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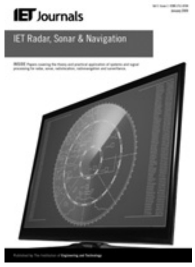

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Experimental verification of maritime target parameter evaluation in forward scatter maritime radar

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Abstract: Maritime security is related to national economic and political interests and is strategically important. One efficient way to accomplish maritime border protection is to use the netted forward scatter radar (FSR). FSR is a special type of bistatic radar that operates in a relatively narrow scattering area along the transmitter–receiver baseline, where the effect of the electromagnetic waves forward scattering on targets is dominant above other scattering mechanisms, and in this case, a forward scatter (FS) cross section may increase by orders of magnitude in comparison with the monostatic radar cross section (RCS). Considered in this study are the major problems of marine forward scattering radar detection and estimation of length of low-profile (small and slow) marine targets using a pre-processing approach. It is based on the assumption that the variation of the phase and amplitude in the Doppler signal signature is stronger inside the FS zone than in an outside region. Two variants of pre-processing algorithms are presented in the study, one for the envelope and the other for the phase. Both variants are based on the use the local variance filtering. The results obtained prove the sufficient improvement in a signal-to-clutter ratio (SCR). Estimation of the marine target length under the low SCR is designed using the assumption of known or previously estimated velocity. Presented results demonstrate high accuracy of length estimation. Considered steps of targets detection and target attributes evaluations are necessary for maritime targets classification. The designed algorithms are verified using a set of experimental records of signals from different marine targets obtained using marine FSR developed by the teams from University of Birmingham, UK and Sofia University, Bulgaria.

1 Introduction

Protection of homeland territory, offshore assets and exclusive economic zone as well as the related national economic and political interests are strategically important areas of maritime security. A number of systems are currently employed for remote monitoring of sea surface. Each system has its own capabilities and limitations. Radars which are fixed to the shore or to offshore installations have an operational limit of the local horizon. By using air and ship-borne radar, any remote sea area could be kept under surveillance. However, permanent coverage of vast areas is expensive and weather dependent. Radar imaging from satellites is an extremely powerful tool, but the revisit time of satellites in many practical situations is too long and not capable of low-profile targets detection. Over-horizon radar requires a large area for the antenna system installation and also operates against large and medium rather than small targets. It is worth mentioning here that the application of conventional radar does not solve the problem of automatic non-cooperative target identification, specifically when relatively small and a priori unknown targets need to be identified. Electro-optical systems, including airborne examples, provide imaging liable for confident identification but are essentially weather dependent. It seems unlikely, therefore, that any single system could be developed to solve all the problems of sea monitoring with a resolution sufficient to permit the detection and automatic identification of small objects. The general solution lies in a combination of systems, which can complement each other by providing additional information or data fusion. For this reason, the introduction of new tools, and specifically those which are capable of filling the gaps in existing security systems, are very much welcomed.

Recently an efficient way to accomplish this was proposed and investigated utilising a maritime netted forward scatter radar (FSR), originally published in [1, 2]. This research in the maritime domain is essentially the continuation of the netted FSR study for low-profile ground target detection and parameter estimation, originally discussed in [3, 4].

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FSR is a special type of bistatic radar that operates in a relatively narrow scattering area along the transmitter–receiver baseline, where the effect of the electromagnetic wave (EMW) forward scattering on a target is dominant above other scattering mechanisms. Owing to the in-phase summation of the EMW components in the forward scatter (FS) direction from the overall target silhouette, the target radar cross section (RCS), or more specifically for this case – forward scatter cross section (FS-CS), may increase by orders of magnitude in comparison with the monostatic RCS. FS-CS mainly depends on the electrical size of a target's physical cross section and does not depend on its three-dimensional shape or material. These properties make FSR effective against stealth targets. Typical layout of FSR for surface target detection is shown in Fig. 1*a*.

Two major problems of FSR will be the focus of this paper: detection of low-profile maritime targets and rough estimation of their parameters, that is, target speed and length. In [5], similar problems of ground surface target detection and parameter evaluation have been addressed. However, there are essential differences between ground and maritime system operations. In [5], ground system operating in very-high frequency and ultra-high frequency band has been presented with the nodes separated by distances of hundreds of metres. The majority of targets of interest were in Rayleigh and Mie scattering regions. Maritime radar has baselines in the order of kilometres, operate in C band and all targets are strictly in an optical region [6], so that the radar operation is predominantly in Fraunhofer diffraction region [7, 8]. Other essential difference lies in the clutter and signal spectrums. Detection of both ground and maritime low-profile targets are clutter rather than noise limited, but if the spectra of ground targets and ground clutter are essentially overlapping (Fig. 1*b*), in maritime case these spectra are well separated and corresponding whitening filter has to be used for an optimal signal processing (Fig. 1*c*).

A number of the papers published by the authors were dedicated to target speed and length estimation [9–18]. In [11], the rough approach for calculation of the velocity and length of marine targets in an FSR, based on FSR constant false alarm rate (CFAR) detector and estimator, was preliminarily considered in order to evaluate the signal dwell time. An occupied frequency band was calculated as the distance between the first minimum and the maximum frequency of the scattered signal power spectrum density. The error of estimation of the velocity and length of the target was about 15–20%. Further algorithm improvement has been proposed in [12, 14], where the target parameter estimation was carried out after target detection. The centre of the dwell time was taken where the signal envelope is maximum. This approach uses a multi-channel cross-correlator/estimator that chooses the maximum of the cross-correlation function, similar to the approach described in [18]. The instantaneous frequency of the reference signal was modelled by a two-sided chirp signal. In the real experiment, the accuracy of the target velocity and length estimation was 3–5% at a low sea state 1–2% by using this approach. In [14], another possible sub-optimal algorithm for signal processing has been analysed, which can be used in FSR systems for detection and velocity and target length estimation of maritime targets. The algorithm is based on a matched filtering approach that operates in the current sliding window where the filter parameters are previously estimated if the target signal is present in the current window. For estimation, the same multi-channel estimator with the maximisation of the cross-correlation in each 'velocity-angle of the border of the FSR zone' channel has been used. As an impulse response of the matched filter, a chirp signal with a unity envelope has been used. The matched filter improves the signal-to-clutter

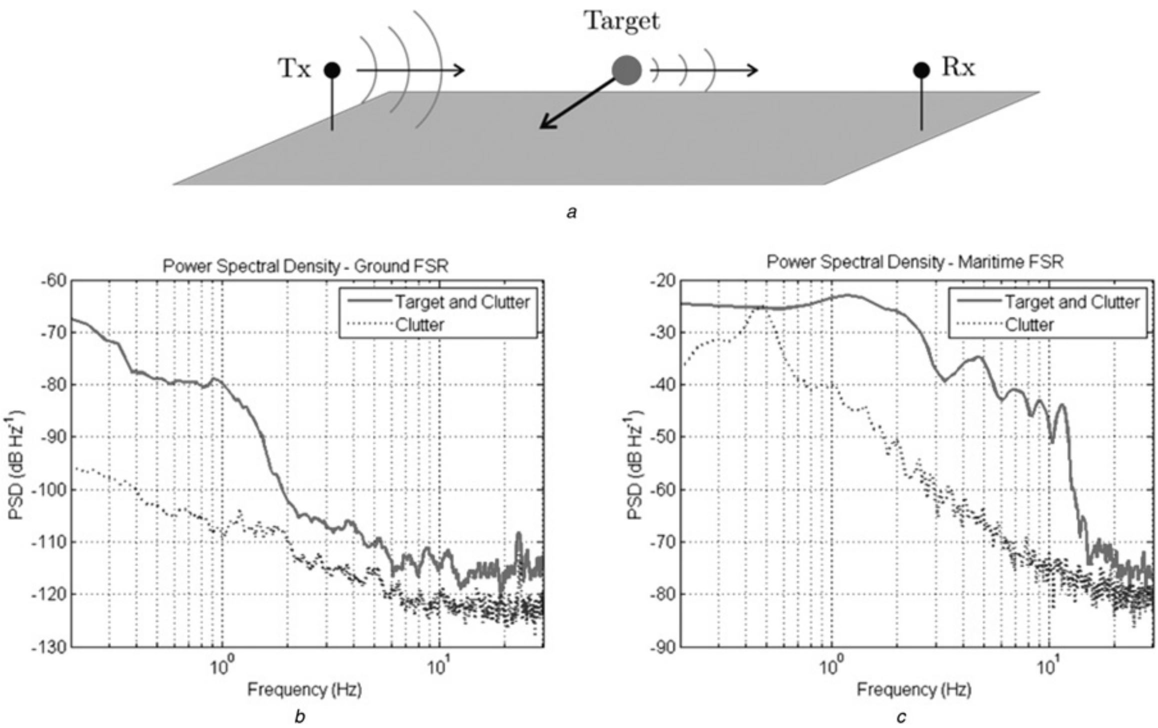

Fig. 1 *Typical layout of FSR for surface target detection*

a Typical FSR topology
b Target signal and clutter spectra in ground FSR
c Target signal and clutter spectra in maritime FSR

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ratio (SCR) by approximately 10 dB. In the real experiment, the accuracy of the target velocity and length estimation is 2–3% and 13%, respectively.

In this paper, further development of the maritime low-profile target detection/parameter estimation is presented. The proposed algorithms are applied to the experimental data obtained during the sea trials. Section 2 of the paper is dedicated to the description of the experimental setup and methodology of the experimentation. In Section 3, the process of data extraction is presented, while signal processing algorithms are described in Section 4. Section 5 of the paper discusses the main results of the target velocity and length estimation followed by the conclusion.

2 Data collection and experimental setup

The signal and data processing are performed on experimental records kindly provided by the team from University of Birmingham, UK. The experimental topology of the FSR system used for data collection at the experimental sites in the UK and Bulgaria is shown in Figs. 2*a* and *b*, respectively. The transmitter (Tx) and receiver (Rx) are both stationary and are situated on opposite sides of the area of sea surface over which the target is to traverse, pointing towards each other by means of directional horn antennas, thus creating a baseline across the surface through which the target will cross. The actual target used for experimentation was a small (~3 m long) fully inflatable dinghy, and was chosen as a typically difficult target because of its slow speed and low RCS (in traditional bi/monostatic terms). For calibration purposes, the dinghy has occasionally towed a 0.65 m diameter metallic sphere 15 m behind.

The radar itself is designed to operate at a frequency of 7.5 GHz, consisting of a non-modulated continuous wave (CW) transmitter and a receiver with the general structure shown in Fig. 2*c*. As indicated, the signal received at the antenna, which comprises of direct path (leakage) signal and any reflected signals from target and/or sea surface, passes through a low noise amplifier and band pass filtering, and then passes to the diode/non-linear detector and a programmable gain stage. At the output, the signal is divided into two separate output channels. The first output is the received signal strength indicator (RSSI) channel. This is essentially the raw output of the detector, containing contributions from both direct path signal, which is related to the direct current (DC) level of this output as well as the effects of any Doppler modulated returns from targets or the sea surface, shown as a variation of the signal on top of the DC. The second channel is referred to as the Doppler channel. Here, the signal from the detector undergoes a high pass filter to remove the direct path DC and a programmable low pass filter (to remove sum components from the detector and limit the noise and Doppler spectrum) and another amplifier. Both channels then pass to an analogue-to-digital converter (ADC) to be stored in a laptop. This ADC also has digital outputs used to control the programmable filters and gain sections of the receiver [19].

3 Signal processing in maritime forward scatter maritime radar

The tasks for radar systems usually include detection, tracking, parameter estimation and classification/recognition of targets. As a long term study, we are considering to fulfil these functions for FSR operating against low-profile maritime targets. The flow chart of the signal processing in a maritime FSR system is shown in Fig. 3. Different aspects and subsystems of the presented flow chart have been investigated and reported by the authors [9–18].

In [9, 10], moving target indication (MTI) was used to reject sea clutter in maritime FSR. The other approach was proposed in [16], where a local variance filter (LVF) was used for pre-processing of both envelope and phase. Unfortunately, for small targets (low SCR) and slowly moving targets, MTI and the LVF in the form from [16] are not always appropriate. In order to increase the SCR before signal detection, a new two-step modification of the LVF for pre-processing of the signal envelope is proposed in this

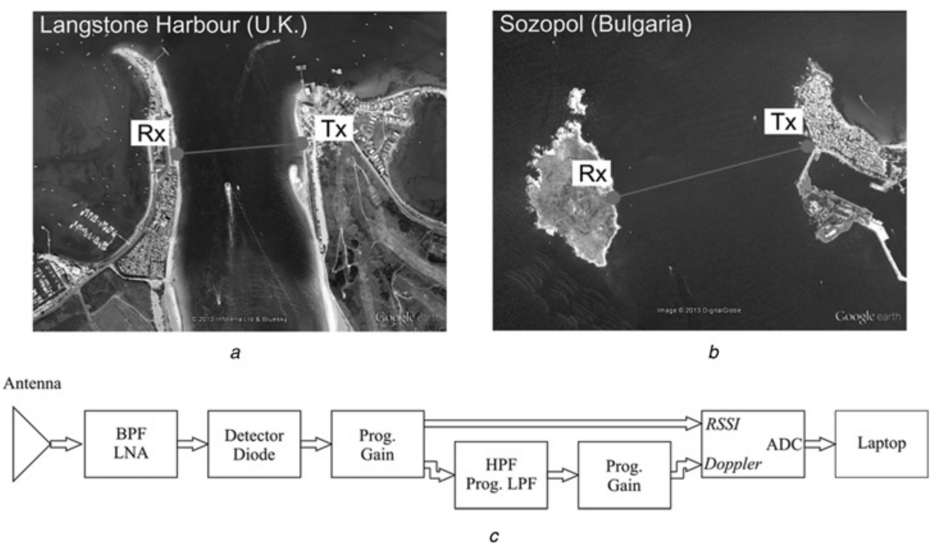

Fig. 2 *Experimental topology of the FSR system used for data collection at the experimental sites in the UK and Bulgaria*

a and *b* Shows the typical experimental topology, utilising directional antennas positioned on either side of the area of sea surface under interrogation, transmitter positioned at Tx facing the receiver Rx
c Shows the basic block diagram of the FSR receiver architecture

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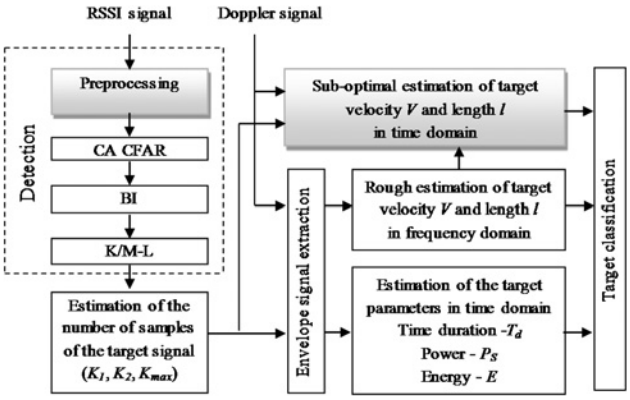

Fig. 3 *Flow chart of the signal processing in marine FSR*

paper. In Fig. 3, signal detection is carried out after pre-processing of the signal envelope.

The CA CFAR detector detects samples of the target signal. The final detection of the target signal is carried out through the use of the binary non-parametric rule 'K/M-L' after binary integration of all detected samples. At the output of the 'K/M-L' detector estimations are given for the positions of the signal beginning – K1, the signal end – K2 and the maximum of the envelope – Kmax. In [9, 10], these parameters have been calculated with/without MTI, and in this way have been evaluated the following signal parameters – duration, average power and average energy. These attributes of the target signal are used for classification of maritime targets with the data mining approach using the WEKA software [15].

The rough estimation in the frequency domain of two target parameters, velocity and length, have been evaluated in [11]. The error of rough estimation was about 20%. The sub-optimal estimates of the target velocity and length are obtained with two multi-channel estimators (using the main lobe of the target pattern in [12] and using the entire target pattern in [14]), which sufficiently improve the accuracy of estimation. The accuracy of the sub-optimal estimates equals the size of the selected intervals of the measured parameters divided by the number of channels. In this paper, it is proposed to use the rough estimates of target parameters from [11], in order to minimise the size of the intervals of the measured parameters (velocity and length) in the sub-optimal estimators, and in this way to achieve the desired accuracy of estimation, under the desired computational load.

Within the scope of this paper, the main attention will be given to estimation of the target length (l) (highlighted in Fig. 3), whereas the automatic classification itself is the subject of further publications. In the next section, the main steps of the targets attributes evaluations for maritime targets classification are presented.

4 Clutter rejection algorithms

As soon as the spectrum of the sea clutter (see Fig. 1) lies in the lower part of the target spectrum, let us consider a method of clutter rejection that is the further development of the LVF proposed earlier by the authors [14].

The problems of the use of FSR to detect slow-moving sea targets in conditions of reflections from the sea surface are still poorly understood. The main limiting factor in the design of such systems is that the range of the Doppler frequency of signals received from sea targets is almost completely overlapped with the spectrum of sea clutter. Thus the application of the classical methods for MTI is not appropriate in radar systems of this class. Traditionally, the target detection is performed by algorithms using the envelope (after the amplitude detector) or power (after the square-law detector) of the input signal [3, 9, 16, 17, 18]. In this paper however, we present two possible detection algorithms based on the processing of both the phase and the amplitude of signals received from sea targets in a FSR system. The idea of the paper is that the Doppler frequency shift of the target signal when the target enters the FS zone and the Doppler frequency shift of the target signal when the target leaves the FS zone have high values and opposite signs. When the target crosses the baseline, that is, when the target is in the dead zone, the Doppler frequency shift is almost zero. Hence, the phase variation of the signal received from the target, which successively crosses the FS zone, the dead zone and again the FS zone, will be much more than the phase and the amplitude variation than those of sea clutter in these three zones.

4.1 Local variance filtering algorithm

From Figs. 1*a* and *b*, it can be seen that the spectrum of the 'target + noise' is much broader than the spectrum of reflection of the sea, and they overlap. It follows that for fast moving targets the MTI can be used for suppression of signals from the sea, but in the case of slowly moving targets this method of suppression is not effective, which we have shown in [9].

We investigated the properties of the amplitude and phase of a series of experimental recordings of signals from different targets obtained in the clean channel without any further processing (RSSI), and noted that the variation of the phase and amplitude of the Doppler signal reflected from the target in the FS area is much greater than the variation of the phase and amplitude of the signals reflected from the sea, and therefore the variance of the amplitude and phase of the Doppler signal from the sea and the 'target + sea' will be quite different. However, this fact is not evident upon the analysis of the spectra (in Figs. 1*a* and *b*) and also in the processing of the experimental data.

Based on this fact, we propose to replace each sample of strongly fluctuating phases (amplitudes) of signals from the sea and the target by their local variance. Hence, the magnitude of the current variance of the phase (amplitude) will be smaller where only the signal from the sea is present and will be much greater where the target is present. This procedure can be viewed as an algorithm for extraction of the useful signal against the sea, or suppression algorithm (rejection) of interference from the sea. This procedure suppresses the reflections from the sea and improves the signal-to-noise-ratio like suppression filters in radar. Therefore this heuristic algorithm, implemented as LVF, effectively detects both large and fast moving targets and also small slow-moving targets against strong reflections from the sea.

Our algorithm includes two stages: determination of the length of the sliding window to extract the signal from clutter and the formation of the filter output – sample by sample (one sample inputs–one sample outputs). In case of low SNR, we have a three stage algorithm: phase detector, the additional filter (Filter-1) to improve SNR before determining the parameter N, determination of the length of the sliding window to extract the signal from clutter and the formation of the LVF output.

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The block-diagrams of the signal pre-processing algorithm for the cases of high SCR and low SCR at the detector input are shown in Figs. 4*a* and *b*. Typical high and low SCR signals, $S(t)$, are shown in Figs. 4*c* and *d* correspondingly. The LVF algorithm for high (about 15–20 dB) SCR includes two stages of signal processing: (i) determination of the appropriate length of the sliding window to extract the signal from clutter; and (ii) the formation of the filter output sample by sample (one sample inputs–one sample outputs). In this figure, the $S(t)$ is the signal at the output of the RSSI channel (see Fig. 2*c*) converted into a digital format. The pre-processing can be applied to the envelope $A_S(t)$ or to the absolute (angle + unwrap) phase $\Phi_S(t)$ of the Doppler signal $S(t)$.

According to Fig. 4*a*, each sample Y_i at the filter output is formed as an estimate of the signal phase variance calculated within the sliding window of the input signal phase ($\Phi_{S,i-N}$, $\Phi_{S,i-N+1}$,.. $\Phi_{S,i,\ldots}$ $\Phi_{S,i+N-1}$, $\Phi_{S,i+N}$), or input amplitude ($A_{S,i-N}$, $A_{S,i-N+1}$,.. $A_{S,i,\ldots}$ $A_{S,i+N-1}$, $A_{S,i+N}$). The computational algorithm calculates the phase (envelope) variance as the difference between the second initial moment and the squared mathematical expectation of the phase (envelope). In our case it takes the form

$$Y_i(t) = a_i - \frac{1}{4N^2} b_i^2, \quad \text{and} \quad N < i < K - N \qquad (1)$$

where K is the total number of samples in the signal record. In the input signal phase case, the parameter a_i is the local second initial moment and $b_i/2N$ is the local mathematical expectation of the phase (envelope). They are calculated as

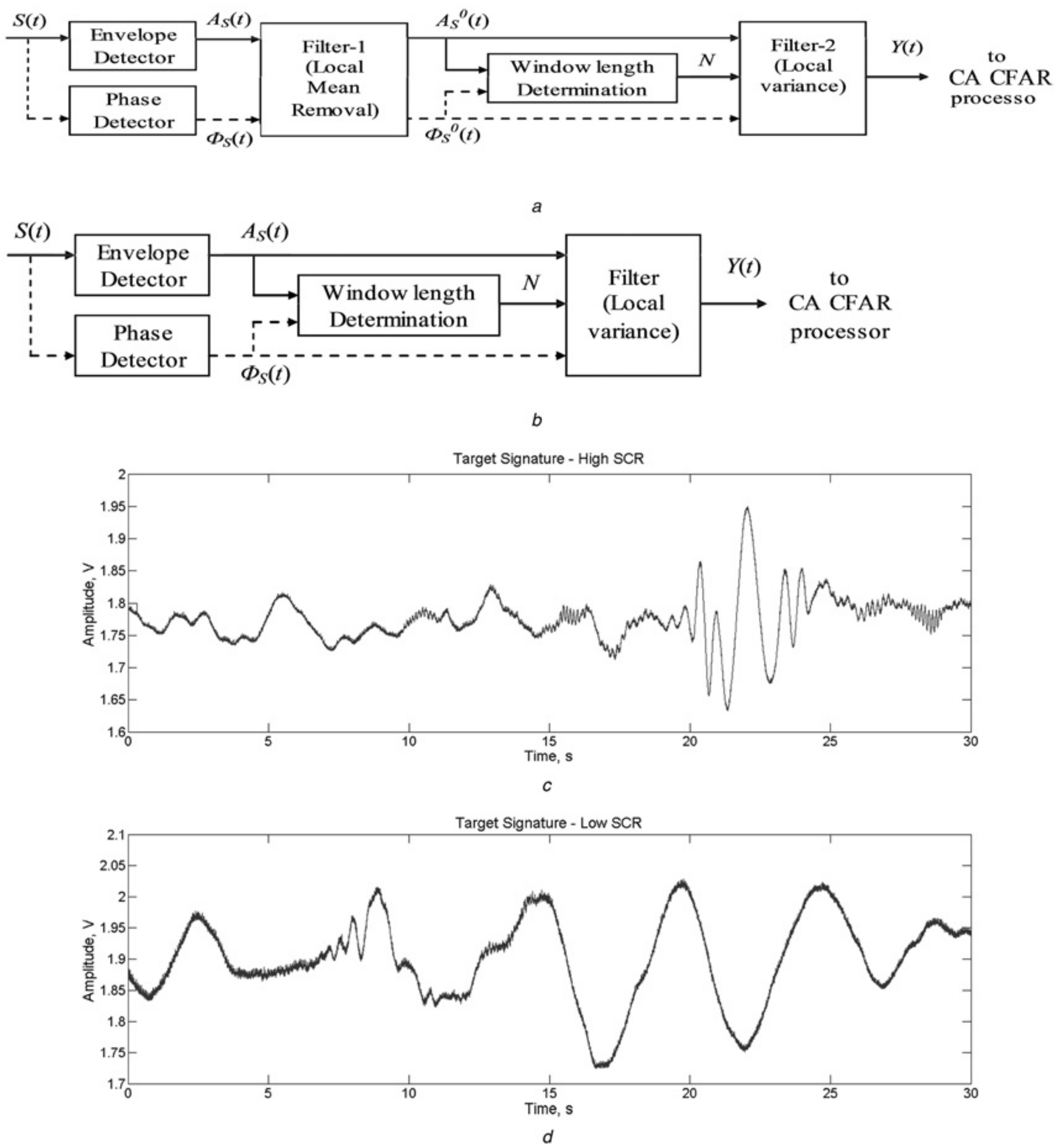

Fig. 4 *Signal pre-processing for SCR improvement*

a High SCR
b Low SCR at the input, with examples of target Doppler signatures with
c High SCR
d Low SCR

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follows

$$a_i = \begin{cases} \sum_{u=-N}^{N} \Phi_{S,i+k}^2, & i = N+1 \\ a_{i-1} + \Phi_{S,i+N}^2 - \Phi_{S,i-N-1}^2, & i < K-N \end{cases}$$
$$b_i = \begin{cases} \sum_{u=-N}^{N} \Phi_{S,i+k}, & i = N+1 \\ b_{i-1} + \Phi_{S,i+N} - \Phi_{S,i-N-1}, & i < K-N \end{cases} \quad (2)$$

In the input signal amplitude case, the parameters (a, b) are also calculated by (2) where the input signal phase Φ_S is replaced by the input signal amplitude A_S. A key problem with the filtering algorithm (1)–(2) is the proper selection of the window length, that is, the parameter N. When the target enters the FS zone and approaches the receiver the phase of the target Doppler signal has a maximal value. When the target leaves the FS zone and goes away from the receiver the phase of the target Doppler signal has a minimum value. The window length of $2N$ should correspond to the time of target motion in the FS zone to the receiver.

For that reason we propose to determine the parameter N for the case of the high SCR as

$$N = [\arg\{\max(\Phi_S)\} - \arg\{\min(\Phi_S)\}]/2 \quad (3)$$

As shown in Fig. 4*b*, for the case of small targets or slow-moving targets, where we can expect low SCR, the first filter (Filter-1) decorrelates the input signal and after that smoothes it. This filter is intended to improve SCR before determining the parameter N by (3). At the first step of Filter-1, the sample mean is subtracted from each sample of $\Phi_{S,i}$ or $A_{S,i}$. The local sample mean is estimated in the sliding window with size $2Ns$ located symmetrically about the current input sample $\Phi_{S,i}$ or $A_{S,i}$, described by the expressions

$$\Phi_{S,i}^0 = \Phi_{S,i} - b_i/N_S \text{ or } A_{S,i}^0 = A_{S,i} - b_i/N_S \quad (4)$$

where b_i is calculated by (2) and N is replaced by N_S. At the second step of Filter-1, the filtered signal Φ_S^0 or A_S^0 is smoothed by the estimate of the sample mean calculated in a 10-element window located symmetrically about $\Phi_{S,i}^0$ or $A_{S,i}^0$. In the experimental system, the ADC sampling frequency has been selected as $f_S = 200$ Hz to cover all possible range of targets. As it is seen from Fig. 1*c*, the signal from a low speed inflatable boat occupies a Doppler frequency band about 5 Hz (by 10 dB roll-off), whereas a jet-ski may have ten times higher speed and hence a wider Doppler band. The experimental data processing shows that the parameter N_S in (4) can be chosen according to the sampling frequency, for example, for $f_s = 200$–400 Hz, the parameter N_s can be 200 samples.

4.2 Experimental results

A version of the algorithm described above, corresponding to the envelope analysis, has been verified by fusing a set of experimentally recorded data for each type of target: first case – MISL boat (inflatable dinghy of approximately 3 m long), medium speed, second case – Big boat (non-MISL target), third case – MISL boat, low speed and fourth case – MISL boat and towed metallic ball. For simplicity, all records relate to the particular case of target crossing the baseline at an angle of approximately 90°.

4.2.1 Experimental results – high signal-to-clutter ratio (SCR): The records of signals for cases 1 and 2 have been chosen to test the algorithm. The input signal envelope (top) with the squared envelope formed at the filter output (bottom) is shown in Figs. 5*a* and *b* for different targets. The signal formed at the filter output can be successfully detected by comparison with a threshold.

4.2.2 Experimental results – low SCR: The records of signals for cases 3 and 4 have been chosen to test the detection algorithm for low SCR case. The input signal envelopes (top), the filtered envelope at the output of Filter-1 (medium) and of Filter-2 (bottom) are shown in Figs. 5*c* and *d*. The graphical results show that at the output of Filter-1 the small target signal is improved while the clutter signal is suppressed. The output signal of Filter-2, shown in Figs. 5*c* and *d* for the envelope channel, is improved further and the clutter is absent. It can be seen that, in spite of the low input SCR, the signal formed at the output of Filter-2 can be successfully detected by CA CFAR processor. As one can see from these figures, even 65 cm diameter sphere can be clearly detected in the background of strong sea clutter. Therefore, the signal visibility is dramatically increased by means of the proposed signal processing algorithms.

5 Target length estimation

5.1 Algorithm description

To estimate a target length we propose to analyse the target visibility (dwell) time in the receiver for a given speed and baseline crossing point. It is important to note here that in the proposed methods the target length and speed estimation are two intertwined problems. Two technically similar methods have been preliminarily investigated for estimation of a target velocity. The first of them analyses the full signal dwell time [14, 18], the second selects the main lobe of the FS target shadow pattern [12]. Here we will further develop the latter method for estimation of a target length for a given speed (known or previously estimated). A number of papers [11, 12, 14, 18] describe the speed estimation procedure in FSR by means of analysis of the target signature. In [18] it is specifically shown that not only the velocity vector but also the baseline crossing point could be estimated by means of the signature analysis. For air targets, historically the first proposed method of speed and crossing point estimation was using a 'zig-zag' FSR network structure [5] and much later by application of the tracking algorithm [17]. In this paper we are considering the case of approximately a mid-baseline normal crossing point, however all which is proposed is applicable for any target trajectory. Hence, it is assumed here that the target of an unknown length (l) moves with a given speed V and crosses the baseline at the angle $\psi \simeq 90^{\text{o}}$. The point of crossing divides the baseline into two parts d_T and d_R (Fig. 6*a*). In the FS zone the aspect angles α_T and α_R are very small ($\alpha_T \simeq \alpha_R \simeq \alpha$). According to [18], the Doppler frequency of the target,

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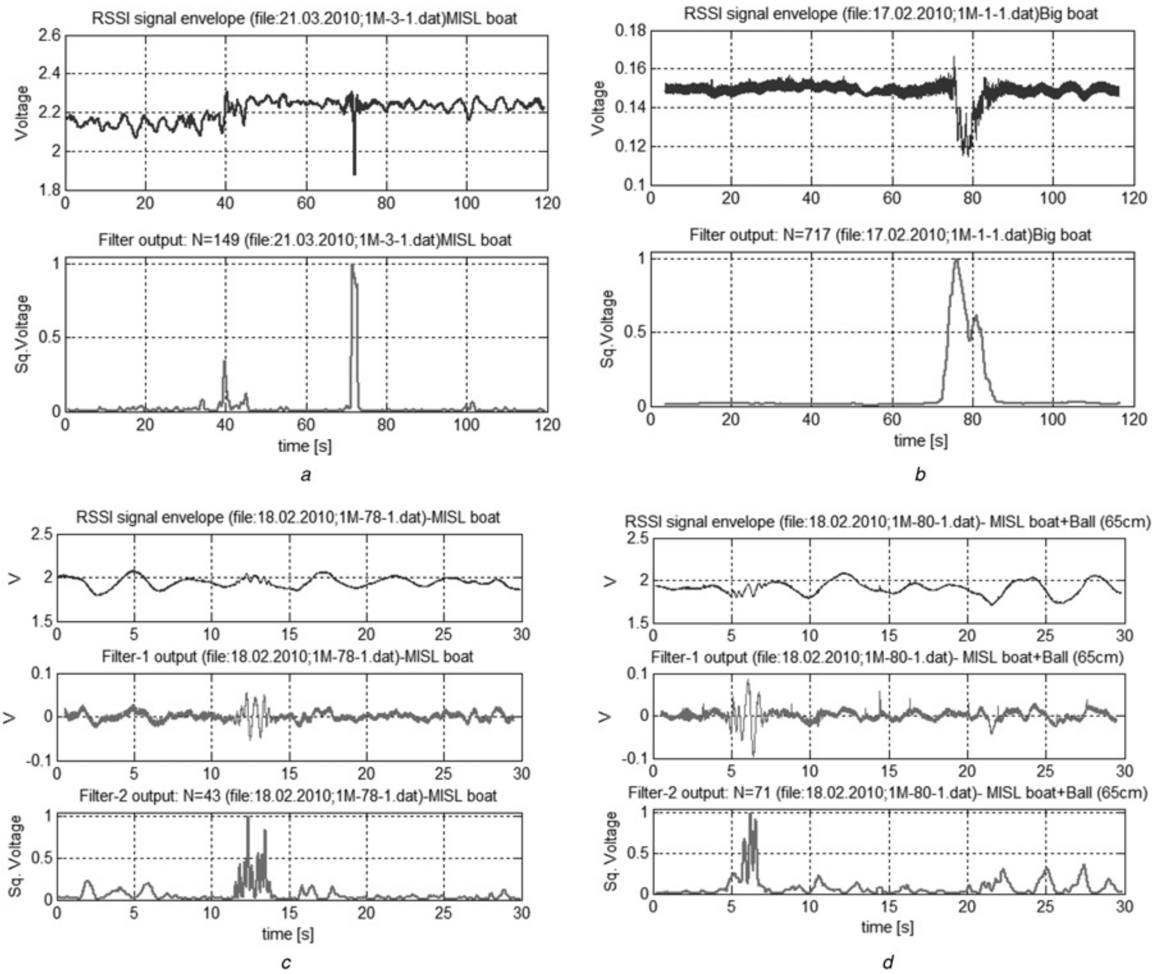

Fig. 5 *Input signal envelope with the squared envelope formed at the filter output*

a Case 1
b Case 2: Signal at the input (top) and output (bottom) of the envelope LVF filter
c Case 3
d Case 4: Signal at the input (top), output (middle) of the Filter-1, and the output (bottom) of envelope Filter-2

crossing the FS zone, varies in time according to a linear law

$$f_D(t) = \frac{2V}{\lambda}\sin(\alpha(t))\sin\psi \simeq \frac{2V^2}{\lambda d_R}\cdot t\cdot \sin\psi,\quad t\in[-T, T] \tag{5}$$

where T is a half of the maximum target visibility time in the main lobe of the target shadow pattern. Following the topology of Fig. 6*b*, T can be written as [14]

$$T = d_R\lambda/(V\cdot l\cdot \sin\psi) \tag{6}$$

where l is the target length and λ is the wavelength of transmitted CW.

In order to estimate the target length, the entire range of expected lengths is divided into M equal parts, forming a set $\{l_1, l_2, \ldots, l_n, \ldots, l_M\}$ of possible targets lengths. The set of parameters $\{T\}_M$ is formed on the base of this set $\{l\}_M$ as

$$T_m = d_R\lambda/(V\cdot l_m\cdot\sin\psi),\quad m = 1\ldots M \tag{7}$$

As shown in Fig. 6*c*, the block-scheme of the signal processing for estimation of a target length has N channels, each of them is performed on the target signal extracted from the time interval $[-T_m, T_m]$. Let the parameter $\boldsymbol{T_{l,v}}$ denote the optimal estimate of the time interval $[-\boldsymbol{T_m}, \boldsymbol{T_m}]$ obtained on the set of target lengths $\{\boldsymbol{l}\}_{\boldsymbol{M}}$ for a given velocity V. The criterion of optimisation for $\boldsymbol{T_{l,v}}$ is maximisation of the cross-correlation coefficient $\boldsymbol{r}$ between the frequency ($\boldsymbol{f_X}$) of the input Doppler signal and the reference frequency ($\boldsymbol{f_{ref}}$) at the time interval $[-T_m, T_m]$. The reference frequency ($\boldsymbol{f_{ref}}$) is modelled as a frequency of the two-sided chirp in accordance with (5) for $T = T_m$. Once the optimal estimate $\boldsymbol{T_{l,v}}$ has been found, the estimate of a target length l_V is determined as

$$l_V = d_R\lambda/(T_{lV}\cdot V) \tag{8}$$

5.2 Experimental results

The results presented in this section were obtained by processing the experimental Doppler signature of a small boat. The boat of length l ($l = 2.9$ m) moved at a constant speed of 27 km/h (7.5 m/s) and crossed the baseline at an angle of almost 90°. The distance d_R was nearly 165 m. The Doppler signal from the boat was recorded during 120 s at a sampling rate of 200 Hz. The recorded signal (amplitude, envelope and frequency spectrum) is shown in Fig. 7*a*. In order to estimate the length of the boat by using the algorithm described above, the entire range of possible

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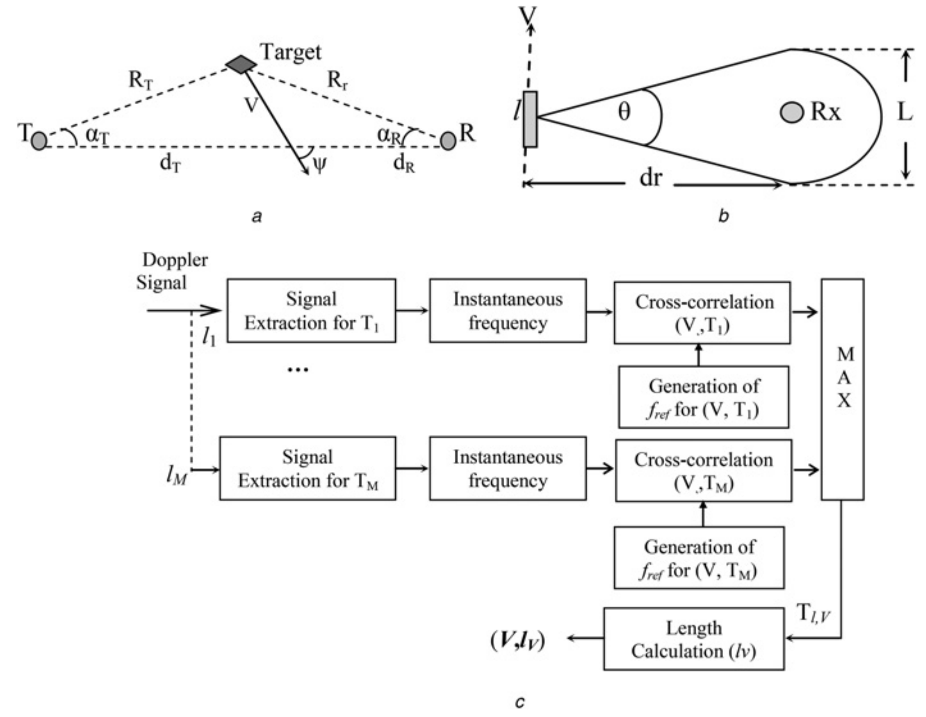

Fig. 6 *FSR topology*

a Target baseline crossing
b FS target shadow pattern ($\psi \simeq 90^o$)
c Target length estimation flow chart

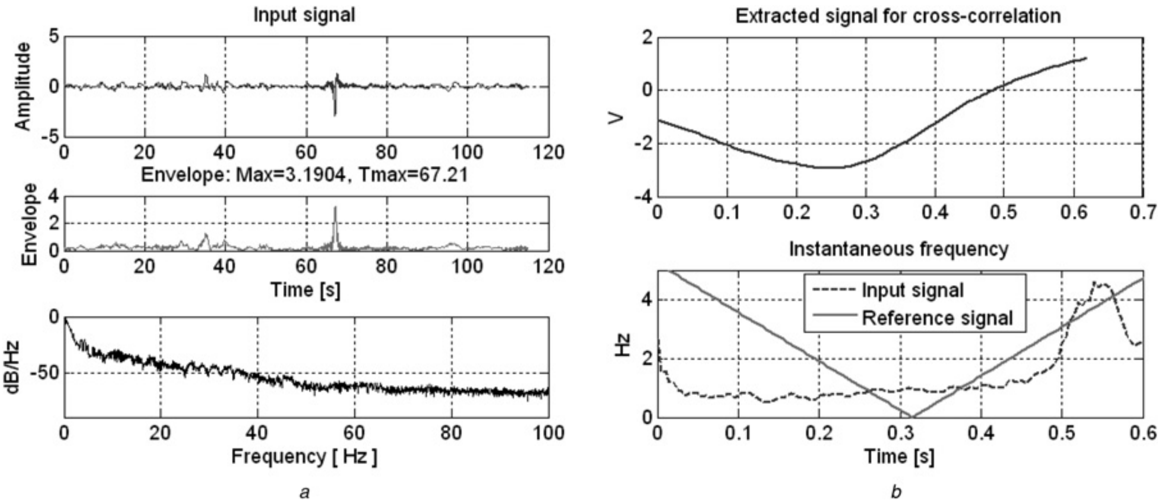

Fig. 7 *Recorded signal (amplitude, envelope and frequency spectrum)*

a Input signal: amplitude, envelope and spectrum
b Target signal (top), and both the frequency of the input signal and the reference frequency (bottom), extracted from the time interval $[-T_{IV}, T_{IV}]$ for $T_{IV} = 0.307$ s

target lengths [1 m, 11 m] was divided into equal parts by a step of 0.25 m. The optimal estimate of the parameter T, that is, $T_{IV} = 0.307$ s, was found using the optimisation criterion described above. The target signal (top) and both the frequency of the input signal (f_X) and the reference frequency (f_{ref}) (bottom) extracted from the optimal time interval $[-T_{IV}, T_{IV}]$ are shown in Fig. 7*b*.

The estimate of the target length was obtained as $l_V = 2.87$ m. It was calculated by (8) for $T_{IV} = 0.307$ s and $V = 7.5$ m/s. As can be seen, the obtained estimate of the target length ($l_V = 2.87$ m) is very close to the real target length ($l = 2.9$ m). As shown in the example, the proposed method is rather effective and could be further used for targets dimension estimation.

6 Conclusion

In this paper we considered two major problems of maritime FSR. The first of them is concerned with detection of low-profile (small and slow) marine targets. This is the case of low SCR, and the idea of the presented pre-processing algorithm for target detection improvement is based on the assumption that the variation of the phase and amplitude in

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the Doppler signal signature is stronger inside the FS zone than outside of that. Two versions of pre-processing algorithms, one for the envelope and the other for the phase, are presented in the paper. Both variants are based on the LVF. In the case of low SCR, the input signal is filtered twice. The first filter is intended for improvement of SCR before the LVF. The obtained results prove the sufficient improvement in SCR. The second problem is concerned with estimation of the marine target length under low SCR. The proposed algorithm is designed under the assumption of known or previously estimated velocity. The obtained results demonstrate the high accuracy of estimation. The considered steps of target detection and target parameters evaluation are necessary for marine targets classification. The designed algorithms are verified using a set of experimental records of signals from different marine targets obtained using marine FSR by University of Birmingham (UK) and Sofia University (Bulgaria) teams.

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