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Adaptive Binary Integration CFAR Processing for Secondary Surveillance Radar*

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Abstract: *In this paper we study some standard problems of SSR (Secondary Surveillance Radar), relating to improving the detection performance of the conventional SSR and Mode S replies in SSR FRUIT environment. We present the algorithm that consists of a conventional two-dimensional CFAR BI processor combined with the estimator of the FRUIT parameters, which is necessary for automatic selecting of the appropriate scale factor. This robust algorithm guarantees the maintenance of the constant false alarm rate in the FRUIT environment. In the study, we used Monte Carlo simulations for calculating the two detection characteristics – the probability of detection and the probability of false alarm. The results obtained show that the proposed adaptive binary integration (ABI) CFAR processor improves detecting the conventional SSR and Mode S replies in the SSR FRUIT environment.*

Keywords: *ABI CFAR (Adaptive Binary Integration Constant False Alarm Rate) processor, SSR (Secondary Surveillance Radar)*

1. Introduction

Secondary Surveillance Radar (SSR) is a **radar** system used in Air Traffic Control (ATC), which not only detects and measures the position of an aircraft but also requests additional information from the aircraft itself such as its identity and

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altitude as well. When the aircraft is in the close vicinity, which is in the close distance and/or close direction, their SSR replies can overlap, the ground decoder is confused and, finally, their information is lost. This term is known as Garbling.

When there are many SSR stations around the aircraft, replies received by the other SSR stations that did not "ask" for these replies, were received and calculated as valid ones resulting in confusion and finally rejection due to errors. This phenomenon is known as FRUIT (False Replies Unsynchronized with the Interrogation Transmissions) and results from the fact that an aircraft SSR reply is received not only by the SSR that triggered it but by all the others around as well. The unexpected reply, received by these other SSRs in the area, results in wrong decoding and/or inconsistent position measurements, which finally force the computer to reject the SSR information.

Both problems result in loss of the aircraft position producing inaccuracies.

A common technique of defruiting makes use of the sliding window process. The replies are stored in the memory in range-ordered cells with a new area of memory used following every interrogation. When a reply is received the contents of the range cells corresponding to the same range, but storing replies to earlier interrogations are inspected to determine whether synchronous replies are being received.

In general, FRUIT replies will not occur at consistent ranges or times following the local interrogations, and few FRUIT replies will appear in the "window" of cells of common range. A requirement for a minimum number of replies to be exceeded in order for a target to be recognized will cause false reports due to FRUIT replies to be rejected.

A novel approach to introduce CFAR in SSR signal processing that allows improving the detection/decoding is proposed by Galati [1].

It is well known that the SSR plot extractor uses a fixed threshold for detection of single impulses of the replies. It also estimates the pulse width in time. However, in condition of randomly arriving impulse interference caused by neighbouring radars or by asynchronous replies the signal to noise ratio is small, and therefore the signal processing in not efficient. For this reason the radar designers utilize the multi-channel (three or four channels) plot extraction processing.

For the first time the improvement of detection and decoding performance of the conventional SSR and Mode S replies in SSR FRUIT environment by using the conventional surveillance radar (PSR) approaches is proposed by Galati [1]. He proposes to use the matched filter for improving the signal to noise ratio, followed by the CA CFAR detector. When the noise at the output of the matched filter is smoothed (averaged) and homogeneous, then the CA CFAR processor can be efficiently used to reduce the false alarms caused by SSR replies in the bracket detector processing. The investigations of Galati were performed with the physical simulations using: RASS, an ATC radar system validation tool, and a mono-pulse SSR equipment. The results obtained demonstrate the more efficient performance than the conventional plot extraction processing.

In our paper we use the approach of Galati in order to improve the detection of the conventional SSR and Mode S replies in SSR FRUIT environment. Our purpose is to evaluate the performance of the conventional two-dimensional CFAR processors operating in this situation using the mathematical simulation approach,

Our hypotheses is to investigate the signal plus noise situation and to study what the CFAR technique can be used for detection of the conventional SSR and Mode S replies in the SSR FRUIT environment. We deduce the task of detection of the conventional SSR and Mode S replies to detection of only the brackets of these SSR replies.

Since we don't know whether the received replies in our plot extraction processor are the conventional SSR or Mode S replies, as S t e v e n s [2] we propose to use only the first pulse of the repeated bracket pulses (with equal spacing) of the synchrony SSR replies for detection of the target replies in SSR FRUIT environment.

We assume that the SSR replies occurring in a CFAR moving window can be described as a random pulse flow distributed according to the Poison law [3-6]. The amplitude of these SSR replies fluctuates with the Rayleigh distribution.

For this case we propose to use the conventional two-dimensional CFAR BI processor for detection of the first or the second bracket pulse of the SSR replies (repeated by the equal spacing) without the preliminary integration in the matched filter. These CFAR BI processors are very efficient under conditions of impulse interference with known parameters, such as the average value of the interference power and average pulse repetition frequency [3-6].

However, since the average pulse repetition frequency is apriori unknown in SSR FRUIT environment, such CFAR processors do not maintain the false alarm rate correctly. Therefore we propose to slightly modify the structure of a CFAR processor adding to it the average pulse repetition frequency estimator for the correct adaptive selecting of the scale factor, as it is shown in [7, 8].

Such a modified algorithm (ABI CFAR processor) is the robust algorithm whose estimator adaptively evaluates the parameters of the conventional SSR and Mode S replies in SSR FRUIT environment [9].

The study is performed by Monte-Carlo simulations in MATLAB computation environment. The results obtained show that our ABI CFAR processor improves the detection performance of the conventional SSR and Mode S replies in SSR FRUIT environment.

2. Adaptive BI CFAR processor

The Adaptive BI CFAR processor is efficient under conditions of a strong flow of random impulse interference with unknown parameters [8, 10]. This processor automatically selects the scale factor T_{ABI} in order to form the adaptive detection threshold. The ABI CFAR algorithm (Fig. 1) uses a sorting and censoring approach proposed by Himonas in [10].

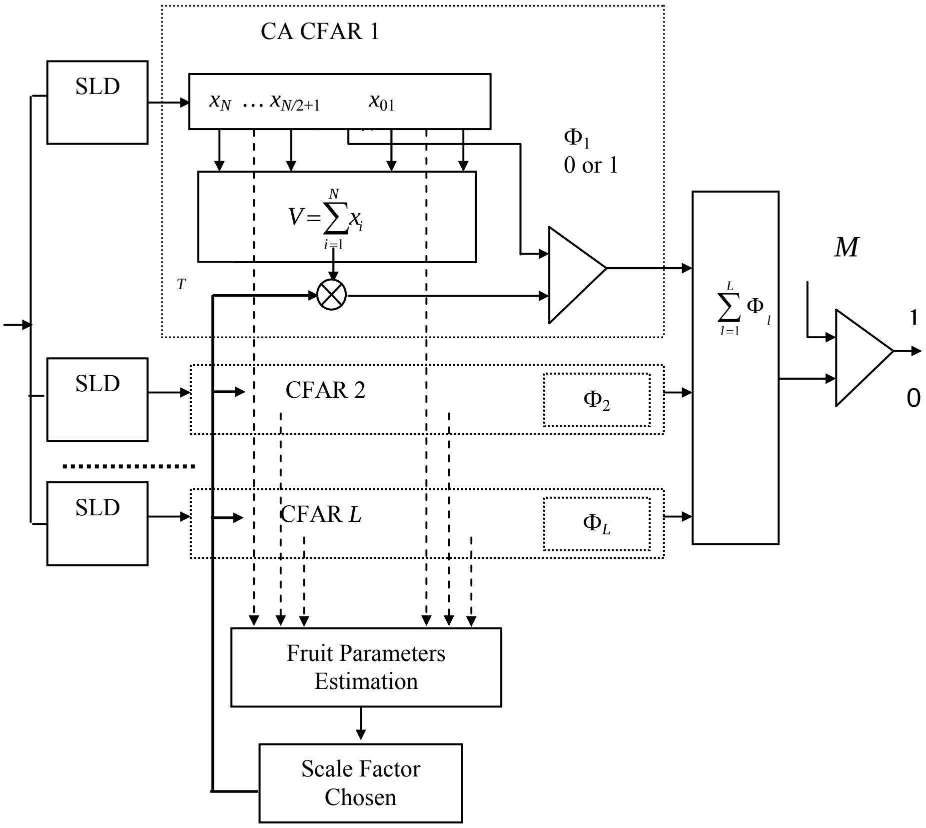

Fig. 1. ABI CFAR detector (SLD – Square Law Detector)

The elements of the reference windows are rank-ordered according to the increasing magnitude. This processor censors all elements with high intensity of signal from the reference windows in order to form the adaptive detection threshold.

2.1. FRUIT parameters estimation

The elements of the reference windows $\vec{x} = \left(x_1, x_2, ..., x_{\mathrm{NL}}\right)$ are rank-ordered according to the increasing magnitude. Each of such ranked elements is compared to the adaptive threshold according to the following rule:

$$x_{i+1}^{(1)} \geq s_i^x T_i^x, \quad i = 1, \ldots, \mathrm{NL} - 1 \tag{1}$$

where $s_i^x = \sum_{p=1}^{i} x_p^{(1)}$.

The constants T_i^x are determined in accordance with the given level of probability of false censoring [10]:

(2) $$P_{\mathrm{fc}} = \binom{\mathrm{NL}}{i} \frac{1}{\left[1 + T_i^x \left(\mathrm{NL} - i\right)\right]^i}.$$

The recursive procedure is stopped when condition (1) becomes true. In this way the reference cells are divided into two parts: The first part contains the "clean" elements, i.e. without FRUIT. We suggest the parameters of the interference (FRUIT) to be estimated by using the second part of the reference window. The FRUIT power (F_p) estimate and the probability of appearance (F_f) can be calculated as:

(3) $$F_\mathrm{p} = \begin{cases} x^{(1)}_{\left(\mathrm{NL}+k^*+1\right)/2} & \text{if } \mathrm{NL} - k^* \text{ is odd} \\ \left(x^{(1)}_{\left(\mathrm{NL}+k^*\right)/2} + x^{(1)}_{\left(\mathrm{NL}+k^*+2\right)/2}\right)/2 & \text{if } \mathrm{NL} - k^* \text{ is even} \end{cases}$$

and $F_\mathrm{f} = \left(\mathrm{NL} - k^*\right)/\mathrm{NL}$ where k^* is the point, in which the adaptive algorithm is stopped.

Using the FRUIT parameters estimates, the ABI CFAR processor automatically selects the scale factor T_{ABI} from a matrix of preliminary calculated values. The selected scale factor guarantees the maintenance of the constant probability of false alarm.

2.2. Target detection

In a CFAR pulse train detector with binary integration, the binary integrator counts "L" decisions (Φ_l) at the output of a CFAR pulse detector. The pulse train detection is declared if this sum exceeds the second digital threshold M. The decision rule is:

(4) $$\begin{cases} H_1 & \text{if } \sum_{l=1}^{L} \Phi_l \geq M, \\ H_0 & \text{otherwise}, \end{cases}$$

where H_1 is the hypothesis that the test cells contain target and H_0 is the hypothesis that the test cells contain the receiver noise only, L is the number of pulse transmissions, $\Phi_l = 0$ if no pulse is detected, and $\Phi_l = 1$ if pulse detection is indicated.

The pulse detection is declared, if the sample x_0 from the test resolution cell exceeds the threshold:

(5) $$\begin{cases} \Phi_l = 1: & x_{ol} \geq VT_{\mathrm{ABI}} \\ \Phi_l = 0: & x_{ol} < VT_{\mathrm{ABI}} \end{cases}$$

where $V = \sum_{i=1}^{N} x_i$.

3. Numerical results

The presence of FRUIT in SSR can cause drastic degradation of detection/decoding performance.

The SSR replies in a CFAR sliding window is described as a random pulse flow distributed according to Poison law. The amplitude of these SSR replies fluctuates according to Rayleigh law. We assume that the average probability of occurrence (F_f) of asynchronous replies in each range resolution cell with the same azimuth can be expressed as $F_f = \tau.F$, where F is the average pulse repetition frequency and τ is the transmitted pulse duration [3-7]. Our study shows that the FRUIT rate about 10 000 s^{-1}, mentioned by Galati, corresponds to the following probability of occurrence $F_f = 0.01 \div 0.05$.

The FRUIT with unknown parameters corresponds to the situation when the CFAR processors fail to maintain the constant probability of false alarm. In calculations of the false alarm probability for the case of strong FRUIT with varying parameters, we used the value of a scale factor obtained for the homogeneous background. For the probability of false alarm, the numerical results are obtained for the following parameters: the FRUIT power varies from 15 to 25 dB, the probability of FRUIT occurrence is 0.02 and 0.05, the number of reference cells (N) equals 16, the probability of false alarm is $P_{fa} = 10^{-4}$ and, the binary decision rule is $M/L = 3/4$. The numerical results, depicted in Fig. 2 show the influence of a scale factor over the probability of false alarm in ABI CFAR processor, which operates with the fixed scale factor in the presence of strong FRUIT.

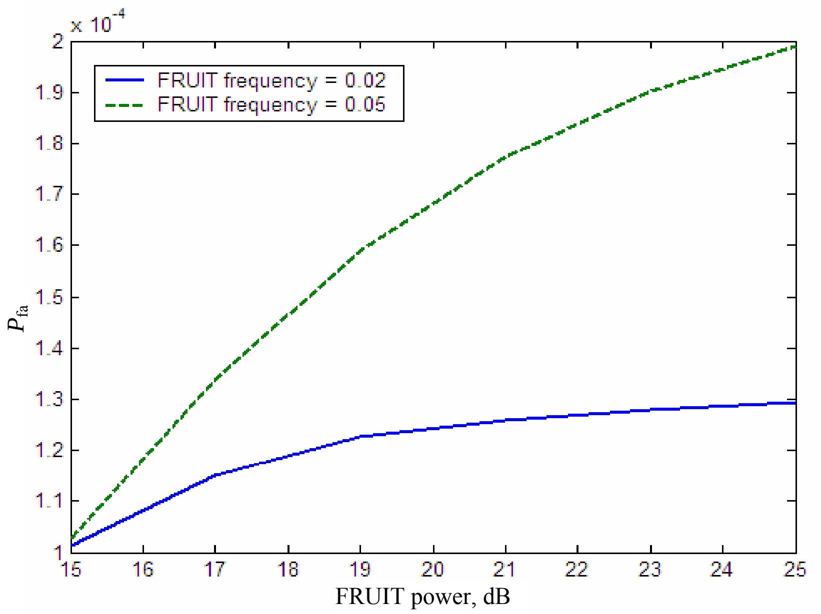

Fig. 2. False alarm probability of ABI CFAR detector for different probability for appearance of asynchronous replies (F_f=0.02 and 0.05)

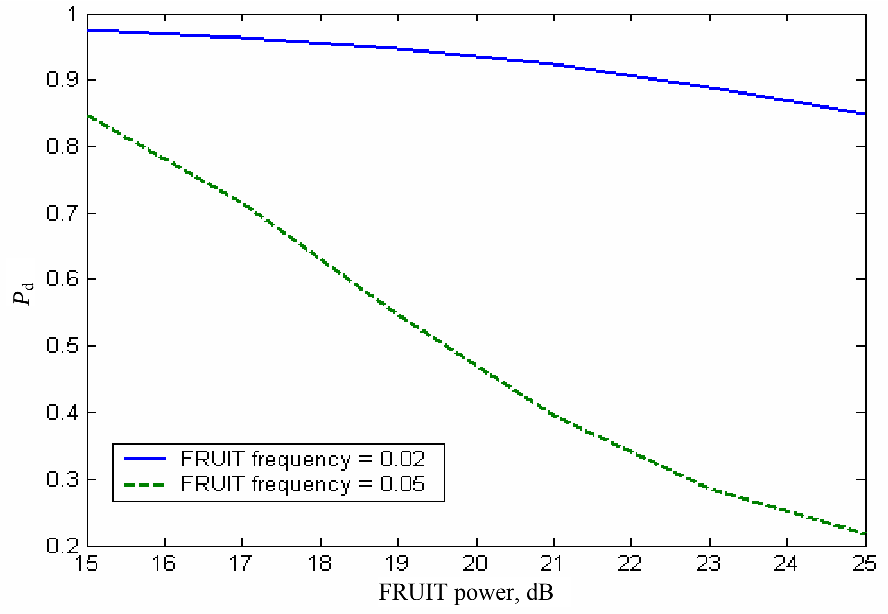

Fig. 3. Detection probability of ABI CFAR detector for different probability of appearance of asynchronous replies (F_f = 0.02 and 0.05)

This problem can be overcome if the scale factor is adapted to varying parameters of impulse interference. We propose to select the value of a scale factor from a matrix, which contains the values of a scale factor, preliminary calculated for different FRUIT parameters (Table 1).

Table 1. Scale factor of ABI CFAR detector ($P_{fa}=10^{-4}$)

F_f	FRUIT power, dB		
	15	17	19
0.02	0.28	0.289	0.292
0.05	0.54	0.68	0.84

F_f	FRUIT power, dB		
	21	23	25
0.02	0.293	0.296	0.297
0.05	1	1.17	1.32

The use of ABI CFAR processor allows the improvement of the conventional detection performance reducing false alarms.

The detection probability of an ABI CFAR detector calculated for the case when FRUIT has the probability of appearance of 0.02 and 0.05 and the power between 15 and 25 dB is plotted in Fig. 3. The simulation results are obtained for the following parameters: the average signal value is 20 dB, the number of reference cells is N = 16, the probability of false alarm is $P_{fa} = 10^{-4}$ and the binary decision rule is M-out-of-L (3/4). The study is carried out using Monte-Carlo simulations in the MATLAB computation environment.

It can be seen that the increase of FRUIT parameters, the probability of occurrence and the power, lead to reduction of the detection probability. The false alarm probability is kept to be constant.

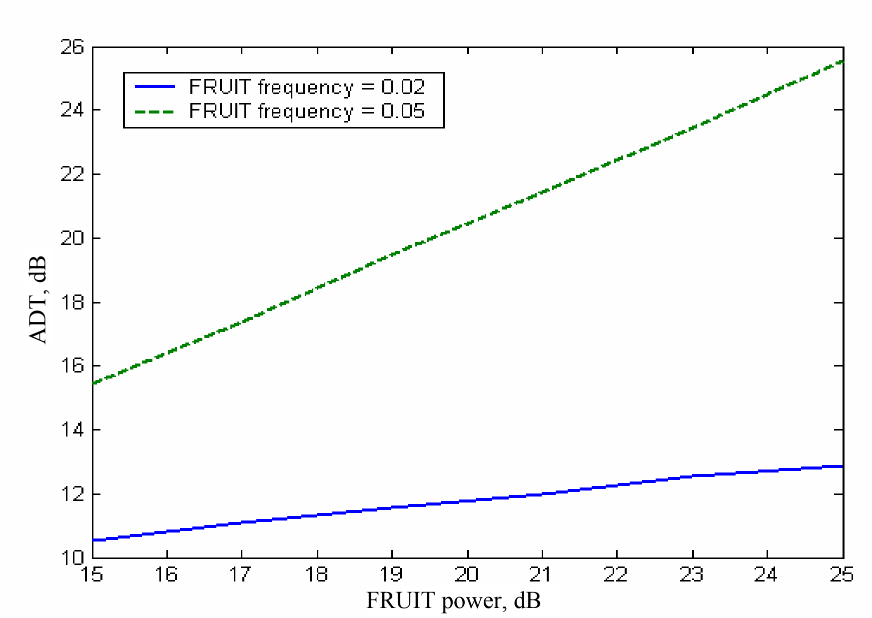

Fig. 4. Average decision threshold (ADT) of ABI CFAR detector for different probability for appearance of asynchronous replies (F_f = 0.02 and 0.05)

The efficiency of the detection algorithm is also estimated in terms of the average decision threshold. The ADT for an ABI CFAR processor calculated for the FRUIT environment is shown in Fig. 4.

It is shown that the average decision threshold (ADT) increases with the increase of the FRUIT power when the probability of FRUIT occurrence varies from 0.02 up to 0.05.

4. Conclusions

In this paper the efficiency of ABI CFAR detectors under conditions of SSR FRUIT with unknown parameters is studied. The efficiency of the ABI CFAR algorithm is expressed in terms of the probability of detection and false alarm and the average decision threshold (ADT).

Combined with the estimator of the FRUIT parameters, the conventional CFAR BI detector automatically selects the appropriate scale factor and thereby maintaining the constant probability of false alarm in SSR FRUIT environment. The average decision threshold is small when the two FRUIT parameters, the power and the probability of occurrence, are small. The use of the ABI CFAR processor makes possible to improve the detection of the synchrony conventional SSR or Mode S replies, when reducing false alarms in SSR FRUIT environment.

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