Analysis of models and algorithms used operationally in methods for the continuous monitoring of bird collision hazards

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The results of the analysis of factors influencing the emergence of dangerous situations in the air (in short, aviation incidents) in the Polish Army show a significant negative impact of the environment on the flight operations performed. The most common cause of an aviation incident in the area of the environment is the collision of the aircraft with birds. The lack of methods for the continuous monitoring and forecasting of the level of risk of collision between aircraft and birds makes a significant gap in a proactive approach to the safety of flights in the Air Force of the Republic of Poland. This paper presents an overview of the most important methods for detection and forecasting of bird flight intensity, which have been used for construction of systems aiming to prevent collisions with birds and which are employed by the air forces of the United States, the Netherlands, Belgium and Israel. An accurate analysis of the models and algorithms used in the selected methods shows contemporary trends in research on the negative impact of the environment on flight safety. These methods show incomplete usefulness in Poland's conditions, which justifies the need to develop a more appropriate method.

Keywords: safety, aviation, bird strike.

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1. Introduction

Contemporary flight safety management theories place emphasis on a comprehensive analysis of the individual areas of the aviation system in order to detect any anomaly in operation and to undertake an immediate response reducing the level of risk to an acceptable state. The Flight Safety Manual [18] uses two of them "5-Factor Model" and the Reason's "Swiss Cheese" model [25, 4] to identify the causes of aviation incidents and the areas of the aviation system in which hazards occur.

After analysing the causes of aviation incidents, it was found that, leaving aside the area of the machine, one of the most important factors in their occurrence was the negative impact of the environment. Figure 1 contains the distribution of the incidents' causes grouped by areas and management levels of the aviation system according to the "5-Factor Model" theory and the Reason's "Swiss Cheese" for jet aircrafts [26].

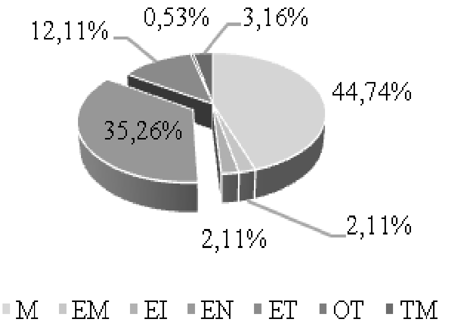

Fig. 1. The percentage of air incidents for jet aircrafts due to the cause of occurrence without the machine area in 2016–2018. Separated slice is for the environment

It is worth noting that 80% of all aviation incidents, which were caused by negative environmental impact, were caused by collisions with birds. All the more worrying is the fact that the trend of intensity of such incidents is not decreasing, as shown in Figure 2.

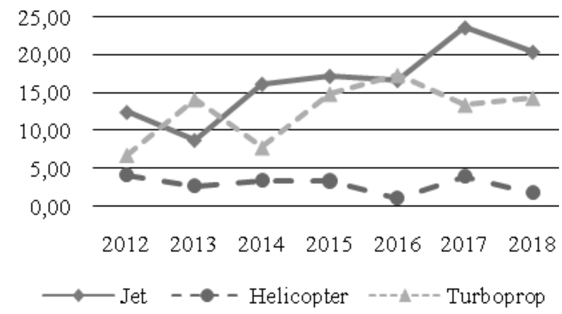

Fig. 2. The marker indicating the intensity of incidents resulting from collisions with birds in relation to the air flights, with a division into type of aircraft in 2012–2018

Fig. 3. Examples of the consequences of a collision between an aircraft and a bird. Above, an example of a collision between a Czech L-159 fighter and a vulture[1]. Below, an example of a Sikorsky UH-60 Black Hawk helicopter colliding with a common crane[2]

The collision of aircrafts with birds is a significant problem in both civil and military aviation although there are some differences in the two branches. The most important are the altitude and velocity of flight operations. Civil aviation focuses primarily on the control of the aerodrome site and its neighbourhood, as a result of the nature of the air operations. Passenger aircraft usually operates at the altitude of 10 km a.s.l., where there is virtually no movement of birds. Military flights are usually conducted at significantly lower altitudes, implying the sharing of airspace with birds and the hazard of collision throughout the flight. Another important factor is the higher flight velocity for fighter aircraft operations. Since the collision energy of an aircraft with a bird is proportional to its mass and to the square of its velocity, even a seemingly small individual can do serious damage. In view of the above differences, it should be noted that not all methods used by civil aviation to counter collisions with aircrafts will be equally effective during military operations.

A collision between an aircraft and a bird, although seemingly harmless, can lead to serious consequences. For US Army military aviation, the average cost of a single aircraft-bird collision is about $0.5 million based on data from 2011–2017[3]. Figure 3 shows selected effects of aircraft collisions with birds.

Unfortunately, there are no methods to effectively control the movement of birds in any airspace chosen. However, in contrary to civilian flights, greater tolerance is allowed for delays, cancellations as well as re-routing during military exercises. In view of the above military flight properties, many countries have developed systems to monitor the current airspace, as well as predict the migration of birds in order to amend flight plans due to the excessive risk of collision with birds.

Based on an analysis of 1991–2000 data on collisions between military aircraft and birds in the air forces of France, the United Kingdom, Germany and the Netherlands, it was found that the rate of the above incidents per 10000 flight hours is 45% lower for countries that have an active bird collision warning system. It has been estimated that the costs associated with a collision with a bird in an air force with a functioning system are more than half the costs in an air force where no monitoring solutions and predicting the movement of birds in the airspace have been applied [32]. It is worth noting that the air forces of France, the United Kingdom and Germany are among the top European countries in terms of the size of their air fleets.

Selected methods of counteracting collisions with birds, applied in the information systems of NATO countries and countries cooperating with the Alliance, in which there are intense migratory movements of birds, are presented below. When selecting the methods,

[1] https://www.natoaktual.cz/zpravy/letoun-se-srazil-se-supem.A151030_152043_na_zpravy_m00
[2] https://commons.wikimedia.org/wiki/File:IAF_UH-60_after_birds_strike_inside.jpg
[3] https://www.militarytimes.com/news/your-military/aviation-in-crisis/2018/04/14/wildlife-strikes-add-to-air-force-and-navys-mishap-count

both the size of the bird migration in a given country and the potential of the air force were taken into account. After a short characterization, selected methods were compared in terms of risk reduction potential, mathematical models used, methods of matching models and results of correctness tests. Then each of the methods was analysed in terms of the possibility of using it, taking into account Polish conditions.

2. The method used in AHAS system

A significant level of risk in low altitude flight operations was already highlighted by the USAF[4] in the 1970s. Due to the involvement of the BASH team[5], a spatio-temporal model of bird occurrence in the territory of the United States was developed, which was used in the implementation of the United States Bird Avoidance Model (US BAM) [23, 5]. The next step in supporting flight safety in the area of environmental hazards was the development of a new method in the late 1990s based on both US BAM, weather data and also weather radar readings. The method was developed by a team consisting of the Air Combat Command Bird Hazard Working Group and Geo-Marine Inc. The method was used in the implementation of a new GIS type system called Avian Hazard Advisory System (AHAS). Positive system tests were carried out during the autumn migration in 1998 for selected locations on the east coast. Subsequently, the monitored area was gradually extended to the continental part of the United States, until 2005 when the territory of Alaska was added [20, 6]. The system is available on the Internet as a web application[6].

The method allows to estimate the level of risk on a 3-step scale for any selected area. Depending on the prediction horizon, a maximum of 2 of the 3 available models shall be used in the appropriate order. First, a model based on the NEXRAD network[7], then a model based on the weather forecast, and finally a spatio-temporal model contained in the US BAM [19, 22] is used.

The model using the NEXRAD network determines a prediction of the risk level for the next hour and can be used if current radar data is available. In simple terms, birds are bags of water, so they scatter similar amount energy as some precipitations. But rain tends to have the difference in the horizontal and vertical distribution and for some type of meteorological objects difference in the levels of the measured reflectivity. For example, a storm can reflect radio waves at an altitude of 6 to 10 kilometres and cover many square kilometres of the Earth's surface. Bird migrations usually do not have a significant vertical distribution. Most of them do not exceed an in-flight altitude of 4 kilometres. The above distinctions allows to classify the radar images by the model which is based on a neural network [23, 20, 210].

The soaring model and the migration model determine the prediction level for the next 24 hours based on selected weather forecast parameters. Their absence precludes the use of the above models. The prediction concerns 12 bird species considered most dangerous in case of collision with an aircraft. The soaring model estimates the possibility and depth of thermals that are used by some bird species. Due to the above calculations the maximum altitude of bird activity is determined [20, 21]. The migration model based on the neural network allows to estimate whether the migration of birds is possible for given weather conditions [20, 19, 29, 7]. In case of favourable weather conditions, the level of risk is determined with using US BAM.

The US BAM is the model showing the time-spatial distribution of bird populations in the territory of the United States. The model allows an estimate of the level of risk at any time during the year. Based on this model, the risk area is calculated with a resolution of 1 square kilometre for two-week periods during the year, divided into four times of the day: dawn, day, dusk and night. The model includes over 60 different species that pose a significant hazard in the event of a collision [5].

3. The method used in the FlySafe-BAM project

Collisions with birds have also been an important problem for the air forces of European countries. In order to combine the efforts of research groups from different countries, including the Netherlands, Belgium, France,

[4] United States Air Force (USAF) – one of the branches of the United States Armed Forces.

[5] Bird/wildlife Aircraft Strike Hazard (BASH) – a team within the USAF to reduce environmental hazards affecting air operations in order to maintain the combat capability of these forces.

[6] http://usahas.com

[7] Next-Generation Radar (NEXRAD) – a network of 160 NATO standard E/F Doppler weather radars, which are subordinate to the U.S. National Weather Service (NWS) and are used to monitor weather conditions in the United States.

Germany and Switzerland, the FlySafe project was launched under the IAP[8] programme of the European Space Agency [8, 33, 13]. One of the effects of this project is the FlySafe-BAM application used by the Dutch and Belgian Air Force. The method developed for the application allows the estimation and prediction of the risk of collision with birds in the next 72 hours in the vicinity of the weather radar. It consists of a vol2bird algorithm for estimating the current level of risk, as well as the hazard prediction model based on Generalized Additive Models (GAMs).

The use of weather radar to detect and monitor bird migration is due to the well-developed network of weather radars across Europe. The studies carried out in the years 2007 and 2008 in the Netherlands, Belgium and France confirmed the possibility of automatic bird migration detection using weather radars [9]. The vol2bird algorithm, which is the result of the above mentioned studies, uses simple features that distinguish the radar image created on the basis of meteorological objects from moving birds [10].

It turns out that continuous areas of measured radial velocity containing bird echoes have a characteristic granularity which translates into a high value of the standard deviation of radial velocity differences between gates in the scanned sweep. The characteristic granular form is shown in Figure 4b. Migratory birds rarely exceed a predetermined reflectivity factor depending on the wavelengths generated by the radar. Another difference is the larger error when adjusting radar velocity measurements to the modelled homogeneous wind field. It is over 2 m/s as shown in Figure 4d. For double-polarized radar, the scanned areas where the birds are located are characterized by a correlation coefficient $\rho_{HV} < 0.9$.

The result of the algorithm is information on the intensity, direction and velocity of bird migration with a breakdown into layers of altitude, which such information is estimated on the basis of data from an area around the radar with a radius of 25 km. The authors of the algorithm suggest to study the airspace up to the altitude of 4 km above sea level, which should capture almost all occurring migrations in Europe [2].

In the case of prediction, the method shall use a weighted average using GAMs that seek to estimate how intense bird movements are based on time spot during the year, weather data and accumulation of individuals due to adverse weather conditions. In practice, around 50 best suited GAMs are used. The most important weather parameters used for prediction include wind direction and velocity, diurnal variations in temperature, pressure, cloud cover, temperature deviation from an average at a given time instant and precipitation [24].

4. The method used by the Israeli Air Force

Due to the current geopolitical situation, the State of Israel has a high density of military aircrafts in its airspace. As there is a strong migration of birds over the territory of Israel from Europe to Africa and Asia in the autumn and returning over the territory of Europe in the spring, it was quickly recognized that the problem of bird collisions in military air traffic causes significant losses. According to ornithologists, there can be up to 500 individual birds within 1 km^2 of Israel's airspace during the height of migration [11]. High quality MRL-5 weather radar was used to monitor moving birds.

The developed algorithm allows for the detection of bird migration within a radius of up to 60 km from the radar regardless of weather conditions and time of day [11, 12]. The radar specification is further discussed in the following paper [1].

The algorithm, due to the way the radar echoes of birds are extracted, requires a specific radar operating configuration. In order to amplify the reflected radar echo and distinguish it from electromagnetic noise, it sends 16 pulses in one direction, summing up the energy obtained. Another requirement is to scan a given area 8 times with a constant antenna inclination, which should allow for the analysis of the movement of the scanned objects. Research has shown that in the case of bird detection, it is best to use 10 cm wavelengths, which allows to reduce interference caused by insects. The 3 cm long waves significantly enhanced a signal reflected from the insects in relation to the birds.

The idea of the algorithm is based on the analysis of radar images with using a still camera, which superimposes successive images on a single shot. While viewing photos created in this way, you can notice that flying birds form streaks, which distinguishes them from other objects.

[8] Integrated Applications Promotion – a programme aimed at creating a service combining space technology with ground systems.

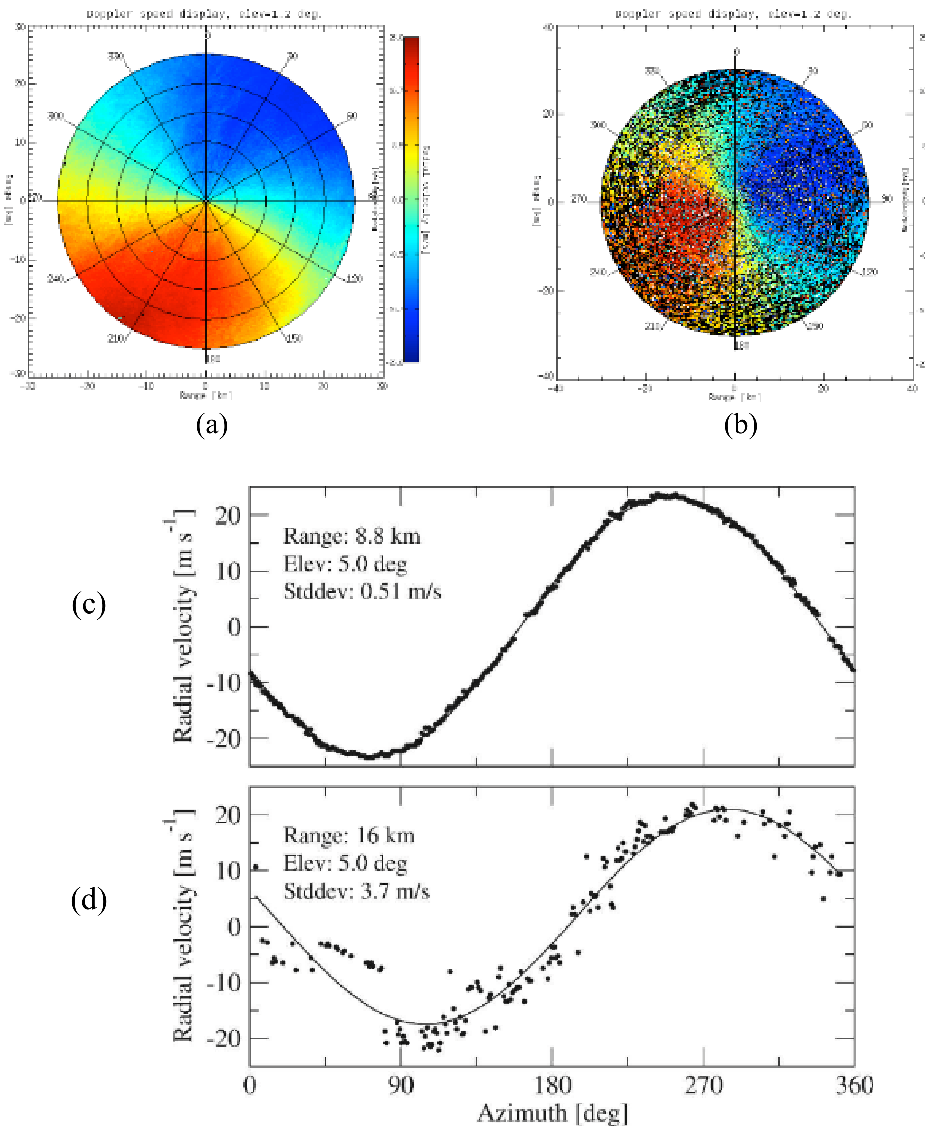

Fig. 4. Comparison of the radial velocity values Plan Position Indicators (PPI) of precipitation (a) and birds (b) [9] and comparison of the measured radial velocity (points) when there are no birds (c) and when there are birds (d) to the estimated radial velocity of linear lift model (continuous line) [17]

The most important steps of the algorithm are [11]:

1. Analysis of the returned signal power and rejection of measurements with too high a value that is unlikely to be seen by flying birds.
2. Summarizing the value of the returned power from m scans obtained for a given elevation angle.
3. Rejection of measurements repeating at the same place.
4. Filtering out echoes from birds based on the change in echo position and bird movement patterns, according to the criteria of velocity range, uniformity of velocity and uniformity of movement direction.
5. Estimation of velocity vectors for each echo group representing an individual or group of birds using the method of linear regression of changes in position in the plane.
6. Rejection of velocity vectors that cannot come from birds based on a special method based on additional properties (energy return, velocity and chaotic directions).

The results of the algorithm are classified echo samples returned to the radar in terms of their echo affiliation to the echo of birds, as well as velocity vectors of echo groups. This allows us to determine how many birds are currently migrating and what is the distribution of migration velocity. The algorithm's operating diagram is shown in Figure 5.

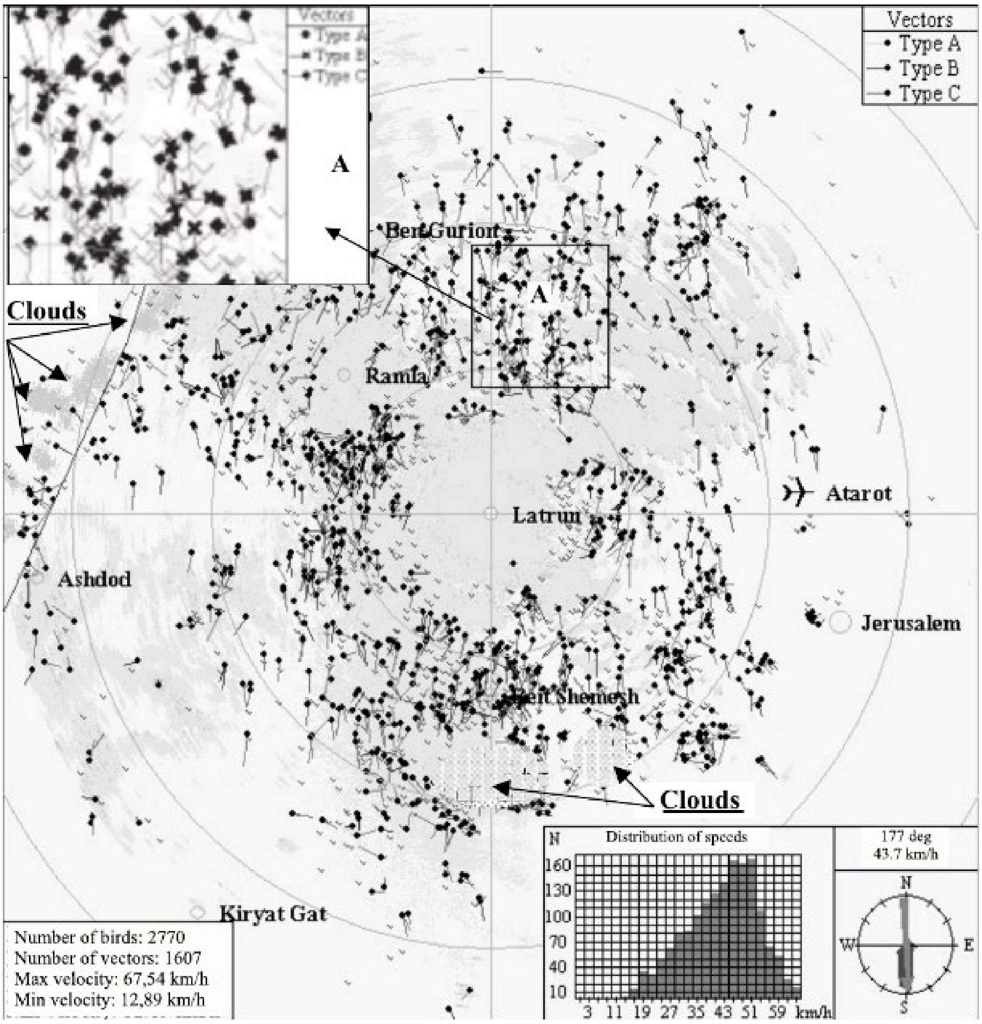

Fig. 5. An example of the application of the method by the IAF [12]

5. Comparison of the selected methods

Due to the large variety of the above methods in terms of the algorithms and models used, the possibility of detection and prediction of the risk level as well as the required input data, a comparative analysis will be presented below.

Each of the methods allows to detect the passage of birds and estimate the level of the risk of an aircraft collision with birds in near real time based on radar data, however, different approaches to the problem were used here. The method used in the AHAS system uses a multi-layer feedforward neural network model [7]. Thanks to the non-linear transformation, the network allows for the classification of a given fragment of space into meteorological or biological objects. Unfortunately, due to the nature of the model, it is hard to interpret the resulting transformation and to define rules on which the classifier is based.

The method used in the Flysafe-BAM system is based on the statistical differences in the measurements made by the weather radar mentioned in the previous sections. The algorithm's operating principle can be summarized by the following steps [10]:

1. For each sweep in the radar file, mark continuous areas that may not belong to birds.
2. Assign bins to the appropriate layers of altitudes.
3. If necessary, first perform a dealiasing operation of the velocity measurements for each layer of altitude by using a mapping of the measurements to the torus surface [15].
4. Determine parameters of homogeneous wind field by using the SVD method for each layer of altitude [16].
5. For each layer characterized by a major matching error, determine the density, velocity and direction of the migration of birds, excluding areas which are not associated with birds.

A "Connected component labelling" algorithm was used to label the continuous areas in step 1 [28]. For each k-th tagged area a simple rule has been used to classify it. If $\overline{\sigma_k} < 5\left[\frac{m}{s}\right]$ or $\overline{Z_k} > 15\,[dbZ]$ it is the area containing precipitation, otherwise there are birds where $\overline{Z_k}$ is the average of the reflectivity factor and $\overline{\sigma_k}$ is the above-mentioned average of the standard deviations expressed by the following equation:

$$\overline{Z_k} = \sum_{i\in A_k}\frac{Z_i}{|A_k|},\quad \overline{\sigma_k} = \sum_{i\in A_k}\frac{\sigma_i}{|A_k|}$$
$$\sigma_i^2 = \sum_{j\in O_i}\frac{\left(V_r^{(i)}-V_r^{(j)}\right)^2}{|O_i|} - \left(\sum_{j\in O_i}\frac{V_r^{(i)}-V_r^{(j)}}{|O_i|}\right)^2 \quad (1)$$

where A_k is a set of observation indices of the k-th area, Z_i is i-th reflectivity factor, $V_r^{(i)}$ is i-th velocity measurement and O_i is a set of indices of adjoining measurements. In order to eliminate the problem of velocity aliasing in weather radars, a method were used to convert measurement space into torus surface. Using a homogeneous wind model expressed by the following equation:

$$V_m\,(u,v,\Phi,\Theta) = = (u\cdot\sin\Phi + v\cdot\cos\Phi)\cdot\cos\Theta \quad (2)$$

where u, v stands for the wind velocity east-west and north-south, and Φ, Θ are spherical coordinates standing for the angular height of the antenna inclination and azimuth. After superimposing the measurement points on the torus surface for dealiasing, determine the wind model parameters u^*, v^* for the following objective function:

$$F(u^*,v^*) = \min_{u,v} F(u,v) = \sum_{\langle i,\Phi,\Theta\rangle\in P}\left[\left|\begin{matrix}\frac{V_N}{\pi}\cdot\cos\left(V_m\,(u,v,\Phi,\Theta)\cdot\frac{\pi}{V_N}\right) + \\ -\frac{V_N}{\pi}\cdot\cos\left(V_{\Phi\Theta}^{(i)}\cdot\frac{\pi}{V_N}\right)\end{matrix}\right| + \\ + \left|\begin{matrix}\frac{V_N}{\pi}\cdot\sin\left(V_m\,(u,v,\Phi,\Theta)\cdot\frac{\pi}{V_N}\right) + \\ -\frac{V_N}{\pi}\cdot\sin\left(V_{\Phi\Theta}^{(i)}\cdot\frac{\pi}{V_N}\right)\end{matrix}\right|\right] \quad (3)$$

where V_N is the Nyquist velocity, $V_{\Phi\Theta}^{(i)}$ means i-th velocity measurement for given spherical coordinates and P is a set of observation indices. The Least square method was used to determine the velocity and direction of objects in steps 4 and 5 of the algorithm, assuming that objects form a homogeneous velocity field according to the following formula:

$$V_m\,(u,v,w,\Phi,\Theta) = = u\cdot\sin\Phi\cos\Theta + v\cdot\cos\Phi\cos\Theta + w\cdot\cos\Theta \quad (4)$$

where additionally w is the vertical wind component. The above problem can be reduced to the problem of resolving the following equation:

$$0 = \sum_{\langle i,\Phi,\Theta\rangle\in P}\left[V_{\Phi\Theta}^{(i)} - V_m\,(u,v,w,\Phi,\Theta)\right]^2 \quad (5)$$

with respect to the unknowns u, v and w. Writing the above equation in matrix form we obtain:

$$\boldsymbol{Ap} = \boldsymbol{b}$$
$$\boldsymbol{p} = \boldsymbol{A}^{-1}\boldsymbol{b} \quad (6)$$

where the vector $\boldsymbol{p} = [u\ v\ w]^T \in \mathbb{R}^3$ means the parameters sought, the vector

$\boldsymbol{b} = \left[V_{\Phi\Theta}^{(1)} V_{\Phi\Theta}^{(2)} \dots V_{\Phi\Theta}^{(N)}\right]$ means the values

observed and the matrix $\boldsymbol{A}$ is in the form of:

$$\boldsymbol{A} = \begin{bmatrix}\cos\theta^1\sin\phi^1 & \cos\theta^1\cos\phi^1 & \sin\phi^1\\ \cos\theta^2\sin\phi^2 & \cos\theta^2\cos\phi^2 & \sin\phi^2\\ \vdots & \vdots & \vdots\\ \cos\theta^N\sin\phi^N & \cos\theta^N\cos\phi^N & \sin\phi^N\end{bmatrix}$$

Since the above matrix is not square, pseudo-inversions are made with using SVD decomposition. The matrix

$$\boldsymbol{A} = \boldsymbol{U}\cdot[diag(w_k)]\boldsymbol{V}^T \quad (7)$$

after pseudoinversion, it looks as follows

$$\boldsymbol{A}^+ = \boldsymbol{V}[diag(1/w_k)]\boldsymbol{U}^T \quad (8)$$

where for $w_k = 0$ the element $diag(1/w_k)$ assumes a 0 value. Using the above transformation, the estimated parameters of vector $\boldsymbol{p}$ minimize the mean square error $\|\boldsymbol{Ap}-\boldsymbol{b}\|_2$ [29]. The model error shall be estimated according to the following formula:

$$\sigma_m = \sqrt[2]{\frac{\sum_{\langle i,\Phi,\Theta\rangle\in P}\left[V_{\Phi\Theta}^{(i)} - V_m\,(u,v,\Phi,\Theta)\right]^2}{|P|-3}} \quad (9)$$

In the case of the method used by the Israeli Air Force, the method is based on an analysis of images of successive radar sweeps and results from surveillance of a radar image taken at long exposure time. Following the rejection of the radar echo with inadequate energy and the radar echo that did not change its position, the movement analysis described in point 4 of the algorithm follows. At each scan made at one antenna height, the centres of the continuous area formed by the radar echo shall be determined according to the following formula:

$$\overline{X_J} = \frac{\sum_{i=1}^{n_j} p_i^j x_i^j}{\sum_{i=1}^{n_j} p_i^j} \quad \overline{Y_J} = \frac{\sum_{i=1}^{n_j} p_i^j y_i^j}{\sum_{i=1}^{n_j} p_i^j} \tag{10}$$

where $\overline{X_J}, \overline{Y_J}$ are the coordinates of the j-th centre, formed by the individual recorded observations forming a "spot" with coordinates x_i^j, y_i^j having the power p_i^j. The "spot" has a limit of the size, which is 27 scatters. Lines are then created which connect the centres of "spots" recorded on the first sweep with the centres of "spots" on subsequent sweeps, limited according to the distances the birds may have travelled in the time between successive antenna rotations. The next step is to leave lines whose length from the centre increases with subsequent scans and lengths are directly proportional to time with a 20% tolerance, which allows for homogeneous movement of birds to be taken into account. Then "spots", which are close to the line drawn by the centre from the first and last sweep, are left, to account for the rectilinear movement of the birds. The movement is rectilinear if the centres are not more away from the designated line than 10%÷40% of the line length. The chaotic nature of the movements is checked at the end. This shall be tested by checking the probability distribution of the directions of the designated lines. If a given "spot" centre has delineated multiple lines with a directional distribution close to a uniform variable, it is expected that the delineated segments do not belong to the bird displacement vectors and can be used for subsequent rejection of "spots". The remaining centres of the "spots" that met the above criteria are combined and form displacement vectors used to determine bird velocities. Knowing the subsequent i-th coordinates of the centre of the j-th spot at the i-th instant of time $\langle x_i^j, y_i^j, t_i \rangle$, the linear regression parameters can be estimated:

$$X^j = v_x^j t + b_x^j \quad Y^j = v_y^j t + b_y^j \tag{11}$$

where v_x^j, v_y^j are the orthogonal components of the velocity vector of the j-th spot.

All the above methods estimate the level of risk on the basis of data obtained from weather radars with a delay of up to 15 minutes. In the case of the method used in AHAS, the construction of the network is based on historical weather radar data on which the relevant areas have been designated as meteorological or biological objects. The methods used in the Flysafe-BAM system and in the Israeli Air Force do not need historical data to operate, however, it is worth noting that in the latter case, the method assumes the use of a dedicated and properly configured weather radar.

The methods used in AHAS and Flysafe--BAM may predict the level of risk. In the first case, the level of risk shall be determined on the basis of the US BAM model. If the prediction horizon is less than 24 hours, the soaring model and the migration model additionally allows for prediction of bird activity in airspace on the basis of the predicted weather conditions. The development of the US BAM model was based on a wide range of sources, including federal, state and private agencies collecting data on bird abundance, day-to-day modes of operation and information on bird migration intensity and directions acquired from ornithology experts. Once the number of individual birds has been determined, the areas without relevant data have been estimated using the Inverse distance weighting. This method allows for the estimation of the values for any point with $\langle x, y \rangle$ coordinate, based on the values of neighbouring observations. For the above model, the value is determined on the basis of 12 adjacent observations according to the formula [30]:

$$z_{xy} = \frac{\sum_{i=1}^{12} \frac{z_i}{d_i^2}}{\sum_{i=1}^{12} \frac{1}{d_i^2}} \tag{12}$$

where z_i is the size of the i-th neighbouring observation and d_i is the distance to it. After the creation of a standardized risk area based on expert knowledge, patterns of behaviour of individual species during the day were added [6, 14].

For the method used in Flysafe-BAM, ensemble learning was used, with using a non-linear GAMs regression method. The explained variable d, which is the density of passing birds, summed up at all the altitudes considered, is determined by using the formula [24]:

$$\hat{d} = \frac{\sum_{k=1}^{L} w_k \cdot \widehat{d_k}}{L}$$
$$w_k = \frac{MAE_{max} - MAE_k}{MAE_{max} - MAE_{min}} \tag{13}$$

where $\widehat{d_k}$ is the density determined by the k-th model, and w_k is the weight resulting from the accuracy of the given model, where the weight is estimated by the mean absolute error (MAE). The weights are obtained on the basis of a cross-validation result from 50 variants of a given model. Any k-th GAMs in its general form can be written up as:

$$g_k(\mu) = \alpha + \sum_{i \in Z_k} f_{ki}(x_i) \qquad (14)$$

where it was assumed that d_k is based on a "quasi" Poisson distribution with expected value $\mu = E\left(d_k | x_{k_1}, x_{k_2}, \ldots, x_{k_l}\right)$, $g_k(\cdot) = \ln(\cdot)$ is a link function that binds the expected value to the model, x_i are the predictor variables, f_{ki} is the non-linear function of the i-th predictor variable in k-th model, α is the constant, and Z_k is a set of indices of predictor variables used in k-th model. Each model shall contain a unique combination of predictor variables, which shall consist of a maximum of 6 variables, including a time variable. A *gam*() function implemented in R language as part of the *mgcv* package was used to estimate individual models [34]. The algorithm of estimation in this function is based on penalized regression splines. Estimation is done by direct penalized likelihood maximization with integrated smoothness estimation. An important feature is the possibility of estimating functions with a larger number of variables when they are dependent on each other. This was used for variables such as time of day and season, and the wind velocity vector.

Regarding the estimation of model parameters for the method used in the AHAS, statistical data on the number of bird occurrences and expert knowledge on daytime bird behaviour and migration routing were needed for its construction. For the Dutch method, historical data on migration intensity (estimated using vol2bird algorithm) and historical data with weather parameters are required to build the prediction model.

In the case of the AHAS method, it is possible to predict the level of risk of collision with birds for any moment in time and for any selected area on a 2D plane with a resolution of 1 km^2. The accuracy of the estimate depends on the prediction horizon. For the Flysafe-BAM method, this method allows for prediction of the level of risk of bird collision within a radius of 25 kilometres from the weather radar with a time horizon of 72 hours, due to the current effectiveness of weather forecasting.

The validation data of algorithms are available only for the method used in Flysafe-BAM and IAF. The Dutch method has a probability of detection (POD) of 97% and a false alarm ratio (FAR) of 42% when detecting birds at densities over 1 per km^3. However, a large number of erroneous bird detections occur when the number of birds is small. For detection of bird density above 10 per km^3 POD is 100%, FAR 97% [10]. An absolute mean error was used to evaluate the prediction model. The error was considered by migration period, time of day and location of measurement. At best, it was 0.2 and at worst 2.44. The model was undervalued when there was a large increase in migration intensity in a short period of time. Tests conducted on the Israeli method indicate that the probability of detecting birds decreases as the distance from the radar increases. The probability decreases more quickly in case of night migration, which is connected with the smaller size of birds flying at night. The developed method allows the detection of more than 80% of birds within 5 km to 30 km from the radar. For distances up to 60 km, a total of about 40% of the birds were detected during the night migration. In case of daily migration, over 70% of birds were detected [12].

6. Usage under Polish conditions

In Poland in autumn and spring there is an intensive migration during which even 2 million birds may move during the day [31, 27]. The biggest difference in migration patterns compared to other areas of Europe are the complex migration routes of birds [3].

In the Air Force of the Republic of Poland (SPRP) there are appropriate structures to counteract the hazards resulting from the negative impact of the environment on safety, as exemplified by the Programme for the Reduction of Environmental Threats in the Air Force of the Polish Armed Forces. However, there is no expert group dealing exclusively with such hazards. As the example of other countries shows, a good solution is to use the existing radar infrastructure. Taking into account the deployment of available weather radars in Poland as shown in Figure 6, both civilian and military radars should be used to monitor the movement of birds throughout the airspace. Only through such synergies of action is it possible to construct a continuous system for a bird collision risk analysis that will allow for the introduction of proactive flight safety prevention in the environmental area.

A dedicated solution should be able to continuously estimate the current level of the risk of an aircraft colliding with birds, taking

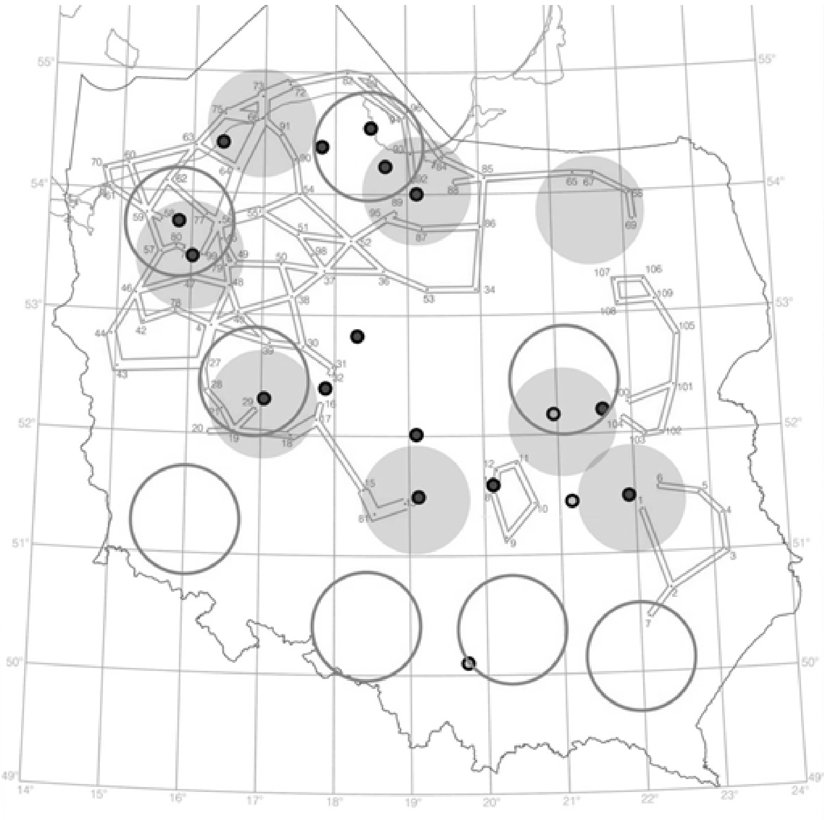

Fig. 6. Approximate locations of military (wheels) and civil (circles) weather radars that can be used for the construction of a risk analysis system for bird collision (Skakuj M., in litt.)

into account the amount of a hazard. In addition, it should predict the hazard level over a time horizon of 72 hours including altitude. The method should be based on available digital data such as radar, weather, GIS data on terrain topography, water reservoirs or terrain use. It should also take into account local environmental conditions such as complex migration routes or existing bird species. The method shall not involve modifications to the radar equipment or its parameters which may interfere with the operation of the services using that radar infrastructure.

The methods set out in the above chapters do not meet all the requirements. The method used by the Israeli Air Force only allows the determination of the current level of risk and is based on dedicated radar infrastructure. The method used by Flysafe-BAM enables the monitoring and prediction of the risk level for the area around the radar. Additionally, the method assumes that birds move in one direction and that there is a preferred direction of bird migration. This assumption is invalid for Polish conditions. The vol2bird algorithm should estimate the distribution of the main birds velocity vectors during migration. In the case of the method used in AHAS, the sources used to create the US BAM model were collected over many years and with the help of many government agencies, organizations and volunteers. The data collected had to be analysed by a team of ornithological experts for further use. In addition, the method is based on the behaviours of bird species that live in the territory of the United States.

7. Conclusions

The paper presents the most important methods used by the air forces of various countries to estimate the current level of risk of collision with a bird and its prediction. This knowledge is used in the planning and management of air operations in order to minimize the risk of a plane crash. The paper presents a short description of each method, as well as the main features allowing for comparison in terms of their capabilities. Subsequently, each method was analysed in terms of models and algorithms used, required data, local conditions and results of validation. Available algorithms for bird radar echo detection have been based on both artificial intelligence methods (AHAS) and dedicated solutions based on differences in weather radar images containing different object types

(Flysafe-BAM, IAF). In the first case, an adequate amount of data is required for the model learning process. In the latter case, it is easier to interpret the results of algorithms. As regards prediction due to the complex relationship between weather conditions and the intensity of bird migration, artificial intelligence methods such as neuron networks (AHAS) and the non-linear regression method using GAMs (Flysafe-BAM) have been used in both cases.

Then each of the methods was analysed in terms of the possibility of using it, taking into account Polish local conditions. All of the above mentioned methods have certain properties which significantly hinder their application. Most of them use models that take into account the environmental conditions prevailing in the area. Some of them are based on data sources that are not available for our airspace. It is also unacceptable that a change in radar station parameters could interfere with the operation of services based on the radar infrastructure concerned.

It is therefore necessary to develop a method of its own which meets the requirements set out in Chapter 6. The method developed will be able to support those responsible for air operations planning in the Polish Air Force. In addition, monitoring and prediction of bird migration can be used in a dynamically developing and innovative field of science – aeroecology.

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Analiza modeli i algorytmów wykorzystywanych operacyjnie w metodach nadążnego monitorowania zagrożeń zderzenia z ptakami

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Wyniki analizy czynników wpływających na powstawanie niebezpiecznych sytuacji w powietrzu (w skrócie zdarzeń lotniczych) w Wojsku Polskim wskazują na istotny negatywny wpływ środowiska naturalnego na wykonywane operacje lotnicze. Najczęstszą przyczyną powstania zdarzenia lotniczego w obszarze środowiska naturalnego jest zderzenie statku powietrznego z ptakami. Brak metod nadążnego monitorowania oraz prognozowania poziomu ryzyka wystąpienia kolizji statku powietrznego z ptakami stanowi istotną lukę w proaktywnym podejściu do bezpieczeństwa lotów w ramach Sił Powietrznych RP. W artykule został przedstawiony przegląd najważniejszych metod detekcji oraz prognozowania intensywności przelotu ptaków, metody te zostały użyte do budowy systemów przeciwdziałających kolizjom z ptakami i są wykorzystywane przez siły powietrzne Stanów Zjednoczonych, Holandii, Belgii oraz Izraela. Dokładna analiza modeli i algorytmów zastosowanych w wybranych metodach pokazuje współczesne trendy w badaniach dotyczących negatywnego wpływu środowiska naturalnego na bezpieczeństwo lotów. Wspomniane metody wykazują niepełną przydatność w warunkach Polski, co uzasadnia potrzebę opracowania bardziej adekwatnej metody.

Słowa kluczowe: bezpieczeństwo, lotnictwo, zderzenie z ptakiem.