Radio-Heat Contrasts of UAVs and Their Weather Variability at 12 GHz, 20 GHz, 34 GHz, and 94 GHz Frequencies

Nikolay Ruzhentsev[1], **Simeon Zhyla**[1†], **Vladimir Pavlikov**[1], **Valerii Volosyuk**[1], **Eduard Tserne**[1], **Anatoliy Popov**[1], **Oleksandr Shmatko**[2], **Ivan Ostroumov**[3], **Nataliia Kuzmenko**[3], **Kostiantyn Dergachov**[4], **Olga Sushchenko**[5], **Yuliya Averyanova**[3], **Maksym Zaliskyi**[6], **Oleksandr Solomentsev**[6], **Olena Havrylenko**[4], **Borys Kuznetsov**[7], and **Tatyana Nikitina**[8], Non-members

ABSTRACT

This work describes the procedure for determining the expected values of UAV radio-heat contrasts (ΔT) and discusses its angular dependences, as well as the estimation of UAV detection distances at four points cm and mm ranges (12 GHz, 20 GHz, 34 GHz, and 94 GHz). This paper reveals the pronounced frequency dependence on brightness temperature (T_b) and ΔT of a fiberglass unmanned aerial vehicle (UAV) made from composite fiberglass materials. The quantified experiments are conducted against a sky background under various weather conditions and wave ranges. The qualitative physical interpretation of these properties and their frequency dependence is proposed, reflecting the coefficient values and radio brightness of the background. The weak influence of weather on the observed UAVs in the X and Ku bands are demonstrated along with the multiple decreasing detection characteristics and advantages of the W band under bad weather conditions (the appearance of rain or thick cloud). This work presents data on the values of UAV contrasts, observed against the background of the sky and the regularities noted could be useful for predicting the effectiveness of the proposed radiometric detection and tracking system.

Keywords: Radiometry, Aircraft, Brightness Temperature, Weather Conditions, Detection Distance

1. INTRODUCTION

The search for appropriate methods for developing airspace control devices is traditionally based on the use of acoustic, optical, infrared, and radar methods for active and passive monitoring [1–13]. Each of these methods has its own advantages and disadvantages [14–20]. However, these systems have certain disadvantages. For instance, optoelectronic devices are dependent on the weather and time of day, radar is subject to suppression and low reflected signals, while acoustic systems tend to be short-range and inaccurate. Furthermore, there is the possibility of counteracting passive systems in identifying the direction of communication channels, etc. In this regard, it is of practical interest to consider the possibility of using microwave radiometry to solve the above problem. There are many reasons for considering this method as an alternative or addition to those mentioned above, despite its poor development. It can be assumed from the general physical considerations that the advantages of this approach are its secrecy, increased noise immunity, relative all-weather resistance, etc. However, few works can be found on the radiometric passive detection of artificial objects in millimeter wave ranges (WR). Furthermore, against the background of earth cover, the data on radiometric contrasts and the probability of detecting UAVs against a sky background are completely absent in the literature.

Knowledge of radio-heat contrasts in various observed objects and prediction of their detection distance with a given probability are required when developing a means of detecting and tracking airborne objects by radiometry. One of the obstacles to making reasonable assessments and forecasts is the almost complete absence of initial data on the values of UAV radio brightness

Manuscript received on March 10, 2021; revised on July 29, 2021; accepted on October 31, 2021. This paper was recommended by Associate Editor Susamay Samanta.

[1]The authors are with the Department of Aerospace Radio-Electronic Systems, National Aerospace University “Kharkiv Aviation Institute”, Kharkiv, Ukraine.

[2]The author is with the Laboratory of Electron Microscopy, Optics and Laser Technologies, National Aerospace University “Kharkiv Aviation Institute”, Kharkiv, Ukraine.

[3]The authors are with the Air Navigation Systems Department, National Aviation University, Kyiv, Ukraine.

[4]The authors are with the Department of Aircraft Control Systems, National Aerospace University “Kharkiv Aviation Institute”, Kharkiv, Ukraine.

[5]The author is with the Aerospace Control Systems Department, National Aviation University, Kyiv, Ukraine.

[6]The authors are with the Department of Telecommunication and Radioelectronic systems, National Aviation University, Kyiv, Ukraine.

[7]The author is with the Magnetic Field Control Problems Department, State Institution “Institute of Technical Problems of Magnetism of the National Academy of Sciences of Ukraine”, Kharkiv, Ukraine.

[8]The author is with the Technical Disciplines Department, Kharkiv National Automobile and Highway University, Kharkiv, Ukraine.

†Corresponding author: s.zhyla@khai.edu

Digital Object Identifier: 10.37936/ecti-eec.2022202.246878

temperatures.

This work describes the procedure for determining the expected values of radio-thermal contrasts and discussing the angular dependencies obtained, as well as the estimation of the detection distances for UAV at four points of cm and mm ranges (12 GHz, 20 GHz, 34 GHz, and 94 GHz). These frequencies, located in all transparency windows of the atmosphere in the 10–100 GHz range, are chosen to minimize the destructive effect of atmospheric attenuation and intrinsic radio-thermal radiation on the observability and detection of flying objects. Obtaining and forecasting such data in a wide frequency range is complex and multifaceted, requiring the development of theoretical concepts and related model calculations.

This complexity is due to the significant influence of frequency differences in the intrinsic, re-reflected characteristics, through the transmitted and background radiation of UAV, as well as the different seasonal weather conditions and viewing angles on the values of predicted contrasts. However, this kind of theoretical research is impossible without experimental data, and this plays a role in some benchmarks, allowing the researcher to assess the degree of adequacy in the theoretical models and approaches used. This complex approach is used in this work to predict estimates for the values of radio-heat contrasts in aircraft, observed against the background of the sky and detection parameters in different frequency ranges.

2. METHODOLOGY

The methodology used for predicting radio-heat contrasts of UAVs in this work involved an experimental assessment of the radio brightness temperature (T_b) in the sector of average viewing angles with subsequent extrapolation to a wider sector. Accordingly, model estimates of the sky T_b were also carried out in various weather conditions for the cm and mm wavelength ranges (WR).

The radio brightness temperature of the UAV (T_{UAV}) observed against the sky background can be written as the summary of own (T_{own}), reflected (T_{refl}), and passed through UAV (T_{pas}) radio-heat emission:

$$T_{UAV} = T_{own} + T_{refl} + T_{pas} \tag{1}$$

where $T_{own} = \varkappa T_0$, $T_{refl} = K_{refl} T_{es}$, $T_{pas} = T_{ph}\left(1 - K_{refl}\right) K_{tr}$, $T_{ph} = T_{eff}\left(1 - e^{\tau \sec\theta}\right)$. τ is the optical thickness of the atmosphere in the considered meteorological conditions and frequency range. $\varkappa = (1 - K_{refl})$ is the emissivity of the UAV, which depends on its dielectric properties and shape. $_{es}$ is the effective (average) value of the earth's surface T_b (depending on the type, shape, dielectric properties, viewing angle, and seasonal weather conditions). T_0 is the thermodynamic temperature of the earth's surface. K_{refl} is the effective value of the UAV reflection coefficient. K_{tr} is the effective value of the AV transmission coefficient. T_{pas} is the effective value of T_b representing the sky passing through the UAV. T_{ph} is the effective value of the sky T_b. T_{eff} is the effective value of the thermodynamic temperature in the atmospheric layer that forms the T_b of the sky. θ is the zenith angle of sight.

***Fig. 1**: The UAV with a projection area of 0.4 m^2, recorded above the measurement site.*

Analysis of the Eq. (1) shows the difficulties involved in obtaining an exact mathematical description of the procedures forming the radio-thermal contrast of AV for an adequate solution to the problem. Consequently, some assumptions were used, proceeding from the data experimentally obtained for T_b UAVs in various WRs. Therefore, a number of measurements were carried out on this fundamental contrast-forming parameter in the range of mean viewing angles due to a lack of data in the literature.

Experimental studies on T_b UAVs were carried out in carefully controlled conditions on the territory of the National Aerospace University "Kharkiv Aviation Institute" (KhAI), measuring range with the help of radiometric equipment on the cm and mm ranges specially designed for this purpose. The measurement procedure involved monitoring the distances, sight angle, projection area of the UAV, and periodic calibration of the radiometric equipment using the two-load method. The cycle of full-scale measurements was preceded by measurement of the radiation pattern in the radiometers' horn antennas using the KhAI anechoic chamber, modernized for this purpose.

The UAV sample image made at the KhAI from fiberglass was fixed above the roof of its five-story radiophysical building, using a specially created measuring stand as shown in Fig. 1. The example in Fig. 2 shows an image of a 3 mm range radiometer block located on the rotary support, to determine the T_b of UAV against the

Fig. 2*: The 3 mm range radiometer unit located on the rotary supports.*

(a)

(b)

(c)

Fig. 3*: (a) View of the complex, (b) test quadcopter, and (c) during instrument testing.*

background of the sky. The radiometers of other WRs were located on similar rotary supports.

The axisymmetric horn antenna patterns of the measuring complex for static UAV T_b measurements (Fig. 2) are 38°, 28°, 33°, and 36°, respectively, for frequencies 12 GHz, 20 GHz, 34 GHz, and 94 GHz.

Calculations of T_b in a clear atmosphere for all considered WRs were carried out using the set developed in the ESA meteorological model ERA-15 and the radiophysical MPM model of Liebe [21]. The values of the total vertical absorption in the clear atmosphere (τ) were obtained by integrating them with those of the horizontal attenuation coefficient (γ), calculated for different heights and frequencies. These calculations were based on the MPM model using the normal meteorological conditions of July in Kharkiv, Ukraine and the altitude profiles of meteorological parameters taken from ERA-15. The sought-for values of sky T_b were calculated from the expression

$$T_{sky} = T_{eff}\left(1 - e^{\tau \sec\theta}\right). \qquad (2)$$

Atmosphere γ calculations under cloud cover conditions were carried out using the MPM model to collect a layer of fine droplets with the total columnar liquid water cloud content of 0.4 kg/m^2. The probability of exceeding such values according to ITU [22] is no more than 1% of the time per year. Here, the similar expression in Eq. (2) is used to calculate the T_b of clouds. The T_{eff} values for these calculations were taken from the ERA-15 model using the average cloud height of the Ukrainian summer season [23].

The atmosphere T_b calculations under rain conditions were also determined as in Eq. (2). The values of T_b and γ for an 8 mm WR were obtained in the case that the attenuation of rain exceeds 1% in the year term. These values were determined according to the data obtained from a one-year cycle of continuous observations of atmospheric radiation in Kharkiv [24, 25]. The subsequent recalculation to other frequencies was carried out according to the ratios in the rain also using the MPM model.

The estimated ranges for the reliable detection of UAVs

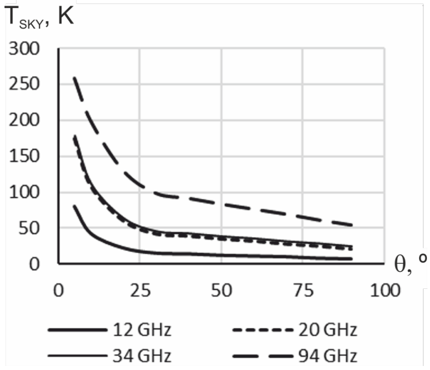


***Fig. 4**: The radio brightness temperatures of a clear atmosphere for the frequency range from 12 to 94 GHz.*

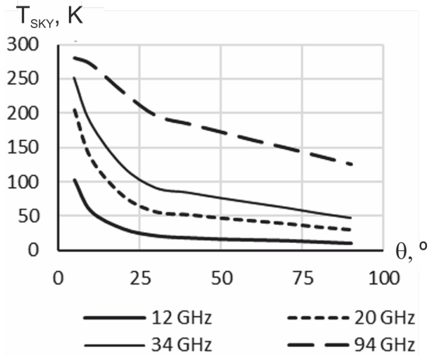


***Fig. 5**: The radio brightness temperatures of a cloudy atmosphere for the frequency ranges from 12 to 94 GHz.*

were calculated according to the maximum likelihood method [26] for the various values of observed projection area onto the antenna region for four frequency bands, namely 12 GHz, 20 GHz, 34 GHz, and 94 GHz.

The experimental test verification of the calculated estimates was performed for a miniature flying quadcopter with a projection area of 0.01 m^2 at the distance of several tens of meters, using a three-frequency measuring complex developed for this purpose (Fig. 3). The axisymmetric antenna system block of the measuring complex (Fig. 3) consisted of two mirrors with a diameter of 300 mm (the Cassegrain system of a 3 mm range with an antenna pattern width of $\theta = 0.7°$) and a three-frequency paraboloid with a diameter of 900 mm and ranges of 3 cm ($\theta = 2.5°$), 1.5 cm ($\theta = 1.5°$), and 8 mm ($\theta = 0.9°$).

This experimental data made it possible to carry out the subsequent recalculation to determine the detection range of devices with a larger projection area, for comparison with our calculated theoretical estimates.

3. RESULTS

The calculated values of T_b for the clear sky at the frequency ranges 12 GHz, 20 GHz, 34 GHz, and 94 GHz and their angular dependences are depicted in Fig. 4. Here, the viewing angle θ is measured from the horizon plane. These data are used in subsequent estimates of

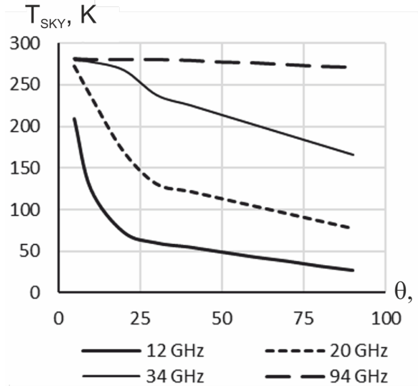


***Fig. 6**: The radio brightness temperatures of a rainy atmosphere for the frequency ranges from 12 to 94 GHz.*

UAV contrasts observed against the sky background.

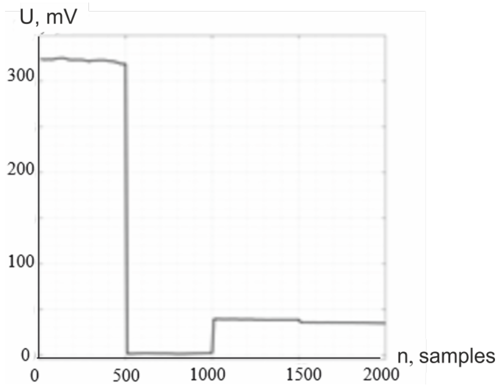
The radio brightness temperature values of the sky in thick cloud and intense rain conditions, respectively, are presented in Figs. 5 and 6. Unfavorable meteorological parameters for UAV detection, characteristic of no more than 1% of the annual weather conditions in Ukraine, were used in these calculations.

Comparison and analysis of the dependencies shown in Figs. 4–6 indicate multiple differences in T_b values of the background (sky) for the considered wave ranges, as well as the significant influence of weather conditions on these values. Moreover, the destructive manifestation concerning the influence of weather conditions is especially significant with a shortening of the wavelength, up to the disappearance of the angular dependence of T_b in the sky at 3 mm WR due to the saturation effect under intense rain conditions.

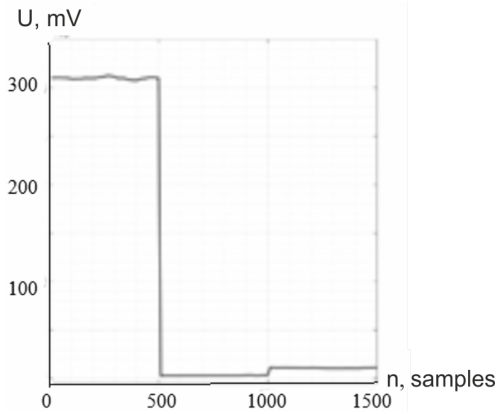
The measurements of the radio-heat radiation for a fiberglass UAV (Fig. 1) shows that the values of its T_b at average viewing angles in a clear atmosphere at horizontal polarization are about 245 K, 120 K, 95 K, and 85 K, respectively, for 3 mm (W), 8 mm (Ka), 1.5 cm (Ku), and 3 cm (X) wave ranges. An example of a radiometric signal recording fragment in the presence and absence of a UAV at 8 mm WR is given in Fig. 7. The angular dependencies of the expected T_{UAV} values and their contrasts (ΔT) against the sky background were modeled and plotted according to the results of the measurement series in the four above-mentioned WRs.

Radiometric recording fragments of the horizontal polarization signals in 8 mm WR from the antenna matched load (discrete sample (n) 0–500), zenith region of the sky (sample 500–1000), sky at an angle of 40° in the presence (sample 1000–1500), and absence of UAV (sample 1500–2000) are depicted in Fig. 7(a). The radiometric recording signal results of a UAV (sample 1000–1500) against the background radiation of the sky in the zenith angle are shown in Fig. 7(b).

To extrapolate these experimentally obtained values to other viewing angles, the exponential model was used in this work,

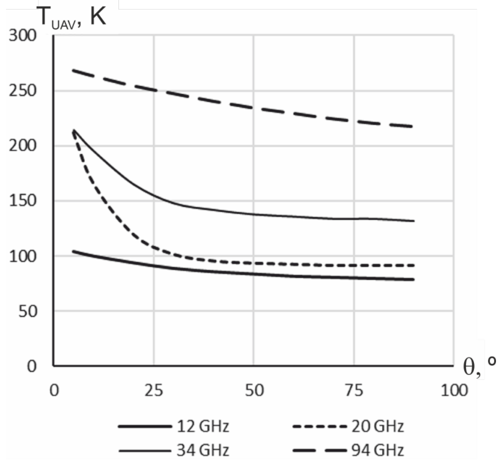


(a)

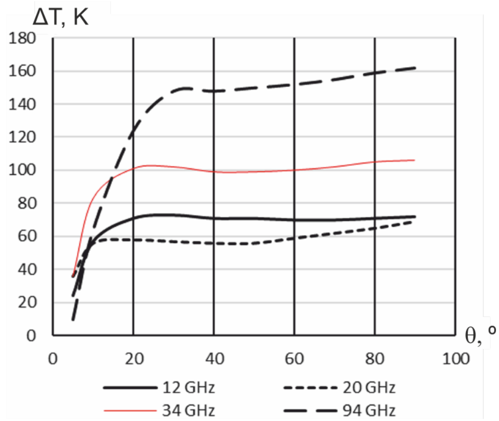


(b)

***Fig. 7**: Radiometric recording fragments of the horizontal polarization signals; (a) sky at an angle of 40° in the presence (sample 1000–1500), and absence of UAV (sample 1500–2000) and (b) UAV against the background radiation of the sky (sample 1000–1500).*



(a)



(b)

***Fig. 8**: Values of (a) T_{UAV} and (b) ΔT of a UAV mainly made from fiberglass under clear atmospheric conditions.*

$$T^{\circ}_{UAV} = k_1 e^{-k_2 \theta} + k_3 \tag{3}$$

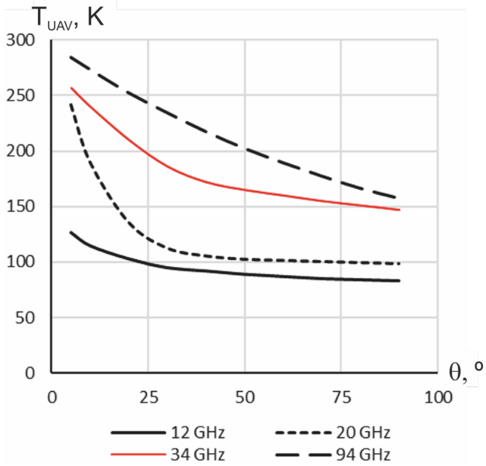
where k_1, k_2, and k_3 model coefficients depend on frequency and T°_{atm}. Using this expression, as well as the experimental results and approximate theoretical estimates of the reflection coefficients for surfaces at sliding angles, the T°_{UAV} values were calculated for the four frequency bands mentioned above. Joint processing of these data and the data presented in Figs. 5–7 make it possible to estimate the angular dependencies of T_b and radio-heat contrasts ΔT of the UAV against the sky background in various weather conditions (Figs. 8–10).

The analysis of the obtained data shows that in the sector close to the sliding viewing angles, in comparison to other angles, the contrast values are significantly reduced and their differences decreased for the considered WR (Figs. 8–10). At the same time, maximum contrast values are observed in Ka WR under clear sky conditions. The contrast is maximal in Ku WR in the presence of thick cloud cover and for X WR in rainy weather.

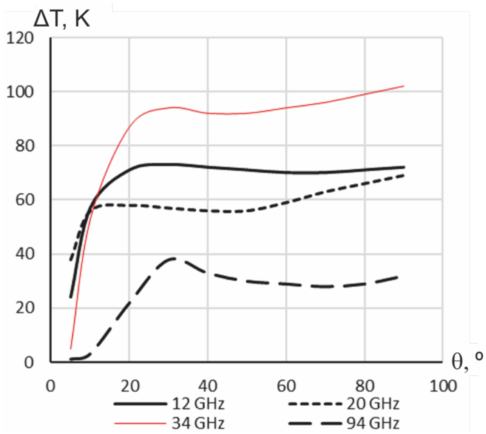
In the sector of all other (non-sliding) viewing angles, the significant frequency dependence of T_b in this type of UAV and its contrasts is manifested. Its magnitude decreases by almost three times in a clear atmosphere when going from 3 mm to 3 cm WR (Fig. 8).

This tendency can be explained qualitatively by the fact that the relatively radio-transparent material of the UAV body at lower frequencies becomes non-radio-transparent with increasing frequency. A decrease in radio transparency can lead to an increase in the loss and emissivity of the airframe. Furthermore, an increase in reflective performance results in more intense radio brightness of the earth's surface due to a rise in the reflection coefficient of the UAV body. This is indirectly confirmed by the presence of significant polarization differences in the T_b of the UAV, observed during 3 mm WR experiments in the sector of average viewing angles.

Multiple decreases occur in the contrast magnitude at 3 mm WR, reaching the maximum level at 8 mm WR under the weak influence of cloudiness, while there is a practical absence of such influence on the ranges of cm waves when strong clouds appear (Fig. 9). The appearance of intense rain (Fig. 10) leads to an intensification of the tendency to view the same angles, up to the complete disappearance of the contrast in 3 mm WR, while the maximum contrast values shift in 3 cm

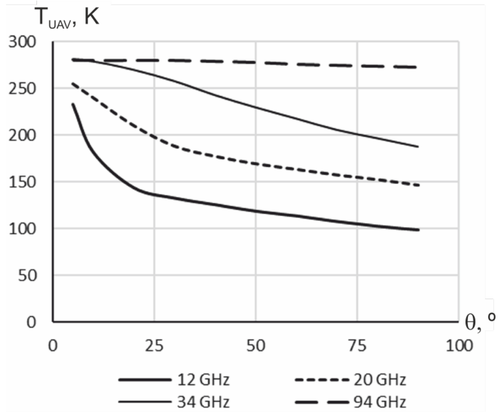


(a)

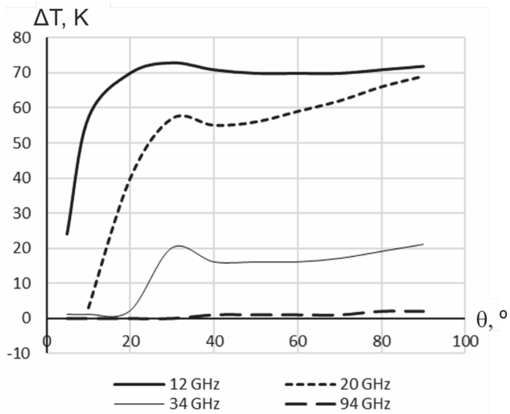


(b)

Fig. 9: *Values of (a) T_{UAV} and (b) ΔT of a UAV mainly made from fiberglass under cloudy atmospheric conditions.*



(a)



(b)

Fig. 10: *Values of (a) T_{UAV} and (b) ΔT of a UAV mainly made from fiberglass under rainy atmospheric conditions.*

WR.

It is pertinent to recall that all the foregoing results refer to a UAV made from fiberglass material. However, it is possible to suppose from general physical consideration that the T_b of a glider with a metal body will be concentrated within 200–250 K in all WRs, with the weather and frequency dependencies of these values being weakly expressed. Accordingly, the frequency dependence on the radio brightness of the sky will probably still lead to the frequency dependence of the contrast value ΔT.

An additional comparative assessment on the efficacy of using radiometers of one WR or another was conducted by calculating the detection distance values of the UAV using radiometric systems based on the maximum likelihood method [24] for a probability of 0.9. In this case, the size of the antenna aperture of various WRs was taken to be the same (0.5 m) for all four considered frequencies, making it possible to compare the detection efficiency between different WRs. The hardware parameters of radiometers realized at the modern stage of low-noise microwave input circuit development [27–30] and the amplifying elements [31, 32] of receivers were used in these calculations. The noise temperatures (and frequency bands) of radiometers operating in the frequency ranges 3 mm, 8 mm, 1.5 cm, and 3 cm were taken to be 600 K (6 GHz), 400 K (5 GHz), 120 K (4 GHz), and 70 K (3 GHz), respectively. Figs. 8–10 show the data on the magnitude of the expected contrast values in the calculation of the UAV detection distances. The results of such estimates concerning the detection distance of the UAV with a projection area of $S = 5\,\mathrm{m}^2$ for 30° sight angle and similar gradations of weather conditions are presented in Fig. 11.

The 3 mm WR provides multiple distance advantages over analogs operating in lower frequency WRs under clear weather conditions at non-sliding viewing angles, as shown in Fig. 11. In addition, in the 3 mm WR, it is possible to provide better spatial resolution for the area, thereby improving the quality of the observed images.

Differences in the detection distance capability of flying objects between cm and mm WR noticeably decrease under overcast conditions with high droplets of water content. The 3 mm and 8 mm channels significantly decrease in efficiency under heavy rain conditions. At the same time, the results indicate very weak susceptibility to the influence of weather conditions for both channels at cm WR. (It is useful to note here, that such unfavorable

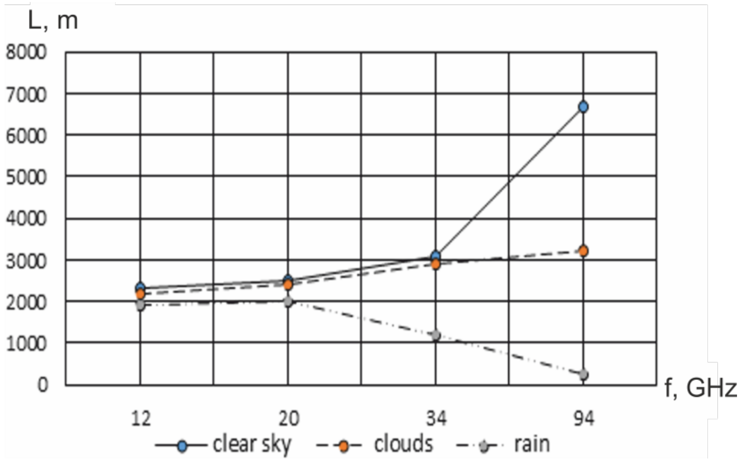


***Fig. 11**: Dependence of the detection distance (m) on frequency (GHz) for S = 5 m^2 and antenna apertures of the same size (Φ = 0.5 m) with a probability of 0.9.*

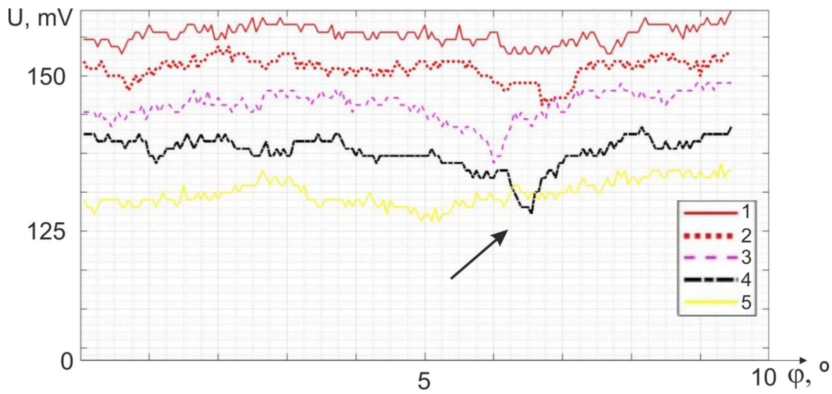


***Fig. 12**: Inverted recording fragment of the output signals, following azimuthal scans of the sky sector (φ, degrees) in the 8 mm channel with a burst caused by the UAV.*

synoptic situations considered in this study occur only for a small percentage of the time during the year and can often be considered as the UAV not flying.)

Additional measurements were taken using a system of scanning radiometers built for this purpose (Fig. 3) to confirm the reliability of the aircraft detection distance estimates (Fig. 11). Fig. 12 shows an example fragment of the 8 mm channel recording of several scans for the sky sector at the developed three-frequency radiometric system output. The response of the radiometer output signal to the entry of the miniature quadcopter into the directional pattern of the antenna system can be observed (noted by the arrow on the second scan from the bottom). Recalculation of the object detection distance with a projection area of 0.01 m^2 onto an UAV projection area of 5 m^2 showed satisfactory agreement between the calculated estimates (Fig. 11) and the primary data, as indicated in Fig. 12.

4. CONCLUSION

As a result of this research; the pronounced frequency dependence of T_b and radio-heat contrast ΔT of a UAV made from composite fiberglass material against a sky background is revealed, along with its quantified estimation. The qualitative physical interpretation of these properties is proposed, due to the frequency dependence of the reflection coefficient values and the radio brightness of the background. The weak influence of weather on the results for the observed UAVs in the X and Ku bands is demonstrated along with the multiple decreasing detection characteristics and advantages of the W band under bad weather conditions (the appearance of rain or a thick cloud layer). The joint use of 2–3 frequency modes for detecting flying objects is recommended based on the analysis of revealed angular and contrasting weather features, typical of each considered frequency range. The data presented in the work and the regularities noted could be useful to conduct a forecasted assessment on the effectiveness of the radiometry method, and selecting the most preferable set of operating frequencies when designing such systems.

ACKNOWLEDGMENTS

The work was supported by the Ministry of Education and Science of Ukraine; under the state registration numbers 0120U10208 and 0119U100968.

REFERENCES

[1] L. Sommer, A. Schumann, T. Muller, T. Schuchert, and J. Beyerer, "Flying object detection for automatic UAV recognition," in *2017 14th IEEE International Conference on Advanced Video and Signal Based Surveillance (AVSS)*, 2017.

[2] C. Aker and S. Kalkan, "Using deep networks for drone detection," in *2017 14th IEEE International Conference on Advanced Video and Signal Based Surveillance (AVSS)*, 2017.

[3] H. Liu, Z. Wei, Y. Chen, J. Pan, L. Lin, and Y. Ren, "Drone detection based on an audio-assisted camera array," in *2017 IEEE Third International Conference on Multimedia Big Data (BigMM)*, 2017, pp. 402–406.

[4] B. Jang, Y. Seo, B. On, and S. Im, "Euclidean distance based algorithm for UAV acoustic detection," in *2018 International Conference on Electronics, Information, and Communication (ICEIC)*, 2018.

[5] J. Vilímek and L. Buřita, "Ways for copter drone acustic detection," in *2017 International Conference on Military Technologies (ICMT)*, 2017, pp. 349–353.

[6] J. Ochodnický, Z. Matousek, M. Babjak, and J. Kurty, "Drone detection by ku-band battlefield radar," in *2017 International Conference on Military Technologies (ICMT)*, 2017, pp. 613–616.

[7] M. Jahangir and C. Baker, "Robust detection of micro-UAS drones with l-band 3-d holographic radar," in *2016 Sensor Signal Processing for Defence (SSPD)*, 2016.

[8] S. Björklund, "Target detection and classification of small drones by boosting on radar micro-doppler," in *2018 15th European Radar Conference (EuRAD)*, 2018, pp. 182–185.

[9] C. Liang, N. Cao, X. Lu, and Y. Ye, "UAV detection using continuous wave radar," in *2018 IEEE International Conference on Information Communication and Signal Processing (ICICSP)*, 2018.

[10] J. Klare, O. Biallawons, and D. Cerutti-Maori, "UAV detection with MIMO radar," in *2017 18th International Radar Symposium (IRS)*, 2017.

[11] B. Nuss, L. Sit, M. Fennel, J. Mayer, T. Mahler, and T. Zwick, "MIMO OFDM radar system for drone detection," in *2017 18th International Radar Symposium (IRS)*, 2017.

[12] I. V. Ostroumov, N. S. Kuzmenko, and K. Marais, "Optimal pair of navigational aids selection," in *2018 IEEE 5th International Conference on Methods and Systems of Navigation and Motion Control (MSNMC)*, 2018, pp. 32–35.

[13] N. S. Kuzmenko and I. V. Ostroumov, "Performance analysis of positioning system by navigational aids in three dimensional space," in *2018 IEEE First International Conference on System Analysis & Intelligent Computing (SAIC)*, 2018.

[14] Y.-K. Kwag, I.-S. Woo, H.-Y. Kwak, and Y.-H. Jung, "Multi-mode SDR radar platform for small air-vehicle drone detection," in *2016 CIE International Conference on Radar (RADAR)*, 2016.

[15] S. J. Lee, J. H. Jung, and B. Park, "Possibility verification of drone detection radar based on pseudo random binary sequence," in *2016 International SoC Design Conference (ISOCC)*, 2016, pp. 291–292.

[16] S. Deligeorges, G. Cakiades, J. George, Y. Wang, and F. Doyle, "A mobile self synchronizing smart sensor array for detection and localization of impulsive threat sources," in *2015 IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI)*, 2015, pp. 351–356.

[17] C. Schupbach, C. Patry, F. Maasdorp, U. Boniger, and P. Wellig, "Micro-UAV detection using DAB-based passive radar," in *2017 IEEE Radar Conference (RadarConf)*, 2017, pp. 1037–1040.

[18] G. Fang, J. Yi, X. Wan, Y. Liu, and H. Ke, "Experimental research of multistatic passive radar with a single antenna for drone detection," *IEEE Access*, vol. 6, pp. 33 542–33 551, 2018.

[19] B. Knoedler, R. Zemmari, and W. Koch, "On the detection of small UAV using a GSM passive coherent location system," in *2016 17th International Radar Symposium (IRS)*, 2016.

[20] P. Andraši, T. Radišić, M. Muštra, and J. Ivošević, "Night-time detection of UAVs using thermal infrared camera," *Transportation Research Procedia*, vol. 28, pp. 183–190, 2017.

[21] H. J. Liebe, "MPM—an atmospheric millimeter-wave propagation model," *International Journal of Infrared and Millimeter Waves*, vol. 10, no. 6, pp. 631–650, Jun. 1989.

[22] *Attenuation due to clouds and fog*, Rec. ITU-R P.840-8, International Telecommunications Union, Geneva, Switzerland, Aug. 2019.

[23] V.M. Lipinsky, V.A. Dyachuk, V.M. Babichenko, Eds., *Climate of Ukraine*, Kyiv, Ukraine: Raevsky Publishing House (in Russian), 2003.

[24] O. Odokienko *et al.*, "Cumulative distribution of rain rate and rain attenuation in ukraine," in *2019 3rd International Conference on Advanced Information and Communications Technologies (AICT)*, 2019, pp. 62–66.

[25] S. Zhyla *et al.*, "Cumulative functions of vertical atmospheric attenuation of millimeter radio waves over kharkov," (in Russia), *Radiotekhnika*, vol. 4, no. 199, pp. 83–90, Dec. 2019.

[26] V. K. Volosyuk, S. S. Zhyla, V. V. Pavlikov, A. D. Abramov, and V. G. Yakovlev, "Optimum algorithm for estimating radio brightness in spatially distributed radiometer systems," *Telecommunications and Radio Engineering*, vol. 77, no. 18, pp. 1649–1658, 2018.

[27] L. B. Knyaz'kov and N. V. Ruzhentsev, "Quasioptical polarization multipath diplexer," *International Journal of Infrared and Millimeter Waves*, vol. 27, no. 2, pp. 211–217, Jan. 2006.

[28] L. B. Knyaz'kov and N. V. Ruzhentsev, "Quasi-optical diplexer and filter based on a polariza-

tion ring interferometer," *Technical Physics Letters*, vol. 33, no. 9, pp. 761–763, Sep. 2007.

[29] L. B. Knyaz'kov and N. V. Ruzhentsev, "Foamy-dielectric lens transmission lines for millimeter and submillimeter wavelength range," *Technical Physics Letters*, vol. 34, no. 10, pp. 888–890, Oct. 2008.

[30] N. V. Ruzhentsev and Y. A. Kuzmenko, "Flare angle changes antenna of the millimeter wave band," *International Journal of Infrared and Millimeter Waves*, vol. 17, no. 4, pp. 779–784, Apr. 1996.

[31] "Low Noise Amplifiers." MI-WAVE. https://www.miwv.com/low-noise-amplifiers/

[32] Z. Chen, H. Gao, D. M. Leenaerts, D. Milosevic, and P. G. Baltus, "A 16–43 GHz low-noise amplifer with 2.5–4.0 dB noise figure," in *2016 IEEE Asian Solid-State Circuits Conference (A-SSCC)*, 2016, pp. 349–352.

Nikolay Ruzhentsev is Chief Researcher and Professor of the Department of Aerospace Radio-Electronic Systems, National Aerospace University of N. E. Zhukovsky, Kharkiv, Ukraine. Field of scientific interests: development of hardware-methodological maintenance and researching of the radiophysical properties of the environment in the millimeter wave range.

Simeon Zhyla received the master's degree in radio engineering at National Aerospace University "Kharkiv Aviation Institute", Ukraine. He obtained his Ph.D. degree in radio-engeneering and television systems in 2015 and D.Sc. in 2021 at National Aerospace University "Kharkiv Aviation Institute", Ukraine. Since then, he has been a head of the department of aerospace radio-electronic systems at National Aerospace University "Kharkiv Aviation Institute". His research interests focus on statistical theory of aerospace radar design with optimal space-time signal processing, extended field of view and high spatial resolution; optimal methods of forming high-precision coherent optical and radar images for promising autonomous systems; statistical theory of ultra-wideband active aperture synthesis systems for high-precision remote sensing from high-speed aerospace platforms; principles of optimal processing of signals of own radio thermal radiation of objects of different physical nature and technology of their realization.

Vladimir Pavlikov is the vice rector for science at National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine. He was Dean of Radio Electronics, Computer Systems and Info-Communications Faculty (April 2017 – September 2018) and Head of the department of aircraft radio-electronic systems design (April 2015 – March 2017). He received his Doctor of Technical Sciences in January 2014. He is a Senior Researcher since April 2015. In 2016–2018, he was the head of the scientific work "New principles of processing signals of own radio-thermal radiation of objects of different physical nature and technologies for their implementation". In 2019–2021, he was the head of scientific work "The development of the theory of ultra-wideband active aperture synthesis systems for high-precision remote sensing from high-speed aerospace platforms".

Valerii Volosyuk received his Doctor of Technical Sciences in 1996. He is a Professor of the Department of Aerospace Radio-electronic Systems of the Kharkov Aviation Institute, Kharkiv, Ukraine, since 1997. He is a specialist in decision theory, statistical theory of radio systems, radar, digital signal processing and radio physics. He is also a specialist in the field of statistical theory of radio systems for remote sensing and radar. His scientific interests include a wide range of modern problems related to radar mapping of the earth's surface, radiophysical measurements of electrophysical parameters and statistical characteristics of natural environments, measurements of the parameters of earth covers according to the registration of their own radiothermal radiation, improving the accuracy and efficiency of spatiotemporal processing of aircraft and rocket signals, space systems with synthetic aperture.

Eduard Tserne received the master's degree in telecommunications and radio engineering at National Aerospace University "Kharkiv Aviation Institute", Ukraine. Since September 2020, he has been a graduate student and assistant of the Aerospace Radioelectronic Systems Department of the National Aerospace University "Kharkiv Aviation Institute", Ukraine. His research interests are focused on statistical theory of optimal signal processing algorithms synthesis for passive radar systems; active aperture synthesis systems; embedded systems; high-speed digital signal processing algorithms and systems based on FPGAs.

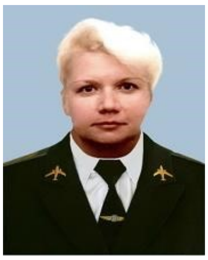
Anatoliy Popov received his degree in radio engineering in 1984, Ph.D. degree in special-purpose radio engineering systems from Kharkiv Aviation Institute (USSR) in 1991 and D.Sc. degree from National Aerospace University "Kharkiv Aviation Institute", Ukraine, in 2021. Within the years 1984 to 1998, he was a Researcher of Radar Laboratory of Kharkiv Aviation Institute. Since 1999, he is an Associate Professor of the department of aerospace radio-electronic systems of National Aerospace University "Kharkiv Aviation Institute", Ukraine. He is a specialist in the field of radar design, radar measurements, laboratory and field experiments, radar signals processing and automatic target recognition. Research interests include remote sensing, radar polarimetry, statistical theory of radio signal scattering, multichannel signal and image processing, pattern recognition.

Oleksandr Shmatko received his Ph.D. degree in radio-engeneering and television systems in 2015 at National Aerospace University "Kharkiv Aviation Institute", Ukraine. Since then, he has been a head of the Laboratory of electron microscopy, optics, and laser technologies at National Aerospace University "Kharkiv Aviation Institute", Ukraine. His research interests focus on broadband antennas,distributed antenna systems, passive radar, radar antennas, radar imaging, radar signal processing, remote sensing, remote sensing by radar.

Ivan Ostroumov received the B. Eng. degree in aviation and spacecraft engineering and the master's degree in maintenance and services of airspace systems engineering from National Aviation University of Kyiv, Ukraine. He obtained his Ph.D. degree in Navigation and Traffic Control in 2009 and D.Sc. in 2020 from National Aviation University of Ukraine. Since then, he has been a Senior research scientist and professor at National Aviation University. He is a faculty of Air Navigation Systems Department of the National Aviation University of Ukraine since September 2007. In 2017/2018 has being a Fulbright scholar in the school of Aeronautics and Astronautics at Purdue. His research interests focus on developing navigation and surveillance methods. He is currently working on improving availability and accuracy estimation of navigation, risk analysis, and developing advanced methods for alternative positioning, navigation, and timing.

Nataliia Kuzmenko received the B. Eng. degree in aviation and spacecraft engineering and the master's degree in maintenance and services of airspace systems engineering from National Aviation University of Kyiv, Ukraine. She obtained her Ph.D. degree of Engineering in Navigation and Traffic Control in 2017 at the National Aviation University of Ukraine. Nataliia is certified aviation security instructor by International Civil Aviation Organization (ASTP/Basic, ASTP/Instructors). She has had a traineeship in Tool Development for support to CAA/NSA at Regulatory Division within the Directorate Single Sky (Eurocontrol, Brussels). Nataliia is a head of innovative educational projects department of the National Aviation University of Ukraine. Current research projects include aviation safety, collision detection, and avoidance, artificial intelligence, Software development, Navigation and positioning, Intelligent Transport Systems, video stream object detection and recognition, kernel density estimation, neural networks.

Kostiantyn Dergachov is the Head of the Department of Aircraft Control Systems, Candidate of Technical Sciences, Associate Professor, Senior Research Fellow. His research interests including rational management of complex technical objects; avionics; computerized systems of technical vision; navigation of mobile robots with technical vision systems. He is author of more than 100 scientific publications, including 12 textbooks and monographs, 15 patents.



Olga Sushchenko received the Master's degree in gyroscopic devices and units from Kyiv Polytechnic Institute, Ukraine. She obtained her D.Sc. degree in Automation Systems of Design Works in 2015 from National Aviation University of Ukraine. She is currently a Professor of the Aerospace Control Systems Department, the National Aviation University. She has authored 250 published papers on stabilization and control systems of the wide class and navigation systems of moving vehicles. Her research interests include design and improvement of the stabilization system for aviation equipment, navigation systems, control systems of quadrotors.

Yuliya Averyanova received the master's degree in radio engineering from National Aviation University of Kyiv, Ukraine. She obtained her Ph.D. degree in Navigation and Air Traffic Control in 2005 and D.Sc. in 2017 from National Aviation University of Ukraine. Since then, she has been a professor at National Aviation University. Her research interests focus on Meteorological Radar, Aviation Meteorology, Remote sensing, Radar Polarimetry, Navigation and Surveillance, Risk Analysis.

Maksym Zaliskyi received the B. Sc. degree in radio engineering and the Master's degree in design and operation of radioelectronic devices, systems and complexes from National Aviation University of Kyiv, Ukraine. He obtained his Ph.D. degree in Operation and Repair of Transport Equipment in 2012 and D.Sc. in 2021 from National Aviation University of Ukraine. He is currently a Professor of the Department of Telecommunication and Radioelectronic Systems, the National Aviation University. He has authored 170 published papers on maintenance and operation of radio equipment, statistical data processing and heteroskedasticity analysis. His research interests include design and improvement of the operation system for radio equipment, statistical analysis of operational data.

Oleksandr Solomentsev received the Master's degree in operation of aviation radio equipment from Kyiv Institute of Civil Aviation, Ukraine. He obtained his Ph.D. degree in Aircraft Equipment Operation in 1981 and D.Sc. in 1988 from Kyiv Institute of Civil Aviation of Ukraine. He is currently a Professor of the Department of Telecommunication and Radioelectronic Systems, the National Aviation University. He has authored 250 published papers on maintenance and operation of radio equipment, statistical data processing and reliability theory. His research interests include design and improvement of the operation system for radio equipment, statistical analysis of operational data.

Olena Havrylenko received the master's degree in program engineering at the National Aerospace University "Kharkiv Aviation Institute", Ukraine. She obtained her Ph.D. degree in Information technologies in 2005 at the National Aerospace University "Kharkiv Aviation Institute", Ukraine. Since then, she has been a docent of the Aircraft Control Systems department of the National Aerospace University "Kharkiv Aviation Institute", Ukraine. Her research interests focus on information technologies in transport and avionics; decision-making support systems; intelligent tutoring systems.

Borys Kuznetsov received the B. Eng. degree in automated control systems engineering and the master's degree in systems engineering from National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine. He obtained his Ph.D. degree in Automation of Control Processes in 1980 and D.Sc. in 1990 from National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine. Since then, he has been a Senior research scientist and professor at Ukrainian Engineering Pedagogical Academy, Kharkiv, Ukraine. Since 2022 he has been working as the head of the laboratory of the department of magnetism of technical objects of the A.M. Pidgorny Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine. For a series of monographs devoted to the development of methods for the synthesis of multi-channel control systems for technological processes and moving objects he received the State Prize of Ukraine in the field of science and technology in 2000. His research interests focus on developing the scientific basis for the creation of multi-channel systems for high-precision control of various objects and processes. He is currently working on improving robustness and accuracy electromagnetic and electromechanical systems control.

Tatyana Nikitina received the B. Eng. degree in automated control systems engineering and the master's degree in systems engineering from National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine. She obtained his Ph.D. degree in Automation of Control Processes in 2002 and D.Sc. in 2012 from National Technical University «Kharkiv Polytechnic Institute», Kharkiv, Ukraine. Since then, she has been a Senior research scientist and professor at Kharkov National Automobile and Highway University Yaroslava Mudroho, Kharkiv, Ukraine. Since 2022 she has been working as the professor of the Educational Scientific Professional Pedagogical Institute Ukrainian Engineering Pedagogical Academy Bakhmut, Ukraine. His research interests focus on developing the new methods for the synthesis of electromechanical systems. She is currently working on improving accuracy electromechanical systems control.