Detection Possibility of UAVs using Acoustic Camera

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***Abstract*— Over the past decade, a huge increase in production and operation of UAVs has been present on a global scale. To maintain the required level of safety and to accommodate the expanding traffic, the governments worldwide have implemented regulations to operations of UAVs. Nonetheless, in recent years there have been numerous safety and security incidents with UAVs which prompted an increase in research of surveillance and interdiction methods tailored for UAVs. Detection of UAVs using acoustic camera, which is primary topic of this paper, is possible due to UAV's propeller noise which is predominant noise source, at least in multicopter UAVs. We performed a detectability test of commonly used custom made UAV type – multirotor with 6 motors. We concluded that small multirotor UAVs can be detected with acoustic camera, human interpreter is necessary for detection due to the background noise, maximum range of detection can be greater than visual detection, and UAV detectability depends on UAV noise spectrum, its ratio to background noise, dynamic range of acoustic camera, and its frequency resolution.**

Keywords: UAV; acoustic camera; surveillance; detection.

I. Introduction

Over the past decade, a huge increase in production and operation of UAVs has been present on a global scale. According to Federal Aviation Administration (FAA) Aerospace Forecast for fiscal years 2017-2037 there are currently over 1.1 million registered UAVs in the United States (US). By the year 2021, in the United States alone, the number of registered UAVs is expected to reach 6 million units. Of these, three quarters will be hobbyist UAVs and model aircraft in the 0.25kg – 25kg category [1].

To maintain the required level of safety and to accommodate the expanding traffic, the governments worldwide have implemented regulations to operations of UAVs. In 2012 US government regulated operation of UAVs by publishing *Public Law 112-95 - FAA Modernization and Reform Act of 2012* [2]. Operation of UAVs in Europe has been regulated by the act of European Comission in 2008 with *Regulation (EC) No 216/2008* for UAVs heavier than 150 kilograms, and with national regulations for UAVs lighter than 150 kilograms [3]. In 2017, however, a new regulation was proposed with the purpose of regulating all categories of UAVs in European Union and it is expected to be adopted during the 2018 [4].

Notwithstanding the attempts at regulating the UAV operations, the increase in number of operations alone has increased the probability of incidents. In [5] UAV sighting reports published by FAA dating from December 17, 2013 to September 12, 2015 were analyzed. FAA reports were organized in two categories: *Sightings*, which included incidents where a pilot or an air traffic controller spotted an UAV flying within or near the flight paths of manned aircraft though not posing an immediate threat or collision, and *Close Encounters*, where a manned aircraft came close enough to an UAV that it met the FAA's definition of a "near mid-air collision" or close enough that there was a possible danger [5]. They have analyzed 921 incident reports and deduced that 35.5% of recorded incidents were *Close Encounters* and that over 90% of all incidents occurred above allowed maximum altitude [5].

For safety and security reasons it is necessary to develop methods for detection and monitoring of UAV operations in predetermined areas. Conventional methods of UAV detection are via radar, visual detection, thermal or acoustic sensors. Radar detection of UAVs based on differentiating Doppler signatures of various UAVs was successfully performed by [6] and [7], however, there are obvious difficulties in using this method in urban areas. Visual detection method by analyzing images gained from camera using image processing algorithms was proven somewhat successful, with shortcomings typical of visual identification systems, namely false positives in case of other flying objects (e.g. birds) [8].

Another method of UAV detection is thermal imaging that can be used for ground-based detection or for airborne collision avoidance during night-time operations. To prove that UAV detection using thermal imaging can be used as a viable detection system, thermal images obtained via FLIR Lepton micro thermal camera which was mounted on a Raspberry Pi processing unit were analyzed [9]. UAVs used for testing were *DJI Phantom 4*, *Parrot AR.drone 2*, and custom made hexacopter which has been used also for this test.

Beside conventional methods of detection, possibility of detecting UAVs controlled via wireless devices (such as *Parrot AR Drone*) was successfully tested [10]. Authors have successfully detected and gained control of targeted drone as third party users. One shortcoming of this detection method is requirement of wireless receiver installed on UAV.

Detection via acoustic sensors relies on sound emission of different units. Authors of [11] state that UAV detection with acoustic array, unlike radar detection and visual detection methods, does not depend on the size of observed object for detection, but rather on the sound of the engine. For their method, however, a requirement is a comprehensive database of UAV sounds.

Detection of UAVs using acoustic camera, which is primary topic of this paper, is possible due to their propeller noise which is predominant noise source, at least in multicopter UAVs. Propeller noise is composed of tonal and broadband components. Tonal component contains basic frequency and harmonics. The basic frequency f_1 or BPF (blade pass frequency) is the product of propeller rotation speed and number of propeller blades [12]:

$$BPF = N_R N_B 60^{-1}, \quad (1)$$

where is:
BPF - basic frequency of tonal propeller component,
N_R - propeller rotation speed (rotations per minute),
N_B - number of propeller blades.

Beside base frequency harmonic components also appear [12]:

$$f_N = f_1 N, \quad (2)$$

where is:
f_N - frequency of the n-th harmonic,
f_1 - basic tonal frequency,
N - number of particular harmonic.

Besides propeller noise, UAV noise consists of airframe and structure borne noise. Airframe noise is the result of air flow (wind around airframe). It is of the broadband flow mixing type except where a resonant cavity is formed. Its main characteristic is a great dependence on UAV speed. In multirotors this type of noise is quite low. Structure borne noise results from airframe vibrations. Various vibration modes excite structural modes. Acoustic space again has its acoustic modes that are excited by structural modes. This noise is quite complex and in UAV operations it doesn't have a great importance.

The primary scope of this paper is detection possibility of UAVs using acoustic camera. In next section of the paper we describe the methods and apparatus used for the test. In section three we show and interpret results of the test, and in the final section we draw conclusions and suggest ideas for future work.

II. METHOD AND APPARATUS

A. Test track

In order to test the ability of acoustic camera to detect small airborne UAV, we flew custom built UAV over a 170 m long test track (Fig. 1). The goal was to determine at what distance the UAV could be detected without trying to identify it. UAV was flown at the approximately 15 – 45 m above ground level and at a steady velocity of around 2 m/s. The test was performed on a relatively cold winter day (4 °C) with little to no wind. The terrain of the polygon was grassy, without significant noise sources and without any sound sources with predominant tonal components. The test was performed in the early afternoon. Equivalent A-weighted residual (background) noise was 42.5 dB with 41.3 dB exceeded for 99 % of the measured time.

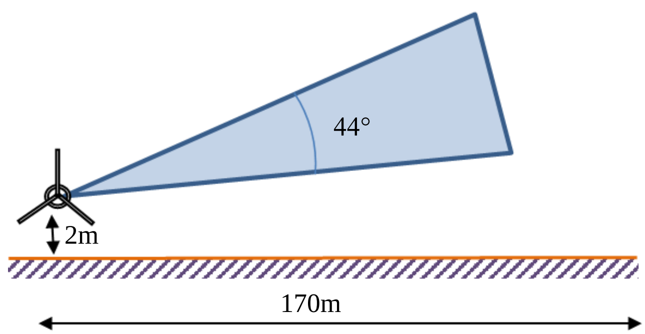

Figure 1. Test track

B. Acoustic sensor

For this test an acoustic camera produced by Faculty of Mechanical Engineering from Ljubljana, called SoundEye, has been used. The SoundEye consists of a microphone array and an optical camera in the centre. It can work in two different configurations, basic (Fig. 2, left), with 30 microphones equally distributed on the circular disc carrier, and extended, with 54 microphones – 3 flat extensions with 8 microphones each attached to the basic circular carrier at the angle 120° to each other (Fig. 2, right). The camera has fixed field-of-view (FOV) angles, a horizontal FOV of 58° and a vertical FOV of 44° (these are angles at which the scene is covered by both optical and acoustic camera). Detailed camera specifications can be found in Table 1.

TABLE 1. SoundEye Acoustic Camera Specifications

Specification	Description
Function	Imaging device used to locate and characterize sound sources
Producer	Faculty of mechanical engineering, Ljubljana, Slovenia
Configuration	Basic and extended
Number of microphones	30 (basic), 54 (extended)

Microphone frequency range	20 Hz – 20 kHz
Mapping frequency range	800 Hz – 12.5 kHz (basic), 100 Hz – 12.5 kHz (extended)
Sampling frequency of AD converter	48 kHz
Sampling resolution	16 bit/sample
Algorithm	Cross Spectral Matrix Beamforming
Analysing spectrum	1/1 octave, 1/3 octave, FFT
Optical/acoustic covering angle	± 58° horizontal, ± 44° vertical
Optical camera resolution	
Optical camera frame rate	
Operating distance	
Temperature range	
Humidity range	
Mains supply	
Disc diameter	
Extension length	
Weight	

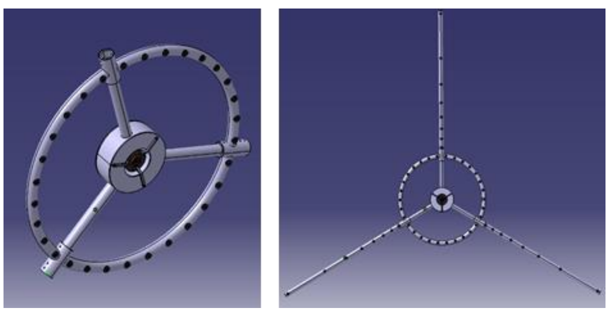

Figure 2. Two configurations of acoustic camera

The working principle of acoustic camera is based on a microphone array. The signals from the microphones are acquired simultaneously or with known relative time delays to be able to use the phase difference between the signals. As the sound propagates in the air at a finite known speed, a sound source is perceived by the microphones at different time instants and at different sound intensities that depend on both the sound source location and the microphone location. One of the methods to obtain an acoustic image from the measurement of the microphone array is to use beamforming. By delaying each microphone signal relatively to each other and adding them together, the signals coming from a specific direction are amplified while signals coming from other directions are canceled. The power of this resulting signal is then calculated and reported on a power map at a pixel corresponding to the specific direction. The process is iterated at each direction where the power needs to be computed. The algorithm to obtain acoustic picture used by SoundEye acoustic camera is Cross Spectral Matrix Beamforming. The working principle is presented graphically in Fig. 3.

Dynamic range of acoustic image (the ratio of the largest to the smallest intensity of sound that can be presented, measured in decibels) depends on the frequency of the sound source. For the frequencies above the 1000 Hz, dynamic range is 24 dB, while for the lowest frequencies is smallest – at the frequency of 100 Hz it is about 2 dB. This understanding is crucial for interpretation of acoustic images.

Next three figures present examples to better understand the interpretation of acoustic images. Directivity function of acoustic camera for a certain angle depending on the frequency is presented in Fig. 4. For this theoretical example extended configuration of camera is used and the source that emits white noise (random signal having equal intensity at different frequencies, giving it a constant power spectral density) is situated right in the middle of the camera's FOV at the distance of 100 m (far field). Fig. 4 shows the ability to distinguish the emitted sound levels of a single source at a selected frequency. The range of angles on the vertical axis is chosen to correspond to the horizontal FOV of acoustic camera and is equal to 58°. The angle of 90° is situated at the middle of the axis. Based on the calculation, the camera would show the acoustic image of the same size at a given frequency as presented in Fig. 4. For example, at the frequency of 1000 Hz the red area (highest level) will be

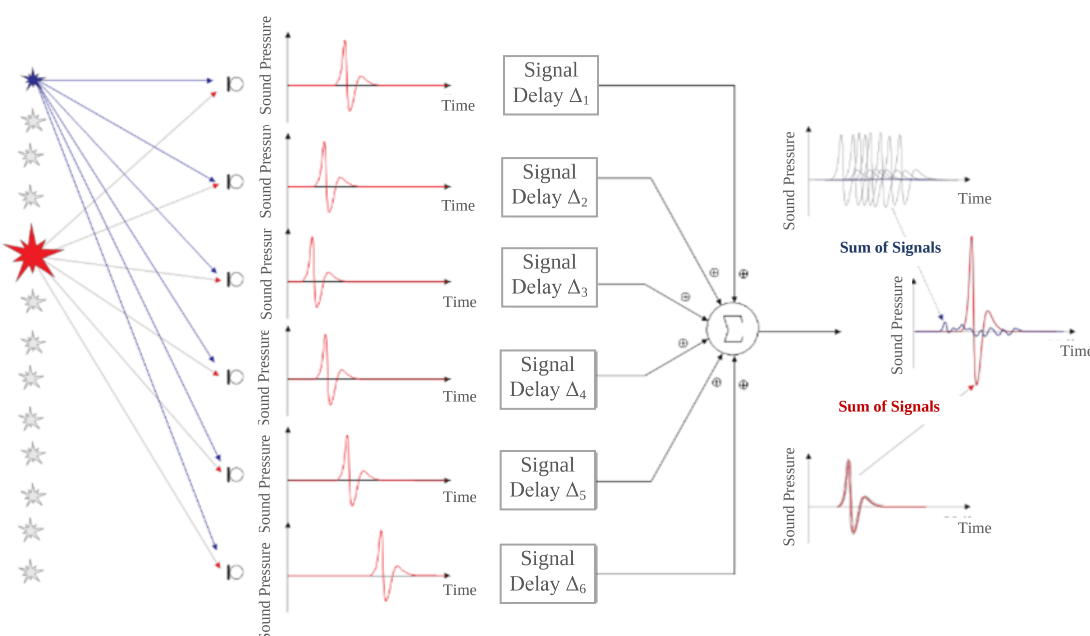

Figure 3. Work principle of acoustic camera

slightly larger than the red area at a frequency of 10000 Hz, although the noise emission at both frequencies is the same. The ratio between dark red and dark blue colour is 24 dB. At the frequency range between 1000 and 12500 Hz, the dynamic range of the acoustic image is 24 dB. This does not apply to a frequency range below 1000 Hz.

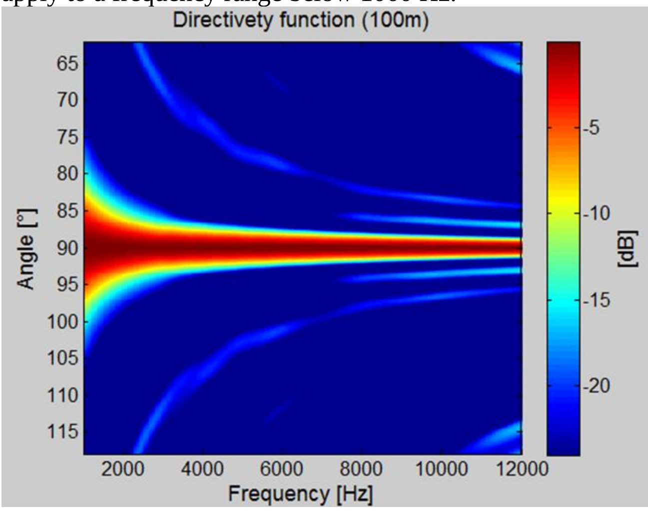

Figure 4. Directivity function of acoustic camera in the frequency range 1000 - 12000 Hz with acoustic image dynamic range of 24 dB

Fig. 5 shows directivity function of acoustic camera in the frequency range 100 - 1000 Hz with acoustic image dynamic range of 5 dB. As can be seen, dynamic range is much narrower than that in Fig. 4, especially at frequencies lower than 200 Hz (for the same sound emission at all frequencies). If the source would emit a sound at 100 Hz (source location right in the middle of the camera's FOV and at the distance of 100 m) and if the camera would have image dynamics (scale on the right side of the characteristics) 5 dB, the algorithm would calculate the acoustic image which would be shown in red over the entire picture.

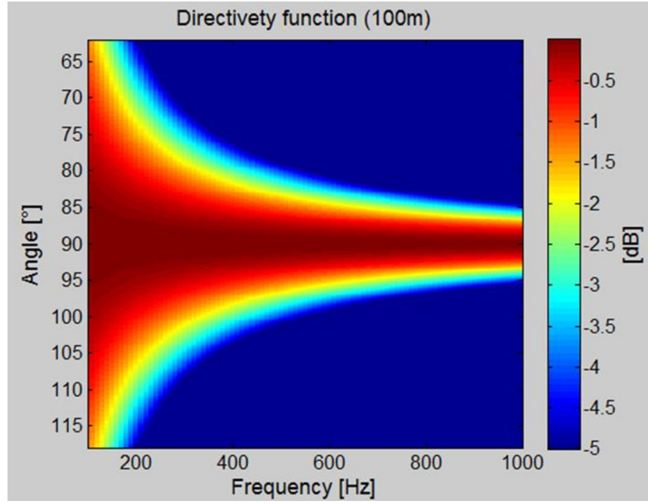

Figure 5. Directivity function of acoustic camera in the frequency range 100 - 1000 Hz with acoustic image dynamic range of 5 dB

If the dynamic range would be reduced to 0.5 dB, the algorithm would calculate an acoustic image whose characteristics would be as shown in Fig. 6. A large red circle would be displayed at more than a half of the image. The results of the acoustic image calculation by an acoustic camera algorithm at frequencies lower than 1000 Hz and especially lower than 500 Hz should be considered only conditionally, both in terms of the range of noise level and in terms of the exact position of the noise source. At these frequencies, the dynamic range of acoustic images, some of which are presented in the results at the next paragraph, is set to lower values - from 0.1 dB to 2 dB.

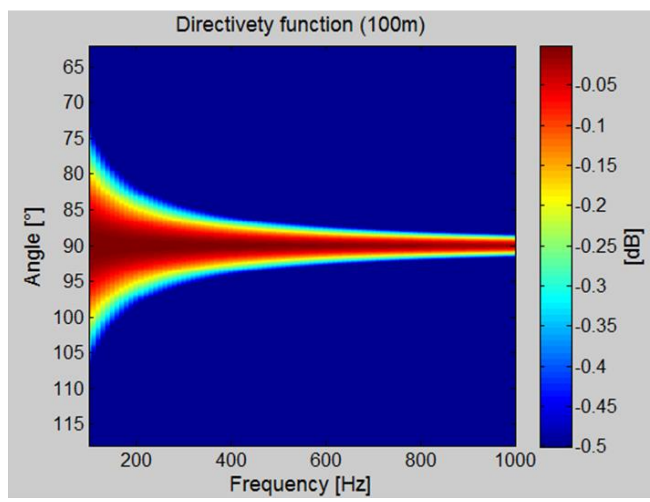

Figure 6. Directivity function of acoustic camera in the frequency range 100 - 1000 Hz with acoustic image dynamic range of 0.5 dB

C. UAV

A custom built hexacopter was used in this test. It is of multirotor kind and it has 6 motors. The specifications are available in Table 2. The most important parameter which determines UAVs acoustic footprint is propeller rotation speed. This UAV has 6 motors and their rotation speed varies within certain limits to achieve a satisfactory control and stability of UAV. This rotation speed range is unknown so we did 1/3 octave band premeasurements of its noise to define a frequency band where basic frequency of tonal propeller component and its harmonics are situated.

TABLE 2. Specifications of tested hexacopter

Specification	**Description**
Size (w/o propellers)	75 × 75 × 37 cm
Weight	4420 g
Number of motors	6
Motor power	480 W
Motor type	Outrunner
Battery	LiPo, 6S, 5000 mAh
Propeller type	2-blade
Propeller diameter	12’’

III. Results and Discussion

First, we did 1/3 octave band measurements of UAV’s noise to define a predominant frequency bands. The noise was measured by means of Nor140 Sound Analyzer with an extensive set of functions available in its expanded version. UAV’s noise was recorded in time period of 5 seconds at the distance of 20 m at stabilized UAV flight mode. The noise levels are calculated and the characteristics are presented

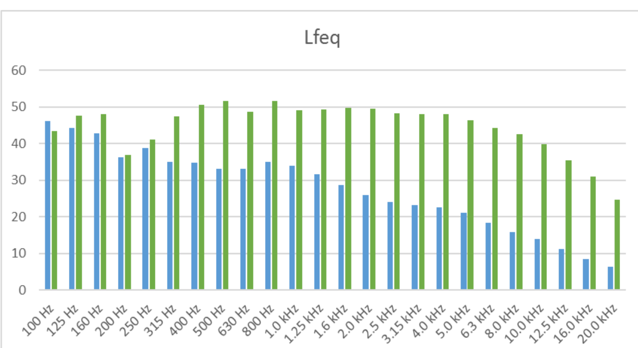

Figure 7. One-third octave band measurement results of UAVs noise

in Fig. 7. Residual noise is presented in blue colour and the UAV’s noise in green colour. It is obvious that the UAV has broadband noise with basic frequency of tonal propeller component in 1/3 octave bands of central frequency of 125 Hz or 160 Hz. The difference of UAVs noise and background noise is at least 20 dB for the frequency range 100 Hz – 20 kHz.

Next four figures present the most interesting results of UAV visibility measurements using acoustic camera. All figures consist of four parts. At the top left side is situated a black and white photograph with the indicated position of the UAV. At the top right side is the overall spectrogram with the indicated part of the spectrogram (frequency components which originate from UAV) used for calculation of specific

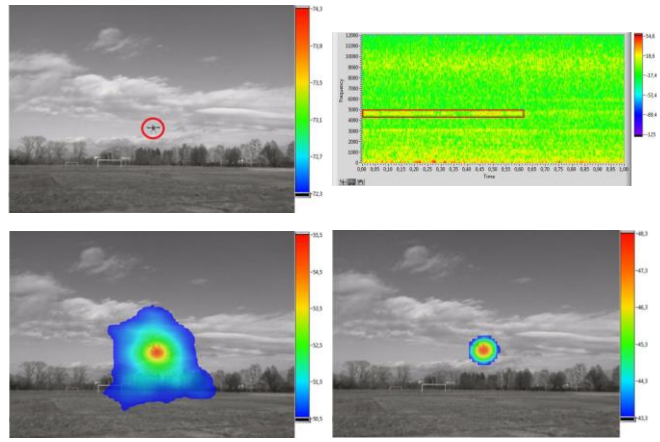

Figure 8. Measurement results at the distance of 20 m

acoustic image. At the bottom left side is acoustic image calculated from overall spectrogram and at the bottom right side is acoustic image calculated from indicated part of the spectrogram. Measurement results at the distance of the 20 m are presented in Fig. 8. UAV is visually clearly visible. It stands out as the dominant noise source within the overall sound image. The overall spectrogram highly expresses frequency components that come from the UAV. By using the selected part of the spectrogram, after signal processing, it is possible to determine the location of the UAV very well.

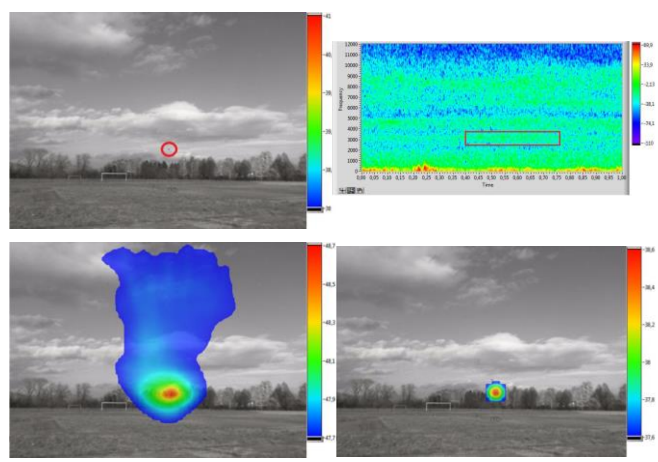

Figure 9. Measurement results at the distance of 60 m

Results of the measurements at the distance of 60 m are presented in Fig. 9. UAV is discernible visually. It stands out as the dominant noise source within the overall sound image. The spectrogram shows frequency components that come from the UAV. By using the selected part of the

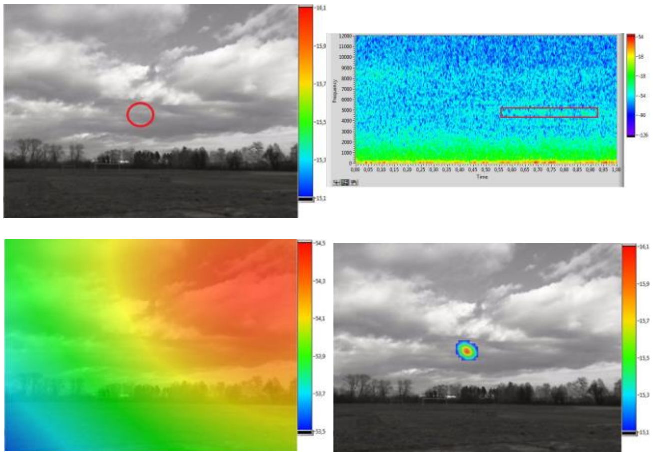

Figure 10. Measurement results at the distance of 100 m

spectrogram, after signal processing, it is possible to determine the location of the UAV. Measurement results at the distance of the 100 m are presented in Fig. 10. The UAV is visually noticeable. Within the overall sound image it does not stands out. In the spectrogram, the frequency components that come from the UAV are poorly visualized. By using the selected part of the spectrogram,

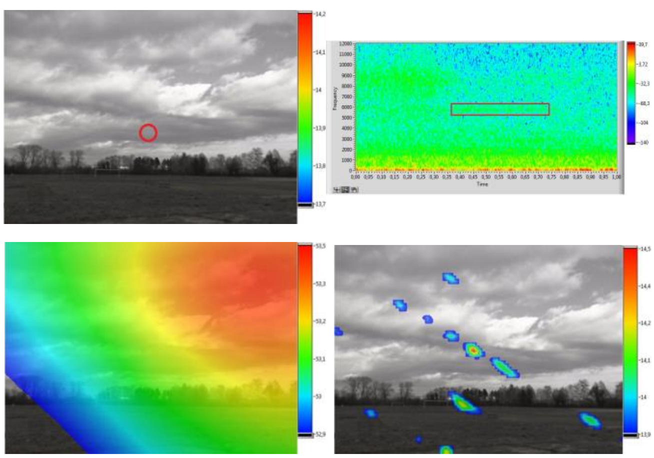

Figure 11. Measurement results at the distance of 170 m

after signal processing, it is possible to determine the location of the UAV. Measurement results at the distance of the 170 m are presented at Fig. 11. The UAV is visually hardly noticeable. Within the overall sound image it does not stand out. In the spectrogram, the frequency components that come from the UAV are poorly visualized. By using the selected part of the spectrogram, after signal processing, it is possible to determine the location of the UAV with uncertainty. This is the detection limit based on existing background noise.

IV. Conclusions

In summary, we performed a detectability test of commonly used custom made UAV type. Our goal was to determine whether an acoustic sensor could be used to detect multirotor UAV for the purpose of air traffic surveillance or collision avoidance. To achieve this, we have flown custom built UAV over a test track and recorded its movement with SoundEye acoustic camera.

We concluded that:

- Small multirotor UAVs can be detected with acoustic camera in some conditions,
- Basic four parameters on which detectability depends on are: UAV noise spectrum, its ratio to background noise, dynamic range of acoustic camera, and its frequency resolution,
- Due to background noise, human interpreter is necessary for detection,
- Maximum range of detection can be greater than visual detection,
- Due to necessity of human interpreter and time for processing, it is questionable whether the acoustic camera can be used for air traffic surveillance purposes.

In future work we will test detectability of UAVs against noisier background conditions. A more rigorous test of detectability will be performed with UAV appearing from unknown directions. Finally, methods for reducing the noise signature of the UAV will be tested.

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