DETECTION, PARAMETRIC IMAGING AND CLASSIFICATION OF VERY SMALL MARINE TARGETS EMERGED IN HEAVY SEA CLUTTER UTILIZING GPS-BASED FORWARD SCATTERING RADAR

C. Kabakchiev[1], V. Behar[2], I. Garvanov[3], D. Kabakchieva[4], H. Rohling[5]

[1]SU, [2]IICT-BAS, [3]ULSIT, [4]UWNE, Sofia, Bulgaria, [5]TU-HH, Hamburg, Germany

ABSTRACT

In this paper, we address a technique and related algorithms for precise detection, parametric imaging and classification of small marine targets in a harsh sensing environment attributed for heavy sea clutter via non-cooperative processing of the GPS-based Forward Scatter Radar (FSR) data. In contrary to GPS L5 detection approach, the proposed technique utilizes civil GPS L1 signal formats in FSR exploiting GPS as a non-cooperative transmitter. In our previous studies it is shown that the use of the new power GPS signal L5, and the Forward Scattering effect providing a high SNR, at the detector input allows reliably to detect small air targets in conditions of the intense interference. In this paper we propose another approach, to enhance SNR, at the input of the detector in Forward Scattering Radar (FSR). The use of the effective filter (Local Variance Filter) for suppression of intensive sea clutter allows FSR reliably to detect small marine targets emerged in harsh sea clutter, but with GPS L1 signal, whose SNR is very small. At the classification level, the data mining approach is adopted, in which the target feature parameters are extracted from the preliminary filtered signals by utilizing the modified structure of a processor for target detection and parameter estimation in the time domain. Both, the decision tree-based and the neural network classifiers are featured and adapted for real-time implementation. The efficiency of the proposed technique is verified via analytical performance evaluations and experimental demonstrations.

Index Terms— *FSR, GPS, detection, classification, harsh sensing environment*

1. INTRODUCTION

Forward Scattering Radar (FSR) is bistatic radar that operates in the narrow area of the forward scattering effect where the bistatic angle is close to 180^0. In FSR, when the target moves near the transmitter-receiver baseline, the Babinet's principle is exploited to form the forward scatter signature of a target [1]. According to this principle, the drastic enhancement in scattering is created due to the forward scattering effect. This type of radar provides a countermeasure to 'stealth' technology because due to the forward scattering effect, the Radar Cross Section (RCS) of targets extremely increases (by 2-3 orders) and mainly depends on the target's physical cross section and is independent of the target's surface shape and the absorbing coating on the surface. However, FSR has some fundamental limitations, which are the absence of range resolution and operation within very narrow angles (±100) [2]. The civil L1 signal is transmitted by satellites at 1572.42 MHz and contains the coarse acquisition (C/A) code, which is unique for each satellite. The idea to apply a GPS L1 receiver to FSR for air target detection is firstly discussed in [3]. Some experimental results of a GPS L1 receiver concerning detection of air targets are shown and discussed in [4]. Modernization of GPS provides another good opportunity to use the improved properties of a new designed civil GPS signal L5 in FSR, which exploits GPS as a non-cooperative transmitter. A possible algorithm for air target detection in a GPS L5-based FSR system is described in [5], and the detection probability characteristics are calculated in [6] for the case when low-flying and poorly maneuverable (for example, helicopters) air targets are detected on the background of a white Gaussian noise, or in the presence of: Urban Interference Environment or a Stand-off-Jammer (SOJ). The other variant of GPS-L5-based FSR systems to reliably detect ground or marine targets when GPS satellites are located at small elevation angles, presented in [7]. As shown in our previous studies, the use of the new power GPS signal L5, and the Forward Scattering effect providing a high SNR, at the detector input allows reliably to detect small air targets in conditions of the harsh sensing environment. In this paper we propose another approach, to enhance SNR, at the input of the detector in Forward Scattering Radar (FSR). The use of the effective filter (Local Variance Filter) for suppression of intensive sea clutter allows FSR reliably to detect small marine targets emerged in harsh sea clutter, but with GPS L1 signal, whose SNR is very small. Our aim is to show that even in this harsh sea clutter environment it is possible to detect, estimate and classify small marine targets using GPS-L1 FSR. A set of experimental records of FSR signals from a small MISL boat provided by the team of Birmingham and Sofia University is used in order to verify the proposed signal processing algorithms for detection, estimation and

978-1-4799-2893-4/14/$31.00

classification. This is possible because the parameters of real experiments are equal to parameters of our investigation, like - distance of FSR and target, signal-to-clutter-plus-noise ratio, and the same target. The GPS FSR system includes different variants of the antenna (directional and omnidirectional), a conventional GPS receiver and a FSR Signal Processing block for detection, estimation and classification. In the FSR signal processing block we propose to use one original algorithm for detection marine targets, in which before thresholding the input signal amplitude is filtered and the output signal samples are formed as values of a local variance of the signal amplitude calculated in the sliding window. For marine target classification we propose to use the Data Mining approach. The target parameters needed for classification procedure are extracted from the preliminary filtered signals by using an original structure of a processor for target detection and parameter estimation in the time domain that includes rough estimation (pre-classification) of the time duration and the energy/power reflected from the target [8-10].

2. SIGNAL PROCESSING

The general block-scheme of the signal processing for target detection, parameter estimation and classification is shown in Fig 1. According to the signal processing block-scheme, the signal is non-coherently integrated at the output of the Code & Carrier Tracking block, and the integrated output is used further for detection, parameter estimation and classification of targets.

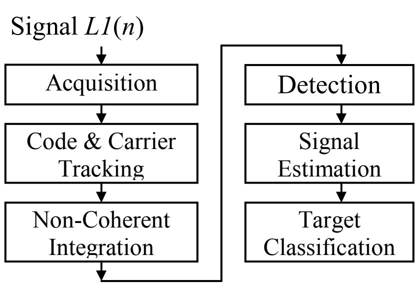

Fig.1 FSR signal processing

The signal-to-noise ratio at the RF front-end output of the GPS receiver can be written as [1]:

$$SNR = P_{rec} / N_r = P_t G_r \sigma / (4\pi R_{tg}^2 N_r) \qquad (1)$$

Where P_{rec} is the power of the signal received from the target at the GPS receiver input, P_t is the GPS L1 signal power near the Earth's surface, G_r is the receiver antenna gain, R_{tg} is the distance to the target, and Nr is the receiver noise power. According to [11], the forward scatter RCS of a target (σ) depends only on the physical cross section of the target (A_{tg}) and the wavelength of the transmitted signal (λ). It can be calculated approximately as:

$$\sigma = 4\pi A_{tg}^2 / \lambda^2 = 4\pi (hl)^2 / \lambda^2 \qquad (2)$$

In (2), the parameters h and l are geometrical dimensions of a target. After replacing σ by (2), the expression (1) takes the form:

$$SNR = P_t G_r (hl)^2 / (\lambda^2 R_{tg}^2 N_r) \qquad (3)$$

After non-coherent integration at the output of the Code & Carrier Tracking block the SNR can be calculated as:

$$SNR = P_t G_r (hl)^2 G_{SP} M^{0.8} / (\lambda^2 R_{tg}^2 N_r) \qquad (4)$$

where G_{SP} is the processing gain of the cross-correlator, and M is the number of integrated bits of a message. The number of integrated samples M and the corresponding integration time T_{int} , in case when the target moves at velocity V_{tg} and crosses the FS zone perpendicular to the baseline, can be calculated as:

$$T_{int} = 2R_{tg}\lambda / (V_{tg} l) \quad \text{and} \quad M = T_{int} / T_{code} \qquad (5)$$

In (5), λ is the wavelength, and T_{code} is the C/A code duration equaled 1ms. The SNR values calculated according to (4) are plotted in Fig.2. For calculation are used the following parameters of the GPS L1 signal: carrier frequency – f_o=1572.42 MHz (λ=0.19m); frequency bandwidth – ΔF=2.046MHz, the GPS L1 signal power near the Earth's surface – P_t=-160dBW.

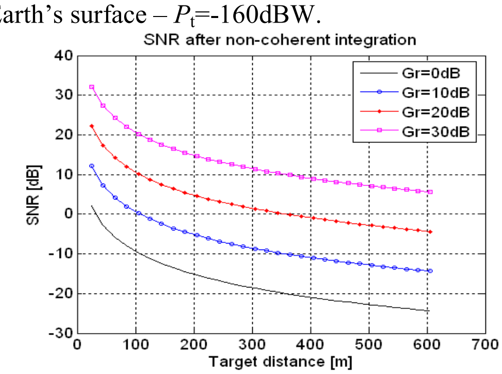

Fig.2 SNR after non-coherent integration

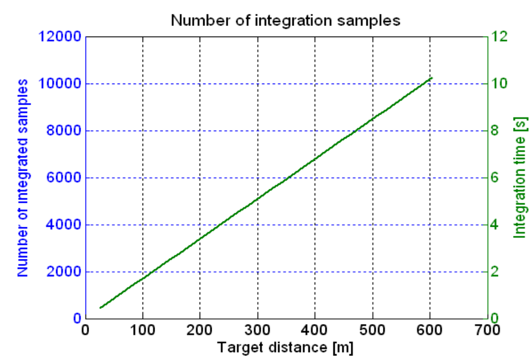

Fig.3 Number of integration samples (left) and the corresponding integration time (right)

The SNR is calculated for four values of the antenna gain: G_r= [0; 10; 20; 30] dB. The number of integrated samples and the corresponding integration time calculated for the case when the target crosses the forward scattering zone perpendicular to the baseline at velocity 7.5 m/s (27km/hour) are plotted in Fig. 3 depending on the distance to the target. It can be seen that the integration time can be very large and can reach to several seconds for relatively small distance to the target.

3. DETECTION

In case of fast moving targets (large SNR), the detection algorithm is shown in Fig.4. The detection algorithm includes two steps of the signal processing: determination of the appropriate length of the sliding window and formation of the filter output sample by sample.

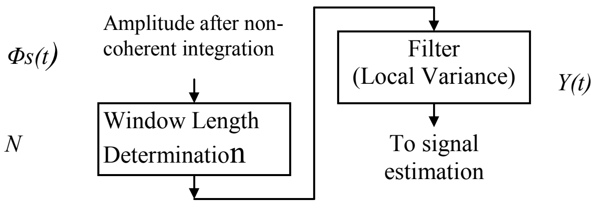

Fig.4 Detection algorithm

The signal denoted as $\Phi_S(t)$ is formed at the output of the Code & Carrier Tracking block and after non-coherent integration. The idea of the detection algorithm is based on the assumption that the amplitude variation of the target signal is larger than the amplitude variation of sea clutter. According to Fig.4 each sample Y_i at the filter output is formed as an estimate of the variance calculated in the sliding window of the input amplitude ($\Phi_{S,i-N}$, $\Phi_{S,i-N+1}$,.. $\Phi_{S,i,...}$ $\Phi_{S,i-N-1}$, $\Phi_{S,i-N}$). The computational algorithm takes the form:

$$Y_i(t) = a_i - b_i^2/(4N^2)\,;\quad N < i < K - N \qquad (6)$$

where K is the total number of samples in the signal record and the parameters a and b are calculated as follows:

$$a_i = \begin{cases} \sum_{u=-N}^{N} \Phi^2{}_{S,i+k}\,, & i = N+1 \\ a_{i-1} + \Phi^2{}_{S,i+N} - \Phi^2{}_{S,i-N-1}\,, & i < K - N \end{cases} \qquad (7)$$

$$b_i = \begin{cases} \sum_{u=-N}^{N} \Phi_{S,i+k}\,, & i = N+1 \\ b_{i-1} + \Phi_{S,i+N} - \Phi_{S,i-N-1}\,, & i < K - N \end{cases} \qquad (8)$$

A key problem is the appropriate selection of the window length N. In case when the SNR is large, we propose to determine the parameter N according to the following rule:

$$N = [\arg\{\max(\Phi_S)\} - \arg\{\min(\Phi_S)\}]/2 \qquad (9)$$

The detection algorithm is tested using experimental signal records provided by the team of the Birmingham University. The experimental records have been made in Island, 2010. The topology of the used FSR system is shown in Fig.5.

Real records of the signal, the duration of which is 120s or 60s was obtained during the experiment. The distance between the point of crossing and the receiver was nearly R_{tg}=165m. The input and output signals of the filter are presented in Fig.6 –for the experimental MISL boat and Fig.7 – for the huge boat.

Fig. 5 Experimental FSR topology

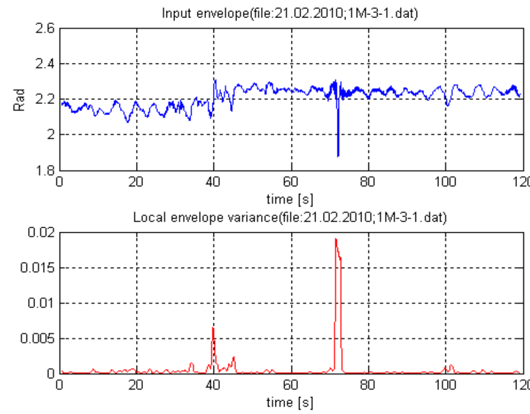

Fig. 6 MISL boat

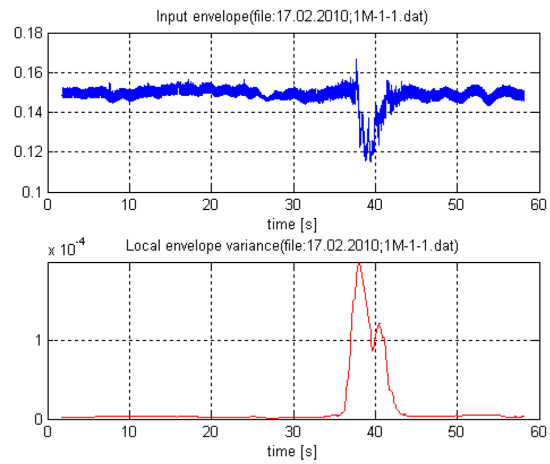

Fig.7 Huge boat

4. SIGNAL PARAMETER ESTIMATION

The time duration of the target signal is estimated by the number of samples divided by the sampling frequency (f_S), after extraction of the detected target signal (Fig.8).

$$T_d = (B - A)/f_S \qquad (10)$$

Parameters A and B are the start and the end samples of the detected target signal, respectively. The time duration of the target signal is related to the target profile. The average time duration is calculated for two types of boats (MISL, big). The average target signal power estimate is formed as square of the average difference between the amplitude of the target signal and the CFAR detection threshold.

$$\overline{P}_s = \left(\sum_{i=A}^{B} (signal_i - threshold_i) / T_d \right)^2 \qquad (11)$$

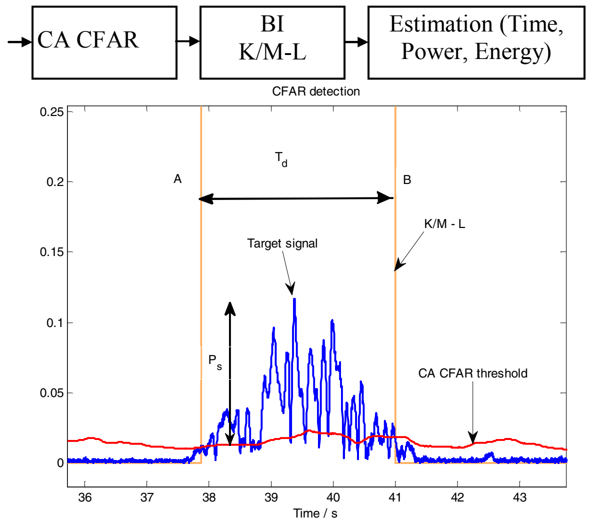

Fig.8 Signal parameter estimation

The average energy of the signal is as a product of the time duration and the average power. The target parameter estimates calculated for two types of boats are presented in Table 1.

TABLE I. Target parameter average estimates

	MISL Boat	**Big Boat**
Time	4.1649	14.2575
Power	11.256	12.25
Energy	0.3548	1.0227

5. TARGET CLASSIFICATION

The target classification task is implemented following the CRISP-DM (Cross-Industry Standard Process for Data Mining) model [12]. The open source data mining software WEKA is used for the implementation of the classification task [13]. However, since the available data for the analysis is very limited (80 instances), the actual radar targets are organized in three classes - MISL Boat, Big Boat and Average Boat. The target parameters needed for classification procedure are extracted from the preliminary filtered signals by using an original structure of a processor for target detection and parameter estimation in the time domain of the time duration and the energy/power reflected from the target. Several different classification algorithms are applied during the performed research work, selected because they use different classification techniques and have potential to yield good results. Popular WEKA classifiers are used in the experimental study, including common decision tree algorithms J48 (based on the C4.5 algorithm) and RandomForest, two Bayesian classifiers (NaiveBayes and BayesNet), a Nearest Neighbour algorithm (IBk), two rule learners (OneR and JRip), a Neural Network (Multilayer Perceptron), and a SimpleLogistic algorithm. The data mining classification task is performed, using the 10-fold cross validation test option because it proves to be very effective when the available data is very limited. The classification models achieved by applying the selected data mining algorithms are compared by using well-known evaluation criteria – *Confusion Matrix* and evaluation measures based on it (*Classification Accuracy/Error*, *ROC Area*, *Model Correct/Incorrect Ratio*; *Model/Naïve Correct/Incorrect Ratio)*. The *Confusion Matrix* is a table for visualizing the performance of a classification algorithm, each column representing the instances in a predicted class and each row representing the instances in an actual class. The *Classification Accuracy/Error* reveals the percentage of correctly/incorrectly classified instances. The *Model Correct/Incorrect Ratio* reveals the number of correct predictions for every error made. The ratio between the *Model Correct/Incorrect Ratio* and the *Naïve Correct/Incorrect Ratio* (calculated by using the Naïve Confusion Matrix based on the test data) shows how the model performs compared to random classification. The achieved results for three of the best performing algorithms are presented in Table II.

TABLE II. Classification models evaluation results

***Data Mining* Algorithms**	***Decision Tree (J48)***	***Neural Network***	***Rule Learner (JRip)***
Classification Accuracy	81.0127%	78.481%	82.2785%
Classification Error	18.9873%	21.519%	17.7215%
ROC Area	0.596	0.551	0.583
Model Correct /Incorrect Ratio	4.27	3.65	4.64
$\frac{Model\ \frac{Correct}{Incorrect}\ Ratio}{Naïve\ \frac{Correct}{Incorrect}\ Ratio}$	2.62	2.24	2.85

The best performing classifiers, with the highest overall accuracy of prediction, are the rule-learner JRip (82% correctly classified instances) and the decision tree algorithm J48 (81%), the neural network algorithm also performing well (about 79%). However, the detailed results show that the high overall accuracy of prediction is due to the high accuracy of predicting class MISL boat (98%, 97% and 92% for the three models respectively). The three algorithms perform with much lower accuracies for the other two classes – class Average Boat (33%, 50%, 17% respectively) and class Big Boat (18%, 9%, 36% respectively). The results reveal that the signal energy is the most informative parameter for predicting the class of the detected marine targets **a**nd this seems reasonable because the energy accounts for the average power and time duration of the useful FSR signals.

6. ACKNOWLEDGMENT

This work is partially supported by the Bulgarian Science Fund DDVU02/50/2010 and MU-FS-05/2007.

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