A Real Time Test Bed for 2D and 3D Multi-Radar Tracking and Data Fusion with Application to Border Control

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Abstract. **This paper describes part of the activities required to model and assess the performance of a notional integrated system (NIS) in the context of Homeland Security and in particular on border control issues. The border control requires an accurate surveillance of the terrestrial, maritime and overland boundaries, thus involving a wide number of heterogeneous sensors, command and control centres, platforms and communication networks. One of the layers of the integrated system is composed by radar sensors; these sensors can be ground or ship based, 2D or 3D. The paper deals with the problem of correlation and fusion of track data pertaining to ground and ship based, 2D and 3D radar sensors directly in the radar sites. Then, the improved (i.e. more accurate) information can be soon made available for a number of radar functions, such as: (i) re-pointing of the beam along the threat direction of arrival, (ii) energy and time management, (iii) cue of other sensors (i.e. infrared) or proper reaction means (patrol boat), (iv)preliminary classification of potential hostile targets. The updating and testing of the data extractor (DE) of a notional surveillance radar system is presented; the modified hardware and software is capable of acquiring, managing and fusing tracks pertaining to the radar system housing the DE and to other systems connected to the DE itself.** *(Abstract)*

I. INTRODUCTION

Homeland Security is a very broad and complex theme that requires coordinated action on the part of national and local governments, the private sector and concerned citizens across the country; it covers issues such as border control, critical infrastructure protection, transportation security and the relationship and interaction amongst these various components needs to be further analyzed. The activity has been focused initially on border control, which may be achieved via an accurate surveillance of the terrestrial, maritime and overland boundaries, thus involving a wide number of heterogeneous sensors and large bandwidth communication links. One of the layers of the integrated system is composed by radar sensors; these sensors can be ground or ship based, 2D or 3D. One of the crucial point is to properly fuse the radar data among these sensors directly in the radar site so that the improved (i.e. more accurate) information can be soon made available for a number of radar functions, such as:

re-pointing of the beam along the threat direction of arrival,
energy and time management,
cue of other sensors (i.e. infrared) or proper reaction means (patrol boat),
preliminary classification of potential hostile targets.

The updating and testing of the data extractor (DE) of a notional 2D or 3D surveillance radar system is presented in this paper; the modified hardware and software is capable of acquiring, managing and fusing tracks pertaining to the radar system housing the DE and to other systems connected to the DE itself.

It is currently proposed to apply the data fusion to a network of surveillance systems having a reasonable overlap of coverage such that the target is detected and tracked by at least two of the systems involved in the radar network, as shown in following **Figure I-1**.

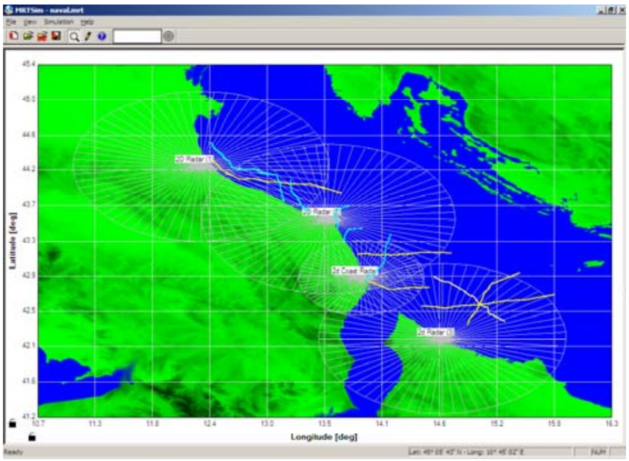


Figure I-1 Typical surveillance fence

The paper is organized as follows: next section 2 briefly recalls the hypothesized border control study case; section 3 resumes the data fusion techniques applied for achieving the accurate estimation of target position and velocity ; section 4 is dedicated to the hardware and software demonstrator description; section 5 presents the achieved results; section 6 reports some conclusions and section 7 a list of references.

II. MULTI-RADAR TRACKING AND FUSION TECHNIQUES IMPLEMENTED IN THE TEST BED

A. Linear and non linear tracking algorithms

The implemented tracking architecture consists of a bank of filters designed to match non linear (i.e. ballistic) and linear target state equations. The rationale for chosing the bank of filters approach are manifold:

1) Radar systems operate in a “dense” environment, i.e. in presence of a number of different threats like Air Breathing Target (ABT), anti-radiation missile (ARM), Ballistic Target (BT) and others.
2) Targets may in general change their dynamics as a function of the flight time; as an example, for balistic targets, the boost is present in the first part of the trajectory and it is followed by the cruise and the re-entry phases. Thus, in general, it is required to take into account the target maneuvers starting at some time during the estimation interval, in which case a target state change occurs.
3) The probability of choosing one of the filters existing in the bank o gives a clear indication of the confidence of the tracker on the type of target under analysis; this is an intrinsic capability of non co-operative target classification, available “for free” by the bank of filters architecture.

The technique based on Kalman Filter (KF) is used for ARM and ABT tracking; this technique fails in presence of BT, thus a set of filters based on Extended Kalman Filter (EKF) theory have been implemented to permit the accurate estimation of BT position and velocity ([2] and [6]).

The correlation windows are evaluated via conventional techniques based on the tracking filters covariance matrices while the association problems have been solved with Nearest Neighbor approach.

B. Fusion of independent tracks

A number of strategies have been conceived for fusing information (plots and/or tracks) generated by N sensors. In the case of N tracks, they are combined in order to achieve a single multisensor track for each target. This is performed after having associated the corresponding tracks by resorting to a statistical test [5-7]. If the tracks are independents, they are merged into a single equivalent track as follows (see [4-5]).

$$\hat{\mathbf{s}} = \hat{\mathbf{P}} \cdot \sum_{i=1}^{N} \left[\hat{\mathbf{P}}_{\mathbf{i}}\right]^{-\mathbf{1}} \hat{\mathbf{s}}_{\mathrm{i}} \,, \quad \hat{\mathbf{P}} = \left\{ \sum_{i=1}^{N} \left[\hat{\mathbf{P}}_i\right]^{-1} \right\}^{-1}$$

where:

$\hat{\mathbf{s}}$ = state vector of multisensor track,

$\hat{\mathbf{P}}$ = covariance matrix of $\hat{\mathbf{s}}$,

$\hat{\mathbf{s}}_i$ = state vector of i-th single radar track,

$\hat{\mathbf{P}}_i$ = covariance matrix of $\hat{\mathbf{s}}_i$.

A schematic drawing of this fusion algorithm is shown in **Figure II-1** for N=2, where $(\theta_m)_{1,2}$ represents the target measurements from the two sensors.

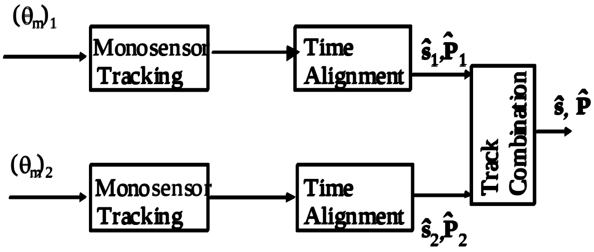


Figure II-1 Multi-sensor filtering through combination of tracks

C. Fusion of correlated tracks

As described in [4], the equation for correlated track fusion are the following:

$$\begin{cases} \hat{\mathbf{s}} = \hat{\mathbf{s}}^i + \left(\mathbf{P}^i - \mathbf{P}^{ij}\right)\left(\mathbf{P}^i + \mathbf{P}^j - \mathbf{P}^{ij} - \mathbf{P}^{ji}\right)^{-1}\left(\hat{\mathbf{s}}^j - \hat{\mathbf{s}}^i\right) \\ \mathbf{M} = \mathbf{P}^i - \left(\mathbf{P}^i - \mathbf{P}^{ij}\right)\left(\mathbf{P}^i + \mathbf{P}^j - \mathbf{P}^{ij} - \mathbf{P}^{ji}\right)^{-1}\left(\mathbf{P}^i - \mathbf{P}^{ji}\right) \end{cases}$$

where $\mathbf{P}_k^{ij} = E\left\{\mathbf{s}_{k/k}^i \cdot \left(\mathbf{s}_{k/k}^j\right)^T\right\}$ is the correlation matrix between *i-th* and *j-th* tracks to be combined (the notation $A_{l/m}$ stands for the quantity A at time step l estimated by using measurements acquired up to time step m). If the tracks are obtained via Kalman Filter based trackers, the following relations hold:

$$\begin{cases} \mathbf{s}_{k/k}^i = \mathbf{s}_{k/k-1}^i + \mathbf{K}^i\left(\mathbf{z}_k^i - \mathbf{H}\mathbf{s}_{k/k-1}^i\right) = \left(\mathbf{I} - \mathbf{K}^i\mathbf{H}\right)\mathbf{s}_{k/k-1}^i + \mathbf{K}^i\mathbf{z}_k^i \\ \mathbf{s}_{k/k}^j = \mathbf{s}_{k/k-1}^j + \mathbf{K}^j\left(\mathbf{z}_k^j - \mathbf{H}\mathbf{s}_{k/k-1}^j\right) = \left(\mathbf{I} - \mathbf{K}^j\mathbf{H}\right)\mathbf{s}_{k/k-1}^j + \mathbf{K}^j\mathbf{z}_k^j \end{cases}$$

Therefore:

$$\begin{aligned} \mathbf{P}_k^{ij} &= E\left\{\mathbf{s}_{k/k}^i \cdot \left(\mathbf{s}_{k/k}^j\right)^T\right\} \\ &= E\left\{\left[\left(\mathbf{I} - \mathbf{K}^i\mathbf{H}\right)\mathbf{s}_{k/k-1}^i + \mathbf{K}^i\mathbf{z}_k^i\right]\left[\left(\mathbf{I} - \mathbf{K}^j\mathbf{H}\right)\mathbf{s}_{k/k-1}^j + \mathbf{K}^j\mathbf{z}\right]^T\right\} \end{aligned}$$

Assuming that radar measurements are totally independent we obtain

$$\begin{aligned} \mathbf{P}_k^{ij} &= E\left\{\left[\left(\mathbf{I} - \mathbf{K}^i\mathbf{H}\right)\mathbf{s}_{k/k-1}^i\right]\left[\left(\mathbf{I} - \mathbf{K}^j\mathbf{H}\right)\mathbf{s}_{k/k-1}^j\right]^T\right\} \\ &= \left(\mathbf{I} - \mathbf{K}^i\mathbf{H}\right)E\left\{\mathbf{s}_{k/k-1}^i\left(\mathbf{s}_{k/k-1}^j\right)^T\right\}\left(\mathbf{I} - \mathbf{K}^j\mathbf{H}\right)^T \end{aligned}$$

Note that, by definition, $E\left\{\mathbf{s}_{k/k-1}^i\left(\mathbf{s}_{k/k-1}^j\right)^T\right\} = \mathbf{P}_{k/k-1}^{ij}$, which is the cross-correlation of the single radar tracks before the acquisition of a new measurement.

The distributed track fusion architecture described in this paper implies that, for each target followed by more than one radar, its relevant tracks may be combined repeatedly scan after scan. After the fusion, each radar associates the same fused track to the target. Therefore, before the acquisition of a new measurement, we can assume that the tracks are totally correlated. Hence, under the hypothesis of identical radars and synchronous measurements, we can assume that $\mathbf{P}_{k-1}^{ji} \cong \mathbf{P}_{k-1}^{j}$. Finally we obtain:

$$\begin{aligned}\mathbf{P}_k^{ij} &\cong \left(\mathbf{I}-\mathbf{K}^i\mathbf{H}\right)\left(\mathbf{P}_{k-1}^{j}\right)^T\left(\mathbf{I}-\mathbf{K}^j\mathbf{H}\right)^T \\ &= \left(\mathbf{I}-\mathbf{K}^i\mathbf{H}\right)\left[\left(\mathbf{I}-\mathbf{K}^j\mathbf{H}\right)\left(\mathbf{P}_{k-1}^{j}\right)\right]^T = \left(\mathbf{I}-\mathbf{K}^i\mathbf{H}\right)\left(\mathbf{P}_{k}^{j}\right)^T\end{aligned}$$

III. REAL TIME TEST BED DESCRIPTION

A. *Functional Description*

The Multi-Radar Scenario Simulator allows simultaneous plots sending towards the tracker systems placed on each radar.

Track data, exchanged via a dedicated LAN (see **Figure III-2**), are received and forwarded by the simulator to the tracker systems, in order to perform the fusion as described in section II.

Simulations data are written by the tracker systems in independent files in order to be analyzed “off-line” by the Performance Evaluation System (PES).

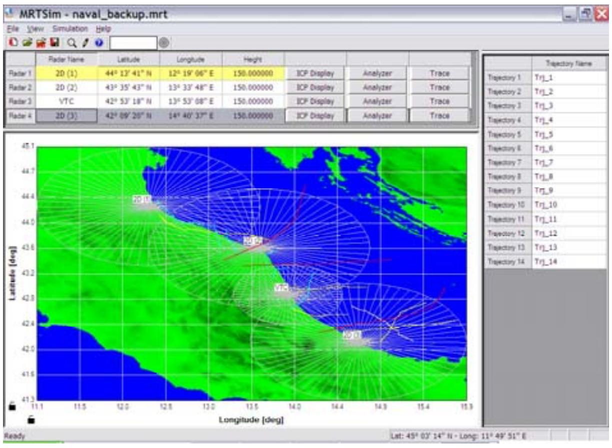
The scenario creation, using the Multi-Radar Scenario Simulator (see **Figure III-1**), consists of the following steps:

Radar modelling; for each defined radar, the set of characterizing parameters consists of: radar position; antenna initial azimuth; radar scan rate; instrumented coverage during surveillance activity and during dedicated tracking activity; probability of detection for different range sectors and operative mode; measurements errors (variances of zero-mean independent Gaussian distributions) for each operative mode; false alarms distribution; communication settings.

Trajectory generation; a database containing characterizing parameters for different target models has been defined. The tool allows for the generation of air, naval and ballistic targets.

Simulation settings; the number of Monte-Carlo trials and the number of scans for each simulation have to be defined. During the scenario simulation, the following real time activities are performed by the Simulator: (i) for each Radar, at each beam-target coincidence, plots are sent according to the defined detection probability for the current operative mode; (ii) random noise (as specified in the scenario creation) is added before sending plots to each Radar; (iii) random false alarms are generated in the coverage volume of each radar.

Out of surveillance coverage, re-pointing messages (which govern the dedicated tracking beam pointing for radars having this capability), sent by the trackers, are checked by the simulator before sending the related plots.



MRTSim - naval_backup.mrt

	Radar Name	Latitude	Longitude	Height			
Radar 1	2D (1)	44° 13' 41" N	12° 19' 06" E	150.000000	ICP Display	Analyzer	Trace
Radar 2	2D (2)	43° 35' 43" N	13° 33' 48" E	150.000000	ICP Display	Analyzer	Trace
Radar 3	VTC	42° 53' 18" N	13° 53' 08" E	150.000000	ICP Display	Analyzer	Trace
Radar 4	2D (3)	42° 09' 20" N	14° 40' 37" E	150.000000	ICP Display	Analyzer	Trace

	Trajectory Name
Trajectory 1	Trj_1
Trajectory 2	Trj_2
Trajectory 3	Trj_3
Trajectory 4	Trj_4
Trajectory 5	Trj_5
Trajectory 6	Trj_6
Trajectory 7	Trj_7
Trajectory 8	Trj_8
Trajectory 9	Trj_9
Trajectory 10	Trj_10
Trajectory 11	Trj_11
Trajectory 12	Trj_12
Trajectory 13	Trj_13
Trajectory 14	Trj_14

Figure III-1 Multi-Radar Scenario Simulator

The Performance Evaluation System consists of a statistic analyzer which performs a set of computations (namely the track accuracies) after a Monte-Carlo simulation.

B. *Hardware and Software description*

In order to set up a realistic test-bed environment only few elements are required.

Real Data Extractors can be executed (without any relevant software modification) on Linux based computers although the code is written for LynxOS 4.0.

Each DE unit is therefore installed on a common PC with SUSE Linux 10.0.

A Windows based machine is used to run the Multi-Radar Scenario Simulator and the Performance Evaluation System.

The messages exchange is performed using the UDP protocol on a 10/100 Mbits LAN.

The configuration layout is reported in figure:

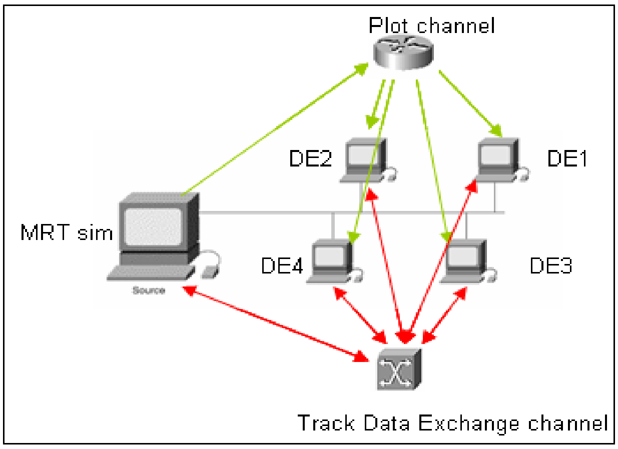


Figure III-2 Real Implemented system; the green arrows represent the channel for plot data exchange, whilst the red ones represent the channel for track data exchange.

IV. BORDER CONTROL STUDY CASES

The notional simple Border Control system is constituted by the following sensors:

- one long range surveillance radar,
- three multifunctional radars,
- a number of Vessel Traffic Control (VTC) systems.

For sake of simplicity, we assume the presence of two VTC in the angular sector of interest, but the test bed does not have any “practical” limitation in the number or radar systems to be controlled.

Two different study cases have been conceived, one for air defense and the other for naval defense. The remaining part of this section is dedicated to the study cases description and to the presentation of the achieved results.

It has to be noted that the air and naval threats are contemporaneously present in the scenario and the test bed processes the long range, multifunctional and VTC data at the same time.

Air Defense

To react properly to a hostile target, the hypothesized Border Control systems executes functions for air defense:

-Air target detection by means of the ground-based long range radar.

-Long Range radar cueing to a multifunctional radar.

-Multifunctional radar target acquisition to proper reaction guidance.

It is well known that the multifunctional radar can effectively guide a friend missile towards an hostile target if the cue volume (i.e. the volume of the uncertainty ellipsoid around the true target position) is not too large. Thus, the cue volume reduction after the fusion of long range and multifunctional radar data will be assumed as a metric to quantify the performance of the air defense system. The comparison will be done with the cue volume computed by the multifunctional radar only.

Naval defense

Naval target detection by means of the multifunctional radar.

Multifunctional radar cueing to a VTC systems.

The VTC system is composed by a radar and an infrared sensor (IR). The IR is generally cued by the VTC radar and it needs of a reduced cue volume size to achieve a meaningful probability of target recognition.

The cue volume reduction after the fusion of multifunctional and VTC radar data will be assumed as a metric to quantify the performance of the naval defense system.

Achieved results

It is assumed that the border control system is composed by one long range, three multifunctional radars and two VTC system whose performance are:

- *Long range radar (LR)* : azimuth accuracy=0.4°, elevation accuracy=0.4 °, range accuracy =50 m, scan rate=10 seconds.

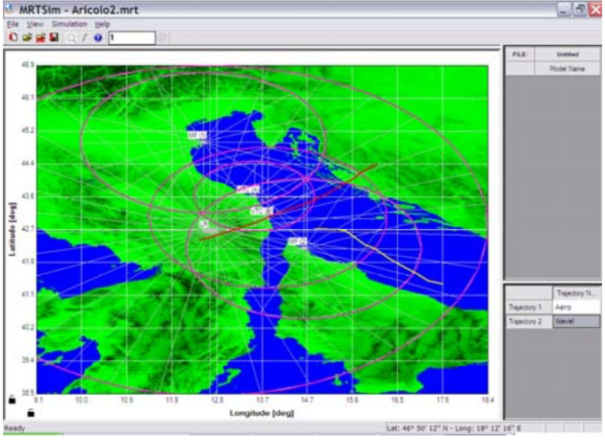
- *Multifunctional radar(MF)*: azimuth accuracy=0.2°, elevation accuracy=0.2 °, range accuracy =30 m, scan rate=5 seconds.

- *VTC radar*: azimuth accuracy=0.1°, elevation accuracy=0.1°, range accuracy =20 m, scan rate=2.5 seconds.

The presence of the following two targets is hypothesized;

-one aircraft approaching the border with constant velocity equal to 300 m/s, and

- one small boat approaching the coast line with velocity equal to 25 m/s.



Trajectory 1: Aero

Trajectory 2: Naval

Lat: 46° 50' 12" N - Long: 18° 12' 16" E

Figure IV-1 Pictorial view of the scenario under analysis

Next figures 4.2 ÷4.5 reports respectively the results obtained for the air defense and for the naval defense scenarios. The tracks have been assumed independent; this limitation will be removed in the full paper. The major semi-axis of the 3σ uncertainty ellipsoid (km) is reported in both figures as a function time expressed in seconds. The 3σ statistic is required to assure that the 99% of the simulation results falls inside the uncertainty ellipsoid volume. Figure 4.2 reports the geometry between the aircraft trajectory and the LR, MF radars and figure 4.3 the obtained accuracy results. Figures 4.4 and 4.5 presents the same information for the naval defense study case

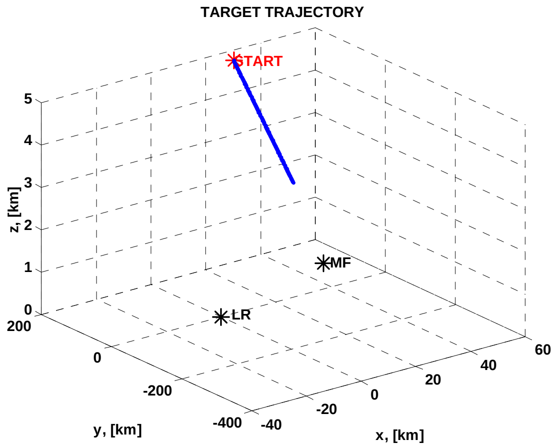


Figure IV-2 radars-target geometry for the air defense study case

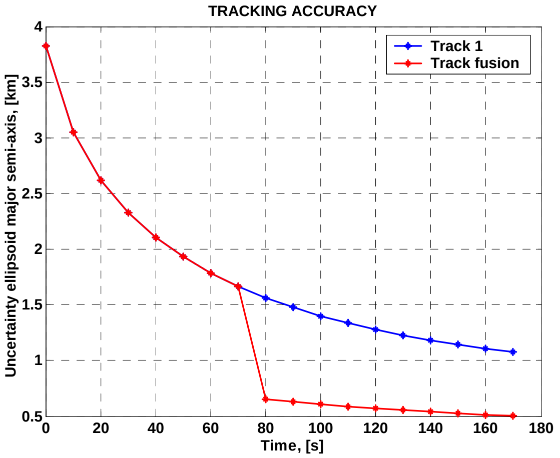


Figure IV-3 Results obtained for the air defense study case

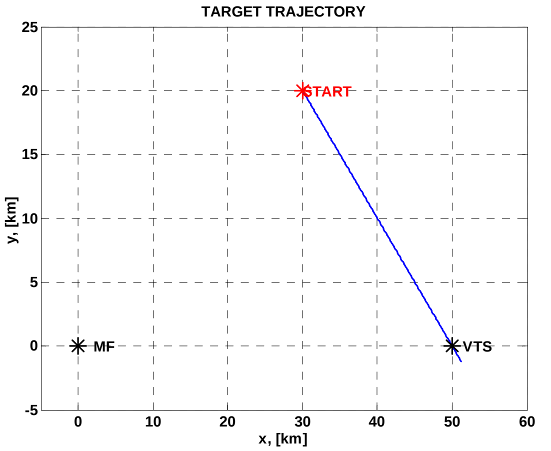


Figure IV-4 radars-target geometry for the naval defense study case

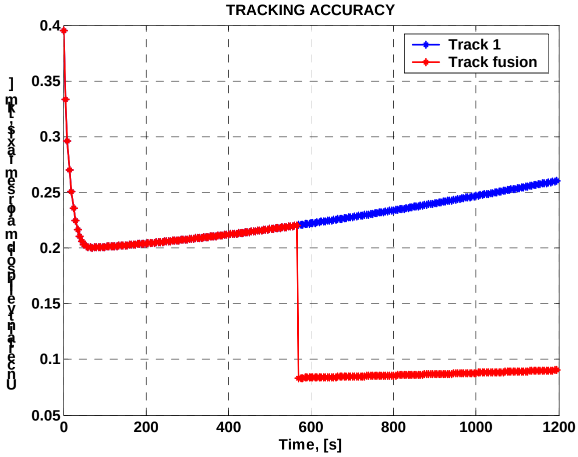


Figure IV-5 Results obtained for the naval defense study case

V. CONCLUSIONS

A track fusion procedure has been implemented in a test bed which uses the same hardware and software architecture of a real radar system. The selected application is the improvement of border control via the fusion of surveillance, multifunctional and VTC radar tracks. To this aim the following activities has been performed:

- a convenient and cost effective data fusion architecture has been conceived;
- a multi-radar scenario simulator capabilities has been realized;
- a communication network between the radars has been designed and implemented;
- the data extractor test bed has been modified in order to allow for multiple tracks fusion;
- a set of simulated experiment has been designed and used for testing the whole system performance.

It has been shown that the existing Radar hardware and software is capable of supporting the tracks fusion providing an average improvement in tracking accuracy around 35%. Let us remark that performing the track fusion directly on the radar system and not in remote centers allows for side effect benefits like (i) re-pointing of the beam along the threat direction of arrival, (ii) energy and time management, (iii) cue of other sensors (i.e. infrared) or proper reaction means (patrol boat), (iv) preliminary classification of potential hostile targets.

VI. REFERENCES

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