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Chapter 38

Determining Marine Movements of Australasian Pinnipeds

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Chapter 38
Determining Marine Movements of Australasian Pinnipeds

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INTRODUCTION

The Australasian region (plus Australian and New Zealand Antarctic Territories) is home to 11 seal (Suborder Pinnipedia) species belonging to two families: the Phocidae (true or earless seals) and the Otariidae (eared seals) (King, 1988). The taxonomy of this fauna (with breeding areas) is summarized in Table 1. The diversity of habitats occupied by these amphibious mammals (i.e., both marine and terrestrial), the history of their exploitation by humans and subsequent re-establishment, and their accessibility for study provide many opportunities for theoretical, conservation and management research within Australasia.

Understanding the causes of these changes in population size is important for the conservation of these species and for an assessment of the magnitude of natural and anthropogenic changes to the marine environment. Questions regarding the processes and repercussions of these sometimes rapidly expanding populations are many. From an environmental perspective, we still do not fully understand the relationship that seals have with the variability of ocean productivity. What oceanographic and climatic factors influence, or ultimately control population trends? Further, potential anthropogenic changes in climatic and oceanographic processes or prey distribution and abundance may have important impacts on these populations. Global warming, increased variability in El Niño-Southern Oscillation (ENSO) events, human fisheries and expanding human populations can be expected to play a role in influencing population trends.

Many otariid species in the region have been heavily exploited by humans, but have subsequently re-colonized much, if not most, of their former ranges. Exploitation included hunting for food by indigenous peoples (Davidson, 1984; Smith, 1989), or for fur or blubber from the late 18th century to the early 20th century by Europeans (Strange, 1973; Best and Shaughnessy, 1979; Chapman, 1981; Richards, 1982, 1994; Ling, 1999). However, Antarctic ice seals (i.e., Weddell, leopard, Ross, crabeater seals), escaped much of the broad-scale exploitation observed for other species. Seal harvesting decimated otariid populations, resulting in mass extirpation from most of their previous ranges, while elephant seal populations were severely reduced at all major breeding sites (Laws, 1960, 1994; Bonner and Laws, 1964; Bonner, 1982; King, 1983; Hindell and Burton, 1988; Richards, 1994). In recent times, all pinniped species within the region have come under some national and international protection (Antarctic Treaty, 1980; Bonner, 1982; Warneke, 1982; Wildlife Protection Act, 1982; Warneke and Shaughnessy, 1985; Robinson and Dennis, 1988; Shaughnessy, 1999).

With the cessation of the major harvesting of otariids near the end of the 19th century, most populations have been increasing rapidly in number and extent (Payne, 1977; Bester, 1980, 1990; Hes and Roux, 1983; Roux, 1987; Smith, 1988; Shaughnessy and Goldsworthy, 1990; Wilkinson and Bester, 1990; Guinet *et al.*, 1994; Laws, 1994; Lalas and Harcourt, 1995; Hofmeyr *et al.*, 1997; Shaughnessy, 1998; Bradshaw *et al.*, 2000a). For example, Antarctic fur seals on South Georgia increased from approximately 369,000 in 1976 (Payne, 1979) to nearly 1.2 million by 1984 (McCann and Doidge, 1987). New Zealand fur seals in Australia and New Zealand have reoccupied much of their former range and are increasing rapidly (Shaughnessy, 1999; Bradshaw *et al.*, 2000a). Whether populations will return to equilibrium with respect to the available resources is unknown. For example, with the southern elephant seal there was rapid recovery immediately after exploitation followed by significant declines in some populations (Hindell and Burton, 1987; Laws, 1994; Hindell *et al.*, 1994); although they are among the world's rarest pinnipeds, there are insufficient data to determine what is happening to populations of either the Australian sea lion (*Neophoca cinerea*) or the New Zealand sea lion (*Phocarctos hookeri*) (Gales and Costa, 1997).

Changes in population trends and distribution combined with potential climatic changes make the study of pinniped behaviour a useful tool for improving our understanding of oceanographic processes. However, up until the 1980s, most of the at-sea distribution and behaviour of pinnipeds was unknown or poorly understood. Studies of pinniped foraging ranges are difficult to assess due to the often-extensive area used while at sea; New Zealand fur seals travel up to 220 km from the colony (Harcourt and Davis, 1997), southern elephant seals >3,000 km (McConnell and Fedak, 1996; Hindell and McMahon, 2000). With advances in communications technology, biologists have begun to accumulate data on foraging behaviour and ranges as well as variability in

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Table 1. List of pinniped species found in the Australasian region (modified from Shaughnessy, 1999).

Family	Scientific Name	Common English Name	Breeding Area
Phocidae	*Mirounga leonina*	southern elephant seal	subantarctic islands
	Hydrurga leptonyx	leopard seal	Antarctica (sea ice)
	Lobodon carcinophagus	crabeater seal	Antarctica (sea ice)
	Leptonychotes weddelli	Weddell seal	Antarctica (fast ice)
	Ommatophoca rossii	Ross seal	Antarctica (sea ice)
Otariidae	*Phocarctos hookeri*	New Zealand sea lion	New Zealand (subantarctic islands and mainland)
	Neophoca cinerea	Australian sea lion	mainland Australia
	Arctocephalus forsteri	New Zealand fur seal	mainland Australia/NZ/subantarctic islands
	Arctocephalus pusillus doriferus	Australian fur seal*	mainland Australia
	Arctocephalus gazella	Antarctic fur seal	subantarctic islands
	Arctocephalus tropicalis	subantarctic fur seal	subantarctic islands

* A subspecific designation is given to distinguish these populations from the Cape fur seals (*A. pusillus pusillus*) of southern Africa.

time and space. In addition, the availability of broad-scale satellite imagery has improved to the point where biologists can use bio-physical measures of ocean productivity to understand the relationship between pinnipeds and their marine environment (McConnell *et al.*, 1992; McCafferty *et al.*, 1998, 1999; Bornemann *et al.*, 2000; Guinet *et al.*, 2001).

The main technological advance enabling biologists to collect data on seals' at-sea behaviour was the development of a data-archiving tag known as the Time-Depth Recorder, commonly abbreviated to 'TDR' (Gentry and Kooyman, 1986b). The original devices were large, cumbersome and collected data on depth and time using a mechanical clock and inscribing trace. Nevertheless, they permitted a first glimpse into the clandestine life of diving animals (Kooyman, 1965; Kooyman *et al.*, 1976; Gentry and Kooyman, 1986b). By the late 1980s, microprocessor-controlled TDRs were collecting data on the at-sea behaviour of seals and other marine animals (Gentry and Kooyman, 1986a; Le Boeuf *et al.*, 1989; Goebel *et al.*, 1991; Hindell *et al.*, 1991b; Bengston and Stewart, 1992; Boness *et al.*, 1994; Boyd and Croxall, 1996). Technology has continued to improve to the point where today's TDRs have not only increased archiving capacity, but can also record a variety of additional variables including temperature, light levels, conductivity, swim velocity, heart rate and stomach temperature. In addition, other devices such as animal-mounted, miniature video cameras, electronic compasses, accelerometers and inclinometers can provide more precise behavioural information (Davis *et al.*, 1999).

It is not our intention to review the vast literature describing the applications and data recorded by TDRs and other behavioural data archival tags; we have devoted this chapter to the description of techniques available for the study of the spatial use of the sea by pinnipeds (i.e., marine movements). Many of these techniques can enhance information collected from TDRs, or they can be used independently to provide other types of data. Here we provide detailed descriptions of the applicability and efficiency of each technique using recent examples of research on three Australasian pinnipeds. These techniques include satellite telemetry, geo-location, acoustic tracking and radio tracking. We also discuss the future of potential technological advances in these techniques to continually improve the information available on this group of marine mammals.

SATELLITE TRACKING

PLATFORM TRANSMITTER TERMINALS (PTTs)

One of the more common methods employed to locate seals at sea is satellite telemetry, which requires a platform transmitter terminal (PTT) to be attached to the animal (Plate 132). PTTs transmit a UHF (ultra-high frequency) pulse to satellites orbiting the Earth. The system employed by ecologists for tracking animals is the ARGOS satellite-based system, which was implemented in 1979 by the French space agency (CNES), U.S. National Oceanic and Atmospheric Administration (NOAA) and the U.S. National Aeronautics Space Administration (NASA) (Argos, 1989). The system works in four simple stages: 1) the ARGOS transmitter is deployed on the seal and automatically sends a message at a pre-determined rate to multiple low-Earth orbit satellites; 2) these messages are then relayed from satellite to a ground station; 3) which then automatically forwards the data to the ARGOS processing centre in France. The data are then processed to calculate the location of the transmitter and; 4) the results are delivered to the researcher. Locations can vary in accuracy and are divided into quality classes by ARGOS. These are: **Z** = invalid location; **A/B** = no estimate of accuracy; **0** = >1000 m; **1** = >350 to <1000 m; **2** = >150 to <350 m; and **3** = <150 m (Argos, 1989).

PTTs can vary in complexity with the simplest device containing only the transmitter, battery and antenna all housed in a waterproof casing. Seals spend much of their time submerged during their foraging trips and signal transmission at these times is a waste of battery power. Another way to save on battery power and costly satellite time (Table 2) is to inhibit the number of signals emitted while the animal is on land or ice. These type of transmissions are controlled by a conductivity switch which, when not activated by salt water for a predetermined period, inhibits the signal (i.e., the 'haul-out threshold').

Other possible modifications to PTTs for pinnipeds may include modified TDRs with a pressure transducer that suspends signal transmission while the animal is diving and restarts transmission as the seal approaches the surface (McConnell *et al.*, 1994). Attaching archival tags, such as TDRs to collect dive behaviour, swim speeds, light intensity and water temperature and then transmit those data to the satellites can further increase the data collected for each deployment. However, there are limitations in the amount of supplementary data that can be transferred via satellites due to restricted transmission rates.

However, the size (i.e., frontal surface area) and weight of the instruments, caused by the requirement for large batteries (e.g., up to 400 g), can cause excessive drag on the seal while swimming. Even with the continued miniaturization of electronic components, large devices can limit the number of species and age-classes on which instruments can be deployed (see also Boyd *et al.*, 1991; Culik *et al.*, 1994; Walker and Boveng, 1995; Boyd *et al.*, 1997; Harcourt and Davis, 1997 for results on the effects of deploying instruments on marine animals).

In addition, an important consideration when using PTTs is that large samples (i.e., >10 PTT units) are uncommon due to the cost of the devices themselves and the use of the satellites (Table 2). Often the most expensive component of studies employing PTTs is the charge incurred by using the ARGOS satellite system rather than the initial cost of the devices. One advantage of this high cost is that data retrieval occurs whether or not the instrument itself is recovered. When the population to be studied is in an extremely remote, or difficult to access area (e.g., pack ice or islands at high latitudes) or the species being studied is elusive and difficult to re-catch, time and money do not need to be invested to retrieve archived data (this is the case when using TDRs). Researchers therefore need to assess not only the minimum sample size required to answer their proposed questions, but also must determine the magnitude of difficulty in accessing the data.

FUR SEALS AND FISHERIES: USING SATELLITES TO ASSESS OVERLAP

After the initiation of commercial sealing in the late 18th century, Australian fur seal populations were severely reduced, although the exact degree of the reduction is unknown (Warneke and Shaughnessy, 1985). The Australian fur seal has been protected for most of the last century and its numbers are now increasing (Warneke and Shaughnessy, 1985; Shaughnessy *et al.*, 1995;

Table 2. Approximate costs per unit (1999–2000 prices in Australian dollars*) and additional costs (e.g., data retrieval, necessary equipment, etc.), for a range of remote data-collection devices. Examples of unit sources are given (for a more comprehensive list, see the website http://www.biotelem.org/). Figures quoted should only be used as relative guides, since actual market costs fluctuate rapidly.

Unit Type	Unit/Cost ($)	Other Costs	Source
PTT	1,700–3,000	data retrieval (30/day/unit)	Sirtrack, N.Z.; Microwave Telemetry, U.S.A.; GFT, Germany (unit); Argos, France (data retrieval)
GPS§	400–600§	unit retrieval (manual costs)	B. Philips, Australian Antarctic Division; private development
geo-locating TDR	2,000	unit retrieval	Wildlife Computers, U.S.A.; Vemco Ltd., Canada; Lotek Marine Technologies, Canada
acoustic transmitter	1,075 (depth modulated)	47,000 (4-buoy array); unit retrieval	Vemco Ltd., Canada; Lotek Marine Technologies, Canada; HTI, U.S.A.
VHF radio	220	1,500 (scanner & aerial) 9,200 (data logger)	numerous sources
mini-CTD	400–600	unit retrieval	Star-Oddi, Iceland
route recorder	500–600†	unit retrieval	IEI‡, Italy; F. Bonadonna, CNRS, France

* Some AUD prices are converted from USD at a rate of 0.60 AUD/USD.
§ Projected cost.
† Non-commercial construction cost.
‡ Instituto per l'Elaborazione dell'Informazione, Pisa.

Arnould and Littnan, 2000). They are now found throughout south-eastern Australian coastal waters and as far north as Jervis Bay, N.S.W. (Shaughnessy, 1999). As is the case with many seal species, the Australian fur seal has been suggested to be a major competitor with fisheries, in particular with the South-east Trawl Fishery (SETF) (Anon., 1998, 1999). Several other smaller fisheries occur within the range of Australian fur seals including the South-east Non-Trawl Fishery (SENTF), the Southern Squid Jig Fishery (SSJF), and the Jack Mackerel Fishery (JMF) (Anon., 1998, 1999).

To determine if overlap (i.e., using the same resources, as opposed to 'competition', which is 'an interaction in which one organism consumes a resource that would have been available to, and might have been consumed by, another'—Begon *et al.*, 1986, p. 199) exists between seals and the fisheries two basic criteria must be met: (1) overlap in prey species eaten or harvested (Harwood, 1992; Fea and Harcourt, 1997), and (2) overlap in areas fished (Harwood, 1992; Harcourt and Davis, 1997). With regard to criterion number one, Australian fur seals do eat commercially hunted fish. Indeed, 60% of the prey species of Australian fur seals (Gales *et al.*, 1993; Gales and Pemberton, 1994; Littnan, unpublished data) are fished commercially (Anon., 1998, 1999). However, the effect this overlap may have on the subsistence of both fur seals and the fisheries is unclear. Further research is required to determine annual, seasonal and spatial variation in Australian fur seal diet, fur seal prey consumption rates, and population dynamics of both fur seals and fish stocks.

The second part of the equation is obtaining information on the overlap between areas used by seals and commercial fishing grounds (Harwood, 1992; Harcourt and Davis, 1997). This is important for managing fish stocks for sustainable use while ensuring the persistence of seal populations. TDRs and PTTs have been deployed on animals in Tasmanian and Victorian waters to determine foraging locations and dive behaviour (Arnould, Harcourt, Hindell, Kirkwood, Littnan, Pemberton, unpublished data). Much of the work has been done with adult female fur seals for a number of reasons. First, they return to the colony to suckle their pups and so expensive instruments may be recovered. Second, females are significantly smaller and therefore, more tractable and more easily handled than males. Third, and most importantly, females provide information on the reproductive performance (and thus trends) of the population.

A majority of dives recorded from female fur seals on Kanowna Island (see Figure 1) were to 65–85 metres, suggesting that animals feed primarily on the continental shelf within Bass Strait (Arnould, Hindell, Littnan, unpublished data). This is supported by data from ten females fitted with PTTs: Kanowna Island (n = 3), The Skerries (n = 1) and Tenth Island (n = 6). Figure 1 shows a composite of these data expressed as the amount of time spent in hours per 20 km x 20 km grid cell. Data from Kanowna Island and The Skerries (Arnould, Harcourt, Littnan, unpublished data) show females foraging within Bass Strait between Tasmania and Victoria, but also along the east coast of Victoria near Lakes Entrance. One female even foraged along the N.S.W. coast as far north as Merimbula. The Tenth Island females foraged entirely within southern Bass Strait and within 200 km of the colony (Hindell, Pemberton, McCarrey, unpublished data). In addition, four adult males have been tracked from Seal Rocks in northern Bass Strait (Kirkwood, Gales, Lynch, Dann, 2000, personal communication). These seals foraged mostly in western Bass Strait, where water depths are <100 m, and >20 km from any land (Kirkwood, 2000, personal communication).

With the limited data available, it appears that seals foraging in Bass Strait and Tasmanian waters may have some spatial overlap with the relatively small Jack Mackerel Fishery. The greatest region of overlap is along the east coast of Victoria, near Lakes Entrance, where the continental slope occurs very close to shore (see Irvine *et al.*, 1997). It may be that some fur seals in colonies to the north of eastern Bass Strait forage in areas where there is substantial commercial fishing, but much more information is still required to comment on the degree of overlap between Australian fur seals and Australian commercial fisheries.

GEO-LOCATION

LOCATIONS AT SEA (FROM TEMPERATURE AND LIGHT RECORDINGS)

An alternative to satellite location of animals at sea is to record environmental parameters that can be processed later to provide an indication of where the seal was at the time that the recordings were made. In the late 1980s and early 1990s, this technique began by using water temperatures that were recorded concurrently with depth data in early TDRs (Hindell, 1991; Slip *et al.*, 1994). Comparisons of temperatures when the animal is at the surface with concurrent sea surface temperature data (generally derived from satellite imagery) can be used to estimate in which general oceanographic regions (e.g., south of the Antarctic Polar Front—Hull, 1999) the animals were foraging. In deeper diving animals, these locations can be refined by including temperature data at a range of depths, for example 100, 200 and 500 m, and relating them to oceanographic temperature-depth profiles (Hindell *et al.*, 1991a). These additional data enable animals to be located to more precise areas of the ocean (Slip, 1997). The precision of these estimates depends on the magnitude of variation in the vertical thermal structure of the water column and on the detail and accuracy of the oceanographic data. Unfortunately, the latter are sparse for some regions of the ocean and for some times of the year. Nonetheless, this technique remains a powerful analytical tool in marine ecology.

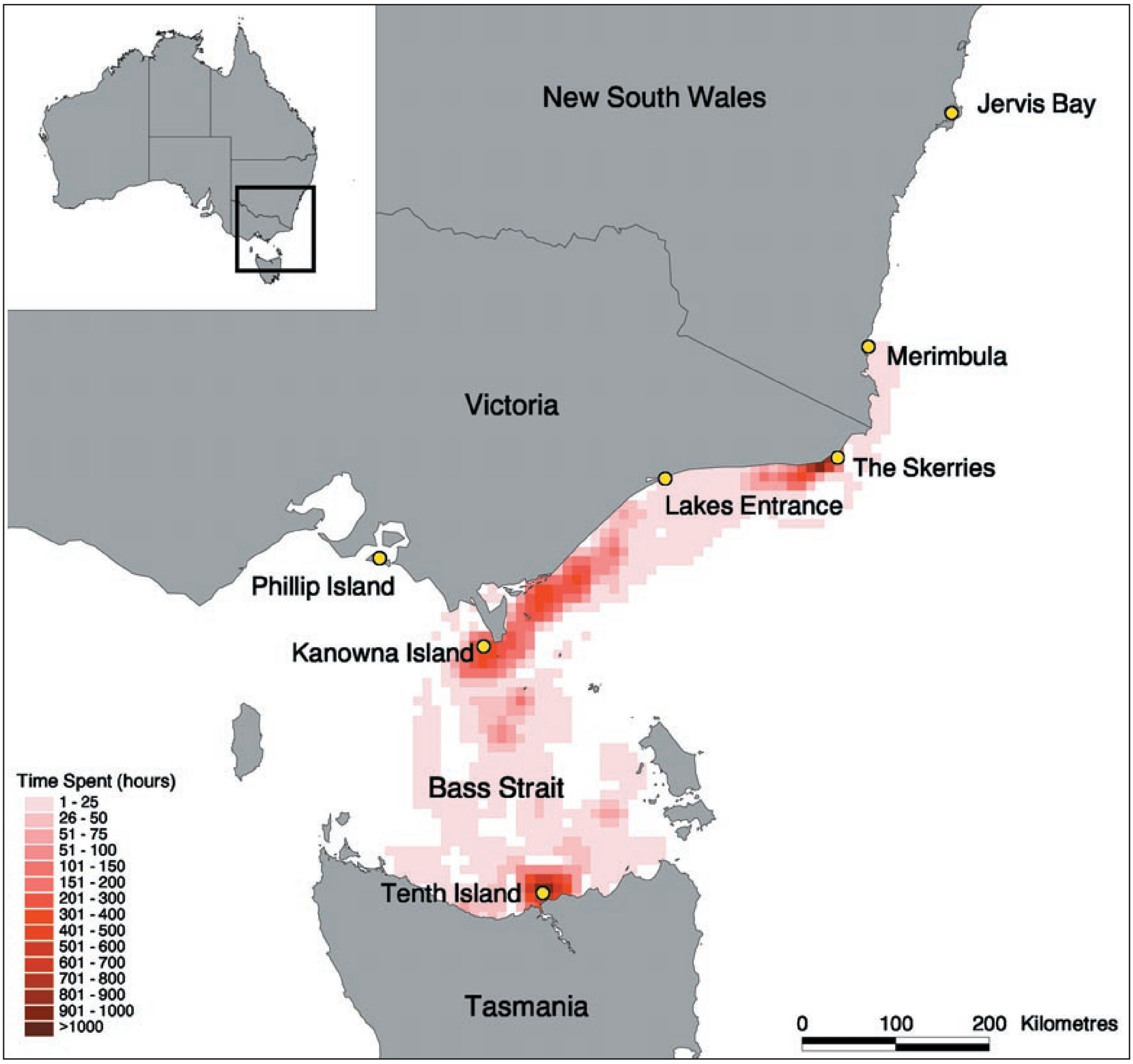


Figure 1. Plot of the time spent at sea by Australian fur seals equipped with satellite transmitters. Animals were captured and released from The Skerries (n = 1; 21 Jun.–27 Aug. 1999), Kanowna Island (n = 3; 27 May–18 Nov. 1999) (Littnan, Harcourt, Arnould, unpublished data) and Tenth Island (n = 6; 18 Dec. 1996–26 Feb. 1997) (Hindell, Pemberton, McCarrey, unpublished data).

An alternative parameter used to locate animals is light intensity (DeLong *et al.*, 1992). Again, this is done conventionally in association with a TDR, which is programmed to record light intensity at set time intervals, or when the animal is within a set distance from the surface. The basic data of light intensity, time and depth can be processed to calculate the time of sunrise and sunset for each day that the animal has spent at sea. Standard equations for solar navigation (Nautical Almanac Office, 1991) can then convert this information into estimates of latitude and longitude for that day.

The use of light levels to estimate position on the Earth's surface is not as accurate as locations derived from satellite telemetry. Even at their very best, locations will be accurate only to within approximately one degree of latitude (i.e., 111 km), and often they are less accurate than this (Hill, 1994). One problem is estimating the time of sunrise and sunset from light data recorded on actively swimming and diving animals. The resultant light curves are rarely smooth, and the algorithms employed to smooth and interpolate between the points often have trouble identifying the time of sunrise or sunset with sufficient accuracy. Another source of error occurs when an animal moves several hundred kilometres in a day. Movements to the east or west will artificially increase or decrease the apparent day length, and subsequently provide inaccurate locations. Perhaps the main limitation to the method is the occurrence of the equinoxes. During an equinox, day length is the same over the entire globe, making accurate assessment of latitude impossible, although longitude is not affected. This means that there are generally several weeks each year for which latitudinal fixes cannot be made. Polar regions offer special problems because they have extended periods of complete daylight, or complete darkness, which again prevents the derivation of a location. Likewise, equatorial regions with their limited variation in day length provide few navigational cues. Geo-location is therefore most effective when used in mid-latitudes between 10 and 60 degrees.

Some studies have attempted to validate geo-location from light levels against known at-sea locations either from ships (DeLong *et al.*, 1992), or from animals carrying both geo-location TDRs and satellite transmitters (van den Hoff, unpublished data). The validation studies have confirmed that, under ideal conditions, locations at sea derived from light levels are accurate to ±100 km, and that biases increase with increasing latitude. These validations are a crucial component of geo-location studies as they determine the appropriate scale for the subsequent analysis of location data, and for the calculation of adjustment algorithms.

Despite the problems associated with light levels in estimating the location of animals at sea, this technique has been used successfully on a number of species (Goldsworthy *et al.*, 1997; Stewart, 1997; Hull, 1999). There are two prerequisites for the successful use of light data:

(1) A suitable question: studies need to address questions that are concerned with meso-scale events (i.e., in the order of $\geqslant 100$ km^2). Ecological variables that operate on these scales are events such as ocean currents, frontal systems, bathymetry and some types of fisheries activity.

(2) A suitable species: studies need to focus on species that cover a large area of ocean (Stewart and DeLong, 1993). As the best accuracy possible is to within one degree of latitude or longitude, species that do not move >100 km during a foraging trip will reveal little of value. Alternatively, animals that travel too far too quickly, such as far-ranging sea birds, will have large errors associated with their locations. Ideal species are those that make foraging trips of more than 10 days, range over at least several hundred kilometres, and do not move more than 200 km per day.

ADVANTAGES OF GEO-LOCATION

Geo-location systems have several advantages over existing telemetric systems. Telemetric devices have antennae that need to leave the water before they can transmit a signal, which restricts where on the body the devices can be placed, and may increase the drag while the animal is submerged and swimming (see Boyd *et al.*, 1991; Walker and Boveng, 1995; Harcourt and Davis, 1997). The relatively compact size of light-archiving units reduces the amount of drag, thus permitting deployment of the devices on small marine animals such as penguins and small fur seals (Hull, 1997). TDRs with light-archiving capability record depth and water temperature (and sometimes other parameters such as swimming speed), enabling all of these data to be referenced spatially and greatly enhancing the usefulness of conventional diving behaviour data. To collect similar information using radio or satellite telemetry requires much larger units incorporating additional sensors and archival capacity, or even two separate units (e.g., a transmitter and a TDR shown in Plate 134). Both of these options increase size and drag and restrict both the choice of species and duration of deployments. However, the single biggest advantage to geo-location TDRs is cost. The initial purchase of a satellite transmitter can be up to twice or three times that of a TDR, and then there is an additional daily charge while the units transmit (Table 2). There is therefore a trade-off between using satellite transmitters and getting more high-quality locations per animal (but for fewer animals) without the burden of unit retrieval, or using light-archivers and getting fewer, less accurate locations per animal but from a far greater number of animals after unit retrieval. The resolution to this dilemma lies in the nature and scale of the questions being asked, and the probability of retrieving instruments after initial deployment.

ELEPHANT SEALS FORAGING IN THE SOUTHERN OCEAN

One species that is particularly well suited to geo-location is the southern elephant seal. This species has a circumpolar distribution, breeding on subantarctic islands, and dispersing into the Southern Ocean for periods of up to eight months at a time (Hindell and Burton, 1988; Hindell *et al.*, 1991a; McConnell *et al.*, 1992; Fedak and McConnell, 1993; Figure 2). Geo-location has been used to track these animals from several of their major breeding sites, and has revealed much about their migration patterns (Bester and Pansegrouw, 1991; Jonker and Bester, 1998). Adult seals migrate twice each year: the first migration is after the breeding season when the animals need to re-build their fat reserves for the coming moult. During this time, they can disperse up to 2,500 km from the breeding site. In females, this post-breeding migration lasts for a mean of 70 days, and in males it lasts for about 90 days (Le Boeuf and Laws, 1994). For elephant seals that breed on subantarctic Macquarie Island, males tend to concentrate their post-breeding foraging effort over the Antarctic continental shelf, and to a lesser extent over subantarctic ridges such as the Campbell Plateau (Slip *et al.*, 1994). Dispersal of adult females is

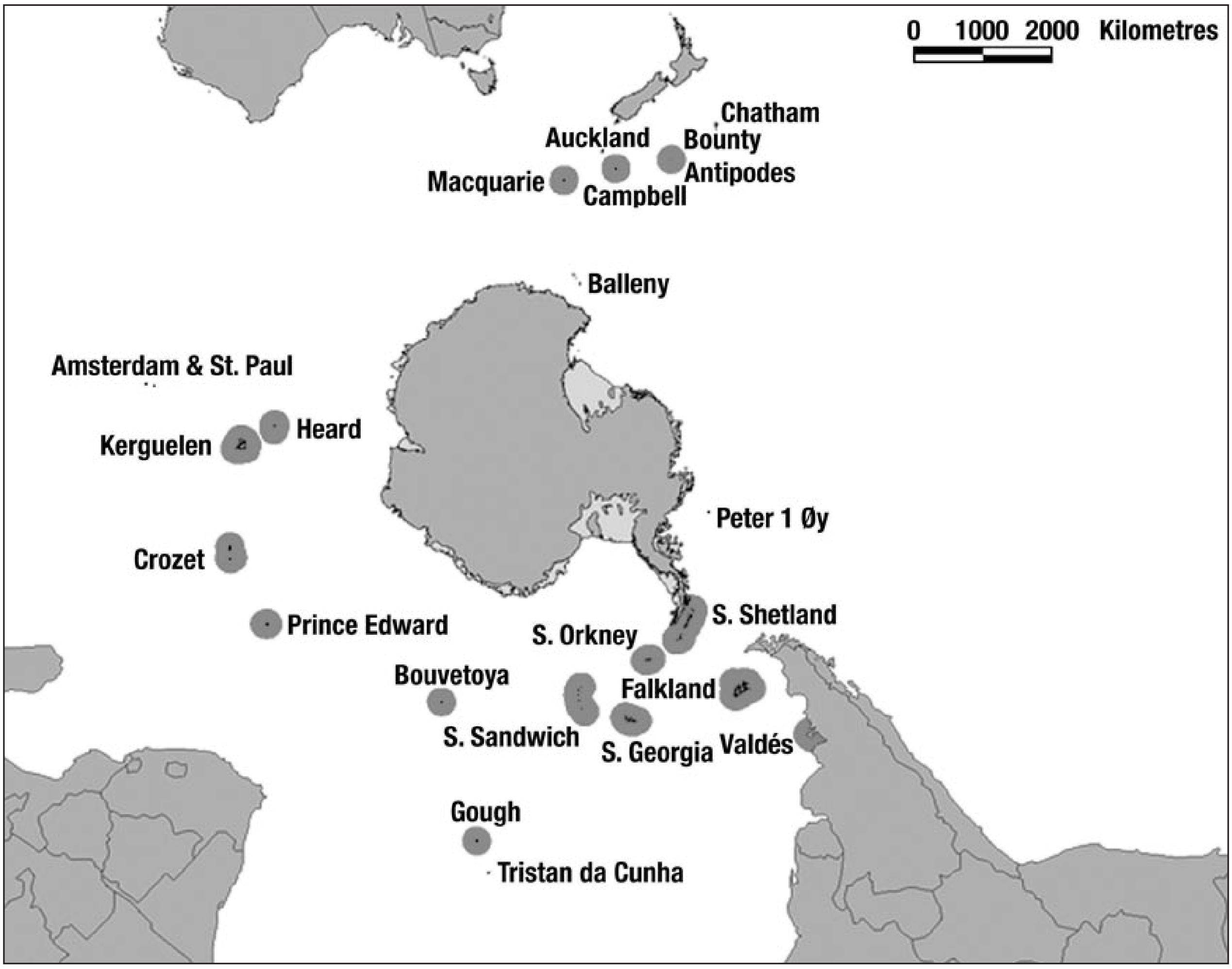


Figure 2. The breeding distribution of southern elephant seals (*Mirounga leonina*) in the Southern Ocean (after King, 1983; Ling and Bryden, 1992; Slade, 1997).

more variable and often more pelagic; females have been located in a range of marine habitats from the Antarctic continental shelf, to oceanic waters north of the sub-antarctic convergence (McConnell *et al.*, 1992; Slip *et al.*, 1994). The second migration is longer (up to 8 months in females and 6 months in males) and takes place after the annual moult. General patterns of dispersal seem to be the same as during the post-breeding migration, although less is known about this phase (Slip *et al.*, 1994).

Due to the wide-ranging and protracted nature of their migrations, elephant seals are ideal subjects for questions that are directed towards meso-scale events. One example of this type of study is recent work using geo-locating TDRs, which aims to quantify the physical and biological oceanographic characteristics that determine the foraging grounds, and ultimately the foraging success, of adult females (Bradshaw, Hindell, Michael, unpublished data). A study on female foraging ecology began in the summer of 1999–2000. Here, 17 female elephant seals from Macquarie Island were instrumented with TDRs (Plate P2) and the data collected confirmed that there was considerable individual variation in the areas of the Southern Ocean used by these seals (Figure 3). Animals from Macquarie Island moved to the west, the north-east (adjacent to the Campbell Plateau), to the south-west into the Antarctic pack ice, and >2,000 km to the east.

Although helpful in indicating general dispersal patterns, the plotted tracks of seal locations themselves yield little quantitative information. A more informative way to represent these data is to calculate the time that the animals actually spent in each part of the ocean. For elephant seals tracked with geo-location, an appropriate spatial resolution is reflected by a raster grid consisting of 100–200 km^2 cells. Presenting the data for all 17 seals as 'time spent' per grid cell produces a much clearer picture of their spatial use (Figure 4). There is a clear trend for the seal activity to be concentrated along a band extending in an approximately north-west to south-east direction, and within the band there are regions of high use. Similar regions of high use are associated with the Antarctic continent, and near

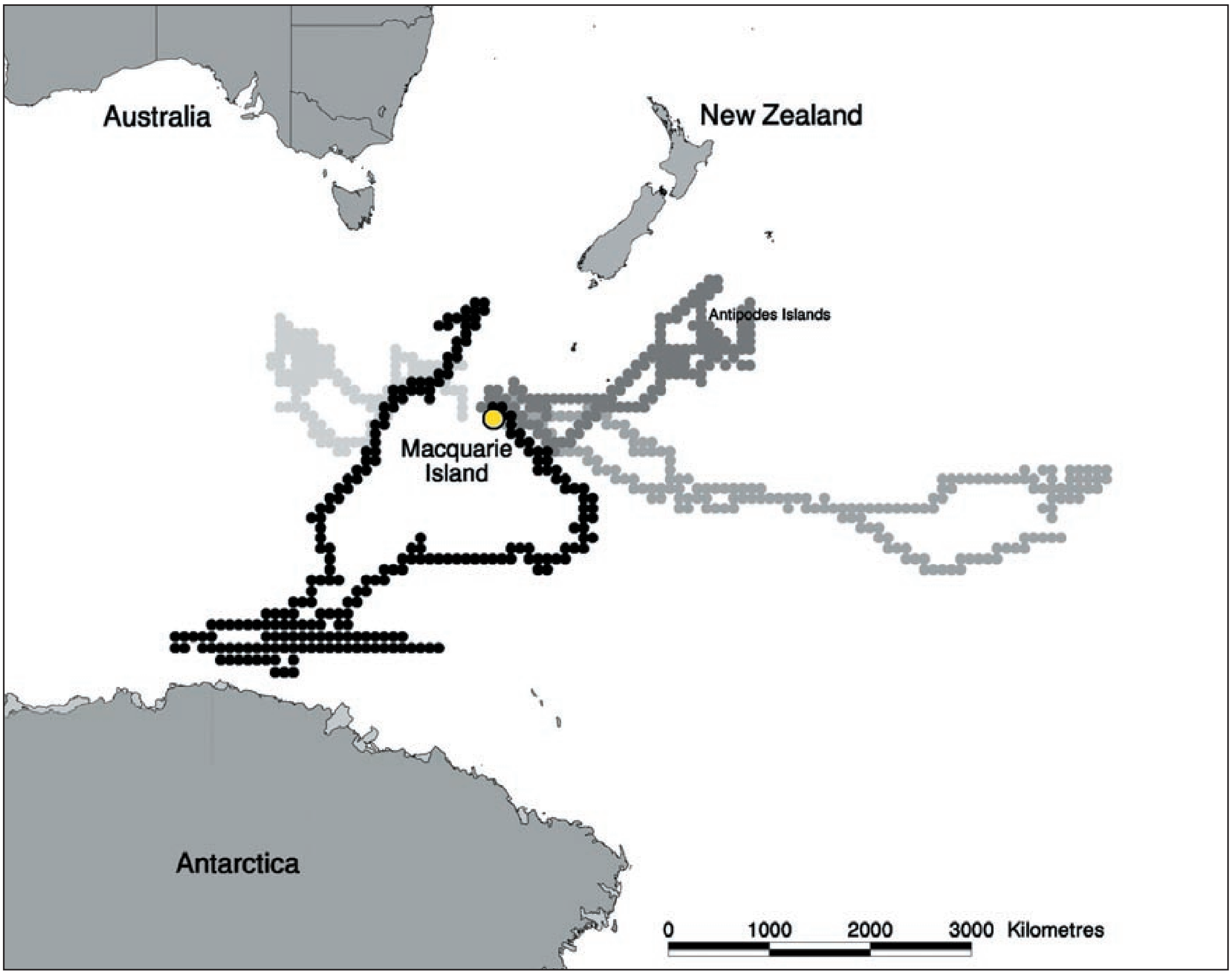


Figure 3. Plot of the four extreme female elephant seal tracks made in the 1999–2000 post-lactation foraging trip (Oct. 1999–Jan. 2000).

the Antipodes Islands (Figure 3). This figure represents all the data combined over a 100-day period, but it is also helpful to represent the data on more restricted time scales (Figure 5). This representation indicates that the areas of the Southern Ocean visited and time spent there differ throughout the spring and summer, reflecting the outward part of their migrations, the time spent at remote feeding grounds, and the return phase.

How top predators respond to variation in the intensity and location of food patches in their environment will, in the long term, influence population trends (Testa *et al.*, 1990; Boyd and Arnbom, 1991; Burton, 1998). Spatial and temporal distribution data from seals can be incorporated into models that help us interpret how they vary their movements in relation to prey abundance. An extension of these models would allow the prediction of elephant seal behaviour as a function of a range of physical and biological ocean variables (Croxall *et al.*, 1988; Whitehead *et al.*, 1990; Testa *et al.*, 1991; Trillmich and Ono, 1991; Burton, 1998; McCafferty *et al.*, 1998, 1999; Bornemann *et al.*, 2000; Guinet *et al.*, 2001).

At this time it is still difficult to estimate the configuration of oceanographic features, but we do have access to some data that are at least partially related to the biological productivity of the Southern Ocean (Vincent *et al.*, 1991; Ansorge *et al.*, 1999). Measurements of sea-surface temperature, bathymetry, ocean currents and ocean colour (a proxy for chlorophyll A, produced by phytoplankton) are made through satellite imagery of the ocean surface at a variety of temporal and spatial scales. Assessing these properties at scales similar to those produced by the remote data for elephant seals at sea can produce models that best explain the observed patterns of seal distribution and foraging behaviour. Spatial data for all input variables are best organized and presented using geographic information systems—see pp.873–887 (Flemons and Cassis, 2006)—and associated using standard spatial correlations (Odland, 1988), or more recently, artificial neural networks (Bradshaw *et al.*, 2002). Such analyses are starting to provide powerful predictive tools that describe elephant seal distribution under various oceanographic scenarios (Bradshaw, Hindell, unpublished data). The analyses will

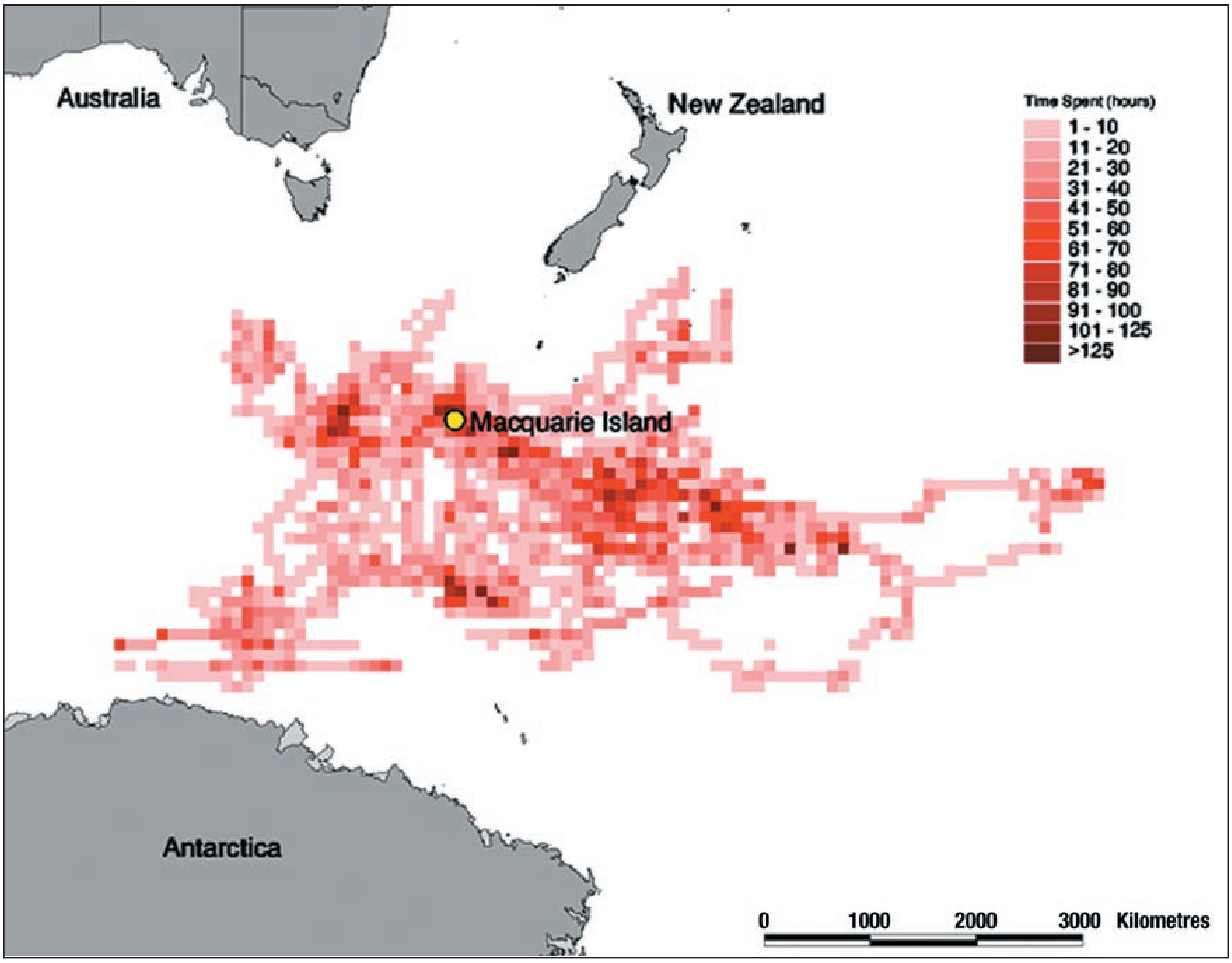


Figure 4. Plot of the time spent at sea for 17 female southern elephant seals during the 1999–2000 post-lactation foraging trip (Oct. 1999–Jan. 2000). Darker shades indicate more time spent in those grid cells.

be made even more powerful by incorporating behavioural data recorded simultaneously with location data that can provide indices of foraging effort (such as number of dives, total time spent at depth, and total vertical distance) at the same scales. Although in its infancy, the integrative modelling approach to marine predator studies is an exciting, new development that will shed light on linkages between biology and the environment that could not be explored in the past.

ACOUSTIC TRACKING

MEASURING BEHAVIOUR IN THREE DIMENSIONS

TDRs have revolutionized our understanding of the ecology of diving animals (Gentry and Kooyman, 1986a). Yet despite their technical sophistication, to date they have one major limitation: dive profiles for records produced by archival tags are limited normally to two dimensions: time and depth. However, diving animals inhabit a three-dimensional world (four dimensions if time is included). Although satellite telemetry allows us to visualize movements over broad spatial scales, it cannot provide information on fine-scale directional changes, that is, within individual dives. Although archival tags record other parameters, such as swim velocity, that provide a mechanism for calculating dive angle and activity changes in different phases of each dive (Ponganis *et al.*, 1990; Thompson and Fedak, 1993; Boyd *et al.*, 1995; Horning and Trillmich, 1997), most still do not provide information on finer-scale activity; however, for further discussion of route recorders, see the Other Techniques section (p.901).

To counter this problem, alternative methods of studying dive behaviour of seals are available. One method employs an acoustic tracking system that enables the reconstruction of the movements of individual seals in four dimensions (the horizontal X and Y coordinates, the vertical Z coordinate (or depth and time) (Wartzok *et al.*, 1992a, b; Harcourt *et al.*, 2000). The degree of precision with this technique is high (within 1–2 m^3), and it can be used with a number of animals simultaneously. Therefore, it allows for the measurement of changes in the underwater behaviour of individual seals relative to each other, and is thus a powerful tool in the study of social behaviour.

FORAGING OF WEDDELL SEALS UNDER ANTARCTIC ICE

Acoustic tracking has been used on Weddell seals (Hindell *et al.*, 1999; Harcourt *et al.*, 2000) which give birth and suckle their pups on fast ice at the coastal margins of Antarctica during the Austral spring (Castellini *et al.*, 1992a). Females leave the water along tide-cracks in the ice to give birth and feed their pups during the five- to six-week lactation period (Tedman and Green, 1987). During this time, territorial males spend the majority of their time under the ice competing for, or maintaining, territories (Kaufman *et al.*, 1975; Siniff *et al.*, 1977; Bartsh *et al.*, 1992; Harcourt *et al.*, 1998). Because females are concentrated along the cracks, the movements of males are also localized nearby. Females dive frequently towards the end of lactation but are constrained by the limited number of gaps through the ice surface to the air, and also by the need to return to their pup at the breeding site. Males that successfully hold territories rarely stray more than a kilometre from the tide crack (Harcourt *et al.*, 1998); therefore, it is possible to use acoustic tracking on many free-ranging animals *in situ*.

Movements under the ice have been monitored using a Cabled Acoustic Positioning System (CAPS) manufactured by Vemco Limited (Canada). An acoustic transmitter is attached to the seal using quick-dry epoxy glue (Plate 133). The attached device transmits a series of ultrasonic signals at a single, predetermined frequency in the range 60–80 kHz every 1.5 seconds. The signal contains four pulses, the first three occur at fixed time intervals and the last varies with depth. Only transmitters using frequencies >60 kHz are used currently because it has been observed that these frequencies produce no noticeable effects on the behaviour of seals and should be beyond the upper range of their hearing sensitivity (Wartzok *et al.*, 1992b). Very High Frequency (VHF) radio transmitters (Sirtrack 150–152 MHz) are attached simultaneously to the dorsal surface of the seal, both for in-water time budgets (see below) and to find animals that might leave the study area. An array of three or four omnidirectional hydrophones (Vemco VH65, 50–80 kHz) each connected to an Ultrasonic Acoustic Receiver (Vemco VR20) is placed around the area where the density of seals is highest (Figure 6). Hydrophones are placed through 80 mm diameter holes drilled in the sea-ice (thickness 1.4–2.2 m), or alternatively, for studies in ice-free areas, they can be connected to moored buoys to float on open water (see below). The cables to the hydrophones are suspended inside three-metre-long PVC pipes to hold the hydrophone in place and also to protect the cable and prevent it from being frozen permanently into the ice. Each hydrophone must be held securely at approximately the same depth and well clear of the undersurface of the ice to avoid echoes and reverberations. A four-part, diamond-shaped array gives a larger area of maximum precision, although a three-part triangular array still provides an area of coverage of >200,000 m^2. The distance between receivers is critical to the area to be tracked; typically, a distance of 400–500 m. Each receiver is connected via communication cables (length 308 m) to a central base station. Radio links between buoys are also possible.

Locations of each animal can then be determined using custom software, such as POSITION V3.07© (Vemco Ltd., Canada) which calculates the X and Y co-ordinates of the transmitter based on differences in the arrival time of pulses at each of the three hydrophones, and determines depth (± 1 m) from the modulating changes in pulse interval with depth (Figure 6). Within the area under the array, the X, Y and Z values are accurate to approximately ± 1–2 m^3. Outside the array area precision is lower, but measurement for animals up to 1 km from the area can be made with satisfactory precision. Transmitters have a custom depth range, and for deep diving Weddell seals (Kooyman, 1981), the maximum possible of 0–680 m was chosen.

The procedure for calculating locations requires the central base-station to interrogate each of the buoys in turn, and each interrogation takes a number of seconds, as several transmitted pulses are required to calculate a position. This equates to a sampling rate of one location every 15 or 30 seconds, depending on the number of animals being recorded. For fine-scale movements, minimum sampling intervals (e.g., a rule-of-thumb is a minimum of 20 sampling points per dive) are required to prevent artefacts arising in the dive profile as a result of an infrequent sampling regime (Boyd, 1993; Wilson *et al.*, 1995; Hindell and Lea, 1998). In this case, detailed analysis is restricted to dives exceeding five minutes in duration.

The data output collected using POSITION consists of a number of files containing all locations for all animals at each period sampled. Erroneous positions are occasionally recorded, presumably due to echoes and reverberations in the acoustic signals. Therefore, data are always filtered to remove consecutive X, Y and Z positions that require a swim velocity >4 ms^{-1}, twice the modal velocity of adult Weddell seals (Castellini *et al.*, 1992b, Davis *et al.*, 1999, Harcourt *et al.*, 2000).

It is only possible to display TDR dive profiles in two dimensions. However, for three-dimensional profiles several perspectives are needed to view the nuances of each dive. Figure 7 illustrates two dives by a female Weddell seal with the three-dimensional dive rotated three times through 90° in order to see the dive from several angles. In Figure 7(a), a female 'moving' dive, the female dives rapidly to approximately 150 m and then swims more slowly in a large loop before returning rapidly to the surface. Her entry and exit holes in the ice are in different positions. In Figure 7(b), a female 'flat' dive, the same female again swims rapidly to approximately 150 m, but there her velocity falls to zero ms^{-1}. After spending considerable time (approximately 9 minutes of a 19-minute dive) waiting in this place, the female returns rapidly to the surface. In this dive, the entry and exit holes are identical. From our knowledge of the bathymetry under the array, it is known that the females were close to, if not on, the bottom for most of these dives. As females may be diving to feed (Testa *et al.*, 1989; Hindell *et al.*, 1999) these two dives may illustrate alternate foraging strategies. Moving dives (Figure 7(a)) may indicate a seal actively searching for sedentary prey, while flat dives (Figure 7(b)) may illustrate a 'sit and wait' strategy as would be expected when the animal is preying on sparse, active prey (Thompson *et al.*, 1993). As has been shown recently with diving male Weddell seals (Harcourt *et al.* 2000), two-dimensional TDR profiles of these two dives would indicate that they were comparable; it is only when the third dimension is added that they become so distinct.

This illustrates that, for a single animal, three-dimensional dive profiles can enhance our understanding of foraging tactics of marine predators. There are limitations in the system given the large-scale movements by most marine predators, as described elsewhere in this chapter. It may also be possible to apply this technology to other seal species not restricted to the fast ice. Identifying areas of preferred foraging by other means (e.g., satellite, geolocation), and then establishing a floating acoustic array on the ocean surface above these areas could provide finer-scale details on the foraging habits of many fur seal species. It may even be possible to track individuals of seal prey species simultaneously to provide concurrent distributional and behavioural data on both the predators and their prey. Given the fine-scale (10–100 m) at which patchiness in the distribution of many prey species occurs (Zamon *et al.*, 1996), the insights offered by this type of system in appropriate environments will enhance our understanding of behaviour at broader scales. Interpreting dive behaviour becomes simultaneously more complex and more realistic when the entire three-dimensional path is apparent.

RADIO TRACKING

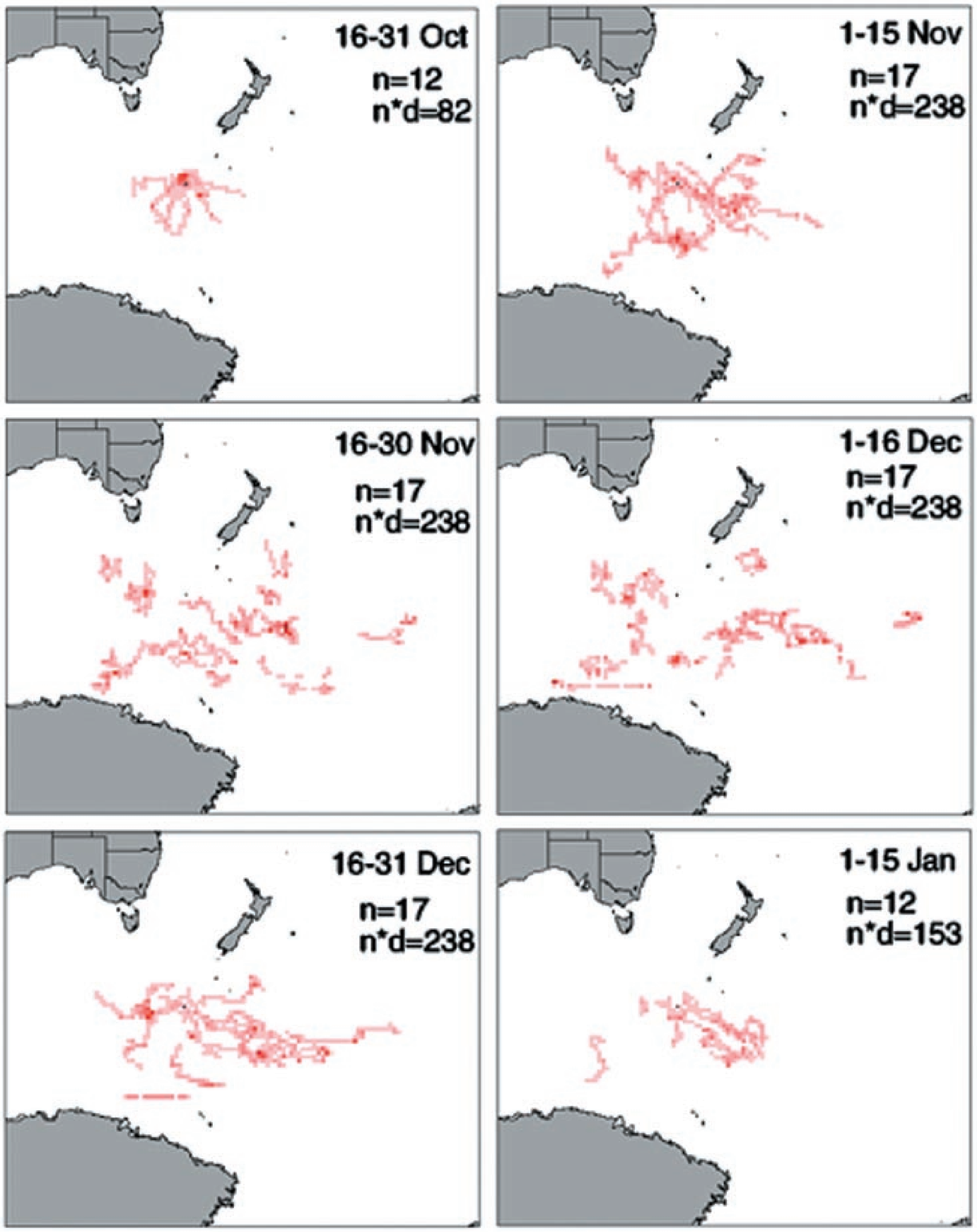
VERY HIGH FREQUENCY (VHF) TELEMETRY

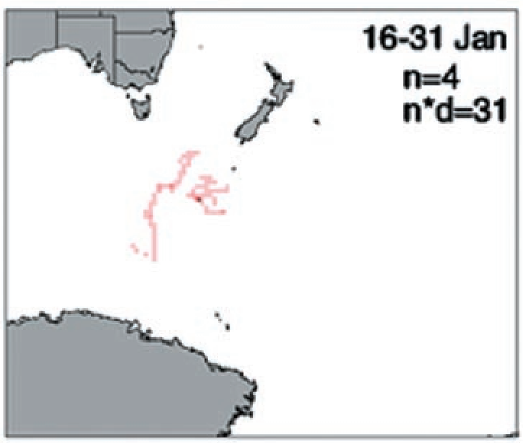
Very High Frequency (VHF) radio tags have been employed for many years to monitor movements of wild animals ranging in size from large arthropods (e.g., giant weta, Sirtrack, New Zealand) to the great whales (Goodyear, 1993). VHF transmitters work by emitting a series of pulsed signals at very high frequencies (30–240 MHz) via a transmitting antenna. These signals are received by another, directionally sensitive antenna, which is connected to a receiver within line-of-sight of the transmitter (i.e., there must be a clear path between the transmitter and receiver) (McDonald and Amlaner, 1980). The directional properties of the receiving antenna allow the location of the animal to be calculated by taking bearings on the signal from at least two places and noting where the bearings intersect (i.e., 'triangulation'). Yagi, loop or Adcock antennae are required for taking bearings (see Kenward, 1987).

VHF signals do not transmit through the air-water interface, so locating marine animals can only occur when the animal is ashore or has breached the surface. Errors arise in four main ways: (1) system error (antennae flex and twist in the wind, especially when mounted on aircraft or other vehicles); (2) animal movement while bearings are being taken (a particularly important problem for triangulation of marine animals that breach the surface only briefly); (3) topographical error arising from reflection and refraction of the signal creating false bearings (McDonald and Amlaner, 1980); and (4) determining direction depends on the human ear or some other measure of signal strength, and these are often not very accurate over distances of several hundred metres.

In Australia, wildlife transmitters operate on frequencies between 150–152 MHz. Transmitters for diving animals such as seals usually have the batteries and electronic parts embedded in an epoxy resin to prevent leakage and implosion due to pressure at depth, and have an attached whip antenna (plastic-coated, stainless-steel cable approximately 25–30 cm long). For these sealed units, an external, magnet-reed switch activates and de-activates the transmitters. For most purposes, VHF units transmit at a fixed rate, and the current drain and hence the life of the transmitter is a function of battery size and the pulse rate. For example, with a pulse rate of 40 pulses per minute (ppm) the average current drain may be 30 microamps, whereas with a pulse rate of 60 ppm, the current drain would be approximately 45 microamps. Since seals are large animals, the current drain is not usually a problem as large, long-life batteries can be packaged readily with the transmitter and still not approach the 'rule-of-thumb' for wildlife tracking that the package not exceed 2–3% of the animal's weight (Kenward, 1987). For example, using VHF transmitters with a pulse rate of 40 ppm and a battery life of 9.6 months requires a minimum weight of 40 g. These units have been attached to fur seal females weighing 30–90 kg (i.e., 0.04–0.13% of body weight).

The maximum range for a signal is a function of the power of the transmitter, whether it is a one- or two-stage transmitter, and a number of other factors including the length and position of the transmitter antenna, the receiver sensitivity, the receiver antenna gain, the height above the ground or sea of both the transmitter and the receiving system, the humidity and the topography (Kenward, 1987). A quarter-wavelength antenna with a good Earth plane is the optimal solution for maximizing the tracking range of a transmitter, although it is not always realized. VHF operates on 'line-of-sight', although VHF waves can be detected slightly over the horizon, by a factor of 1.4 in





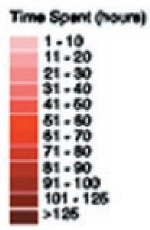


Figure 5. Fortnightly breakdown of the time spent at sea by female southern elephant seals (Oct. 1999–Jan 2000). Sample sizes (n) refer to the number of females tracked during each period, and the number of seal-days (n*d) is the sum of the number of days per seal for which geo-location positions were calculated.

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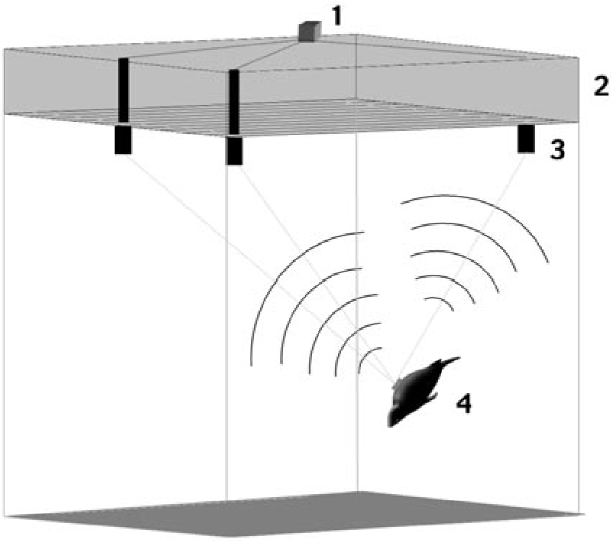


Figure 6. Schematic representation of an acoustic hydrophone array embedded within the sea ice. The Ultrasonic Acoustic Receiver (1), sea ice (2), omni-directional hydrophones (3) and seal with acoustic transmitter attached (4) are shown.

ideal propagation conditions (Kenward, 1987). Thus, there are severe limitations in tracking marine mammals from land-based stations. At sea level the effective range is only 5–20 km, and even with an elevation of 100 m this increases to only about 33 km (Thompson, 1993).

USING VHF TELEMETRY TO TRACK SEALS

Early attempts to determine where fur seals and other otariids forage at sea included aircraft flying transects over areas where seals equipped with VHF transmitters were foraging (see Antonelis *et al.*, 1990; Loughlin *et al.*, 1987; Goebel *et al.*, 1991). This method is effective, but extremely expensive, allows only for the tracking of a few animals at any one time, and is constrained by the range of the aircraft. With the advent of effective satellite telemetry, except in particular circumstances (e.g., fjords and other semi-enclosed areas), VHF transmitters are rarely used today to determine foraging areas of seals; but they are still used widely for measuring the presence of instrumented individuals at breeding colonies.

An example of the value of VHF telemetry in current research is the measurement of foraging trip duration. Otariid seals alternate time at sea feeding with time ashore suckling their pups, so the proportion of the time spent foraging has provided a surrogate measure of foraging effort (Gentry and Kooyman, 1986a; Boyd *et al.*, 1991; Gales and Mattlin, 1997; Goldsworthy *et al.*, 1997; Gentry, 1998). An automated receiver with an omni-directional whip antenna that scans a range of frequencies and then archives the data measures the time ashore relative to the time at sea for large numbers of females. Due to the line-of-sight limitation for VHF transmitters, deploying medium power transmitters (with a range of 2–3 km) and a strategically-placed receiver at a colony allows accurate records to be obtained with relative ease. It is important when setting up a system such as the one described that the signal strength be checked throughout the colony area because shadow effects from large objects (e.g., boulders, outcroppings, etc.) can mask signals and thereby produce misleading attendance patterns.

Similar methods have been used to determine haul-out patterns and activity budgets of phocid seals. Siniff *et al.* (1969) first employed VHF transmitters in the 1960s to record the proportion of time individual Weddell seals spent hauled out on the ice during the breeding season. A similar system has been used with success on breeding Weddell seals (Harcourt, Hindell, Waas, Bell, unpublished data). VHF transmitters do have a tendency to drift in frequency when used in severe cold such as that found in Antarctica, so caution is required when establishing an automated receiving station.

Finally, VHF transmitters are of immense worth when animals need to be found again after a period at sea. Therefore, VHF transmitters are most often used in combination with other archival tags such as TDRs so that the devices can be recovered when animals come ashore in large colonies or to inaccessible areas (Gales and Mattlin, 1997). Under these circumstances, they act as an effective and inexpensive form of insurance.

OTHER TECHNIQUES

GLOBAL POSITIONING SYSTEM (GPS)

The Global Positioning System is a worldwide, satellite-based, radio-navigation system developed by the U.S. Department of Defence (DOD) (Anon., 1996; Dana, 1999). The GPS includes a constellation of 21 operating and three spare satellites that orbit the earth. A ground-based GPS receiver calculates the time it takes for individual signals to arrive from at least three satellites to the receiver to compute a two-dimensional, horizontal fix (latitude and longitude) given an assumed height (with marine mammals assumed to be sea level). The acquisition (i.e., the detection of satellite signals) of four satellites can determine three-dimensional positions and time, while five or more can provide position, time, redundancy and the certainty of the greater position fix (Dana, 1999). There are two services available in the GPS, the Precise-Positioning Service (PPS), and the Standard-Positioning Service (SPS). The PPS is a highly accurate military positioning, velocity, and timing service that is under the control of the DOD and unavailable to the public. The SPS is a positioning service available to all GPS users on a continuous, worldwide basis with no direct charge. The SPS was, however, degraded intentionally by the DOD by use of Selective Availability (time varying bias). Most receivers were capable of using the SPS signal and its predictable

(a)

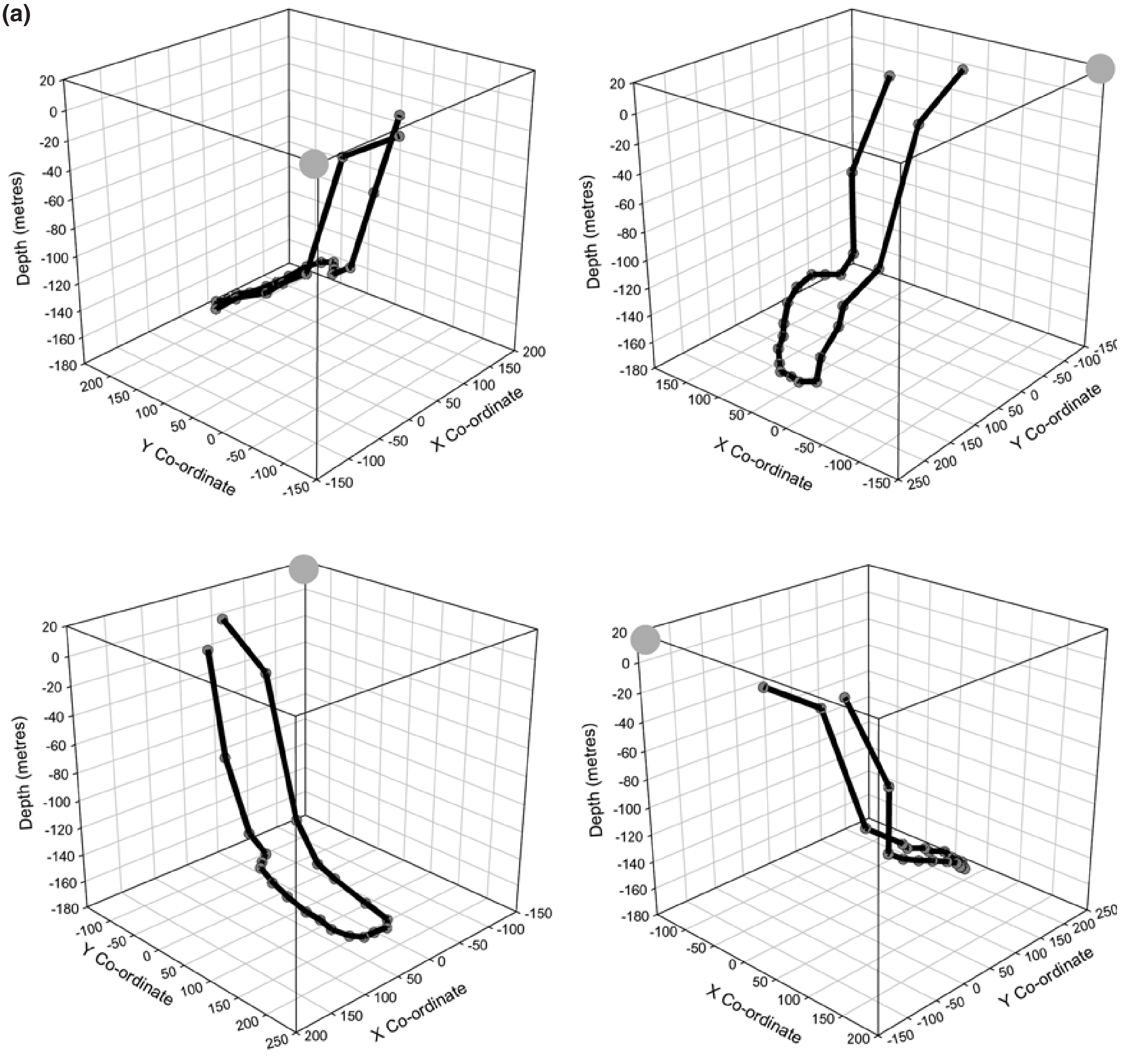
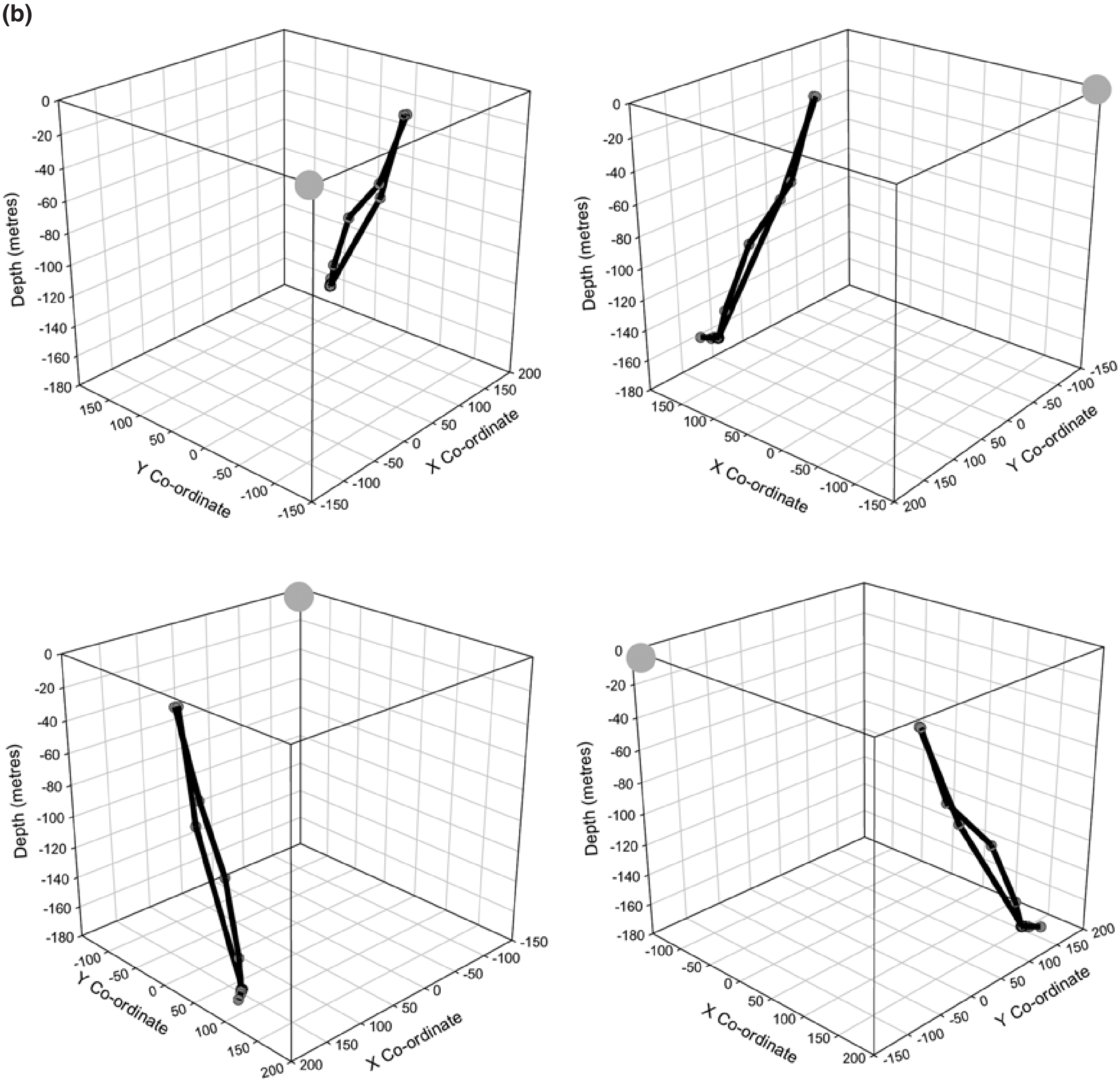


Figure 7. Multiple, three-dimensional views of two types of female Weddell seal dives (during the lactation): **(a)** a female 'moving' dive; and **(b)** a female 'flat' dive.

accuracy was 100 m (horizontal), 156 m (vertical), and 340 nanoseconds (time). In May 2000, the DOD lifted the restrictions on the PPS service and its predictable accuracy is now 22 m (horizontal), 27.7 m (vertical), and 22 nanoseconds (time) (Anon., 2000).

GPS as a method for studying seals is limited by the cost, size and speed of satellite acquisition by the commercially available devices (Lotek, 1996). Most GPS devices in the domain of biotelemetry were developed for large terrestrial mammals since these taxa could carry the excessive bulk of the units. Consequently, GPS units were impractical for all but the largest marine mammals due to drag and weight. However, a far more important limitation, has been the time that it took GPS devices to lock onto (i.e., acquire) the necessary number of satellites to predict accurately a location (e.g., up to ten minutes). Smaller (~6 g), faster units have now been produced and these, with further improvements in battery efficiency and reduced bulk, could be attached to a seal without compromising swimming efficiency (e.g., GXB2000 GPS receiver, Sony Corporation). Acquisition times can now be as short as two seconds, which reduces the constraints imposed by short between-dive intervals at the surface. However, acquisition times of this interval represent only the best possible scenarios; more realistic acquisition times range from 20–40 seconds. The satellites also send regular updates on the satellite orbits and positions (ephemeris data) and a receiver must update these stored

(b)



signals approximately every four hours at the most (Dana, 1999). This adds to the time required to acquire all the necessary data to provide an accurate location.

However, the improvements in acquisition time and the associated reduction in power demand combined with lower costs (Table 2) and greater accuracy (<100 m) compared to those of PTTs (~500 m) make GPS devices one of the best candidates for future studies of seal movements. Apart from power drain, the greatest drawback is the need to recover the device in order to download the archived data. This could be avoided by using a GPS archival tag combined with a PTT or, more economically, a VHF transmitter, to download remotely the data upon the seal's return to land or ice. GPS will be able to answer the same questions as PTTs, including location and rate of travel, but with far greater accuracy, far more locations per day and at much less expense (Table 2). Of course, the main limitation of GPS units on some pinniped species would be the recovery of the units themselves. Pack-ice seals such as crabeater, leopard and Ross seals are not easily re-captured after the deployment of units. Therefore, relying on archival tags for location data in these species is not advised.

CONDUCTIVITY-TEMPERATURE-DEPTH (CTD) ARCHIVAL TAGS

To advance both the precision of models combining oceanographic variables and biological activity as well as our basic understanding of ocean structure, there is an increasing emphasis on precise measurement of oceanographic variables while at sea (Ancel *et al.*, 1992; McCafferty *et al.*, 1999). Therefore, more sensitive and complex communications equipment is needed. Another type of archival data tag is the miniature Conductivity-Temperature-Depth (CTD) sensor (Figure 8) analogous to the larger oceanographic CTDs available for oceanographic sampling. These are miniature archival tags designed mostly for deployment on fish species, but have been deployed on both larger and smaller taxa (ICES Anadromous and Catadromous Fish Committee, 1997; Freire and González-Gurriarán, 1998; Sturlaugsson and Johannsson, 1998). The available parameters for measurement include temperature, light, pressure (depth), salinity (conductivity) and tilt angle.

Figure 8. A mini Conductivity-Temperature-Depth (CTD) archival tag (Data Storage Tag, Star-Oddi Marine Device Manufacturing, Reykjavik, Iceland). Reproduced with permission from Star-Oddi.

ROUTE RECORDERS

Another type of device, known as a 'route' or 'direction' recorder, was developed to track homing pigeons (Bramanti *et al.*, 1988; Papi *et al.*, 1991). However, it has now been applied to sea birds (Dall'Antonia *et al.*, 1995; Benvenuti *et al.*, 1998), green turtles (Luschi *et al.*, 1996), and fur seals (Georges *et al.*, 2000). These devices detect and archive the headings of an animal during its movement path by measuring the angle between the horizontal component of the Earth's magnetic field and the instrument's main axis at regular intervals. Prototypes were equipped with a compass and a transducer that converted the angular values to electrical resistance values (Bramanti *et al.*, 1988; Dall'Antonia *et al.*, 1992); but more recent route recorders have been improved with the addition of a microprocessor to control other components (Benvenuti *et al.*, 2001). With further technological developments, these devices may provide more fine-scale information on pinniped movements unavailable from the other methods described in this chapter.

FUTURE DEVELOPMENT OF ARCHIVAL TAGS

The real advantage in the improvements in archival tag technology is the precision with which one can measure a series of oceanographic variables (McCafferty *et al.*, 1999). There is growing interest in the use of marine mammals as sampling units for physical oceanography data collection (see Ancel *et al.*, 1992; Wilson *et al.*, 1994; Weimerskirch *et al.*, 1995). Of primary importance to both biologists and to oceanographers contemplating using marine animals for this role is the precise measurement of temperature (McCafferty *et al.*, 1999). Sensors now available can measure temperature accurately to 0.001ºC within fractions of a second. The data are useful to describe the temperature gradients in which animals select to forage and the physical data are sufficiently precise to model oceanographic trends in time and space.

The real test for scientists will be the development of multi-platform measurement devices that satisfy the requirements of both biologists and physico-chemical oceanographers. Individual ecological laboratories are now in the process of developing such systems to attract the interest of oceanographers to invest in the continued development of these systems and their applications.

CONCLUSIONS AND MANAGEMENT CONSIDERATIONS

In this chapter, we have described a variety of techniques available for the remote study of pinniped movement during the essentially clandestine phase of their life history—foraging at sea. Within the last 20 years, there has been impressive development in technology allowing for the collection of data that now begin to describe the nuances of these fascinating predators. Of course, many of the methods described herein are not restricted to the study of marine mammals such as pinnipeds. In fact, most of the methods were developed for deployment on terrestrial organisms. However, the most exciting aspect to the understanding of at-sea behaviour of marine mammals is that we are now beginning to understand the complexities of their behaviour. In addition, we now have the means to begin the immense task of collecting information that can unlock the biophysical secrets of the oceans. Applying archival measuring devices to organisms that must live and feed within these vast regions is a promising means to achieve these goals.

The application of a particular method of remotely tracking seals depends on the research questions to be addressed for each specific study. The temporal or spatial scale of concern, the target species, and the domain of research (behaviour, population dynamics, management, etc.) will dictate to what extent the specific advantages and disadvantages of each technique affect a researcher's choice. We have summarized in Table 3 the type of information one can expect to collect for each of the main methods described in this chapter. The main consideration appears to be the spatial scale at which one intends to investigate behaviour. Fine-scale movements can be achieved by acoustic arrays and perhaps GPS satellite telemetry, whereas more broad-scale questions should be addressed using PTT, geo-location or even VHF telemetry. Of course, with continued advances in technology the options available to researchers will undoubtedly increase.

One of the most practical management applications for telemetric data of seal distribution, foraging effort and at-sea behaviour is the delineation of regions of potential conflict between these predators and human industry. Domestic and international policies are evolving toward the recognition of sustainable practices in fisheries, with the need for increased information on ecosystem relationships among constituent species (Staples, 1996; Caton and McLoughlin, 2000). Recognizing that single-species management fails to embrace a realistic perspective of ecological relationships, management is promoting the concept of multi-species models to account for predator-prey relationships, by-catch issues and complex interactions within marine food webs (National Research Council, 1999). Fisheries managers must pursue the objectives of long-term, ecological sustainability and the reduction of impacts on non-target species (Fisheries Management Act, 1991). To achieve these objectives it is essential to have reliable data on the distribution, abundance, consumption rates, growth, biomass and behaviour of all species involved (National Research Council, 1999). Establishing areas of spatial and dietary overlap between pinnipeds and Australasian commercial fishing industries is the first step in prescribing management restrictions or recommendations to achieve the sustainability of marine living resource use. Currently, multi-species management is in its infancy within the fisheries sector, but more information is required to develop the necessary models.

The example of Australian fur seals tracked within and around Bass Strait has shown that there may be some overlap with breeding females and many commercial fishing zones (Figure 1), although more data are required to elucidate the amount of overlap and possible competition. With fewer commercial fisheries operating in regions where southern elephant seals forage, the potential for overlap is less, although the spatial scale at which one assesses the degree of competition must concur with how animals exploit this area of ocean. In addition to assessing diet composition, distribution and spatial use, spatially-allocated indices of foraging (i.e., dive behaviour data from TDRs) are required to delineate the more important regions of the Southern Ocean required to maintain healthy populations of these marine predators. Of course, seasonal and annual changes in ocean resources must be assessed continually to update biophysical models.

Another practical application of telemetric data can be the establishment of marine reserves (Clark and Dingwall, 1985; Cooper and Ryan, 1994; Scott, 1994; Dingwall, 1995; Shaughnessy, 1999). Without a detailed understanding of the biological communities that are supported in highly-productive areas of the ocean, it is impossible to isolate and protect sensitive regions. Pinnipeds are important higher predators within a number of marine ecosystems. Determining where their important feeding areas are located contributes to our knowledge of the importance of these regions as areas of high biological productivity (Croxall and Wace, 1995). It makes sense that pinnipeds must locate and exploit areas of high productivity to survive; therefore, protecting such areas from over-exploitation by human industry will contribute to the protection of entire biological communities. The literature available on this type of approach is vast and does not fall within the context of this chapter. However, improving methods required to track and monitor higher predators such as pinnipeds is an important step in the conservation, management and theoretical understanding of ocean life.

Table 3. Movement and dive parameters available from satellite telemetry, geo-locating TDRs, acoustic tracking and VHF transmitters.

Parameter	PTT	Geo-locating TDRs	Acoustic	VHF
Horizontal Distance				
–horizontal distance	yes	broad-scale	fine-scale	yes
–bearing	broad-scale	broad-scale	fine-scale	no
–large-area coverage	yes	yes	no	no
Diving				
–start-end distance of dive	only with additional sensors	no	yes	no
–depth	only with additional sensors	yes	yes	no
–dive duration	only with additional sensors	yes	yes	yes
–distance during dive	only with velocity meter	only with velocity meter	yes	no
–shape of dive	limited	limited	yes	no
–ascent/descent rate	partial	yes	yes	no
–directional changes	broad-scale	broad-scale	within dives	between dives
–velocity of dive phases	partial	only with velocity meter	yes	no
–conspecific interactions	broad-scale	broad-scale	yes	no

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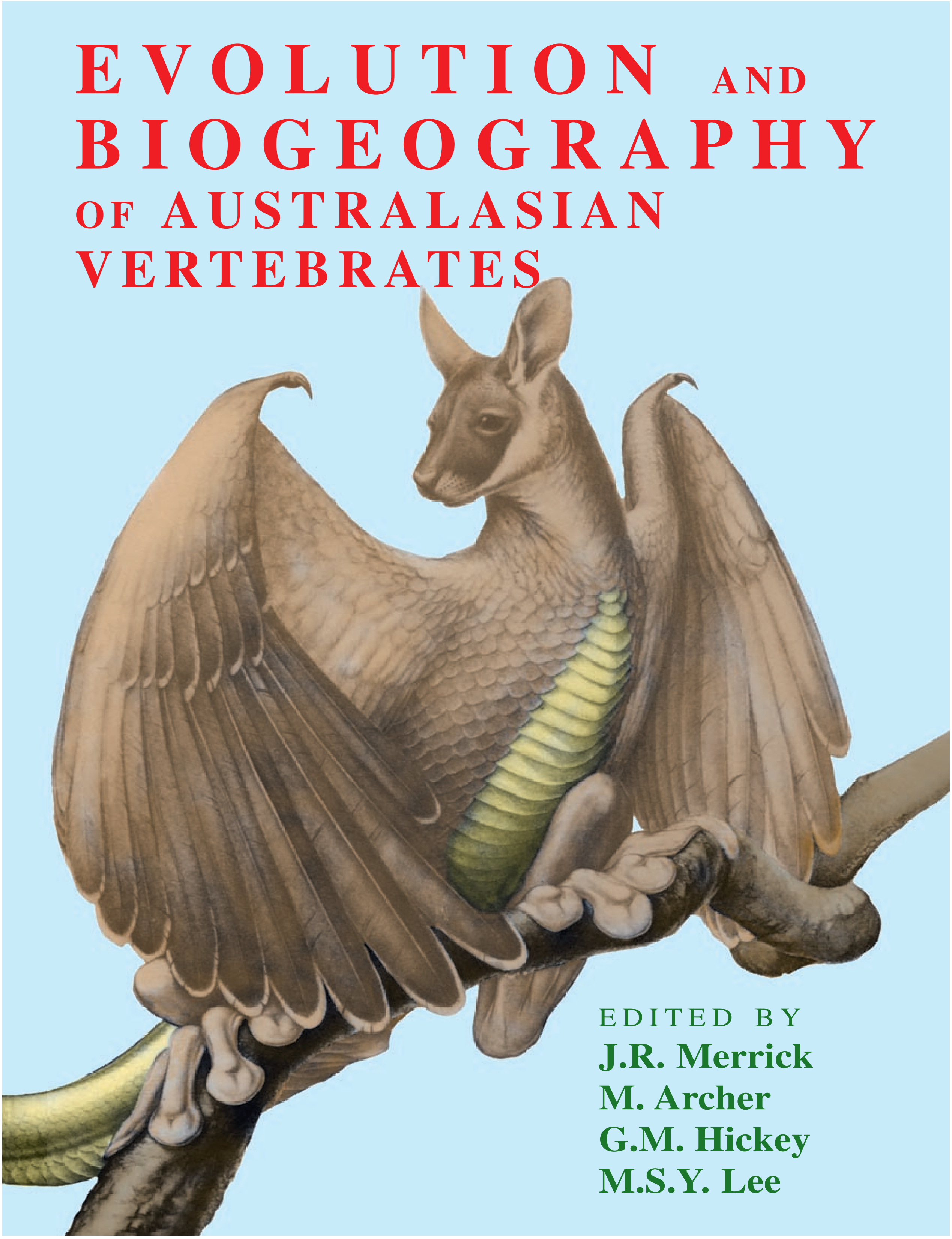

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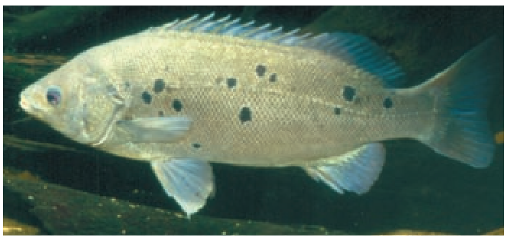

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