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UNMANNED AERIAL VEHICLE FLIGHT SPEED OPTIMIZATION FOR SPECTRUM SENSING

Nowadays, small unmanned aerial vehicles are increasingly used for spectrum sensing. The movement of the unmanned aerial vehicle relative to the radio source leads to variability in the level of the received signal. This is due to small-scale signal fading, which occurs when the unmanned aerial vehicle moves by only half the wavelength of the radio signal carrier frequency. To reduce the influence of this factor on the characteristics of algorithms that use amplitude methods and are often used on unmanned aerial vehicles due to their simplicity, it is necessary to optimize the speed of its flight. The aim of the article is to develop a mathematical apparatus for calculating the optimal unmanned aerial vehicles flight speed for wideband spectrum sensing in conditions of small-scale fading. In the course of the research, the optimization criterion was determined to be the maximization of the scanning area, which depends on the range of detection of radio sources and the unmanned aerial vehicles flight speed. The dependence between the unmanned aerial vehicles flight speed and the duration of signal sample is established to reduce the effect of fading on errors in estimating the received signal strength.

An analytical expression has been obtained that relates the scanning area of the unmanned aerial vehicles to its flight speed and the frequency of the radio signal, which is described by a monotonous increasing function of the flight speed. It has been established that in order to detect the maximum number of radio sources, a unmanned aerial vehicle should move at maximum speed. The signal sampling duration is calculated for a given speed and maximum signal frequency. The proposed solution will allow detecting the maximum number of radio sources for a given unmanned aerial vehicle flight time. The developed mathematical apparatus can be implemented in the development of modern radio monitoring systems for unmanned aerial vehicles.

Keywords: *unmanned aerial vehicle; spectrum sensing; radio frequency spectrum; flight speed; sensing interval*

Problem statement in general. At the present stage of development of radio-electronic systems, small unmanned aerial vehicles (UAVs) are increasingly used to solve a wide variety of tasks, in particular for spectrum sensing (SS) [1–6]. A distinctive feature of detecting and determining the location of radio emission sources (RES) using an SS device mounted on a UAV is the variability of the received signal parameters caused by the movement of the device itself relative to the source. This phenomenon is mathematically described by modeling signal fading along the propagation path [7–11]. Rapid changes in the received signal power are associated with small-scale fading, which occurs when the UAV moves only half the wavelength of the radio signal carrier frequency. In this way, the spatial distribution of the electric field intensity is converted into the temporal variability of the received signal level. To reduce the impact of this factor on the operation of algorithms that use amplitude methods and are often used on UAVs due to their simplicity [5], it is necessary to reduce the speed of its flight. However, due to the limited flight time of the UAV for surveying the maximum area, it must move as quickly as possible. In this case, it is necessary to reduce the signal sampling time, which will lead to a decrease in the detection range of the RES. Thus, the choice of the flight speed of the SS UAV contains contradictions and requires the development of approaches for calculating its optimal value.

Analysis of the latest research and publications. In recent years, there has been a significant increase in the number of scientific publications devoted to research on SS using small drones. [12] describes the process of flying a UAV around a known DRV and measuring the parameters of the received signals. The problem of radio frequency spectrum (RFS) analysis to improve its use in organizing UAV radio links for non-Gaussian interference is described in [13]. Ways to optimize flight trajectories and redistribute frequency resources during SS are proposed in [14]. In [15], a method for analyzing the RFS when using large networks with UAVs is presented. A distributed system for collecting data on the radio-electronic environment using a group of UAVs and transmitting it to a central information processing point is proposed in [16]. In [17], an approach to planning the flight of SS UAVs for radio-electronic reconnaissance is presented, which includes the distribution of time for analyzing the radio-electronic situation and transmitting data. In [18], the process of optimizing the analysis of the RFS for a group of UAVs is considered.

However, the works considered focus mainly on the distribution of time for analysis of the radio-electronic situation and transmission of collected data to the information processing center. The issue of optimizing the flight speed of UAVs in conditions of small-scale pauses, which is critical in the context of conducting SS in urban and suburban areas, is not addressed.

Formulation of the research task. The purpose of the article is to develop a mathematical apparatus for calculating the optimal flight speed of a UAV during panoramic SS in conditions of small-scale pauses.

Core material. During signal analysis in the frequency band ΔF the environment (radio wave propagation conditions) should not change significantly in terms of small-scale fluctuations so as not to introduce distortions in the measured value of the received signal power. In this case, a UAV moving at a speed of υ, must move a distance significantly less than half the wavelength. It is at this distance that deep small-scale fading manifests itself [9]. With this approach, the analysis time (signal sampling duration) T_a can be calculated according to the expression [19]:

$$T_a \ll \frac{\lambda}{2\upsilon} \approx \frac{c}{20\upsilon f_0}, \qquad (1)$$

where λ – wave lenght;

c – speed of radio waves;

f_0 – radio signal carrier frequency.

Fig. 1 shows the dependence of the analysis time on the flight speed of the UAV for some values of the signal carrier frequency (according to expression (1)). If the speed of the device can vary from 10 km/h to 200 km/h (2.8–55.5 m/s), then when scanning the frequency band in the range from 300 MHz to 6 GHz (the lower limit is selected taking into account the acceptable antenna sizes), the minimum analysis time should not exceed 45 μs, and the maximum should not exceed 18 ms.

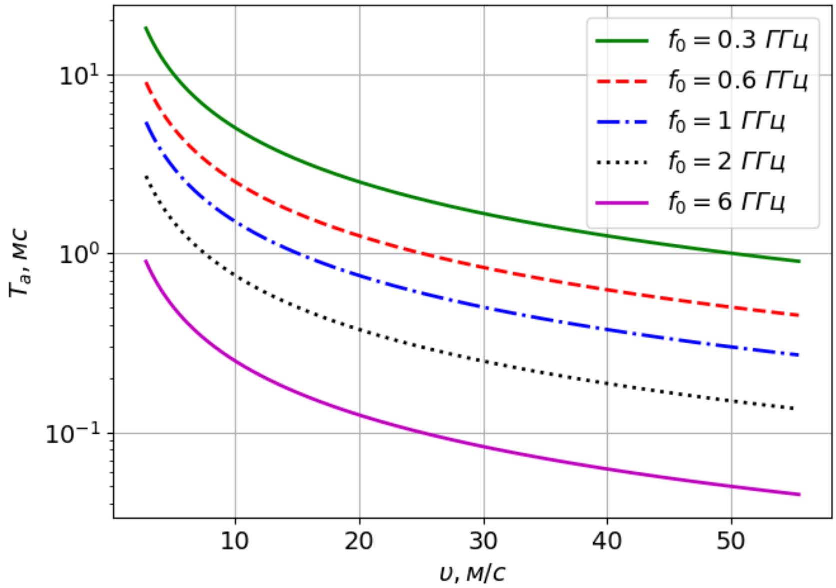

Fig. 1. Dependence of analysis time on UAV flight speed for certain radio signal frequency values

If the flight duration of the UAV T_F does not depend on its speed, then high flight speed will require low values T_a. This, in turn, will lead to a decrease in the signal-to-noise ratio (SNR) and a reduction in detection range of RES R. However, with a fixed flight duration and maximum speed, the UAV will fly the maximum distance. At low flight speeds, the analysis time T_a will be greater (according to expression (1)), which will cause an increase in the SNR and the detection range of the RFS. However, the flight path of the UAV will decrease, so its speed υ is a parameter whose value is subject to optimization.

Value υ We will search based on the criterion of the maximum number of RFS that can potentially be detected by the SS tool. Since their number and location are unknown a priori, the optimal value of υ should ensure the maximum viewing area for a given detection range. R and fixed flight time of the UAV T_F (fig. 2). The significance of this area in the assumption that the flight altitude of the UAV h much shorter detection range than a typical RFS R, can be approximately calculated using the following expression:

$$S \approx 2R\upsilon T_F \, . \tag{2}$$

This expression does not include the frequency of the radio signal, since the detection range only reflects the energy availability of the RFS.

RFS detection range R in the case of specified detection quality indicators: probability of correct detection P_D and the probability of false alarms P_F – is a function of SNR q. The value of SNR is also a function of the signal analysis (accumulation) time. T_a, which is determined by the flight speed of the UAV for a given radio signal frequency (1). Therefore, the detection range of the RFS is generally a function of the speed of the UAV. $R(\upsilon)$, which depends on the selected detection algorithm.

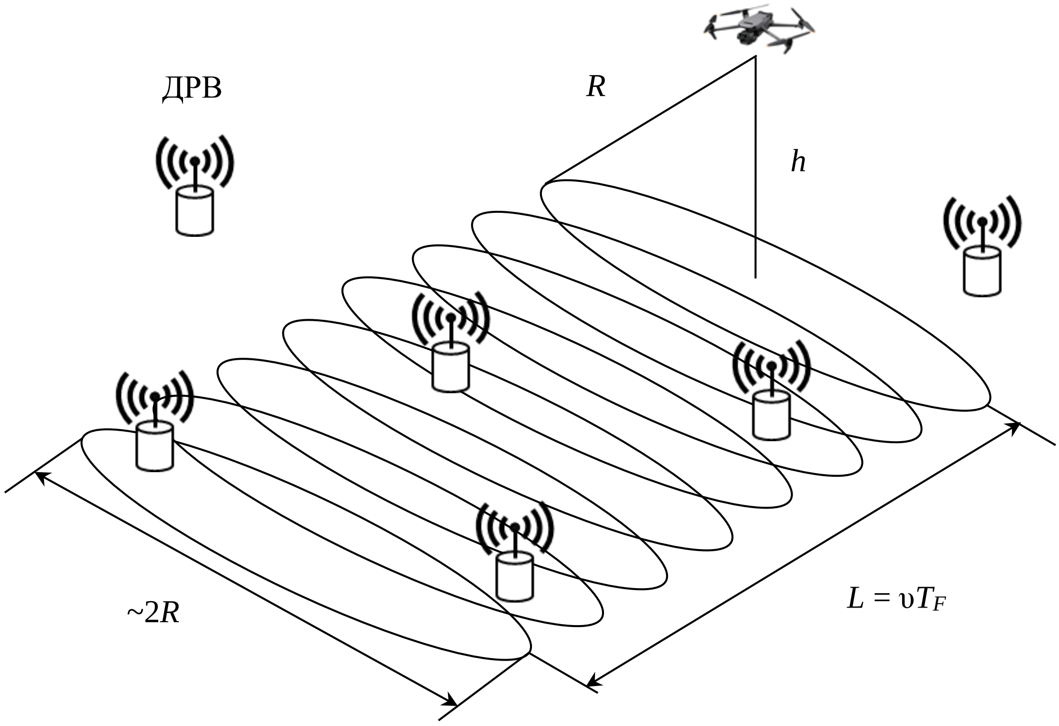

Fig. 2. RFS search area

Detection quality indicators are related to the SNR value, which, in turn, is determined as the ratio of the received signal power P_r to the noise power in the receiver P_n:

$$q = \frac{P_r}{P_n}. \quad (3)$$

The power of the received signal can be calculated by knowing the radiation power. P_t RFS and the distance to the SS device on the UAV, according to the following expression:

$$P_r = A_{ef} \frac{G(\theta,\gamma) P_t}{4\pi R^2}, \quad (4)$$

where A_{ef} – effective antenna area of the SS device,

$G(\theta, \gamma)$ – antenna directional pattern for a given azimuth θ and the angle of the place γ.

Then the SNR can be written as follows:

$$q = A_{ef} \frac{G(\theta,\gamma) P_t}{4\pi R^2 P_n}. \quad (5)$$

Determine the detection range from this equation R:

$$R = \sqrt{A_{ef} \frac{G(\theta,\gamma) P_t}{4\pi P_n q}} . \qquad (6)$$

In conditions of a priori uncertainty regarding the structure of the RFS signal, it is advisable to use an energy detector. If we consider a typical case of detecting a random normally distributed signal against a background of white Gaussian noise, then for large sample lengths *N* (more than 30) the dependence between the required number of readings and the value of the SNR can be described using the following equation [20–21]:

$$N = 2\left(\frac{Q^{-1}(P_F) - Q^{-1}(P_D)(q+1)}{q} \right)^2 , \qquad (7)$$

where $Q(x)$ – component of the cumulative function of the standard normal distribution $\Phi(x)$ – $Q(x) = 1 – \Phi(x)$.

Find the value of BCH from equation (7), taking into account that the sample size *N* for a given sampling frequency F_s is $N = T_a F_s$:

$$q = \frac{Q^{-1}(P_F) - Q^{-1}(P_D)}{\sqrt{\frac{T_a F_s}{2}} + Q^{-1}(P_D)} . \qquad (8)$$

After substituting expression (8) into equation (6), obtain

$$R = \sqrt{\frac{A_{ef} G(\theta,\gamma) P_t \left(\sqrt{\frac{T_a F_s}{2}} + Q^{-1}(P_D) \right)}{4\pi P_n \left(Q^{-1}(P_F) - Q^{-1}(P_D) \right)}} . \qquad (9)$$

Adding the following notation:

$$k = \sqrt{\frac{A_{ef} G(\theta,\gamma) P_t}{4\pi P_n \left(Q^{-1}(P_F) - Q^{-1}(P_D) \right)}} . \qquad (10)$$

Then expression (9) can be written as follows:

$$R = k\sqrt{\sqrt{\frac{T_a F_s}{2}} + Q^{-1}(P_D)} . \qquad (11)$$

We will ignore the second term in the sub-expression, since it is significantly smaller than the first. After that, equation (11) can be written in the following form:

$$R \approx k\left(\frac{T_a F_s}{2}\right)^{\frac{1}{4}}. \quad (12)$$

Substituting into this expression T_a from equation (1), obtain:

$$R = k\left(\frac{cF_s}{20\upsilon f_0}\right)^{\frac{1}{4}}. \quad (13)$$

Dependence of detection range on sampling frequency F_s signal in this expression is due to the fact that when it increases, the number of readings for a given analysis time increases. However, for a software-defined receiver, the sampling frequency is approximately equal to the passband, an increase in which leads to a decrease in its sensitivity (increase in noise power) P_n in (9)) and a decrease in detection range, so in general, the detection range does not depend on the signal sampling frequency.

As we can see, the detection range is a monotonically decreasing function of the UAV flight speed. Similarly, for a fixed UAV speed, the flight range is a monotonically increasing function of speed. After substituting expression (13) into equation (2), we obtain the dependence of the viewing area on the UAV flight speed:

$$S = 2k\left(\frac{cF_s}{20 f_0}\right)^{\frac{1}{4}} \upsilon^{\frac{3}{4}} T_F. \quad (14)$$

The value of this expression is a monotonically increasing function of velocity, so it follows from equation (14) that in order to survey the maximum area, the UAV must move at maximum velocity. The dependence on the signal frequency in this expression reflects the fact that as the frequency increases, the spatial variability of the electromagnetic field distribution caused by small-scale fading increases. This leads to a decrease in the signal analysis time T_a, which reduces the SNR and detection range.

Fig. 3 shows the dependence of the viewing area on the UAV flight speed and radio signal frequency for a flight duration of 1 hour. As we can see, the maximum viewing area is achieved at the minimum radio signal frequency and maximum flight speed. During UAV-based SS, RFS analysis is performed by scanning, i.e., at each point (local area) in space, the radio receiver is retuned to a new frequency with a step equal to its passband, and this transition must occur within a few microseconds. Obviously, it is practically impossible to change the flight speed of the UAV in such conditions to ensure that condition (1) is met, so it is advisable to select the analysis time for each frequency corresponding to the maximum receiver frequency value. In this case, the UAV must move at the maximum possible speed. Under such conditions, the time required to scan the entire frequency band will be:

$$T_{\Delta\Pi} = \frac{(f_{\max} - f_{\min})c}{20 F_s \upsilon_{\max} f_{\max}}, \quad (15)$$

where f_{min} and f_{max} – minimum and maximum operating frequencies of the receiver;

υ_{max} – maximum flight speed of UAV.

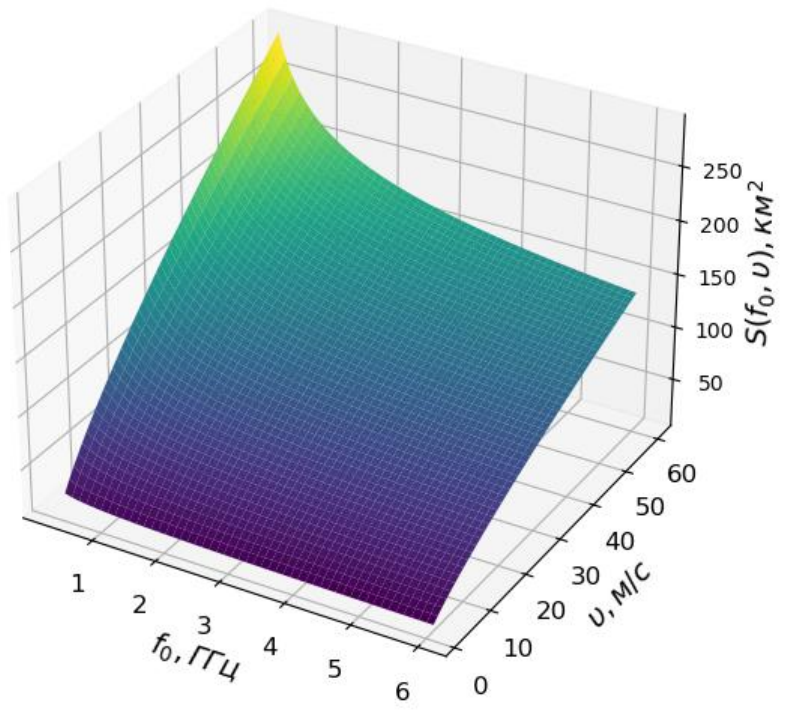

Fig. 3. Dependence of the viewing area on the flight speed of the UAV and the radio signal frequency

For a signal sampling frequency of 20 MHz, the minimum number of readings to be analyzed (for an analysis interval duration of 45 μs) will be 900, and the maximum number of readings (for an analysis interval duration of 18 ms) will be 360,000. For a probability of correct detection of 0.9 and a probability of false alarm of 0.001, signal detection by an energy detector for the specified signal sample volumes is possible at SNR values of -20 dB and -33 dB, respectively, provided that the signal spectrum width is equal to the receiver's passband. If the signal has a narrower spectrum, it can be detected with the same quality indicators at higher SNR values, which is equivalent to a reduction in detection range.

For a UAV flight speed of 200 km/h using a radio receiver with an upper frequency of 6 GHz, signal detection is possible at an SNR of -20 dB and above in a band equal to the signal spectrum width.

Conclusions. During the research, an approach was developed to calculate the optimal flight speed of UAVs and the duration of signal sampling during SS in conditions of small-scale pauses. The proposed solution will allow the maximum number of RFS to be detected within a given flight time. The developed mathematical apparatus can be implemented in the development of modern SS systems for UAVs. Prospects for further research in this area lie in the construction of a mathematical model of the received signal and the corresponding methods for its processing in the case of conducting SSof a given area using several UAVs. This will make it possible to implement distributed reception of radio signals and reduce the negative impact of fading.

REFERENCES

1. Chen, F., Rezatofighi, S. H., & Ranasinghe, D. C. (2024). GyroCopter: Differential Bearing Measuring Trajectory Planner for Tracking and Localizing Radio Frequency Sources. *Computer Science. Robotics.* https://doi.org/10.48550/arXiv.2410.13081

2. Dressel, L., & Kochenderfer, M. J. (2018). Pseudo-bearing Measurements for Improved Localization of Radio Sources with Multirotor UAVs. In *IEEE International Conference on Robotics and Automation. Brisbane.* QLD, Australia,. (pp. 6560–6565). https://doi.org/10.1109/ICRA.2018.8460734

3. Hoffmann, F., Schily, H., & Krestel, M. et al. (2023). Non-myopic Sensor Path Planning for Emitter Localization with a UAV. In *26th International Conference on Information Fusion*. https://doi.org/10.23919/FUSION52260.2023.10224174

4. Dressel, L., Kochenderfer, M. J. (2019). Hunting Drones with Other Drones: Tracking a Moving Radio Target. In *International Conference on Robotics and Automation. Montreal.* QC, Canada. (pp. 1905–1912). https://doi.org/10.1109/ICRA.2019.8794243

5. Zhyla, S., Popov, A., Tserne, E. et al. (2023). UAV-born Narrowband Radar Complex for Direction Finding of Radio Sources. In *13th International Conference on Dependable Systems, Services and Technologies.* Athens, Greece. (pp. 1–6). https://doi.org/10.1109/DESSERT61349.2023.10416434

6. Kwon, H., & Guvenc, I. (2023). RF Signal Source Search and Localization Using an Autonomous UAV with Predefined Waypoints. In *IEEE 97th Vehicular Technology Conference (VTC2023-Spring).* Florence, Italy. (pp. 1–6). https://doi.org/10.1109/VTC2023-Spring57618.2023.10200783

7. Sklar, B. (2003). *Digital Communications. Fundamentals and Applications.* (2^{nd} ed.). Prentice Hall.

8. *Recommendation ITU-R P.1406-2.* (07/2015). Propagation Effects Relating to Terrestrial Land Mobile and Broadcasting Services in the VHF and UHF Bands P Series Radiowave Propagation.

9. Goldsmith, A. (2020). *Wireless Communications.* (2^{nd} ed.). Stanford University.

10. Lu, S., May, J., & Haines, R. (2014). Efficient Modeling of Correlated Shadow Fading in Dense Wireless Multi-hop Networks. In *Wireless Communications and Networking Conference (WCNC).* (pp. 311–316). https://doi.org/10.1109/WCNC.2014.6951986

11. Karagiannis, G. A., & Panagopoulos, A. D. (2019). Dynamic Lognormal Shadowing Framework for the Performance Evaluation of Next Generation Cellular Systems. *Future Internet, MDPI*, *11* (5), 1–18. https://doi.org/10.3390/fi11050106

12. Liu, X., Guan, M., Zhang, X., & Ding, H. (2018). Spectrum Sensing Optimization in an UAV-Based Cognitive Radio. *IEEE Access.*, *6*, 44002–44009. https://doi.org/10.1109/ACCESS.2018.2862424

13. Zhang, J. et al. (2023). Spectrum and Energy Efficient Multi-antenna Spectrum Sensing for Green UAV Communication. *Digital Communications and Networks*, *9*, 4, 846–855. https://doi.org/10.1016/j.dcan.2022.09.017

14. Yan, L., Cai, Y., & Wei, H. (2024). Unmanned Aerial Vehicle-assisted Wideband Cognitive Radio Network Based on DDQN-SAC. *EURASIP J. Adv. Signal Process, 43.* https://doi.org/10.1186/s13634-024-01141-3

15. Wang, W., & Peng, J. (2022). Cooperative Spectrum Sensing Algorithm for UAV Based on Deep Learning. In *IEEE 96th Vehicular Technology Conference.* London, United Kingdom. (pp. 1–5). https://doi.org/10.1109/VTC2022-Fall57202.2022.10013034

16. Tekbıyık, K., Kurt, G. K., & Lesage-Landry, A. (2024). Federated Learning for UAV-Based Spectrum Sensing: Enhancing Accuracy Through SNR-Weighted Model Aggregation. *Computer Science*. https://doi.org/10.48550/arXiv.2411.11159

17. Gul, N., Kim, S. M., Ali, J., & Kim, J. (2023). UAV Aided Virtual Cooperative Spectrum Sensing for Cognitive Radio Networks. *PLoS ONE*, *18* (9). https://doi.org/10.1371/journal.pone.0291077

18. Wu, J. et al. (2021). Optimisation of Virtual Cooperative Spectrum Sensing for UAV-based Interweave Cognitive Radio System. *IET Commun*, *15*, 1368–1379. https://doi.org/10.1049/cmu2.1210

19. Buhaiov, M. V. (2024). Matematychna model pryiniatoho syhnalu panoramnym zasobom radiomonitorynhu na bezpilotnomu litalnomu aparati [Mathematical Model of the Received Signal by Panoramic Means of Radio Monitoring on an Unmanned Aerial Vehicle]. *Vseukr. mizhvidomchyi nauk.-tekhn. zbirnyk "Radiotekhnika" [All-Ukrainian Interdepartmental Scientific and Technical Collection "Radio Engineering"], 219.* https://doi.org/10.30837/rt.2024.4.219.09 [in Ukrainian].

20. Kay, S. M. (1998). *Fundamentals of Statistical Signal Processing: Detection theory.* Vol. 2. Prentice Hall, New Jersey.

21. Zhang, W. (2019). *Handbook of Cognitive Radio.* Springer. https://doi.org/10.1007/978-981-10-1394-2