

## Editorial

### Taking radar aeroecology into the 21st century

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#### The discovery of radar and the start of radar aeroecology

During World War II radar (RADio Detection and Ranging) was developed as a way to track enemy aircraft, but was soon recognized as a potential tool for ecological research. Military reports had shown that ‘angels’ or ‘phantoms’ observed by military radar could be attributed to birds based on concomitant visual observations. It was only after the war that non-military applications for the new technology could be explored and published, including ecological research (Brooks 1945, Lack and Varley 1945), as well as meteorological applications (Maynard 1945). The fact that radar originally designed for air and marine surveillance and defence could be used to measure aerial movement of animals, was an exciting revelation for ecologists but a consternation for engineers that were trying to rid their monitoring systems of unwanted noise. For radar operators, trying to identify enemy aircraft was especially challenging when the radar screen was saturated by millions of tiny unexplained echoes on a night of mass bird migration (Fox and Beasley 2010). The first pioneers willing to explore this new technology realised that radar could reveal information about flight behaviour and aerial biomass of birds and insects (Bonham and Blake 1956) like no other tool available at that time and at spatial scales which could not be studied otherwise. Even today, more than half a century later, radars are one of the best tools for measuring aerial biomass flows.

Radar aeroecology is a fast-growing inter-disciplinary field focusing on aerial movement of organisms and their interactions with the aerial environment. While the term ‘aeroecology’ was coined by Kunz et al. (2008), the field of radar aeroecology actually began in the 1940s. In the early years of radar aeroecology, researchers studied migration by spending hours in front of a radar monitor in a dark room or mobile radar unit. Researchers filmed radar screens or took time lapse photographs which had to be developed before they could be sure migration was actually occurring, a technique which continued into the 1990s (Bruderer 1971, Alerstam and Ulfstrand 1972, Buurma 1987, Alfiya 1995) (Fig. 1a). Distinguishing biological information



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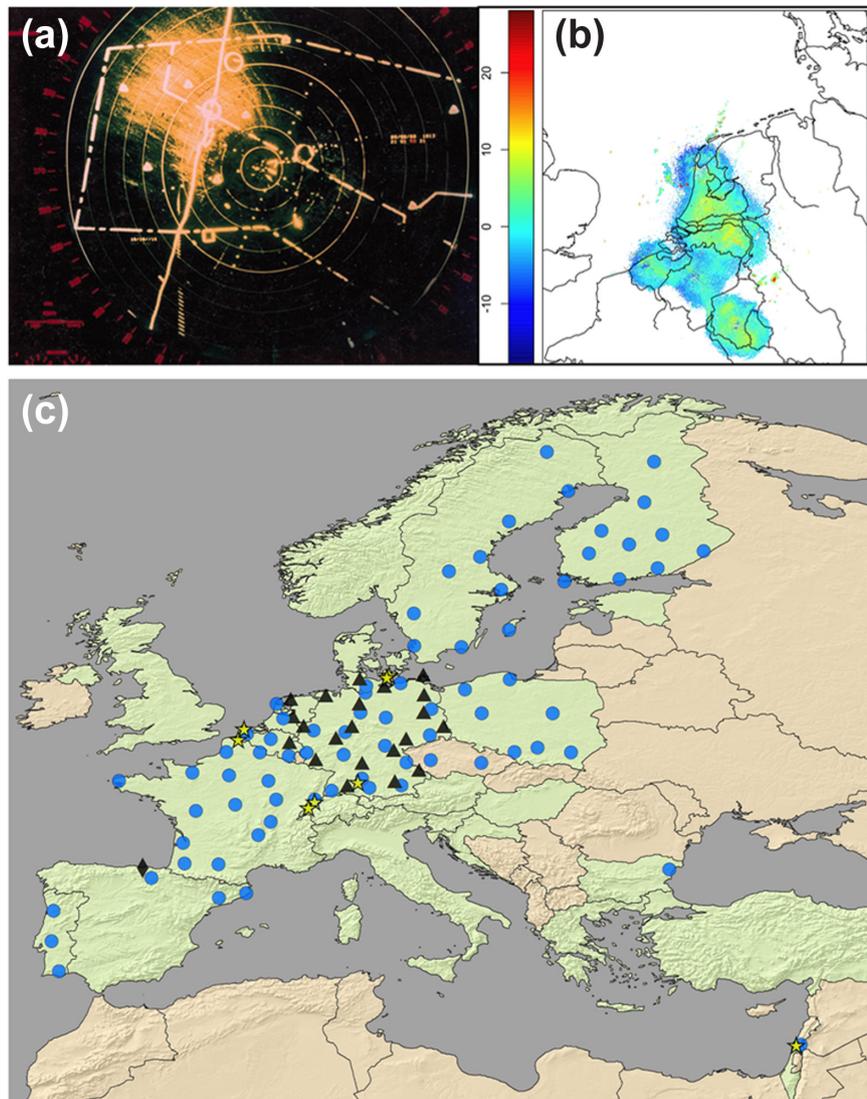


Figure 1. Taking radar aeroecology in the 21st century. (a) Time lapse photograph of an air surveillance radar monitor on a night of intense bird migration over Israel (photo courtesy of Yossi Leshem), thin yellow streaks due to birds; (b) composite image of reflectivity (dBZ) measured on 6 radars in the Netherlands and Belgium on a night of intense bird migration (c) location of different radar systems used in the special issue on radar aeroecology, countries participating in ENRAM shown in light green. The following types of radar systems are shown: weather surveillance radar (blue circles), air surveillance radar (black triangles), vertical radar wind profiler (black diamond) and bird radars (yellow stars).

from meteorological phenomena, aircraft, ground clutter and anything else picked up by the radar and subsequently quantifying migration was done by hand and with expert knowledge (Eastwood 1967, Drake and Reynolds 2012). Some of the co-authors of this special issue still remember these old days, but many others do not; they have entered the field in the digital age and can utilize these powerful tools from their laptop (Fig. 1b). Today radar aeroecology has gone from a labour intensive field to a computationally intensive field, a transition which is inherent with the rise of big data in ecological research (Hampton et al. 2013).

Ecologists have used a range of different radar systems to study the aerial movements of animals, from systems

originally designed for air traffic control, air defence, and weather forecasting, to systems reengineered to improve their capacity to monitor animal movement, and systems custom made for studying animal movement, including small insects (Gürbüz et al. 2015). Due to the myriad of systems available, logistical and technical difficulties in accessing and comparing data from systems with different properties has hampered the broad use of radar among ecologists. Comparative analysis across large spatial scales or over long time frames used to be almost impossible and was often conducted by moving mobile radars to different locations (Drake and Reynolds 2012, Bruderer et al. 2018). In the early 1970s, researchers in North America began exploring the possibilities of using

operational weather radar networks to monitor bird migration (Gauthreaux 1970). Operational weather radars, installed for meteorological purposes, are available world-wide and a single radar can provide biological information at the scale of tens of kilometres horizontally and several kilometres in altitude. Weather radars provide information on general flow patterns which can be converted into numbers of animals by assuming a mean cross section generally representative of the organisms in the air. A key advantage of operational weather radar is the ability to quantify and study aerial biomass across large areas and, if data are archived, over long time periods providing longitudinal data of biomass flows (Dokter et al. 2018). While this approach was very promising from the beginning, it is only recently that diverse researchers could utilize this incredible resource.

## A renaissance in radar aeroecology

Radar aeroecology has experienced a renaissance in the last decade (Bauer et al. 2017, Shamoun-Baranes et al. 2017a) gaining significant momentum from tools and methods developed to use these sensor networks and to integrate information from different systems. These developments required the use of big data science, improved computational infrastructure, and an interdisciplinary approach to migration research. In order to overcome the challenges of accessing and utilizing data from radar, the European Network for the Radar surveillance of Animal Movement (ENRAM) was established. The initiative began informally among a group of researchers with expertise in entomology, ornithology, meteorology and radar engineering. In 2012 the network became a COST Action with 24 member countries (Shamoun-Baranes et al. 2014), primarily aimed at establishing a coordinated network of monitoring radars in order to provide information on aerial animal movement for researchers and various stakeholders. In February 2017, ENRAM organised an international conference ('Radar aeroecology: applications and perspectives') bringing together researchers and practitioners from Europe, Asia, North America and Australia. The establishment of an international research network integrating expertise and interests from different stakeholders and fields of science created a successful synergy for new scientific developments and opened up a new era of radar aeroecology.

## From research to applications presented in this special issue

This special issue brings together international and multidisciplinary expertise addressing many of the aims of ENRAM. Fifty-four authors from seventeen countries, with backgrounds in aviation safety, computer science, conservation, ecology, meteorology, and radar technology have contributed to this special issue, highlighting the benefits and necessity of the interdisciplinary collaboration that was achieved

within ENRAM (Fig. 1c). Together, these contributions provide a broad spectrum of studies reflecting the state-of-the-art in radar aeroecology, the challenges and opportunities for addressing scientific and societal question on local to continental scales. It is our intention that this special issue is a resource for scientists and practitioners interested in monitoring, understanding and forecasting aerial movements of animals using radar.

One major challenge to the widespread use of radar in ecological research are issues related to data access, processing and harmonization, especially when data collection is not standardized across countries or measurement systems (Bauer et al. 2017). In Europe, national meteorological institutes have come together to address these challenges by establishing the operational program for weather radar networking (OPERA) (Huuskonen et al. 2014). OPERA has greatly facilitated the access to meteorological weather radar data for other user groups, including ecologists. A second major challenge is extracting biological information from the weather radar data. Great improvements have been made in automating the extraction and visualization of bird migration data from weather radars with the development of an R package ('bioRad') (Dokter et al. 2019). After a concerted effort to acquire a test dataset of weather radar data across much of Europe, the bioRad toolbox (Dokter et al. 2019) was applied to provide a first overview of spatio-temporal patterns of migration across Europe during a mass migration event in the autumn of 2016 (Nilsson et al. 2019). This is the first time migration has been studied with weather radar in Europe at such a large spatial scale, revealing intriguing migration patterns, and demonstrating the potential of systematic analysis of weather radar data to study migration.

While the spatial coverage of weather radars is potentially large, often the lowest altitudes (< 200 m above ground level) are not monitored due to ground clutter. Short range radars (1–10 km) can fill the gap in altitudinal information, as well as collecting information in specific areas of interest or at a higher level of biological identification (Nilsson et al. 2018). Cross calibration experiments are an important method for understanding the strengths and weaknesses of different measurement systems (Dokter et al. 2011, Nilsson et al. 2018). Through simultaneous measurements with different radar systems (Liechti et al. 2019), show that in many conditions, short and medium range radars operated in Europe and the Middle East show strong correlation in migration patterns. However, fine scale differences in flight behaviour may be missed when working only with medium range radar such as weather radars. As with any remote sensing techniques, understanding the constraints of different measurement systems are essential for correct data interpretation. One of the great advantages of radar systems is that they detect even the smallest aerial migrants which cannot be tracked with other methods. Furthermore, radar provides a means to monitor aerial biomass flow without the need to capture organisms and disrupt their behaviour. However, target size does influence radar detection and (Schmid et al. 2019) demonstrate

the importance of linking radar sensitivity, biological target size and measured aerial volume when quantifying biomass flow. Based on their findings (Schmid et al. 2019), propose a new method for estimating bird size and corrected biomass flow values.

Over the years, radar has been used to answer a range of ecological questions (Bauer et al. 2019) review the most recent contributions of radar based research to address these questions and identify some of the outstanding challenges and priority research areas in migration ecology research. The most urgent challenges across all taxa are methodological in nature as well as understanding the impact of man-made structures and humans activities on migration. Becciu et al. (2019) review how radar has contributed to our understanding of how environmental factors, such as atmospheric conditions and geographic features, influence birds and insects during migration, highlighting both similarities and differences among taxa. In addition to contributing to fundamental research on drivers of movement patterns, radar can also be used as a tool to address societal issues. Hüppop et al. (2019) provide an overview of how radar systems are or could be used for conservation biology. The authors also note some of the limitations of current systems for conservation, especially when species-specific information is needed. Just as radar can be used to facilitate species or habitat conservation, radar can also be used to warn stakeholders of the influx of large numbers of birds which can pose a risk to human safety. Through a comparative analysis (van Gasteren et al. 2019), demonstrate how early warning systems powered by radar have been used to improve aviation safety in Europe and the Middle East. The authors also show how radar is being used as a tool for near real-time warnings of intense bird migration as well as data input for developing models that forecast migration.

## The future of radar aeroecology

Radar systems can be powerful tools for monitoring aerial movement, understanding drivers of movement patterns and

developing early warning systems, but they are not a silver bullet. Many challenges are still ahead for radar aeroecology. Improving target recognition of birds and especially bats and insects, harmonizing data across different radar systems, exchanging and archiving data to facilitate research and development, efficiently processing huge volumes of data, and creating intuitive visualizations representing the spatio-temporal complexity of movement (Shamoun-Baranes et al. 2016) are challenges the radar aeroecology community will address in the coming years. Improved open access to data, and utilizing developments in machine learning techniques and cloud computing, will create exciting opportunities for advances in aeroecological research, just as these changes have facilitated the use of satellite remote sensing data in ecological research (Pettorelli et al. 2014). For example, in the United States data from a network of 159 Doppler weather radars (NEXRAD, NEXt generation RADar) is openly available via an online data repository (Ansari et al. 2018), facilitating long term studies on continental biomass flow (Dokter et al. 2018). Integrating information on biomass flow from medium- to long-range weather radar networks, with fine-scale and trait-specific information from specialized short-range radars, species-specific information from individual tracking, visual observations and other sampling methods, create opportunities to address exciting new questions (Van Doren et al. 2017, Horton et al. 2018). Currently most animal movement research with weather radar networks have been conducted in North America and Europe, yet operational weather radar stations are positioned globally (Fig. 2). Utilizing weather radar networks in conjunction would enable us to compare migration patterns across flyways, characterise world-wide trends in migratory populations and identify threats from global factors. Increasingly scientists will have at their fingertips the tools they need to address societal issues and find science based solutions for how animals and humans can jointly and sustainably utilize the aerial environment (Davy et al. 2017, Shamoun-Baranes et al. 2017b). We have experienced first-hand the advantages of international and interdisciplinary collaboration to make such tools more accessible and

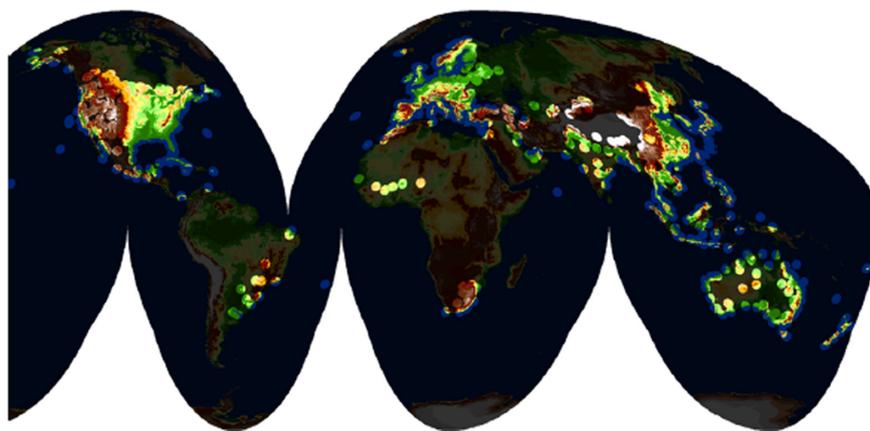


Figure 2. Weather radar coverage of national weather radars. Illuminated areas represent a 200 km range around each radar. This figure is reproduced from Fig. 1 in Heistermann et al. (2013), CC by 3.0 license.

compatible. We hope this special issue inspires researchers to join this fast growing field of research, and establish future collaborations that bring together diverse expertise in the pursuit of knowledge.

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