SEA 7 Technical report: Underwater ambient noise (Non-technical summary)

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Non-Technical Summary

Introduction

This report has been prepared for Geotek Ltd acting on behalf of the Department of Trade and Industry (DTI) as part of the Strategic Environmental Assessment (SEA) process for the UK Continental Shelf (UKCS). This process has been divided into a number of stages covering eight areas of the UKCS. This report is part of the SEA 7 process which covers the area from the northern Irish coast northwards through western Scottish coastal waters to Cape Wrath then northwards to 60 degrees north and westwards to 24 degrees west

The aim of the SEA process is to establish an environmental baseline for the area so that the impact of offshore exploration and development can be assessed before the work takes place and this will then allow the changes caused by the work to be determined.

In recent years there has been an increasing awareness that offshore activities have contributed to significant increases in the levels of underwater ambient noise and in SEA 7 this concern is being addressed in some detail.

What is ambient noise?

Ambient noise is that sound received by an omni-directional sensor which is not from the sensor itself or the manner in which it is mounted. Ambient noise is made up of contributions from many sources, both natural and anthropogenic. These sounds combine to give the continuum of noise against which all acoustic receivers have to detect required signals

Ambient noise is generally made up of three constituent types – wideband continuous noise, tonals and impulsive noise and covers the whole acoustic spectrum from below 1 Hz to well over 100 kHz. Above this frequency the ambient noise level drops below thermal noise levels.

Ambient noise mechanisms

There are a number of basic mechanisms by which ambient noise is generated. All of the sources of ambient noise involve one or more of these basic generation mechanisms.

Impact noise

Impact noise occurs when water strikes water, e.g. breaking waves; water strikes solid, e.g. waves hitting a rock; solid strikes water, e.g. hail hitting the water surface; or solid strikes solid underwater, e.g. sediment noise (“saltation”). It is usually a broadband, transient noise, possibly with resonant peaks if solids are involved.

Bubble noise

There are several types of bubbles in sea water. Passive bubbles are quiescent and do not generate noise. Active bubbles are formed during an energetic process such as breaking waves or rain striking the surface. These bubbles oscillate and generate comparatively narrowband signals centred on the resonant frequency of the bubble, typically in the range 15 to 300 kHz. Collective oscillations of bubble clouds, particularly under breaking waves, can have resonant frequencies which are much lower than this.

Turbulence

Turbulence associated with surface disturbance or turbulent tidal flow around an obstruction generates low frequency continuous noise.

Seismic

Movement of the seabed can be coupled into the water column and generate very low frequency noise.

Cavitation

Propellers and other fast moving objects in the water can cause cavitation noise when the pressure in the flow around the moving object goes sufficiently negative. This causes a cavitation bubble which very quickly collapses, causing a loud transient sound. The resulting spectrum is wideband but generally has a peak between 100 Hz and 1 kHz.

Machinery noise

Machinery generally produces a broadband continuous spectrum with tonals superimposed resulting from the rotation rates of the various parts of the machinery. There may also be impulsive sounds.

Tonals

Some systems either deliberately, or as a by-product, generate high levels of tonal signals e.g. sonar systems, seal scarers.

Sources of ambient noise

Wind-sea noise

Noise is generated by the interaction between wind and the sea surface. At higher wind speeds this results in breaking waves which produce noise by impact and bubble mechanisms. At lower wind speeds noise results from flow noise as the wind passes over the sea surface and from bubbles entrained at the sea surface. There is likely to be a diurnal and annual cycle in the contribution from wind-sea noise due to changes in the meteorological conditions

Precipitation noise

Precipitation hitting the sea surface generates noise by impacting the sea surface and, in some instances, by oscillation of the bubbles entrained by the impact. Small raindrops generate noise with a spectral peak around 15 kHz due to the entrained bubbles while large raindrops only generate impact noise. Hail generates a spectrum with a broad peak between 2 and 5 kHz. Heavy snow produces a rising spectrum above 20 kHz.

The noise from all forms of precipitation can be modified by increasing winds. In particular, the bubbles formed by small raindrops are less likely to form so the level of bubble oscillation noise reduces significantly as the wind speed increases.

Surf noise and sediment transport

Noise generation in the surf zone is a highly complex process but the resulting noise can be heard up to 9 km off shore. The noise results from individual and collective bubble oscillation in the water column, sediment transport in the backwash, splashing, pounding and turbulence. The character of noise from surf is dependent on the beach profile, the wave direction relative to the beach and the sediment size. If the dominant beach material is cobble, pebble or gravel then sediment transport noise will dominate. For small sediment sizes, such as sand or clay, bubble noise will dominate.

The noise characteristics are further modified by the immediate offshore bathymetry which will determine the acoustic propagation conditions for the sound out into deeper waters.

Sediment transport can also occur away from the shoreline if the water is very shallow (<10 m) and a current is running and/or there is a significant wave height to disturb the seabed.

Aggregate extraction

The noise resulting from aggregate extraction is made up of three contributions: ship noise; dredge noise; and sediment noise. Dredge noise is that noise from the dredging machinery over and above normal ship noise while sediment noise results from the movement of the seabed material across the seabed and through the suction tube.

Commercial shipping and leisure craft

The SEA 7 area carries a considerable amount of traffic made up of commercial shipping, ferry traffic and leisure craft. The contribution of commercial shipping to ambient noise has been well studied, particularly in deep water and the resulting spectra are well understood. The noise spectrum from all powered craft is composed of a low frequency broadband spectrum with a number of tonal lines resulting from the rotating machinery. Above 1 kHz machinery noise diminishes and the dominant noise source is caused by water displacement and the resulting entrained bubbles. The noise of distant shipping tends to dominate the 50 to 300 Hz part of the spectrum.

The SEA 7 area carries a significant amount of commercial shipping. This mostly originates from traffic to and from the major ports of Liverpool, Dublin, Belfast and the Clyde moving into and out of the North Channel. In addition, shipping passing around the north of Scotland and out into the Atlantic will also make a significant contribution. There are no major ports within the SEA 7 area, but within the coastal waters of Scotland a significant contribution to shipping noise will be from the inter-island ferries.

Away from the main shipping lanes a major contribution is likely to come from fishing boats. There is a variety of fishing activity in the SEA 7 area, ranging from inshore potting to offshore deep-water trawling. As the fishing boats move around the area they are likely to provide a significant contribution to shipping noise. Shipping noise will vary on a diurnal cycle (ferry and coastal traffic) and an annual cycle (seasonal activity).

Industrial noise

Industrial noise can result from a number of offshore activities including oil and gas production, wind farms, construction activities and power transmission. Some onshore industrial activity can also generate sound in the water

Military noise

The military can generate underwater noise by the use of ships, aircraft, explosives and active sonar transmissions. There are a number of areas where military exercises and trials may take place in the SEA 7 area, including the Benbecula ranges, the Raasay BUTEC range and the Cape Wrath bombing range. In addition, the whole area, particularly out to 12 degrees west, is widely used by the Royal Navy for research trials, exercises and live firings.

Sonar

Active sonar generates a high power pulse in the water and then listens for the echo from a desired target to determine range and direction. The most common sonar in use in the SEA 7 area is the echosounder carried by most ships. Other sonars in use include fish finders and fishing gear control sonars, acoustic modems, air guns for seismic geological exploration and military sonars. The region to the west of the continental shelf is a true deep-water area for acoustic propagation, and seismic surveys can result in basin-scale reverberation.

Aircraft

The noise of aircraft can couple into the water, particularly in the case of helicopters operating low over the surface of the water.

Fishing activity

The act of dragging a trawl across the seabed is an inherently noisy operation. Other contributions are from ship noise and fishing sonars

Biological noise

Many marine organisms can generate noise. There is a widespread source of clicks which can be found in the very shallow waters of the west coast of the UK thought to be made by a crustacean. Fish and cetaceans also make sounds that contribute to ambient noise levels.

Thermal noise

In the absence of all other sources of noise, thermal noise will dominate. This originates from the thermal agitation of molecules. The noise rises at 6 dB/octave and in a real environment is only important above 100 kHz.

Ambient noise field modifiers

Acoustic propagation

Sound produced by the various ambient noise sources has to propagate through the very complex underwater environment. Because of variations in temperature, salinity and pressure the path followed by the waves can deviate markedly from a straight line. The structuring is most marked in the vertical plane, causing the waves to be refracted upwards or downwards, depending on the sound speed gradient, but horizontal structuring can also be encountered. As the waves are refracted up or down they may interact with the surface and the sea bed by reflection and scattering. The level of signal arriving at a distant point is therefore a complex sum of many paths that may or may not interact with the seabed and sea surface.

The multiple paths followed by the sound waves can cause dispersion in time of the acoustic energy and can also cause a variation in propagation loss with frequency.

Propagation loss varies on a diurnal and annual basis as the air temperature variations warm and cool the water.

Source and receiver depths

Because of the temperature structuring of the water column, if the source and receiver depths vary the propagation loss can vary significantly. If a surface duct is formed by an isothermal layer near the surface this variation can be very large.

Tides

The variation in water depth through the tidal cycle can significantly modify acoustic propagation paths, particularly in very shallow water. In the extreme case, two areas of water that are acoustically linked at high water may be isolated by a sand bank that is exposed at low tide.

Dominant noise sources

Based on the information gleaned during this study, from the experience of the authors when working in the SEA 7 area and from a much wider experience of studying the various sources of ambient noise over many years of sonar trials, the most likely sources of ambient noise across the SEA 7 area are mapped in Figure 1.

Note that this map represents the situation at low wind speeds and no precipitation noise. When the weather deteriorates it is likely that wind and rain noise will dominate over large areas and that the area in which shore and surf noise dominates will extend further offshore. The remainder of the SEA 7 area is not shown here in order to show the more complicated coastal region in more detail, but it is all comprised of deep, offshore waters in which the dominant noise source will be distant shipping in the absence of wind and precipitation. It should also be noted that the areas affected by different noise contributions will vary through the year as acoustic propagation loss varies through the seasons.

From Figure 1, it can be seen that distant shipping noise is likely to dominate across large parts of the SEA 7 area. The coastline is likely to be dominated by surf noise and shore noise. The map shows the areas in which local shipping activity is likely to dominate the ambient noise level. These areas include the shipping lanes which pass through the region and also the shelf edge, which is where fishing activities are likely to be most prevalent. In addition there are a number of ferry routes operating between the Hebrides and the mainland which will also contribute to the local shipping noise. Also plotted is the location of the Foinaven offshore oil production facility at 60° 19' N 4° 17' W. Although this installation is actually in the SEA 4 area rather than SEA 7 it is possible that, under the right conditions, sound could propagate into the SEA 7 area.

It should be noted that just because a particular noise source is dominant in a given area it does not necessarily mean that other sources may be neglected in that area: the total noise level from all sources may be significantly higher than the level due to the dominant source alone; different sources may dominate in different parts of the spectrum; and bio-receptors may be more sensitive to a less dominant noise source in a different frequency range.

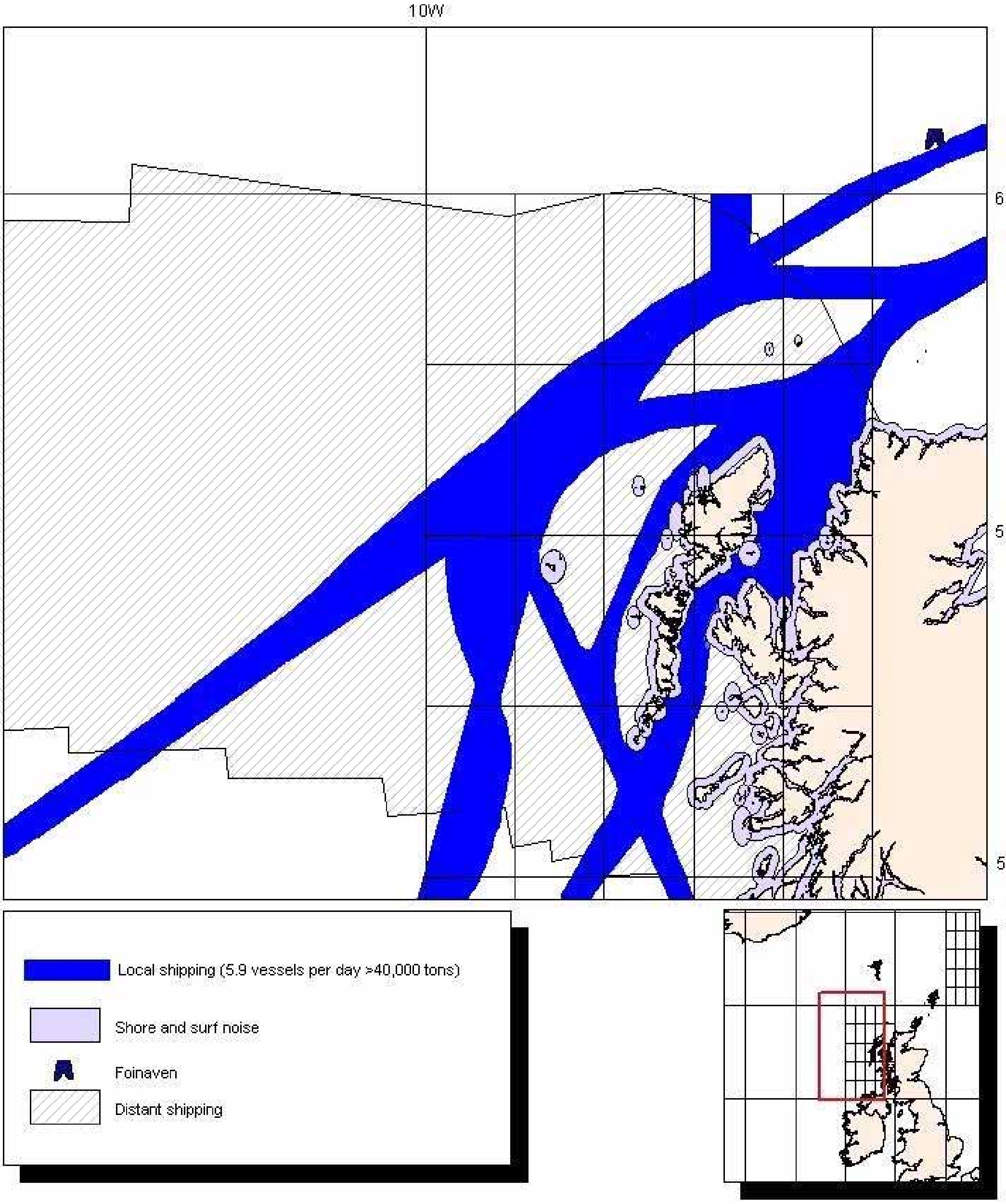

Figure 1: SEA 7 area dominant noise sources

Characterising ambient noise

Early work characterising deep water ambient noise levels used long time-constant averaging of spectra. In shallow water the noise is much more variable as the different contributions vary and although it is possible to obtain average spectra in the same manner as deep water they contain no information on the variability of the noise.

Recently there has been an increased interest in characterising shallow water ambient noise and a number of research groups have produced specialised equipment to make measurements in the shallow water environment. Making noise measurements can be very challenging with problems of ensuring the self-noise of the measuring system does not interfere with the measurements and the problems of building suitable measuring systems that do not introduce their own artefacts.

In order to obtain true baseline data for a site it is necessary to measure continuously for a complete annual cycle. To characterise a complete area such as the SEA 7 area these measurements have to be repeated at many sites. It is estimated that the SEA 7 area would need around 100 measurements sites to characterise the area fully.

An alternative approach recommended by the authors is to characterise each type of sound source, obtain the statistics of the distribution and occurrence of the sound sources and then use propagation models to predict the sound field across the area. This approach is dependent on high quality data for the sound sources and also environmental data such as bathymetry and meteorological data.

Measurements and modelling

Measurements of ambient noise in the SEA 7 area have been analysed to provide spectral characteristics of the ambient noise at a limited number of sites in the SEA 7 area, together with indications of the temporal and spatial variability of the relative spectrum level.

Predictions of spectrum level as a function of frequency have been carried out for different locations in the SEA 7 area for a range of wind speeds under summer and winter oceanographic conditions. These predictions have been compared, within the limitations of the modelling and measurements, with the real measured data.

The dominant source of the ambient noise measured during a short deployment in the summer of 2004 was found to be wind-generated surface noise, and the predictions of an ambient noise model were consistent with the measured data. However, the existing models do not include all of the important sources of ambient noise, and further development is required to predict the ambient noise when these other sources are important.

Identified information shortfalls

The report identifies a number of areas where there is a shortfall in the available information required to understand the ambient noise fields in the SEA 7 area. These include little or no information on some anthropogenic noise sources such as leisure craft, sonar usage and aggregate extraction and a lack of knowledge on some natural sources such as rocky foreshore surf noise and sediment transport noise.

Recommendations

In order more completely to baseline the ambient noise field in the area it is therefore recommended that a more extensive programme of modelling and measurement be undertaken. Datasets which should be analysed include:

a. the ARU dataset partially analysed in this study;

b. towed array and sonobuoy data held by QinetiQ; and

c. long time series data from the fixed seabed array.

It is recommended that the following method be used to characterise noise in the SEA 7 area:

a. collect data on sound sources within the SEA 7 area in order to meet the shortfalls in information on these sources set out in Section 8 above. Data should provide spectra, source levels and variability information for each source;

b. collect information on the distribution and number of the sources to be included in a model of ambient noise;

c. assemble the input data required to run the ambient noise model;

d. modify an existing ambient noise model to operate in the required manner. SANE is suitable for modelling surface generated noise, which may dominate much of the spectrum under many weather conditions, but it does not include shipping noise, for example, which will be dominant over much of the SEA 7 area under low wind conditions;

e. run the model to provide the required noise field data. Depending on computation times this may be a set of pre-calculated plots or it may be on a ‘run as required’ basis;

f. collect and analyse data from a selected number of sites within the SEA 7 area to validate the model. QinetiQ has an extensive archive of data from sonar trials in the area which could make a useful contribution to the required dataset, but it is likely that further measurements would be required to provide high quality, dedicated ambient noise data from calibrated sensors, with large dynamic range and flat frequency response, and with low self noise levels; and

g. make incremental improvements to the model to improve geographic resolution and include additional sources

This programme of work will provide a good understanding of the ambient noise fields across a large proportion of the SEA 7 area. It will also provide information on how the field will vary with the different cycles affecting noise levels.

This work will complement the detailed baseline measurements required to understand the ambient noise field at specific sites for possible construction activities. It is recommended that long term underwater acoustic monitoring of these specific construction sites, carried out to meet environmental impact requirements, is used to further refine the recommended modelling of the whole SEA 7 area noise field.

It is recommended that consideration be given to an acoustic dose system for geographic areas in order to limit the impact of high power sounds sources.

Conclusions

This report has set out the sources of ambient noise likely to be found in the SEA 7 area. This information is based on the many years of experience built up within QinetiQ and its predecessor organisations while supporting research into military sonars.

Measurements and simulations of ambient noise in the SEA 7 area have been conducted and analysed. The model predictions have been compared, within the limitations of the modelling and measurements, with the real measured data.

The dominant source of the ambient noise measured during a short deployment in the summer of 2004 was found to be wind-generated surface noise, and the predictions of an ambient noise model were consistent with the measured data. However, the existing models do not include all of the important sources of ambient noise, and further development is required to predict the ambient noise when these other sources are important.

The modelling and data analysis conducted in this short study has been necessarily limited, and a much more extensive programme of modelling, measurement and analysis is recommended in order fully to characterise the ambient noise in the SEA 7 area. This programme needs to cover a large number of sites in the area over a full annual cycle, with sufficient temporal and spatial resolution to capture the important temporal cycles and spatial variability.

Ambient noise depends on a wide range of anthropogenic and natural sound sources. These sources add together in a complex manner resulting in significant spatial and temporal variations in the noise field. Thus short term measurements at a single location can only provide a snap-shot of the noise field and cannot be used to extrapolate to other locations and times.

A suggested alternative is to characterise each sound source and use this information with occurrence statistics for each source to model the ambient noise field across the SEA 7 area.

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Abstract

This report has been prepared for Geotek Ltd., acting on behalf of the Department of Trade and Industry as part of the Strategic Environmental Assessment (SEA) process for the UK continental shelf. This non-technical summary is part of the SEA 7 process which covers the area from the northern Irish coast northwards through western Scottish coastal waters to Cape Wrath then northwards to 60 degrees north and westwards to 24 degrees west. This report looks at the sources of underwater noise that combine to provide the background ambient noise levels in the waters of the SEA 7 area and considers the mechanisms by which the sound is generated and may then be modified by the environment. Summary recommendations and conclusions of the technical report are given.

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SEA 7 Technical report: Underwater ambient noise

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List of contents

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1 Introduction

1.1 Background

This report has been prepared for Geotek Ltd. acting on behalf of the Department of Trade and Industry (DTI) as part of the Strategic Environmental Assessment (SEA) process for the UK continental shelf (UKCS). This process has been divided into a number of stages covering eight areas of the UKCS. This report is part of the SEA 7 process which covers the area from the northern Irish coast northwards through western Scottish coastal waters to Cape Wrath then northwards to 60 degrees north and westwards to 24 degrees west (see Figure 1-1 for map).

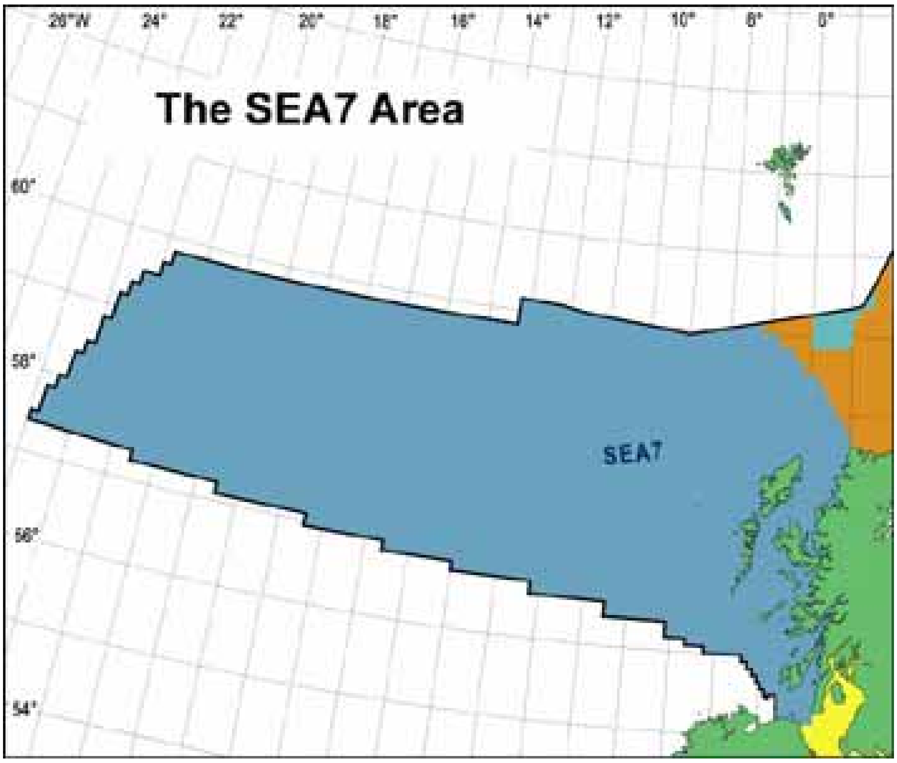

Figure 1-1: The SEA 7 area

The aim of the SEA process is to establish an environmental baseline for the area so that the impact of offshore exploration and development can be assessed before the work takes place. This will then allow the changes caused by the work to be determined.

In recent years there has been an increasing awareness that offshore activities have contributed to significant increases in the levels of underwater ambient noise and as part of the SEA 6 process this concern was addressed in some detail.

This report extends the work started for the SEA 6 process to the SEA 7 area and looks at potential sources of underwater noise that combine to provide the background noise levels in the area. In addition, acoustic data from work carried out previously in this area have been processed and the data compared with modelled data to investigate the quality of modelled data for the area.

1.2 This report

This report initially gives a general introduction to underwater ambient noise and the underlying mechanisms that generate sound.

The report then identifies a number of sources of underwater acoustic noise, describes the characteristics of the noise including frequency content, levels and variability, and also identifies the current state of knowledge on each source. In all cases the sources are considered in the context of the SEA 7 area. Mechanisms that can modify the ambient sound levels are described. The dominant noise sources in the SEA 7 area are identified.

Recommendations are then made for the methodology to be used to obtain meaningful characterisation of noise levels in order to establish baseline levels.

The report then goes on to present an analysis of measured ambient noise data in the SEA 7 area, model predictions of spectrum levels, and compares the measured and modelled data.

It should be noted that the comments on noise sources are appropriate for the shallow and deep waters of the SEA 7 area and may not be appropriate for other SEA areas or where the water is very shallow.

2 Underwater ambient noise

2.1 What is ambient noise

Ambient noise is that sound received by an omni-directional sensor which is not from the sensor itself or the manner in which it is mounted. Noise from the sensor or its mounting is termed self-noise. Ambient noise is made up of contributions from many sources, both natural and anthropogenic. These sounds combine to give the continuum of noise against which all acoustic receivers have to detect the signals they are looking for.

Some researchers define ambient noise as the residual when identifiable sources, such as passing shipping, are removed. For this document the definition used is all contributions of noise, both local and distant, since this is the level that impacts bioacoustic receivers.

Ambient noise is generally made up of three constituent types – wideband continuous noise, tonals and impulsive noise. Impulsive noise is transient in nature and is generally of wide bandwidth and short duration. It is best characterised by quoting the peak amplitude and repetition rate. Continuous wideband noise is normally characterised as a spectrum level, which is the level in a 1 Hz bandwidth. This level is usually given as intensity in decibels (dB) relative to a reference level of 1 micro Pascal (µPa). Tonals are very narrowband signals and are usually characterised by their amplitude in dB re. 1 µPa and frequency. Ambient noise covers the whole acoustic spectrum from below 1 Hz, to well over 100 kHz. Above this frequency the ambient noise level drops below thermal noise levels.

In deep water the levels of ambient noise are now well defined and the contributions from various sources well understood. Urick (1983) summarised this in the curve shown in Figure 2-1. In regions I and II the sound originates from turbulence and hydrostatic sources (e.g. tides). In region III the sound is more variable and is due to distant shipping. Region IV is dominated by sea surface noise originating close to the point of measurement while region V is dominated by thermal noise. In the context of this report, regions III and IV are the most important in the comparatively shallow Scottish coastal waters while all regions will apply in the deep water off the continental shelf.

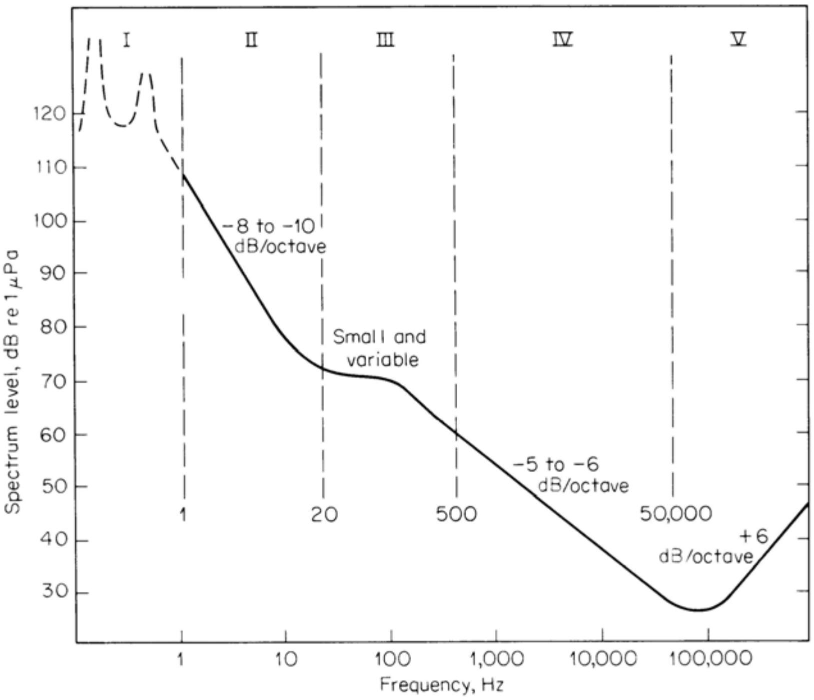

Figure 2-1: Deep water ambient noise (adapted from Urick, 1983)

Wenz (1962) summarised the noise levels in this part of the spectrum as shown in Figure 2-2. These are known as Knudsen spectra from the pioneering work carried by Knudsen to measure the levels of ambient noise (Knudsen et al. 1948). The ambient noise spectrum will normally lie between the two thick black lines and is made up from a number of contributing sources. At the lower frequencies shipping noise will dominate, while at the higher frequencies noise from waves and precipitation will dominate. The frequency at which the change occurs is a complex function of local bathymetry, propagation conditions, shipping levels and weather.

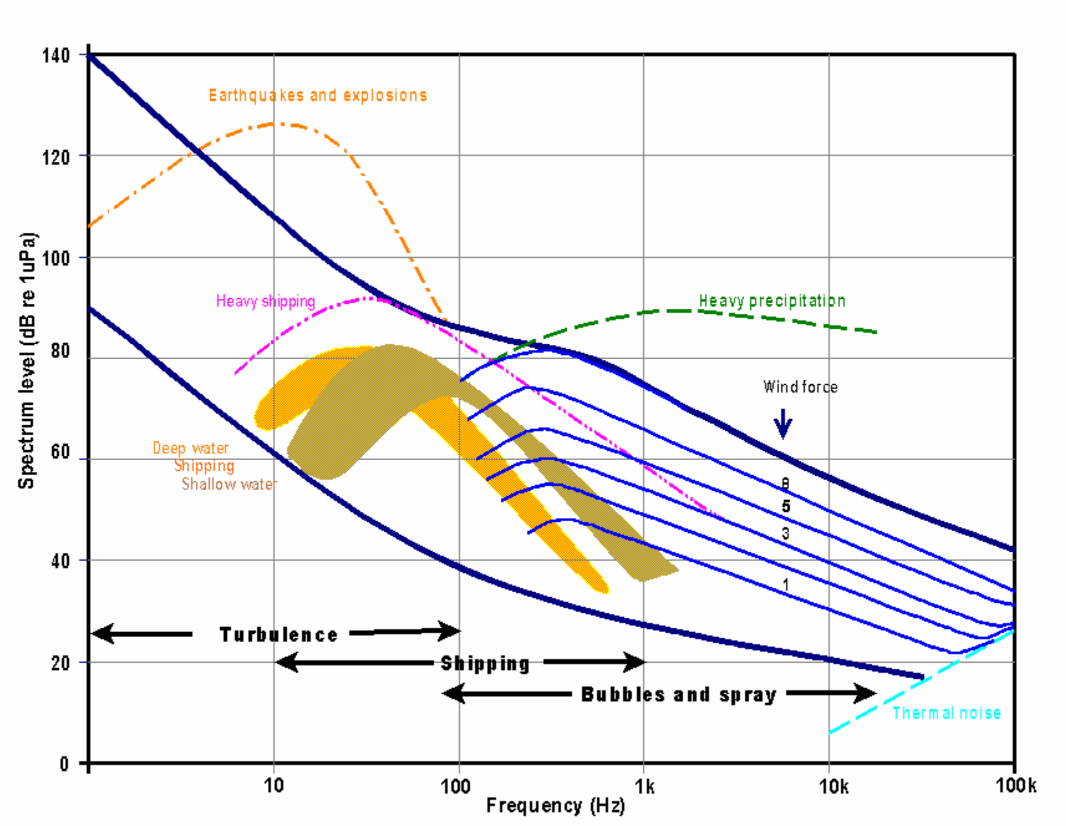

Figure 2-2: Composite of ambient noise spectra. (Adapted from Wenz, 1962)

In the deep waters of the SEA 7 area the curves in Figures 2-1 and 2-2 will be a good approximation to the levels found. At low frequencies shipping noise will dominate, particularly in the south of the area near the shipping lanes. At high frequencies (>10 kHz) increasing absorption prevents sound propagating over great distances so the ambient noise is dominated by local sound sources. Values for absorption are typically around 1 dB/km at 10 kHz rising to around 30 dB/km at 100 kHz. At 100 kHz, only very local sources contribute to ambient noise and above this frequency thermal noise takes over as the dominant source of noise.

In the shallower coastal waters around Scotland and Northern Ireland, the water is too shallow to support long range propagation of very low frequencies so the ambient noise at these frequencies will generally be lower than these curves suggest. Above about 100 Hz, depending on water depth, the Knudsen spectra will again provide a good approximation away from the coasts.

Close to the coasts, and particularly amongst the Scottish islands, the ambient noise levels are likely to be severely modified by shielding and the contribution from very local noise sources, such as surf noise.

2.2 Noise generation processes

Underwater noise can be generated by a number of processes:

Impact noise

Impact noise occurs when water strikes water, e.g. breaking waves; water strikes solid, e.g. waves hitting a rock; solid strikes water, e.g. hail hitting the water surface;

or solid strikes solid underwater, e.g. sediment noise (“saltation”). It is usually a broadband, transient noise, possibly with resonant peaks if solids are involved.

Bubble noise

There are several types of bubbles in sea water. Passive bubbles are quiescent and do not generate noise. Active bubbles are formed during an energetic process such as breaking waves or rain striking the surface. These bubbles oscillate and generate comparatively narrowband signals centred on the resonant frequency of the bubble, typically in the range 15 to 300 kHz. Collective oscillations of bubble clouds, particularly under breaking waves, can have resonant frequencies which are much lower than this.

Turbulence

Turbulence associated with surface disturbance or turbulent tidal flow around an obstruction generates low frequency continuous noise.

Seismic

Movement of the seabed can be coupled into the water column and generate very low frequency noise.

Anthropogenic

Anthropogenic noise can be generated by all of the above processes. As an example, a ship moving through the water will generate impact noise by wave slap, bubble noise from entrained bubbles due to the propulsion and passage through the water and turbulence noise due to the disturbed water. In addition a number of additional generation processes may be encountered:

Cavitation

Propellers and other fast moving objects in the water can cause cavitation noise when the pressure in the flow around the moving object goes sufficiently negative. This causes cavitation bubbles which very quickly collapse, causing a loud transient sound. The resulting spectrum is wideband but generally has a peak between 100 Hz and 1 kHz.

Machinery noise

Machinery generally produces a broadband continuous spectrum with tonals superimposed resulting from the rotation rates of the various parts of the machinery. There may also be impulsive sounds.

Tonals

Some systems either deliberately, or as a by-product, generate high levels of tonal signals e.g. sonar systems, seal scarers.

3 Sources of ambient noise

3.1 Wind-sea noise

A number of early observations of ambient noise suggested that between 500 Hz and 25 kHz the ambient noise levels were dependent on wind speed. Based on these observations the Knudsen spectra were defined relating noise level to wind speed, or sea state, as shown in Figure 2-2. Later observations showed that that the noise level was dependent on wind speed in the vicinity of the receiver.

The dominant mechanism for the generation of wind-sea noise at the ocean surface is breaking waves, although this mechanism is still not fully understood. Laboratory measurements reported by Medwin *et al*. (Medwin and Beaky 1989; Medwin and Daniel 1990) demonstrated that the characteristic 5 dB/octave slope of the Knudsen wind-sea noise spectra results from the incoherent sum of the noise from individual resonant bubbles. At higher sea states, with vigorous breaking waves, large amounts of air are entrained and bubble oscillations may be coupled, leading to collective oscillation of bubbles in a plume (Prosperetti 1988). Melville *et al*. (1993) found that the sound radiated by breaking waves increases with sea state and is related to the volume of air entrained as a result of waves breaking.

The dependence on wind speed holds even below the speeds that produce breaking waves and this may be due to noise from flow noise as the wind passes over the sea surface and/or by bubbles induced from capillary waves produced at the sea surface by the wind.

To determine wind-sea related ambient noise levels in a particular area a knowledge of the wind statistics is needed and from this an assessment of the contribution of wind-sea noise can be made. The contribution is made up of locally generated noise at all frequencies plus a contribution from more distant sources at lower frequencies. Because of interaction with the seabed and sea surface, particularly in areas on the continental shelf, a knowledge of acoustic propagation conditions is also needed to determine the overall contribution from wind-sea interactions

There is likely to be a diurnal and annual cycle in the contribution of wind noise to ambient noise levels due to seasonal and diurnal changes in the meteorological conditions and water column properties. In those areas with a significant tidal flow there will also be tidal and lunar cycles.

3.2 Precipitation noise

Precipitation in the form of rain or hail can cause significant elevation of ambient noise levels in the 1 to 100 kHz region. The noise is generated by a number of mechanisms, including impact noise as the rain or hail impacts the surface of the water and oscillation of the bubble entrained by the raindrop. Large raindrops can cause a more complex acoustic signature through multiple impacts and entrainment of more than one bubble. At low wind speeds bubble oscillation is the dominant noise source in UK waters, with impact noise dominating at higher wind speeds. Precipitation noise was dealt with in some detail in the SEA 6 technical report and the reader is referred to this for more information.

In the SEA 7 area, particularly during the winter months, precipitation is likely to be a significant contributor to ambient noise. To estimate the contribution of precipitation noise to ambient noise, knowledge of the statistics of precipitation for the area of interest is needed. The annual cycle may then be integrated to calculate the relative contribution of precipitation to ambient noise levels. There will be an annual cycle in the variation of the contribution of precipitation noise to ambient noise.

3.3 Shore and surf noise

Shore and surf noise was dealt with in some detail in the SEA 6 technical report and the reader is referred to this for more information. Unlike the SEA 6 area, the shoreline around the SEA 7 area is predominantly rocky and exposed to extreme wave action. The few beaches are predominantly sandy.

Because of the exposure to waves coming in off the Atlantic, it is likely that shore and surf noise will be a major contributor to ambient noise in coastal waters in the SEA 7 area. The noise will mostly be impact noise as the wave hits the rocks, spray noise as the water falls back onto the sea, bubble oscillation noise and some limited sediment transport noise.

It should be remembered that apart from the Scottish coastal waters, there are three offshore island groups: the St Kilda group, the Flannan Isles and Rockall. Because of the extreme wave action they are likely to contribute high levels of noise into their immediate environment.

There will be an annual cycle associated with the contribution of shore and surf noise to overall ambient noise.

3.4 Sediment transport noise

Under some circumstances it is possible for the surficial sediment on the seabed to become highly mobile. The surf zone is perhaps the obvious example, but sediment transport can also occur away from the shoreline. Sediment transport occurs where the water is shallow (<10 m) and there is a current running and/or there is significant wave height to disturb the seabed. This occurs most readily with light sediments such as clays or fine sand. The sediment collides with itself and obstacles on the seabed and this generates high frequency noise. The noise is mostly above 10 kHz with peak frequencies at a few tens of kHz. The actual spectrum depends on particle size and material. The effect has been observed in the English Channel (pers obs[1]), (Thorne 1985), the North Sea (Voglis and Cook 1970), and the Bristol Channel (pers obs[2]). The effect can last for periods of less than a minute up to periods greater than an hour, depending on the tidal conditions.

Measuring sediment transport noise is very difficult. Deploying a hydrophone can result in measurements of noise levels which are elevated by up to 40 dB above the background level during major events, but most of this noise is caused by the particles hitting the hydrophone and its surrounds and it is then questionable whether one is measuring ambient noise or self noise. In terms of impact on a

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[1] A hydrophone 1.5 metres above the mixed sand and broken shell seabed in Durlston Bay in Dorset detected noise levels raised by 40 dB at 15-20 kHz during easterly gales and mid-tide.

[2] A hydrophone deployed mid-water in the tidal rip off Bull Point in Devon detected noise levels raised by ~20 dB at 15-20 kHz for 30 minutes during the flood tide.

biological receptor, the impact noise is likely to be less because of the nature of flesh compared with metalwork or hard epoxy encapsulant. It is also likely that the receptor would choose to move out of the main sediment flow for a number of reasons. Within the SEA 7 area there are no major areas which meet the requirements for wholesale movements of sediments. There will be some sediment transport noise associated with surf, and there will be some movement associated with the very strong tides around some of the Scottish islands

The noise contribution to ambient noise will vary with the tidal cycle, the lunar cycle and the annual cycle.

3.5 Aggregate extraction

The dredging of deep deposits of gravel is inherently a noisy operation. The resulting noise is a mixture of mechanical noise from operation of the dredge and a noise similar to sediment transport noise resulting from the disturbance of the gravel.

No published information on noise levels from aggregate extraction in the SEA 7 area has been identified in the course of this study. There is some published information on aggregate extraction in the English Channel (CEFAS 2003) and dredging activity associated with oil field development (Greene 1987) but this is likely to have been carried out in different water depths, over different sediment types and with different types of dredgers. It is believed that a number of other acoustic measurements have been made of aggregate extraction activity but the information is in company reports and could not be obtained during this short study.

3.6 Commercial shipping

Shipping noise is the dominant contribution to ambient noise in shallow water areas close to shipping lanes and in deeper waters. Shipping noise is most evident in the 50-300 Hz frequency range. At longer ranges the sounds of individual ships merge into a background continuum. At higher frequencies the dominant noise source is likely to be wind generated noise. Shallow water acts as a high pass filter, with the cut-off frequency increasing as the water get shallower. In very shallow coastal waters distant shipping noise makes little or no contribution to ambient noise.

Close to ships under way the noise spectrum splits into a number of regions. At low frequencies below 1 kHz there is a continuous wideband spectrum of noise with a number of tonals originating from rotating machinery superimposed. Above 1 kHz the machinery noise diminishes and water displacement noise becomes dominant. This drops below other sources of noise above 20 kHz. Additional noise may be caused by propeller cavitation and faulty machinery. Strong tonals can be generated by a singing propeller[3], a faulty gearbox or by electrical generation machinery. As an example a recent set of measurements for an 11 metre workboat revealed a tonal at 800 Hz that was 40 dB above the other noise sources on the boat. This was traced to a faulty gearbox (Wharam et al. 2004).

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[3] Propellers can oscillate strongly when the blade resonance is excited by vortex shedding from the blade tips. The tonal is usually in the 100-1000 Hz region. See Anon (2003) Singing propellers. Hydrocomp Inc, Report 138, Durham, NH, USA (www.hydrocompinc.com/knowledge/library.htm) for a more detailed explanation of the effect.

Different types of ships have different contributions from the different noise sources. For a fast ferry, the major noise sources are from displaced water in the 5-20 kHz region plus strong tonals in the region of a few hundred Hz from the machinery, while for a small coaster virtually all of the noise is from the propulsion machinery below 200 Hz.

The SEA 7 area carries a significant amount of commercial shipping. This mostly originates from traffic to and from the major ports of Liverpool, Dublin, Belfast and the Clyde moving into and out of the North Channel. In addition, shipping passing around the north of Scotland and out into the Atlantic will also make a significant contribution. There are no major ports within the SEA 7 area, but within the coastal waters of Scotland a significant contribution to shipping noise will be from the inter-island ferries.

Away from the main shipping lanes a major contribution is likely to come from fishing boats. There is a variety of fishing activity in the SEA 7 area, ranging from inshore potting to offshore deep-water trawling. As the fishing boats move around the area they are likely to provide a significant contribution to shipping noise. See Section 3.13 for information on noise arising from fishing activities.

Shipping noise will vary on a diurnal cycle (ferry and coastal traffic) and an annual cycle (seasonal activity).

3.7 Leisure craft

Over a number of years there has been a steady increase in the numbers and types of leisure craft in use around the UK. There has also been a steady increase in the engine power available to such craft. This has resulted in a considerable increase in underwater noise levels produced by this class of sound source and in holiday areas this can be the dominant sound source through the summer months. A number of workers have attempted to gather statistics on leisure craft traffic, particularly with regard to environmental impact (Gibbons 2000; Haviland *et al*. 2001).

Leisure craft can generally be grouped into a number of classes:

a. sailing craft;
b. slow motorboats;
c. high speed motorboats; and
d. personal watercraft.

Sailing craft are generally very quiet with the only sound coming from flow noise, wave slap and rigging noise. Racing yachts produce higher noise levels because of their increased speed, but are still much quieter than motorboats travelling at the same speed.

Slow motorboats generally produce low frequency noise from propulsion machinery containing broadband and tonal components, plus higher frequency broadband noise due to water impact and disturbance.

High speed motorboats use one or more high-powered engines to achieve planing speeds and generally cause considerable disturbance to the water surface. As well as the low frequency sounds, often with loud tonal components from the machinery, the high frequency sounds are enhanced by the disturbed water thrown up by the passage of the boat impacting the surface of the water and generating broadband noise. This noise typically dominates the signature in the region 5-25 kHz.

Personal watercraft, such as jet skis, are generally very small craft capable of carrying just one person, but fitted with a high power engine. The propeller is normally ducted and this reduces the noise output. The engines and impellers usually operate at high speeds so the predominant noise output is higher in frequency than other leisure craft.

Leisure craft activity is highest around their home ports where they are used for day running. Other common activities include racing and port to port cruising. Because they generally use smaller ports or purpose built marinas the main leisure craft routes are generally separated from the commercial shipping routes and are usually closer inshore.

Variations in leisure craft noise occur on a number of cycles. The diurnal cycle is generally bimodal with a morning peak as craft leave harbour and move out to whatever activity they are undertaking plus a second peak in the late afternoon as the craft return to harbour. These two peaks are superimposed on a broader day/night cycle with much reduced activity through the night. On a weekly basis there is a broad peak in noise corresponding to weekend activity. There is also an annual cycle with much increased activity through the summer months and very little activity through the winter months.

Within the SEA 7 area, leisure boating is virtually confined to the Scottish coastal waters, but during the summer months there can be a high level of activity.

There is generally a good understanding of the noise levels produced by the different vessel classes but there appears to be little information on the numbers and distribution of such craft through the year. It is also not clear how the very different noise contributions from the different types of craft combine to contribute to the ambient noise levels and spectra.

3.8 Industrial noise – offshore

Offshore industrial noise includes the noise generated by the operation of offshore wind farms, oil and gas rigs and offshore construction noise. Noise from exploration surveys is included in Section 3.11.

Oil and gas rigs generate underwater noise by conduction of the noise from machinery on the platform into the water column. This is likely to comprise low frequency tonal noise from the rotating machinery (<1 kHz) and a wideband noise level made up of many individual contributions from all the noises sources on a typical rig. A literature search of peer-reviewed journals did not find any information on the noise fields around oil and gas rigs.

Wind farm operational noise is likely to originate from machinery noise coupling via the tower into the water column and/or substrate and also from the rotating blades coupling via air movement into the water surface. A likely third source will be noise from the power cables to the shore. When cables carry high alternating currents the magnetic field around each core causes alternate attraction and repulsion and this can result in physical movement and hence a signal in the water. Again, a literature search failed to find any papers on the noise from wind farms in the peer-reviewed journals and only a very small number in the grey literature (Koschinski et al. 2003; Danneskiold-Samsoe 2005).

The construction of offshore and near-shore facilities such as wind farms or harbours may involve pile driving and this is inherently a noisy operation. Nedwell claims source levels as high as 262 dB re. 1µPa @ 1 m, inferred from measuring the noise of piling associated with the construction of the North Hoyle and Scroby Sands wind farms (Nedwell et al. 2004). Sounds from harbour construction pile driving have been heard 50 miles away (pers obs[4]). Attempts have been made to reduce the radiated noise by using bubble curtains around piling sites (Wursig et al. 2000) with limited success.

Within the SEA 7 area there are no operational oil or gas platforms and no wind farms.

3.9 Industrial noise – onshore

Industrial activity onshore adjacent to the coastline can produce underwater noise by coupling through the substrate. Noise levels are only significant if the noise is intense e.g. quarry blasting[5], or if there are a number of noise sources e.g. an area of heavy industry.

Transport systems close to the coastline e.g. motorways or railway lines can also couple noise into the underwater environment via the substrate.

The coupling through the substrate will generally only occur at very low frequencies (<100 Hz).

A literature search found no information on levels or spectra from this type of source.

In the SEA 7 area this is not a major contributor to ambient noise. Although a few quarries are operating adjacent to the coasts, their contribution to ambient noise levels will be insignificant.

3.10 Military noise

The military can generate underwater noise by the use of ships, aircraft, explosives and active sonar transmissions. Active sonar use within the SEA 7 area is described in the next section.

Military ships are generally very quiet and make only a small contribution to overall shipping noise. The sounds generated by explosives are very impulsive close to the event, but long-distance propagation smears the energy in time and frequency to give sounds above ambient for many seconds. There are a number of areas where military exercises and trials may take place:

a. Benbecula ranges;
b. Raasay BUTEC range; and
c. Cape Wrath bombing range.

In addition, the whole area, particularly out to 12 degrees west, is widely used by the Royal Navy for research trials, exercises and live firings. Although explosives are used across the whole area, the only area where this is likely to be significant is the Cape Wrath bombing range. No statistics were available on usage of the range so it is not possible to identify the contribution to ambient noise.

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[4] During a cruise in the Tyrrhenian Sea, pile driving in Monaco harbour was clearly heard off the north coast of Sardinia.

[5] Quarry blasting in the Purbecks, Dorset, can be clearly heard on a hydrophone 400 metres offshore and 3 miles from the quarry.

3.11 Sonar

Sonar is widely used by leisure, fishing and commercial vessels and there is also military usage within the SEA 7 area. Typical sonars currently in use are:

a. echosounders;
b. fish-finding sonars;
c. fishing net control sonars;
d. research sonars;
e. acoustic modems;
f. air guns for seismic geological surveys and reservoir monitoring; and
g. military sonar.

By far the most prevalent of these is the ubiquitous echosounder. Most vessels from small leisure craft up to the largest commercial ships have at least one echosounder. These work on frequencies from 26 kHz to 300 kHz with source levels up to 220 dB re. 1 µPa @ 1 m. These sonars direct their energy downwards into the seabed but there is significant energy travelling horizontally either from the sidelobes of the transducer or by scatter off the seabed. The higher frequencies are attenuated over short distances by absorption, but the contribution to ambient noise is significant due to the high numbers of such units.

Commercial fishing sonars can also make a major contribution to ambient noise because of their lower frequencies, higher power and greater power directed horizontally. The contribution is mostly limited to the grounds favoured for fishing, but it should be noted that this is also the most sensitive region, with the highest density of fish and cetaceans.

Research sonars are used to map the seabed and to study oceanographic conditions. The SEA 7 area has been visited by research ships on many occasions over the years to either map the area in some detail, or to test new equipment.

Acoustic modems are used to carry data from seabed installations to the surface and typically work in the range 2 to 20 kHz, depending on data rate and range required. They are generally omnidirectional and can generate high power levels. It is not known how many are in use in the SEA 7 area but it is likely that they will be in use by scientific equipment deployed throughout the area.

Air guns are used to generate very high level impulses of low frequency sound directed downwards into the seabed for geological survey work. Source levels may be as high as 250 dB re. 1 µPa @ 1 m with a centre frequency between 50 and 100 Hz. These system have been widely used in the area and on a number of occasions the authors have observed ambient noise levels raised by >50 dB for many hours due to operation of multiple profilers along the shelf-edge and deeper waters of the SEA 7 area. In more recent years there has been a downturn in survey activity but there is still some activity around the SEA 7 area. In the summers of 2004 and 2005 weak signals could be heard from survey activity well outside the SEA 7 area.

Figure 3-1: Lines of identified 2D seismic surveys during 2004 and 2005 (source: www.ukdeal.co.uk)

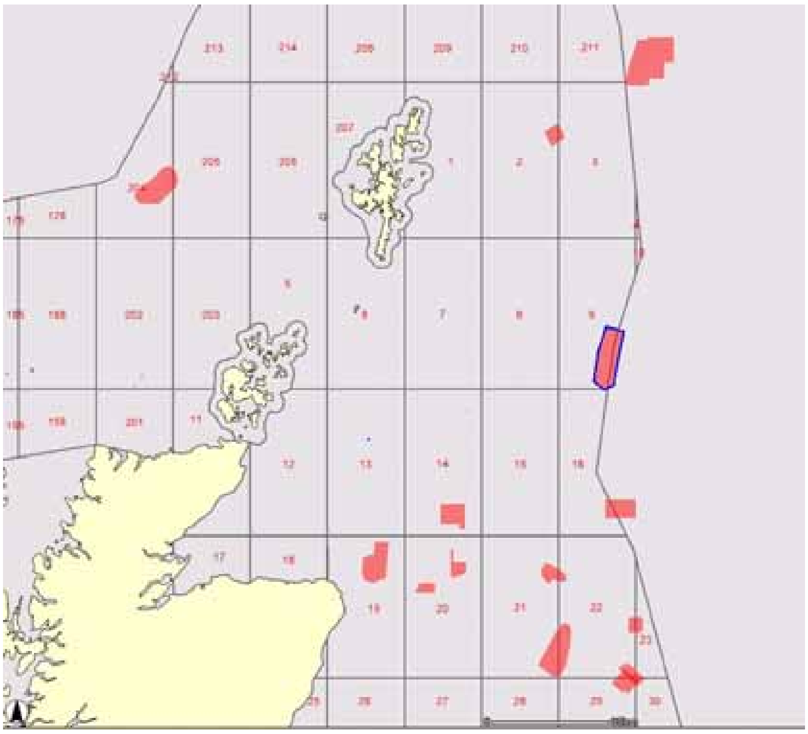

Figure 3-2: Areas of identified 3D seismic survey during 2004 and 2005 (source: www.ukdeal.co.uk). The highlighted survey in box 9 was coincident with the acoustic measurements discussed in Section 7

Figures 3-1 and 3-2 show locations of seismic surveys during 2004 and 2005 (www.ukdeal.co.uk). These sites are not within the SEA 7 area, but it is possible that the acoustic signals from these surveys propagated into the area. The authors do not believe that all surveys which took place during this period are included in this database, and that there may have been some surveys within the SEA7 area.

Military sonars use high power transmitters to generate tonal signals in the range 1 to 300 kHz and with pulse lengths between 0.1 and 4 seconds, depending on mode of operation. High frequencies above 80 kHz are used by mine hunters and the high attenuation at such frequencies means that any impact is limited to a very small area around the ship, typically less than 3 km. Lower frequencies (<3 kHz) are used in the deeper waters but can insonify a whole ocean basin. In the shelf region to the west of the Hebrides medium frequencies are most likely to be used (3 to 10 kHz).

No published information has been identified by this study on the statistics of sonar usage. It is not clear how many civilian and military sonars are operating in the SEA 7 area at any one time so it is not possible to judge the contribution to ambient noise levels.

The impact of an active sonar on the marine environment is dependant on the acoustic environment in which it operates. Enhanced propagation can significantly increase the volume insonified. In the shallow water to the west of the Hebrides ducts can form that give low propagation loss, particularly during the early summer months.

Another aspect that influences the impact of active sonars is reverberation. Reverberation is the backscatter of the sound by discontinuities on the seabed, by surface waves and by scatterers such as bubbles, debris, or fish within the water column. The reverberation characteristics of the shallow waters of the SEA7 area are typical of many areas around the UK. However, the deep water area is particularly prone to reverberation due to scattering from the edge of the continental shelf, the Wyville-Thompson Ridge, the Rockall bank and seamounts. At the low frequencies used by seismic exploration and some military sonars this can cause the build-up of reverberation leading to the masking of lower level sounds.

It is recommended that consideration be given to setting an acoustic dose for a geographic area. This is particularly recommended for the deep water part of the SEA7 area. Any users of high power sound should be allocated a proportion of that dose to use during their work. Once the annual dose has been exceeded then no further operations should be allowed. The concept is similar to the principles used in the noise at work regulations where personnel working in noisy areas have a maximum permitted noise dose. It would be necessary to calculate the natural noise dose, then calculate a permissible incremental dose. This incremental dose should include the contribution from reverberation.

Each noise generating activity would then apply to a central authority for a portion of this dose. The military already operate a rudimentary form of acoustic planning within the military exercise areas within the SEA 7 area. There are also a number of precedents established within the RF licensing field for this type of control.

This dose system should apply to all sonar users. Echosounders and fishfinding sonars can be incorporated into the background dose but all other users, including seismic exploration, military sonars and research sonars such be subjected to this dose system.

3.12 Aircraft noise

Aircraft noise can couple through the sea surface when an aircraft flies low over the sea (Urick 1972). This can happen when fixed wing aircraft approach a runway located on the coast, or a helicopter operates low over the sea.

Helicopter noise originates from the disturbance of the sea surface by the down wash from the blades and by coupling of blade noise directly into the sea. The down wash noise is very similar to wind noise in frequency characteristics and is greatest in the 2 to 20 kHz region. Blade noise contains a number of components originating from the rotation of the blades and the machinery that drives the blades. There are a number of strong tonals in the 10 to 100 Hz region associated with rotor operation and a strong tonal component at the turbine blade rate which is typically around 10 kHz[6].

Within the SEA 7 area, there are no major airports so aircraft noise is not a significant contributor to ambient noise. Noise caused by helicopters servicing lighthouses is significant during the event, but these events happen so infrequently that there is unlikely to be any major impact on the environment.

Desharnais (Desharnais and Chapman 2002) showed that sonic booms from aircraft can also penetrate into the water column, producing a low frequency pressure pulse. The only current source of such booms in the SEA 7 area is likely to be military aircraft and such booms happen so infrequently that their contribution to ambient noise levels is negligible.

3.13 Fishing activity

Commercial fishing can make a contribution to ambient noise in a number of ways. Apart from the contribution of the vessel noise and the use of sonar to find fish and monitor nets, the most significant contribution is trawl noise, particularly from bottom trawls. The sound of chains and rollers being dragged across the seabed can often be heard several miles from the activity.

The overall noise field from the fishing gear consists of low frequency noise from the rollers, mid and high frequency noise from the general disturbance of the seabed and high frequency noise from the chains. No published information on absolute levels or typical spectra has been found.

No appropriate statistics on fishing activity were available during the preparation of this report to judge the level of the impact of this noise source. Personal observation suggests that the major area for trawling is along the shelf-edge to the west of the Hebrides, where trawling noise has been tracked on military sonars at ranges in excess of 8 km.

Fishing noise is likely to vary on a diurnal cycle, a lunar cycle and an annual cycle.

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[6] Most information on helicopter noise is classified by the military. This information was derived from an opportunistic measurement of the Portland Coastguard search & rescue Sea King helicopter.

3.14 Biological noise

Many fish can produce sound, particularly as part of the mating process. Although the UK does not have the highly vocal species to be found in tropical seas, many UK fish can produce some sound.

The most vocal of marine species are the cetaceans, and species to be found in the SEA 7 area can produce sounds over the range 15 Hz to 200 kHz. In the deep waters off the shelf fin whales (*Balaenoptera physalus*) and sperm whales (*Phyceter macrocephalus*) can be major contributors to ambient noise levels. In the inshore waters there are many of the smaller species, particularly Atlantic white-beaked dolphins (*Lagenorhyncus albirostris*) and harbour porpoises (*Phocoena phocoena*). These also contribute to the ambient noise levels.

Cetacean sounds are either tonal whistles in the range 2 to 25 kHz, or wideband echolocation clicks with maximum energy in the 40 to 140 kHz region. Source levels for the tonals sounds are around 170 to 180 dB re. 1 µPa @ 1 m while echolocation clicks range from a source level of 170 dB re. 1 µPa @ 1 m for the harbour porpoise up to 226 dB re. 1 µPa @ 1 m for the bottlenose dolphin (*Tursiops truncatus*).

Seals are also very common in the waters around the Hebrides and, although not as vocal as the cetaceans, can make a significant contribution to ambient noise at certain times of the year.

Biological noise has been observed to vary on a diurnal cycle, a tidal cycle and an annual cycle.

3.15 Thermal noise

In the absence of all other sources of ambient and self noise, the underlying noise level is determined by thermal agitation of the molecules. This noise rises proportionally with frequency and for real systems is only important above 100 kHz. Ambient noise generally falls with increasing frequency until thermal noise dominates when the slope changes to a 6 dB per octave rise with increasing frequency. The noise spectrum level from thermal noise is given by

$$N_{\text{thermal}} = -15 + 20\log_{10}(f) \qquad \text{dB re 1 µPa,}$$

where f is the frequency in kHz.

4 Ambient noise field modifiers

4.1 Introduction

Section 3 set out the variety of sources of ambient noise in the SEA 7 area. The sound field at any one site is a composite of many of these sources. In addition to the complicated sum of components there are additional effects which will modify the level and spectral content of the ambient sound field. This section will describe these effects and the sound field modification that may be observed.

4.2 Acoustic propagation

Sound produced by the various ambient noise sources propagates to a receiver through the very complex underwater environment. Because of variations in the sound speed profile, caused by variations in temperature, salinity and pressure, the path followed by the sound waves can deviate markedly from a straight line. The structuring is most marked in the vertical plane, causing sound to be refracted upwards or downwards, depending on the sound speed gradient, but horizontal structuring can also be encountered. As sound is refracted up or down it may interact with the surface and the sea bed by reflection and scattering. The level of signal arriving at a distant point is a complex sum of many paths that may or may not interact with the seabed and sea surface.

Variations in salinity are generally very small, except perhaps at the mouth of major rivers, and pressure variations are due almost entirely to depth so temperature variations have the major effect on sound propagation in shallow water.

Under some conditions, a mixed isothermal layer forms close to the sea surface that traps the acoustic signals, and a source and receiver located within this surface duct experience significantly less propagation loss than when there is no surface duct. During the day the sea surface can heat up and introduce a temperature gradient close to the sea surface that causes downwards refraction and hence increased propagation loss.

Because the sound can interact strongly with the seabed, the sediment types and sea bed roughness can affect propagation loss. Similarly, waves on the surface can also affect propagation loss by scattering the sound interacting with the surface rather than just reflecting it.

Suspended sediments or bubbles can also cause additional propagation loss.

Propagation loss varies on a diurnal basis, particularly during the early summer, and on an annual cycle, as the air temperature variations through the year warm and cool the water. A period of sustained strong wind can also disrupt the temperature structuring.

4.3 Multi-path effects

Because of the surface and sea bed reflections sound can travel between a source and receiver by a multitude of paths. This has the effect of dispersing the arrived signal in time. This effect is particularly import for wideband impulsive sounds such as explosions, pile driving or seismic exploration air guns. If any of the propagation effects are frequency sensitive then frequency dispersion will also occur. A common example of this is the sound of air guns operating at distances of 30 to 50 km in which the low frequencies travel more slowly than the high frequencies so the single impulse at the source turns into a pronounced frequency sweep at the receiver. The effect of time dispersion is to reduce the peak energy in the received signal. The integrated level is unchanged by time dispersion, but the peak levels can be significantly reduced. When considering the contribution to ambient noise levels this can be an important factor.

4.4 Source and receiver depth

The vertical sound speed structure described above can lead to significant variations in the propagation loss between a sound source and the receiver as the depth of the source and/or the receiver is varied. The most extreme example is the surface duct where a shadow zone may form under the duct. Within the shadow zone levels from a distant sound source in the duct are much reduced compared with the level from the same source within the duct.

4.5 Tides

In the deep waters to be found in west of the SEA 7 area, the variations in depth due to tides is insignificant. However, in inshore waters the effect is much more pronounced and can significantly alter ambient noise fields through the tidal cycle.

Sand banks that dry at low water can also break acoustic paths so a receiver hearing a loud noise source across a sand bank at high tide may not receive it at low tide.

5 Dominant noise sources

Section 3 listed the possible contributors to ambient noise within the SEA 7 area and Section 4 showed how this sound can be modified by a number of environmental factors. In this section the most likely dominant noise sources across the area are mapped. This information is based on the information gleaned during this study, from the experience of the authors when working in the SEA 7 area and from a much wider experience of studying the various sources of ambient noise over many years of sonar trials.

Figure 5-1 is a map of the eastern section of the SEA 7 area showing what, in the opinion of the authors, will be the dominant noise sources across the area. Note that this map represents the situation at low wind speeds and with no precipitation noise. When the weather deteriorates it is likely that wind and rain noise will dominate over large areas and that the region within which shore and surf noise dominates will extend further offshore. The remainder of the SEA 7 area is not shown here in order to show the more complicated coastal region in more detail, but it is all comprised of deep, offshore waters in which the dominant noise source will be distant shipping in the absence of wind and precipitation. It should also be noted that the areas affected by different noise contributions will vary through the year as acoustic propagation loss varies through the seasons.

From Figure 5-1, it can be seen that distant shipping noise is likely to dominate across large parts of the SEA 7 area. The coastline is likely to be dominated by surf noise and shore noise. The map shows the areas in which local shipping activity is likely to dominate the ambient noise level. These areas include the shipping lanes which pass through the region and also the shelf edge, which is where fishing activities are likely to be most prevalent. In addition there are a number of ferry routes operating between the Hebrides and the mainland which will also contribute to the local shipping noise. Also plotted is the location of the Foinaven offshore oil production facility at 60° 19’ N 4° 17’ W. Although this installation is actually in the SEA 4 area rather than SEA 7 it is possible that, under the right conditions, sound could propagate into the SEA 7 area.

It should be noted that just because a particular noise source is dominant in a given area it does not necessarily mean that other sources may be neglected in that area: the total noise level from all sources may be significantly higher than the level due to the dominant source alone; different sources may dominate in different parts of the spectrum; and bio-receptors may be more sensitive to a less dominant noise source in a different frequency range.

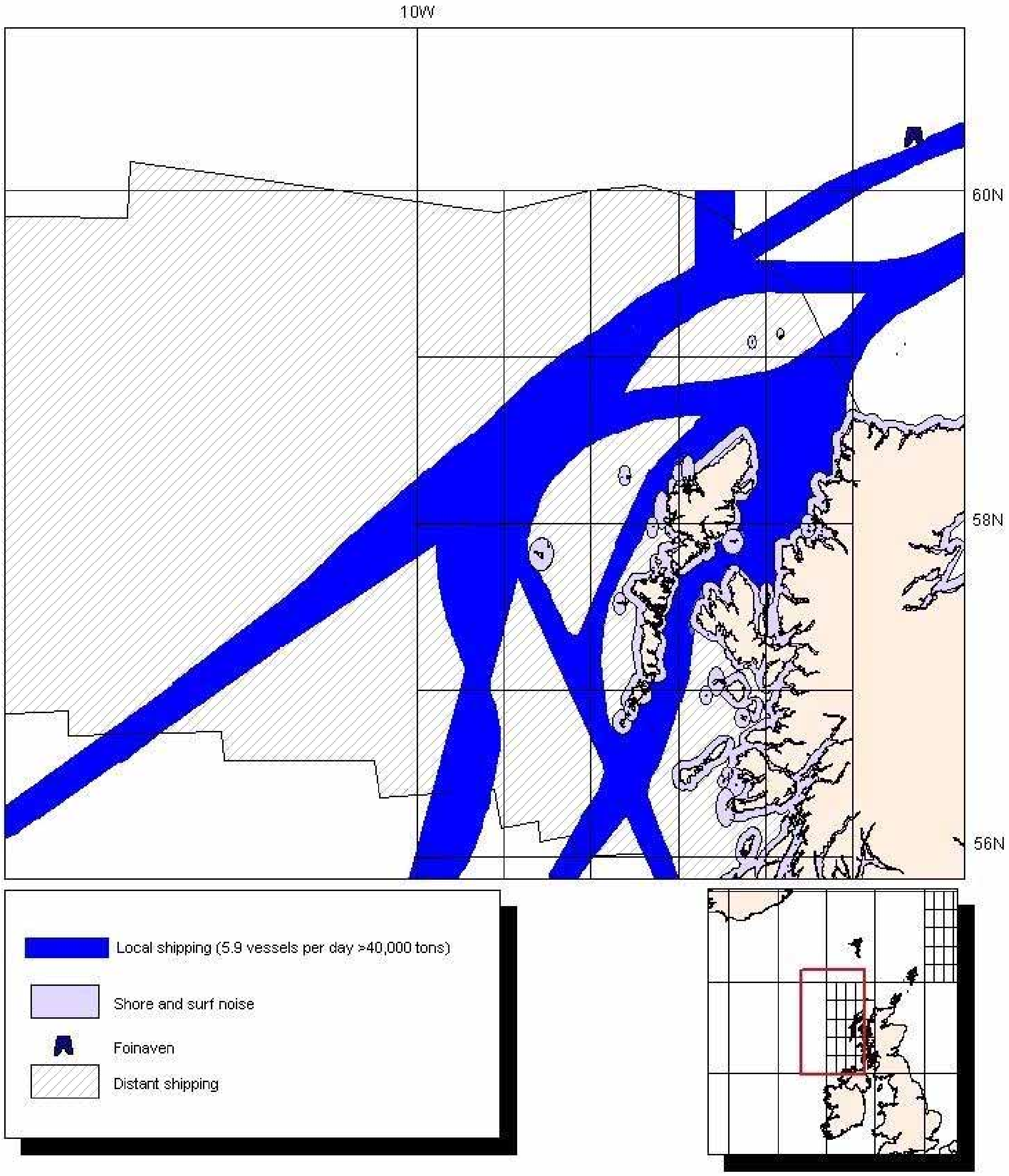

Figure 5-1: Dominant noise sources in the SEA 7 area when there is little or no wind and precipitation

6 Characterising sites for ambient noise levels

6.1 Current techniques

When considering the location and impact of offshore developments, knowledge of the baseline ambient noise levels are required in order to be able to judge the likely impact of underwater noise resulting from construction work, the operational phase and decommissioning. The problem is defining what measurements are needed in order to characterise ambient noise levels over a wide geographic area such as the SEA 7 area, which encompasses many types of acoustic environment. The problem is compounded by the variations in ambient noise spectral content and levels on timescales varying from seconds to many years.

Early work used long time-constant averaging, typically with averaging periods measured in minutes. The majority of this early work was in deep water where there is much lower variability compared with shallow water noise levels and this work led to the reference curves shown in Section 2.

More recently there has been renewed interest in characterising shallow water ambient noise and this has resulted in a number of specialised measuring systems that look not just at ambient noise spectra and levels, but also assess the anisotropy of the noise. Typical of these systems are the Ambient Noise Sonar (ANS) produced by the Florida Atlantic University (Glegg and Olivieri 1999; Glegg et al. 2000), Prototype Ambient Noise Directional Array (PANDA) produced by QinetiQ for the UK MOD (Clarke 2000) and the Pop-up Acoustic Noise Data Acquisition system (PANDA) produced by the National University of Singapore (NUS) (Koay et al. 2002). These arrays have been used to acquire data for periods up to 2-3 days to study the composition of shallow water ambient noise. These time series are still comparatively short compared with the annual cycle of noise variation, but they have started providing an insight into the significant contributors to shallow water ambient noise.

Measuring ambient noise is a very difficult process. Separating ambient noise from self noise problems such as cable strum, flow noise and own ship noise can be exceedingly difficult. Data quality control is also very challenging with problems of dynamic range and flat response across the full frequency range proving challenging. Modern systems using computer-based data collection systems can introduce a number of unwanted tonal artefacts generated within the data collection system. Choice of measuring methodology is also important, depending on the eventual use of the collected data. A number of questions need to be addressed, including; whether the whole water column should be sampled; what the optimal integration time is; and what frequency resolution is needed.

In order to obtain true baseline data for a site it is necessary to collect data throughout all cycles that can affect ambient noise characteristics. For most sites this means monitoring through the annual cycle of variations. Sampling the data for short periods, even if that period is repeated a number of times through say a tidal cycle can miss important short-lived events. Measuring for, say, five minutes every hour could completely miss a ferry passing, a heavy shower or a sediment transport event. However, sampling continuously for long periods, at sampling rates sufficient to capture the frequencies of interest, results in huge quantities of acoustic data which require significant resources to analyse completely.

6.2 Options for characterising noise levels

Realistically, measuring for long periods of time can only be achieved by autonomous data loggers deployed on or near the sea bed at the site of interest. The limits of current data storage media mean that it is not possible to record raw acoustic data with bandwidths up to 200 kHz for this period of time. Processing the incoming data so that averaged spectrograms plus information on transient events are stored makes it is possible to achieve three month deployments with current technology in a physically small unit. Longer deployments are feasible if unit size is increased to include larger batteries. Such a unit can also be programmed to search for specific acoustic events such as marine mammal tonal and echolocation calls, signals from sonars and local shipping noise. QinetiQ has a system under development using a proprietary algorithm to build the statistics of ambient noise and also to classify operator-selected sounds such as animal calls or sonar pulses.

In order to characterise a noise field as large and as varied as the SEA 7 area a large number of measurement sites will be required to obtain a realistic characterisation of the ambient noise. Data measured at these sites would be stored in a database which could be accessed by a geographic information system (GIS) to allow contour plots of noise levels to be obtained. A very limited demonstration of this is presented in Section 7, but many more measurement points will be required to produce meaningful noise maps.

An alternative to large scale measurements is to attempt to understand the contributions of the various sound sources by specifically characterising each source, then using the statistics of occurrence of that source to estimate the contribution of that source to ambient noise levels across the area. Measurements would need to be made of source level and spectra for each source where data do not exist. These data could then be used with various computer models to calculate the ambient noise field.

Although this report does not recommend the large scale use of autonomous recorders, the authors do strongly recommend their use to characterise individual sound sources or individual construction sites.

6.3 Use of models to characterise ambient noise

An alternative to large scale measurements of the levels and spectra of ambient noise is to combine a number of models covering the various sources of sound and sound propagation and use these to predict the sound field in the area of interest. This has the advantage of being considerably lower cost than making real measurements and could be available in a much shorter timescale than could be achieved by a programme of measurements. There is also the possibility of trading computation time for resolution so that the user can work at a resolution and speed appropriate for their needs.

The main disadvantage of the use of models is that while current models are good, they do not achieve 100% accuracy, and in some areas, particularly very shallow water, can only achieve an approximation to the real noise field. Nevertheless, for looking across large complex areas they can give an excellent overview and provide an insight that may not be achievable by real measurements. They can also allow the data to be viewed in ways that would not be possible with data derived only from measurements.

Ambient noise models have been used by the military for some years as part of more complex models investigating the performance of active and passive sonars. This has led to the development of a number of ambient noise models, each with their own strengths and weaknesses. Most models include directionality, as well as spectra and source levels. Directionality is important when considering the performance of sonars with directional receivers.

Ambient noise modelling can be separated into two categories, either complex models, which propagate sound from the noise source to the point of interest, or simple semi-empirical formula which, for example, would relate a wind speed to a noise level.

Complex models

In complex ambient noise models, noise sources are defined at particular locations in terms of source level and frequency. These sources are then propagated to the point of interest using a propagation model. The propagation model can be high fidelity or low fidelity depending on the application.

Modelling of ambient noise has developed over many years and different approaches have been adopted. Sophisticated models use wave model solutions of the wave equation whilst other models use ray theory. Each model has strengths and weaknesses in terms of complexity to run, fidelity of results, computation time and frequency and environmental applicability. Some of the complex models recommended for use in military applications are:

a. RANDI-2 (Research Ambient Noise Directionality Model). This model was developed by the US Naval Research Lab. The model uses sophisticated wave propagation algorithms to produce directional noise predictions from low and mid frequency sources;

b. SANE (Synthetic Ambient Noise Environment). Developed by QinetiQ (formerly DERA) in conjunction with SEA Ltd to provide rapid estimation of the ambient noise field directionality and level. This model uses ray theory and has been validated against real data and CANARY;

c. CANARY (Coherence and Ambient Noise for Arrays) Developed by QinetiQ in conjunction with BAe Systems Ltd to provide rapid estimation of the ambient noise field level and directionality. This model uses ray theory and has been validated against real data and SANE;

d. QUEST (Ambient Noise Map) This model was developed by QinetiQ to provide a framework for generating ambient noise maps on a high resolution grid worldwide; and

e. ANPS (Ambient Noise Prediction System) This model was developed by SEA Ltd.

Each of these models uses input parameters for the noise sources and the acoustic environment and then propagates the noise through the environment model to the point of interest, providing ambient noise as a function of frequency.

Semi-empirical formulae

Formulae are available for the main sources of ambient noise that have received attention in the military domain, such as wind noise and rain noise. These formulae are generally available in the open literature. Less work has been performed on other coastal or shallow sources of ambient noise such as port noise.

To model comprehensively ambient noise for the SEA 7 area, it is recommended that omni-directional levels should be used and that annual, lunar, diurnal and tidal variations be included (lunar and tidal cycles are expected to be of lesser significance in the deep water areas in the west of the area). Environmental ambient noise (due to wind and rain) should be modelled using local wind and rain conditions at the point of interest. Sources located away from the point of interest, but from where sound propagates to that point, should be modelled using expected propagation conditions. This is important since the source of noise may remain at a constant level but environmental conditions may or may not support propagation.

A number of organisations, including QinetiQ, have access to ambient noise models. None of the existing models is fully capable of characterising the SEA 7 ambient noise field. However a number of these models could be adapted or extended to make them directly applicable. Given sufficient resources, these models can be used to provide predicted noise maps for the SEA 7 area throughout the annual cycle and for variable source and receiver depths.

One difficulty is providing data of adequate quality as input to the models. The input data required include:

a. characteristics of noise sources;

b. statistics of source distributions;

c. weather statistics;

d. bathymetry;

e. sea bed types;

f. beach profile information; and

g. historic sound speed profile data.

QinetiQ holds an extensive database of ship noise signature data obtained over many years of noise-ranging a variety of ships on behalf of the military. It is well placed to provide the characteristics of shipping noise for such a model. Research work also carried out on behalf of the military means that QinetiQ also has the necessary expertise on wind-related noise, precipitation noise and surf noise to populate an ambient noise model.

7 Measurements and modelling

7.1 Measurements

Archive data have been analysed to provide a measure of ambient noise in the SEA 7 area. The primary source of these data was a series of autonomous recording units (ARUs) developed by Cornell University. These devices, also known as a "pop-ups," include a microprocessor, one or more hard disks for data storage, acoustic control circuitry, and batteries, all sealed in a single 17-inch glass sphere. An external hydrophone is connected to the internal electronics through a waterproof connector. Once deployed the ARU sits on the seabed recording the ambient sound and, at the conclusion of a mission, the positively buoyant sphere separates itself from its anchor and "pops up" to the surface for retrieval.

QinetiQ was also asked to attempt to get access to the military fixed seabed arrays that are believed to be deployed in the SEA 7 area. These would allow a long time history of ambient noise data to be obtained. The initial approach was met with a favourable response by the military, but no data could be provided within the timescales of the current contract. To obtain these data a joint request from QinetiQ and the DTI will be required. Access will allow a detailed study of the ambient noise levels at low frequencies to be carried out in the deep waters of the SEA 7 area.

Analysis of data from long towed arrays was also considered, but it was not possible to analyse these data within the timescales of this study. Therefore the present analysis is limited to the ARU data.

Figure 7-1 shows the positions of the pop-ups deployed by QinetiQ in June 2004, and Table 7-1 shows the depths at which they were deployed. The ARUs labelled A to C were deployed in shallow, coastal waters near to the south east corner of the SEA 7 area, and ARUs E to R were deployed in deep water off the continental shelf. One other unit (ARU D) was deployed between the two areas, but failed to provide meaningful data.

ARU	Depth (m)	ARU	Depth (m)
A	50	J	800
B	120	K	1200
C	40	L	1400
D	130	M	1800
E	1800	N	2300
F	1300	P	1000
G	350	Q	1800
H	1300	R	1850

Table 7-1: Deployment depths of ARUs

Figure 7-2 shows the time history of the ambient noise level for the deep water ARUs, excluding sensors E, K, L and M which either were not recovered or failed to provide reliable data. Calibration data for the ARUs are not available, so absolute level cannot be determined. These curves were obtained by computing the mean of the signal squared (to give a measure of power) over a 10 second sample of data every 30 minutes. This data reduction was necessary to reduce approximately 0.5 terabytes of acoustic data to manageable quantities for further analysis. However, the dataset from each unit contains comprises a continuous recording of ambient noise, sampled at 20 kHz, for the entire duration of the deployment. This presents the possibility of significant further analysis of this dataset given sufficient time and resources.

The figure shows the data plotted in dB relative to an arbitrary reference. The sensors are nominally identical, and for the purposes of this analysis it is assumed that they each have the same sensitivity and the data are plotted with a common reference level.

Figure 7-3 shows a similar plot for the three units deployed in the shallow area nearer the coast.

The data from ARU R in the deep region and ARU A in the shallow region show noticeably higher levels overall, with apparently lower variability, than the other units. The probable explanation for this is that these units have a higher internal noise level than the other units. The apparent reduced variability is a direct consequence of the higher noise level when plotted in dB (i.e. logarithmically). Examination of the data from these units shows a constant, broad peak centred on 70 Hz. It is speculated that this may be due to the rotation of hard disks in the recording units (70 Hz = 4200 rpm).

It may be seen from these figures that there is considerable temporal and spatial variability in the ambient noise measured through the deployment period and across the deployment area (as evidenced by the variation between ARUs). Most of the sensors in the deep water area show a marked increase in noise level beginning around the 12th June, and this is believed to be due to increasing wind speed, which was typically around 3.5 knots at the beginning of the deployment, increasing to typical values of 7.5 knots near the end of the deployment.

Data from the Marine Automatic Weather System buoy K5, located near the deep water trial area, were requested from the Met Office in order to examine any correlation between the variations in noise level and the wind speed and wave height, however these data were unavailable for the deployment period. To investigate correlations between wind speed, wave height and ambient noise in the absence of local measurements, contemporaneous predictions have therefore been obtained from the Met Office wave model, for the nearest model grid point at 59.00ºN 10.06ºW.

The top graph in Figure 7-4 shows the wind speed, the middle graph shows the resultant wave height and the wind wave height, and the lower graph shows the mean noise level of all the ARUs in the deep water area, i.e. the mean of the curves shown in Figure 7-2, noting that, for plotting convenience, a different arbitrary reference level has been used in this figure. Figure 7-5 shows the same data normalised such that each curve can be plotted on the same scale in order that any correlations may be observed more easily. It may be seen from this figure that, if we ignore the large noise peaks due to specific events (see below), the underlying trend of the background noise level does indeed show significant correlation with the wind speed and the wind wave height. It is therefore likely that the dominant underlying noise source in this dataset is due to wind, with other noise sources dominating during specific acoustic events. It should be noted that gusts in excess of 30 knots were observed towards the end of the deployment, which are not shown in the Met Office data. These may be responsible for some of the increased noise levels apparent in the later part of the dataset.

In addition to the general trends observed in the time history of the measured noise levels there are a number of short duration events and transients with levels significantly higher than the background level, shown as large peaks in the data. Some of these events are specific to individual sensors, indicating local sources, whilst others are recorded by more than one sensor. There are a number of potential sources of these events, including: local ship noise (e.g. one of the trial vessels passing close to one of the sensors); operation of military sonars (these measurements were conducted during a sonar trial); marine mammal vocalisations; and seismic surveying activity. Most notable of these are perhaps the events observable in the data from ARU C, showing large increases in noise level with peaks separated by approximately 25 hours. This 25 hour period between events strongly suggests that they are tidal in origin, and their occurrence is correlated with the tidal data from a tide gauge located in Stornoway. The tide data show that there is asymmetry in the two diurnal tides, and the acoustic events are correlated with the larger of the two, indicating that at these times the tidal currents in the location of the sensor exceed the threshold for some noise-generating mechanism around the sensor, such as turbulence, cable strumming or sediment impact noise. These events may therefore be classified as self-noise as opposed to ambient noise.

Many of the units show two large peaks in noise level between the 10th and 12th June. These are associated with sonar trials which were being conducted in the area, and the increase in noise level is due to a combination of the active sonar transmissions and the noise of the trial vessels.

Figures 7-6 and 7-7 show examples of some of the distinct events. Figure 7-6 is a spectrogram of 30 seconds of data from one of the deep water sensors on the 9th June which shows 3 discrete events at 485 seconds, 495 seconds and 505 seconds, having significant energy up to a frequency of about 300 Hz, with a very short rise time and a decay time of a few seconds. These are the signatures of seismic air guns used as seismo-acoustic sources in a distant seismic survey – the slow decay with reducing frequency content is a consequence of multipath propagation between the source and receiver. Figure 3-2 shows the locations of a number of 3D seismic surveys during 2004 and 2005, including one in the Devenick field in the North Sea between 2nd June and 7th August 2004. It is possible that these observed air gun signals were from that survey. Figure 7-7 is another spectrogram of 30 seconds of data, this time from one of the shallow water sensors (ARU A) on the 7th June, showing marine mammal vocalisations – these broadband impulses with a repetition rate of approximately 2 Hz are believed by the authors to be produced by a minke whale.

Figures 7-8 to 7-10 show snapshots of the spatial distribution of ambient noise level measured on 9th, 12th, and 14th June respectively in the shallow and deep water deployment areas. Some care is required in the interpretation of these figures. Firstly, they just represent snapshots of data obtained by taking a 6-point running average of the curves shown in Figures 7-2 and 7-3 to filter out the short period random variability and then taking a single point in time from each of the smoothed curves for each of the three days. The plots should not therefore be taken to represent the mean level for each day. The contour colour scheme is consistent between the three plots and the data are shown in dB relative to the lowest noise level in the three plots. Secondly, the noise maps are obtained by contouring the available data from the sparse, irregular array of sensors. These figures cannot therefore be used to determine with any great confidence the noise level at points which are not close to one of the measurement points. Rather, they are provided to give a general overview of the spatial distribution of the noise and to show how that distribution changes between the three days. They also show how noise data could be mapped in a GIS across the entire SEA 7 area if sufficient measurement points were available.

These three plots show that, for these snapshots at least, the noise level is generally higher in the shallow water area than in the deep water area. It is not possible to determine from these measurements whether this is due to the fact that the depth of the water is less in the shallow region, or because the measurements were made at shallower depths (although still at the seabed). This point will be revisited in Section 7.2. It is also clear from these plots that the noise levels are generally higher on 14th June than on either 6th or 9th June.

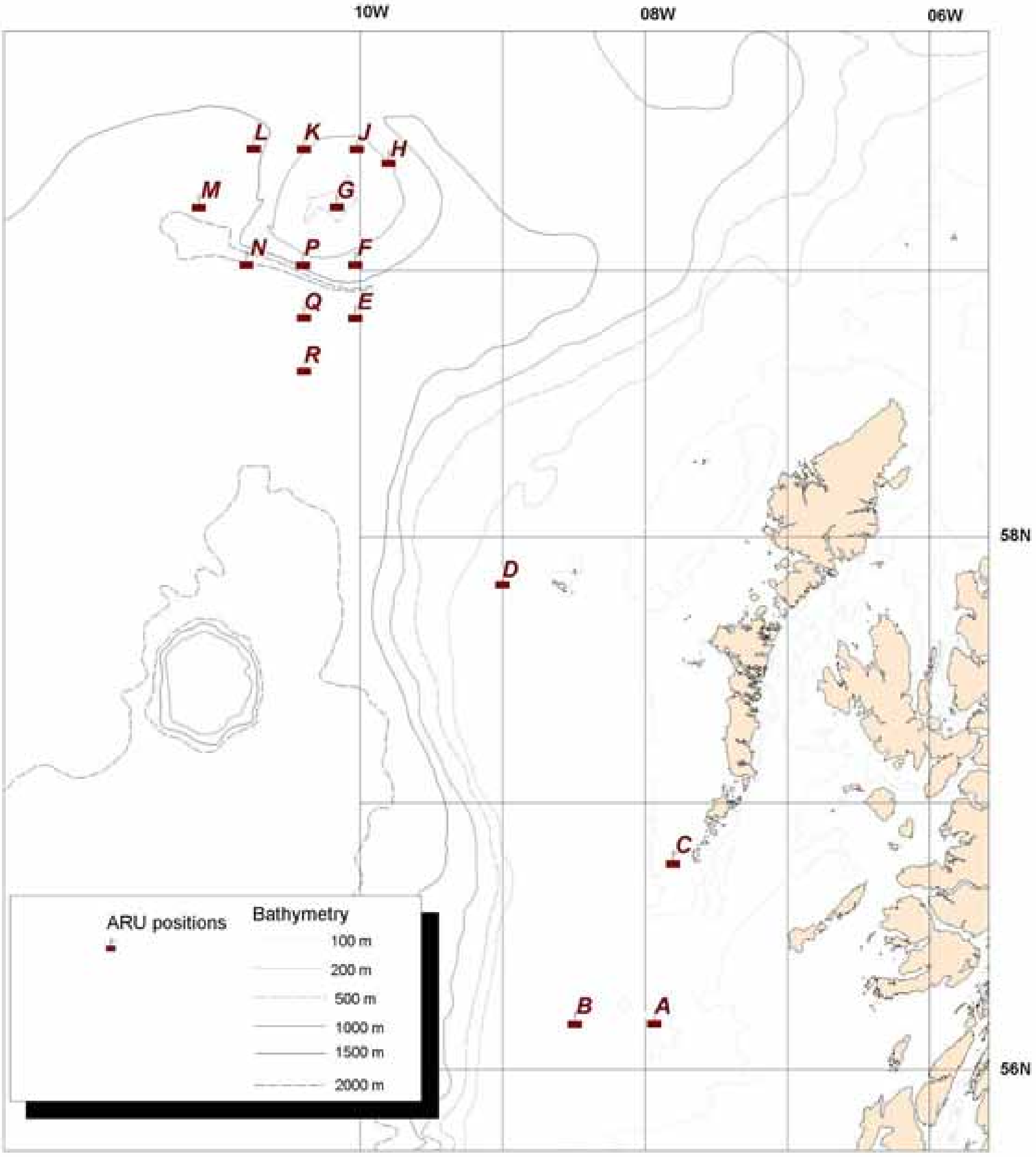

Figure 7-1: Positions of the ARU deployments in the SEA 7 area in June 2004

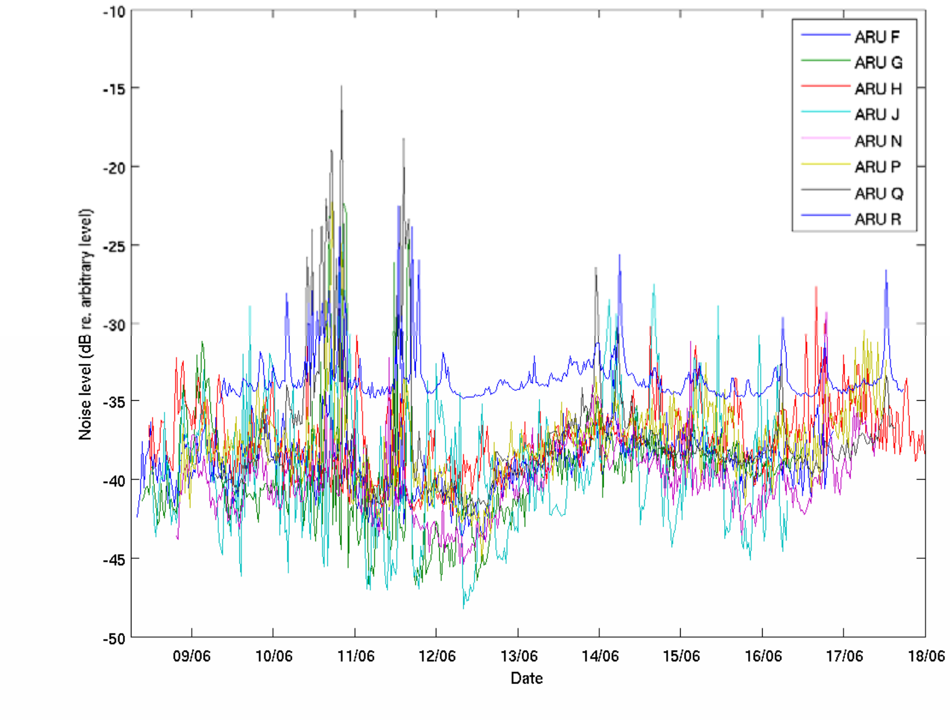

Figure 7-2: Time history of ambient noise level measured by the deep water ARUs

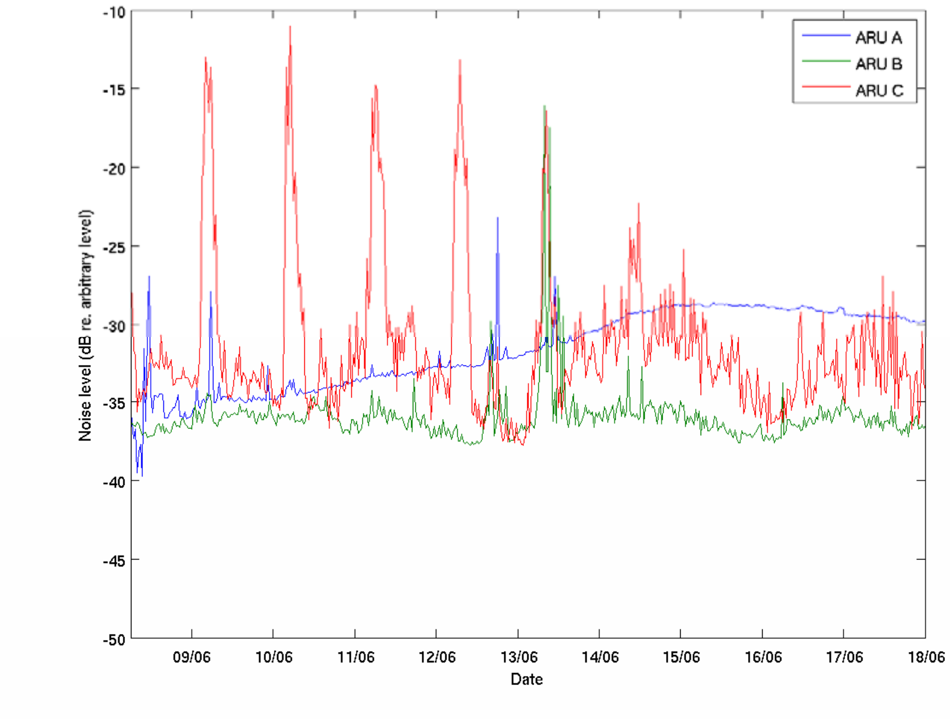

Figure 7-3: Time history of ambient noise level measured by the shallow water ARUs

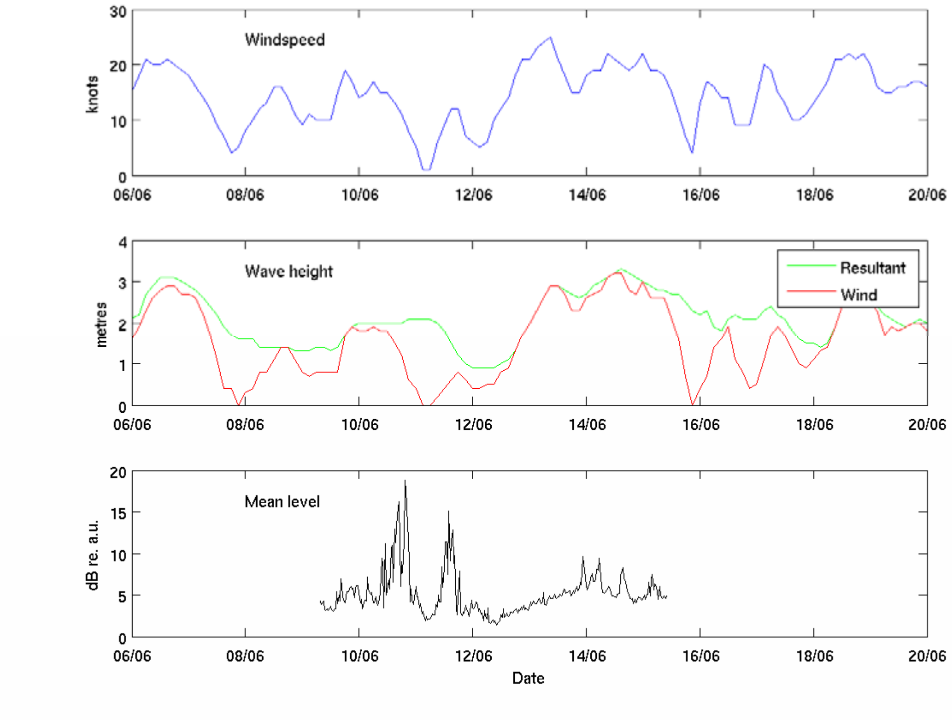

Figure 7-4: Modelled wind speed, wave height and mean measured noise level in the deep water area

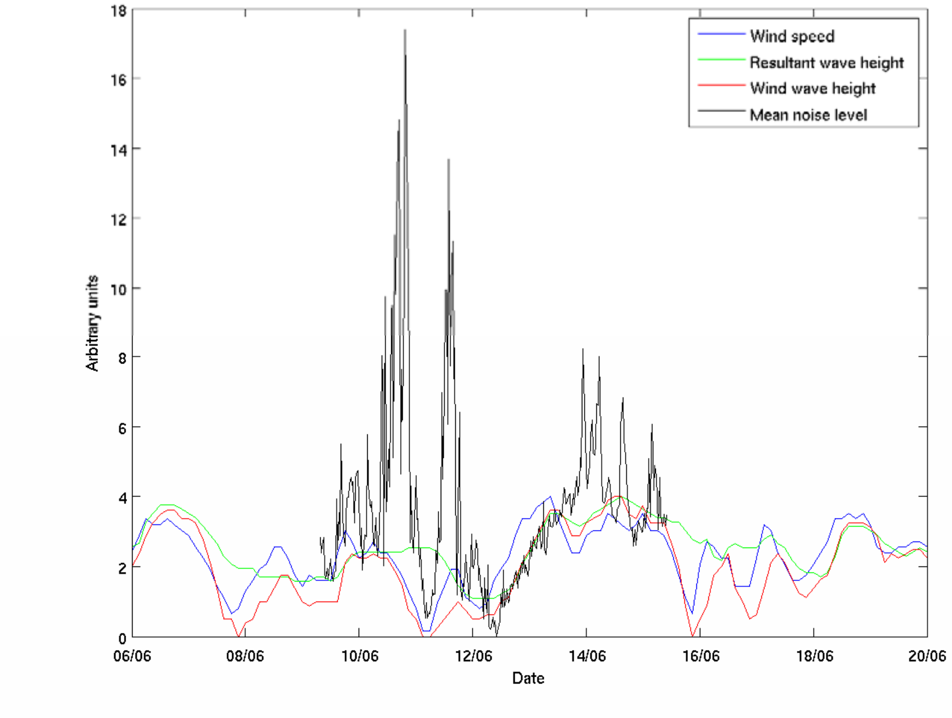

Figure 7-5: Normalised wind speed, wave height and mean measured noise level in the deep water area

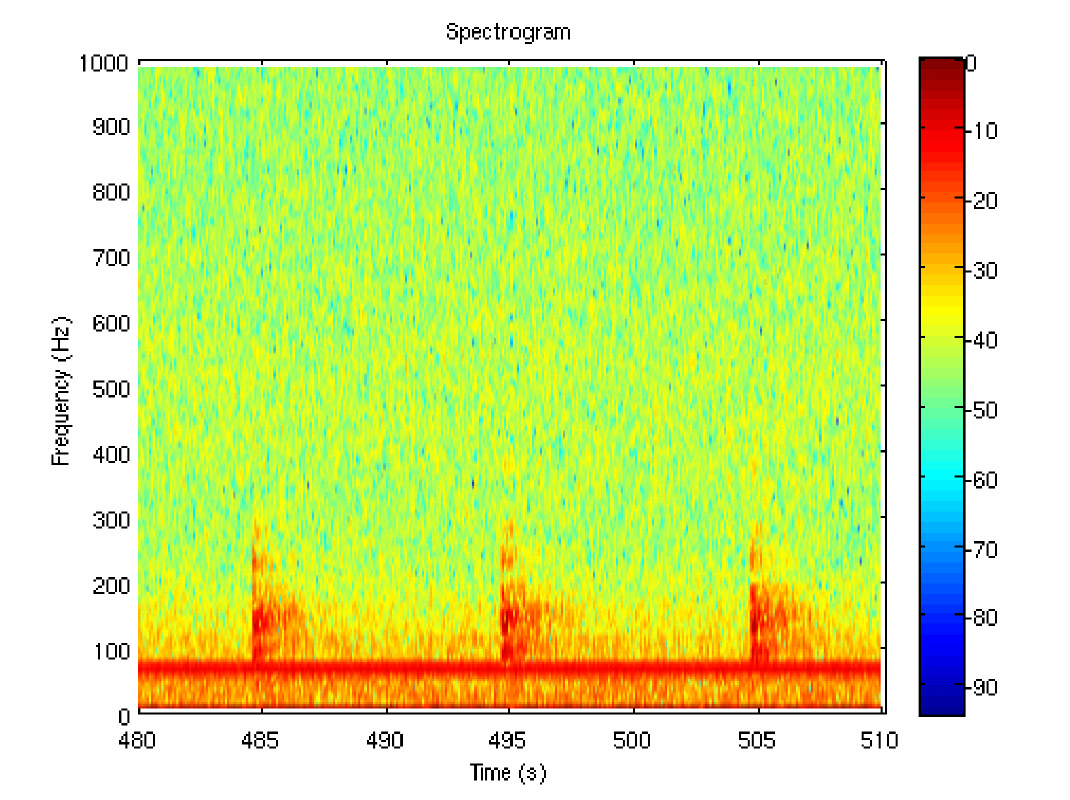

Figure 7-6: An example of a spectrogram showing distant seismic air gun activity

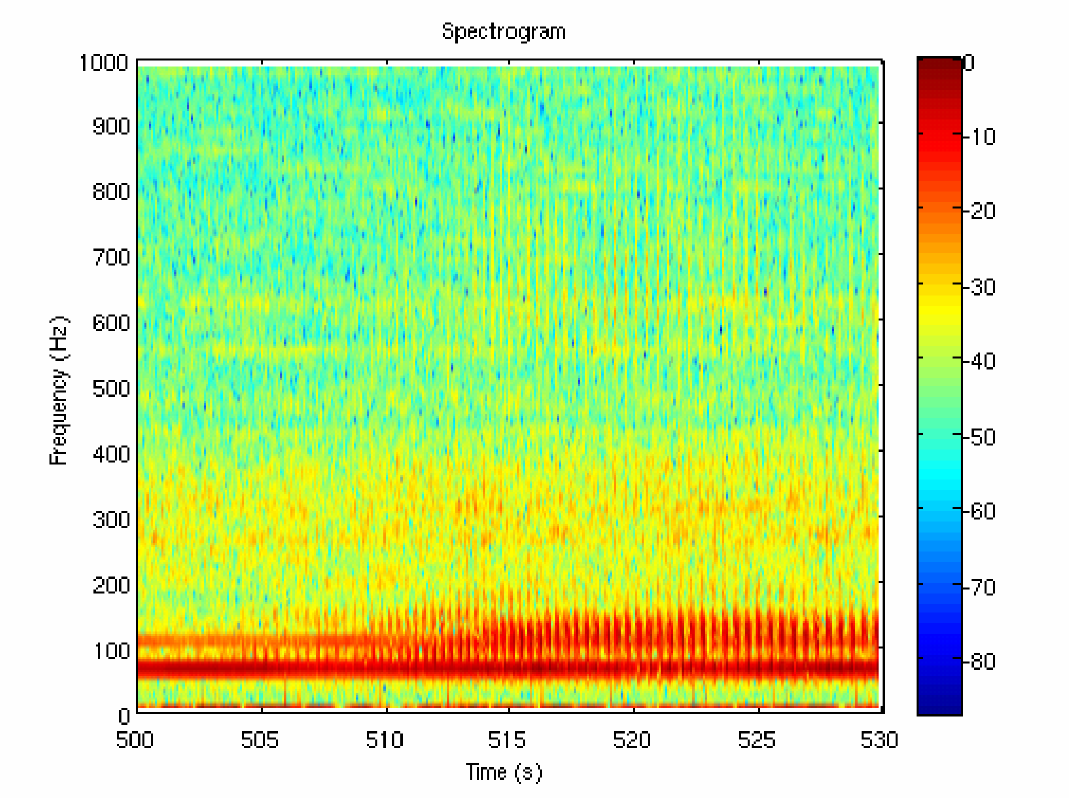

Figure 7-7: An example of a spectrogram showing minke whale vocalisation

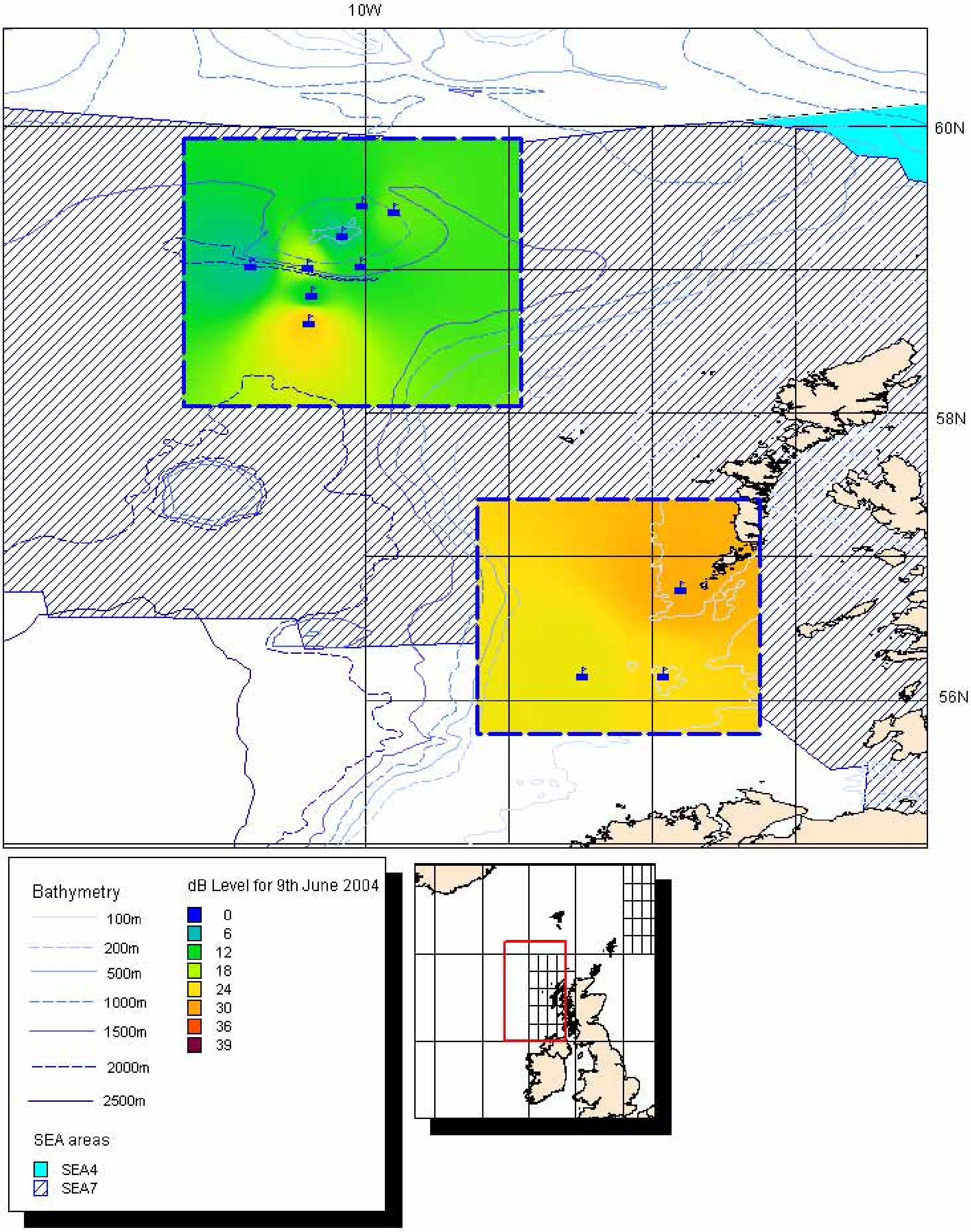

Figure 7-8: Snapshot of ambient noise distribution on 9th June 2004

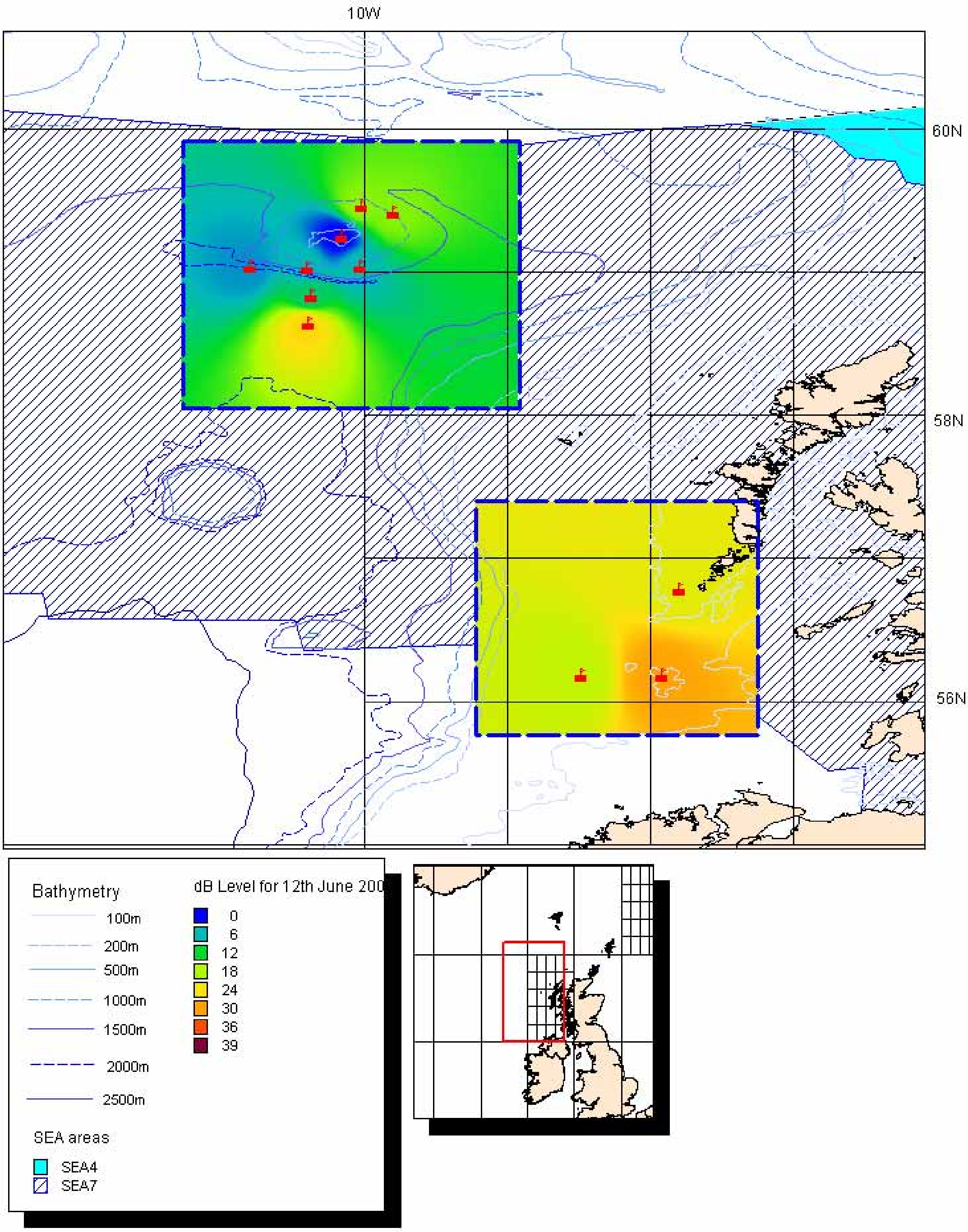

Figure 7-9: Snapshot of ambient noise distribution on 12th June 2004

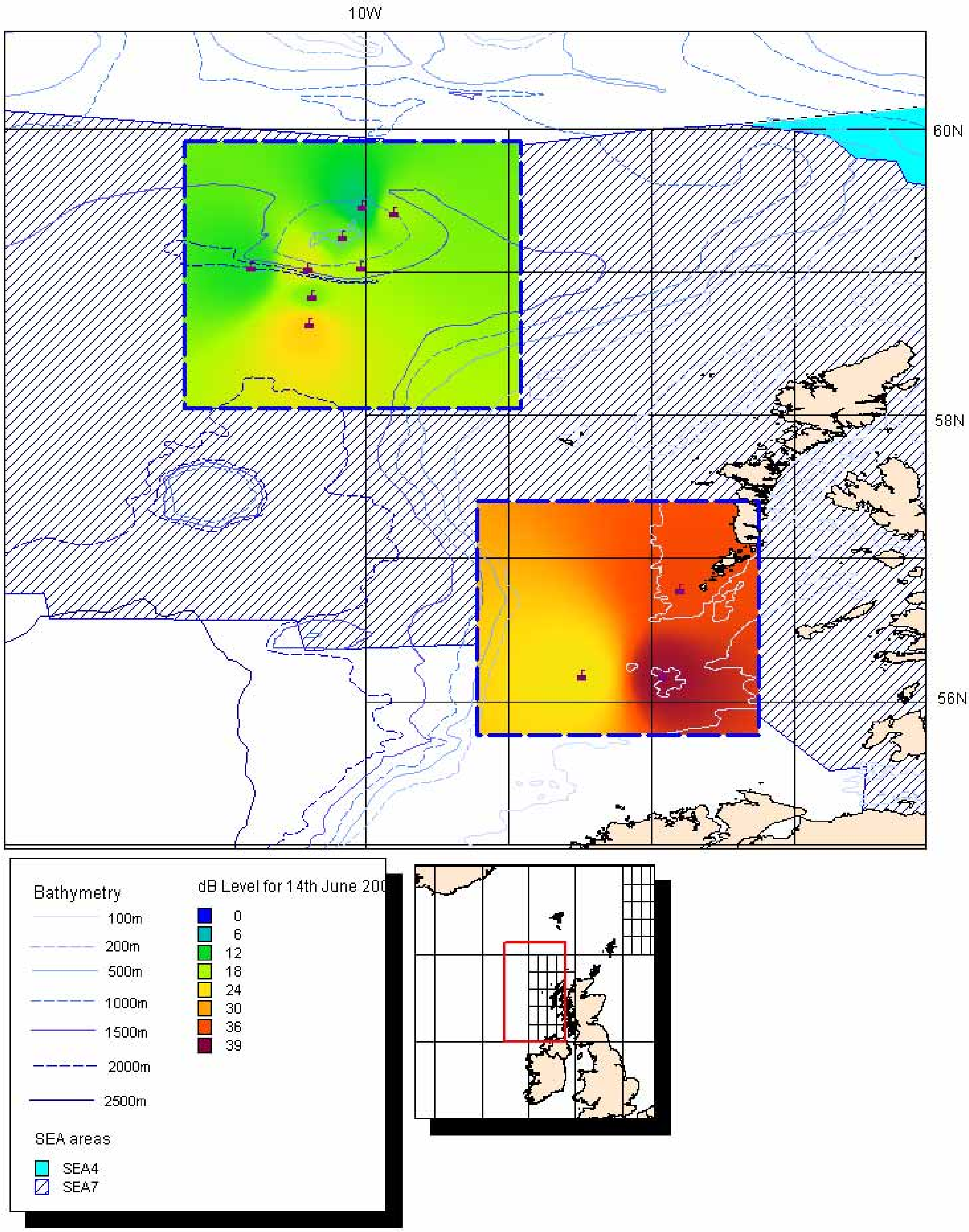

Figure 7-10: Snapshot of ambient noise distribution on 14th June 2004

7.2 Modelling

The modelling of ambient noise in the SEA 7 area has been carried out using the SANE model described in Section 6.3.

SANE models the noise generated at the surface of the ocean by a distribution of dipole sources and can produce synthetic signals with appropriate statistics. The received intensity at a specified frequency, receive angle and depth can be obtained from the model and converted to an isotropic sound pressure level by integrating over all angles at the desired location. The model does not include shipping noise.

The sea surface reflection loss data used are based on the Bechman-Spizzichino formula (Eller, 1986) and are related to wind speed. The surface noise level and surface noise spectrum data are based on Kuperman, Ferla and Ainslie (2001) and are also dependant on wind speed.

Acoustic absorption in sea water absorption is modelled within SANE using the Francois-Garrison formula (Francois and Garrison, 1982a,b) and sea bed reflection loss is produced from geoacoustic parameters using LARES (Langer Approximation for Reflection from the Seabed) (Ainslie, 1999a,b).

Figures 7-11 to 7-14 show the results of running SANE to predict the ambient noise spectra at the locations of two of the ARUs: ARU B in the shallow area and ARU R in the deep area. Simulations of the noise spectra have been carried out for both summer and winter conditions and at a range of different wind speeds.

Figure 7-11 shows the SANE predictions for the shallow, coastal area under summer conditions. The sound speed profile used in the model was one measured close to the location of ARU B during the deployment period. The figure shows results for a sensor at the seabed (representative of the ARU deployment) and at the sea surface, and for wind speeds of 3.5 knots and 7.5 knots, which the trial log states to be representative of the wind speeds at the start and end of the deployment, respectively. It may be seen from the figure that the effect of sensor depth is very small, with very similar spectrum levels predicted both at the sea surface and at the seabed (120 m), although the level at the surface is very slightly higher. This is to be expected, as the dominant noise source will be at the surface in the location of the sensor, and sound propagating vertically downwards in shallow water will experience very little loss. It may also be seen that the wind speed has a significant effect on the overall level – again this is expected as the dominant source of noise modelled is wind generated.

Figure 7-12 shows the predicted spectrum levels at the same location under winter conditions. In this case the sound speed profile has been modelled as isovelocity, which is a good approximation for shallow water which has been well mixed by winter storms. Results are shown for wind speeds of 3.5, 7.5, 15 and 30 knots. Again, we can see the dependence on wind speed clearly demonstrated in the simulation results. There is no discernible difference between the spectrum level at the sea surface and the spectrum level at the seabed for a wind speed of 30 knots, and the two curves overlay one another. The same was true at other wind speeds and the sea surface results have been omitted for clarity.

Figure 7-13 shows the results for the deep water location in summer, using a sound speed profile measured close to ARU R during the deployment. Here the surface and bottom curves begin to diverge at higher frequencies. This may be attributed to acoustic absorption, which depends on frequency, temperature, salinity, pH, and pressure and is typically of the order of 1 dB per kilometre at 10 kHz. This would therefore explain the observed 2 to 3 dB drop in noise level between the surface and the seabed at a depth of almost 2 km. Figure 7-14 shows the modelled noise spectrum level at the deep water site under winter conditions. In this instance the sound speed profile has been derived from climatology for that area in winter. Again we see the expected increase in spectrum level with increasing wind speed, and the reduction in noise level at high frequencies at depth, attributable to the absorption of surface-generated noise in the water column.

Finally, it should be noted that ambient noise typically has vertical directionality, as shown by Figure 7-15, which is a SANE prediction of the vertical directionality with a mud bottom type, and Figure 7-16, which shows the result for an olivine[7] bottom type (Clarke and David, 2002). The upper and lower hemispheres are the very similar over the highly reflective olivine bottom, but the lower hemisphere shows lower noise levels over the absorbing mud sediment.

7.3 Comparisons between modelling and measurements

Figures 7-17 and 7-18 show some of the measured data compared with SANE predictions. The spectra of the measurements are produced using 2048-point discrete Fourier transforms of 10 seconds data. Ideally many such spectra would be averaged to remove the variability which is characteristic of real measurements in order to compare the measured spectra with the model predictions. However, given the time constraints inherent in this study this was not feasible. Therefore, for clarity, Figures 7-19 and 7-20 show the same spectra as Figures 7-17 and 7-18 respectively, with the spectra of the measured data smoothed using a 32-point running mean.

Figures 7-17 and 7-19 show measurements in the shallow area from ARU B, on 7th June and 16th June, together with the model predictions for that location, using a locally measured sound speed profile. The modelled wind speeds of 3.5 knots and 7.5 knots are thought to be representative of conditions near the beginning and end of the deployment respectively.

Because the ARU data are uncalibrated the reference level has been adjusted such that the measurements have an overall level which is comparable with the model curve. This simply corresponds to a vertical translation of the data on the graph. No conclusions about the validity of the predicted level are therefore possible, but it can be seen that the general form of the spectrum agrees well with the measured data over the range of plotted model results (0.6 to 10 kHz). It may also be seen that the overall increase in level observed between the two sets of measured data is consistent with the increase in level predicted by the model as a result of the increase in wind speed. At very low frequencies there is a marked increase in the measured noise level. In this region of the spectrum the dominant noise source is expected to be shipping, and this is not accounted for in SANE, so the model results would not be expected to agree with measurements.

Figures 7-18 and 7-20 show the comparison between modelling and measurement at the deep water site. The data plotted are from ARU R on 9th and 17th June and the SANE predictions are for that position using a locally measured sound speed profile and for wind speeds of 3.5 knots and 7.5 knots. These data are plotted in dB

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[7] The mineral olivine is a magnesium iron silicate.

relative to the same reference level as was used in the previous figure. In this case the agreement between spectral forms of the measured and modelled data is moderately good, but there is an apparent increase in the measured spectrum level above about 5 kHz which is not accounted for in the model. The reason for this is not known, although one possibility is that it is a feature of the frequency response of this sensor. Again the measured data show the increased noise level below a few hundred Hz which is due to shipping noise.

It may be noted that the measured and modelled spectra presented in this section are generally consistent with the Knudsen spectra discussed in Section 2.1 and lies within the limits identified in Figure 2-2.

In such a short study it has only been possible to analyse a small fraction of the available data. The ARU dataset alone comprises some 0.5 terabytes of acoustic data, and QinetiQ have further datasets from numerous trials in the SEA 7 area. Given sufficient time and resources, further analysis and model comparisons could be carried out.

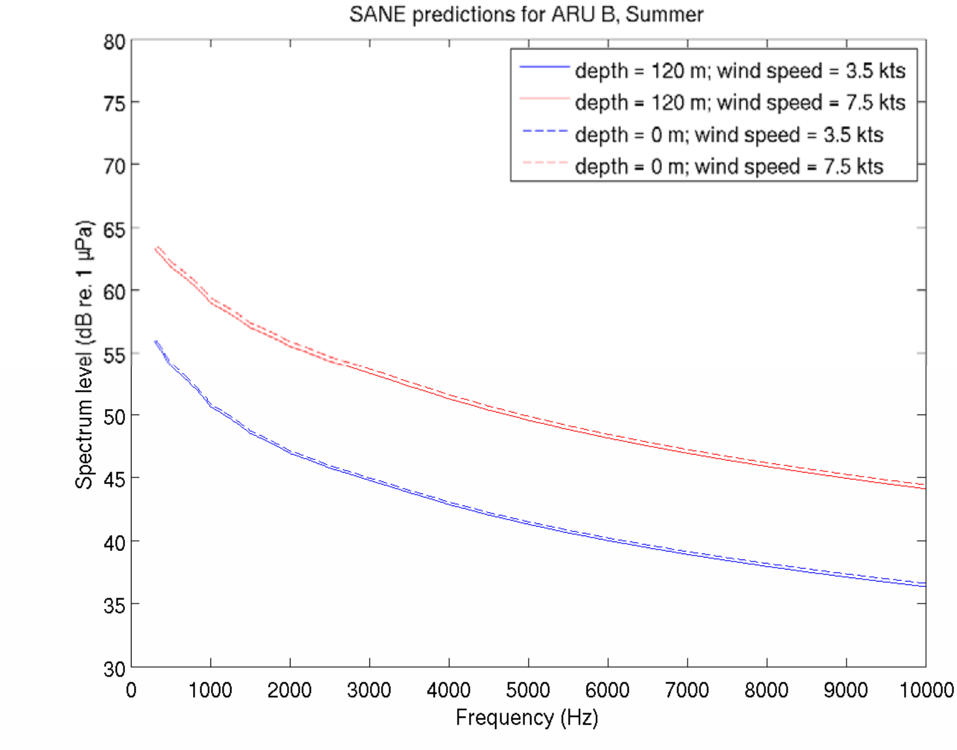

Figure 7-11: SANE predictions for the position of ARU B (shallow water), calculated using a locally measured sound speed profile for the month of June

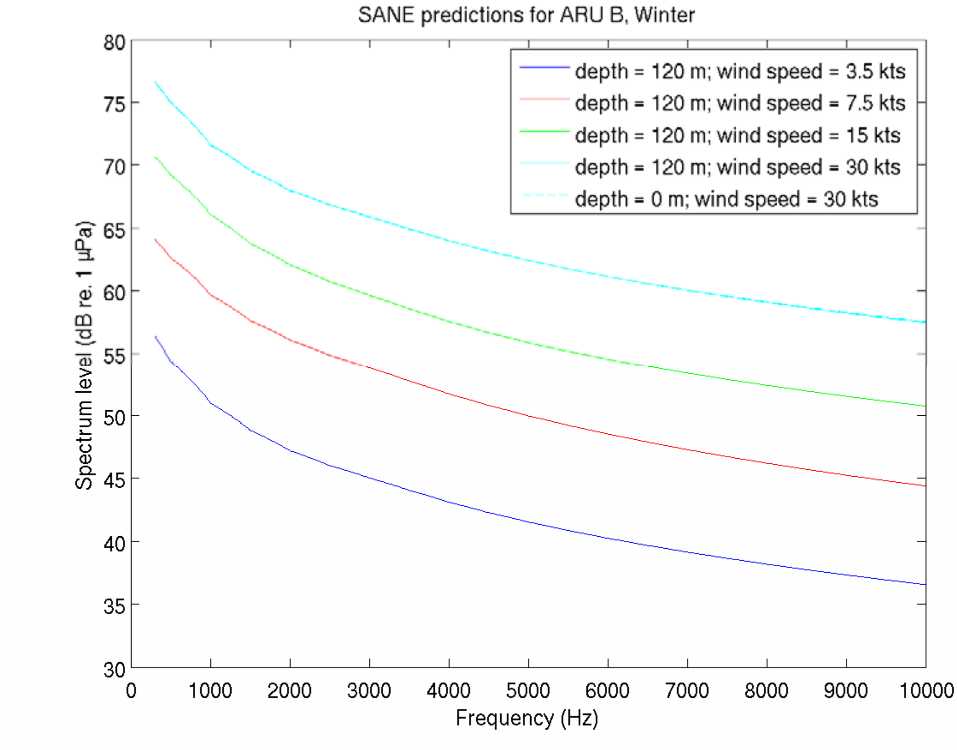

Figure 7-12: SANE predictions for the position of ARU B (shallow water), calculated using an isovelocity sound speed profile representative of winter conditions

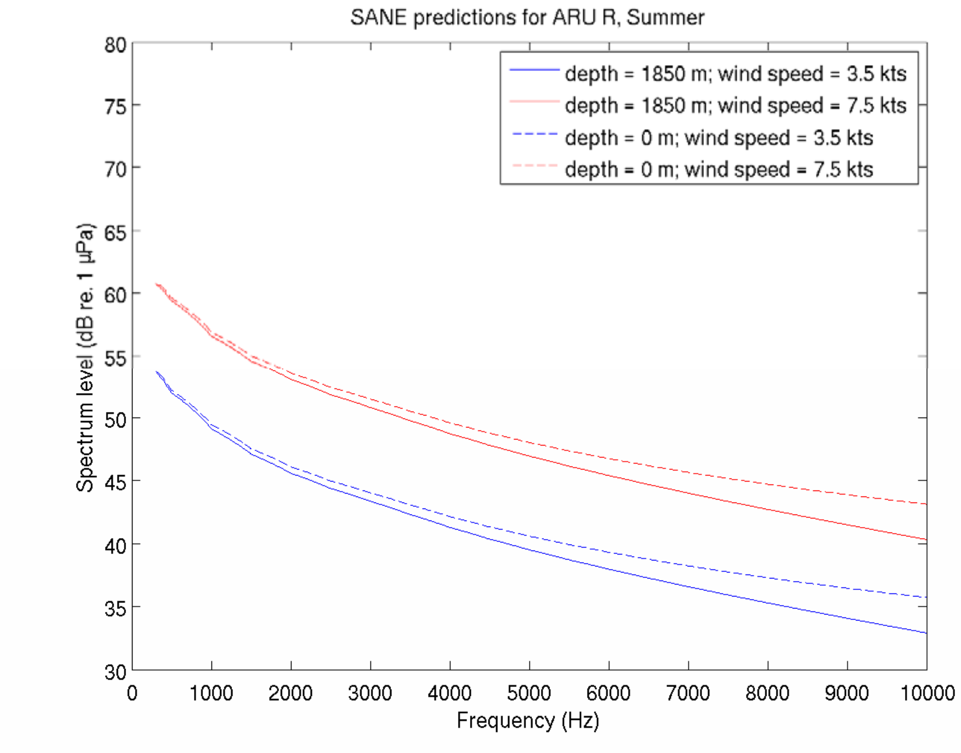

Figure 7-13: SANE predictions for the position of ARU R (deep water), calculated using a locally measured sound speed profile for the month of June

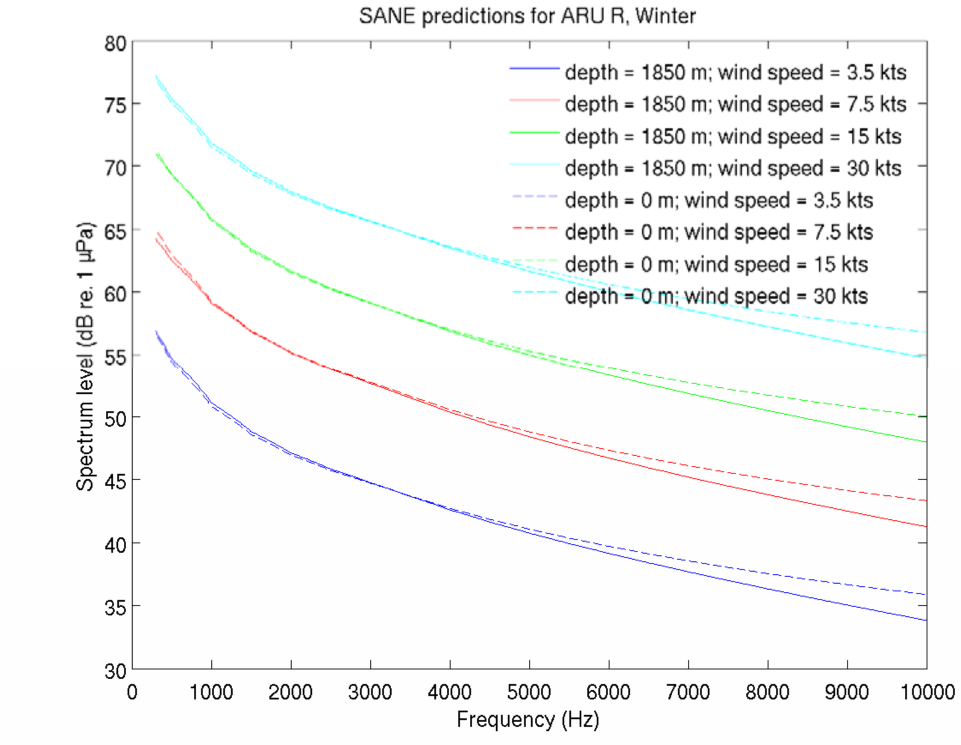

Figure 7-14: SANE predictions for the position of ARU R (deep water), calculated using a climatological sound speed profile representative of winter conditions

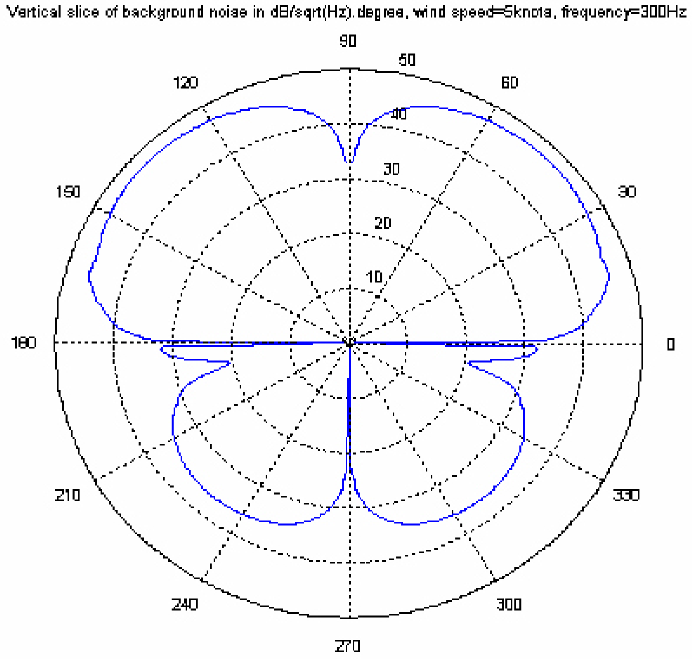

Figure 7-15: Vertical directionality of ambient noise for a mud bottom type

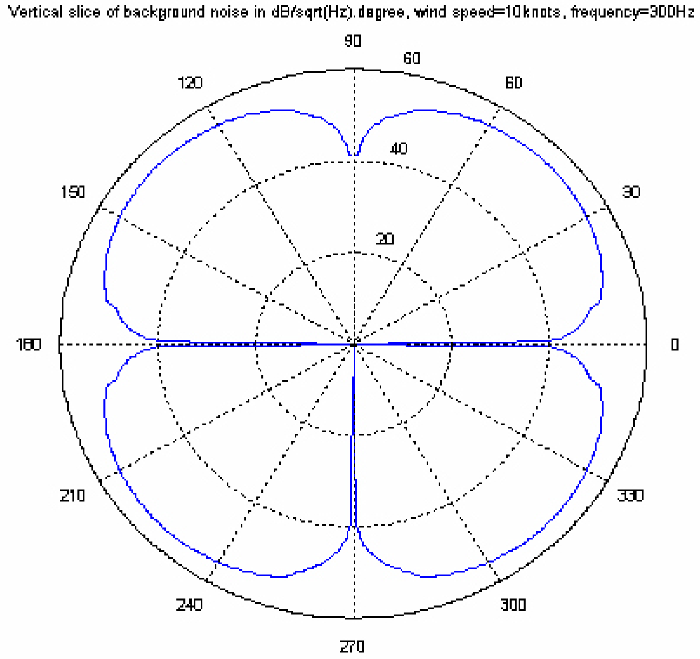

Figure 7-16: Vertical directionality of ambient noise for an olivine bottom type

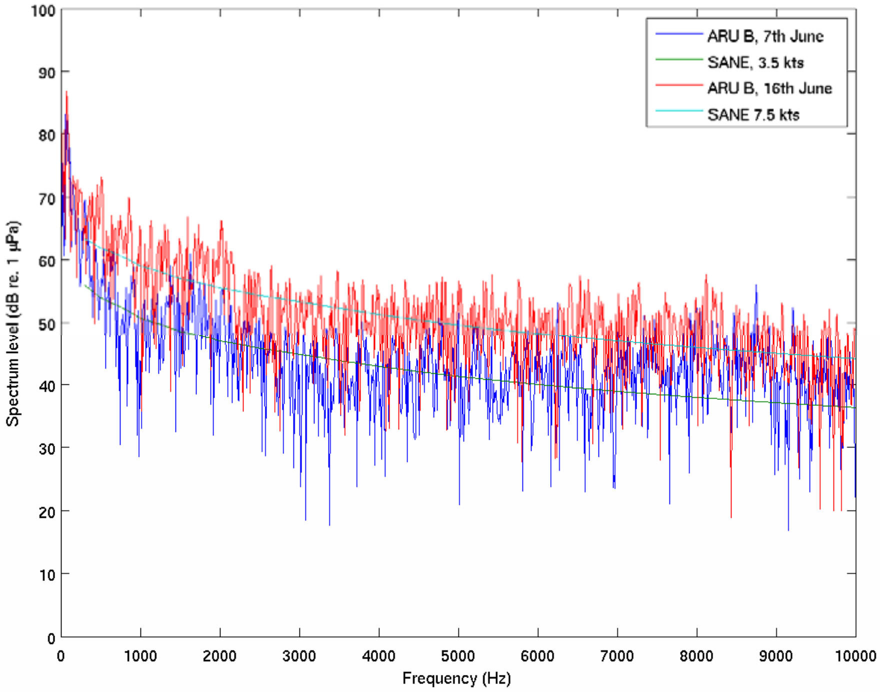

Figure 7-17: SANE predictions for the position of ARU B (shallow water), compared with measurements made by ARU B

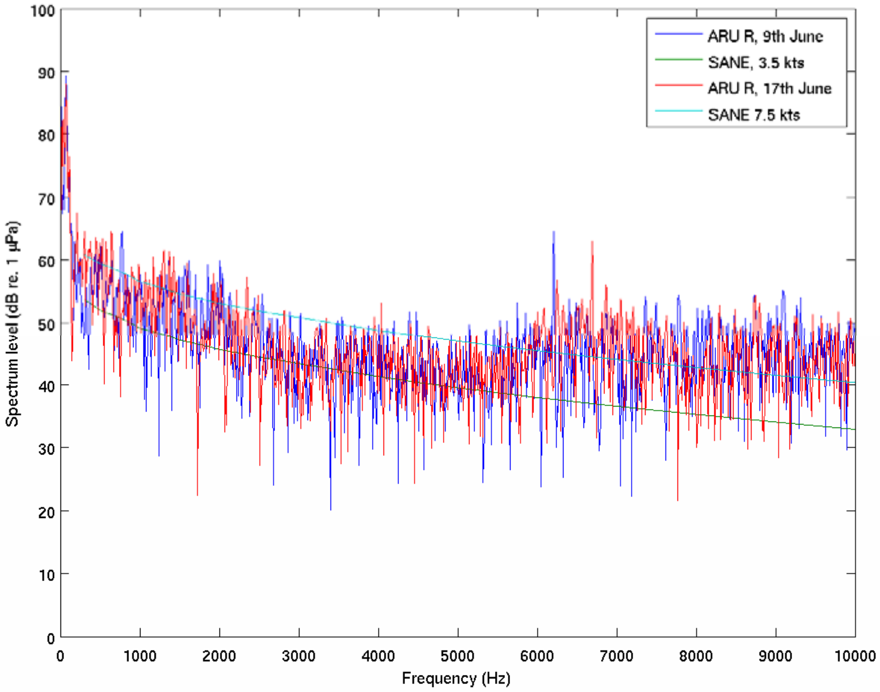

Figure 7-18: SANE predictions for the position of ARU R (deep water), compared with measurements made by ARU R

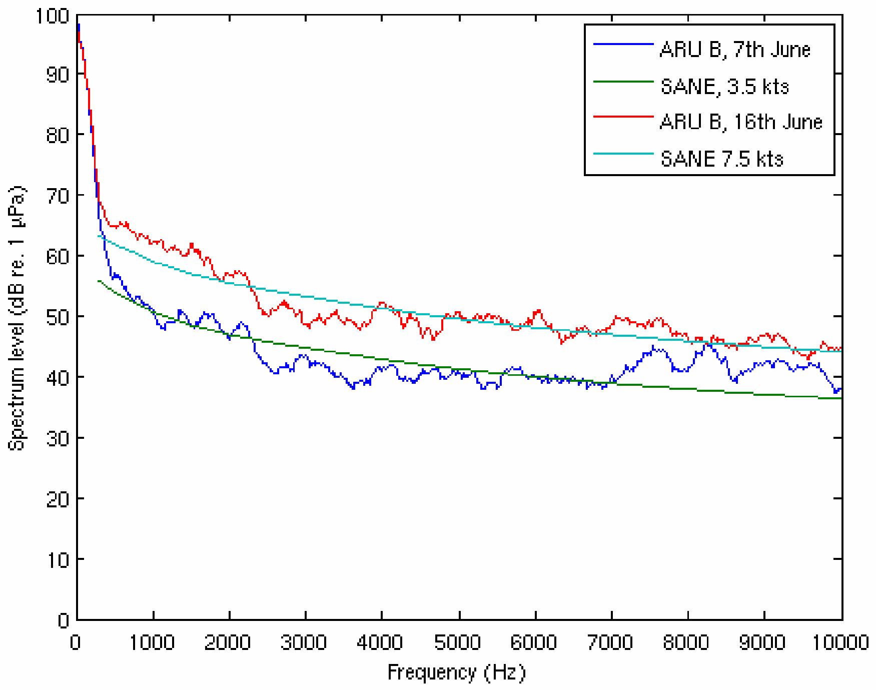

Figure 7-19: As Figure 7-17, but with the measured spectrum smoothed using a 32-point running mean

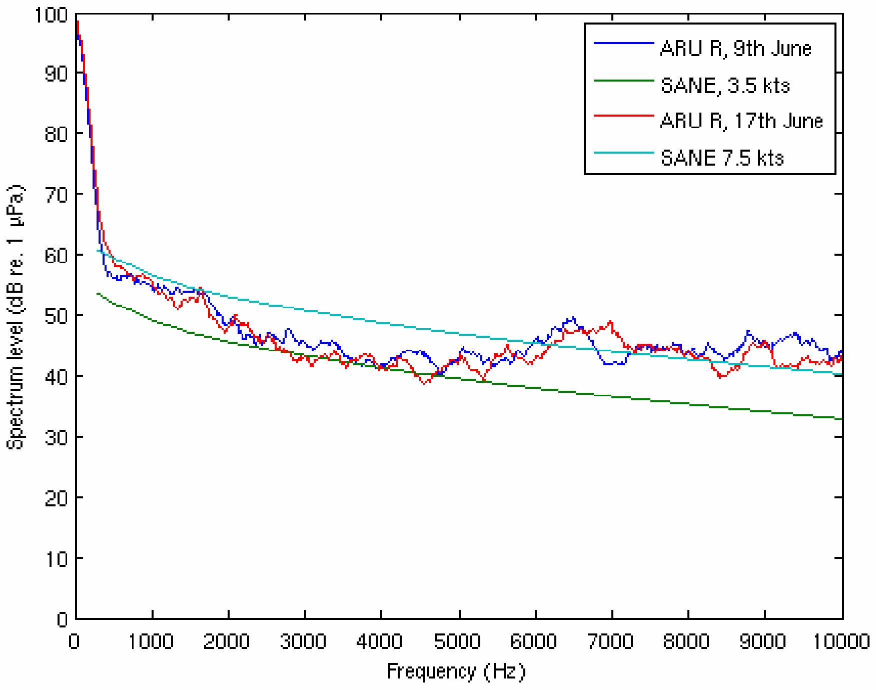

Figure 7-20: As Figure 7-18, but with the measured spectrum smoothed using a 32-point running mean

8 Identified information shortfalls

8.1 Natural sounds

Wind, waves and precipitation

Although there is still some doubt about the exact mechanisms by which noise is generated from these processes, there are a number of theoretical models available which give good agreement with measured levels and which can therefore be used to predict the level of contribution to ambient noise based on weather statistics.

A quick search for weather statistics for the SEA 7 area failed to find data with the level of detail needed to model the contribution of these sources.

Surf noise

The mechanics of noise generation in the surf zone are still not fully understood, but again there are a number of empirical models that give good agreement with measured levels and which can be used to predict sound levels. These models need weather statistics, sea and shore contour, and sediment information as input. There is also a need for a better understanding of the noise levels from rocky shorelines.

Sediment transport noise

No published information on the contribution of sediment transport noise to the total ambient noise in the SEA 7 has been found in the course of this study.

Biological noise

No detailed maps of biological noise sources exist. Whilst the authors have a good understanding of the distribution of cetaceans in the area, much less is known about the presence of sound-producing fish species. Work is therefore required to identify and map these species. This should allow temporal and spatial distribution maps to be produced so that the level of contribution to ambient noise can be assessed. Since the sound-producing species are also likely to be the species most affected by increases in ambient noise levels this information will also assist later environmental impact studies.

8.2 Anthropogenic sounds

Aggregate extraction

No information on noise levels associated with this activity in the SEA 7 area was indentified during the course of this short study.

Shipping noise

This has been well studied over the years and shipping statistics for the SEA 7 area ports combined with acoustic propagation models will give a good assessment of noise fields within the SEA 7 area. The major shipping lanes and shipping density were identified in Section 5, but information on the tracks and numbers of ships using the smaller ports is needed to characterise shipping noise fully.

Leisure craft

No statistics exist for levels of leisure craft activity within the SEA 7 area. It may be possible to extrapolate the data gathered elsewhere by scaling for port size, but ideally a more controlled data gathering exercise is needed.

Industrial noise

Industrial noise has only been characterised in very haphazard manner. Some aspects have been well documented, driven by specific environmental impact requirements, while others have not been documented at all. No oil and gas installations have been identified in the SEA 7 area, although the Foinaven field in SEA 4 may contribute to ambient noise levels in SEA 7 under the right propagation conditions. No operational wind farms have been identified in the SEA 7 area. Power cables have been identified in the area, but no data have been found on the likely noise levels associated with these cables. Areas of high onshore industrial activity should be identified and measurements made of the noise coupled into the sea.

Military noise

There are a number of submarine exercise areas around the Scottish coastline in the SEA 7 area, and a number of trials locations including BUTEC, Benbecula and Cape Wrath. It is unlikely that it will be possible to obtain detailed information on military activities in the area. Acoustic data collection in the main exercise areas will give a good guide to the level of any contribution by such activities to ambient noise levels.

Sonar

No statistics on sonar usage are available for the SEA 7 area at the current time. This may well be a major contributor to ambient noise levels in some areas so a data gathering exercise could prove useful.

Aircraft noise

It has not been possible to identify aircraft movement statistics during this short study, but it is believed that fixed wing aircraft make a very small contribution to underwater ambient noise levels. However, the use of helicopters to service marine facilities is increasing and it would be useful to gather data on this activity in order to assess the level of the contribution this activity makes to ambient noise. The noise signatures of the aircraft commonly in use also need to be established.

Fishing activity

No information on trawl noise could be found during this study and it would be useful to make measurements of a range of trawls typical of those in use in the SEA 7 area. Detailed fishing statistics combined with information on sound levels would enable the contribution to ambient noise levels to be judged.

8.3 Noise measurements

The measurements analysed in the study were made over a limited time period, at a small number of sites. Ideally a large number of measurement sites should be sampled continuously over a period of one year. The authors estimate that approximately 100 sensors would be required to sample the SEA 7 area adequately for the purposes of mapping ambient noise. The sensors should be calibrated and ideally should have a flat, or at least well characterised, frequency response.

9 Recommendations

In this short study it has only been possible to carry out limited modelling and analysis of ambient noise measurements in the SEA 7 area. In order more completely to baseline the ambient noise field in the area it is therefore recommended that a more extensive programme of modelling and measurement be undertaken. Datasets which should be analysed include:

a. the ARU dataset partially analysed in this study;
b. towed array and sonobuoy data held by QinetiQ; and
c. long time series data from the fixed seabed array.

It is recommended that the following method be used to characterise noise in the SEA 7 area:

a. collect data on sound sources within the SEA 7 area in order to meet the shortfalls in information on these sources set out in Section 8 above. Data should provide spectra, source levels and variability information for each source;
b. collect information on the distribution and number of the sources to be included in a model of ambient noise;
c. assemble the input data required to run the ambient noise model;
d. modify an existing ambient noise model to operate in the required manner. SANE is suitable for modelling surface generated noise, which may dominate much of the spectrum under many weather conditions, but it does not include shipping noise, for example, which will be dominant over much of the SEA 7 area under low wind conditions;
e. run the model to provide the required noise field data. Depending on computation times this may be a set of pre-calculated plots or it may be on a ‘run as required’ basis;
f. collect and analyse data from a selected number of sites within the SEA 7 area to validate the model. QinetiQ has an extensive archive of data from sonar trials in the area which could make a useful contribution to the required dataset, but it is likely that further measurements would be required to provide high quality, dedicated ambient noise data from calibrated sensors, with large dynamic range and flat frequency response, and with low self noise levels; and
g. make incremental improvements to the model to improve geographic resolution and include additional sources

This programme of work will provide a good understanding of the ambient noise fields across a large proportion of the SEA 7 area. It will also provide information on how the field will vary with the different cycles affecting noise levels.

This work will complement the detailed baseline measurements required to understand the ambient noise field at specific sites for possible construction activities. It is recommended that long term underwater acoustic monitoring of these specific construction sites, carried out to meet environmental impact requirements, is used to further refine the recommended modelling of the whole SEA 7 area noise field.

It is recommended that consideration be given to an acoustic dose system for geographic areas in order to limit the impact of high power sounds sources.

10 Conclusions

This report has set out the sources of ambient noise likely to be found in the SEA 7 area. This information is based on the many years of experience built up within QinetiQ and its predecessor organisations while supporting research into military sonars.

In addition, measurements of ambient noise in the SEA 7 area have been analysed to provide spectral characteristics of the ambient noise at a limited number of sites in the SEA 7 area, together with indications of the temporal and spatial variability of the relative spectrum level.

Predictions of spectrum level as a function of frequency have been carried out for different locations in the SEA 7 area for a range of wind speeds under summer and winter oceanographic conditions. These predictions have been compared, within the limitations of the modelling and measurements, with the real measured data.

The dominant source of the ambient noise measured during a short deployment in the summer of 2004 was found to be wind-generated surface noise, and the predictions of an ambient noise model were consistent with the measured data. However, the existing models do not include all of the important sources of ambient noise, and further development is required to predict the ambient noise when these other sources are important.

The modelling and data analysis conducted in this short study has been necessarily limited, and a much more extensive programme of modelling, measurement and analysis is recommended in order fully to characterise the ambient noise in the SEA 7 area. This programme needs to cover a large number of sites in the area over a full annual cycle, with sufficient temporal and spatial resolution to capture the important temporal cycles and spatial variability.

Ambient noise depends on a wide range of anthropogenic and natural sound sources. These sources add together in a complex manner resulting in significant spatial and temporal variations in the noise field. Thus short term measurements at a single location can only provide a snap-shot of the noise field and cannot be used to extrapolate to other locations and times.

A suggested alternative is to characterise each sound source and use this information with occurrence statistics for each source to model the ambient noise field across the SEA 7 area.

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Abstract

This report has been prepared for Geotek Ltd., acting on behalf of the Department of Trade and Industry as part of the Strategic Environmental Assessment (SEA) process for the UK continental shelf. This technical report is part of the SEA 7 process which covers the area from the northern Irish coast northwards through western Scottish coastal waters to Cape Wrath then northwards to 60 degrees north and westwards to 24 degrees west. This report looks at the sources of underwater noise that combine to provide the background ambient noise levels in the waters of the SEA 7 area and considers the mechanisms by which the sound is generated and may then be modified by the environment. Analysis of underwater ambient noise measurements in the SEA 7 area, and numerical simulations of ambient noise levels are presented and compared. Options for further characterising ambient noise levels in the SEA 7 area are presented.

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