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Extended Target Tracking Applied to X-band Marine Radar Data

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***Abstract*—X-band marine radar systems are flexible and low-cost tools for monitoring multiple targets in a surveillance area. They are able to provide high resolution measurements in both space and time. Such features offer the opportunity to get accurate information not only about the targets' kinematics but also about the targets' extents. The tracking of these kinds of data is usually called extended target tracking (ETT).**

In this paper, we propose a signal processing chain mainly composed by a pixel-wise detector and a joint probabilistic data association tracker to handle the problem of multiple ETT. The performance assessment is conducted on real data acquired by an X-band marine radar located in the Gulf of La Spezia, Italy. The experimental results demonstrate that the processing chain is able to reach high performance with a limited computational burden.

I. INTRODUCTION

The oceans connect nations globally through an interdependent network of economic, financial, social, and political relationships. The maritime environment includes trade routes, choke points, ports, and other infrastructures such as pipelines, oil, and natural gas platforms and trans-oceanic telecommunication cables. Thus, securing the waterways becomes of critical importance and surveillance activities take on a central role.

Radars are widely exploited technologies for maritime surveillance. Inside this category, pulse compression X-band marine radar systems represent flexible and low-cost tools for tracking multiple targets (*e.g.* cargo ships). Features such as high resolutions in both space and time make these kinds of systems very appealing. On one hand, this further information can aid some subsequent signal processing steps, such as target identification and classification. On the other hand, one of the main assumptions of tracking algorithms, *i.e.* the target can generate at most one detection per frame, is no longer valid. Thus, the development of new techniques is required to properly track extended targets (*i.e.* targets that occupy more than one radar cell). This research area is often named extended target tracking (ETT).

Several approaches can be found in the literature. Bar-Shalom *et al.* [1] propose to feed a standard probabilistic data association (PDA) algorithm with clustered data. A data association strategy for a large number of closely spaced (and overlapping) objects is presented in [2]. Sequential Monte Carlo methods are considered in [3], [4], where track-before-detect theory is exploited. The random hypersurface model is introduced in [5]. A different framework to track extended targets under the hypothesis of elliptical spread of targets is pioneered by Koch in [6]. Finally, Mahler proposed in [7] an extension of the probability hypothesis density filter to address the multiple ETT problem.

In this paper, we propose to deal with the multiple ETT problem developing a signal processing chain. It consists of a pixel-wise detector, a post-processing based on Morphological operators [8], a clustering and feature extraction step, and a standard joint PDA (JPDA) tracker [1]. This processing chain enables high tracking performance estimating both the targets' kinematics and sizes with a limited computational burden, which is a desirable feature when a huge amount of data is processed. The validation is conducted on real data acquired by an X-band marine radar located in the Gulf of La Spezia, Italy. Automatic identification system (AIS) messages are used as ground-truth. A set of performance metrics (*i.e.* time-on-target, track fragmentation and accuracy, and false alarm rate) are used for the performance assessment.

The rest of the paper is outlined as follows. Sect. II is devoted to the description of the signal processing chain, while the performance assessment on real X-band radar data is provided in Sect. III. Finally, conclusions are drawn in Sect. IV.

II. PROCESSING CHAIN

One of the most common approaches to deal with the target tracking problem is to divide it into two sub-problems: Target detection and tracking [1]. In the following sections, the main steps of the processing chain will be described.

A. Pixel-wise Detector

The data frames acquired by the X-band marine radar are processed by a pixel-wise detector. The detector outcomes are represented by the targets' clouds of detections, which are used as input for the post-processing step. A conventional maximum likelihood detector is exploited here, and an assumption of conditional independence among pixels is made. Furthermore, the radar data amplitudes are modeled as exponential distributed with rate parameters $\lambda_t > 0$ under the *target* hypothesis and $\lambda_{nt} > 0$ for the *non-target* case. These parameters characterize the whole exponential distributions and are estimated by the means of the *k-means* clustering algorithm [9].

B. Post-Processing

A land mask is applied first. Indeed, land and other man-made structures (*e.g.* dykes) can provide a strong backscattering, which can be considered as provided by a target. Afterwards, due to computational constraints, morphological operators [8] can represent a good choice to increase the spatial coherence of the clouds of detections provided by the pixel-wise detector. More specifically, an application of a closing operator [8] is performed first. Whereas the acquired image is compact along the azimuth direction due to the spreading effects of the acquisition system (*e.g.* due to the radar's antenna pattern), the target density is drastically reduced along range and thus areas of missed detections can be observed. Stripped targets are expected, see *e.g.* Fig. 3. Therefore, the closing operator is applied along the range direction in order to compensate this effect compacting the target detection clouds. Finally, an opening operator along the azimuth direction to remove some artifacts on the clusters' edges is exploited. This operator reduces the target size and partially compensates some non-ideal radar effects, *e.g.* the effect of the radar's antenna pattern.

C. Clustering and Feature Extraction

A clustering is carried out to group the clouds of detections that are likely to be generated by the same targets. The clustering procedure exploits the concept of 8-connectivity, *i.e.* the spatial relation of a detection with its neighbors.

As a suitable and simple model for target extents, we exploit an ellipsoidal representation, see *e.g.* [4], [6], [10]. Starting from the output of the pixel connectivity procedure, the parameters that fully characterize the elliptical model are estimated. The estimation is carried out using the normalized second central moments [11].

D. Multi-Target Tracking: The Joint Probabilistic Data Association

This section is devoted to briefly introduce the multi-target tracking (MTT) procedure relied upon the joint probabilistic data association (JPDA) algorithm [1], [12].

1) Target Motion and Measurement Models: The target state vector $\boldsymbol{x}_k$ at frame k is defined into Cartesian domain with the addition of the target's extensions. Hence, we have

$$\boldsymbol{x}_k \triangleq [x_k, \dot{x}_k, y_k, \dot{y}_k, l_k, w_k]^{\mathrm{T}} \tag{1}$$

where x_k, y_k and $\dot{x}_k$, $\dot{y}_k$ are the position and velocity components along x, y directions, respectively, while l_k and w_k represent the target's length and width, respectively.

The target dynamic can be described by the nearly constant velocity model [1]

$$\boldsymbol{x}_k = \mathbf{F}\ \boldsymbol{x}_{k-1} + \boldsymbol{\Gamma}\ \boldsymbol{w}_k, \tag{2}$$

where

$$\mathbf{F} = \begin{bmatrix} \mathbf{I}_2 \otimes \widetilde{\mathbf{F}} & \mathbf{0}_{4\times 2} \\ \mathbf{0}_{2\times 4} & \mathbf{I}_2 \end{bmatrix}, \tag{3}$$

$$\boldsymbol{\Gamma} = \begin{bmatrix} \mathbf{I}_2 \otimes \widetilde{\boldsymbol{\Gamma}} & \mathbf{0}_{4\times 2} \\ \mathbf{0}_{2\times 2} & \mathbf{I}_2 \end{bmatrix}, \tag{4}$$

$$\widetilde{\mathbf{F}} = \begin{bmatrix} 1 & T_s \\ 0 & 1 \end{bmatrix}, \tag{5}$$

$\widetilde{\boldsymbol{\Gamma}} = [T_s^2/2,\ T_s]^{\mathrm{T}}$, $\mathbf{I}_d$ is the identity matrix with size d, $\mathbf{0}_{r\times c}$ represents the null matrix with r rows and c columns, T_s is the sampling time, $\otimes$ denotes the *Kronecker product*, and $\boldsymbol{w}_k$ takes into account the target acceleration and the unmodeled dynamics, and it is assumed to be Gaussian with zero-mean and covariance matrix

$$\mathbf{Q} = \mathrm{diag}\left(\sigma_v^2, \sigma_v^2, \sigma_l^2, \sigma_w^2\right), \tag{6}$$

where diag$(\cdot)$ denotes the diagonal matrix, and σ_v^2, σ_l^2, and σ_w^2 are the variances for the acceleration, length, and width components, respectively.

The measurement vector $\boldsymbol{z}_k$ at frame k is defined as follows

$$\boldsymbol{z}_k \triangleq \left[z_k^r, z_k^\phi, z_k^l, z_k^w, z_k^\theta\right]^{\mathrm{T}} \tag{7}$$

where z_k^r and z_k^ϕ are the range and azimuth measurements of the center of the ellipse that fits the cluster, z_k^l and z_k^w are its lengths of the major and minor axes, while z_k^θ represents the ellipse's orientation.

The target-originated measurement equation is

$$\boldsymbol{z}_k = \boldsymbol{h}(\boldsymbol{x}_k) + \boldsymbol{\omega}_k \tag{8}$$

where

$$\boldsymbol{h}(\boldsymbol{x}_k) \triangleq \left[\sqrt{x_k^2 + y_k^2}, \arctan\left(y_k/x_k\right), l_k, w_k, \arctan\left(\dot{y}_k/\dot{x}_k\right)\right]^{\mathrm{T}} \tag{9}$$

is the measurement function and $\boldsymbol{\omega}_k$ is the instrumental noise vector assumed to be Gaussian with zero-mean and covariance matrix

$$\mathbf{R} = \mathrm{diag}\left(\sigma_{rr}^2, \sigma_{r\phi}^2, \sigma_{rl}^2, \sigma_{rw}^2, \sigma_{r\theta}^2\right), \tag{10}$$

where σ_{rr}^2 and $\sigma_{r\phi}^2$ represent the variances in range and azimuth, σ_{rl}^2 and σ_{rw}^2 are the variances for the two sizes, and $\sigma_{r\theta}^2$ represents the variance for the target's orientation.

2) Multi-Target Tracking Procedure: The tracking procedure is based on the JPDA paradigm [1], [12], which is a Bayesian approach that associates all the validated measurements to the tracks by probabilistic weights. The track management relies upon the popular M/N logic [1]. The filtering stage is performed using the unscented Kalman filter (UKF) [13] in order to handle the non-linearities in the measurement model.

III. PERFORMANCE ASSESSMENT

The proposed approach is tested on real data provided by an X-band marine radar data located in the Gulf of La Spezia, Italy. For performance assessment purposes, automatic identification system (AIS) messages are used as ground truth, as already proposed in [14]. The association procedure is based on a nearest neighbor approach between the radar tracks and the AIS tracks. The performance metrics exploited are: The time-on-target (ToT), the false alarm rate (FAR), the track fragmentation index (N^{TF}), and the track accuracy (TA) measured as error in position (ϵ^{pos}), velocity (ϵ^{vel}), length (ϵ_k^{len}), and width (ϵ_k^{wid}). Readers can refer to [14] for further details.

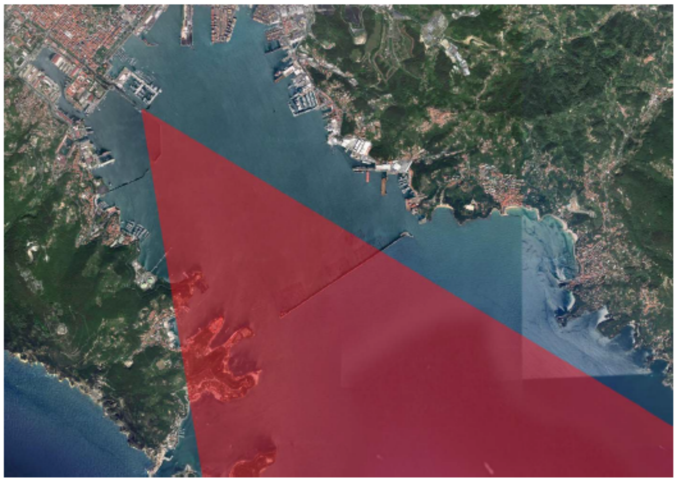


Fig. 1. The X-band marine radar's field of view (red).

TABLE I. X-BAND MARINE RADAR SPECIFICATIONS

Parameter	**Specification**
Frequency	9.6 GHz
Bandwidth	Adjustable up to 150 MHz
Resolution	Adjustable down to 1 m
Antenna type	Rotating slotted waveguide
Angular aperture azimuth	$\approx 1^\circ$
Angular aperture elevation	$\approx 20^\circ$
Gain	32 dBi
Azimuth antenna speed	0 (stopped) up to 40 revolutions per minute
Azimuth angular accuracy	0.1°
Polarization	Linear horizontal
Transmitted power	Adjustable 50 mW - 5 W (17 - 37 dBm) CW
Pulse repetition frequency	Adjustable 350 Hz - 10 kHz

TABLE II. PARAMETER SETTINGS

Parameter	**Value**	**Specification**
λ_t	$4.1 \cdot 10^{-13}$	Rate Parameter $target$
λ_{nt}	$1.8 \cdot 10^{-9}$	Rate Parameter $non - target$
T_s	2 s	Sampling time
σ_v	0.4 m s^{-2}	Process noise
σ_l	4 m	Process noise
σ_w	4 m	Process noise
σ_{rr}	1 m	Std. dev. range
$\sigma_{r\phi}$	1°	Std. dev. azimuth
σ_{rl}	4 m	Std. dev. length
σ_{rw}	4 m	Std. dev. width
$\sigma_{r\theta}$	60°	Std. dev. orientation
P_D	0.9	Detection probability
λ	10^{-11} m^{-2}	Clutter density
γ	5	Gate threshold
v_{max}	10 m s^{-1}	Maximum velocity
M/N	$5/6$	Track initialization logic
M^*/N^*	$6/6$	Track termination logic

A. X-band Marine Radar Experiment

The radar exploited in the experiment is a coherent high resolution X-band marine radar that is part of the CMRE's radar sensor network located in the Gulf of La Spezia, Italy. It uses pulse compression and transmits a linear frequency modulated continuous wave [15]. This leads to a low power, compact, quick deployable, and lightweight system, while still maintaining a high performance with relatively simple electronics.

The radar field of view is depicted in Fig. 1. The radar specifications are shown in Tab. I. The system is used for research in the areas of target and extended target detection and tracking, with application to surveillance of small crafts and port protection.

B. Experimental Results

The description of the experimental results on real data acquired by the X-band marine radar is provided. The main parameters used for the signal processing chain are shown in Tab. II.

The proposed algorithm is applied to 260 frames acquired by the X-band marine radar. Figs. 2(a)-(f) show the estimations for both kinematic and size parameters. Solid lines denote the values provided by the AIS, while dashed lines represent the estimations provided by the JPDA tracker. It is worth pointing out that the proposed approach reaches overall good performance. More specifically, we can note only a small displacement between AIS information and the tracker's position estimation due to the fact that our approach estimates the center of the ellipse that represents the target (*i.e.* the ship), while the AIS returns the position of the transponder located on-board (usually not the ellipse's center). A further remark is related to the size estimation. Indeed, the tracker's estimations show a bias (*i.e.* an overestimation) with respect to the AIS values. This behavior can be justified due to the non-idealities of the acquisition system (*e.g.* the width of the radar antenna pattern's main lobe can cause this target spread phenomenon) that have to be taken into account to increase the accuracy of the targets' size estimation. However, the compensation of the radar's non-ideal effects is considered here out-of-scope.

Regarding to the performance metrics, the TA indexes confirm the previous analysis. Indeed, Tab. III shows limited errors both in the position and velocity estimations. Average errors are 39.7 m and 1.50 m s^{-1}, respectively, mainly due to the discrepancy between the information provided by the radar and the one that the AIS is able to provide, see for instance the discussion above with regard to the error in position. Greater errors are shown for the targets' size estimation. Average errors of 30.0 m in length and 17.5 m in width are often considered high.

The ToT is always very high (except for the ship with maritime mobile service identity (MMSI) equal to 247031200, which is on the border of the surveillance area and is not properly detected for some frames). The overall ToT is 85%. Furthermore, the track fragmentation index N^{TF} is almost ideal (with average value equal to 1.50). Regarding to this index, an interesting case to point out is the missed detection of the target with MMSI$=351361000$ for about 30 frames. This track fragmentation is caused by an obscuration phenomenon. Indeed, a ship interposed between the target and the radar can be observed, see Fig. 3. Finally, the FAR index is equal to $4 \cdot 10^{-8}$ s^{-1} m^{-2}. The total number of false contacts is 199, but most of them (*i.e.* 102) are due to a signal leakage in the electronics.

A final remark is devoted to the computational times. A frame of 3800×200 pixels (disk size about 6 MB), generated by the X-band marine radar every 2 s, requires about 1 s to be processed by the proposed signal processing chain using a Quad 3.73 GHz Intel Xeon processor. Thus, the important real-time requirement is met by our approach.

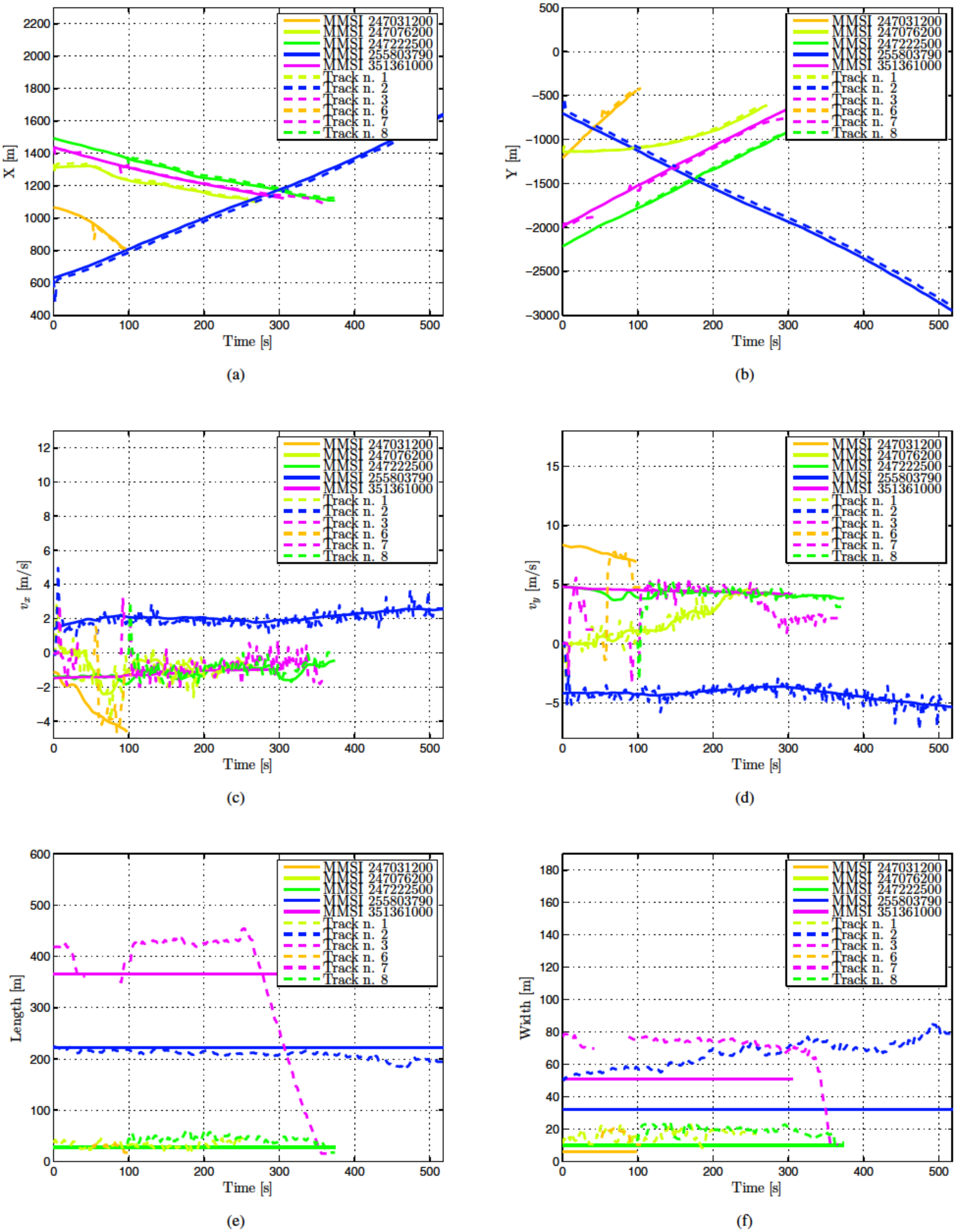


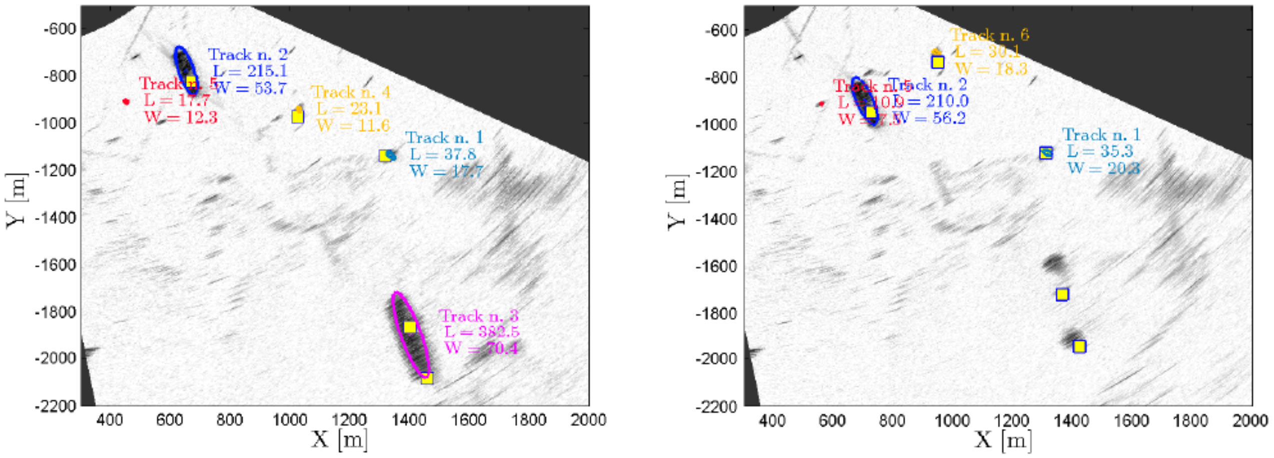
Fig. 2. Dashed lines represent tracks estimated by the JPDA tracker, while AIS contact information are depicted using solid lines. The association between JPDA estimated tracks and AIS tracks is indicated exploiting different colors.

IV. CONCLUSIONS

A signal processing chain, mainly relying upon a pixel-wise detector and a JPDA tracker, has been developed to address the multiple extended target tracking problem.

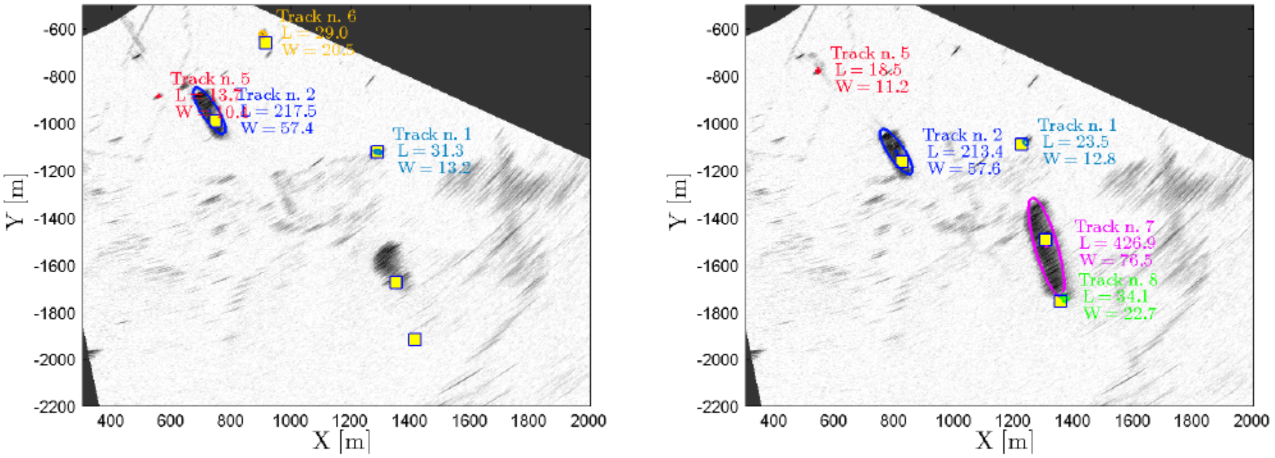
TABLE III. TRACKING METRICS

JPDA track id number **MMSI ship**		1 255803790	2 247076200	3 351361000	6 247031200	7 351361000	8 247222500	**Average Results**
ϵ^{pos}	[m]	50.1	17.6	41.8	39.7	65.8	23.1	39.7
ϵ^{vel}	[m s^{-1}]	0.53	0.64	3.12	2.70	1.43	0.58	1.50
ϵ^{len}	[m]	13.5	6.7	34.5	4.5	104.8	16.3	30.0
ϵ^{wid}	[m]	34.5	6.3	22.8	10.4	22.3	9.0	17.5
ToT		1.00	0.95	0.86	0.70	0.86	0.74	0.85
N^{TF}		1.00	1.00	2.00	2.00	2.00	1.00	1.50
FAR	[m^{-2} s^{-1}]	$4 \cdot 10^{-8}$						



(a) Frame 15

(b) Frame 30



(c) Frame 35

(d) Frame 55

Fig. 3. The obscuration phenomenon of the pink target with track id 3 in (a) and track id 6 in (d) is depicted. The target is disappeared in (b) and (c), where only AIS contacts are depicted with yellow squares.

The performance has been assessed on real data provided by an X-band marine radar located in the Gulf of La Spezia, Italy. AIS messages have been used as ground-truth. The ability of the processing chain in properly tackling the multiple extended target tracking problem has been validated by means of several performance metrics. Finally, the computational analysis has demonstrated that the proposed approach is also able to meet the real-time requirement that is of great importance for maritime-surveillance applications.

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Keywords

Radar tracking, target tracking, radar antennas, estimation, detectors, azimuth

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