IMPACTS OF MARINE ACOUSTIC TECHNOLOGY ON THE ANTARCTIC ENVIRONMENT

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SCAR Ad Hoc Group on marine acoustic technology and the environment

Executive Summary

Equipment using sound waves to investigate the sea bed and the water column are essential to the understanding of the Antarctic marine environment. At the same time, there is active research into the effects of such technology on marine animals, particularly cetaceans. The potential risks posed by equipment are a combination of source level, frequency and local effects that define the likelihood of interacting with animals. Many acoustic instruments are of sufficiently low power and high frequency as to pose a minor risk to the environment. The equipment with the highest risk potential are airgun arrays and low frequency, high power transducers with wide beam angles.

Cetaceans have been observed avoiding powerful, low frequency sound sources and there is now a documented case of injury to whales from multiple, mid frequency (2.6-8.2 kHz) military echo sounders. At the same time, some whale populations co-exist with commercial seismic exploration surveys. In the case of other animals, there is some evidence for short term displacement of some seals and fish by seismic surveys but there is little literature available.

The working group felt that the evidence available did not justify a ban on seismic surveys or scientific echo sounders in Antarctic waters, however, surveys should be examined on a case by case basis and mitigation strategies should be used to reduce the risk to Antarctic wildlife from high power, low frequency sources. Acoustic releases and similar low power, occasional source were not considered a threat to wildlife. Mitigation strategies should be investigated to evaluate their effectiveness and there should be a regular review of mitigation strategies and the progress of research in the field to ensure that new research findings will be avalable to the Antarctic community. Research into the hearing and rection to noise of Antarctic animals should be encouraged as should research into sound propagation conditions arounnd Antarctica. Records of the locations, timing, duration, frequency, and nature of hydroacoustic and other activities should be maintained to permit retrospective assessment of the likely causes of any future observed changes in the distributions, abundance, or productivity of the potentially affected species and populations

Some mitigation strategies in use are:

1. Use of the minimum source level to achieve the result.
2. Use of "soft starts" whereby power is increased gradually over periods of 20 minutes or more.
3. Care should be taken with line lay outs to avoid restricting animals' ability to a avoid the source.
4. Equipment should be shut down if cetaceans are observed within a distance of the vessel defined by the source power, directionality and propagation characteristics.
5. Surveys should be planned to minimise repeated surveying of areas in consecutive years with high risk equipment.
6. Care should be exercised to minimise impacts in known sensitive areas and times.

Further research is needed to assess whether these measures work and to better monitor the proximity of wildlife to a vessel. The Antarctic community and permitting agencies will need to monitor research progress to ensure practices are up to date.

Workshop participants and contributors

Philip E. O'Brien*, Geoscience Australia, convener.
Wolf Arnt, Alfred Wegner Institute, Bremerhaven, Germany.
Inigo Everson, British Antarctic Survey.
Karsten Gohl, Alfred Wegner Instutute, Bremerhaven, Germany.
Jonathan C.D. Gordon, Sea Mammal Research Unit, University of St Andrews, United Kingdom
Cathy Goss, British Antarctic Survey
Ulrich Kremser, Federal Environmental Agency (UBA), Germany
Robert Laws, Schlumberger Pty Ltd
Tony Martin, British Antarctic Survey.
Joachim Ploetz, Alfred Wegner Instutute, Bremerhaven, Germany
Paul G. Rodhouse, British Antarctic Survey.
Tracy Rogers, Australian Marine Mammal Research Centre, University of Sydney, Australia.
David Thompson, Sea Mammal Research Unit, University of St Andrews, United Kingdom.
Michael Sexton, Geoscience Australia, Canberra, Australia.
Rory Wilson, University of Kiel, Germany.
Eric Woehler, Australian Antarctic Division.

*Address correspondence to: Dr. P. E. O'Brien, Geoscience Australia, GPO Box 378, Canberra, Australia, 2601. Email: phil.obrien@ga.gov.au

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INTRODUCTION

Purpose

Marine acoustic technology provides fundamental tools for almost all marine science research. In the Antarctic, echo sounders map the sea floor, study the distribution of fish and plankton and allow safe navigation in poorly charted waters. Acoustic releases enable the deployment and retrieval of seabed moorings without long lines that could entangle animals and icebergs. Seismic reflection equipment images the sediments beneath the sea floor enabling the interpretation of past climate. Pingers enable us to map where samples come from on the sea floor and the water column. Without acoustic tools, our understanding of the world's oceans would have made little progress since the early 20th century. At the same time, it has been increasingly recognised that marine animals use sound for a variety of purposes and that high energy sound can potentially damage animals.

This report arose from the XXVI th SCAR meeting in Tokyo where it was recognised that there were inconsistencies in the way various nations were treating the assessment of the environmental impact of marine acoustic equipment in research programs. Some national approval agencies regarded the impacts as minor or transitory but others demanded full assessments of all acoustic equipment, not just the higher powered systems such as seismic airgun arrays. It was decided that a report should be prepared that reviewed the literature on the effects of acoustic technology on major animal groups and commented on the situation in the Antarctic.

The ad hoc group charged with preparing the report was constituted from the Working Groups on Geosciences and Biology. The group sought out people with expertise in the acoustic response of wildlife, knowledge of the distribution of Antarctic wildlife and knowledge of the various survey equipment. They also sought people with recognised expertise in the field to review the draft report. This report cannot hope to comprehensively cover a large field that is the subject of active, multidisciplinary research, rather, it seeks to review the literature, provide pointers to the major works that cover topics in greater detail and provide guidance as to how the available knowledge applies to Antarctica.

Methods

The approach taken is to provide succinct summaries of knowledge concerning the reactions of important animal groups to underwater sound, the distribution of these animals in the Antarctic and how that varies through the year and a brief description of the various marine acoustic equipment, its output and how it is used. From these reviews we aim to come up with some general pointers to the level of impact possible and some guidelines for assessing the risks posed by a particular survey. Some mitigation strategies in use are suggested, -although they are found more often in unpublished government guidelines and permits making a comprehensive review difficult.

Although definitive answers cannot be provided at the moment, an understanding of animal characteristics and distribution and an understanding of equipment and survey design can identify the broad level of risk posed by a survey. The report draws on a growing body of literature and should be seen as an introduction to the field. Readers requiring more detail should refer to such important texts such as Richardson et al. (1995).

Because marine acoustics is a complex, highly specialised area, the report commences with a very brief introduction to the field to define units and terms and the basic physics of sound in the marine environment. Again, readers should consult the many excellent publications on the topics to go beyond what is a very basic introduction.

Environmental Impacts
In assessing the potential for environmental impacts of acoustic technology, we try to address two major themes:

Injury
The questions that need to be addressed are:
- Can the equipment physically kill or injure an animal and if so at what range?
- Can the equipment damage an animals hearing and if so over what range?

This area is difficult because there is little research on injuries to wild animals and most literature relates to humans and to the use of explosives, which are rarely used for scientific purposes.

Disturbance
The major questions to be answered are:
- Does the use of the equipment affect animal behaviour and over what area?
- Does the behavioural disturbance constitute a threat to populations by changing behaviour at critical times and in critical areas?
- Will a survey affect large numbers of animals, a small important group of animals or will the area be free of most species during the survey?
- Will a survey affect prey species in a way that will increase or decrease their availability to predators?
- What proportion of an area used by the animals is affected by the survey?

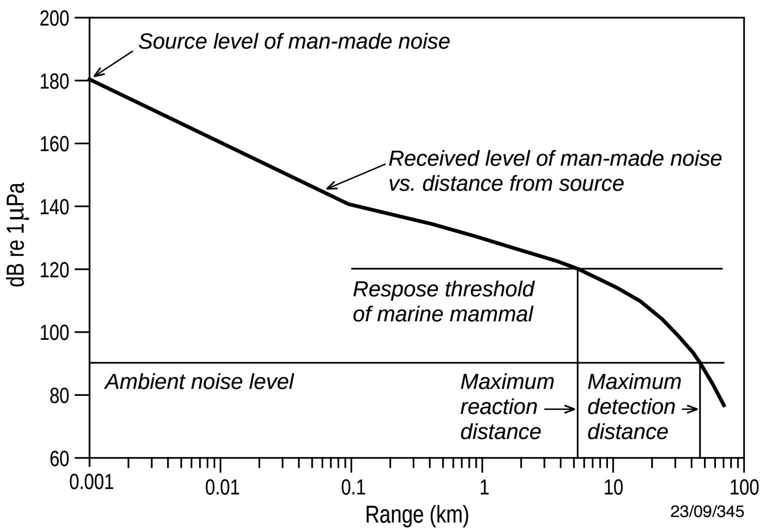


Figure 1: Schematic diagram showing zones of influence around a sound source in the ocean (Richardson et al., 1995).

The area of influence of an acoustic survey can be understood using the schematic diagram of Richardson et al. (1995) (Fig. 1). The *maximum detection distance* is the distance at which a sound is audible above the ambient noise. The *maximum reaction distance* is the distance at which animals exhibit behaviour changes. In between these distances, survey noise may mask animal communication in some species. These distances depend on the level of ambient noise, the animal's hearing and behaviour, the source level of the equipment and the decay of the signal intensity with distance. Closer to a powerful source, there may be a *hearing impairment distance*, and closer still an i*njury distance* where an animal experiences physical damage to tissues in addition to hearing organs. These distances are even harder to estimate in wild species than reaction distances but some guidance can be obtained from studies of explosive safety and from the levels of sounds generated by animals themselves.

Risk assessment

For several animals groups, we have attempted to develop an assessment of risk under the following headings:

Behavioural effects direct:
What are the possible behavioural effects of the disturbance on the species both short and long term?

Pathological effects:
What are the possible physiological implications for the species concerned?

Geo*graphical scale:*
What is the geographical scale of the disturbance and does this overlap with the range of the species or space crucial to the species of interest?

Timing/duration of action:
Does the timing of the disturbance overlap with a crucial event for the species? Does the disturbance occur over a sustained or short period of time?

Cumulative effect of action:
Does any effects of the disturbance add to similar disturbance types displaced in time or space, or to different stresses for the species of interest?

Other sources of impacts

In understanding the absolute level of risk posed by acoustic surveys, some consideration should be given to other sources of risk. For example, Clapham et al. (1999) examined whale population data and concluded that ship strikes and entanglement in fishing gear were the most significant threats to endangered baleen whales, although they regard the data as insufficient to permit an assessment of other types of activities. We have not reviewed all such issues because to do so would have increased the work beyond manageable levels.

SOUND IN THE OCEAN

Marine Acoustic measurement

Sound in the ocean travels as vibrations of water molecules that exert push-pull pressure on objects in their path. Sound is heard by push-pull of the ear or hearing mechanism of an animal and it similarly exerts pressure on the rest of the animal. Some important properties of sound are:

Frequency – the rate of oscillation or vibration measured in cycles per second or hertz (Hz). Ultrasonic frequencies are too high to be heard by humans (>20,000 Hz) but may be heard by some animals such as dolphins and bats. Infrasound is too low to be heard (<20 Hz) but can be heard by baleen whales (Richardson et al., 1995).

Wavelength – is the length of the fundamental oscillation of the sound in the propagation medium.

Basic units

Sound pressure is the parameter measured by most instruments. It is expressed in pressure units, microPascal (µPa) in the SI system, microbars (µbar) or bars are still used in the geophysical industry. Microbars and microPascals can be related

$1\ \mu Pa = 10^{-5}\ \mu bar$

Acoustic intensity is the acoustic power per unit area in the direction of propagation. Its units are watts/m^2. The *intensity, power* and *energy* of an acoustic wave are proportional to the average of the pressure squared (*mean square pressure*).

In presenting sound measurements ratios of pressure, or pressures squared are used, requiring the adoption of a standard reference pressure. For acoustics in water, this is 1 µPa.

Waveform of a signal is a graph of strength versus time (eg. Fig. 2). The waveform of a pure tone is a sinusoid whereas a pulsed sound rises sharply to a peak then decays in a complex manner (Fig. 2). Waveforms are important in seismic surveys and echo sounders.

Sound Spectra graph the distribution of sound power as a function of frequency (Fig. 2). They may be *narrowband* spectra that show the levels in 1 Hz bands or *proportional bandwidth* spectra that show levels in 1/3 octave or 1 octave bands.

Continuous sources are characterised by an output of power in μPa^2 whereas impulsive sources are characterised by an output energy in μPa^2.seconds.

The Decibel Scale

The human ear responds in a logarithmic fashion to increases in sound intensity, therefore a scale has been adopted to reflect this response. The decibel scale is a logarithmic scale used to measure the intensity (power) of sound. It is defined as:

$$dB = 10 \log_{10}(I/I_0)$$, where I_0 is a reference intensity.

However sound measuring devices usually respond to sound pressure (P) and the intensity of sound varies as the square of the pressure. Consequently, the level of sound intensity can be rewritten as:

$$dB = 20 \log_{10}(P/P_0), \text{ where } P_0 \text{ is a reference pressure.}$$

In air the reference pressure is 20 μPa which chosen to be near the limit of human hearing and in water it is 1 μPa, again chosen to be near the limit of human hearing.

The advantage of the decibel scale is that a large range of values can be handled by smaller numbers. For example a pressure ratio of 10 is equivalent to 20 dB, whilst a pressure ratio of a million equals 120dB. A convenient value to remember is: 6 dB represents approximately a doubling of the pressure.

The standard unit of continuous source level in underwater acoustic is the $(\mu Pa\text{-}m)^2$. However, source levels are typically quoted as 'x dB re 1 μPa at 1 m' or 'x dB re 1 μPa-m'.

Pulsed Sounds

Most acoustic devices use pulsed sound. As yet, there is no standard way to describe pulsed sounds and inconsistencies within the literature produce major confusion when different studies are being compared. Readers are advised to consult references such as Richardson et al. (1995) to ensure a clear understanding of the units involved and issues relating to their use.

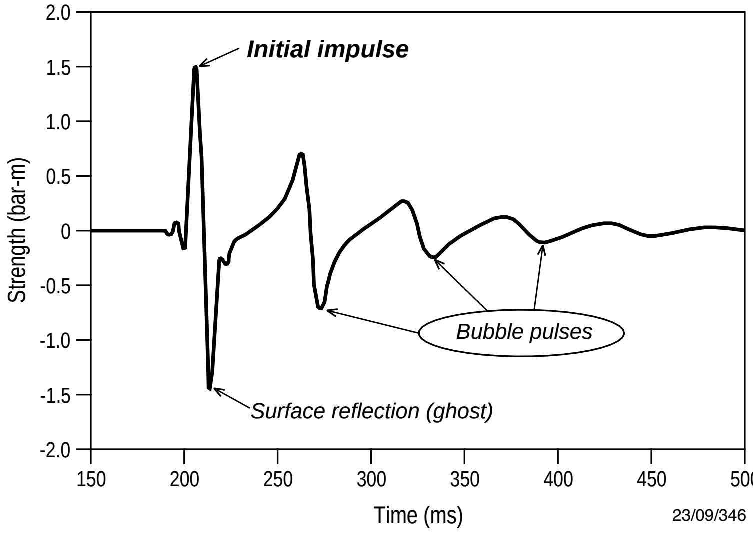


Figure 2: Pulsed sound produced by a single air gun (Dragoset 2000) showing the major features of a pulsed sound wave form.

Figure 2 illustrates the waveform of an airgun which is a typical pulsed output. The sound can be characterised by the zero-peak pressure which is the maximum pressure of the rising part of the wave and the peak-to-peak pressure which is the sum of the pressure of first peak plus the absolute value of the first trough. This form of measurement is common in the geophysical industry. They can be expressed in pressure units or converted to $(\mu Pa\text{-}m)^2$ or expressed in 'dB re 1 μPa-m'. Seismic source energies are usually quoted for the downgoing signal because this is of primary interest for seismic imaging of the subsurface. It is not straightforward to calculate the side-radiated energy. The side-radiated energy depends on the array dimensions and towing depth and the sea-state.

Those interested in the effects of pulsed sounds on the environment recommend some measure of the energy of the pulsed signal (Richardson et al., 1995, McCauley et al., 2000). Received energy is proportional to the pressure squared and thus is expressed in μPa^2-s (microPascal squared-seconds). Measurement of energy is difficult because it depends on the time over which the measurement is taken and the shape of the pulse and can be distorted by other noises (McCauley et al., 2000). McCauley et al. (2000) present conversions for their surveys from equivalent energy to mean squared pressure measurement and to peak-to-peak figures. They point out that the peak-to-peak conversion is not technically valid however, many other studies use peak-to-peak values and the potential damage to animal hearing may be proportional to peak pressures so they use an empirical calculation. Peak-to-peak pressures are the standard measure of airgun array power used by the geophysical industry. *Sound pressure density spectrum* is the mean square pressure per unit frequency measured in μPa^2/Hz. This measure is that used for continuously distributed sound and is dependent on the filter bandwidth used in the calculation. A method used for sounds in which tones are important calculates a power spectrum without a bandwidth correction and has units of 'dB re 1 µPa'. Theses two measures can be confused and it is not always clear which is being used in publications.

In considering the impact of any activity, great care should be taken to ensure that the same units are being used when comparing equipment outputs and data on animal behaviour or other effects. Publications commonly use poorly defined measurements and use incorrect or abbreviated units. Some crude generalisations can be made about conversions of different measures to provide guidance but actual conversion figures w ill vary depending on measuring equipment, filtering, time integration of the signal, signal waveform and the local environment in which the measurements are made (Table 1). While these conversions are inexact and, in some instances not strictly valid, it is useful to know that, for example, 0-p values will always be lower p-p or RMS values for the same source or that a spectral value will be substantially lower than a p-p value. Major confusion can occur if direct comparisons are made between measurements made in air and those in water. Decibel figures for air are calculated for a reference pressure of 20 µPa (as opposed to 1 µPa in water). Furthermore,the acoustic impedence of air and water are very different. This means a sound pressure in air will be 62 dB (re 20 µPa) lower than the dB figure for a signal of the same power in water (Gausland, 2000).

Table 1: Approximate conversion of different measures of sound intensity. This table is based on figure used for impulsive sources (airguns) and the figures will vary with the pulse shape. They are intended only as a guide to the direction and order of magnitude difference between the different methods of quoting sound energy.

Unit from	To unit	Conversion	Typical values
Zero-to-peak	RMS	add	3 dB re 1 µPa
Zero to peak	Peak to peak	add	~9 dB re 1 µPa
Spectral level (dB re 1 μPa^2/Hz at 1m)	Peak to peak	Add (not physically valid)	~40 dB re 1 µPa
Sound pressure in air	Sound pressure in water with the same power	Add	62 dB re 1 µPa

Transmission Losses

The propagation of sound in the oceans is complex and the subject of much study. A more detailed review is available in Richardson et al. (1995) and in texts such as Clay and Medwin (1977). Precise calculation of transmission loss can be very complicated and the appropriate model varies from area to area. In the absence of studies in most of the Antarctic region, a simplistic model can be used to provide conservative estimates for sound levels at distance from a given source. More realistic models require field studies and will tend to reduce the estimates of sound levels.

In the deep ocean, sound energy from a point source spreads out much like light from a light source. Consequently the energy density (or intensity) drops off according to a $1/R^2$ relation (Figure 3, which means that the sound pressure reduces according to a 1/R relationship (as $I \sim P^2$).

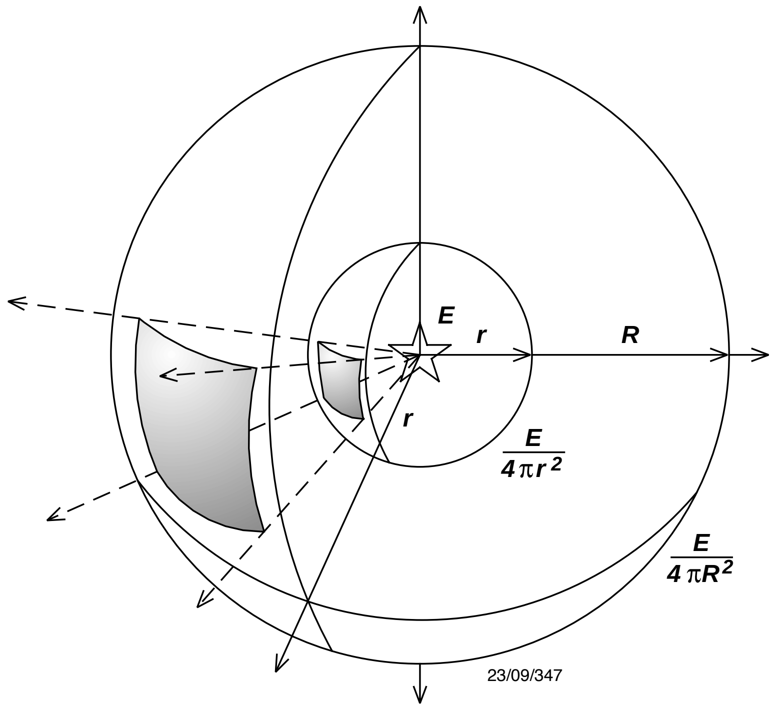


Figure 3 Spherical spreading of sound. The same energy is spread over a larger area that varies as the square of the distance.

From the definition of the decibel scale for sound pressure, it is easy to see that the attenuation of sound pressure with distance is equal to $20\log_{10}R$, where R is the distance from the source, and is subtracted from the value in dB determined at a distance of 1 m from the source. The "sonar equation" is (Clay and Medwin, 1977):

$$SPL = SL - 20 \log_{10} (R/R_0)$$

-SPL is sound pressure level at distance R
SL is source level at reference distance R_0
For each doubling of the distance (R), SPL decreases by 6 dB (6 dB ~ $20\log_{10}2$) (Clay and Medwin, 1977).

In shallow water, the surface and seabed boundaries effectively channel the sound energy in the water into a horizontal direction. In this situation cylindrical divergence applies with a lesser attenuation equal to $10\log_{10}R$. A similar situation applies when the sound energy is trapped within a thermal layer or sound channel. In the case of airgun arrays, and most ship mounted echo sounders, the maximum sound levels are directed in a vertical direction. Amplitude levels emitted horizontally are typically 20-40 dB lower than those emitted vertically so smaller amounts of energy can make its way into a sound channel produced by surface stratification.

Attenuation Losses.
Besides losses due to spreading, losses due to absorption, scattering and interaction with the bottom also occur.

Absorption involves the conversion of acoustic energy into heat and can occur by a number of processes. Experimentation has shown that temperature, the concentration of magnesium sulphate in seawater and in particular the frequency of the sound wave are the key factors. Richardson et al. (1995) suggest that an empirical equation for the absorption coefficient for seawater under range of conditions is:

$$A = 0.036f^{1.5}$$

where f is the frequency in kilohertz and A is absorption in dB/km.

This equation can be used to illustrate the importance of frequency in sound propagation. At 12 kHz, absorption is 1.49 dB/km and reaches around 3.2 dB/km for sounds at 20 kHz. Clay and Medwin (1977) give similar calculations that show absorption in the range of 10 dB/km for frequencies above 100 kHz. When compared to spherical spreading, for frequencies >5 kHz, absorbtion is important at ranges > 10 km. For frequencies <1 kHz, it is not significant for ranges < 40 km (Richardson et al., 1995).

Scattering occurs when sound strikes objects in the water and is reflected. These objects can be boundaries (surface, bottom and shores), bubbles, and suspended solid and organic particles, marine life and changes in the thermal structure of the ocean. Sound reflected from the ocean floor usually suffers a significant loss in intensity. The amount of energy lost varies with the bottom composition, sound frequency and striking angle of the sound wave. In general bottom loss will tend to increase with frequency and with angle of incidence. Soft bottoms such as mud are usually associated with high bottom loss, hard bottoms such as smooth rock and sand produce lower losses. In some circumstances, sound may refract through the sea bed as head waves. McCauley et al., (2000a) found that these may be important additions to noise levels on shallow shelves.

Regional variations in Transmission Losses
While it is possible to derive equations that will compute precise values of these losses, ocean characteristics are so variable that little is gained in doing so. Regional variability is such that, if the losses need to be known for a particular area, it is probably better to conduct a specific survey to measure them. Other wise, a simple calculation using spherical or cylindrical divergence will give a conservative approximation. For example, a number of results can be found in submissions to the United States Environmental Protection Agency for conducting seismic surveys. The USGS uses an overall transmission loss (TL, transmission and attenuation losses) equation of:

$$TL = n\log_{10}R$$

Where R is the distance from the source. A number of experiments have produced a range of values for n. In certain areas they have observed n as high as 43 (Santa Barbara Channel) and 29 (Puget Sound). Sodal, (1999) conducted a rather detailed experiment in deep (4000 m) and shallow (40 m) water. In the deep water it measured n = 50 which is twice that expected from spherical spreading and in the shallow water measured n= 20 which is the rate for spherical spreading, when a rate closer to cylindrical spreading was expected. McCauley et al., (2000a) measured transmission losses from a 3-D seismic array where n = 34.3536 in Exmouth Gulf, Western Australia, (water 5 – 200 m depth, mixed carbonate hardground, carbonate mud and sand sea floor).

Predicting survey radius of impact

In the absence of pre-survey data for most Antarctic waters, some method of estimating the sound levels at distance from a survey is needed. Theoretically, in water that has depths greater than the sound wavelength, spherical spreading transmission loss should apply whereas for depths near or smaller than the wavelengths, cylindrical spreading transmission loss should apply. This means that for frequencies of a few Hertz, wavelengths are in the hundreds of meters, so quite deep water should be treated as "shallow". High frequencies, in the kiloHertz range, have wavelengths <1.5m so most water is "deep" (Richardson et al., 1995). However, the empirical studies mentioned above demonstrate that that Transmission Losses in even quite shallow water are commonly higher than that predicted using the spherical divergence. On the other hand, stratification of the water column may produce conditions in deep water where cylindrical spreading is a better description.

The differences between models become greater with distance from the source. Gordon et al. (1998) illustrate that a range of possible models produce estimates of the radius at which a particular sound level will be reached differ by hundreds of meters for estimates of sound levels near a high powered source. At greater distances and lower sound levels, the different models produce estimates that differ by hundreds of kilometers (Table 2). These uncertainties in estimating sound propagation make it highly desirable that there be studies of sound propagation in Antarctic waters. Accurate estimates of propagation or actual measurements of sound levels would be particularly important in studies of animal behaviour at larger distances.

Table 2 Ranges (km) for different received levels with different propagation models (from Gordon et al., 1998)

Received level dB_{p-p} re. µ Pa	Model 1 (km)[1]	Model 2 (km)[2]	Model 3 (km)[3]	Model 4 (km)[4]
220	0.03	0.10	0.02	0.03
210	0.10	0.46	0.04	0.10
200	0.32	2.2	0.10	0.32
190	1.0	10.0	0.25	1.00
180	3.2	46.4	0.63	10.
170	10.0	215	1.6	100
160	31.6	1,000	4.0	1,000
150	100.	4,641	10.0	10,000
140	316.	21,544	25.1	100,000

[1]Model 1: transmission loss = 20 log(r) (spherical spreading)
[2]Model 2: transmission loss = 15 log(r)
[3]Model 3: transmission loss = 25 log(r)
[4]Model 4: transmission loss = 10 log(1000) + 10 log(r) (spherical spreading to 1,000 m, then cylindrical spreading).

Noise sources and levels in the ocean

The sea is a noisy place with background noise generated by physical processes as well as biological agents. Wind generated waves, sea ice and sediment movement can all produce sound pressure levels up to 180 dB re 1 μPa-m (Richardson et al., 1995, Harris et al., 1991). The level of wind-generated noise is an indirect function of sea state and peaks in the 1 kHz range (Richardson et al., 1995). Noise from sea ice deformation is strongest in the infra sound range. Both wind and wave noise and sea ice noise form at the surface so ambient sound levels decrease with depth. Sounds produced by animal groups will be discussed below in the appropriate sections.

Injury by sound

Non-auditory injuries

There is no published research on impulsive injuries by non-explosive sound sources. There is a small amount of work relating to chemical explosives which have a shorter rise time than other sound generators. Richardson et al., (1995) review studies that found blast injury to be less likely with increasing size. Although there are various factors that influence the potential for injury from a shock wave, there are some estimates of maximum pressures for animals and humans in water. Marine Technologies Directorate (1996) recommend for humans in water a maximum Peak Pressure of 170 kPa for a single exposure, which translates into 224 dB re 1 μPa. Experiments on terrestrial animals in water quoted in Richardson et al. (1995) found low incidence of injuries including eardrum rupture below levels of 216 dB re 1 μPa and no injuries at 210 dB re 1 μPa.

These figures suggest that non-auditory injuries would only occur close to the most powerful sound sources, however, anecdotal evidence from divers (Marine Technologies Directorate, 1996) and examination of beaked whales affected by military sonar (Balcombe and Claridge, 2001) suggest that animals and humans can be injured by resonance effects in body cavities. Research into this problem is at an early stage but it is likely that it would be most pronounced for continuous or long sound pulses. Gordon et al., (1998) quote theoretical studies that suggest sounds may induce bubble growth in the blood stream of a diving animal. Sound pressure levels above 190 dB re 1 μPa would be required to induce this effect if it takes place. McCauley et al., (2000) take the view that animals must be able to cope physiologically with their own sounds, concluding that whales can cope with levels of 188-192 dB re 1 μPa. (p-p). However, animals generally project sounds forward and may have mechanisms for blocking transmission of potentially harmful sounds into the inner ear (D. Ketten, pers. Comm, 2002).

Auditory damage

The thresholds of auditory damage in marine animals is difficult to assess and the subject of ongoing research and will be reviewed with the different animal groups. Richardson et al. (1995) and Gordon et al., (1998) review the problem. They note that damage is more likely and thus thresholds are lower for repeated exposure. They come up with thresholds for auditory damage from as low as 178 dB re 1 μPa for 100 long (>200 ms) pulses in sensitive species to 244 dB re 1 μPa for a single short (25 μs) pulse for insensitive species. However they are at pains to point out that the lack of data makes such conclusions highly speculative.

ACOUSTIC TECHNOLOGY

MARINE SEISMIC SURVEYS

Seismic reflection and refraction surveys are used by geophysicists and geologists to image the arrangement of sediments and basement beneath the sea floor. The method can also be used on land and has been used to measure ice thickness on the Antarctic Ice Sheet as well. Seismic reflection methods are one of the most important tools for imaging the earth's crust and are used world-wide in research into almost all aspects of marine geology and geophysics and for providing images of the subsurface for engineering works. It is also an important tool in petroleum exploration. For these applications, seismic surveys vary in areas covered and most importantly, in the size of the seismic sound source employed. This review will discuss the basic tools of seismic surveys and the differences in survey design and the likely variation in potential impacts in Antarctica of different survey designs.

Basic Survey Design

Marine seismic systems consist of a sound source towed behind the vessel within a few meters of the surface that produces sound pulses at a controlled frequency range at set time intervals. The sound pulse travels through the water column and penetrates the sea floor. Sound is partially reflected and efracted by each change in acoustic properties it encounters. These waves return and are recorded by hydrophones towed further behind the vessel in a streamer or seismic cable or by seismic recorders deployed on land or temporarily placed on the sea-floor (ocean-bottom seismographs). The vessel travels in a straight line at constant speed so the same point in the seabed can be measured repeatedly and the signals added during post-survey processing. Seismic lines are shot usually in intersecting groups so reflectors can be traced from line to line.

Line spacing for reflection will depend on the purpose of the survey. In Antarctica, where lines are surveyed exclusively for research purposes, lines are generally many kilometers apart, producing widely spaced, two dimensionals images of ”slices” through the earth's crust. These are normally known as 2-D surveys. In petroluem provinces, 2-D surveys tend to have closer line spacing or 3-D surveys are carried out where a relatively small area is crossed by two sets of parallel seismic lines several 10s of meters apart. Such 3-D surveys are unlikely in Antarctic waters in the foreseable future because of their very large cost and ellaborate techonlogical requirements.

The survey collects data at individual,evenly spaced *shot points* along the survey lines so to give the section through the earth's crust, the vessel moves forwards at a fixed rate. The rate of movement depends on the purpose of the survey. Deep surveys require longer times for reflections to return from depth so shots occur at intervals of 9-20 or even 30-60 seconds for refraction surveys and the vessel will move at speeds around 4-5 knots. Shallower surveys will move faster and have faster shot rates but speeds much faster than 10 knots produce so much ship noise and turbulance along the hydrophone streamer that the data become degraded.

Sea Ice and timing of surveys

Environmental conditions are major factors in the execution of seismic reflection surveys in the Antarctic. Seismic surveys require the towing of electronic and compressed air devices behind the ship so it is difficult to survey with large scale equipment in sea ice. Some surveys using equipment towed in the wake of an ice breaker have been successful (e.g. O'Brien et al., 1995) however seismic reflection is largely restricted to open water. Therefore, such surveys are mostly carried out during the minimum sea ice period, from early January to March, depending on local conditions. Wind and swell noise also degrades seismic data so bad weather also halts surveys.

Sound sources – Basic types

Seismic surveys use different sound sources depending on their purpose. For imaging shallow sediments in great detail, a survey will use a small, higher frequency source and a short hydrophone streamer. The source could be one or two small air guns or electrically driven sparker or a swept frequency echo sounder (chirper). For imaging deeper in the earth, several larger airguns are used and with longer streamers. Sparkers are becoming quite rare because of their difficulty of use and low power, particularly in deep Antarctic waters so the discussion of sources will concentrate on air guns and air gun arrays. Chemical explosives have not been used for seismic surveys for many (25-30) years because of their danger, unreliability, high environmental impact and poor signal quality.

AIR GUNS AND AIR GUN ARRAYS

An air gun is a mechanical device that stores high pressure air in a chamber and releases it suddenly through ports in response to an electrical trigger. When the air escapes, part of the energy is released as sound, which travels into the subsurface and is reflected back. The pulse rise time is of the order of a few millseconds. Air guns typically vary from 10 cu in (0.16 litres) to 500 cu inches (8.21 litres) in volume of air discharged. Large-volume airguns especially designed for seismic refraction work can be up 60 litres.

The vertical, downgoing acoustic signal from firing an airgun is termed its pressure signature and is shown in Figure 2. The main features of this signature are the initial impulse produced when the airgun's ports first open. The source "ghost" is the reflection of the initial impulse from the sea surface is of opposite polarity to it (see Figure 4), and the bubble pulses which are produced by the over-expansion and collapse cycles of air-bubbles produced by the airgun, as they rises to the surface. The ghost production creates a sound shadow near the surface where the direct pulse and the surface reflection interfere destructively. The source radiates predominantly downwards. This interference effect with the sea surface reflection is also known as the Loyd Mirror Effect and occurs with most underwater sound sources and is important in considering safety. A diver or animal at the surface will experience much lower sound levels than one at depth (Marine Technology Directorate, 1996).

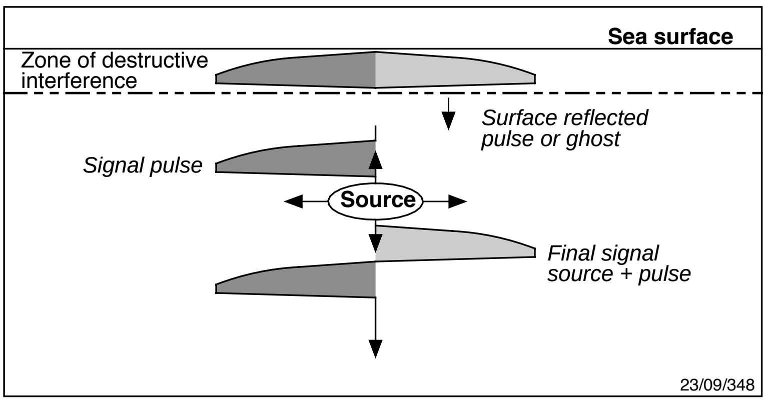


Figure 4. Mechanism for producing the source ghost and Loyd Mirror effect.

A signal from a single airgun such as shown above is of limited use as it differs substantially from the ideal impulse. In particular the bubble pulses are essentially secondary sources of low-frequency acoustic energy that result in unwanted signals being returned from subsurface reflectors and interfering with reflections of the initial impulse. The strength and period of bubble pulses depend upon the size of the guns, depth of the guns in the water and air pressure used.

This has led the seismic industry to deploy numbers of different sized airguns triggered simultaneously in “arrays” in order enhance the initial impulse through coherent addition, whilst suppressing the bubble pulses through destructive interference. Figure 5 shows how six different sized airguns fired simultaneously can be utilised to give a resultant signature far closer to an impulse than that resulting from a single airgun. The various seismic contractors have established their own “tuned airgun arrays” depending on the equipment and seismic vessels they have at their disposal. Figure 6 shows the lay out of an array used for 2-D seismic. Guns are deployed in parallel strings 15.2 m apart with single guns spaced every 2.5 m along each string. Thus the sound is produced over an area 12.5 m by 15.2 m, rather than a point source. As ice flows could cause damage on the airguns and their umbilicals, arrays or airgun clusters of smaller dimensions are often used in Antarctic waters.

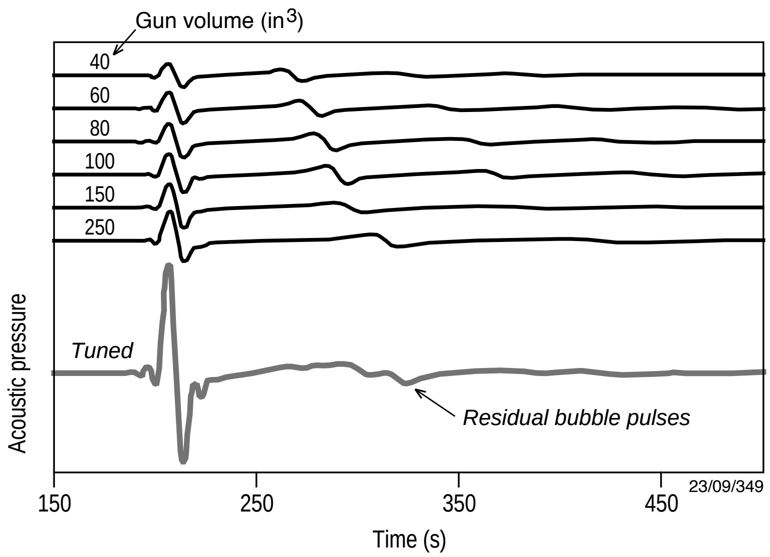


Figure 5. Principle of a tuned array where several small guns generate a large far-field signal with a suppressed bubble pulse (Dragoset, 2000).

The simple summation of the individual gun signatures to yield an overall signature is an oversimplification. If the individual guns are sufficiently close together, their bubbles can coalesce and result in quite complex signatures. Such guns are said to “interact”. Even for guns that are sufficiently separated to not interact, the resultant signature has a directional dependency depending on the placement of the guns in the array, and the computations can be quite complex especially when dealing with positions within the array.

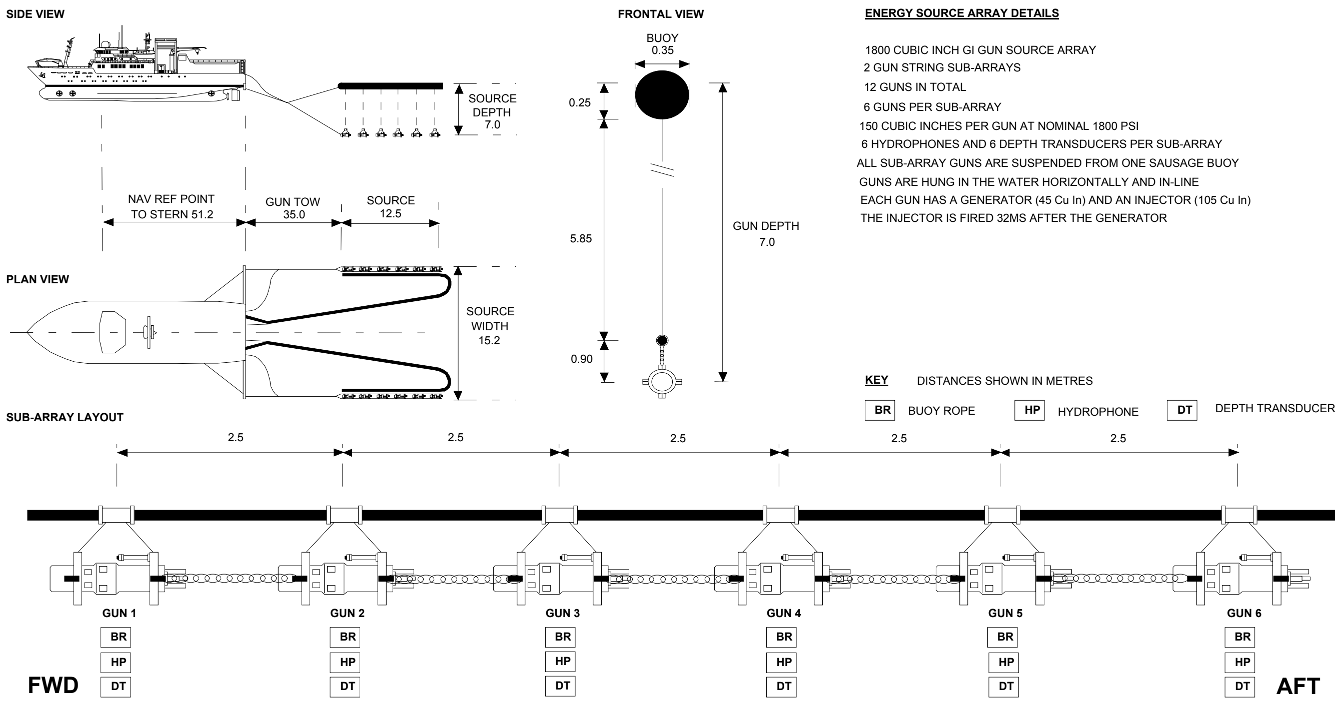


Figure 6: Lay out of an airgun array. Guns are towed behind the ship on cables and fed by air hoses and control wires. Total signal is produced over the area of the array.

In order to give some standard measure to compare arrays and sources, the notion of a “far-field signature” was developed. This involved measuring the signature at some distance (300 –500 m) from the source array using a calibrated hydrophone. In order to remove directional effects this needs to be done vertically below the array and is typically carried out in the deep ocean or in a quiet fiord. The resultant far-field signature yields amplitude values which are then scaled back to what would be observed at a distance of 1 metre (assuming a 1/r spreading loss – simple spherical spreading) from the source.

Considerable work has also gone into numerical modelling of airgun array signatures (one does not want to have to conduct an expensive marine survey every time one changes the array configuration). The comparisons with actual field observations are moderately good.

The far-field signatures that are supplied for guns and arrays show the signatures that would be observed vertically below the source and at some distance (> 300 m) from the source, but with the pressure units scaled back to those of a corresponding point source at the cntre of the array with units of MPa (megaPascals) at 1m from the source or in bar.m (bars at 1 m). One bar is equivalent to 10^{-1} Mpa. However it must be kept in mind that the array is NOT a point source so, the "back-calculated" values obtained are for a "notional" point source. Dragoset (2000) and Caldwell & Dragoset (2000) show that the values obtained for the notional source are never actually encountered at close distances (ie within the airgun array). In fact the pressures encountered are substantially less. Dragoset (2000) suggests that the maximum pressure levels within an array will be found between the two largest adjacent airguns. This level can be estimated by calculating the pressure produced by each of the two guns at that point, using the spherical divergence calculation, then adding the two pressures. This produces a theoretical maximum that is seldom reached in a real array.

The advantage of the far-field signature display is that the specifications are relatively easy to obtain, are easy to visualize and understand and are standard for the seismic industry. One can readily determine the zero-to-peak (0-P), peak-to-peak (P-P) amplitudes and the peak-to-bubble ratio (P/B) and these are usually supplied by the gun manufacturers and array modellers. The disadvantages are that the total energy and spectral content are not known and the source strength measure can be misleading without proper specification of the recording bandwidth.

For these reasons, it is also usual to supply an amplitude spectrum for the source (or array). Because of the large range of amplitude values versus frequency it is convenient to display the amplitudes in decibels (dB). The reference amplitude used is 1 μPa at 1m. The advantages of describing the seismic sources in this domain are that:

1. Absolute values of energy for the total passband and for specific frequency components are readily obtainable,
2. The resolution and penetration capabilities of a seismic source can be estimated,
3. It is a common display used for most noise analyses and allows one to compare with other sources of acoustic energy (ships, echosounders, etc), and
4. During processing of the seismic data, phase information can be readily determined.

Figure 7 shows the two complementary displays for a fairly typical gun array used in the exploration industry (Dragoset, 2000).

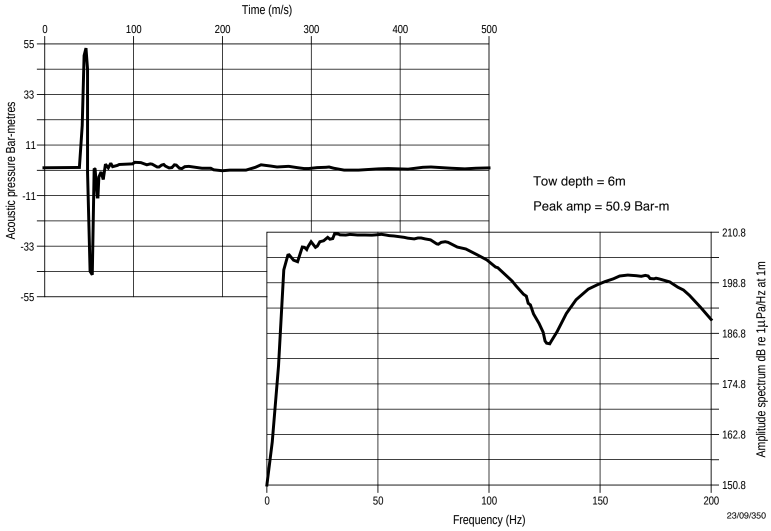


Figure 7. Two complementary displays of source signature and amplitude spectrum for a fairly typical gun array used in the exploration industry (Dragoset, 2000).

Airgun Source Levels

Airguns as small as 10 cu in are used for shallow surveys requiring high frequencies. Such guns have a source levels of 210-220 dB re 1 μPa-m (p-p). Larger airguns which have been used extensively in intermediate resolution surveys in the Antarctic (e.g. Shipp and Anderson, 1997, O'Brien et al., 1995) have source levels, in the order of 220 dB re 1 μPa-m (p-p) but the energy is more concentrated in lower frequency ranges (10 Hz- 1 kHz) and the main pulse is only a few milliseconds in duration. Caldwell and Dragoset (2000) state that arrays used in petroleum industry surveys typically have far field source levels in the range of 240-246 dB re 1 μPa-m (p-p) for vertical propagation but 10-30 dB re 1 μPa-m (p-p) lower for horizontal propagation. Gulland and Walker (1998) illustrate an array where the maximum sound levels are found in a roughly conical region beneath the array with an apex angle of 90^o. It should be remembered that these are signatures of the notional point source with the same far field signature and that closer to the array, the sound levels do not reach as high as the notional point source. The small guns used in high resolution work are fired from every 7 sec. to as rapidly as every 0.25 sec. Large arrays are designed to image deep into the earth's crust and so fire every 8 to 19 sec.

TRANSDUCER-BASED EQUIPMENT

TRANSDUCERS

Active sonars including echo sounders use transducers that are most commonly blocks of piezoelectric materials that expand, contract or change shape when electrical voltages are applied and generate voltage when they vibrate in response to impinging sound waves (Clay and Medwin, 1977). Most transducers are made of ceramic material so they can be shaped to produce the desired beam pattern and respond preferentially to sound coming from the direction of interest. Shaped sound reflectors have also been used much in the same way as mirrors to focus the outgoing and incoming sound. Transducers are constructed of multiple elements to produce omnidirectional, focussed or wide beams depending on the application.

Commonly used devices that use transducers are: Echo sounders, multibeam echo sounders, sidescan sonars, Acoustic Doppler Current Profilers, acoustic releases, positioning transponders and positioning beacon.

ECHO SOUNDERS

Echo sounders emit a short pulse of sound and listen to reflected energy from the sea bed or things in the water column such as schools of fish or plankton. Every large vessel has an echo sounder directed vertically downwards to measure depths under the keel. This is essential for safe navigation so echo sounders are the most commonly used acoustic technology. Sonars are used for applications requiring higher frequencies than those used in seismic reflection, usually higher than 1 kHz, although there is a continuum of applications. Lower frequency sonars can be used for high resolution sub-bottom profiling. Their frequency range is higher than airguns so they can resolve thinner beds but absorption of the signal is much higher so penetration is limited.

Echo sounder frequencies vary depending on their use. For fine-scale imaging of shallow subsurface sediments, frequencies around 3.5 kHz are used, although better subsurface images are obtained if the transducer sweeps through a range of frequencies, such as 1.5-11.5 kHz or 0.4-8 kHz depending on the make, model and application. These swept frequency units are known as chirpers because of their “chirp” sound rather than the typical “ping” of a single frequency unit. Twelve kHz units are commonly used for ocean-depth echo sounders and some subbottom profiling, although the higher frequencies do not penetrate far into sediments. Depth measurements are made with units up to 36 kHz but the higher frequency units are used in shallow water. Higher frequencies still are used for detecting scattering from plankton and fish and are therefore important in studying their distribution. Table 3 summarises the range of frequencies needed to detect different components of the oceanic biomass (Medwin and Clay, 1977).

Table 3. Elements of the marine biomass, their equivalent diameters and their range of detection frequencies (modified from Clay and Medwin, 1977).

Plants or animals	Equivalent diameter	Detection frequency range
Whales and sharks	2-6 m	3 – 250 Hz
Large nekton & largest plankton	0.2-2 m	10 – 2500 Hz
Small nekton & larger plankton	2 – 20 cm	100 Hz – 2.5 kHz
Megaplankton (e.g. krill)	2 – 20 mm	1 kHz – 250 kHz
Macroplankton	0.2 – 2 mm	10 kHz – 2500 kHz
Microplankton	20 – 200 µ	100 kHz – 25 MHz

Single beam echo sounders

Transducers can produce a variety of beam patterns. The most common is a single beam. A single square transducer produces a main lobe of maximum intensity at right angles to the transducer surface (Fig. 8, Clay and Medwin, 1977). For example, in the transducer tested in Figure E-1, intensities propagating at 15° away from the axis of the main lobe are 20 dB less than the main lobe (Clay and Medwin 1977). By 60° from the main lobe axis, intensities are nearly 40 dB lower. This falls even further parallel to the transducer face. The aim of transducer design for echo sounding is to reduce the side lobes to a minimum because they could produce spurious echos.

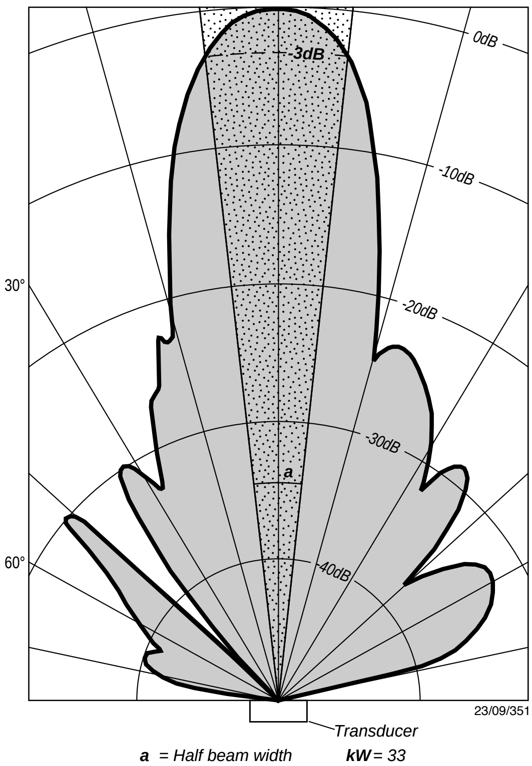


Figure 8: Polar plot of the beam pattern for a 26 cm square transducer at 30 kHz (Clay and Medwin, 1977). The response is plotted in decibels relative to the axial (maximum) value. Beam width is given by the angle at which beam power is 75% of the axial value (-3 dB), in this case about 6°.

Transducers are described in terms of beam angle which is the angle between the points at which the beam is 3 dB less than maximum power. Beam width is partly a function of frequency with higher frequency transducers having narrow beams. Advertised beam widths for commercial transducers vary from as low as 1.5^o to 50^o (e.g. Grant and Schreiber, 1990). “Virtual end-fire” or “parametric” arrays make use of non linear propagation effects to generate very narrow beams of lower frequency sound by superimposing two high frequencies to generate another, lower frequency signal with the narrow beam width of the high frequencies (Clay and Medwin, 1977). The low frequency signal is generated only in the main beam, meaning that side lobes are quickly attenuated or virtually non-existant (Grant and Schreiber, 1990). This principle is used in the Atlas Parasound system to give a single, 5^o beam for subbottom profiling.

Echo sounder power is usually quoted in kilowatts because the actual source level will vary with water salinity and temperature however some manufacturers do quote maximum source levels for transducers. Full ocean depth sounders have maximum source levels from 200-230 dB re 1 μPa.m (0-p). Shallow water units and navigational echo sounders have lower source levels. Because of beam shaping in modern transducers, this level applies only to the main beam. Levels may be much lower away from the main beam so there is a very small horizontal radius of influence for most modern echo sounders. Sound pressure levels can still be estimated in the main beam using the spherical spreading approximation but the higher frequencies of many echo sounders means that the absorption term should be included. For sound levels outside the main beam, the initial source level will be lower depending on the side lobe pattern.

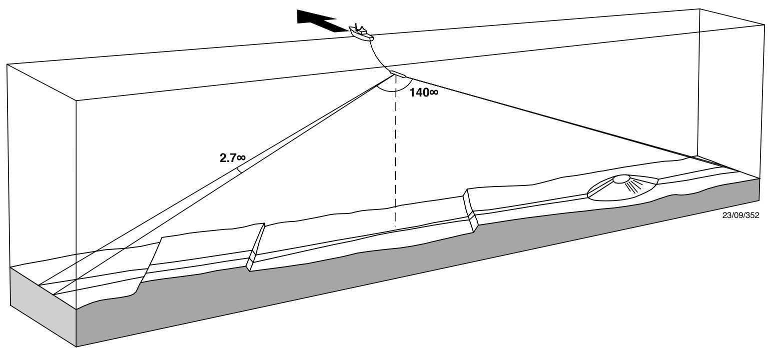
Area of influence

The area influenced by an echo sounder depends on the beam width and frequency as well as the source level. Because absorption is a function of frequency, it becomes significant for higher frequency transducers. Beam focussing means that horizontal source levels around a vertically-directed echo sounder may be 40 dB lower than the main beam so the area of high sound pressures around a ship will be quite small. The zone of maximum intensity will be given by the beam width. A 5^o beam width will mean that the area of +75% intensity will be a circle of radius 8.7 m in 100 m of water (240 m^2). For beam width of 2^o, this falls to a circle of 3.49 m radius (38 m^2). This means that the zone of influence of most single beam echo sounder will be a small region below the ship.

MULTI BEAM ECHO SOUNDERS AND SIDESCAN SONARS

Single beam echo sounders map virtually a point beneath the ship as it passes. To get greater areal coverage, sidescan and multibeam echo sounders are used. These units direct sound pulses and receive echos from transducers pointing sideways from the ship or towed body. The pulses are transmitted at regular intervals then the echos recorded against time so echos from an object near the ship are displayed ahead of those further out. The result is an acoustic image analogous to an aerial photograph of the sea floor, albeit with distortions caused by changes in angle of the beam and other effects. These images can be used for studying seafloor geology, benthic habitats, finding lost ships and aircraft and foundation studies for offshore structures.

Conventional sidescan sonars use 1 or 2 beams with reasonably large widths on either side of a towed body or vessel. Figure 9 shows the beam geometry for the long range sidescan GLORIA (Searle et al., 1990). GLORIA is the largest of this type of unit in use, mapping swath widths in the order of 45 km, depending on water depth. Most conventional sidescans are used to map much smaller swaths, in the order of 1 km or less. Frequencies used in GLORIA and deepwater sidescans are in the range of 6-7 kHz. Higher resolution units in common use employ frequencies from 36 kHz to 500 kHz. Outputs are usually quoted in watts, like echo sounders, however some manufacturers quote maximum source levels of 228 dB re 1 µPa.m (0-p). Beam widths fore and aft vary from maximum values of 2.7^{o} to as low as 0.3^{o} (Belderson et al., 1972 and manufacturers technical data sheets).



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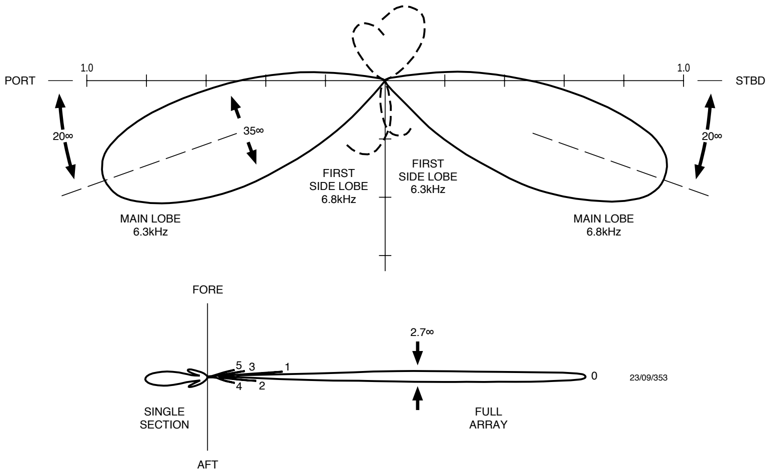

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Figure 9. a. Diagram of a sidescan sonar mapping survey. Sonar is in a towed body behind the ship. Ship moves forward and the sonar sweeps the sea floor, recording echos from a wide swath (Searle et al., 1990).
b. Beam pattern of the GLORIA sidescan system. Main lobes are projected 20^{o} from the horizontal. Individual seam widths are 35^{o} normal to the ship's track and 2.7^{o} fore and aft. Side lobes are very small (Searle et al., 1990).

Multibeam systems

Multibeam echosounders perform a similar function to sidescan sonar except they use transducers that produce a fan of pre-formed beams (Grant and Schreiber, 1990, Pohner and Hammerstad, 1991, Hill et al., 1995). The fan can vary from 45^{o} to up to 150^{o} depending on the unit (Fig. 10). The returns from these beams can be processed with GPS position information and ship motion compensation to give bathymetry as well as the backscatter information that is obtained by conventional sidescans. A single ship's track can map a swath between 2 and 7.4 times water depth, depending on the system. Beam widths fore and aft vary between 1.5^o and 4.5^o depending on the system.

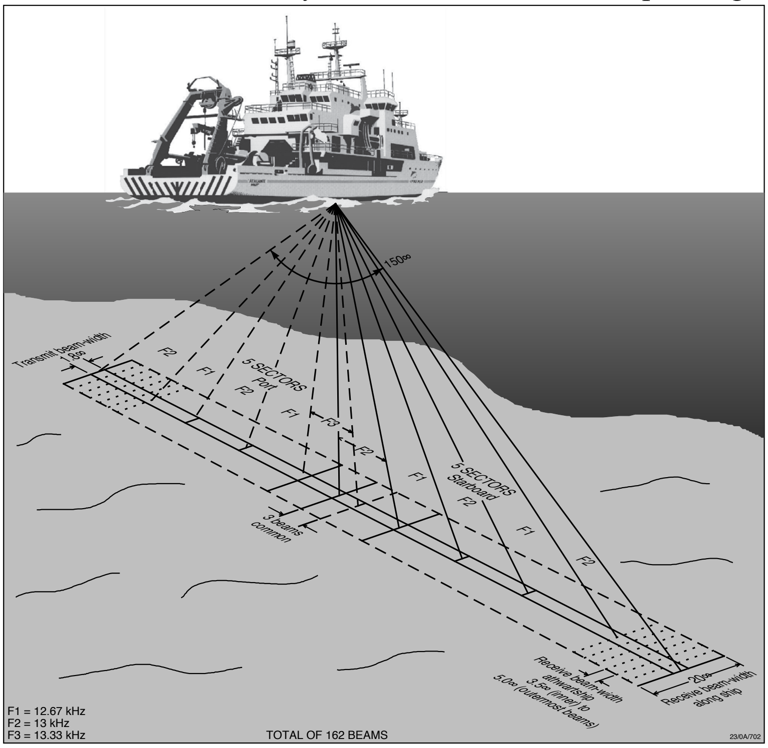

Figure 10. Beam pattern for a hull mounted multibeam echo sounder from Hill et al. (1995).

Multibeam systems operate with frequencies above 12 kHz with deep water systems using frequencies below 20 kHz. Source levels for the largest deep water systems are quoted as maximums of 236-238 db re 1 µPa.m (0-p). Systems for shallower water are both higher frequency and lower power, down to small systems deployed on launches.

Survey design and area of influence

Single beam echo sounders commonly run port to port with data being logged continuously on most research cruises. Likewise, navigational echo sounders run continuously on most ships. Therefore the area affected will be a region beneath the vessel where ever it goes. The size of the area affected by a single beam echo sounder will depend on the power, frequency and beam pattern of the sounders and the duration of ensonification will depend on ship speed. Hull mounted echo sounders can operate in ice. Thus the area of impact will vary depending on the individual cruise plan and equipment. Because of the high frequencies used and the highly directional nature of most echo sounders, the area affected will be quite small.

Multibeam surveys have a footprint up to 7.4 times water depth wide and 1.5^o wide. Such a system mapping in 1000 m of water would ensonify a moving area 7.4 km wide by 50 m. Multibeam surveys typically work in parallel tracks with some overlap between swaths and move at speeds up to 12 knots (6 msec^{-1}). At this speed, a point 1000 m away from the ship would experience sound levels >50% beam strength for <10 seconds. The systems are designed to minimise the size of side lobes so the sound levels outside the swath are much lower than within.

ACOUSTIC DOPPLER CURRENT PROFILERS

Acoustic Doppler Current Profilers (ADCPs) provide a continuous measurement of water movement within a certain range of the instrument. Ocean-going ADCPs are hull mounted transducers that project four beams into the water column (Fig. 11). The instrument records backscatter from the water column and compares the Doppler shift between the 4 beams to resolve a water velocity profile and may also provide sediment concentration information.

Advertised ADCPs range in frequency from 38-150 kHz. Output is quoted in Watts, in the range of 1 kW, but the instruments aim to gather data out to a maximum of 1000 m so source levels will be low compared to deep water echo sounders. Beam angles are very narrow, quoted as less than 1^{o} and units aim to measure scatter from cells < 25 m.

Figure 11. Diagramatic beam arrangement of an Acoustic Doppler Current Profiler. Picture from RD Instruments web site, www.rdinstruments.com, reproduced with permission.

Acoustic releases

Acoustic releases are devices that attach floating instruments to a mooring. They communicate with a shipboard transponder via a digital signal that gives a range from the transponder so the vessel can locate the mooring. The sending of a digital code from the ship then causes the devices to release the instrument package from the mooring. Acoustic releases work at frequencies from 7 - 15 kHz, have source levels up to 192 dB re 1 (Pa.m (0-p) and are omnidirectional. They are activated by the shipboard unit only when it is time for the mooring to be recovered and so emit sound for only a few hours maximum.

Positioning transponders and beacons

Positioning transponders and beacons are used to locate submarine equipment or for dynamic positioning of vessels. They operate at frequencies from 7 to 54 kHz and have source levels from 180 dB re 1 (Pa.m (0-p) to 205 dB re 1 (Pa.m (0-p). They can be omnidirectional or have focused conical beams (60^{o}). This sort of equipment is used for the duration of an activity. In the case of dynamic positioning, for the time a vessel is on station. The Ocean Drilling Program has used such beacons in the Antarctic but only for a maximum of 15 days in one location.

Passive sonars

Passive sonars are listening devices, (hydrophones) that determine the presence, characteristics and direction of submarine noise sources. This sort of equipment makes no sound and therefore has no potential to disturb marine life.

CETACEANS

CETACEANS IN THE ANTARCTIC

Cetaceans are generally widespread in the Antarctic region. All species of large whales, except Bryde's whale, are known to have populations that migrate from winter breeding grounds in the tropics to summer feeding grounds in the Antarctic (Kasamatsu, and Joyce, 1995, Kasamatsu et al., 2000). Migrating whales seem to arrive in the region in December and depart around mid to late Febraury although beaked whales are known to be present in October (Kasamatsu and Joyce, 1995).

Their distribution could depend on the distribution and abundance of prey species (Kasamatsu et al., 2000). High productivity areas in Antarctic waters are found in areas of oceanic front, eddies and upwellings, the marginal sea ice zone and in coastal waters. Various studies have found concentrations of balleen whales in such areas (quoted in Kasamatsu et al., 2000).

Kasamatsu et al., (2000) attempted to define the spatial structure of whale populations in the Antarctic and found that it was possible to make a few generalisations:

1. Krill-feeding species concentrate in the zone of maximum krill concentration. This tends to be the retreating ice edge in spring and early summer and about 60 nm seaward of the continental shelf edge later in the season for large parts of the margin but covers a wider belt in the South Atlantic (Fig. 18, Nicol et al. 2000).
2. Killer whales are widespread but tend to concentrate near the ice edge.
3. Minke whales show the highest densities near the ice edge.
4. Sperm whales and Ziphiids (beaked whales) have low densities on the Antarctic continental shelf, concentrating on the continental slope, rise and in the ocean basins.
5. Fin whales are most common far from the ice edge.

These relationships probably reflect prey distribution with killer whales preying on minke whales, seals and penguins and so follow the ice edge whereas sperm whales and ziphiids prey on squid that are found in deep water.

There is some evidence for longitudinal peaks in whale abundance. Kasamatsu and Joyce, (1995) noted peaks in sperm whale abundance in areas bounded by 62°-66°S and 090°-120°E and south of 66°, 150°-180°E. They also comment on high encounter rates with beaked whales between the Southern Atlantic (90°W) and the eastern Indian Ocean (120°E). Ichii (1990) documents some longitudinal variation in minke whale catch locations around East Antarctica, more or less reflecting the distribution of krill. The most concentrated regions are along the shelf edge and the ice edge.

Sensitive areas

Whales are distributed widely in Antarctic waters so that there are some whales are likely to be present in most areas with little or no ice cover. The areas in which whale concentrations are likely to be highest are zones of high krill abundance (Fig. 18). This zone is also favoured by deep-diving sperm and beaked whales which are potentially more vulnerable to surface noise sources (Gordon et al., 1998).

CETACEANS AND SOUND

BALEEN WHALES

Baleen whales produce a rich and complex range of underwater sounds ranging from about 12 Hz to 8 kHz but with the most common frequencies below 1 kHz (McCauley 1994). This combined with studies of their hearing apparatus suggests that their hearing is also best adapted for low frequency sound (McCauley, 1994, Richardson et al., 1995). Baleen whales make individual sounds that last for up to 16 sec. (Richardson et al. 1995) and can "sing" for long periods. These sounds are thought to be used in social interaction and communication between individuals and pods. Richardson et al. (1995) summarised published Baleen whale sound characteristics. Table 4 lists the estimated source levels, frequency ranges and dominant frequencies of baleen whale calls. The individual papers from which these figures are obtained are listed in Richardson et al (1995), Table 7.1. It can be seen that some species produce quite high sound levels. Likewise, McCauley et al. (1998) report Humpback and Southern Right whale song components reaching 192 db re 1 μPa^2 (p-p) as well as levels of 180-190 db re 1 μPa^2 (p-p) for humpback flipper slapping and breaching sounds.

Species	Frequency (Hz)	Dominant frequency	Estimated Source Level (dB re 1 μPa.m)
Southern right	30 - 2200	50 - 500	172 - 192
Pygmy right	300 +	60 - 135	165 - 179
Humpback	25 - 8200	25 - 4000	144 - 192
Fin	10 – 28,000	20, 1500 - 2500	155 - 186
Blue	12 – 31,000	16-25, 6000-8000	130 - 188
Bryde's	70 - 950	124 - 900	152-174
Sei	1500 - 3500		
Minke	60 – 20,000	60 – 12,000	151 - 175

Table 4. Sounds produced by baleen whales found in the Southern Ocean (Richardson et al., 1995, McCauley, et al., 1998). Source levels are likely back calculated from far field levels.

The dominant frequencies of marine seismic surveys and lower frequency echo sounders coincide more or less with the range of frequencies used by baleen whales for communication and other purposes. The rise of whale watching and the presence of whale populations in areas of active oil exploration has led to studies of both their reaction to vessel noise and to marine seismic surveys. Controlled experiments with airguns have been carried out (e.g. McCauley et al., 2000a,b). Observations of whale reactions to echo sounders have also been reported. The following summary relies on more extensive ones published in Richardson et al., (1995), McCauley (1994) and McCauley et al., (2000a,b) and the review of Popper et al., (2000). Most work relates to whale species that migrate through or use regions of active hydrocarbon exploration and are sufficiently numerous to be studied. There is little or no information on rare species even though they may visit the same regions.

Responses to Seismic surveys

Whale responses to seismic noise described in Richardson et al.,(1995) and McCauley et al (2000a) are mostly based on studies with grey, bowhead and humpback whales and fall into the following categories:

- Startle response where a resting or slow moving whale commences rapid movement away from the source or changes surfacing-dive-respiration behaviour.
- Avoidance where the animals change course or speed to maintain a minimum distance from the source. Whales tend to alter course to maintain sound levels in the range 140-180 dB re 1 μPa mean squared pressure (McCauley et al., 2000a, Table 34).
- Follows where a whale swims directly towards the source up to a certain stand off distance. McCauley et al. (2000a) observed what they presumed to be male humpbacks that were attracted to a single operating airgun. They suggest that the similarity of the sound level and frequency content of the airgun to a breaching event caused the whales to approach to investigate. They speculate that this behaviour may account for an increase in sightings of whales > 3km from a commercial seismic vessel with array firing compared to when the array was off.
- Changes in calling. Some whales change their calling patterns in response to echo sounders however Richardson et al., (1995) cite only one study which found that fin and blue whales continued calling in the presence of airgun noise. Popper et al., (2000) report that total humpback song levels continued unchanged through periods when the ATOC experiment sound source was switched on. This source emits pulsed sound at 190 dB re 1 μPa (broadband) and 60-90 Hz. The received levels experienced by the whales is unknown. There are also instances of seismic survey data quality being degraded by whale calling. Hutchinson and Lee (1989) concluded from the whale calls recorded on a survey in the Gulf of Maine that the whales calls came from all directions. This suggests that the passing of the survey vessel did not cause the whales to become silent.

This wide range of sound levels at which avoidance behaviours are observed reflects the fact that whales respond differently to sound levels depending on their activity at the time. Observations of humpbacks on the North-West Shelf of Australia (McCauley et al., 2000a,b) and studies of humpbacks, Bowhead and Grey Whales (quoted in Richardson et al., 1995) indicate that the whales are less responsive when migrating or feeding than when suckling, resting or socialising. There are also variations between individuals in populations. Richardson et al., (1995) quote a study which found ~10% of migrating grey whales showed avoidance at 163 dB re 1 μPa and ~50% at 173 dB re 1 μPa. Popper et al. (2000) report a study that found grey whales were more or less inclined to divert around a sound source depending on its location in their migratory path. In areas of the North-west shelf where humpbacks were not migrating, sexually active males swim rapidly around the area and are less reactive to airguns unless they follow the vessel, sometimes circling it before swimming off, receiving a maximum sound level of 165 dB re 1 $\mu Pa^2.s$ (equivalent energy, ~190 dB re 1 μPa p-p).

McCauley et al.(2000a) found in their study that humpback cows with young calves, which exhibited avoidance behavior at sound levels of 126-129 dB re 1 $\mu Pa^2.s$ (equivalent to 156-159 dB re 1 μPa p-p) (McCauley et al., 2000a), were the most sensitive to air gun noise.

Response to echo sounders and other transducers

Richardson et al, (1995) review literature that indicates whales react to lower frequency echo sounders, sometimes showing strong avoidance behaviour. Baleen whales seem to react to frequencies up to 28 kHz but do not react to pingers, acoustic tags and echo sounders at 36 kHz and above. The review does not include information on transducer source levels, levels received by the animals or whether the devices used were omnidirectional or focused. It is thus hard to assess the significance of the observations. The observation of normal behaviour from whales with attached acoustic tags suggests that these high frequency tools have no influence on them. The only case of whales around acoustic beacons in Antarctic waters known to the authors took place on ODP Leg 188 in January to March 2000. While drilling, the vessel uses a beacon to control its dynamic positioning system. On 2 of the 15 days on site 1165, pods of humpback whales swam around and under the vessel for about 1 hour. Several individuals indulged in “spy hoping” within 30 m of the vessel and commenced breaching displays before departing.

Possible Impacts

Injury

Very little is known about the sound levels at which hearing damage or physical injury to whales could take place (Richardson et al., 1995, Popper et al., 2000). Examination of whales probably killed by sound pulses have all involved animals found near sites of chemical explosions. McCauley et al. (2000a) suggested that whales must cope physiologically with the highest level sound produced by whales themselves (192 dB re 1 µPa p-p) while singing or breaching. Thus, for a 220 dB re 1 µPa.m (p-p) airgun, a whale would not receive sound levels higher than 192 dB re 1 µPa (p-p) unless it were closer than 25 m to the gun. For airgun arrays, the distance will vary from array to array depending on array design and power. McCauley et al. (2000a) found that the industry array (2678 cu in., ~240 dB re 1 µPa, p-p) they studied produced sound levels of 192 dB re 1 µPa, p-p out to 1.4 km abeam. For focussed echo sounders, such sound levels will be found in the narrow main lobe immediately below the transducer.

The most likely scenario for injury of an animal by acoustic equipment would be if the equipment were turned on full power while the animal was close to it. In many jurisdictions, seismic surveys are required to “soft start” or “ramp start” by gradually increasing gun numbers and pressures over a period so that animals have time to swim away before sound reaches dangerous levels. Popper et al. (2000) describe this as a “common sense” measure but note the lack of any actual studies to verify that it works. Gordon et al. (1998) point out that the “soft start” assumes animals will respond appropriately by swimming away from the sound source.

Disturbance

The effects of disturbance on whale activities is still uncertain. However, Popper et al. (2000) concluded that the studies on the effect of the ATOC experiment which uses a high intensity, low frequency sound source found “no evidence of short term catastrophic effects in the area such as strandings or mass desertion”. Concerns relate to persistent displacement of animals from important, localised habitats and masking of acoustic cues interfering with socialisation and breeding. Persistent displacement of cows and young calves could make the calves vulnerable to exhaustion and predation (McCauley et al., 2000a,b). Major displacement of prey species could also pose a threat (see below).

For humpback whale populations in Australian waters, McCauley (1994) made the point that the population on the west side of the continent that had been exposed to intense industry seismic activity for several decades had the same annual rate of growth as that on the eastern side. The eastern population is not exposed to seismic surveys, suggesting that seismic activity poses little threat to humpback whales. This is not to say that an increase in the number of surveys and a change in survey design in certain key areas might not pose a problem in the future.

Even though little is known about the many whale species that frequent Antarctic waters during the austral summer, feeding on zooplankton is likely to be a major activity except for Sperm, beaked and killer whales. Stewardson and Child (1997) lists most baleen whales as breeding in temperate waters to the north of Antarctica. Therefore the amount of time and area of a survey in the zone of maximum krill concentrations will likely be important in assessing its impact. Thus, the impact of a survey will depend on how much of this area is affected and how much time in the spring to summer season is affected. Experience with humpback whales suggests that feeding is one activity where the whales are relatively insensitive to acoustic disturbance (McCauley pers. comm. 2001). Likewise, calves are presumably older and stronger by the time pods reach Antarctic waters, making short term displacement less of a problem compared to the whale breading areas in the north. These things suggest that humpback whales are possibly less sensitive to disturbance in the Antarctic than in their wintering areas.

McCauley and Duncan (2001) discuss the risks posed to blue whales by petroleum exploration seismic surveys off southeastern Australia and summarised their conclusion in a table (Table 5).

Event	Blue whale (from McCauley and Duncan 2001)
Behavioural effects direct	Subtle changes to tens km, local avoidance from 3 to 20 km depending on animals sensitivity and behavioural state at time of exposure
Pathological effects	Possible but unlikely, very low risk and animals need to be at less than 1 km to be at any risk
Geographical Scale	Relatively small at scale of individual signal but larger when considered through time. Single air-gun vessel can work any one region so easily by-passed
Timing/duration of action	Depend on the activity
Cumulative effect of action	unknown

Table 5. Risk assessment for blue whales and seismic surveys on the southern Australian continental margin (McCauley and Duncan, 2001).

TOOTHED WHALES

Toothed whale sounds

Toothed whales produce a wide range of whistles, clicks, pulsed sounds and echolocation clicks. Table 6 summarises the frequency and source levels for Southern Ocean species reported in Richardson et al., (1995). The frequency range of toothed whale sounds excluding echo location clicks are mostly <20 kHz with most of the energy typically around 10 kHz, although some calls may be as low as 100-900 Hz. Source levels range from 100-180 dB re 1 μPa, (Richardson et al., 1995). The sounds produced other than echo location clicks are very complex in many species and appear to be used for communication between members of a pod in socialising and coordinating feeding activities.

Species	Call frequency (kHz)	Dominant frequency (kHz)	Source level (dB re 1 μPa.m)	Echo location frequency (kHz)	Eco location source level (dB re 1 μPa.m)
Sperm	0.1 - 30	2-4, 10-16	160-180		
Pygmy sperm	60-200	120			
Killer	0.5-25	1-12	160	12 - 25	180
False killer		4-9.5		25-30, 95-130	220-228
Long-finned pilot	1-18	1.6-6.7		6-11?	
Short finned pilot	0.5-20	2-14	180	30-60	180
Common dolphin		2-18		23-67	
Bottlenose dolphin	0.8 - 24	3.5-14.5	125-173	110-130	218-228

Table 6. Sounds used by toothed whales found in the Southern Ocean (Richardson et al., 1995). Long-finned pilot whales produce clicks like echo location clicks of other species.

Echo location has been demonstrated in a number of toothed whales. The animals project pulsed sound of high intensity and frequency ahead of them. Pulse timing and intensity are adjusted by the animal to optimise performance in the prevailing conditions. Pulse lengths are short, typically 50-200 μsec. and spaced depending on the range to the target. Frequencies are typically high. Some species may use pulses as low as 2 kHz but most use pulses in the range 20-130 kHz. The sound is produced in a directional beam with the angle between maximum intensity and levels 3 dB lower being in between 6^o and 12^o (Richardson et al., 1995). Source levels are very high in some species reaching up to 220-230 dB re 1 μPa.m (p-p), although being of short duration, their energy content is low compared to many anthropogenic sounds. Richardson et al., (1995) note studies which found instances where odontocetes seem to avoid direct echo location pulses from neighbouring animals of the same species.

Response to seismic surveys

Although most of the energy in airguns is in frequency ranges below the optimum hearing of toothed whales, airguns still produce sufficient high frequency noise to be heard by them. Richardson et al. (1995) comment on the paucity of systematic data on the reactions of toothed whales to seismic surveys even though anecdotes of dolphins near operating airguns are common in the seismic industry. Sperm whales seem to react by moving away from surveys and ceasing to call even at great distances from a survey (Richardson et al., 1995). The Northern Gulf of Mexico has been one of the most intensely surveyed areas on earth for about 40 years. The fact that there are still studies of sperm whales' response to seismic surveys in the northern Gulf of Mexico taking place suggests that seismic surveys do not produce permanent displacement of sperm whales from an area or that it requires a level of activity unlikely ever to be reached in Antarctic waters.

Response to echo sounders and other transducers

Richardson et al. (1995) found more observations of reactions to echo sounders and other transducers that produce sound in the animals' optimum hearing range. Sperm whales stop calling when exposed to sounds in the 6-13 kHz range at quite low intensities in some instances but the reaction varies with different studies. Continuous pulsing from an echo sounder seemed to produce less reaction compared to short sequences of sound pulses followed by longer pauses. Reaction thresholds in dolphins, porpoises and Delphinids can be as low as 110-130 dB re 1 µPa.m but responses diminish with time even for levels as high as 170 dB re 1 µPa.m (Richardson et al, 1995). This variation may be caused by habituation or changes in whales' behaviour state, as seems to occur with baleen whales. The authors have observed Antarctic killer whales approach and swim alongside vessels operating echo sounders at 12, 18, 38, 120 and 200 kHz. Field observations and anecdotes lack information about echo sounder source levels and beam patterns, making conclusions very difficult.

An area that is being investigated is the possible affect of military sonars. Popper et al. (2000) quote source levels of +230 dB re 1 µPa.m and frequencies of 2 – 5kHz and refer to a US Navy system that broadcasts at 100-500 Hz and a NATO system that broadcasts simultaneous signals at 450-700 Hz and 2.8-3.3 kHz at just below 230 dB re 1 µPa (figure not fully quoted, presumed 0-p). The NATO system emits the sound for 4 seconds, a very long time compared to most scientific echo sounders. Siwecki and Neal. (1993) describe a towed 600-750 Hz system with an adjustable "spotlight" beam size.

There has been great concern caused by recent cases of stranding of beaked whales in the Bahamas and Mediterranean Sea (Balcomb and Claridge, 2001). Although military sonars are not known to be in use in Antarctic waters, what is known of these systems and their use and the stranding events may provide some indication of potential risks in the use of scientific equipment. The Bahamas stranding event is reviewed in Balcomb and Claridge (2001). Providence Channel is a narrow seaway between 35 and 80 km wide and >3000 m deep at its oceanward end, shallowing westwards to <1000 m and surrounded by the Bahama Banks and islands. The incidents involving naval echo sounders suggest that equipment with potential for injury would be powerful, mid frequency echo sounders and airguns. The naval echo sounders involved in the Bahamas strandings had similar source levels and frequency to some scientific echo sounders. The main differences were number of vessels, vessel speed and the beam pattern. The naval exercise had the effect of ensonifying a large area to high levels whereas scientific single beam echo sounders ensonify a circular region vertically below the vessel and multibeam units sweep a narrow fan below the vessel.

The vessels transited for the deep ocean end in the east through to the shallow western end (Balcomb and Claridge, 2001, Anonymous, 2001).The NOAA-US Navy review reports that the region featured surface conditions that produced a surface duct 120 to 150 m thick that gave enhanced sound propagation. Subsequent investigations by NOAA and the US Navy concluded that the whales were injured by active sonars (Anoymous, 2001). Two types of echo sounders were involved, one with centre frequencies from 2.6-3.3 kHz and source levels of 235 dB re 1 µPa-m or higher and the other operated at 6.8, 7.5 and 8.2 kHz and source levels of 223 dB re 1 µPa-m. The echo sounders have beam widths of 30^o to 40^o and are oriented horizontally. Multiple echo sounders (3 or more) were operating with pings staggered so there would be the only a few seconds between pings. Sound pressure levels are unknown in this incident apart from being higher than 160 dB re 1 µPa. over much of the Providence Channel. Subsequent investigations by NOAA and the US Navy concluded that the strandings likely were a consequence of the sonar exercises, but that the animals would have survived had they not beached themselves.

Possible impacts

Injury

Again very little is known about the sound levels at which hearing damage or physical injury to toothed whales could take place (Richardson et al., 1995, Popper et al., 2000). The wide variety of sizes, body shapes and presumably hearing apparatus in toothed whales suggest that it will vary considerably with species. The levels of sound produced by toothed whales (Richardson et al., 1995, tables 7.2 and 7.3) reach maxima of 180 dB re 1 µPa.m for general sounds and 228 dB re 1 µPa.m (p-p) for echo location clicks. Echo location clicks should not be taken as a maximum allowable peak to peak level because of their short duration compared to man-made sounds. Gordon et al., (1998) review studies that have observed temporary decreased sensitivity in dolphins exposed to sound pressure levels of 192-201 dB re 1 µPa. at 0.4, 3, 10, 20 and 75 kHz. Experience with human hearing suggests that similar but prolonged exposure would produce permanent hearing impairment.

Balcomb and Claridge (2001) report evidence of internal bleeding in chambers in the skulls of some of the beaked whales stranded in the Bahamas. They suggest that such damage may be caused by resonance in the chambers. However, the tissue damage found in the whales that died and were necropsied could have been a consequence of disease as well as exposure to the sonar or other sounds (D. Ketten, pers.comm. 2002). Gordon et al., (1998) raise concerns over the potential vulnerability of deep-diving animals such as beaked and sperm whales. They point out that deep-diving animals are committed to a tight energy budget and specialised physiological adaptations, limiting their avoidance options and making it harder for them to move laterally to avoid an approaching source.

Disturbance

The potential for disturbance of toothed whales also is poorly understood. It seems to vary with species, their behaviour state and degree of habituation (Richardson et al. 1995). Sperm whales seem to cease calling or move away from noise sources at quite large distances in some instances. Other studies found that they seem to adapt to echo sounders. The AOTC experiment near Heard Island found that Sperm whales ceased calling during transmission and there was some inconclusive evidence for avoidance of the area around the source. Hourglass dolphins did not avoid the area (Bowles et al, 1994, quoted in Richardson et al., 1995).

Risk assessment

Cetaceans may be displaced by powerful, low frequency sound sources and there is now a documented case of injury to whales from multiple, mid frequency military echo sounders. At the same time, some whale populations co-exist with commercial seismic exploration surveys, maintaining population growth while experiencing some displacement. Clapham et al. (1999) regard ship strikes and fishing gear entanglement as posing a higher risk to cetaceans.

The equipment with the highest risk potential are airgun arrays and low frequency, high power transducers with wide beam angles. **The working group felt that the risk was not so high as to justify a ban on such equipment in Antarctic waters, however, mitigation strategies should be used to reduce the risk to cetaceans in the Antarctic.** Also, though the Providence Channel strandings are still being investigated, they seem to point to a set of circumstances that should be avoided. The mitigation strategies in use elsewhere are:

1. Use of the minimum source level to achieve the result.
2. Use of "soft starts" whereby power is increased gradually.
3. Care should be taken with line lay outs to avoid blocking animals' ability to a avoid the source.
4. Equipment should be shut down if cetaceans are observed within a distance of the vessel defined by the source power, directionality and propagation characteristics.

Further research is need to assess whether these measures work and to better monitor the proximity of whales to a vessel (Gordon et al., 1998).

PENGUINS

There is very little known about the risks to penguins from underwater sound. The submission comprises:

• A summary of the information available on the hearing abilities of penguins, and their sensitivity to pressure in air and water,

• Regional maps of penguin colonies around the Antarctic continent, the Antarctic Peninsula, the South Shetland Islands, the South Orkney Islands, but excluding the South Sandwich Islands, South Georgia, the Falkland Islands and South American breeding localities,

• A brief summary of the breeding timetables of the penguins that breed in the nominated areas.

The maps, census data tabulation and breeding timetables will permit an assessment of where and when, and in what numbers, breeding penguins are present in colonies south of 60°S each year.

Hearing abilities of penguins

Hearing in birds is a complex ongoing topic (see e.g. Dooling 1992, Necker 2000) with most recent work in this area being conducted on pigeons. Despite the obvious complexities in penguin ears that must function at least in air and possibly also under high pressure in water, relatively little has been done on penguin ear morphology (Anisimov 1977, Ilichev 1977) and the capacities of penguins to perceive sound. Penguin hearing capacities can be partially alluded to by consideration of bird behaviour. For example, many penguin displays are based on voice recognition (three types recognised according to Jouventin (1982): contact, agonistic and sexual). On land it is known that penguins use sounds extensively for intraspecific communication including mate and chick recognition (Jouventin 1972, Jouventin et al. 1979, Aoyanagi 1981, see Williams 1995 for review). The sound range used for this varies between about 0.3 and 3 kHz (Williams 1995). These contact calls may be heard up to 1km from the originating bird(s).

However, only contact and agonistic vocalisations are likely to occur at sea, the agonistic cases being unlikely to be used extensively. Contact calls may be used extensively in some species although these have been primarily recorded for birds at the surface (e.g. Broni 1985). There is, however, some limited evidence that some species of penguins may vocalize underwater (Markov 1974, 1977). If underwater vocalisation involves beak opening, recent data collected using beak angle sensors in free-living Magellanic Penguins *Spheniscus magellanicus* indicate that this species, at least, does not communicate underwater (Wilson et al. in press, unpublished data). Clearly more work is needed in this area to determine whether Antarctic penguins may communicate with each other while underwater. Studies also are needed to determine if any of the prey species produce sounds that can be detected and used by penguins to locate prey such as krill swarms by other than random searching.

The in-air hearing abilities of penguins have been examined and reviewed by Jouventin (1982), and are summarised here:

Species	Frequency range (Hz)	Maximum intensity freq (Hz)	Auditory range (Hz)
Emperor Penguin	500 – 6000	2000	30 – 12,500
Adélie Penguin	800 – 5000	2000 - 5200	No data
Chinstrap Penguin	500 – 4000	2000	No data
Gentoo Penguin	400 – 4000	2000 - 3000	No data
Macaroni Penguin	1000 – 8000	1000 - 3800	No data
Rockhopper Penguin	1000 – 8000	800 - 3000	No data

The auditory range for Emperor Penguins is the only species that has been investigated, and clearly exceeds the frequency range of recorded calls.

Sensitivity to noise levels by penguins

Only one study has quantified the noise from aircraft operations within a breeding colony of Emperor Penguins (Giese & Riddle 1999). Noise levels were measured using a Cesva SC-2 sound level meter mounted on a tripod approximately 50m to the side of the aircraft flight line. The meter calculated a frequency weighting incorporating signal frequency and amplitude [dB(A)]. Significant changes in the behaviours of the penguin chicks in response to the overflights were reported (Giese & Riddle 1999). There are no other empirical data available, and there are no empirical data on the sensitivity of penguins to pressure in air or water.

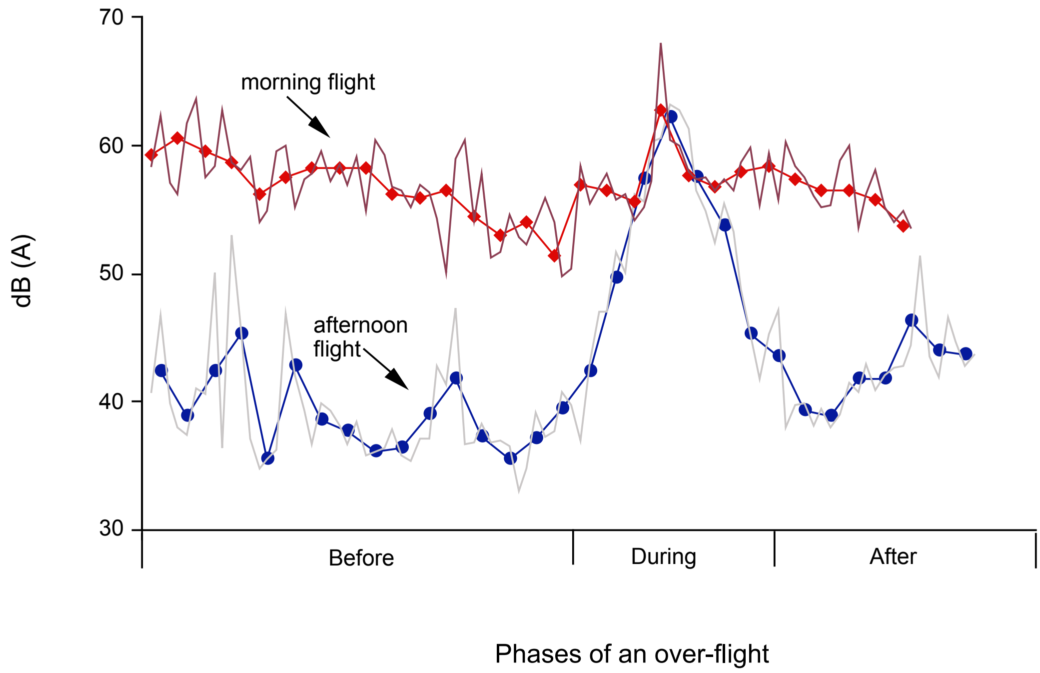

Figure 12. Results from a study of the impacts of helicopter overflights on Emperor Penguin chicks that recorded noise levels [db(A)] from helicopter overflights with 10kn katabatic wind (morning data) and in the absence of wind (afternoon flight). The helicopter was a Sikorsky S76, twin engine aircraft that flew at 1000m altitude at 60kn air speed. The heavy lines are running means (3 * 5–sec intervals). From Giese & Riddle (1999), used with permission of the authors.

Potential impact of marine acoustic surveys on penguins.

This review does not cover direct tissue damage resulting from high intensity sounds produced by underwater blasting (see e.g. Cooper 1982, Brown and Adams 1983) since such damage is expected to be similar for most species. Instead, it briefly assesses the extent to which penguins use sound, considers their sensitivity to it and the extent to which they are likely to be affected by marine acoustic surveys.

It is to be expected that species using underwater sonar would be particularly sensitive to sounds produced during marine acoustic surveys. Following work using Humboldt Penguins *Spheniscus humboldti* in a purported light-tight tank, Poulter (1969) suggested that these birds use sonar to detect their prey underwater. This work was followed by examination of cochlear potentials in the conspecific African Penguins *Spheniscus demersus* where no evidence of enhanced acoustic capabilities (either in terms of intensity or frequency) was found that might suggest that these birds could use sonar. Indeed, compared to other birds (Necker 2000), African Penguins were considered to be relatively insensitive to sounds both in terms of frequency and intensity (Wever et al. 1969). Excellent vision (e.g. Sivak et al. 1987) and perhaps an ability to determine prey whereabouts by smell (see Nevitt et al. 1995, Wilson in press) may explain Poulter's (1969) findings rather than the use of sonar. Despite the apparent insensitivity of penguins to sound (Wever et al. 1969), these birds are known to respond to underwater vocalisations of predators (Frost et al. 1975) and, as such cannot be disregarded in marine acoustic studies.

Maps of penguin colonies

Figures 13-18 show the distribution of Emperor, Adélie, Chinstrap, Gentoo, Macaroni and Rockhopper Penguin colonies around the Antarctic continent, the Antarctic Peninsula, the South Shetland Islands, the South Orkney Islands, but excluding the South Sandwich Islands, South Georgia, the Falkland Islands and South American breeding localities. The species' breeding populations south of 60°S have been mapped; their breeding localities north of 60°S have not. Full details of breeding populations are presented in Woehler (1993) and Woehler and Croxall (1997).

A 300nm buffer has been drawn around each colony to indicate the estimated maximal foraging range of breeding penguins from each colony. It should be noted that this 300nm buffer is a conservative estimate – there are insufficient data on foraging ranges based on satellite tracking studies to describe accurately the at-sea ranges of breeding individuals of the species reported here. Further, their non-breeding ranges at sea are largely unknown and will extend substantially further north than the 300nm buzzer zone mapped.

There is one map of the entire Antarctic continent (Fig. 13), then a series of four overlapping maps to provide detailed regional information. An approximate indication of the size of the breeding population at each colony is provided by the size of the symbols. The maps are supplemented by a tabulation of breeding population data extracted from Woehler (1993) and Woehler and Croxall (1997). It is clear that virtually the entire Antarctic continental margin is within foraging range of penguins. However, the maps do serve to indicate which areas have the likely highest density of birds. For example, the number and size of colonies in the northern Antarctic Peninsula or western Ross Sea make it more likely that penguins will be encountered in those regions than in the Bellinghausen Sea.

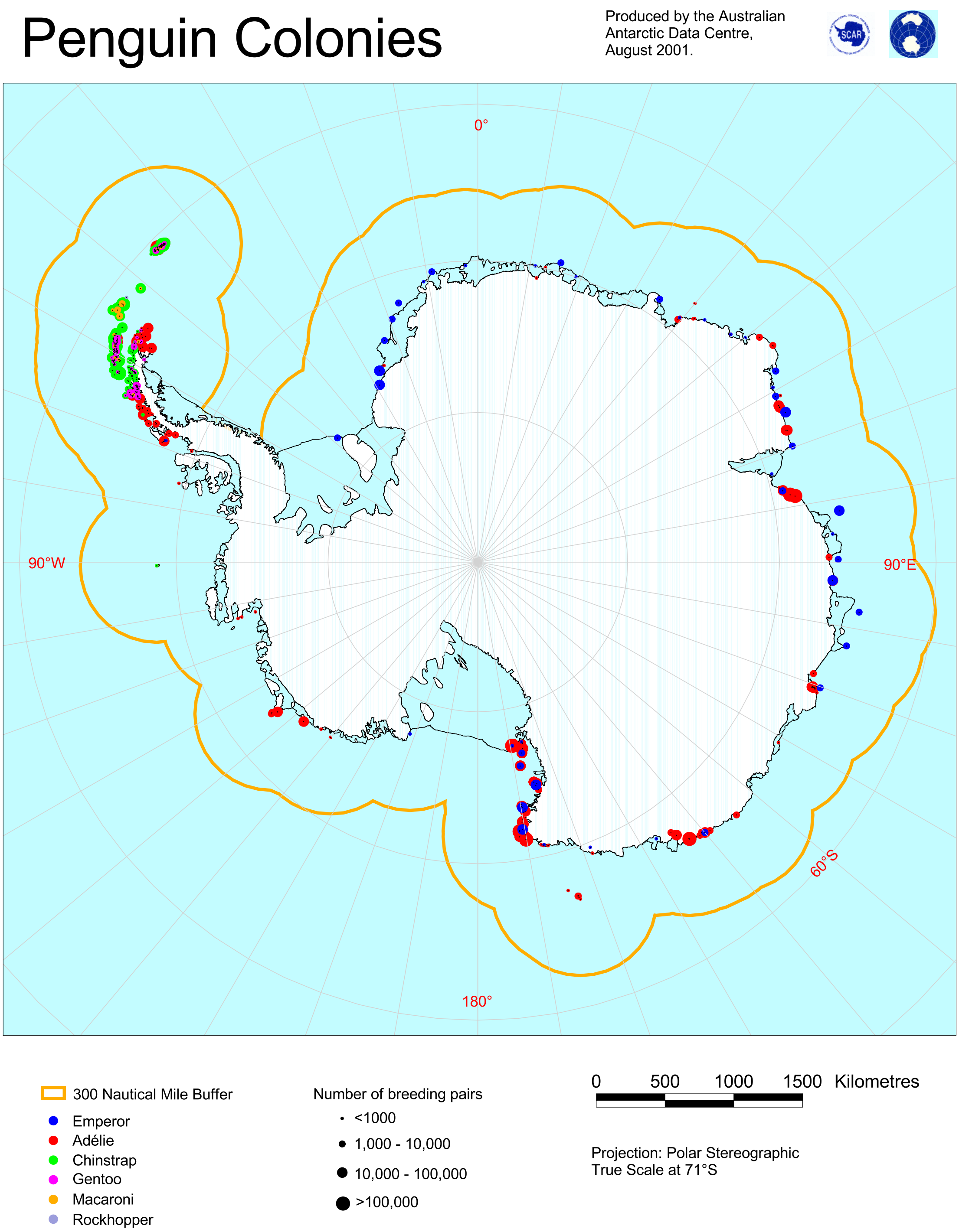

Figure 13. Distribution and size of penguin colonies around Antarctica.

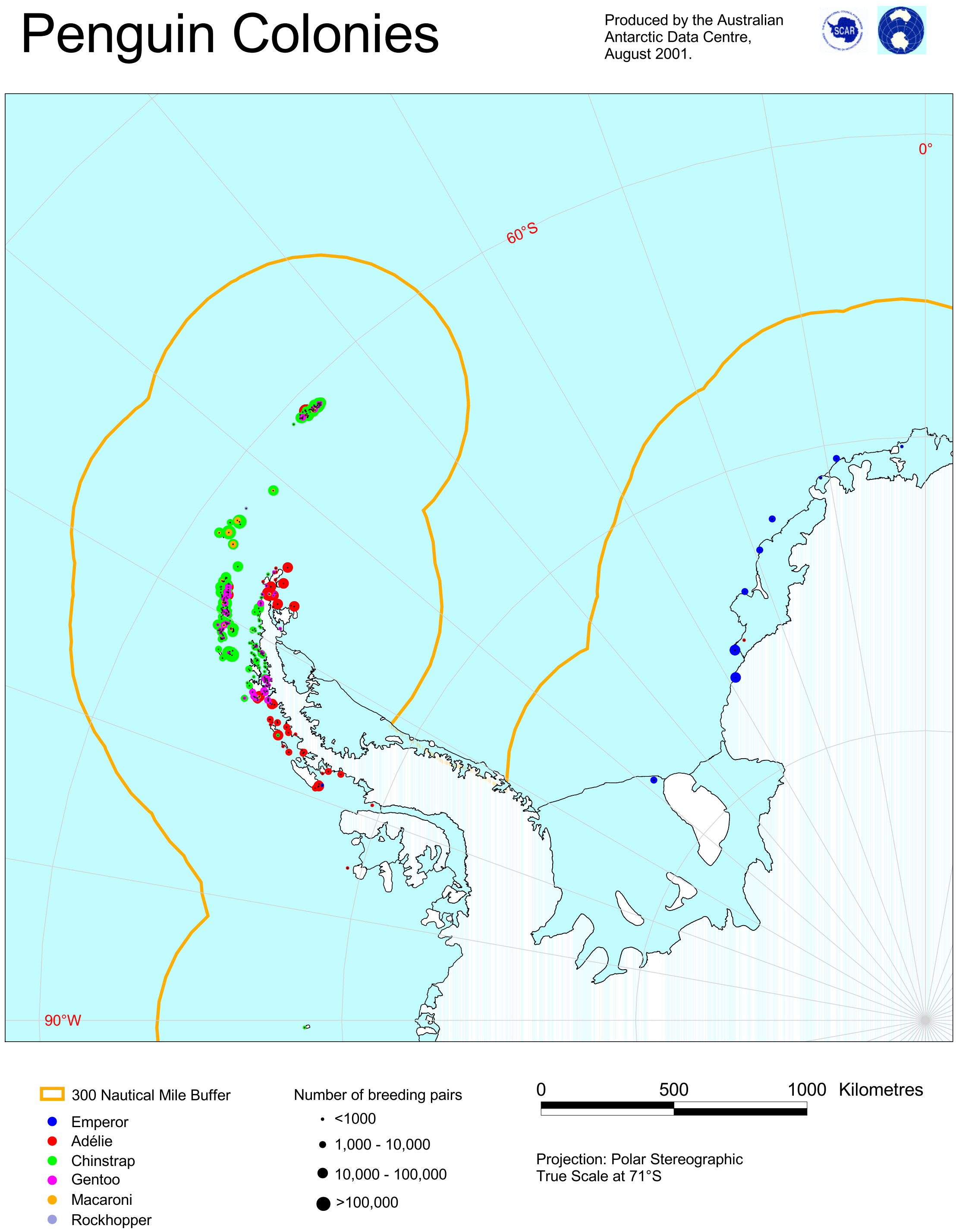

Figure 14. Distribution of penguin colonies, Bellinghausen Sea, Antarctic Peninsula and the Weddell Sea. 300 nautical mile foraging range shown.

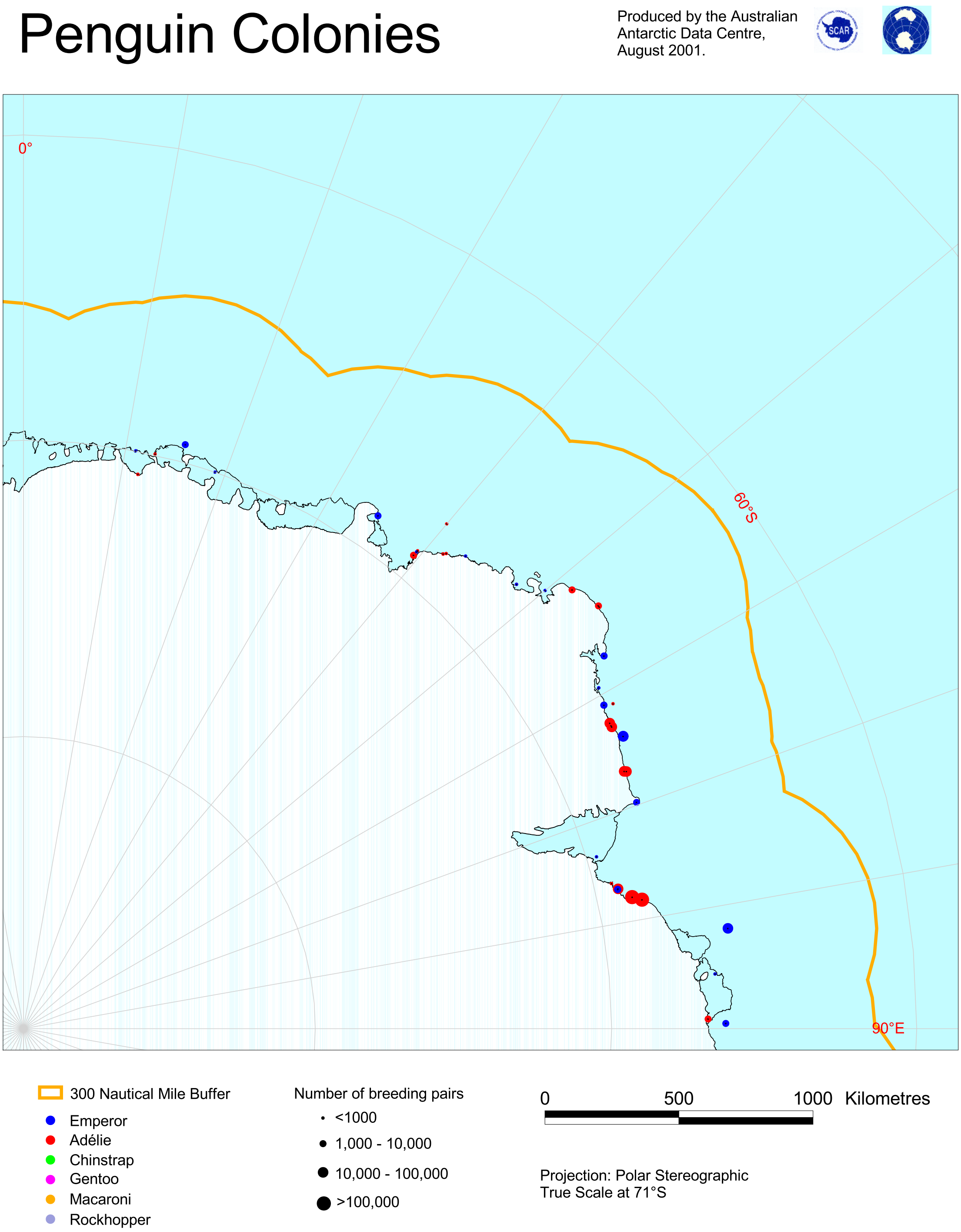

Figure 15. Distribution of penguin colonies, Longitude 000° to 090°E. 300 nautical mile foraging range shown.

Penguin Colonies

Produced by the Australian Antarctic Data Centre, August 2001.

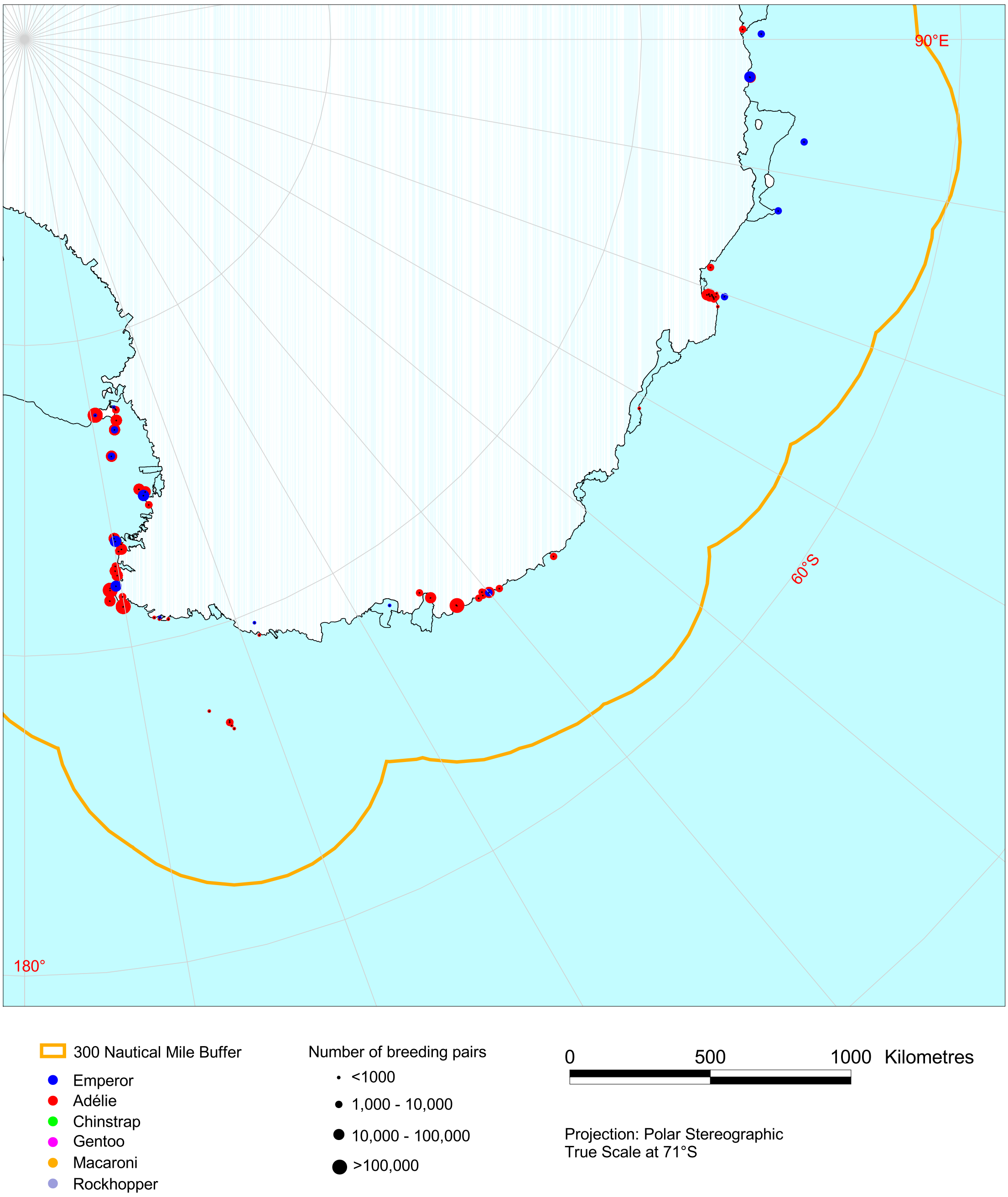

Figure 16. Distribution of penguin colonies, Longitude 090° to 180°E. (Shackleton Ice Shelf to western Ross Sea). 300 nautical mile foraging range shown.

Penguin Colonies

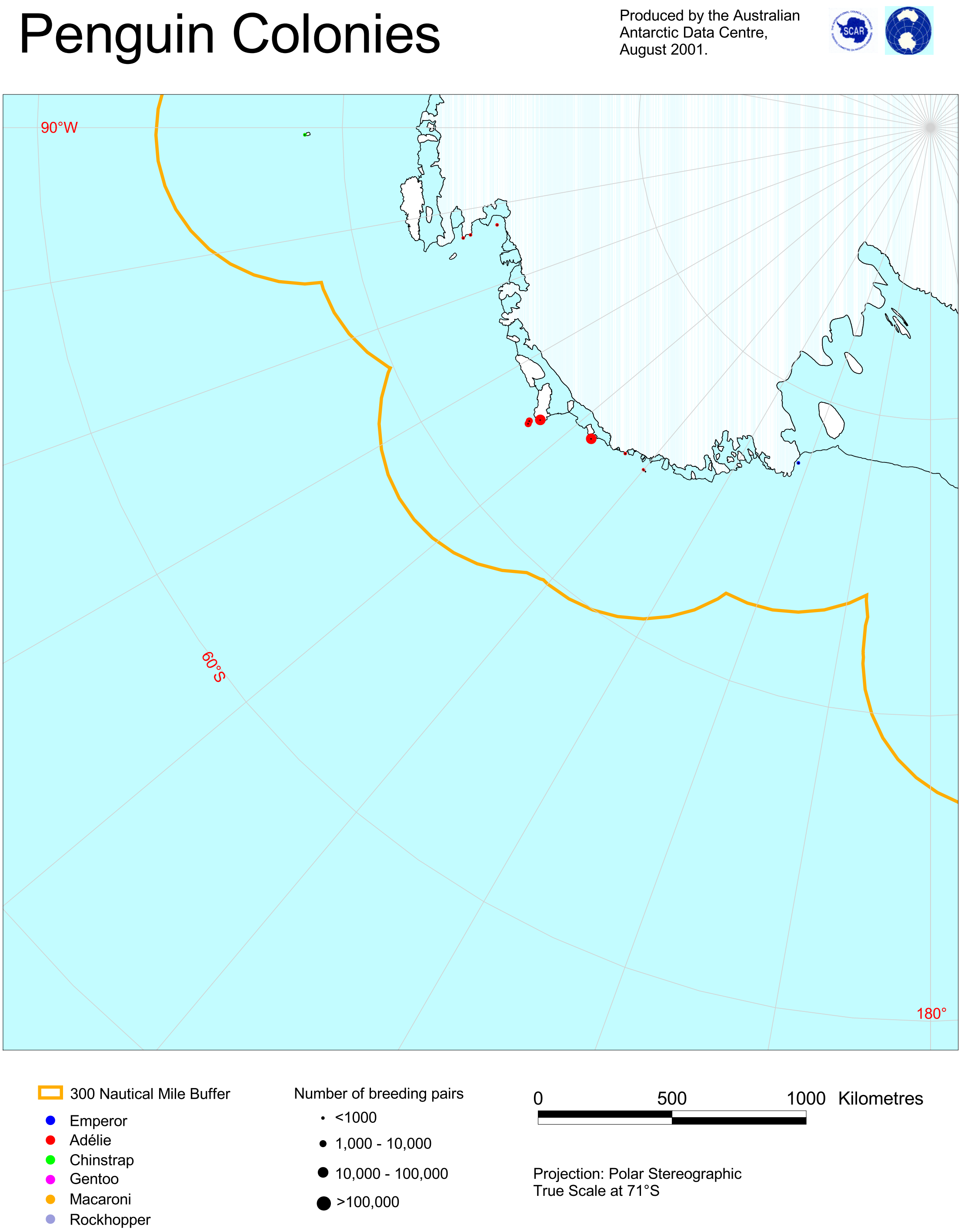

Figure 17. Distribution of penguin colonies, Longitude 180° to 090°W. Ross Sea to Amundsen Sea. 300 nautical mile foraging range shown.

Breeding timetables

Approximate arrival and departure times for breeding penguins at their colonies. These dates are generalisations only – for most species there are latitudinal gradients, with breeding birds generally arriving later at colonies further south than at more northerly colonies, and departing earlier at southerly colonies than at northerly colonies. Also, environmental conditions can introduce substantial inter-seasonal variability.

Table 7. Breeding timetables for Antarctic penguins.

Species	Arrival at colony	Departure from colony
Emperor Penguin	March	December
Adélie Penguin	October	March
Chinstrap Penguin	October	April
Gentoo Penguin	August	May
Macaroni Penguin	October	March
Rockhopper Penguin	August	March

Non-breeding penguins are not constrained to remain in proximity to colonies, and generally could be expected to be more widely distributed at sea. All penguins, breeding and non-breeding, are required to moult annually; this typically occurs at the end of the breeding season and may not occur at colonies.

Risk assessment

Overall, it would seem that although penguins are not as liable to be impacted by marine acoustic surveys disturbance as much as cetaceans, these birds do use acoustics underwater and as such may disturbed by such surveys. There is a clear need for further research in this area but, for the present, penguins be ranked on a susceptibility scale comparable to humans.

SEALS

Seals are a conspicuous part of the Antarctic and Sub-Antarctic environments. Seven species inhabit the Antarctic and Sub-Antarctic. Many aspects of their biology are fairly well established however there are still much to be learned about their foraging, migration and other aspects of their behaviour. The reaction of Antarctic seals to underwater anthropogenic noise is still to receive much attention anywhere in the world.

In considering the risk posed to seals by acoustic technology, their distribution and sensitive periods in their breeding cycle should be considered. We regard the pupping season as a critical period because displacement of females may interfere with mother-pup bonding. Other critical periods in the year are harder to identify. Anthropogenic sound could interfere with foraging by mothers with pups and affect the quantity and quality of milk available to and the survival of the pups. Similarly interference with feeding during the post-pupping and implantation period could cause decreased survival and productivity of adults. Another period may be the period when weaners leave breeding beaches and first go foraging.

Distribution

Weddell seal, *Leptonychotes weddellii*
Circumpolar in fast ice around the coast of Antarctica, ranging as far south as the bay of Whales and the Filchner Ice Shelf at 78^{O}S; a disjunct resident population at South Georgia.

Leopard seal, *Hydrurga leptonyx*
Pack-ice zone around the Southern Ocean, south to the shores of Antarctica including the Ross and Filchner ice shelves at 78^{O}S; year round populations at Palmer Peninsula, South Shetland Islands, South Orkney Islands, South Sandwich Islands, South Georgia, Bouvetoy, Heard Island and Macquarie Island.

Crabeater seal, *Lobodon carcinophaga*
Circumpolar throughout the pack-ice zone of the Southern Ocean, south to the shores of Antarctica, including the Ross and Filchner ice shelves at 78^{O}S.

Ross seal, *Ommataphoca rossii*
Circumpolar in pack-ice zone of the Antarctic Ocean, south to Ross and Filchner ice shelves at 78^{O}S during the austral spring and summer while breeding and moulting. Moving north to the open water north of the pack ice in the austral autumn and winter.

Southern elephant seal, *Mirounga leonina*
Circumpolar in Southern Hemisphere, mainly in the sub-ataractic zone. Rookeries and hauling grounds mostly on oceanic islands in three sectors of the Southern Ocean: South Atlantic sector, Indian Ocean sector and western South Pacific sector. In South Atlantic sector there are or were rookeries on Peninsula Valdez in Argentina, the Falkland Islands, South Georgia, the South Sandwich Islands, the South Orkney Islands, the South Shetland Islands, Tristan da Cunha, Gough Island and Bouvetoy, Peterson Island on the coast of Antarctica. In the Indian Ocean sector, rookeries are located on Prince Edward Island, Marion Island, Iles Crozet, Iles Kerguelen, Heard

Island and McDonald Island. In the western South Pacific sector rookery sites are on Macquarie Island, Campbell island and Antipodes Island.

Antarctic fur seal, *Arctocephalus gazella*
Primarily Antarctic Zone of South Atlantic, Indian, and western South Pacific sectors of Southern Ocean. Rookeries, historical or present, on islands mainly south of the Antarctic Convergence: South Georgia, South Sandwich islands, South Orkney Islands, South Shetland Islands, Bouvetoy, Marion Island, Iles Crozet, Iles Kerguelen, Heard Island, McDonald Island, and Macquarie Island.

Subantarctic fur seal, *Arctocephalus tropicalis*
Primarily Subantarctic Zone of South Atlantic, Indian and western South Pacific sectors of Southern Ocean. Rookeries, historical or present on islands mainly north of the Antarctic Convergence: Tristan da Cunha, Gough Island, Prince Edward Island, Marion Island, Iles Crozet, Heard Island, Ile Amsterdam, Ile St. Paul and Macquarie Island.

Breeding timetables

Weddell seal, *Leptonychotes weddellii*
Pupping is from September to early November with later dates at more southerly locations.

Leopard seal, *Hydrurga leptonyx*
Pupping is from late October to mid November (Laws 1984; Siniff and Stone 1985).

Crabeater seal, *Lobodon carcinophaga*
Pupping is from October and early November (Laws 1979b; Bengtson and Siniff 1981)

Ross seal, *Ommataphoca rossii*
Pupping is from November based on few observations mostly in the South Pacific Ocean (Tikhomirov 1975).

Southern elephant seal, *Mirounga leonina*
Pupping is from September to October (Laws 1979a; Carrick et al. 1962)

Antarctic fur seal, *Arctocephalus gazella*
Pupping is from November-December. At Heard Island 90% of pups born over a 26 day period with 11 December the median date of birth (Shaughnessy and Goldsworthy 1990). At Macquarie Island the median date of birth of a mixed colony of A. gazella and A. tropicalis was 10 December (Shaughnessy et al. 1988)

Subantarctic fur seal, *Arctocephalus tropicalis*
Pupping is from November to January. At Macquarie Island the median date of birth of a mixed colony of A. gazella and A. tropicalis was 10 December (Shaughnessy et al. 1988)

Seals and Sound

There has been no measurement of the hearing of Antarctic seals and a small amount on captive seals from the northern hemisphere (Richardson et al., 1995, Thompson et al., 1998).

The phocid or true seals are divided into two subfamilies, the phocinae (the northern phocids) and the monachinae (the monk, elephant and Antarctic phocids). The phocinae phocid seals tested (harbour, ringed, harp and gray seals) had consistent frequency response between 1 kHz and 40-50 kHz with sensitivity dropping rapidly above 50 kHz.

From the subfamily monachinae which includes all the Subantarctic and Antarctic phocids (the Weddell, crabeater, Ross, leopard and Southern elephant seal) there have been two species studied, the Hawaiian monk and Northern elephant seal. The Hawaiian monk seal study (Thomas et al. 1990) involved only one study of a single individual. It found that the monk seal tested had narrower best frequency range than the phocinids tested and a high frequency cut off of about 30 kHz. The studies with the Northern elephant seal have also involved only the one individual. Their sensitivity is best between 3.2 and 45 kHz, with greatest sensitivity at 6.4 KHz (58 dB re 1 uPa) but that they are more sensitive to low frequencies (below 1 kHz) than any other pinniped tested (Kastack and Schusterman 1998, 1999; Southall et al. 2000).

Otariid seals (fur seals and sea lions) seem to have worse hearing than phocids below 1 kHz, similar to slightly worse hearing between 1 kHz and their high frequency cut offs at 36-40 kHz. (Richardson et al., 1995, Thompson et al., 1998). Their high frequency cut off is 10-15 kHz below that of phocids.

Antarctic seals are quite vocal underwater (Table 7). Weddell seals produce a variety of calls from 0.1-12.8 kHz with source levels of 153-193 dB re 1µPa. The calls are quite directional (Richardson et al., 1995). Calling rate is lowest in winter, rising to a peak in spring. Leopard seals produce a variety of calls with frequency range from 0.1 to 5.9 kHz (Richardson et al., 1995) and there has been some detection of ultrasound produced by leopard seals up to 163 kHz with peak energy at 50-60 kHz. Leopard seals use low frequency sound for socialising over ranges up to 20 km. Crabeater seals produce low frequency groans with harmonics to > 8 kHz.. Ross seals make a sound that sweeps between 0.1 and 4 kHz. Fur seals and sea lions are known to bark underwater and make clicks with most energy below 4 kHz. (Richardson et al., 1995).

Response to tranducers
There is very little published information on the response of seals to transducer-generated sound. Richardson et al. (1995) report 3 studies. One found that harp seals altered swimming patterns when they encountered a 200 kHz echo sounder. However, they comment that the transducer probably produced lower frequency sound as well, that would be audible to the seal. The other studies note that ringed and Weddell seals were apparently unaffected by 60-69 kHz acoustic tags fixed to them. Unpublished observations of 20 instrumented Weddell seals in Drescher inlet, a 1-2 km wide, 25 km long re-entrant in the Riiser-Larsen Ice Shelf, found no difference in diving behaviour between days when a vessel was operating in the inlet and those when it was not (J. Ploetz, unpublished). The vessel operated bathymetric and fisheries echo sounders (12-150 kHz).

Response to seismic
Again there is little published information on the response of seals to airguns. Thompson et al. (1998) refer to one published paper and unpublished data in which harbour and grey seals showed avoidance reaction to small airguns at ranges of around 2 km. These seals returned to the area from which they had been displaced quite

quickly after shooting ended. In contrast, Richardson et al. (1995) report a paper which observed no reaction by grey seals to seismic surveys and another report that found that air guns were ineffective in scaring South African fur seals away from fishing gear. This accords with geophysical industry experience that South African and Australian fur seals swim near operating seismic equipment and consistently damage it by biting. This may be related to their relative insensitivity to sound below 1 kHz and their tendency to swim at or near the surface, exposing them to reduced sound levels.

Other sources

Other studies of seals and loud noises involve attempts to frighten them away from fishing activities (Richardson et al., 1995). Most cited examples found rapid habituation to the sounds, possibly because the animals rapidly associate the noise with food. Australian fur seals have colonised oil production facilities in Bass Strait suggesting they habituate to a certain amount of noise. Recording of leopard seal calls in Prydz Bay in 1998 illustrate the difficulty of interpreting calling behaviour in terms of disturbance (T. Rogers, unpublished data). Leopard seals ceased to call when mechanical breakdown suddenly ended mechanical and icebreaking noise from a vessel, suggesting animals react to change rather than noise as such.

Risk assessment

Injury to seals other than hearing damage is only likely close to powerful sources (Table 8). Sound levels at which seal hearing may be damaged are not known. From what is known about their hearing, they are most at risk from transducers with outputs below 50 kHz. At high frequencies, absorption is important and most scientific equipment tends to have narrow beam widths so regions of potential hearing damage will be relatively small. Therefore the equipment with most potential risk would be lower frequency echo sounder used for sub-bottom profiling. Seismic sources also have potential risk because of the very high source levels.

Any risk to pack ice seals from seismic surveys is likely to be reduced because seismic surveys trail equipment behind the vessel and so cannot operate easily in ice. This also means that most Antarctic marine seismic surveys take place from late December to March and so avoid the breeding seasons of pack ice seals. High risk areas would be near Subantarctic breeding colonies during the spring and the times when weaners leave the beach. Possible displacement effects require study. The small amount of available information on short term displacement suggests that some species are more likely to be displaced than others.

Table 8. Sounds used by seals found in the Southern Ocean.

	Signal type	Frequency range kHz	Dominant frequency kHz	Estimated Source Level DB re 1 upa.m	Occurrence	Seasonal Occurrence	Behavioural context	Reference
Weddell seal	34 + call types	0.1 - 12.8		153 - 193	Frequent	Nov - Jan	Territorial maintenance/sexual advertisement/ agonstic behaviour	Thomas & Kuechle 1982: Thomas et al. 1983; Thomas & Stirling 1983
Leopard seal	Trills	0.1 - 5.9		140 - 165	Frequent	Nov - Jan	Territorial maintenance & sexual advertisement	Stirling & Siniff 1979; Rogers et al. 1995; Rogers unpublished data
	Broad-band	0.04 - 8.0		120 - 140	Rare events	Year round	Agonistic behaviour	Rogers et al. 1995, 1996, Rogers unpublished data
	Ultrasonic	up to 164			Rare events	Unknown	Chasing fish in dark	Thomas et al. 1983, Rogers unpublished data
Crabeater seal	Groan	0.1 - 8.0	0.1 - 1.5		Rare events	Unknown	Unknown	Stirling & Siniff 1979
Ross seal	Trills Siren	0.25 - 1.0			Common	December	Unknown	Watkins & Ray 1985, Rogers unpublished data
Southern	Unknown							

elephant seal								
Antarctic fur seal	Unknown							
Sub-antarctic fur seal	Unknown							

Table 9. Risk assessment for Antarctic and Subantarctic seals and seismic surveying

Event	Leopard seals	Weddell seals	Ross seals	Southern elephant seals	crabeater seals	fur seals
Behavioural effects direct	Subtle changes, likely avoidance.	Subtle changes, likely avoidance.	Subtle changes, likely avoidance.	Subtle changes, likely avoidance.	Subtle changes, likely avoidance.	Subtle changes, likely avoidance.
Pathological effects	Possible but unlikely, very low risk as animals likely to move away and animals need to be at less than 1 km to be at any risk	Possible but unlikely, very low risk as animals likely to move away and animals need to be at less than 1 km to be at any risk	Possible but unlikely, very low risk as animals likely to move away and animals need to be at less than 1 km to be at any risk	Possible but unlikely, very low risk as animals likely to move away and animals need to be at less than 1 km to be at any risk	Possible but unlikely, very low risk as animals likely to move away and animals need to be at less than 1 km to be at any risk	Possible but unlikely, very low risk as animals likely to move away and animals need to be at less than 1 km to be at any risk
Geographical Scale	Relatively small at scale of individual signal but larger when considered through time depend on activity	Relatively small at scale of individual signal but larger when considered through time depend on activity	Relatively small at scale of individual signal but larger when considered through time depend on activity	Relatively small at scale of individual signal but larger when considered through time depend on activity	Relatively small at scale of individual signal but larger when considered through time depend on activity	Relatively small at scale of individual signal but larger when considered through time depend on activity
Timing/duration of action	Depend on the activity	Depend on the activity	Depend on the activity	Depend on the activity	Depend on the activity	Depend on the activity
Cumulative effect of action	unknown	unknown	unknown	unknown	unknown	unknown

PREY SPECIES

Introduction

A significant number of studies have addressed the effects of seismic surveys on fish. These studies have looked at either injuries to caged fish (McCauley et al., 2000) or the effects on fishing success (e.g. Engås et al. 1993). There are few studies on crustacean, benthic molluscs and cephalopods (Hirst and Rodhouse, 2000) and there has been no study of the effects on krill. There has been a little research work on fish eggs and juveniles which could provide an indication of effects on other zooplankton.

Fish and sound

Some fish species make use of sound for communication. The review by Myrberg (1981) found 35 families of marine and freshwater fish that were known to produce noise. Of these the best known are the Croakers, members of the Scianidae, are the most vocal and widespread (Harris et al., 1991). These fish make noise by rapidly contracting muscles attached to their swim bladders and have been recorded making sounds in the range of 350 Hz to 1.5 kHz with levels of 140 dB re 1 µPa (0-p?, Harris et al., 1991). Their sound production varies during the day with feeding behaviour, with peak sound production in the evening. Many other noises have been recorded in the ocean that may be attributable to fish and identification and study of the sources of these sounds is ongoing.

Effects of transducer based equipment

Nothing has been published on effects of transducers on fish, plankton or cephalopods. Given that echo sounders with frequencies > 12 kHz are used to locate fish and plankton, for fishing and research, it seems unlikely that any displacement or measurable response would have gone unnoticed.

Effects of airguns

Injury

Hirst and Rodhouse (2000) state that studies of caged fish indicate that received sound pressure levels > 180 dB re 1 µPa. from air guns and explosives produce significant physiological damage to fish, ranging from ear and eye damage to swim bladder rupture and death although studies found variation in the level at which injury is severe. Some studies that found minimal damage up to levels as high as 231 dB re 1 µPa (Weinhold and Weaver, 1973, Dalen and Knutsen, 1987). Gausland (1993) claims that damage is confined to a radius of 2-3 m around an airgun but does not provide source levels. Both Gausland (1993) and Hirst and Rodhouse (2000) observe that fish with swim bladders are more likely to be killed at greater distances than those without because the rarefaction part of the wave following the initial pulse can rupture the bladder. McCauley et al., (2000a,b) report modelling studies of fish otoliths and examined otoliths of fish that had been exposed to a single airgun and concluded that extreme movement of the otoliths would take place a received sound pressure levels >171 dB re 1 µPa. rms. Hirst and Rodhouse (2000) question whether longer term increases in mortality rates have been missed by short term studies of caged fish. However, Gausland (1993) quotes a study of the effects of explosives on cod that found that no deaths in addition to those caused by the initial explosion occurred in the sample population over a 6 month period after exposure. These studies suggest that injury to fish will be limited to the immediate region around a powerful source.

Behavioral effects

Studies of caged fish have found that startle responses in the form of C-turns and diving to the bottom take place at received sound levels >156-161 dB re 1 μPa. rms (McCauley et al., 2000a, Gausland, 1993). Behaviour changes seem to produce the observed declines in fishing success in areas that have experienced an industry seismic survey. Hirst and Rodhouse (2000) quote 8 studies that found catch reductions of between 17% and 83% for trawl and longline vessels in surveyed areas. They also quote one study that found a major increase in catch associated with a seismic survey suggesting that the fishing method is important and therefore the effect is caused by displacement and possible changes in feeding behaviour. Engås et al., (1993) concluded that a the differences observed between longline catches and trawling resulted from the fact that longlines can only measure the number of fish up to the number of hooks deployed. They concluded that a seismic array produced a "ploughing" effect whereby fish were displaced laterally and downward from the ship's track. This concentration of fish fleeing the affected area may account for the occasional increased catches observed. The durations of the observed catch reductions are in excess of 5 days in some studies reported in (Hirst and Rodhouse, 2000), however Engås et al., (1993) concluded that fish were returning to the survey area within one day of the end of shooting.

Although these effects clearly cause problems for fishing activities, McCauley et al., (2000b) point out that they may not necessarily cause problems for viability of the fish populations. Avoidance responses would tend to reduce the risk of injury. Even though diving to the bottom may increase the sound exposure in areas of shallow water where significant energy is transmitted through the bed, such behaviour would remove the fish from close proximity to the guns and the zone of possible injury.

Many studies have pointed out the long term effects of displacement by seismic surveys is unknown. Observations of slow return on the scale of days to surveyed areas are not surprising because there is probably no external stimulus to cause a rapid return once fish have moved. This effect will probably vary depending on food availability and whether the fish are migrating (Engås et al., 1993). The longer term effects are difficult to address because many of the areas of intense seismic surveying are also area of active fishing so distinguishing between the effects of seismic surveying and fishing practices is very difficult. Given that this debate is still taking place over areas such as the Norwegian continental shelf which has seen more than 100,000 line kilometers of industry seismic shot per year for several decades suggest that any effect must be small (Gausland, 1993).

Squid

Little is known about the hearing ability of cephalopods. The few papers on cephalopod hearing suggest that their hearing is less sensitive than most fish and that the most sensitive frequencies are between 10 and 200 Hz. (Packard et al., 1990) however, Japanese squid boats use a sound at 600 Hz to attract some squid (Hanlon and Budelmann, 1987).

Squid are important prey species for toothed whales and seals. Most is known about squid in the Subantarctic because of the fishery in the area (Rodhouse et al., 1990, 1994, 1995). In this region, squid spawn and hatch in the period April-early November and so those important parts of their life cycle are outside the optimum weather/ice window for seismic surveys.

Injury

Only one paper on the lethal effects of seismic shots on squid was found (Norris and Møhl, 1983). They report short term tolerance of sound levels to 260 dB re 1 μPa by one species but lethal effects at levels of 246-252 dB re 1 μPa for another. If confirmed by further work, these levels would suggest that squid would only be killed within a few meters of individual, large airguns. This would still apply for arrays because sound levels within arrays are at maxima around the individual guns or at particular places between guns depending on array design (see above).

Behaviour

We have only two studies of squid reaction to airgun noise. McCauley et al., (2000a) report the reactions of caged squid to an airgun. They found alarm responses at 156-161 dB re 1 μPa. rms. and strong startle response at 174 dB re 1 μPa. rms involving ink ejection and rapid swimming. The caged squid also moved to use the sound shadow near the surface to reduce the sound pressure levels. Hirst and Rodhouse (2000) quote a study that found no change in squid catch for trawling in an area exposed to < 149 dB re 1 μPa. The observed alarm response suggest that squid would likely move outside the lethal range of a sound source. Any possible effects on squid mortality produced by extra swimming caused by the alarm response are unknown.

Eggs and larvae

Dalen and Knutsen, (1987), Kostyuchenkov (1973) and Kosheleva (1992) described studies of the effects of airgun shots on fish eggs and juveniles. The lowest sound pressure level for which lethal effects can be demonstrated is 220 dB re 1 μPa. No lethal effects were observed at 214 dB re 1 μPa. If this is a reasonable indication of the situation, the injury radius for eggs and juveniles will be a few meters around large airguns. This will also apply in an array, where the total source level is a far field sum of the total number of guns. Such a radius would be comparable to that of a ship's propeller. The volume of water affected by an airgun array and hence the number of eggs and juveniles would be similar to a ship's propeller because the propeller runs continuously whereas the array fires at intervals of up to 20 seconds (Gausland, 1993). Gaulsand (1993) estimated the effect on plankton of the guns on the 100,000 line kilometers of industry seismic shot per year in Norwegian waters as equivalent to the feeding of 30 whales. In the case of large, ship-mounted transducers with outputs in excess of 220 dB re 1 μPa, lethal effects would be confined to a similar range as the turbulence around the ship's hull. Thus, the magnitude of effects would be determined by the miles of trackline in areas where eggs and larve are present.

Krill

Distribution

Krill are the most important prey species in Antarctic waters. Their distribution and abundance is fundamental to many other animals therefore their areas of highest concentration will also be areas of high concentrations of other animals (Ichii, 1990) As a broad approximation, krill concentrate along the retreating ice edge in spring and early summer and in a zone 60 nautical miles seaward of the shelf break for large parts of the Antarctic margin (Fig. 18, Ichii, 1990, , Nicol, et al., 2000). More detailed descriptions of krill density and swarming patterns are evolving with further study.

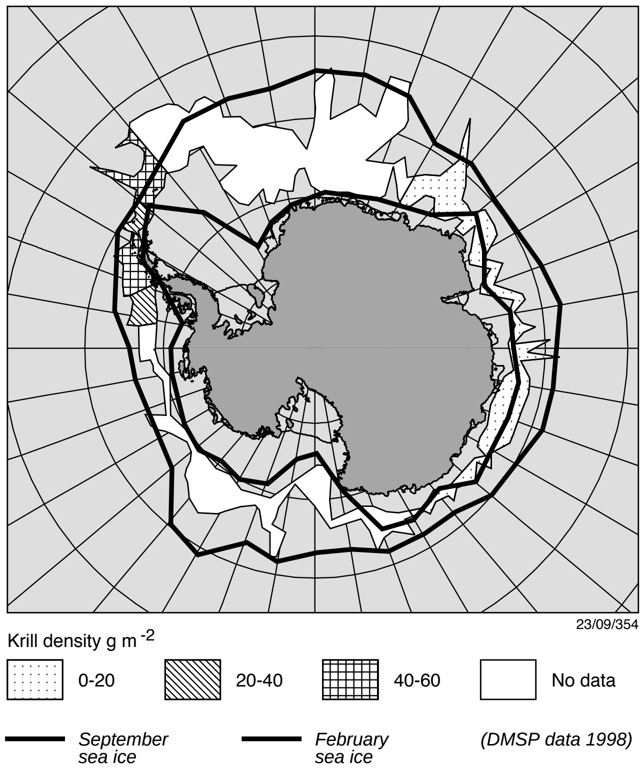

Figure 18. Distribution and density esitmates of krill (Euphasia superba) from Nicol et al. (2000).

Effects of sound

There have been no studies specifically on the effects of noise on krill. Crustaceans are thought to be insensitive to sound which they detect through mecahnoreceptors. Hirst and Rodhouse (2000) suggest that most invertebrates would only detect seismic shots within about 20 meters. Likewise, transducers are unlikely to be detectable over large distances by crustaceans. Snapping shrimps must be able to withstand there own sound production that reaches sound pressure levels of 200 dB re 1 μPa (0-p?) (Harris et al., 1991). Hirst and Rodhouse (2000) found only two studies that observed catch levels of shrimp and lobster in areas surveyed with airguns. Both studies reported no change during surveys.

Assuming that krill will be affected in a similar way to fish eggs and juveniles (see below), there will be increased mortality in an area a few meters in radius around an operating low frequency, high energy source. An argument similar to that of Gausland (1993) can be made that the effect of acoustic surveys on krill in Antarctic waters will be very small compared to predation and fishing, especially with the low level of activity in the Antarctic. The importance of krill is that they attract predators which are more likely to be adversely affected by acoustic equipment. Also, track lines through or near krill swarms may cause the swarms to separate or disperse or to coalesce, making the krill more or less vulnerable and available to predators

Risk assessment

Pathological effects are probably confined to close proximity to airguns or the largest, low frequency transducers. The effect on the total populations of prey species is probably small given the low level of activity in Antarctic waters. There seems to be clear evidence of displacement of fish by large airgun arrays. There is insufficient evidence to say if this is also the case for squid. The effects of fish displacement on higher predators is not known.

ISSUES IN EVALUATING SURVEY IMPACTS

The variety of issues and uncertainties involved in assessing the impact of acoustic technology on the Antarctic environment make it impossible to make hard and fast guidelines as to the impact of any survey without considering the individual characteristics. Therefore, the workshop decided that the best approach was to highlight factors that should be considered in evaluating any survey. The following issues should be taken into account

Equipment characteristics

Source level
The output of the equipment in terms of maximum sound pressure is a key consideration. Although it is not clear from this review what constitutes "safe" levels for different animals, equipment with an output of < 190 dB re 1 μPa (0-p) produce sound levels similar to natural source. Outputs of 190-210 dB re 1 μPa (0-p) will produce levels above most natural sources in a small area (1-10s of meters radius). Above 210 dB re 1 μPa (0-p), sound levels could be above natural levels over large areas. The area affected by a survey will vary with source level and sound propagation characteristics.

We suggest that for powerful sources, mitigation strategies in use elsewhere in the world should be adopted. Such as:
1. Surveys should be planned to use the minimum source level necessary to achieve the required result.
2. Powerful sources should have there output increased slowly at the start of a line. Theoretically, such "ramped" or "soft" starts should allow animals time to avoid the equipment. Further research is needed to see if such measures really work.
3. Shut down zones around the source should be considered to minimise the exposure of animals that do not avoid the source.

Frequency
The dominant frequency and the band width of the equipment determine the sensitivity to animal hearing and the degree of propagation of sound. Sound sources such as airguns produce more noise in the hearing range of baleen whales than low frequency echo sounders which produce more noise in the ranges used by seals and toothed whales. Sounds above 50 kHz are inaudible to most animals or have very high absorption levels making them a very low risk to animals.

Pulse shape and length
The energy of the pulse is a time integral over the pulse duration so longer pulses impart higher energy than shorter signals of the same peak source level. Pulse rise and fall times are also important. Chemical explosives are much more dangerous than airguns because of their very short rise and fall times.

Directionality
Omni-directional or wide beam sources will affect a much larger area than focussed beam equipment with the same source level. Most scientific transducers are focussed. Exceptions are acoustic beacons and fish-finding sonars which tend to be relatively

low power and high frequency. Ocean depth, multibeam echo sounders sweep a swath up to 7 times water depth and so affect a wide area, although the beams are narrow fore and aft. Airguns arrays are the least-focussed apparatus used in Antarctic waters.

Duty Cycle
The proportion of time that the source is actually emitting acoustic energy. Continuous sound has more potential to disrupt animal communications than pulsed or intermittent signals. Continuous noise is more damaging to human hearing than pulsed sounds so a similar effect is possible in animals (Richardson et al., 1995).

Survey Region

Survey area geography
The area affected The morphology of the sea floor and any adjacent coast might restrict the ability of animals to avoid high source levels. It may define a choke point in animal migration paths so that high numbers of animals or a significant proportion of a population are present. Close proximity to a breeding colony during the breeding season is likely to expose more animals to a sound source than a survey removed from the area. Sensitive areas such as regions known for prey aggregations should be considered.

Sound propagation model
Sound propagation models vary with oceanography, sea floor morphology and characteristics and sea ice coverage. This is particularly important in defining the area over which sound levels will exceed a defined level. For the area close to the source, this is not as important with errors in the order of 100s of meters but for more distant levels, errors can be substantial (see above).

Survey Design

Ship speed
The speed at which the ship moves plus duty cycle and beam shape of the equipment governs the number of pulses of a given intensity a point in the survey area will receive. Likewise it governs the ability of animals to avoid the noise.

Line spacing
The line spacing will determine the temporal dose level in the survey area and the size of the survey area.

Survey duration
The length of time a particular area is surveyed influences the degree of impact.

Exposure levels
The combination of survey layout, source characteristics and survey area can be used to determine an exposure level. This could be expressed as the number of shots per unit area distributed over a survey area. Survey planning involving large sources should consider whether there will be other vessels using similar sources in the region. Several ships producing high sound levels in a region would make it harder for animals to avoid exposure.

Survey direction
The direction in which a ship progresses during a survey may determine if it herds animals into a bathymetric restriction or an embayment in fast ice. Care should be taken to provide an "escape route" to allow avoidance. This particularly applies to cetaceans that cannot haul out to avoid sounds.

Biological Issues

Sensitive times
The timing of surveys relative to important stages in the annual cycles of animals should be considered. For examples, seal mating, pupping and the time of bonding between mothers and pups are times when animals should not be disturbed. There are also times when feeding is important in ensuring survival of cohorts of young seals or penguins.

Proportion of population effected
Consideration should be give as to the proportion of the total or a local population of animals that will be affected. A survey close to an occupied breeding colony will affect a higher proportion of a population than one in the open ocean. Likewise a survey in a migration path during migration will affect a higher proportion of animals. At present, the distribution of animals at any time of year is poorly known. As knowledge improves more sensitive areas will be identified as will areas of low animal density.

Proportion of the available habitat affected
A survey that occupies most of a foraging area that is important to a colony could have significant impact. At the same time, a focused beam instrument may affect only a very small part of the foraging area.

Proportion of the season affected
The amount of a particular part of a season should be considered. A survey that disturbs animals for a large part of a season could potentially have more effect than a brief disturbance. Surveying a sensitive area may have a small impact if the visit is brief.

Re-surveying interval
The number of times an area has been exposed to high sound levels at the same time of year should be considered. The risk of long term, cumulative effects of disrupting a key time of year could be minimised if surveys do not return to an area in consecutive years. International coordination of seismic or multibeam surveys and data sharing should be encouraged. The level of activity in Antarctica has been very low compared to many other parts of the world and the best way of avoiding unforseen problems caused by long term disturbance and displacement is to minimise repeat surveying and ensure that areas are not subjected to surveys in consecutive years. **Care should be taken as to how the "area" is defined. It should be scaled with the power of the source, directionality and sound propagation characteristics**. For example geographic terms such as "the Ross Sea" are not very useful as it is a very large area in which several surveys might take place without overlap. Information on the survey history of the Antarctic is available in the SCAR ANTOSTRAT Seismic Data Library System and survey planners should consult this to minimise resurveying.

Future work
Assessing the biological impacts of acoustic technology in the Antarctic is still very uncertain because of the many unknowns in animal hearing, acoustic propagation and animal distribution and behaviours. Some uncertainty will always remain. The ideal situation would be the development of quantitative risk analysis techniques so that the risks posed by acoustic technology could be compared with risks posed by other human activities and natural hazards and by human activities in other parts of the ocean where the animals move. For the time being, qualitative risk definition and classification methods should be considered in survey evaluation such as defining a Likelihood-Consequences matrix (Standards Association of Australia, 1999, Table 9).

Table 10. Example of a qualitative risk analysis matrix (Standards Association of Australia, 1999).

Likelihood	Consequences				
	Insignificant	Minor	Moderate	Major	Catastrophic
A (almost certain)					
B (Likely)					
C (moderate)					
D (unlikely)					
E (rare)					

Further quantification might be achieved by estimating the number of animals within a radius of a source defined by the power of the source, the duration of the survey and the duty cycle of the equipment, the propagation conditions, the safe level of sound for the species and the density of animals in the region. Clearly further research is needed to be able to define the last three of these parameters.

CONCLUSIONS AND RECOMMENDATIONS

1. The meeting concluded that there was insufficient evidence to justify a ban on marine acoustic technology in the Antarctic particularly given the importance of such equipment in marine research. However, there was insufficient evidence to suggest that all equipment and surveys were safe. Therefore, surveys and applications need to be considered on a case by case basis.
2. High energy, low frequency sources have greater risk of impact than low energy, high frequency sources.
3. For applications using high energy, low frequency sources, mitigation strategies involving survey design, timing, ramping of source levels and shut down zones should be used.
4. Mitigation strategies should be investigated to evaluate their effectiveness.
5. There should be a regular review of mitigation strategies and the progress of research in the field to ensure that new research findings will be avalable to the Antarctic community.
6. Research into the hearing and rection to noise of Antarctic animals should be encouraged.
7. Research into sound propagation conditions arounnd Antarctica should be encouraged.
8. Records of the locations, timing, duration, frequency, and nature of hydroacoustic and other activities should be maintained to permit retrospective assessment of the likely causes of any future observed changes in the distributions, abundance, or productivity of the potentially affected species and populations.

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