Research and survey plan for RERI project: pinnipeds and offshore wind farms in Australia

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SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE

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A report prepared for the Commonwealth Department of Climate Change, Energy, the Environment and Water

Roger Kirkwood[1], Christine Erbe[2], Chong Wei[2], Sam Thalmann[3], David Slip[4], Ben Pitcher[5], Vanessa Morris[5] and Simon Goldsworthy[1]

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Cover Photo: Australian fur seals at Seal Rocks, Victoria (Photo R. Kirkwood).

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SUMMARY

In 2022, the Australian Government identified six priority areas within which offshore wind farms could be developed, three in the Bass Strait region (recognised here to be shelf waters between Victoria and Tasmania), two on the NSW coast and one on the west coast of Western Australia. These areas overlap with the ranges of numerous species protected under the EPBC Act, including three otariids seals, the Australian fur seal (*Arctocephalus pusillus doriferus*), the Long-nosed (New Zealand) fur seal (*Arctocephalus forsteri*) and the Australian sea lion (*Neophoca cinerea*).

This report outlines research and field survey plans to be conducted in the 2025/26 financial year as part of a federally funded project investigating potential impacts of offshore wind farms on seals in Australian waters. The first Australian offshore wind farm constructions are forecast to commence in 2030.

Key threats to seals from offshore wind farm development include direct disturbances and indirect impacts from habitat and ecosystem changes. Noise from shipping, construction and operation of offshore wind farms is a key direct and indirect threat. Repeated negative impacts could lead to population-level consequences for seals.

Development of the research and field plan for this project was guided by the recognition that, for seals to be adversely affected they must a) rely on resources within the development area, and b) experience reduced access to those resources.

Two research approaches were designed to address knowledge gaps:

a) Spatial overlap between seals and offshore wind farms.

   A field survey plan was developed to assess seal distribution in the Bass Strait region, focusing on counts at colonies and haul-outs. On-land distribution data provide an index of at-sea distribution, and a potential means to monitor impacts of wind farm development. The Bass Strait is the region of greatest overlap between proposed turbines and seal populations, and is also where wind farm proposals are most advanced.

b) Hearing capability of Australian seals.

   Understanding if seal behaviour could be impaired by wind farm noise requires two steps: 1) Establishing how well seals can detect sound across different frequencies and loudness levels, and 2) assessing how seals respond to different sound exposure levels. A research plan was developed to obtain audiograms (hearing capability profiles) for Australian seal species. This includes modelling of auditory capacity (CT-scans of skull and auditory structures along with tissue testing) and validation of the

audiograms through behavioural testing of trained seals exposed to controlled sound frequencies and levels.

This research will provide stakeholders with information on how wind farms in Australia may affect seals, along with guidance for preparing impact assessments and implementing measures to minimise harm.

Keywords:

Arctocephalus pusillus doriferus, *Arctocephalus forsteri*, *Neophoca cinerea*, offshore wind farm impacts, underwater sound, underwater hearing, pile-driving

1. INTRODUCTION

The Australian Government's Renewables Environmental Research Initiative (RERI, within the Department of Climate Change, Energy, the Environment and Water, DCCEEW) aims to deliver resources and information to support decision-making for offshore wind farm developments in Australia. The developments will need to comply with the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). Projects supported by RERI aim to provide relevant information to assist both proponents and assessment officers, when drafting and assessing impact and risk reports and methods of operation that will minimise impacts on marine communities.

This RERI project aims to improve understanding and mitigation of potential negative impacts on pinnipeds (seals) from offshore wind farm developments in Australia. In 2022, six offshore wind farm areas were identified by the Australian Government: Hunter and Illawarra off the NSW coast, Gippsland, Bass Strait and Southern Ocean in the Bass Strait region (recognised in this report as being shelf waters between Victoria and Tasmania), and Bunbury in south-west Western Australia. All are in Commonwealth waters, with boundaries at least 5.5 km (3 nm) from any land, including islands, and at least 10km from shore to reduce visual amenity impacts. The areas include no islands or coastal sections.

Pinnipeds are mammals in the order Carnivora. There are three extant families of pinnipeds, two families are collectively referred to as the seals, Otariidae or eared seals, comprising fur seals and sea lions, and Phocidae or 'true' seals. The third family, Odobenidae, is represented by a single walrus species, which occurs in Arctic waters of the Northern Hemisphere. All pinnipeds derive from a single lineage that emerged ~40 million years ago, with divergence of otariids from phocids and odobenids ~25-30 million years ago (Berta et al. 2018, Paterson et al. 2020). The otariids and phocids have contrasting life-history strategies, physiologies and behaviours.

Ten seal species have been recorded in Australian waters. Seven of these species breed on Antarctic sea-ice or subantarctic islands, with the most common seals to visit Australian continental waters being Southern elephant seals *Mirounga leonina*, Leopard seals *Hydrurga leptonyx* (both phocids) and subantarctic fur seals *Arctocephalus tropicalis* (an otariid). This research project focusses on three otariid species that have resident populations along the southern Australian coast: the Australian fur seal *Arctocephalus pusillus doriferus*, the Long-nosed or New Zealand fur seal *Arctocephalus forsteri*, and the Australian sea lion *Neophoca cinerea*. The Australian sea lion is listed as 'Endangered' and has an approved conservation advice and Recovery Plan. There is currently no approved federal conservation advice, recommendations for a species' conservation status, or national survey guidelines for the Long-nosed fur seal or the Australian fur seal.

Otariid seals cycle between periods at sea, foraging and transiting, and periods on land, resting, breeding and, for adult females, suckling a pup. There are no seal breeding or haul-out sites within the designated offshore wind farm areas. The nearest boundary to a breeding site is 6km – between the Gippsland Offshore Wind Farm Area and the Rag Island Australian fur seal colony. At sea, seals range hundreds of kilometres from resting and breeding sites, however, they are present year-round in all of the wind farm areas.

Seals forage throughout southern Australian shelf waters, from Shark Bay on the west Australian coast, around the southern coast and up to about the NSW-Queensland boarder on the east Australian coast (Figure 1.1). The range of Long-nosed fur seals overlaps with all six offshore wind farm areas, the range of Australian fur seals overlaps with all except the Bunbury area, and the range of Australian sea lions only overlaps with the Bunbury area.

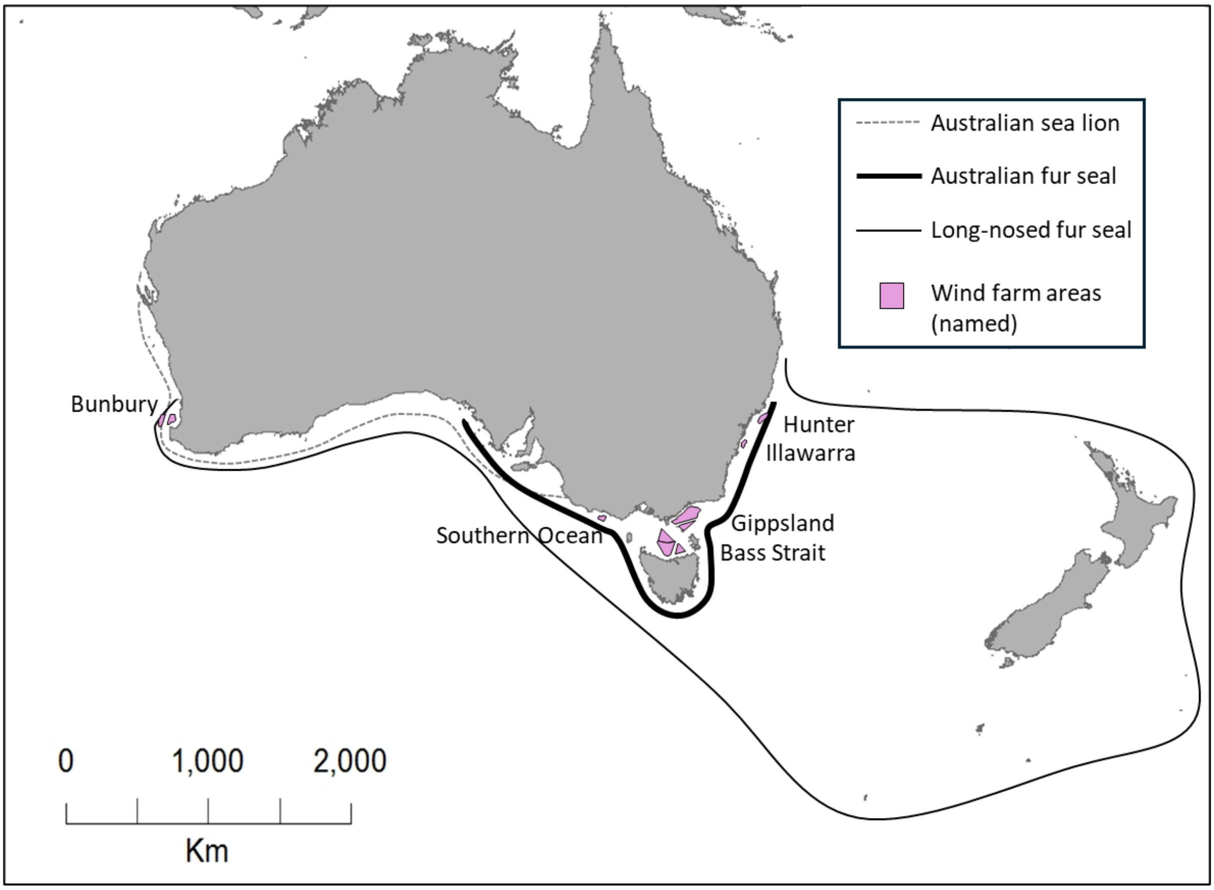

Figure 1.1. Ranges of the three seals with breeding populations in Australian shelf waters, and the declared offshore wind farm areas (figure adapted from Kirkwood and Goldsworthy 2013).

The number of seals that may encounter offshore wind farm activities will vary greatly between the wind farm areas. There are >200,000 seals in Australian coastal waters, with the greatest densities being in the south-east (Table 1.1). The greatest abundances of both Long-nosed fur seals and Australian sea lions are in South Australia (Chilvers and Goldsworthy 2015, Goldsworthy et al. 2021) and the greatest abundance of Australian fur seals is in the Bass Strait region, between Victoria and Tasmania (McIntosh et al. 2022).

Table 1.1. Seal populations in mainland Australian waters and estimates of indicative numbers in 2025, based on available data.

Seal	Species name	Total population	Region of greatest abundance	Source
Australian sea lion	*Neophoca cinerea*	~12,000	South Australia	Goldsworthy et al. 2021
Australian fur seal	*Arctocephalus pusillus doriferus*	~90,000	Bass Strait	McIntosh et al. 2022
Long-nosed (NZ) fur seal	*Arctocephalus forsteri*	~120,000	South Australia	Chilvers and Goldsworthy 2015

Seals that transit and forage within offshore wind farm areas will be at risk of impacts from the developments (Draget 2014). One important risk to recognise comes from the noise produced (Erbe et al. 2018). Research in Europe can provide insights into hearing capability and behavioural responses to noise, and to noise impact thresholds of phocid seals, particularly Harbour seals *Phoca vitulina* and Grey seals *Halichoerus grypus*. For example, noise during construction from pile driving is known to cause reduced foraging and avoidance by phocid seals (Thompson et al. 2020), and if individuals receive sufficiently high sound exposure levels, their hearing capability may be damaged (Kastak et al. 2005, Kastelein et al. 2013a). The hearing capability, and physiological and behavioural responses to anthropogenic noise by Australia's seal species, are poorly understood.

In addition to noise, offshore wind farm developments may directly impact seals through increased risk of vessel collision and exposure to pollutants from vessels or turbine structures. In addition to direct effects, seals will be affected by changes to their trophic networks and habitats caused by wind farm developments. The noise emitted during wind farm construction and operation will be detected by other marine species, including odontocete (toothed) cetaceans and fish, which may influence their behaviour and abundances and thus the way they interact with the seals (Galparsoro et al. 2022). Trophic network and habitat impacts may have positive and/or negative outcomes for the seals, for example, prey availability may be increased or decreased in the wind farm areas (Bergström et al. 2014). In addition, there may be cumulative effects with other contemporary factors that drive change for the seals, such as rapid climate change, fisheries activities, and diseases.

This RERI project has a 1-year timeframe in which to recognise and report potential impacts on Australia's seals from offshore wind farm developments. Reporting seeks to provide regulatory guidance and survey standards. Here, the plan for one component of the project deliverables – conducting original research to reduce knowledge gaps – is described.

1.1. Objectives

Following a review of the literature and wide-ranging discussions, two approaches were taken for this project to redress contemporary gaps in knowledge that could aid determinations of potential impacts from offshore wind farms on pinnipeds: 1) How many seals could overlap with the wind farm developments? and 2) What noise levels produced by wind farm development could be detected by the seals? Understanding how a seal species could respond to particular sound frequency spectra was beyond the scope and timeframe for this project. The following research themes were adopted.

1. To improve knowledge of the spatial overlap between seals and wind farm areas.
2. To improve knowledge of the hearing capability of the seal species that breed at colonies around southern Australia.

2. ADDRESSING KNOWLEDGE GAPS ON THE OVERLAP OF SEALS WITH WIND FARM AREAS

This component of the project will be undertaken by researchers from the Natural Resources and Environment Department, Tasmania.

2.1. Background

Seals will predominantly encounter wind farm developments and associated activities when they go to sea to forage or transit between resting/breeding sites and foraging areas. There are gaps in knowledge about how many seals could overlap spatially with the wind farm activities, of seal movement in general and the importance of the wind farm areas to seals from particular colonies.

Due to the abundance and advanced stage of proposed wind farm developments in the Bass Strait region, the importance of this region for Australian fur seals, and recognition that data on movement mostly came from females at a few more accessible colonies near the Victorian coast (Kanowna Island, Seal Rocks and Deen Maar Island), foraging movements by seals from lesser studied populations close to wind farm areas (such as Judgement Rocks) was recognised to be an important knowledge gap.

Knowledge of the spatial distribution of seals at sea, and the importance of particular areas or habitat types, can be gained in two ways. One is through tracking of a subset of animals and assuming their foraging behaviour is representative of the population. The other is through direct or indirect surveys of seal numbers.

2.1.1. Assessment of seal tracking method

Most knowledge of which areas at sea are most important to seals in Australian coastal waters, (i.e., where they spend most time foraging, have better foraging success, and travel to get to other areas) comes from tracking studies of individual seals (Kirkwood et al. 2006, Arnould and Kirkwood 2007, Page et al. 2008, Baylis et al. 2012, Kirkwood and Arnould 2012, Hoskins et al. 2017, Salton et al. 2019, Salton et al. 2021, Goldsworthy et al. 2022, Bartes et al. 2024). Tracking individual seals can provide detailed information on movement of the individual during several weeks to months of its life, and indications of the movement and habitat use by cohorts of seals. But there is substantial individual, spatial and temporal variability in foraging patterns. Large sample sizes and multi-year tracking studies are required to progress knowledge from individual variability to population-level requirements.

Most tracking studies of seals in Australia have been of adult females that are supporting pups at breeding sites (Page et al. 2008, Baylis et al. 2012, Kirkwood and Arnould 2012, Bartes et al. 2024). Breeding females are potentially the most important single component of the population. They need to routinely return to the colony to support their pup, which constrains their foraging range. This need to return to support pups provides researchers with opportunities to measure trip durations and to recover recording devices. Adult males, juveniles and females not supporting pups may travel further and remain away from a single site longer than females with pups. Therefore, where the females move during pup rearing, represents a subset of the foraging areas that are important for a population.

Use of tracking data to predict areas of use and importance to a seal population also has the logistical constraints of typically small sample sizes, due to high cost and logistical complexity (obtaining permits, site accessibility, seal catchability, attachment of devices to fur and limits to device size because of its influence on hydrodynamic ability), high levels of individual, spatial and temporal variability between seals, and temporal imbalance in sampling due to the seals’ moult-cycle. Most fur seal movement data are collected between May (after the annual moult) and November (when deteriorating fur condition means devices are likely to shed. Accordingly, the period of the year with the least information on foraging areas is December to May.

Tracking studies typically incorporate deployments over multiple years, to account for foraging area variability due to interannual changes in ocean currents and prey availabilities (Hoskins et al. 2015, Foo et al. 2019). The single-year time frame of this RERI project was considered to be too short for a tracking project to reasonably fill knowledge gaps in spatial overlaps between seals and wind farm areas. The July commencement also limited a window of opportunity for tracker deployments. Such deployments would require obtaining ethics and research permits, field and tracking equipment, and coordinating a field team and transport to isolated sites. This could not be guaranteed prior to November, when the breeding period commences and access to seal colonies becomes restricted. Deployments after the breeding and moult periods (i.e., in May) would be inadequate for tracking and interpretation before completion of this project in June 2026. Consequently, this approach will not be used in this RERI project.

2.1.2. Assessment of at-sea surveys for seals

Surveys of seals at sea are problematic because the seals are continually diving, so are only briefly near the surface and available to be seen. Then, it can be difficult to observe the seals and identify the species as they may barely break the surface to inhale. Because of the low chance of sighting and identifying seals to species at sea, obtaining good density information requires intensive effort (Herr et al. 2009, Warren et al. 2009, Viola et al. 2024). Surveys of seals at sea could be appropriate to monitor trends in seal abundance within a single wind farm lease.

2.1.3. Assessment of monitoring seal numbers on land

An alternative approach for approximating seals' at sea habitat use is to monitor their abundance on land or on ice (Southwell et al. 2012, Fritz et al. 2013). Assuming the majority of the seals will rest at the established haul-out and/or breeding site closest to where they forage, estimates of numbers of seals on land can provide an indication of the numbers foraging in an area. Such estimates may be improved by data on the mean proportion of time seals spend in the water versus on land, which can be obtained from previous tracking studies. Numbers of seals on land will vary temporally, depending on time-of-day, weather patterns, and time of year. Detailed monitoring at a selection of sites will improve the accuracy of estimates of seal numbers in an area. Such data are available for some locations and species, for example, for Australian fur seals at Seal Rocks in northern Bass Strait (Garlepp et al. 2014).

Research on seal numbers onshore has focused on pups, because pups less than 2-3 months old are the only cohort that is entirely land-based (Kirkwood et al. 2005, Kirkwood et al. 2010, Shaughnessy et al. 2015, Goldsworthy et al. 2021). Counts of pups provide an index of population size and a means of monitoring population trends.

Counts of non-pup seals on land are less commonly conducted to monitor populations in regions where there are breeding colonies. In contrast, counts of seals on land are more commonly conducted in regions where breeding sites are small or scarce, such as on the NSW coast, to provide indications of the abundance of seals foraging nearby (Shaughnessy et al. 2001, Burleigh et al. 2008). The fact that seal numbers resting on land could provide valuable information on seal numbers foraging in the vicinity has been under-utilised in areas where the seals are most abundant.

Within the Bass Strait region, previous information on seal numbers at breeding and haul-out sites come from several previous surveys. Indications of numbers can come from estimates of pup numbers at breeding sites (Pemberton and Gales 2004, Kirkwood et al. 2005, Geeson et al. 2022) and several counts of seal numbers at haul-out sites (Stamation et al. 1998, Puskic et al. 2024). There have been two previous aerial surveys over Tasmanian islands in Bass Strait, in April 1975 (Pearse 1979) and in December 1986 (Warneke 1988).

Australian and Long-nosed fur seals exhibit strong seasonal changes in their spatial distribution, abundance and attendance patterns at both haul outs and breeding colonies (Baylis et al. 2012, McIntosh et al. 2022). In particular, there is minimal information on numbers that forage around non-breeding haul-out sites. The number of seals that haul out at a location will change over time, with different weather conditions and with disturbances. Even so, routine methods to estimate numbers ashore will provide comparative estimates of seals foraging in surrounding waters.

Knowledge of the distribution and abundance of seals foraging in the vicinity of the designated offshore wind farm areas in the Bass Strait region may be improved from monitoring of seal numbers ashore at haul-out and breeding sites nearby.

To address the knowledge gap on the abundance of seals using wind farm areas, we will:

1. Conduct large-scale aerial surveys of fur seal abundances at breeding and haul-out sites in Tasmanian waters of Bass Strait, 40 years after the only previous such survey.
2. Review available data on haul-out site usage across Tasmania, NSW, Victoria, South Australia, and Western Australia.
3. Quantify change in seal numbers ashore, due to seasonal cycles, weather conditions, and time of day, and quantify variability, to improve the ability for counts of seals on shore to provide an estimate of total seals in an area.

2.2. Aerial survey of seal abundances at sites in Tasmanian waters of Bass Strait

This research will provide significant advancement into the understanding of distribution patterns for Australian and Long-nosed fur seals in the Bass Strait region. The project will comprise two aerial-based surveys across all coastal and island shorelines in Tasmanian waters of Bass Strait. The majority of colony and haul-out sites for Australian fur seals in the Bass Strait region are within Tasmanian waters – which includes all islands south of 39°12’S, which is just 7 km south of the tip of Wilson’s Promontory, Victoria. The survey will record numbers of adult male, adult female, juvenile, and pup Australian fur seals.

Long-nosed fur seals have recently recolonised sites along the Victorian coast in northern Bass Strait (Arnould et al. 2000, Kirkwood et al. 2009, Reinhold 2023). The aerial surveys provide an opportunity to survey many rarely visited Tasmanian islands of Bass Strait for the presence of Long-nosed fur seals. Both Long-nosed fur seals and Australian sea lions were breeding in the Bass Strait region prior to the 1800s, but were eliminated by sealers (Ling 2002). Because many islands are rarely surveyed, new haul-outs for Long-nosed fur seals may be recorded.

Components of the aerial survey are:

1. Synthesise current knowledge of breeding and haul-out areas within Tasmanian waters including existing data on seasonal use and abundance.

2. Undertake the first large-scale survey in 40 years of seal abundance at non-breeding haul-out sites and breeding colonies in Bass Strait and adjacent waters.
3. Repeat the aerial survey to investigate seasonal changes in distribution and abundance. One survey will be in September-October, prior to the breeding period; and the second survey in March-April, following the breeding period.

2.2.1. Methods

Distribution and abundance surveys will be calculated from high resolution aerial imagery captured from fixed wing aircraft surveys. Analysis will be performed on desktop GIS software according to the methodology outlined below.

2.2.1.1. *Survey design / desktop review*

We will perform a desktop review of all known breeding and haul-out locations for Australian and Long-nosed fur seals in Tasmania. This will include literature search and data obtained through the NRE Tasmania, long-term seal monitoring program. Any additional sites providing suitable habitat for haul-outs and breeding colonies will be added to the survey plan to ensure that newly colonised haul-outs are not omitted.

To provide contemporary data, we will survey all island groups within Tasmanian waters of Bass Strait. Survey area will encompass the area between longitudes 143°W and 149°W, and latitudes south of 39°12'S to the Tasmanian coast) (Figure 2.1). Two surveys will be conducted across Bass Strait with timing scheduled to investigate maximum shift in distribution within the period of field research. Surveys will avoid the November to January period, corresponding with the seals' breeding period, to avoid disturbance to breeding seals and potential impacts on new-born pups. The plan is to have one survey during September and October 2025 and the second during March and April 2026. Within each period, surveys will take advantage of forecasts for suitable flying and photographic conditions.

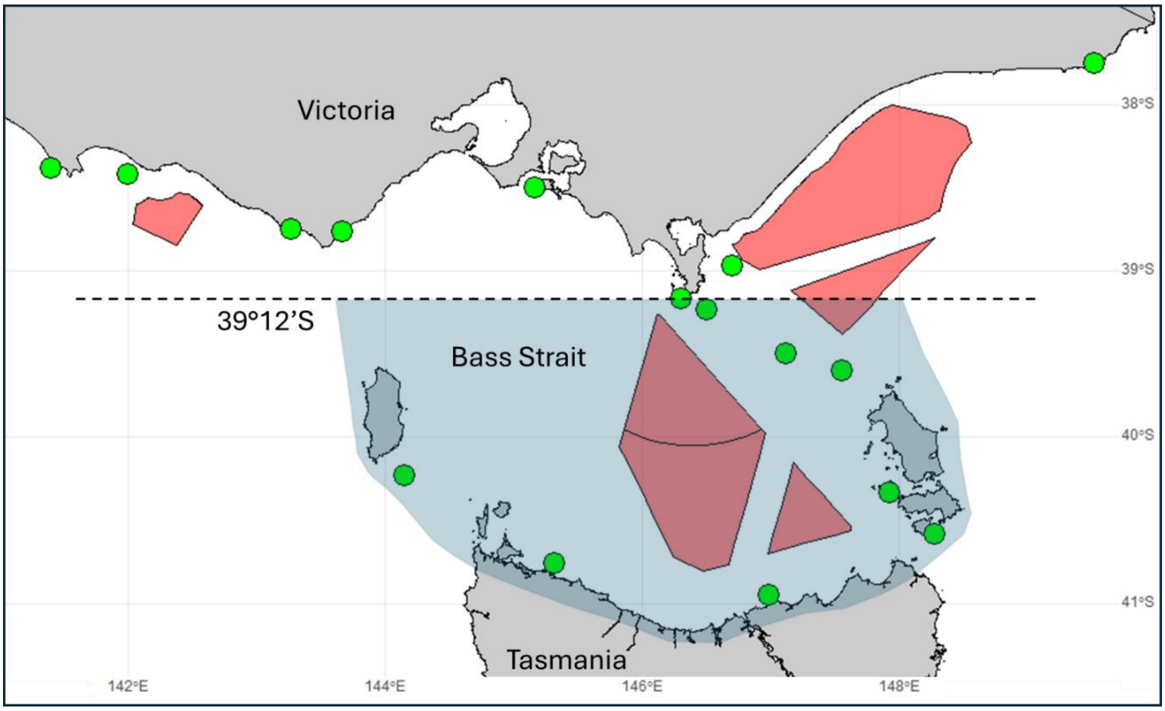

Figure 2.1. Proposed aerial survey area within the Bass Strait region (blue shading) indicating the state boundary between Victoria and Tasmania, Australian fur seal colony sites (green dots) and declared Offshore Wind farm Areas (pink shapes).

2.2.1.2. *Aerial survey and image capture*

Surveys will be performed from a fixed-wing Cessna 182RG, fitted with differential GPS, and various optical and thermal sensors. For our surveys, images will be taken using a Phase One XMP150 camera fixed to the undercarriage of the aircraft. Image resolution for the camera is 150 megapixels. The camera provides a continuous ortho-mosaic image that is georeferenced. Performing the survey at a nominal flight height of 1,500 ft (457 m) allows high resolution imagery for analysis and results in an image width of 500 m swath, thereby reducing the number of aerial passes required to capture whole colony and haul out areas.

2.2.1.3. *Image analysis and data preparation*

Resulting imagery will be analysed using GIS software. Individual seals will be identified to species, sex and age-class. The location of each seal will be digitised and georeferenced. Spatial analysis will be performed to examine patterns of distribution and abundance.

Changes in the distribution and abundance of seals between survey periods will be quantified. We will investigate the drivers and potential mechanisms influencing these changes, including temporal variability (seasonal cycle and time of day), environmental parameters (season, temperature, weather, sea state) on the survey day, and on days prior to survey.

3. ADDRESSING KNOWLEDGE GAPS ON THE HEARING CAPABILITY OF AUSTRALIAN SEALS

This component of the project will be undertaken by researchers from Curtin University. Seal behavioural audiograms will be validated based on the hearing capability of trained seals at Taronga Zoo, in collaboration with researchers from Macquarie University and the Taronga Conservation Society, Australia.

3.1. Background

Underwater noise production from offshore wind farms is the most frequently cited means of potential impact on seals (Teilmann et al. 2004, 2006, Tougaard et al. 2006, 2009, Kastelein et al. 2013a, 2013b, Thompson et al. 2013, Kirkwood et al. 2015, Russell et al. 2016, Aarts et al. 2018, Brasseur et al. 2018, Kastelein et al. 2018, 2020, Thompson et al. 2020, Tougaard et al. 2020). Noise can change the seals' behavioral patterns, damage their hearing, and potentially have population-level consequences (Southall et al. 2007). All pinnipeds are sensitive to sound in air and underwater, so are likely to be susceptible to loud noise emissions in both media. Currently, there is a dearth of information on the hearing capability and vulnerability to anthropogenic noise of otariid seals in Australia. Any current assessment of potential impacts of noise produced by offshore wind farms would need to rely on studies of phocid seals in Europe.

A first step to identifying potential impacts of Australian seals to any anthropogenic noise is to determine what the seals can hear. There are two approaches to achieving this: one is to examine the seals' hearing anatomy and physiology, and the second is to conduct controlled tests on trained individuals, either by training them to respond when they detect sounds or to monitor brain-wave responses, indicating sound detection, during sound playback sessions. Detection of brain waves can be difficult even on trained seals, and for seals it would require either shaving their heads to be able to attach suction caps, or the use of implants. This approach was not feasible for the current project. The approach taken was to combine modelled hearing audiograms with behavioural hearing trials. The models provide estimates of hearing capability over a full spectrum of sound frequencies and the trials target a subset of frequencies to calibrate the models.

Accordingly, assessment of the hearing capability of Australian seals had two components:

1. Modelling audiograms of hearing capability based on auditory anatomy of seal skulls.
2. Validation of models through testing the hearing capability of trained seals.

3.2. Finite-element modelling of hearing in Australian seals

3.2.1. Introduction

This part of the project aims to estimate hearing sensitivity and range in Australian seals by building anatomical finite element models based on CT-scans (computed tomography scans) of seal skulls and tissue measurements. Fresh carcasses of seals – Australian sea lions and Long-nosed fur seals found dead along shorelines in Western Australia, and Australian and Long-nosed fur seals found dead on beaches in Victoria and Tasmania – will be collected opportunistically for this project (in collaboration with state departments responsible for handling these carcases).

We will pass the seal heads through a medical-grade CT-scanner (Figure 3.1). We will also dissect the ears and pass these through a micro-CT-scanner. Tissues from the head will be collected for the measurement of acoustic properties (density, velocity, and absorption). Based on these 3D scans and tissue measurements, we will build digital anatomical models. These can then be subjected to impinging sounds (e.g., pure tones as used in real-life audiogram experiments) and the inner-ear response can be modelled (Wei and Erbe 2024). In this way, audiograms (curves of hearing sensitivity) may be derived. Audiograms may differ with age and sex, so we will scan and model multiple individuals of each species. Resulting audiograms will be presented in spreadsheets and graphs.

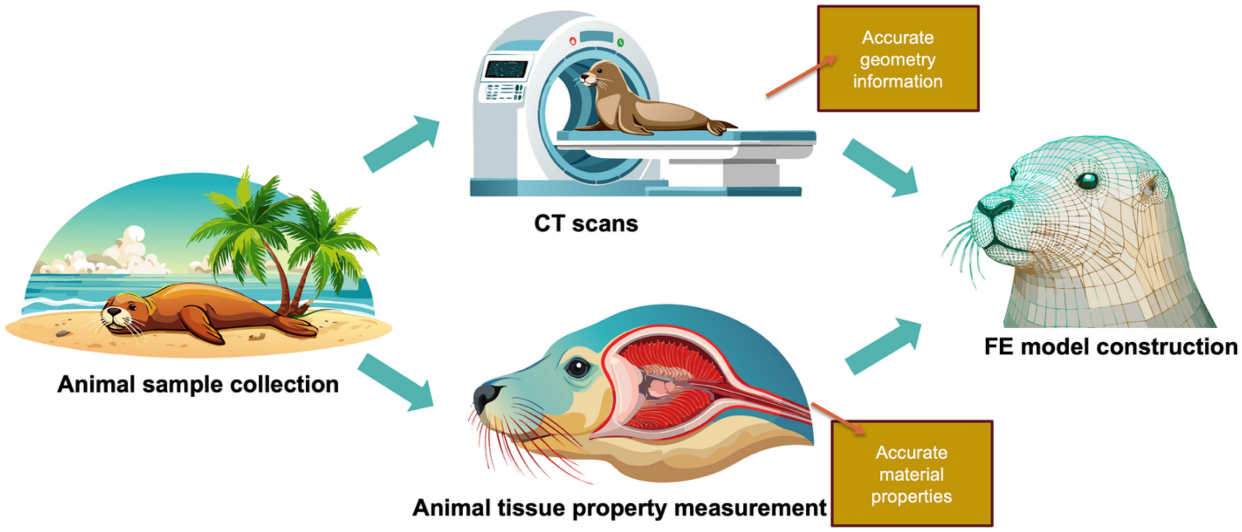

Figure 3.1. Workflow for developing finite element models of pinniped auditory systems.

3.2.2. Methods

3.2.2.1. *Specimen collection*

In Western Australia, the Western Australian Department of Biodiversity, Conservation and Attractions (DBCA) has pledged support for this project, and DBCA staff will collect and supply fresh post-mortem specimens. Carcasses may be collected any time of the year. While tissue testing requires fresh samples, CT-scans can be of material that has been frozen and then thawed. In Victoria, fur seal skull CT-scans are available from a previous study of skull morphology at Monash University while from Tasmania, fur seal frozen seal skulls are available from the Tasmanian Museum, and freshly dead seals from beaches will be made available through the NRE Tasmania. Since sampling will be opportunistic, the total number of seals that will be available for this project cannot be determined, however, as of August 2025, 4 x Australian sea lions and 1 x Long-nosed fur seal had been collected and made available. Ideally, at least 5 x individuals of each species will be processed.

For imaging and anatomical analysis, the project requires freshly dead animals with intact head structures. Collected carcasses will be securely packaged and transported to veterinary or research imaging facilities for medical CT-scanning, ensuring tissue integrity and high-quality imaging for subsequent analyses.

3.2.2.2. *Medical CT scan and data analysis*

Medical CT-scans will be conducted using a Siemens SOMATOM go.Up® high-resolution CT-scanner. During scanning, pinniped heads will be securely positioned on the scanner table, and images will be acquired helically in the trans-axial plane (perpendicular to the body’s long axis) using an X-ray source operating at 130–140kV and 300–500mA, depending on specimen size. Transverse slice thickness will be approximately 0.6–0.8 mm, with a 512 × 512 matrix. The acquired images will be saved as Digital Imaging and Communications in Medicine (DICOM) files and imported into Horos™ software (Horos Project, Geneva, Switzerland) for CT data analysis and geometrical model reconstruction.

The DICOM image stacks will be segmented to isolate key structures of interest, including soft tissues, the skull, and the auditory apparatus (e.g., ear canals, inner ears, stapes footplate, and tympanic bone). After segmentation, each structure will be exported as a stereolithography file and undergo optimisation processes, such as smoothing and removal of overlapping elements or self-intersections, to prepare for subsequent modelling and analysis.

3.2.2.3. *Finite-element modelling*

Anatomically accurate, high-resolution Finite-Element (FE) models of sound reception will be developed from CT imaging data. Stereolithography files generated from segmented CT data will be imported into the software program COMSOL Multiphysics 6.3 (Stockholm, Sweden) for FE analysis and acoustic simulations. The models will simulate sound transmission from the external environment (air or seawater) to the inner ear structures of each specimen. To recreate realistic acoustic conditions, spherical computational domains filled with air or seawater will be positioned around the heads to represent free-field sound propagation. A low-reflecting boundary condition (Bérenger 1994) will be applied to the outer surfaces of these spheres to minimise acoustic reflections and approximate unbounded environments (Figure 3.2).

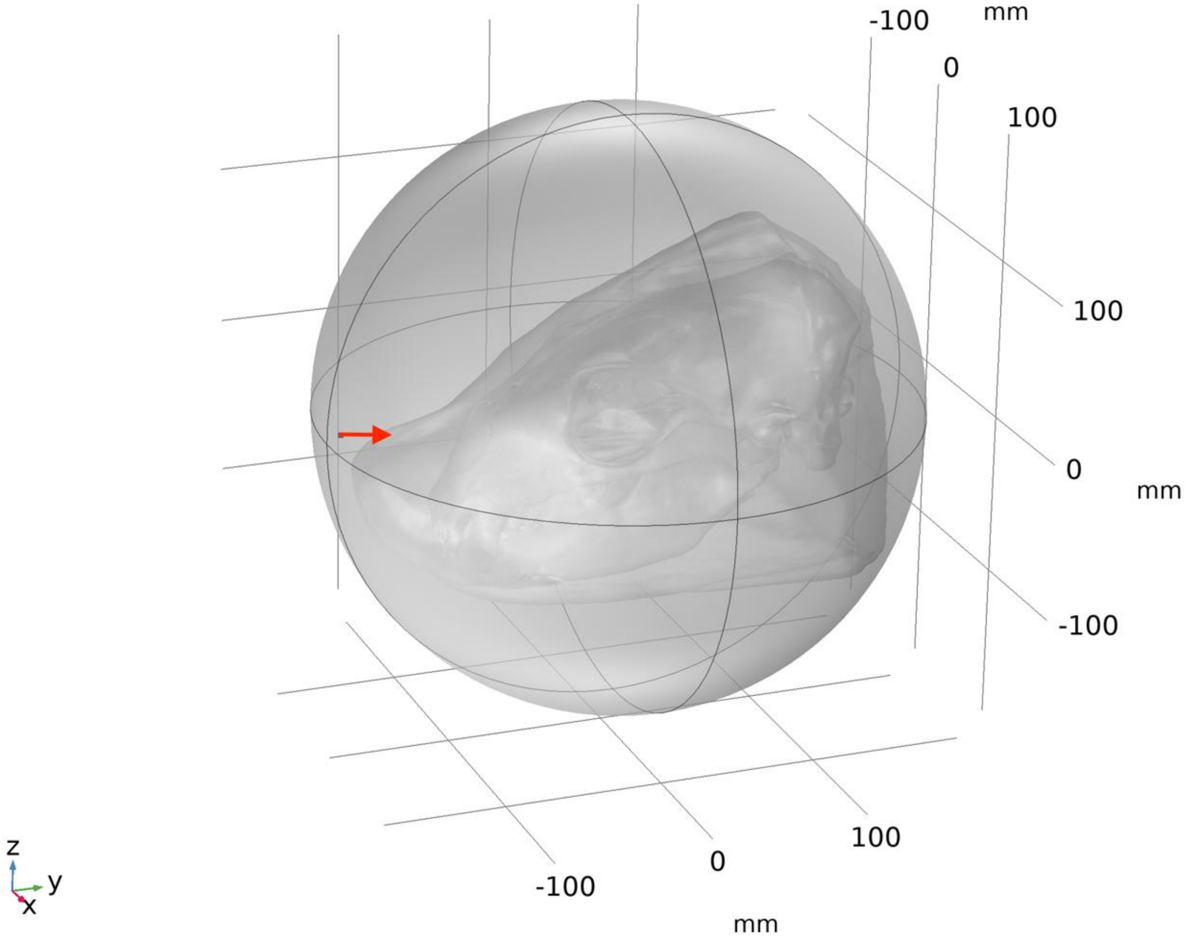

Figure 3.2. Example of a 3D, finite element, sound reception model of a seal's head. The model illustrates the reconstructed head structures within the computational domain used for acoustic simulations. The red arrow indicates the direction of receiving sound.

In each FE model, an incident plane acoustic wave will be introduced, directed toward the head as illustrated in Figure 3.2. Example of a 3D, finite element, sound reception model of a seal's head. The model illustrates the reconstructed head structures within the computational domain used for acoustic simulations. The red arrow indicates the direction of receiving sound.. Given the linear nature of the models, the absolute input pressure is arbitrary because only relative frequency-dependent responses are required. The acoustic waves will propagate through the external medium (air or seawater) and interact with the complex anatomical structures of the seals' heads, inducing traction loads on the ear surfaces and simulating natural sound reception pathways. This modelling approach uses generalised sound inputs (rather than specific turbine noise) to simulate the sound reception process in pinniped heads. This enables calculation of energy transfer through the auditory pathway and prediction of hearing sensitivity curves. Once hearing curves are established, they can then be applied to assess whether specific noise sources, such as turbine noise, are audible to the animals.

Tetrahedral meshes will be generated for the entire model using COMSOL's free mesher, which automatically detects fine anatomical features and narrow regions, adjusting element sizes to resolve complex curvatures and interfaces. In element-based acoustic simulations, mesh resolution is typically determined by the wavelength, with a common guideline requiring at least five second-order elements per wavelength to accurately resolve wave propagation in both fluid and solid domains (Thompson and Pinsky 1994, Ihlenburg 1998). Mesh refinement analysis will be performed by progressively refining the mesh and comparing results to confirm numerical accuracy and determine the optimal element size.

The FE Pressure Acoustics-Frequency Domain module coupled with Solid Mechanics and an Acoustic-Structure Boundary will be applied for the models. When acoustic waves propagate within the liquid medium, the longitudinal waves can be written as:

$$\frac{1}{\rho_0 c_s^2}\frac{\partial^2 p}{\partial t^2} + \nabla \cdot \left(-\frac{1}{\rho_0}\nabla p\right) = 0 \tag{1}$$

where c_s is the speed of sound (m/s), p is the sound pressure (Pa) and t is time. ρ_0 is the density (kg/m^3), which is included in the equation because of its variations in different computational domains within the model. $\partial^2 p/\partial t^2$ relates to the temporal evolution of the pressure field: essentially, how the pressure wave changes with time. For the harmonic solution of the pressure $p(\boldsymbol{x}, t) = p(\boldsymbol{x})e^{i\omega t}$, with the angular frequency ω (rad/s), Eq. 1 can be simplified as:

$$\nabla \cdot \left(-\frac{1}{\rho_0}\nabla p\right) - \frac{\omega^2 p}{\rho_0 c_s^2} = 0 \tag{2}$$

While the acoustic waves interact with the solid medium, the multi-physics coupling provides and assigns the boundary conditions for the two-way acoustic structural coupling between the liquid (e.g., water and soft tissues) and the solid (e.g., skull). The fluid-solid boundary condition includes the following interaction between fluid and solid domains:

$$\boldsymbol{F} = -\boldsymbol{n}_s p \tag{3}$$

$$-\boldsymbol{n}_a \cdot \left(-\frac{1}{\rho_0}\nabla p\right) = a_n \tag{4}$$

$$a_n = (\boldsymbol{n}_a \cdot \boldsymbol{u})\omega^2 \qquad (5)$$

where $\boldsymbol{F}$ is a pressure load (force per unit area) on the boundaries where the fluid interacts with the solid, $\boldsymbol{n}_s$ is the outward-pointing unit normal vector seen from inside solid domain, $\boldsymbol{n}_a$ is the outward-pointing unit normal vector seen from inside liquid, a_n is normal acceleration of the solid surface in the liquid domain boundary, and $\boldsymbol{u}$ is the calculated harmonic displacement vector of the solid structure.

3.2.2.4. *Acoustic property measurements*

Fresh tissue samples will be collected from the specimens for property measurements. All measurements will be conducted in a controlled temperature room at 25°C, to minimise potential variability associated with temperature fluctuations, which would alter the acoustic properties.

3.2.2.5. *Measurement of sound speed*

The sound speed of tissue samples will be measured using a custom-designed ultrasonic measurement system (Figure 3.3). Each tissue sample will be positioned in its natural orientation on a smooth metal baffle plate. A plexiglass sheet mounted parallel to the plate will be gently lowered onto the sample using a controlled mechanical button system to ensure consistent contact. Ultrasound signals will be transmitted through the tissue using a GS200 echoscope (GAMPT, Merseburg, Germany), a high-resolution ultrasonic measurement system connected to a computer running GS-EchoView software.

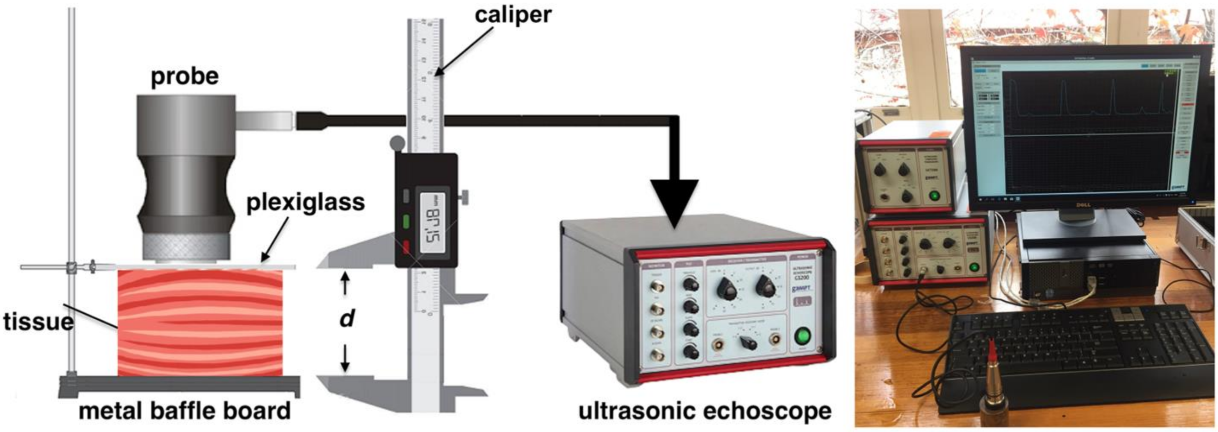

Figure 3.3. Measurement system to determine sound passage properties of seal tissues.

The system is equipped with a 25 mm diameter ultrasonic probe with robust snap-in connectors, which can function as either a combined transmitter/receiver or as separate transmitting and receiving units. The probe output power will be adjustable to maintain optimal signal quality. An operating frequency of 4 MHz will be selected based on tissue thickness to provide clear, distinguishable reflected signals, enabling accurate calculation of sound propagation time and, subsequently, sound speed in each tissue sample.

As the ultrasonic pulse propagates through the sample, a portion of the signal is reflected at the interface between the plexiglass and the tissue, producing the first reflected signal (t_1). The remaining portion of the pulse continues through the plexiglass and tissue and is subsequently reflected by the underlying metal plate, generating the second reflected signal (t_2). The time difference (Δt) between these two reflections ($\Delta t = t_2 - t_1$), will be computed using GS-EchoView software to quantify the acoustic travel time through the tissue.

During measurements, the received signal waveform will be continuously displayed on the computer screen. Gentle pressure will be applied via the plexiglass to ensure full contact with the tissue surface while avoiding significant deformation, as indicated by stable signal amplitude. Once optimal contact is achieved, the separation distance (d) between the plexiglass and the metal plate will be measured using vernier callipers.

Because the ultrasound pulse travels through the tissue to the metal plate and is then reflected to the probe, the total propagation distance is $2d$. Measurements of both Δt and d will be repeated at least five times at each position to ensure precision and repeatability. The mean sound speed ($\bar{c}$) will be calculated as:

$$\bar{c} = 2\bar{d}/\overline{\Delta t} \qquad (6)$$

where $\bar{d}$ and $\overline{\Delta t}$ represent the averaged distance and time difference across all replicates, respectively.

3.2.2.6. *Measurement of density*

Following the sound speed measurements, several cubes will be cut from the tissue samples. The mass of each cube will be measured using an electronic balance with a precision of 0.001 g. To ensure accuracy and consistency, each cube's mass will be measured at least five times, and the average mass $\bar{m}$ will be calculated. The volume of each cube will be determined using the water displacement method, following procedures described in Wei et al. (2015). Each volume measurement will be also repeated a minimum of five times to calculate the average volume $\bar{V}$. The average density $\bar{\rho}$ of each tissue cube will be calculated using the relation:

$$\bar{\rho} = \bar{m}/\bar{V} \qquad (7)$$

3.2.2.7. *Acoustic impedance model reconstruction*

Hounsfield unit (HU) values will be obtained for each tissue cube in the density measurements. These values will be derived in the software Mimics 21.0 (Materialise, Leuven, Belgium) based on CT-scan data. A univariate regression analysis will be performed to establish linear regression equations for 'HU versus sound speed' and 'HU versus density'. Using these equations, the HU distribution exported from the CT-scan data will be converted into sound speed and density distributions. The acoustic impedance (Z_s) distribution will be subsequently calculated using the formula:

$$Z_s = \rho c, \tag{8}$$

where ρ is the density and c is the sound speed. This will allow for the reconstruction of an acoustic impedance model of the head of each seal and seal species.

3.2.2.8. *Transfer function and audiogram curve prediction*

The synergistic response of the ear components (i.e., external, middle, and inner ear) to incoming acoustic signals can together determine the audiogram (Tubelli et al. 2012, Cranford and Krys 2015, Tubelli et al. 2018, Wei and Erbe 2024). During sound reception, when an incident acoustic wave p_{input} interacts with the animal's head, part of the wave is reflected at the skin surface, while the remainder propagates through the soft tissues (e.g., muscle) and, as elastic waves, through denser bony structures.

The ears respond to the incident sound wave, leading to vibrations of the stapes at the oval window, a thin connective-tissue membrane that forms the boundary between the middle and inner ears. The motion of the stapes footplate v_{st} is driven by the ossicular chain in response to p_{input}. This motion generates fluid movement within the cochlea, causing vibrations in the inner ear. To characterize this process, numerical hearing models will be employed to compute the frequency-dependent mechanical response of the ear. The models generate a transfer function (TF), defined as the ratio between the velocity magnitude at the stapes footplate v_{st} and the amplitude of the incident sound pressure p_{input}, expressed in units of nm/s/Pa. Since the mammalian hearing apparatus functions as a bandpass system, the TF primarily reflects the middle-ear contribution that shapes the frequency-dependent hearing threshold (Ruggero and Temchin 2002). Using the calculated TFs, audiogram curves will be predicted and subsequently calibrated against minimum audible pressure, enabling direct comparison with results from behavioural hearing response experiments.

The outputs of this project directly support the objectives of the RERI by providing critical data and tools to assess and manage potential impacts of offshore wind development on pinnipeds. Specifically, we will deliver species-specific audiograms derived from both CT-imaging based hearing modelling and behavioural experiments, along with spatial data on seal distribution in Bass Strait. These outputs will enable regulators and industry to evaluate whether wind farm noise falls within the detectable hearing range of pinnipeds, to predict the likelihood of disturbance or impact, and to develop effective mitigation strategies. In doing so, the project provides a scientific evidence base that informs environmental approvals and long-term monitoring frameworks under the RERI program.

3.3. Behavioural audiograms of trained seals at Taronga Zoo

3.3.1. Introduction

Behavioural audiogram measurements will be collected on trained seals at Taronga Zoo, Sydney, to validate the Finite Element (FE) models (see previous section, 3.2) and to add the process of ‘perception’ into the anatomical-to-neural auditory pathway. Behavioural audiograms provide direct frequency-specific measurements of pinniped hearing that can be applied to validate the complete, modelled audiograms. Together, these outputs allow us to assess whether offshore wind farm noise is detectable by pinnipeds and to inform the development of appropriate mitigation measures, which directly addresses the objectives of this RERI project.

Individual Australian sea lions and Long-nosed fur seals will be trained at Taronga Zoo to respond to sounds (pure tones of different frequencies and levels) for behavioural audiogram measurements. The seals at Taronga have received training already, for husbandry procedures, but will require specialist training to provide responses to sounds.

We aim to train up to two Australian sea lions and two long-nosed fur seals at Taronga Zoo for behavioural hearing tests. Each animal will be stationed at a custom-built listening station, positioned 1 m in front of a loudspeaker. Pure tones across a frequency range of 100 Hz to 21 kHz will be presented in randomised order. Sound levels will begin at a low intensity and gradually increase until the animal provides a detection response. Animals will be trained in a go/no-go paradigm. If the animal detects the tone, it will press a response paddle, if not, it will hold station. From experience, otariids are rapidly trained, in particular if the transmission of the test tone can initially be paired with an already learned go/no-go response (Erbe and Farmer 1998). The 50% response threshold at each frequency determines the audiogram.

Wind farm noise is generated during both construction (e.g. pile driving, vessel activity) and operation (e.g. turbine mechanics and blade movement), producing sound in both air and underwater. To evaluate potential impacts on pinnipeds, it is essential to understand their hearing sensitivity across both media. This project combines finite element modelling with behavioural hearing tests to produce species-specific audiograms that can be applied to realworld noise scenarios. For the behavioural tests, we will begin with in-air experiments, as these are more feasible and reliable as a starting point. Based on experience with other species, in-air training is generally easier and more controllable for trainers, and once established, the approach can be extended to underwater testing in future studies. The behaviours learned by seals for in-air hearing are typically easily transferred to underwater experiments hearing tests.

Behavioural audiograms will be presented in spreadsheets and graphs. They will be compared to the FE model audiograms generated for the same seal species.

3.3.2. Methods

Behavioural audiograms will be measured at a testing station that will be custom-built. A dedicated listening station is necessary to ensure each animal is consistently positioned at the same location (e.g., head resting on a chin-plate or against a nose ball), at 1m in front of a speaker.

Once animals have been trained for hearing tests in a go/no-go paradigm, a hearing test session will progress in the following steps:

1. Animal enters listening station and positions itself, with its chin on chin-rest.
2. Once the animal is correctly stationed, a light turns on to indicate the start of a trial. (We could also use a whistle or other sound, so the animal knows when the experiment starts).
3. If a light is used, it can stay on for the duration of each trial (4 s).
4. There will be a mix of signal-present and signal-absent (control) trials. The latter are needed to reinforce stationing (the animal will want to leave station and get a reward, so there is tendency for bias towards this response) and to assess the animal's bias (false alarm rate).
5. In a signal-present trial, the signal (tone) will occur 1.5 s into the trial and last 1 s.
6. If the animal indicates that it heard the tone within the 2.5 s after onset of the signal (i.e., before the end of the 4 s trial, which is before the light goes off), the trial will be considered a 'correct detection', the animal will be released and rewarded a quantity of fish.
7. If the animal holds station for the full 4 s, the trial will be considered a missed detection, and the animal will not be rewarded. This will include signal-present trials where the signal was too quiet, i.e., below detection threshold.
8. In a signal-absent trial, no tone will be played. If the animal holds station for the full 4s, it will be released (hand signal or whistle, or a release signal the animal already knows) and rewarded with a quantity of fish. If the animal leaves the station before the 4s are

over and/or gives the tone-detection response, it will not be rewarded, because no signal was played.

9. From trial to trial, the tone level will be varied. Each session will start with levels that we expect are easily audible, to start off with a series of positive reinforcements.
10. We anticipate running 20–30 trials within each 15 min session.

The aim is to provide direct measurements of seal hearing sensitivity at a range of frequencies and sound levels. From this, we can determine the hearing threshold at which each frequency can be detected (the 50% detection point).

- Test frequencies will range from 100 Hz to 30 kHz, in octave-band steps (i.e., 100 Hz, 200 Hz, 400 Hz, 800 Hz, 1.6 kHz, 3.2 kHz, 6.4 kHz, 12.8 kHz, and 26 kHz). There will be 9 frequencies to measure.
- Sound levels will be varied from 0 to 80 dB re 20 µPa to identify the quietest detectable tones.
- At each frequency, the hearing threshold will be defined as the sound level detected in 50% of trials.
- These thresholds together form the behavioural audiogram, providing direct measurements of pinniped hearing sensitivity.

When combined with the modelling results, the audiograms will define the full hearing range of Australian sea lions and Long-nosed fur seals and show whether construction or operational wind farm noise is likely audible to them, directly addressing RERI objectives.

4. EXPECTED OUTPUTS

1. A final report to the DCCEEW that consolidates methods, data, and implications for offshore wind farm assessments, aligned with the objectives of the RERI project plan.
2. Materials relevant to the guidance of wind farm proponents and assessors for their use when developing and addressing impact assessments.
3. Materials for development of guidelines to monitor seals during wind farm construction and operation, in order to facilitate detection and mitigation of negative impacts.

4.1. Seal spatial overlap with wind farms

1. Counts of seals at haul-out and breeding sites on Tasmanian islands of Bass Strait.
2. Spatial layers and summary outputs for raw data and results from spatial analysis.
3. Improved knowledge of the distribution of seals across Bass Strait.
4. Interpretation of the feasibility of monitoring seal numbers on land to provide an index of in-water distributions.
5. Interpretation of monitoring seal numbers at sites near areas of anthropogenic activity as a means of assessing changes in seal distribution and abundance patterns, which may occur in response to disturbance caused by wind farm development activities.

4.2. Seals hearing capability

1. Species-specific behavioural audiograms for Australian sea lions and Long-nosed fur seals, showing the range of frequencies they can detect and their relative sensitivity. These will be delivered as figures (see examples from other otariid species in Figure 4-1, spreadsheets, and a technical summary.
2. Validation of finite element models through direct comparison of behavioural data with modelled predictions, providing confidence that the modelling approach can be applied to other individuals and species in future.
3. Integrated hearing dataset combining modelled and behavioural results to define the full hearing capabilities of pinnipeds relevant to Australian offshore wind development.
4. The audiograms will enable interpretations of whether noises from construction (e.g., pile driving, vessel activity) and operation (e.g., turbine mechanics, blade movement) fall within pinniped hearing ranges.
5. Guidance for impact assessment and mitigation, including recommendations on which noise sources are most likely to be audible to Australian seals and therefore may require management.

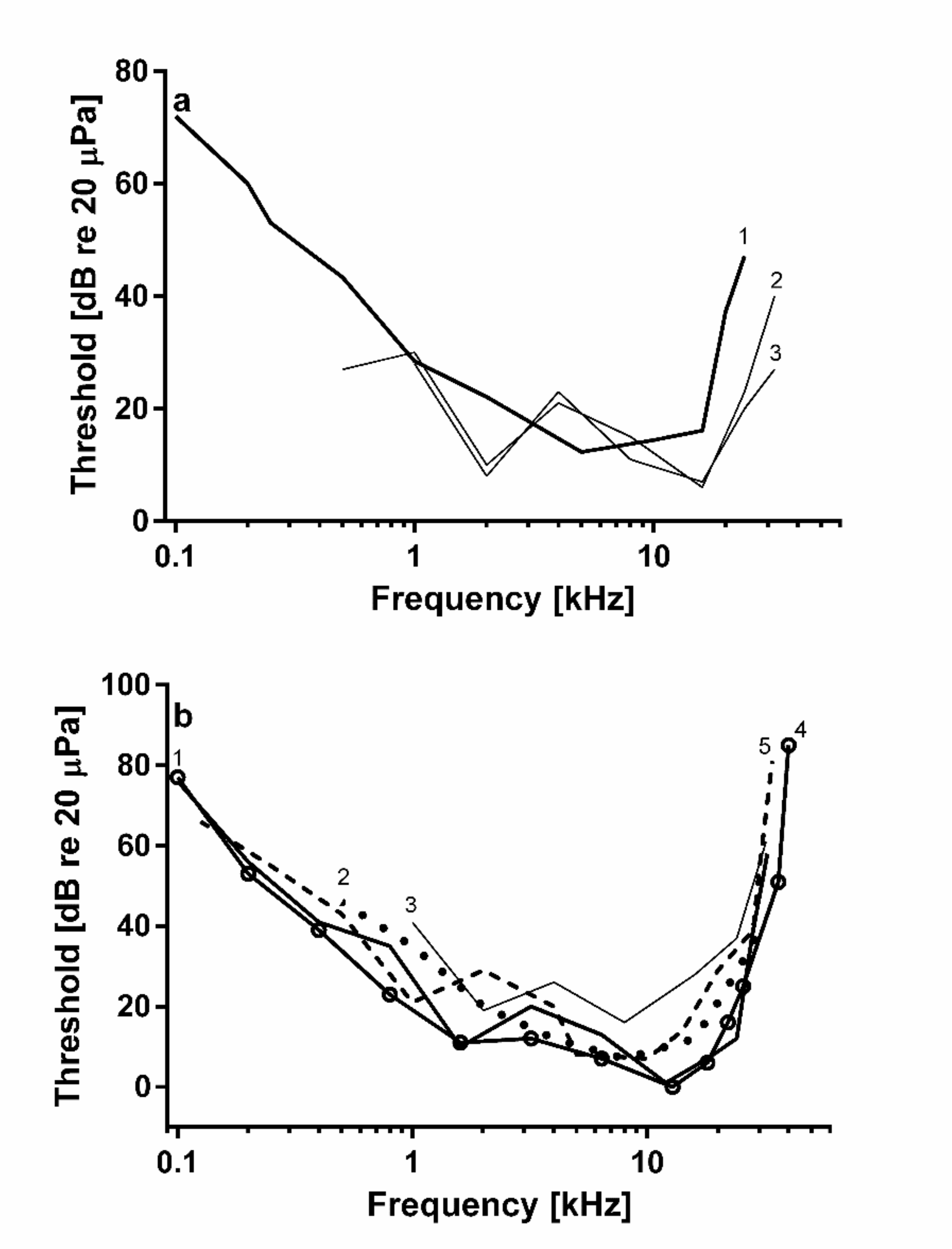

Figure 4.1. Aerial behavioural audiograms of otariids. (a) Northern fur seal *Callorhinus ursinus*: 1. thick line (Babushina et al. 1991), 2. and 3. (Moore and Schusterman 1987); (b) Sea lions: California sea lion (*Zalophus californianus*: 1. thick line (Reichmuth et al. 2013), 2. dotted line (Mulsow et al. 2011), 3 thin line and 4. solid line, open circles (Reichmuth et al. 2017); Steller sea lion *Eumetopias jubatus* 5. dashed line (Mulsow and Reichmuth 2010). Figure from Houser (2025), reproduced with permission.

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