Multi-sensor ISAR technique for translational motion estimation

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Multi-sensor ISAR technique for translational motion estimation

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Abstract— **In the last years a lot of interest has grown concerning the exploitation of data acquired by multiple sensors belonging to multistatic or Multiple Input Multiple Output systems. Indeed increased information and/or better performance can be retrieved using a network of cooperating sensors. In this paper, data acquired by a pair of Inverse Synthetic Aperture Radar sensors is exploited to estimate both radial and cross-radial components of a target's translational motion. The target is observed from different points of view in the long range surveillance operative case. The simulated cost function of the estimation procedure is used to show the feasibility of the proposed technique, confirmed by the analysis of the results of its application against real data acquired by the Radar Sensor Network installed at the NATO Centre for Maritime Research and Experimentation.**

Keywords— Inverse Synthetic Aperture Radar, motion estimation, multiple sensor systems.

I. INTRODUCTION

Currently, much Maritime Surveillance activity relies on cooperative sensing (transponder-based) systems, which needs to be validated by non-cooperative systems such as radar. X-band marine radar [1] and High Frequency surface wave radar [2] systems currently proposed for Maritime Surveillance can be augmented by Inverse Synthetic Aperture Radar (ISAR) techniques which provide enhanced feature information also aiding in classification. As it is well known [3], ISAR techniques allow 2D high resolution images of 3D moving targets to be obtained. Generally while high slant range resolution is achieved through standard pulse compression and depends on the system's bandwidth, in ISAR the Doppler resolution depends on the motion of the target with respect to a fixed acquiring sensor. Since the target motion is unknown, it has to be estimated directly from the data.

The formation of the image is achieved exploiting the rotation and the cross-range component of the translational motion (if relevant), therefore the first step in ISAR imaging is the estimation and the removal of the radial component of the motion. Several techniques have been proposed in literature to deal with this problem [4]-[8].

The previous approaches are single-sensor based, while the exploitation of multiple sensors (MS) could help in extracting more information about the target motion. In the last years a lot of interest has grown concerning the exploitation of data acquired by multistatic or Multiple Input Multiple Output (MIMO) ISAR imaging systems. Concerning the problem of target motion estimation, data from multiple ISAR sensors were used in [9]-[12] to retrieve the target rotational motion components with increased accuracy. Moreover the estimation of trajectory was achieved with a multilateration approach in [13] and extending the entropy minimization based autofocusing approach in [14].

Starting from approaches in [11]-[12], the possibility of exploiting data acquired by a pair of sensors observing the target from different points of view in the long range surveillance operative case is investigated to estimate both radial and cross-radial components of its translational motion. It is supposed that one sensor is active; therefore a monostatic image and a bistatic image of the same target can be achieved. Based on the modelling of the signals received from a generic scatterer of the target, a multiple sensor translational motion estimation technique based on a Maximum Likelihood (ML) approach is here devised. It uses Doppler frequencies alignment between the same dominant scatterers identified in both monostatic and bistatic images and Point Spread Function (PSF) focusing in the Doppler frequency dimension to provide estimation of the target radial and cross radial translation motion. The analysis of the simulated cost function of the estimation procedure shows the feasibility of the proposed technique to estimate both the radial and cross-radial components of the translation velocity of the target along with the need of a proper initialization. Moreover results achieved against real data prove its effectiveness; data were acquired by the Radar Sensor Network installed in the Gulf of La Spezia, Italy, at the NATO Centre for Maritime Research and Experimentation (CMRE).

This paper is organized as follows: after the definition of the geometry and signal model in Section II, the description of the technique is provided in Section III. Results are shown in Section IV. Finally Section V concludes the paper.

II. GEOMETRY AND SIGNAL MODEL

Typically the target can be modelled as a rigid body composed by a set of I dominant scatterers with constant reflectivity during the aperture time and its motion can be decomposed in the translation of a reference point called *fulcrum* and the rotation of the body around the fulcrum. In Fig. 1 the acquisition geometry is shown: sensor *A* transmits and receives while sensor *B* is a receiving only device. In this case two acquisitions are provided by the sensor network: the first is the monostatic acquisition from sensor *A*, while the second is the bistatic acquisition arising from the signal received by sensor *B* after the transmission from sensor *A*. To account for this bistatic acquisition a fictitious sensor *C* is defined. The $\eta\rho\upsilon$ reference system embedded in the target represents the point of view of the reference fictitious radar *C*: in the following, the position vector for sensors $\Gamma=\{A, B, C\}$ is shown, assuming that the grazing angles ξ_A and ξ_B with respect to the plane containing both the reference sensor position and the target fulcrum are negligible.

$$\mathbf{P}_\Gamma=\left[\eta_{S_\Gamma}\ \rho_{S_\Gamma}\ \upsilon_{S_\Gamma}\right]^T=R_\Gamma\cos(\beta_\Gamma)\left[\sin(\alpha_\Gamma)\ -\cos(\alpha_\Gamma)\ 0\right]^T \quad (1)$$

In (1) the superscript T indicates the transpose operation, R_A and R_B are the distances of the sensors *A* and *B* from the target fulcrum respectively, while the bistatic distance R_C for the fictitious sensor *C* is defined as their mean value. α_A and α_B are the aspect angles for sensors *A* and *B*, respectively, and $\alpha_C=0$ rad by definition. Moreover, it is possible to define the bistatic angles for each sensor as

$$\beta_A,\ \beta_B=0 \text{ and } \beta_C=(\alpha_A-\alpha_B)/2 \quad (2)$$

In the $\eta\rho\upsilon$ reference system the radial and cross-radial components of the translational motion can be described according to the velocity vector **v** projections on ρ and η axes respectively, while the complex rotation of the target at first order (described by the effective rotation vector $\boldsymbol{\omega}_\mathbf{E}$) is modeled as a rotation around υ axis.

The expression of the distance of the ith scatterer of the target from real sensor $\Gamma=\{A, B\}$ as a function of the acquisition time t can be written after some mathematics as

$$\begin{aligned}R_{i\Gamma}(t)=\left\|\mathbf{P}_\Gamma-\mathbf{T}_\mathbf{i}(\mathrm{t})\right\|\approx R_{i\Gamma}+\Bigg[&\frac{\eta_i(0)v_\eta+\rho_i(0)v_\rho}{R_{i\Gamma}}+\\ &R_\Gamma\frac{\left|\boldsymbol{\omega}_\mathbf{E}\right|_\Gamma\eta_{i\Gamma}(0)}{R_{i\Gamma}}-R_\Gamma\frac{\left(\sin(\alpha_\Gamma)v_\eta-\cos(\alpha_\Gamma)v_\rho\right)}{R_{i\Gamma}}\Bigg]t+\\ &\left[\frac{1-\frac{R_\Gamma^2}{R_{i\Gamma}^2}\sin^2(\alpha_\Gamma)}{R_{i\Gamma}}v_\eta^2-\frac{1-\frac{R_\Gamma^2}{R_{i\Gamma}^2}\cos^2(\alpha_\Gamma)}{R_{i\Gamma}}v_\rho^2-\left|\boldsymbol{\omega}_\mathbf{E}\right|_\Gamma^2\frac{R_\Gamma}{R_{i\Gamma}}\rho_{i\Gamma}(0)\right]\frac{t^2}{2}\end{aligned} \quad (3)$$

where the vector $\mathbf{T}_\mathbf{i}(t)=[\eta_i(t),\ \rho_i(t),\ \upsilon_i(t)]^\mathrm{T}$ represents the position varying with time of the ith scatterer of the target, $\eta_i(0)$ and $\rho_i(0)$ are its cross-range and range coordinates at central aperture instant respectively. $\rho_{i\Gamma}(0)$ is the projection on the line of sight of sensor Γ (LOS_Γ) of the vector $\mathbf{T}_\mathbf{i}(0)$ while $\eta_{i\Gamma}(0)$ is its projection on an axis orthogonal to LOS_Γ and υ. Finally $R_{i\Gamma}=R_\Gamma+\rho_{i\Gamma}(0)$. The previous expression has been achieved computing a 2nd degree Maclaurin polynomial. The distance of the ith scatterer from the fictitious sensor C can be derived as $R_{iC}(\mathrm{t})=[R_{iA}(\mathrm{t})+R_{iA}(\mathrm{t})]/2$.

In this work we suppose that the active radar system A transmits a Linear Frequency Modulated Continuous Wave (LFMCW) signal with m_α as modulation rate; therefore the time axis can be decoupled in fast time axis t_k and slow time axis t_n and represented in its sampled version as $t=t_k+t_n=kT_s+nPRT$ for k=0, ..., K-1 and n=0, ..., N-1, where T_s is the fast time sampling period and *PRT* is the sweep period of the FMCW waveform. The expression of the signals received from sensors $\Gamma=A, C$ can be written as

$$y_{i\Gamma}(k,n)=A_{i\Gamma}\exp\left(j\frac{4\pi}{c}(f_c+m_\alpha kT_s)R_{i\Gamma}(k,n)\right)+\nu_{i\Gamma}(k,n) \quad (4)$$

$A_{i\Gamma}$ is the complex reflectivity of the ith scatterer as seen by the sensor Γ and $\nu_{i\Gamma}(n,k)$ is white Gaussian noise with power equal to σ_n^2, therefore the joint probability density function of the collected data is given by

$$\mathrm{p}(\mathbf{y})=(\pi\sigma_\mathrm{n}^2)^{-2\mathrm{IKN}}\exp\left\{-\left[(\mathbf{y}\text{-}\mathbf{Sa})^\mathrm{H}(\mathbf{y}\text{-}\mathbf{Sa})\right]/\sigma_\mathrm{n}^2\right\} \quad (5)$$

In the previous expression the following vector notation has been used

$$\begin{aligned}&\mathbf{y}=[\mathbf{y}_\mathbf{1}\cdots\mathbf{y}_\mathbf{I}]^T\in N^{+2INK\times 1}\ \text{where}\ \mathbf{y}_\mathbf{i}=[\mathbf{y}_\mathbf{iA}\ \mathbf{y}_\mathbf{iC}]^T\in N^{+2NK\times 1}\\ &\text{and}\ y_{i\Gamma}(k+nK+1)=y_{i\Gamma}(k,n)\end{aligned} \quad (6)$$

$$\mathbf{a}=[\mathbf{a}_\mathbf{1}\cdots\mathbf{a}_\mathbf{I}]^T\in N^{+2I\times 1}\ \text{with}\ \mathbf{a}_\mathbf{i}=[A_{iA}\ A_{iC}]^{T^T} \quad (7)$$

$$\begin{aligned}&\mathbf{S}=diag(\mathbf{S}_\mathbf{1}\cdots\mathbf{S}_\mathbf{I})\in N^{+2INK\times 2I}\\ &\text{where}\ \mathbf{S}_\mathbf{i}=diag(\mathbf{S}_\mathbf{iA},\mathbf{S}_\mathbf{iC})\in N^{+2NK\times 2}\\ &\text{and}\ S_{i\Gamma}(k+nK+1)=\exp\left(-j\frac{4\pi}{\lambda}(f_c+m_\alpha Ts)R_{i\Gamma}(k,n)\right)\end{aligned} \quad (8)$$

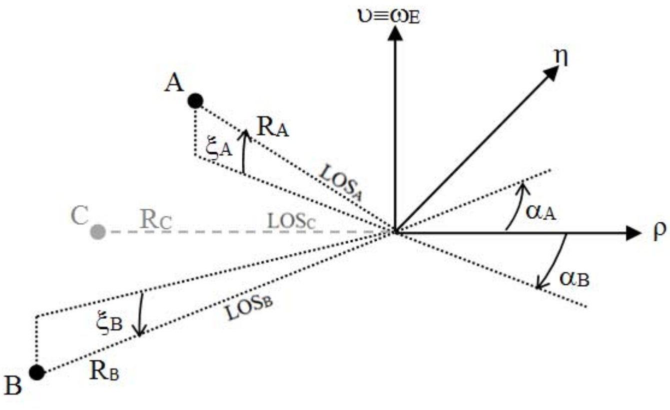


Fig. 1. Multistatic acquisition geometry in $\eta\rho\upsilon$ reference system

III. MS TRANSLATION MOTION ESTIMATION TECHNIQUE

A multiple sensor translational motion estimation technique is devised starting from the signal model described in (4) – (8). A Maximum Likelihood approach is used to find cross radial and radial velocities, when rotation is considered negligible with respect to translational motion. In the following, it is supposed that an association is possible between main scatterers in the available uncompensated Range Doppler (RD) images I_A and I_C. Therefore it is supposed that contributions of the same scatterer can be isolated in the monostatic raw data acquisition *A* and bistatic raw data acquisition *C*. A procedure based on Doppler frequency alignment and PSF focusing in the Doppler frequency dimension is then intended to provide estimation of the target motion radial and cross radial translation.

Recalling that the amplitudes of the signal received from the ith scatterer of the target $A_{i\Gamma}$, its Doppler frequency $f_d^{i\Gamma}$ and the noise power σ_n^2 are unknown, the ML estimator can be written as

$$\left(\hat{v}_\eta,\hat{v}_\rho\right)=\underset{v_\eta,v_\rho}{\operatorname{argmax}}\left\{\underset{\mathbf{a},\sigma_n^2,f_d^{i\Gamma}}{\operatorname{argmax}}\left\{\ln\left[p(\mathbf{y})\right]\right\}\right\} \tag{9}$$

By carrying out the maximization with respect to σ_n^2 and **a** (9) can be proved equal to

$$\left(\hat{v}_\eta,\hat{v}_\rho\right)=\underset{v_\eta,v_\rho}{\operatorname{argmax}}\left\{\sum_{i=1}^{I}\underset{f_d^{i\Gamma}}{\operatorname{argmax}}\left\{\sum_{\Gamma=A,C}\left|S_{\mathbf{i\Gamma}}^{\mathbf{H}}\mathbf{y}_{\mathbf{i\Gamma}}\right|^2\right\}\right\} \tag{10}$$

Based on (10), the MS-ML estimation of the cross radial and radial velocities are achieved through the processing chain in Fig. 2. The signal from the ith scatterer is first compensated for the phase term depending on the distance difference $\Delta R_{i\Gamma}=R_{iC}-R_{i\Gamma}$ which is assumed known since $R_{i\Gamma}$ is directly estimated from image I_Γ. Then for every pair of values (v_η,v_ρ) under test, the signal is re-aligned to its Doppler frequency $f_d^{i\Gamma}=2[\eta_{i\Gamma}(0)v_\eta+\rho_{i\Gamma}(0)v_\rho]/\lambda R_\Gamma$ compensating the frequency amount $\Delta f_d^{i\Gamma}=2(\sin(\alpha_\Gamma)v_\eta+\cos(\alpha_\Gamma)v_\rho]/\lambda$ and dechirped according to $\gamma_\Gamma=(\cos^2(\alpha_\Gamma)v_h{}^2+\sin^2(\alpha_\Gamma)v_h{}^2]/R_\Gamma$. The previous expressions have been derived from (3) in the hypothesis of long range surveillance, i.e. when the distance of the target from the radar is much greater than the dimension of the target itself ($R_{i\Gamma}\approx R_\Gamma$). RD focusing is performed and a scaling of the Doppler axis is then needed, if the distances R_A and R_C are significantly different, to make the Doppler positioning of the ith PSF in the final RD images sensor-independent. The squared modulus of the phase compensated, Fourier transformed and axis scaled signals from sensors A and C are averaged to provide the contribution of the ith scatterer to the final motion compensated, incoherently integrated RD image. The values of (v_η,v_ρ) which maximize the useful signal mean power is assumed as the estimated values (□;v_η, □;v_ρ).

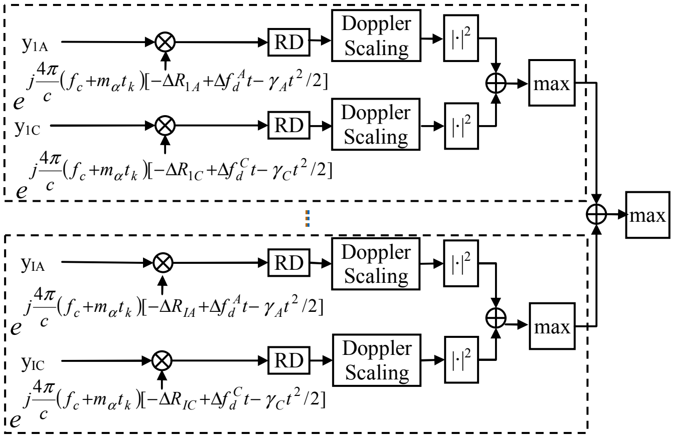


Fig. 2. MS-ML technique for radial and cross-radial velocity estimation.

IV. RESULTS

Data received from a LFMCW radar by a single point-like scatterer were firstly simulated as in (4) using the non-approximated version of the distance in (3) without noise contribution according the following parameters. The transmitted signal is linearly modulated with bandwidth B=150 MHz, Pulse Repetition Frequency $PRF=1/PRT$=600 Hz. N=2048 sweeps are considered for imaging purposes. The acquisition geometry is defined according to distances $R_A=R_B$=10 km with aspect and grazing angles $\alpha_A=\alpha_B=2.5°$ and $\xi=0°$, respectively. In the simulation the same amplitude is considered for the signals received from both sensors A and C, therefore $A_\Gamma=1$ $\forall\Gamma$. Finally the simulated scatterer is located at the origin of the reference system, so it is considered the fulcrum of an extended target, and it moves with translational motion according to velocity $v=[v_\eta\ v_\rho\ 0]=[8\ 4\ 0]$ m/s. Rotational motion is considered negligible.

The simulated noise-free data have been used to investigate the objective function of the proposed estimation technique in (10) and the achieved result is shown in Fig. 3. As it is apparent, the maximum can be found in correspondence to the correct velocity values; differently from the single sensor case also the cross-radial component of the translation velocity is retrieved. However the flatness of the objective functions around the true velocity values (visible in the zooms in Fig. 3b) suggests that a fine initialization of the estimation procedure is needed in order to allow a fast convergence to the correct estimation.

In addition, here we show some results achieved applying the proposed technique to real data. They have been acquired by the Radar Sensor Network (RSN). It is formed by two radar nodes with a baseline of nearly 2.6 km transmitting Linear Frequency Modulated Continuous Wave (LFMCW) signals in X band installed in the Gulf of La Spezia, Italy, at the NATO CMRE (see Fig. 4): the Marine Radar Node (MRN) is usually employed for detection and tracking while the Inverse Synthetic Aperture Radar Node (ISARN) is normally used to obtain high resolution images of targets. The X band LFMCW technology allows for low cost, low power, compact and lightweight sensors and fosters the possibility of deploying a scalable network.

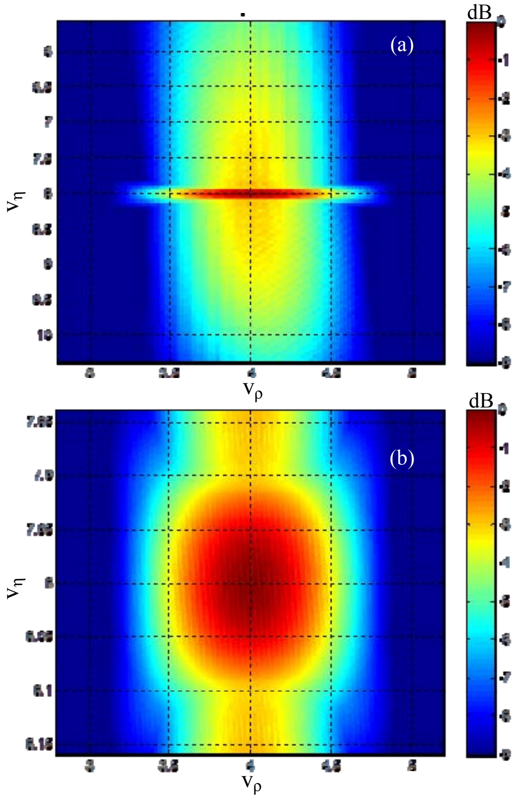


Fig. 3. Multi-sensor maximum likelihood normalized objective function (a) and its zoom (b) around the true velocities values.

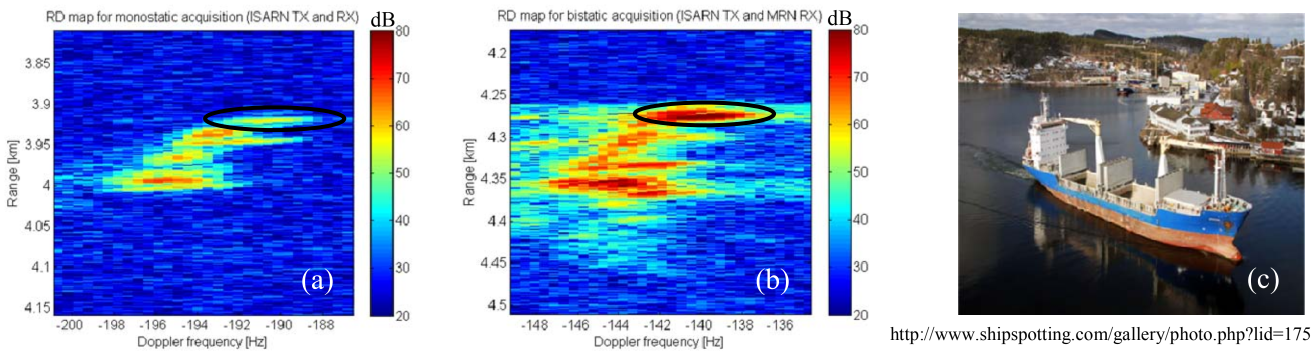
Fig. 4. RSN topology.

A multistatic dataset was acquired forcing the MRN to observe the target with fixed bearing of 151° with respect to the North (therefore in ISAR mode) according the following parameters: bandwidth B=150 MHz, PRF=490 Hz, N=512 or 1024. The MRN was set to receive echo signals from the transmission of the ISARN. RD images corresponding to the monostatic and the bistatic acquisitions of the target I_A and I_C respectively are shown in Fig. 5, where it is apparent how asymmetric the acquisition geometry is also in terms of target fulcrum to sensor distance ($R_A \neq R_C$). The Maritime Mobile Service Identity (MMSI) of the imaged target has been extracted from Automatic Identification System (AIS) data and for the sake of completeness an optical image of the corresponding target is shown in Fig. 5 (c). AIS data show the target approaching both radars in the network, therefore a spread of the Doppler frequency spectrum around a positive Doppler centroid would be expected. Indeed in Fig. 5 (a) and (b) the opposite happens, meaning that the target is acquired by multistatic radar system in Doppler ambiguity.

When considering real datasets acquired according the RSN geometry two issues arose:

- Model issue: the standard approximations for the "long range surveillance" case used in Section III appear to be no longer valid since distances between the target and the radars are in the order of 4 km. In this case the finer approximation in (3) needs to be considered.
- Geometry issue: the bistatic angle is very large (much greater than 5° where the radar cross section is supposed to be in the quasi-monostatic region [15]), implying a very different electromagnetic behavior of same point reflectors in the target. The association between PSFs of the same scatterer in different images becomes difficult and the spatial coherency could not be maintained.

Nevertheless the presence of stable isolated and point-scatterer like structures in the acquired ship target in Fig. 5 (c) (i.e. the masts and the bow) could allow the application of the proposed technique to the available dataset. In order to prove its effectiveness on real data acquired by the RSN, a manual selection and association of a single dominant scatterer (I=1) has been performed on several frames of the acquired data, both considering low and medium Doppler resolution (N=512 and N=1024 respectively).



http://www.shipspotting.com/gallery/photo.php?lid=175085

Fig. 5. Target: (a) image from ISARN acquisition, (b) image from bistatic acquisition , (c) real image MMSI: 249585000, EMONA 126m x 20m

An example of this association is shown in Fig. 5 (a) and (b), where it is supposed that the first strong return in both images pertain to the same scatterer. Moreover inspection of Fig. 5 (a) and (b) allows us to make two observations. The first is related to the electromagnetic behavior of the target: it is confirmed that the radar responses from same point scatterers in the monostatic and bistatic RD images show huge differences, depending on the very wide bistatic angle. The second observation concerns the higher intensity of the bistatic image with respect to the monostatic one: this is due to the different gain of the ISARN and MRN node antennas. Specifically the gain of the MRN antenna is nearly 20 dB higher that the gain of the ISARN antenna and the corresponding effect must be compensated before performing the final incoherent sum.

The searching procedure has been implemented using the Nelder-Mead method (NM), an Ant Colony Optimization (ACO) tool and an extensive search (ES). The initialization has been carried out extracting the barycenter ($R_{0\Gamma}, f_d^{0\Gamma}$) from both images I_Γ with Γ=A,C. Recalling the experienced Doppler ambiguity, the initial velocity values are computed as

$$\left(v_\eta^0, v_\rho^0\right) = \frac{\lambda}{2}\begin{bmatrix} -\sin(\alpha_A) & \cos(\alpha_A) \\ -\sin(\alpha_C)\cos(\beta_C) & \cos(\alpha_C)\cos(\beta_C) \end{bmatrix}^{-1}\begin{bmatrix} PRF+f_d^{0A} \\ PRF+f_d^{0C} \end{bmatrix} \quad (12)$$

It has to be emphasized that the barycenters extracted from both monostatic and bistatic images don't necessarily relate to the same point scatterer, therefore (12) must be used only as low accuracy initialization values.

Table I shows the results: in order to be compared with the AIS speed reports, the estimated radial and cross-radial velocities have been properly converted in x and y velocity components according to the reference system shown in Fig. 4 centered in generic point of the target at center aperture. It is apparent how the proposed technique is able to almost correctly estimate the x and y component of the target translation velocity: indeed estimation from ACO and SIMPLEX algorithm approaches the ones achieved by the extensive search. The bias with respect to the velocities values retrieved from the AIS speed over ground (SOG) and course over ground (COG) values, experienced also in the extensive search case, may depend on the target maneuvering (and not only shifting) to pass the breakwater of the port of La Spezia.

TABLE I. OUTPUT OF THE MS- ML MOTION ESTIMATION TECHNIQUE

Low Doppler Resolution				***Medium Doppler Resolution***			
Frame #		Vx (m/s)	Vy (m/s)	Frame #		Vx (m/s)	Vy (m/s)
12	ACO	-4.015	-4.713	11	ACO	-3.8742	-4.8276
	NM	-4.314	-4.332		NM	-3.8768	-4.6904
	ES	-4.0112	-4.7726		ES	-3.8746	-4.8464
	AIS	-4.0338	- 4.7679		AIS	-4.071	-4.794
21	ACO	-3.877	-5.069	12	ACO	-3.9299	-4.6817
	NM	-3.875	-5.129		NM	-3.9212	-5.0342
	ES	-3.8736	-5.1618		ES	-3.9235	-4.8590
	AIS	-4.0707	- 4.7935		AIS	-4.078	-4.799

V. CONCLUSIONS

A multiple sensor translational motion estimation technique has been devised. A network formed by an active and a passive radar sensor was considered providing a monostatic and a bistatic acquisition from the same surveillance area. In the hypothesis that responses from the same scatterers in the detected target can be isolated and associated in both acquisitions, a ML procedure based on Doppler frequency alignment and PSF focusing in the Doppler frequency dimension has been devised to provide estimation of the target radial and cross radial translation in the long range surveillance case with limited bistatic angle. The simulated cost function of the estimation procedure proved the feasibility of the retrieval of both the translational motion components differently from what is achievable in the case of a single sensor based estimation technique. Moreover properly tailored trials on real data acquired by the RSN installed at NATO CMRE in the gulf of La Spezia, Italy, proved the potentialities of this technique.

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Abstract

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Keywords

Inverse Synthetic Aperture Radar, motion estimation, multiple sensor systems

Issuing Organization

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