Supplementary Material 2:

MARINE MAMMAL MONITORING MATRIX

Prepared by:

MMSIG Marine Mammal Monitoring Innovation Team

Marine Mammal Monitoring Matrix

As part of the **Marine Mammal Monitoring: Methods, Technologies, and Opportunities for Innovation** project, led by the Institute of Marine Engineering, Science and Technology (IMarEST) Marine Mammal Special Interest Group (MMSIG) in collaboration with the Department for Environment, Food and Rural Affairs (Defra) under the Marine Natural Capital and Ecosystem Assessment (mNCEA) programme, this initiative aims to advance the understanding and application of marine mammal monitoring technologies.

This resource has been developed to support the assessment of monitoring tools and methodologies, ensuring alignment with industry needs and scientific best practices. The matrix provides a structured overview of monitoring approaches and their effectiveness across different offshore environments.

The matrix includes:

- **Marine Mammal Technology/Methodology** – A categorisation of marine mammal monitoring techniques.
- **Technology Examples** – Specific technologies currently in use or emerging within the field.
- **Strengths** – Key advantages and applications of each method.
- **Identified Limitations and Areas for Improvement** – Challenges observed in real-world deployment from insights drawn from literature reviews and stakeholder survey responses.

Authors

Institute of Marine Engineering Science and Technology (IMarEST):

- Niru Dorrian
- Elizabeth Ferguson
- Lorenzo Scala
- Andrew J. Wright
- Ashley Noseworthy
- Ashleigh Kitchiner

Supporting MMSIG Analysts:

- Denis Kovshov

Disclaimer

The information presented in this matrix has been compiled from a range of sources. While every effort has been made to ensure accuracy, some uncertainties or errors regarding specific technology strengths or limitations may remain. Additionally, the capabilities of certain technologies are evolving rapidly. Readers are advised to verify the current specifications and limitations of any technologies of interest.

References and Acknowledgements

This matrix was developed as part of a desktop research project led by the IMarEST MMSIG in collaboration with Defra's Marine Natural Capital and Ecosystem Assessment (mNCEA) programme.

We extend our gratitude to the 133 stakeholder survey participants and targetted interviews, whose insights contributed significantly to this study.

This matrix reflects a synthesis of publicly available data, expert feedback, and literature review to support the advancement of marine mammal monitoring technologies within UK waters.

Citation:

Dorrian, N., Ferguson, E. L., Scala, L., Wright, A. J., Noseworthy, A. S., & Kitchiner, A. (2025). *Marine mammal monitoring: Methods, technologies, and opportunities for innovation (Supplementary Material 2).* Institute of Marine Engineering, Science & Technology & Department for Environment, Food & Rural Affairs – Marine Natural Capital and Ecosystem Assessment Programme.

Contacts:

IMarEST Technical and Policy Team - **technical@imarest.org**

TECHNOLOGY (CATEGORY)	Visual & Other Optical Monitoring	Satellite Imaging	Passive Acoustic Monitoring
TECHNOLOGY EXAMPLES	• Infrared and thermal imaging • Light detection and ranging (LiDAR) • Cameras • Thermal sensors • Binoculars & Big Eyes	• Satellite Imaging	• Real-time Passive Acoustic Monitoring (PAM) systems • Hydrophones, hydrophone arrays (fixed or mobile) • Autonomous Recording Units (ARUs) • Automated Click Detectors (FPODS) • Moorings • Buoys • Multi-sensor seabed mounted or lander systems • Underwater sound, ambient and impulsive measurement recording systems
STRENGTHS	• Blow detection • Effective for species identification in good conditions • Addresses limitations of PAM towed arrays for baleen whale detection from survey vessels • Effective for detection of non-biological obstacles at sea (other vessels, sea ice, fishing gear) • Non-invasive	• Effective for species identification in good conditions • Potential for high spatial coverage • Access to visual data from remote or inaccessible regions by conventional methods • Effective for detection of non-biological obstacles at sea (other vessels, sea ice, fishing gear) • Non-invasive	• Broadband systems with configurable sampling rate, gains settings • Recording cycles with application in research • Mitigation and ambient sound measurements • Flexible and adaptive setups for a variety of deployment methodologies to suit monitoring requirements • Continuous, all-weather monitoring • Effective for acoustically active visually evasive/cryptic, nocturnal and deep-diving species • Temporal monitoring • Cost effective for long-term monitoring • Non-invasive
LIMITATIONS AND AREAS FOR IMPROVEMENT	• Limited geographical coverage • Limited temporal coverage • Dedicated surveys may be expensive if not simply opportunistic. • Detection rates may be lower for smaller or less common species, particularly if they spend limited time at the surface or are more cryptic in appearance (e.g., porpoises) • Environmental conditions affect efficacy of visual sensors (sea state) • Requires animals to surface • Correction and availability factors are not known or estimated • Visual species identification challenges: due to size, morphometric and meristic view • Vessel-based activities introduce ship noise, which may have impacts	• Images may be expensive • Detection rates may be lower for smaller or less common species, particularly if they spend limited time at the surface or are more cryptic in appearance (e.g., porpoises) • Environmental conditions affect efficacy of visual sensors (sea state, cloud cover) • Requires animals to surface • Image resolution insufficient for some analyses • Correction and availability factors are not known or estimated • Lack of data storage space for archiving • Lack of access to computer power for processing large datasets • Lack of data standardisation • Visual species identification challenges: due to size, morphometric and meristic view	• Loss and damage to moorings through biofouling and fisheries interactions • Require animals to vocalise • Sound production rates vary with behaviour • Self-noise issues (from moorings or towing ship) • Environmental and anthropogenic noise can inhibit detections • Humpback whale chorusing masking other signals of interest • Species-level classification can be problematic with difficulty in identification to species level in delphinids • Localisation may require multiple systems and requires more robust internal clocks • Lack of data on cue rates and other biological information necessary to extrapolate population and group parameters from acoustic monitoring • Access to data from archival tools or streaming is generally difficult • Reliability issues due to battery life and electrical leakage • Lack of standards and annotated database for training artificial intelligence algorithms • Equipment can be expensive - especially more capable systems and especially if deployed as part of an oceanic mooring • Vessel-based activities introduce ship noise, which may have impacts

TECHNOLOGY (CATEGORY)	Active Acoustic Monitoring	Radio Detection and Ranging (Radar)	Biotelemetry – Satellite Tagging
TECHNOLOGY EXAMPLES	• Acoustic releases • Telemetry systems • Multi-sensor seabed mounted or lander systems • Sonars	• Radar systems	• Tags either implanted in cetacean blubber and sometimes into muscle or affixed to pinnipeds • Smart positioning and temperature tags
STRENGTHS	• Continuous, all-weather monitoring • Effective for visually and acoustically evasive/cryptic, nocturnal and deep-diving species • Temporal monitoring • Cost effective for long-term monitoring	• Continuous, all-weather monitoring • Detection of surface movements on water	• Provides movement and limited behaviour data, • Useful for habitat use studies - insights into habitat use and anthropogenic interactions
LIMITATIONS AND AREAS FOR IMPROVEMENT	• Loss and damage to moorings through biofouling and fisheries interactions • Range is limited, unless frequencies within the range of marine mammal hearing are used, which may produce impacts • Difficulty in identification to species level • Access to data from archival tools or streaming is generally difficult • Reliability issues due to battery life and electrical leakage • Lack of standards and annotated database for training artificial intelligence algorithms • Vessel-based activities introduce ship noise, which may have additional impacts	• Lack of species identification • False detections (non-biological objects) • Surface detection only	• Deployment difficulties (e.g., weather, vessel availability, species access) • Tag size and animal behaviours can lead to shorter-than-intended deployments • Battery life limitations • Attachment reliability • Data transmission challenges; • Invasive • Limited satellite coverage • Data access via satellites is challenging because of limited bandwidth or access to cellular networks • Offers broader spatial coverage but rely on surfacing behaviours and can be cost-prohibitive for large-scale studies • Permitting and animal safety restrictions • Logistical challenges with accessing animals • Invasive nature of deploying technology directly on animals • Biases in which individuals are accessible and appropriate for tagging

TECHNOLOGY (CATEGORY)	Biotelemetry – Archival Tagging	Environmental DNA (eDNA)	Unmanned Aerial Vehicles (UAV)
TECHNOLOGY EXAMPLES	• Datalogging tags including retrieval units platforms incorporating accelerometers, acoustic and visual sensors, and physiological and behavioural monitoring tools. Attachment can be through suction cups or using pins.	• eDNA sampling kits • Autonomous eDNA samplers	• Rotor drones (e.g., quad- or hexicopter drones) • Fixed wing drones
STRENGTHS	• High data resolution with multiple sensors • Biologging provides unique detailed individual subject data • Can provide a lot of 'ground-truthing' data on detection rates, in terms of time at the surface or acoustic production rates.	• Potential for species detection in low-visibility environments • Immediate proximity to animals is not required • Non-invasive	• High-resolution imaging • Effective for species identification • Effective to support photo ID & body condition assessments • Focal follow • Low operational costs (comparatively) • Multiple novel applications for biological sampling • Allows access to remote or inaccessible areas • Non-invasive
LIMITATIONS AND AREAS FOR IMPROVEMENT	• Deployment difficulties (e.g., weather, vessel availability, species access) • Tag size and animal behaviours can lead to shorter-than-intended deployments • Attachment improvements are needed to minimise impacts on animals, while maximising duration of deployment • Constrained by battery life, data retrieval, and the potential behavioural impact of the tags on the animals - compromises between battery life, sampling rate, and storage space on tags • Data generally provides only a snapshot in time • Lack of safe, low impact, and effective long-term tag attachments • Permitting and animal safety restrictions • Logistical challenges with accessing animals • Invasive nature of deploying technology directly on animals • Biases in which individuals are accessible and appropriate for tagging • The difficulty in semi-automatically detecting and classifying tagged animal vocalisations versus nearby conspecifics.	• Lack of reference data • Lack of assessment of error factors • Sensitivity influenced by environmental factors • No regulator guidance published yet. • Samplers - Long term power availability, eDNA sample count (limited to 9 per cassette), lab qPCR and/or metabarcoding lead times • On-board sample processing is under development	• Battery life limitations • Range limitations • Standardisation needed across platforms • Limited existing protocols for automated image analysis (manual analysis requires significant personnel time) • Influenced by environmental factors for deployment and data collection • Aviation regulations • Manufacturing regulations - country of origin are a problematic as international politics evolve

TECHNOLOGY (CATEGORY)	Uncrewed Marine Vehicles (AUVs, ASVs and USVs)	Data Integration & Management	Health Monitoring
TECHNOLOGY EXAMPLES	• Gliders • Remote piloted or autonomous motorised vessels • Wave-propelled zero emission battery/renewable powered • Autonomous vessels • Drifters	• Large-scale integration of multiple data streams • Cloud-based marine data repositories • AI-powered sensor networks • Edge computing for marine AI • Data fusion models • Predictive AI for dynamic ocean management • Multi-data stream integration • Standardised data interoperability frameworks • Real-time data streaming for marine monitoring • AI-driven data cleaning and anomaly detection • Blockchain for marine data security & integrity	• Biopsy • Blow collection and other biological sampling methods • Omics technologies • Body condition through photogrammetry
STRENGTHS	• Long-duration monitoring • Near real-time data transmission • Easy deployment • Embedded instrumentation options • Cost effective for long-term spatial coverage compared to ship-based surveys • Multi-sensor platform • Data processing, transmission and communications hub	• Potential for multi-source data fusion (PAM, visual, environmental datasets) • Potential enhanced accuracy and reliability • Real-time monitoring and decision support • Scalability across regions and ecosystems • Improved predictive modelling • Automated anomaly detection • Streamlined data processing and storage • Reduction of human error • Enhanced collaboration and interoperability, greater contextual awareness	• Opens up the ability to study sub-lethal impacts and baseline health of animals in a population • Enables disease monitoring • Provides contextual information that may lead to better understanding of behaviour (and thus availability for detection)
LIMITATIONS AND AREAS FOR IMPROVEMENT	• Propulsion or hull cavitation noise may interfere with acoustic detection • Lack of manoeuvrability • Speed limitations • Payload limitations • High costs limiting accessibility to research community (including for vessel-based deployment and retrievals) • Influenced by environmental factors for deployment and data collection	• Lack of comparable methodologies for data collection and recording • Differences in temporal and geographic scales • Lack of robust datasets for modelling • Lack of environmental datasets at appropriate temporal and geographic scales • Lack of data standardisation • Lack of integration across disciplines (e.g., biology and oceanography) Data access and storage are limited • Mainly record surface conditions and not subsea conditions • Quality of data dependent on environmental factors like cloud coverage, glare, and Beaufort sea state • No existing off-the-shelf solutions currently for integration and processing of various complementary detection systems (e.g., PAM, MMOs, Infrared cameras, opportunistic detections) • High computational costs for large-scale integration, challenges in integrating proprietary data sources • Data gaps in remote or under-monitored regions	• The number of biomaterial samples from specific animal species with the exact location, time of the sampling site, description of clinical symptoms • Lack of full documentation of metadata, including any observed symptoms with biopsies or other biological materials. • Access to carcasses for necropsy • Challenges with data sharing between groups • Challenges with funding • Expensive instruments, cost versus benefit uncertainty, and clinical stringency make the use of omics still limited

TECHNOLOGY (CATEGORY)

AI & Data Processing

TECHNOLOGY EXAMPLES

- Data processing and management, classification and filtering algorithms
- Automated video and image analysis
- Acoustic monitoring processing
- Predictive modelling and risk assessments
- AI enhanced underwater autonomous vehicles and drones
- Dynamic ocean management for shipping lanes and fishing zones
- Ship strike avoidance systems
- Sonar and lidar detection tools
- Satellite image based monitoring
- Citizen science that feed AI
- Body condition scores via AI and imagery or lidar
- AI tools for policy analysis

STRENGTHS

- Some open source options available (e.g. PAMGuard)
- Automated image and acoustic analysis, potential for large-scale data integration
- Near real-time detection and alerts
- Enhanced predictive modelling scalability and efficiency
- Reduction in human bias and human error
- Cost reduction of long-term monitoring
- Integration with dynamic management systems

LIMITATIONS AND AREAS FOR IMPROVEMENT

- Many parallel efforts without a cohesive approach and standardisation
- Training datasets for developing algorithms are not available
- Bias in AI training data
- Commercial tools can be expensive
- Lack of user-friendly interfaces and customisation capabilities
- Lack of effective classification and filtering algorithms for many species or in some environmental conditions
- Lack of integration of citizen science to maximise overlap between researchers' effort and general public
- Lack of apps that are accessible, transferrable, and relatable to encourage maximum buy-in from the public
- Difficulty in error quantification.
- Not typically generalisability across environments
- Ethical and privacy concerns
- High computational and energy costs
- Dependence on high-quality sensor inputs
- Real-time capabilities limited by processing speeds and human conformations
- Difficulty in model interpretability
- Integration challenges with existing conservation frameworks
- Requirement for continuous model updates
- Challenges in identifying individual marine mammals, risk of false sense of accuracy
- Limited availability of open-source ai models
- Cybersecurity - model and data poisoning