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SOFTWARE ALGORITHM FOR DRONE PRESENCE DECISION ON THE BASE OF RADAR SPECTROGRAMS

DEJAN STANOJEVIĆ
IRITEL a.d., Belgrade, dejan.stanojevic@iritel.com

JOVAN RADIVOJEVIĆ
IRITEL a.d., Belgrade, jovan.radivojevic@iritel.com

ALEKSANDAR LEBL
IRITEL a.d., Belgrade, lebl@iritel.com

Abstract: *FMCW radars and spectrograms obtained by its implementation are very powerful and reliable technique for malicious drones' detection and identification. But, the challenge is to differentiate drone and birds spectrograms which are very similar. The most often applied software algorithms to achieve this functionality are based on artificial intelligence implementation principles. The special problem when these algorithms are practically applied is to previously make a huge data base of spectrograms with flying drones and other targets. Our objective was to develop a software algorithm with only limited set of decision criteria which would analyze maximum simplified spectrograms without the need to have spectrograms base. Our decision program implements only four decision criteria and in a great majority of situations allows drones detection from only one spectrogram of an appreciated target. The limitation in this first variant of software algorithm is that it is limited to distinguishing hovering drones from flapping wing birds.*

Keywords: *FMCW radar, birds and drones spectrograms, software algorithm, decision criteria.*

1. INTRODUCTION

Various sensor types are applied in modern solutions for malicious drones' detection. Among these sensors the most often we find radars, RF detectors, acoustic detectors and optical and thermal cameras. Each of these sensors has its benefits and drawbacks. In the case that radar detection is considered, the benefits are very important for the final solution reliability. These benefits comparing to other sensor types may be summarized in several points: 1) when implemented in environment without obstacles, radar is suitable for long range detection, at higher distance than other sensor types, especially cameras or acoustic sensors; 2) it is possible do detect drones, which are autonomous when they are moving, i.e. when there is no their communication with a pilot or supervisory centre, thus overcoming the possibilities of RF detectors which are effective only in detecting this communications between drone and its controller; 3) the satisfactory drone detection is possible in bad weather conditions and in low or no light conditions – such degree of independence of weather conditions is not evident at acoustic or optical sensors [1]. The benefits of radar implementation for drone detection are also emphasized in [2]. As a consequence of these benefits, radar sensors are usually a part of each multisensor drone detection system. Frequency Modulated Constant wave (FMCW) radars are usually applied for this purpose [3].

A great challenge in radar detection of malicious drones is to reliably separate drones from other targets, especially from birds. This is, in some way, the drawback of radar sensors comparing to thermal and, even more, optical cameras, but this drawback may be significantly mitigated by precise and comprehensive definition of drone detection software algorithm. In many applied solutions different artificial intelligence algorithms are used to increase detection reliability, especially related to deep neural networks [4]. The main objective of this paper is to present our originally developed software algorithm for drone detection, identification and localization. The paper is the logical extension of the contribution [3].

The section II of this paper presents several drones and one bird spectrogram. Two spectrogram variants are considered: in six colours and in two colours, the second one being very suitable for software analysis. Initial definition of software algorithm for drone presence decision is described in the section III including a survey of situations when each one of the four decision criteria is suitable for the right decision. At the end, conclusions are in the section IV.

2. SPECTROGRAMS PREPARATION FOR SOFTWARE ANALYSIS

Spectrograms for the analysis by our software decision algorithm are a little bit modified spectrograms presented in [3], [5], [6]. They are obtained implementing our original calculation program developed in Excel. The whole area of possible signal levels in a spectrogram is divided into six sub-areas. The shape of higher level sub-areas is used for decision making. That's why these sub-areas cover lower width of spectrum. For the spectrograms in figures 1-8 the highest level sub-area has the designation 1 (i.e. 0.5-1.5) and its level spectrum is 10dB wide. The sub-areas with the designation 2 (i.e. 1.5-2.5) and 3 (i.e. 2.5-3.5) are two steps below the first area, also 10dB wide each one. The next two sub-areas with the designation 4 and 5 are 20dB and 40dB wide, respectively, while all the lower signal levels are covered by the sub-area 6.

The other implemented way of spectrograms presentation is with only two areas. The area with higher signals level (designation 1, i.e. 0.5-1.5 on the black-white spectrogram) covers the areas with designations 1-3 according to the first presentation style on the coloured spectrograms while the area with lower signals level (designation 2, i.e. 1.5-2.5 on the black-white spectrogram) covers the areas with designations 4-6 on the coloured spectrograms. Thus obtained graphs in the black-white style are also presented. Spectrograms in both styles are presented for all analyzed situations, but decisions may be made according to black-white spectrograms.

The spectrograms in the figures 1-7 correspond to hovering drones while the spectrogram in the figure 8 is for the bird whose only movement is wings flapping. Each spectrogram is presented in two shapes with the designations a and b. The figures with designation a are in six colours while figures with designation b are "black" -"white" where brown, red and orange parts in the "a" figures are replaced by black parts in the "b" figures and yellow, green and turquoise parts in the "a" figures are replaced by white parts in the "b" figures. The physical and movement characteristics of a target are emphasized in the figures legends. The most important parameters are written in different colour letters in the legend of each figure. When considering birds spectrograms, data dealing the birds flapping rate are limited to maximum 20flapps/s according to [7]-[9] with only one exception non-important for our development [9] (Figure 8). On the other hand, the minimum multicopter drone propellers rotation rate is about 30rotations/s (2000rotations/min) [10] (as in Figure 2). In our analysis we are going to even lower value of 20rotations/s (figures 1, 3, 4, 7), equal to the number of birds flaps/s, or even lower at 10rotations/s (Figure 6). The spectrograms in this paper are the further insight into the spectrograms recorded in [3]. They are the valuable support to define concrete values of four decision algorithms described qualitatively in [3].

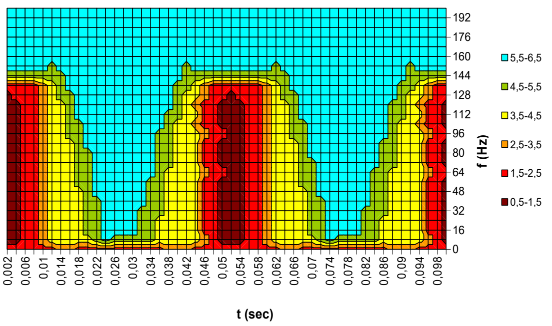

Figure 1a.

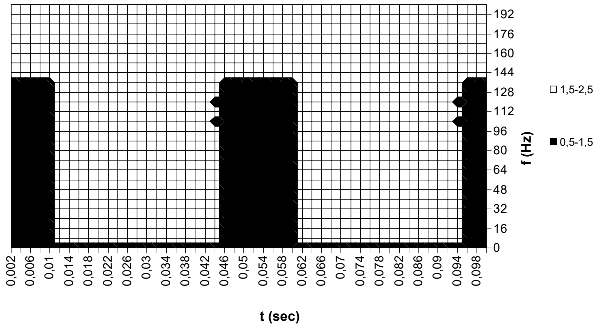

Figure 1b.

Figures 1a and 1b. Drone spectrogram for **one rotor** with **one blade**, the blade length ***L*=0.48m**, blade rotation speed **Ω_{rot}=20rotations/s**, drone height *h*=70m, drone distance from radar R_0=100m, drone elevation angle towards radar ***β*=arcsin(0.7)**.

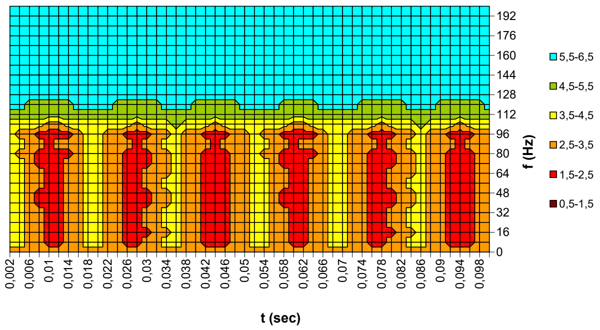

Figure 2a.

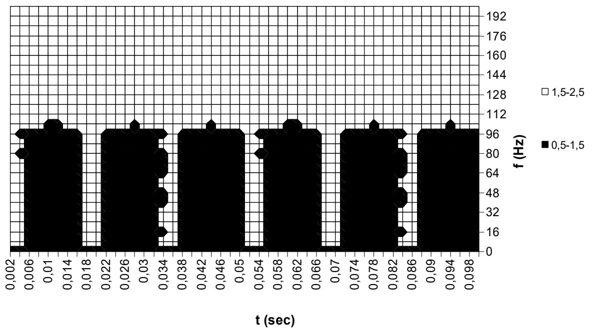

Figure 2b.

Figures 2a and 2b. Drone spectrogram for **one rotor** with **one blade**, the blade length ***L*=0.12m**, blade rotation speed **Ω_{rot}=60rotations/s**, drone height *h*=70m, drone distance from radar R_0=100m, drone elevation angle towards radar ***β*=arcsin(0.7)**.

The spectrograms in the figures 1-6 are for helicopter type drones having only one rotor. The rotors of helicopters have 2-7 blades where 2, 3 and 5 are the most often found number [11]. We haven't found data about aircrafts of helicopter type with only one blade in their rotor, but such a case is also analyzed in this paper due to the fact that it would be the most demanding task to distinguish these drones from birds. The spectrograms in the figures 1 and 2 are for such a hypothetical case that helicopter has only one rotor. The figures 3, 5 and 6 are for the two-blade rotor and Fig. 4 corresponds to the three-blade rotor. The spectrogram in the Figure 7 is for a quadcopter (which has four rotors). The majority of presented examples consider the spectrograms when 20 repeatable parts appear in one second because this is the maximum expected bird wings flapping rate i.e. the distinguishing threshold between drones and birds. The number of repeatable parts in drone spectrograms is directly proportional to the number of blades in each rotor (comparing figures 1 and 4), then to the rotors rotation rate (comparing figures 3 and 6), while the width of important frequency components (black spectrogram parts) is proportional to the blades length and the rotors rotation rate (comparing figures 2 and 5).

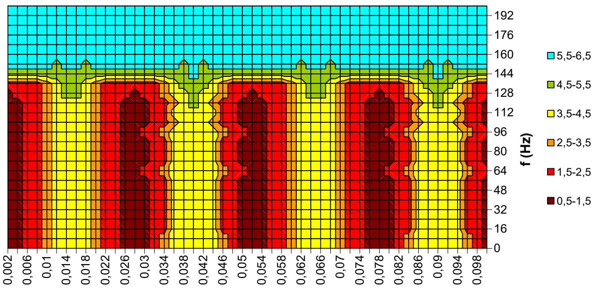

Figure 3a.

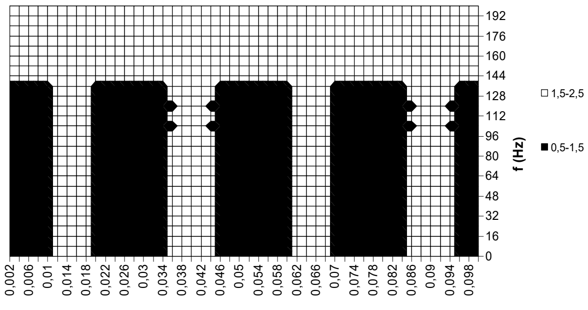

Figure 3b.

Figures 3a and 3b. Drone spectrogram for **one rotor** with **two blades**, the blade length ***L*=0.48m**, blade rotation speed **Ω_{rot}=20rotations/s**, drone height *h*=70m, drone distance from radar R_0=100m, drone elevation angle towards radar **β=arcsin(0.7)**.

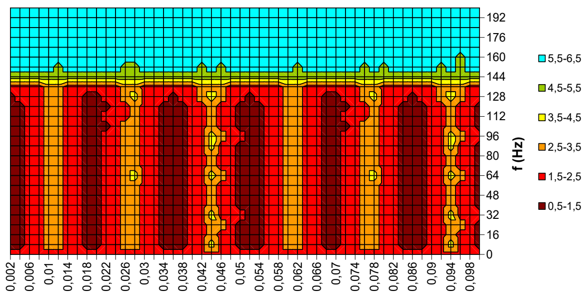

Figure 4a.

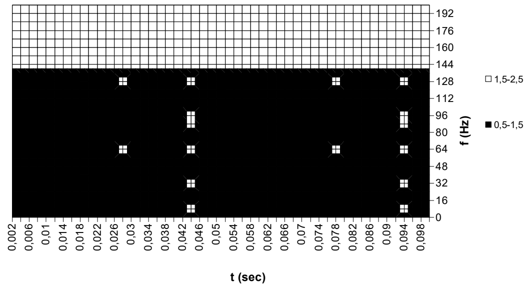

Figure 4b.

Figures 4a and 4b. Drone spectrogram for **one rotor** with **three blades**, the blade length ***L*=0.48m**, blade rotation speed **Ω_{rot}=20rotations/s**, drone height *h*=70m, drone distance from radar R_0=100m, drone elevation angle towards radar **β=arcsin(0.7)**.

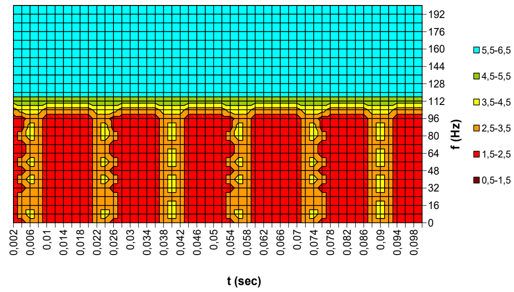

Figure 5a.

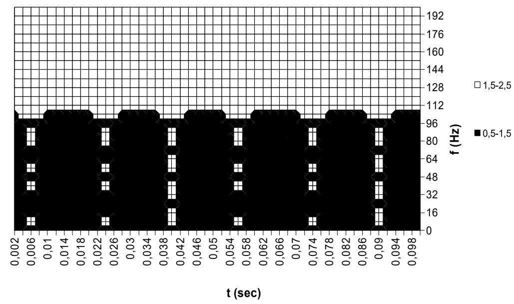

Figure 5b.

Figures 5a and 5b. Drone spectrogram for **one rotor** with **two blades**, the blade length ***L*=0.24m**, blade rotation speed **Ω_{rot}=30rotations/s**, drone height *h*=70m, drone distance from radar R_0=100m, drone elevation angle towards radar **β=arcsin(0.7)**.

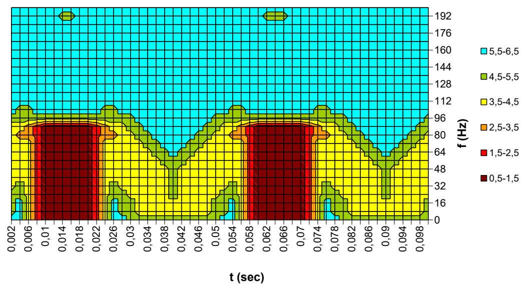

Figure 6a.

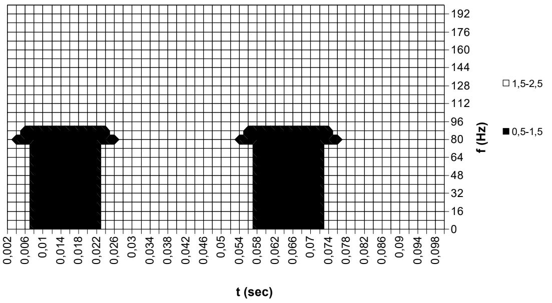

Figure 6b.

Figures 6a and 6b. Drone spectrogram for **one rotor** with **two blades**, the blade length $\boldsymbol{L}$**=0.64m**, blade rotation speed $\boldsymbol{\Omega_{rot}}$**=10rotations/s**, drone height h=70m, drone distance from radar R_0=100m, drone elevation angle towards radar $\boldsymbol{\beta}$**=arcsin(0.7)**.

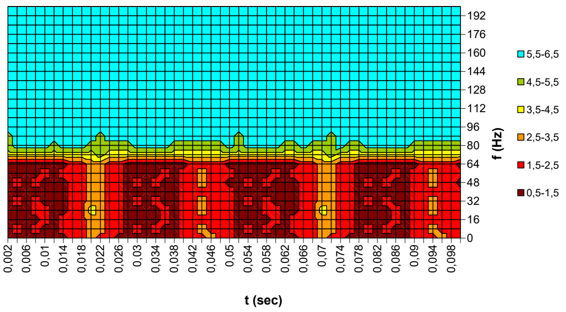

Figure 7a.

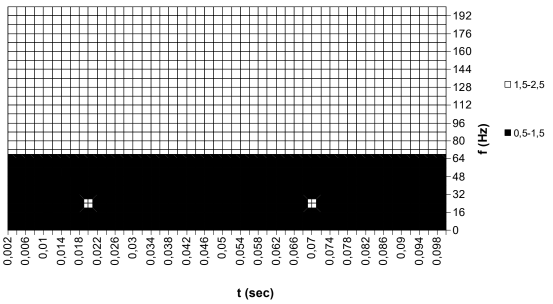

Figure 7b.

Figures 7a and 7b. Drone spectrogram for **four rotors** with **one blade**, the blade length $\boldsymbol{L}$**=0.24m**, blade rotation speed $\boldsymbol{\Omega_{rot}}$**=20rotations/s**, drone height h=70m, drone distance from radar R_0=100m, drone elevation angle towards radar $\boldsymbol{\beta}$**=arcsin(0.7)**.

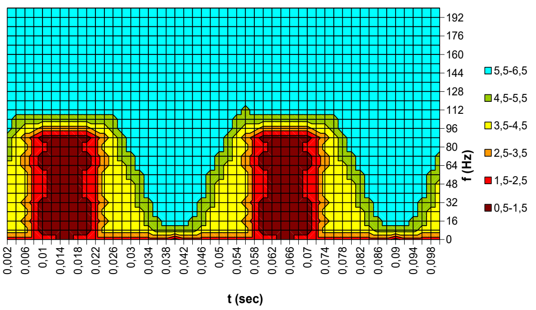

Figure 8a.

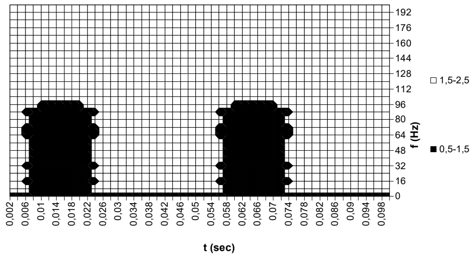

Figure 8b.

Figures 8a and 8b. Spectrogram of bird with flapping wings, the wing length $\boldsymbol{L}$**=0.48m**, wing flapping rate $\boldsymbol{f_{fl}}$**=20flaps/s**, maximum flapping angle $\boldsymbol{\varphi_{max}}$**=40º**, bird height z_1=70m, bird distance from radar R_0=100m, bird elevation angle towards radar $\boldsymbol{\beta}$**=arcsin(0.7)**.

3. PROGRAM FOR SPECTROGRAM ANALYSIS

The first step in spectrogram analysis is to process it in a suitable sense to allow reliable decision making. Black-white variant of spectrograms is processed. The flow-chart of the program for spectrograms analysis is presented in the Figure 9.

The spectrogram graphs are 2D pictures of the dimension $M\times N$ where M and N are the number of time samples for any frequency value and frequency samples for any time moment, used for the presentation. The first step in the program flow is to read the values for M and N. After that follows the input of black-white samples: $S(i,j)$=1 for black and $S(i,j)$=0 for white samples. The values of i are changed from 1 to M to cover all time samples and j is changed from 1 to N to cover all frequency components.

The principle in the spectrogram analysis is to first consider each row of data, i.e. the samples value during time for each frequency. It is necessary to determine the period of this signal and the time interval while the signal is $S(i,j)$=1 and while it is $S(i,j)$=0. The signal processing starts in the moment when the instantaneous signal value is changed from 0 to 1. According to the Figure 9, it is when the answer to both questions "$S(i,j)$=1?" and "$S(i-1,j)$=0?" is "yes". Considering time domain, it is when signal sample from "white" goes over to "black". The register k with the number of periodic time cycles is increased for 1 and the register $T_1(k,j)$ intended to follow the duration of the state $S(i,j)$=1 is initiated to 0. After that the register $T_1(k,j)$ is incremented after each time interval when it is $S(i,j)$=1. The similar processing is performed when signal goes over from "black" to "white" (the answer to the first question "$S(i,j)$=1?" is "no" and the answer to the second question "$S(i-1,j)$=1?" is "yes") and while it is in the state "white" with the exception that the value of register k is not changed and that the values of the register $T_2(k,j)$ is varied instead of $T_1(k,j)$.

It is already proved by spectrogram in the Figure 4 that "white" areas are very narrow considering variation in time already at 20rotations/s for helicopter type drones when the rotor has 3 blades. When the rotor has 2 blades, such behaviour is obvious at only bit higher rotations speed of 30rotations/s (Figure 5). The similar behaviour is obvious when helicopter type drones are replaced by quadcopters (Figure 7). Such types of spectrograms as in the figures 5, 6 and 7 are characteristic for the great majority of situations and the last software processing in the Figure 9 is intended to separate these spectrograms. According to the last decision block, whenever the time interval of “white” part is lower than the minimum threshold T_{min} and the duration of $T_2(k,j)$ interval is lower than interval $T_1(k,j)$, this “white” interval is eliminated ($T_2(k,j)$=0), the number of signal periods for the furtherto evaluation is decreased and the duration of “white” interval is added to the “black” interval $T_1(k,j)$. The value of T_{min} according to graphs in the figures 4a and 5b is 4ms. In this way it is allowed that spectrograms may be further easily processed according to the step 1 from [3] if they satisfy conditions of this step.

The flow-chart of a program for drone presence decision is presented in the Figure 10. The decision is the result of four criteria implementation according to [3]. The analysis is performed separately for each of N frequencies in the spectrogram to investigate whether it is candidate to be a part of drone spectrogram.

The decision about the first criterion separates multirotor drones from other targets (birds or non-drones objects and slow rotating helicopter type drones) – spectrogram in the Figure 7. This criterion also distinguishes helicopter type drones when they have three or more blades – spectrogram in the Figure 4 or when helicopter type drones have two blades which rotate at a bit higher rate than the minimum 20rotations/s – spectrogram in the Figure 5. In this case the number of repeatable parts in each frequency line is always k=1 as the result of processing in the last part of the flow-chart according to the Figure 9. If a spectrogram consists of a single “black” part (i.e. k=1 and T_1 area exists – $\Sigma T_1 > T_{min}$), the value of register *dec* is increased. Such processing is performed for each frequency line in a spectrogram. If the final value of register *dec* is higher than the minimum value dec_{min}, the decision about drone presence is positive. There is no one unique value dec_{min} because the spectrogram frequency bandwidth depends both on blades length and rotors rotation rate. That’s why it is necessary first to determine rotors rotation rate from the spectrograms periodicity, if it is possible. After that, for example, in the case of 60rotations/s, the dec_{min} would be about 140Hz for very short 0.12m blades (example in the Figure 2).

The criterion 2 separates helicopter type drones when they have two blades rotating at low rate (10-20rotations/s – Figure 3) and the hypothetical helicopter drone with only one blade rotating at higher rate than 20rotations/s – Figure 2. In this case there are $k > k_{min}$(=20) alterations of “black” and “white” parts and vice versa during time interval of 1s. The following processing in this case is the same as for the criterion 1.

The difference between criteria 1 and 2 from the criterion 3 is that criterion 3 does not allow decision on the base of only one spectrogram. It is necessary consider at least two time-lagged spectrograms. The results of decisions for each frequency line in spectrogram for the criterion 3 is accumulated in the separate register $dec1_l$, in a similar way as it is in the register *dec* for the first two criteria. Then the decision about a drone presence depends on the relation between the elevation angle β_l in some moment l and the value obtained in $dec1_l$. The drone is detected if the increase in β_l value ($\beta_l > \beta_{l-1}$) causes decrease of dec_l value ($dec1_l < dec1_{l-1}$). The same decision is also in the case of opposite combination of values ($\beta_l < \beta_{l-1}$ and $dec1_l > dec1_{l-1}$). In the remaining two combinations the considered target is a bird, not a drone. The criterion 3 is used to define a target when the spectrogram as the one presented in the figures 1, 6 and 8 is recorded. It is important to emphasize, as in [3], that elevation angle is determined using some other algorithm on FMCW radar.

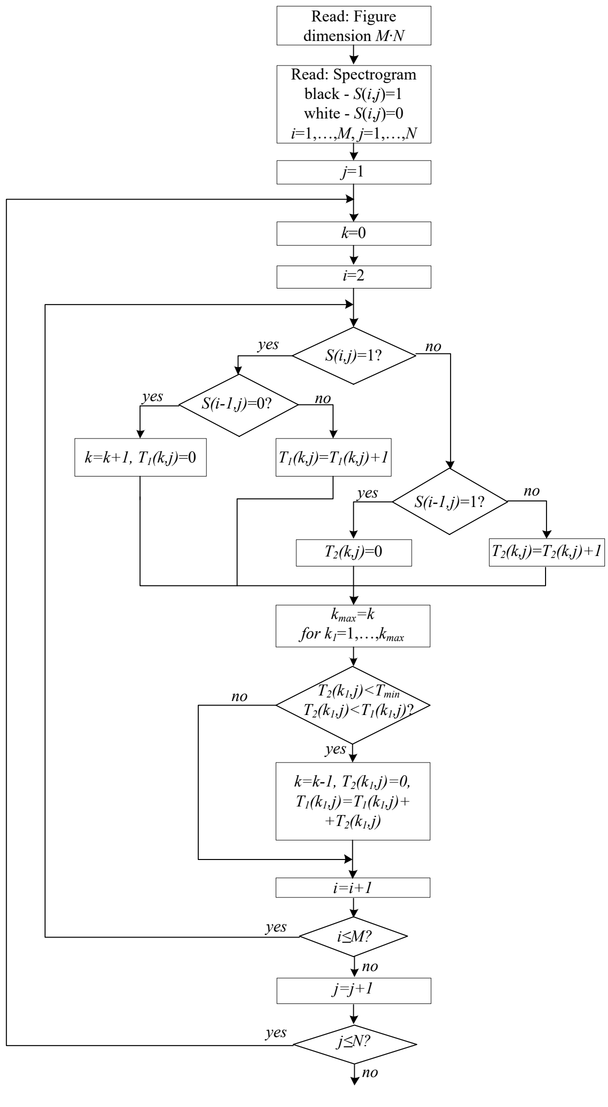

Figure 9. The flow-chart of a program for spectrograms processing

The criterion 4 follows after the criterion 3 if the elevation angle β is approximately not changed with time, i.e. for $\beta_l \approx \beta_{l-1}$ (the target is moving directly towards radar or directly away from radar). In this case the decision follows from the fact that birds’ higher wing flapping rate means that the birds’ wings length is lower. Among the birds’ species and their characteristics important for our analysis which are presented in [12], there is only one example where the flapping rate is a little higher than 20 flaps/s and the wings length in this case is only 0.09m. The bird species with the nearest flapping rate to 20 flaps/s from the lower side has wing length 0.164m. Both these wing lengths are lower than it is usual for helicopter drone causing the lower value in the register $dec1_l$. The other important conclusion follows from the comparison of spectrograms in the figures 1 and 8. All parameters for these spectrograms are the same including drone blade length in the Figure 1 and the wings length in the Figure 9, but about 25% lower value in the register $dec1_l$ follows from the fact that wings maximum flapping angle is 40^o and the rotor makes full rotations. In this way both factors contributing to the value of $dec1_l$ are higher in the case of drone presence i.e. the minimum threshold $dec1_l$ may be determined for each specific rotation (flapping) rate and elevation angle.

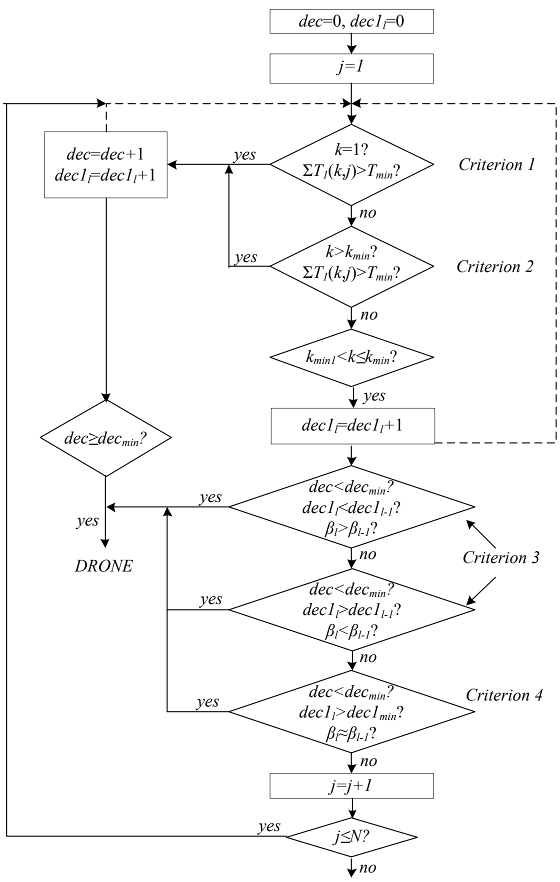

Figure 10. The flow-chart of a program for drone presence decision

4. CONCLUSION

This paper presents original software algorithm to reliably distinguish spectrograms of drones and flying birds. The spectrograms are obtained by FMCW radar. In this program development phase we have limited ourselves to hovering drones and birds with only flapping wing movements. The paper is logically an extension of the contribution [3]. The spectrograms obtained by the implementation of our original calculation program in [3] are partially simplified in two steps: first to six signal level areas and after to only two areas. The variant with only two areas ("black" - "white" spectrograms) are used for software analysis to decide about the drone presence.

The decision program is relatively simple. It is not necessary to have huge data base with previously recorded spectrograms of various drone types and flying birds' species to allow decisions making using artificial intelligence principles. In the great majority of situations it is enough to analyze only one spectrogram to make a decision. Only in very rare cases when helicopter type drones have low rotation rate or are flying directly towards or away from radar it is necessary to consider several spectrograms separated by some time interval.

The developed software algorithm is verified only on calculated spectrograms for hovering drones and birds with flapping wings. Our developed algorithm was able to distinguish that spectrograms in figures 2-7 from this paper ("black" - "white" versions) belong to drones and that the spectrogram in the figure 8 is for a bird. The algorithm has also successively distinguished spectrograms from [3]. In the future it is necessary to test it in real applications and to modify it to allow differentiation of flying drones and birds, not only hovering drones and flapping wing birds.

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