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Detection, tracking and fusion of multiple HFSW radars for ship traffic surveillance: experimental performance assessment

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DETECTION, TRACKING AND FUSION OF MULTIPLE HFSW RADARS FOR SHIP TRAFFIC SURVEILLANCE: EXPERIMENTAL PERFORMANCE ASSESSMENT

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ABSTRACT

Low-power HF surface-wave radars fit well the role of long-range early-warning tools in maritime situational awareness applications, by virtue of their over-the-horizon coverage capability and continuous-time mode of operation. In fact, these sensors, developed for ocean remote sensing, can represent also a further low-cost source of information for ship detection and tracking. Unfortunately, many shortcomings, like poor range and azimuth resolution, high non-linearity and significant presence of clutter, may degrade their performance.

In this paper, multi-target tracking and data fusion techniques are applied to experimental data collected during the NATO Battlespace Preparation 2009 HF-radar campaign, which took place between May and December 2009 in the Mediterranean Sea. The system performance is defined in terms of time-on-target, false alarm rate and accuracy. Experimental results are presented and discussed.

Index Terms**—** high-frequency surface-wave (HFSW) radar, real data, target detection, target tracking, data fusion.

1. INTRODUCTION

At present, significant efforts go into developing more reliable and cost-effective surveillance systems for maritime situational awareness (MSA). For this reason, in the last decade great interest has being tributed to low-power/cost High-Frequency Surface-Wave (HFSW) radars as an early-warning tool for over-the-horizon (OTH) applications. Unfortunately, these sensors, developed solely for ocean remote sensing applications, exhibit poor range and azimuth resolution, high non-linearity, and significant false alarm rate. In order to properly address all these issues, the Joint Probabilistic Data Association (JPDA) logic, followed by the Unscented Kalman Filter (UKF) was proposed in [1]. In this paper, the tracking algorithm behavior is investigated by comparing the tracks generated by two HFSW radars, with overlapping fields of view, and the ship reports from the Automatic Identification System (AIS). Furthermore, the single-sensor JPDA-UKF is followed by a track-to-track association and fusion (T2T-A/F) logic, [2]. Single-sensor versus multi-sensor tracking performance are investigated using real data, collected during the Battlespace Preparation 2009 (BP09) HF-radar experiment, which took place between May and December 2009 in the Ligurian Sea, Italy. Special attention is paid also to the output of the 3D (range, azimuth, range-rate) Ordered Statistics Constant False Alarm Rate (OS-CFAR) algorithm [3]. See [1, 2] and references therein for further information about the experiment setup and the proposed algorithms. The Doppler-coupling effect of CW signals, responsible of the range shifts in the detections, was addressed in [4]. In order to evaluate the algorithms capabilities, a set of performance metrics is proposed, such as the time-on-target (ToT), the false alarm rate (FAR), the root mean square error (RMSE). This paper is organized as follows. In Section 2, both the track validation procedure and the performance metrics are presented. Preliminary results are shown and discussed in Section 3, while conclusions are provided in Section 4.

2. PERFORMANCE ASSESSMENT

AIS reports can be used as ground-truth information for ship detection and tracking assessment [5], stated some key assumptions. Ships equipped with AIS are assumed to be the only ones present in the surveyed region and their identifiers are unique. The information they transmit are reliable and not corrupted by any errors. Since AIS reports are linearly interpolated on the HFSW-radar timestamps, the new data vectors are assumed true. The JPDA-UKF and T2T-A/F outputs are labelled as *true tracks* or *false tracks* if the tracks are successfully associated to the AIS reports or not, respectively.

2.1. Performance Metrics

Time-on-target

The ToT is the percentage of time during which the tracker follows a given ship route. This operation is performed for all the vessels in each day and the average value is then evaluated over all the days in the recording interval. The ToT can be evaluated at the varying of both kinematic (*i.e.* range, azimuth, range-rate) and static (*i.e.* size) information.

False alarm rate

The FAR is defined as the number of false alarms, normalized by the recording interval and the area of the surveyed region. Statistically, the FAR is related to the ToT and an increase of the probability of detection leads to an increase of the probability of false alarm. Like its counterpart, FAR is evaluated in the specific range, azimuth or range rate interval. On each interval, FAR values are normalized first such that their weighted sum provides the total FAR per unit of time and area for that day.

Tracking error

The error committed by the tracking algorithms is evaluated in terms of RMSE for the position and velocity components of the state vector.

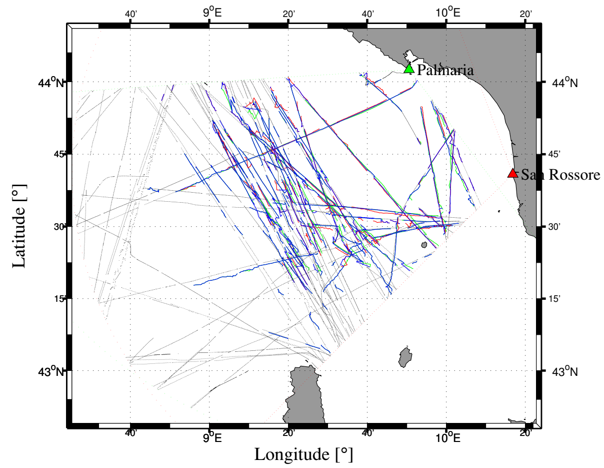


Fig. 1. True active HFSW radar tracks and AIS data in the fusion region on May 10^{th}, 2009. Interpolated AIS data (black), Palmaria JPDA-UKF (green), San Rossore JPDA-UKF (red), T2T-A/F (blue).

3. EXPERIMENTAL RESULTS

The proposed algorithms are tested on the dataset collected between 10 and 14 May, 2009. The analysis is carried out on the region in common at the sensors, namely the *fusion region*. This choice allows the two sensors to look at the same vessel trajectories and to have the possibility of data fusion.

3.1. Analysis of true tracks

The average number of AIS-carrying vessels varied from a minimum of 60 on May 11^{st}, to a maximum of 81 on May 12^{nd}. Fig. 1 depicts the true active tracks on May 10^{th}. The output tracks from T2T-A/F algorithm (blue) are shown w.r.t. the AIS ship routes (black) in the fusion region. Output tracks from the two JPDA-UKFs of Palmaria and San Rossore are depicted in green and red, respectively. Trackers are able to follow the AIS ship routes up to about a 100 km distance, and close to the edges of the area covered by each sensor.

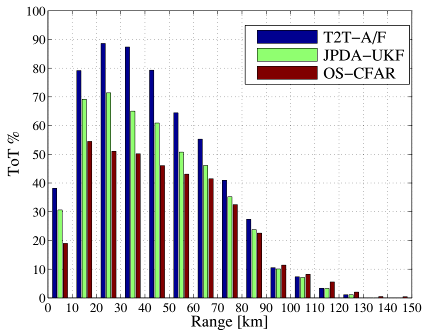
3.1.1. Time-on-Target analysis

The ToT evaluated over 10 km range intervals is depicted in Fig. 2. At Palmaria, see Fig. 2(a), the peak ToT values occur in the first 50 km, where it is about $62 - 72\%$ for the JPDA-UKF (green) and about $50-60\%$ for the OS-CFAR algorithm (red). The T2T-A/F (blue) grants a peak value of about 88% in the same interval, then falls below 50% over 70 km. For San Rossore, the peak value is smaller than 57% in the same interval, for both the JPDA-UKF and OS-CFAR, while the data fusion leads to a final maximum value of about 75%. No AIS reports were available in the first 10 km from San Rossore, see Fig. 2(b). A comparison between Figs. 2(a) and 2(b) shows how the T2T-A/F output depends mostly on the JPDA-UKF at Palmaria. A possible reason can be found in the geometry of the ship routes w.r.t. the sensors positions.

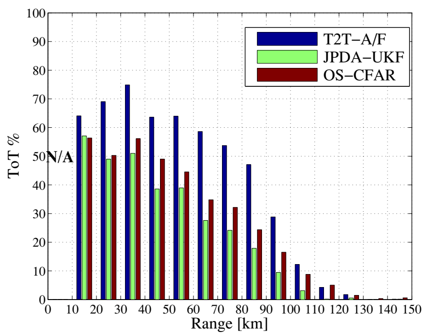
The ToT versus range-rate is shown in Fig. 3. The most interesting region is the one comprised between the two first-order Bragg velocities. For a carrier frequency of 12.50 MHz, these contributions are about ± 4.32 m/s. Concerning the T2T-A/F strategy, Palmaria achieves a larger ToT than San Rossore, with a maximum value of 57% compared to 45%. It is interesting to observe how the OS-CFAR ship detection performance degrade with increasing radial speed in modulus for Palmaria but not for San Rossore. The joint analysis of Figs. 2(a) and 3(a) reveals that this improvement mainly concerns large radial speeds of targets moving at near-medium range. Moreover, both the detector and the tracker do not work properly for those ships moving close to the first-order Bragg scattering region. Nevertheless, aspect diversity allows to overcome this problem. The final improvement (larger at San Rossore than Palmaria), however, comes at the cost of an increase of the FAR, as it will be discussed in Section 3.2.1.

3.1.2. Tracking error analysis

The RMSE has been computed for both the position and velocity components of the target state vector. Results are shown in Fig. 4, in sub-figures (a) and (b) respectively. Curves are estimated considering only the cases in which the T2T-A/F system output is obtained from the fusion of the tracks at both sensors. Let us consider the RMSE of the position estimate, see Fig. 4(a). The error is about $0.5 - 1.0$ km for both Palmaria (green) and San Rossore (red). As ex-



(a) ToT vs range w.r.t. Palmaria.



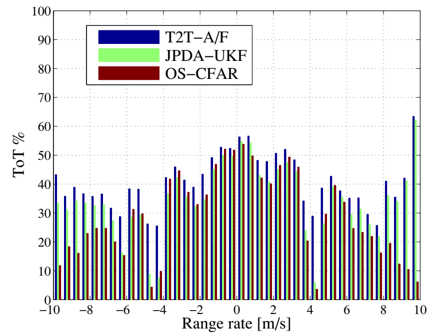
(b) ToT vs range w.r.t. San Rossore.

Fig. 2. Estimated ToT percent versus range [km], w.r.t. Palmaria (a) and San Rossore sites (b): T2T-A/F (blue), JPDA-UKF (green), OS-CFAR (red).

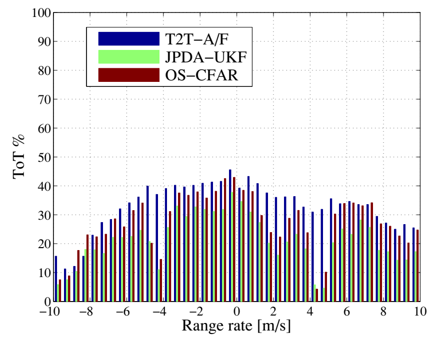
pected, the error of the two standalone systems are very close. The T2T-A/F system (blue) provides an RMSE significantly below the two JPDA-UKFs, about 250 m on average. The RMSE of the velocity estimate is presented in Fig. 4(b). Significant differences arise from the analysis of the transitory error, almost eliminated for the T2T fusion algorithm, except for the presence of some outliers. When one of the two sensors loses its track, the other one most likely is able to follow it, see also Fig. 3.

3.2. Analysis of false tracks

False tracks recorded on May 10^{th} are shown in Fig. 5. There is a significant number of active false tracks with good time-coherency but not validated by the AIS reports. Some of them closely follow the ship routes we observed in Fig. 1, and most of them, especially at far distance, exhibit a fragmented behaviour. There is also a significant amount of false tracks in front of the coasts of Tuscany, Italy. It is possible that in the surveyed area there are ships not carrying any AIS transponder (*e.g.* fishing boats, military vessels).



(a) ToT vs range-rate w.r.t. Palmaria.



(b) ToT vs range-rate w.r.t. San Rossore.

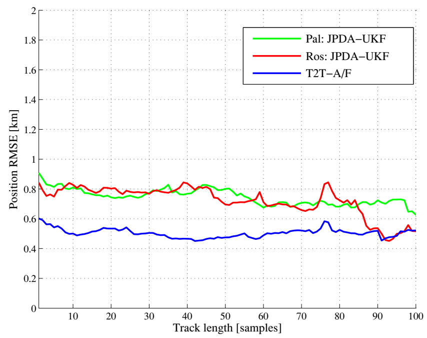
Fig. 3. Estimated ToT percent versus range-rate [m/s], w.r.t. Palmaria (a) and San Rossore sites (b): T2T-A/F (blue), JPDA-UKF (green), OS-CFAR (red).

3.2.1. False alarm rate analysis

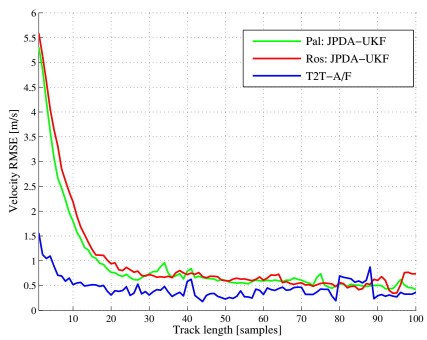
Results are shown in Fig. 6, in sub-figures (a) and (b) respectively. As expected, the tracking algorithm significantly reduces the number of false alarms and cancels most of those originated by clutter, as shown by the green (JPDA-UKF) and red (OS-CFAR) lines. The T2T-A/F strategy (blue) brings an increase of the number of false alarms w.r.t. the standalone trackers. This can be explained by the *OR* fusion strategy, which produces a track whenever at least one track at the two sensors is active.

4. CONCLUSIONS

Low-power HFSW radars have demonstrated to be reliable long-range early-warning tools for MSA applications. In this paper, the performance of a whole detection/tracking/data fusion processing chain have been investigated by means of experimental data. The JPDA-UKF has been compared with the OS-CFAR algorithm, showing a significant reduction of the false alarms. Moreover, the T2T-A/F strategy has demonstrated its effectiveness w.r.t. single-sensor results, in terms of ToT and accuracy, but at the cost of an increase of the FAR.



(a) RMSE for position.



(b) RMSE for velocity.

Fig. 4. RMSE of the position (a) and velocity (b) state vector components: T2T-A/F (blue), Palmaria (green), San Rossore (red).

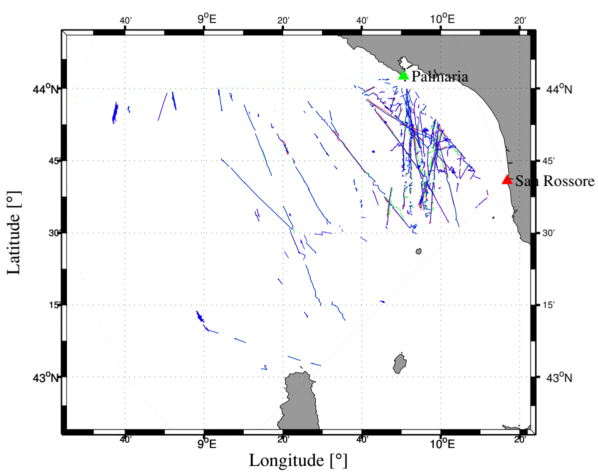
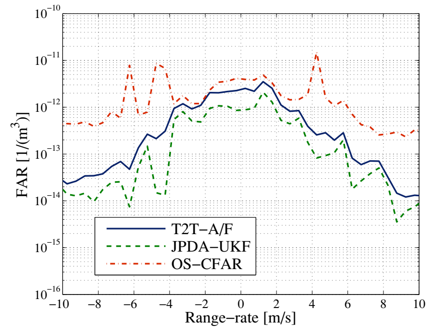
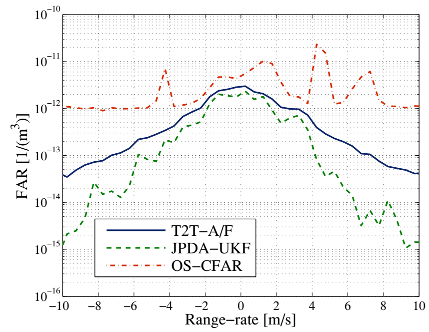


Fig. 5. False active tracks in the fusion region on May 10^{th}, 2009: Palmaria (green), San Rossore (red), T2T-A/F (blue).



(a) FAR vs range-rate w.r.t. Palmaria.



(b) FAR vs range-rate w.r.t. San Rossore.

Fig. 6. Estimated FAR versus range-rate [m/s], w.r.t. Palmaria (a) and San Rossore sites (b): T2T-A/F (blue), JPDA-UKF (green), OS-CFAR (red).

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Keywords

High-frequency surface-wave (HFSW), radar, real data, target detection, target tracking, data fusion.

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