenger	Tug	Precision(%)
Tanker	771	28	0	1	0	96.38
Cargo	60	732	3	3	2	91.50
Fishing	0	1	799	0	0	99.88
Passenger	3	1	0	796	0	99.50
Tug	0	0	0	0	800.0	100.00
Recall(%)	92.45	96.06	99.63	99.50	99.75	

Accuracy metrics						
Label	Tanker	Cargo	Fishing	Passenger	Tug	Overall
IoU(%)	89.34	88.19	99.50	99.00	99.75	95.16
F-Score(%)	94.37	93.73	99.75	99.50	99.88	97.44
Accuracy(%)	97.70	97.55	99.90	99.80	99.95	97.45
$\kappa$	0.93	0.92	1.00	0.99	1.00	0.97

**Table 5.** Confusion matrix and accuracy metrics for the proposed network with 5 classes.

Architecture	Length mean error (m)	Classification overall accuracy (%)
MLP	-7.50 ± 128	25.00
R-CNN	-	88.57
Our network	4.65 ± 8.55	97.25

**Table 6.** Results of all the tested architectures for the classification (4 classes) and length estimation.

262 We further analyse the proposed scheme and the relevance of the multi-task setting, compared  
 263 with task-specific architectures. To this end, we perform an ablation study and train the proposed  
 264 architecture using (i) length estimation loss only, (ii) classification loss only, (iii) the combination of  
 265 length estimation and classification losses (i.e., without the detection loss). We report in Table 7 the  
 266 resulting performances compared to those of the proposed end-to-end learning strategy. Regarding  
 267 the classification issue, combined losses result in an improvement of about 1.3% (above 25% in terms  
 268 of relative gain). The improvement is even more significant for length estimation with a relative gain  
 269 in the mean error of about 36%. Interestingly, we note that the additional use of the detection loss also  
 270 greatly contributes to the improvement of length estimation performance (mean error 2.85m without  
 271 using the detection loss during training vs. 1.93m when using jointly detection, classification and  
 272 length estimation losses). As an illustration of the detection component of the proposed architecture,  
 273 we illustrate in Figure 7 a detection result. As mentioned above, the thorough evaluation of this  
 274 detection model is not the main objective of this study. Furthermore, without any precise ship footprint  
 275 groundtruth, it is impossible to quantitatively evaluate the performance of the network for this specific  
 276 task. Let us recall that the detection task has been widely addressed in the literature [14–16]. Overall,  
 277 this complementary evaluation supports the idea that Neural Network architectures for SAR image  
 278 analysis may share some low-level task-independent layers, whose training can highly benefit from  
 279 the existence of multi-task datasets.

### 280 3.4. Application to a full SAR image

281 We illustrate here an application of the proposed approach to a real SAR image acquired on April 4,  
 282 2017 in Western Brittany, France. We proceed in several steps as follows. First, a CFAR-based ship  
 283 detector is applied. Then, for each detected ship, we apply the trained deep network model to predict

	Length mean error (m)	Classification overall accuracy (%)
(i)	$3.07 \pm 9.0$	-
(ii)	-	96.10
(iii)	$2.85 \pm 8.9$	97.50
Full network	$1.93 \pm 8.8$	97.45

**Table 7.** Ablation study, performance of the network for different scenarii: (i) only length estimation, (ii) only classification, (iii) length estimation and classification without detection.

284 the ship category and its length. For illustration purposes, we report in Figure 8 the detected ships  
 285 which could be matched to AIS signals.

286 For the considered SAR image, among the 98 ships detected by the CFAR-based ship detector, 66 ships  
 287 have their length documented and 69 ships belong to one of the 5 proposed classes after AIS matching.  
 288 We may point out that the *Tug* class is not represented. We report classification and length estimation  
 289 performance in Table 8. Ship classification performance is in line with the performance reported above.  
 290 Regarding length estimation, the mean error  $14.56 \text{ m} \pm 39.98 \text{ m}$  is larger than that reported for the  
 291 groudtruthed dataset. Still, this error level is satisfactory given the pixel resolution of 10 m of the SAR  
 292 image. Let us note that, given the limited samples available, the standard deviation is not fully relevant  
 293 here. While a special care was undertaken for the creation of our SAR-AIS dataset, this application to  
 294 a single SAR image exploits the raw AIS data. AIS data may be significantly corrupted, which may  
 295 partially explain these differences.

Confusion matrix					
Ground Truth \ Prediction	Tanker	Cargo	Fishing	Passenger	Precision(%)
Tanker	13	3	0	2	72.22
Cargo	5	30	0	0	85.71
Fishing	0	0	14	0	100.00
Passenger	0	0	0	1	100.00
Recall	72.22	90.91	100.00	33.33	

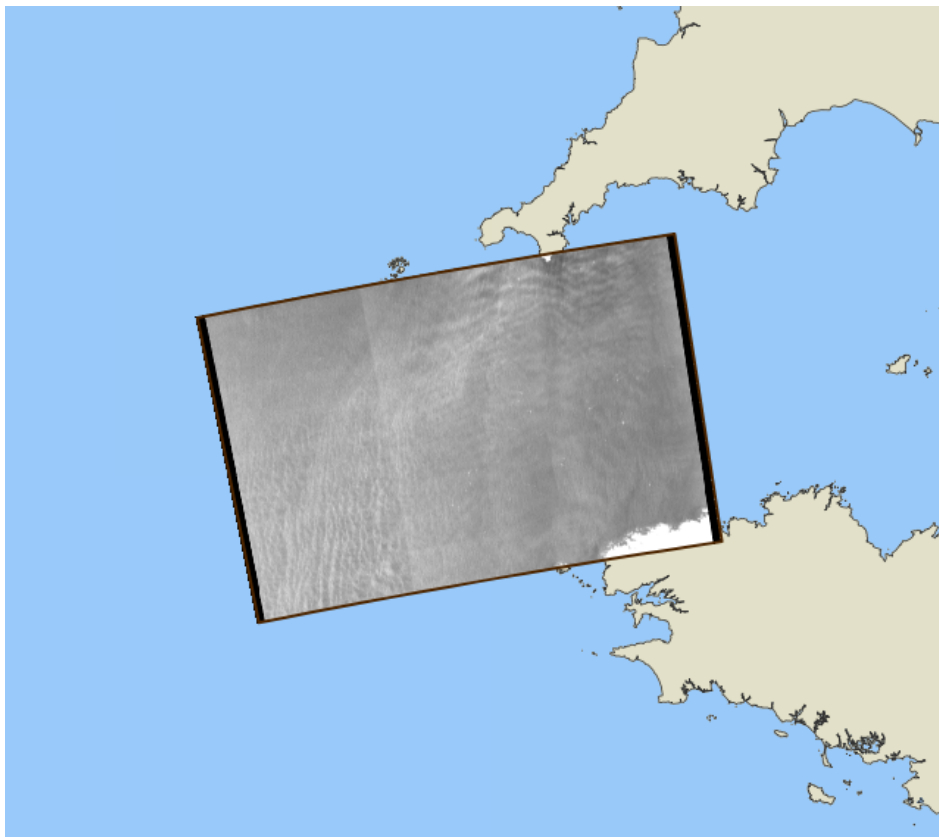
Accuracy metrics					
Label	Tanker	Cargo	Fishing	Passenger	Overall(%)
IoU	56.52	78.95	100.00	33.33	67.20
F-Score	72.22	88.24	100.00	50.00	77.61
Accuracy	85.29	88.24	100.00	97.06	85.29
$\kappa$	0.62	0.76	1.00	0.49	0.85

**Table 8.** Classification scores of the proposed network on small patches extracted from a SAR scene.

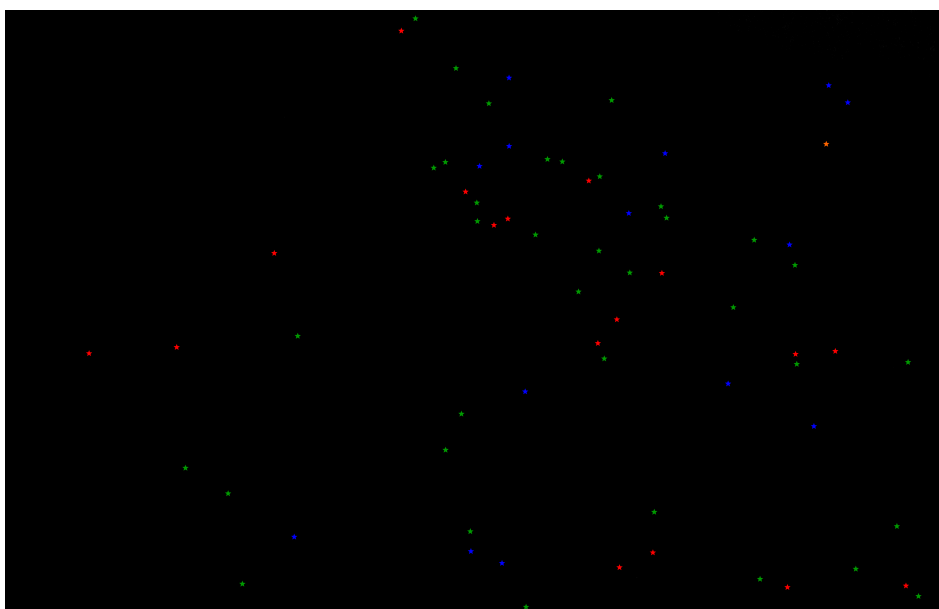
### 296 3.5. Application to the OpenSARShip dataset

297 The OpenSARShip dataset [29] has recently been made available to the community. We report here the  
 298 results obtained with our framework when applied on this dataset. This dataset comprises SAR data  
 299 with different polarization characteristics and also includes ship categories. With a view to ease the  
 300 comparison with the previous results, we focus on SAR images that are in VV polarization and the ship  
 301 categories considered, which leads to considering the following four categories; tanker, cargo, fishing  
 302 and passengers. Overall, we considered a dataset of 5,225 ships (80% were employed for training  
 303 and 20% for testing). In the OpenSARShip dataset, the classes are not equally represented. We report  
 304 classification and length estimation performance in Table 9. We also evaluate the performance of the  
 305 model trained on our dataset and applied on OpenSARShip dataset and conversely.  
 306 The results show that our model produces good results when trained and tested on the same  
 307 database. However, the results do not transfer from one dataset to an other. We suggest that this





(a) Image location



(b) SAR image with ships identified from the matching of CFAR-based detection and AIS. ★ Tanker, ★ Cargo, ★ Fishing, ★ Passenger (best viewed in color).

**Figure 8.** SAR image acquired on April 4, 2017 in Western Brittany, France.

308 may relate to differences in the maritime traffic and environment between Europe (our dataset) and  
 309 Asia (OpenSARShip dataset). The comparison to previous work on OpenSARShip dataset is not  
 310 straightforward. For instance, [36] considers only a three-class dataset (*Tanker*, *Cargo* and *Other*). The  
 311 reported accuracy score (76%) is lower than our 87.7% accuracy score for the considered 5-class dataset.  
 312 We may also emphasize that [36] does not address ship length estimation.

		Train				Train			
Test		Ours	OpenSARShip	Test		Ours	OpenSARShip		
		Ours	97.45		22.18		Ours	$1.93 \pm 8.8$	$56.78 \pm 314.78$
		OpenSARShip	34.05		87.71		OpenSARShip	$-102.51 \pm 123.94$	$-0.23 \pm 11.04$

Classification overall  
accuracy (%)

Length mean  
error (m)

**Table 9.** Comparison of the results of the network on our database and on the OpenSARShip database.

#### 313 4. Discussion

314 The reported results show that a dedicated architecture is necessary for ship classification and length  
 315 estimation, while state-of-the art architectures failed to achieve satisfying performances. The MLP  
 316 is sufficient for ship detection on SAR images (from a visual assessment). But this should not be  
 317 considered as a good result since we only have (positive) examples of ships in our database (no negative  
 318 samples, so we can not assess the false positives). Thus, the network only learns a thresholding  
 319 and can not discard a ship from other floating objects (e.g. icebergs). Indeed, iceberg detection  
 320 and discrimination between iceberg and ship are specific research questions [37,38]. Overall, the  
 321 performance of the MLP stresses the complexity of the classification and length estimation tasks.  
 322 In terms of classification accuracy, the R-CNN performs better than the MLP, with an overall accuracy  
 323 of **88.57%**. These results support the proposed architecture with three task-specific networks which  
 324 share a common low-level network. The latter is interpreted as a feature extraction unit which the  
 325 task-specific networks rely on.

326 Compared to the state-of-the art architectures (MLP and R-CNN), our model produces better results  
 327 for ship classification and length estimation from Sentinel-1 SAR images with only few confusions  
 328 between classes. A multi-task architecture is well adapted for simultaneous ship classification and  
 329 length estimation. Our model also performs well when a new class is added (e.g. Tug). Furthermore,  
 330 adding a detection task (even with a coarse ground truth) tends to improve the length estimation.  
 331 Our experiments also show that the learnt models do not transfer well from a dataset to an other. We  
 332 suggest that this may relate to differences in the characteristics of the maritime traffic and/or marine  
 333 environment. Future work should further explore these aspects for the application of the proposed  
 334 model worldwide.

#### 335 5. Conclusion

336 In this paper, a multi-task neural network approach was introduced. It jointly addresses the detection,  
 337 classification and length estimation of ships in Sentinel-1 SAR images. We exploit synergies between  
 338 AIS and Sentinel-1 to automatically build reference datasets for training and evaluation purposes, with  
 339 the ultimate goal of relying solely on SAR imagery to counter lack or corruption of AIS information that  
 340 correspond to illegal activities. While the polarization type has a significant effect on SAR backscatter,  
 341 we were able to train a model which jointly processes HH or VV polarisation without prior information  
 342 on the type of polarisation. Our results support the assumption that HH and VV polarizations share  
 343 common image features and that differences in backscatter distributions can be handled through an  
 344 appropriate parameterization of the network.

345 Regarding the considered architecture, a mutual convolutional branch transforms raw inputs into  
346 meaningful information. Such information is fed into three task-specific branches. Experimental  
347 evaluation shows improvement over standard MLP or R-CNN. Ship detection cannot be totally  
348 assessed, but a visual inspection supports the relevance of this detection stage. Besides, it was  
349 shown to significantly contribute to improved performance of the classification and length estimation  
350 components. Overall, we report promising performance for ship classification (above 90% of correct  
351 classification) and length estimation (relative bias below 10%). Considering a residual architecture  
352 appears as a critical feature to reach good length estimation performance, but this would require  
353 further investigation.

354 Future work may further investigate the training and evaluation of the detection stage. The automation  
355 of the matching process between AIS data and SAR images has the potential for significantly increasing  
356 the size and diversity of the training and evaluation datasets. This may provide new avenues to address  
357 generalization and transfer issues between geographic areas pointed out in our results. Furthermore,  
358 while SAR imagery less affected by weather conditions than optical imagery, a specific analysis of  
359 the impact of weather conditions onto identification performance would also be of interest. Finally,  
360 the specificity of the SAR imagery would call for dedicated operations, while our network relies on  
361 standard techniques issued from computer vision.

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