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SURVEY PAPER

Large-scale bird surveillance technology using operational weather radar

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Abstract

The operational weather radar network is highly suitable for large-scale bird monitoring and early warning systems. This study discusses, compares and contrasts current state-of-the-art technologies for large-scale bird surveillance – including manual observation, satellite tracking, dedicated avian radar and the operational weather radar network – evaluating their respective strengths, limitations and applicability for different monitoring scenarios. Key research questions focus on how to extract reliable bird movement information from weather radar data and how such data can support ecological studies and aviation safety. From the perspective of radar signal analysis, we examine the characteristics of bird echoes in terms of reflectivity, altitude distribution, flight speed and direction. We further review and compare methodologies for distinguishing bird echoes from weather and ground clutter, including clutter suppression, meteorological echo removal, feature extraction, machine learning classification and cross-validation with auxiliary data. Our synthesis demonstrates that weather radar can effectively identify and track bird movements over wide areas, providing valuable data on migration patterns and flight behaviours. These findings have practical significance for applications in avian ecology research and bird strike prevention in aviation.

Nomenclature

NEXRAD	Next Generation Weather Radar
OPERA	Operational Program on the Exchange of Weather Radar Information
AHAS	Avian Hazard Advisory System
ENRAM	European Network for the Radar surveillance of Animal Movement
e-COST	European Cooperation in Science and Technology
ODIM	OPERA Data Information Model
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
FAA	Federal Aviation Administration
FlySafe-BAM	FlySafe Bird Avoidance Model
KNMI	Royal Netherlands Meteorological Institute
MTR	Migration Traffic Rate
WR	weather radar
AR	avian radar
MR	maritime radar
RCS	radar cross section
CNNs	convolutional neural networks
RNNs	recurrent neural networks
BAM	Bird Avoidance Model

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1.0 Introduction

With the rapid development of civil aviation transportation, bird strike, as one of the major hidden dangers affecting flight safety, continues to increase its impact on flight safety [1]. Spring and autumn are the high-incidence periods of bird strike events, showing an obvious seasonal law. The high-altitude and night bird strike of migratory birds in the migration season are extremely difficult to prevent and control, and its occurrence law is highly consistent with the bird migration rhythm [2].

Around the world, hundreds of millions of birds meet their survival and reproduction requirements through long-distance migration every year, including migrating to the best seasonal habitat, looking for resources and mates, avoiding predators and foraging [3]. Satellite tracking is an important means of bird migration research. The continuous miniaturisation of satellite positioning equipment and technological innovation have continuously improved its tracking ability. However, the relative weight of this equipment is still the main factor limiting the development of this technical route [4]. Therefore, only a few large birds can be tracked by installing satellite positioning sensors, and usually the number of individuals located each time is very limited, accounting for only a very small part of the total population. A key application of radar is quantifying the large-scale temporal and spatial distribution of biological targets, a capability that has been instrumental in studying bird migration since the 1940s [5]. In recent years, advances in radar technology have led to the development of dedicated avian radars. However, these systems are typically designed for localised, high-resolution monitoring, resulting in a limited detection range and sparse deployment. Consequently, it is challenging to employ them in a networked configuration for large-scale bird migration observation. Weather radar is especially suitable for target detection of migratory birds on a large scale and is convenient for effective networking [6]. Therefore, the establishment of a nationwide early warning system for bird migration monitoring based on weather radar is essential to mitigate the serious threat that bird strikes pose to aviation safety. These incidents can compromise flight operations and aircraft integrity, particularly during critical phases like takeoff and landing. By providing timely alerts on bird activity, this system will enable pilots and air traffic controllers to take proactive measures, thereby significantly reducing the safety risks to aircraft and passengers.

This review is motivated by the need to consolidate the fragmented research on weather radar as a tool for bird strike prevention and avian ecology studies. Based on a comprehensive review of weather radar-based bird warning systems in the United States and Europe, this paper aims to achieve three main objectives: first, to assess the capabilities and limitations of weather radar in large-scale bird migration monitoring, with a focus on the echo characteristics of bird targets and the technologies for extracting avian biological information from meteorological radar data; second, to analyse the complementary characteristics of different radar systems in terms of spatial scales and monitoring coverage and third, to explore the potential of multi-source data fusion in constructing a multi-scale observational framework, integrating heterogeneous radar data to support bird strike prevention for civil and military aviation. These objectives guide the subsequent discussion and ultimately align with the conclusions presented in this paper.

2.0 Large-scale bird surveillance technology

At present, ornithological research institutions try to establish a global bird situation database by widely collecting bird observation information provided by bird observers from all over the world, to explore the migration laws of various birds around the world. In addition, the installation of satellite tracking equipment for individual birds is also a common method of bird migration research used by ornithologists. Radar data can provide information about the spatial distribution, density, height, general speed and direction of biological targets in flight. Dual polarisation radar can even provide target shape information, which greatly improves the recognition ability of birds, insects, bats, precipitation and other targets [7]. Since the 1940s, radar-based bird surveillance technology has evolved from fragmented research into a coordinated scientific endeavor. Currently, continental-scale networks such as the Next Generation Weather Radar (NEXRAD) in the United States [8] and the Operational Program on the Exchange of

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Weather Radar Information (OPERA) in Europe [9] routinely collect raw volumetric weather data – including radar reflectivity and radial velocity – across vast geographical areas. Through specialised processing and interpretation, these data are transformed into biologically meaningful information on bird migration, such as migration traffic rates, flight directions and intensities over time. This capability has established effective collaboration channels between meteorologists and biologists. By providing continuous, standardised and continental-scale insights into avian movement, these operational radar networks constitute a unique and extensive information source for ecology. They not only facilitate a deeper understanding of migration behaviour but also create foundational conditions for related ecological research and bird strike prevention.

2.1 Manual observation

Manual observation of birds refers to the use of telescopes and other observation and recording equipment to observe and record wild birds and their living environment in a natural state. The observation content includes observing the morphology, song and other characteristics of birds, identifying the species of birds, observing the feeding, habitat, reproduction, migration and other behaviours of birds, understanding the relationship between birds and their living environment, as well as the dynamic changes of bird populations in a certain area [10]. At present, the ecological investigation of the bird situation at airports is still mainly carried out by manual observation, which investigates the species, quantity and distribution of birds, insects and vegetation in the area by setting up a number of survey sample lines in and around the airport flight area.

The development of information network technology provides convenient conditions for the collection and utilisation of bird observation information. A bird database called eBird, established by the Cornell Lab of Ornithology, uses millions of observation data submitted by bird watchers around the world to provide the latest information on the status and trends of bird populations [11]. eBird is among the world's largest biodiversity-related science projects, with more than 100 million bird sightings contributed annually by eBirders around the world and an average participation growth rate of approximately 20% year over year. The team uses the recorded data to model the bird species around the world based on the relative abundance, which refers to the number of certain birds that a bird watcher can see in a certain area in an hour. By drawing the bird abundance distribution map once a week, the dynamic distribution of various birds could be described, and their migration around the world is analysed. Figure 1 illustrates the modeled relative abundance distribution of the cattle egret during the spring breeding season of 2023, based on analysis of eBird citizen science data. Relative abundance, defined as the expected count of individuals per standardised survey unit (e.g. a 1-hour, 1-km traveling count), is quantified using a spatio-temporal model (e.g. SpatioTemporal Exploratory Models (STEM)). The model output reveals core distribution areas with the highest quantifiable relative abundance, including the Indian subcontinent, Eastern Africa and parts of South America. In regions such as Southern North America and Eastern China, the species exhibits a migratory pattern, with presence primarily during the spring and summer. In contrast, populations in Southern China and Southeast Asia are predominantly year-round residents.

2.2 Satellite tracking

Conventional methods, such as banding and visual observation, can only record the migratory activities of birds in a certain place or region, and it is difficult to continuously track the whole process of bird migration. With the miniaturisation of radio transmitters, the satellite tracking technology for data transmission through satellites can track the whole migration process of birds in real time, covering the whole world. Satellite tracking technology can collect a large amount of data that is difficult to obtain by conventional methods, such as migration time, route, breeding place, resting place and overwintering place, which play an important role in understanding bird migration activities [12]. Satellite tracking can identify species, as it targets known individuals, enabling species-specific monitoring.

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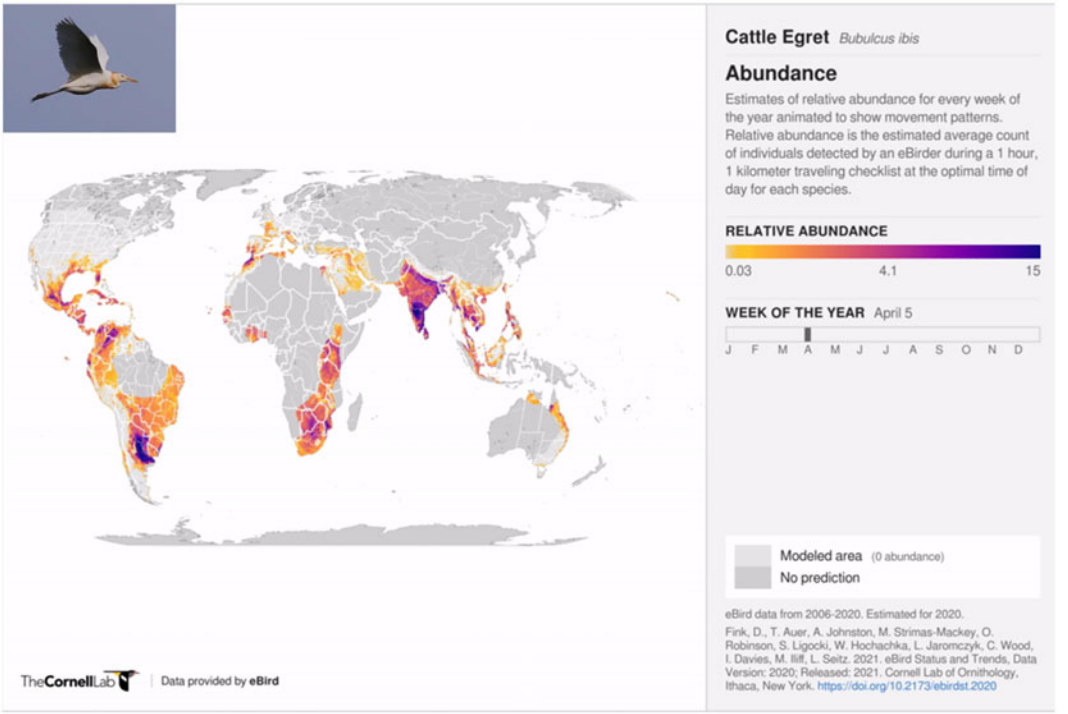


Figure 1. *Global abundance distribution of cattle egrets [11].*

This study aims to enhance the type of individual movement trajectory data collected by avian satellite trackers. The critical constraint for this technology remains transmitter mass, which should not exceed 3% of a bird's body mass to avoid impacting behaviour. Consequently, its application has been largely limited to larger bird species, which aligns with the need for monitoring high-risk bird activities. Recent advancements in communication and photovoltaic technologies are pivotal for our objectives. The adoption of global mobile communication systems has significantly reduced power consumption, while high-efficiency solar cells now enable a substantial, continuous power supply. These developments permit trackers to transmit high-frequency, real-time data streams – including latitude, longitude, altitude, speed and ambient temperature – directly to researcher terminals without recapture. This capability, depicted in Fig. 2, which shows a heron's migration route between China and Russia, fundamentally improves the success rate and timeliness of obtaining migration data. It is this real-time, quantifiable trajectory and environmental data that our research seeks to leverage and refine for enabling dynamic bird activity warning systems.

Kays published a review in Science in 2015, describing the current application status and future development trends of satellite tracking-related technologies [13]. The Institute of Zoology, Chinese Academy of Sciences, has established a long-term migration route database for the Arctic peregrine falcon by satellite tracking and revealed the genetic basis of the bird's long-distance migration. The relevant results were published in Nature in 2021 [14].

2.3 Avian radar

The primary advantage of radar is its capacity for all-weather monitoring of flying bird targets. It can record the number of birds at high altitudes and measure their flight direction and speed, unaffected by lighting conditions. However, a key limitation is its inability to identify bird species [15]. Early

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(a) The heron (b) Migration route

Figure 2. *Satellite tracking results of a heron.*



(a) System platform (b) Flying bird tracks

Figure 3. *Typical robin radar system [21].*

bird surveillance systems were developed to support military aviation safety. These systems extracted information on bird activity such as location and movement from the display interfaces of air surveillance radars. In the Netherlands, radar station personnel would consult biologists to help estimate bird densities based on radar screen readings [16]. In Denmark, Belgium and Germany, such analyses were generally performed by the radar operators themselves. In Israel, during migration seasons, wildlife managers and radar specialists collaborate on this task. Upon detecting a large flock – primarily known from external knowledge to consist of species such as white storks, white pelicans and various raptors – they promptly notify the relevant air traffic control towers and route management units in affected areas [17].

The earliest electronic bird warning system was put into use in Denmark in 1971 and the Netherlands in 1978 [18]. These systems functioned as electronic counters of bird migration intensity, embedded within multiple display windows on military air surveillance radar screens. Their core technology relies on algorithms for detecting, tracking and recognising bird targets to distinguish them from aircraft. Customised software then displays the speed, altitude and flight direction of the detected birds. Such radar data processing-based bird warning systems have been deployed in countries including Germany and the Netherlands. The German system, for instance, has evolved into a network incorporating 19 air traffic control radars and 32 air surveillance radars from Germany and neighbouring countries [19]. A key advantage is the automatic data generation across all radars connected within the military network. However, the visualisation of bird activity on radar screens is contingent upon the specific parameter settings of the radar system. As shown in Fig. 3, the Dutch Robin radar system can detect birds based on military air surveillance radar data and distinguish bird tracks from ground clutter and precipitation [20, 21].

It is important to clarify the distinction between specialised avian radars, like those discussed in this section and designed specifically for bird detection, and weather radars, which are primarily designed

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for meteorological observation but can also detect biological targets such as birds and insects. The differentiation between birds and insects by radar typically relies on analysing target characteristics within the radar returns, such as flight speed, altitude, movement patterns (e.g. flapping vs. drifting) and sometimes polarimetric properties (e.g. reflectivity, differential reflectivity). While weather radars offer the significant advantage of extensive existing networks, facilitating large-scale migration monitoring (e.g. the NEXRAD system in the United States and the OPERA system in Europe, detailed in Section 2.4) [22, 23], their accuracy in distinguishing and characterising biological targets is generally lower compared to purpose-built avian radars. This is because their algorithms and parameters are optimised for weather phenomena, not biological targets.

A key aim of this paper is to discuss technologies, including potential algorithmic improvements and multi-parameter analysis, that can enhance the differentiation between birds and insects and improve the accuracy of biological target identification within radar systems, particularly leveraging or adapting existing infrastructure like weather radar networks where feasible.

In terms of migration warning models, a large number of studies have shown that the migration behaviour of birds is related to meteorological factors [24]. The relationship between migration behaviour and meteorological conditions has promoted the establishment of prediction models for bird migration density and flight height. According to meteorological forecast data, bird migration can be predicted for 24 to 72 hours. In the early 1970s, Denmark took the lead in developing the flight safety prediction model, but it was not put into practical application [25]. Germany developed the first practical flight safety model, which used multiple weather parameters to predict bird strike risk. At present, the prediction model also considers the actual bird migration information of the radar system and slightly adjusts the prediction results [26]. Based on meteorological data and the measurement data of migration intensity by two military air surveillance radars deployed in the Netherlands and Belgium, the Netherlands established a regression model and put it into operation in 2001 [27].

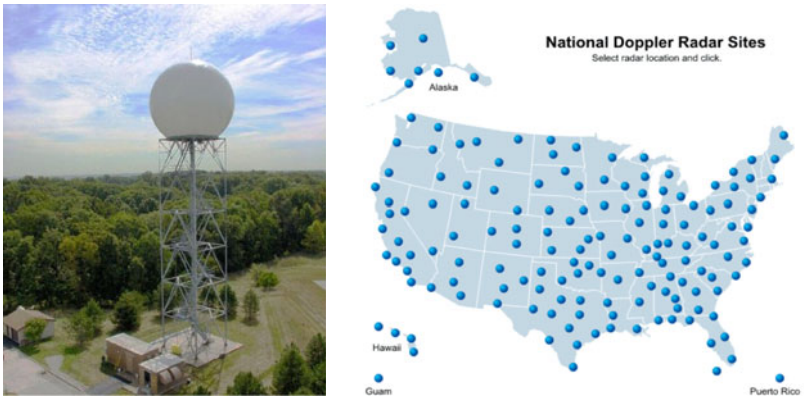
2.4 Weather radar

The Avian Hazard Advisory System (AHAS), developed and operated for the U.S. Air Force, aims to mitigate bird strike risks by providing automated, data-driven risk assessments [28]. To achieve this aim, the system quantifies bird strike risk by automatically processing data from the NEXRAD network. This network, comprising the U.S. National Weather Radar Network, utilises a nationwide array of S-band WSR-88D Doppler weather radars. These specialised ‘weather radars’ are instrumental for this application as their signals can be analysed to identify and quantify biological targets, such as birds, based on their characteristic radar cross-sections and movement patterns.

As shown in Fig. 4, the NEXRAD network consists of 160 S-band WSR-88D Doppler weather radar stations. The raw radar data (e.g. reflectivity, velocity) collected by this network are received via satellite by the AHAS platform. Subsequently, these data undergo a specific quantification and analysis process: bird-related information is algorithmically identified and distinguished from weather phenomena. This processed information, representing the spatial density and movement of birds, is then synthesised into a real-time bird strike risk assessment. The final output provides critical, quantified risk information for all U.S. Air Force training routes and activity areas, directly supporting the application of flight safety management and mission planning.

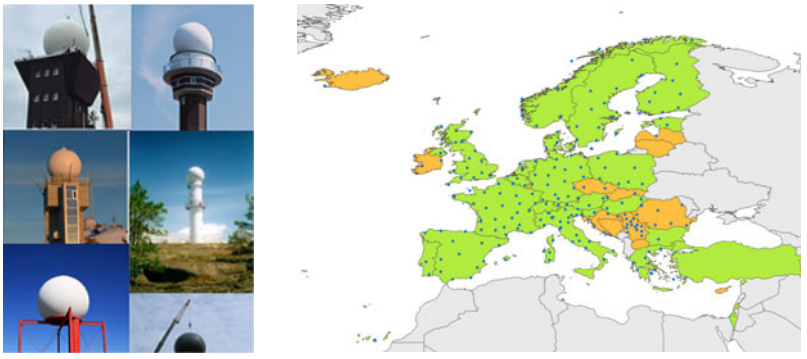
Since the initial deployment of the U.S. meteorological surveillance radar infrastructure (WSR-57) in 1957, several successive upgrades of the radar network have enhanced its meteorological observation capabilities and provided a better database for bird surveillance [29]. Every progress in weather radar technology is accompanied by a new exploration process of bird information extraction technology, which must be fully combined with the professional knowledge of ornithology. Early weather radar can only provide the radar reflectivity factor. Only after it was upgraded to WSR-88D radar in the NEXRAD network in 1988 did it have Doppler detection capability. Since then, the parameters of Doppler radial velocity and radial velocity spectral width obtained are usually used to describe the echo characteristics of migratory targets, distinguish birds and insect targets and identify the echo of bird habitats

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(a) WSR-88D (b) NEXRAD Radar Sites in USA

Figure 4. *Distribution and coverage of NEXRAD network [29].*



(a) Various OPERA radars (b) Geographical distribution of OPERA radars

Figure 5. *Distribution and coverage of OPERA network in Europe.*

[30]. The improvement of radar resolution also provides more spatial details and a more detailed scale distribution description ability for bird detection. In 2013, the NEXRAD weather radar network completed the upgrade of dual polarisation technology of all WSR-88D radars, added three conventional data products of total differential phase, differential reflectivity and polarisation correlation coefficient and established a standard data format with target polarisation characteristics. Relevant data products can be downloaded free of charge through the Amazon cloud computing service platform, creating favourable conditions for the detection of migratory birds and related research [31].

In Europe, all operational weather radars are used as members of the OPERA system to continuously monitor atmospheric conditions for data exchange and measurement within the European continent. The OPERA system was established in 1999 and has absorbed 200 radars from 30 member countries, as shown in Fig. 5 [32]. From 2013 to 2017, the European Network for the Radar surveillance of Animal Movement (ENRAM) was established under the support of the European Cooperation in Science and Technology (e-COST) programme and operated under the organisation of the OPERA system. Its main goal is to integrate professional knowledge, establish a multidisciplinary research network in Europe, including ecology, ornithology, entomology, meteorology, engineering, mathematics, visual analysis and computer science, and use OPERA weather radar to monitor the migration of animals in various parts of Europe, to serve the majority of stakeholders. At present, ENRAM has adopted 70 weather radars in the OPERA system covering parts of Western Europe, and the number is still growing [33].

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Table 1. *NEXTRAD and OPERA network performance comparison*

Network	NEXTRAD	OPERA
Land area	9.8 million km^2	4.3 million km^2
Population	315 million	500 million
Organisation	NEXRAD tri-agencies of National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS), Federal Aviation Administration (FAA) and Air Force	Joint effort of 30 independent nationalweather services
Number and frequency	160: all S-band	200: 163 C-band, 29 S-band and 8 X-band
Polari metric radars	Network upgrade completed in spring 2013	106 at present, a gradual increase is ongoing
Radar systems	Single manufacturer and model	Various manufacturers and models
Operating modes	Two modes: clear air and precipitation, and eight distinct volume coverage patterns (chosen by operator)	National operating modes
Data format	All radars use the same data format	Agreed data format for exchange

The European radar network was independently established by national meteorological departments of various countries, and experience exchange, coordination and data exchange started in the 1990s [34]. European countries are at different stages of the development of their radar operation networks, and have different plans for radar renovation or updating. More than half of the radars were built before 1998, and the time span between the oldest and newest radars in the network exceeds 40 years. Among the current 200 radars in the OPERA system, 184 have Doppler function and 106 have dual polarisation, and these two numbers are still growing steadily. In addition, most of these radars work in C-band, and only some of the radars deployed in southern Europe are in S-band. Therefore, Europe's OPERA radar network is diversified in terms of installation date, manufacturer, scanning strategy, signal processing and product output, which is different from the NEXRAD radar network in the United States. Their performances are compared in Table 1 [9]. This undoubtedly adds difficulties and challenges to the operation of a continental network and requires cooperation and information exchange among countries. Therefore, the OPERA system has established the data centre called 'Odyssey' in 2011, and established the OPERA Data Information Model (ODIM). However, since the radar networks of various countries are still operating independently, this difference cannot be fully bridged in the short term [35].

One of the important functions of the ENRAM project is to extract and release bird warning information through the FlySafe Bird Avoidance Model (FlySafe-BAM) [36]. FlySafe-BAM is jointly developed by several scientific research institutions in Europe, which realises the automatic detection and quantification of bird migration and can give the distribution density, speed and flight direction of bird targets at different heights. In 2009, the Dutch and Belgian air forces proposed to provide bird warning service based on FlySafe-BAM, which was organised and completed by the Royal Netherlands Meteorological Institute (KNMI) [37]. At that time, the radar data used in this service were provided by two air defense radars (one in Belgium plus one in the Netherlands) and five weather radars (three in Belgium plus two in the Netherlands), which could predict the migration of birds in the North Sea, northern Netherlands, central Belgium and eastern Belgium. With the launch of the ENRAM project in 2013, KNMI has further enriched its radar data sources through cooperation with the Polish Air Force, the Netherlands Air Force, the Belgian Air Force and the German Bundeswehr. The function of FlySafe-BAM has been further improved. It can make a quasi-real-time forecast of bird situation in the Netherlands, Belgium and Germany and release it to pilots as a bird notice to aircraft to avoid bird strike incidents [38]. At present,

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the bird detection algorithm in FlySafe-BAM is still continuously improving. With the increase in the number of member countries joining the flight safety plan, the scope of FlySafe-BAM information services will continue to expand.

3.0 Echo characteristics of bird targets in weather radar

This section analyses the echo characteristics of the flying bird target obtained by the weather radar from the aspects of target echo amplitude, flight height, flight speed and direction, and discusses the difference between the weather radar and the professional avian radar, to lay a foundation for the extraction of bird information based on the weather radar.

3.1 Target echo amplitude

The comparison of radar echo amplitude between precipitation and migratory birds has certain guiding significance. The *Z*-*R* relationship in meteorology reflects the relationship between radar reflectivity Z and precipitation intensity R, which is usually expressed by the following formula [39],

$$Z = 200 \cdot R^{1.6} \tag{1}$$

where the unit of Z is mm^6/m^3, and the unit of R is mm/h, and $Z_{dB} = 10\log(Z)$.

The relationship between reflectivity and liquid water content in air can be expressed by an empirical formula [40],

$$M = 3.44 \times 10^3 Z^{4/7} \tag{2}$$

where M is the liquid water content in unit volume with the unit of kg/km^3. The liquid water content in the air under moderate precipitation ($R = 1$ mm/h, $Z = 200$ mm^6/m^3) is $M = 7\times10^4$ kg/km^3. The distribution density of migratory birds in the peak migration period can reach 100 $birds/km^3$. According to the assumption that a single bird of Passeriformes is equivalent to 50 ml of water ball, the liquid water content can reach 5 kg/km^3, which is far lower than the moderate precipitation [41].

Radar backscatter not only depends on the mass and density of the scatterer, but is also closely related to the shape of the scatterer. Under Rayleigh scattering conditions, the reflectance corresponding to a precipitation density of 5 kg/km^3 is very low (−27 dBZ). However, due to the size of bird targets being close to the radar wavelength, their scattering characteristics do not follow Rayleigh scattering but are closer to resonance scattering. Therefore, in the C-band, 100 $birds/km^3$ will produce a reflectivity of about 3 dBZ, but it is still much lower than the reflectivity of moderate precipitation. Figure 6 shows the relationship between bird target distribution density and radar reflectivity derived from two independent experiments [42]. The solid lines represent the mean bird target distribution density, and the shaded areas represent the associated standard deviation for each experiment. Both experiments utilised C-band weather radars within the OPERA network. However, the experiments differed in their geographical location and observational period (season), leading to likely differences in the bird communities sampled (e.g. species composition, size distribution). These ecological differences can significantly influence the scattering properties of the targets. Consequently, as Fig. 6 illustrates, the empirical relationship between reflectivity and inferred bird density varies between the two datasets. For instance, at a given radar reflectivity value, Experiment 2 generally suggests a lower bird distribution density compared to Experiment 1, particularly evident at higher reflectivity levels. This highlights the context-dependent nature of converting radar reflectivity directly to bird density and underscores the importance of considering local and seasonal factors.

3.2 Target height distribution

The migration height of birds is generally less than 1,000 m, and the migration height of small songbirds does not exceed 300m. Large birds can reach 3,000 m∼6,300 m, and some species can fly over 9,000 m. Birds often migrate at a lower altitude at night than during the day. The height of migratory birds is also

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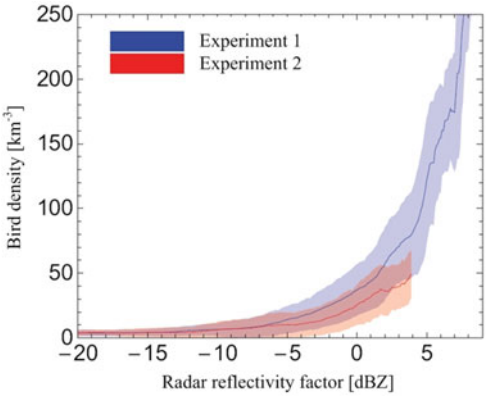


Figure 6. *Relationship between bird target distribution density and radar reflectivity [42].*

related to weather [43]. On clear days, birds fly higher; when there are clouds or strong headwinds, they fly at low altitude.

European researchers used weather radar to observe migratory bird flocks in autumn, collecting data that includes large-scale migration activities of bird flocks on multiple nights, and cross-validation was conducted using professional avian radar. To avoid interference from ground clutter, observations are only conducted in airspace above 200 m, and both weather radar and professional avian radar can achieve good coverage. This study uses the migration traffic rate (MTR) to compare the migration intensity observed by different radar systems. The MTR is defined as the number of birds passing through a one-kilometre line transect oriented perpendicular to the migration direction per hour. It is a flow measurement method that combines bird distribution density and flight speed, and can reflect the number of birds passing through a given area, measured in units of birds/(km·h) [44]. Figure 7 compares the MTR distribution of birds at different heights obtained by three radar systems [45]. The weather radar (WR) and avian radar (AR) were compared for the entire migration season from September 5th to October 31st (9.5∼10.31), and the vertical scanning maritime radar (MR) data between October 5th and October 16th (10.5∼10.16) was added. Overall, the MTR height distribution data obtained by these three types of radar systems have a high correlation. However, at lower altitudes (200 m∼400 m), the number of bird targets detected by professional avian radar is significantly higher than that of weather radar and vertically scanned maritime radar. It can be seen that weather radar is susceptible to ground clutter interference in low altitude detection, and it is more suitable for detecting migratory bird flocks with a certain flight altitude.

3.3 Target flight speed and direction

Figure 8 shows the distribution of flight speed and direction of bird targets on a specific day, obtained from the OPERA system's C-band weather radar, compared with the detection results from a dedicated avian radar [42]. In measuring the flight direction of bird targets, differences exist between the two systems, though they mutually verify each other's data. Particularly at lower altitudes, the flight directions detected by the weather radar appear more concentrated than those from the avian radar. This is because the weather radar provides an average direction for all targets within each sampling volume, whereas the avian radar can track the direction of individual targets. On nights of large-scale migration, however, the flight directions of individual birds become more uniform. Consequently, the average direction provided by the weather radar shows a higher degree of agreement with the distribution of individual directions from the avian radar [42].

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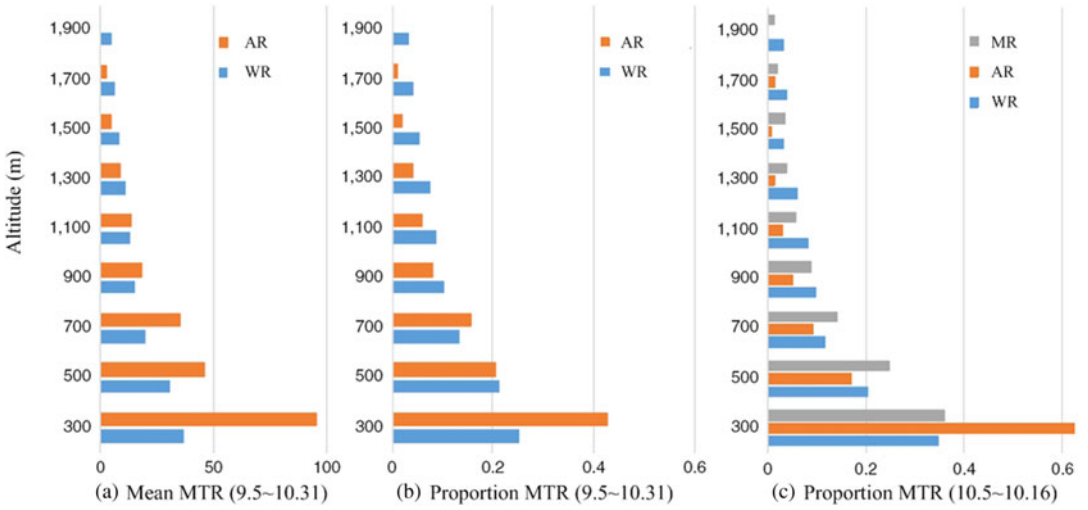
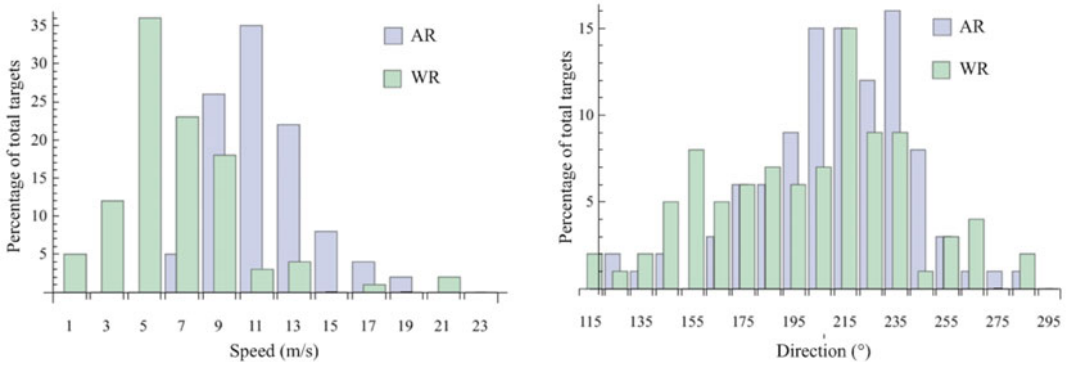


Figure 7. *Distribution of bird migration flight altitude [45]. (a) Mean MTR per height bin during the entire season (9 September-31 October) for WR and AR. (b) Proportion of mean MTRs in different height bins for the WR and AR during the entire season (9 September-31 October). (c) Proportion of mean MTR in the different height bins during the period the MR was deployed (5–6 October). Y axis is labeled with the middle of each height bin (for example, bin 1100 contains data from 1000 to 1200 m), altitude in meters above sea level. MTR is measured in units of birds/(km·h).*



(a) Flight speed (b) Flight direction

Figure 8. *Example of the distribution of flight speed and direction of bird targets [42].*

4.0 Bird information extraction from weather radar

In this section, we will systematically elaborate on the key processing pipeline for extracting avian information from weather radar data. The workflow generally involves three core steps in sequence: first, ground clutter removal to suppress non-meteorological static interference; followed by weather echo elimination to separate precipitation and other meteorological signals; finally, feature extraction and classification specifically for biological targets to achieve effective bird identification. These steps are interconnected and sequential, progressively refining the avian information within the radar signals, collectively establishing a robust bird detection pipeline and providing a reliable data foundation for subsequent analysis. In addition, this article introduces a bird behaviour pattern analysis method based on weather radar data and deep learning, as well as cross-validation techniques.

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4.1 Clutter suppression

Clutter refers to unwanted echoes that need to be removed when Doppler radar observes meteorological reflectivity and average radial velocity. These interfering signals originate from non-meteorological scatterers. In low altitude airspace, clutter may be caused by back-scattering from the ground or local beam obstruction from high-rise buildings around the radar [46]. Ground clutter caused by the backscattering from antenna sidelobes often appears as radial lines or sectors of enhanced reflectivity along specific azimuth directions on the radar display. This typical ground clutter is generally strongest at close range to the radar, and its intensity decreases significantly with increasing distance due to the radar beam spreading with range and rising in altitude. Temperature inversions in the lower atmosphere, particularly within the boundary layer, can cause anomalous propagation (super-refraction) of the radar beam, bending it downward towards the Earth's surface. This may result in enhanced ground clutter echoes from areas farther away from the radar than under standard atmospheric conditions. Bird density estimation relies on the echo signals from bird targets under clear-air conditions, which are often weak. Therefore, accurate bird reflectivity estimation is highly sensitive to contamination by spurious clutter echoes. Furthermore, clutter can degrade the quality of the observed average radial velocity, a parameter vital for bird detection. Related studies have shown that ground clutter superimposed on precipitation signals can reduce velocity data quality and bias the average radial velocity towards zero [47]. This section describes the key clutter suppression strategies integrated into our developed weather radar bird target detection algorithms. The selection and implementation of these strategies are crucial for obtaining reliable bird reflectivity and velocity estimates in the presence of ground clutter interference.

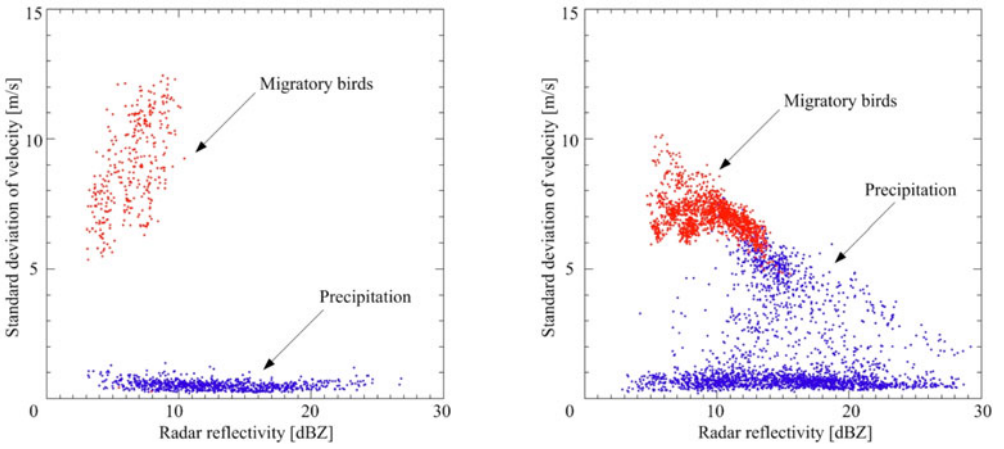
The ground clutter interference in Doppler signals can be suppressed through digital filtering in the time or frequency domain. In the Doppler spectrum, ground clutter produces a narrow peak near zero frequency. This low-frequency component can be removed from the Doppler signal by applying a sharp high-pass filter, resulting in a radial velocity field and reflectance field that eliminate clutter. During bird migration, the effectiveness of Doppler clutter filtering is not as good as under clear sky conditions. First, there is a significant overlap in radial velocities between migratory birds and ground clutter. Conventional clutter filters are designed to suppress echoes from stationary or slow-moving ground objects. However, when birds migrate with or against the wind, a substantial portion of their radial velocities fall within this conventional 'clutter' velocity range. Consequently, they are misclassified as ground clutter and filtered out, resulting in signal loss. Second, the high density of biological targets exceeds the filter's fundamental design assumptions. Traditional filters are based on models for sparse, point-like targets. During peak migration, radar simultaneously detects vast numbers of birds, creating distributed, volume-filling 'biological clutter'. This high-density scenario leads to severe masking effects and complex multiple scattering, causing filter performance to saturate and become mismatched, thus failing to effectively separate bird signals from background clutter. Under normal circumstances, the intensity of ground clutter is about 0∼15 dBZ, while the echo of birds is about −2∼5 dBZ [48]. The clutter echo close to the radar has a similar or larger amplitude than the bird echo, which means that the strength of the clutter signal is at least a few decibels higher than that of the signal. During bird migration, the effectiveness of dynamic Doppler clutter filtering is significantly reduced.

A commonly used clutter suppression method is to generate static clutter maps by calculating the average reflectance of all distance gates during several sunny days during non-bird migration seasons [49]. All distances with an average reflectivity above −10 dBZ will be permanently excluded. Due to the narrow peak generated by ground clutter near the zero frequency of the Doppler spectrum, all distance gates within the Doppler velocity range of −1∼1 m/s can be excluded.

4.2 Elimination of meteorological information

In the process of bird detection, precipitation is another 'clutter' source that needs to be fully considered. Compared to the scattering of bird targets, the echo intensity of precipitation is usually greater [50]. Misunderstanding a small amount of precipitation signals as birds may lead to an overestimation of bird target density, so it is crucial to eliminate all non-bird target echo areas. Meteorologists at KNMI

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(a) Experiment 1 (range gate length of 250 m) (b) Experiment 2 (range gate length of 500 m)

Figure 9. *The characteristic distribution of migratory bird flocks and precipitation signals [42].*

typically use a low reflectivity threshold of 7 dBZ to distinguish precipitation signals from low reflectivity clear sky echoes [44]. In the C-band, typical bird reflectivity is generally less than 7 dBZ. However, the reflectance of various insignificant precipitation signals is also the same, so it is necessary to use Doppler radial velocity for differentiation [51].

For each elevation angle scan result, areas with reflectivity above a certain threshold could be screened out by searching each unit. The threshold needs to be set low enough to ensure that all precipitation areas are included, but inevitably some bird migration areas will be selected, so additional analysis steps are needed to confirm the precipitation units. Setting the reflectance threshold to 0 dBZ can include most of the observed precipitation meteorological signals. Although in many cases, precipitation filtering is more effective when selecting a threshold below 0 dBZ, in some cases it may lead to the merging of precipitation and bird migration areas into one unit, thereby reducing the accuracy of meteorological exclusion. Therefore, analysing the overall distribution characteristics of radial velocity is essential for subsequently eliminating these precipitation echoes [52]. The cells in the precipitation area are usually uniformly filled, but the echo area of bird targets generally does not meet the requirement of uniform filling. For the selected precipitation units, it is required to be adjacent to at least five other units above the reflectance threshold, which ensures that only uniformly filled cells are selected.

From the radial velocity field, a derived texture field is computed that equals the local radial speed standard deviation. For each range gate, a block of directly neighbouring gates is considered. We compute an additional texture field, which equals the local standard deviation in the radial velocity V_r [42],

$$\sigma_v(R,\theta) = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N-1}\left(V_{r,i}(R,\theta) - \bar{V}_r(R,\theta)\right)^2} \tag{3}$$

where $V_{r,i}(R,\theta)$ denote the eight direct neighbours of the range gate at range and azimuth (R,θ), and $\bar{V}_r(R,\theta)$ represents the local mean velocity of the nine-pixel window.

Figure 9 illustrates the relationship between the unit average velocity standard deviation σ_v and reflectivity Z observed by weather radar during intense bird migration and convective precipitation events. Data points in red represent migratory bird echoes, while blue points represent precipitation echoes [42]. The data were collected by two different weather radars at separate experimental sites during the autumn migration season. Ground truth verification confirmed the absence of precipitation during the bird observation periods.

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A key quantitative finding from Fig. 9 is that the majority of bird echo data satisfy the dual conditions of $\sigma_v > 5$ m/s and $Z < 15$ dBZ. This criterion effectively separates birds from precipitation echoes based on their distinct physical characteristics: the elevated σ_v values correspond to the non-coordinated motions characteristic of bird flocks (e.g. flapping wings, turbulent flight), while the lower Z values distinguish them from the typically stronger echoes of convective precipitation cores. However, it is crucial to note that these specific threshold values are empirical and derived from the context of these particular C-band radar studies. Their general applicability to other radar systems or different geographical regions should not be assumed without further validation.

Significant differences are observable between the datasets from Experiment 1 and Experiment 2, underscoring the importance of radar system parameters and local environment. The clearer separation in Fig. 9(a) is attributed to the higher range resolution of the radar used in Experiment 1 (with a fine range gate length of 250 m). A smaller sampling volume reduces spatial averaging within the resolution gate, leading to less 'smearing' of the intrinsic σ_v and Z values of the targets, thereby yielding more accurate reflectivity calculations and a sharper distinction between classes. Conversely, the larger sampling volume in Experiment 2 (with a coarser range gate length of 500 m) incorporates more bird targets and their varying velocities within a single gate. This spatial averaging effect can dampen the observed σ_v (texture) for bird flocks. Furthermore, strong ground clutter in Experiment 2's observation area could introduce velocity dealiasing errors, potentially increasing the σ_v values for some precipitation echoes and contributing to the observed data scatter. These inter-experimental variations highlight that while the (σ_v, Z) parameter space is powerful for discrimination, the exact boundaries and data distributions can be influenced by system configuration and local conditions. This understanding is vital for developing robust, transferable bird detection algorithms.

4.3 Feature extraction of flying bird target

For single-polarisation weather radar, the target reflectivity Z and radial velocity standard deviation σ_v mentioned earlier are the main characteristic basis for identifying bird targets. Among them, the radial velocity standard deviation σ_v, also known as spectral width, is the statistical standard deviation of the radial velocities of all scatterers in a body scanning unit, describing the consistency of the motion velocities of all scatterers within the body scanning unit. With the increasing popularity of dual polarisation weather radar, it can provide richer target echo data, including differential reflectance Z_{DR} (in dB), differential phase ψ_{DP} (in degrees) and polarisation correlation coefficient ρ_{HV}, creating better conditions for feature extraction and recognition of flying bird targets [53].

Under dual polarisation conditions, reflectivity can measure the contribution of both horizontal and vertical waves, and is typically related to the size of scatterers in each polarisation direction. Using the logarithmic transformation rule, the differential reflectance Z_{DR} can be defined as the difference in radar target reflectance measured under horizontal polarisation Z_H and vertical polarisation Z_V [54]:

$$Z_{DR} = Z_H - Z_V \tag{4}$$

It should be noted that all reflectance values here are in dB. For meteorological scatterers and scatterers with wavelengths greater than the size of the scatterer, the Z_{DR} value is directly related to the physical shape (i.e. aspect ratio) of the measured scatterer. Therefore, a large positive value of Z_{DR} represents a flat circular object in the horizontal direction, a large negative value represents a long object in the vertical direction and a value close to zero represents a collection of spherical or randomly oriented particles. However, this simple explanation usually does not apply to biological scatterers and has some bias. For non-spherical scatterers like birds, each polarisation direction will be affected by resonance. For bird targets located in the resonance zone, slightly increasing the size of the bird may lead to an increase in vertically polarised radar cross section (RCS) and a decrease in horizontally polarised RCS, resulting in lower Z_{DR} values. Obviously, there is no simple correspondence between Z_{DR} and target aspect ratio for flying bird targets. The target RCS not only depends on its size, but also on the radar wavelength. To avoid radio interference between adjacent radar stations, there are slight differences in the radar wavelength settings between adjacent stations in the NEXRAD network. Melnikov et al.'s

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study showed that slight changes in wavelength (10.0 cm vs. 11.1 cm) can cause variations in the ZDR value of the same bird scatterer from+10dB to −5dB [55].

The differential phase difference ψ_{DP} is the total measured phase difference between horizontal and vertical polarisation, including the initial differential phase difference ψ_t at the time of emission, the phase shift of $0.5\Phi_{DP}$ during electromagnetic wave emission, the phase shift caused by target scattering δ, the phase shift of $0.5\Phi_{DP}$ during electromagnetic wave return and the phase shift of ψ_r during wave reception. It is represented by the following equation [56]:

$$\psi_{DP} = \psi_t + 0.5\phi_{DP} + \delta + 0.5\phi_{DP} + \psi_r \tag{5}$$

The result of the above equation is a value between 0° and 360°. In meteorological applications, this value is interpreted as the degree to which horizontal waves lag behind vertical waves. In biological target detection, vertical waves may lag behind horizontal waves, resulting in a negative phase shift. In fact, when detecting biological targets under clear sky conditions, the phase shift (Φ_{DP}) caused during transmission can be almost negligible, and the total differential phase can be reduced to the contribution of the radar system (combination of ψ_t and ψ_r) and the phase shift caused by scatterers (δ). To fully consider the contribution of radar systems, most radar systems will perform system phase calibration. For example, the NEXRAD radar system will set a differential phase of 60° as the calibration standard for all stations in application. It is worth noting that many real-time radar visualisation tools typically cannot provide differential phase ($^\circ$), but instead provide distance derivatives ($^\circ$/km), as these products are specifically designed for meteorological applications and therefore cannot provide any feature data for specific biological targets.

The echo recorded by the radar receiver is a complex combination of atmospheric propagation, biological target scattering and hardware changes in the radar system itself, which may result in different effects on the amplitude and phase of the measured signal under each polarisation condition. Therefore, the correlation between the two can be compared by calculating the polarisation correlation coefficient ρ_{HV}. For each resolution unit, the magnitude of this correlation coefficient depends on the similarity of the received signals across multiple pulses of two kinds of polarisation. For sampling units containing fixed scatterers, there is no pulse-to-pulse variation caused by scatterers, and the value of ρ_{HV} is 1. If the motion, shape or direction of the scatterer becomes more variable, the correlation between each polarisation signal will decrease, and the value of ρ_{HV} will decrease. Unlike raindrops, the shape, body position, direction and spatial distribution of biological targets such as bird flocks are highly variable, directly leading to a decrease in the value of ρ_{HV}. In addition, the substantial changes in the geometric structure of birds caused by wing flapping and bending during flight can also alter their backscatter characteristics [57]. Indeed, these scattering mechanisms and their variations with animal position remain to be studied.

Based on the above weather radar target feature data, spatial feature texture images can be generated. The texture of a specific radar product at a certain pixel position is usually defined by some variability statistical value of its surrounding pixels. The pixels included in such calculations may span different regions in terms of distance and azimuth. Polarisation texture is related to the variability of characteristics and behaviours of biological targets within and between resolution units. For example, when the composition of sampling units is uneven, adjacent units will have different polarisation characteristics, resulting in a higher spatial standard deviation. If the target behaviour is different, there will still be a high standard deviation when composed of similar targets. For example, two adjacent units may contain the same bird species, but if observed from different angles, they will still produce different Z_{DR} values and higher Z_{DR} textures. Figure 10 shows multiple indicator data products generated by a weather radar located in Nashville, Tennessee, in the NEXRAD network on May 3, 2015, including reflectivity Z, radial velocity V_r, spectral width σ_v, differential reflectance Z_{DR}, differential phase ψ_{DP} and correlation coefficient ρ_{HV}. The radar's elevation angle at this time is 0.5 degrees, and the detection radius shown in the figure is 300 km. Obviously, Z_{DR} varies significantly with orientation, with negative values extending westward in a wedge-shaped manner and positive values extending southeastward in a wedge-shaped manner [8]. In fact, it is unlikely that there will be spatial variations in the flight behaviour of bird flocks in the above areas, and the changes in Z_{DR} are purely caused by different observation angles of the radar.

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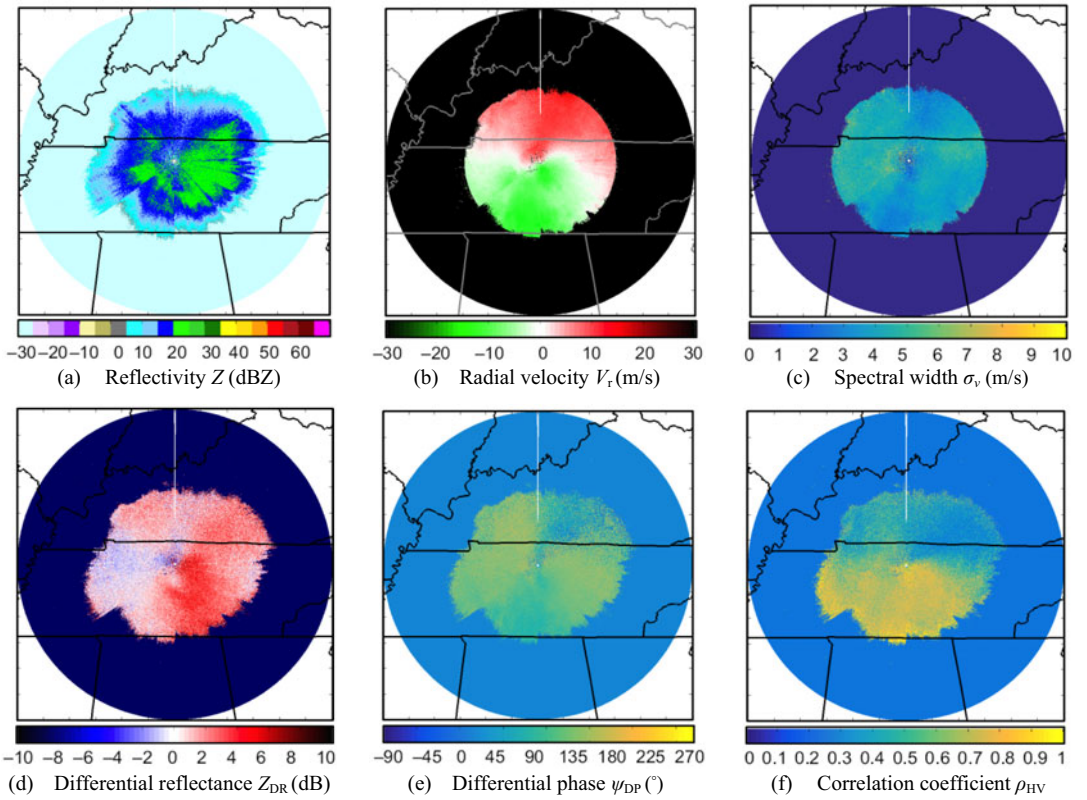


Figure 10. *Radar products for the Nashville, Tennessee, NEXRAD radar and derived features for characterising bird flocks [8]. Map domain is 600km by 600km.*

In addition, these negative values of Z_{DR} do not indicate that the vertical size of bird targets is larger. Based on multiple feature indicators, it is determined that the migratory bird flock is moving towards the northeast direction.

In fact, there is a certain degree of uncertainty in the flight direction and speed of birds during migration, and there are differences in migration patterns among different bird populations, resulting in low accuracy of weather radar in estimating bird migration direction and flight speed. In addition, due to the fact that radar can only obtain radial velocity information of targets based on the Doppler characteristics of echoes, the actual flight direction and velocity are unknown, which also increases the difficulty of estimating the flight direction and velocity of migratory bird flock targets. The current main solutions include: researching wind direction and speed evaluation models based on meteorological radar data; combining the flight characteristics of migratory bird flocks and target echo information on different spatial and temporal windows to evaluate the migration direction and speed of bird flock targets; and combining other observation methods and information sources to make corrections, constructing a comprehensive evaluation system for bird flock migration patterns with meteorological radar observation data as the core. In fact, the target information obtained by the above methods is still an overall grasp of the target situation of migratory bird flocks and cannot obtain refined features of a single target.

4.4 Machine learning technology

Every year, billions of animals cross the Earth during seasonal migrations, but their unpredictable activities are obviously difficult to predict. The massive bird information extracted and accumulated

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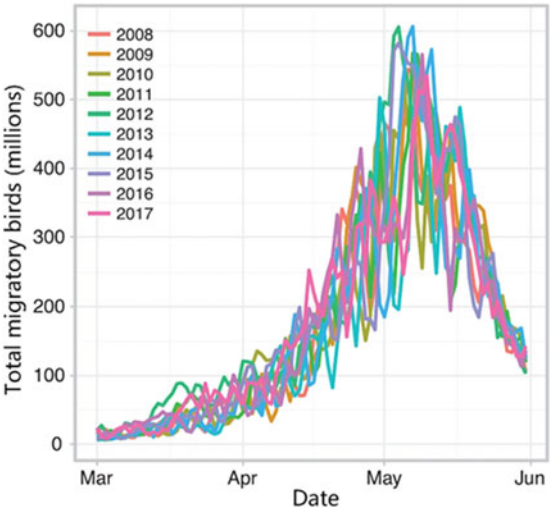
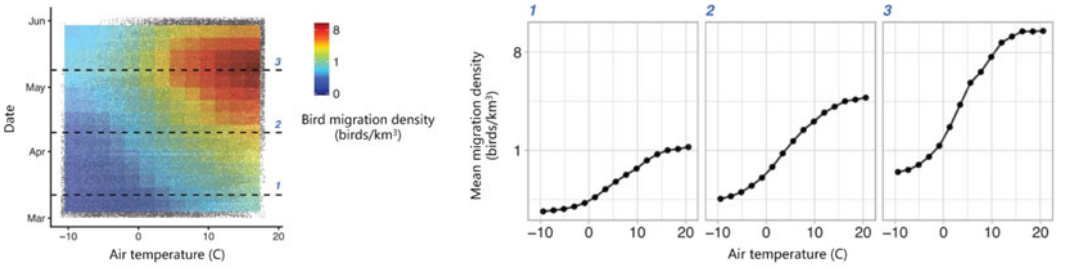


Figure 11. *Number of nighttime bird migrations in the continental United States [59].*



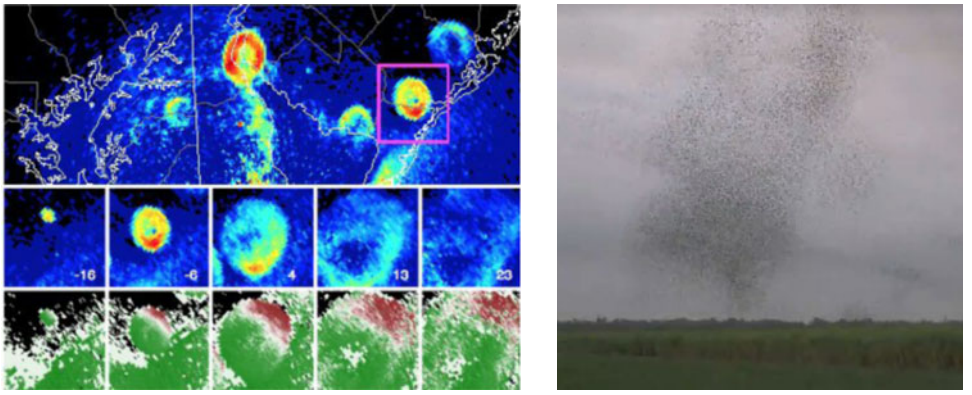
(a) Heat map (b) Cross sections of model predictions for three spring dates

Figure 12. *Migration density predictions by air temperature and date [59].*

by weather radar can be used to discover patterns through machine learning technology [58]. Scientists from Oxford University and Cornell University used bird information obtained from the NEXRAD meteorological radar network and established a continental-scale bird migration prediction model based on 23 years of spring observation data using gradient boosting regression trees to determine the correlation between meteorological conditions such as temperature, pressure and wind speed and bird migration intensity. The relevant results were published in the 2018 issue of Science [59]. This model explains 81% of the changes in bird migration intensity within the altitude range of 0–3,000 m in the United States and can predict migration changes well —one to seven days in advance (explaining 62% ∼76% of the changes). The model also found that during peak migration periods, the number of birds migrating across the United States may exceed 500 million per night. Figure 11 shows the changes in the number of birds migrating from the mainland of the United States during the peak migration period from 2008 to 2017, with the migration scale reaching its peak in May [59]. Figure 12 shows the predicted values of migration density under different dates and temperature conditions [59]. Each point in the heat map shown in Fig. 12(a) represents data obtained by a meteorological radar at night. Temperature values correspond to air temperatures at altitudes up to 3,000 m. Figure 12(b) shows the variation of bird migration density with temperature on three specific dates in spring.

Researchers at the University of Massachusetts Amherst also utilised bird information obtained from the NEXRAD weather radar network, combined latent variable models with expectation maximisation

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(a) Weather radar image (b) Photoelectric image of the swallow flock

Figure 13. *Radar echoes of bird habitats obtained by weather radar and on-site verification images [60].*

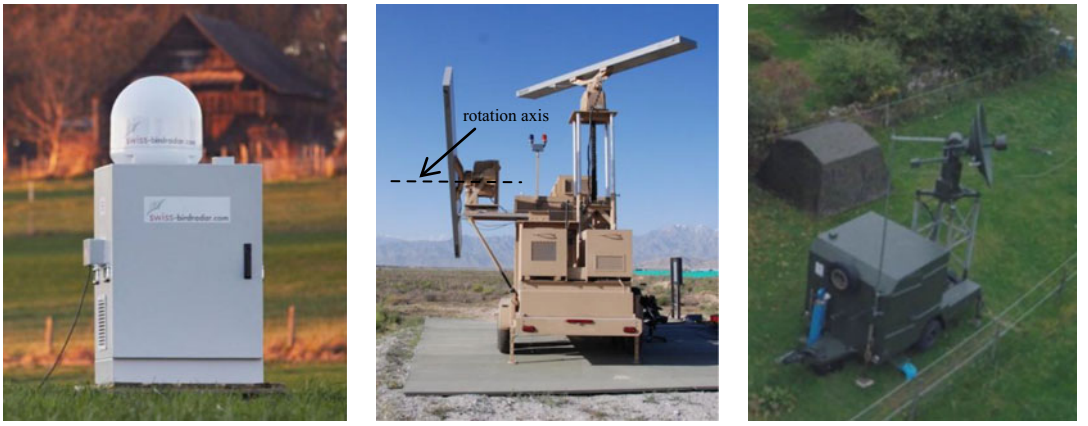
algorithms, and used deep learning techniques to establish more accurate target detectors. They discovered previously unknown bird habitats, providing important information for biologists to understand the activity patterns of social birds [60]. Research has found that a large number of social birds usually leave their habitats 15–30 minutes before sunrise, making them difficult for humans to detect. The first row of Fig. 13(a) is the weather radar echo image, and the position in the box is the swallow colony habitat with a 'circular' feature discovered using the above machine learning techniques. The middle row reflects the reflectivity changes of the swallow colony during its flight away from the habitat, and the bottom row shows the radial velocity changes of the swallow colony as it flies away from the centre of the habitat. The radial velocity of birds near the radar station is negative (green), and the radial velocity of birds far away from the radar station is positive (red); Fig. 13(b) shows an image of a group of swallows taken on site.

At present, the existing bird flock observation methods based on meteorological radar can only distinguish between flying birds and other meteorological targets, as well as clutter, and there is still room for improvement in accuracy. They do not yet have the ability to distinguish different types of bird flock targets. Therefore, the existing bird flock detection methods of meteorological radar can only currently solve the problem of 'presence or absence', and they cannot accurately determine the type of migratory bird flock and achieve a precise description of the migratory bird flock. The current main solutions include: conducting in-depth research on the influence of different types of bird species, densities and flight formations on the characteristics of bird flock targets from the perspective of meteorological radar from a theoretical modeling perspective and combining other observation methods and information sources such as avian radar, cameras and satellite tracking to construct a feature library of migratory bird information targets, achieving comprehensive and multi-scale description of migratory bird flock information.

Furthermore, artificial intelligence technologies, particularly deep learning, are bringing revolutionary advances to weather radar-based migratory bird identification. Traditional methods often struggle to distinguish biological targets such as birds from non-meteorological echoes, including precipitation and ground clutter. Deep learning approaches, especially convolutional neural networks (CNNs) and recurrent neural networks (RNNs), can automatically learn and extract hierarchical features from vast radar datasets, enabling more robust discrimination.

A critical challenge in training such models is the severe class imbalance between bird echoes (rare positive samples) and meteorological/clutter echoes (abundant negative samples). Standard training procedures tend to bias models towards the majority class, resulting in poor detection performance for bird targets. To address this, several strategies have been employed. Common loss functions designed for

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(a) BS-MR1 Avian radar (b) Vertical scanning radar (c) Tracking radar

Figure 14. *Several avian radars used for cross-validation [45].*

imbalanced data include weighted cross-entropy loss, which assigns higher penalties to misclassified minority class samples, and focal loss, which automatically down-weights easily classified samples to focus training on hard-to-classify examples. Data augmentation strategies are also widely adopted, such as geometric transformations (rotation, flipping and cropping), synthetic echo generation based on physical scattering models and temporal augmentation that mixes samples from different time periods to artificially balance class representation.

With these techniques, deep learning models not only accurately differentiate biological targets (e.g. bird flocks) from non-biological targets (e.g. rain, snow, ground clutter) but also show promise for further classification of bird species, estimation of flock density and prediction of flight trajectories. This significantly enhances the accuracy and automation of radar data analysis, providing unprecedented technical support for research on bird migration, aviation safety and biodiversity conservation.

4.5 Cross-validation technique

The correctness of the bird information extraction algorithm based on weather radar data needs to be verified by other bird observation techniques, such as manual observation, satellite tracking and professional avian radar [61]. The Swiss Institute of Ornithology conducted extensive cross-validation experiments using BS-MR1 avian radar, vertical scanning maritime radar and target tracking radar. Several avian radars are shown in Fig. 14 [40]. In the previous section, a comparison was made between the bird target flight altitude, velocity and direction data obtained by the avian radar and meteorological radar. The statistical characteristics of the data distribution tended to be consistent between the two, fully verifying the effectiveness of the bird situation information extraction algorithm based on weather radar.

The BS-MR1 avian radar shown in Fig. 14(a) was developed by the Swiss Institute of Ornithology and specifically designed for bird observation, using a vertical aerial gaze antenna system. The radar is a 25 kW pulse X-band and uses a combination of long and short pulses. It can not only obtain the speed and flight direction of bird targets but also preliminary classify birds based on wing flapping patterns. At the same time, this type of radar can calculate the MTR values of various types of targets while considering the detection probabilities of targets of different sizes. In this study, the BS-MR1 radar used four operating modes to detect echoes, namely static short pulse, rotating short pulse, static long pulse and rotating long pulse. The calculation limit of MTR is short pulse echoes detected within a height range of 200–800 m, as the maximum detection range of birds under short pulse conditions does not exceed 800 m. Within the height range of 800–1,400 m, only long pulses are used to detect echoes. Only in rotation mode can bird flight behaviour data be retrieved.

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Figure 14(b) shows a 25 kW X-band vertical scanning radar equipped with a 2.17-meter T-shaped antenna, a beam width of 22°, an azimuth angle of 1° and 34 rotations per minute. The rotation direction of the antenna should be consistent with the expected main flight direction of birds to detect their longer trajectories. Due to only vertical rotation, the flight direction of the bird within the radar beam cannot be determined, which limits the acquisition of certain information. During the data acquisition process, the radar selects the long pulse working mode. In order to exclude insect targets, trajectories shorter than 200 m and with fewer than four consecutive echoes were ignored in data processing. Trajectories within 300 m of the radar and trajectories with speeds below 30 km/h or above 100 km/h were also excluded. The calculation of MTR and bird flight speed is based on the assumption that all birds pass through a beam parallel to the radar rotation axis. Therefore, for birds whose flight direction deviates from the radar rotation axis, their trajectory length and flight speed may be underestimated.

The tracking radar shown in Fig. 14(c) is a 200 kW X-band radar with a beam width of 1.5°. It is manually operated for target tracking and positioning and can only track one bird target at a time. When tracking the precise position of the target, data is recorded once per second to accurately measure the target's flight altitude, speed and trajectory direction. In the case of a single target, non-bird targets, bird targets, Passeriformes or bird flocks can be identified based on the echo characteristics of wing flapping patterns. This tracking radar is used for cross-validation of target trajectory direction and velocity. Due to manual selection of tracking targets and the potential deviation in the number of tracked targets caused by the duration of target tracking, tracking radar data is not used for the validation of estimating migration intensity and altitude distribution.

Meteorological radar is primarily designed for full-volume observation of large-scale weather targets. Its inherent low spatial/temporal resolution results in limited detection capability for small-scale biological targets such as migratory bird flocks. Due to low scanning rates and insufficient spatial resolution, a bird flock is often compressed within a single radar resolution volume, leading to low signal-to-noise ratio, high spatial/temporal uncertainty and insufficient capture of effective information. Currently, the main mitigation strategies involve extending observation times to acquire a sufficient number of samples and employing big data methods to achieve statistical characterisation of migratory bird activity patterns.

Furthermore, the operational modes designed for weather radar to adapt to different meteorological conditions (e.g. clear-air mode and precipitation mode, and Volume Coverage Patterns in NEXRAD) pose a direct challenge to the consistency and quality of biological data extraction. These modes differ significantly in pulse repetition frequency, beam scanning strategy and spatial coverage. Clear-air mode employs slower scanning speeds and longer dwell times to enhance the signal-to-noise ratio, making it more conducive to detecting weak-signal targets like bird flocks. In contrast, precipitation mode, aimed at rapidly capturing severe weather events, scans faster. This may lead to under-sampling of bird flocks, causing signal aliasing or omissions.

These inter-mode differences cause extracted biological metrics (e.g. bird flock density, flight altitude distribution and movement speed) to lack direct comparability across different times or radar sites. Mode switching introduces non-biological data discontinuities, significantly compromising the reliability of monitoring long-term migration trends and assessing population dynamics in ecological studies. This constitutes a practical bottleneck for continuous bio-monitoring using weather radar networks. Consequently, developing more intelligent scanning strategies and data standardisation algorithms is necessary to mitigate the differences between modes and ensure the consistency and quality of biological data within long-term time series.

5.0 Research and application of ornithology based on weather radar

The bird detection technology based on weather radar networking has unique advantages in monitoring and early warning of bird situations at the continental scale and is increasingly becoming an important technical support for bird ecology research and military and civil aviation bird strike prevention.

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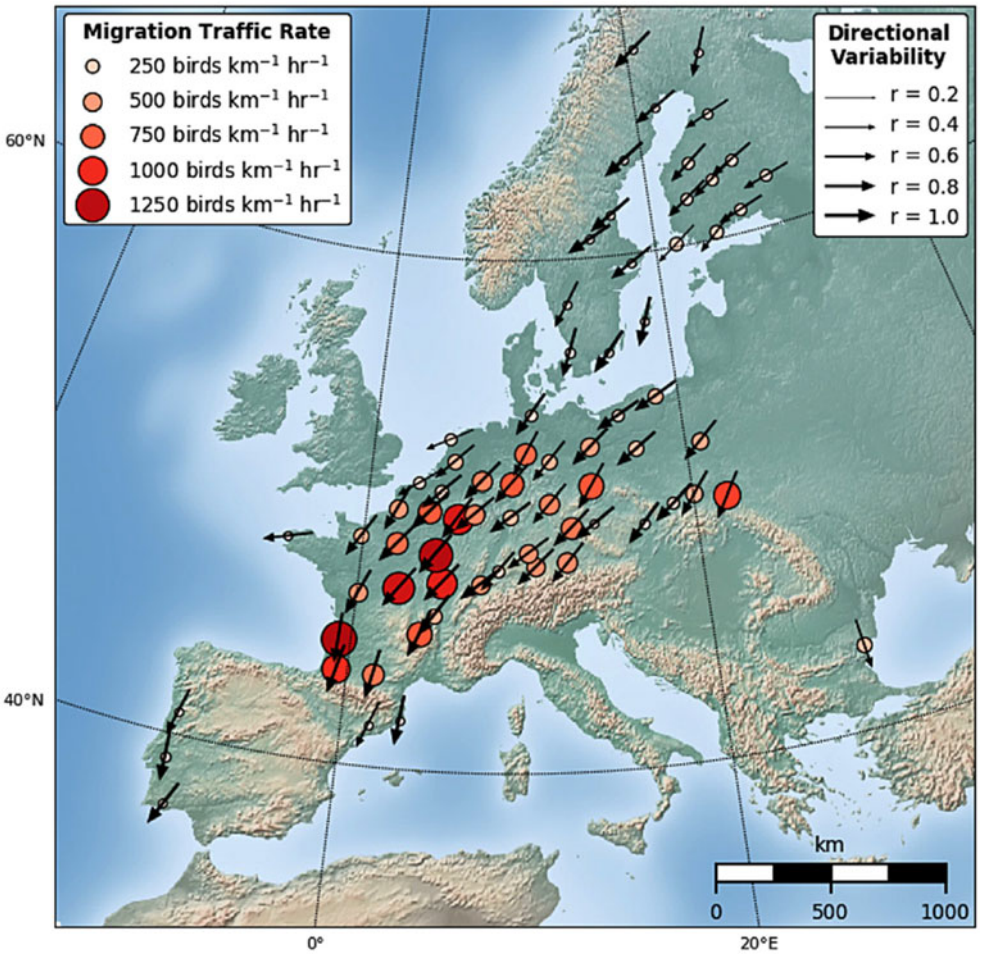
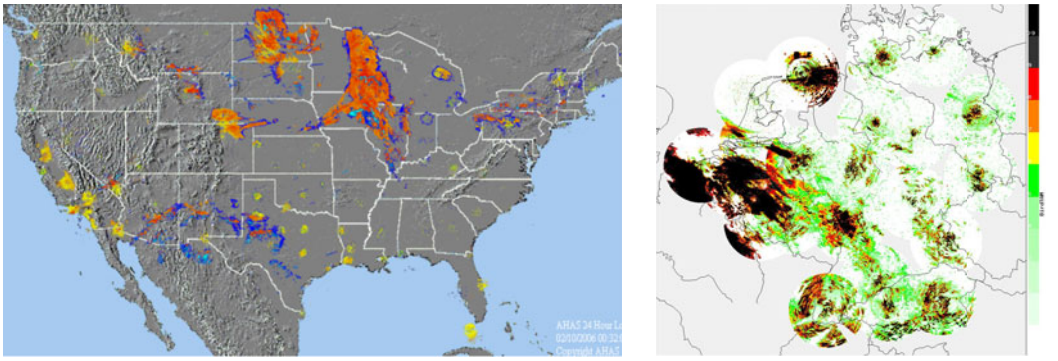


Figure 15. *Seasonal bird migration in western Europe.*

5.1 Avian ecology

For a long time, mastering the flight routes of nocturnal bird migration has been a scientific challenge due to the lack of technical means for large-scale bird observation. European researchers used the OPERA weather radar network to investigate the nighttime flight routes of birds across Europe, marking the first time that a large-scale bird migration activity at the continental scale has been studied using the European weather radar network [62]. Figure 15 shows a bird migration main direction map based on biological information extracted from 70 meteorological radar stations from northern Scandinavia to Portugal during the autumn migration season. It displays the migration intensity in some parts of Europe [63]. The average migration direction of each monitoring location in Fig. 15 is represented by black arrows, and the average MTR of each location is represented by the size and colour of circles. The average value of the entire sampling period (from September 19th to October 8th, including nighttime data only) is taken. The width of each arrow represents the concentration of migration directions, with wider arrows indicating more concentrated migration directions and thinner arrows indicating more dispersed directional distributions. On average, based on 20 nighttime radar data collected from all monitoring locations, 389 birds pass through every kilometre of transect per hour. On the night with the highest migration intensity, the average value of MTR monitored by each radar station is 1,621 birds/km·h, but the migration intensity varies greatly in geographical location and time distribution. The overall

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(a) AHAS of USA (b) BirdTAM of Europe

Figure 16. *Display interface for the distribution of bird populations in the United States and Europe.*

migration direction is southwest, with the highest intensity in central France. Research has found that migration behaviour is closely related to wind conditions. Normally, under downwind conditions, for every 1m/s increase in wind speed, the MTR value will correspondingly increase by about 33 birds/km·h.

5.2 Bird strike prevention

AHAS is developed based on the US Air Force Bird Strike Hazard Reduction Program, Bird Avoidance Model (BAM) and NEXRAD weather radar network [64]. Among them, the US Air Force Bird Strike Hazard Reduction Program began in the 1970s, initially focusing on active and passive management of birds at airports. Since the mid-1980s, it has been implementing low-altitude flight mission bird avoidance programmes, emphasising modeling and analysis of historical bird strike event data and real-time bird avoidance research. The construction of the US Air Force BAM began in 1983, and the model achieved the integration of geographic information systems and radar data in 1998, providing information on the distribution and quantity of birds throughout the United States [65]. The NEXRAD National Weather Radar Network in the United States has 160 weather radars and is the only detection network that can cover the entire United States, updating data every 6∼10 minutes.

AHAS utilises data provided by the meteorological radar network and employs recognition algorithms such as neural network models to extract real-time bird activity information from meteorological radar data. The system utilises radar detection data and accumulated analysis of historical bird situation data to assess the danger level of bird situations in specific areas. The risk level is divided into low, medium and high levels, and the assessment information can be displayed in conjunction with geographic information systems or sent to users through email or short messages for warning. AHAS evaluates bird strike risk through two factors: the 'severity' is based on radar echo intensity, and the 'bird strike probability' depends on the percentage of polygonal areas occupied by bird flock activity, which are multiplied to obtain the bird strike risk value. The advantage of AHAS is that it is based on the existing NEXRAD weather radar network covering the entire United States, suitable for detecting birds flying in groups, along coastlines, or on large migrations, and can be identified in geographic information systems to visually display the bird situation distribution in a certain area or route, making it easier for the Air Force to prepare for bird defense in advance or adjust training arrangements. Since the use of AHAS by the US Air Force in 2003, the number of bird strike incidents and losses has decreased by more than 50%, and the bird strike prevention effect is significant. Figure 16(a) shows the AHAS National Bird Alert, where red indicates high risk, yellow indicates moderate risk, green indicates low risk and blue indicates meteorological signals.

The data and bird strike risk assessment model FlySafe BAM, based on the OPERA meteorological radar network in Europe, can achieve the release of BIRDTAM information in some parts of Europe

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[66, 67]. Figure 16(b) shows the low altitude distribution of biological targets such as birds and insects synthesised by radar in Germany, the Netherlands and Belgium, below approximately 1 kilometre. The BIRDTAM value represents the density of birds or insects. The BIRDTAM values follow a logarithmic scale of 0∼8 and are extended to values of 9 and above to distinguish large-scale bird migration and rainfall information. The echoes of birds and insects are displayed in green, yellow, orange, red and sometimes even darker colours. Larger precipitation ranges are indicated by black or dark areas. Ground clutter, such as mountains, appears as small dark areas, such as southern and southeastern Germany and eastern Belgium.

6.0 Conclusions and prospects

Based on a comprehensive review of weather radar-based bird warning systems in the United States and Europe, this article discussed the echo characteristics of bird targets in meteorological radar data and technologies for extracting avian biological information. It also introduced the application of weather radar in ornithological research and bird strike prevention. The main findings and perspectives are summarised as follows.

Weather radar serves as a powerful tool for large-scale bird migration monitoring, despite its technical limitations compared to specialised avian radars. Its primary limitation is the inability to resolve individual bird tracks due to its inherent design and resolution. However, its unparalleled strength lies in its capacity to detect and characterise the collective movement of bird flocks at certain altitudes across vast continental scales. This capability, provided by extensive operational networks, establishes weather radar as an indispensable source of data for macro-ecology and the study of bird migration patterns, offering insights unattainable through localised ground-based methods.

Looking ahead, the continuous advancement of weather radar hardware and software promises higher spatial resolution and faster data update rates. These potential technological improvements could create opportunities for a more refined perception of bird distribution and movements in the future, enhancing the detail of biological information derived from these systems.

Beyond operational meteorological services, other sectors such as air traffic control and military departments also deploy dedicated weather surveillance radars. The detection ranges of these systems often overlap or complement those of national meteorological networks. Furthermore, air traffic control radar and specialised avian radars are theoretically capable of detecting birds in different airspace volumes with high accuracy. This capability stems from their complementary characteristics; for instance, specialised avian radars excel at detailed local monitoring of flight behaviour and abundance, while air traffic control and weather radars provide broader continental-scale coverage of migration intensity and pathways. Therefore, the strategic integration, or fusion, of data from these diverse radar systems presents a significant opportunity. By developing data fusion techniques, researchers and operational users can achieve a multi-scale observational picture of bird migration across the entire airspace. This integrated approach, facilitated by evolving data-sharing mechanisms, can combine broad-scale context from weather radars with localised detail from other systems, ultimately leading to enhanced bird strike prevention capabilities for both civil and military aviation.

To advance this field, several promising research avenues are proposed. These directions directly respond to the limitations and challenges identified in the preceding sections, offering concrete pathways to address them.

(a) **Direction 1: Developing Global Data Standards and Intelligent Fusion Frameworks.** As discussed in Section 4.5, the operational modes of weather radar – such as clear-air mode versus precipitation mode – differ significantly in pulse repetition frequency, beam scanning strategy and spatial coverage, leading to inconsistencies in extracted biological metrics (e.g. bird density, flight altitude distribution) across different times and radar sites. Furthermore, Section 4.3 highlighted the impact of radar wavelength variations on differential reflectivity (Z_{DR}) values,

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complicating cross-site comparisons. To overcome these barriers, this research aims to establish globally unified standards for radar biological data, breaking down data silos. Simultaneously, the focus is on developing deep learning-based multi-modal fusion models to intelligently align and integrate radar data with heterogeneous sources such as acoustic and optical information. This integrated approach will generate a more comprehensive and reliable picture of bird flock activity, supporting the large-scale ecological studies called for earlier.

(b) **Direction 2: Developing Deep Learning Models for Species-Level Classification.** Section 4.4 noted that existing meteorological radar-based bird detection methods can only distinguish birds from meteorological targets and clutter-solving only the 'presence or absence' problem – without the capability to identify different bird species or types. Additionally, Section 4.3 discussed the complexity of polarimetric features (Z_{DR}, ψ_{DP}, ρ_{HV}) for biological targets, where the relationship between these features and target characteristics is nonlinear and influenced by resonance effects. To achieve fine-grained identification of species or groups, specialised deep learning models must be developed. These models will combine CNNs and temporal networks to extract both spatial patterns and dynamic behavioural features (e.g. wing-beat patterns) from radar echoes, thereby disentangling the unique 'fingerprints' of specific species and advancing monitoring capabilities towards precision.

(c) **Direction 3: Researching AI-Driven Real-Time Adaptive Scanning Strategies.** Section 4.5 explicitly addressed the challenge of volume coverage pattern discontinuities, where mode switching between clear-air and precipitation modes introduces non-biological data inconsistencies, significantly compromising the reliability of monitoring long-term migration trends. These sampling gaps arise because traditional scanning strategies are optimised for meteorological monitoring and do not adapt to the sporadic, rapidly changing nature of bird migration. To fundamentally address this data inconsistency, research into AI-driven adaptive scanning systems is essential. Using technologies such as reinforcement learning, radar can dynamically optimise scanning parameters based on real-time detected targets and environmental conditions, automatically switching to an optimal biological monitoring mode. Such adaptive scanning strategies can mitigate the sampling gaps inherent in fixed scanning schemes by increasing temporal resolution in regions of active migration while maintaining broader spatial coverage. This provides high-quality, consistent time-series data for scientific research.

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