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Long-term monitoring of bird migration across the North and Norwegian Seas

Migration for Development

Line Cordes
Roel May

Norwegian Institute for Nature Research

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Abstract

Cordes, L.S. & May, R. 2023. Long-term monitoring of bird migration across the North and Norwegian Seas. NINA Report 2350. Norwegian Institute for Nature Research.

Renewable energy developments are expanding offshore in order to meet the world's energy demands, and floating structures permit previously undisturbed areas to be utilised. As a result, there are growing concerns over impacts on migrating birds, however, very little is known about the amount, timing, or position of offshore migration due to the challenges involved in obtaining such data. Long-term monitoring of offshore bird migration is necessary to be able to discriminate inter-annual variability from temporal trends in migration patterns, as well as to capture how migrating species are responding to offshore human developments and climate change.

Here we summarise the sensor and non-sensor-based approaches that are suitable for monitoring offshore bird migration in the long-term including weather and avian radars, biologging, acoustics, laser scanners, camera technology, and citizen science. Each of these sensor-based and observational-based approaches come with their own strengths and weaknesses in terms of, for example, their spatial and temporal scale and resolution. Biologging, avian radar, and satellite imagery would provide the better offshore coverage, but weather radar and citizen science data are readily available, and if combined, could provide useful information on species-specific numbers of birds migrating towards the sea. We outline a plan including core activities for long-term monitoring of bird migration across the North and Norwegian Seas, including a network of weather radars, network of offshore radio telemetry, citizen science data, and collating information from avian radars at sea. We also propose research and development activities which require piloting, but which could provide important data offshore. These activities include analysis of satellite imagery, network of offshore acoustic monitoring, and utilising LiDAR offshore. All listed R&D activities provide offshore data on bird migration at different temporal and spatial scales and resolution as well as different levels of key information on flight behaviour. If successfully tested, these R&D activities should become part of the core activities.

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Sammendrag

Cordes, L.S. & May, R. 2023. Langvarig overvåkning av fugletrekk over Nordsjøen og Norskehavet. NINA Rapport 2350. Norsk institutt for naturforskning.

Fornybare energiprosjekter utvider seg til havs for å imøtekomme verdens energibehov, og flytende strukturer tillater tidligere uberørte områder å bli utnyttet. Som et resultat er det økende bekymringer knyttet til påvirkningen på trekkende fugler, men det er svært begrenset kunnskap om omfanget, tidspunktet eller posisjonen for fugletrekk utenfor kysten på grunn av utfordringene knyttet til å skaffe slike data. Langvarig overvåking av fugletrekk utenfor kysten er nødvendig for å kunne skille interårlig variasjon fra tidsmessige trender i trekkmønstre, samt for å fange opp hvordan trekkende arter reagerer på menneskelig utvikling til havs og klimaendringer.

Her oppsummerer vi sensor- og ikke-sensorbaserte tilnærminger som egner seg for langvarig overvåking av fugletrekk til havs, inkludert vær- og fugleradarteknologi, biologging, akustikk, laserskanning, kamerateknologi og frivillig innsats fra publikum. Hver av disse sensorbaserte og observasjonsbaserte tilnærmingene har sine egne styrker og svakheter når det gjelder for eksempel romlig og tidsmessig skala og oppløsning. Bare biologging, fugleradar og satellittbilder vil gi data fra åpent hav, men værradar og data fra frivillig innsats fra publikum er lett tilgjengelige og kan, hvis de kombineres, gi nyttig informasjon om artsbestemte antall trekkfugler som trekker mot havet. Vi skisserer en plan som inkluderer kjerneaktiviteter for langvarig overvåking av fugletrekk over Nordsjøen og Norskehavet, inkludert et nettverk av værradarer, et nettverk for radiotelemetri til havs, data fra frivillig innsats fra publikum og sammenstilling av informasjon fra fugleradarer til havs. Vi foreslår også forsknings- og utviklingsaktiviteter som krever testing, men som kan gi viktige data til havs. Disse aktivitetene inkluderer analyse av satellittbilder, et nettverk for akustisk overvåking til havs og bruk av LiDAR til havs. Alle de nevnte FoU-aktivitetene gir data fra havet om fugletrekk på ulike tidsmessige og romlige skalaer og oppløsninger, samt ulike nivåer av nøkkelinformasjon om flygeatferd. Hvis testing av disse FoU-aktivitetene blir vellykket, bør de bli en del av kjerneaktivitetene.

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Contents

Foreword

Beyond the upcoming concession applications for offshore wind development, there will be a need to monitor future trends in migration patterns as well as provide a better spatial coverage in marine waters in the years to come both regarding pre- and post-construction monitoring and impact assessments as well as for designating future new development areas towards 2040. This activity will assess the needs for an improved temporal baseline monitoring on bird migration, and the possibilities for future monitoring of bird migration across the North- and Norwegian Seas. Offshore bird migration, e.g., across the North Sea, is as yet relatively uncharted territory.

This long-term monitoring plan for bird migration across the North Sea is a product as part of the Joint Industry Project “Migration for Development”, which is to complement the collaborative research project VisAviS (RCN Grant no. 336457). This JIP includes the identification of longer-term knowledge and monitoring needs on offshore bird migration across the North and Norwegian Seas, which is presented in this report.

Trondheim, October 2023
Roel May, Project leader

1 Introduction

Climate change is progressing at a rapid pace and there is pressure to find alternative renewable energy sources to reduce CO_2 emissions. This has driven the development of wind energy and the setting of ambitious targets to cover energy demands. However, there are growing concerns over potential collisions between birds and moving turbine blades as well as impacts of displacement and barrier effects (Furness *et al*. 2013; Fox & Petersen 2019), especially during the migration seasons where many birds of different species perform highly directed movements along predetermined routes. Populations of migratory birds are already under pressure from illegal killings, habitat degradation and loss, and climate change (Bairlein 2016). For example, European and North American long-distance migrants are declining significantly faster compared to bird species that remain and overwinter in these regions (Vickery *et al*. 2014). In the Mediterranean region between 11-36 million birds are killed or illegally taken every year (Brochet *et al*. 2016). Additionally, most Eurasian migratory species overwinter in the Sahel and Guinea Savanna zones, which are also the regions most impacted by habitat degradation and loss. Between 1975 and 2000, agriculture increased by 57% in sub-Saharan Africa and nearly 5 million hectares of natural habitat were lost per year. Furthermore, climate change is causing a mismatch between the arrival of migrants at breeding grounds and the insect prey that they rely on as birds and insects are responding to cues in completely different geographical regions. For example, the Dutch pied flycatcher population has declined by up to 90% because of this mismatch between the timing of breeding and peak occurrence of their prey (Both *et al*. 2006). Therefore, the additional potential impact from wind energy developments on these populations needs significant attention.

Monitoring bird migration is particularly challenging due to the spatial scale and diversity of species involved. Furthermore, most migrating birds are small (<30g; Bridge *et al*. 2011) and a significant proportion of migration takes place at night which further amplifies the challenges of continuous monitoring over long time periods. There is growing evidence of avoidance with turbines in larger birds, whereas less if know about avoidance in smaller species. Knowledge of over-land migration has grown rapidly with the development of radar ornithology and utilization of networks of weather radars covering the appropriate spatial scale of migration. Such studies have flagged concerns over impacts of light pollution and collisions with wind turbines. To date most wind energy development has taken place on land, while countries with relatively shallow seas have taken the lead on offshore wind (e.g., Denmark, UK, Netherlands, Belgium). Offshore winds are stronger, more consistent and space is less limiting. As a result, Norway recently set a target to produce 30GW of offshore wind capacity by 2040, and already two North Sea areas have been opened for development of up to 4.5GW from both floating and bottom-fixed turbines. Of concern is the almost complete lack of knowledge of offshore bird migration and the potential impacts of a growing offshore wind energy sector. The development of floating turbines means that ever more remote areas of the sea open up for the development of wind farms, and monitoring these areas becomes ever more challenging. Brust & Hüppop (2022) revealed significantly more offshore migration in songbirds than previously thought. Offshore migration has also been revealed in other nocturnal migrating species, namely bats, using acoustic monitoring from ships or permanent structures close to shore (Peterson *et al*. 2014; Sjollema *et al.* 2014). Nevertheless, these previous studies are still relatively small-scale and/or relatively close to shore.

The wind industry requires information on potential impacts to accelerate the consenting process and to be able to put in place mitigation measures where relevant. Measures of importance to industry, including for collision risk models, involve species-specific numbers of birds migrating in the area, the location of migration flyways, the timing of migration, the proportion of nocturnal activity, flight speed and height in different environmental conditions, avoidance rates (macro, meso and micro), and collision rates. While short-term studies highlighting these measures at the local scale are important, broad-scale and long-term studies are required to monitor bird migration and understand changes in space and time. Only long-term studies can separate inter-seasonal or inter-annual variability from trends in bird migration. Furthermore, climate change is not only predicted to affect temperatures, but also winds and current patterns, which may in turn impact bird migration. The impact of wind farms on migrating birds in other words is likely to be dynamic and a comprehensive understanding will not be attained without long-term monitoring. Furthermore, the number of offshore wind farms are increasing and will likely result in cumulative impacts, which will be missed, or baselines will shift, without monitoring over relevant spatial and temporal scales. Importantly, as migrating birds do not obey national boundaries, their flight paths often cross multiple different countries, which can create challenges for establishing monitoring programs at appropriate spatial scales. It is a similar case for monitoring offshore migration, as several seas, including in Europe, are bordered by multiple different countries (e.g., North Sea, Baltic Sea, Mediterranean Sea). Therefore, a collaborative system-level effort is required to fill these knowledge gaps (Kelly & Horton 2016). Also, so far, no single monitoring approach has provided all the answers, emphasizing the importance of integrating different technological approaches and data streams, including existing infrastructure where possible.

Here we aim to summarize the current state of knowledge on offshore bird migration monitoring techniques appropriate for long-term monitoring covering large spatial scales, and the metrics these provide whether for quantification or extracting flight behaviour. Furthermore, based on this summary, we propose a mechanism for establishing a long-term monitoring program to improve our understanding of offshore bird migration across the North and Norwegian Seas. The plan will involve a set of core activities, as well as suggestions for research and development opportunities, which could become part of the core monitoring program once piloted. The long-term monitoring plan will have a particular focus on obtaining species-specific metrics, including flyway positions, migration traffic rates, proportion of nocturnal activity, timing of migration, and flight height.

2 Current state of knowledge of monitoring techniques

2.1 Sensor-based approaches

2.1.1 Radar ornithology

Radar provides a useful tool for studying broad scale aerial movements including the timing and spatial distribution of organisms, their responses to environmental conditions and human developments, as well as the temporal and spatial abundance of organisms in the air (Shamoun-Baranes *et al*. 2014). Radars emit microwaves, which are reflected by objects in the air as echoes. Therefore, microwaves are not just reflected by birds but also by clouds and precipitation, clutter such as mountains or wind turbines, as well as bats and insects. The ability to differentiate between birds and non-birds is therefore essential in this respect. Radar has been used to study bird movements since the 1940's (Lack & Varley 1945), but there have been significant advances in radar ecology recently, including improved data management, processing capacity, and algorithms for extracting biological targets (Shamoun-Baranes *et al*. 2014; Bauer *et al.* 2017). Radar systems most commonly used and commercially available for monitoring migrating birds include doppler, tracking radar and surveillance radar (Desholm *et al*. 2006; Gürbüz *et al*. 2015). We provide a general description of weather, avian and tracking radars below.

Weather radars comprise a network of sensors already in place and therefore provide a unique opportunity to study broad-scale animal movements (Gürbüz *et al.* 2015). Weather radars have the widest detection range, but due to the curvature of the earth birds will often be under the radar at larger distances, and detection probability therefore declines with distance. Furthermore, closer to the radar, there is likely to be a lot of clutter. Therefore, weather radars have the most reliable detection range for birds between 5-25 km, but this range can sometimes be extended to 40 km (Holleman 2005; Van Gasteren *et al.* 2008). These radars scan their surroundings every 4-15 mins resulting in 96-360 scans per day. Typically, multiple weather radars are positioned around a country, region or continent allowing large scale networks of weather radars to be established. Examples of networks of weather radars include both NEXRAD in the US (~160 radars) and ENRAM in Europe involving collaboration between multiple countries (~200 radars; Huuskonen *et al*. 2014). Both large radar networks have shown how radar networks can successfully monitor the aerial movements of animals at more appropriate continental-scales involving entire migration systems (e.g., Shamoun-Baranes *et al.* 2014; Kelly & Horten 2016; Van Doren & Horton 2018; Nilsson *et al.* 2019; Nussbaumer *et al.* 2019; Rosenberg *et al.* 2019). Networks provide information on temporal and/or spatial changes in migration traffic rate, phenology, position of flyways, airspace usage (flight altitude), and night-time migration activity. In the U.S., BirdCast showcases live bird migration maps collected from radar data as well as location specific migration tallies, flight direction, speed and altitude (https://birdcast.info), while ENRAM's visualization Aloft (https://crow.aloftdata.eu/#/) provides near real time information on migration traffic rate and flight height. Predictive models based on weather radar data are already used for aviation safety near airports (Van Gasteren *et al.* 2019; Kranstauber *et al.* 2022; see also https://www.flysafe-birdtam.eu/). But spatio-temporal predictive modelling has previously been a challenge due to the sometimes sparse spatial distribution of radars and more limited range for detecting birds, but deep learning approaches are facilitating this important step (Lippert *et al*. 2022).

Avian radar: Marine surveillance radars or navigational radars have been used frequently by radar ornithologists. These are relatively inexpensive, easy to operate and commercially available (Cooper *et al*. 1991; Urmy & Warren 2017). The radars also use a wavelength appropriate for observing birds. Marine radar systems typically scan at S, C or X band frequencies and the size of the birds that can be detected is strongly influenced by this frequency with upper C band and lower S band being ideal for detecting small birds (Gürbüz *et al.* 2015). Marine radars are typically positioned on ships and offshore platforms and are designed to scan horizontally (360°) for moving targets on the sea surface (e.g., ships). This can also work well for lower flying birds, although sea state and waves can heavily interfere with data collected. With increasing distance from the radar, the beam widens which increases the altitude at which birds can be detected. Nevertheless, these radars are unable to provide the altitude of detected targets. Several marine radars are in operation on ships and platforms on any given day, and there could be a potential to exploit these data for monitoring offshore bird migration. However, given the range of different types of radars used it would require a huge investment to develop a fairly automated framework for acquiring these data unfiltered, as well as processing these data in a standardized fashion. Additional issues will include space limitations on platforms, dealing with sea clutter at lower altitudes, missing birds flying at higher altitudes, and sway for data collected from ships.

To also collect information on flight height, these radar systems have been modified to include a vertical scanning radar as well. This has either involved a standard radar, which has been tilted vertically (e.g., STRIX' BirdTrack radar, DeTect's MERLIN avian radar system), or more modified systems. The Robin 3D FLEX system includes an S-band horizontal radar and an X-band FMCW vertical scanning radar. More recently, this has been updated to their 3D MAX system with a single fully 3D FMCW antenna. The vertical radar provides height and 3D information on flight trajectories. Rotating blades from a turbine can produce strong disturbance and affect the ability to detect birds. Therefore, radars are typically deployed outside the wind farm area. Species groups can be identified, but the radar needs to be coupled with other technology to provide species identification. The detection range for the Robin radar ranges between 5-10km for ducks and geese and 2-5km for songbirds, although in practice these ranges may be significantly shorter (Shamoun-Baranes pers. comm.). On the vertical plane, the radar can detect birds up to a height of 1.5km. Data collected include macro and meso-avoidance, flight height, speed and direction. BirdScan (pulsed X-band) is a purpose-built pencil beam radar based of a conventional ship radar and a military tracking radar. The radar quantifies birds that fly through the radar beam. The X-band radar allows detection of small birds including passerines up to 1km away and larger birds up to 2km away (Hill *et al*. 2014; Nilsson *et al*. 2018).

Tracking radars are typically modified military radars, which can only track a single target at any point in time (e.g., Karlsson *et al*. 2012; Nilsson *et al.* 2017). Tracking radars are typically relatively large. The radar beam is a narrow pencil type and typically the airspace needs to be scanned manually before locking on to a target although automatic scanning can also be applied. The radar returns 3D tracks of birds from which speed, direction and wing-beat frequencies can be extracted which can help with species identification. While the data collected from tracking radars are incredibly valuable, this method is less useful for long-term offshore monitoring.

2.1.2 Passive acoustic monitoring

Some migratory birds use relatively simple species-specific flight calls during nocturnal migratory flights (Farnsworth 2005), most likely to facilitate communication with conspecifics (Gayk *et al*. 2021). Acoustic monitoring is a cost-effective way of monitoring bird migration at large spatial scales and presents some advantages when the area of interest is inaccessible and inhospitable. Acoustic monitoring has proven very effective at certain land sites at informing quantities and phenology of migration fluxes similar to that of radar (Van Doren *et al*. 2022). In fact, acoustic data explained 75% of the variation in radar data (when combined with weather data as well as day of the year). However, acoustic monitoring has not been a common method for monitoring offshore bird migration. In fact, where offshore acoustic monitoring has taken place, this has mostly focused on bat migration using ultrasonic detectors mounted ships (Sjollema *et al*. 2014), or relied on more permanent structure such as islands, rocks, lighthouses, and trees (Peterson *et al*. 2014). Given the short detection range of high frequency bat echolocation, this monitoring technology should also be useful for detecting bird calls in offshore environments, and there are some good examples to draw on. Sanders and Menill (2014) monitored bird flight over the Great Lakes, whereas Farnsworth & Russel (2007) successfully detected bird flight calls at an offshore oil platform in the Gulf of Mexico over a short temporal window. Acoustic monitoring has also taken place in the German Bight from the research platform FINO 1, which confirmed the presence of intensive migratory waves across offshore areas (Hüppop *et al.* 2006; Hüppop & Hill

2007; Hill & Hüppop 2008). Other studies have found that birds tend to use ships and oil platforms as stopover sites during migration when encountering bad weather (Farnsworth & Russel 2007; Sara *et al*. 2023).

Acoustic monitoring offers a useful opportunity for obtaining species-specific occurrence data and information on peak timing of migration. Especially considering that most migratory flight takes place at night which is also the time of day that most collisions with turbines occur. Furthermore, most migrating birds are small, and therefore difficult to detect using other methods that must capture an “image” of the individual. Previous studies suggest that detection ranges for low-frequency calls (e.g., thrushes, tanagers, and grosbeaks) should range to around 600 m and for high frequency calls (e.g., warblers and sparrows) to 250–300 m above ground level (Evans and Mellinger 1999; Evans and Rosenberg 2000; Farnsworth *et al*. 2004). However, flight height and atmospheric conditions also significantly influence detection range and must be taken into account (Horton *et al*. 2015). The quality of recordings can be degraded by noise from high winds, rain, and waves on days with high sea state, but also depending on where the microphone is placed, e.g., near the turbine, operating machinery, or close to the sea surface. Although, wind barriers have been successfully fitted to reduce background noise. Furthermore, some bird species don’t call at all or only call intermittently during migration so acoustic monitoring should be coupled with other technology for non-vocal species to be detected. Acoustic monitoring also does not reveal anything about the behaviour of the birds or potential collision risk in the vicinity of turbines, so the technology it is coupled with should ideally be able to decern bird behaviour, either long-range, such as bird radar, or short-range, such as cameras.

Importantly, there is potential for acoustic monitoring to provide more than species identification. Research has demonstrated the use of acoustics to estimate abundance or density of species (Dawson *et al*. 2009; Marques *et al*. 2013; Perez-Granados & Traba 2021) even in extreme-climate regions accounting for wind conditions (e.g., Adelie penguins; Zhao *et al*. 2022). Fundamental research on the relationship between group size and call rate, and how this is influenced by weather, flight height, flight speed, season, and behavioural state would be incredibly valuable, as well as how the detection range for different species varies in different weather conditions. This could allow us to estimate bird density and identity from acoustic data alone (at least for some species). Abundance/density can be inferred by birds call rate or vocal activity rate (VAR), which is expected to increase with population density. This has been shown to be effective for seabirds (Buxton *et al*. 2013; Borker *et al*. 2014; Oppel *et al*. 2014) but has been less conclusive for breeding terrestrial birds (Zwart *et al*. 2014, Perez-Granados *et al*. 2019). Its application to monitor abundance of migrating birds outside the breeding season (both terrestrial and marine) is promising.

In order to convert vocal rate activity to abundance in any monitoring program, Perez-Granados *et al*. (2019) recommended 1) estimating the distance that calls from individual species can be detected at, 2) identifying the time of day when calling activity is highest and limit recordings to this period, 3) assess the performance of the recognizer, 4) estimate VAR at a number of different sites and correlate with abundance estimates within the same effective distance from the ARU, and 5) evaluate the effectiveness of the entire procedure. Once assessed, VAR could be an effective method for discerning bird abundance in both new and archived recordings (Perez-Granados *et al*. 2019).

2.1.3 Stereo video camera systems

Stereo video camera systems have been used for a variety of different purposes including remotely measuring body size of wild animals (Siegfried *et al*. 2021) as well as monitoring the flight path of bats and birds in three dimensions to mitigate the impact of wind turbines (Holderied *et al*. 2005). For flying birds, it is also possible to identify species based on their shape and size from infrared cameras (Drewitt & Langston 2006). Camera systems should be coupled with radar, so they only turn on when the radar has detected a bird or alternatively be activated by motion detection, which significantly reduced the amount of footage collected. Motion detection and artificial intelligence enable cameras to track objects providing more continuous movement data. When conditions are good such camera systems can have a range of hundreds of meters, but during bad weather conditions the range can be significantly reduced, depending on the density of water droplets in the air. Thermography is also less effective in high humidity and rainy conditions because infrared radiation gets absorbed by water. Camera systems can be set up to survey activity around a single or a couple of turbines and thereby monitor meso-avoidance behaviour. Alternatively, cameras can be set up outside the windfarm area with the potential of monitoring macro-avoidance behaviour, but identifying species at this distance might be more difficult. It is recommended that camera systems are paired with surveillance radar to obtain species-specific information, including flight height, flight speed and macro, meso- and micro-avoidance behaviour.

Daylight stereo video camera systems: Some wind farms have implemented the IdentiFlight system (https://www.identiflight.com/) to detect and mitigate the impact of turbines on birds (see Linder *et al*. 2022). IdentiFlight is an automated monitoring system utilising eight fixed wide-field-of-view (WFOV) cameras positioned in a ring and a high-resolution stereo camera mounted on top of a six-meter-high tower. Where multiple towers are positioned, these operate autonomously as a network. The WFOV cameras detect moving objects and track them. Once a flying object is detected two moveable high resolution stereoscopic cameras are pointed at the object with the purpose of estimating distance as well as determine if the object is of special interest. Machine learning techniques determine whether the object matches the features of a programmed protected species. Based on the distance, speed and heading of the flying object IdentiFlight can decide if and when curtailment of a turbine should happen based on a set of criteria.

Thermal camera systems: Single thermal cameras, such as the Thermal Animal Detection System (TADS), have been used to record birds flying in the rotor swept zone and to estimate collision frequency of migrating birds at offshore wind turbines (Desholm 2003). Stereo systems on the other hand, such as the ThermalTracker-3D system developed by PNNL, can generate three dimensional tracks of birds in real time. This technology was designed specifically to monitor the behaviour of birds and bats in offshore areas and how these are affected by the presence of wind turbines. Thermal cameras were used in this setup as these are equally effective during both day and night-time and as mentioned above a significant proportion of bird migration takes place at night which is when collision risk is highest too. The ThermalTracker-3D system was tested using a small drone and had a range of at least 325 m and an accuracy of +/-10 m in the horizontal plane and +/-20 in the vertical plane (Matzner *et al*. 2020). This system is particularly useful for assessing collision risk and quantifying avoidance behaviour at operating offshore wind farms.

2.1.4 Satellite imagery

A variety of different satellites and constellations of satellites continually orbit the earth and offer a unique opportunity to obtain coverage in offshore areas. However, the types of satellites appropriate for monitoring the distribution of birds are more limited and involve the very high-resolution satellites (e.g., WorldView-3, Pleiades Neo, SuperView Neo, WorldView Legion). For example, very high-resolution satellite imagery (30 cm) was recently used to monitor the abundance of Wandering albatross on Bird Island and Chatham Islands (Fretwell *et al*. 2017), as well as penguin colonies in the Antarctic either by directly counting individuals or monitoring faecal staining (Edney & Wood 2021). These birds are large bodied with either predominantly white or black plumage, and therefore stand out against the background of vegetation or ice, respectively. For smaller birds with plainer plumage, it is uncertain how well individuals would stand out against a sea surface, although flocks should be detectable. The super-high resolution satellite constellations Albedo with 0.1m accuracy, which should soon become available, will improve the usefulness of this monitoring technique for migrating birds in remote and not easily accessible areas. The launch of the first Albedo satellite should take place during 2024 with plans to complete the constellation of 24 satellites in 2027. The revisit rate of a single satellite is 15 days, but for the constellation the revisit rare will be 1.5 revisits per day (at <53 latitude). Image size per pass will be 35x7km. However, images from the very high-resolution satellites (<1m) are not freely available and costs of obtaining images can be prohibitive. Furthermore, the satellites schedules cannot be changed should it pass over the target area (e.g., North Sea) on a cloudy day or at night when a large proportion of migration occurs.

In contrast, Synthetic Aperture Radar (SAR) satellites use a radar beam and can therefore both see through clouds and at night. Images are black and white and the brightness results from the strength of the backscatter signal. SAR data can therefore be very difficult to process and interpret. Water will absorb most of the energy and will as a result look black in the image. Objects with high metal content reflect most of the energy and will appear much brighter. SAR satellite images have a 100km strip width and are capable of 25x50cm resolution (slant versus along track), which is not yet good enough to detect individual small birds but might be enough to detect flocks of migrating birds.

2.1.5 Biologging

Available tracking technologies: Tracking provides an avenue for collecting information on individual bird movements in areas that are difficult to monitor, including offshore areas. Tracking studies have documented offshore migration in both seabirds (e.g., Fayet *et al*. 2017; Amelineau *et al*. 2021), and non-seabirds (e.g., Gill *et al.* 2009; Nourani *et al.* 2020; Nourani *et al*. 2021; Brust & Hüppop 2022), some revealing much larger proportions of offshore migration in songbirds than previously thought (using automated radio telemetry).

Continued miniaturization of tags means that ever smaller species can be tagged, although there are still limitations in available technologies for very small birds. The long-standing general rule has been that a tag must weigh no more than 5% of the animal's body mass, although many use a more conservative 3%, i.e., for a 30g bird the tag must weigh less than 0,9g (Kenward 2001). However, current GPS technology still makes it a challenge to tag small birds, especially when considering tags that transmit data. Any deployment of tags and/or handling of animals requires a permit from the relevant authority which in Norway is the Norwegian Food Safety Authority. Furthermore, sample sizes are often relatively low, generally on the order of several to tens of individuals per study. The amount of effort required to tag a representative sample of birds from each species and populations across different environments and countries is challenging and requires a collaborative effort. Regarding migration this is a particularly small amount considering the vast number of birds of different species involved in migration each year. Another consideration is that some birds may be more sensitive to tagging and behave differently when tagged, and the tag may therefore fail to capture their natural behaviour (Green et al. 2019).

There are other important considerations when it comes to choosing the most appropriate tagging technology which is in relation to the trade-offs between data retrieval, sampling frequency, location accuracy, battery size, and tag weight, especially when the purpose is to study migration systems or at least some parts of them. Some of the important differences between tag types are eloquently summarized in Bijleveld *et al.* (2022).

Tags that have been especially useful for long deployments where the purpose is to cover a large spatial area have typically involved geolocators and satellite tags. Such tags would be capable of covering migration routes, but they only record a single or a couple of locations per day, and the spatial resolution is typically quite poor, which makes it difficult to ascertain whether migration flyways are positioned across areas targeted for renewable energy development. Nevertheless, a multi-colony study using geolocators showed how Atlantic puffin migration patterns were driven by competition as well as geographical and environmental factors (Fayet *et al*. 2017). Furthermore, a recent multi-species study analysing geolocator data found that seabirds tend to overwinter at lower latitudes compared to their breeding colonies and that migration flights followed specific routes (Amelineau *et al*. 2021).

GPS tags are receivers and are localized with time-of-arrival of radio signals from orbiting satellites. GPS tags now come with solar panels extending their battery lives whereby with flexible duty cycles these are also capable of covering migration journeys (e.g., Brown *et al*. 2021). However, in most cases these tags need to be retrieved from the animal. Some tags do have the capability of transmitting location data to a receiving station or network, but the energy costs to the battery are large and this has consequences for the size and weight of the tag.

ARGOS tags, also referred to as frequency-of-arrival tags, uses a satellite system and Doppler shifts for estimating the location of the transmitter (i.e., the tag). The spatial resolution of these systems is often coarse with a spatial resolution for ARGOS tags of 250–1500m. These are therefore useful for long deployments monitoring large-scale movements, but less useful for understanding fine-scale movement behaviour.

Radio tags act as transmitters rather than receivers. They have low-power requirements and therefore smaller batteries, which means they can be deployed on smaller species. Radio telemetry tags uses a direction-of-arrival tracking system where an animal's location is estimated from measurements of distances or angles of a transmitted radio signal at receivers. Radio signals from the tags are picked up by receiving stations positioned across target locations. MOTUS and ARTS are examples of these and provide localizations at reasonable accuracies. However, the detection ranges are limited to hundreds of metres up to a few km, and localization error increases with the distance between the tag and receivers. Therefore, studies using this technology have to establish a dense receiver network in order to successfully obtain accurate localizations. The MOTUS Wildlife Tracking System is an international collaborative network using automated radio telemetry to track migratory animals, including birds, bats and insects, led by Birds Canada (Taylor *et al*. 2017; Dossman *et al.* 2023). The MOTUS network currently involves 34 countries, >1600 receiver stations, and >320 species tagged with larger networks established in Canada, the USA, and the Netherlands. The receiver includes either the SensorGnome or SensorStation, which are manufactured by Compudata.ca and Cellular Tracking Technologies, respectively. There are two tag types which are supported by the MOTUS network, namely Lotek tags and CTT tags. In Europe, the existing network and tagging efforts are heavily skewed towards Lotek tags. However, for long-term monitoring it is important that new receiver stations are set up recording in dual-mode supporting increased CTT tagging in the future. Nanotags were specially designed for use with MOTUS. The NanoPin is the smallest tag at just 0.13g, which can be used on the smallest songbirds and even insects. NanoTags lifespans depend on tag size but range from 367-1969 days (with a 30 second burst interval). It is also possible to set a duty cycle (e.g., 12 hrs ON/OFF or OFF during certain daylight hours) to extend the battery life even further. Solar NanoTags have also become available with a provisional minimum size of 1.5g which could be deployed on birds as small as 50g. NanoTag VHF transmitters can typically be detected up to 5km away. However, the actual detection range of a NanoTag is dependent upon a variety of factors such as the type of Yagi antennas on the base station, orientation of the birds to the station, topography, vegetation density and even the weather. An offshore receiving station will likely have a better detection range than a land-based station as there aren't any hills or trees to absorb the signal. For example, a 9-Element antenna on a base station pointed out to sea has a theoretical maximum detection range of up to 15km, whereas a 3-Element Yagi used on foot in dense vegetation could have a detection range of 500m to 3km.

The Icarus system (International Cooperation for Animal Research Using Space) is another example of using transmitting tags to study migration and movement in general of animals (Curry 2018). However, Icarus transmitters also have GPS function and accelerometers. Data are stored on the tag until a satellite passes at which point the data are transmitted by radio to the receiver station which then makes contact and send the data to the ground station, where the data are forwarded to the Icarus data centre for processing and is then made available in the Movebank database. The tags are fitted with solar panels and energy use is optimised so that batteries can last months or even years. Existing Icarus tags weigh five grams which is still prohibitive for small migrating birds. However, the current ambition is for the next generation of Icarus tags to weigh just one gram.

Time-of-arrival tracking systems, also referred to as reverse-GPS, tends to be more accurate and provides high-resolution data, but also requires a dense receiver network. Locations are estimated in real-time based on differences in signal arrival times at a minimum of three receivers and works best for producing location data at more local scales. The spatial and temporal resolution of these systems is similar to that of GPS tracking within a specific study area. ATLAS is a recently developed reverse-GPS system providing regional-scale detailed and high-resolution data from a large number of individuals (Beardsworth *et al*. 2022; Nathan *et al.* 2022). There are currently 6 ATLAS systems operating across the world with the largest, WATLAS, being based in the Wadden Sea (Bijleveld *et al.* 2022).

Direction-of-arrival (i.e., radio telemetry) and time-of-arrival (i.e. reverse-GPS) tags offers an interesting avenue for monitoring offshore bird migration. Particularly in situations where the focus is knowing whether birds cross the land-sea boundary, and whether they migrate across offshore areas that are designated for wind energy development. Receiving stations or antennae could be positioned on land at the land-sea boundary as well as on existing offshore platforms. In offshore environments, the detection range should be fairly long as there are no structures blocking the signals.

Existing tracking databases and projects: Online databases archiving tracking data also exist which could be a useful resource for understanding offshore flyways (the MOTUS and ATLAS projects are described above). **Movebank** is an online database of animal tracking data established in 2007, which is hosted by the Max Planck Institute of Animal Behaviour. MoveBank helps researchers and wildlife managers worldwide to manage, share, analyze and archive animal movement data. Data are archived here from over a 1000 different species, including more than 2 billion locations. **BirdLife** Seabird Tracking database (started in 2004) is said to hold the largest collection of seabird tracking data, and recently revealed a major seabird hotspot in the North Atlantic (Davies *et al.* 2021). Such databases could provide information on offshore flight patterns across a wide variety of birds. Data on flight height could also be obtained from birds making offshore flights. Although elevation data comes with some level of error and may not be reliable for understanding collision risk with turbines for individual birds, it would give a coarse view of how bird use the airspace in different regions. However, to access data held in such databases, approval is required from each data owner, which is not a very sustainable option for long-term monitoring. Furthermore, there are no controls over which species are tagged or where or when this happens, potentially resulting in large gaps or biases. The **SEATRACK project** is hosted by SEAPOP (a long-term monitoring program for Norwegian seabirds) and is led by the Norwegian Polar Institute (NPI), NINA and the Norwegian Environment Agency. SEATRACK was created following developments in light-logging technology which enabled the monitoring of multi-year movements including tracking of birds during migrations in the non-breeding season. The study area of the SEATRACK project involves 56 study sites encircling the Labrador, Greenland, Barents, Norwegian, North and Irish Seas, which includes colonies in Canada, Greenland, Russia, Norway incl. Svalbard and Jan Mayen, Iceland, the Faroe Islands, Ireland and United Kingdom. Eleven seabird species have been tracked as part of the project, including Atlantic puffin, black-legged kittiwake, Brünnich's guillemot, common eider, common guillemot, European shag, Glaucous gull, herring gull, lesser black-backed gull, little auk and northern fulmar. Light-loggers have collected twice daily locations year-round and often for multiple years, providing important information on the timing and location of migration routes. Although the error around light-logger locations can be large (up to 180 km), when exploring large-scale movement patterns this error is less of a problem. Data are of course species-specific and loggers record data day and night and in all weather conditions (issues can arise at certain times of the year in locations with 24-hour daylight or nighttime).

There is clearly a growing interest in quantifying offshore bird migration utilizing different tracking technologies with several shorter term European projects having been funded recently, such as TRACKBIRD (2019-2023) “Bird migration across North Sea and Baltic Sea: Migratory patterns and possible impacts of offshore wind farms”, BIRDMOVE (2015-2019) “Bird migration over the open sea”, and OWF-Seabirds (2020-2023) “Expansion of offshore wind energy in Germany: effects on seabirds in the North Sea and Baltic Sea”.

2.1.6 LiDAR

Light Detection and Ranging (LiDAR) systems are a relatively new technology for use in understanding bird migration and potential impacts of wind farms. **Stationary (also referred to as “terrestrial”) laser scanners** positioned on offshore structures offer the possibility of continuous monitoring of bird flight height from a fixed position. The laser scanner can be controlled, and data retrieved, and processed (for example including computation of bird flying height and geographical coordinates) by a connected computer. The scanner can operate in a continuously scanning “radar mode”. A suitable laser scanner is the RIEGL VZ-6000, which has a range of up to 6 km, and uses a laser wavelength that also enables acquiring sea surface. However, it is not dependent on recording the sea surface to determine flying height. The benefit of this system is the range (6km), but it would still need to be coupled with a camera system or acoustics to identify species, although species ID can only be obtained for birds flying within the range of the camera or ARU (not out to 6km). Stationary laser scanners could be deployed on offshore platforms where space and technology allow the continuous scanning of the airspace around the location.

Aerial LiDAR surveys: While stationary laser scanners can obtain continuous data in a fixed location, aerial LiDAR surveys can obtain data on species-specific flight height across a broad spatial area, but only within the relatively short temporal window of the survey. LiDAR systems used to monitor flight height of seabirds has included a Riegl 780i LiDAR, which is a near-infrared waveform system with a high laser pulse repetition rate of up to 1 MHz (Cook *et al*. 2018). The LiDAR system is usually attached to the underside of the plane and emits short duration laser pulses during flight, which illuminate targets and measure its location in three dimensions (x, y, and z). LiDAR systems are coupled with daylight camera (e.g., Phase One iXA180) to photograph birds for species identification. Cook *et al*. (2018) demonstrated that from an altitude of 300m above sea level, the LiDAR had a point density of 11 points/m^2 and a strip width of 300m. During traditional digital aerial surveys, flight height estimates are influenced by the error associated with the estimation of the altitude of the aircraft (Thaxter *et al*. 2016). In contrast, LiDAR estimates of flight height are made in relation to the sea surface and error is reduced to approximately 1m. Depending on sea swell, a minimum height threshold above the sea surface will have to be set to avoid inclusion of waves (Cook *et al*. 2018). However, this is fairly minimal and most flying birds should still be captured by the LiDAR.

2.2 Observational approaches

2.2.1 Visual surveys

European Seabirds at Sea (ESAS) was initiated in 1979 and collects monitoring data from large scale ship surveys on seabirds and marine mammals within the North Sea and NE Atlantic. The spatial coverage in the North Sea is extensive, however in the past 10 years, this has been more limited, possibly rendering it less useful in our long-term monitoring plan (**Figure 1**). Nevertheless, it may still hold useful historical information, although the overlap of ship surveys with the migration seasons would have to be explored (**Figure 2**).

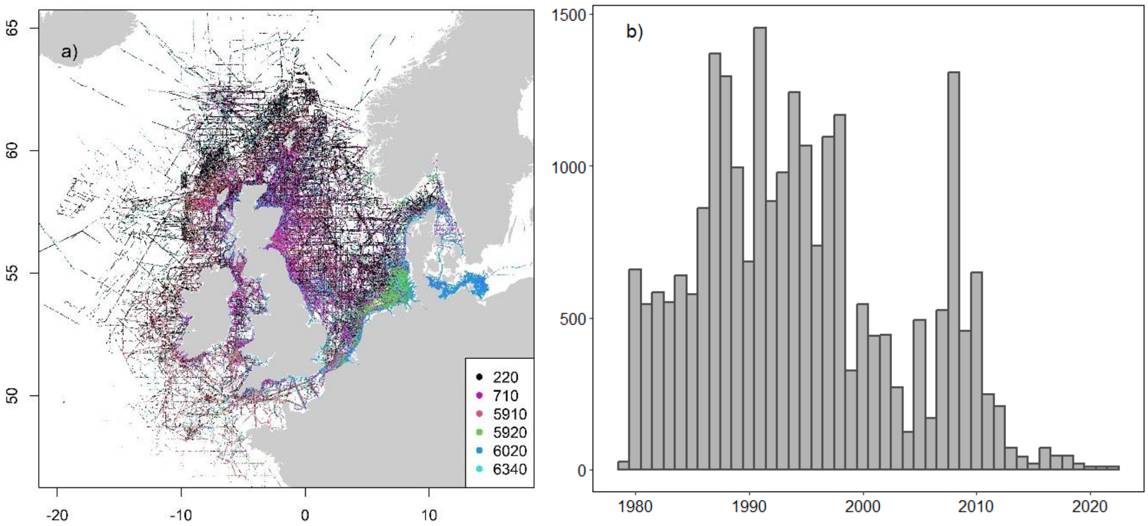

***Figure 1**. a) Map of data from the top six most sighted birds during ESAS surveys (220=northern fulmar, 710=northern gannet, 5910= lesser black-backed gull, 5920=herring gull, 6020=black-legged kittiwake, 6340=common guillemot), and b) the frequency of records over time (1979-2022).*

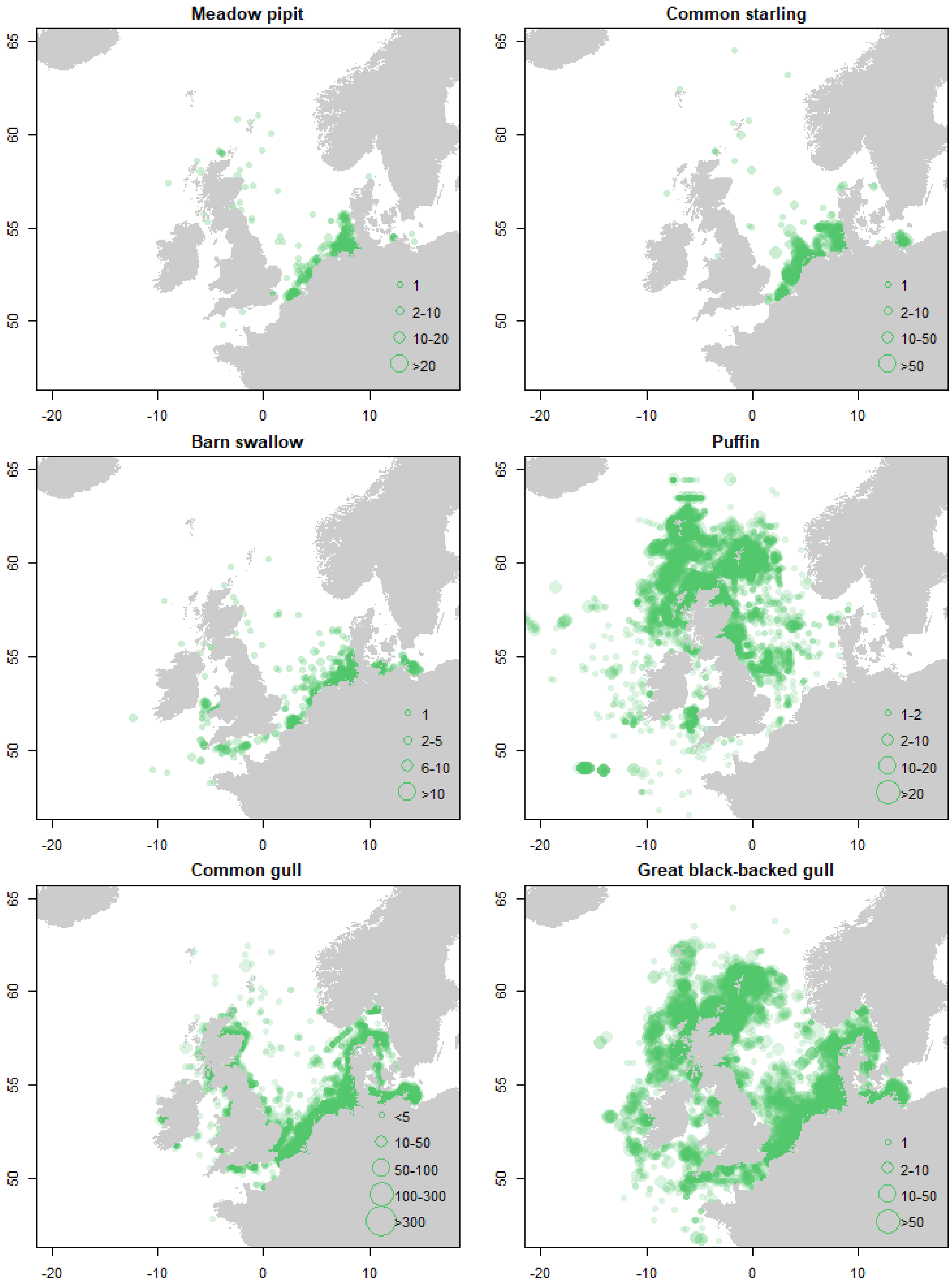

Figure 2. *Examples of data collected as part of ESAS. Here showing spring data only (Mar-May) for the entire time series. Points are scaled by numbers of birds detected.*

2.2.2 Ringing data

Scientific bird ringing involves the marking of birds with metal rings inscribed with a unique serial number and a reporting address. For over 100 years, leg rings have been used to mark hundreds of millions of individuals. Subsequent reports of the birds from qualified ringers or members of the public provide information on apparent survival and other aspects of their biology. Furthermore, when migrating birds are captured or sighted at separate geographical locations either side of their seasonal migration, the probable movement path between the two locations can be modelled. Bird ringing as a result represents a very positive example of mostly citizen science-based research operating on a global scale.

The European Union for Bird Ringing (EURING) coordinates the national bird ringing schemes in Europe. As a result, the EURING Data Bank (EDB) was established in 1977 as a central repository for European ringing recovery records. EURING recently developed the Eurasian African Bird Migration Atlas (https://migrationatlas.org/) involving collaboration of researchers from 10 different institutions, and data gathered from over 50 different organizations. This represents a first attempt to produce a migration atlas covering the huge geographical area represented by two continents, encompassing the whole flyway between Eurasia and Africa. Movements in time and space of millions of birds are mapped and analysed, each based on ringing and recovery locations, with the results drawing on data gathered over more than a century. The coarse movements of 300 bird species are mapped using ringing data alone, while for over 100 species, ringing data are complemented by tracking data held in MoveBank (GPS or geolocator tags).

2.2.3 Citizen science data

Citizen science can be referred to as the public participation in scientific research, where members of the public partner with professional scientists to collectively gather, submit, or analyse large quantities of data. **Global Biodiversity Information Facility (GBIF)** is an international network and data infrastructure aimed at providing open access to a broad range of biodiversity data. Several species occurrence datasets feed into GBIF, including those from **eBird,** which is the largest dataset in GBIF and the world's largest biodiversity related citizen science project, **iNaturalist** (global), **Artportalen** (Sweden), **Artsobservasjoner** (Norway), and **DofBasen** (Denmark) and others. Observations in **EuroBird Portal** (EBP) are manyfold including large amounts of casual records as well as some more or less standardized counts. Analyses of these data asks a lot of understanding of how they are collected. **Trektellen** collates systematic counts made by the public or bird observatories of migratory birds from a fixed point. Trektellen started in the 1970's in the Netherlands and has since grown in popularity and spread to other European countries and even the USA. Several counting stations are located on the coast aimed at sea-migration. Data from Trektellen are also uploaded to EuroBird Portal. Both the data of EBP and Trektellen are not freely available but involve data request formalities. Recognizing that most bird migration takes place at night, **Nocmig** is the nocturnal equivalent of visual daytime migration counts. This involves members of the public purchasing relatively inexpensive acoustic recording equipment to capture the flight calls of migrating birds at night. Data on recording effort and the species and numbers of individuals or calls can be submitted to Trektellen.

2.3 Summary of different approaches

To provide an overview of the technologies discussed in the report, we summarize these here in both figures and tables below.

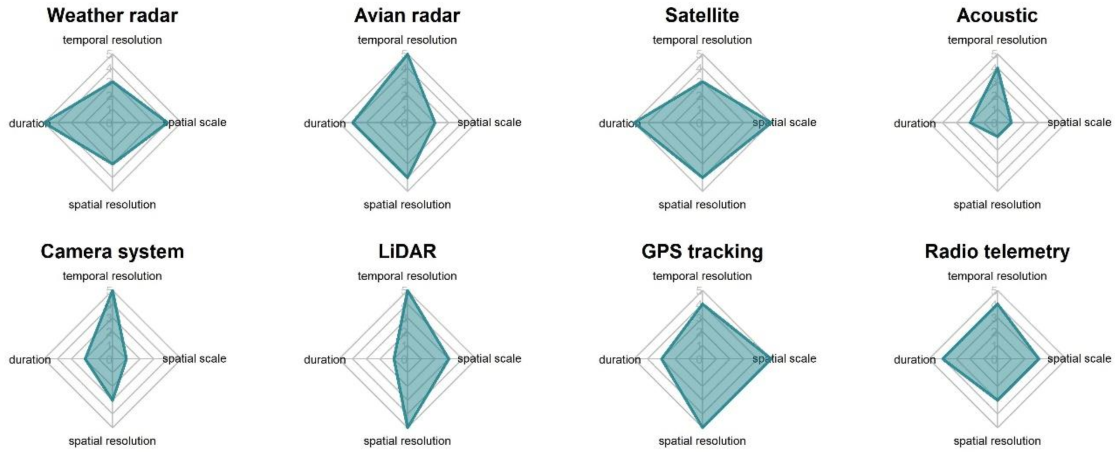

Figure 3. *Showcasing a qualitative evaluation of four key criteria for each of the eight technologies. The technologies are evaluated as a network of sensors rather than individual pieces of equipment as this is what is relevant in the context of this report. For GPS tracking and radio telemetry we are evaluating the tags themselves rather than the receivers. The criteria include 1) the* ***temporal resolution*** *of the data obtained, 2) the* ***duration*** *the technology can last without needing intervention, 3) the* ***spatial resolution*** *of the data, and 4) the* ***spatial scale*** *covered by each technology. Each criterion is scored from 0 - 5 with 5 indicating the best performance.*

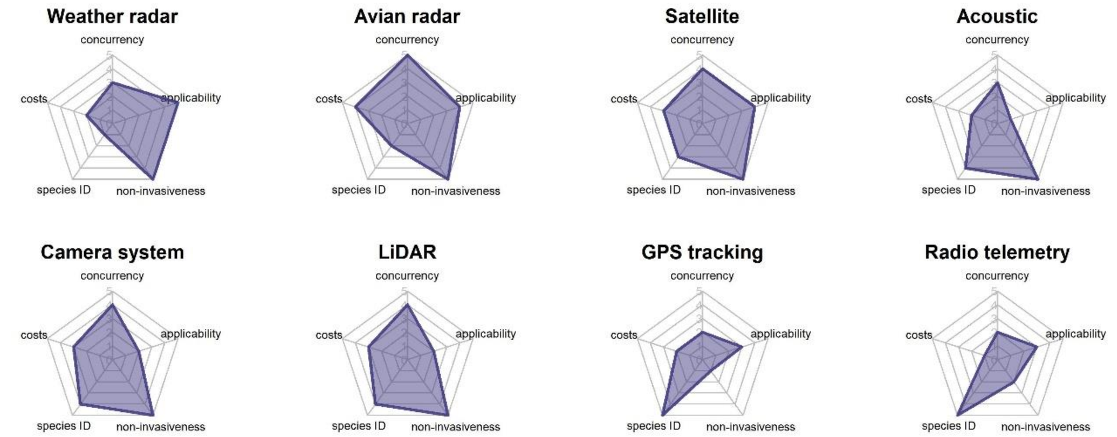

Figure 4. *Showcasing a qualitative evaluation of five criteria for each of the eight technologies. The technologies are evaluated as a network of sensors rather than individual pieces of equipment as this is what is relevant in the context of this report. For GPS tracking and radio telemetry we are evaluating the tags themselves rather than the receivers. The criteria include 1)* ***concurrency*** *which reflects the technology's ability to monitor multiple individuals at the same time, 2) the* ***applicability*** *which reflects how ready the technology is for use in long-term monitoring (e.g. how automated the technology is, whether infrastructure is in place already, how much input is required), 3)* ***non-invasiveness*** *in relation to the birds, 4)* ***species ID*** *indicating what information is obtained in terms of identifying the species monitored (i.e. do you get species ID for all birds, or just some, or alternatively does the technology provide some coarser information, such as size class, or none at all), and finally 5)* ***costs*** *of establishing large scale monitoring. Each criterion is scored from 0 - 5 with 5 indicating the best performance, except for costs where a score of 5 indicates the highest cost.*

Table 1. *Key metrics that can be obtained by the different sensor and non-sensor based approached.*

	SPECIES ID	24-HOUR	MTR	FLYWAY POSITION	TIMING	FLIGHT HEIGHT	FLIGHT DIRECTION	FLIGHT SPEED	AVOIDANCE RATE
WEATHER RADAR	✗	✓	✓	✓ Where radar networks exist	✓	✓ Elevation data collected within each 250 m horizontal distance band	✓ Coarse information	✓	✗
AVIAN RADAR	(✗) Can collect species groups based on speed	✓	✓	✗	✗	✓	✓	✓	✓ Macro and meso scale
ACOUSTIC	✓	✓	✓ Where information exists on basic relationships, vocal activity rate can be converted to abundance	✗	✓	✗	✗	✗	✗
CAMERA	✓	✓ Infrared cameras allow nighttime monitoring	✗	✗	✗	✓	✓	✓	✓

	SPECIES ID	24-HOUR	MTR	FLYWAY POSITION	TIMING	FLIGHT HEIGHT	FLIGHT DIRECTION	FLIGHT SPEED	AVOIDANCE RATE
SATELLITE	(✓) Species groups	✓ With SAR satellites	✓	✓	✓	✗	✓	✗	✗
BIO-LOGGING	✓	✓	✗	✗ Typically not enough individuals, populations, or species are tagged	✗ Typically not enough individuals, populations, or species are tagged	✓ Flight height can be estimated from pressure sensors on tags, however, accuracy might vary. Could give an indication of whether birds fly in the rotor swept zone	✓ Using relatively high-resolution GPS tags	✓ Using relatively high-resolution GPS tags	✓ Using high-resolution GPS tags
LiDAR	✓ Daytime only unless coupled with IR camera	✗	✗	✗	✗	✓	✓	✗	✗
CITIZEN SCIENCE	✓	(✓) Visual day time observations can be combined with night-time acoustic recordings	✗	✗	✓	✗	✗	✗	✗

Table 2. *Summary of relevant information, including scale, costs, and strengths and weaknesses of the different sensor- and non-sensor-based approaches, as well as any advice or recommendations of other approaches to couple these with.*

	INFO	SCALE	RELATIVE COSTS	STRENGTHS	LIMITATIONS	RECOMMENDATION
WEATHER RADAR	Scans the airspace every 4-10 mins (144-360 locations per day).	Horizontal: ~25-40km detection range. Collects data in each 250m radius band from the radar. Vertical: Elevation data collected within each distance band as well. Temporal: Continuous.	Low/medium (time for data processing and analysis).	Extensive range. Nocturnal observations. Multiple radars can be joined in a network. Data can be extrapolated.	No offshore data. Lack of species-specific data. Can't detect collisions.	Couple with acoustic monitoring, citizen science, or radio telemetry for species ID.
AVIAN RADAR	>1000 locations per day. 'Max': 3D flight paths in macro and meso space.	Horizontal: 10km detection range for larger birds; 6 km detection range for songbirds. Vertical: 1.5 km. Temporal: Continuous.	High (equipment). Medium (time for data processing and analysis).	Most appropriate radar for monitoring bird behaviour around wind farms due to costs, versatility and availability. Possibility to position offshore. Nocturnal observations. Multiple continuous individual tracks. Can be combined into a single sensor (horizontal and vertical; 'Max') collecting full 3D information. More locations and more accurate compared to weather radar.	Lack of species-specific data. Rain and waves (sea state >=4) creates clutter on horizontal scans. Can't monitor absolute intensities of movement. Can't detect collisions.	Combine with cameras and/or acoustics to record species ID. Such data could then feed into CRMs.

	INFO	SCALE	RELATIVE COSTS	STRENGTHS	LIMITATIONS	RECOMMENDATION
ACOUSTIC		Detection range is likely relatively short (i.e., a few hundreds of meters).	Equipment can be relatively inexpensive, e.g., AudioMoth ~1300 NOK	Nocturnal observations. Species-specific detections. Equipment is small.	Dependent on birds vocalizing. Doesn't measure flight parameters. Weather conditions and flight height will influence detections.	Vocal activity rate can be converted to abundance or density. Can be positioned on land within weather radar zones or on offshore platforms.
CAMERA		Systems such as thermal-tracker-3D can detect larger birds over 300m away.	Medium	Nocturnal observations. Species-specific data. Produce 3D flight paths.	Relatively short range. Doesn't work well in cloudy or rainy conditions. Works better in winter.	
SATELLITE		Horizontal: Any spatial coverage is possible. Temporal: Revisits depend on the schedule of the satellite or satellite constellation. Could be 1.5 revisits per day.	High cost of acquiring high resolution images	Offers broad spatial coverage to map flyways and peak timing of migration.	Costs of obtaining images.	Couple with LiDAR for data on flight height and cameras or acoustics for species ID in certain locations.
BIO-LOGGING	Can offer other valuable sensors, such as accelerometers for energetics.	Depends on the tag used. GLS tags provide temporal coverage of multiple years including migration flights, while GPS tags have shorter battery life but provide high spatial resolutions. Radio telemetry only logs a location if in the vicinity of a receiver.	Depends on the technology and tag size (1300 – 30000 NOK per tag)	Species-specific information. Flight behaviour. Low resolution migration data over several years. High resolution data on foraging hot spots and fine scale flight behaviour through a wind farm site. Day and night data collection. All weather conditions. Solar panels can increase battery life.	Bias towards larger species. High resolution data restricted to breeding season. Some tags require recapture. Low sample size. Tagging multiple species logistically challenging.	

	INFO	SCALE	RELATIVE COSTS	STRENGTHS	LIMITATIONS	RECOMMENDATION
LiDAR		Aerial surveys flown at approximately 300m altitude had a swath of 300m. Can cover large spatial area, but short temporal window. Stationary laser scanners have a range of ~6km and can scan continuously (radar mode).	LiDAR equipment is very expensive (1.8 MNOK)	Estimates of numbers of birds. Estimates of flight height.	Doesn't work in bad weather and can't get species ID during the night. Sea state influences how high above the sea surface birds can be recorded.	Couple with cameras or acoustics for species ID.
CITIZEN SCIENCE		Large spatial scale. Patchy temporal resolution.	Low	Species-specific occurrence or presence data.	No data collected during the night – except nocmig. No offshore data.	

3 Long-term monitoring plan

Short-term studies covering a single season or year or those the length of a typical research council funded project can highlight the position of flyways, relationships between flight behaviour and landscape characteristics and weather, and the peak timing of migration for different species within this time window. However, it is well known that there are inter-seasonal and inter-annual differences in migration patterns. Furthermore, the conditions and landscape that birds migrate within is constantly changing because of climate change and the expansion of human development both on land and in the ocean. Therefore, long-term monitoring is necessary to capture how migrating species are responding to these changes, and to be able to discriminate between inter-annual variability and temporal trends in migration patterns. While there are several methodologies available for studying bird migration (as shown in section 2), only some qualify for long-term monitoring over a large spatial scale, and a smaller set of those will be appropriate for an offshore environment.

There has been an increase in the use of large-scale monitoring networks using advanced sensors in the past couple of decades. Often these involve an integration of different technologies in order to increase the spatial and temporal coverage (Marvin *et al*. 2016) as there is rarely a single method/technology that can collect all the data required. Below we have chosen those sensor- and observational-based approaches we believe are most suitable for establishing a core monitoring programme as well as those worth exploring through R&D opportunities. Where relevant we provide suggestions outlining and/or visualising what these activities could look like in order to start discussions. Some activities involve technology or systems already in place, while others will need developing from scratch requiring funds and logistical input.

3.1 Core monitoring

3.1.1 Network of coastal weather radars

The first part of the long-term monitoring plan will involve a collaborative integration of coastal (or near-coastal) meteorological radar systems from all countries surrounding the North Sea, including Norway, UK, Germany, Denmark, the Netherlands, and Belgium (**Figure 5**). Thus, we foresee the network of coastal weather radars to form under ENRAM or GloBAM (e.g., NSNRAM - North Sea Network for the Radar surveillance of Animal Movement). This would provide an opportunity for analyzing and utilizing historical data stored in the ENRAM data repository from 2013. Similar outputs as those showcased in Lin *et al*. (2019) could be produced including changes in the position of coastal migration flyways, the phenology of peak migration, nightly migration activity, and changes in flight altitude over time. However, it is important to point out that more work is still needed in terms of how to deal with issues surrounding the quality, comparability and availability of data obtained from these national sensor networks. So, while the potential is great, there is not yet an established framework where analyses such as this are simple plug and play (Shamoun-Baranes et al. 2022).

Due to their size, weather radars cannot be positioned offshore, and therefore cannot be used to inform on actual offshore migration patterns (despite providing the best spatial coverage compared to other radar types). However, weather radars can quantify the number of birds that are migrating near the coast as well as the number of birds with migration routes apparently heading out to sea. Algorithms and visualization tools have already been developed and can be implemented to automate the process of for example separating precipitation from biology (e.g., MistNet; Lin *et al*. 2019), producing standard metrics and visualizing outputs (e.g., R package bioRad; Dokter *et al*. 2019), and predicting across areas with no radar data (e.g., FluxRGNN; Lippert *et al*. 2022). Nevertheless, quantifying actual offshore migration traffic will require other approaches (see radio tracking under biologging, citizen science and acoustic monitoring).

Furthermore, as a wide range of different bird species migrate it is important to establish species identification when birds are detected. Radars do not have this capability. Therefore, we recommend coupling this radar network with other approaches, such as citizen science data from the EuroBird portal (similar to BirdCast) or setting up acoustic monitoring inside the individual radar zones (similar to Van Doren *et al*. 2023) in order to help establish which species are detected in radar images.

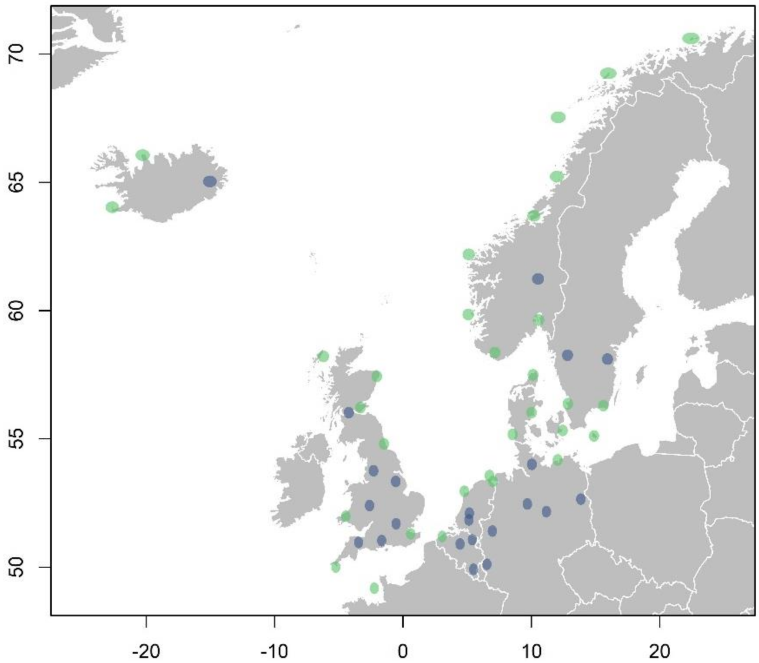

Figure 5. *Map showing the location of relevant weather radars with a 25km buffer (green circles indicate radars with good coastal coverage, and blue circles denote near coastal radars) in the countries bordering the North Sea and Norwegian Sea.*

3.1.2 Strategic biologging

The tagging technology most appropriate for monitoring offshore migration depends very much on requirements and research questions. If flight paths are needed then GPS tracking would be most suitable, but this may involve some restrictions on the sizes of birds tagged. If on the other hand, information on whether birds visit or fly through a certain area is sufficient then radio telemetry using a network of receiver station would be appropriate. Radio telemetry carries less restrictions on what size of bird can be tagged and batteries can last a very long time. While we certainly see the value multi-species GPS tracking across multiple locations and acknowledge that this warrants further exploration in terms of monitoring offshore bird migration, we dedicate the rest of this section to outlining a plan for radio telemetry and establishing a network of receiver stations. However, we acknowledge also the great potential of the Icarus system. Receiver stations can be positioned in areas of interest or can form boundaries that birds have to cross flying in and out of the area of interest. For the time being, we keep the possibility open for using either MOTUS or ATLAS receivers, although the MOTUS network is already fairly extensive. Currently, there are only a few MOTUS receiver stations located offshore (**Figure 6**), but interest in the use of MOTUS receivers on offshore platforms is growing.

We propose two plans for deploying receiver stations 1) on **offshore** platforms in the North Sea and/or on vessels that make regular trips across the North Sea, and 2) at **onshore** coastal locations creating a boundary around the North Sea which migrating birds heading out over the North Sea would have to cross (**Figure 7**). This would allow us to detect the location where birds head out over the North Sea, and the location where they leave the North Sea on the other side. Using time between detections it would be possible to build a probability bridge between the locations given the likely average speed of movement (e.g., Brownian Bridge). We will explore options for acquiring free access to any data recorded on our own receivers, and to establish collaboration with other projects that have deployed receivers and tags. Furthermore, we propose to establish collaborations with Bird Observatories in the countries bordering the North Sea to deploy Lotek NanoTags during regular seasonal bird ringing campaigns where typically 100s of birds are ringed at each year at each observatory (e.g., Norway: Utsira, Lista, Jomfruland; Sweden: Ottenby Bird observatory, Falsterbro Fågelstation; Denmark: Gedser Fuglestation, Skagen Fuglestation; Netherlands: De Guel (Den Hoorn); United Kindgom: Sandwich Bay, Dungeness, Long Nab). This would involve birds across a range of weight categories from 30g – 3kg. Any deployment of tags and/or handling of animals requires a permit from relevant national authorities.

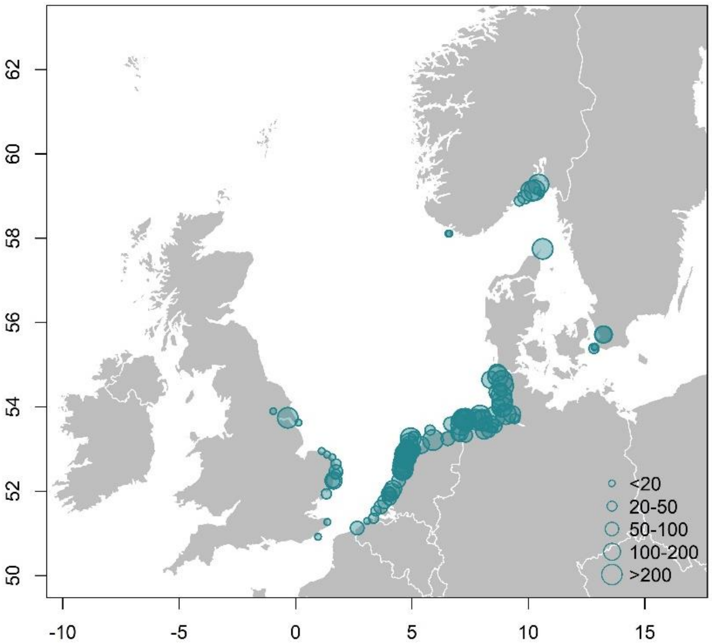

Figure 6. *The location of all current MOTUS receivers in coastal areas surrounding the North Sea scaled according to the detection rate of receiver stations that have been operating for at least one full year.*

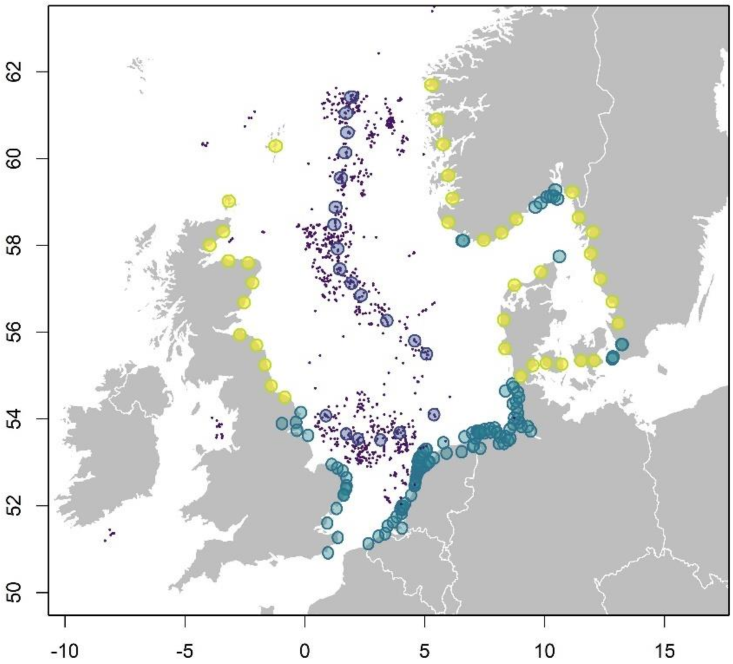

Figure 7. *A suggested strategy for building an offshore network (purple circles) as well as creating an onshore North Sea boundary (yellow) in addition to the existing receivers (blue) to detect offshore migration. The offshore network is positioned on the same offshore platforms (dark purple) as our suggested offshore acoustic monitoring plan (see 3.2.1).*

Lastly, for the birds tracked as part of the SEATRACK project, and the data available in MoveBank and Birdlife, we propose to explore how much data are available on approximate flight heights depending on the types of tags used. This information could be collated to form a 3D species-specific map of the use of the airspace over the North Sea and overlay this with the areas proposed for renewable development to identify areas where birds could be at higher risk of collision.

3.1.3 Network of citizen science

Use of existing coastal data: We propose extracting citizen science observations of birds from the EuroBirdPortal and Trektellen within a 25 km buffer zone of each weather radar involved in our proposed coastal weather radar network (3.1.1). To obtain data from EuroBird Portal or Trektellen, a data request must be submitted, but we would explore options for becoming more permanent collaborators or partners. Data from the EuroBirdPortal and Trektellen can highlight species with coastal and potential offshore migration across the North Sea, as well as times of high fluxes of certain species. Opportunistic citizen science data could be coupled with more standardized observations of migrating birds at fixed locations, namely from coastal bird observatories located across the seven countries. Furthermore, we propose to explore ringing data stored in the EURING database and investigate the potential to quantify coarse flyways using Brownian bridge methods.

Collection of offshore data: We propose developing a smartphone app for collecting citizen science data offshore. The app will be distributed to industry (including wind, oil, and the shipping industry) and ferry companies. The app will be simple to use for recording approximate categories of numbers of birds (e.g., 1-10, 10-100, 100-1000, 1000+) and most likely species group by collecting information on the closest size (e.g., tennis ball, handball, football and larger), colour (white, black, grey, brown, grey/white, black/white etc.) and shape (e.g., of the neck and wings) of the birds sighted. For more keen birders, there will be options for filling in more detailed information of species ID as well as recording main flight direction (using the phone compass). GPS and time will be automatically recorded from the phone. The app will be accompanied by a short video or animation clearly explaining what the purpose of the data collection is, what these are used for, and some data outputs when these become available. This will be distributed to the companies to increase engagement. Short follow up animations or videos showcasing interesting results will also be released as the project progresses to maintain engagement over time.

3.1.4 Collating 3D avian radar profiles

Acquiring enough bird radars to monitor birds across a larger offshore area would not be feasible both in terms of costs and logistics. However, where bird radars exist or where such radars might be set up in the future as part of new wind farm developments, and where industry is interested in collaborating, we propose to incorporate data from bird radars into our long-term monitoring. These would provide crucial high-resolution information including multiple continuous individual tracks (with 3D possibilities) and data on flight height, speed, and direction. Importantly, such radars fulfil multiple purposes including rendering data both in the short and long-term, i.e., monitoring bird migration both pre-, during and post-construction. Furthermore, in terms of long-term monitoring and increasing coverage, it would be beneficial to completement with radar sites in other countries. NINA can develop a centralized database where relevant and cleaned data (including hourly fluxes, vertical profiles, directions etc.) from these radars are stored (NB! it will not be possible to store all raw data here).

We also recommend coupling avian radars with acoustic monitoring (see 3.2.1), MOTUS receivers (3.1.2), or cameras for species ID. We have identified strategic sites where we would encourage the deployment of avian radars (see **Figure 8**). There is already an avian radar in place at Hywind Tampen, which should be operational in the near future.

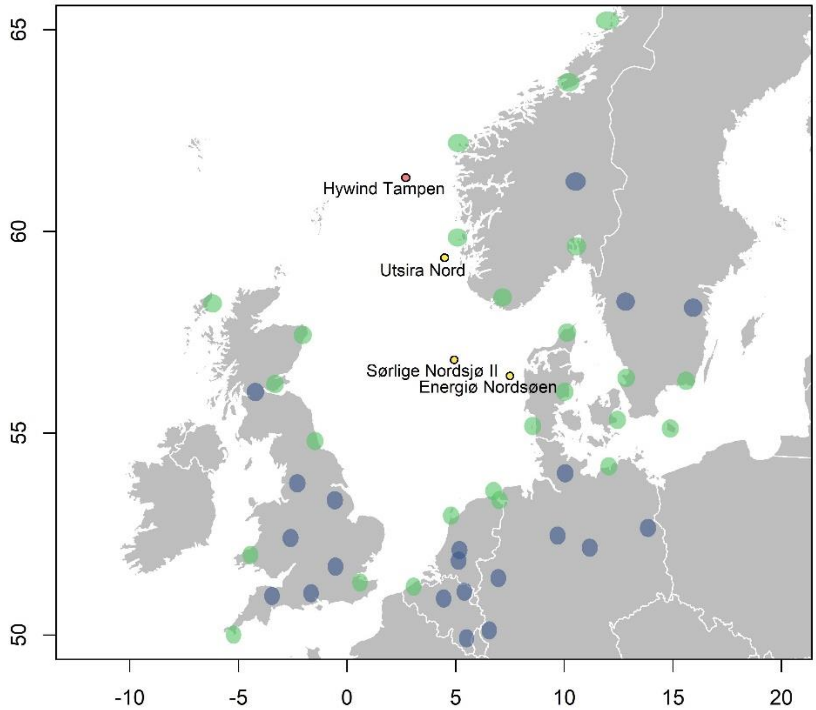

Figure 8. *Weather radar locations with 25km buffer zone (blue) and the location of existing 3D avian radars (red) as well as possible strategic locations for additional 3D avian radars (yellow). A 10km buffer has been drawn around the avian radar locations.*

3.2 Research and development opportunities

3.2.1 Satellite

By far the best offshore spatial coverage will be provided by satellite imagery with increased temporal coverage where satellite constellations exist increasing the revisit rate. We therefore suggest testing images from WorldView-3 satellite with a 30cm resolution and SAR satellite to detect flocks of birds. We recommend obtaining images from areas with weather and avian radar coverage to validate detections and non-detections in satellite images. When the Albedo satellite with 10cm resolution becomes available, we recommend exploring the possibility of detecting individual birds. If this is successful, deep learning software should be developed for automatic processing, counting of individuals, and dividing into "species" groups (size, colour). If this proves successful as a monitoring technique, we recommend promoting this to become one of the core activities. Satellite monitoring would provide the clearest picture of the position of offshore flyways but would likely have to be coupled with other technology for species ID and flight height.

3.2.2 Acoustic monitoring

Following a review of methods used to monitor bird migration, acoustic monitoring is a promising approach for long-term monitoring in offshore environments. While the number of bird radars will likely build up near offshore windfarms over time, the purpose of the acoustic deployments is to increase monitoring in logistically challenging offshore areas where we know very little about bird migration. Although this approach doesn't provide all the answers, it would provide information on which vocal species are found offshore at different times of the year. Acoustic recorders are relatively low cost, equipment set ups are small, and automated data processing methods have been developed. However, the logistics of deploying the devices on offshore platforms is a greater challenge and will likely carry the highest costs.

Before investing in a larger network of acoustic recorders, we propose testing ARUs using playback experiments under different weather conditions (mainly wind) and anthropogenic background noise. Playbacks of different bird calls varying in frequency should be conducted at different distances and heights (e.g., using a hill or mast with a clear view) to the ARU under different wind speeds and directions, preferably at a coastal setting with increased natural background noise. This would allow us to explore the relationship between detection range, frequency, weather, distance, and height. Furthermore, ARUs should also be coupled with avian radar and direct visual observations to explore the proportion of birds that vocalise out of the total number detected by the radar within a given radius.

Following these tests, should acoustic monitoring prove successful we propose two plans: Firstly, we propose deploying 3-5 ARU's within the zones of strategically selected coastal weather radars. This is a lower risk option given that ARUs have been deployed and animal vocalisations successfully recorded on land previously. Acoustic recordings of bird calls would provide species identification to MTR and flight height data collected by the radar.

Secondly, we propose an ambitious plan to deploy acoustic monitors on offshore operational platforms (e.g., oil and gas) distributed throughout the North Sea (**Figure 9**). These will detect flight calls of vocal bird species when flying over or stopping over on the platforms. ARUs should be set up with a duty cycle to record at certain times of day and certain periods of the year (i.e., covering the peak spring and autumn migration) to extend the recording window. Due to the relatively short detection range of bird calls, most likely several acoustic monitoring stations would be needed. In case an ARU should fail, we propose doubling up ARUs in all locations. These recordings would provide information on species-specific occurrence and peak timing of migration.

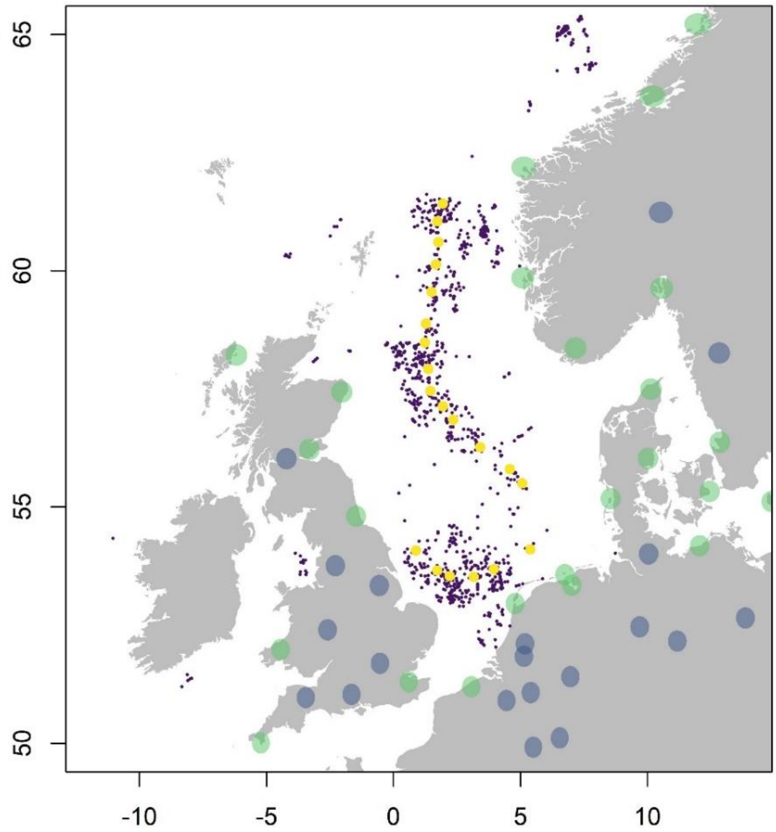

Figure 9. *Location of the acoustic monitoring network (yellow dots) amongst the existing off-shore platforms (dark purple dots) in the North Sea and Norwegian Sea.*

Should remote download of acoustic data not be possible (as is the case currently for Wildlife Acoustics SM4), consideration should be given to deploying ARUs on ships and ferries making regular journeys across the North Sea. However, detection range must then be tested against both wind and ship noise, and ARUs should be positioned as far away from engines as possible and ideally somewhat sheltered against the direction of travel.

Coupling acoustic monitoring with avian radars when these become available would provide unique opportunities to quantify the relationship between vocal activity rate (VAR), group size, flight height, flight speed, and weather. Understanding how VAR varies in relation to these other factors would allow us to convert VAR into abundance/density, providing direct measurements of migration traffic rates in offshore areas where no radar or other technology exist. Once VAR can be converted to abundance/density, offshore acoustic monitoring should become part of our core long-term monitoring. A new and on-going research project called ArtSurf, which NINA is involved in, using an avian radar and acoustic monitoring, will begin to test these relationships, likely at a near-shore location.

For large-scale monitoring and networks of acoustic recorders, automated processes are required for processing acoustic data (Van Doren *et al*. 2022). Automated processing, such as AROMA, would be used to separate bird calls from background noise, and machine learning software and deep neural networks, such as BirdVoxDetect or BirdNET, could be used to process acoustic recordings and produce species-specific numbers and timing of calls (Van Doren *et al*. 2022; Kahl *et al*. 2021). Such automatic detection and identification would allow for continent or ocean-wide networks monitoring nocturnal migration (Van Doren *et al*. 2022).

In terms of instrumentation, we consider in more detail here ARUs developed by Wildlife Acoustics, but also acknowledge Open Acoustic Devices, including the AudioMoth. Wildlife Acoustics offers two ARUs of interest namely the SM (Song Meter) Mini and the SM4. These ARUs have a number of options in terms of recording schedules. The microphones come with windscreens and there is the option to add another layer by purchasing extra-large windscreens which fit over the original ones. Furthermore, Wildlife Acoustics Kaleidoscope Pro analysis software can help deal with wind noise when analyzing the recordings. No detection ranges are quoted for these devices as this can vary due to a range of different factors and will need to be tested first. In terms of power supply, the SM Mini uses 4AA batteries which equates to around 250 recording hours (~10 days). Alternatively, the optional li-ion battery lid can be added, and li-ion batteries used, which would give up to 1100 recording hours. The SM4 can connect to external power with an optional external power cable. The SM4 has space for 2 SD cards, and these cards can be up to 1 TB in size. However, given these ARUs will be positioned on remote offshore platforms and trips to and from the platforms to change SD cards are logistically too challenging for long term monitoring, remote download and transmission of data must be an option. Currently for SM Mini and SM4 this is not possible for bird calls, only for ultrasonic recordings.

3.2.3 Laser scanner

Static terrestrial laser scanner: Although terrestrial laser scanners are costly (e.g., approx. 1.8 MNOK for RIEGL VZ-6000), they are cheaper compared to avian radars. LiDAR systems do not offer data outputs that are as rich as avian radars, but they would nonetheless provide long-term information on offshore flight height. Compared to ThermalTracker-3D, LiDAR systems offer a significant longer detection range which is less dependent on the size of the target.

We propose deploying LiDAR systems on offshore platforms to monitor patterns and changes in flight height. These should be deployed on some of the same platforms as we have proposed for acoustic monitoring and radio telemetry (MOTUS receivers). LiDAR systems should be coupled with high resolution cameras for species ID, and at night species ID could be extracted either from acoustic recordings or radio telemetry detections (although acoustics or camera technology would only be able to cover a fraction of the range of the LiDAR system). We also propose that in designated wind farm sites, which are not suitable for avian radars, that LiDAR systems be used to collect pre-construction data on flight height through the area and specifically the rotor swept zone as well as long-term data once the wind farm is in place. As this is a novel technology for monitoring bird migration, we suggest first testing the system within the range of an avian radar.

Aerial LiDAR surveys: All of the proposed offshore monitoring techniques, except satellite monitoring, provide continuous data collection from a fixed position with varying (but all relatively short) detection range. Satellite imagery provides excellent spatial coverage rendering information of the offshore distribution of birds and position of potential flyways, but it lacks any information on flight behaviour. To fill this gap, during peak migration, aerial LiDAR transect surveys could be performed as outlined in Cook *et al*. (2018). Survey designs could vary in scale depending on priorities, i.e., 1) covering the North Sea as achieved during the SCANS-III transect surveys (**Figure 10**; Hammond *et al*. 2021, SCANS-III report), 2) along the entire Norwegian coast, or 3) more targeted around wind farm sites to get an understanding of species-specific flight height in offshore migrants in different locations and weather conditions.

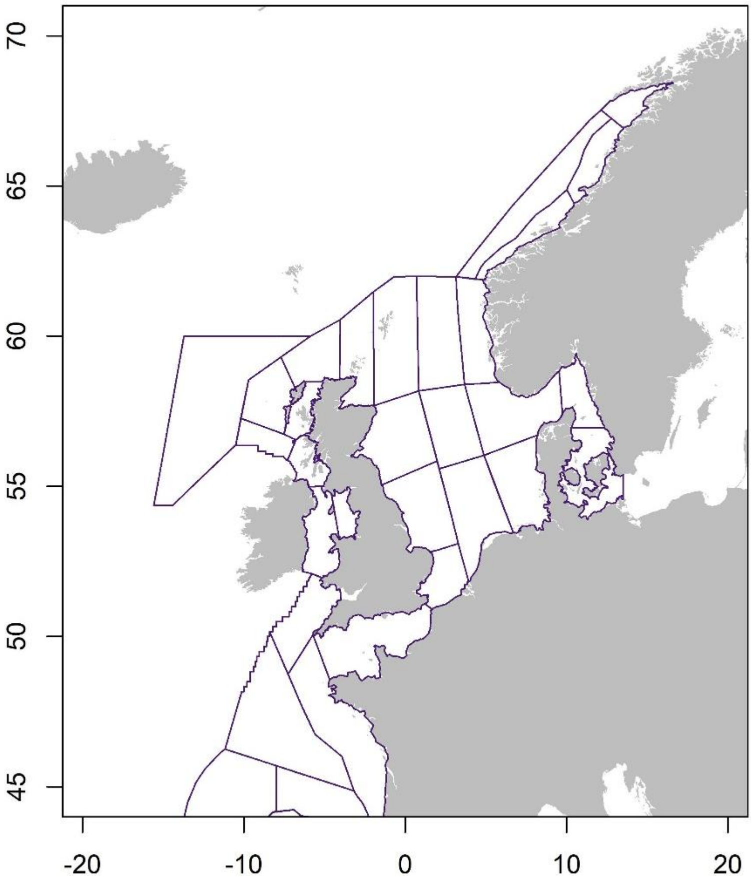

Figure 10. *Area blocks covered aerial and ship-based transects during the SCANS-III survey (https://scans3.wp.st-andrews.ac.uk/resources/).*

3.2.4 Platform-based marine radars

While there are several challenges with building a network of platform-based marine radars, we still want to highlight their potential for long-term monitor as the infrastructure is already in place and data are being collected continuously. It is important to further evaluate platform-based marine radars against establishing a network of stationary platform-based laser scanners. Marine radars are already in place, but the challenges exist as described in Section 2 around filtering out waves, creating a network of marine radars, downloading, and processing of unfiltered data, which will not provide data on flight height. A network of marine radars offers great potential, but further detailed investigation into how this might work is required. For static laser scanners, the equipment would have to be purchased and put in place, but high-resolution data on flight height can be obtained.

4 Budget & logistics

4.1 Core activities

Until priorities and funding streams have been decided, we are only providing approximate costs for equipment required for the different activities, and brief descriptions of the logistical requirements. The **network of weather radars** does not require any additional equipment as weather radars are already in place and data are uploaded to OPERA. The network has also been established as part of ENRAM and GloBAM, although these projects have now finished. Costs for this activity will involve staff time for developing a long-term collaboration providing access to data, as well as time for processing and analysing data each year (see description of costs and logistics for acoustic monitoring in relation to deploying ARUs within the radar zones).

In terms of **radio telemetry**, several MOTUS receivers are already in place around parts of the North Sea coast and this network seems to be expanding. Requirements for this activity includes funds to purchase receiving stations and tags. Individual receiving stations costs around $2000, while the costs of Lotek tags vary by tag size from $300-380 per tag. Therefore, placing 20 receivers on offshore platforms would costs $40000 and placing up to 30 receivers on land surrounding the North Sea would cost $60000. Each year, a large number of tags should be distributed to bird observatories in each of the four countries, namely Norway, the Netherlands, the UK, and Denmark to be deployed during ringing campaigns of migrating birds, and other tagging activities (exact number of tags to be decided but needs to be meaningful for understanding migration systems). Funds would also be required each year for time to analyse data from the receivers.

The onshore **citizen science** activity would require funds initially for time to develop and implement code to extract and analyse species occurrence data either from coastal areas or from within the weather radar zones. Therefore, most funds for establishing this activity are required upfront, after which requirements will be relatively low. Similarly, development of the smartphone app and associated videos/animations to monitoring offshore species occurrence also requires most funds to be available upfront for app development and implementation. Some funds will be required longer term to maintain engagement of app users and analyse data. Where **avian radars** are put in place by industry, NINA offers support for processing, analysing and storing cleaned data, including database development. Funds will be required to cover time for these activities, likely involving high input from the outset and long-term funding for data management and analysis.

4.2 R&D opportunities

Satellite technology is already in place, and their resolution and revisiting rates are improved over time. However, obtaining images from commercial satellites with the appropriate resolution is very costly. For example, the price for WorldView-3 images is around $23/km^2 (other higher resolution or SAR satellites may cost more). The Greater North Sea has a surface area of about 750000km^2. The costs to cover the entire area once would therefore be around $33000, which would need to be repeated at least once per day covering the peak migration period. Furthermore, funds would be required to process images either manually or developing a deep learning approach for recognising birds automatically.

Acoustic monitoring requires the most logistical effort. Firstly, instruments will need to be tested as described above, then deployed on offshore platforms, and on land within the weather radar zones. Access and travel to and from suitable platforms as well as setting up remote download will be demanding. Following deployments, processing and analysing data will again be highly costly in terms of time. Once remote download is working and automated procedures put in place to process and analyse the data, long-term funds are required for data management and access to platforms when equipment fails etc. The costs for Wildlife Acoustics SM4 are $900 per unit, so equipment costs for setting up the offshore acoustic monitoring network would be $18000 plus extra ARUs to account for equipment failures over time. Additional ARUs would be required to deploy 3-5 ARUs within the zones of selected weather radars.

The costs of a single **stationary laser scanner** (RIEGL VZ-6000) is ~1.8 MNOK, and we propose deploying at least 10 in offshore areas, for example, on every other platform also selected for acoustic monitoring and radio telemetry. This involves similar considerations around access to power supply, remote download facilities and maintenance.

5 Organization of programme

The organisation of the long-term monitoring programme is left open. One possibility is that the project sits as a module under SEAPOP (similar to SEATRACK) but with its own project staff. In this case, the project would have a steering committee involving stakeholders (e.g., wind energy companies, the Norwegian Water Resources and Energy Directorate, the Norwegian Environmental Agency, the Norwegian Coastal Administration) and NINA. This would also involve a science group involving relevant NINA researchers providing recommendations to the steering group.

NINA would try to secure funding for R&D activities, such as for example 1) a project testing acoustic monitoring offshore and converting vocal activity rate to density, 2) a project testing the use of satellite imagery for monitoring bird migration offshore, or 3) a project developing and integrating multiple sensor-based approaches. This would require co-funding by industry within either a Competence research project for industry or an Innovation project for industry.

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