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Drone Detection Technologies

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Abstract: The use of drones for both military and civilian purposes has significantly increased in recent years. Their affordability and extensive capabilities for solving a wide range of tasks, including entertainment, make them very attractive to a broad audience. Unfortunately, incidents involving drones are constantly increasing, necessitating the introduction of regulatory requirements for their use in conjunction with the use of technologies for their detection, classification, tracking, and eventual interception. This article attempts to classify existing unmanned aerial vehicles based on their parameters and purposes. The article also analyzes the results of testing optical-electronic, thermal imaging, acoustic, radio frequency, and radar systems for drone detection. The technologies discussed can be used simultaneously to increase the effectiveness of drone detection.

Keywords: Drone classification, drone detection, opto-electronic, thermal imaging, acoustic, radio frequency, radar systems.

1. Introduction

With the development of technologies in the 19th and 20th centuries, scientific progress inevitably led to revolutionary discoveries that enabled humanity to achieve one of its millennia-old dreams – flight in the sky. The emergence of manned aircraft was followed by the idea of creating an unmanned one, which could be remotely controlled. In the modern world, unmanned aerial vehicles are commonly known as "drones". The beginning of the drone era can be traced back to 1917 when the first radio-controlled aircraft (drone) called the "Aerial Target" was produced in the United Kingdom in collaboration with the United States [1]. The commonly accepted term "drone", which is still in use today, was introduced in 1935, inspired by the designation of the British development "DH.82B Queen Bee". According to some sources, this is considered the first modern drone [1].

Over time, these aircraft have solidified their position as a significant achievement in the field of aviation technology and gradually gained popularity. The development of information technologies in recent decades has further contributed to their integration, making them extremely user-friendly.

Today, drones are used for various purposes – military, industrial, humanitarian, recreational, and others. One of their main advantages is their capability for easy and remote operation, making them extremely effective in complex conditions such as reduced visibility, strong winds, hazardous terrains, etc. Additionally, drones provide a unique opportunity for aerial observation of hard-to-reach places where traditional maneuvers with other aircraft are impossible. This makes them effective not only for observation but also for detecting objects and people [2], environmental protection, disaster and emergency response, delivery of materials (life-saving products, medical supplies, etc.) to hard-to-reach areas, and many other purposes [3].

With the advancement of technology, drones are becoming increasingly diverse in shape, type, propulsion method, size, flight altitude, and other characteristics. As a result, classifying drones becomes a more challenging task. Currently, there are numerous classifications attempting to standardize drones based on certain characteristics. The EU proposes a similar classification, which aims not so much at practical drone classification but rather focuses on imposing rules and restrictions regarding their use [4].

In the context of this discussion, we propose a classification of drones based on their functional characteristics and areas of application. Acknowledging the richness of variations and the dynamic development of unmanned aerial vehicles, our goal is to provide a foundation for further supplementation and refinement, thus accurately reflecting the current state of drone technology. The anticipated diversity of drones necessitates the development of a comprehensive and adaptive classification model capable of adapting to the continuous innovations in the sector.

The emergence of cheap and user-friendly unmanned aerial vehicles has enabled their widespread use for both civilian and military purposes. This is due both to the developed constructive solutions and night vision technologies [5, 6, 7]. Unfortunately, there are also incidents with drones, as the damage they cause is significant [8]. These incidents can be both accidental and intentional, necessitating the development of systems for detection, recognition, and, if necessary, the blocking of drones. Detection technologies are also diverse, possessing various technological characteristics that make them effective under certain conditions and ineffective under others. The most common drone detection technologies utilize radar, video cameras, thermal cameras, radio receivers to detect drone communication, microphones, and combinations thereof [9, 10, 11, 12].

The current article proposes a tentative classification of drone types and analyzes the results of testing optical-electronic, thermal imaging, acoustic, radio frequency, and radar systems for drone detection. The technologies examined can find application in the design and construction of counter-drone systems.

2. Drone Classification

Over the past few years, the utilization of drones has increased manifold. Unlike manned aircraft, they are highly cost-effective, capable of prolonged aerial presence, and are finding an expanding array of practical applications. Drones exhibit significant diversity in their technical and physical attributes. Depending on their operational domain, drones can be categorized as airborne, terrestrial, or aquatic. Presently, the most prevalent and extensively employed are airborne drones. These can further be classified based on their flight technology, construction materials, control mechanisms, payload capacities, flight altitudes, ranges, and various other factors. The practical utility of a drone is contingent upon its specific technical specifications.

One of the most important characteristics of drones is their weight, as it directly affects many flight-related factors (such as endurance, altitude, stability, etc.), both technically and legally. Primarily, based on weight (including the own weight and payload), drones can be classified into weight categories as shown in Table 1. This categorization has been performed considering the regulations imposed by the EU in [4].

Table 1. Drone classification based on weight.

Very lightweight drones (T1)	**Lightweight drones (T2)**	**Medium-weight drones (T3)**	**Heavy drones (T4)**	**Super heavy drones (T5)**
up to 250g.	250g. to 900g.	900g. to 4kg.	4kg. to 25kg.	over 25kg.

Functional categorization is another important step in classifying drones. As the first and most crucial part of functional classification, they can be primarily divided into two types: drones with military purposes (military drones) and drones with civilian purposes (civilian drones).

2.1. Military Drones (M)

According to their purpose, the following distinct groups can be distinguished here:

- Reconnaissance (M1): This type of military drones is used for reconnaissance purposes, terrain mapping, surveillance, etc.
- Tactical (M2): These military drones are used for defense and offense purposes.
- Logistics (M3): Their role is the delivery of equipment, life-saving, and other materials for the needs of the military.
- Hybrid (M4): These can be models that represent a combination of two or more types listed above.
- Other (M5).

2.2. Civilian Drones (C)

Civil drones can be classified into the following groups:

- Hobby Drones (C1): This group includes non-specialized drones intended for general purposes. Typically, they are small in size and do not have specialized equipment. They are mainly used by hobby photographers and enthusiasts for entertainment purposes. This category encompasses drones with very small dimensions.
- Media and Photography Drones (C2): This group encompasses all drones intended for media purposes and professional photography. The difference from hobby drones is expressed through the presence of professional equipment, larger size, and a significantly greater flight range. Here, drones can range from very small to medium-weight.
- Industrial Drones (C3): Drones in this group are used in the industry for inspection and management of machinery and structures in hard-to-reach areas and under adverse conditions for humans. Depending on their weight, they can range from very small to super heavy. This depends on the tasks they perform.
- Delivery and Logistics Drones (C4): These drones are specialized in delivering various types of parcels. Particularly popular lately are

applications in the pharmaceutical field, where drones deliver necessary medications to individuals with limited mobility. They can also deliver various types of purchases and materials within urban areas. Given the cargo they need to carry, these drones are typically lightweight to heavy. Super-heavy drones are avoided for this purpose due to legal restrictions and the urban environment in which they operate.

- Topographic and Geodetic Drones (C5): These drones are used for mapping and geodetic surveys, and with appropriate equipment, they can provide high-quality 3D models of both terrestrial terrain and buildings and structures. These drones are typically lightweight to medium-weight.
- Agricultural drones (C6): They are used for monitoring and analysis of agricultural terrains and wooded areas. They can monitor the health of crops, identify areas affected by diseases or pests, and assess water needs. They can also be equipped with spraying systems for precise application of fertilizers, pesticides, and herbicides onto crops. A full range of drones from very lightweight to super heavy can be used in this category.
- Security and Defense Drones (C7): These aerial vehicles are used by law enforcement agencies and fire departments for surveillance and protection of the population. They are used for traffic control, security, and fire safety. In this class, drones typically range from lightweight to heavy.
- Search and Rescue Drones (C8): These drones are equipped with special equipment designed for rescue and search missions, such as those conducted by mountain rescue services. This equipment includes sensors and cameras for detecting objects in hard-to-reach and remote areas. In this class, drones typically range from lightweight to heavy.
- Research (Scientific) Drones (C9): These drones are used by almost all researchers in the field of science to gather information. What is specific to them is that they are equipped with special equipment needed by researchers in a given area (meteorology, volcanology, biology, etc.). Given the equipment, these drones can range from lightweight to super heavy.
- Others (C10): This category includes drones with different applications or those representing a combination of the aforementioned categories.

The relationship between the functionality of drones and their weight is visualized in Table 2.

Table 2. Classification of drones based on their weight and functionality.

Weight / Functionality	T1	T2	T3	T4	T5
M1	x	x	x	x	x
M2	-	-	x	x	x
M3	-	-	-	x	x
M4	x	x	x	x	x
M5	x	x	x	x	x
C1	x	-	-	-	-
C2	x	x	x	-	-
C3	x	x	x	x	x
C4	-	x	x	x	-
C5	x	x	x	-	-
C6	x	x	x	x	x
C7	-	x	x	x	-
C8	-	x	x	x	-
C9	-	x	x	x	x
C10	x	x	x	x	x

3. Drone detection technologies

The drone detection systems are based on the following technologies: optical-electronic, thermal imaging, acoustic, radiofrequency, and radar. Each of these technologies has specific advantages and disadvantages and is suitable for detecting certain types of drones. The principles of operation of these technologies, as well as results from their practical use, are demonstrated in the present article.

3.1. Optical-electronic system

One of the most commonly used technologies for drone detection is video surveillance, allowing for a moderate detection range and acceptable localization accuracy. This method is inexpensive and easily implementable, but it is ineffective during low light conditions or when visibility is reduced due to clouds or air pollution.

Various algorithms exist for processing video recordings to detect and recognize drones, but one of the most effective ones today is the YOLO software, which utilizes machine learning algorithms and artificial intelligence to make decisions regarding the presence or absence of drones. For this software to work well, the video needs to be of high quality. The advantage of the algorithm over others is that it allows for simultaneous detection and recognition of the drone. Example results from the operation of the YOLO software are shown in Figures 1 and 2, where flying objects are detected and recognized. For the experiment, the XMART OPTICAL FLOW SG900 drone with dimensions of 29x29x4 cm was used.

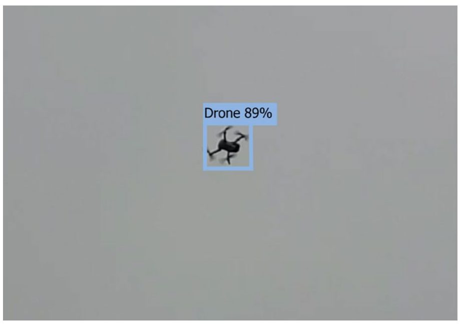

Fig. 1. Detecting a drone at a distance of 30 meters from the video camera

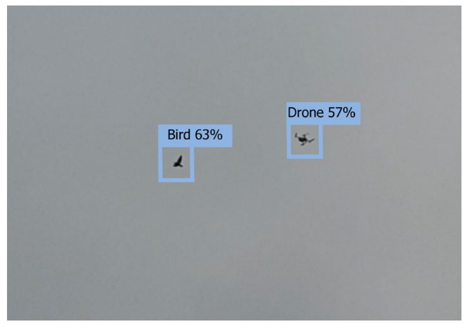

Fig. 2. Detecting a drone at a distance of 50 meters from the video camera

The obtained results indicate that the algorithm detects and recognizes the drone, with a higher probability of recognition when the drone is closer to the camera and the image quality is higher [11]. The same algorithm can be applied for detecting drones through processing thermal images obtained from a thermal camera, with successful recognition requiring the use of a specially trained model for this purpose.

3.2. Thermal imaging system

The drawback of detecting unmanned aerial vehicles during the dark part of the day can be compensated for by using thermal cameras, which are not affected by illumination but rely solely on the infrared emission of heated objects [13]. By utilizing thermal images captured by a drone XMART OPTICAL FLOW SG900 during flight and applying a video processing algorithm, it is possible to detect the drone, as shown in Fig. 3 and 4.

The distance between the camera and the drone is 3 and 9 meters.

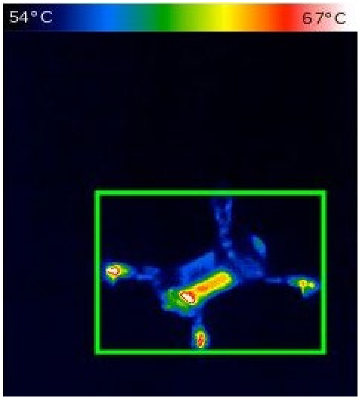

Fig. 3. Detecting a drone at a distance of 3 meters from the thermal camera

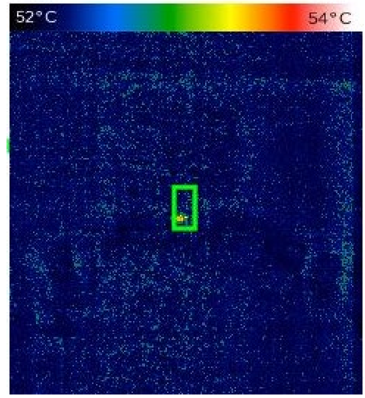

Fig. 4. Detection of a drone at a distance of 9 meters from the thermal camera

This technology is convenient for use during the dark part of the day, but it also has its drawbacks such as: a small usage perimeter, difficulty in drone recognition, and issues with detection in the presence of multiple heated objects. The technology is suitable for use in combination with another technology.

3.3. Acoustic system

Acoustic sensors represent another technology for drone detection and can be implemented using inexpensive microphones capable of capturing and identifying the distinct sound characteristics of different drone rotors [10]. These systems are effective both during daylight hours and in conditions of poor visibility. However, a significant drawback of acoustic systems is the relatively short detection range of drones due to the rapid attenuation of sound signals in space. Acoustic systems are well-suited for monitoring small areas, such as inter-block spaces in urban environments. Expanding the operational range of an acoustic system is achieved by deploying multiple sensors distributed over a large area.

An algorithm has been developed in the MATLAB environment to explore the capabilities of this technology, processing audio signals from UAVs. To test the developed algorithm, audio signals obtained from a parabolic microphone (Fig. 5) during the flight of the XMART OPTICAL FLOW SG900 drone were used. A portion of the audio signal is shown in Fig. 6.

Fig. 5. Parabolic microphone

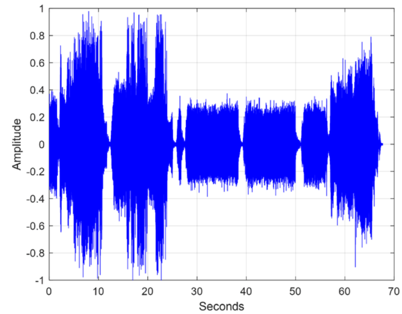

Fig. 6. Audio signal from drone

For the processing and subsequent recognition of the drone, signal processing needs to be performed in both the time and frequency domains of the signal. The spectrum of the signal, as well as its spectral characteristics, are shown in Figures 7, 8 and 9. To detect and recognize the drone, it is necessary to evaluate some of the characteristics of the audio signal.

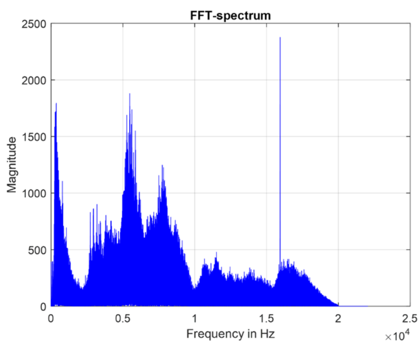

Fig. 7. Signal Spectrum by FFT

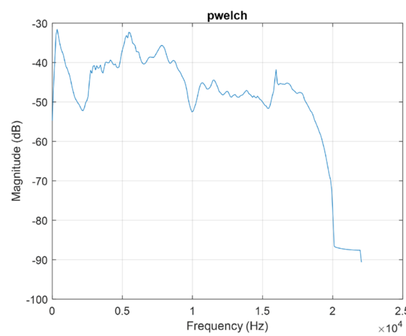

Fig. 8. Signal Spectrum by Pwelch

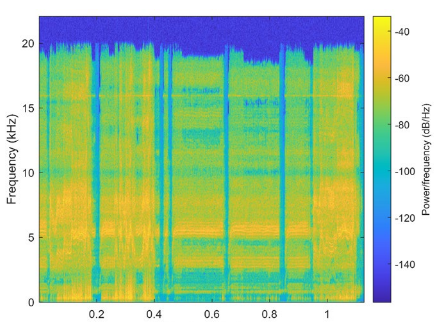

Fig. 9. Spectral Characteristic

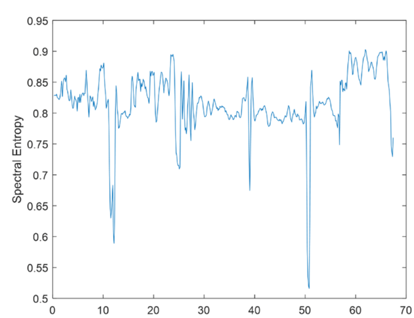

Fig. 10. Spectral Entropy

On Figures 10, 11 and 12, the spectral Entropy, the spectral Centroid, the spectral Roll-Off characteristics are shown. Figures 13 and 14 present the Zero-crossing rate and the Kurtosis of the signal.

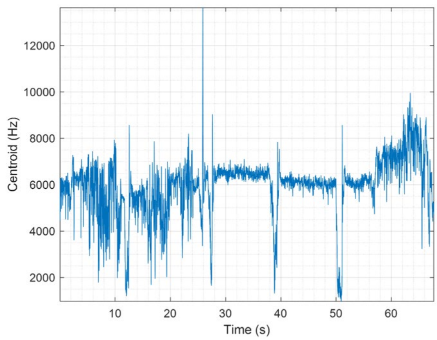

Fig. 11. Spectral Centroid

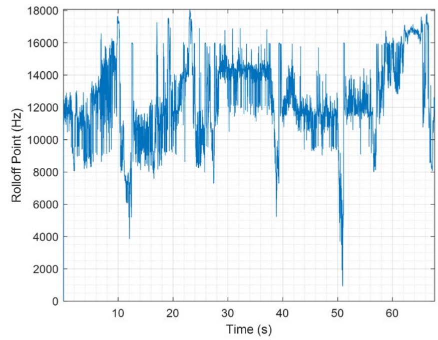

Fig. 12. Spectral Roll-Off

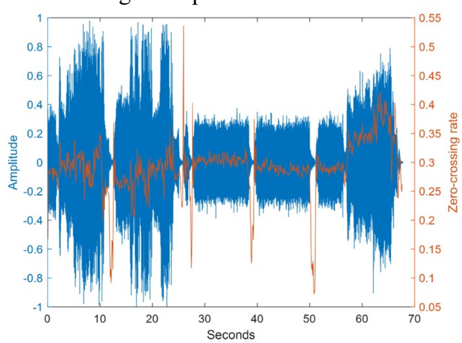

Fig. 13. Zero-crossing rate

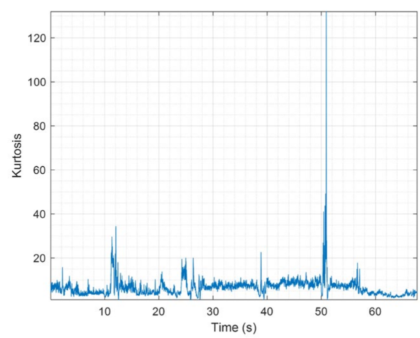

Fig. 14. Kurtosis

Figures 15 and 16 present the Mel Frequency Cepstral Coefficients and the Gamma Tone Cepstral Coefficients of the signal for time from 40.8 to 45.3 s.

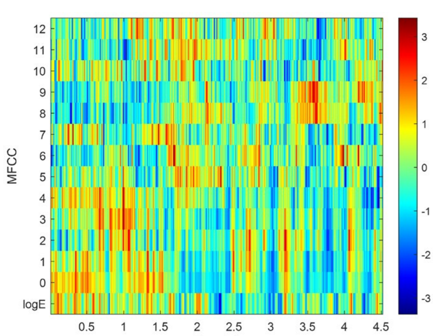

Fig. 15. Mel Frequency Cepstral Coefficients

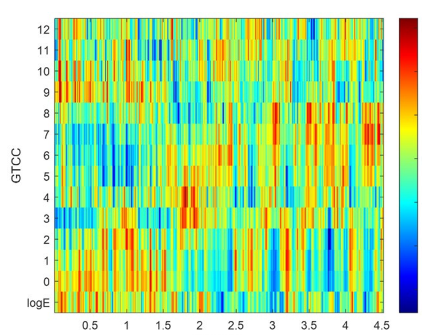

Fig. 16. Gamma Tone Cepstral Coefficients

Detection of drones through analysis of their audio signals can be effectively achieved by using spectral diagrams and Mel Frequency Cepstral Coefficients (MFCCs) as forms of visual representations. These visual representations serve as the basis for training models of the YOLO (You Only Look Once) algorithm, which is designed for object recognition in images. Once trained with drone-specific audio-visual data, YOLO neural networks become capable of identifying audio signals from drones. This approach requires converting the audio information into spectral diagrams or images of MFCCs, which can then be analyzed by YOLO for efficient and rapid drone recognition based on their audio characteristics.

3.4. Radio Frequency System

The Radio Frequency (RF) approach to detecting and classifying drones is applicable to radio-controlled drones or drones that support radio communication with the control center [9]. By utilizing the radio frequency characteristics of drones, they can be detected, identified, and categorized. Applying Software Defined Radio (SDR) for processing radio signals from drones is a relatively inexpensive and convenient way to detect and recognize them. By receiving signals from the drone's radio controller through high-gain signal reception antennas combined with highly sensitive receiving systems, drone detection at long distances is achieved (Fig. 17). In the presence of suitable equipment for recognizing the radio-controlled signals of the drone, they can be jammed to block the drone's control or more powerful control radio signals can be transmitted, allowing the drone's control to be taken over by an anti-drone system.

Through software-defined radio PlutoSDR, a recording of the control radio signal for the PHANTOM 3 ADVANCED drone was made, and with the help of an algorithm implemented in MATLAB, this radio signal was detected. The spectrum of the signal in the presence of the drone, obtained with FFT, is depicted in Fig. 18, where the signal from the drone exhibits a clearly pronounced peak.

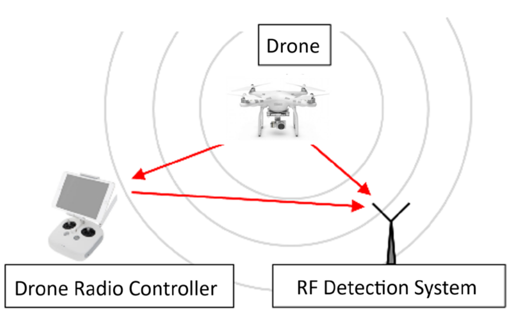

Fig. 17. Experiment topology

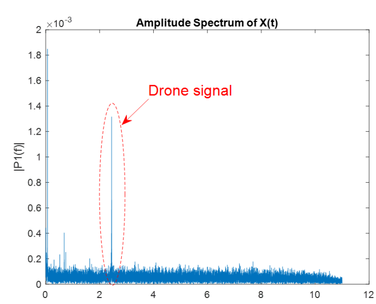

Fig. 18. Signal spectrum in the presence of a drone

Automatic detection of this frequency component can be achieved using the Constant False Alarm Rate (CFAR) detector. For this purpose, a program was created to obtain the spectrum of the signal based on Fast Fourier Transform (FFT), followed by peak frequency detection using the CFAR detector in the range around 2.4 GHz (Fig. 19). The spectrogram of the signal is shown in Fig. 20.

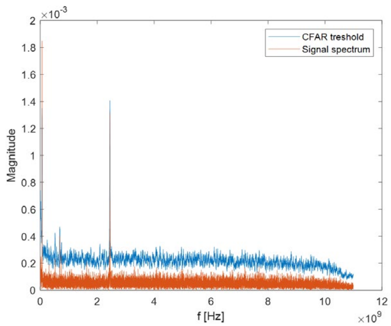

Fig. 19. RF Detection

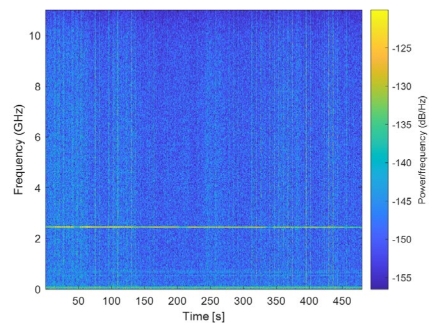

Fig. 20. Signal spectrogram

3.5. Radar System

Radar systems are complex and expensive technologies used for detecting relatively large UAVs, constructed with radio-transparent materials and flying at high speeds along ballistic trajectories at high altitudes. Radars operate effectively regardless of environmental factors and lighting levels, but they do not possess good classification capabilities. Radar detection principles can be applied to all possible configurations, including monostatic, bistatic, and Forward Scattering Radars [12].

To test the capabilities of detecting UAVs with forward scattering radar, an SDR with a GPS signal from a GPS satellite during the passage of an airplane was used (Fig. 21). As the airplane crossed the radio barrier between the satellite and the receiver (Fig. 22), it briefly blocked the GPS signal (Fig. 23).

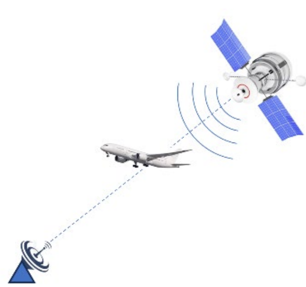

Fig. 21. Forward Scattering Radar

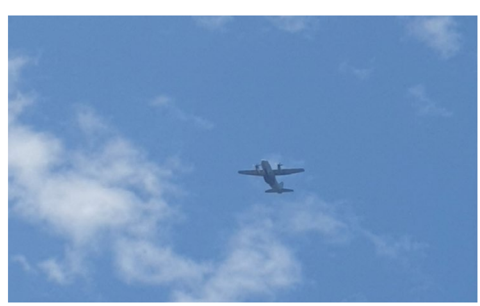

Fig. 22. Aircraft crossing the radio barrier GPS-SDR

After appropriate processing of the GPS signal in the MATLAB environment, the result shown in Fig. 24 is obtained, indicating the moment of crossing the radio barrier.

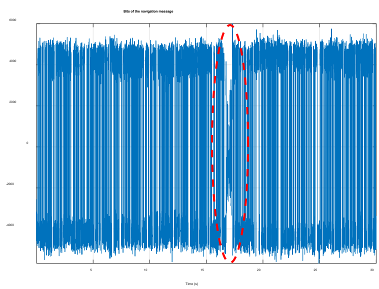

Fig. 23. GPS signal at the moment of passing aircraft

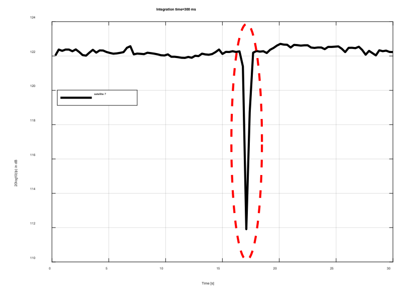

Fig. 24. GPS signal after integrating the signal with a sliding window

4. Conclusion

The investigated technologies for drone detection possess various advantages and disadvantages, making them applicable for detecting drones with different technical parameters and characteristics. The discussed technologies can find applications in the design and construction of counter-drone systems. Combining these technologies would significantly enhance the process of detecting and recognizing drones.

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