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## RECOGNITION OF PROPELLER-DRIVEN AIRCRAFT IN PASSIVE BISTATIC RADAR<sup>1</sup>

**Abstract.** Nowadays passive bistatic radars (PBR) allow for detection, determination of coordinates and tracking of moving objects. In order to enable PBR integration into air traffic control systems, it is necessary to solve the problem of recognizing airborne objects, in particular, propeller-driven aircraft (AC). This will increase the degree of aviation safety. To solve the recognition problem, the analysis of propeller-driven aircraft echo signals, such as helicopter and propeller airplane, is performed. The informative features that can be used for recognition of propeller-driven aircraft in PBRs are defined. The method for propeller-driven aircraft recognition is proposed, that is based on extraction of modulation components originated from the rotational parts of the aircraft and estimation of their rotation parameters. The algorithm for echo signal processing is developed, which makes it possible to apply the proposed recognition method for PBRs.

The experimental results of the processing algorithm are presented on the example of real signals reflected from the Mi-8 helicopter and the Cessna 172 propeller aircraft. The experimental data are recorded by two different PBRs using DVB-T2 digital terrestrial television signals standard for airspace illumination. The estimated rotation parameters of the aircraft propeller blades correspond to the actual values. Such a correspondence allows not only to recognize the aircraft group, but in some cases to identify its type.

**Key words:** radar recognition, passive bistatic radar, time-frequency analysis

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## РАСПОЗНАВАНИЕ ВИНТОМОТОРНЫХ ЛЕТАТЕЛЬНЫХ АППАРАТОВ В ПАССИВНОЙ БИСТАТИЧЕСКОЙ РЛС

**Аннотация.** Пассивные бистатические радиолокационные станции (ПБРЛС) в настоящее время позволяют осуществлять обнаружение, определение координат и сопровождение движущихся объектов. Для обеспечения возможности интеграции ПБРЛС в системы управления воздушным движением необходимо решить задачу распознавания воздушных объектов, в частности винтомоторных летательных аппаратов (ЛА). Это позволит увеличить степень обеспечения безопасности полетов авиации. Для решения этой задачи проведен анализ эхосигналов от винтомоторных ЛА – таких, как вертолет и винтовой самолет. Сформулированы информативные признаки, которые могут быть использованы при распознавании винтомоторных ЛА в ПБРЛС. Предложен метод распознавания винтомоторных ЛА, который основан на извлечении модуляционных составляющих эхосигнала, обусловленных вращающимися частями двигательной установки ЛА, и на оценке параметров их вращения. Разработан алгоритм обработки эхосигналов, позволяющий реализовать предложенный метод распознавания на практике в ПБРЛС. Представлены экспериментальные результаты работы алгоритма обработки на примере реальных сигналов, отраженных от вертолета Ми-8 и винтового самолета Cessna 172. Экспериментальные данные записаны двумя разными ПБРЛС, использующими сигналы цифрового эфирного телевидения стандарта DVB-T2 в качестве радиолокационного подсвета воздушного пространства. Оцененные параметры вращения лопастей винтов винтомоторных ЛА соответствуют фактическим значениям. Такое соответствие позволяет не только распознавать класс, но и в некоторых случаях идентифицировать тип ЛА.

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**Ключевые слова:** радиолокационное распознавание, пассивная бистатическая РЛС, частотно-временной анализ

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**Introduction.** In recent decades, passive bistatic radars (PBRs) have been actively developed and have found wide range of applications [1]–[4]. The PBR special feature is the use of third-party transmitter signals as radar illumination. Nowadays PBRs are used mainly for detecting, position determining and tracking of moving objects. Moreover, they represent the most advanced tool for modern security systems, air traffic control and ship traffic control. However, the problem of airborne object recognition by means of PBR is still unsolved. Recognition should be understood to mean the solution of the problem of assigning detected object to a certain class, i.e., a group of aircraft (AC) similar in their design features. Of particular interest is the recognition of propeller-driven aircraft of such classes as helicopter and propeller aircraft, since they have similar informative features (radar cross-section, speed and altitude). This makes recognition of such AC more complicated.

Recognition of propeller-driven objects in conventional active radars is based on the reflected signal structural feature analysis [5]–[7]. The signal reflected from the objects of these classes has a complex structure, which consists of a powerful signal component reflected from the fuselage and weaker signal components caused by rotating blades and hubs of the propellers [8]. In pulse radars, recognition of propeller-driven aircraft requires quite a long accumulation time and applying of recognition algorithms requiring high computation power [5].

In their turn, PBRs do not have such requirements that are typically applied to pulse radar signal parameters as PBRs use continuous signal for object illumination. Capabilities for helicopter detection and recognition by means of PBRs using GPS, DVB-T and FM signals as illumination ones have been extensively studied over the last years [9]–[11]. For helicopter recognition, the same features are used both in PBRs and in active radars. For successful and actual recognition, the information on rotary parameters for the main and tail rotors is required. However, the modulation components of the helicopter echo signal caused by tail rotor are weak or not at all noticeable in experimental measurements. The use of the main rotor parameters alone complicates the recognition process.

Problems arising from recognition of propeller-driven AC in PBR are mainly related to the parameters of third-party transmitter signals used as a radar illumination. The use of digital signals of terrestrial broadcasting appears more preferable than analog ones, since their frequency band is wider (and therefore, the range resolution is better) and their characteristics do not depend on the transmitted content (which ensures the PBR characteristics stability). Russia has a well-developed infrastructure with a large coverage area of digital terrestrial television (DTTV) of DVB-T2 standard. Signals of this standard are used as illumination for PBR developed in Saint Petersburg Electrotechnical University "LETI" and providing detection and tracking of moving objects, including helicopters and propeller-driven aircrafts [4], [12].

Solution to a problem of propeller-driven AC recognition will expand the PBR application area. The ability to recognize weakly distinguishable propeller-driven AC will make PBRs an effective tool for detecting and signaling unauthorized flights. This will allow, in particular, the integration of PBRs into the air traffic control systems of civil airports and private airfields for the purpose of flight operation safety.

**Research objective.** To solve a problem of propeller-driven AC recognition in PBRs it is necessary to carry out the helicopter and propeller-driven AC echo signal structure analysis, to define their informative features, develop an algorithm for processing echo signals reflected from propeller-driven AC. The processing algorithm efficiency is to be verified on experimental data obtained by means of PBR using DVB-T2 DTTV signals as radar illumination.

**Reflected signal structure.** Signal reflected from propeller-driven AC is unique from the point of view of radar recognition due to specifics of the secondary radiation. It is caused by reflections from the fuselage, rotor blades (main and tail for a helicopter) and rotor head. The most useful for recognition is the signal reflected from the rotating rotor blades, as in the frequency domain there are quasi-symmetric modulation components around the fuselage line. Such a multi-component signal structure is called micro-Doppler or micro-Doppler signature, i.e. mo-

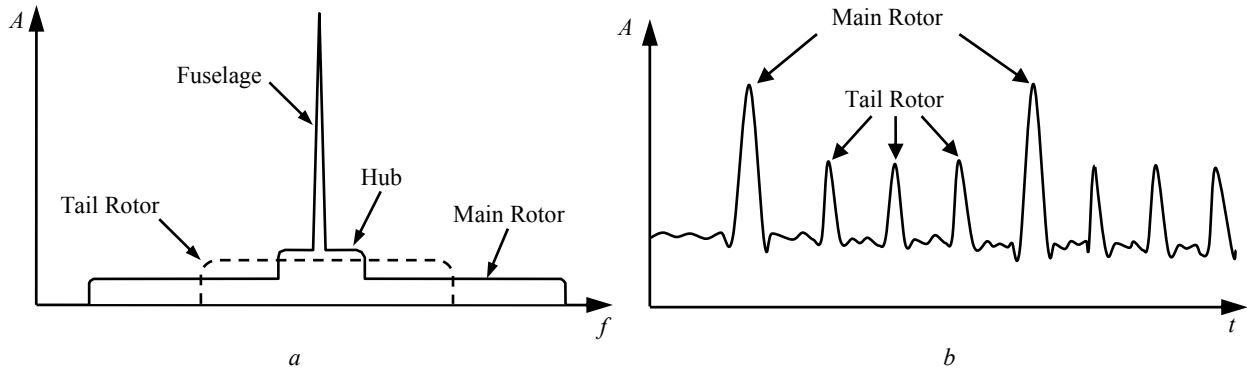


Fig. 1

tion characteristic containing the law of modulation of the Doppler frequency of an echo signal [13].

Micro-Doppler signature is represented as distribution in frequency and time domains. The typical structure of the amplitude spectrum for the signal  $A(f)$ , reflected from propeller-driven objects is shown in Fig. 1, *a*. The most powerful component corresponds to the reflection from the fuselage, while the quasi-symmetrical components around the fuselage line are caused by the blades and rotor hubs rotation. The approaching tip of the rotor blade corresponds to the component with the highest Doppler frequency, whereas the component with the lowest Doppler frequency results from the receding tip of the rotor blade.

The echo signal in the time domain consists of periodic modulation components (characteristic peaks) caused by rotating blades at a time when the blade is perpendicular to the direction of illumination. As an example, Fig.1, *b* demonstrates  $A(t)$  signal structure reflected from helicopter in the time domain. Characteristic peaks with bigger repetition interval correspond to reflections from the main rotor blades, and with smaller repetition interval correspond to reflections from the tail rotor blades of the helicopter. In turn, the echo signal of an aircraft with one propeller in the time domain contains one set of periodic components with the same period. These features can be used as informative for recognition of propeller-driven AC. Repetition period of modulation components  $T_m$  strongly depends on the AC propeller

actual parameters, i.e. rotation frequency  $f_r$  (or rotation period  $T_r$ ) and the number of blades  $N_b$ :  $T_m = 1/(f_r N_b) = T_r/N_b$ . Thus, this ratio determines the relationship of the echo signal features selected for recognition and the actual parameters of the propellers. As an example, we will provide calculation of the modulation components desired repetition period for the Mi-8 helicopter main rotor, which consists of  $N_b = 5$  blades and rotates with the frequency of  $f_r = 192$  r.p.m. or  $f_r = 3.2$  Hz. The repetition period of modulation components of the main rotor echo signal is to amount  $T_m = 1/(3.2 \cdot 5) = 62.5$  msec.

**Processing algorithm.** Fig. 2 provides block diagram of the developed algorithm for propeller-driven AC echo signal processing for the purpose of their recognition. The algorithm allows estimating parameters of the AC propeller rotation, determining the class and in some cases the type of aircraft, i.e. performing recognition. The input data for the algorithm are the samples of the two-dimensional cross ambiguity function (CAF)  $|\Psi(l, d)|$ , which, when implemented in PBRs, is calculated according to the expressions [14]

$$|\Psi(l, d)| = \left| \sum_{m=0}^{M-1} r_m(l) e^{-j2\pi d \frac{m}{M}} \right|; \quad (1)$$

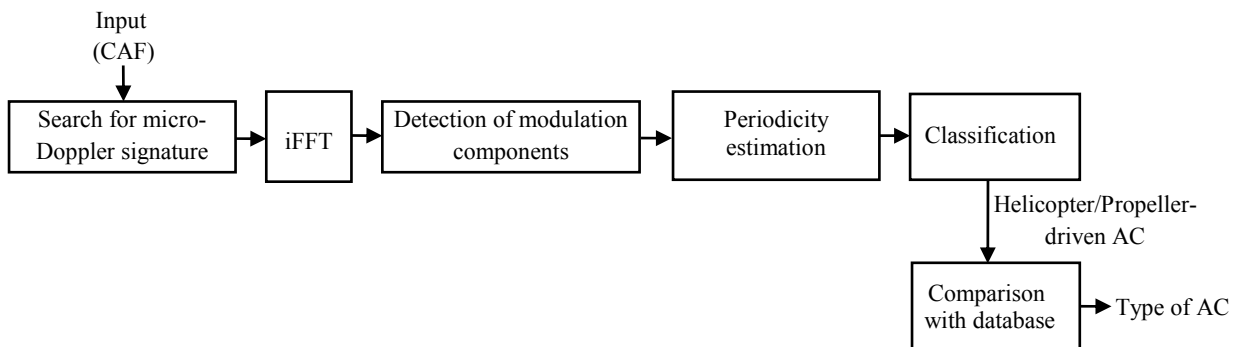


Fig. 2

$$r_m(l) = \sum_{n=0}^{N-1} s(mN+n)s_{\text{ref}}^*(mN+n-l), \quad (2)$$

where  $l$  is sampled delay;  $d$  is sampled frequency (Doppler) shift;  $M$  is the number of segments into which the signal is decomposed when processed;  $m = \overline{0, M-1}$  is the segment number;  $N$  is the number of samples of the received signal in the processed segment;  $n = \overline{0, N-1}$  is the sample number within the segment;  $s$  is the received signal;  $s_{\text{ref}}^*$  is complex-conjugate reference signal ("\*" is a symbol character for complex-conjugate).

When calculating the CAF, reconstructed reference copy of the transmitter signal, free of noise and distortion, is used as a reference signal  $s_{\text{ref}}$ . In addition, the received signal  $s$  first pass through adaptive filtering stage designed to suppress the direct signal and its powerful copies in the channel, arising due to reflection from local objects and multipath propagation. Detailed description of all the signal processing stages in PBRs is provided in [4].

Besides, the matrix  $X$  of the same dimension as the CAF array, which contains units in those cells where the targets are detected, arrives at the input of the algorithm from the target detector. To detect targets in PBRs, two-dimensional cell-averaging constant false alarm rate (Cell-Averaging CFAR, CA-CFAR) adaptive algorithm is used [4], [15]:

$$X = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1j} \\ a_{21} & a_{22} & \dots & a_{2j} \\ \dots & \dots & \dots & \dots \\ a_{i1} & a_{i2} & \dots & a_{ij} \end{bmatrix},$$

where  $i \in \overline{1, 2D+1}$  is a number of the line ( $D$  is a maximum frequency shift, the number of lines corresponds to the number of frequency shift elements  $2D+1$ );  $j \in \overline{1, L}$  is a number of column (the number of columns corresponds to the number of delay elements  $L$ ).

At the first algorithm step, on all the elements for delay in the matrix  $X$  of detected targets, there performed a search for the delay element  $l_{\mu D}$ , in which there is a micro-Doppler signature ( $\mu D$  comes from the English micro-Doppler), caused by the AC rotating parts. As a criterion for making a decision on micro-Doppler signature detection in the delay under investigation, the parameter  $c$  (the number of detections in one delay element) is used, which is set in relation to interference environment. If the number of detections

(amount of units in  $X$  matrix) in one of the delay elements exceeds the parameter  $c$  value, for further processing the CAF cross sections is selected in this delay:

$$l_{\mu D} = j \left| \sum_{i=1}^{2D+1} a_{ij} > c, \right.$$

where "|" is a symbol of condition.

For each CAF cross section, i.e. for each value of the delay  $l$ , the expression (1) represents the discrete Fourier transformation of the vector  $[r_0(l), r_1(l), \dots, r_{M-1}(l)]$  and is calculated by means of discrete fast Fourier transformation (DFFT) [14]. The result of DFFT of signal convolution (2) is their cross spectrum [16]. Thus, the CAF cross section is a vector of values  $\mathbf{W} = \Psi(l_{\mu D}, d)$  of the received and reference signal cross spectrum. Applying the inverse fast Fourier transformation (IFFT) to the CAF cross section at the next step of the algorithm, we obtain the received and reference signal cross correlation vector  $\mathbf{b}$  with the length of  $2D+1$  in the selected delay  $l_{\mu D}$ :

$$\mathbf{b} = F_D^{-1}[\mathbf{W}],$$

where  $F_D^{-1}$  is IFFT.

The obtained vector of cross correlation values can serve as an estimate of the propeller-driven AC echo signal and can be used to detect modulation components and estimate their periodicity. The detection of modulation components caused by blade rotation is performed using CA-CFAR one-dimensional adaptive detection algorithm the output of which is vector  $\mathbf{b}'$ , containing  $\mathbf{b}$  vector element numbers in which the detection of modulation components occurred.

At the next step, the modulation component repetition periods are evaluated. Instant vector is formed

$$\mathbf{t}_i = \frac{i}{\Delta f (2D+1)},$$

where  $i \in \overline{1, 2D+1}$  is frequency shift element number;  $\Delta f$  is frequency step when calculating CAF.

Elements that correspond to the  $\mathbf{b}'$  vector values are selected from the  $\mathbf{t}$  vector and a vector of instants of modulation components  $\mathbf{p}$  is formed. Next, we solve the problem of separating the detected modulation components into groups of periodicities with respect to repetition factor within the given confidence error according to the following system of hypotheses:

$$H_0 : \text{mod}[\mathbf{p}(k), \mathbf{p}(k')] > \Delta t;$$

$$H_1 : \text{mod}[\mathbf{p}(k), \mathbf{p}(k')] < \Delta t,$$

where  $H_0$  hypothesis specifies that the investigated modulation components are not periodic;  $H_1$  specifies that modulation components are periodic with the period of  $T_i$ ;  $k, k'$  are the  $\mathbf{p}$  vector investigated element numbers;  $\Delta t$  is the confidence error.

If the repetition periods of all the modulation components are similar, then the decision is made to detect one-propeller or two-propeller object with the same rotation period. Such object can be classified as "propeller-driven airplane" or single-propeller "helicopter". If the two groups of modulation components with different repetition period are observed, then the decision is made to detect the "helicopter" class object. In this case, the modulation components with longer repetition period are caused by reflections from the main rotor blades, and the modulation components with shorter period are caused by reflections from the helicopter rotor blades. The obtained estimates of the modulation component repetition periods can be used to further identify the AC type by comparing these values with the developed database.

**Experimental investigation.** Experimental campaign was performed by means of PBR developed in the Saint Petersburg State Electrotechnical University "LETI" [12]. The signal reflected from the Mi-8 helicopter was recorded by PBR located in the city on the roof of the building of the St. Petersburg Electrotechnical University "LETI". The signal of the first multiplex of the Leningrad Radio and Television Transmitting Center (LRTTC) on the 35th channel of the DVB-T2 standard (586 MHz) is used for radar illumination. The distance between the receiver and the DVB-T2 transmitter is 600 m, and the transmitter is allocated at the height of about 300 m. The helicopter was in the PBR observation sector at the distance of 2.5...3 km from the receiver position. Cross-ambiguity function in the "delay ( $\tau_b$ )-Doppler frequency ( $f_D$ )" coordinates calculated during the recorded signal processing, is shown in Fig. 3.

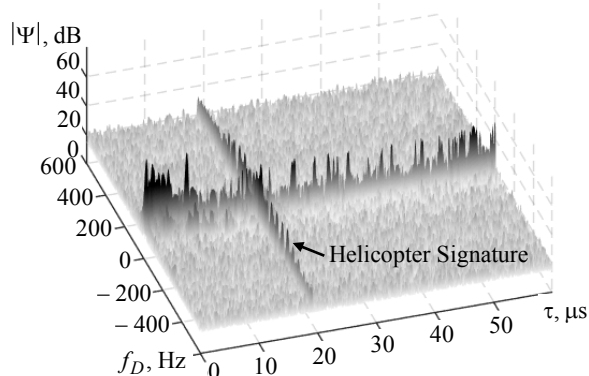


Fig. 3

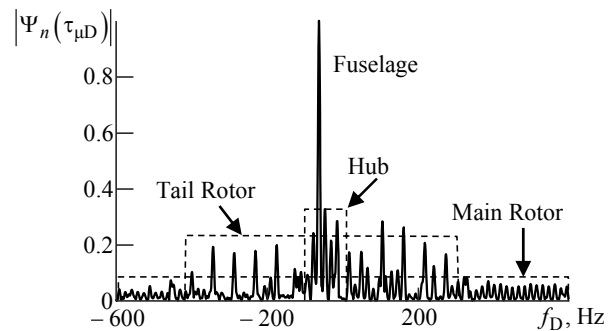


Fig. 4

The helicopter signature is clearly visible and can be extracted from the CAF. In the micro-Doppler signature of the helicopter, it is possible to distinguish the component of the signal reflected from the fuselage, and the Doppler spectrum expansion caused by the rotation of the main rotor and tail rotor blades (Fig. 4).

Fig. 5 shows the helicopter echo signal in time domain after Micro-Doppler signature conversion using IFFT. Modulation components with long repetition period of 62.44 msec are caused by reflections from the main rotor blades (triangular markers). The modulation components with shorter repetition period of 17.48 msec are caused by reflections from the helicopter tail rotor blades (square markers). The obtained estimates of repetition periods can be used for the helicopter classification by comparing with the typical parameters of the helicopters from the database. The derived values correlate with the theoretical repetition periods of the modulation components for the Mi-8 helicopter, which amount to 62.5 msec for reflections from the main rotor blades and 17.5 msec for the tail rotor blades.

The Cessna 172 airplane echo signal was recorded by experimental PBR located at the distance of 49.2 km from the transmitter. The signal of the second multiplex of the LRTTC on the 45th channel of the DVB-T2 standard (666 MHz) is used for radar illumination. The Cessna 172 airplane was located in the PBR observing sector at the height of 300 m at the distance of about 3.5 km from the receiver.

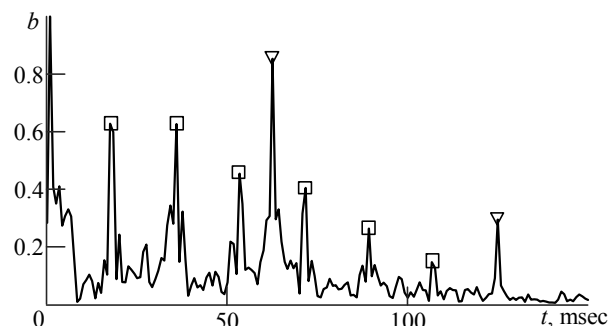


Fig. 5

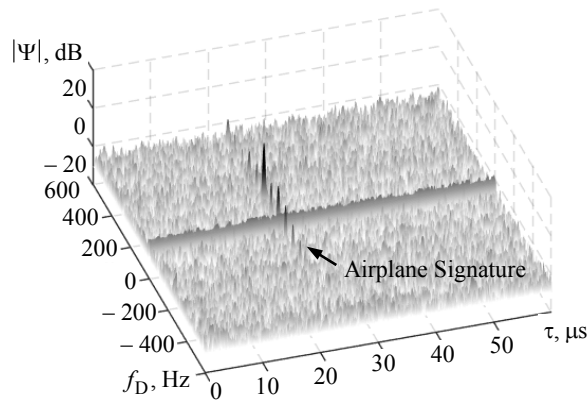


Fig. 6

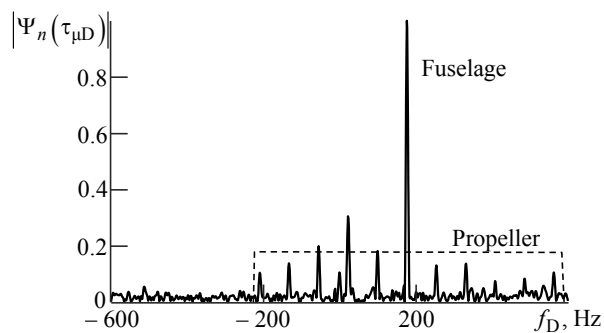


Fig. 7

The calculated CAF with micro Doppler signature of propeller-driven aircraft is given in Fig.6. The CAF values around the zero Doppler frequency were normalized for better visualization of the signature caused by the rotation of the airplane propeller blades.

The derived micro Doppler signature of the Cessna 172 airplane is provided in Fig. 7. It consists of the powerful reflection from the fuselage and the weaker components around the fuselage line, corre-

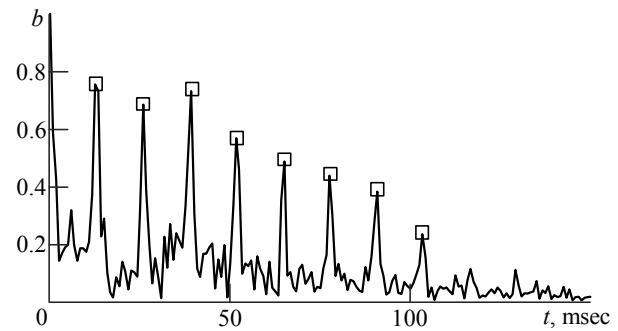


Fig. 8

sponding to the illumination signal reflection from the aircraft rotating propeller blades.

In the time domain in Fig.8 the Cessna 172 echo signal is shown, received after IFFT was applied to the micro Doppler signature. Only one group of periodic components with the same repetition period (square markers) was found. The derived value of the peak repetition period makes 13.3 msec, which strictly corresponds to the real value of the Cessna 172 three-blade propeller rotation period in its cruising flight ( $f_T = 1500$  r.p.m.).

**Conclusion.** The proposed echo processing algorithm can be used for recognition of propeller-driven AC in PBR using third-party transmitters for radar illumination. The experimental results have demonstrated the algorithm performance efficiency. However, to evaluate the efficiency and probabilistic characteristics, as well as to adjust the proposed algorithm for processing echo signals reflected from AC with different propeller configurations, at various bistatic angles and aspect angles of AC, a large number of additional field or simulation experimental investigations are required.

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