Monitoring Framework for Automated Radio Telemetry at Offshore Wind Projects in the U.S. Atlantic

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Table of Contents

Summary of Key Recommendations 4
Introduction 5
Monitoring framework goals and objectives 6
Coordinated automated radio telemetry 8
Motus station deployment for offshore monitoring 9
  Stations on buoys 9
  Stations on offshore wind turbines 10
  Optimizing placement of stations within a project area 10
  Station calibration 12
  Stations along Atlantic Coast 12
Guidelines for Motus tag deployment for offshore monitoring 13
  Operating frequencies 13
  Tag types 14
  Number of tags and stations in Motus per frequency 15
  Focal species 15

ESA-listed species 16
Birds of Conservation Concern 16
State-listed species 17
Surrogate species 17
Shorebirds 17
Marine Birds 17
Passerines and other nocturnal migrants 18
Motus database 18
Expert opinion 18
Tagging methods 19
Timing and locations of tag deployment 19
Duration of data collection 19
Number of tags to deploy 20
Minimum metadata to collect in field 20
Monitoring 21
Permits 21
Data coordination 22
Data analysis 22
Data analysis for station data 23
Data analysis for tag deployments 23
Using Motus R package to summarize detection data: 23
Using other R packages to add covariate information 24
Recommended reporting elements for tagging studies 24
Recommended elements for methods section 24
Tag deployment information 24
Station information 25
Data cleaning and filtering methods 25
Information about covariates: 25
Recommended elements for results section: 25
Summary of detection data collected per animal 25
Trackline maps 26
Summaries of flights across wind energy project areas 26
Recommended elements for supplemental information 26

Site-specific monitoring 27
Pre-construction 27
Construction and operations 28
Avian and bat monitoring frameworks 28
Avian and bat monitoring plans 28
Site-specific reporting standards 29
IDIOMS reports 29
Motus reports 29
Calibration reports 30
Data availability statements 30
Supplemental information 30
Detailed analysis of tag deployments 30
Regional coordination 30
Station deployment and calibration 31
Offshore stations 31
Coastal stations 31
Station calibration 32
Tag deployment 32
Data analysis 33
Implementation 33
Adaptive monitoring 33
Future actions 34
Technology development 34
Hardware improvements 34
Improvements to Motus receivers 34
Identify the optimal frequency for offshore studies and evaluate tag power outputs 35
Evaluate suitability of other offshore platforms 35
Integration to design phase of wind turbines and buoys 35
Analytical 36
Conduct an analysis of coastal and offshore station coverage 36
Determine the role that attraction and displacement from the project area will affect Motus study design 36
Quantify effects of nearby turbines on detection coverage 36

Calibrate 166 MHz using methods for 434 MHz 36
Incorporating detection probability 37
Motus Data Dashboard updates and developments 37
Improve process for reporting station health data updates to Motus 37
Improvements to the Motus station management 37
Improve identification of false positives in detection data 37
Data streams from Iridium connected stations 38
Improvements to the Atlantic Offshore Wind Group's online interface 38
Improvements to data workflows for standardized tag data analysis 38
Tool updates and developments 38
Calibration workflow updates 38
Study design tool updates 39
Develop a power analysis tool 39
Develop analysis tools for detection data 39
Stochastic Collision Risk Assessment for Movement (SCRAM) 40
Research questions 40
Integration with other monitoring methods 41
Conclusions 41
References cited 42
Statement of use 45

Summary of Key Recommendations

Strategically deployed offshore Motus stations can be used to collect site-specific presence and movement data from individually tracked birds and bats at offshore wind energy project areas. The broader network of Motus stations provides information on regional-scale movement patterns among wind energy project areas in the U.S. Atlantic. This framework aims to facilitate consistency, transparency, and efficiency of Motus studies and help to address specific avian and bat monitoring needs during multiple phases of offshore wind energy development (site characterization, construction, operations, and decommissioning) using the best available science.

Key recommendations are summarized below.

- We recommend that offshore wind project proponents support the following: deployment and calibration of receiving stations on offshore buoys and wind turbines within their wind project areas; support of ongoing data fees and maintenance of nearby priority coastal stations; contribute to centralized funding for tagging efforts for species of interest; and follow established guidelines for full transparency of all data in the Motus as part of the Atlantic Offshore Wind Group.

- Offshore wind turbine stations should be deployed during the construction phase of the wind facility and operated through the lifetime of the project to help address priorities for consistent, long-term monitoring data. Monitoring should be conducted in an adaptive framework that is reevaluated and updated over time as technology and information needs evolve.
- All Motus station data, tag data, and metadata should be provided as non-proprietary information so that data are available for use and assessments at regional scales. Regional assessments are necessary for use of best available science when studying migratory species at scales that are ecologically meaningful.
- To standardize detection coverage of offshore stations, we recommend that all offshore stations are configured for dual frequency monitoring and operated following specific guidance in the Guidance Document and IDIOMS study design tool.
- To standardize detection probability of tags, we recommend that tagging studies focused on offshore wind monitoring use power regulated tags programmed to standardized transmit rate of 5 seconds where possible.
- Coordinated tagging efforts are necessary to maximize population level inferences from individually tagged animals, to minimize animal safety and welfare risks by reducing the number of individuals subjected to tagging activities, and to most effectively leverage time, funding, and other resources for monitoring efforts.

Introduction

Automated radio telemetry systems consist of radio tags (small transmitters attached to birds, bats, or insects) and stations (receivers with antennas that record signals from “tagged” organisms within detection range). The Motus Wildlife Tracking System (‘Motus’; www.motus.org) is an international collaborative research network that uses cooperative automated radio telemetry to track tagged organisms on coordinated frequencies (currently 166.380 MHz and 434 MHz in North America). Collaborators using Motus have collectively tagged tens of thousands of birds and bats and tracked their movements using an international network of automated radio telemetry stations. Motus also serves as a hub for data from thousands of receiving stations and tagged animals worldwide representing hundreds of species. A centralized database at the Birds Canada National Data Centre manages and disseminates data and metadata in a standardized format across all projects in the network.

This document is part of an effort to develop standardized protocols for using Motus to monitor birds and bats in offshore environments. The overall study includes the following components:

- A ‘Guidance Document’ describing technological specifications and operation of Motus stations on offshore structures, in order to guide and standardize station deployment processes and obtain standardized, site-specific data on the movements of tagged animals through offshore wind project areas.
- An online ‘Study Design Tool,’ known as IDIOMS (‘Informing the Design and Implementation of Offshore Motus Systems’), to help design, optimize, and assess coverage of wind energy project areas and adjacent waters from simulated arrays of Motus stations located on offshore structures.

- A 'Simulation Study' that evaluates Motus design challenges and informs IDIOMS and monitoring recommendations by estimating detection probability of select avian taxa moving through simulated arrays of Motus stations within wind energy project areas.
- A 'Data Framework' within the Motus Wildlife Tracking System to facilitate coordination and dissemination of detection data, metadata, and summary reports from all tagged animals and Motus stations deployed for offshore wind energy applications in the Atlantic region of North America.
- A 'Monitoring Framework' that contains guidance on applications of automated radio telemetry technology for monitoring birds and bats in offshore environments at site-specific to regional scales, including specifications of transmitters for deployments to inform offshore wind energy development activities.

All products from this effort are publicly available at: https://motus.org/groups/atlantic-offshore-wind/. The products are intended to be living documents that are updated as new information and technology becomes available.

Monitoring framework goals and objectives

This document provides a strategic framework for using Motus to monitor movements of birds and bats in the U.S. Atlantic region relative to offshore wind energy development. Previous studies established a network of Motus stations along a portion of the U.S Atlantic coast to collect data on regional movements of birds in the U.S. Atlantic (Loring et al. 2018, 2019, 2020), with an emphasis on small-bodied terns and shorebirds including ESA-listed species such as the Roseate Tern (*Sterna dougallii*), Piping Plover (*Charadrius melodus*), and *rufa* Red Knot (*Calidris canutus rufa*). However, Motus stations are typically limited to detecting tagged birds and bats within a radius of about 15 km (Taylor et al. 2016), so data collection from the coastal array was limited to nearshore areas.

Data gaps within offshore lease areas, typically located >15 km from the coast and thus outside the range of land-based stations, can be addressed by deployment of Motus stations on offshore structures (e.g., buoys, offshore wind turbines). Deployment of Motus stations within multiple wind project areas throughout the Atlantic Outer Continental Shelf (OCS) would establish a network of stations that could be used in more detailed assessments of offshore animal movements at site-specific and regional scales.

Site-specific Motus data can be collected to inform different phases of offshore development, from pre-construction risk assessments (using stations on buoys) to monitoring during construction and operations through the lifetime of a project (using stations on turbines). At the most basic level, these stations can be used to determine species presence in a project area, defined as the occurrence of one or more focal species within a project area during a specified time period.

Standardizing monitoring methods at the site level will also help to inform regional-level offshore energy assessments. Regional-scale questions that can be addressed using the broader network of Motus stations in the U.S. Atlantic include:

- Spatial and temporal variability of tagged animals within and across sites, species and individuals
- Exposure of tagged animals to multiple wind project areas throughout the U.S. Atlantic region
- Proportion of tagged individuals within a species or population using offshore vs. coastal migration routes

- Geographic variation in migration routes, including migratory departure points along the coast where migrating animals might begin migratory flights over open water

The utility of using automated radio telemetry to address these questions depends on two important factors: 1) the coverage of active Motus stations within and outside wind project areas and along the U.S. Atlantic coast during the time period of interest; and 2) the sample size of tagged animals from regional population(s) of interest that are actively transmitting within the Motus network during this period. Strategic collection of Motus data to target the above questions could ultimately be used to inform some of the primary information gaps in offshore wind energy assessments at regional scales, including cumulative effects of estimated collision risk or avoidance behavior for various species of interest.

The overall goals of the monitoring framework are to: 1) develop a process to optimize coverage of Motus stations for site-specific and regional-scale science needs for offshore wind; 2) coordinate strategic tag deployment efforts to best inform population-level inferences, and 3) develop standard workflows and tools to facilitate timely, efficient, and consistent data collection, analysis, and delivery using the best available science.

Specific objectives of the Monitoring Framework are to:

- Provide a comprehensive overview of how to use Motus to track birds and bats offshore as part of research, monitoring, and assessments of offshore wind projects in the U.S. Atlantic
- Standardize methods for site-specific monitoring and reporting
- Coordinate methods and information across sites for regional-scale analyses
- Develop centralized tag deployment strategies to facilitate population level inferences from individual-based tracking data
- Identify standardized data analysis methods to address high priority information needs
- Facilitate regional coordination opportunities to maximize resources
- Recommend high-priority future actions, including improved workflows, analysis tools, and integration with other avian and bat monitoring technologies

It is important to place the monitoring framework objectives in the context of limitations of Motus technology. Limitations of using Motus to address questions on offshore movements of tagged birds and bats include the following considerations:

- Motus technology uses radio signals to detect birds that are moving within range of fixed tracking stations, and detection range of stations increases with altitude of tagged birds, so it is best suited for tracking movements of birds or bats in flight. Detection range to birds on water is limited (<1 km) due to signal attenuation. Research questions on marine habitat use of seabirds are better addressed with GPS or other satellite-based (i.e. Argos tracking) technology.
- Motus is limited to detecting animals that are within range of automated radio telemetry stations (typically <15 km to birds in flight). When animals are outside detection range of automated radio telemetry stations, their locations are unknown. Research questions aimed at range-wide movement patterns are better addressed with satellite-based tracking technology for global detection coverage.
- User-friendly methods to convert station detections into movement data have yet to be developed. Motus tag detections at automated radio telemetry stations typically include the

following data: unique bird ID, time stamp, receiving antenna (bearing), and signal strength. Thus, Motus data have some limitations for very fine-scale movement questions (for example, it is not an effective approach for monitoring micro-avoidance and collisions at turbines).

Coordinated automated radio telemetry

Motus uses uniquely coded radio transmitters ('Motus tags') operating on common frequencies monitored by a collaborative network of automated radio telemetry stations ('Motus stations') that provide detection data to a centralized database at Birds Canada National Data Centre. This database serves as a central data processing hub and repository, allowing any Motus tag to be detected on any Motus station throughout the network (Birds Canada 2022a).

Motus tags are radio transmitters that are attached to birds, bats, or insects. In North America, all Motus tags transmit on one of two frequencies: 166.380 MHz or 434 MHz (166.380 MHz is hereafter also referred to as "166 MHz"). Motus tags are very light weight (starting at 0.2 g) and transmit signals with high temporal resolution. Time between transmissions (burst intervals) are unique to each transmitter and typically range from 1 second (e.g., for calibration tags, where temporal resolution is prioritized over tag longevity) to >20 seconds (for tags where minimizing weight and maximizing longevity are prioritized). All transmitters are uniquely identifiable on the shared frequency using a combination of an encoded tag ID and burst intervals. Longevity of transmitters depends on the combination of burst interval and transmitter weight, which relates to battery size and drain. Depending on the programming of the burst interval, transmitters weighing <1 g may operate for a few weeks, while transmitters weighting > 1 g may operate for several months or longer. In addition to battery powered tags, solar-powered and hybrid solar-battery Motus tags are available but not currently recommended for offshore studies (see "Tag Types," below).

Motus stations monitor signals from tagged animals. A Motus station consists of one or more antennas (tuned to a specific frequency), a mast, coaxial cables, a receiver, and a power source. Typically, antennas used at Motus stations are either Yagi-Uda (directional) or omni-directional. Each antenna is tuned to one of the specific monitoring frequencies in Motus (434 MHz or 166 MHz), so monitoring multiple frequencies requires use of multiple antennas. The antenna(s) are attached to an elevated mast that provides line-of-sight to the surrounding airspace. Coaxial cables are used to attach antennas to the receiver, which records detection data from antennas. There is currently one type of receiver that is capable of monitoring both frequencies in Motus: the SensorStation (Cellular Tracking Technologies, Rio Grande, NJ, USA). A power source is needed to provide a continuous power supply to the receiving unit and can be configured for either an AC or a DC power source.

To participate in Motus, users: 1) sign up for a free Motus account; 2) register their tags and stations and associate them with a project within the Motus database; 3) periodically upload data from their stations to the database (this can be automated via WiFi, LTE, or ethernet connectivity); and 4) use the Motus R-package to download data from Motus tags and stations throughout the network. Summary-level data is made publicly available for exploration on the Motus website (www.motus.org). In addition, Motus has developed an online 'Atlantic Offshore Wind Group' specifically focused on deployments related to offshore wind energy development in the Atlantic. When setting up a project that includes stations and/or tags deployed for offshore wind energy applications in the US Atlantic, the project should be assigned to the 'Atlantic Offshore Wind Group' in order to facilitate consistent data summaries and automated reports of data at the regional scale. More information on the Motus system and Atlantic Offshore Wind Group is found in the Motus Data Framework.

Motus station deployment for offshore monitoring

Estimating locations of birds and bats tagged on the Motus system is only possible when they are within detection range of at least one station. Accuracy of location estimates can improve through triangulation methods when multiple stations can detect a tagged animal simultaneously (Janaswamy et al. 2018). Therefore, strategically deployed offshore Motus stations provide essential detection coverage for tracking tagged birds and bats within wind project area(s) and regionally. In general, detection coverage improves as the number of stations within a wind project area increases, since the volume of air space covered by receiver stations increases. Deployment of strategic station arrays within multiple wind project areas throughout the Atlantic OCS will create a network of stations for monitoring, research, and assessments at site-specific and regional scales. Deployment of offshore Motus stations requires availability of offshore platforms to mount equipment. Within offshore wind project areas, this can be accomplished through mounting Motus stations on buoys (during site-assessment and pre-construction phases of a wind project) and on wind turbines (during construction and operations phases of a wind project).

Stations on buoys

Motus stations on offshore buoys provide important information on the presence of tagged birds and bats during the site assessment and pre-construction phases of an offshore wind project, when limited infrastructure is available for locating Motus stations offshore. However, the turbulent motion of buoys makes them difficult platforms for non-gyroscopically stabilized directional antennas, such as Yagi antennas. Omni-directional antennas are less affected by motion on buoys and are recommended for this use case. Omni-directional antennas have relatively short detection ranges (approximately 1 km), so information from buoy-based stations is more limited relative to stations on larger, more stable platforms such as turbines that can support multiple directional (Yagi) antennas with longer-rage detection capabilities. Despite these limitations, buoy-based Motus stations can provide pre-construction monitoring coverage offshore for species that are not typically detected during periodic boat-based or aerial surveys, such as nocturnal migrants.

During the site assessment phase of an offshore wind project, stations should be deployed on monitoring buoys to collect pre-construction data. Ideally, Motus stations should be deployed on all buoys planned for deployment in the lease area for the entire deployment schedule of the buoys, to achieve the maximum possible coverage given the limited detection range of each station.

Pilot efforts in the Atlantic have successfully deployed Motus stations on a variety of buoy designs, including LiDAR and metocean buoys. We recommend integration of Motus stations into buoy designs early in the planning process to ensure that there is sufficient space and power available to meet design and operation standards for offshore Motus stations. Motus stations on buoys should be designed and operated following recommendations in the Guidance Document and Appendix B: Description and Equipment List for Motus Stations on Buoys.

Stations on offshore wind turbines

Strategically deployed Motus stations on offshore wind turbines provide detailed information on movements of birds and bats within and around offshore wind project areas. These stations use a combination of four directional (Yagi) antennas and a single omnidirectional antenna to achieve optimal detection ranges and coverage for both monitoring frequencies in Motus (166 MHz and 434 MHz). At each station, all four Yagi antennas should be tuned to the same frequency (i.e. 166 MHz or 434 MHz), and the omni antenna should be tuned to the alternate frequency. The frequency that the Yagi antennas are tuned to is considered the station's "priority frequency". Therefore, stations with four Yagi antennas at 166 MHz and an omni antenna at 434 MHz are considered "prioritized" for 166 MHz. Each wind project area should deploy multiple stations with alternating configurations such that there are an equal number of stations prioritized for 166 MHz as there are for 434 MHz.

Motus stations on turbines should be designed and operated following recommendations in the Guidance Document and Appendix A: Description and Equipment List for Motus Stations on Offshore Wind Turbines. We recommend consideration of Motus stations on turbines early in the planning process to ensure that there is sufficient space and power available to meet operation and design standards on the turbines where stations are to be placed. Offshore wind turbine stations should be deployed during the construction phase of the wind facility and operated through the lifetime of the project to help address priorities for consistent, long-term monitoring data.

Optimizing placement of stations within a project area

At the site level, strategic placement of offshore Motus stations is necessary to achieve specific monitoring objectives. Along with this framework, we developed an online web application 'Informing the Design and Implementation of Offshore Motus Systems' (IDIOMS; https://briloon.shinyapps.io/IDIOMS/) to help facilitate the study design process. The main functions of IDIOMS are to help users plan and optimize various station and antenna configurations within an offshore wind project area, and to allow for (generalized) estimation of the coverage of existing station arrays.

For buoy-based stations, the IDIOMS web app can be used to estimate detection coverage for different design scenarios. For example, IDIOMS can be used to estimate coverage of Motus stations on buoys in pre-determined locations and to help optimize siting of buoy stations to achieve maximum detection coverage for monitoring a specified geographic area. Output from IDIOMS provides a map of estimated coverage from buoy arrays that can be used in study planning and interpretation of animal detection data collected by the stations.

IDIOMs can also be used to evaluate different configurations of stations deployed on a subset of turbines within an offshore project area. Different types of station configurations can be used to target data collection for addressing specific questions, including optimizing coverage to detect birds and bats within the project area and optimizing directional coverage around the wind project area to assess avoidance rates of tagged animals. During the study design phase, IDIOMS should be used to help optimize siting of Motus stations to best address monitoring goals.

There are two main study design options in IDIOMS:

- Coverage optimized: used to place stations and orient antennas with the goal of optimizing detection probability of tagged animals within a wind project area.

- Avoidance optimized: used to place stations and orient antennas with the goal of specifically estimating macro-avoidance (proportion of tagged animals that fly around versus through a wind project area).

In general, the number of Motus stations within an offshore wind project area is determined by the project's total array area and the number of turbines within the array. Smaller scale (< 25 turbines) offshore wind projects should have a minimum of two offshore wind turbine Motus stations. Larger scale offshore wind projects should have a minimum of two offshore wind turbine Motus stations for every 25 turbines in their array (Table 1). Each offshore wind project should have an equal number of stations prioritized for 434 MHz and 166 MHz. Therefore, an offshore wind project with 100 turbines should have a minimum of 8 Motus stations, with 4 stations prioritized for 166 MHz and 4 stations prioritized for 434 MHz. If there is more than 1 nm distance between turbines, or the wind farm is a highly irregular shape, additional stations beyond this rule of thumb may be needed to produce the same proportional coverage of the project area.

Results from IDIOMS should be viewed as an estimated coverage pattern (assuming ideal conditions) and provide the base number of stations to deploy in a given area. Additional stations may be required to achieve coverage targets if calibration data show that coverage from the stations is limited. For example, IDIOMS currently assumes that coverage of receiving antennas within a wind project array is not affected by interference or blockage from neighboring turbines. Future updates of IDIOMS will allow users to input station calibration data to determine the extent to which each station's actual antenna coverage aligns with estimated coverage patterns under ideal conditions.

Table 1. Number of turbines in an offshore wind project and minimum number of Motus stations per frequency, assuming wind turbines are separated by a distance of 1 nm or less.

Number of turbines in wind project	Number of stations prioritized for 166 MHz	Number of stations prioritized for 434 MHz	Number of stations (total)
1 to 25	1	1	2
26 to 50	2	2	4
51 to 100	4	4	8
101 to 125	6	6	12
126 to 150	8	8	16
151 to 200	10	10	20

For offshore wind projects with 25 turbines or less, station placement should be determined manually in consultation with USFWS and BOEM, and IDIOMS should be used to map coverage of each station. For offshore wind projects with 26 or more turbines, placement of stations within a wind project area should be informed by running IDIOMS first for 166 MHz with the target number of stations (Table 1) and 'coverage optimized' selected. After generating results from 166 MHz, IDIOMS should be run for 434 MHz with the target number of stations and 'avoidance optimized' selected. This allows for stations to be configured within a wind project area to maximize detection coverage for the two frequencies and address complimentary research questions for monitoring programs. For consistency across sites, we recommend that 166 MHz is used to optimize coverage and 434 MHz is used to optimize avoidance. Note that IDIOMS recommends different station locations to optimize for different flight heights. For consistency, we recommend that station selection corresponds to 25 m height for 166 MHz (coverage optimized) and 50 m flight height for 434 MHz (avoidance optimized). For more information, see the example scenario in the IDIOMS manual.

After running IDIOMS for each frequency, users should produce an automated report for each frequency for submittal to regulatory agencies to include within their post-construction monitoring plan. For more information, see the section titled ‘Avian and bat monitoring plans’ (below).

When IDIOMS is provided with user input data on the location of turbines within a wind project area and Motus station parameters, it will recommend the placement of stations and antenna bearings to achieve optimal coverage. These bearings should be used as a starting place when positioning the bearings of the Yagi antennas on site. When installing the station on the turbine, it may be necessary to rotate the orthogonal array of Yagi antennas to avoid pointing any of the antennas towards the turbine tower or other metal structures to the best extent possible. For rectangular platforms, locating the mast on the corner (or protrusion) of a turbine platform is ideal for optimizing angles of antennas. After installation of stations, IDIOMS should be re-run using actual station placement and antenna bearings to map coverage and produce an automated report for each frequency for submittal to regulatory agencies. For more information, see ‘Site specific reporting standards’ (below).

Station calibration

After stations are deployed within a project area, station calibration must be conducted to quantify the actual detection range and coverage of the stations. The calibration step is critical because radio waves emitted by transmitters, at these frequencies, travel within line of-sight and factors such as the ocean surface, adjacent infrastructure, and electronic noise can block, reflect, or attenuate the signal (Kenward 1987). Field calibration data are collected using a test tag along transects at varying distances and orientations to receiving stations(s) with a high-resolution GPS unit continuously recording the tag’s location and altitude. These calibration data are essential for quantifying detection patterns of stations to ensure accurate interpretation of detection data from tagged animals. Calibration of each station is important because the detection pattern of stations vary depending on each station’s unique environment (Carlson et al. 2022). Detailed information on station calibration is available in the Guidance Document and Appendix E: Calibration Guide for Offshore Motus Stations. Priority future efforts include integration of calibration workflows, data, and automated reporting into the IDIOMS study design tool.

Stations along Atlantic Coast

Motus stations along the Atlantic coast of North America provide important information on regional movement patterns of tagged birds and bats. Standardized, consistent operation of coastal Motus stations is needed to provide core infrastructure for a regional array. For adequate coverage of coastal and nearshore areas, these receiving stations should be placed within 1 km of open water with clear line of sight to the water. The stations should be placed in locations with as an open a field of view as possible, to maximize detection range and minimize obstructions. Areas with buildings, trees, topography that can block or attenuate signal should be avoided. Ideal sites for placement of coastal stations include offshore islands, “jumping off points” along the coast where migrating animals might begin migratory flights over open water (such as the Boston/Cape Cod area, Long Island, and Cape Hatteras; e.g., Adams et al. 2015), and regions that lack coverage from existing receiving stations. Receiving stations should be designed with sufficient numbers of antennas for full directional coverage and strategically placed on the landscape to sample likely movement corridors (Lamb et al. 2023).

We recommend that coastal stations are configured, operated, and calibrated in a similar way as specified in guidance for offshore wind turbine stations. These similarities include dedicated receiving antennas monitoring 166.380 MHz and 434 MHz, remote data acquisition (using WiFi, ethernet, or cellular LTE), and continuous, year-round operation. Calibration of coastal Motus stations is important due to the presence of obstructions to line of sight within the surrounding landscape (e.g., buildings, trees, topography). Recommended workflows for offshore station calibration can be modified for coastal Motus stations. The use of unmanned aerial vehicles (UAVs) for calibrating coastal Motus stations offers the most flexibility for collecting data across a range of distances, directions, and flight altitudes.

Although providing specific guidance for configuration of coastal stations is outside the scope of this effort, guidance for offshore wind turbine stations can be generally adapted with a few key differences Coastal stations require use of a taller mast to elevate antennas above ground level (as compared to stations on turbine platforms, which are already typically >20 m ASL). If the coastal station is in an open area, antennas should be elevated on a mast that is at least 6 m ASL. Typically, coastal stations use a guyed tower with an equilateral triangle mast that is galvanized for durability (e.g., https://www.rohnnet.com/rohn-25g-tower). Because these stand-alone stations typically have more space for mounting antennas relative to stations on offshore wind turbines, it is possible to use Yagi antennas for each frequency (166 MHz and 434 MHz) on a single mast. A common configuration uses three Yagi antennas at 434 MHz, and three Yagi antennas at 166 MHz, with 120-degree separation of main beams at each frequency. More information about design and operation of coastal stations is available from Motus: https://docs.motus.org/motus-docs/stations/stations.

Guidelines for Motus tag deployment for offshore monitoring

Strategic deployment of Motus tags is essential for ensuring sufficient sample sizes, species, and populations of birds and bats are represented in monitoring efforts. There are currently two operating frequencies and several tag options available to Motus network users. Each frequency and tag type has unique characteristics and trade-offs associated with its physical properties, coding system, and technological specifications. Below, we describe some key details related to monitoring frequencies, tag types, and available technology to help Motus users make informed decisions about which frequency and tag will best meet the objectives of their tagging studies. Additional information on technical trade-offs between the two monitoring frequencies can be found in Appendix F: Considerations Regarding the Use of Different Motus Frequencies.

Operating frequencies

The Motus network monitors transmitters on two different frequencies (166.380 MHz and 434 MHz) in North America. Use of coded transmitters allows individually tagged animals to be uniquely identified on shared monitoring frequencies. Motus currently supports coded radio transmitters operating on 166.380 MHz that are manufactured by Lotek Wireless Inc. (Newmarket, ON, Canada) and coded radio transmitters on 434 MHz that are manufactured by Cellular Tracking Technologies (Rio Grande, NJ, USA).

Motus tags transmitting at 434 MHz are coded using frequency-shift keying (FSK), which allows for approximately 4 billion unique ID codes utilizing a digital signal. This digital signal carries a digital checksum which enables automatic rejection of noise associated with signal bounces, reflections and radio frequency interference (RFI).

Motus tags transmitting at 166.380 MHz are coded using amplitude modulation, which allows for 521 unique ID codes. By varying the burst rate interval of tags (between 2.3 to 39.7 seconds), over 36,000 uniquely identifiable tags are possible. These tags do not utilize digital checksum for noise rejection, so stations monitoring 166.380 MHz may require more calibration relative to 434 MHz stations due to the lower signal-to-noise ratio. The higher levels of RFI and corresponding lower signal-to-noise ratio associated with 166.380 MHz may result in higher data transfer fees per month for stations configured with GSM or satellite modems. Additionally, 166.380 MHz codes are not unique and thus are at a higher risk of issues with tag aliasing (i.e. tags appearing as duplicates in data base) that may require additional data processing steps to resolve.

Other factors to consider include power consumption, detection range, and hardware required for monitoring (Table 2). Higher frequency tags (e.g., 434 MHz) innately require more power to generate a signal and thus tags will have a reduced lifespan relative to lower frequency tags (e.g., 166 MHz) given the same battery capacity. Tags operating at 434 MHz will also have a shorter range than 166 MHz tags as they will have a higher probability to interact with particulates in the air. However, due to the differences in the size of the wavelength between the two frequencies, stations monitoring 166 MHz will require use of larger antennas relative to 434 MHz to achieve similar gain. Stations monitoring 166 MHz using SensorStation receivers also require "Software Defined Radios" that need specific formatting and testing prior to use. For more information, see: Antennas, Cables, and Dongles - Motus Docs

Tag types

There are two main types of transmitters in the Motus network: solar tags and power-regulated tags. Solar tags are powered either entirely by a solar panel (e.g., CTT 'LifeTags') or using a battery that is recharged by a solar panel (e.g., CTT 'Hybrid Tags' or Lotek 'Solar Nanotags'). The primary advantage of using a solar tag is that the tag longevity is extended, allowing individuals to be tracked over longer periods of time. However, a main disadvantage of solar powered tags is that the signal strength and transmission schedule vary with available light and power levels. Tags that are entirely solar (e.g., LifeTags) do not transmit at night, for example. Therefore, these tags are not recommended for offshore wind monitoring because data collection at night is a top priority; many focal species migrate offshore at night and Motus is one of the few technologies that can address information gaps on these nocturnal movements. Solar tags with a battery cell (e.g., CTT 'Hybrid Tags' or Lotek 'Solar Nanotags') may stop transmitting for periods of time, or transmit weaker signals, depending on the charge state of the battery and available light. These gaps in transmission time and variations in transmitted signal strength result in significant gaps in detection coverage, especially during night and other low-light conditions (e.g., fog, salt accumulation on solar panel) that are prevalent offshore. Therefore, use of solar tags is not currently recommended for offshore wind monitoring because exposure estimates assume constant detection probability, and this cannot be achieved or accounted for using current solar tag technology. In addition, because the power output of solar tags varies with available light, these tags are not suitable for use in signal-strength based estimates of tag location and altitude (e.g., Janaswamy et al. 2018).

Power-regulated tags are battery-powered transmitters that transmit consistent signals on a consistent transmission rate until the tag expires. There are currently two main types of power-regulated tags on the Motus Network: Lotek 'Nanotags' (166 MHz) and CTT 'PowerTags' (434 MHz). Transmission rate (time between signals) is configurable and typically ranges from 5 seconds to 15 seconds. Because a tag's transmit rate is related to its detection probability, we recommend configuring tags to a standardized transmit rate of 5 seconds where possible (e.g., for tags weighing ≥1 g or for studies with temporary attachment methods for short term data collection). The lifespan of power-regulated tags depends on the transmit rate and battery size, which affects tag weight. Overall, tags transmitting on 166 MHz tend to be longer lasting relative to tags transmitting on 434 MHz. For example, 166 MHz power-regulated tags weighing 1 g with a five second burst interval have an estimated longevity of 203 days (Lotek Wireless, pers. comm.), whereas tags with the same specifications at 434 MHz have an estimated longevity of 28 days (CTT, pers. comm.).

Current information on tag weights, burst intervals, and longevity can be obtained through the tag manufacturers (Lotek Wireless for 166 MHz and CTT for 434 MHz).

Number of tags and stations in Motus per frequency

Originally, the Motus network only operated at 166 MHz (starting in 2012). The second frequency, 434 MHz, was introduced to Motus in 2019. Therefore, there are more Motus stations monitoring 166 MHz relative to 434 MHz. There have also been more tag deployments at 166 MHz because the frequency has been used by Motus for a longer period, and therefore has had more field testing relative to 434 MHz. However, the number of stations monitoring 434 MHz and tags deployed at 434 MHz has increased in recent years and each frequency has unique advantages and disadvantages to consider when planning a tagging study (Table 2).

Table 2. Technological considerations of using Motus tags operating at 166 MHz and 434 MHz.

Consideration	166 MHz	434 MHz
Tag weight (power regulated tags)	Lighter (starting at 0.13 g)	Heavier (starting at 0.35 g)
Tag longevity	203 days (weight: 1 g, burst: 5 sec)	28 days (weight: 1 g, burst: 5 sec)
Unique IDs	521 (36,000 by varying burst rate)	Billions
Coding system	Amplitude modulation	Digital check sum
Radio receiver	Requires separate radio receiver if using SensorStation receiver	Radio receiver integrated with SensorStation
Receiving antennas	Larger (requires more space)	Smaller
Signal to noise ratio	Lower	Higher (better)

Focal species

The small size and light weight of Motus tags makes it possible to use the technology to track nearly any species of bird or bat in North America. This flexibility offers the potential to address information gaps relative to offshore wind for a wide variety of taxa. In particular, the light weight of Motus tags, and ability of Motus stations to track movements around the clock, makes this technology especially suitable for monitoring small-bodied birds that migrate offshore at night, such as shorebirds and passerines. However, use of this technology has broader implications to address additional information gaps on offshore movements for many species of interest, which is further leveraged by the collaborative structure of the tracking network that facilitates monitoring of large sample sizes of animals tagged by many cooperators throughout the migratory range.

Decisions on which species to tag and monitor are often driven by regulatory responsibilities and other conservation priorities. Information regarding potential effects of offshore wind energy development to species listed as "Threatened" or "Endangered" under the U.S. Endangered Species Act (ESA) is needed to inform risk assessments using the best available science. Effects to non-ESA listed species are addressed through the National Environmental Policy Act (NEPA) and Migratory Bird Treaty Act (MBTA). Due to the large number of species covered by NEPA and MBTA, it may be necessary to prioritize monitoring efforts using factors including population status, vulnerability to effects of offshore wind energy development, and potential occurrence of the species in the affected area. High priority species include federally listed, proposed, and candidate bird and bat species likely to occur in the offshore environment and other flying species of concern in the offshore environment such as certain Bird Species of Conservation Concern, At-Risk species, State-listed species, and Species of Greatest Conservation Need as identified in State Wildlife Action Plans. Below, we summarize some key factors to consider when deciding which species to tag for offshore Motus studies.

ESA-listed species

ESA-listed bird species that may occur in the U.S. Atlantic are the Piping Plover (*Charadrius melodus*), the *rufa* sub-species of the Red Knot (*Calidris canutus rufa*) and the Roseate Tern (*Sterna dougallii*). An ESA-listed bat may also occur in the U.S. Atlantic, the Northern Long Eared Bat (*Myotis septentrionalis*).

The Piping Plover is a migratory shorebird with an Atlantic coast nesting population that extends from the Canadian Maritimes to North Carolina (Elliott-Smith and Haig 2020). The Piping Plover may occur off the coast of North America during migration between breeding areas and wintering areas in the southeastern US and Caribbean (Loring et al. 2019). The Atlantic Coast population of the Piping Plover is listed as 'Threatened' under the U.S. ESA (USFWS 1996) and is listed as 'Endangered' in Canada under the Species at Risk Act (Environment Canada 2012).

The *rufa* Red Knot is a long-distance migratory shorebird that occurs along the U.S. Atlantic coast and OCS during spring and fall migration between breeding areas in the Canadian Arctic and non-breeding areas that extend to southern latitudes of South America (Burger et al. 2011). The *rufa* Red Knot is listed as 'Threatened' under the U.S. ESA (USFWS 2014) and is listed as 'Endangered' under Canada's Species at Risk Act (Environment and Climate Change Canada 2016).

The Roseate Tern is a small-bodied colonial seabird. In North America, Roseate Terns breed on a limited number of islands off the northeastern coasts of the U.S. and Canada and occur off the coast of North America during the breeding period and migration. The northeastern breeding population of the Roseate Tern is listed as 'Endangered' under both the U.S. ESA (USFWS 1987) and Canada's Species at Risk Act (Environment Canada 2006).

The Northern Long Eared Bat (*Myotis septentrionalis*) is a migratory bat that is listed as 'Threatened' under the U.S. ESA. Although there is little known about movements of Northern Long Eared Bats, acoustic monitoring has detected them in areas offshore of the northeastern U.S. (Stantec 2018).

Birds of Conservation Concern

The Birds of Conservation Concern 2021 List (BCC 2021) identifies migratory non-game bird species that represent highest conservation priorities, beyond those ESA-listed. The list is based on an assessment of several factors, including population abundance and trends, threats on breeding and nonbreeding grounds and size of breeding and nonbreeding ranges. This list can be used to help inform selection of species for monitoring studies that are non-ESA listed but of high conservation priority. For a complete list, see: https://www.fws.gov/media/birds-conservation-concern-2021pdf

State-listed species

States along the U.S. Atlantic coast have identified high priority species for conservation within their jurisdiction, including species designated as 'Endangered', 'Threatened', or Special Concern' within ESAs of individual states. In addition, each state has a State Wildlife Action Plan (SWAP) that designates priority species of Greatest Conservation Need. This information should be considered when designing tagging projects for state-specific or regional offshore monitoring activities. For more information, see: https://www.fishwildlife.org/afwa-informs/state-wildlife-action-plans

Surrogate species

Surrogate species are used to represent other species or aspects of the environment to attain a conservation objective (Caro 2010). There may be situations that warrant consideration of tagging non-ESA listed species that could inform movements of ESA-listed species while providing important information on species that are not ESA-listed but may be identified as a species of conservation concern elsewhere. One example is using information from Common Tern tracking studies to infer movements of Roseate Terns. Common and Roseate Terns are colonial seabirds that nest sympatrically on islands off the US Atlantic coast (Arnold et al. 2020, Gochfeld and Burger 2020). Both species occur in offshore areas of the Atlantic during the breeding period and migrate across the Atlantic outer continental shelf while traveling between northern breeding grounds and the southern nonbreeding range that extends along the coast of South America (Arnold et al. 2020, Gochfeld and Burger 2020). The Common Tern is listed as a Threatened or Special Concern species by the states comprising its U.S. Atlantic coast breeding range (Maine to South Carolina). Studies tagging Common Terns and Roseate Terns using the same methods have documented significant adverse effects (i.e. injury, mortality, and behavioral abnormalities) to Roseate Terns but not to Common Terns (Nisbet et al. 2011, Mostello et al. 2014, Paton et al. 2020). Therefore, while tagging Common Terns may help provide movement data that are insightful for Roseate Terns, differences in behavior and life history strategies limit the direct inferences between the two species.

Shorebirds

Shorebirds are a high priority for Motus tagging studies relative to offshore wind energy due their over-water regional staging movements, long-distance offshore migrations, dependency on coastal stopover habitats, and declining populations. Many shorebird species are small-bodied and migrate at night, so little is currently known about their occurrence in specific offshore areas because they cannot be reliably monitored by boat-based or aerial surveys typically used for site assessment activities. In the Atlantic Region of North America, information on population status of shorebirds in North America can be found in Andres et al. (2012) and Smith et al. (2023).

Marine Birds

Marine birds use offshore habitats year-round and are a high priority for consideration in offshore wind assessments. Marine birds tend to be large-bodied, and many species spend a large proportion of their time on the water. Specific questions on their marine habitat use may be better addressed using satellite-based tracking technologies that provide specific location estimates and associated error, such as GPS or Argos transmitters. However, Motus tags can be deployed on marine birds to provide complimentary information on their movements within and between sites, if sufficient coverage is available from offshore Motus stations within sites of interest.

The Nature Conservancy Developed a Marine Mapping Tool that shows estimated relative abundance for individual marine bird species across the year. Estimated abundance maps are based on models using boat-based and aerial seabird survey data (Winship et al. 2018). Species represented are primarily marine birds (including seabirds, sea ducks, and loons). The tool ranks species by estimated relative abundance in various categories, including conservation status, life history characteristics, and vulnerability to displacement or collision risk from offshore wind energy. This is a useful tool to consider when planning tagging studies for marine birds. For more information, see: https://maps.tnc.org/marinemap

Passerines and other nocturnal migrants

Passerines and other nocturnal migrants are high priorities for Motus tagging studies because relatively little is known about their offshore movements due to challenges of monitoring birds offshore at night. Information on the timing and direction of movements of species in coastal areas can help identify focal species for regional tagging studies to address offshore information gaps. The BirdCast Migration Dashboard from Cornell Lab of Ornithology summarizes radar-based measurements of nocturnal bird migration, including estimates of the total number of birds migrating, their directions, speeds, and altitudes. It combines this information with E-bird data to estimate expected nocturnal migrants (including passerines, waterbirds, other taxa) by state or county. A live data feed runs from March 1 to June 15 during spring migration and from August 1 to November 15 during fall migration. Historical data are available from 2013 to present. This is a useful tool to consider when planning tagging studies for passerines and other nocturnal migrants. For more information, see: https://birdcast.info/migration-tools/migration-dashboard/

Motus database

The Motus database has publicly available summaries of tag detection data at all Motus stations across the network. Detection data from Motus stations in geographic regions of interest can be used to help determine species to prioritize for future tagging studies aimed to address information gaps on offshore movements. In addition, these data can be used to identify investigators that are conducting Motus tagging efforts on species of interest. For more information, see: www.motus.org

Expert opinion

When initiating a tagging study, it is helpful to consult with species subject matter experts in geographic regions of interest. In the Atlantic Region of North America, many subject matter experts participate in regional stakeholder efforts for wildlife and offshore wind. For example, in 2020, the New York State Energy Research and Development Authority (NYSERDA) funded the development of a scientific research framework to guide the long-term study of potential impacts to birds and bats from offshore wind energy development in the eastern United States, including convening subject matter experts in a workshop that begin to identify science priorities and focal species for future tagging studies (NYSERDA 2020). Building from this effort under the auspices of the Offshore Wind Environmental Technical Working Group (E-TWG), several workgroups arose out of the 2020 State of the Science Workshop for Wildlife and Offshore Wind to further identify research priorities for understanding cumulative biological impacts to birds and bats as the offshore wind industry progresses (Cook et al. 2021, Hein et al. 2021, Gulka et al. 2022). Most recently, the Regional Wildlife Science Collaborative for Offshore Wind (RWSC) was cooperatively established in 2021 and is led by four Sectors (federal agencies, states, eNGOs, and the offshore wind industry) to support research and monitoring for offshore wind. The RWSC Bird and Bat Subcommittee is available to help provide expertise and coordination for avian and bat tagging studies. Coordinating with species and subject matter experts can provide opportunities to leverage resources, maximize information gains, and help facilitate the use of best available science when planning and conducting studies.

Tagging methods

There are many factors to consider when designing tagging studies, including study objectives, focal species, technology limitations, and other logistics. Below we summarize some of the key factors that are important to consider when designing tagging studies for offshore monitoring. We strongly recommend that project proponents coordinate with species experts and subject matter experts when designing tagging studies to help ensure the best possible outcomes.

Timing and locations of tag deployment

Animals should be tagged during target time periods and geographic locations for data collection to best meet study objectives. For example, studies on migratory movements relative to offshore wind project areas should consider focusing tagging efforts on staging or stopover areas as close to the wind project area as possible and consider available information on likely direction of travel, which may vary by population or sub-population (Loring et al. 2020). Studies on movements of marine birds should aim to tag individuals as close to the focal offshore wind project area(s) as possible to ensure that the individuals are representative of populations that may use the area. In these circumstances, capture sites could include nesting colonies that are closest to offshore wind project areas or at-sea capture efforts in or near the offshore wind project areas.

For many species, tags will be deployed outside the offshore Motus coverage area due to logistical issues, and researchers must establish a reasonable expectation of detection for the tagged animals. Some *a priori* knowledge of migratory pathways or movement patterns is needed to ensure that tag deployments will be useful. If that is not possible, pilot studies will be critical to avoid misspent resources and unnecessary risk to wildlife.

Duration of data collection

Duration of data collection can be limited by battery life of the tag, which directly corresponds to its size and weight, and weight limitations that focal species can carry. All bands, auxiliary markers and attachment materials should not exceed 2% body weight for leg attachments and should not exceed 3% body weight for all other attachment types (USGS 2018).

A variety of tag attachment methods are available for short-term (days to weeks), medium-term (weeks to months), or long-term (months to years) tracking durations. Tag retention time varies widely by method, species, and individual. Short-term tag attachment methods include using glue or tape to attach the tag to skin, feathers, or trimmed feathers. Medium-term attachment methods include use of biodegradable attachment materials (e.g., sutures, harnesses with built in “failure points”). Longer term attachment methods use harnesses made of more robust materials or other permanent methods (e.g., surgical implants, gluing to leg bands) to track animals over the course of multiple years.

In general, shorter term attachment methods that use minimal materials and minimize the amount of time the tags are carried by animals have lower risk of adverse effects to tagged individuals relative to longer lasting or more invasive tag attachment procedures. In addition, heavier, longer lasting and more invasive attachment methods may cause behavioral or physical abnormalities that may put tagged individuals at risk, bias the movement data, and provide misleading results. However, tags using short-duration attachment methods may result in less data collection overall if tags fall off before the data collection period is complete. Therefore, researchers must determine optimal tag attachment methods for focal species given a variety of tradeoffs around species size and weight, weight of attachment materials, sensitivity and conservation status of focal species, life history characteristics of focal species, target duration of data collection, and other considerations. When possible, we recommend conducting studies to determine how transmitter attachment longevity and detectability can be increased without increasing negative impacts to the animal.

Decisions on how best to tag focal species are best made in consultation with subject matter experts. Resources include working groups for species or taxa of interest (e.g., Roseate Tern Working Group, Atlantic Marine Bird Cooperative, Atlantic Flyway Shorebird Initiative, Bat Marking Working Group) and the RWSC Bird and Bat Subcommittee.

Number of tags to deploy

The number of tags to deploy for tagging studies depends on the specific study objectives. Ideally, these decisions should be informed by a power analysis for species and questions of interest. As part of this effort, we collaborated on a retroactive power analysis conducted using Motus data from a temperate nesting shorebird (Piping Plover) and a colonial seabird (Common Tern), representing two taxonomic groups of interest for tagging studies relative to offshore wind in the U.S. Atlantic. The analysis found that for assessments of baseline site occupancy, each species required ~100-150 individuals to model 90% of used sites at the population level, with ~40-50 additional individuals needed to achieve 95% representativeness (Lamb et al. 2023). Evaluating more complex metrics (e.g., abundance, migratory routes), as well as associating changes in distribution with specific covariates (e.g., demographic variation, atmospheric condition) would require higher sample sizes (Lamb et al. 2023). Results from power analyses indicate that information gains increase when transmitters are deployed among multiple sites and years. Therefore, a coordinated approach is necessary to optimize information gains from tagged individuals and provide data that are comparable across wind project areas (Lamb et al. 2023).

Minimum metadata to collect in field

Each time an animal is tagged, minimum metadata should be collected in the field. The following minimum metadata should be collected for all offshore Motus tagging studies:

- Site name and location (latitude and longitude) of capture and tagging activities
- Capture date and time
- Release date and time
- Species
- Age: if known
- Sex: if known
- Weight
- Measurements (e.g., wing cord, bill length, tarsus)
- Tag type (manufacturer and model)
- Tag ID number: manufacturer ID and serial number (if available)

- Tag attachment type
- Band number
- Auxiliary marker(s): e.g., leg flag, color bands, marker characteristics (alpha-numeric codes, color)
- Institution and contact info
- Agent and contact info
- Notes on animal or tag status: e.g., date and location of mortality, dropped tag, failed tag, etc.

These minimum metadata must be entered in Motus to consistently archive information on individually tagged animals. For species where sex is undeterminable in the field based on plumage and other characteristics, we recommend collecting 3-5 contour (body) feather samples for molecular sex determination where possible. Multiple companies are available that provide molecular genetic sexing of wild birds using feather samples. We recommend contacting different companies to ensure that services are available for the target species.

Monitoring

Where possible, tagged birds and bats should be monitored at the capture site following release to evaluate any behavioral abnormalities associated with tagging and to assess tag retention. Monitoring of tagged animals can be conducted using manual telemetry surveys, which allows for direct observation of locations and behavior. In addition, Motus stations deployed in capture locations can provide information on how long animals were detected at tagging sites.

For studies tagging ESA-listed species, monitoring of potential tag effects is critical to ensuring that individuals are not adversely affected. Additionally, when using new tag technology or attachment methods on ESA-listed species, it is recommended to deploy transmitters in phases, starting with 1-2 individuals that are closely observed for 48-72 hrs to ascertain that there are no adverse impacts before continuing to mark additional birds (Paton et al. 2020). Tagging and monitoring plans for ESA-listed species should be developed in close coordination with species leads from federal and state agencies where activities will be conducted and requires specialized permits.

Permits

A variety of permits and permissions are needed to conduct tagging studies. Obtaining individual permits may require submittal of a detailed study plan or other specific documentation. Permits authorizing capture and tagging of ESA-listed species require lead times of at least 6 months to one year. Therefore, sufficient lead time should be allocated when planning studies in order to complete all permit requirements before the target period for data collection. It is the responsibility of study investigators to identify and obtain all necessary permits and permissions to carry out their proposed work legally.

These permits may include:

- Animal Care Approval from an institution or approved organization
- U.S. Geological Survey Federal Banding and Marking Permit
- State collecting or marking permits
- Federal and state permitting requirements for ESA (for listed species)
- Local permits and permissions (as needed for activities on town properties, parks, etc.)

Data coordination

Tracking animals provides invaluable movement data that are otherwise unattainable. However, capture and tag attachment can be risky, with potential for injury, mortality, increased stress, and increased energetic demands. Sample sizes of tagging studies are limited by factors including funding for tags, field effort, capture logistics, and minimizing risks to tagged individuals. However, larger sample sizes provide better information for population-level inferences and strategic tag deployment across sites leads to better information at regional scales. Therefore, it is important to optimize sample sizes and tag deployment as much as possible to obtain the best possible information from these studies.

Coordinated, strategic deployment of Motus tags is critical to ensuring that the best available science is used in offshore wind energy research, assessments, and monitoring. Various factors (including sample size, tagging location, and timing of tag deployment) affect the precision and accuracy of population-level inferences drawn from samples of tagged individuals. Thus, is important that all relevant information is strategically collected and available for assessments at site-specific and cumulative scales.

The Motus collaboration policy (Birds Canada 2022a) specifies two main levels of data availability: summary (basic) data that are publicly available and detailed (complete) data that are available to project PIs and designated Motus collaborators. The basic dataset includes deployment metadata from all Motus tags and stations from all projects and daily summaries of tag detections at each station. The detailed dataset includes full metadata from tags and stations deployed by a project, and full detection data from project tags at all stations throughout the Motus network. For more information on the specific and metadata included within each dataset, please refer to the Motus collaboration policy (Birds Canada 2022a).

Offshore wind energy projects that operate Motus stations but are not collaborators on tag projects will therefore only have basic-level access to data that their stations collect. While these data can be useful for opportunistic monitoring of species presence within a project area, dedicated tagging efforts and data coordination across efforts are needed for access to detailed data for use in analysis (e.g. estimating timing of movements through a site, using triangulation to estimate locations of animals within a site, etc.). More robust estimates of exposure at site-specific and cumulative scales require data from sample sizes and tagging efforts representative of regional populations of interest. Such sample sizes are most effectively attained through regional tagging and data coordination efforts.

Data analysis

Analysis of Motus data can be used to meet a variety of objectives across a range of spatial and temporal scales. For offshore applications, these objectives range from addressing general information gaps on regional movement patterns of different species, to targeting more specific research questions such as the timing and weather conditions associated with flights through wind energy project areas.

Site-specific Motus data can be collected to inform different phases of offshore development, from pre-construction risk assessments (using stations on buoys) to monitoring during construction and operations through the lifetime of a project (using stations on turbines). At the most basic level, these stations can be used to determine species presence in a project area, defined as the occurrence of one or more focal species within a project area during a specified time period. Analysis of site-specific species presence data with covariate information (including demographic, temporal, and atmospheric data) can provide additional information on variation in the exposure of populations to offshore wind energy projects and the conditions under which exposure may occur.

When combined across the network, data from site-specific stations can be used to inform regional-scale analyses. Regional-scale questions that Motus can address for offshore wind energy assessments using the broader network of stations in the U.S. Atlantic include:

- Spatial and temporal variability within and across sites
- Cumulative exposure of tagged animals to multiple wind energy project areas throughout the U.S. Atlantic region
- Proportion of tagged individuals using offshore vs. coastal migration routes
- Geographic variation in migration routes, including migratory departure points along the coast where migrating animals might begin migratory flights over open water

Data analysis for station data

Projects that operate offshore Motus stations can access summary data from any tagged animal detected at their stations. Summary data can be explored, summarized, and downloaded in automated reports and csv files from the web interface on www.motus.org. For more information on using the Motus interface for offshore applications, see the Offshore Motus Data Framework.

Detailed detection data are typically analyzed by Tag PIs and their designated collaborators. Station operators interested in conducting more detailed analysis of detailed detection data collected at their stations should contact the Tag PIs associated with the project(s) of interest. For assistance with facilitating these requests, please contact Stuart Mackenzie (smackenzie@birdscanada.org).

Data analysis for tag deployments

Projects that deploy tags have access to detailed detection data from those tags via the 'motus R' package (Birds Canada 2022b) in Program R (R Core Team. 2022). For offshore wind applications, these data can provide information on the number of tagged individuals detected in wind energy project area(s), the timing associated with occurrence in wind energy project area(s), and their regional movement patterns.

We recommend including the following elements in workflows for standard analyses of tag deployment data for an offshore wind project. These data could include birds and bats tagged as part of a project's monitoring plan, or data collected across tagging studies for use in site-specific and regional analyses. The workflow assumes a working knowledge of Program R. Steps for downloading, cleaning, formatting, and summarizing Motus data are described in the 'motus R' documentation with various chapters referenced in the workflow below. Additional packages are suggested to interpolate points, add weather and timing covariates, calculate derived flight metrics, and summarize flights across wind project areas.

Using Motus R package to summarize detection data:

1. Download full detection data using Motus R package
    - Install packages: https://motuswts.github.io/motus/articles/02-installing-packages.html
    - Access detection data: https://motuswts.github.io/motus/articles/03-accessing-data.html

2. Data verification and cleaning

- Check tag and receiver deployments: https://motuswts.github.io/motus/articles/04-deployments.html
- Clean data to remove false positives: https://motuswts.github.io/motus/articles/05-data-cleaning.html

3. Summarizing, plotting and mapping detection data relative to BOEM Lease and Planning Areas
    - Add sunrise and sunset times to detection data: https://motuswts.github.io/motus/articles/06-exploring-data.html
    - Map detection data: https://motuswts.github.io/motus/articles/06-exploring-data.html
    - Adding Bureau of Ocean Energy Management (BOEM) Lease and Planning Areas to map: https://www.boem.gov/renewable-energy/mapping-and-data/renewable-energy-gis-data

Using other R packages to add covariate information

Additional R packages are available (e.g. 'RNCEP', Kemp et al. 2012) that allow users to add weather covariates (including wind speed, wind direction, precipitation, visibility) to movement data and calculate derived flight metrics (air speed, ground speed, heading, wind support). These methods can be used in conjunction with the Motus R package to summarize movement patterns across project areas, including timing, weather conditions, derived flight metrics, and demographic variation (e.g. species, age, sex, etc.). It is important to note that movement tracklines generated from the Motus R package represent station to station interpolations and as such, may not accurately represent actual movement paths of tagged animals. Efforts are underway to develop additional analysis tools to triangulate locations of tagged animals when they are within detection range of multiple antennas simultaneously. These methods intend to improve the accuracy of location estimation (and associated spatial error) using Motus detection data.

Recommended reporting elements for tagging studies

The following section summarizes recommended elements to include in reports from Motus tagging studies with applications for offshore wind energy monitoring or research. The elements are categorized by report section, with a focus on methods and results. Project PIs are encouraged to add additional content and research questions specific to their study objectives. The standardized elements below provide baseline information for reporting consistency across sites. This list will evolve as additional data analysis tools, methods, and research questions are developed and implemented.

Recommended elements for methods section

Tag deployment information

- Name and number of Motus Project under which tags are deployed
- Number, locations, and dates of tag deployments within the Motus Project
- Map of tag deployments
- Table of required tag deployment metadata (see above section 'Minimum metadata to collect in field')
- Specifications of tags used, including tag model, burst rate interval, attachment type, estimated duration

Station information

- Number, locations, and dates of station deployments within the Motus project
- Map of station deployments
- Table of required station deployment metadata (see 'Station Metadata' section in Guidance Document)

Data cleaning and filtering methods

- Specific criteria used to QA/QC and filter detection data to remove false positives (workflows described in 'motus R' documentation and summarized in 'Data analysis for tag deployments' section above)

Information about covariates:

If covariates are used in tag data analysis, the following information is recommended:

- Metadata (source, link, resolution) of all covariates, for example:
    - Daylight (time of local sunrise/sunset) and criteria used to categorize light conditions (e.g., day, night, dawn, dusk) or treat as continuous variable (e.g., hours from sunrise/sunset)
    - Weather data (e.g., wind speed, wind direction, precipitation, visibility) - source, link, spatial resolution, temporal resolution
- List methods or R-package used to calculate derived metrics (e.g., air speed, ground speed, heading, wind support)

Recommended elements for results section:

Summary of detection data collected per animal

Summaries of detection data collected for each tagged animal should include a table with the following information:

- Tag IDs
- Band number
- Flag IDs (where relevant)
- Age class
- Sex (if known)
- Body mass
- Tag deployment date
- Tag deployment site
- Date of last station where detected
- Geographic site of last station where detected
- Total number of stations where detected (excluding any poor-quality locations with filter criteria identified above)
- Total number of days tracked
- Total distance tracked (km)
- Offshore wind planning or lease area(s) with detections from offshore Motus stations
- Offshore wind planning or lease area(s) intersected by interpolated tracklines between station detections (see 'Trackline maps' section, below)

Trackline maps

Reports should include maps of each tagged animal's trackline with the following information displayed:

- Locations of active Motus stations in the study area
- Locations of Motus detections (points) per animal
- Tracklines (interpolated line connecting points)
- Polygons of current BOEM Lease and Planning Areas
- Focal offshore wind project area(s) highlighted (where relevant, e.g. for site-specific studies)

Summaries of flights across wind energy project areas

For tracks that intersect wind energy project areas, additional summaries could include information such as timing, weather conditions, demographic variation (e.g., age, sex if known), and other metrics (speed, heading, altitude) of flights across specific lease areas and regionally.

These summaries could include a table and a series of plots/histograms of flights across wind energy project areas summarizing:

- Time of day
- Light (e.g., day, night, dawn, dusk)
- Date
- Wind speed
- Wind direction
- Precipitation
- Visibility
- Air speed
- Ground speed
- Heading
- Wind support

Recommended elements for supplemental information

For data consistency and transparency, we recommend providing the following supplemental information with all reports from tagging studies.

- R data output file(s) as .Rdata or .rds file(s) of processed data (cleaned Motus data, with metadata and weather covariates)
- Motus Project Report summarizing data from all stations and tags within the Motus project (see Motus Data Framework, "Project reports")
- Supplemental summary-level data downloaded with Motus Project Report in .csv format:
    - Station deployments
    - Antenna configurations
    - Detections
    - Animals tagged

Site-specific monitoring

Site-specific monitoring of offshore wind project areas should occur during each phase of the project's lifetime: pre-construction (site assessment), construction, operation, and decommissioning. Collecting standardized monitoring data for the lifetime of the project is necessary to document baseline conditions at the site and monitor changes that may occur over time. Standardizing elements of site-specific monitoring plans is necessary so that data can be used for comparisons across sites and for regional-scale analyses. The recommendations below identify elements for pre- and post-construction monitoring plans to collect consistent site-level information following minimum data standards. Collection of additional information to address site-specific and regional science needs is encouraged and should be coordinated with regulatory agencies and regional coordination groups.

Pre-construction

Prior to construction of the offshore wind energy project, project developers must prepare a Site Assessment Plan (SAP) that includes characterization of avian and bat resources. Site Assessment activities should include deployment of Motus stations on offshore buoys to help address information gaps on the presence of birds and bats offshore.

Site Assessment Plans should include the following elements that are conducted following recommendations in the Guidance Document, Motus Data Framework, and Monitoring Framework:

- Deploy Motus stations on buoys
- Register all buoy stations with the Atlantic Offshore Wind Group in Motus
- Use the IDIOMS tool to estimate detection coverage of buoy stations
- Conduct calibration surveys to quantify detection coverage from the buoy stations
- Use the Calibration Data Analysis Tool to produce an automated reports for each calibration survey
- Download detection data and conduct routine maintenance of all buoy stations minimum of every three months (recommended) to every six months (where access is limited).
- Submit all detection data and metadata to Motus within timeframes identified in Offshore Motus Guidance (i.e. within 7 business days of data collection)
- Generate an automated 'Project Report' and supplemental data (downloaded as .csv files) from Motus to summarize data from all stations and tags within the Motus project
- Conduct more detailed analyses of animal movements and any site-specific covariate data (e.g., visibility sensors required as part of SAP conditions)
- Submit all calibration reports, automated reports, and reports with results of detailed data analysis to regulatory agencies
- Provide regulatory agencies access to all detailed detection data and metadata through the Motus database by designating agency contacts from Department of Interior as 'Collaborators' on the Motus project(s).

Additionally, developers should consider funding regional tag deployment efforts for species with high priority information needs during the SAP. These tag deployment efforts should be planned in coordination with BOEM, the USFWS, and the RWSC. Information from the site assessment period should be summarized in the Avian and Bat section of the Construction and Operations Plan.

Construction and operations

During the environmental review process of an offshore wind project's construction and operations plan, project proponents develop an avian and bat monitoring framework that identifies monitoring objectives, proposed monitoring elements, and reporting requirements. This framework forms the basis of a more detailed 'Avian and Bat Post-Construction Monitoring Plan' that is included in terms and conditions of COP approval.

Avian and bat monitoring frameworks

Avian and bat monitoring frameworks should refer to and follow all recommendations in the Guidance Document, Motus Data Framework, and Monitoring Framework including protocols for the following elements:

- Motus stations: description, specifications, numbers and frequencies, deployment, operation, calibration
- Motus tags: description, specifications, numbers and frequencies, focal species, deployment, regional coordination
- Data: metadata standards, data management, storage, and availability
- Analysis and reporting: data delivery, use of standardized analysis methods and reporting standards

Avian and bat monitoring plans

Avian and Bat monitoring plans should include detailed information on objectives and protocols for Motus stations, tagging studies, data management, and reporting. Monitoring plans should also provide information on regional coordination of tagging efforts and data analysis. All Motus station data, tag data, and metadata should be provided as non-proprietary information so that data is available for use and assessments at regional scales. Regional assessments are necessary for use of best available science due when studying migratory species at scales that are ecologically meaningful.

Avian and Bat monitoring plans should detail how protocols and objectives will be implemented following the 'Monitoring Protocols and Guidance' and should include the following elements:

Station design

- Station specifications and configurations
- Number of stations related to number of turbines (e.g., two stations per 25 turbines, prioritized for each frequency)
- Placement informed by IDIOMS tool

Station calibration, maintenance, and data workflows:

- Station deployment schedule
- Calibration survey design and schedule
- Regular maintenance activities and schedule
- Data download and delivery protocols, workflow, and schedule

Tagging studies and regional coordination

- Tag specifications, numbers, focal species

- Schedule and plan for coordinating tagging studies with BOEM, USFWS, and the RWSC Bird and Bat subcommittee
- Detailed plans for funding tags, tag deployment (including species, sites, schedule, and identified partners), associated monitoring and other field activities, data analysis, and reporting elements and schedule
- Data management and storage protocols
- Funding for maintenance and data fees for coastal stations: number of stations, duration of funding

Data availability

- All detailed station detection data, tag detection data and metadata should be made available to USFWS and BOEM by designating agency contacts from Department of Interior as ‘Collaborators’ on the Motus project(s), so that they are provided access in the Motus database.
- All Motus projects deploying tags or stations for offshore wind permitting requirements and other applications should add designated agency contacts from Department of Interior to the Motus project as 'Collaborators' with full access to view and download data.

Site-specific reporting standards

The following automated reports should be included with all site-specific monitoring reports as minimum standards. The most recent versions of these reports should be included in all pre-construction site assessment reports and post-construction monitoring reports as minimum reporting standards.

IDIOMS reports

- Initial IDIOMS report (proposed coverage of a wind project area) included in station design reporting, above
- Final IDIOMS report (actual coverage). This report should be updated any time that a station configuration or array configuration changes, including changes in station antenna angles or removal or movement of a receiver station.
- Within IDIOMS the “minimum flight height” value should be set to the lower limit of the project’s RSZ and the “maximum flight height value” should be set to the upper limit of the project’s RSZ. For more information, see the IDIOMS user manual. Increments should be 25-50 m.
- Simulate shorebird and seabird data tracks to display typical bird crossings and include in results. Flight height minimum/maximum should be same as above; direction of flight should be that most aligned with the general angle of the coastline (the default of NE should work for most locations from MA to VA); number of birds to simulate should be at minimum 25 (which is the default); and number of bootstrap resamples to develop a measure of uncertainty in the detections estimates) should be at least 1000 for seabirds and 500 (the default) for shorebirds.

Motus reports

- Motus Project Report summarizing data from all stations and tags within the Motus project during the reporting period (see Motus Data Framework, “Project reports”)
- Supplemental summary-level data downloaded with Motus Project Report in .csv format:
    - Station deployments

    - Antenna configurations
    - Detections
    - Animals tagged

Calibration reports

- Use Calibration Data Analysis Tool to generate a calibration report for each station in project (https://birdsdev.uri.edu/) and calibration survey conducted

Data availability statements

List Motus project(s) numbers associated with all site-specific monitoring. For each project, identify the designated agency contacts from Department of Interior that are listed as 'Collaborators' on the Motus project(s).

Supplemental information

Supplemental information should be provided with each report, including:

- R data output file(s) as .Rdata or .rds file(s) of processed data (cleaned Motus data with metadata, and weather covariates as applicable)
- Photos of each Motus station in the project (for more information, see Guidance Document section 'Site photos of finished installation')
    - Each installed antenna, showing line of sight to surrounding airspace
    - Full mast with all antennas visible
    - Inside electronics box
    - Photos of completed 'Metadata Field Sheet for Offshore Motus Stations'
    - Photos from maintenance trips
- Additional information on key details of equipment set up, including any challenges or maintenance needs and station downtime. This section should also indicate station maintenance schedule and any maintenance performed.

Detailed analysis of tag deployments

In addition to providing the automated reports listed above, projects that deploy tags or are involved in regional tag deployment efforts should submit reports on an annual basis with a detailed analysis of tag deployment data. These reports should contain all elements in the 'Data Analysis' section (above) to provide consistent, standardized information across sites. Project PIs are encouraged to include additional reporting elements and data analyses to address other research and monitoring objectives at their discretion.

Regional coordination

Effective use of Motus technology depends on strategic deployment of tags and receiving stations to address research questions of interest. Coordination of Motus studies in the Atlantic region of North America is important for reducing burdens on species of interest, leveraging resources, sharing information, and facilitating consistency in data collection for offshore wind energy applications. Key aspects of regional coordination for offshore Motus studies include station deployment, station calibration surveys, tag deployment, and data analysis across efforts.

Offshore Motus studies involve coordination across many sectors and entities. This coordination could be centralized through the RWSC in their role as the regional cross-sector group that supports research and monitoring for offshore wind energy projects and wildlife in the U.S. Atlantic. Regional coordination would benefit all sectors involved through more efficient and effective use of time, funding, resources, and information. Examples of these benefits to various cooperating entities include:

- Regulators: improving consistency and reducing duplication in permitting activities
- Species and land managers: minimizing risk to species, centralizing requests for site-specific access, simplifying tag deployment, station deployment, and monitoring logistics, and obtaining funding to support field efforts
- Project managers: efficiency of time and funds, ability to outsource logistics, and making it easier to learn and follow technical guidance and protocols for offshore Motus studies
- Scientists: larger sample sizes, standardized data formats, and more robust information for analyses
- Agencies: providing the best available science to inform decision making, more timely information, consistent analytical methods and reporting formats for efficient comparisons of results across projects

Station deployment and calibration

A coordinated approach is needed to facilitate strategic deployment and management of coastal and offshore Motus stations in the Atlantic region of North America. Benefits of a coordinated approach include optimizing coverage, leveraging resources, and maximizing information gains. For example, research projects using Motus to estimate displacement or meso-avoidance would need stations placed at key distance thresholds (project footprint and areas < 20 km from the project) and would benefit from coordinated station placement outside the project footprint and at adjacent coastal sites. In addition, regional coordination could be used to design and fund calibration surveys to collect calibration data from coastal and offshore stations within targeted geographic areas.

Offshore stations

Motus stations in the Atlantic region of North America are deployed, operated, and managed by a variety of entities. In offshore environments, stations within wind energy planning areas (under consideration for leasing) may be agency-funded whereas stations in wind energy lease areas are typically funded by the lease holders as part of their monitoring plan. Access to offshore stations is typically limited to site-specific personnel due to restrictions and logistics of working offshore. The RWSC is available to help facilitate information sharing across agencies, leaseholders, and other project proponents deploying Motus stations on various offshore structures. RWSC could consider additional roles in facilitation and coordination of offshore stations depending on funding levels and needs identified by managers of offshore Motus stations.

Coastal stations

Stations in coastal areas are currently funded by individual Motus projects, including agencies, NGOs, and academic entities. The RWSC could help identify existing high priority coastal stations for regional offshore wind energy applications and centralize funding for data fees, maintenance, and any necessary upgrades on an ongoing basis. These stations would provide a core array of coastal coverage in the Atlantic Region of North America. To qualify for funding, coastal stations would need to be set up and operated to minimum standards identified by this and related guidance documents and as defined by the RWSC. We recommend involving regional Motus coordination groups in discussions of upgrading and maintenance of coastal stations. These groups are listed on www.motus.org/collaboratives.

Station calibration

Aerial calibration surveys provide detailed information for analysis of detection data and should be completed annually while stations are in operation. Multiple calibration techniques are used to collect aerial high-altitude calibration data, including attaching test tags to UAVs and small aviation aircraft. For both options, the United States Civil Air Patrol (US CAP) can be contracted to perform calibration surveys in any of the 50 states and Puerto Rico. The RWSC could centralize logistics with US CAP or other qualified contractors to conduct regional calibration efforts across multiple wind energy project areas and coastal stations within a targeted geographic area. The RWSC could also help coordinate logistics for other opportunities to collect opportunistic aerial calibration data, including flying calibration equipment (test tag and lightweight barometric GPS unit) on aircraft during wildlife surveys.

Tag deployment

Coordinated tagging efforts are necessary to maximize population level inferences from individually tagged animals, to minimize animal safety and welfare risks by reducing the number of individuals subjected to tagging activities, and to most effectively leverage time, funding, and other resources for monitoring efforts. Optimizing sample sizes and tag deployment strategies is critical to maximizing information gains, ensuring target populations are adequately represented by sample data, and minimizing biases in results.

The following recommendations provide an approach for coordinated tag deployment across sites, aimed to maximize timely availability of information, reduce uncertainty in risk assessments, and increase efficiencies in monitoring programs through strategic collaboration.

A strategic, centralized approach to tag deployment for studies using offshore Motus could include the following elements:

- Expert stakeholders develop a common strategic framework to help identify the greatest regional science needs.
- Project proponents coordinate efforts through a centralized entity (e.g., RWSC), including plans for tag purchasing, deployment, monitoring, analysis, reporting, and administration.
- The RWSC could also function to centralize logistics for project proponents who desire more support, including purchasing, data workflows, permitting, and coordination with resource managers.
- Proponents centralizing logistics through RWSC could choose to have full control of tag deployment details (including species, sites, and numbers of tags) or direct funding towards species and locations of greatest regional need, as defined by the strategic research framework.
- All data are uploaded to Motus following minimum standards for metadata and data availability as described in the Guidance Document, Motus Data Framework, and Monitoring Framework.
- All data contribute to analyses that addresses site specific and regional questions.
- RWSC facilitates data access across projects for analyses that are regional in scale in coordination with all PIs on individual projects that contribute data.

This overall aim of this approach is to lower the barrier to entry for conducting offshore Motus studies by leveraging expertise in planning, designing and implementing the work instead of having multiple disparate efforts. Coordinating data collection across individual projects is essential for conducting regional-scale analyses using the best available science. This is particularly important for threatened and endangered species where the potential for adverse effects due to capture and tagging activities must be minimized and the maximum possible information must be produced from each transmitter that is deployed.

Data analysis

A coordinated approach to data analysis would benefit offshore Motus collaborators by providing more robust information for site-specific analyses and for facilitating analyses of regional movements using data collected across sites. Data coordination is particularly important for more complex analyses (e.g., quantifying effects of covariates) that require large sample sizes of tagged individuals from a variety of tagging locations. A strategy for regional data coordination should include long-term support for development and hosting of online analytical tools (e.g., R-Shiny applications) that facilitate standardized and transparent analysis methods for offshore Motus data.

Implementation

A stakeholder workshop was held in June 2022 to introduce the Offshore Motus Monitoring Framework, discuss ideas for centralized tag deployment strategies, and obtain initial feedback from participants. Results from the workshop and stakeholder feedback are summarized in Gulka et al. (2022b) and posted on the project's website: https://briwildlife.org/offshore-motus-guidance/.

Next steps for development and implementation of the Offshore Motus Monitoring Framework will be coordinated with the RWSC. The RWSC Bird and Bat Subcommittee will build off the Offshore Motus Monitoring Framework to develop a regional tagging strategy. Elements of a regional Motus tagging strategy may include:

- Identifying subregions and species of interest off the Atlantic coast
- Identifying research questions and objectives to address using tagging studies
- Proposing study designs for optimal or strategic tag deployment given research objectives
- Identifying key participants (tag project funders, species managers, site managers, academic partners, etc.)
- Describing data management, storage, and sharing best practices
- Establishing a pooled "tagging strategy fund" to implement a holistic science plan to address high priority regional science needs
- Addressing potential challenges with a centralized approach, e.g., site-specific needs for timing of information, balancing data use with scientific interest in publication of results, identifying barriers to participation.

The regional tagging strategy will be incorporated into a broader RWSC science plan that is being developed during 2023.

Adaptive monitoring

Over operational lifetimes of offshore wind energy projects, new and improved technologies and methods are likely to emerge that improve our ability to estimate avian and bat movements in offshore environments. Therefore, it is necessary to regularly assess new and improved technologies and methods for estimating the presence and risk of species in offshore wind energy project areas. New methods and technologies for data collection should be considered and incorporated in coordination with subject matter experts throughout the operational lifetime of offshore wind projects. Monitoring and research activities should be coordinated across wind energy projects throughout their operational lifetimes, along with sharing of data and research results on an ongoing basis. Information from offshore Motus should be used in an adaptive context to inform siting and other minimization measures implemented at future projects.

The framework and guidance documents are intended to be living documents. As such, a plan for updates must be developed that includes review of the current state of the science, technology changes, data storage and transmittal, and analytical methodologies. The documents should be reviewed and revised annually in coordination with stakeholder groups (e.g., RWSC). Revisions will be tracked according to the dates that updates are finalized.

Future actions

The following actions were identified as high priorities for future efforts for offshore Motus research, monitoring, technical development and coordination.

Technology development

Hardware improvements

During the current effort, we worked with an antenna manufacturer to design and test a custom circularly polarized Yagi antenna optimized for 434 MHz. Use of circularly polarized Yagi antennas at Motus stations is recommended to optimize tag detections from free-flying birds and bats (when tag orientation is uncontrolled). Future actions should aim to design and test a circularly polarized antenna for 166.380 MHz for use in dual-mode offshore stations where 166.380 MHz is prioritized. Future efforts should also aim to design a custom, waterproof omni antenna tuned to 434 MHz as an alternative to the off-the-shelf version at 433 MHz.

In addition, future efforts should standardize antenna mast and hub designs with a CAD/engineering design specific to each type of structure that offshore stations are mounted to (e.g. turbine platform type, buoy type, etc.).

Improvements to Motus receivers

The guidance currently recommends use of SensorStation Motus receivers due to the capacity for multi-frequency monitoring (currently 166.380 MHz and 434 MHz) and availability of multiple data acquisition options (including the use of satellite connectivity such as Iridium at remote sites). However, SensorStations with Iridium connectivity are currently only able to send summary-level data (i.e., a daily list of tag IDs detected and system health status reports). Iridium tag summary data is currently restricted to tags on 434 MHz; 166.380 MHz tags are excluded. Full download of data from Iridium-connected stations or from stations that lack connectivity requires manual download in person, either by connecting the station to a laptop computer using an ethernet cable and running command line functions or by downloading data to a USB drive. The USB download method is prone to errors associated with large file sizes or other technical issues (e.g. USB formatting). Workflows for manual downloads should be fully debugged by equipment manufacturers.

Future efforts should explore use of cost-effective methods for automating transfer of full detection data from remote areas that are outside of cellular coverage. Such methods could include the use of a satellite modem. A fiber optic cable could also be used for data transfer, where available, with appropriate security measures in place.

Identify the optimal frequency for offshore studies and evaluate tag power outputs

There are currently two frequencies in the Motus network, 166 MHz and 434 MHz. Current trade-offs associated with tag technology between the two frequencies include: size, weight, temporal resolution, and quality of tags; tag ID coding system; levels of interference and electromagnetic noise on frequency; and antenna size. While in some cases the selection of a certain type of tag or frequency is needed to address unique study objectives, standardization of key tag characteristics (i.e. operating frequency and duty cycle) is necessary to reduce variability and uncertainty in analyses. In the long term, a protected frequency should be considered for addition to Motus, as both current frequencies (166 and 434 MHz) have a lot of other activity near them, and a quieter frequency band might reduce interference. Future efforts should identify the best frequency, optimize tag technology on that frequency, and standardize tag deployments on that frequency. Future efforts should also develop standardized protocols for testing and quantifying tag power outputs using a spectral analyzer. Future tag deployment efforts should focus on using tags of the optimized frequency with a known power output.

Evaluate suitability of other offshore platforms

Our current guidance pertains to deployment of offshore Motus stations on turbines and buoys that were tested through pilot efforts and calibration surveys to determine detection range and coverage. Deployment of offshore Motus stations on other platforms would require additional information on detection coverage and electromagnetic interference from dedicated field tests and calibration surveys.

Previous efforts have deployed Motus stations on boats (including research vessels, passenger ferries, and whale watching ships) and identified issues with detection range due to electromagnetic interference and the moving platform. Therefore, Motus stations on crew transfer vessels and other vessels that do short back and forth trips to project areas are not recommended. However, stationary vessels in a project area (e.g., a larger vessel that houses crew offshore for 1-2 week stints) could be considered for Motus station deployments if interference issues are minimal (as determined from calibration surveys) and timing of vessel activities corresponds with time periods of interest (e.g., migration). These stations may be useful for targeted data collection during the construction period, for example, to evaluate movements of birds during migration relative to lighting.

Other offshore platforms that may be suitable for deployment of offshore Motus stations include Electric Service Platforms (offshore substations). However, pilot receiver stations on these platforms would need to be evaluated for electronic interference and detection probability using calibration surveys prior to use for monitoring efforts. Therefore, use of these stations for monitoring is not recommended until further testing is conducted.

Integration to design phase of wind turbines and buoys

The current guidance pertains to late-stage (ad-hoc) installation of Motus stations on offshore wind turbines and buoys. Future efforts should explore integration of Motus stations into the design phase of offshore platforms. Offshore wind turbine platforms are designed around requirements from developers and turbine manufacturers, and there are many foundation types available including monopiles, jackets, and floating structures. Offshore buoy designs also vary substantially in their purpose and structure. Installations in offshore lease areas typically include LiDAR buoys with instruments for atmospheric and oceanographic measurements with limited space available for dedicated antenna masts. The current guidance can be incorporated into a design standard that includes dedicated space for the antenna mounting area and a list of basic common components that go in all installations for Motus stations on offshore wind turbines and buoys.

Analytical

Conduct an analysis of coastal and offshore station coverage

An analysis of station coverage along the Atlantic could be used to identify areas of good and poor coverage to detect coastal and offshore movements. The study could look at historic and inactive station locations to target those that should be re-activated and provide recommendations for where additional stations should be placed. An analysis of optimal antenna bearings would also be useful for maximizing this coverage given the goal of assessing coastal and offshore movements. Results from this analysis would help to inform station deployments and address broader questions about regional movements, including strategic buoy-based stations outside of lease areas.

Determine the role that attraction and displacement from the project area will affect Motus study design

Research from Europe has provided consistent evidence that offshore wind developments influence the movements and habitat use of seabirds. Moreover, there is reason to think that offshore wind turbines can influence behaviors of migratory landbirds based on changes to offshore lighting. Taken together, we should assume that offshore wind development will alter animal movements and thus change the efficacy of Motus stations in detecting animals. Data from individually tagged animals should be used to determine the strength of these effects and additional methods needed to maximize Motus station detection rates, particularly if displacement is moving animals outside of a optimal detection range around the wind development.

Quantify effects of nearby turbines on detection coverage

The IDIOMS study design tool currently assumes that coverage of receiving antennas within a wind project array is not affected by interference or blockage from neighboring turbines. The effects of interference or blockage of signals by turbines could greatly influence the total detection coverage of stations within a wind energy project array. These effects should be quantified empirically via calibration of antenna arrays, and results used to update coverage estimates in the Study Design Tool.

Calibrate 166 MHz using methods for 434 MHz

In this effort, we used a new calibration method to evaluate the detection coverage of 434 MHz. This calibration method is more data-driven than previous calibration methods used for 166 MHz (Janaswamy et al. 2018) and therefore may be more suitable for representing deviations in antenna beam patterns due to environmental factors including salt buildup on antennas and interference of signals from nearby structure(s). Future efforts should calibrate 166 MHz using methods developed for 434 MHz so that results between the two frequencies are directly comparable. These efforts should include an evaluation of false positive detections and electromagnetic interference between the two frequencies to help determine the optimal frequency for offshore use. In addition, power output of 166

MHz tags should be compared with 434 MHz tags to better understand factors associated with detection range of transmitters operating at each frequency.

Incorporating detection probability

Future efforts should develop standardized methods to incorporate detection probability into analyses. Variation in detection probability can be associated with various factors including tag failure, tag loss (e.g., from temporary attachment methods), station detection coverage, uptime/downtime of stations and antennas during the data collection period, flight height of tagged animals, height of receiving station antennas, and signal loss from animals moving outside the range of the regional Motus array.

Motus Data Dashboard updates and developments

This section describes actions that were identified during development of the offshore Motus Data Framework and are outside of the scope of the current effort. These actions are high priorities to address in future Motus updates as capacity allows.

Improve process for reporting station health data updates to Motus

There is an ongoing need for accurate, standardized, and timely information on uptime and downtime of receivers and individual antennas. Improvements to this process could include a requirement that station health data must be reported on a regular basis to continue receiving tag detection reports. Many of the limitations from health reports come from the data available from each receiver type. For instance, receivers listening to 434 MHz tags do not report radio noise and therefore we cannot verify antennas are functioning at all times, whereas 166.38 MHz antennas do report these data. One solution to this issue is to include an integrated transmitter with each receiver which can 'ping' each antenna to ensure it is functioning correctly. In future updates, Projects PIs will have an option to set up E-mail alerts when stations are offline. If this option is enabled, the project PI will receive an e-mail from Motus is a station is offline for 72 hours. All Atlantic Offshore Wind Group stations should opt into e-mail alerts to help facilitate monitoring of remote sites.

Improvements to the Motus station management

Improvements to station deployment management section of Motus web interface include implementing a functionality for users to enter standardized information from in-person maintenance activities. Additional improvements include adding an upload form that allows users to upload:

- Station photos (e.g. each antenna with line of sight visible, inside electronics box, photos from maintenance trips)
- Calibration reports (pdf format)
- Shapefiles of antenna beams generated by calibration data analysis methods (currently under development)

Supplemental information associated with each station would be stored in the station's page and available for download.

Improve identification of false positives in detection data

False positive detections introduce error into Motus data sets and can result in inconsistencies in data interpretation and results depending on the filtering process used to clean raw data. Motus currently uses a broad filter to identify and remove obvious false positives from data that appears in their public online interface. Future development of a tool that would allow data PIs to identify and remove additional false positives from the Motus database would increase data quality and reliability. It would be helpful to include in datasets an indication of whether the investigator has proofed their data. Minimizing false positive detections from Motus data is process is especially important for Motus data sets with open detailed data available for public download to help ensure that any inferences made from the data are error-free.

Data streams from Iridium connected stations

Most offshore Motus stations use a satellite (Iridium) modem for remote connectivity. The Iridium data stream includes system health information and daily summaries of tag detections. However, summaries of daily tag detections from Iridium connected stations are not currently included in the Motus online interface. Future efforts should include tag summary data into the Motus online interface so information on tag detections can be accessed in near real time. This is especially important for offshore stations where full data downloads are infrequent (e.g. every 6 months) due to access limitations. This feature has been prioritized since it has been anticipated to be very important for offshore deployments.

Improvements to the Atlantic Offshore Wind Group's online interface

The dynamic summaries and standardized reports generated within the Atlantic Offshore Wind Group's online interface currently include data from Atlantic Offshore Wind Group stations, Atlantic Offshore Wind Group tags, and other Motus tags detected on Atlantic Offshore Wind Group stations. Future updates to the Motus database should include the option to incorporate data from other Motus stations in the Atlantic region of North America in data summaries within the Atlantic Offshore Wind Group. This could be accomplished by pre-populating a polygon of the Atlantic region of North America that allows users to select all Motus receivers within 1 km from coast for inclusion within data summaries and reports. In addition, stakeholders identified a need to select tracks that pass through a chosen area (acknowledging that the tracks are interpolated) to preliminarily assess possible habitat/airspace use in that area.

Improvements to data workflows for standardized tag data analysis

Future efforts will develop standardized R code within the Motus R package to conduct standardized summaries of animal detection data from Motus tagging studies with applications for offshore wind energy monitoring or research. The code will include reproducible example data from an offshore study.

Tool updates and developments

Calibration workflow updates

In the current project, we developed a preliminary web application for calibration data and analysis that is hosted at the University of Rhode Island (https://birdsdev.uri.edu/). We aim to incorporate additional calibration workflow and tools within Motus for broader applications and use in future efforts.

Future efforts will include:

- Integration of the calibration data workflows with the Motus R package with reproducible example data provided from Block Island Wind Farm
- Identifying quantitatively where additional coverage is needed for calibration
- Exploring the use of automated UAV surveys

- Developing a fully standardized calibration process, including field work, data delivery process, data storage, reporting of results
- Explore setting up a data stream for the calibration tool to access data from Motus directly
- Including functionality in the Motus Wildlife Tracking System to host shapes of antenna radiation patterns generated by the calibration tool
- Workflows to generate automated reports of calibration surveys and upload those reports to station page in Motus

Study design tool updates

In the current project, we developed an online study design tool (IDIOMS) that is hosted by Biodiversity Research Institute (https://briloon.shinyapps.io/IDIOMS/).

High priority items for future updates of IDIOMS would include:

- Multifrequency optimization (for 166 MHz and 434 MHz): develop a scheme to conduct coverage and avoidance optimization for both frequencies at the same time. Calibrate 166 MHz antennas with methods developed for 434 MHz and incorporate into study design tool.
- Input and map calibration data: provide the ability to import the calibration data collected for the Motus stations and map for automated reports.
- Incorporate calibrated omni-directional antenna patterns: fully calibrate omni-directional antenna patterns and incorporate these patterns into study design tool.
- Generate antenna patterns based on wind turbine structures: test antenna array patterns deployed on different wind turbine structures (e.g., monopile, jacket foundation) and provide options to display the appropriate antenna pattern depending on hosting structure and/or turbine model.
- Allow for multiple optimization strategies and incorporate the suggestions from the study design analysis into the tool.
- Provide means of incorporating preliminary movement data into the study design tool to allow for study design optimization for the expected habitat use and movements of relevant species.

Develop a power analysis tool

As part of this effort, Lamb *et al.* (2023) conducted a retroactive power analysis of Motus data from two species (Piping Plover and Common Terns) to help inform target sample sizes to address simple questions of baseline site occupancy. Future efforts could generalize code from Lamb *et al.* (2023) for use with other species and data sets to help guide sample size decisions. These methods from could be further expanded for assessments of variability and uncertainty for more complex questions (e.g., quantifying effects of temporal, demographic, and atmospheric covariates on offshore occurrence within wind project areas). Ultimately, it would be valuable to turn this power analysis into a tool that can be used across different species and contexts to inform sample sizes and tag deployment locations for different studies. This tool could be integrated into the Motus R package for general use.

Develop analysis tools for detection data

To help improve consistency and efficiency in data analysis, future efforts should develop reproducible R code to analyze data from offshore Motus to answer key questions (e.g., site occupancy relative to demographic, temporal, and atmospheric covariates). Future code development could incorporate more complex analyses such as estimates of tag location and flight height using simultaneous multi-antenna detections, which is an area that project collaborators will continue pursuing in 2023-2024 with funding from the Department of Energy and BOEM as part of Project WOW (https://offshorewind.env.duke.edu/). This code could be served in Motus R package, or as an online web application to facilitate ease of use and automated report generation.

Future actions should also development of infrastructure to support efficent workflows and analyses of Motus data and include long-term funding to host, manage, and update the infrastructure.

Stochastic Collision Risk Assessment for Movement (SCRAM)

With funding from BOEM, project partners are currently working on a stochastic collision risk model and online web application to estimate collision risk of ESA-listed species using data collected from previous tracking studies (including GPS tracking studies and Motus studies using land-based stations). The initial version of SCRAM will be able to conduct analyses for Red Knot, Piping Plover, and Roseate Tern. These models and the SCRAM web application should be updated in the future to include data from offshore Motus stations and newly deployed tags on current species, and to allow for inclusion of additional species.

Research questions

During development of the guidance, several high-priority research questions were identified by project co-leads and stakeholders. Addressing these research questions requires coordinated tag and station deployment, and development of analytical methods. These questions and methods to address them should be considered in development of the RWSC regional science plan.

- Passage rates through project area: defined as the number of tagged individuals per unit time that transit through a project area during a specified monitoring period
- Macro-scale avoidance of project area: defined as number of individuals that encounter a wind energy project area and fly around the perimeter of the wind energy project, as compared to the number of individuals that fly through the wind energy project area, during a specified time period.
- Detection probability: use to adjust estimates of species presence and passage rates within an area
- Movements relative to fine-scale atmospheric conditions (e.g., wind speed, wind direction, visibility) and demographic variation (age, sex, population)
- Linking individual-level migratory connectivity with breeding and wintering locations and population status: help to identify at-risk populations for conservation actions including compensatory mitigation.
- Understand variation in movement patterns relative to wind energy project characteristics such as: turbine size/spacing, distance from shore, effects of lighting during construction (e.g., attraction/entrapment) and during operation (differences in lighting regime, e.g., ALDS)
- Understand and address cumulative effects of collision risk and displacement for species of interest using strategic deployment so that tracking data are representative of populations
- Quantify, predict, and minimize risk using relationships between offshore occurrence and covariates (e.g. temporal, demographic, and atmospheric variation associated with offshore movements)

Integration with other monitoring methods

Future efforts should explore integration of Motus technology with other monitoring methods used for birds and bats in offshore environments. These efforts should explore opportunities to leverage technical expertise across agencies (such as the Department of Energy) for integration with other technologies.

Potential methods to investigate include:

- Use of satellite-based tracking technologies (e.g., GPS and Argos systems). Potential research topics could include:
    - Double-tagging large-bodied birds with GPS tags that collect fine-scale location and altitude data (e.g., GPS/GSM) and Motus tags. Data from GPS tags can be used to calibrate tracking stations and movement models from Motus tags for applications on smaller-bodied species that are unable to carry heavier GPS tags. GPS tags with built-in barometers could be used for highest accuracy altitude data, where possible (e.g., barometric sensors add weight, and are sensitive to water and malfunction when submersed)
    - Design tagging studies that deploy GPS (3-d, satellite data relay) and Motus tags on different individuals of target species in target areas (e.g., Red Knots in mid-Atlantic) adjacent to lease areas that have tracking stations. GPS transmitters will provide fine scale data on altitude and routes, while Motus tags will provide information on use of wind energy areas from a larger sample size of individuals (due to lower costs of Motus tracking per bird) where active Motus stations are present in wind energy areas.
- Integrate data from offshore Motus stations with other remote avian and bat monitoring technologies. This would require detailed information on the area sampled by each technology/sensor and exploration of where/how the data can be used collectively. Technologies for potential consideration include: acoustic recorders, visual and thermal cameras, and radar, including on-site portable radar and land-based modeling efforts using weather radar (e.g., Cornell BirdCast)
- Technology development for tags
    - Develop a power-regulated Motus tag with w/barometer for flight-height data
    - Develop Motus tags that can be detectable by radar units (in early development phase by researchers at USGS; R. Diehl pers. comm.)

Conclusions

A variety of guidance and protocols have been developed to inform the use of Motus technology to study bird and bat movements in relation to offshore wind energy development. Additional details on the study design and implementation of station deployments on offshore infrastructure, calibration processes, and data sharing and reporting, are available in other products developed in conjunction with this Monitoring Framework. In addition to summarizing the results of these efforts, this framework makes targeted recommendations for station and transmitter deployment, reporting, and data analysis to inform site-specific and regional-scale studies of birds and bats in the offshore environment. This includes a recommendation for regional coordination of these efforts to best meet stakeholder needs and maximize information gain. There remain a variety of development and research needs to further facilitate the standardized use of Motus to study animal movements at offshore wind energy areas, and we encourage further discussion of these opportunities through regional collaborations such as the RWSC.

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