Motus as a Tool for Offshore Wind Assessment and Monitoring: a Knowledge Review

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Introduction to Motus

Understanding the movement patterns and behaviours of migratory wildlife is central to identifying population threats and guiding conservation efforts. Information on wildlife movements can be collected through various tracking devices, such as Global Positioning System (GPS) receivers, satellite transmitters, light-level geolocators, or digital Very High Frequency (VHF) transmitters. Specifically, digital VHF telemetry or radio telemetry, has been widely used to track wildlife movements since the 1960s. However, traditional methods require significant effort in the field, involving manual tracking by foot, car, or plane, which substantially limits the number of individuals tracked, the spatial scale sampled, and the number of detections collected at a given time (Taylor et al. 2017). Additionally, studies tracking small-bodied organisms (<100 g) have been limited due to size and weight constraints of available tracking devices. To address these limitations, advances in automated radio telemetry, through the Motus Wildlife Tracking System (Motus), and the development of lighter-weight technology (>0.2 g) have revolutionised our ability to monitor small flying organisms with great precision, thereby enhancing our knowledge of species-specific movements and the factors that influence them (Taylor et al. 2017).

Motus is the world's largest collaborative network of researchers using automated radio telemetry to study the movements and behaviours of small flying animals (birds, bats, and insects). The system enables a community of researchers, educators, organisations, and citizens to undertake research and education focused on the ecology and conservation of migratory species. Developed as a program of Birds Canada in partnership with Acadia University and other various collaborating researchers and organisations, Motus provides a framework for global collaboration that amplifies migration research efforts while maximising collective resources and conservation dollars. Currently, the Motus network consists of more than 700 research projects that maintain over 1,900 receiver stations in 34 countries.

Motus uses coordinated arrays of automated radio telemetry receiver stations that are strategically distributed across the landscape and independently maintained by collaborating researchers, organisations, government agencies, and individuals. Motus stations detect animals carrying digitally coded radio transmitters (Motus tag). Unlike traditional radio telemetry, Motus tags emit uniquely identifiable signals on a single frequency (166.38 MHz and 434 MHz in North America) that can be detected by any frequency-compatible Motus station in the network. Detections are recorded when a "tagged" individual flies within the detection range of an antenna on a Motus station (e.g., <20 km for a 9-element Yagi antenna). Data are relayed to a centralised database managed by Birds Canada, where, detection data are filtered, archived, disseminated to project collaborators, and made publicly available through the Motus website (see Motus data dashboard section below). Detection data that data owners receive includes the antenna that each signal was detected on, the signal strength of the detection, and antenna direction. Thus far, detection data from Motus projects have been used to estimate various aspects of bird, bat, and insect movements, including but not limited to, stopover duration, site fidelity, departure and arrival times, flight orientation, distance, flight speed, and types of movements (Taylor et al. 2017).

The collaborative framework of Motus has enabled researchers to study species movements at local to continental scales with high temporal precision. Over 44,000 animals of over 350 species have been tagged and tracked using Motus worldwide, and nearly 160 peer-reviewed publications have included Motus data. The ability to study migratory movements throughout all phases of the annual cycle and across a range of habitats has furthered our understanding of important breeding, stopover, and overwintering sites. Specifically, Motus has been key to the development of bird monitoring methodologies for wind energy development in remote offshore areas in the northeastern Atlantic region of the United States. The deployment of Motus stations in the marine environment fills a data gap within offshore lease areas to help determine species presence and movements that may inform different phases of wind energy development within a project area. In Atlantic Canada, coastal Motus arrays have successfully tracked numerous species of migratory birds during their seasonal migrations. However, the current lack of stations in the marine environment confine detection ranges to the coastline, often limiting the study of offshore movements.

Coastal and marine habitat use by flying animals in Atlantic Canada

Atlantic Canada’s vast coastal and marine habitats support large communities of migratory birds year-round. These habitats include offshore islands, coastal cliffs, beaches, intertidal mudflats, inshore shallow waters, and offshore banks (Allard et al. 2014). Various populations of shorebirds, seabirds and waterfowl congregate within these habitats seasonally, although distribution varies according to species’ ecological requirements (e.g., breeding, foraging, moulting, migration, and wintering). Moreover, the unique coastline of Atlantic Canada offers a distinct migratory pathway that several species of landbirds, bats, and insects follow during their latitudinal migrations.

Breeding seabirds

During the breeding season in Canada, from April to August, large influxes of seabird populations use Atlantic waters. Seabirds are central place foragers at their colonies, limiting their foraging range to distances constrained by the needs of nests or chicks (Hedd et al. 2018). For example, Roseate Terns (*Sterna dougalli*) are specialist foragers in the nearshore environment and require shallow waters (<5 m), primarily feeding within 7 km of their colonies (Williams et al. 2009). Currently, there are only three tern colonies in Canada occupied by Roseate Terns: North Brother, Country, and Sable islands in Nova Scotia (COSEWIC 2009). In contrast, highly pelagic seabirds such as Leach’s Storm-Petrel (*Oceanodroma leucorhoa*) forage over or beyond the continental shelf and have been observed undertaking multi-day foraging trips, travelling cumulative distances of 1,300 – 2,200 km (Hedd et al. 2018). Large colonies of Storm-Petrels can be found along the east coast of Newfoundland (e.g., Baccalieu Island and Witless Bay Ecological Reserve) and the southern coast of Nova Scotia. Additionally, the islands of the Witless Bay Ecological Reserve host North America’s largest Atlantic Puffin (*Fratercula arctica*) population (Wilhelm et al. 2015). These diving seabirds feed on foraging fish, such as herring, and have been observed travelling mean maximum distances of 83 km between nesting burrows and foraging sites (Hedd et al. 2018).

Migratory shorebirds

Coastal beaches and intertidal mudflats provide suitable foraging habitat for numerous species of shorebirds to replenish energy stores during their transcontinental fall migrations to South America. For example, the Bay of Fundy, Shepody Bay, Southern Bight-Minas Basin, Cumberland Basin, and Cobequid Bay have collectively been designated as a "Landscape of Hemispheric Importance" by the Western Hemisphere Shorebird Reserve Network (WHSRN) (McKellar et al. 2020). Furthermore, the upper Bay of Fundy has been identified as an important fall migration staging site for a large portion of the global population of Semipalmated Sandpipers (*Calidris pusilla*) (Linhart et al. 2023). Tracking data from Motus projects revealed sandpipers were present in the Bay of Fundy for three weeks on average between August and September, with smaller populations staging in the Northumberland Strait and along the southwestern coast of Nova Scotia, before departing across mainland Nova Scotia to the southeast coast and continuing their migration offshore (Linhart et al. 2023; Neima et al. 2022). Non-tidal areas also provide suitable stopover habitat for berry-foraging wading birds, such as the Mackenzie Delta subpopulation of Whimbrels (*Numenius phaeopus*) that migrate between breeding sites in the Beaufort Sea and overwintering areas in northern South America (Watt et al. 2021). Previous satellite tracking of the Mackenzie Delta subpopulation show terminal staging sites used by Whimbrels within Atlantic Canada before engaging in nonstop, transoceanic flights to South America (Watt et al. 2021).

Wintering waterbirds

While Atlantic Canada is predominantly known for its significance to fall migrants, notable populations of shorebirds and waterfowl overwinter throughout the region along exposed rocky headlands, offshore reefs, and islands. In a recent inventory update of potential WHSRN sites in Atlantic Canada, nearly half of potential sites that met WHSRN designation criteria were based on overwintering populations of Purple Sandpipers (*Calidris maritima*) (McKellar et al. 2020). Purple Sandpipers have high site fidelity within and between wintering seasons and have been observed along the South and Eastern Shore of Nova Scotia and the entire coastline of Newfoundland from December to March (Gutowsky et al. 2019). Roughly a third of the eastern population of wintering Harlequin Ducks (*Histrionicus histrionicus*) also share these rugged coastal habitats with sandpipers, foraging on benthic prey nearshore between depths of 10 – 20 m (Gutowsky et al. 2019). Additionally, Common Eiders (*Somateria mollissima*) have been observed wintering in Atlantic Canada, although declines in mid-latitude populations around Nova Scotia have suggested a redistribution of their wintering range to sites further north in southeast Newfoundland and the Gulf of St. Lawrence (Gutowsky et al. 2023; Robertson et al. 2021). Moreover, Peck et al. (2022) deployed satellite transmitters on American Black Ducks to monitor the movements of migrants and residents from their inland terminal wintering grounds in Windsor, Nova Scotia. Spring migrants were observed departing across the Gulf of St. Lawrence in a north-northeast direction to reach terminal nesting locations on the east coast of Labrador, while resident ducks remained in Nova Scotian waters with local movements of less than 10 km per day (Peck et al. 2022).

Landbirds

The marine environment presents a large ecological barrier to many neotropical migrant landbirds that breed and stopover within the islands of Atlantic Canada. Several Motus tracking studies have followed the fall migratory movements of thrushes, warblers, and sparrows departing from islands and engaging in non-stop flights over water (see Brown and Taylor 2015; Woodworth et al. 2015; Crysler et al. 2016; Cormier and Taylor 2019). Additionally, DeLuca et al. (2015) used light-level geolocators to track the fall movements of Blackpoll Warblers (*Setophaga striata*) departing from Bon Portage and Seal islands in Nova Scotia to wintering areas in northern South America, revealing extensive minimum flight distances of 2,270 – 2,770 km over water.

Bats

Similar to birds, migratory bats exhibit patterns of seasonal regional movements, although these behaviours are more closely associated with hibernation and not breeding (Fleming 2010). For example, migratory species of lasiurine bats (Silver-haired Bats *Lasionycteris noctivagans*, Hoary Bats *Lasiurus cinereus*, and Eastern Red Bats *Lasiurus borealis*) have been observed migrating south from inland, coastal, and offshore locations in Nova Scotia to winter roost sites during August to late October (Lucas and Hebda 2011). Furthermore, True et al. (2023) used Motus to track the movements of Eastern Red Bats in the mid-US Atlantic demonstrating their capability of transiting across large bodies of water like Chesapeake and Delaware bays.

Large insects

Few species of long-distance migratory insects have been documented annually in Atlantic Canada. For example, Nova Scotia hosts a small portion of the eastern North American population of Monarch butterflies (*Danaus plexippus*) throughout the spring and summer months. Monarch butterflies in the region are known to aggregate in coastal areas during late summer and early fall, particularly in the southwest (Nova Scotia Department of Natural Resources and Renewables [NSDNRR] 2021). Increased Monarch presence at coastal sites indicates possible stopover behaviour before transiting over water, similarly documented in southern Ontario and southern Quebec (NSDNRR 2021). Species of Odonata, like the Common Green Darner (*Anax junius*), have also been extensively surveyed throughout the Atlantic provinces through the Atlantic Dragonfly Inventory Program. Like Monarchs, dragonfly populations in North America generally peak in spring from March to June and in fall from August to October, and have been observed congregating along coastlines during migration. In a tracking study by Wikelski et al. (2006), green darners migrating along the U.S. Atlantic coastline were found to exhibit similar behaviours as migratory songbirds when presented with a large water crossing (i.e., Delaware Bay) by either circumnavigating the barrier or directly flying offshore. Additionally, in southern Ontario, Motus has been successfully used to track Monarch and Common Green Darner southbound movements during fall migration (Knight et al. 2019).

Motus research that inform impacts of offshore wind

As offshore wind energy development continues to rapidly expand worldwide to aid in the transition from fossil fuels to renewable energy, assessing the impact of offshore wind energy areas on wildlife has become increasingly important. Insights into movement patterns of migratory aerofauna can offer valuable information on the potential risks associated with offshore wind energy development, particularly if movements are predictable in time and space (Howell et al. 2020). Both site-specific and regional studies are crucial for anticipating the potential exposure of migratory species to wind energy developments (Loring et al. 2020b). The current understanding of the impacts of offshore wind turbines on birds and bats primarily stems from studies in eastern North America and western Europe, where wind energy development has rapidly expanded in recent decades (Loring et al. 2020b), but information gaps remain. To further enhance risk assessments, information is required on the timing, frequency, and altitudes of flights over offshore wind energy areas during migration. Additionally, understanding how these migratory decisions are influenced by intrinsic and extrinsic factors such as age, sex, physiological condition, habitat, and weather is necessary when establishing future mitigation measures to avoid and minimise collision risk and avoidance behaviours.

This section provides an overview of the different variables that may be useful to represent the impacts of offshore wind development in Atlantic Canada based on previous Motus tracking studies. These studies provide direct evidence of migration and associated movement patterns for various species of songbirds, shorebirds, and bats, using Motus to identify and quantify habitat use during different phases of a bird's annual cycle in both space and time. Moreover, these studies use Motus to uncover basic migratory behaviours such as the timing of migration events, orientation and route of travel, and the influence of weather conditions on migratory decisions.

Important spatial areas and length of stay

Protecting and managing important areas for animals during their different life history events is important to halting the long-term declines seen in some of these species populations. Identifying important spatial areas in and around the focal offshore wind development areas can help in planning where development should occur.

A common metric indicating site importance to a species is the number of animals that are using an area. Motus can be used to estimate length of stay in an area, which is particularly important in calculating staging population size (Bishop et al. 2020; Smith et al. 2023). A decrease or increase in length of stay can bias the results so that they appear as though the population is increasing or declining when it is actually stable. Length of time that individuals remain at each site can therefore be applied to estimate turnover rates. There are different methods for estimating length of stay using Motus. For one, we can estimate the minimum length of stay at stopover regions, being the time from when the bird was radio-tagged to their last departure in the region (Neima et al. 2022). This method includes uncertainty with the minimum length of stay method in how long birds were around before they were caught. Another option is to use mark-recapture modelling, which can account for time at a site prior to capture. The minimum length of stay method is shown to be more accurate for many shorebirds (Neima et al. 2022) that stage at just one or two sites for long periods of times and arrive light and leave heavy since the estimate can be improved by choosing birds that weigh less (i.e., likely just arrived). However, mark-recapture models are shown to increase accuracy for songbirds that have shorter stopovers (Schaub et al. 2001).

Many studies have used Motus to identify important areas by determining where animals are spending their time. Linhart et al. (2023) found that Semipalmated Sandpipers tagged in the Bay of Fundy stayed there for the duration of their stay in the Maritimes, while most birds tagged along the Northumberland Strait used sites outside the BOF. This highlights the importance of conserving not only large sites with significant numbers of staging shorebirds, but also smaller sites with lower numbers of birds. In another study on their non-breeding grounds in Northeast Brazil, Linhart et al. (2022) found that Semipalmated Sandpipers made notable use of habitat that have been heavily modified by humans such as salinas or shrimp farms, and therefore recommend that protected area management plans for the region be broadened to include converted mangroves and salt flat habitats, as well as other areas modified by human activity. Boynton et al. (2020) discovered that crop habitat appears to be important for fledgling Barn Swallows, since they used crop habitat disproportionately more than its availability in relation to other habitat types such as pastures. Grahame et al. (2021) found that although landscapes dominated by rock barrens interspersed with patches of shrubland and deciduous and mixed forests are uncommon, these habitats are important foraging and roosting habitats for northern breeding Whip-poor-wills and warrant protection. Most studies highlighted that food availability, threat of predation, or habitat structure are thought to influence habitat use (e.g., Smetzer et al. 2017; Hengst 2021; Linhart et al. 2022; Linhart et al. 2023; Poirier et al. 2023).

Arrival/landing time

A high number of collisions with turbines occur at wind energy developments located in areas of high bird density, such as stopover, staging and breeding sites (Howell et al. 2020). To reduce collision risk or other avoidance behaviours within wind energy areas (WEA), migratory patterns require characterization at a finer temporal scale (minutes and hours) to inform mitigation measures for current and future WEA development. Motus detection data can be used to determine the arrival time of individually tagged animals to a site or region with high temporal precision by analysing the signal strength of detection(s) by a receiver within the Motus network. Past Motus studies have defined arrival time as the moment of maximum signal strength during the first set of detections within a given receiver array or the time at which a series of high-amplitude signals are recorded for several minutes (Bach et al. 2022, Howell et al. 2020). For long-distance migratory shorebirds, arrival time is associated with regional stopover behaviour at high-quality staging sites used for refuelling and resting along migration. Few studies have explored factors influencing arrival time and duration at these ecologically important sites due to constraints on sample size and collaborative tagging efforts.

A study conducted by Howell et al. (2020) investigated whether environmental extrinsic cues (time of day, wind direction and speed, temperature, pressure, and visibility) influenced the arrival time of Sanderling (*Calidris alba*) during their spring migration from the Gulf of Mexico to an inland staging site in Saskatchewan. Interestingly, the study found that arrivals to the study area did not show any significant relationship with time or weather, indicating that these factors may not be selected for by arriving birds (Howell et al. 2020). Instead, arrivals may be a consequence of intrinsic factors (e.g., fuel load) and extrinsic factors (e.g., weather) previously experienced along the migratory route prior to reaching staging grounds (Bach et al. 2022; Howell et al. 2020). For long-distance migratory species, especially shorebirds, poor environmental conditions as far south as the wintering grounds may delay arrival times as far north as the breeding grounds. This has significant cumulative implications for WEA located near important staging sites because long-distance migrants may opt to avoid these areas to find less suitable sites to refuel, further delaying arrival at their breeding grounds and potentially reducing reproductive opportunities. Alternatively, shorebirds that experienced drought at their subarctic stopover sites had a higher probability of making subsequent stopovers in Atlantic Canada and northeastern United States, which may slow migratory pace and delay their arrival at their wintering grounds, as well as create dependencies on additional stopover areas (Anderson et al. 2021).

Similar to arrival time, individual landing time may also be assessed to determine the impacts of offshore wind development. Landing time differs from arrival time as it refers to the initiation of shorter and more irregular stopover events at lower-quality sites along migration. However, limited information is available regarding factors influencing landing decisions and initiating stopover, particularly for nocturnal migrants (i.e., species that migrate at night). A European study by Ruppel et al. (2023) evaluated the relationship between landing decisions and prevailing weather conditions for three species of migratory songbirds (Garden Warbler *Sylvia borin*, Greater Whitethroat *Sylvia communis* and Sedge Warbler *Acrocephalus schoenobaenus*). Landing events were assumed when a sustained flight was interrupted within the local Motus receiver array, and landing time was recorded when detections at a certain receiver spanned over an hour or slow flight movements ($<5ms^{-1}$) with consecutive detections occurred within three days at ranges less than 32 km. The study identified deteriorating weather conditions as potential cues that initiate landing as songbirds were more likely to land during migratory flights under overcast conditions or during an increase in headwinds or decrease in supporting tailwinds. Additionally, this study highlights not only the role of weather as a common driver of individual landing decisions but also the ecological importance of stopovers to avoid adverse conditions. In the context of offshore wind development, such conditions may cause birds to fly at lower altitudes while searching for stopover sites nearshore, and potentially collide with wind turbines under poor visibility due to rain or fog (Ruppel et al. 2023) Further offshore, there are limited options for birds to land, and songbirds are known to be attracted to illuminating artificial structures, which might increase their risk further of colliding with offshore wind structures.

Further analysis of arrival and landing time across multiple migration seasons may reveal predictable patterns that can be used to anticipate the arrival of larger flocks of birds at stopover sites. Although Howell et al. (2020) found no patterns in arrival time for Sanderling, this may have also been attributed to their small sample size (see Sample size section below for more details). Moreover, Loring et al. (2020b) recommends that tagging efforts should occur at locations along migration and before arrival at study sites to detect more accurate arrival times (e.g., tagging shorebirds on their wintering grounds to determine arrival timing at staging sites during spring migration). Anticipating when birds initiate stopover and understanding how weather may impact these decisions may be useful when determining curtailment procedures for offshore wind energy operations. For example, to reduce the risk of collision for nocturnal migrants within WEA, turbines can be shut off between sunset and sunrise during periods of strong headwinds and poor visibility.

Timing of migratory departure

Assessing factors influencing the departure time from breeding or stopover sites has received extensive research using Motus. Generally, departure time can be determined by visually inspecting the signal strength of tag detections on a station in the moments before the tag is no longer detected within a local Motus array (Cooper-Mullin et al. 2022; Smetzer et al. 2017; Taylor et al. 2017; True et al. 2023). In other words, departure time can be defined as the moment of maximum signal strength during the last set of detections within a given Motus array (Cooper-Mullin et al. 2022; Howell et al. 2020; Smetzer et al. 2017). The probability of departure may be influenced by a variety of factors such as time of day, weather, seasonality, individual fuel stores, and age.

Time of day has been found to have a direct influence on departure timing for some migratory species of songbirds, shorebirds, and bats. Most of the departures observed across each taxon have been within evening hours closest to sunset (Cooper et al. 2023; Howell et al. 2020; Loring et al. 2020a; True et al. 2023; Woodworth et al. 2015; Wright et al. 2018). For example, Cooper et al. (2023) found that the majority (90%) of individuals from songbird species that initiated long-distance migratory flights departed within 69 minutes after civil dusk. Wright et al. (2018) tracked Rusty Blackbirds (*Euphagus carolinus*) within the U.S. Great Lakes Region and found that nearly all fall (95%) and spring (82%) departures occurred at night. Loring et al. (2020a) also found that 78% of Piping Plovers (*Charadrius melodus*) in their study departed within 3 hours of local sunset. These results reaffirm that nocturnal migration is both strategic and advantageous for some species because it increases diurnal foraging opportunities and reduces predation risk (Loring et al. 2020a). Furthermore, the decision to depart at night may be influenced by typically more favourable atmospheric conditions for migratory flights occurring at night, such as higher humidity and weaker winds, resulting in less evaporative water loss and turbulence for the bird.

Seasonal weather patterns and local atmospheric conditions also have a significant influence on timing of departure within and between species. Commonly investigated variables in past Motus studies have included temperature, wind direction, wind component, wind speed, visibility, precipitation, cloud cover, and atmospheric pressure to estimate the relationship between departure probability and local weather conditions (Bach et al. 2022; Brust et al. 2019; Cormier 2017; Howell et al. 2020; Linhart et al. 2023; Loring et al. 2020a; Ruppel et al. 2023; Wright et al. 2018). For example, migratory Nathusius' pipistrelle *(Pipistrellus nathusii*) bats in Europe were found to extend their stopover duration to wait for tailwinds to assist with flights over large water crossings (e.g., the North Sea) (Bach et al. 2022). Several shorebird studies also found that Semipalmated Sandpipers prefer north to northwesterly winds of low to moderate speeds and high pressure for departure from the Maritime region during their fall migration (Linhart et al. 2023; Neima et al. 2022). Loring et al. (2020a) found that Piping Plovers also initiated fall migration on evenings with wind assistance and rising atmospheric pressure. Additionally, seasonality and the direction of migration may influence the effects of weather on departure decisions. During spring migration, Sanderling were more likely to depart when wind direction was toward the northwest at intermediate speeds (22km/h) (Howell et al. 2020), whereas for fall migration, departure probability was highest for some songbirds during increased tailwinds or when westward and southward winds were weak (Brust et al. 2019; Ruppel et al. 2023; Wright et al. 2018). Shorebirds may be more likely to migrate during inclement weather in the spring, relative to fall, since atmospheric conditions are generally less stable and there are time constraints to reach breeding areas, which may lead to an increased risk of exposure to offshore wind turbines in the spring (Loring et al. 2020a). These results demonstrate that individuals choose to depart under favourable weather conditions for sustaining flight such as tailwind assistance, high air pressure, clear skies, and no precipitation to reduce energetic costs during longer migratory flights (Brust et al. 2019; Loring et al. 2020; Ruppel et al. 2023). This link between weather and departure timing from stopover/staging areas is a source of large annual variation in departure timing from these important areas, and therefore offshore migratory flights.

The effects of age and individual physiological condition on departure timing have been investigated through the tracking of adult and juvenile songbirds that migrate over large water bodies, like the Gulf of Maine. Within species, age class has been shown to determine migratory routes and therefore the timing of departure. For example, Crysler et al. (2016) tracked adult and juvenile Ipswich Sparrows (*Passerculus sandwichensis princeps*) migrating from Sable Island to the U.S. Atlantic coast and found that juveniles, who circumnavigated the Gulf of Maine, departed 24 days earlier on average than adults, who made over-water flights (see Migratory trajectory/routing section below). The differences in knowledge and experience between age classes may be acquired through multiple migration events and cause birds to take alternative routes throughout their lifetime. The perceived risk of crossing large water barriers can further delay departure timing from a given location since routes with longer overwater flights have increased risks related to weather, but also impact individual physiological condition (Crysler et al. 2016). This may explain why adults who made more and longer over-water crossings also had later departures. Timing of migratory departure may also differ between age groups if they have different physiological needs. For example, adults may leave later than juveniles because they must moult or gain additional energy after breeding.

While difficult to measure during the time of departure, fat score and other metrics of physiological condition may affect departure decisions to cross or circumnavigate a large water crossing (Cooper-Mullin et al. 2022; Woodworth et al. 2015). A fuel store manipulation study conducted by Cooper-Mullin et al. (2022) found that Blackpoll Warblers, Red-eyed Vireos (*Vireo olivaceus*), and Hermit Thrushes (*Catharus guttatus*) departed sooner from their stopover locations after being fed a supplementary diet when compared to those fed a maintenance-level diet. However, these results were found to be related to species-specific migration strategies (long vs. short-distance) as diet had no effect on the departure timing of Yellow-rumped Warblers (*Setophaga coronata coronata*) which migrate over shorter distances. This study demonstrates how rebuilding fuel stores at stopover can directly influence departure timing and the pace of migration, particularly for long-distance migrants.

As previously discussed, most birds and bats decide to depart at night during optimal weather conditions. Night time departures may create an ecological trap within wind energy development areas, since the risk of collision is potentially higher at night due to the reduced visibility of turbines and attraction or disorientation effects from artificial lighting on turbine towers (Loring et al. 2020b). Strong weather and temporal patterns that are associated with the timing of departure may be used to predict these high-risk periods around offshore wind energy facilities (Howell et al. 2020; Ruppel et al. 2023). Since different ecological factors drive fall and spring migration events, environmental conditions during each season should be analysed separately and mitigation measures for wind energy development be designed accordingly (Wright et al. 2018).

Migratory trajectory/routing

The routing decisions made by birds and bats when faced with large ecological barriers can have a substantial impact on the costs associated with migration, such as time, energy, and survival rates (Woodworth et al. 2015). A prominent ecological barrier that birds and bats encounter during migration is large bodies of water. Recent regional-scale Motus tracking studies have shown that some individuals may choose to avoid these barriers when possible to minimise the risks associated with extended flights over water (Brust et al. 2019; Crysler et al. 2016; Ruppel et al. 2023; Smetzer et al. 2017; True et al. 2023; Woodworth et al. 2015). Understanding the factors that drive these routing decisions is crucial in predicting over-water occurrences within offshore WEA. To differentiate between flights over water (offshore) and flights along the coastline (onshore), previous Motus studies tracking songbirds through offshore WEA in the North Sea have used geographic latitude and longitude boundaries to define flight types (e.g., offshore flights were defined to start at geographical latitudes north of 54.135°N and to end at geographical longitudes west of 8.08°E, with no detections along the coastline between these two points) (Brust et al. 2019, 2022; Ruppel et al. 2023). By analysing tag detection data to estimate and map the flight paths of individuals, Motus can be used to determine the proportion of offshore and onshore flights within the boundaries of an offshore WEA.

Individuals have been found to remain at, or return to, stopover sites and wait for optimal weather conditions to initiate water crossings (Crysler et al 2016). Considering environmental factors, wind direction is one of the strongest predictors of routing decisions (Brust et al. 2019; Loring et al. 2020a; Ruppel et al. 2023; True et al. 2023). Individuals are more likely to initiate offshore flights at night when winds are blowing in a seasonally favourable direction to sustain longer flight durations. For example, during fall migration, landbirds favoured offshore flights across the German Bight during weaker westward winds and favoured onshore flights during stronger eastward winds (Brust et al. 2019).

Similarly, Loring et al. (2020a) found Piping Plovers were more likely to cross the mid-Atlantic Bight when winds were blowing to the southwest at low speeds during fall, when visibility and air pressure were high, and temperatures were warm. For bats, True et al. (2023) found that tagged Eastern Red Bats engaged in over-water flights across the mid-Atlantic during low wind speeds (probability increased from approx 5 m/s to 0 m/s), higher temperatures, and after the passage of storm fronts. These results emphasise the influence of weather on routing decisions as extended over-water flights reduce feeding and resting opportunities and can lead to mortalities if there is inclement weather during departure or at sea (Smetzer et al. 2017). Conversely, onshore flights are more likely than offshore flights during suboptimal weather conditions because there are more opportunities along the coastline for suitable stopover sites (Woodworth et al. 2015).

While weather patterns can help anticipate offshore flights, routing decisions remain highly flexible and are not exclusively influenced by environmental factors (Ruppel et al. 2023). The selection for offshore flights to minimise the overall duration of migration may also be associated with individual body condition and age class. Migrants require adequate energy reserves to undertake non-stop flights over water, and Motus studies have indicated that the probability of offshore flights increases with longer stopover durations, likely because individuals are departing in better physiological conditions (Brust et al. 2019; Crysler et al. 2016). However, accurate fat scores and other physiological metrics at take-off are often underrepresented in research since departure rates after capture can be variable (Crysler et al. 2016). Neima et al. (2022) found that Semipalmated Sandpipers departed from their Maritime stopover region to fly non-stop over the Atlantic Ocean to South America by crossing Nova Scotia and heading offshore from the southern and eastern coast of the province. A greater proportion of birds that exclusively staged in the Bay of Fundy, a high-quality staging site for this species, departed via this route than birds that staged at sites outside the bay, which may relate to differences in energy gained during stopover (Linhart et al. 2023). However, additional work is required to identify this alternate route, as there is currently no evidence that Semipalmated Sandpipers are moving down the U.S. Atlantic Coast, which would be considered a less energy-demanding route (Smetzer et al. 2017). Alternatively, routing decisions may be species-specific and vary by age due to differences in migratory experience and risk perception, similar to departure timing (Brown et al. 2015; Crysler et al. 2016; Smetzer et al. 2017; Woodworth et al. 2015). For example, only juvenile Ipswich Sparrows were detected travelling across mainland Nova Scotia to reach the north coast of the Gulf of Maine, whereas adult sparrows were detected directly crossing the Gulf of Maine, demonstrating an inherent difference in routing decisions between age classes (Crysler et al. 2016).

Current tracking of offshore flights using Motus is limited to the detection coverage within the receiver array, which is especially limited in the offshore environment. In most Motus studies, the network of receivers is predominantly coastal, and it is plausible that offshore flights are often underestimated (Brust et al. 2019; Ruppel et al. 2023). To address these detection gaps, the deployment of Motus stations on offshore structures is recommended for collecting more detailed data for collision risk assessments within WEA (Loring et al. 2020b; see Distribution of stations section below for more details). Additionally, understanding the weather conditions that are optimal for offshore flights of certain guilds can further direct collision mitigation strategies like season-specific turbine curtailment protocols (Loring et al. 2020a; True et al. 2023). Finally, the variation in route choice at ecological barriers has important implications for mitigation measures within WEA because it can lead to different exposure rates to risks and mortalities between age classes (Smetzer et al. 2017).

Flight altitude

Fully estimating exposure and collision risk of aerofauna to offshore wind turbines requires tracking technology capable of collecting high-resolution movement and altitude data. Fine-scale 3D flight paths are required to fully assess the risk of exposure to the Rotor Swept Zone (RSZ) and avoidance behaviour during offshore flights. Further, determining the altitudes where birds have the highest exposure will help establish appropriate setback distances for wind turbines (e.g., Loring et al. 2020b). While Motus can provide valuable insights into the horizontal movements of tagged individuals, obtaining accurate estimations of flight altitude is beyond the current abilities of Motus technology. Data collected by automated radio telemetry stations typically consists of unevenly-spaced time series of signal strength values received by single beams or sporadically by multiple antenna beams. Radio telemetry and the Motus network are therefore unable to identify three-dimensional locations, including altitude, of tagged animals from station detections alone (Courbis et al. 2023). As a result, information on flight altitudes relative to the RSZ of offshore wind turbines represents a significant knowledge gap, and more information is needed for collision risk assessments (Loring et al. 2020a, 2020b).

Recent studies have developed offshore station calibration methods to improve the ongoing development of 3D movement models (see Calibration protocols for offshore Motus stations section below). These models are based on the theoretical relationship between the horizontal detection range of signals received by Motus stations to estimate flight altitudes when tagged individuals are detected by two or more spatially separated stations simultaneously (Loring et al. 2020a, 2020b). Notably, received signal strength (dBm) varies with the horizontal and vertical distance to a receiver, the angle between a receiver and transmitter, the altitude of a tagged bird, and the height of the receiving antennas (Loring et al. 2020b).

In a revised multi-step modelling approach, Loring et al. (2020b) estimated the 3D locations of tagged species of shorebirds from all possible multi-antenna and single-antenna detection events. These estimates are based on the received signal strength and bird behavioural state (stopover behaviour vs. non-stop flights) constrained by species-appropriate ranges in flight speed and altitude. Specifically, high-altitude non-stop flights were identified by closely timed detections between receivers 50 km apart or more, indicating a tagged bird was at an appropriate distance for a high-altitude flight, based on the established behavioural state constraints. The modelled non-stop flight estimates were then examined relative to daylight during spring and fall migration. The results showed that most flight altitudes during non-stop flights over water occurred above the upper limit of the RSZ for the U.S. Atlantic Outer Continental Shelf Region (250 m a.s.l.), with mean altitudes being substantially higher in spring (914 m) when compared to fall (545 m). Therefore, the exposure rates to the RSZ for shorebirds were slightly lower during spring. It is worth noting that these flights are also mostly above the proposed RSZ for offshore developments in Atlantic Canada (25 - 300 m a.s.l.), but testing in the area is recommended in case of different flight behaviours across areas. Lastly, the time of day appeared to also influence exposure rates to the RSZ. All flights in the RSZ occurred during the day in the spring, whereas approximately half of all flights occurred during the day in fall.

Despite the limitations of current Motus technology, the application of 3D movement models has provided evidence of collision risk within the offshore environment for shorebirds. As previously mentioned, weather is an important driver of migratory decisions and birds may descend to lower altitudes when visibility is limited due to fog or precipitation, thereby increasing their exposure rate to the RSZ of offshore wind turbines (Loring et al 2020a; 2020b). The risk of exposure to the RSZ may also be highest during takeoff and landing at stopover sites, further emphasising the need to determine appropriate setback distances, being the minimum horizontal distance it would take an individual to clear a wind turbine, prior to turbine construction (Howell et al. 2020; Loring et al. 2020b). Howell et al. (2020) used Motus and published reports of shorebird climb rates to estimate the setback distance needed for Sanderling to clear maximum turbine heights of 165 m when making overwater departures from their staging site in the Chaplin and Reed Lakes, Saskatchewan. They estimated setback distances by calculating estimates of ground speed (i.e., distance between two towers that were more than 15 km apart divided by the time between maximum signal strength at each tower) and relating them to low, medium, and high climb rates reported from Piersma et al. (1997) for the species. This study found that the fastest flying Sanderling may clear 165 m turbine heights approximately 2 km from take-off, but most would need 3-14 km under optimal conditions (Howell et al. 2020). Assessments of exposure risk should occur during WEA siting and preconstruction monitoring to obtain species-specific information on migratory routes and flight altitudes to develop more targeted site-specific mitigation measures, which can then be applied regionally (Loring et al. 2020b). Additional recommendations include the strategic deployment of Motus stations to maximise the number of overlapping detection ranges to improve the accuracy of altitude and location estimates (Loring et al. 2020b, 2023a; see Distribution of stations below for details).

As an alternative to radio telemetry, known technology to estimate altitude include GPS tags, which calculate altitude based on their distance from satellites, and altimeters, which compares the pressure of outside static air to the standard pressure of air at sea level. GPS transmitters have the greatest locational accuracy and precision, and may provide a viable solution for collecting high-resolution, 3D movement data for small-bodied aerofauna as lightweight transmitters become more widely available (minimum 2.9g device, Lotek Wireless, Ontario, Canada). Alternatively, VHF radio tags with embedded altimeters (Bowlin et al. 2015) may provide a viable option for tracking fine-scale 3D flight paths of small-bodied aerofauna in the near future (reviewed in Courbis et al. 2023).

Flight direction

Flight direction and orientation are closely associated with departure decisions and routing during migration. Generally, flight direction refers to the bearing of travel between detections recorded at two or more Motus stations separated in time and space (Bach et al. 2022; Crysler et al. 2016; Howell et al. 2020; Loring et al. 2020b; True et al. 2023). Past Motus studies have also calculated the departure bearings for individuals to estimate flight trajectories over water. For example, Loring et al. (2020b) calculated the departure bearings of individuals to map outbound movements from their study area and determine their intersection with offshore wind energy project areas. Alternatively, vanishing bearings may also be used to infer flight directions if subsequent detections following a departure event are absent. This method relies on characteristics of signal detections across multiple antennas on a single station. It involves calculating the mean of the receiving antenna bearings over the last detections, with the bearing of each detection weighted by strength of the signal (see Crewe et al. 2018 for detailed methodology). For individuals that were not redetected beyond their local Motus array, Smetzer et al. (2017) used vanishing bearings and the time of day to indicate departure type. For example, vanishing signals on 299, 215, 173 or 120° antennas that occurred at night were considered migratory flights.

Since weather conditions, seasonality, and time of day influence departure and routing decisions, flight directions are assumed to be affected similarly. During fall migration, Bach et al. (2022) detected bats moving in a seasonally appropriate southeastern direction (157°-202°) approximately one hour after sunset during light tailwinds. Howell et al. (2020) found comparable results during spring migration, as more departures were recorded to the northwest (357°) during the evening and under favourable wind conditions. Although these findings reaffirm that migratory species choose to depart in seasonally appropriate directions under optimal weather conditions, flight direction and routing remain highly variable between subpopulations and individuals (Loring et al. 2020b).

Flight direction appears to be associated with flight behaviour, with differences observed between migratory flights and stopover flights. These differences in flight behaviour may be attributed to species-specific migration strategies (long vs. short distance migrants) and the knowledge of alternative routes acquired with age, as previously stated. For example, Smetzer et al. (2017) documented substantial differences in the orientation of flights from their study area, with migratory flights oriented to the southwest (220°) and stopover flights oriented to the north (357°). Further, Loring et al. (2020b) observed high variability in the departure bearings of tagged Red Knots (*Calidris canutus*) migrating through the U.S. Atlantic region, demonstrating inherent differences in migratory routes between different subpopulations.

Flight direction during departure may have implications for the siting of WEA that are situated near high-occupancy stopover sites (Howell et al. 2020). By predicting the general direction of offshore flights from these sites, WEA can be built in strategic locations that reduce collision rates with turbines.

Travel speed

Flight speed is another important variable that can help researchers determine the level of exposure of a species to offshore WEA. By estimating flight speeds, researchers can differentiate between flight behaviours, such as nonstop and stopover flights. The estimation of flight speeds is particularly useful when assessing the movement patterns of individuals and their capacity to reach a focal point(s) when crossing large bodies of water during migration within offshore WEA, and can therefore help determine when curtailment measures should be prescribed.

To estimate flight speeds during nonstop flights over water, past Motus studies have used models to calculate airspeeds from ground speeds while accounting for wind conditions. Ground speeds are simply defined as the distance travelled divided by the time between the departure from one station and the detection at the next (Mitchell et al. 2015; Wright et al. 2018). Similar to departure timing and routing decisions, wind assistance significantly influences flight speeds and should be accounted for to generate more accurate speed estimations. Using ground speed calculations, airspeed is then estimated by accounting for tailwind assistance and crosswinds (Anderson et al. 2019; Cormier 2017; Mitchell et al. 2015; Loring et al. 2020a).

Loring et al. (2020a) estimated Piping Plovers travelling offshore at mean speeds of 42 km/hr when winds were blowing in a seasonally favourable direction (to the southwest) at low to moderate speeds, indicating the decision to travel when conditions supported direct offshore flights. Conversely, Wright et al. (2018) found no relationship between flight speeds and tailwind conditions at departure for Rusty Blackbirds, but instead found that speeds were greater for birds that travelled longer minimum distances. Although tailwind conditions may act as proximate cues for the initiation of offshore flights, the selection for these conditions is likely more associated with internal time constraints and the overall pace of migration relative to age class and species-specific migration strategy (Anderson et al. 2019; Cormier 2017; Mitchell et al. 2015; Wright et al. 2018).

Supportive winds during migration can reduce an individual's energy expenditure during extended periods of flight, thereby increasing overall migration pace and minimising the time costs related to stopover events (Anderson et al. 2019). Motus studies have investigated whether age class affected tailwind selectivity, and found adult songbirds favoured more supportive wind conditions aloft than juvenile birds (Cormier 2017; Mitchell et al. 2018). However, age class was found to have no direct effect on flight speed specifically, with adults and juveniles travelling at similar airspeeds (Cormier 2017; Mitchell et al. 2018). Like the routing decisions discovered by Crysler et al. (2016), the lack of tailwind selectivity by juveniles may be attributed to their lack of migratory experience and that their decisions are initially based on innate knowledge (Mitchell et al. 2018). Lastly, species-specific migration strategy has been explored using Motus. Anderson et al. (2019) found that adult long-distance migrants (e.g., White-rumped Sandpipers) travelled at faster airspeeds when compared to short-distance migrants (e.g., Semipalmated Sandpipers).

Akin to flight altitudes, reasonably accurate airspeed estimates of offshore flights rely on precise 3D location estimates, which are enhanced by increasing the effective detection ranges of Motus stations. See Distribution of stations and Calibration protocols for offshore Motus stations sections below for recommendations on strategic distribution of stations and calibration protocols to estimate 3D location using Motus tag detections.

Recommended decision points for Motus research related to offshore wind

The utility of antennas to detect movement patterns is highly dependent on the distribution of stations, configuration of the antenna array, nuances of each station's deployed environment, number of tagged individuals, and the population selected for transmitter deployment being representative of the population using the location or route of interest. This section provides recommendations for preliminary work to conduct when designing a Motus project, especially to study the impacts of offshore WEA development on small flying animals.

Distribution of stations

Any tag that requires detection by a receiver is limited by the number and density of tracking stations. Representative distribution of stations is especially limited in offshore environments, compared to coastal (Loring et al. 2020b; Brust et al. 2019; Brust et al. 2022; Lamb et al. 2023). The current network of receivers in Atlantic Canada is predominantly coastal and more likely to detect birds following the coastline as compared to birds heading offshore. As offshore lease areas move into development phases, deployment of automated radio telemetry equipment on offshore structures offers a promising approach for collecting more detailed data needed for collision risk models, such as information on passage rates through individual lease areas and coarse information on avoidance rates and flight altitudes (e.g., Carlson et al. 2022).

Several research groups are focused on expanding the Motus station network offshore (Carlson et al. 2022; Loring et al. 2023a; New Jersey Department of Environmental Protection 2023). Platforms that could host a radio station include turbines, buoys, and electrical service substations. However, these platforms may be limited in space, power activity, stability, and accessibility for data download and station maintenance. For example, it is not possible to install an array of Yagi antennas provided with shore-based stations on buoys because of physical space limitations. Instead, only omnidirectional antennas can be mounted on buoys (Loring et al. 2023a; New Jersey Department of Environmental Protection 2023), which have a uniform radiation pattern within a short range and lack spatial precision compared to Yagi antennas. Yagi antennas instead have a radiation pattern directed into a beam which varies in length and width based on the number of directing elements.

Antenna radiation pattern

Current Motus technology cannot provide accurate location or flight height data from tag detections. Estimated antenna detection ranges ("radiation patterns") are purely theoretical and based on ideal conditions, which do not reflect the true ranges or shapes of any real antenna (Taylor et al 2017; Crewe et al. 2019). The actual range of an antenna depends on several factors: the transmitted signal (by a tag), antenna type and orientation, length and type of coaxial cable, receiver type, line-of-sight (e.g., surrounding trees, buildings or hills), and environmental conditions. Theoretical radiation patterns do not consider the nuances of each station's deployed environment. Several Motus researchers have created methods to calibrate Motus stations and have developed processes to turn this raw calibration data into a numerical approximation of an antenna's radiation pattern. Such calibration data will inform the ongoing development of models to estimate 3D locations of animals.

Calibration surveys involve analysing the received signal strength values by each of a station's antennas as test tags move along transects, covering a range of distances, altitudes, and orientations from the station. Carlson et al. (2022) tested three stations (land-, shore-, and offshore-based) near and within a wind energy area (Block Island Wind Farm, Rhode Island, US). For calibration studies in offshore environments, tags were elevated on a pole, kite, Unmanned Aircraft System (UAS), and airplane. More specifically, they affixed a Motus tag on a dead carcass and suspended the carcass (with tag) and a barometric GPS from a kite attached to the back of a boat while travelling at a constant speed. They attached a second tag on a non-conducting pole at the highest point of the boat. To have more control of tag positioning during flight, they suspended a tag and GPS from a small UAS. Finally, to gather high altitude data (>300m), they suspended a tag and GPS from a small aviation aircraft. See Appendix E in Carlson et al. (2022) for equipment requirements, transect patterns, etc.

For each detection of the tag on one of the three receivers, tag signal strength was associated with the GPS location at the time of detection based on matching timestamps. The GPS data was used to correlate the track (altitude, latitude, and longitude) with tag detections, and relate tag signal strength to relative position from each antenna (based on known locations of each station). They then used this data in a k-nearest neighbours (KNN) regression to estimate signal strength for 100,000 arbitrary points around each station. This method can approximate the received strength of a tag to within an average of 8 dbm, which represents a small error for detections close to the station and a much larger error farther away from the station. The above surveys and calibrations should be repeated on a yearly basis to allow for the quantification of any change in detection range or receiver pattern that might occur due to the buildup of white dielectric material on the antennas and resulting precision loss in signal strength (Carlson et al. 2022).

Results from this calibration study found that the station with a clear line of sight to the horizon and without surrounding large conducting materials had the best results when reproducing the calibration data for its own station. However, the stations with large reflectors around them had more errors due to interference (see Radio noise section below). Additionally, no two stations reproduced each other, which is not surprising given each station's unique environment, but this emphasises the need for numerical methods for calibrating Motus stations. Calibration surveys should therefore be completed at every Motus station to better understand the detection range and coverage of the station's antennas. See Resources Available section below for resources created to help perform offshore and coastal-based station calibration surveys.

Sample size

Several studies have identified sample size as a limiting factor in adequately answering their questions related to offshore wind (Smetzer et al. 2017; Lagerveld et al. 2023). When designing a tagging study, it is important to maximise representation across a relevant portion of the target species' range to avoid biasing results. Individuals selected for tracking should therefore represent underlying spatial, temporal, and individual variation in movement patterns in the target population. A priori power analyses and foreknowledge of migratory routes and annual-cycle connectivity can be used to help determine minimum sample size, population distribution, and year requirements.

Lamb et al. (2023) performed a retrospective power analysis to test the effect of sample size on the detection probability of free-flying Motus-tagged Piping Plovers and Common Terns (*Sterna hirundo*). They tested an array of stations (n= 30) in an offshore environment (mid-Atlantic coast of the United States) during the birds' breeding season and fall migratory departure. They used a bootstrapping approach to assess how well different subsamples of the population represented occurrence patterns of birds outside the subsamples. To do this, they determined the number of stations used by the subsample population that were also used by non-subsample individuals (i.e. inclusion). They then calculated representativeness of different sample sizes (n=50) as the projected inclusion divided by asymptote of fitted non-linear function of the means of the bootstrapped samples. They also calculated the representativeness of capture site and year, and their combinations (n = 2 and 3, respectively) as the asymptote of the subsample divided by the asymptote across the full tagging population.

Lamb et al. (2023) found that the probability that any given receiver station used by the population would be included in a subsample increased with the number of birds tracked. This study investigated confidence intervals commonly used to detect significant effects, and determined that 90-143 tracked individuals were required to include 90% of locations known to be used by the larger, tracked population, and an additional 40-50 individuals were required to achieve 95% of used locations. Importantly, they only evaluated baseline site occupancy, and acknowledged that evaluating more complex metrics (e.g., abundance, migratory routes, flight altitudes, habitat use), as well as associating changes in distribution with specific drivers, likely require higher sample sizes.

According to Lamb et al. (2023), the required sample size may also vary between species with different migratory patterns and habitat requirements. Piping Plovers tagged in a single site and year had lower representativeness in station detections than the same number of terns, but higher when considering multiple sites and years. Because plovers are relatively solitary and nest diffusely along coastlines, they likely have high inter-individual variability in timing and direction of movement. In contrast, terns nest in high densities and forage in large flocks outside of breeding. The literature supports that species with higher degrees of sociality require relatively small samples to represent their population. However, this study also suggests that birds that exist in patchy distribution, like terns, may require larger sample sizes to represent all populations.

Plovers were detected on more stations as the number of tagging sites and years (to a lesser extent) increased, whereas inclusion only increased slightly with additional years for terns. The magnitude of spatial variation is therefore greater than the magnitude of annual variation for plovers, whereas terns had low inter-site variability. This may be explained by the fact that terns from different breeding sites overlap at non-breeding sites, whereas plovers remain separated from breeding to non-breeding sites. So far, the above results indicate that species with different social behaviour and migratory connectivity impact not only the required sample size, but also the optimal spatiotemporal distribution of capture locations to represent variation across the regional population. Since inclusion continued to increase across all sampling years, long-term studies are required to determine how many years of sampling are required to maximise inclusion values.

Plovers were detected on more stations the longer their tracking period, whereas this result was not true for terns. Common terns use offshore migration routes and were therefore likely out of detection range from land-based coastal antennas during migration. Plovers have nearshore migration strategies and were detected further south where there are additional receiving stations. This highlights the need to create station arrays that capture seasonal movements of interest and time tag deployment to ensure battery life and tag retention lasts the duration of the study period of interest. However, longer battery life requires larger tags and costs, which enforces a tradeoff between high sampling rates and long-term deployments (Courbis et al. 2023).

The probability of a subsample having detection(s) on a station used by the full tagging population also increased with closer proximity to a migratory stopover/staging site, the number of receiving antennas per station, and the percentage of the tracked population present. These results emphasise the need to set up receiving stations with an adequate number of antennas and design station networks to sample potential movement corridors. Motus stations are only useful if a sufficient number of tags are deployed in the area of interest, and vice versa; both stations and tags must be deployed in order to acquire the desired data.

Radio noise

Some existing Motus stations are completely ineffective due to radio noise or interference. We consider noise to be any kind of radio pulse that is received by a station that was not produced by the intended target (i.e., a radio tag). Not only can this noise mask the pulses of real tags—preventing a receiver from picking it up—it can also produce signals that resemble real tags, resulting in a false positive detection. Antennas can receive interference if placed too close to metal objects or other antennas, or sources of electromagnetic noise (even air conditioners, generators, lawn mowers). Depending on frequency and location, radio interference from third-party broadcasters and cellular can also be problematic.

It is recommended that users test for station interference when choosing where to place their station(s). See [Motus guides](#) section below for resources to help test for interference and address excessive station or antenna noise.

Resources Available

A variety of resources are publicly available on the Motus website for those interested in using automated radio-telemetry to monitor wildlife within offshore wind energy project areas. Here, we provide a list of resources and a summary of their contents. With interest from multiple project groups focusing their research efforts on offshore wind impacts, an Atlantic Offshore Wind project group was also established to facilitate consistency, transparency, and efficiency of data workflow and procedures across all Motus projects involved.

All resources summarised below can be found directly on the Motus website (https://motus.org) or accessed through the link provided in each summary.

Motus guides

Link: https://motus.org/dashboard/

Motus Central created guides, with contributions from Motus collaborators, to help Motus users with several aspects of Motus, such as best practices to join the Motus network, select, install, and maintain stations, select and deploy radio tags, manage projects, and explore motus data. These guides are working documents and are subject to regular updates as new information becomes available.

Motus data dashboard

Link: https://motus.org/dashboard/

The Motus Data Dashboard is a comprehensive online tool that allows users to freely explore open Motus data directly on the Motus website. The dashboard serves as a centralised platform with a user-friendly interface, aiming to make wildlife tracking more accessible to a broader audience, including project collaborators, researchers, educators, and the general public. This exploratory tool provides project metadata and the most recent location and movement data of tagged animals that have been submitted by Motus collaborators to the central repository managed by Birds Canada. In combination, these data contribute to interactive maps that illustrate migration routes and spatial patterns.

Public summary data can be readily viewed on the Motus Data Dashboard as visualisations, plots, tables, summaries, maps, and track animations. This summary data consists of basic project information, limited tag and station metadata, and daily summaries of tag detections and track maps. Users may browse available data by station name, project name, individually tagged animals, species group, or geographic region depending on the scope of interest. The dashboard will then populate a list of results and display associated receiver locations, tagging sites, and migration tracks on the interactive map. Furthermore, data can be filtered by date to view historical changes across the Motus network, such as station locations. Detection timelines, station activity, and customizable summary reports can also be generated and downloaded through the Motus Data Dashboard for specific stations or projects of interest.

The Motus Data Dashboard is intended to cater to a wide audience, but has features that help coordinated groups (like the Regional Wildlife Science Collaborative for Offshore Wind) use it for their own purposes. It is a valuable tool and resource for researchers, offering publicly available summaries of tag detection data collected by all Motus stations across the network. The detection data gathered from various geographic regions and species of interest can then be used to help identify and guide the prioritisation of future tagging projects and species conservation efforts.

Monitoring framework for Motus station deployment in offshore wind energy areas

Link: https://motus.org/groups/atlantic-offshore-wind/

A collection of interrelated products was published in 2023 to develop standardised protocols for using Motus to monitor birds and bats in offshore environments within the U.S. Atlantic region. This collaborative project was funded by the New York State Energy Research and Development Authority (NYSERDA) and consists of project partners from the US Fish and Wildlife Service (USFWS), Biodiversity Research Institute (BRI), University of Rhode Island (URI), Applied Physics Systems, LLC, and Birds Canada. This foundation of work is being actively built on through the Regional Wildlife Science Collaborative for Offshore Wind and associated initiatives.

The overall project consists of five core components that have been designed to help guide station operators with the deployment of Motus stations offshore, assist with station calibration, and data workflow. The components include:

1. A Guidance Document that describes standardised recommendations for the deployment and operation of Motus stations on offshore structures. See Methods for Motus station deployment on offshore structures section below for more details.
2. A Study Design Tool referred to as “Informing the Design and Implementation of Offshore Motus Systems’” (IDIOMS) that helps with station design and assesses detection coverage within a WEA from simulated arrays of offshore Motus stations.
3. A Simulation Study that estimates the detection probability of a target species travelling through a simulated array of Motus stations within a WEA to inform IDIOMS and monitoring recommendations.
4. A Data Framework that describes workflows within Motus to coordinate and disseminate detection data, metadata, and summary reports amongst project collaborators who are gathering data for offshore wind applications.
5. A Monitoring Framework that contains guidance on the application of using Motus to monitor birds and bats to inform conservation efforts in offshore wind energy project areas.

Specifically, the Monitoring Framework provides an extensive overview of how to use Motus to track birds and bats during all phases of offshore wind energy development projects (e.g., site characterization, construction, operations, and decommissioning). The framework consists of guidelines, standardised protocols, and key recommendations for station and tag deployment, reporting, and data analysis. These resources were developed to not only standardise methods at the site-level to document baseline changes within a project area, but to allow for data comparison across sites and to facilitate the regional coordination of offshore monitoring and tagging efforts.

Methods for Motus station deployment on offshore structures

To obtain site-specific data on the movements of radio-tagged animals through offshore wind project areas, a guidance document was developed to outline technical specifications for deploying and operating Motus stations on offshore wind structures. This guidance document is part of a series of products developed by the US Atlantic Offshore Wind working group and is composed of a main guidance document and supplemental appendices to assist with installation, calibration, operation, and maintenance of Motus stations. The main document provides an overview of Motus stations deployed on offshore wind turbines and buoys, summarising the station components, configuration, and operations. Additionally, detailed technical information, including equipment specifications, maintenance activities, calibration, data collection, and delivery, are provided in the appendices. All guidelines provided are to inform and assist station operators with metadata collection and routine maintenance information following required data standards for offshore Motus stations.

Calibration protocols for offshore Motus stations

Calibration surveys are an essential step when deploying Motus stations in offshore environments and contribute to a better understanding of the detection range and coverage of a station's antennas (see Antenna radiation pattern section above for further information). The surveys not only help collect data required to determine a station's detection range, but also to reveal antenna blind spots and determine the detection probability of receiving antennas at each station. A Calibration Guide for Offshore Motus Stations was developed by Loring et al. (2023b) to provide an overview of the calibration survey protocols and standards. This document is part of a series of products developed by the US Atlantic Offshore Wind working group and is included as an appendix within the Guidance Document for Deploying Motus Stations on Offshore Wind Turbines and Buoys. Information provided in this manual includes types of calibration surveys, survey equipment preparation, types of calibration tags, and workflow for calibration data.

In addition to the calibration survey guidelines and best practice protocols, a Motus Station Calibration Data Analysis Tool was created to simplify the calibration data workflow for station operators. A pilot version of the data analysis tool is available online as a web application (https://birdsdev.uri.edu/) where station operators can input their metadata for (1) survey planning, (2) data analysis, and (3) automated reporting. The analysis tool has two main functions designed to generate simple transects for calibration survey planning and produce summary reports of data gathered during surveys. The "Initial Transect Calculator" function can be used for calibration survey planning and allows operators to add the latitudes and longitudes of stations to generate sample transects including waypoints and a field metadata sheet that helps guide survey design for boat-based calibration surveys. For post-calibration survey analysis, the "Calibration Report Generator" function can be used to provide station operators with a report on the location and signal strength of the calibration tag detections. Motus calibration detection data and calibration survey GPS data can be uploaded as .csv files to the web application to also generate summary statistics showing the number of detections per antenna, overall calibration efficiency, and the detection range of each antenna.

Integrated Science Plan for Offshore Wind, Wildlife, and Habitat in U.S. Atlantic Waters

Link: https://rwsc.org/science-plan/

The Regional Wildlife Science Collaborative for Offshore Wind (RWSC) serves as a central hub for coordinating and standardising offshore wind research projects in the U.S. Atlantic. RWSC is cooperatively led by a steering committee that includes equal representation from federal and state government agencies, industry groups, and non-governmental organisations. The objective of this collaborative partnership is to ensure that the development and operation of offshore WEA aims to avoid and minimise impacts to wildlife and the environment while promoting sustainable energy practices. To identify and prioritise the research needs across all sectors, RWSC and six expert Subcommittees developed the "Integrated Science Plan for Wildlife, Habitat, and Offshore Wind Energy in U.S. Atlantic Waters" (hereafter known as the Science Plan). The Science Plan aims to 1) share ongoing and planned research, 2) build on prior collaboration efforts, 3) identify data and research gaps and needs, 4) standardise new data collection methodology and facilitate data sharing, and 5) align and leverage funding from multiple sources.

The Science Plan is a living document that is updated as new and pending research is gathered by RWSC Subcommittees and participants. The plan is divided into various Subcommittee chapters (Marine Mammal, Bird & Bat, Sea Turtle, Habitat & Ecosystem, Protected Fish Species, and Technology) where existing data collection standards and protocols are outlined and key gaps and recommendations are defined for each taxon. For example, the Science Plan encourages the coordination of regional approaches to telemetry data collection for birds and bats and recommends using Motus and relevant monitoring protocols (see Monitoring framework for Motus station deployment in offshore wind energy areas section above) to achieve this goal.

To streamline collaboration between Subcommittee groups and the research community, an online database was developed to serve as the most current source for U.S. Atlantic offshore wind research and data collection activities. The Offshore Wind & Wildlife Research Database (https://database.rwsc.org/birds-and-bats) contains ongoing data collection projects that have been shared with RWSC subcommittees or obtained from publicly available sources. The database allows users to easily filter projects by taxa or research theme to view overall project goal(s), study area, methodology, and other details. Additionally, the database is intended to improve the ability of RWSC to address research questions and develop future recommendations included in the Science Plan.

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