

Exploring the Skies: Technological Challenges in Radar Aeroecology

Sevgi Zübeyde Gürbüz¹, Don R. Reynolds², Jarmo Koistinen³, Felix Liechti⁴,

Hide Leijnse⁵, Judy Shamoun-Baranes⁶, Adriaan M. Dokter^{6,7}, Jeffrey Kelly⁸, Jason W. Chapman^{9,10}

¹TOBB University of Economics and Technology, Dept. of Electrical and Electronics Eng., Ankara, Turkey, szgurbuz@etu.edu.tr

²University of Greenwich, Natural Resources Institute, Central Ave., Chatham Maritime Kent ME4 4TB, UK, d.reynolds@gre.ac.uk

³Finnish Meteorological Institute, Earth Observation, Helsinki, Finland, jarmo.koistinen@fmi.fi

⁴Swiss Ornithological Institute, Seerose 1, 6204 Sempach, Switzerland, felix.liechti@vogelwarte.ch

⁵Royal Netherlands Meteorological Institute, R&D Observations and Data Technology, De Bilt, Netherlands, hidde.leijnse@knmi.nl

⁶University of Amsterdam, Institute for Biodiversity and Ecosystem Dynamics, Amsterdam, NL, shamoun@uva.nl

⁷Netherlands Institute of Ecology, Centre for Avian Migration and Demography, Wageningen, NL, a.m.dokter@uva.nl

⁸University of Oklahoma, Oklahoma Biological Survey and Dept. of Biology, OK, USA, jkelly@ou.edu

⁹Rothamsted Research, West Common, Harpenden, Hertfordshire, AL5 JQ2, UK, jason.chapman@rothamsted.ac.uk

¹⁰Environment and Sustainability Institute, University of Exeter, Penryn, Cornwall TR10 9EZ, UK

Abstract—Aeroecology is an emerging interdisciplinary science focused on the study of airborne organisms with the aim of deepening understanding about the ecological functions of the atmosphere and the bio-organisms that move through it. In addition to having important applications to the understanding of animal migration and foraging movements, global pest and disease control, biodiversity and conservation issues, and monitoring of the effects of climate change, aeroecology has also been critical in ensuring the safety of military and civilian aircraft from bird strikes. Although the capability of radar to observe bioscatter has been known for nearly 70 years, radar aeroecology has now entered an exciting new phase, with the prospect of continent-wide monitoring of flying animals by means of networks of operational weather radars. In this work, the technological challenges of using radar for the detection, characterization, and monitoring of birds, bats, and insects is discussed in detail. Current efforts to further develop radar signal processing algorithms for aeroecology is discussed in light of a multi-national European research initiative, ENRAM.

I. INTRODUCTION

Aeroecology is an emerging interdisciplinary science focused on the study of airborne organisms with the aim of deepening understanding about the ecological functions of the atmosphere and the bio-organisms that move through it [1]. In addition to having important applications to the understanding of animal migration and foraging movements, global pest and disease control, biodiversity and conservation issues, and monitoring of the effects of climate change, aeroecology has also been critical in ensuring the safety of military and civilian aircraft from bird strikes.

The use of radar in ornithology dates back to 1945, when the presence of birds was first observed in data collected from two Royal Air Force radar stations [2]. The movement of birds was observed for 79 miles and average bird speeds of

33-35 mph were recorded. Especially after the advent of high power S-band surveillance radars in 1943, birds were routinely observed on radar screens. In the 1960's, researchers from Switzerland [3], United Kingdom [4], the United States of America [5], and Netherlands [6], among others, pioneered the application of surveillance radar in ornithology.

Initially, at least, ornithological studies primarily advanced using “radars of opportunity” – i.e., radars that were actually designed for other applications, such as surveillance, tracking, weather, and marine radar, but exploitable for bird studies. As examples, the “Superfledermaus” military tracking radar [7], the ASR-4 and ASR-8 airport surveillance radars [8-9], the WSR-57 weather surveillance radar network of nine radars positioned about the Gulf of Mexico, the WSR-88D Doppler weather surveillance radars deployed in Oklahoma and Florida, and most recently, the NEXRAD network of weather radars [10] have all been utilized in bird studies.

Over the past twenty years, efforts have been made to design radars specific for the detection and identification of birds and avian biological studies. One of the first such “bird radars” is the Radar Observation of Bird Intensity (ROBIN) system developed by the Dutch Research Institute for Applied Science (TNO) in 1989. The ROBIN system was specifically designed for bird strike applications – an area of increasing concern as it has been reported that collisions have increased at least 50% over the past ten years, especially near airports and military airbases [11]. Other examples include the Swiss Bird Radar [12], designed for ornithological research, the MERLIN Avian Radar System [13] and Turkish KUŞRADAR [14], designed for airport bird strike prevention. Bird radars also have important application in the

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study of the risk of bird collisions with wind farms, which is a significant cause of fatalities and can disrupt migration routes [15].

But birds are not the only airborne organisms to appear unwittingly on radar screens. Amazingly, the first radar detection of insects was confirmed in January 1949 by A.B. Crawford of Bell Telephone Laboratories in Arizona, USA [16]. A fixed vertical beam radar operating at wavelengths of 3.2 and 1.3 cm was utilized with detections corroborated by visual observations of insects in the beam of a searchlight. Such vertically directed radars continue to be used as a key device for observing insect motion to this day [17]. As with birds, however, insects also appear on surveillance, tracking, and weather radar. Discriminating between birds and insects in the radar data has been a challenge. The first entomological radar was adapted from a commercial marine system of 3.2 cm wavelength in 1968 by G.W. Schaefer, who used the radar to record both daytime and night-time insect movements during a field study in West Africa. Since then many different types of entomological radars have been developed, including scanning pencil-beam radars, vertical beam radars, and airborne radars.

The goal of this paper is to provide an overview of how several different types of radars may be exploited to learn more about birds, bats, insects and other bioscatter for the purposes of conservation, biological science, global pest and disease control, climate change monitoring and collision avoidance. In particular, the goals and recent results of the multi-national European COST Action, the European Network for the Radar Surveillance of Animal Movement (ENRAM) [18,19] will be presented. Based on the current state-of-the-art in radar aeroecology, technological challenges currently being tackled will be discussed.

II. WEATHER RADAR AEROECOLOGY

Weather radars provide a unique opportunity to observe animal movements because they comprise a network of sensors already in place with coverage over large expanses of territory. Weather radar outputs are also a prime example of data sets that can be “contaminated” with returns from birds, bats, or insects to the detriment of meteorological products, especially radial wind products key to accurate short-term weather prediction. Improved algorithms for extracting biological information from weather radars will thus not only provide valuable aeroecological information, but will also improve the quality of operational meteorological products and weather forecasting.

For example, the European operational weather radar network OPERA (Operational Program for Exchange of Weather Radar Information) [20] has agreed to implement a bird migration algorithm for test use at the pan-European real time datahub ODYSSEY for the quantification of bird migration [21]. To distinguish bird migration events from bioscatter by insects or precipitation, the algorithm utilizes the fact that the local variation in Doppler velocity (the radial velocity texture) is relatively high in the case of birds. Contrary to insects and precipitation, birds have a high self-speed and only few individuals occupy a single resolution volume, allowing variability in speed and directions of targets

to be resolved. The same property can be used to quality-control vertical wind retrievals (VAD or VVP): by discarding events dominated by birds, improved meteorological wind products have been obtained [22].

Bird migrations also pose a significant threat to flight safety due to damage to aircraft incurred as a result of bird strikes. Specialized bird radars have been developed for use in airports to improve safety, but such radars are only able to alert operators to immediate threats. In Europe, weather radars have been exploited to establish a system for monitoring trans-national bird migrations and thus form ‘bird early warning’ systems to improve military flight safety [23].

Finally, weather radar networks have been fruitful in yielding information about the flight altitude distributions of birds during migration in response to varying atmospheric conditions [24-25], in modeling the mass movement of insects, especially agricultural pests [26], as well as in monitoring bird response to man-made disturbances, such as fireworks [27]. From Doppler and reflectivity measurements, the density, mean ground speed, and track direction may be recorded for different altitudes [21]. Based on these quantitative measures combined with knowledge of the time of year, the general species group being observed may be estimated.

However, identification remains a key challenge – not only of bird species, but also for discriminating various types of flying animals, such as birds from insects and bats. In this regard dual-polarization weather radar has yielded promising results enabling the extraction of more information about the size and shape of organisms, and thus, more accurate species or species group information. In particular, differential reflectivity factor (ZDR) of birds and insects appear to be rather differentiable [28]. In the separation of biological scatterers from hydrometeors, the copolar correlation coefficient (ρ_{HV}) is very significant. Useful additional quantities for biological classification include differential phase shift (Δ_{DP}), linear depolarization ratio (LDR) and differential Doppler velocity (DDV) [29]; the latter two, however, are not commonly available in operational weather radar systems.

III. WIND PROFILERS

Radar wind profilers are a specialized type of meteorological radar transmitting in the range between 50 MHz and 1 GHz, which are designed to detect atmospheric turbulence in the atmosphere. From a meteorological perspective, birds comprise an important source of “contamination” that can alter wind measurements by as much as 15 m/s [30]. Consider, for example, the scatter plots shown in Figure 1 for a 915 MHz wind profiler recording data during a bird migration in spring 1997 [31]. The effect of birds is observable in the scatter plots. A clearer way of visualizing the birds is to compute the spectrogram of the demodulated receiver signal. As shown in Figure 2, the time-varying frequency fluctuations incurred due to migrating birds is quite distinct [32].

Much research to-date has been focused on removing any bird artifacts (e.g. [33]), as opposed to exploiting such data. However, wind profilers have been successfully used by ornithologists to observe the direction, intensity and speeds of

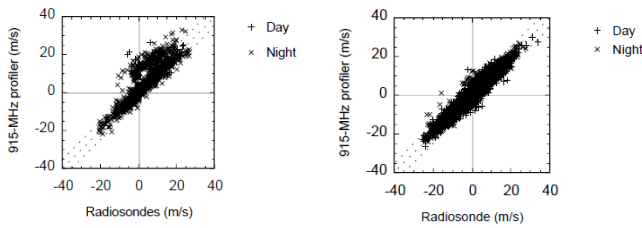


Figure 1. Scatterplot of north wind component as measured from a 915 MHz radar wind profiler in spring 1997 [31]. Left: data for the case with birds. Right: clean data with no birds.

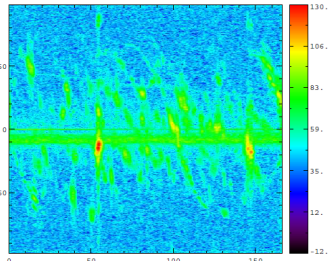


Figure 2. Gabor spectrogram of demodulated return from a 482 MHz wind profiler recording bird migrations in Oct. 2007 [32].

seasonal migrations [34]. Precipitation has been observed to have a detrimental effect on observations: oftentimes, rainfall can mask the presence of birds in data. Although birds tend to avoid heavy precipitation by either adapting their routes or waiting until more favorable conditions, precipitation inhibits monitoring of such movements. A similar challenge is incurred from late spring until autumn, when bird densities are low and result in weak signals that are also difficult to detect in radar wind profiler data. Moreover, a key processing challenge is to identify the different types of biological data detected, as bird data may be confused with that of bats or insects. Currently, identification is not possible from the profiler data, so that circumstantial evidence or observations from other types of sensors, such as thermal IR, is used to identify biological targets. For example, in a three year study (2010 - 2012) of the Basque coast [34], it was hypothesized that the high number of nocturnal migrations of individuals was due to birds, because typically bats and insects did not migrate in such large numbers. But, there was no way to know for sure, and identification remains a key issue.

IV. AVIAN RADAR DESIGN AND PROCESSING

Specifically designed avian radar systems typically transmit at S, C, or X band frequencies. The size of birds that can be detected, as well as the radar's susceptibility to precipitation and contamination by smaller organisms, such as insects, is strongly influenced by the frequency of the radar used. The radar cross section (RCS) of birds is dependent upon frequency – a useful rule of thumb is that if the dimensions of the target are smaller than one-third of the wavelength, the RCS decreases as one-sixth of the target circumference. Thus, upper C band (3.8 cm – 7.5 cm / 4 GHz – 8 GHz) and lower S band (7.5 cm – 15 cm / 2 GHz – 4 GHz) is optimal for small birds. Lower frequencies, such as

L band, hinder detection of smaller birds, while even lower frequencies can minimize returns from even larger birds. Clutter becomes proportionally more pronounced and problematic when using longer wavelengths to detect Rayleigh-scattered targets, such as birds in the upper S-band. The main disadvantage of utilizing higher frequency radars is the higher sensitivity to precipitation and other small objects, such as insects. Bird detection [35, 36] is a critical topic that requires accurate characterization and validation.

With avian radar systems, information about birds may be obtained using both echo and micro-Doppler signatures. The amplitude of a single bird echo exhibits periodic fluctuations consistent with the wing beats of the bird [37]. These fluctuations, or wing-beat pattern, are directly related to the flight characteristics of the bird, which generally also varies for different species. For example, thrushes (*Turdus sp.*) exhibit significant variation in the flapping and pausing stages during ascent and descent; in contrast, crows continuously beat their wings, and exhibit a strong correlation between vertical speed and wing-beat frequency. Thus, analysis of wing-beat patterns can not only aid in identifying species, but can also yield important information about the flight mechanisms of different birds. Examples of wing-beat patterns are given in Figure 3.

Another technique that can be used to identify targets is the micro-Doppler signature. Micro-Doppler refers to frequency modulations about the central Doppler frequency that are caused by any vibration or rotation of the target's parts in addition to the average translational motion. Many animals exhibit a unique micro-Doppler signature as a result of the kinematic constraints imposed by the skeletal structure and patterns of motion. In this way, horses, dogs, cattle, birds and humans may be seen to have visually distinct micro-Doppler signatures, which may then be exploited for identification. Sample human and bird micro-Doppler signatures are shown in in Figure 4.

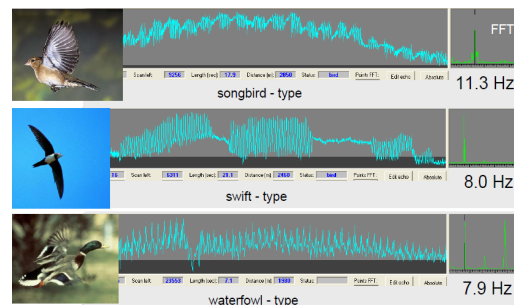
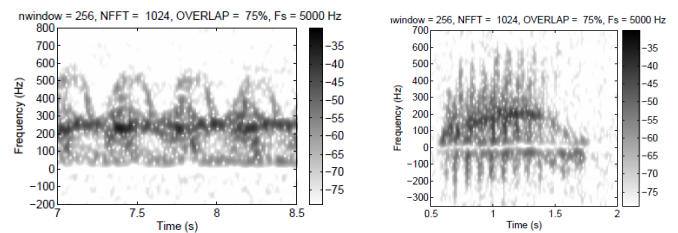


Figure 3. Wing-beat pattern for different bird species [38].



(a) walking human (b) bird

Figure 4. Sample spectrograms [39].

As compared to studies of using micro-Doppler signatures for human activity recognition, there are relatively few studies on avian micro-Doppler. In one of the earlier works [40], synthesized bird micro-Doppler signatures are generated and it is proposed that features extracted from the signal be used to identify birds. In other works, micro-Doppler signatures are used to discriminate between birds and unmanned aerial vehicles [41], as well as between single birds and flocks of birds [42]. In [39], micro-Doppler was used to explicitly classify several different sub-classes of animals (bird, goat, dog, deer) as either human, vehicle, or animal. Interestingly, it was found that birds, goats, and dogs were consistently correctly recognized as animals for at least 93% of the subjects, while deer were confused with humans 88% of the time (just 12% correct classification). Nevertheless, much work yet remains to be done in exploring the full extent that micro-Doppler information may be used to shed light on distinguishing between species and understanding biological phenomenon; in particular, distinguishing various species of birds from each other as well as from bats.

V. ENTOMOLOGICAL RADAR

The use of special-purpose entomological radars to make direct observations of insects in flight is the subject of a recent monograph [16]. This covers topics such as entomological radar designs, procedures for characterizing insect targets from returned echo and quantifying the insect activity observed by radars. After Schaefer’s pioneering 1968 study (see above), radar entomology research units were established in various countries – the UK, Australia, USA and China – mainly to work on the migration of insect pests within their respective countries, although the UK radar units originally directed their efforts mainly at agricultural pests in developing countries [43]. These programmes usually employed modified marine scanning radars, normally operating at X-band, but shorter wavelength Ka-band systems have been built to observe small insects (rice planthoppers) [44]. After about 2000, due to the difficulty and expense of maintaining manual observations over extended periods, scanning radars were generally replaced by autonomously-operating vertical-looking systems [16]. As well as being automated, these insect monitoring radars incorporated both narrow-angle conical scan and rotating linear polarization and so were able to acquire extra information on target identity (e.g. estimates of mass and indications of body shape) (see Fig. 5).

Two other entomological radar designs might be mentioned here. First, an aircraft-mounted, downward-looking X-band system with rotating polarization, which was used to fly long transects over extensive concentrations of migrating moths in Canada and the USA in the 1980s [45]. Secondly, a harmonic scanning radar has been designed to observe low-altitude foraging movements, or short distance dispersal, of insects tagged with small passive transponders, over distance of several hundred meters [46].

From their first deployment, dedicated entomological radars revealed striking and, in some cases, completely

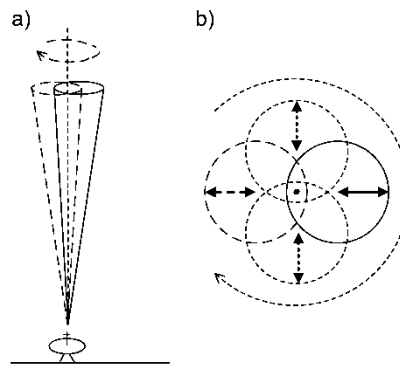


Fig. 5. The narrow-angle conical scan with rotating polarization used by special-purpose vertical-looking entomological radars. (a) Side view, showing two beam positions; (b) View from above, showing four positions and the corresponding polarization (E-field) [16].

unanticipated phenomena, particularly as regards the high-altitude migration behavior of the larger insect species (which had previously been inaccessible to observation). Radar-based studies have contributed new information on topics such as: diel flight periodicity, selection of flight altitudes, common orientation behavior, and the concentration of insects in small-scale convergence zones [16] – all these topics highlight the complex responses of insects to features of the atmospheric environment. An example of previously unsuspected findings was the sophisticated suite of behaviors used by the moth, *Autographa gamma*, to achieve its long-distance migrations between northern Europe and the Mediterranean Basin [47]. In addition, data on the intensity, direction and speed of insect migrations has been acquired, which in turn allow estimates of integrated quantities like ‘total overflights’ which characterize the nature of seasonal migration of particular species in particular regions [48].

Turning to the scanning harmonic radar system, this technique has already contributed to studies on bee neuroethology and navigation, pollination ecology, and optimal searching strategies [17]. In total, well over 200 publications with significant radar entomology content have been produced (see the inclusive bibliography on *The Radar Entomology Website* [49]).

Radar has already had some operational role in support of day-to-day forecasting of migratory insect pests. For example, information from the dedicated insect-monitoring radars in inland Australia is used in operational decision-making and forecasting by the Australian Plague Locust Commission [50], and observations from Doppler operational and research weather radars in southern Finland have been incorporated into a warning system for pest aphids and diamondback moths invading that country [26].

An obvious way to expand the operational use of radar in entomology is to increase the present (very small) numbers of insect-monitoring radars into a wide-area (ideally continent-wide) network. For example, a network of, say, ~10 units in Europe or in Australia, collecting data on migration intensity and flight behavior simultaneously at key locations, would allow continental-scale insect migration pathways to be elucidated for the first time. For example, in Europe one can

envisage radar units arranged in two chains – one monitoring suspected migration pathways over the Mediterranean (with units in, say, Gibraltar, southern Italy, and the Levant) and another monitoring movement into northern Europe. The migration ‘flyway’ up the Mississippi Basin in the USA is another possible location for such a radar chain.

The Finnish pest warning system, mentioned above, currently relies on particular operator experience to distinguish between insect, birds and precipitation. It would be more satisfactory if an operational algorithm for distinguishing insect targets (similar to that used for birds) could be devised and implemented on the Europe-wide network of Doppler weather radars, particularly the newer dual-polarisation units which have advantages for biological target classification procedures. ENRAM is currently pursuing a physics-based approach to an insect-target extraction algorithm which may utilize combinations of factors such as reflectivity, spectrum width, vertical gradient of reflectivity and velocity, and spatial variability (‘texture’) variables.

VI. EUROPEAN NETWORK FOR RADAR SURVEILLANCE OF ANIMAL MOVEMENT

As detailed in the previous sections, many different types of radars have been used to study animal migration, both for the purposes of biological science and to prevent material and human losses due to bird strikes. Yet, a major handicap of these studies has been that research efforts have often been local as well as uncoordinated, while the phenomena being observed are in fact regional or even continental in nature. Even for the purpose of bird strike prevention, which at first glance may seem to be a local problem, widespread, coordinated observation of bird motion is critical to providing early warning.

A good case in point would be the situation of Israel, which is uniquely situated at a junction of bird migration from Africa, over Israel, to Turkey, Eastern Europe, the Caucasus, and Asia. Bird strikes have resulted in the loss of two fighter jets and the death of two pilots over the past 10 years [51], and threaten Israeli Air Force (IAF) operations as well as civilian aviation. In response, Israel has developed a detailed bird monitoring and early warning system comprised of regional monitoring with weather radar, air surveillance radar, and human bird watchers. Flocks entering Israel are tracked and informed to the IAF so that potential operations may be timed and located such as to not be threatened by bird activity. Thus, in the case of Europe, continental-scale study and monitoring of avian activity is of vital importance both scientifically and for effective collision avoidance.

The European Union COST Action “European Network for the Radar Surveillance of Animal Movement” (ENRAM) is a research network that aims at facilitating coordinated, continental-scale studies of the aerial movement of animals across Europe [19]. More specifically, the project aims at exploiting the OPERA network of European weather radars to enable widescale aeroecological studies and to advance the radar signal processing algorithms for a variety of radar systems, to extract information about aerial movements.

Specific signal processing challenges include intra-continental migration visualization, organism identification, and mitigation of anthropogenic hazards to bird and bats (e.g. from the effect of wind turbines). For this aim, four working groups have been established within the Action to focus on biological radar algorithm improvement, data interpretation and visualization, and integration of animal movement data across taxa. A major component of the research programme is validation of the biological-detection algorithms, and there are plans to do this with a large-scale test to be conducted at Lund, Sweden. Weather, bird, entomological radar and other portable radar systems will be used to monitor the aerial fauna, and the data cross-validated to assess the quality of detection algorithms.

VII. CONCLUSION

The main goal of this work is to introduce radar systems engineers and signal processing engineers to the unique application of radar to aeroecological studies. An overview of the main types of radar systems being exploited and example applications is given. The goals and scope of the EU COST Action ENRAM are outlined, along with up-to-date information on current algorithms being developed under ENRAM, their performance and critical technical challenges still being tackled. It is hoped that this work will serve to inspire radar engineers to get more involved in radar signal processing challenges faced in aeroecological applications, and through ENRAM and similar programs, provide a platform to unify and focus algorithm development efforts.

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