Acoustic Cetacean Monitoring
1996 to 1999:

Towards the Development of an
Automated System

Summary Report

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2 Summary

This report summarises work carried out for Shell UK by Birmingham Research and Development Ltd during the period 1996 to 1999. Details of this work can be found in the periodic reports listed in Appendix 2. The work summarised here includes hydrophone and software developments made throughout this period and offshore trials and monitoring work carried out during the summers of 1996 to 1998.

Twenty different species of cetacean are found in UK waters. Cetaceans are acoustically orientated animals, using sound both actively and passively to communicate, to navigate and to find food. The intense sounds produced by the air guns used during seismic surveys are capable of disturbing and potentially harming cetaceans and UK Government guidelines stipulate that seismic survey activity should not start if cetaceans are known to be within 500 m of an airgun array.

Many species of cetacean are hard to spot even in ideal sighting conditions. On the other hand, the sounds that they make can often be heard over considerable distances. The purpose of this project was to investigate the potential of passive acoustic monitoring for cetaceans in the vicinity of seismic vessels and to develop detection equipment which would be appropriate for use in the course of offshore seismic surveys, would be largely automatic, require the minimum of operator intervention, and would be easily reproducible.

Monitoring and equipment testing was carried out at sea over three summers. An analysis of acoustic and visual detection rates shows that cetaceans are ten times more likely to be detected with acoustics as opposed to visual methods. However, some species (such as fin and minke whales) rarely vocalise in this area, or their vocalisations are hard to detect in the noisy environment around a survey vessel and these species are still best detected by trained visual observers.

The types of vocalisation made by cetaceans are many and varied. The level of information that can be extracted from an acoustic detection depends on the type of vocalisation. For instance, the regular clicks of sperm whales allow accurate positions for that species to be determined. For faster moving species travelling in groups (many species of dolphin) on the other hand, it is still difficult to determine position, and acoustic information can currently only reliably indicate presence / absence.

Detections were made using a passive hydrophone towed on 400 m of cable from the guard vessel positioned approximately 1 nautical mile ahead of the seismic vessel. The hydrophone was designed to be adaptable and deployable from almost any type of boat. Although the UK Government’s guidelines do recommend the use of hydrophones to detect the presence of cetaceans, the airgun start up procedure has been designed primarily with visual monitoring in mind. The paucity of accurate position data from many acoustic detections and the fact that acoustic monitoring had to be carried out from a vessel positioned some distance from the airgun array may require the development of different start up procedures.

Software to automatically detect many types of vocalisation has been developed. The software, in its final form, consists of a suite of three detection programs, each designed to detect a different type of sound. All three programs can run together on a single high performance PC, along with three other programs which control digitising cards, provide a simple user interface to the three detection programs and collect position data from the ship’s navigation equipment. Information on all detections and monitoring activity is stored in a database for later analysis.

Routine acoustic monitoring prior to seismic start-up was carried out in the summers of 1997 and 1998. During this period, of the 123 planned line starts, 6 were aborted due to the presence of acoustically detected cetaceans while the start positions of a further 20 lines were either advanced or delayed due to the presence of detected cetaceans.
3 Introduction

The following sections give background information which presents a persuasive argument for the use of acoustic monitoring to aid the detection of cetaceans prior to the start of seismic lines. The UK Government’s ‘Guidelines for minimising acoustic disturbance to marine mammals from seismic surveys’ state that no seismic source should be used while cetaceans are within 500 m of the source.

3.1 Seismic surveys

3.1.1 Overview

Marine seismic surveys involve generating regular pulses of acoustic energy behind a moving survey vessel. These pulses travel to the seabed where they reflect off the bottom and interfaces within the underlying rock strata. The reflected sound is picked up by one or more hydrophone arrays streamed behind the survey vessel allowing a profile of the underlying rock strata to be constructed.

These acoustic pulses are usually generated using arrays of air guns, which release compressed air into the water column. Released from the gun, the air expands rapidly forming a bubble, which then collapses, generating the primary pulse. Arrays are configured so that the pulses from the individual guns add constructively and most of the acoustic energy is directed downwards (McCauley, 1994). The primary pulse is the pulse of interest to the geophysicist. It is typically short, lasting 5-30 ms, with peak sound levels in the range 6100 Hz (Barger and Hamblen, 1980). Several bubble-pulses and reflections of the pulses from the sea surface follow the primary pulse (Dragoset, 1990).

The source level of an airgun depends on design, capacity, air pressure, and detonation depth of the airgun. Typically, they produce broadband peak to peak source levels between 215 and 230 dB re 1 µPa-m with highest energies falling between 6 - 100 Hz. For arrays of airguns this can rise to 230 - 255 dB re 1 µPa-m measured below the source array (McCauley, 1994; Richardson et al., 1995).

Whilst most of the acoustic energy from and array is directed downwards, a significant amount of energy is radiated in other directions. For linear arrays, source levels are greatest abeam of the array and least ahead and astern (McCauley, 1994). Once the seismic pulse reaches the seabed much of its energy is reflected and dispersed in all directions. In deep water, the "loudest" sound may be the reflection from the seabed, not the pulse arriving directly from the source itself. Sound reflected from the bottom and scattered back to the sea surface is reflected off this interface back into the water column.

Marine seismic surveys are commonly either two-dimensional (2D) or three-dimensional (3D). 2D surveys are usually conducted with a single hydrophone array that is towed along single or widely spaced survey lines over the area of interest. This generates two-dimensional cross-sections of the underlying strata. 3D surveys use multiple hydrophone streamers and airgun arrays that are towed along closely spaced parallel survey lines. This method generates a three-dimensional image of the strata. 3D surveys concentrate seismic activity in a small area for prolonged periods (McCauley, 1994).

3.1.2 Seismic operations during the field trials

A typical seismic gun array for 3D surveys, and the one used during most of the monitored surveys 1996-1998, is shown in Figure 1. Typically a seismic survey vessel engaged in a 3D survey will tow two of these arrays, one streamed to port and one to starboard, each array being fired alternately in “flip-flop” mode. This type of array was used during the monitored surveys; the total capacity of each array was 4019 in Sabel (pers. comm.).

During the 1996 field trials in the West of Shetland prospect, measurements of the seismic source were made at various angles and at various distances from the airgun array (Gordon et al., 1996). The primary pulse of the 4017 in³ capacity airgun array produced a mean peak acoustic level of 185.5 dB re 1 µPa/1 Hz re 1 m (n=4, s.d.=2.18), with peak frequencies between 175 - 638 Hz. However, measurements of the pulse reflected off the seabed gave a higher mean peak acoustic level of 207.1 dB re 1 µPa/1 Hz re 1 m (n=18, s.d.=2.74), with peak frequencies between 25-150 Hz. This shows that the reflected pulse is actually louder (for a near surface receptor) than the primary pulse and shows peaks at a lower frequency. This is because the primary pulse is directed downwards whilst the reflected pulse is reflected in all directions from the seabed. Figure 2 shows the
waveform of the pulse as measured during monitoring in 1997. Figure 3 shows the spectrogram for the same shot.

Figure 1 - Airgun array towed by the seismic vessels during the monitoring periods. N.B. two of these arrays were towed 50 m apart behind the seismic survey vessel at a depth of 6 m and fired alternately. Individual air-gun capacities are given to right of the gun in in³. Adapted from (Sabel, pers. comm.).
Figure 2 - Seismic shot waveform produced by 4017 in$^3$ airgun array, Brendan's Dome prospect 1997. Recorded at the guard vessel’s hydrophone 1 NM ahead of the seismic vessel. The primary pulse occurs at 0 s with reflected pulses from 0.27 s. Amplitudes are normalised to the peak amplitude.

Figure 3 - Seismic shot spectrogram produced by 4017 in$^3$ airgun array, Brendan's Dome prospect 1997. Recorded at the guard vessel’s hydrophone 1 NM ahead of the seismic vessel. The primary pulse occurs at 0 s with reflected pulses from 0.27 s (the curved lines are dolphin whistles). N.B. both the primary pulse and the first reflected pulse have broad bandwidths. Amplitudes are normalised to the peak amplitude.

Details of each year’s seismic surveys are shown in Table 1. The location of each of the prospects is shown in Figure 16.

It can be seen from these that seismic surveys affect geographically restricted areas for extended periods of time. For example in 1997 over 2,400 nautical miles of line were shot in the Brendan’s Dome prospect with shots every 10 s over a period of 2 months; allowing for down time, this resulted in over 180,000 shots.
Table 1 - Details of the seismic surveys conducted during the monitoring trials.
This table is based on data provided by Shell UK in the form of shot files and from Sabel (pers. comm.). The seismic data does not include aborted lines, test shots or ramp-up periods.

3.2 Exploration areas
The distribution of seismic exploration areas and their relationship to cetacean distributions determines the degree of overlap between the two. Following initial exploration of the shallower more accessible areas of the UK's continental shelf, exploration has moved into deeper waters. Initially speculative 2D lines were shot in the deeper waters but with the granting of licenses for these areas – particularly the 12th, 16th and 17th ‘Frontier’ rounds - more focused exploration has been and will continue to take place in these deeper waters. The bathymetry of the UK continental shelf, seismic exploration areas planned for the Atlantic Frontier in 1997, the UK continental shelf 17th license blocks and the Irish 3rd Frontier license blocks shown in Figure 4. The areas seismically surveyed during this project are shown in Figure 16.

Information on the distribution and abundance of marine mammals in these waters is limited (see section 3.3). However, the Atlantic Frontier is known to be an area with a diverse cetacean population (Moscrop and Swift, 1999). Species that may be particularly vulnerable to disturbance by seismic surveys, including low frequency specialists such as baleen whales, and deep divers, like the sperm whales, are common on the Atlantic Frontier but rarely found on the North Sea oil fields.

This trend towards increasing oil exploration in deeper waters with more diverse and vulnerable cetacean populations is being seen throughout the world.
Figure 4 - Bathymetry and oil exploration areas on the United Kingdom continental shelf. Shows the bathymetry of the UK continental shelf, seismic exploration areas planned for the Atlantic Frontier in 1997, the UK continental shelf 17th license blocks and the Irish 3rd Frontier license blocks. Adapted from Jackson (1997).
3.3 Cetacean species and their distribution

3.3.1 Sources of cetacean survey data
There has never been a major co-ordinated cetacean survey in the waters to the west of the UK so data on the populations of cetaceans found in Atlantic Frontier waters is far from complete. What information there is comes from a variety of sources. Recent sources of cetacean distribution data in this area - have been summarised by Moscrop and Swift (1999):

- Incidental sightings from various sources including: Joint Nature Conservancy Council’s (JNCC) Seabirds and Cetaceans at Sea Team (SAST) (Stone, 1996; Stone, 1997a), sightings databases including JNCC and UK Mammal Society/Sea Watch Foundation, and observations from seismic vessels operating in the Atlantic frontier region, including for example, (Northridge et al., 1995; Bloor et al., 1996; Stone, 1996; Stone, 1997a; Stone, 1997b; Stone, 1998); Updated UK DMAP; (Evans, 1992; Skov et al., 1995); Shetland Sea Mammal Group (SSMG, 1997; SSMG, 1998).
- Sightings from dedicated sightings surveys including: Greenpeace 1993 (Mayer et al., 1993), SCANS (Hammond et al., 1995), AFEN/JNCC survey 1997-98 (Webb, 1997; Gillon and O’Brien, 1998; Gillon, 1998), Greenpeace / WDCS survey 1998 (Hughes et al., 1998), and a survey off the Irish coast (Berrow and Petch, 1998).
- Acoustic detections including, monitoring of the US Navy’s SOSUS (Sound Surveillance System) bottom mounted hydrophone arrays (Clark et al., 1997; Clark and Charif, 1998), acoustic surveys including SCANS (Hammond et al., 1995; Chappell et al., 1996), Conoco/HWDT survey 1997-98 (Lewis et al., 1998), and acoustic monitoring work from guard vessels working around seismic survey vessels (Gordon et al., 1996; Gillespie et al., 1998; Swift, 1998; Chappell et al., 1999; Swift et al., in review).

3.3.1.1 Summary of cetacean distribution data
Moscrop and Swift (1999) collate recent information available on the distribution and abundance for each species found in the area of the Atlantic Frontier. This information is summarised below:

3.3.1.2 Baleen Whales

3.3.1.2.1 Blue whale
As in most other parts of the world, blue whale populations in the Atlantic were severely depleted by whaling. However, in recent years blue whales have been sighted regularly in low numbers: 2 in 1995 (Bloch, 1998), 2 in 1996 (Stone, 1997b), 4 in 1997 (Stone, 1998). Sightings rates are higher through the summer (Stone, 1997b). Recent acoustic detections using the SOSUS array have shown blue whales are present throughout the year. Peak vocal activity, which is thought to coincide with the breeding season, was reported in November and December (Clark and Charif, 1998).

3.3.1.2.2 Fin whale
Fin whales are more common than blue whales. They accounted for the majority of catches by UK whalers earlier in the century and this species is often seen by observers during seismic surveys (Stone, 1997b; Stone, 1998). Sightings peak in the summer, though this may be related to observer effort and weather conditions. Calves and juveniles have been observed off the UK, indicating that this species may breed and rear its young in these waters. Fin whales are most often sighted close to the edge of the continental shelf. Fin whales were the species most commonly detected by the SOSUS arrays off the UK (Clark et al., 1997; Clark and Charif, 1998). Detections were made throughout the year in all areas monitored; detection rates were highest from October to mid-December. Fin whale vocalisations may be mating calls and breeding is believed to take place during the winter months.

3.3.1.2.3 Sei whale
There have been regular sightings of low numbers of sei whales in waters west and north of the UK in recent years. Similarities between sei and fin whales means sightings are often categorised as ‘fin or sei whales’. There
were 3 positive sei whale sightings in 1997 (Stone, 1998) and 11 in 1998 (Cronin and Weir, 1998; Hughes et al.,
1998).

3.3.1.2.4  Minke whale
This, the smallest of the baleen whales, is common in inshore, coastal and continental shelf waters. Mothers and
calves are often encountered together indicating that calving and calf rearing take place in UK waters. Minke
whales were heard calling in offshore waters, especially during the winter months (Clark, 1995). Minke whales
encountered off the UK are believed to be part of the same population that is hunted by Norwegian whalers.

3.3.1.2.5  Northern right whale
This species is extremely endangered and sightings on the eastern side of the Atlantic are rare. The last known
aggregation on the eastern side of the Atlantic was fished out by UK whalers earlier in the century. There was
one documented sighting in 1993 (Bloch, 1998) and more recently (in October 1999) an individual, previously
photo-identified in the West Atlantic, was seen in a Norwegian fjord (Medlund, pers. comm.).

3.3.1.2.6  Humpback whale
Humpback whales are considered relatively rare off the UK, however they have been regularly reported from
recent visual and acoustic surveys. There have been repeated sightings of up to 2 individuals off Shetland every
summer since 1993 (SSMG, 1997; SSMG, 1998); other sightings include several in 1996 (Stone, 1997b) and 16
in 1997 (Stone, 1998). Singing humpback whales were detected in offshore waters west of UK between
November and mid-March using the SOSUS arrays (Clark et al., 1997; Clark and Charif, 1998). It is thought that
singing is related to breeding and that the lack of calls in other months does not necessarily indicate that
humpbacks are absent; indeed historical whaling records show that catches of humpbacks off NW Scotland
peaked through the summer.

3.3.1.3  Odontocetes (toothed cetaceans)

3.3.1.3.1  Sperm whale
Sperm whales are regularly sighted and acoustically detected in deep waters off the UK and along the continental
shelf edge, typically in waters of 500 m depth or more. During an acoustic survey of an offshore region to the
northwest of the Hebrides, from December 1997 to February 1998, sperm whales were detected at over 33% of
listening stations. The detection range at these stations was about 5 NM and up to 9 whales were heard at any
one time (Lewis et al., 1998). During this survey, only 4 sperm whales were seen by a dedicated visual team. It
seems likely that sperm whales are more abundant off the UK continental shelf than has been generally
appreciated. There has also been an increase in reported sperm whale strandings on UK coasts in recent years
(Evans, 1997).

3.3.1.3.2  Northern bottlenose whale
These shy animals are rarely observed at sea but were once a mainstay for a Norwegian whaling industry and are
thought to be fairly widespread in deep parts of the NE Atlantic. Sightings include 2 in 1997 (Stone, 1998), 2
present around Skye in 1998 (Gill pers. comm.) and Evans (pers. comm.) reports that this species is regularly
seen in the Hebrides.

3.3.1.3.3  Cuvier’s beaked whale
A rarely sighted deep-water species. Evans (pers. comm.) reported a sighting in the Hebrides in 1996. Shetland

3.3.1.3.4  Sowerby’s beaked whale
A rarely sighted deep-water species with a limited distribution confined to the N. Atlantic. Cronin and Weir
(1998) reported a single individual that surfaced close enough to their vessel to allow identification to species
level. Shetland Sea Mammal Group (1997) reported three strandings of Sowerby’s beaked whales around

3.3.1.3.5  Killer whale
Killer whales are widely distributed being seen in coastal as well as offshore waters. Sightings peak during the
summer, but they seem to be present all year round. Sightings include for 1996: 17 (Stone, 1997b), 17 (White,
al., 1999), presence off County Kerry (Berrow and Petch, 1998), 1 in the Hebrides (Gill, pers. comm.). There were regular sightings around Shetland with pods including young calves (SSMG, 1997; SSMG, 1998).

3.3.1.6 Long-finned pilot whale
Pilot whales are relatively common deep waters in the NE Atlantic and live here year round. Often sightings seem to be clustered around the 1000 m isobath. Pilot whales encountered in the Atlantic Frontier are likely to be from the same population that is subject to drive fisheries in the Faeroe Islands.

3.3.1.7 Beluga whale
Rare sightings include single adults off Shetland in 1996 (SSMG, 1997) and 1997 (SSMG, 1998).

3.3.1.8 Risso’s dolphin
Risso’s dolphins are regularly sighted around the UK, often within a few miles of the coast.

3.3.1.9 Bottlenose dolphin
Resident groups of bottlenose dolphins are established in some locations around the coast of the UK e.g. in the Moray Firth, in Cardigan Bay, in Poole Bay, off Land’s End and off the west coast of Ireland. They are also found offshore, sometimes in association with other species. For example, Stone (1998) reports regular associations with pilot whales and *Lagenorhynchus* sp.

3.3.1.10 White-beaked dolphins
Although generally considered less pelagic than white-sided dolphins, there are many reports of this species from offshore and coastal locations. Reports of calves and juveniles indicate that white-beaked dolphins breed and rear young in the waters off the UK. The distribution of this species is limited to the North Atlantic.

3.3.1.11 Atlantic white-sided dolphins
White-sided dolphins are frequently sighted off the UK. They have a more offshore distribution than white-beaked dolphins being most common in shelf waters and over the continental shelf edge. They are the commonest offshore dolphin species in the more northerly offshore waters of the UK. This species breeds and rears young here, as evidenced from strandings data.

3.3.1.12 Common dolphin
Common dolphins are the most frequently encountered offshore species in more southerly UK waters. Juveniles and calves have been observed, and the species has been sighted year round, indicating that breeding and rearing of young must occur in these waters.

3.3.1.13 Harbour porpoise
Harbour porpoises are most common in inshore and coastal waters, being especially abundant in the central North Sea and the Hebrides. However, sightings of harbour porpoises are also reported from shelf and offshore waters. Sightings occur year round, the presence of calves indicates breeding in UK waters.

3.4 Cetacean Acoustics
All cetaceans are thought to be auditory specialists with an acute sense of hearing. They use sound to communicate, often over large distances, and many species also use sound to find food. A number of texts document the possible effects that seismic surveys may have on cetaceans (see for example Richardson et al. (1995), Gordon et al. (1998)). In extreme cases, it is possible that very intense sounds could cause tissue damage or even death (though there is no evidence of injuries of this scale caused by seismic surveys). By their very nature, ears are the organ that is most sensitive to sound and are therefore the organ most likely to suffer damage. Extrapolation from studies of terrestrial species suggest that a cetacean passing close to a seismic survey vessel could suffer either temporary or permanent shifts in its hearing threshold.

Below the level at which damage can occur it is possible that noise can mask other sounds of biological importance to cetaceans such as communication calls, echolocation calls or the sounds made by a predator or prey species. Clearly, any activity by man that reduces the ability of already vulnerable species to feed or communicate is a matter of concern.

Audiograms have been measured for only a few of the smaller odontocetes that can be kept in captivity. These species have generally been found to have their most acute hearing at higher frequencies (10 kHz and above).
For other species, including all of the great whales, hearing sensitivity can only be inferred from the dominant frequencies in their vocalisations and the structure of their ears. Ketten (1994) grouped cetaceans into three functional categories based on the structure and properties of their cochlea. These were, upper-range ultrasonic, lower range ultrasonic and low frequency/baleen whale. Most odontocetes were assigned to the first two classes. The extent to which sperm whales are sensitive to lower frequency sounds is still unclear however. A recent mass stranding event of beaked whales in the Mediterranean, which seems to have been caused by a relatively low frequency military sonar (Frantzis, 1998), indicates that low frequency sound may cause dramatic disturbance, even to species that are thought not to have acute low frequency sensitivity. In the case of the Mediterranean beaked whales, it has been suggested by Ketten (1998) that the sound may have disrupted the animal’s vestibular system.

3.5 Department of the Environment guidelines
Public concern over possible damage to cetaceans from seismic surveys in UK waters, together with the UK’s obligations under the Bern Convention, the EC Habitats and Species Directive (92/43/EEC) and the Agreement on the Conservation of Small Cetaceans in the Baltic and North Seas (ASCOBANS) led the Department of the Environment to introduce the “Guidelines for minimising acoustic disturbance to small cetaceans” in February 1995 (Stone, 1997). These guidelines were aimed at the oil exploration industry and applied to the 16th and subsequent rounds of exploration.

The guidelines were revised in early 1997 (Stone, 1997b) and again in April 1998 (JNCC, 1998). Member companies of the UK Offshore Operators Association (UKOOA) and the International Association of Geophysical Contractors (IAGC) have indicated that they will comply with these guidelines in all areas of the UK Continental Shelf (UKCS) and, in some cases, elsewhere as well (Stone, 1998). The significant points of the guidelines are:

A. Planning
- Consult with JNCC prior to survey.
- Use appropriately qualified and experienced observers when operating in sensitive areas.
- If advised by JNCC, consider both special precautions to avoid cetacean disturbance and the use of scientific studies in liaison with SMRU.
- Plan surveys to minimise marine mammal encounters.

B. During the seismic survey
- At least 30 mins before use of any seismic source look for marine mammals within 500 m of the source.
- Fill in standard JNCC forms recording: source start-up procedure, sightings and details of visual effort.
- Hydrophones and other listening equipment may provide additional information on the presence of inconspicuous species, such as harbour porpoises or submerged animals and should be used whenever possible. This will be particularly appropriate in poor weather, when visual evidence of cetacean presence cannot be obtained.
- Shooting should not commence until any marine mammals have moved well out of range - at least 20 minutes should be allowed after the last sighting.
- Hydrophones may be useful in determining when cetaceans have moved.
- Source power should be built up from a low-energy start to full power over a period of at least 20 minutes.
- The source should be ramped up in this way every time the source is used.
- Throughout the survey, the lowest practicable power levels should be used.

C. Report after the survey should include:
- Appropriately filled in JNCC forms.
- Details of the seismic survey including date, location, source specifications and number of vessels used.
- Details of marine mammal detection methods and any detection or procedural problems.

There are difficulties in translating what are essentially visual orientated guidelines to an acoustic monitoring situation. These difficulties are discussed, and recommendations based on practical experience are made, in section 6.1.2.

It should be noted that the guidelines are primarily designed to minimise physiological damage to marine mammals that it is believed may occur within 500 m of the air guns. They do not address issues of lower level disturbance and possible exclusion from habitats.
3.6 Acoustic Monitoring

In several places, the government guidelines specifically mention the potential for using passive acoustic monitoring to detect cetaceans. For example:

“Hydrophones and other listening equipment may provide additional information on the presence of inconspicuous species, such as harbour porpoises, or submerged animals, and should be used whenever possible. This will be particularly appropriate in poor weather, when visual evidence of marine mammal presence cannot be obtained.”

also:

“Hydrophones may also be useful in determining when cetaceans have moved.”

and:

“Hydrophones are a useful aid to detecting cetaceans. Cetaceans communicate with each other using whistles, creaks, chirps and moans which may be heard over considerable distances. Trains of clicks are used for echolocation and while foraging. They may be heard with a hydrophone at distances of several kilometres. In areas which are known to be frequented by small cetaceans, any hydrophones used should be capable of receiving the high frequency sounds used by these animals.

Submerged cetaceans are much more at risk than those on the surface. This makes it particularly important to use a hydrophone whenever possible to detect vocally active animals that may be invisible from the surface.”

An important part of this project was to explore how passive acoustic monitoring could be useful in determining the presence of cetaceans for seismic mitigation. We might start however by considering some of the limitations of visual observations and how acoustic monitoring can be of assistance:

3.6.1 Why use acoustics?

The presence of cetaceans around seismic vessels prior to start up is usually monitored visually. Visual methods are intuitive and familiar to most people. Acoustic methods, on the other hand, are less familiar and detecting and locating objects by sound is less intuitive. It is therefore worth examining acoustic methods with reference to the more familiar visual methods.

1. Acoustic range is less affected by meteorological conditions than visual range. The range at which cetaceans can be spotted is curtailed rapidly by increasing sea state and visual surveys are rarely continued at sea states above Beaufort force 3; large swells obscure animals while white caps will produce numerous false cues. Fog and precipitation can also seriously affect visual range. Although the level of background noise increases with sea state, and this masking noise can reduce the range of detection in acoustic surveys, the effect is measurable and resultant range reductions are predictable. In practice, effective acoustic monitoring can usually continue in higher seas than visual monitoring.

2. Acoustic range is often superior to visual range. The range at which cetaceans can be seen or heard varies from species to species and with the sophistication of the acoustic equipment being used. However, many can be detected acoustically at a greater range than they can be seen, particularly from non-specialist vessels at sea. For example, dolphins can be detected at ranges of up to 2 km and sperm whales can be reliably heard at ranges of 5 - 9 km using simple hydrophones (Gordon unpubl. obs.) while (Sparks et al., 1993) reported detecting sperm whales at ranges of 18 km using a towed linear array. Some of the large baleen whales can be heard with near-surface hydrophones at ranges of tens of km (Clark and Fristrup, 1997).

3. Sightings can only be made when animals are at the surface; acoustic detections can be made of animals both on and below the surface - as long as they are calling. Some cetaceans spend a large proportion of their time below the surface and may make prolonged dives so limiting their sightability. They may be particularly vulnerable to seismic pulses when they are at depth and can not be seen at the surface. Sperm whales, for example, can make long feeding dives. Gordon and Steiner (1992) showed that feeding adult
male sperm whales in the Azores (the same population sub-group as found in the NE Atlantic) spent, on average, 55 minutes dived followed by 11 minutes at the surface i.e. about 83% of their time dived.

4. A single acoustic monitor can reliably monitor for 360° around the hydrophone; a single visual monitor usually has to concentrate on a limited sector to obtain the similar level of reliability. For example, in dedicated surveys of cetacean abundance, such as SCANS, 6 trained observers working in 2 independent teams of 3 were engaged in observing the 180° arc ahead of the survey vessel (Hammond et al., 1995). Even under these conditions, a significant proportion of animals was missed. With particular reference to visual monitoring on seismic surveys, it is standard practise to implement the Government’s guidelines by using a single observer positioned on the bridge, often doubling as the fisheries liaison officer (FLO), to search for marine mammals within 500 m of the seismic vessel. It is very difficult for a single observer to cover 360° reliably, especially as the view astern may be limited by the vessel’s superstructure and bow riding animals may be obscured by the high bow. Furthermore, the observer may be distracted by their other duties as the fisheries liaison officer.

5. Acoustic surveys are less onerous than visual surveys. Searching for whales is hard work and requires constant vigilance from experienced observers; spotters have to be changed regularly and rested, and consequently large (expensive) field teams are required.

6. Acoustic monitoring can be conducted 24 hours a day, both day and night. Obviously, visual sightings are impossible in poor light conditions and at night. The use of image intensifiers for night-time observations has been investigated; however, they have poor acuity, limited field of view and magnify the ship’s motion, hence they currently have very limited practical use. Most cetaceans continue to vocalise around the clock, although allowances may have to be made for diurnal variation in acoustic output.

7. A complete and permanent record can be made of acoustic monitoring cues. A high quality digital recording provides a remarkably full record of the acoustic information within its band of sensitivity. Such a record is also available for verification by a third party, for example the seismic operators. It is very difficult to obtain an equivalent visual record; photographs and video can be taken, but have to focus on a narrow area of interest.

8. There is a great potential for automation of data collection and detection. Modern digital processing techniques mean that many aspects of acoustic analysis, such as distinguishing, classifying, counting and timing vocalisations, can be performed automatically (Potter et al., 1994; Gillespie, 1997; Fristrup and Watkins, 1993; Stafford et al., 1994). Two distinct advantages stem from automating detection. In the first place, it further reduces the amount of human effort required to complete a survey. Secondly, and most importantly, it removes sources of human error due to inter-individual variability in ability to make detections and provides unambiguous information for operators in the field.

There are also some potential problems with an acoustic approach:

1. Our knowledge of cetacean vocal behaviour, see section 3.6.2, is patchy and far from complete.

2. Vocalising is not obligatory for many species. Echolocating animals may have to vocalise to feed or to orientate themselves but rates of production of all vocalisations are potentially highly variable. By contrast, we know that all cetaceans do have to surface to breathe, although they are not always equally conspicuous when they do this.

3. Some form of hydrophone system is required which inevitably involves some expenditure and the necessity of towing hydrophones can add to the logistic complexity.

As discussed above, visual and acoustic detection methods have their respective strengths and weaknesses. Many of these are complementary and the simultaneous use of both techniques will increase cetacean detection reliability substantially.

3.6.2 Cetacean vocal characteristics

The detectability of cetaceans depends on the physical characteristics of the calls (i.e. its type, frequency range, strength) and the animal’s vocal behaviour (i.e. how often and under what circumstances calls are made).
3.6.2.1 Physical characteristics

Figure 5 summarises published information on vocalisation frequency ranges for cetaceans found in the NE Atlantic. In summary, all the odontocetes (toothed whales), with the exception of the sperm whale and harbour porpoise, produce whistles that lie in the human auditory range. (The vocal behaviour of some of the beaked whales is too poorly known to be sure that this statement applies to them.) Sperm whales produce loud clicks that span our auditory range, while porpoises produce relatively weak ultrasonic clicks. Of the baleen whales, the blue and fin produce tonal calls with much of their energy in the infrasonic range, whereas the minke, sei, humpback and right whale produce tonal calls within the our aural range.

Figure 5 - Tonal and impulsive calls of cetaceans of the NE Atlantic.
Frequency range of calls is plotted against average adult body weight of species (no data for beaked whale calls are available). A thick line indicates the dominant frequency range of calls, a thin line the maximum recorded range, for tonal calls the average call frequency is marked by a square. Where available, source level is quoted as dB re 1 μPa re 1 m.

3.6.2.2 Vocal Behaviour

The extent of information available on vocal behaviour varies from species to species. The delphinids are usually encountered in groups, which seem to be vocally active for a large proportion of their time. There are indications that oceanic dolphins are more vocally active at night (Gordon, 1987; Gordon et al., in review). Killer whales from those populations that hunt marine mammals may be silent for extended periods. Harbour porpoises use echolocation clicks, though the proportion of the time spent clicking is the subject of ongoing research. Sperm whales produce regular loud clicks, at a rate of approximately two per second while submerged but are usually silent when at the surface. Leaper et al (1992) estimated that sperm whales are vocally active for at least 50% of the time.

Knowledge of the vocal behaviour of baleen whales, particularly around the UK, is limited. Recent studies using the US Navy’s SOSUS sea-bed mounted hydrophone arrays in 6 areas to the north and west of the UK have identified the low frequency calls of blue, fin, minke and humpback whales (Clark and Charif, 1998) However the authors point out that there is currently no way of estimating what percentage of the whales present are silent.
nor is it possible to say what percentage of the time any individual spends vocalising. They further speculate that it may only be the males that produce the loud identifiable calls during the mating season.

3.6.2.3 Cetacean vocal characteristics - summary

In contrast to visual surveys, cetaceans can be detected acoustically when not at the surface. Sperm whales are ideally suited to acoustic detection, as they produce loud, regular clicks in the audible range that can be heard over considerable distances. Dolphins, pilot whales and killer whales produce fairly loud calls for much of their time though the range at which they can be detected in the field is somewhat less. Porpoises produce relatively weak ultrasonic clicks for an unknown, but probably large, proportion of the time. Baleen whales produce low frequency and mid frequency calls, however vocalisation rates may be very low and highly seasonal. This, combined with the frequency range that they use, makes their detection during seismic surveys uncertain and problematic.

3.6.3 Capabilities of acoustic equipment

The detectability of cetacean calls also depends on the capabilities of acoustic equipment. From Figure 6 it is clear that to be able to detect vocalisations from all of the cetaceans that are encountered in the Atlantic Frontier region, acoustic monitoring systems will need to be sensitive over a huge range: from the low infrasonic (~15 Hz, for blue whales) to the higher ultrasonic (~140 kHz for harbour porpoises). Listening in different frequency bands poses different problems and it is often more efficient to use individual system to cover specific frequency bands.

At low frequencies (<~100 Hz) the ability to monitor is typically limited by background noise produced by the survey ship, sea state, distant shipping and by hydrophone flow noise. To eliminate flow and ship noise remote static hydrophones are often used; these include bottom-mounted hydrophones with cabling to the shore, e.g. US Navy’s SOSUS array and sonobuoys. (A sonobuoy is essentially a hydrophone suspended from a small buoy, with signals being relayed to a remote vessel or plane using VHF radio.) Specially designed towed arrays can also be used from quiet vessels for low frequency monitoring. These use many hydrophone elements to ‘beam-form’. This involves processing the signals from all the elements to amplify the sound from a specific direction, so eliminating directional noises such as engines. Frequencies of 25 Hz or less are below the sensitivity of the human ear and time compression techniques may be required to make such sound audible.

Monitoring is relatively straightforward in the mid frequency range (100 Hz - 22 kHz). Here, background noise is less of a problem; the human ear has good sensitivity over most of this range.

Humans are not sensitive to sound above 20 kHz so specially designed equipment has to be used to detect the ultrasonic (140 kHz) clicks of the harbour porpoise, and probably some beaked whale clicks. Chappell et al (1996) found that typical detection ranges for porpoises with such equipment was 200 – 400 m.

The systems developed for cetacean monitoring are discussed in section 4.

3.6.4 The acoustic monitoring project

As discussed above, there is an obvious potential for passive acoustic methods to complement good visual surveillance and improve the efficiency of cetacean monitoring before the start of seismic surveys. Indeed, the use of such methods is proposed and encouraged in the UK Government guidelines. However, to achieve this as a routine part of seismic surveys, appropriate equipment and techniques would be required and it was also clear that a degree of computerisation of the detection process would be necessary to allow smaller, less-specialised teams to provide an effective monitoring service. In response to this need, a team of scientists working in marine mammal acoustics in Oxford, and a group working on hydrophone technology at Birmingham University came together under the umbrella of Birmingham Research and Development Ltd to work with Shell UK, to investigate the potential of routine acoustic monitoring of cetaceans from guard vessels ahead of seismic vessels and develop appropriate monitoring systems.

Suitable hydrophone systems and appropriate signal processing software were not available at the outset of the project. Fortunately, the skill base and experience of the participants was wide and included microelectronics, software engineering, marine-mammal acoustics and marine engineering. The project also coincided with a period of an increasing availability of powerful affordable computers capable of performing acoustic processing tasks in real time. This enabled a considerable amount of the signal processing - that would have previously required specialist, and therefore expensive, processing equipment - to be carried out in software running on
standard PCs. This makes the systems developed here more flexible, cheaper, smaller, operator-friendly, easily duplicated and reliable.

The aim of the project was to design a semi-automatic detection system for cetaceans encountered in the “Atlantic Frontier” region, especially those that are difficult to sight. Such a system should allow a single trained operator to simultaneously monitor output from the various detectors, determine the species of detections and their ranges and to track them to ensure they do not fall within the critical 500 m zone prior to firing.

It was appreciated at an early stage that the scope for acoustic detection was greater for odontocetes than for baleen whales. Monitoring at the low frequencies produced by baleen whales is extremely difficult in the noisy environment presented around seismic surveys and, although it is known that baleen whales are vocal in deep offshore waters during the winter months our own experience had been that minke whales at least were rarely vocal in coastal waters. Baleen whales also account for only a small proportion of the individual cetaceans encountered in the field and are relatively easy to sight. Thus, it was decided to concentrate on developing systems to detect the vocalisations of the odontocetes as a first priority, but to also experiment with low frequency hydrophones in the first year.

The project naturally fell into three distinct parts: designing and fabricating hardware, mainly the hydrophone system and conditioning electronics, developing the monitoring software and the offshore monitoring work. To an increasing extent, the first two components of the project were progressed by different teams with Prof. Rodney Coates leading the development of the hardware and Oliver Chappell and Douglas Gillespie writing the software.
4 Hydrophone System

4.1 Introduction

The aim of this part of the project was to design, develop and test a hydrophone system that could be used to better implement the government’s guidelines, using acoustics as a means of augmenting visual methods for detecting cetaceans prior to starting seismic guns. The main considerations for such a system are an ability to detect species that are found on the UK continental shelf, to minimise self noise and the noise from the monitoring vessel, and to be practical to deploy and work with in the difficult conditions of an offshore seismic survey.

4.1.1 Vocal characteristics

The vocal characteristics that influence the hydrophone system design are detailed in sections 3.6, in summary these are:

- Most odontocetes, with the exception of the harbour porpoise (and possibly some beaked whales), vocalise in the aural frequency range.
- Harbour porpoises produce clicks at ultrasonic frequencies.
- Most odontocetes vocalise for considerable proportions of the time.
- Baleen whales produce predominantly low frequency tonal calls.
- The proportion of time that a baleen whale makes calls is unknown, though there is evidence that this may be small. Calls may be associated with breeding and be seasonal. Baleen whales may be less vocal in shelf and coastal waters.
- Minke and humpback whales call in the aural frequency range.

It was therefore decided to develop two hydrophone systems. One would cover the aural frequency range - within which most species could be reliably detected - and the second would be an ultrasonic click detection system. Given the uncertain knowledge of the vocal behaviour of baleen whales and the difficulties of acoustic monitoring at low frequencies from a moving vessel, it was decided to delay the development of a new low frequency detection system until low frequency sounds had been investigated further. Such investigations would be carried out using existing low frequency acoustic detection systems.

4.1.2 Operating considerations

Because of concerns over the noise produced by the seismic vessel’s engines and propellers and possible deployment conflicts, it was decided that the cetacean monitoring work should be conducted from the guard vessel. This is normally required to be stationed about 1 NM ahead of the seismic vessel before line starts and would thus allow monitoring ahead of the seismic vessel. To minimise the engine and propeller noise from the guard vessel the hydrophone would need to be streamed some distance behind it. As the guard vessel might be required to carry out other duties at short notice the hydrophone would need to be capable of being recovered quickly at a range of ship speeds. The hydrophone system should be as portable as possible so that it could be deployed on a variety of vessels.

4.2 1996 – Experimental system

The equipment used in the 1996 offshore trials was put together at short notice and included a selection of existing acoustic equipment, an experimental hydrophone and a variety of test equipment. The objective was to use this equipment to investigate the requirements of a purpose built system for subsequent years. Investigations were made into: deployment and recovery of hydrophones from a guard vessel, safety, equipment reliability and ruggedness, ease of use, equipment size, identification of noise sources (e.g. engine, propeller, flow), methods of reducing signal-to-noise ratios, determination of the detection frequency range and how well the various species could be detected.

The equipment included:

4.2.1 Experimental array

The design of this array was constrained by available time, budget and the fact because of uncertainties over the supply of a winch it needed to be recoverable by hand. To satisfy the latter constraint, the tow cable was restricted to 200 m and the number of signal cores minimised. This array was designed to cover all three frequency ranges and comprised:
• 2 high-frequency elements (15 – 170 kHz) separated by 12 m to provide bearings to porpoises.
• 2 medium-frequency elements (100 Hz – 25 kHz) separated by 3 m to give bearings to clicks.
• 12 low-frequency elements (15 – 200 Hz) in a 30 m array configured in groups of 4, each 0.3 m apart with groups 7.5 m apart. This configuration provided ‘deaf zones’ ahead and astern which minimised ship noise at 100 Hz – a typical minke whale call frequency. To obtain ‘deaf zones’ at frequencies down to 10 Hz the array of low-frequency elements would have to be over 150 m long, which was not considered feasible.

4.2.2 Porpoise array
This was a high-frequency array developed by IFAW for detecting porpoises. It comprised of two high-frequency elements (10 – 170 kHz) set in streamlined solid resin separated by 11 m – with a 200 m tow cable. This array could be recovered by hand at 10 knots and acted as a backup to the high-frequency elements in the experimental array.

4.2.3 Other acoustic arrays
A variety of other acoustic systems were taken offshore for backup and experimentation, these were variously loaned by IFAW, Birmingham University and other sources and included:
• 8 military sonobuoys to be used to listen at low frequencies away from guard vessel noise.
• 2 vertical line arrays for similar deployment as the sonobuoys but with better acoustic characteristics.
• 3 single element medium-frequency hydrophones for use at low speeds. These acted as backups and allowed stereo recordings of dolphin whistles to be made at a range of separations. This provided data for the design of a system to obtain bearings to whistles and other tonal sounds.
• A calibrated broadband hydrophone to measure source levels of the seismic guns over a range of frequencies.

4.2.4 Comments
Experimentally, the system worked well and a considerable amount of valuable data on factors affecting detections including; ship noise, sea-state, seismic shots and their echoes and cetacean call levels were made, and practical experience gained. However, the work was hindered by high levels of ship noise. This was due to circumstances specific to the guard vessel *Telco Dover* – the pitch of its propellers had to be ‘de-tuned’ so that it could go slow enough to keep ahead of the survey vessel and this generated considerable propeller noise. There were also problems interpreting low frequency sounds that fell below the auditory range. There were problems with the winch supplied and the arrays were usually recovered manually.

4.2.5 Recommendations for a purpose built system for 1997
Recommendations were concerned primarily with noise reduction and included:
• Greater computing capacity to handle signal processing.
• Longer towing cables were essential which would require winch deployment.
• If possible, a quieter guard vessel should be used.
• A longer low-frequency array would allow further investigation into beam forming.
• Other recommendations can be found in *(Gordon et al., 1996)*.

4.3 1997 – Purpose built system

4.3.1 Purpose built array
For the 1997 monitoring trials a purpose-built hydrophone was constructed to industrial standards by Prof. Rodney Coates, initially of the University of Birmingham and subsequently of Seiche Ltd. (see Appendix 1 in Gillespie et al., 1998). The array was based on the data and experiences of the 1996 trials. The purpose-built array comprised:
• Towing cable, lengthened to 400 m to reduce ship noise, contained a central Kevlar strain member.
• A customised hydraulic winch to recover this length of cable.
• 50 m polyurethane hydrophone tube filled with Isopar M (kerosene) to house elements.
• 2 high-frequency Vernitron resonant sphere elements (15 – 170 kHz) positioned 5 m apart to give bearings to porpoises.
• 12 medium-frequency Benthos AQ-4 elements (100 Hz – 25 kHz) at a variety of separations throughout the tube giving a capability for ‘beam-forming’. Several elements were 3 m apart to allow determination of click directions.
• The rearmost medium-frequency element was configured as a ‘first arrival’ trigger to switch out seismic shots.
• No low frequency elements were incorporated.
• Signal conditioning electronics to feed signals to headphones and computers via sound and A to D cards.

4.3.2 Comments and recommendations
The system worked well, with the exceptions detailed below, and facilitated routine acoustic monitoring prior to ramping up and at other times, see section 6.1. There were several minor problems during the work; for details see Coates (1998). These included problems with the hydrophone elements and their mountings and the following:
• The new winch was not available at the start of the 1997 trials so the 1996 experimental array was deployed manually during July. The new winch was eventually fitted and the purpose built hydrophone was used in August and September. There were practical difficulties with manually deploying and recovering the 50 m element tube that could not be recovered by the winch.
• Although no serious damage occurred it was noted that the array tube was very flexible rendering the elements and their circuit boards housed within it vulnerable to damage from flexing – it may be necessary to pot up these components and to employ different tube supports. Furthermore damage to one board may stop power from reaching boards beyond it; it may therefore be prudent to bypass the boards with an independent power cable.
• The porpoise detection box – which processes the high-frequency signals from the array – was damaged in transit and only functioned after repair in September. Built-in redundancy in the system meant that none of the above problems prevented acoustic monitoring operations.

4.4 1998 – Refurbished purpose built system
The array and winch used in 1997 were refurbished through the winter of 1997/1998 and used throughout the 1998 fieldwork. Again the system worked well and this, combined with the fact that the guard vessel (the Hunter) was quiet, provided excellent monitoring conditions.
There were a few minor problems detailed below:
• The hydraulics on the ship could not be configured to power the winch; the hydraulic power pack used in 1997 was employed instead. This, however, did not provide enough power to release the winch’s brake and also turn the drum. In order to get the turning power to the winch the brake was removed. The lack of brake was not critical as when the drum was not being turned hydraulically there was sufficient resistance in the mechanism that it would not turn, though extra cable tethers were used as insurance.
• There were intermittent problems with the winch control unit; it was found that a number of internal connections had come loose – these were repaired.
• There were problems with the high-frequency detection system in the main array. The elements in the hydrophone shared a common power supply with the medium frequency elements, and it was discovered that this power supply was introducing interference into the signal. The immediate solution was to use the separate porpoise hydrophone that had been taken as backup; the long-term solution is to have a separate power supply to the high-frequency part of the array.
• Damage occurred to the towing cable during recovery of the array in poor weather. This resulted in a cut to the outer cover and to a couple of the signal lines. Fortunately, due to built-in redundancy in the system, temporary repairs enabled the array to continue functioning to the end of the work. However, it is likely that as a result of ingress of seawater into the towing cable, it may need to be replaced for future work.
• The array connector on the side of the winch was found to leak and the socket rotated independently of its mounting with the risk of damage to the connection pins and wire connections. The operators also expressed concern over the lack of turgor in the polyurethane tube and the risk of damage to the elements during deployment/recovery of the array in difficult circumstances.

4.5 1999 – Current status of hydrophone system
There was no monitoring work carried out in 1999 but the array and winch were refurbished by Seiche Ltd. to allow for future use. The array was also recalibrated by Seiche Ltd (Coates and Wyatt, 1998a; Coates and Wyatt, 1998b). The tow cable, damaged during the 1998 monitoring has not been repaired or replaced.
5 Software

A suite of detection and data recording programs is an integral component of the complete monitoring system. The objective was to provide a semi-automatic system which will assist a monitor to implement the UK Government’s guidelines for minimising acoustic disturbance to marine mammals from seismic surveys by acoustically detecting, and where possible identifying, locating and tracking odontocetes prior to the starting of seismic guns.

Section 5.1 briefly describes the program development and usage history and gives a summary of the individual programs as they stand at the end of the project. Section 7.2 provides recommendations for future developments.

5.1 Software History

5.1.1 Programs used in 1996 field trials

For the 1996 field trials, a collection of available programs was used to collect data and carry out research. These included:

- ‘Logger’ an MS-DOS based program developed for IFAW for logging: the survey vessel’s position from GPS, environmental data, survey effort and cetacean events such as sightings and acoustic detections.
- ‘Rainbow Click’ a Windows based program developed for IFAW for detecting and determining bearings to clicks, particularly those of sperm and pilot whales. This early version of the program scanned sound files recorded on disk for clicks and did not run in real-time.
- ‘Porpoise’ an MS-DOS based program, developed for IFAW, which differentiates harbour porpoise clicks from the broader band clicks of other odontocetes and noise, and logs them directly to computer.
- ‘Spectralab™’ a commercial software package, which displayed a real-time spectrogram of the sounds. This provided a valuable visual aid to the detection of tonal calls such as dolphin whistles.

From a routine monitoring perspective, one major problem with these programs was that they were not integrated, each needing a separate computer. Hence, the interpretation of the resulting data was difficult, often necessitating further analysis.

5.1.2 Software developments 1996-1997

The main developments are summarised below, for details see Gillespie and Chappell (1997):

- ‘Rainbow Click’ was further developed so that it ran in real time i.e. a stereo hydrophone could be plugged into the computer’s sound card and a scrolling display showed bearings to the source of the clicks. The click-detection algorithms were improved, a new triggering method was introduced, and new noise reduction algorithms implemented.
- A prototype whistle detection program, ‘Whistle’, was developed, which acted as a test bed for a variety of noise reduction and whistle detection algorithms. With the future integration of the various software components in mind, this program was written for Windows 95 and NT. This version did not run in real time.
- A new program, ‘NMEA Server’, was written for collecting data from a GPS unit or any NMEA (National Marine Electronics Association) device such as echo sounders, wind gauges, etc. The ‘NMEA Server’ program then makes these data available to other programs running on the same computer.

5.1.3 Programs used in 1997 monitoring work

- The interface between ‘Rainbow Click’ and the ‘NMEA Server’ program was completed and additional code was written to plot the survey vessel’s position from GPS data, and bearings to detected sperm whales, enabling operators to plot positions for this species (Figure 10).
- As the prototype version of ‘Whistle’ did not run in real time, ‘Spectralab™’ was used during the work and detections made by simultaneously viewing the spectrogram display while listening on headphones. The software was run on two computers, with different sample rates to cover both the mid and low-frequency ranges.
- The harbour porpoise detection program, ‘Porpoise’, was run on a separate computer.

5.1.4 Software developments 1997-1998

The main developments are summarised below, for details see Chappell and Gillespie (1998):
A user interface and data logging program called 'MonDB' was written. This collected data from the detection programs, including effort and detections, and stored it in an MS Access database.

A new version of the ‘Porpoise’ program was written to run under Windows. This allowed it to communicate with ‘MonDB’ and run on the same computer. Click detection was changed from a hardware trigger to a software threshold detector. This was achieved by digitising the smoothed envelope signal with a multi-channel ADC in the PC. This allowed more sophisticated triggers, that could self-adjust to cope with varying noise levels, to be used.

The ‘Whistle’ program was developed to run in real time. New noise reduction and whistle detection algorithms were implemented. The performance of the program was extensively tested using DAT recordings made during previous fieldwork.

A new data-logging program was developed to collect GPS data (via the 'NMEA server' program) and to display summary information on the status and recent detections made by the three detection programs – ‘Porpoise’, ‘Rainbow Click’ and ‘Whistle’. This program was written in Visual Basic for applications and stored information on detections and monitoring activity in a Microsoft Access database.

5.1.5 Programs used in 1998 monitoring work
As each program required its own digitising card, it was still not possible to run all three programs on a single computer in 1998. The data logging programs ‘MonDB’ and ‘NMEA Server’ and the detection programs ‘Porpoise’ and ‘Whistle’ were run on one machine while ‘Rainbow Click’ ran on a second computer.

5.1.6 Software developments 1998-1999
The main developments are summarised below, for details see Chappell and Gillespie (1999):

• The most important development to follow the 1998 field season was a separate program ('ADC Pipe') which could digitise the sound for all three detection programs using a single ADC board and then send the appropriate channels of data to each of the three detection programs. This allowed all three detection programs to run on a single computer for the first time.

• The ‘Porpoise’ program was further improved, both under this contract and under a third party contract. The main improvements were the implementation of new click pattern recognition and display algorithms, and the addition of routines to calculate, display and store bearings to clicks when using a stereo high-frequency hydrophone. Online help was also added to the program.

• Several enhancements were made to the ‘Rainbow Click’ program. A variety of selectable digital filtering algorithms was added, which reduced noise levels and improved the program’s ability to make detections. A routine was added to dynamically set the click trigger thresholds as ambient noise varied. Click pattern recognition routines, based on inter-click intervals, were also added to the program.

• Several improvements were made to the ‘Whistle’ program. The most significant of these was the addition of whistle bearing determination and display routines for use with stereo hydrophones. With the use of the ADC card, the program is capable of measuring absolute sound levels at the hydrophone, to allow estimation of range based on known source levels for the appropriate species. Noise monitoring routines were added which minimise problems caused by fluctuating noise levels. Online help was also added.

• The performance of the data-logging program ‘MonDB’ had proved to be inadequate during the 1998 field trials. This program was therefore re-written in C++. A map showing the vessel’s track and positions of detected cetaceans was also added (Figure 7), as were forms for entering comments and scoring aural detections.

5.2 Software operating environment
The sound cards that are fitted as standard in modern computers are not suitable for making calibrated measurements. They have un-calibrated frequency responses, volume levels and balance can be manipulated by the user and by third party software, and the function of the volume controls is non-linear. Consequently, the software has been adapted so that it can be used with two commercially available types of ADC board (produced by National Instruments and Computer Boards) enabling calibrated measurements to be made. (Only the National Instruments board allows all programs to run on a single machine because it supports channel list sampling.)

Any of the individual detection and monitoring programs will run under Windows 95, 98 or NT 4.0. However, the Windows library functions used to exchange data between the 'ADC Pipe' program and the detection programs are only supported under Windows NT 4.0.
Dynamic Data Exchange (DDE) (which is a standard part of the Windows library) is used to pass information between the detection programs, the 'NMEA Server' and the data logging program 'MonDb'. 'MonDb' uses Open Database Connectivity (ODBC) to create and write data into a Microsoft Access database. ODBC is standard with more recent Windows installations. It is not strictly necessary to have Microsoft Access installed on the computer, since the ODBC drivers allow the C++ programs full access to the database file. Microsoft Access is however required in order to open and view the contents of the database and to analyse collected data.

In total therefore, six programs make up the complete detection system. The three detection programs, 'Porpoise', 'Whistle' and 'Rainbow Click', provide information to a single user interface, 'MonDb', that stores monitoring data in a database. Two smaller programs 'ADC Pipe' and 'NMEA Server' control digitisation of sound data and collection of NMEA data respectively. A schematic diagram of the complete system is shown in Figure 6. Only reasonably powerful PC's are capable of running the entire detection suite simultaneously. The processor should be at least a 500 MHz Pentium II and 128 MB of RAM are required. Computers of this type are, however, now relatively cheap, and the Windows operating system has the advantage that many potential monitoring personnel are already familiar with it.

The operation of the integrated system was extensively tested during another survey carried out in Poole Bay during February 1999. It performed well.
Coastline
Limits of seismic survey
Marked seismic line
Fishing gear
Silurians' position and track-line

Figure 7 - The main display window of the system-monitoring program ‘MonDB’.
5.3 The Detection Programs

5.3.1 ‘Porpoise’ - high frequency click detection program

The high frequency click detector, originally described in Chappell et al. (1996) detects clicks from small cetaceans, such as the harbour porpoise and many delphinids.

It is impractical, using standard PC’s, to analyse the full waveform of these signals that have a bandwidth ranging above 140 kHz. The high frequency click detection system therefore works by filtering the signal coming from the high frequency hydrophone into three frequency bands centred on 50, 75 and 125 kHz and then using rectifier circuits to trace the envelopes of the click waveforms at each of those frequencies. This drops the frequency of the signal down into the audio band (at which point it may be monitored on headphones if desired). The filtering and envelope-tracing are implemented using analogue electronics. The output of the envelope-tracing circuitry is then digitised using a multi-channel ADC board in the PC. Signal processing is then carried out within the ‘Porpoise’ program. The main display window of this program is shown in Figure 8.

![Figure 8 - Example of display produced by the ‘Porpoise’ program.](image)

The top window shows several rows of click histograms, one for each click strength category. Red bars in the histogram show the number of porpoise type clicks, blue bars show the number of broadband clicks. The lower window shows bearings to clicks against time. Again, porpoise clicks are shown in red while broadband clicks are shown in blue. A sound source being passed by the hydrophone will give a sigmoidal pattern of dots in this window.

A trigger threshold is varied dynamically according to the level of ambient noise. In the event of a trigger, the amplitudes of the signal in each of the three frequency bands are stored and analysed to discriminate against background noise and determine which cetacean species are present. The centre window of Figure 8 shows the levels in each of the three frequency bands every time a click exceeds the trigger threshold in one of the three bands.
Porpoise vocalisations are very characteristic: they are narrow band pulses centred at around 125 kHz and this makes them easy to distinguish. If the sound levels within a click are high in all three frequency bands, then the click is broad band and is probably from a dolphin, shrimp or propeller cavitation. If however, the level is high only in the high frequency (125 kHz) band then it is likely the click is produced by a porpoise. The number of clicks falling into each click category are summed for each time bin and for each strength category and displayed as a series of histograms in the top window of Figure 8. Several such clicks in succession indicate a porpoise detection. The program can also discriminate between the different sources of broad band clicks by using the time patterns in which clicks are produced.

When a pair of hydrophones is used, the program will calculate, display and store bearings to clicks. The software measures the arrival time of a click at each of the two hydrophone elements and uses the time difference to calculate the bearing of the click. If a linear two-element array is used then the bearing is in fact an angle relative to the array axis, so the source may lie at any point on the surface of a hemi-cone. This bearing is stored for each click and this can be displayed either in real time or later during data analysis.

This directional data gives an indication of the location of cetaceans, which can be useful in choosing between different mitigation options. It also enhances the system’s ability to reject noise. It can also help to distinguish signals from noise. Some noise sources, such as water noise, self-noise and “shrimp” clicks, tend not to come from a consistent bearing while others, such as the towing vessel’s propeller noise will always originate from directly ahead. Cetaceans vocalisations typically come from consistent bearings which will often gradually move astern as the hydrophones are towed past the vocalising animal. In some cases, ranges to cetaceans can be estimated based on the rate of change of bearing to vocalisations and vessel speed. Examination of the different bearings from which vocalisations are received over a short time period may also provide information on minimum group size for acoustic encounters.

5.3.2 ‘Rainbow Click’ – medium frequency click detection program
This program is designed to detect and analyse medium frequency (100 Hz – 22 kHz) clicks typically produced by sperm and pilot whales in real-time. The program was initially developed by IFAW (Gillespie and Leaper, 1996).

The program receives data through an ADC board or a soundcard. The first stage in the analysis is to remove as much noise from the signal as possible. Much of this is low frequency (<1 kHz) e.g. engine noise and noise reduction is achieved by using any of a number of digital filtering functions written into the program. These include high, low or band pass Butterworth and Chebyshev filter functions.

Putative clicks are now identified from the background noise by applying detection trigger thresholds. These thresholds are adjusted dynamically in response to changes in the ambient noise level. Once the clicks have been identified, they are plotted against time. The dimensions of the plotted points (e.g. Figure 9, upper window) are proportional to the duration (length) and amplitude (height) of the click.

If a two-element array is used then the bearings to the clicks can be determined. This is achieved by measuring the difference in the arrival time of the signal at each of the hydrophone elements. The bottom left window of Figure 9 shows the waveforms of the clicks as they arrive at the forward (blue) and rear (red) elements. The program cross-correlates the click waveforms so that the time difference between the arrival of the click at each of the elements can be calculated. The cross correlation for the click is given in the centre window of Figure 9. Using this time difference and the distance between the elements, the bearing to the click relative to the hydrophone can be calculated. The upper window of Figure 9 shows the bearings of clicks against time. In this case, the time window for the display is 1 minute. On the bearing axis, 0° is ahead, 90° is a beam and 180° is astern. As with the porpoise detector, there is a left right ambiguity, the clicks in fact lie on a hemi-cone. Trains of clicks from a single cetacean will tend to move steadily astern as the animal is passed by the vessel.
Figure 9 - ‘Rainbow Click’ medium frequency click detector display.

The upper window shows the bearings of clicks against time. Here the time window is 60 s wide, the bearing axis ranges from 0° (ahead) to 180° (astern), the horizontal line across the window represents abeam of the hydrophone. Coloured dots represent clicks; the dimensions of each dot are proportional to the duration (length) and amplitude (height) of the click. Clicks of the same colour are considered to be produced by the same whale based upon the click’s bearing, inter-click interval and power spectrum. In this example the click trains of 7 whales have been identified. The dominant sound is produced by a sperm whale at 55° (marked by red dots) which produced loud regular clicks at a rate of approximately 1 every 2 seconds (34 clicks in the 60 s window).

The lower left window shows the waveform of a click on arrival at the front (blue) and rear (red) hydrophone elements; the x-axis is time and the y-axis amplitude. This particular click was from the ‘red’ whale’s click train.

The superimposed window shows the cross-correlation function of the waveforms received at the front and rear hydrophone elements. The function indicates that this click lay at a bearing of 55.4° from the front of the hydrophone.

The lower right window shows the power spectrum of the click.

By using several characteristics of the clicks, the program can attribute the clicks to different whale ‘identities’. The characteristics used, and their respective weightings are controlled by the operator and include: the inter-click interval, the time between successive clicks i.e. the rhythm; the energy spectrum of the click, shown in the bottom right window of Figure 9; and the bearing of the click. As clicks are attributed to whale identities, they are coloured accordingly.

If the program receives position information from the ‘NMEA Server’ program, then the track of the vessel can be plotted in a separate window, see Figure 10. If bearings to clicks are plotted then the approximate position of the whale is where these bearings intersect.
5.3.3 ‘Whistle’ – medium frequency whistle detection program

This program is designed to detect and analyse medium frequency (100 Hz – 22 kHz) tonal sounds in real-time. Whistles, which are produced by dolphins, pilot whales and killer whales, are one of the most commonly detected cetacean tonal sounds. Figure 11 outlines the stages in the whistle detection process.

The program receives digitised signals, through an ADC board or soundcard. The digitised signals are then converted into a spectrogram (frequency versus time format) by taking Fast Fourier transforms of successive, overlapping sections of the digitised data. Average noise levels through the frequency spectrum are measured.
over a period of several seconds and subtracted from the spectrogram to remove consistent noise sources such as engine and propeller tones. If the noise level changes dramatically then the detection procedure is temporarily suspended until a new stable level is achieved.

On the spectrogram display, shown in the upper window of Figure 12, a dolphin whistle appears as a narrow band of higher intensity sound (indicated by colour). The first stage of the detection process is to search for peaks in the frequency spectrum for each time bin. Next, the program searches for links between peaks that are close together in time and frequency and might constitute part of a whistle. Chains of links are then evaluated to determine whether they constitute a genuine cetacean vocalisation. A full description of the algorithms used to detect peaks, links and whistles is described in Appendix A of Chappell and Gillespie (1998). The detected whistles are plotted in the lower ‘detection’ window of Figure 12, with each whistle being individually coloured. It is possible to scroll backwards in the detection and spectrogram windows to review previous detections.

Figure 12 - Display window of the ‘Whistle’ program.

- The top left window shows a spectrogram, the x-axis is time (the width of the window is 5 s), and the y-axis is frequency. Colour indicates intensity. The curved lines are dolphin whistles, the vertical stripes are dolphin clicks, the blue area at low frequency is vessel and flow noise.
- The bottom left window shows the detected whistle segments, the axes are the same as for the spectrogram, the frequency axis is selectable as either linear or logarithmic. Whistles are shown as a solid line, the colour of which can be selected to show the sound intensity, or to rotate through a fixed sequence of solid colours (this latter option helps to distinguish between different whistles on a cluttered display).
- The right hand window shows a ‘radar’ or polar plot of the identified whistles. The angle is the calculated bearing and the radial distance can be either amplitude of calculated range. The colours of the clicks are the same as those use in the detection window.
- This recording of Atlantic white-sided dolphins was made in the Brendan’s Dome prospect at 19:56 on 1/8/99. To hear the recording in the hypertext version of this report click on the figure.
The detection routines have been rigorously tested using tapes of the vocalisations of a wide variety of species and man-made noises. Killer and pilot whales and all the species of dolphins found in the NE Atlantic were detected effectively and some humpback calls were also detected. Occasional false detections have been experienced due to tonal noises produced by drilling platforms and seismic guns (occasional whistles are heard during recharging). These tend to be relatively infrequent events compared to the tens or hundreds of whistles per minute detected during genuine cetacean encounters and can therefore be eliminated by applying a simple threshold based on whistle rate and/or by examining detections manually. There is also scope for recognising and ignoring sources of noise (such as gun whistles) with particular characteristics.

Bearings of whistles are determined by measuring the difference in time of arrival of the signal at the two hydrophone elements, spaced a few metres apart. The calculation of bearings of tonal sounds is complicated by frequency aliasing. That is, if the separation of the hydrophones is greater than half a wavelength, then there is a set of possible times at which the waveforms can match. Fortunately however, most cetacean vocalisations sweep in frequency and it is possible to extract the true bearing to a sound by comparing correlations between the two waveforms at a number of different frequencies. This technique is described in detail in Appendix A of Chappell and Gillespie (1998).

The bearing and the intensity of a whistle are displayed on a radar-like display, shown in the right hand window of Figure 12. The intensity is shown as the inverse of the radial distance from the centre of the display, so that quieter sounds are further from the centre. Bearings are plotted so that a whistle from directly ahead is at the top of the display, a whistle coming from abeam is to the right and a whistle from astern is at the bottom. When using a linear two-element hydrophone there is no information on whether a detection is from the right or the left, hence only a semicircle is shown. The radial axis can be selected to show either the intensity of the whistle or the calculated distance to the vocalising animal. Distances are calculated using the typical source level of the species whistling, if this is known.

Though the source levels for some species have been measured, published data are sparse. During the monitoring work in 1998 research into source levels was carried out, this is discussed in section 0.

5.4 Discrimination of species from whistles

As part of the final year’s work the potential for identifying species from the whistle summary data provided by the whistle program using discriminant analysis was explored (Boisseau and Gordon, in review; and Appendix C in Chappell et al., 1999). The ‘Whistle’ program was used to analyse existing recordings from eight delphinids commonly encountered in the North Atlantic and data summarising the characteristics of each detected whistle were extracted and stored. (Whistle descriptors included: maximum frequency, minimum frequency, duration and number of inflections.) Linear discriminant analysis was then used to classify the whistles produced by the eight species. Out of 34,054 whistles, 55% were assigned to the correct species using this analysis technique. (Correct classification of 12.5% whistles would be expected by chance alone.) Confidence in species identification will increase as more whistles are analysed from any particular encounter. Hundreds of whistles may be detected during a typical encounter with a group of dolphins. Killer whales and both pilot whale species were readily distinguished from the other delphinid species studied.

It is envisaged that discrimination algorithms developed through studies such as this may be incorporated into the software in future to provide real-time identification of species based on acoustic cues alone. This technique may even be used to identify the behavioural state of the animals.

5.5 Software Summary

These programs can detect all odontocete vocalisations recorded from the Telco Dover, the Antares and the Hunter guard vessels from 1996 to 1998.

Both the high frequency and medium frequency click detectors were originally developed for other clients and ownership of the original click detection software rests with them. Under the final year’s contract, considerable modifications were made to the medium frequency click detector (Chappell and Gillespie, 1998) to make it suitable for monitoring in the vicinity of seismic vessels and the software is freely available to be used for offshore monitoring. The whistle detection software has been developed entirely for this project and is the property of Birmingham Research and Development Ltd.
All three detection programs now run in real-time. Information on detections from all three programs are passed to the summary display and database program which provides a unified clear and simple user interface, showing the status of each detector and the locations of any detected vocalisations. A database of all program operation and detections is automatically created for use in data analysis.

The relative ease with which cetaceans can be monitored acoustically has always been one of the attractions of this approach. Whilst automated recognition of cetaceans from visual cues has never been suggested as a likely short-term prospect, the automated detection of certain cetacean vocalisations has been shown to be practical with standard inexpensive computing equipment. The software developed for this project was initially designed to give automated assistance to operators, helping them to detect cetacean sounds and measure parameters such as bearings. It has now, however, been taken forward to a second stage, involving automated detection and analysis of vocalisations with the human operator serving to verify and interpret detections. This reduces both the level of expertise and the size of the team required to provide effective monitoring. Automated acoustic monitoring has thus proved to have a number of very practical advantages in typical offshore seismic survey conditions.
6 Offshore Work

Offshore work was carried out in the summers of 1996, 1997 and 1998 aboard the guard vessels Telco Dover, Antares and Hunter respectively – for details of vessels and areas seismically surveyed see Table 1. The type of work carried out fell into three categories:

1. Pre-start monitoring. The acoustic monitoring of cetaceans in accordance with Government guidelines in the area where the seismic vessel intended to start ramping-up.

2. Testing & developing software/hardware. Carrying out tests, developing hardware and software, collecting data in recordings and on video for testing and developing tools to carry out pre-seismic monitoring more effectively.

3. Opportunistic survey. When possible, using the system to collect information on cetacean distribution to supplement the rather sparse data for the areas in which the seismic surveys were conducted.

Work in these three categories is presented in detail in the following sections.

6.1 Pre-seismic acoustic monitoring

Pre-seismic acoustic monitoring was carried out to comply with the JNCC’s guidelines on minimising risk of injury to marine mammals from seismic sources. In 1996 the monitoring work was largely experimental, but in 1997 and 1998 routine acoustic monitoring was carried out which impacted on the shooting of seismic lines, including a number of aborted lines. It is important to appreciate that the present guidelines are only designed to minimise the risk of actual physical damage to marine mammals at the time of seismic source start up. They do not address issues of lower-level disturbance, nor do they address the risk of damage to cetaceans that approach the seismic source once it is firing. There is no mechanism for stopping the seismic source once it has started. The role of acoustic monitoring is therefore confined to the period immediately prior to start up.

6.1.1 Standard seismic start-up procedure based on visual observations

Two sections in the Government’s guidelines specify how visual monitoring should be conducted and the procedure that should be followed when cetaceans are seen:

“Look and listen: Beginning at least 30 minutes before commencement of any use of the seismic sources, the operator and observers should carefully make a visual check… to see if there are any marine mammals within 500 m…‡ Hydrophones and other listening equipment may provide additional information on the presence of inconspicuous species… and should be used wherever possible. This will be particularly appropriate in poor weather, when visual evidence of marine mammal presence cannot be obtained.”

“Delay: If marine mammals are present, the start of the seismic sources should be delayed until they have moved away, allowing adequate time after the last sighting (at least 20 minutes) for the animals to move well out of range.”

A further two sections detail the procedure that should be followed when firing the guns:

“The slow build-up: Where equipment allows, power should be built up slowly from a low energy start-up (e.g. starting with the smallest air-gun in the array and gradually adding in others) over at least 20 minutes to give adequate time for marine mammals to leave the vicinity. There should be a soft start every time the air guns are used, even if no marine mammals have been seen. The soft start may only be waived for surveys where the seismic sources always remain at low power levels e.g. some site surveys.”

“Keep it low: Throughout the survey, the lowest practicable power levels should be used.§”

There are three important points implicit in these guidelines, these are (referenced to the above guidelines):
‡ The basis of the guidelines is a 500 m radius zone around the seismic guns which should, as far as monitoring techniques can insure, be clear of cetaceans before firing commences.
† In terms of monitoring procedure there is no difference between a line start and test firing.
§ Since no guns are required for seismic work between lines there should be no firing, other than any necessary test firing, at these times.
These guidelines give rise to the standard start-up procedure shown in Figure 13.

![Figure 13 - Visual monitoring and seismic start procedure](image)

### 6.1.2 Adaptation of start-up procedure for acoustic monitoring

Although the guidelines encourage the use of acoustic monitoring, they do not specify how this should be carried out. This is only to be expected as acoustic monitoring techniques are new and are still being developed. The following factors were considered when adapting the visual based procedure to acoustic monitoring:

- A 500 m radius circle on the sea’s surface is appropriate for visual monitoring, but how should this be extended into the water column when using acoustic monitoring? Presumably, this zone should be based on the distribution of a critical level of intensity - as energy from the guns is directed downwards this would probably describe a conical zone.

- For practical reasons, the acoustic monitoring has been carried out from the guard vessel that is usually located 1 nautical mile ahead of the seismic vessel and its guns. This means that it is not possible to site the hydrophones close to the noise source. Instead, a corridor ahead of the seismic vessel is monitored. There is obviously a time delay involved for the seismic vessel to arrive in this ‘swept’ zone which adds a small amount of time to the monitoring process. This delay may also allow cetaceans to move into the “swept zone” before the seismic vessel enters it.

- The acoustic detection range varies for each species. For example, the approximate maximum range using the equipment for sperm whales is 5 NM, for delphinids 1 NM and for harbour porpoises 400 m. Therefore, where possible, it is necessary to consider the range and bearing of detections.

- The acoustic detection range will also vary with background noise levels.
• A question that remains unanswered is what is the maximum allowable period for which the guns can stay silent before it is necessary to go through the whole start-up sequence again? That is, if there is a break in firing how long can this break continue for before it is necessary to carry out visual monitoring and the ramp-up procedure prior to the guns resuming on full power?

The acoustic monitoring procedure that was finally adopted for use in 1997 and 1998, after informal consultations with the client and JNCC, and after several refinements brought about from experience, is shown in Figure 14.

![Flowchart for Acoustic Monitoring Procedure](#)

**Figure 14 - Acoustic monitoring and seismic start procedure.**
The procedure in this figure is based on a speed of 4 knots for the seismic vessel and a separation of 1 NM between it and the guard vessel – though it can be adapted for any speed or separation. This procedure is shown spatially in Figure 15. It is necessary for the seismic operators to give the acoustic monitors at least 45 minutes notice of the time they intend to ramp-up i.e. 1 hour and 5 minutes before the anticipated line start. Acoustic monitoring of the corridor ahead of the seismic vessel will then begin. The seismic vessel will enter the swept corridor after 15 minutes (1 nautical mile / 4 knots x 60 minutes). For the next 30 minutes the seismic vessel will travel along this corridor and so establish the 30 minutes of monitoring time required in the guidelines. At this point, if there had been no detections within the corridor the seismic vessel would be free to start up.

65 minutes to line - The seismic vessel is 65 minutes (4.25 NM) from the intended start of the survey line, travelling at 4 knots. The guard vessel is 1 NM mile ahead of the seismic vessel. The seismic operators inform the acoustic monitors that they intend starting the survey line in 65 minutes i.e. ramping-up in 45 minutes. The acoustic monitors start monitoring, the typical acoustic ranges for different species are shown: porpoises (400 m), delphinids (1 NM) and sperm whales (5 NM).

50 minutes to line - The seismic vessel is 50 minutes (3.75 NM) from the intended start of the survey line. A 1 NM corridor has been ‘swept’ acoustically and the seismic vessel now enters this corridor. The width of the zone varies with species, as shown. At this point visual monitoring on the seismic vessel begins.
35 minutes to line - The seismic vessel is 35 minutes (2 NM) from the intended start of the survey line. The acoustic monitors have now swept a 2 NM corridor, i.e. the 30 minute period specified in the guidelines, but the seismic vessel is only half way along it. From now on the acoustic monitors will be, where possible, monitoring for cetaceans entering the previously ‘swept’ zone, i.e. monitoring the swept zone astern.

45 minutes to line - The seismic vessel is 20 minutes (1 NM) from the intended start of the survey line. The seismic vessel is now at the end of the 30 minute ‘swept’ corridor. If no cetaceans have been detected entering the swept zone and there were no sightings then the seismic vessel can commence the 20 minute ramp-up.

0 minutes to line - The seismic vessel is at the start of the survey line having completed 20 minutes of ramping up. Even if the acoustic monitors detect cetaceans in this final period the detection has no bearing on the procedure under the guidelines because ramping-up has already begun.

Figure 15 - Spatial arrangements of the seismic and guard vessels and the ‘swept’ corridor during monitoring.
6.1.3  Practical considerations
Many practical factors impacted upon the acoustic monitoring procedure. These included:

6.1.3.1  The optimum positioning of the guard vessel for acoustic monitoring
There were times when the guard vessel was not ahead of the seismic ship for all or some of the 45 minutes prior to ramp-up. This was due to the other duties the guard vessels performed including: escorting other ships out of the survey path, escorting work boats, dealing with debris and carrying out CTD profiles (conductivity, temperature and depth). In 1996, the guard vessel was often dispatched to the tail buoys during turns leaving the vessel out of position on the approach to the next line. In 1998, the crew on the guard vessel found it very difficult to follow the course that the seismic vessel would follow during the turn. They would not initiate their own turn after the end of a leg until the seismic vessel started its turn. In such circumstances the guard vessel increased its speed to avoid being overtaken, and the consequent increase in engine noise impacted on monitoring. Furthermore, as the relative position of the seismic vessel moved from astern to the quarter and sometimes abeam during a turn its engine noise became more prominent. As well as causing listening problems, the guard vessel was no longer sweeping an acoustic corridor ahead of the seismic vessel.

6.1.3.2  Guard vessel noise
The noise produced by the guard vessels varied considerably from vessel to vessel. The *Telco Dover* (1996) produced the most noise because it had to de-tune its propellers to go as slow as 4 knots. This severely limited the acoustic detection range and it is suggested that this vessel, or vessels with a similar propulsion system, should not be used as a platform for acoustic monitoring in the future. The *Hunter* (1998) was very quiet and the acoustic range was consequently much greater. For sperm whales at least this range greatly exceeded the 500 m required by the guidelines, and it therefore became important to locate sperm whales to determine whether they fell in the critical zone or not. The noise from the *Antares* (1997) fell between the two.

6.1.3.3  Deployment considerations
The configuration of the working decks on the various guard vessels governed the extent to which weather impacted on the array deployment and recovery. The *Telco Dover* (1996) had a large work deck which made working with the array easy and safe in all weathers. The working deck of the *Hunter* (1998) on the other hand had a very low freeboard; the deck was constantly awash with water even in moderate weather and became covered in seaweed growth. Deployment and recovery of the array on this vessel was often very difficult especially when the array was swept around obstacles on the deck, which in one instance lead to damage to the towing cable. The monitors were always aware that the array might have to be recovered in advance of worsening weather.

6.1.4  Results of pre-seismic acoustic monitoring
The locations of the seismic lines for which pre-seismic acoustic monitoring was carried out are shown in Figure 16. There were two main prospects: West of Shetland (1996) and Brendan’s Dome (1997 & 1998). Several lines were also monitored in the North Cormorant prospect prior to the survey vessel moving to Brendan’s Dome. Details of the pre-seismic acoustic monitoring are to be found in the yearly reports (Gordon et al., 1996; Gillespie et al., 1998; Chappell et al., 1999).

A breakdown of outcomes of the pre-seismic acoustic monitoring procedure for the years it was applied, 1997 and 1998, is given in Table 2.

6.1.5  Pre-seismic monitoring discussion
As a consequence of acoustic monitoring 6 lines were aborted in the two years and a further 13 were delayed. In 10 cases, although cetaceans were detected the monitors were able to determine that they were outside the critical zone so the line could start as planned. In a further 7 cases, the ramp-up was started earlier than planned on advice from the monitors that there were cetaceans ahead that might be close to the location of the planned start. This latter approach became available in 1998 with the use of more sophisticated detection software. There should be some debate as to whether this strategy falls within the spirit of the guidelines.

The fact that only 6 lines out of a total of 174 (3.5%) seismic starts, had to be aborted due to cetacean presence, in areas of such high cetacean density suggests that acoustic monitoring can assist seismic operators follow the Government’s guidelines with minimal disruption.
In 1998, several lines were aborted due to heavy swells that affected the quality of the seismic data. In previous years these lines would probably have been shot, but improvements in real-time data assessment allowed operators to abort these lines. This is a welcome development, as it minimises the number of shots, and therefore noise, that enters the environment.

In 37 (21%) cases out of the planned 174 seismic starts (which included test firing), the correct procedure was not followed. In 14 of these, this was due to the monitors being unable to monitor ahead of the seismic vessel. This was usually due to the guard vessel being out of position (10 cases), but at other times the monitoring array was not deployable (4 cases). Of most concern were the 5 occasions when the guns were started without warning, on 2 such occasions cetaceans were judged to have been within 500 m of the seismic vessel. In the first case, the seismic operators had been told they could ramp-up but had not been ready. After a further 25 minutes they had started firing without warning, but by this time cetaceans had moved in to the critical area. It is important that operators bear in mind that advice on whether they are clear to start firing is only valid at the time it is given. In the second case, test firing started without warning. Test firing, like normal seismic lines, is subject to the start up procedure. On a further 2 occasions, the correct procedure was followed before test firing, however, following periods of 6 and 7 minutes respectively when the guns were quiet test firing recommenced without warning. This is an ambiguous situation as there is no indication in the guidelines of the length of a ‘quiet’ period after which the whole procedure must be re-invoked. In the shot data files received from Shell UK only the positions of shots on normal lines were recorded, whereas data on test-shots and ramp-up shots would be useful when analysing the success of the start up procedure. Such data should also be available for policing purposes.

On 10 occasions, the warning given to the acoustic monitors was too short and the gun start was delayed.

On 5 occasions, the seismic team decided to leave an airgun firing throughout the turn in areas of high cetacean density, their reasoning being that if the guns do not stop then there is no requirement to follow the start up procedure and hence no likelihood of the new line being aborted due to cetacean presence. On one occasion, the acoustic monitors sanctioned this strategy – this is now recognised as an error. The Government’s guidelines state that “Throughout the survey, the lowest practicable energy levels should be used”. Firing guns when not surveying contravenes this rule.
Table 2 – Seismic gun start and monitoring procedure – breakdown of procedure outcomes.

Many of the failures of the procedure stemmed from the seismic operators’ lack of understanding of the acoustic monitoring procedure and from communications problems. This is understandable as this type of procedure was new to most seismic operators, and communications by VHF radio make detailed explanations difficult. Both these problems can be easily addressed by providing clearer information for the seismic operators on the acoustic system and monitoring procedure at a briefing prior to the survey, especially the inclusion of a step-by-step acoustic monitoring/start up procedure.
In summary, the use of acoustic monitoring avoided start-ups that would have conflicted with the JNCC guidelines and therefore might have resulted in damage to cetaceans, while at the same time minimising disturbance to the seismic survey.

6.2 Testing and developing hardware and software

6.2.1 Introduction
Time between the pre-seismic acoustic monitoring periods allowed for the testing and development of the detection system. In particular, software was developed and debugged. Test equipment, electronic supplies, manuals and programs were taken onboard to help with these tasks. Recordings were also made of cetaceans and of background noise in order to test program algorithms on return to the laboratory. In 1996 a number of experiments were made with low frequency hydrophones. In 1998 experiments with video range-finding methods were conducted, these are described in the following section.

6.2.2 Cetacean acoustic source level measurements using video ranging and recordings

6.2.2.1 Introduction
If the source levels of calls produced by different species are known then these values can be used by the ‘Whistle’ program to calculate distances to cetaceans based on the sound levels received at the hydrophone. Such distances, in combination with the bearings (already determined by using the time difference of sounds at two elements) would allow the positions of calling cetaceans to be determined.

6.2.2.2 Methodology
During 1998 work was carried out between pre-seismic monitoring to see if it was feasible to determine source levels of cetaceans (see Appendix B in Chappell et al., 1999). To determine source levels three pieces of information are needed: the absolute amplitude of the sound received at the hydrophone, propagation conditions and the distance of the calling cetacean from the hydrophone. The first quantity is measured by making a recording with a calibrated hydrophone system – i.e. where the sensitivity of the elements and the gain and frequency responses of the amplifiers and filters are known. The use of laser binoculars to measure range proved impractical because of the motion of the vessel and the fleeting views of animals. Instead, a new video range finding method was used (Gordon, In review). Frames were captured from digital videotapes and ranges were calculated from these using a program that measures the angular distance between the horizon and subject from distances (in pixels) between these features on the captured image. Bearings were also required in order to allow for the distance between the observers position and that of the hydrophone array. These were measured by summing the angles subtended by the images obtained when the camera was panned from the cetacean to the stern of the vessel.

When both received levels and range to vocalising animal were measured the source level for each whistle was determined by calculating a transmission loss assuming spherical spreading (loss in dB = 20 log range/m) and adding this to the measured levels.

Source levels were determined in this way for three species using 13 measurements and these and published source levels are summarised in Table 3.

These data are too limited to provide all the information needed to use received whistle levels as a reliable indicator of range. However, the results do suggest that the methods employed could be used to collect the substantial data sets required in the future.

Collecting these data opportunistically from a working vessel has proved very difficult and it is clear that the work could be completed far more effectively (and probably less expensively) from a small dedicated vessel that was free to search out and manoeuvre around cetacean groups. The research could also be conducted more effectively if the majority of the recordings were made in an area with high cetacean abundance, low swell and more clement weather.

The results obtained here are on average 10 dB below published maximums. Considering the paucity of data, and the preliminary nature of this work, it is not possible to draw any firm conclusions from this.
For this preliminary work, spherical spreading was assumed but propagation conditions will vary in time and space and this assumption will not always be valid. It will be important to measure propagation conditions and transmission loss over the transmission paths involved during any future research to determine vocalisation source levels. However, once these data have been obtained it may not be necessary to know transmission loss when using received whistle levels to determine whether animals are at a ‘safe’ range. This is because in regulations that are designed to limit the intensity of sound that a marine mammal might be exposed to range from the source is actually being used as a proxy for transmission loss. Acoustic measurements of whistle intensity might allow transmission loss to be estimated directly. For example, in areas with a low transmission loss, measures of whistle intensity may lead to a dolphin’s physical range being underestimated (if a spherical spreading transmission loss was assumed in the calculation). Therefore, animals that are too distant might be judged to be within a ‘critical range’ but in such conditions transmission loss for the seismic signal will also be reduced and the ‘critical range’ would need to be larger to ensure appropriate protection. One corollary of this argument would be that the monitoring hydrophone should be towed at the same depth as the seismic source so that the ray paths from the cetacean to the hydrophone and the source to the cetacean are equivalent.

Both the results obtained here and those in literature, indicate that different species produce whistles with different intensities. Thus, if intensity measures are to be used to determine range (or transmission loss) it will be important to be able to identify species from their vocalisations. As reported in section 5.4, encouraging progress is being made in achieving this from the data output of the ‘Whistle’ program.

### 6.3 Opportunistic Surveying

#### 6.3.1 Introduction

Time remaining after monitoring and development work had been completed was used for opportunistic acoustic surveying. Data on the distribution of species are extremely limited in the remote areas that the guard vessel worked, so any extra data that can be collected is valuable. Acoustic surveying also allowed the equipment and software to be tested and provided opportunities to make recordings.

In 1997 these additional acoustic data were compared with visual sightings data to assess the relative effectiveness of the two techniques, and this study is summarised in section 6.3.3.

#### 6.3.2 Acoustic Surveys

Acoustic surveying was carried out using various methods; these were dependent upon the configuration of the monitoring system at the time and the time available to the monitors. Manual acoustic surveying was usually carried when the seismic guns were not firing. Automatic detections, using the porpoise click detector and the automatic whistle detector when these systems were available, could also continue when the guns were firing.
The combination of the variety of survey methods and acoustic circumstances obviously does not provide a uniform surveying regimen, however, useful distribution information may still be obtained from the data given appropriate analysis.

6.3.2.1 Acoustic Survey Results
The tracks of the guard vessels for the three years are shown in Figure 17. The area covered by these lines is extensive and most of these track lines were surveyed acoustically. The acoustic detections for each year are detailed in the yearly reports (Gordon et al., 1996; Gillespie et al., 1998; Chappell et al., 1999) and summarised in Table 4. The data from the three years need further analysis so that they can be combined and related to effort so that a cetacean distribution map can be constructed.

![Figure 17 - Guard vessel tracks during acoustic monitoring trials 1996-1998.](image)

6.3.2.2 Discussion
A large amount of acoustic survey data was acquired using a variety of acoustic survey regimens. Six species groups were detected; dolphins had the highest detection rates followed by sperm whales. The data collected needs further processing so that cetacean distribution maps, corrected for effort and acoustic range, can be applied. However, interesting comparisons with visual detection rates can be made using these data, and are discussed in section 6.3.3. Unlike sightings data, which is collected by the JNCC and Sea Watch Foundation, acoustic survey data in the UK is not collected by any centralised database. If acoustic monitoring becomes a regular feature of seismic surveys, this should be addressed.

6.3.3 Comparison of visual and acoustic detection methods
A comparison of visual and acoustic detection methods was carried out using the sightings and detection data for 1997 (Gillespie et al., 1998). Two measures were compared. The first was the overall detection rate (cetacean sightings or acoustic detections per hour) for each method for the periods when there was both visual and acoustic monitoring and there were no guns firing. These data are plotted in Figure 18, and it can be seen that the acoustic detection rate is some 10 times higher than the combined sightings rates for both the guard and seismic vessels even when baleen whales (which could not be acoustically detected) are included.
### Table 4 – Acoustic detections by year and species

<table>
<thead>
<tr>
<th>Species</th>
<th>Detection method</th>
<th>Effort (hr)</th>
<th>Detections</th>
<th>Detection rate (#/hr)</th>
<th>Effort (hr)</th>
<th>Detections</th>
<th>Detection rate (#/hr)</th>
<th>Effort (hr)</th>
<th>Detections</th>
<th>Detection rate (#/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harbour porpoise</td>
<td>automatic click detector</td>
<td>433.0</td>
<td>72</td>
<td>0.166</td>
<td>51.5</td>
<td>13</td>
<td>0.252</td>
<td>331.4</td>
<td>31</td>
<td>0.094</td>
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<tr>
<td>Whistles</td>
<td>automatic whistle detector</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>324.2</td>
<td>66</td>
<td>0.204</td>
</tr>
<tr>
<td>Unidentified dolphin</td>
<td></td>
<td>14</td>
<td>0.182</td>
<td></td>
<td>37</td>
<td>0.155</td>
<td></td>
<td>66</td>
<td>0.229</td>
<td></td>
</tr>
<tr>
<td>Pilot whale</td>
<td></td>
<td>4</td>
<td>0.052</td>
<td></td>
<td>1</td>
<td>0.004</td>
<td></td>
<td>22</td>
<td>0.076</td>
<td></td>
</tr>
<tr>
<td>Killer whale</td>
<td></td>
<td>4</td>
<td>0.052</td>
<td></td>
<td>1</td>
<td>0.004</td>
<td></td>
<td>11</td>
<td>0.038</td>
<td></td>
</tr>
<tr>
<td>Pilot or killer whale</td>
<td>aural monitoring</td>
<td>76.8</td>
<td>238.4</td>
<td></td>
<td></td>
<td>287.8</td>
<td></td>
<td>7</td>
<td>0.024</td>
<td></td>
</tr>
<tr>
<td>Sperm whale</td>
<td></td>
<td>29</td>
<td>0.378</td>
<td></td>
<td>21</td>
<td>0.088</td>
<td></td>
<td>33</td>
<td>0.115</td>
<td></td>
</tr>
<tr>
<td>Unidentified Odontocete</td>
<td></td>
<td></td>
<td>2</td>
<td>0.008</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fin whale</td>
<td></td>
<td>1</td>
<td>0.013</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All species</td>
<td>all methods</td>
<td>509.8</td>
<td>124</td>
<td>0.243</td>
<td>289.9</td>
<td>75</td>
<td>0.259</td>
<td>943.4</td>
<td>236</td>
<td>0.250</td>
</tr>
</tbody>
</table>

Figure 18 - Detection rates by species group and detection method, for times when guns were not firing, 1997.
Secondly, the total number of individual encounters that were detected by the two methods was considered for periods with both visual and acoustic effort and no firing. Acoustic detections are compared with the sightings of the guard vessel Antares in Figure 19 and with the sightings of the seismic vessel Mintrop in Figure 20. Each cetacean encounter was assessed to see whether it had been heard or seen and in which order.
The results show that over three-quarters (78% and 86% for the Antares and Mintrop respectively) of the encounters were heard but never seen, whereas only 12% and 8% - mainly baleen whales – were seen and not heard, only 10% and 6% were heard and seen, with all these being heard first.

These comparisons clearly show the effectiveness of acoustic monitoring. The acoustic detection rate (detections per hour of effort) was shown to be nearly 10 times greater than the combined sightings rate (sightings per hour of effort) for both the guard vessel and seismic vessel. Furthermore as acoustics can be used at times when sightings can not i.e. at night and in poor weather, which might represent between a third and half of all line starts, the overall difference between the two methods may be between 15 and 20 times. The comparison of detection methods shows that at least three quarters of all encounters would be missed using sightings alone.
7 Conclusions and Recommendations

7.1 Hydrophones

An effective hydrophone system has been developed which is sensitive to all of the odontocete vocalisations, and the calls of at least some baleen whales, while also being robust, practical and suitable for deployment during working seismic surveys.

It is likely that, now that the analysis software is well developed, a somewhat smaller and simpler hydrophone and winch system will be more appropriate. It is now apparent that the detection programs will work well with a simpler streamer comprising two mid-frequency hydrophone elements, two high frequency hydrophone elements and a depth sensor. A reduction in hydrophone elements would reduce the number of cable cores and hence the cable diameter, and this in turn would permit a smaller winch to be used. This would be advantageous because the existing winch proved unwieldy and unreliable.

The hydrophone and its winch system should be viewed as a single operating unit. The simpler system with a smaller winch should be both less expensive and more reliable. Furthermore, agreement on a standardised monitoring system would facilitate manufacture and duplication.

7.2 Software

A fully-integrated suite of processing, acoustic detection and data collecting programs have been developed that allow the automated detection and logging of vocalisations from all odontocetes (and some baleen whale) species. Bearing information, and in some cases, range are also provided. These programs now run on a single standard PC and have a user-friendly interface allowing a small team to provide effective monitoring. A short preliminary project to identify dolphin species based on data from the detectors has yielded results with sufficient promise to warrant further work on incorporating an automated species identification capability into the software.

The following recommendations are made:

- Further research into the automatic discrimination of delphinid species from their whistles is required.
- Further research on using received sound level statistics, as a means of determining range to odontocetes is necessary. This will require directed fieldwork, preferably in an area with reasonable weather and where a variety of species are easily accessible, using a calibrated array and video ranging techniques. Other methods for determining range (perhaps involving long-baseline hydrophone arrays) should also be investigated.
- The detection of baleen whales has not been fully investigated and further work on this is required. This should start with investigations into the vocal behaviour of these species in the areas of interest i.e. the UK continental shelf.
- Currently, the maximum frequency received by the ‘Whistle’ program from the ADC card is 22 kHz, however dolphin whistles extend above this. These higher frequencies may contain information that is useful in species discrimination so faster sampling rates may be required.
- Software should be written to allow recordings of interesting sequences to hard disk to be backed up to CD or DVD, thus eliminating the need for a tape recorder. This would simplify the system, reduce equipment and media costs, and would mean that it would no longer be necessary to read tapes into the computer before recordings could be analysed. CDs also have the advantage of providing instant access to data anywhere on the media unlike tapes.

7.3 The Government guidelines

A preliminary acoustic monitoring procedure, to facilitate compliance with the UK Government guidelines, has been developed and applied during two complete seismic surveys. This has prevented start-ups that would have broken the guidelines with a risk of damage to cetaceans in the area. At the same time, disruption of the seismic survey by cetaceans can be minimised by providing a degree of advanced warning. Observations indicate that acoustic monitoring, in addition to visual monitoring, very substantially increases the probability of detecting cetaceans.
Having now developed an acoustic monitoring system, explored and documented its capabilities and shortcomings, and gained experience of practical issues surrounding acoustic monitoring during seismic surveys, it would be useful to hold a workshop involving interested parties (i.e. acoustic monitors, oil companies, seismic industry, JNCC and NGOs) to draft guidelines and protocols for using passive acoustic monitoring equipment in the course of seismic surveys.

7.4 Practical field considerations

We recommend that initially field teams of two trained personnel should be used for acoustic monitoring. The feasibility of reducing the size of teams further can be explored in the light of this experience. If acoustic monitoring becomes a standard procedure in seismic surveys, it will be necessary to establish a program to recruit and train potential monitoring teams.

7.4.1 Requirements of the guard vessel and its crew

It is useful to reiterate here the attributes that make a guard vessel suitable for acoustic monitoring. Ideally, a guard vessel has:

- Quiet engines and propeller(s). Noisy vessels can significantly reduce the acoustic detection range. For example, the Telco Dover in 1996 had to de-tune the pitch of their propellers in order to travel at 4 knots which made acoustic detection difficult. The Hunter (1998) with diesel engines and twin fixed-pitch propellers was quiet. From experience, diesel-electric powered vessels are also reasonably quiet.
- Good working deck with space for the hydrophone winch and reasonable freeboard.
- Suitable power and hydraulic systems to support the operation of the hydrophone winch.
- Suitable dry indoor work area with reliable power supplies and cable access to winch.
- An enthusiastic crew with significant experience of their vessel and guard vessel duties.
- Good communication systems, ideally access to satellite telephone and fax.

7.5 Acoustic monitoring from the seismic vessel

During this project it was only possible to monitor from the guard vessel, however, there are a number of potential advantages to monitoring from the seismic vessel too. One concern with the current procedure is that fast moving animals, such as dolphins, may "re-invade" the corridor swept by the guard vessel after it has passed. There may also be advantages to working on the seismic vessel in terms of better logistic support, improved communications with the seismic and visual monitoring teams and a more conducive working environment. In addition, some seismic surveys are conducted without a guard vessel, and for these, deployment from the seismic vessel may be the only option. There will undoubtedly be many new issues and problems to face including the possibility of conflict with the other equipment towed from the seismic vessel, high levels of noise from the propellers and the lack of the advanced warning that the guard vessel can provide. We recommend, therefore, that the feasibility of monitoring from the seismic vessel in addition or as an alternative to monitoring from the guard vessel, should be fully investigated with field trials.

7.6 Baleen whales

Acoustic monitoring may well be useful for detecting baleen whales during seismic surveys, but this may require different equipment and a different approach. We recommend that further work should be undertaken to investigate this. However, this must be preceded by a dedicated field project to determine the vocal behaviour of baleen whales on the Atlantic Frontier shelf and shelf edge during the summer season when most seismic surveys take place.
8 References


Sabel, P. pers. comm.


Swift, R. J., J. Butler, P. Gozalbes, and J. Gordon. in review. The effects of seismic airgun arrays on the acoustic behaviour and distribution of sperm whale and other cetaceans in the north east Atlantic / Atlantic Frontier. European Cetacean Society Annual Conference, .


9 Appendices

Appendix 1 – Abbreviations and acronyms used in this report

The full meaning of an abbreviation or acronym is given with its first occurrence in the text of the report, for brevity only the abbreviation or acronym is used for subsequent occurrences. The meanings of abbreviations and acronyms are listed alphabetically below:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC</td>
<td>Analogue to Digital Converter, for converting analogue signals to digital for input to a computer</td>
</tr>
<tr>
<td>AFEN</td>
<td>Atlantic Frontier Environmental Network</td>
</tr>
<tr>
<td>ASCOBANS</td>
<td>Agreement on the Conservation of Small Cetaceans in the Baltic and North Seas</td>
</tr>
<tr>
<td>BRDL</td>
<td>Birmingham Research and Development Limited</td>
</tr>
<tr>
<td>DAT</td>
<td>Digital Audio Tape</td>
</tr>
<tr>
<td>DDE</td>
<td>Dynamic Data Exchange</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>CTD</td>
<td>Conductivity, Temperature and Depth</td>
</tr>
<tr>
<td>HWDT</td>
<td>Hebridean Whale and Dolphin Trust</td>
</tr>
<tr>
<td>IAGC</td>
<td>International Association of Geophysical Contractors</td>
</tr>
<tr>
<td>IFAW</td>
<td>International Fund for Animal Welfare</td>
</tr>
<tr>
<td>JNCC</td>
<td>Joint Nature Conservation Committee</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>NGO</td>
<td>Non-governmental Organisation</td>
</tr>
<tr>
<td>NM</td>
<td>Nautical Mile</td>
</tr>
<tr>
<td>NMEA</td>
<td>National Marine Electronics Association – standard for device communication protocols</td>
</tr>
<tr>
<td>ODBC</td>
<td>Open Database Connectivity</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>SCANS</td>
<td>Small Cetacean Abundance in the North Sea - sightings survey carried out in 1994</td>
</tr>
<tr>
<td>SMRU</td>
<td>Sea Mammal Research Unit</td>
</tr>
<tr>
<td>SOSUS</td>
<td>Subsea Surveillance System</td>
</tr>
<tr>
<td>SSMG</td>
<td>Shetland Sea Mammal Group</td>
</tr>
<tr>
<td>UKCS</td>
<td>United Kingdom Continental Shelf (used in the context of UK oil exploration blocks)</td>
</tr>
<tr>
<td>UKOOA</td>
<td>United Kingdom Offshore Operators Association</td>
</tr>
<tr>
<td>WDCS</td>
<td>Whale and Dolphin Conservation Society</td>
</tr>
</tbody>
</table>
Appendix 2 – Reports by BRDL for Shell UK under contract C10563

Preliminary Monitoring Reports

Monitoring Reports

Software Reports

Hardware Reports

Summary Report (this report)