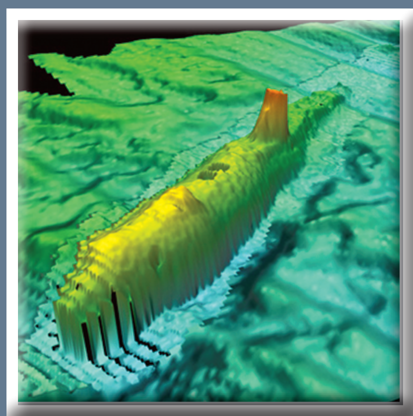
Marine
Aggregate Levy
Sustainability Fund
MALSF

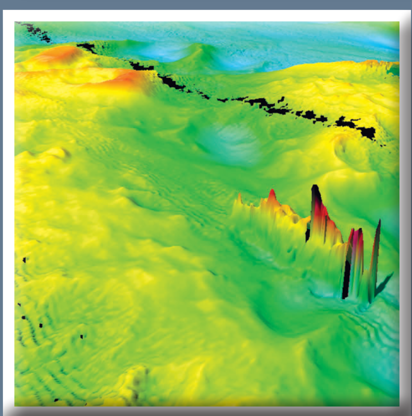
Measurement of underwater noise arising from marine aggregate dredging operations

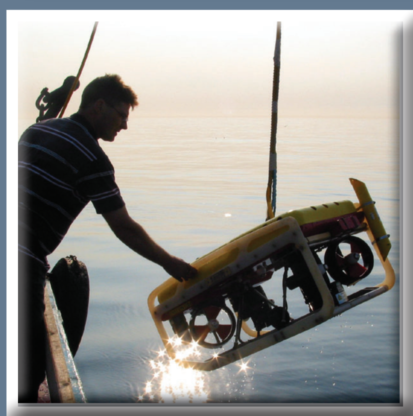
FINAL REPORT

MEPF Ref No: **MEPF 09/P108**

Project Date: **February 2011**







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This report is available at www.alsf-mepf.org.uk. Source term data collected during the project is freely available for use by third parties and can be obtained from project lead contractor NPL. The dstl quality assurance report is also available from www.alsf-mepf.org.uk.

Where applicable, MEPF projects' source data (including project final reports) is available from our Marine GIS secure data storage facility at www.marinealsf.org.uk

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Background to the fund
In 2002 the Government imposed a levy on all primary aggregates production (including marine aggregates) to reflect the environmental costs of winning these materials. A proportion of the revenue generated was used to provide a source of funding for research aimed at minimising the effects of aggregate production. This fund, delivered through Defra, is known as the Aggregate Levy Sustainability Fund (ALSF); **marine** is one element of the fund.

Further information on the ALSF is available at http://alsf.defra.gov.uk/

Governance
The Defra-chaired MALSF Steering Group develops the commissioning strategy and oversees the delivery arrangements of the Fund.

Delivery Partners
The Marine ALSF is currently administered by two Delivery partners - the **MEPF** (based at Cefas, Lowestoft) and **English Heritage**. (www.alsf-mepf.org.uk) (www.english-heritage.org.uk)

Marine Aggregate Levy Sustainability Fund MALSF

GLOSSARY OF TERMS

4P ACA	4 Pole Alternating Current Auxiliary
AUTEC	Atlantic Undersea Test and Evaluation Center – a US navy ship noise range
AIS	Automatic Identification System (shipping tracking system)
ANSI	American National Standards Institute (US standards body)
ALSF	UK Aggregate Levy Sustainability Fund
BST	British Summer Time
CCAUV	Consultative Committee on Acoustics, Ultrasound and Vibration, convened under the auspices of the Bureau of Weights and Measures (BIPM)
Cefas	UK Centre for Environment, Fisheries and Aquaculture Science, an Executive Agency of Defra
CPA	Closest point of approach of the dredging vessel on each dredging run to the recording hydrophone
CFR	Cylinder Firing Rate
CSR	Cylinder Stroke Rate
CTD	Conductivity, Temperature, Depth – or device to measure these parameters in seawater
Defra	Department for Environment, Food and Rural Affairs, a department of UK Government
DERA	Defence Evaluation and Research Agency, part of UK MOD until 2001
DNV	Det Norske Veritas (Norwegian Standards body)
dstl	Defence Science and Technology Laboratory, part of UK MOD, established in 2001
EDA	Engine Driven Auxiliary
EEC	East English Channel (one of the UK licensed dredging region)
EMS	Electronic Monitoring System – autonomous monitoring device used for regulatory compliance tracking on dredging vessels [see Crown Estate/BMAPA 2010].
ERPM	Engine Revolutions Per Minute
Far-field	Region which exists at a substantial distance from the source where sound waves emanating from the source are in phase (and the acoustic pressure and particle velocity are in phase).
FFT	Fast Fourier Transform (a method of determining the frequency content of a signal)
GMT	Greenwich Mean Time
GPS	Global positioning system
ICES	International Council for the Exploration of the Sea
ImTL	Type of propagation/transmission loss model
ISO	International Organisation for Standardisation, Geneva (international standards body)
ISVR	Institute of Sound and Vibration Research, University of Southampton
LOFAR	Term used for LOw Frequency Analysis and Recording
lofargram	Plot showing the LOFAR results
LU	Loughborough University
MALSF	UK Marine Aggregate Levy Sustainability Fund
MEPF	Marine Environment Protection Fund of the MALSF
Near-field	Region close to a real source which has finite size, the sound waves emanating from different parts of the source are out of phase, leading to a region of interference where the acoustic pressure (and particle

	velocity) show considerable spatial variation
NPL	National Physical Laboratory
PE	Parabolic Equation, used as part of an ocean sound propagation model
PL	Propagation Loss in water – reduction of sound level with range, expressed in decibels - same as Transmission Loss. Unit: dB.
RAM	Range-dependent Acoustic Model, an ocean sound propagation model
RL	Received Level – Acoustic sound pressure level at the receiver position
RMS	Root mean squared
RPM	Revolutions per minute (used to describe propeller rotational speed)
SL Source Level	Source Level – a measure of the acoustic output of a source (see Section 3.1). Unit: dB re 1 $\mu Pa^2 \cdot m^2$ The Source Level is sometimes stated as a spectral level (as a function of frequency – *e.g.* in third-octave bands) or as a broadband level (summed over all the frequencies of radiation).
SEL	Sound Exposure Level, a measure of the received acoustic energy at the receptor. Unit: dB re 1 $\mu Pa^2 \cdot s$
Sonde	An oceanographic probe (some times referred to as a CTD) which in this case measures the temperature and salinity of water as a function of depth.
SPL	Sound Pressure Level. Unit: dB re 1 µPa. or dB re 1 μPa^2 (See section 3.1 for definition).
SSP	Sound Speed Profile – sound speed variation with depth. Unit: m/s.
TL	Transmission Loss – acoustic Propagation Loss in the water, reduction of sound energy level with range, expressed in decibels (dB)
TNO	Netherlands Organisation for Applied Scientific Research
TOB	Third Octave Band, frequency band consisting of one-third of an octave, an octave representing a doubling of frequency
TSHD	Trailing Suction Hopper Dredger
UDR	Update Rate
UK	United Kingdom
UNK Aux	Unknown Auxiliary Machinery
WAV	An encoding method for lossless recording of acoustic data

Units

°C	Degrees Celsius – unit of temperature
dB	Decibel; a logarithmic unit expressing the ratio of a quantity, a_1, relative to a reference value, a_0, according to the formula: $10.\log_{10}(a_1^2/a_0^2)$.
Hz/kHz	Hertz or kilohertz - Unit of acoustic frequency
kS/s	Sample rate – kilo-samples per second (sometimes referred to units of frequency - kHz)
µPa	Micro Pascal – unit of pressure (1×10^{-6} Pa)
m	Meter – unit of distance or range
m/s or ms^{-1}	Meters per second – unit of velocity or speed
ms	Millisecond (1×10^{-3} s)
µs	Microsecond (1×10^{-6} s)
ns	Nanosecond (1×10^{-9} s)

For terms relating to marine aggregate extraction and dredging please see 'Marine aggregate terminology – A Glossary' published by Crown Estate and British Marine Aggregate Producers Association (2010).

Measurement of underwater noise arising from marine aggregate dredging operations

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1 EXECUTIVE SUMMARY

This is the final report for project MALSF MEPF 09/P108, funded by the Aggregate Levy Sustainability Fund, the aim of which is to provide data for the typical underwater radiated noise levels from marine aggregate dredgers in the UK fleet during normal operations. The work is aligned with the stated aims of the ALSF-MEPF to reduce the environmental footprint of marine extraction of aggregates, and follows directly from the key knowledge gap identified in the initial scoping study conducted in MEPF Project 08/P21 [Thomsen *et al*, 2009]. The key finding of the study is the noise output of dredging vessels is similar to a ‘noisy merchant vessel’ and is substantially quieter in terms of acoustic energy output than some other anthropogenic noise sources such as seismic airguns and marine pile driving.

This project has been an extensive study of the noise generated by the UK’s fleet of trailing suction hopper dredgers during marine aggregate extraction. The objectives of the work were (i) to develop a suitable methodology for measuring underwater noise radiated by dredgers, (ii) undertake measurements on UK dredgers at up to four sites and report, whilst disseminating the results to the wider stakeholder community. In the report, data is presented for 6 vessels, measured across 3 different areas around the UK’s coast, with one vessel being measured in two different areas as summarised in Table 1.1.

Table 1.1 Summary table of dredging vessels measured during the study.

Vessel	Length (m)	Capacity (m^3)	Total Installed Power (kW)	Operator	Region	Area
Arco Axe	98.3	2890	2940	Hanson	East Coast	240
Sand Falcon	120	4832	2460 x 2	Cemex	East Coast	251
Sand Harrier	99	2700	3824	Cemex	South Coast	137
City of Chichester	72	1418	2720	Tarmac	South Coast	137
Sand Falcon	120	4832	2460 x 2	Cemex	EEC	473
City of Westminster	99.7	2999	4080	Tarmac	EEC	474
City of London	99.9	2652	4080	Tarmac	EEC	458

The Source Levels (a measure of the acoustic noise output) of six dredging vessels have been estimated, and an investigation undertaken into the origin of the radiated noise. To achieve this, a methodology was established based on applicable parts of the ANSI S12.64 standard [ANSI S12.64 2009], augmented by enhanced procedures designed to cope with shallow-water environments. The established methodology employs hydrophone measurements made as a function of range from the source coupled with Propagation Loss modelling to establish the one-third-octave band Source Levels for each vessel. Measurements were made at frequencies up to at least 48 kHz, with data taken up to 100 kHz for 4 of the dredgers, with some data obtained up to 200 kHz. The Source Level results for all the dredgers are shown in Figure 1.1 (left) for full dredging (extracting aggregate from the seabed).

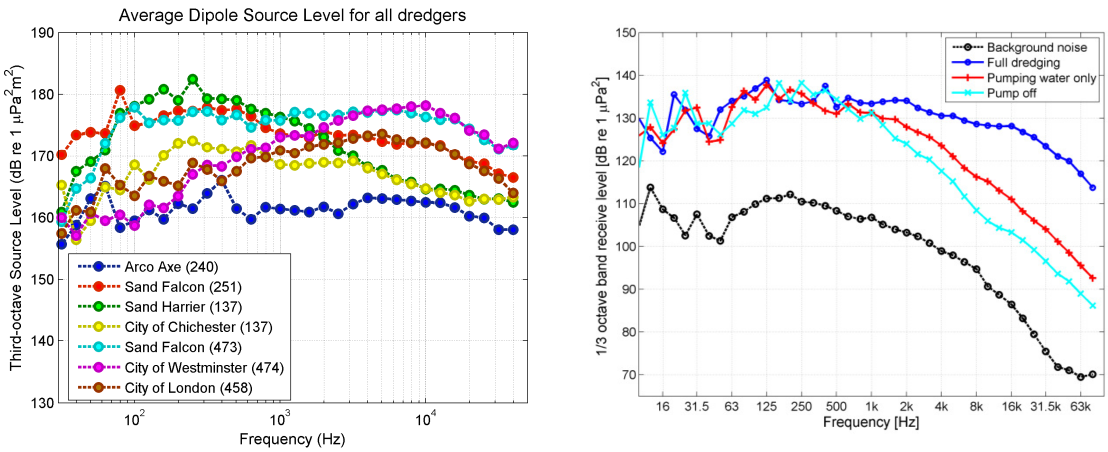

Figure 1.1 One-third-octave band Source Level data measured for six vessels from the UK whilst they were full dredging (left), and the Received Levels for one dredger (Sand Falcon) at a range of 100 m for a range of operating conditions (right).

The measured vessel data was at a higher level than the ambient noise levels in the areas where the measurements were made. This means that the possibility exists for impact on marine life. Considering the results in context, the noise radiated at frequencies less than 500 Hz is similar to that of a merchant vessel travelling at modest speed. An interesting feature of the results is that, while extracting aggregate, the vessels generate higher levels of noise at frequencies above 1 kHz than a typical merchant vessel. Analysis of the measured data for differing operation modes leads to the conclusion that the major source of this higher frequency noise is the impact/abrasion of the aggregate material passing through the draghead, suction pipe and pump (possibly with some additional contribution due to cavitation noise). This is clear from Figure 1.1 (right) which shows Received Levels measured for the same dredger under different operational modes (full dredging, draghead lifted with pump on, draghead lifted with pump off). This means that the overall noise output level is partially dependent upon the aggregate being extracted, and results indicate that extracting gravel is noisier than extracting sand.

Summary statements

For the UK dredger vessels measured:

- **i)** **Source Levels at frequencies below 500 Hz are generally in line with those expected for a cargo ship travelling at modest speed;**
- **ii)** **Source Levels at frequencies above 1 kHz show elevated levels of broadband noise generated by the aggregate extraction process;**
- **iii)** **the elevated broadband noise is dependent on the aggregate type being extracted – gravel generating higher noise levels than sand.**

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2 INTRODUCTION

2.1 PROJECT BACKGROUND

As of 2009, there were 75 licensed areas within UK waters where marine aggregate extraction may take place. In 2009, the total dredged area was 123.6 km^2, with 20.10 million tonnes of sand and gravel extracted [Crown Estate/BMAPA, 2009]. As with many of man's offshore industrial activities, there is inevitably some impact on the environment. One potential source of impact is the underwater noise generated by the vessels during operation. Although a modest amount of noise data does exist in the scientific literature for the operation of commercial shipping, relatively little data has been published on the noise generated during dredging operations. The objective of the work described here is to provide such data in a form that will enable an environmental impact assessment to undertaken using more accurate acoustic source data, and will allow the noise levels generated to be placed in context by comparison with other sources of anthropogenic noise in the ocean.

2.1.1 Research objectives

The objectives of the project are:

- Develop suitable methodologies for measuring underwater noise radiated by dredgers;
- Undertake measurements on a range of UK dredgers and sites;
- Disseminate the results to a wider stakeholder community

The effect on marine life of anthropogenic noise is of increasing concern, leading to the introduction of legislation in the area [Habitats Regulations 1994, OMR 2007, MSFD 2008]. It is recognised that the underwater radiated noise generated by dredging and marine aggregate extraction has been little studied, leading to a lack of published data, thus making a proper assessment of the environmental impact difficult to conduct [Greene, 1984 and Richardson *et al*, 1995]. This project addresses this issue by undertaking a series of measurements of the radiated noise using current best practice. The proposed work is aligned with the stated aims of the MEPF-ALSF to reduce the environmental footprint of marine extraction of aggregates. The work follows directly on from previous Defra funded work [Defra, 2003, Wareham and Roberts, 2002], and attempts to address the key knowledge gap identified in the initial scoping study into the noise associated with marine aggregate extraction: MEPF Project 08/P21 [Thomsen *et al*, 2009].

The deliverables for the project are:

- A critical review of existing knowledge following literature search
- The review and development of measurement protocols
- A draft project report presenting results of measurements and analysis

The outputs of the project are:

- Final project report presenting results of measurements and analysis

- Project data
- dstl quality assurance report

2.1.2 Collaborations

Collaboration with dstl

The Defence Science and Technology Laboratory (dstl) have acted as a "customer friend" within the project to provide quality assurance, and have engaged actively with the project team in a number of ways:

- comparisons were made of the results of third-octave band noise power analysis as a quality check;
- dstl accompanied the project team on two of the sea-trials (City of Westminster and City of London);
- copies of all measured data were supplied to dstl by the project team;
- dstl deployed sonobuoys during City of London trials to enable independent analysis of measured data;
- dstl undertook extra low-frequency analysis to investigate the acoustic signatures of selected vessels;
- two specific project meetings held with dstl (at ISVR and at dstl Portsdown) to discuss methodologies and initial results.

TNO collaboration

TNO in The Netherlands are undertaking a similar project for the Port of Rotterdam which required measurements of noise from dredging activity in the Maasvlakte 2 area [TNO 2010]. With the agreement of the customers, research staff of the two projects consulted extensively on the methodology and made confidential comparisons of results. Differences in the resources and time available meant that there were inevitable differences in the approaches adopted by this project team and by TNO, but there were many similarities and considerable benefit was gained from the collaboration. The collaboration centred on:

- Consultation on measurement methodologies;
- Consultation on the analysis method (*e.g.* selection of propagation models).

2.1.3 Organisation of report

This report is organised so that the main sections provide an overall description of the project background, methodology adopted and results obtained. The appendices at the rear of the report provide much greater detail for all of the above.

The main sections are organised as follows.

- The Executive Summary appears in Section 1,
- Section 2 provides a description of the project background, and gives the results of a review of the existing data available in the literature, including identification of knowledge gaps.

- Section 3 describes the methodology adopted for the measurements, and
- Section 4 the field measurements made as part of this project.
- Section 5 contains a summary of the results obtained, and this is followed by a discussion of the results and conclusions in the succeeding sections.

In the appendices, comprehensive detail is provided on:

(a) the equipment deployed,
(b) the measurements made,
(c) the Propagation Loss estimates and modelling undertaken,
(d) the results obtained for each vessel and location;
(e) analysis of the variability in the radiated noise and uncertainty estimates for the measurements,
(f) results from the use of a vertical array, and (g) results of low-frequency analysis undertaken by dstl.

2.2 REVIEW OF EXISTING DATA

Note that in this section, some reference is made to acoustic terminology, such as Source Level. These terms are defined in Section 3, and appear in the Glossary of Terms.

Noise measurements of dredging activities are extremely rare in the literature and the applicability of these studies to aggregate extraction in UK waters is even further limited. However, given the limited number of studies and measurements of dredging related noise, all the work on suction type dredging available in literature has been considered in this section to provide an overview of existing data. Other dredging activities such as back-hoe dredging used for channel clearing and other related activities such as load discharge, rainbowing *etc.* have been excluded.

The largest study undertaken to-date on the noise generated by dredging activities was carried out in the Beaufort Sea in the 1980's, although the dredgers studied in this case were not of a comparable type to those used in the UK for marine aggregate extraction. The majority of dredgers used in the Beaufort Sea were cutter suction vessels. However a limited number of studies have been carried out in the UK on Trailing Suction Hopper Dredger (TSHD) vessels in the areas of Cross Sands off Great Yarmouth and a further two separate studies off Hastings Shingle Bank in the Eastern English Channel. These studies are described in more detail in this section.

Other studies on the noise generated by dredging activities include one to assess the potential underwater noise disturbance during pipeline construction around Broadhaven Bay (Nedwell *et al*, 2008). Dredging is not considered in detail but it does refer to some unpublished work by Langworthy *et al* in 2004 (not referenced here) stating a Source Level for the Taccola, a TSHD type dredger, whilst undertaking dredging activities. The details of the dredging operation and the acoustic measurements are limited so the method used to establish Source Level (SL) is not stated. However, Nedwell *et al* (2008) state that broadside measurements were performed between 10 Hz and 12 kHz and do provide a Source Level as a function of frequency although the bandwidth used is not stated. The broadband Source Level is however stated to be 188 dB re 1μPa^{2}m^2 (the units shown in the report are for a Received Level (RL) but this is assumed to be a typographical error given the value of the level stated).

A comprehensive report is that by Ainslie *et al* (2009), which compile some third-octave band (TOB) Source Levels for different dredging vessels which include the Gerardus Mercator, a large TSHD used on the Sakhalin Energy Project. The source of the data appears to be part of a report for the Sakhalin Energy Project and can be found at:

http://www.sakhalinenergy.com/en/documents/doc_33_cea_tbl4-7.pdf.

Unfortunately, very limited information is available in the public domain from this study. However, Ainslie *et al* (2009) compare the TOB Source Level of the Gerardus Mercator with other dredgers; the Beaver Mackenzie and the Aquarius when operating in the Beaufort Sea. The Gerardus Mercator is larger than both of these vessels and is also larger than any dredging vessel in the UK fleet (in terms of capacity and length). The Gerardus Mercator shows higher overall TOB Source Levels than the Beaver Mackenzie and higher than the Aquarius in the bands below the 25 Hz band, with the Aquarius having noticeably higher TOB Source Levels between the 25 Hz and 315 Hz bands. The data also shows that for frequencies higher than the 1 kHz band, the TOB Source Levels fall below 160 dB re 1 μPa^{2}m^2, with the peak TOB Source Level of around 183 dB re 1 μPa^{2}m^2 occurring at 10 Hz. The details of each of these dredging activities are not known but the data has been plotted in Figure 2.1 for comparison along with other data extracted during the literature review phase of this project.

2.2.1 Studies undertaken in the Beaufort Sea, 1980's

Several studies were undertaken on a range of man-made noise source in the Beaufort Sea during oil exploration activities in the 1980's, which included a number of examples of suction dredging, although these are cutter suction dredger and differ somewhat from the TSHD's used in the UK fleet (Greene, 1985; Greene, 1987a and 1987b; Malme *et al*, 1989; Miles *et al*, 1986; Miles *et al*, 1987; Richardson *et al*, 1985; Richardson *et al*, 1990; Richardson *et al*, 1995). Greene, 1985 showed results of measurements made of the dredger Cornelis Zanen, a hopper dredger, operating at Ukalerk in 20 m of water and considered a number of other dredgers, some being stationary suction types and some being moving cutter-suction types. The report by Greene, 1985 considers the noise from the dredging activity to be greater below 1000 Hz and further states that the suction dredges and some transfer dredges are amongst the strongest sources of continuous industrial noise of any activities associated with offshore oil exploration in the Beaufort Sea. Overall, the broadband levels measured by Greene, 1985 were similar to those of oil drill ship activities taking place in the area.

Malme *et al* (1989) tabulates a series of TOB Source Level data for industrial type noise during the Beaufort Sea oil exploration, indicating that of the Aquarius, a cutter-suction transfer type dredger which is shown to generate similar levels; during dredging, to that of a >220 m in length oil tanker. The same data is referred to in Richardson *et al* (1995). This Source Level data is obtained from Received Level data from previous work during the Beaufort Sea study (published by Greene *et al* (1987a and 1987b)) and the Propagation Loss data reported by Miles *et al* (1987). The TOB Source Level data obtained from this study are shown in Figure 2.1 for the Aquarius operating in 46 m of water and the Beaver Mackenzie, a moored curter-suction transfer dredger operating in 13 m of water. The broadband Source Levels stated in Table 2.1 for the Beaver Mackenzie and Aquarius are for a bandwidth of 45 Hz and 7070 Hz and were taken from Richardson *et al* (1995). The BBN Propagation Loss data was obtained by a series of range dependent measurements for specific locations from a number of different sources, although Miles *et al* (1987) report that this mostly approximated to cylindrical spreading (a simple Propagation Loss where the level drops off as 10log(range)). The original measurement data reported in Greene *et al* (1987a and 1987b) and used for the TOB Source Level estimates were obtained from Received Level data measured at a distance of 200 m with a single hydrophone, although measurements were performed over greater ranges. It should be noted that the data from the Beaufort Sea study is limited to frequencies below 1 kHz.

2.2.2 Study around Hastings Shingle Bank of the Arco Adur, 2002

This study was carried out by DERA/QinetiQ, UK (with Cefas – see below) during July 2002 as part of a 3-year study funded by Defra to investigate the sensitivity of fish to sound generated by aggregate dredging and marine construction [Wareham and Roberts 2002, Defra, 2003]. It is possibly the most detailed noise assessment of aggregate dredging undertaken in the UK to-date, due to the consideration given to the acoustic spectral characterisation for different operating conditions.

Measurements were undertaken of the noise generated by the Arco Adur, a UK TSHD, for a number of operating conditions and a range of distances from around 50 m to 600 m, in water depths of around 18 m around the Hastings Shingle Bank. Measurements were performed during a single dredging operation, with a measurement bandwidth of 10 kHz. Background noise measurements were also performed, once before and once after the radiated noise measurements, at stand-off distances greater than 1.5 km from the dredging vessel. Measurements were completed of the noise radiated by the dredger whilst it held station with its engines idling, whilst dredging and with the draghead raised off the seabed pumping only water.

Comparison of the radiated noise measurements of the dredger whilst it held station (engines idling), whilst dredging, and with the draghead raised from the sea-bed pumping only water showed a 7 kHz signal that was only associated with the dredging activity. The authors identified this as being cavitation from the propeller. Whilst holding station, the dredger generated higher levels of low frequency noise below around 1 kHz than when underway with its suction pipe lowered, either dredging or raised slightly above the seabed pumping only water. At higher frequencies, the pumping of water or aggregate generated higher noise levels than with the dredger holding station. It should be noted that the Arco Adur uses a starboard overboard pump configuration with the pump submerged in the water column. The results reported showed that above 500 Hz the noise levels for the water pumping fell off slower than whilst holding station so that by 5 kHz the noise level for pumping water was 15 dB higher. Whilst full dredging generated higher levels of high frequency noise than when pumping water alone. Pumping water only and full dredging spectra are similar up to 2 kHz; but above this frequency the full dredging operation shows higher levels of noise. Unfortunately no Source Level terms are stated in the report.

2.2.3 Study around Cross Sands block off Great Yarmouth (Area 328) of the Arco Adur, 2002

This work was carried out by Cefas, UK during April 2002 as part of the above study funded by Defra (Defra, 2003) – sea above. Measurements were undertaken of the noise generated by the Arco Adur over a range of distances on licence Area 328. Measurements were performed during a single dredging operation using a maximum measurement bandwidth of 24 kHz. Several stand-off distances were used during the measurements from 50 m to 750 m, with a 4 km stand-off range used to assess the background noise level. The acoustic data was processed using time-frequency analysis and the authors observed that at a close range of around 50 m, most of the energy is concentrated below 1 kHz, with noise present throughout the measured frequency range, along with periodic signals assumed by the authors to be from the engine/propellers. At stand-off range of 100 m, the periodic tonal frequency components are reported up to 15 kHz. By a range of 500 m, it is reported that it was difficult to acoustically identify the dredger above background noise conditions. This indicates that either the radiated noise was of a low level or that the background noise level was relatively high. No details of the measurement vessel or its operating status during the measurements were provided and no Source Levels were estimated by the authors (Defra, 2003).

2.2.4 Study around Hastings Shingle Bank (Area 460) of the City of Westminster, 2007

A study was commissioned in the UK by the Resource Management Association comprised of CEMEX UK Marine Ltd, Hanson Aggregates Ltd and United Marine Dredging Ltd., as part of a licence application to undertake suction dredging operations in a new area, Area 460 “South Hastings”. The measurements were conducted of the City of Westminster vessel in and around the Hastings Shingle Bank during 2007. Measurements were taken at a number of ranges from approximately 250 m to 16 km from the dredging vessel. The report describes the noise at a close range (250 m) and concludes that by listening to the recordings it was ‘evident that the dominant components of the noise are from aggregates rising up through the suction pipe, characterised by a relatively high frequency broadband ‘*hiss*’. In addition there was a lower frequency component that was attributed to ship noise from the dredging vessel. At the closest range (250 m) an analysis of the noise recordings indicated that the RMS Sound Pressure (calculated over one second periods) varied from Sound Pressure Levels (SPL) of 143 to 144 dB re. 1 μPa^2. Similar measurements at a range of 4.2 km from the suction dredger showed that Sound Pressure Level of the noise varied from 125 to 132 dB re. 1 μPa^2. When, as part of this measurement, the suction dredging stopped, the SPL reduced to between 123 and 126 dB re. 1μPa^2.

The data indicates that vessel noise and the dredging of aggregates from the seabed by the vessel the City of Westminster increased the underwater noise in the region at frequencies from 20 Hz to approximately 80 kHz. The report indicates that this noise can be attributed to noise from the vessel, vessel pumps, drag head on the seabed, noise radiated from aggregate as it is sucked up the suction pipe and the water as it spills over the side of the vessel back into the sea.

The results reported show a number of peaks on the spectra between 20 Hz and 100 Hz which may be attributed to tonal components associated with dredger vessel machinery; the City of Westminster employs an overboard suction pump arrangement, with the pump submerging in the mid-water column. The broadband Source Level obtained for dredging operation produced was report to be 186 dB re. 1 μPa^2m^2. No third octave band (TOB) Source Level data is reported by Parvin *et al* (2008). However, TOB Received Levels were reported by Parvin *et al* (2008) at limited frequencies, which were measured at a distance of 514 m. If the Propagation Loss formula provided by Parvin *et al* (2008), which was used to estimate the broadband Source Level stated in the Parvin *et al* (2008) report, is applied to the TOB Received Levels at a range of 514 m then TOB Source Levels can be obtained. The results of this are shown in Figure 2.1 in green, for the City of Westminster when dredging unscreened aggregate. It should be noted that this Propagation Loss calculation uses a single absorption factor for all frequencies.

Vibration measurements were also attempted on the seabed using a Vibrock Ltd V901 geophone. The velocity vibration measurements reported by Parvin *et al* (2008) appear to be extremely small, with levels which are below the manufacturers stated sensitivity and would put them below typical ambient ground vibration levels by at least an order of magnitude. It is possible that the data is reported with the wrong units which make it difficult to asses the levels of vibration generated on the seabed by the dredging activities. However, the data does show a reducing trend with increasing distance from the dredger which does imply that the geophone is in fact detecting ground borne vibration originating from the extraction location.

2.2.5 Summary of literature survey

Although the amount of available literature on the underwater noise radiated by aggregate dredging is extremely limited, an effort has been made to compile this information, consider the way in which it was obtained and establish the key findings of the work. A number of studies have attempted to estimate the Source Level generated from dredging activities. This data is mostly presented as either third-octave band (TOB) levels or as broadband levels. These are compiled along with other information regarding the surveys in Table 2.1. Where TOB Source Level data is provided, this has been used in Figure 2.1; with the exception of the City of Westminster data which was calculated by the authors of this report from TOB Received Level data obtained from Parvin *et al* (2008) using the Propagation Loss relationship used by Parvin *et al* (2008) for the broadband Source Level estimate. To set the TOB Source Levels in context, TOB Source Level data from a large cargo vessel, the Overseas Harriette has been included. The ship noise data for the Overseas Harriette was measured on the AUTEC range (Arveson and Vendittis, 2000) and is widely considered to be some of the best data of its type for a merchant vessel. However, it should be noted that it is keel aspect Source Level data (receiver directly below the source vessel). This means that the Source Level has been estimated from measurements of noise made by hydrophones placed below the ship. Even if the ship could be considered an omni-directional source, a surface or "beam" aspect measurement (with the receiver to the port or starboard) would yield a slightly different Source Level due to the acoustic interaction of the source with the surface. The Source Levels presented for the different dredgers are all beam aspect Source Levels, obtained from surface measurements at a distance from the vessel.

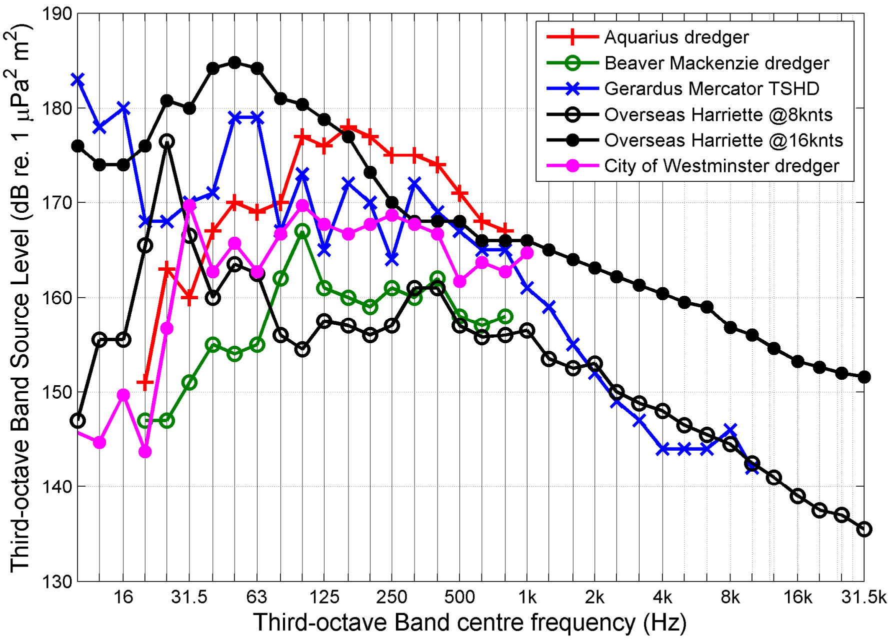

Figure 2.1 Overview of estimated third octave Source Levels obtained from previous dredger studies, including the Overseas Harriette for comparison.

From Figure 2.1, it can be seen that the Source Levels generated by suction type dredgers are generally lower than that generated by a relatively large cargo vessel at a speed of 16 knots for frequencies up to 1 kHz. For slower cargo ship transit speeds where cavitation is not generated, the dredger activity does appear to generate higher levels around 100 Hz and above. However, it should be noted that the dredgers shown are not necessarily representative of the UK dredging fleet, and the Gerardus Mercator is significantly larger than anything in the UK fleet (see Table 2.1 and Table 1.1).

Figure 2.1 also shows only a limited frequency range with much of the data being below 1 kHz, where the more recent studies considered here report increased acoustic activity at frequencies above this. Parvin *et al* (2008) and Defra (2003) which both consider UK aggregate extraction dredging, indicate that noise levels increase considerably at frequencies above 2 kHz, although interestingly the Defra 2003 report indicates that lower frequency noise levels during dredging decrease when compared to the dredging vessel simply holding station. From the previous studies, it can be established that the largest increase in vessel output when dredging occur at frequencies between 2 kHz and 80 kHz, which seem to be related to the pump operation (for overboard pump configurations), noise generated by the movement of pebbles, gravel or sand and the spilling of water and sediment. Conventional vessel noise during dredging seems to be lower due to the lower speeds involved, although bow thruster use could increase this when holding station or turning.

Table 2.1 - Summary of dredging noise surveys reported in the literature.

Dredger name	Hopper capacity (m^3)	Total installed power (kW)	Survey location	Water depth (m)	Sediment type	Source Level (dB re 1 μPa^{2}m^2)		Reference
						Peak TOB	Broad band	
Beaver Mackenzie (cutter suction)	-	-	Beaufort Sea	13	-	167	172	Miles *et al*, 1987/Richardson *et al*, 1995
Aquarius (cutter suction)	2,500	15,620	Beaufort Sea	46	-	178	185	Miles *et al*, 1987/Richardson et al, 1995
Cornelis Zanen (TSHD)	8,530	12,064	Beaufort Sea	20	-	-	-	Miles *et al*, 1987/Richardson *et al*, 1995
Gerardus Mercator (Large TSHD)	18,000	-	Sakhalin	-	-	183	188	Sakhalin energy report/ Ainslie *et al*, 2009
Taccola (TSHD)	4,400	6,300	-	-	-	-	188	Nedwell *et al*, 2008 (from Langworthy *et al*, 2004
Arco Adur (TSHD)	2,700	2,940	Great Yarmouth Cross Sands (Area 328)	-	-	-	-	Defra/Cefas report
Arco Adur (TSHD)	2,700	2,940	Hastings Shingle Bank	~18	Gravelly sand	-	-	Defra/Qinetiq report
City of Westminster (TSHD)	2,999	4,080	Hastings Shingle Bank (Area 460)	~18	Gravelly sand	170*	186	Parvin *et al*, 2008

***** *Obtained from Parvin et al, 2008 TOB Received Level data at 514 m and Propagation Loss equation used by Parvin et al, 2008, with no frequency dependent absorption.*

3 METHODOLOGY

3.1 DEFINITIONS

3.1.1 Sound Pressure Level (SPL)

The Sound Pressure Level (SPL) is defined as the mean square sound pressure expressed in decibels relative to a reference acoustic pressure squared [Morfey 2001]:

$$\mathrm{SPL} = 10\log_{10}\left(\frac{p_{\mathrm{RMS}}{}^2}{p_{\mathrm{ref}}{}^2}\right) \qquad [3.1]$$

where

p_{RMS} is the root mean square (RMS) acoustic pressure
p_{ref} = reference RMS pressure (1 μPa in water).

It is the sound pressure which is the physical parameter measured by the hydrophones used to record the radiated noise. The values of SPL measured by the hydrophone at a specific location is often termed the Received Level (RL). The units of SPL used in this report conform to the above definitions: dB re 1 μPa^2. Note that SPL is sometimes seen described with a variant on equation 3.1, where the squared power is brought outside the logarithm, thus making the multiplier 20 rather than 10. The units are then stated as dB re 1 μPa, which may be regarded as equivalent. However, it is the former unit which is used in this report.

3.1.2 Source Level

The Source Level of an acoustic source is a measure of the acoustic output of that source and is a far-field, free-field property of the source. It is related to the radiant intensity and acoustic power of the source, but it is rarely described in these terms. There are (at least two) common ways of defining the Source Level.

The first (perhaps the more conventional) definition is in terms of a sound pressure level at a reference distance of 1 m from an *equivalent* monopole source [Urick 1988]. This equivalent monopole source must be placed in a lossless uniform medium (of specified density ρ_0 and sound speed c_0) which is unbounded (extends to infinity in all directions), and must produce the same radiant intensity as the actual source if it were placed in the same lossless medium and with identical motion of all acoustically active surfaces as the directional source in the true medium. The position of the equivalent monopole is considered to be at the acoustic centre of the actual source, the acoustic centre being the nominal point from which sound appears to diverge when viewed in the far field. Note that the Source Level cannot be directly measured at the reference distance of 1 m from the real source if that point is not itself in the far field. Note that the units for Source Level in this case are most commonly expressed as dB re 1 μPa at 1 m.

The second definition is in terms of the "source factor", *S,* defined as: [Ainslie 2010]

$$S = p_{FF}^{2}(r).r^{2} \qquad [3.2]$$

where $p_{FF}(r)$ is the far-field and free-field RMS acoustic pressure at distance r from the source.

The Source Level (SL) is then given by

$$SL = 10\log_{10}\left(\frac{S}{p_{ref}^{2} r_{ref}^{2}}\right) \qquad [3.3]$$

and has the units dB re μPa²·m².

Note that these two definitions of Source Level (and the units) may be regarded as essentially equivalent. In this report, the latter unit of dB re μPa²m² will be used for Source Level throughout, partly because this conforms better with SI convention.

To estimate the Source Level, a measurement is made of the SPL at a position in the far-field of the source and the SPL is scaled to account for Propagation Loss (PL). The scaling transformation is done using an appropriate acoustic model, which is a function of the acoustic frequency, f, and range from the source, r. In this way, the Source Level is calculated in decibels from the Received Level, RL, and Propagation Loss, PL, as:

$$SL(f) = RL(f,r) + PL(f,r) \qquad [3.4]$$

One important point to note is that the concept of Source Level is only valid in the acoustic far-field. It provides a measure of the acoustic output of a source when viewed in the far-field, which is the region which exists at a substantial distance from the source where sound waves emanating from the source are in phase (and the acoustic pressure and particle velocity are in phase). For regions close to a real source which has finite size, the sound waves emanating from different parts of the source are out of phase, leading to a region of interference where the acoustic pressure (and particle velocity) show considerable spatial variation. This latter region is termed the acoustic near-field. The range out to which the near-field region extends and at which the far-field begins is dependent on both the frequency of the radiated sound and the radiating dimensions of the source, i.e. for a given frequency, a larger source will have a more extended near-field region. The Source Level is a measure of the far-field radiation, and contains no information about the near-field.

3.1.3 Source Level for surface ships

In practice, ships are extended sources. They consist of a highly complex series of mechanical sources within the vessel, each of which has its own vibration amplitude and frequency. These individual sources include the engine, transmission, and the propeller. For dredgers, there are additional potential sources of sound such as the pump and suction pipe. As with other surface vessels, the dredging vessels considered in this report, although possibly more complex, can be considered continuous sources of noise for the purposes of noise assessment or environmental impact assessment requirements. This makes them different in nature to impulsive type sound sources like seismic airguns or marine pile driving (this is discussed further in sections 5.6.3 and 5.6.5).

For some applications, it is important to study these individual sources of sound. For example, there may be a desire to reduce the radiated noise (through noise-quietening techniques). This may be in order to meet a specification for a “quiet” vessel such as a fisheries research vessel, or for reasons of stealth in military applications. In such cases, the amplitude and frequency of individual sources of sound may require specific study. In applications where the sound field very close to the ship may be important, such as for mine avoidance, the interaction of these sources in the acoustic near-field may also require study.

However, when characterising the acoustic output of vessels for the purposes of environmental impact assessment we may restrict ourselves to the consideration of only the acoustic far-field. In so doing, considerable simplification may be introduced, and the concept of Source Level may provide a useful output metric. However, there are further complications due to the proximity of the source to the medium boundaries.

In practice, surface ships do not behave like monopole sources in free space because of the proximity to the water surface which is a strong reflector of the sound field. In general, the sound field may also be influenced by variations of the sound speed throughout the water depth and, especially for shallow water, by reflections at the interface with the seabed. The reflections from the water surface cause interference with the direct sound waves from the source, a phenomenon often referred to as the *Lloyd’s Mirror* effect. This can have a large impact on the sound radiation by surface ships. When comparing published data for Source Levels of ships, it is important to be aware of the definition used, the measurement conditions, experimental procedures and environmental parameters, as well as inconsistencies in reference distances, units and bandwidths, all of which may be stated in different ways in the literature. The data presented for ship Source Levels in the scientific literature commonly appears in two forms:

<u>Format 1: dipole Source Level</u>

The first is the most common format and is based on the definition provided in Section 3.1.3, but where the scaling for distance is undertaken using a model which does not take into account the effect of interference by reflections from the water surface and seabed, or indeed absorption by the water. The simplest dipole source consists of two point sources, or 'monopoles' of equal strength placed an infinitesimally short distance apart, operating at the same frequency but always vibrating 180^{o} out of phase with each other. The water surface provides a strong reflector with the reflection inverted compared with the incident signal. For this reason, a surface ship may be considered as a dipole source consisting of the noise source on the ship and its image in the reflecting water surface. There are a number of examples where this format is adopted [Arveson & Vendittis 2000, ANSI S12.64 2009].

Format 2: monopole Source Level

The second format is that of a true monopole Source Level as defined in Section 3.1.3. A monopole source is the simplest of all sources, consisting of a “point source” radiating the same energy in all directions (it is omnidirectional). Here, the Source Level is obtained using an appropriate acoustic propagation model of sufficient sophistication to account for all required aspects of the sound transmission. A propagation model describes how the acoustic energy varies as a function of acoustic frequency and range from the source. For accurate results, a model should include interactions with the sea surface and seabed, absorption in the water, and potentially other features such as variation of sound speed and bathymetry. This method requires an assumption for the effective location of the acoustic centre of the ship. This method is less prevalent in the scientific literature when describing ship noise, but has been used by some researchers [Wales & Heitmeyer 2002].

The choice for the Source Level definition (and therefore the necessary measurement and analysis procedure) depends on the intended use of the results. In order to be able to compare directly with the majority of other published data for ship noise, the dipole Source Level is preferred. However, if the Source Level is to be used as input for calculations of noise distributions, for example for impact assessments, the Source Level definition should agree with the definition in the propagation model used to calculate these distributions. The standard models used for such calculations require a monopole Source Level as an input.

In the work of this project, the monopole Source Level has been estimated using equation 3.4 with an appropriate acoustic propagation model which accounts for interactions with the surface and bottom (and absorption). The monopole Source Levels are given in Appendix D. However, the data have been converted dipole Source Level for the presentation in the majority of the report in order that the results may be placed in context with those of other commercial vessels. The dipole Source Level has been calculated so as to conform as far as practicable to the definition given in ANSI S12.64 (see Section 3.2).

3.1.4 Shallow water specific environmental dependence

One effect not always appreciated is that shallow water channels do not allow the propagation of low frequency signals due to the wave-guide effect of the channel [Urick, 1983; Jensen *et al,* 2000]. This effect describes how the sound waves are “trapped” between the boundaries (surface and bottom). A characteristic of this phenomenon is that there will be a critical frequency, below which sound waves will not propagate over any substantial distance from the vessel (instead the sound propagates into the sea-bed). This critical frequency is often called the cut-off frequency.

For an idealised channel consisting of a rigid bottom and a pressure-release surface, the cut-off corresponds to a frequency where the water depth is equal to a quarter-wavelength. However, for a realistic seabed, a slightly more complicated formula depending on the ratio of sound speed in the bottom to that in the water can be used [Jensen *et al,* 2000]. The results of plotting this formula is shown in Figure 3.1.

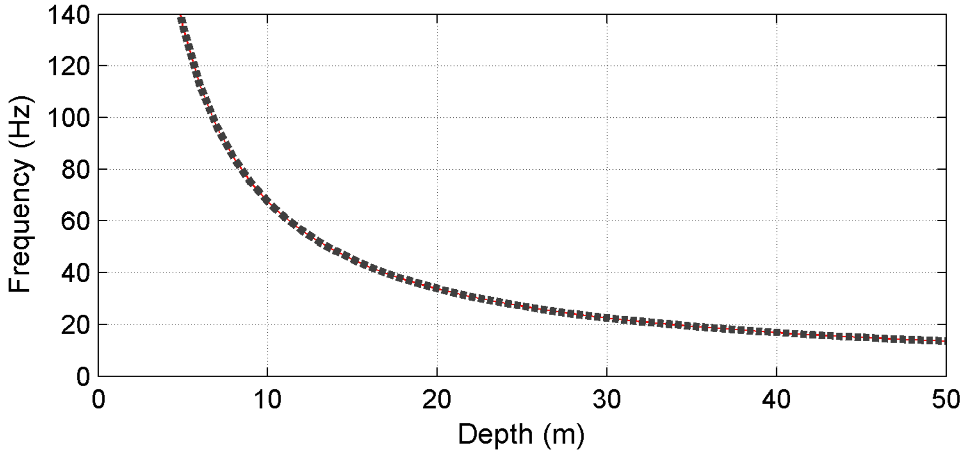

Figure 3.1 The lower cut-off frequency as a function of depth for a shallow water channel with a seabed sound speed of 1805 m/s and water sound speed of 1503 m/s [Urick, 1988; Jensen *et al*, 2000].

It can be seen from Figure 3.1 that for the water depths present in and around the UK licensed dredging areas of 20 m to 45 m, frequencies below around 30 Hz would not be expected to propagate in the water column, and so would not be present in the radiated sound field beyond ranges equivalent to a few water depths (two or more) away from the vessel.

3.2 SPECIFICATION STANDARDS

3.2.1 ANSI S12.64

Currently there are no available international standards describing procedures for measurement of the radiated underwater noise from dredgers operating in shallow water. However, there is a recently published US standard for the measurement of commercial vessels in deep water: ANSI/ASA S12.64-2009/Part 1 [ANSI S12.64]. This document requires that the measurements be made in relatively deep water: a minimum depth of 75 m or one ship length, whichever is greater (though even deeper water is preferred). For many of the vessels studied in the work reported here, this would require water depths of 100 m or more. Since the aggregate extraction by the dredger is limited to a maximum water depth of approximately 50 m, this is simply not feasible. However, a number of the principles described in ANSI S12.64 may still be applied to the measurement of dredger noise, so long as the limitations are recognized.

A feature of the ANSI S12.64 method is the measurement of the radiated noise at “beam aspect” as the vessel transits past the measurement station [ANSI S12.64]. The radiated noise is detected by hydrophones suspended in the water column beneath the measuring station (a survey vessel or measuring buoy). Depending on the accuracy grade required, measurements may be made with one, two or three hydrophones. The recommended measurement range from the source vessel is

100 m (or one overall ship length). The measurement data is recorded over an angular window of ±30º centred around the Closest Point of Approach (CPA). Depending on the grade of the measurement, the data window is analysed as a whole, or is divided into shorter windows of no shorter than one second length for analysis, with the data corrected for the range variation.

To calculate the Source Level, the Received Levels are corrected for the range from the source using a simple spherical-spreading correction, producing a Source Level term described in ANSI S12.64 as the “affected Source Level”. This parameter is related to the monopole Source Level but includes the effect of the reflected energy from the water surface. In effect, this is a form of dipole Source Level, where the vessel is being treated as a noise source in combination with its “image” in the plane of the water surface. This is the format used for most of the data for vessel noise that is available in the scientific literature. This “affected Source Level” is used for the majority of the data presentation in this report.

3.2.2 Other related standards

There are two other standards relevant to the noise radiated by ships.

The ICES:209 report was produced by the International Council for Exploration of the Sea and describes the criteria for radiated noise levels which must be achieved by vessels used as research vessels, specifically those used in fisheries acoustics. The report provides a target Source Level spectrum which has been cited by a number of other researchers as criteria for a vessel to be regarded as quiet. However, the report does not describe a measurement method.

A Norwegian standard has also been produced by Det Norske Veritas: DNV Rules for classification of ships, part 6 chapter 24: Silent Class Notation. [DNV Silent Class, 2010]. As with ICES 209, the aim of this document is to set the criteria for maximum allowable noise levels for various operations, in this case by seismic, fisheries and research vessels. However, this document does give a brief description of a test procedure in an appendix. The procedure requires a minimum water depth of 30 m and hydrophone ranges of between 150 m and 250 m. The data is recorded over 30 second windows with 10 second windows used for range correction. The propagation correction is achieved with very simple geometric spreading laws.

Finally, it is perhaps worth mentioning the work being undertaken by the International Organization for Standardization (ISO). Work is underway in Working Group 6 of ISO Technical Committee TC8 (Shipping and Maritime Technology), Sub-Committee 2 on developing a standard for measurement of noise from commercial ships. Work has also been proposed in ISO Technical Committee TC43 (Acoustics). However, no standard has been published by ISO to date.

3.3 MEASUREMENT METHOD AND ANALYSIS

3.3.1 Objectives

The primary aim of the measurement methodology was:

- to obtain good estimates of the typical Source Level for UK dredgers under normal operating conditions.

However, within this there were some secondary objectives:

- to investigate the potential variation in noise depending on vessel operational mode;
- to investigate possible noise generation mechanisms;
- to investigate the potential variation in noise depending on location and type of load being dredged.

To achieve these aims, the measurement method used was more flexible and more comprehensive than that recommended by ANSI S12.64.

3.3.2 Measurement configuration

A schematic diagram is given in Figure 3.2 showing the configuration used. A survey vessel was used to deploy a range of hydrophones which sampled the acoustic field. The hydrophones were deployed along a transect orthogonal to the nominal direction of the dredger track. Hydrophones were deployed at a minimum of three measurement stations from the closest point of approach, with two hydrophones deployed at each station. This enabled the acoustic field to be measured as a function of range from the source, effectively allowing an empirical estimate to be made of Propagation Loss. A full description of the survey vessel used (MV George D) is given in Appendix A.

For one of the measurement stations, the survey vessel was used to deploy the hydrophones from the surface, the vessel being anchored at a fixed location typically between 100 m and 125 m from the dredger under test. Hydrophones were deployed attached to weighted ropes at nominal depths of between 9 m and 11 m, and between 13 m and 15 m respectively from the surface. The hydrophones used were Reson TC4032 devices which have high sensitivity, a usable frequency range from 5 Hz to 100 kHz, and have very low *self-noise* (below sea-state zero). On some of the trials, a TC4014 hydrophone was used for higher frequency measurements (up to 200 kHz).

For the other measurement stations, autonomous recording buoys were used. These were bottom mounted, with an anchor and weight used to maintain their position, effectively decoupling the surface wave motion from the hydrophones. The two HS70 hydrophones used were attached to a sub-surface buoy and were designed to be positioned at nominal heights of 5 m and 10 m from the seabed. An electronics pod containing digital recording equipment was positioned on the rope between the two hydrophones. A separate line from the bottom weight led to surface floating buoys which were used to locate and retrieve the recording systems. See Figure A2 in Appendix A for more detail of the mounting. At least one buoy was located at a nominal range of 400 m from the dredger under test. Typically, one buoy was located closer to the dredger at a nominal range of 50 m to provide a high signal-to-noise ratio recording of variations in the operational mode.

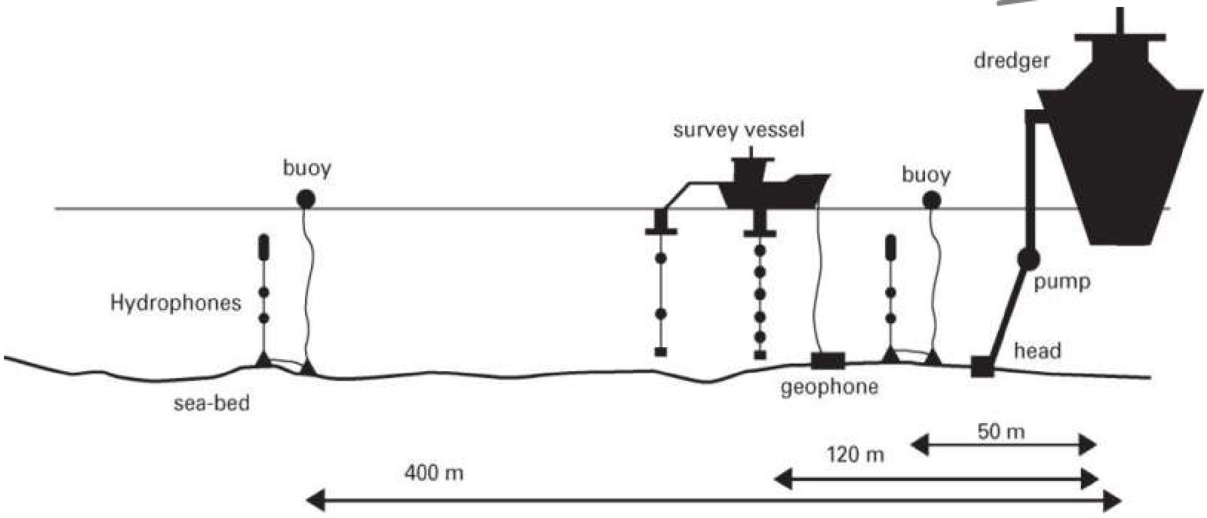

Figure 3.2 Schematic of the measurement configuration.

For some of the trials, a vertical array was deployed from the survey vessel to attempt to ascertain the elevation direction of the incoming acoustic signals. The aim of this was to determine the location of the noise sources on the dredger by performing some beamforming in the vertical orientation. For example, propulsion noise may be expected to originate from close to the surface, but noise from the draghead may originate from the seabed. The array consisted of 7 SRD HS70 hydrophones connected to a multichannel National Instruments acquisition card.

For the sea-trial on the City of Chichester, measurements were made of the seabed vibration using a tri-axial geophone assembly mounted on a heavy steel plate. This was deployed from the survey vessel on long, slack support ropes to minimise the vibrational connection between the survey vessel and the geophone sensors. The geophone assembly was calibrated by an external laboratory specialising in vibration and acceleration calibrations.

3.3.3 Data acquisition

The acquisition system onboard the survey vessel was based on a B&K Pulse system operating at either 16 or 24-bit resolution and capable of sampling at 520 kS/s. For the TC4032 hydrophones, a sampling rate of 262.144 kS/s with 24-bit resolution was used, allowing frequencies up to over 100 kHz to be recorded. For the measurements made using the TC4014 hydrophones, the sampling rate of the B&K Pulse was system doubled, allowing recordings up to 200 kHz to be made.

Each recording buoy system had two SRD HS70 hydrophones and a recording pod containing a two-channel Microtrack MAudio digital recorder which stored the data on removable flash cards. The sample rate for each channel was 96 kS/s, providing a measurement bandwidth of 48 kHz, and the resolution was 24-bit.

All data recorded was saved in uncompressed format. All data was time-stamped with the timers set by reference to UTC via GPS transponders.

All hydrophones were calibrated by NPL over their full frequency range. The calibrations are traceable to the UK national standards maintained by NPL. The primary standards at NPL have been validated by comparison with those of other national metrology institutes in the Key Comparison exercise organised under the auspices of the Consultative Committee on Acoustics Ultrasound and Vibration (CCAUV) [Robinson *et al*, 2005].

A portable hydrophone calibrator based on a B&K 4229 air pistonphone was used to perform in-situ checks on the hydrophones onboard the survey vessel before deployment. These checks were at a frequency of only 250 Hz and were intended as a check on the hydrophone calibration in case of damage during deployments.

3.3.4 Deployment

During measurements onboard the survey vessel, quiet conditions were maintained. This required that the vessel engines and the generator were switched off, as were any echosounders, and attempts were made to avoid mechanical noises due to movement of people on the vessel.

All acquisition equipment was run from battery supplies so that no generator or supply was needed, and any extraneous electrical pick-up could be minimised.

The location of the survey vessel was recorded using portable GPS transponder. The latitude and longitude was recorded typically every 30 seconds. This was done even during the acoustic measurements when the vessel was at anchor since it was possible for changing tides and currents to rotate the vessel about the anchor or even cause the anchor to drag slightly. For the recording buoys, the GPS system was used to mark the point when the anchor hit the seabed during buoy deployment. On buoy retrieval, the point when the anchor and weight lifted was also marked to check for drift during measurements. An electrically-operated capstan and winch was available on the survey vessel for deployment and retrieval of the buoys.

Precautions were taken to avoid interference from parasitic signals such as those caused by water surface motion (causing hydrostatic pressure fluctuation), flow noise, cable strum and mechanical chafing of components. These also included:

- the buoys and hydrophones being bottom-mounted to decouple them from the water surface motion
- an internal 7 Hz high-pass filter was used on the input channels to the B&K Pulse system to reduce the low-frequency signals from wave motion on the recorded signals;
- an anti-heave suspension (consisting of elastic ropes and a damper disc) was available for use on the hydrophones deployed from the surface vessel;
- the hydrophones were stood-off from the supporting ropes by flexible plastic supports to minimise mechanical contact with cables and reduce the influence of strumming;
- no metal parts (*e.g.* shackles or chains) were used in the deployment to avoid metal-on-metal contact;

- spiral wrapping ties were used to attach the hydrophone cable to the support rope in an effort to minimise vortex shedding in high water flows;
- where possible, measurements were attempted at slack tide to avoid times when tides and currents were at their strongest.

3.3.5 Procedure

The vessel under test was asked to transit along its designated track with its Electronic Monitoring System (EMS) recording position via GPS and dredge status. The EMS is an autonomous black box monitoring system used for regulatory compliance onboard every vessel undertaking marine aggregate dredging in UK waters, and records a positional fix and operational status every 30 seconds while dredging is underway, but only every 30 minutes during transit (when not dredging). The dredger track had usually been planned at least 24 hours in advance by the dredging operator and was defined by the GPS coordinates of two end points of a nominal straight line. However, the actual track could vary from this line as the dredger operated in a “mowing the lawn” configuration. The dredger operator provided the data from the GPS log of the vessel some time after the date of the trial.

The measurement stations were deployed co-linearly but at an angle of 90º to the nominal dredger track, with the intersection of the lines usually arranged to be centrally positioned in the dredger track. Figure 3.3 shows a schematic diagram illustrating the geometry of the arrangement.

When traversing its track and under operation, the dredger is typically moving slowly at no greater than 1.5 knots (travelling about 46 m in one minute). The recording buoys were recording throughout the duration of the trial (from just before deployment to just after retrieval). The recordings made on the survey vessel were more limited in time because they could be started and stopped by an operator, but typically they covered a majority of the dredger track.

The data used for the Source Level analysis was taken from the region around the CPA. In this region, the dredger is closest to the measurement stations, and the radiated noise approximates most closely to beam aspect. A similar procedure was followed to ANSI S12.64 in that the data from a relatively narrow subtended angle was used in the analysis (approximately 30º). For the work here, a data sequence of 30 seconds was divided into 2 second data windows and each of these was analysed to provide the third-octave band power. The data for each 2 second window was then corrected for Propagation Loss using the model described in Section 3.4, with the range calculated from the GPS coordinates of the dredger and measurement station for each of the individual 2 second windows. This means that the variation in range throughout the passage of the dredger through CPA was accounted for by the Propagation Loss calculation.

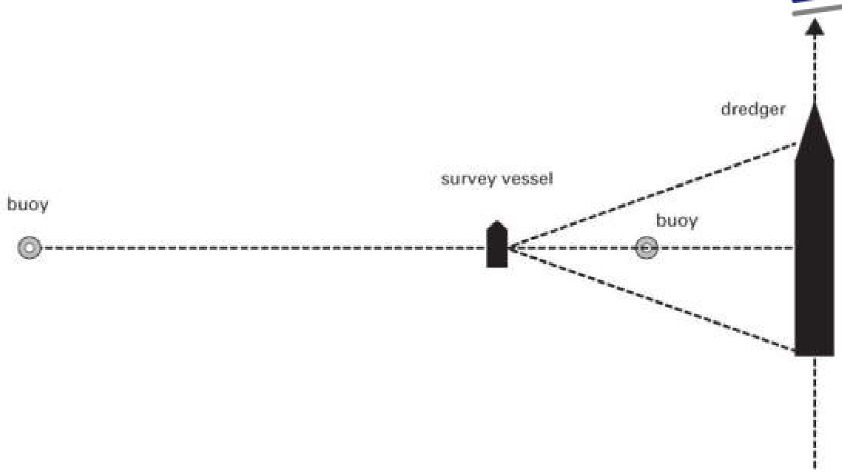

Figure 3.3 Schematic of measurement geometry showing the dredger passing closest point of approach (CPA) and the relative positions of the survey vessel and buoys.

The above analysis is in fact somewhat conservative. For example, the range to the dredger hardly varies at all for the buoy at 400 m during the 30 second sequence, so relatively little is gained by correcting each individual 2 second window. However, for the 50 m buoy, the fractional change in range is more significant and so there is benefit from undertaking the analysis. For comparison, the whole 30 second sequences were also analysed *in toto*. As might be expected, the results were in good agreement with the mean of the 15 two-second windows. However, breaking down the sequences into shorter windows also allows the calculation of standard deviations which reflect the variation in the noise output during the dredger passage.

In a less conservative approach, much longer data sequences could have been analysed, for example while the dredger was approaching from some distance away from CPA. This would allow more data for averaging to obtain a potentially improved value for the mean radiated noise (averaging more of the variations in noise output over a longer section of dredger track). However, there may be some directivity to the noise radiated by the dredger which would limit the usefulness of this approach. In particular, when observing at a partial stern aspect (“looking” through the vessel wake) there may be significant differences in the radiated noise compared to beam aspect.

The third-octave analysis was undertaken using a series of digital filters with the appropriate centre frequencies and bandwidths. This was implemented in the Matlab programming language following the method stipulated in ANSI standard S1.11 [ANSI S1.11, 2004] and following the definition of third-octave bands stated in IEC standard 61260 [IEC 61260:1995]. To check the accuracy of these filters, several comparisons were undertaken. The filter outputs were compared to:

(i) the results of summing the narrow-band levels within the individual third-octave bands, the narrow-band levels being obtained from traditional FFT analysis;
(ii) the results obtained using the third-octave power band analysis available within the B&K Pulse software suite;

(iii) the results obtained by dstl when independently calculating the third-octave band levels for exactly the same data sequences.

The results of these comparisons showed excellent agreement, with the typical differences between results being a small fraction of a decibel. However, it was observed that the filters could produce inaccurate results for very low frequency third-octave bands (less than 50 Hz) if the data windows were very short. For this reason, data windows of less than 2 seconds were not used, and the means of the results of the 2 second windows were always compared with the results obtained by analysing the entire 30 second sequence as a check.

To derive the Source Level, the above analysis was undertaken for each pass of the dredger where full dredging was taking place. For each pass, the 15 two-second data windows from each hydrophone were analysed (generally there was a total of six hydrophones – two for each buoy and two at the survey vessel). The third-octave band data for each hydrophone and data window was then scaled by the appropriate Propagation Loss calculated for the depth and range of that hydrophone at the time of that data window using the model described in Section 4.4, creating a third-octave band Source Level for each hydrophone and each data window. These were then averaged to produce a Source Level for that pass of the dredger. The standard deviations were also calculated to parameterise the statistical variation in the noise output throughout the pass.

For some of the passes on some of the trials, the range to the closest buoy was less than 50 m. In this case, the data from this buoy were not used for the Source Level calculation since the error in the range becomes large for hydrophones close to the source (see Appendix E).

3.3.6 Deviations from ANSI S12.64

Because of the restrictions imposed by the shallow water, the guidance of ANSI S12.64 would be insufficient to characterise the source. Therefore, the procedure was augmented in a number of ways. The following are the major areas where the ANSI procedure was augmented:

- the Propagation Loss model used to derive the Source Level had to be more sophisticated than 20.log(range) – see Section 3.4 for details;
- measurements were made at more than one range for the source;
- measurements could not be made at the suggested look-down elevation angles of 15º, 30º and 45º because of the shallow depth;
- the measurement data windows were more conservative and selected as fixed time intervals of 30 seconds at CPA, rather than the 30º aspect angle allowed by S12.64.

3.3.7 Source characterisation

In addition to the measurements used for deriving Source Level during full dredging, the dredger master was asked to undertake some passes while varying the operational mode of the dredger, and measurements were made of the differences in Received Levels when the modes were changed. This was only possible for some of the dredgers tested, since on occasion logistical factors militated against it (*e.g.* bad weather).

The following operational modes were investigated for at least some of the dredgers:

(i) Full dredging – draghead down, pump on, extracting aggregate;
(ii) Draghead lifted from seabed, pump on, pumping water only (possible state during turning at end of run);
(iii) Draghead lifted from seabed, pump off (also possible state during turning);
(iv) Draghead down on seabed, pump off (highly unlikely in practice);
(v) Drag head down on seabed, pumping aggregate, with and without screening;
(vi) Drag head down on seabed, pumping aggregate, with and without overspill;
(vii) Dredger operating bow thruster;
(viii) In transit – “steaming past” with no dredging operations.

In practice, some of these were more successfully achieved than others. Ideally, to measure the difference in noise level caused by the change in operational mode, the “before-and-after” measurements should be of the same ship, on the same pass, at the same range. For items (ii), (iii) and (iv), this was very successfully achieved for a number of dredgers. However, (v) and (vi) proved logistically too difficult to fully achieve except indirectly – the “with-and-without” screening and overspill was only for different dredgers, and the differences between the dredgers themselves confuses the analysis. Item (vii) was achieved for one dredger. Item (viii) was not satisfactorily achieved because of lack of positional data from the dredger during transit (see Section 5).

To facilitate these measurements requires real-time communication with the dredger, so during the measurement trial, the survey vessel kept in regular contact with the dredger by VHF radio. The master of the dredger was requested to inform the scientist in charge on the survey vessel when the operational mode was altered (for example, when the draghead was lifted, or when the pump was switched on or off). This enabled the mode changes to be correlated with the changes in Received Level at the hydrophones on the survey vessel (or in the buoy recordings). It was sometimes possible to use the GPS log of the dredger to help with identifying the times when a change of mode occurred (some of these are indicated in the GPS log), but these were limited to the 30 second time resolution available from the dredger log file.

In addition, for the Received Levels to properly reflect the “before and after” comparisons with mode change, the changes had to occur close to CPA with the measurements made on the same dredger pass. This is because each pass tended to be at a slightly different range and potentially could have a slightly different Source Level due to dredging a different strip of seabed, which would make the analysis more difficult. Therefore, for all the comparisons of operational modes, the dredger master was asked to effect the change in mode close to CPA and the measurements of Received Level were taken either side of the change where the dredger was still effectively at the same range and on the same pass.

3.3.8 Ambient noise measurements

In addition to the measurements of radiated noise, measurements were also made of ambient noise in the vicinity of the dredging areas. These measurements were made in the manner described in Section 3.3.5 by using the low-noise TC4032 hydrophones deployed from the survey vessel in the same way as for radiated noise measurements. Again, quiet survey vessel conditions were observed - no echosounders, engine off, electrical generator off, with all equipment operated from battery supplies. The precautions against parasitic signals described in Section 4.3.4 were also taken for the ambient noise measurements. One significant difference for the ambient noise measurements was that the survey vessel was not anchored, but was allowed to drift with the current. This helped to minimise some of the parasitic signals mentioned in Section 3.3.4 such as flow noise. The recordings were made for several minutes at a time, with the maximum recording length being 20 minutes. The ambient noise was measured either substantially before or after the dredging activity took place to avoid any contamination from the radiated noise of the dredger. On one occasion, for the East coast dredging areas, the ambient noise measurements were made on a separate day when there was no dredging activity.

During the measurements, a record was kept of any auxiliary data that was regarded as relevant (weather conditions, local traffic, *etc.*). See Section 3.3.9 for details.

It should be noted that the ambient noise in shallow coastal areas will vary spatially, for example with proximity to shipping lanes. It will also vary temporally, for example diurnally, seasonally, or even with the frequency of local ferry timetables. Therefore, any measurement of ambient noise which has any pretence to being a representation of the true noise must be measured at a number of locations, and most of all over a substantial time period. Therefore, the ambient noise levels reported here must be considered as snap-shots of the actual noise which have been sampled very coarsely in time and space. They are useful only as an indication of the background noise that existed in the areas during the sea-trials to characterise the dredgers.

3.3.9 Auxiliary data

As already discussed it was important to record any auxiliary data which may be relevant during the measurements, since these may be correlated with the measured background noise levels, and thereby affect the available signal-to-noise ratio. These include:

- Sea-state;
- Wind speed and associated measurement height;
- Rainfall and other precipitation, including snow;
- Water depth and tidal variations in water depth;
- Change in water temperature with depth and air temperature;
- Hydrophone depth in the water column;
- GPS locations of hydrophones and recording systems;
- Sea-bed type;
- Bathymetry

- Current flow and associated measurement depth;
- Presence of shipping traffic and distance from hydrophone;
- Occasional events like lightning or passing aircraft.

For assessing shipping traffic in the vicinity, an Automated Information System (AIS) receiver was used. In addition, CTD profiles were performed using a sonde providing temperature, density, salinity and sound velocity as a function of depth as the CTD sonde is first lowered and then raised in the water column.

3.4 PROPAGATION LOSS MODEL

3.4.1 The model

The acoustic model used to calculate the Propagation Loss is a source-image model (the implementation of which is referred to as ImTL in this report) which models the sound field of a source as the sum of the acoustic radiation from the source and a series of images of the source reflected in the medium boundaries: in this case, the water surface and seabed [Urick 1983]. The source is modelled as an ideal point source. The arrangement of the source and its images can be seen in Figure 3.4.

A detailed description of the model is given in Appendix C.

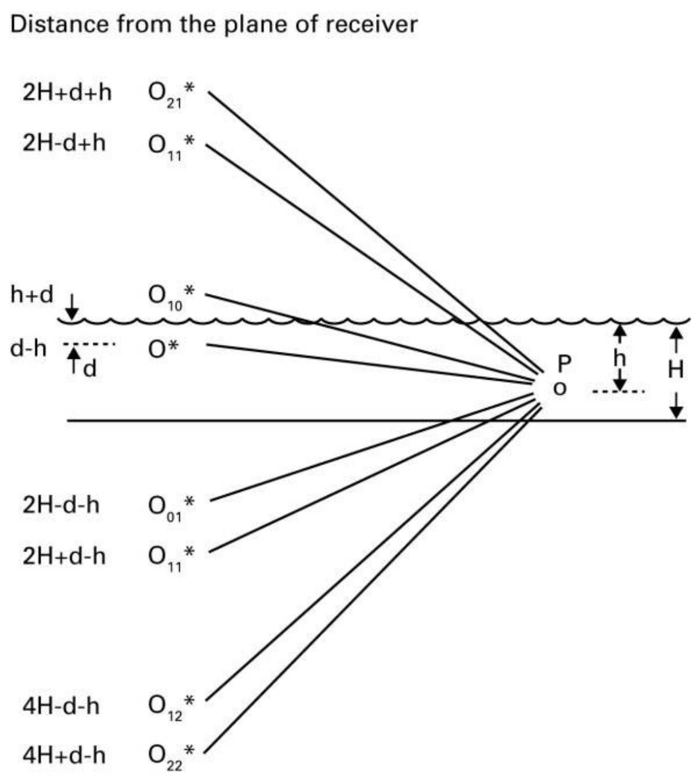

Figure 3.4 Image sources to a receiver in a shallow water channel.

The ImTL model incorporates a number features to account for key acoustic interactions:

Interaction with the seabed
The sea bottom is assumed to be elastic with values for compressional sound speed, shear sound speed and mean density. The theory of Brekhovskikh and Lysanov has been used to describe the reflection of sound waves from such a bottom [Brekhovskikh and Lysanov, 2003].

Interaction with the sea surface
The surface reflection coefficient is obtained with the higher value of two surface reflection/scattering models; a simplified Beckman-Spizzichino model [Coates, 1988] for an incoherent surface scattering and, a Gaussian coherent reflection coefficient [Medwin and Clay, 1998] incorporating the wind speed [Ainslie *et al*, 1994].

Absorption of sound by the water
Sound absorption as a function of frequency is included in the model [Francois and Garrison 1982a, Francois and Garrison 1982b, Ainslie and McColm 1998].

The range-independent nature of the ImTL model makes a number of assumptions:

Flat bathymetry
This is a valid assumption for the areas where measurements were made over the ranges used (typically no more than 400 m). The water depths measured by the echosounder of the survey vessel rarely varied by more than a couple of metres, with overall water depths in the areas varying from 27 m to 45 m. Therefore, the mean water depth in the area was used.

Isovelocity sound speed profile
This was confirmed by measurement of the sound speed in the measurement areas by use of a CTD sonde. The sound did not vary significantly with depth. This is to be expected since the areas are shallow and well mixed by tides and currents, and not close to any fresh water outflows from river estuaries or tidal fronts.

The model was run for each of the source-receiver combinations in each of the environments existing during the measurement trials. The input data (along with units) required by the model were:

a) Hydrophone range (m)
b) Hydrophone depth (m)
c) Source depth (m)
d) Water depth (m)
e) Water density (kg m^{-3})
f) Sediment density (kg m^{-3})
g) Water sound speed (m s^{-1})

h) Sediment sound speed (m s^{-1})
i) Salinity (PSU)
j) pH
k) Wind speed (knots)

The source and hydrophone depths and ranges define the geometry of the model along with the water depth. The hydrophone depths were taken to be the actual deployment depths used during the measurement campaigns and the source depth was taken from specifications provided by Cemex for the F-class (Sand Falcon) and H-class (Sand Harrier) vessels for a mid-fully loaded vessel. The salinity and pH are required for the absorption calculation (obtained from CTD sonde measurements), and the wind speed is required for the surface reflection (based on observations during the measurement campaigns). The water and sediment properties are required to calculate the reflection coefficients. The sediment data were obtained from the paper by Hamilton [Hamilton 1980].

3.4.2 Range averaging

The model calculates the Propagation Loss (*PL*) as a function of range, depth and acoustic frequency. However, in conformance with ANSI S12.64, the analysis of the received data is undertaken in third-octave bands. To obtain a Propagation Loss which is appropriate for an entire third-octave band, some form of averaging must be done. This can be done in the frequency range, but this would require the model to be run many times. Instead, a range averaging technique was used on the PL data for each third-octave band centre frequency. This passes an adaptive Gaussian filter through the data to smooth out the rapid fluctuations which occur in the loss data for single frequency analysis [Harrison and Harrison 1995]. The range averaging technique was checked against frequency averaging for a range of third-octave bands and environmental scenarios and the agreement between the two was found to be excellent.

3.4.3 Conversion to an ANSI S12.64 “affected” Source Level

The model above assumes that the source is a point monopole source positioned below the water surface. Since much of the ship noise data in the literature is published as the dipole Source Level (termed “affected” Source Level by ANSI S12.64), it is necessary to convert the data to this form to compare with data for other ships. This may be done by considering the method of analysis recommended in the ANSI S12.64 standard where the ‘affected’ Source Level is reported as the power average of the results of measurements with hydrophones at three “look-down” angles of 15º, 30º and 45º. Figure 3.5 shows a diagram of the geometrical arrangement of the measurements required for ANSI S12.64.

The conversion between a dipole and monopole Source Level is given by Ainslie as [Ainslie 2010]:

$$SL_{mon} = SL_{dip} - 10\log\left[\frac{1}{2} + \frac{1}{4\,k^2\,d^2\sin^2\theta}\right] \quad (3.5)$$

Where k is the wave number, d the depth of the source and θ is the depression or "look-down" angle relative to the surface. The correction to obtain the ANSI affected Source Level dipole from the monopole Source Level, including the averaging for the three look-down elevation angles, is plotted against frequency in Figure 3.6.

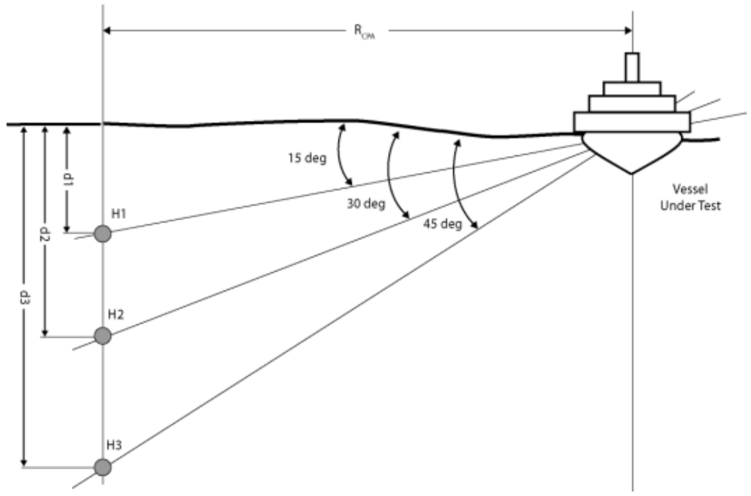

Figure 3.5 Diagram of the geometrical arrangement of the measurements required for ANSI S12.64 showing the three look-down angles over which the averaging is done.

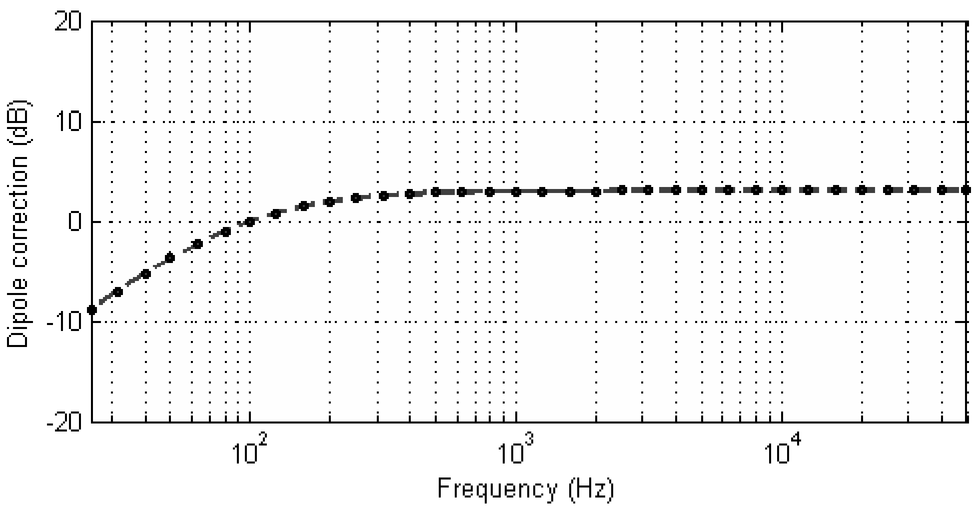

Figure 3.6 The correction applied to the monopole Source Level at 4 m depth to convert to the ANSI S12.64 affected Source Level averaged over look-down elevation angles of 15º, 30º and 45º.

Conversion to a dipole Source Level has the effect of increasing the high frequency loss values (and therefore the Source Level) by 3 dB. At low frequencies, the effect is to suppress the strong dependence on source depth which is present in the monopole loss values. Appendix C provides more detail on the comparison between monopole and dipole Source Levels calculations. Note also that the in Appendix D, the monopole Source Levels are shown in addition to the "affected" Source Levels.

3.4.4 Validation and uncertainties

The Propagation Loss model is a potential source of significant uncertainty in the Source Level calculations. Therefore, the uncertainty has been investigated in two ways. Firstly, the sensitivity of the model to its input parameters has been assessed in order to derive uncertainty in the output loss values. This sensitivity analysis can be used to determine whether errors in the input data can cause significant errors in the results. However, a sensitivity analysis is not sufficient to validate the model since a poor model could simply be systematically biased. For example, the use of a "20.log(r)" geometrical spreading model would not provide accurate results for shallow water since is neglects the surface and bottom interactions and absorption in the water, and any bias would not be illuminated just by a sensitivity analysis. Therefore the model was compared with other standard models in order to benchmark it.

3.4.4.1 Sensitivity analysis

A Monte Carlo method [GUM 2008] was used to investigate the sensitivity of values of Propagation Loss to perturbations in the values of the input quantities listed in Section 3.4.1, and to evaluate the standard uncertainty associated with estimates of Propagation Loss.

Each input quantity in the model, as listed in section 3.4.1, was characterized by a rectangular probability distribution defined by a nominal value (its expectation or mean value) and semi-width. For each Monte Carlo trial, a value for each input quantity was obtained as a random draw from the distribution characterizing the quantity, and the corresponding values of Propagation Loss obtained by evaluating the model for those values of the input quantities. For each frequency, the average of the values of Propagation Loss obtained from 1000 trials provides an estimate of Propagation Loss, and the standard deviation of the values estimates the standard uncertainty associated with the estimate. The results are shown in detail in Appendix C.

The results of this analysis show that for hydrophones at shorter ranges, the standard uncertainty increases substantially. This is mainly due to the error in the range being more significant at shorter ranges. For this reason, the data for the buoy placed at the closest range (nominally at 50 m range) may introduce errors when used for Source Level calculations. However, the decision regarding whether to use the data for the closest buoy was made on a case by case basis since sometimes the buoy which was nominally at 50 m was in fact at 75 m due to the difficulty in deploying the buoy at the nominal position in strong tides and currents. Equally, sometimes the dredger would pass very close to the buoy (less than 20 m away) since there was variability in the dredger track (each pass did not traverse exactly the same track), making any error in estimating the range to the dredger highly significant. At close ranges, it is also possible to introduce errors due to being in the near-field of the Source Vessel [ANSI S12.64 2009]. Therefore, no data measured from buoys at ranges shorter than 50 m was used in the Source Level calculation. In general, this was not a problem for the data obtained from the survey vessel or the more distant buoys.

3.4.4.2 Comparison with other models

The source-image model was compared with a number of well-developed models. These standard models were available in the Acoustics Toolbox available from the Ocean Acoustic Library (www.oalib.hlsresearch.com), compiled versions of which are also available as part of the AcTuP suite of software available from Curtin University, accessed by a front end environment developed within MATLAB [Maggi and Duncan 2010]. The detailed results of these comparisons are summarised here and presented in more detail in Appendix C.

The objective is to benchmark the chosen model with other standard models which are based on different physical principles, and so should have few common sources of error. The other models used for benchmarking the ImTL model were:

BELLHOP	ray tracing based model [Porter 2010]
Kraken	normal model propagation code [Jensen *et al*, 2000]
KrakenC	same as Kraken but allowing complex-valued data [Jensen *et al*, 2000]
RAMGeo	parabolic equation (PE) model that uses a split-step Padé algorithm [Collins, 1993]
RAMsGeo	same RAMGeo but incorporating shear [Collins, 1993]
Scooter	wavenumber integration model [Jensen *et al*, 2000]
OASES	wavenumber integration model [Schmidt, 2004]

Results of the comparisons are shown in Figure 3.7 showing excellent agreement for a frequency of 250 Hz whether the data is unaveraged, or range averaged. Figure 3.8 shows the results of comparisons of range averaged Propagation Loss data for frequencies of 100 Hz and 5 kHz showing excellent agreement.

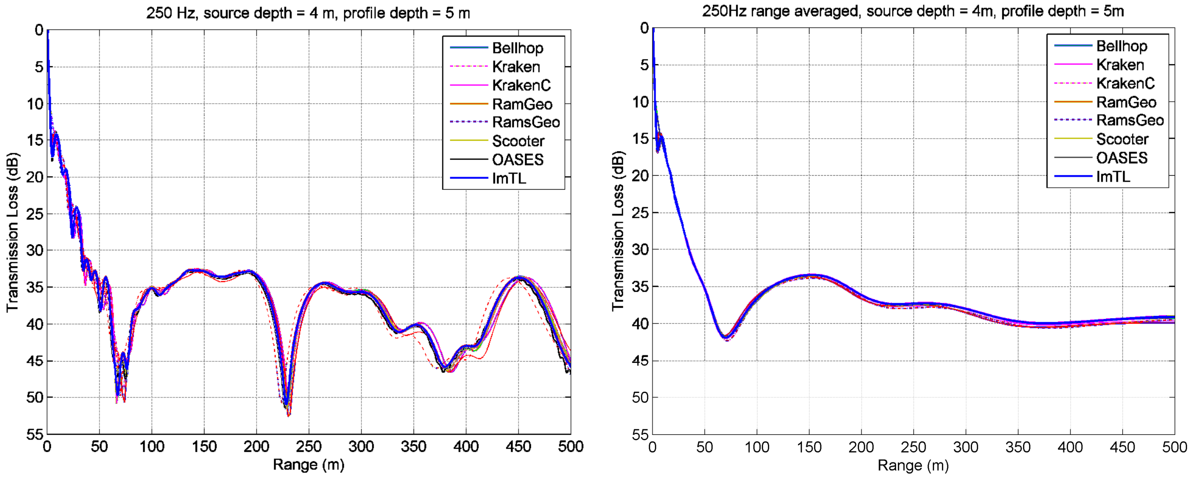

Figure 3.7 Comparison of the Propagation/Transmission Loss model used (ImTL) with other standard models at 250 Hz showing unaveraged data (left) and range averaged data (right).

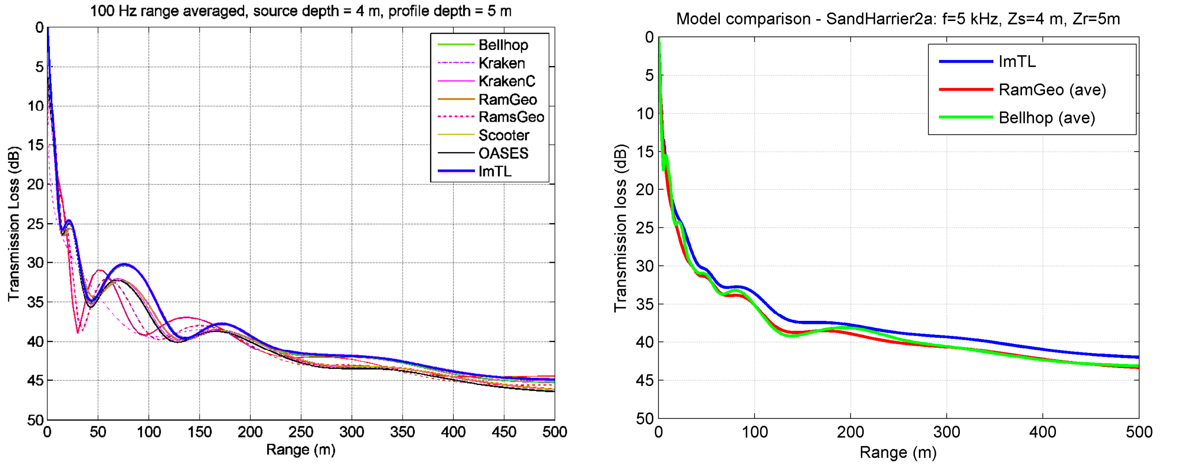

Figure 3.8 Comparison of the Propagation/Transmission Loss model used (ImTL) with other standard models at 100 Hz (left) and 5 kHz (right) showing range averaged data. Some of the benchmark models are difficult to run at kilohertz frequencies, and so the 5 kHz plot is a more limited comparison.

3.4.4.3 Comparison with empirical Propagation Loss data

Since measurements were made at several ranges from the source, it is possible to compare the modelled Propagation Loss with the measured Propagation Loss. When doing this, it is necessary to normalise the absolute Received Levels before plotting, and this was done by normalising to the mean received value over the range. The results of doing this are shown in Figure 3.9.

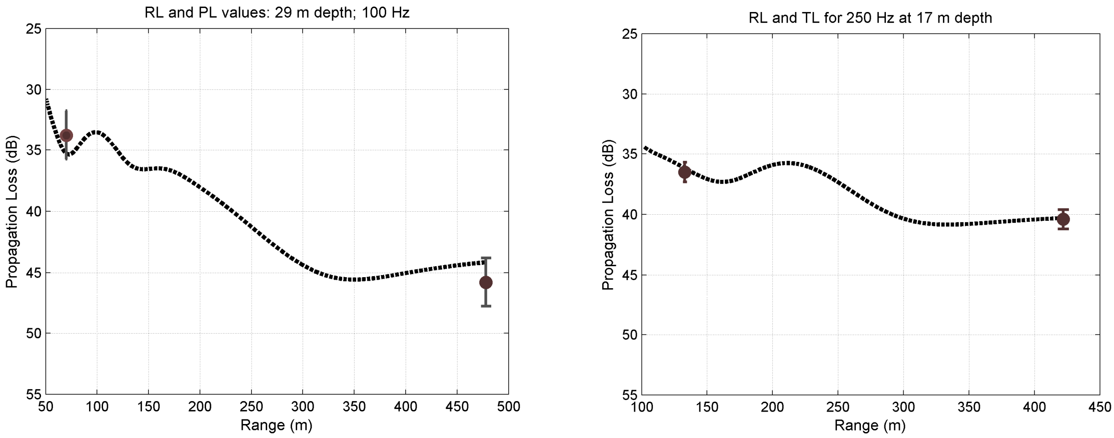

Figure 3.9 Comparison of the Propagation Loss model used with the measured Propagation Loss at 100 Hz and 29 m depth for the EEC region (left) and at 250 Hz and 17 m depth for the South Coast region (left). The dotted lines show the model predictions, and the data points are the relative Received Levels at the ranges shown.

The measured Received Levels shown in Figure 3.9 are obtained from hydrophones attached to recording buoys. The data has been chosen so that signals from hydrophones at the same depth are being compared, with the data sequence chosen to be at the same time on each recording. As can be seen, the model data passes within the error bars showing agreement with the relative Received Levels. The error bars indicate the repeatability standard deviations calculated from the 15 two-second sequences. The results of the comparisons showed that the source-image model could be used to predict the Propagation Loss reliably.

Another method of testing the validity of the Propagation Loss calculation is to compare the results obtained for Source Level estimated from the Received Levels measured on each of the separate hydrophones (for the same data sequence). This analysis has also been undertaken, showing generally very good agreement between Source Levels calculated from the Received Levels on different hydrophones. The results show that in general the Source Level data are grouped together, with a typical mean standard deviation of 2.6 dB. Some other trends can be observed. For example the spread of values is greater below 100 Hz for the Campaign 4 vessels with occasional values of up to 4 dB sometimes observed, indicating that the data at frequencies less than 100 Hz is subject to greater uncertainty.

The above analysis is described in greater detail in Appendix C.

4 MEASUREMENTS MADE

4.1 SUMMARY OF VESSELS MEASURED

A total of four measurement campaigns were conducted, with the original campaign plan being one in March 2010, two in June and one in August. Campaigns 1 and 2 captured two vessels each, and Campaign 4 captured three. However, the third campaign did not result in any measurements being made due to the unavailability of dredgers. The intention was to cover at least three dredging regions, and this was achieved, with measurements made in areas in the East Coast, South Coast and East English Channel regions. Table 4.1 shows a summary of the dredgers measured. Note that one dredger (the Sand Falcon) was measured in two locations loading different cargo. A detailed description of the measurements made on each dredger and the technical specification of each dredger is provided in Appendix B. Examples of dredgers on station during measurements are shown in Figures 4.1 and 4.2. Figure 4.3 shows a plot of the total installed power versus capacity for the UK dredger fleet, indicating the vessels measured in this project. The vessels measured cover a diverse range of power and capacity, with the exception that none of the vessels with less than 2000 kW installed power were measured due to unavailability.

Table 4.1 Summary of dredgers measured.

Date	Vessel	Operator	Region	Area
16 March 2010	Arco Axe	Hanson	East Coast	240
24 March 2010	Sand Falcon	Cemex	East Coast	251
16 June 2010	Sand Harrier	Cemex	South Coast	137
18 June 2010	City of Chichester	Tarmac	South Coast	137
3 August 2010	Sand Falcon	Cemex	East English Channel	473
4 August 2010	City of Westminster	Tarmac	East English Channel	474
6 August 2010	City of London	Tarmac	East English Channel	458

Table 4.2 Technical details of dredgers measured.

Vessel	Built	Length (m)	Total installed power (kW)	No. of engines & shafts	Dredge Pump type	Dredge Pump power (kW)	Screen Config.	Overspill Config.	Maximum dredging depth (m)	Capacity (cubic metres)	Capacity (tonnes)
Sand Harrier	1990	99	3824	1+1	inboard	1591	towers (2) (s'bd)	port & starboard	33	2700	4671
Sand Falcon	1998	120	2x2460	2+2	inboard& overboard (port)	1100 & 1631	towers (2) (s'bd)	port & starboard	50	4832	8359
Arco Axe	1989	98.3	2940	1+1	overboard (s'bd)	1100	towers (2) (port)	port & starboard	48	2890	5000
City of Chichester	1997	72	2,720	2+2	inboard	700	static box	fore & aft, central	35	1418	2300
City of London	1990	99.9	4,080	2+2	overboard (port)	1,100	towers (2) (s'bd)	port & starboard	46	2652	4750
City of Westminster	1990	99.7	4,080	2+2	overboard (port)	1,100	towers (2) (s'bd)	port & starboard	46	2999	5200

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Figure 4.1 The Arco Axe during measurements in Area 240.

Figure 4.2 Sand Falcon on station in Area 473.

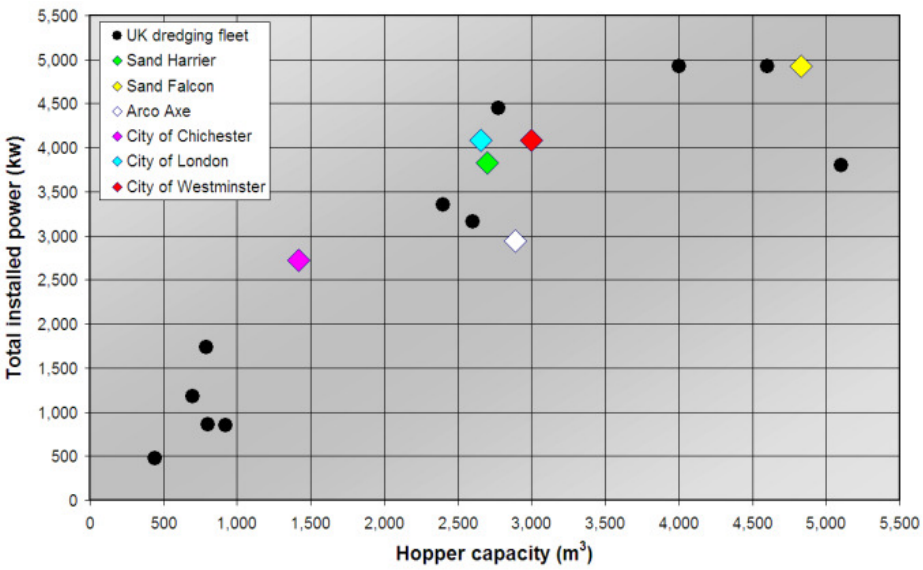

Figure 4.3 Total installed power versus hopper capacity for the UK dredger fleet showing the vessels measured in this project.

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4.2 SUMMARY OF MEASUREMENTS MADE

4.2.1 Acoustic data

For each trial, acoustic data were recorded for several hours. For the total of 44 hydrophone deployments in the whole project, a total of approximately 140 hours of recordings were made, taking up 195 Gbytes of storage. A full description is given in Appendix B of the measurements made during each trial (location, deployments, data recorded, *etc.*).

For each noise trial, recording buoys were deployed at gradually increasing ranges from the dredger track. For logistical reasons, the number of buoys deployed varied from a maximum of 4 buoys for the Arco Axe, to three buoys for the City of London and City of Westminster, and two buoys for the Sand Falcon, Sand Harrier and City of Chichester.

Figure 4.4 Buoy deployment.

For some of the trials, bad weather prevented the survey vessel from being anchored. The measurements are very difficult to perform when both the source and receiver are moving, and in any case the bad weather often prevented the hydrophones being deployed safely from the survey vessel deck. For this reason, there were no hydrophones deployed from the survey vessel for the Arco Axe, or the City of Westminster, for operational reasons, nor were the survey vessel hydrophones deployed for the City of London. In these cases, at least three recording buoys were deployed.

Figure 4.4 shows a buoy being deployed manually; an electrically-operated capstan and winch was used on the MV George D for buoy retrieval. Figure 4.5 shows the survey vessel used for most of the trials (MV George D), and measurements being made onboard during the Sand Harrier trial.

Figure 4.6 shows a typical waveform from a time recording made by the closest buoy during a pass by the dredger (full dredging). The overall level increases as the vessel approaches and then decreases again as the vessel passes beyond CPA. Note that this is just a visual representation in normalised units on the vertical axis, and time in minutes on the horizontal axis.

Figure 4.5 The survey vessel used for most of the trials (MV George D) ready for a 5:30am deployment from Gosport during Campaign 2 (left), and measurements being made onboard during the trial on 16th June 2010 for the Sand Harrier.

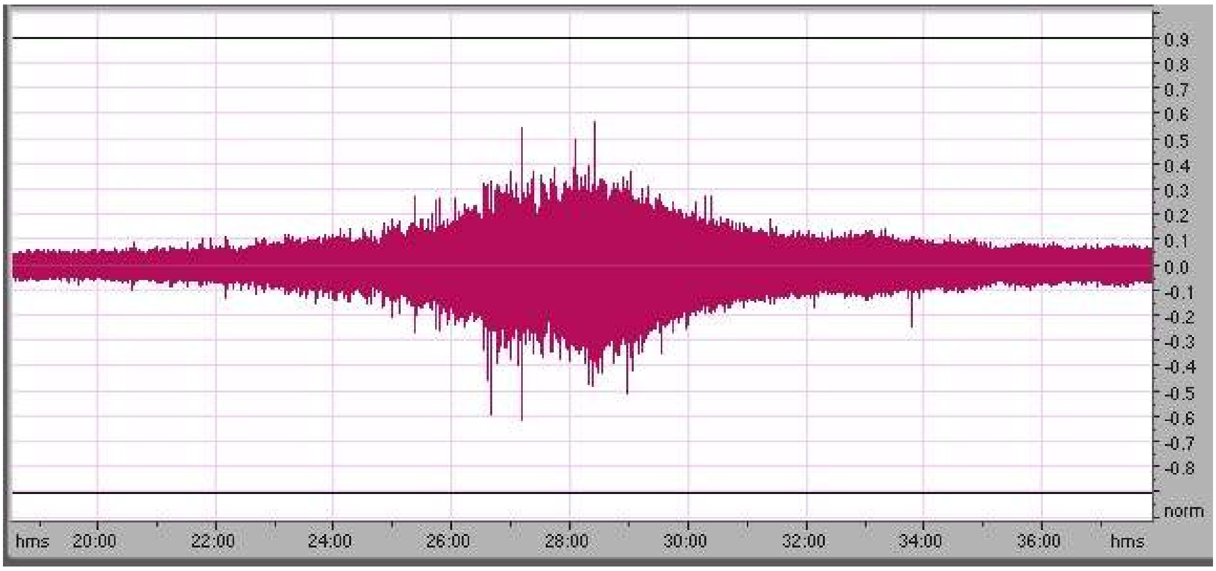

Figure 4.6 Time recording for a dredger pass made on one of the 50 buoys.

4.2.2 CTD data

During the trials, a Valeport CTD Model 602 sonde was deployed to record the environmental conditions in the water column (depth, temperature, salinity, sound speed, density). The water column was found to be close to isothermal in all the areas, and the sound speed did not vary significantly with depth in any of the measurements. This is to be expected since the areas are shallow and well mixed by tides and currents, and not close to any fresh water outflows from river estuaries. Figure 4.7 provides examples of data recorded by the CTD sonde for Area 458.

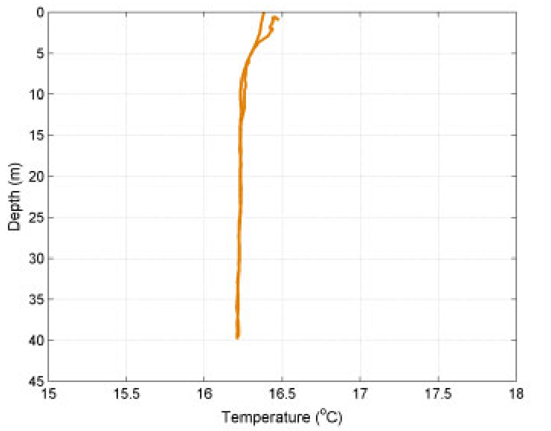

Figure 4.7 Data from CTD sonde, measured on August 6th 2010 in Area 458, showing variation with depth of temperature (left) and sound speed (right).

4.2.3 GPS data

The GPS location of the recording buoys and the survey vessel was recorded using two independent GPS systems. On the survey vessel, this was done every 30 seconds. The vessel could drift very slightly or swing around with tide changes, so the continual GPS recording was needed. For the buoys, the coordinates were marked when the anchor hit the seabed during buoy deployment. On buoy retrieval, the point when the anchor and weight lifted was also marked to check for drift during measurements. Using the GPS data from the onboard systems together with the dredger GPS log provided by the operator after the trial, it is possible to reconstruct the track of the dredger and the range to the measurements stations. Figure 4.8 shows an example of this for the Sand Falcon on Area 473 on 3rd August 2010. Note that the track of the dredger is shown along with the fixed position of the recording buoy positioned at a nominal CPA of 400 m. The range of the dredger from the buoy is also shown as a function of time.

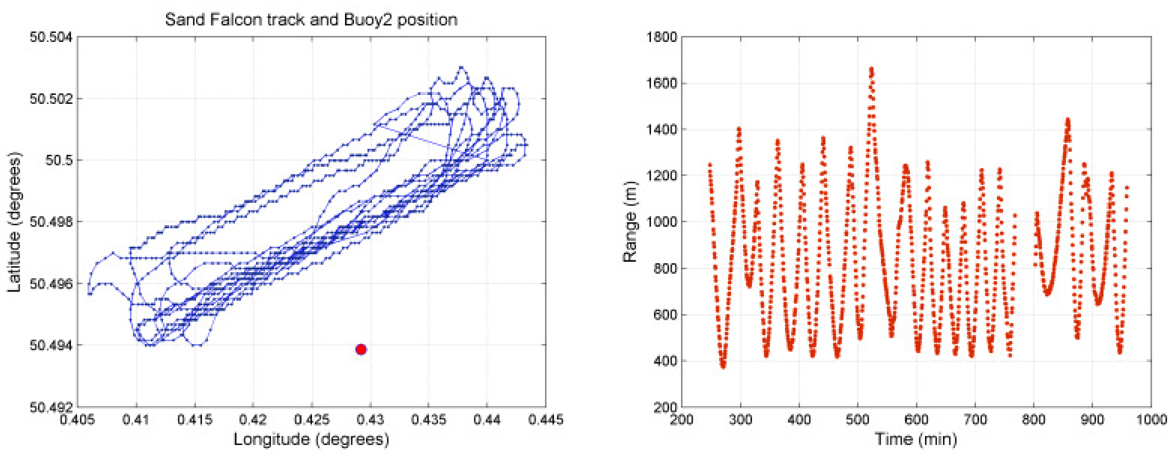

Figure 4.8 Data for the GPS track of the Sand Falcon on Area 473 (left) and range from (nominal) 400 m buoy as a function of time in minutes (right).

There were a number of difficulties in processing the GPS data due to various sources of uncertainty. One issue was that of deciding the correct position for the dredger at any given time. The GPS antenna for the dredger tended to be mounted on the bridge masts, and the position recorded therefore tended to relate to this location rather than being offset to the position of the draghead. For a vessel of 100 m or more, this can lead to considerable uncertainty regarding the correct position of the vessel. In particular, if the main noise source were the propulsion system (at the stern of the dredger), or the draghead (perhaps two-thirds of the way toward the stern), the timing of the CPA using the GPS data will not coincide with the apparent CPA from examination of the noise data itself. In addition, the beam of the dredger could be some 20 m or more, so that the draghead is at a slightly different range depending on the direction of the pass made by the dredger. Where possible, these errors have been corrected by adjusting the data accordingly.

Other potential errors in positioning were caused by the buoys drifting slightly during the deployment due to strong tides and currents. In fact, it was sometimes difficult to position the buoys or anchor the survey vessel at the intended location due to the tidal currents. Since the dredger itself did not always follow the intended track reproducibly, accurate GPS data was vital for determining the actual range at CPA, the nominal values being (in general) poor approximations.

For the above reasons, the data from the closest recording buoy was not used in Source Level determination if the range was less than 50 m since the uncertainty in range leads to potentially large bias in the results (see Appendix C).

5 RESULTS

5.1 SOURCE LEVELS (FULL DREDGING)

Figure 5.1 to 5.4 show the results of calculating Source Level for each of the dredgers under test. Results are shown for the mean calculated from 2-second sequences (see Section 3.3.5 and 3.3.6). The results show the means of the Source Level calculated from all the recording hydrophones, and shows the standard uncertainty as an indication of the statistical spread. The data is only shown for frequencies up to 40 kHz since that is the maximum band covered by the recording buoys which were sampling at 96 kS/s. However, where survey vessel hydrophones were deployed, results are available up to 100 kHz, and these are shown in Appendix D.

The "affected" (or dipole) Source Levels are shown in this section, so that comparisons may be made with other data for vessels and to conform to the ANSI definition [ANSI S12.64 2009]. In Appendix D, the values for the mean affected (dipole) Source Level are tabulated, and examples are presented of the Source Levels estimated for individual passes of the dredger under test.

In Figure 5.1, the results of the Source Level determinations can be seen for two examples of dredgers under full dredging conditions. It can be seen that there is significant variation in the standard deviation with frequency, showing that the noise output is not constant but shows some fluctuation with time. The equivalent plots for all the dredgers can be seen in Appendix D.

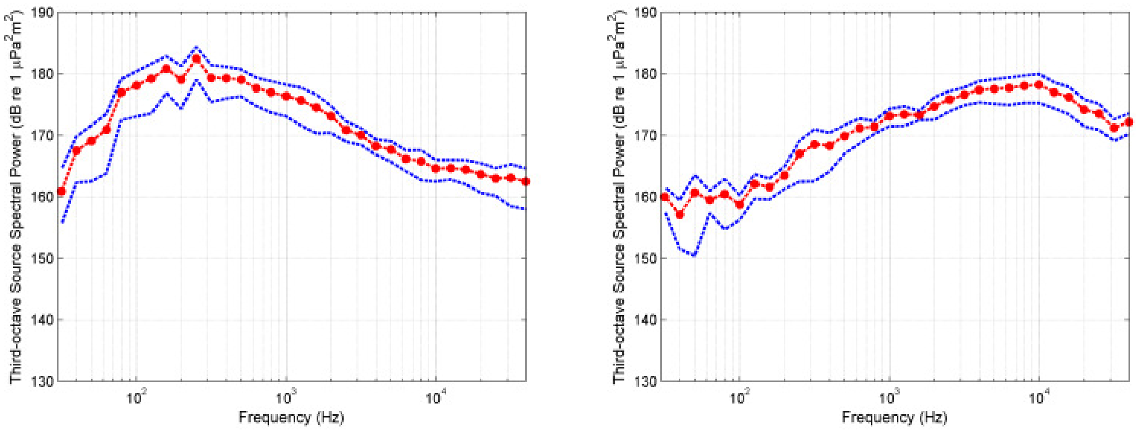

Figure 5.1 Dipole or "affected" Source Levels calculated from 15 two-second sequences showing the mean and standard deviation for the Sand Harrier on Area 137 (left), and the City of Westminster on Area 473 (right).

In Figure 5.2, the dipole or "affected" Source Levels calculated from separate passes of the dredger are shown, along with the mean of the passes. This is done for Sand Falcon on Area 473 (left), and the City of London on Area 458 (right). This shows the typical pass to pass variation in the estimated Source Level. The equivalent plots for all the dredgers can be seen in Appendix D.

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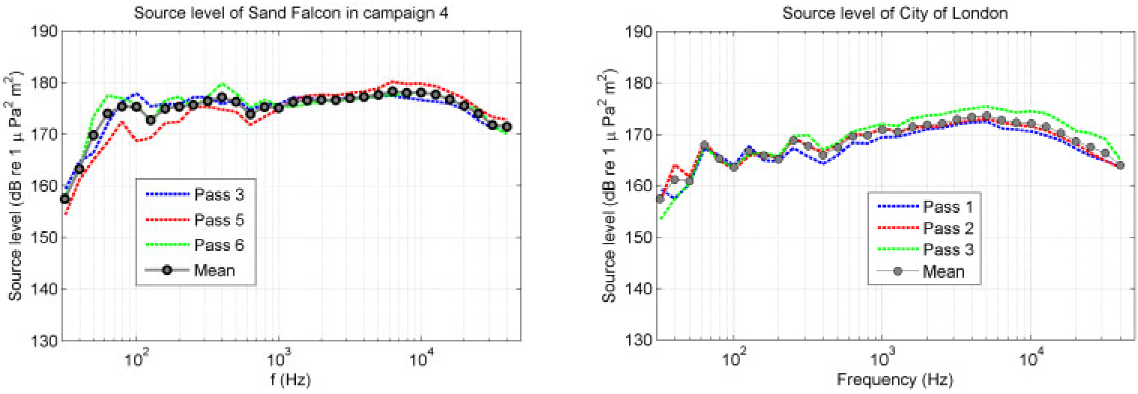

Figure 5.2 Dipole or "affected" Source Levels calculated from separate passes of the dredger, along with the mean of the passes, for Sand Falcon on Area 473 (left), and the City of London on Area 458 (right).

Figure 5.3 shows a plot containing the dipole Source Levels for all the dredgers tested. This allows direct comparisons to be made between the results obtained for each vessel.

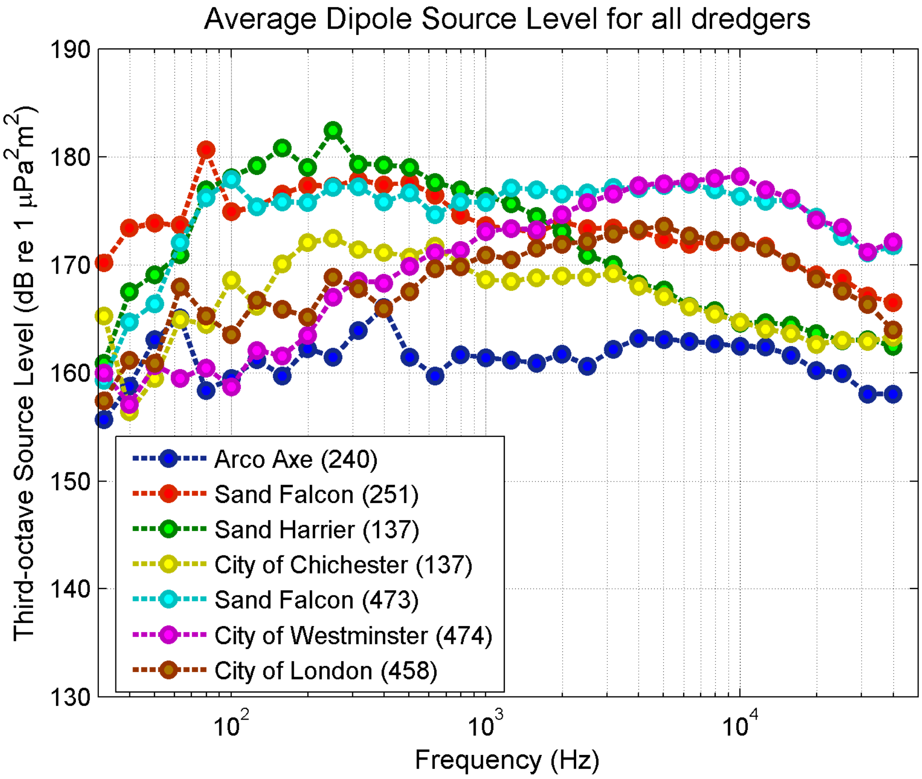

Figure 5.3 Dipole or "affected" Source Levels calculated for all dredgers.

There is considerable variation between the individual dredgers at frequencies less than 500 Hz, with the Sand Falcon and Sand Harrier being the noisiest. The Arco Axe appears to be the quietest vessel. An interesting feature of the results is that there appears to be a higher level of broadband noise at higher frequencies (5 kHz to 40 kHz) than would normally be expected for a ship operating at slow speeds (typical; speeds during dredging being about 1.5 knots). The appearance of such high frequency signals is normally associated with the onset of propeller cavitation, which is normally only seen at higher speeds. This feature is particularly prominent for the vessels measured at the EEC region: Sand Falcon (473), City of Westminster (474) and City of London (458). A potential reason for this unexpectedly high level of high frequency broadband noise is discussed in the following sections.

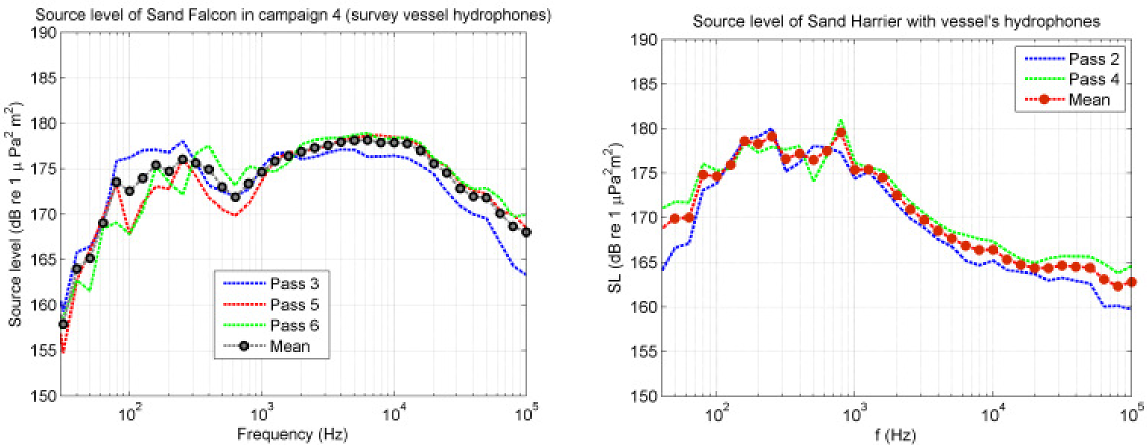

Figure 5.4 Dipole or "affected" Source Levels calculated using only the survey vessel hydrophones but showing frequencies up to 100 kHz for Sand Falcon on Area 473 (left), and the Sand Harrier on Area 137 (right). Individual passes of the dredger are shown along with means.

The results so far have only shown data up to the 40 kHz third-octave band since this is the highest band that can be calculated from the recording buoy data (sampled at 96 kS/s and so having a bandwidth of 48 kHz). However, the hydrophones deployed from the survey vessel were used with broader bandwidth systems (typically sampled at 204 kHz). Calculating the Source Level using only the survey vessel hydrophones allows results to be shown up to a third-octave band of 100 kHz. Figure 5.4 shows dipole Source Levels calculated in this way for the Sand Falcon and Sand Harrier. It should be noted that the Source Level values for frequencies up to 40 kHz will not be the same as the values shown in Figure 5.3 which were averaged over all hydrophones (including recording buoys). Encouragingly, however, the values are quite close over the common frequency range. The high frequency results show a drop off in level at frequencies above 40 kHz, but the levels are still relatively high even at 100 kHz.

5.2 VARIATION IN NOISE WITH OPERATIONAL MODES

Some of the dredgers under test were able to change operational mode during the pass through CPA. In particular, good examples of this type of data were obtained from the Sand Falcon, City of Chichester and Sand Harrier. This allowed the difference in the nature of the sound radiated to be compared "before and after" the change. This helped with the investigation of the noise generation mechanisms on the dredger.

Figure 5.5 shows the Received Level spectrograms for the Sand Falcon (Area 251) as the draghead is lifted and then lowered again to the seabed. The draghead is lifted at 797.5 minutes (left), and it is lowered back to the seabed at 803 minutes (right). The spectrogram is a frequency-time representation of the sound field showing how the frequency content of the signal varies with time. The colour mapping represents the amplitude of the signal (the colour map is scaled to measure in dB re 1 µPa^2) with blue as low amplitude and red as high amplitude. Note how the high frequency content of the signal is lost after the draghead is lifted and is then restored when the draghead is lowered again. This pattern is repeated for the other dredgers tested, and appears to be characteristic of the radiated noise during dredging.

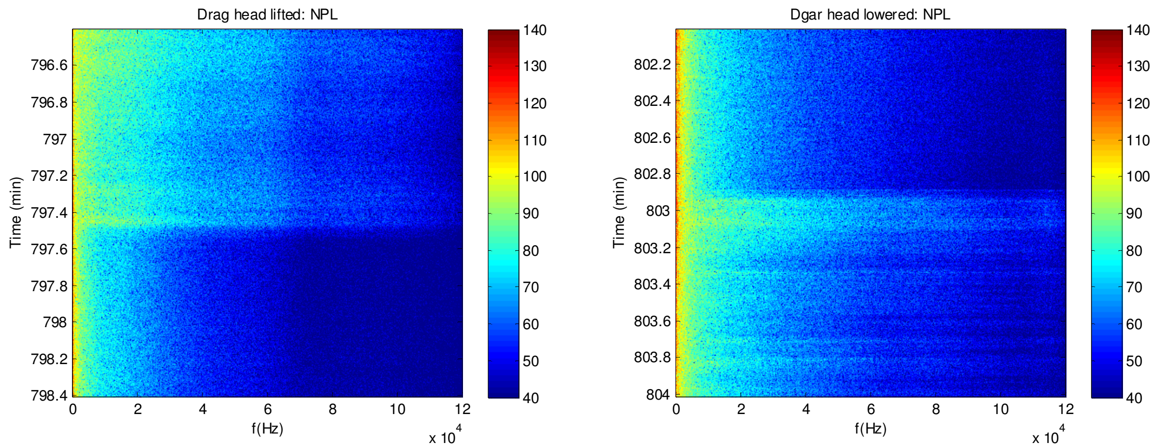

Figure 5.5 Received Level spectrograms showing the moment that the draghead is lifted at 797.5 minutes (left), and the moment when it is lowered back to the seabed at 803 minutes (right).

Figure 5.6 shows the Received Level for selected third-octave bands from the Sand Harrier (Area 137) showing the moment that the draghead is raised (at 37 s) and lowered again (at 123 s). Notice that the levels at the low frequencies (below 1 kHz) do not seem to be affected by the raising of the draghead, but the higher frequencies show a considerable drop in level during the period when the draghead was raised. This confirms the feature seen in the spectrograms of Figure 5.5.

Figure 5.7 shows the changes in Received Levels for the Sand Falcon (251) compared with full dredging (draghead down, pump on), when the draghead is first raised, and then the pump is switched off while the draghead is still raised. The data is the result of third-octave band analysis of the recorded signals just before and after the change of mode using the recorded data from the survey vessel hydrophones at a range of approximately 100 m. Also shown on the plot is the ambient noise level from Area 251 plotted in the same units. The data plotted here confirms that the high frequency broadband noise is only present at this elevated level during dredging, and is higher when aggregate is being pumped, but with some component due to the pump itself.

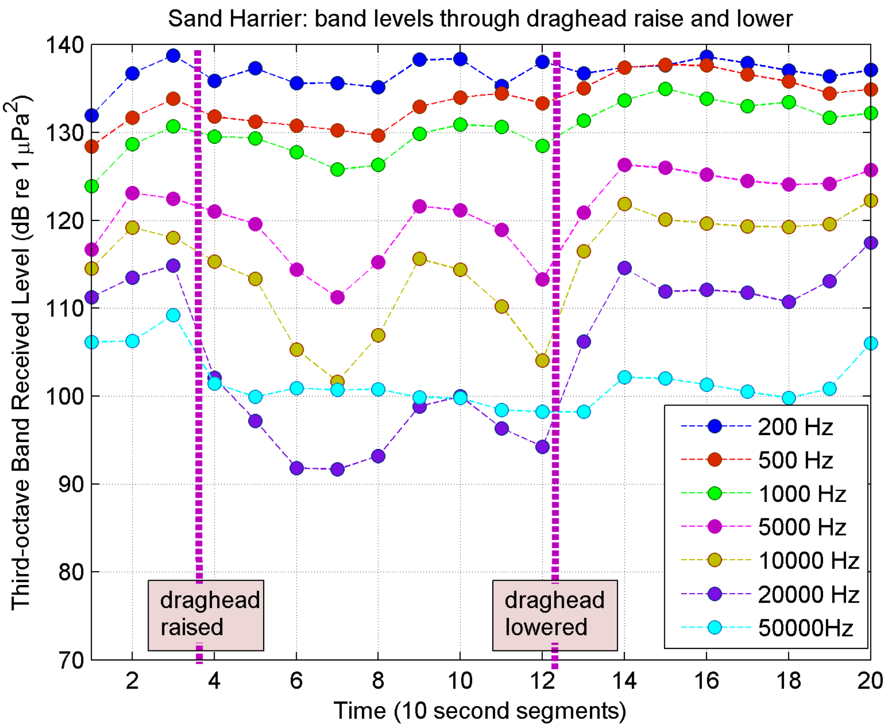

Figure 5.6 Received Level for selected third-octave bands showing the moment that the draghead is raised (37 s) and lowered again (123 s).

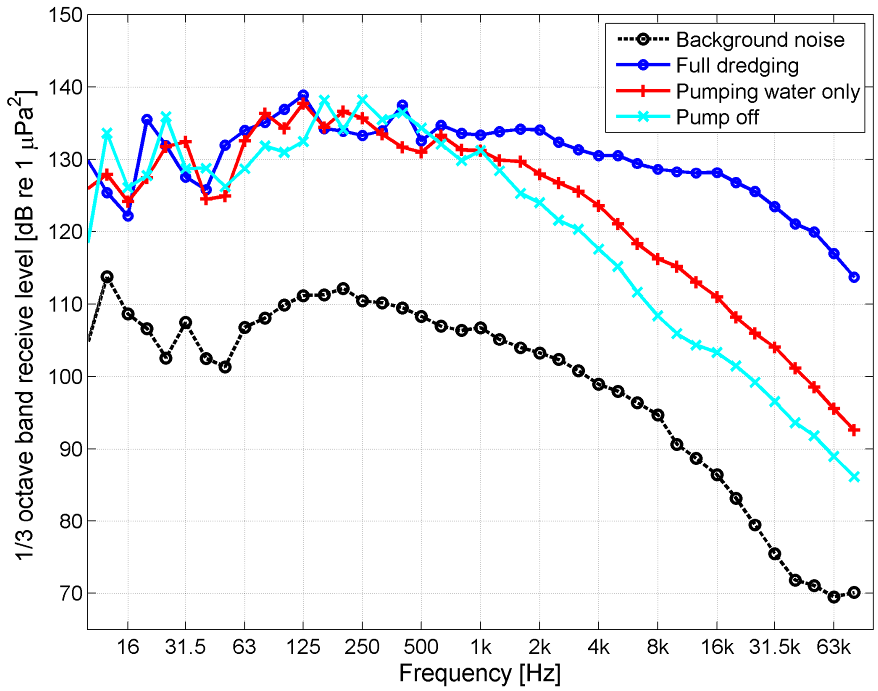

Figure 5.7 Received Levels for the Sand Falcon (251) showing the change in level compared with full dredging, when the draghead is raised whilst pumping water, and when the pump is switched off with the draghead on the seabed. Also shown is the ambient noise level.

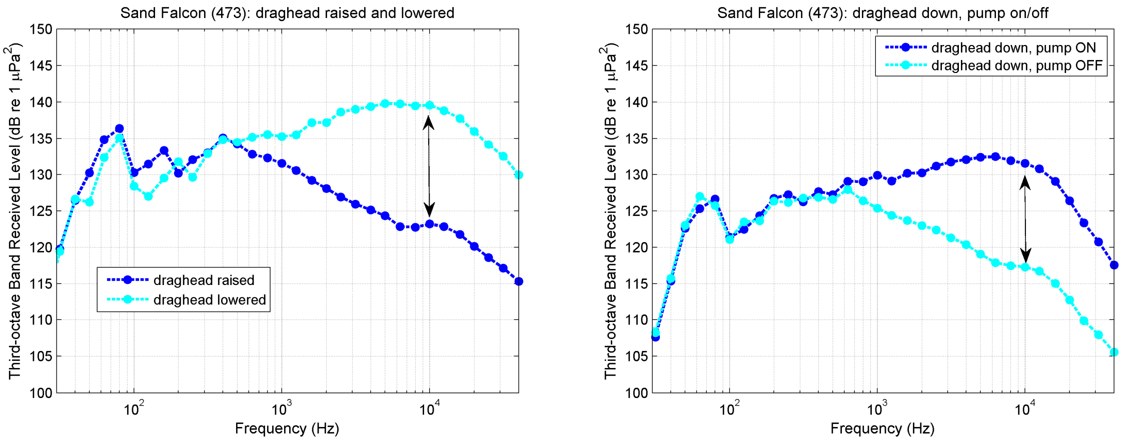

Figure 5.8 Received Levels for the Sand Falcon (473) showing the change in level when the draghead is raised and lowered (left) and when the pump is switched on and off with draghead on the seabed (right). Note that these data sets are from two different passes and so have different absolute Received Levels (different ranges from the dredger).

To investigate this further, the dredger vessel masters were also asked to turn off the pump (so no aggregate or water is being pumped) but leave the draghead on the seabed, in addition to raising and lowering the draghead. Figure 5.8 shows the results of this investigation for the Sand Falcon in Area 473. The left hand plot shows the change in level when the draghead is raised and lowered, and on the right is shown the Received Levels and when the pump is switched on and off with draghead still on the seabed. Note that these data are from two different passes and so have different absolute Received Levels (different ranges from the dredger).

Similar level changes were recorded for both operational mode changes, a strong indication that the presence of aggregate pumped through the pipe is a major source of this broadband noise in the frequency range above 1 kHz. Note also how the Received Levels at lower frequencies are almost unchanged, suggesting that the noise from the engine and propulsion system remains relatively unchanged.

Figure 5.9 shows the Received Levels for the City of Chichester (Area 137) measured on the survey vessel hydrophones, showing the change in level at frequencies up to 100 kHz when the draghead is raised and when the pump is switched off compared with full dredging (draghead down, pump on). This shows that the broadband noise during full dredging extends to high tens of kilohertz.

Figure 5.10 shows the Received Levels for the Sand Falcon (Area 473) measured on the survey vessel hydrophones, showing the change in level at frequencies up to 200 kHz when the pump is switched off compared with full dredging (draghead down, pump on). This shows that the elevated broadband noise due to the dredging activity seems to reduce substantially at frequencies greater than 100 kHz.

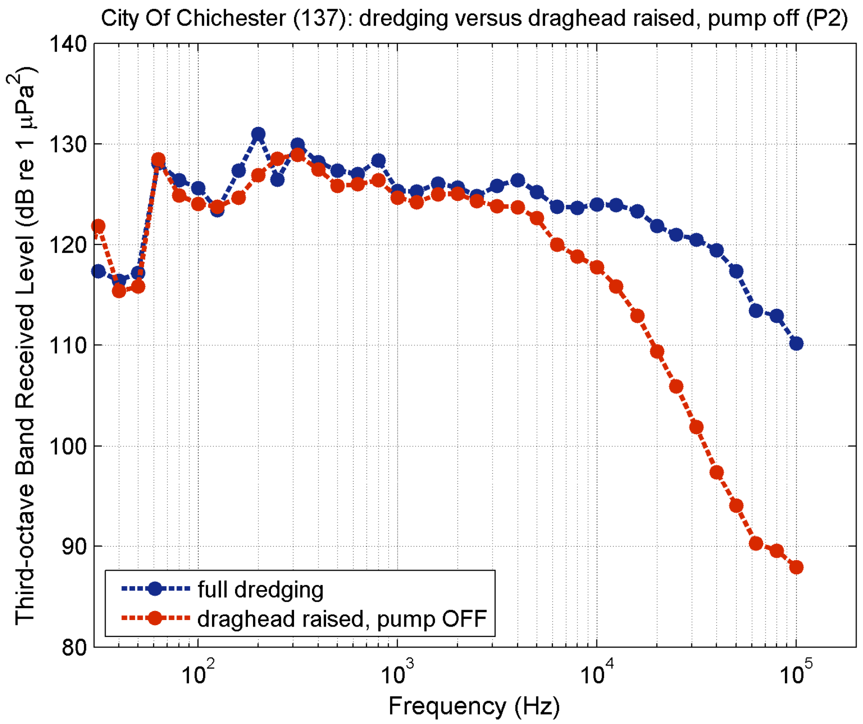

Figure 5.9 Received Levels for the City of Chichester (137) showing the change in level at frequencies up to 100 kHz when the draghead is raised and when the pump is switched off compared with full dredging (draghead down, pump on).

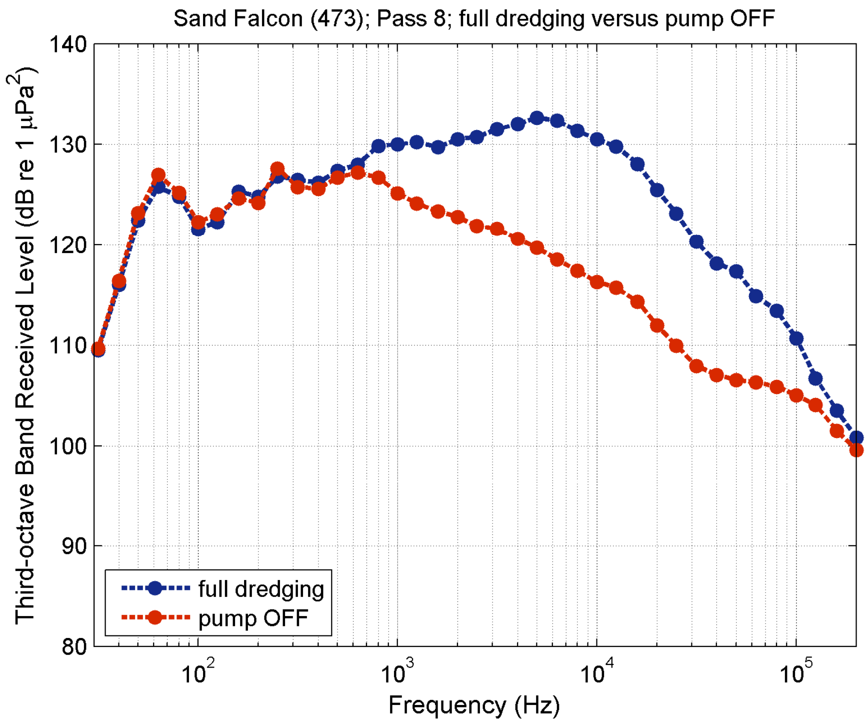

Figure 5.10 Received Levels for the Sand Falcon (473) showing the change in level at frequencies up to 200 kHz when the pump is switched off compared with full dredging.

5.3 SEABED VIBRATION

For the City of Chichester only, measurements were made of the seabed vibration using a geophone assembly. In this design, a triaxial geophone assembly (consisting of three orthogonally mounted linear geophones) was placed inside a watertight canopy which was firmly attached to a base-plate or "sledge" (see Figure 5.11).

Figure 5.11 Geophone sledge deployment.

The assembly was deployed from the survey vessel with care to see that the lifting rope and geophone data cable were slack and did not communicate vibration to the assembly. The data was recorded using one of the acoustic acquisition systems on-board the survey vessel with a bandwidth of 1 kHz. The geophone assembly including the sledge was calibrated at a laboratory undertaking acceleration and vibration calibrations. This revealed resonant frequencies associated with the sledge design in the 300 Hz to 800 Hz region. The signals measured were processed by use of a 200 Hz low pass filter to remove any spurious signals, and to concentrate on the very low frequencies present in the data.

Figure 5.12 shows the results of recordings of the geophone signal on the seabed approximately 100 m away from the City of Chichester (data has already been low pass filtered at 200 Hz). The data sequence shown encompasses the point when the draghead was lowered to the seabed (at approximately 100 seconds). The vibration amplitude levels range from less than 1 mm/s to occasional bursts which are greater than 5 mm/s.

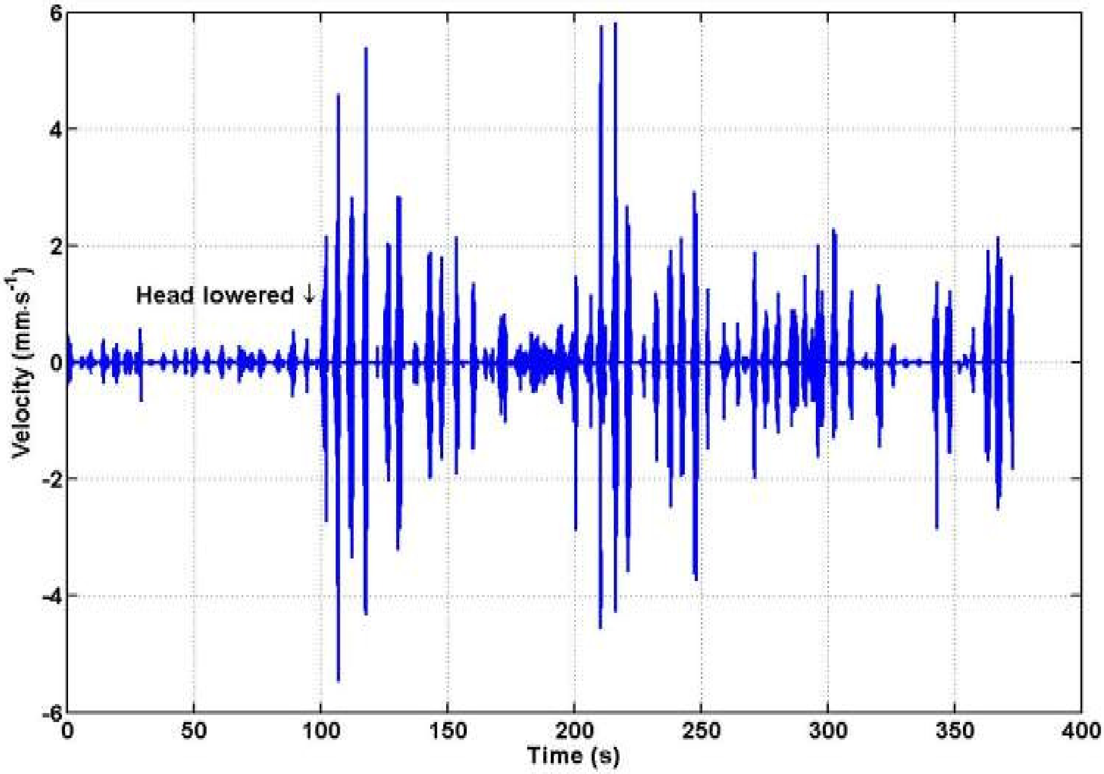

Figure 5.12 Recordings of the geophone signal on the seabed approximately 100 m away from the City of Chichester when the draghead is lowered to the seabed.

This is the only data recorded for seabed vibration, and care must be taken in interpretation since there is no other data to corroborate these results. However, there appears to be an increase in seabed vibration when the draghead is lowered. The vibration appears to have a particular structure with bursts of vibration, almost as if the draghead is bumping and buffeting along the seabed. The short bursts contain signals centred around 20 Hz. This could be the result of the resonance of some structure, possibly the pipe on the dredger, but this cannot be corroborated from any other results within this project. Unfortunately, the City of Chichester was the only dredger for which the geophone could be deployed.

5.4 NOISE DIRECTIVITY

It is considered that a dredger may generate noise via a number of its structural components, for example, the propeller, the pump, the pipe and draghead when it is in operation. In order to identify the distribution of noise sources from a dredger in the vertical plane, a vertical line array with 7 spherical hydrophones (SRD70) was made and used by ISVR to record the noise from a number of the dredgers in the scenario as shown in Appendix F.

The results of beamforming with the array's data are shown in the four plots in Figure 5.13. The plots are the Source Level at the given directions from -90^{o} to 90^{o} in the vertical axis and frequency range from 0 to 20 kHz in horizontal axis. They are for various operations of Sand Falcon in campaign 4:

- top left --- transit,
- top right --- pump off,
- bottom left --- dredging pass 5,
- bottom right --- dredging pass 6.

The details of the data analysis are in Appendix F. (Care needs to be taken when interpreting these results due to the presence of grating lobes at frequencies above 5 kHz.)

It can be seen that the noise level was lowest in transit mode. There is a clear symmetrical pattern about the main beam direction of the noise source (assumed to be the propeller). There was little noise away from this main noise direction at frequencies above 10 kHz. The noise level was higher when pump was off compared with transit. It is interesting to note that the noise also filled the other directions.

The noise level was much higher when Sand Falcon was dredging. The results of pass 5 and pass 6 are similar, but a band of higher level at frequency around 10 kHz to 13 kHz for the pass 6. This may be due to the opposite direction of the two passes; the body of the ship may block some part of the noise, such as the screening noise.

In both these cases the main noise source over the frequency range above 2.0 kHz can be identified to be at 8º below the horizontal plane. This implies a point source at a depth of about 18 m below the sea surface. When the pump is off this source is not present and the higher frequency noise is associated with a much shallower source at a depth of 3 to 5 m (presumably the dredger propulsion system).

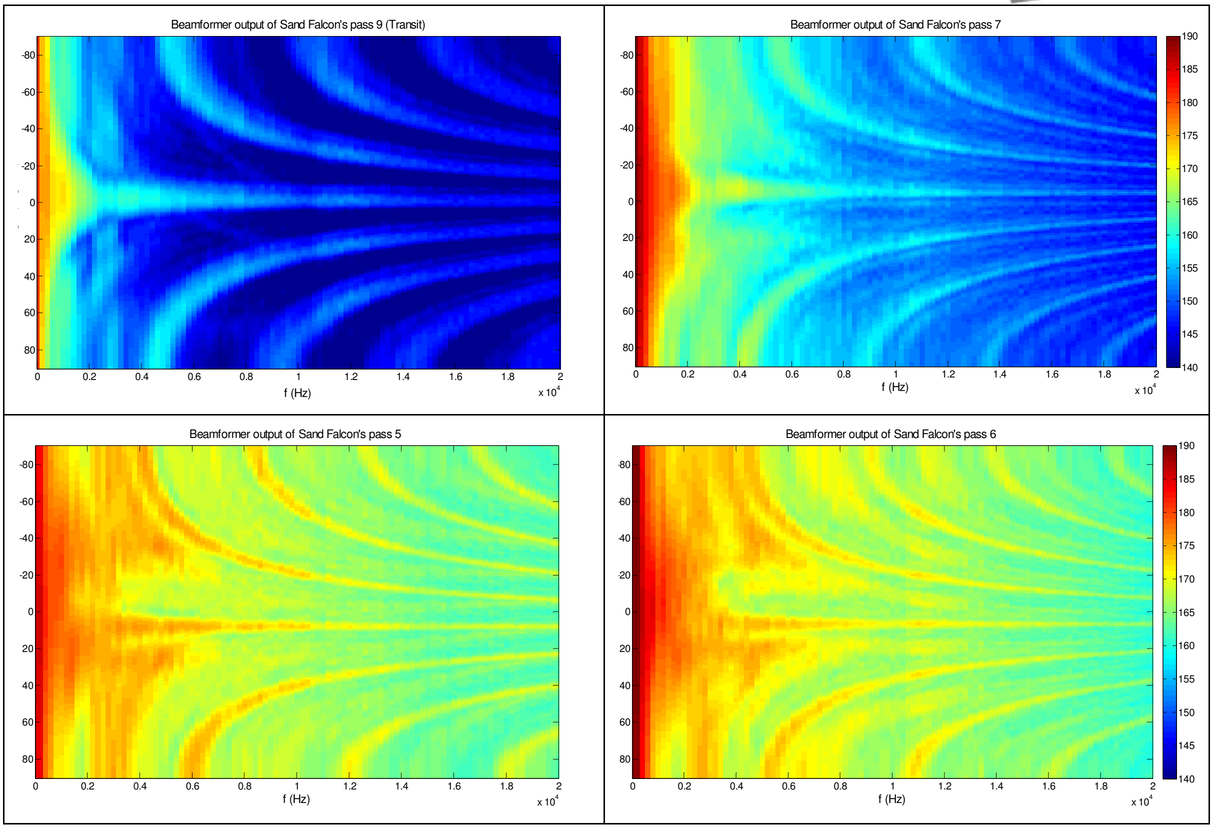

Figure 5.13 Beamformer outputs for Sand Falcon in campaign 4 for various operations, clockwise from top left: vessel transit, pump off, full dredging, full dredging.

5.5 AMBIENT NOISE RESULTS

Measurements were also made of ambient noise in the vicinity of the dredging areas in the manner described in Section 3.3.8. The low-noise TC4032 hydrophones were deployed from the survey vessel in quiet vessel conditions with precautions taken against parasitic signals and with the survey vessel allowed to drift with the current. Of course, the ambient noise levels reported here must be considered as snap-shots of the actual noise field. They are useful only as an indication of the background noise that existed in the areas during the sea-trials to characterise the noise from the dredgers. In practice, the ambient noise will vary spatially (for example, it will be greater close to shipping lanes), and temporally (it can vary with the weather, with the seasons, with the time of day, with the local ferry timetable, *etc.*).

For the East coast region, the ambient noise measurements were made on a separate day when there was no dredging activity. Measurements were performed in the Cross Sands Area (slightly to the east of Area 251 central) with typical water depths of 28 m to 32 m. The maximum distance possible at any one time from a potential noise source was around 3 nm. Sources of noise were the Arco Humber operating around 3 nm north west of the position and a shipping lane around 3 nm to the east. Tidal currents of around 3 – 4 knots were typical although the sea-state was fairly calm during the measurements, varying between around force 2 to 3, with a slight swell. Measurements were taken around slack tide (high water) with some measurements taken during rainfall. The results are shown in Figure 5.14 as noise spectral density level as a function of frequency in units of dB re 1 μPa^2/Hz. These show the lowest overall level of ambient noise measured in the project. An interesting feature on one recording is the increase in levels above 20 kHz (red curve) which is highly likely to be due to rain noise.

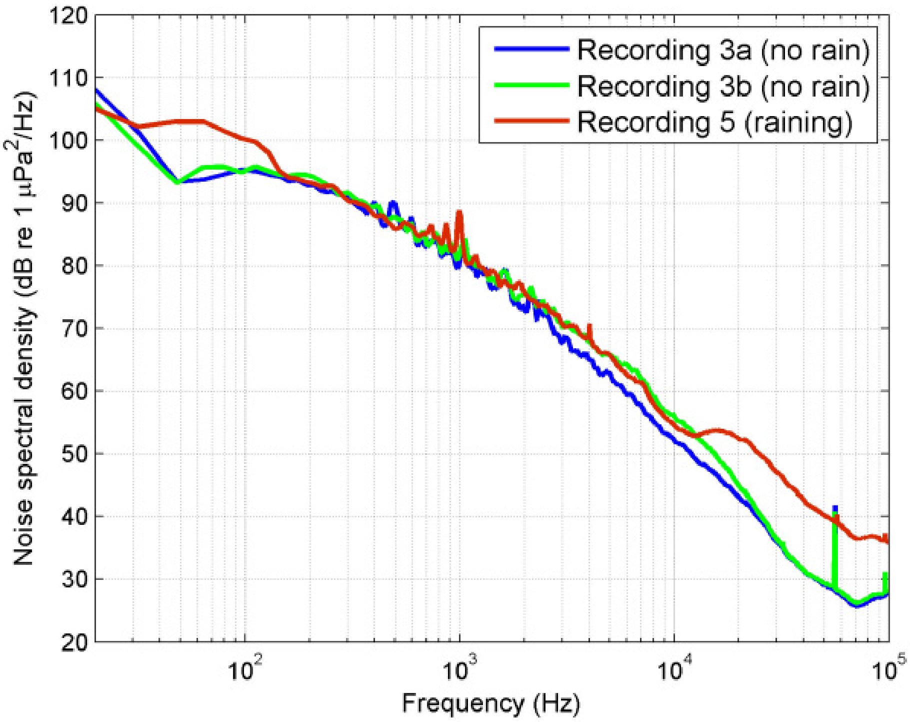

Figure 5.14 Ambient noise levels measured for the East Coast areas showing three recordings, one with rain noise. The plot is the result of 9000 linear averages of a 6400 line FFT with 102.4 kHz span (δF=16 Hz, T=62.5 ms).

For the South coast region, measurements were made substantially after the dredging activity took place and once the Sand Harrier had left the area and no other vessels were in sight to avoid any contamination from the radiated noise of the dredger. The measurements were performed during the rising tide which was predicted to have risen around 1 m since the vessel measurement started. The sea-state was estimated to be around force 5 to 6 with no rain (see Figure 5.15).

For the EEC region, it was not possible to measure in the absence of other shipping, and the survey vessel was moved to a substantial stand-off distance from the dredger under test. The dredging and subsequent ambient noise measurements were being undertaken in the traffic separation zone of the English Channel and so it was not possible to conduct the measurements in isolation from other vessels. The levels recorded show significantly increases in the frequency range 50 Hz to 500 Hz compared to those recorded at the East coast region, perhaps not surprising considering the proximity of the shipping lanes and the fact that the dredger was still operating. During the Sand Falcon sea trial, measurements were at a stand-off distance of around 1.6 nm from the dredger which was still dredging. The sea-state was relatively calm, estimated to be around force 2, with no rain. For the City of

London, measurements were undertaken at a stand-off distance of around 2 nm from the vessel which was still dredging. During these measurements, the MV George D shut down its engine and was allowed to drift, but for operational reasons the generator on board the MV George D had to remain switched on. Also, the measurements were performed in the vicinity of submarine cables marked on the shipping charts. The sea-state was fairly rough, estimated to be around force 4.

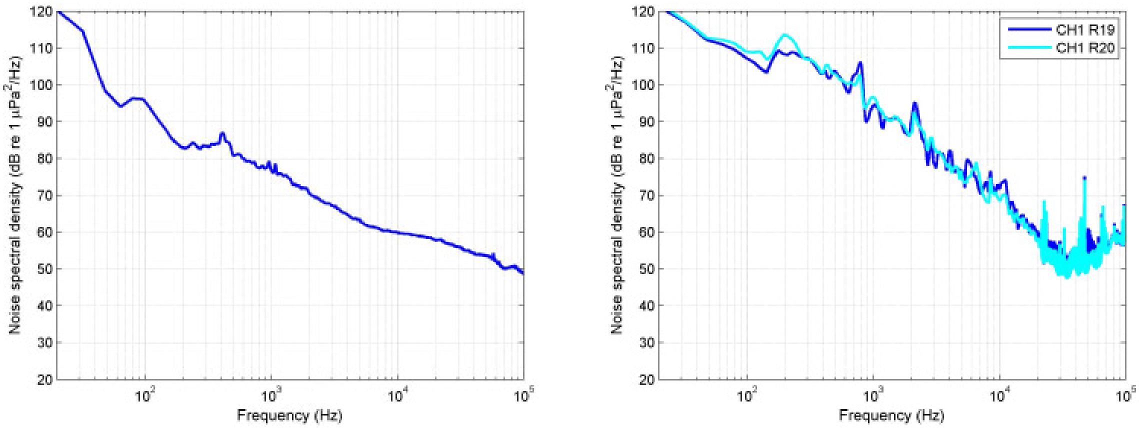

Figure 5.15 Ambient noise levels measured for the South Coast areas (left) and EEC areas (right). The data shown is the result of 1280 linear averages of the data for the South region and 1840 and 2000 averages of the data for R19 and R20 respectively for the EEC region (6400 line FFT with 102.4 kHz span, δF=16 Hz, T=62.5 ms).

The results for the EEC area show significant electrical pick-up at frequencies greater than 10 kHz, rendering the results at high frequencies almost useless (see Figure 5.15). The source of this electrical signal is not known, but it manifests itself as a comb of frequencies in the frequency domain (suggesting perhaps pick up of some kind of timing or communications pulses). Unusually, and for operational reasons, the generator on the survey vessel D was kept switched on for one of these measurements (for the City of London), but the pick-up is present in both signals. It is not known what caused the interference, but it was noted that the region where measurements were done for the EEC area was adjacent to some undersea cables.

It is clear that the ambient noise levels shown here are higher than the classic spectral levels reported for deep water [Urick 1988]. This is to be expected for shallow coastal waters, and these levels are comparable to those reported recently for UK waters [Nedwell *et al*, 2007 and Nedwell *et al*, 2008] and for Dutch waters [TNO, 2010].

5.6 DISCUSSION OF RESULTS

5.6.1 Noise sources

The traditional sources of noise from shipping include low frequency sources from the engine and propulsion system, and broadband noise caused by cavitation from the propeller when the vessel is travelling at reasonably high speed. For the speeds common during dredging (typically 1.5 knots), it is unlikely that the propeller is cavitating. Although it is possible that cavitation noise is contributing to the broadband noise observed when dredging, it seems likely that the cavitation is occurring in the pumps, which are most often centrifugal designs, rather than at the propeller. Evidence for this is shown in Figure 5.7 where first the draghead is raised and then the pump is switched off. It is not possible to exclude the possibility that some cavitation noise might be generated by the propeller, but no evidence has been obtained in this project to support this.

From the results shown in the previous section, it is clear that the high frequency broadband noise correlates strongly with the dredging activity itself, with contributions to the noise coming from the aggregate material travelling up the pipe and through the pump. An example of evidence for this given in Figure 5.8 where a similar reduction in the high frequency broadband noise is obtained when the draghead is raised and when the pump is switched off. This effect has been corroborated by measurements made on four of the vessels in different areas with different aggregate loads. Specifically, the three vessels measured whilst extracting gravel from the EEC region, all showed increased levels of broadband noise at frequencies above 1 kHz when compared to other vessels extracting sand in the East Coast and South Coast regions. It is also consistent with observations of a previous study [Defra, 2003].

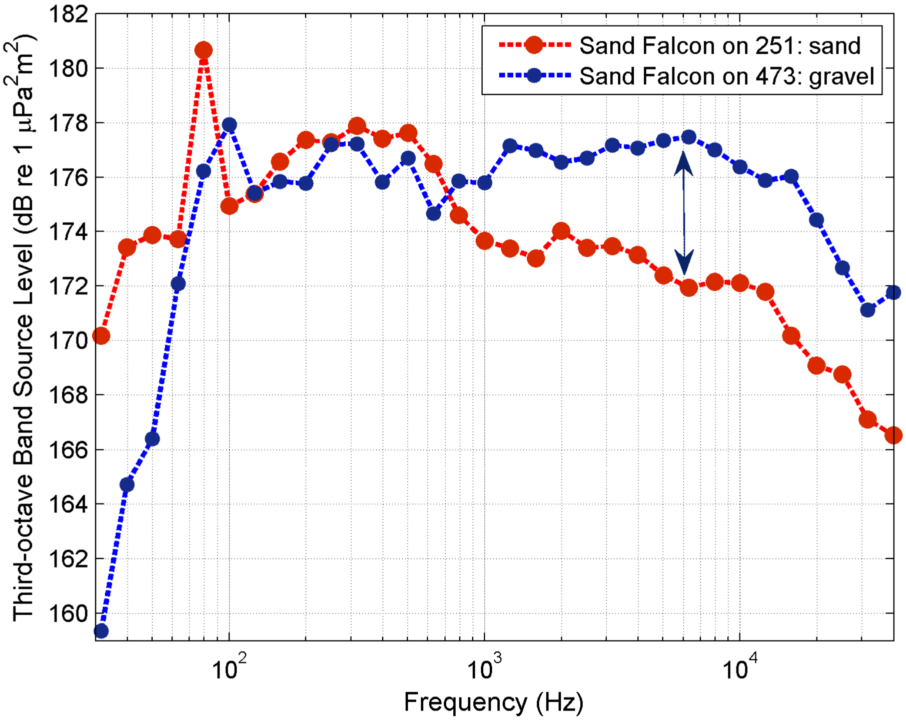

Figure 5.16 The Dipole Source Level for the Sand Falcon measured on Area 251 (loading sand) and Area 473 (loading gravel).

One vessel, the Sand Falcon, was measured in two locations: Area 251 dredging sand, and Area 473 dredging gravel. It is interesting to compare the Source Levels derived from the results measured in each location. Figure 5.16 shows the two results of measurements in each location. It is very noticeable that the high frequency broadband noise is as much as 5 dB higher for the case of loading gravel in Area 473 compared to loading sand in Area 251. However, at frequencies below 1 kHz, the Source Levels are in general very similar, as might be expected since the measurements are of the same vessel. Note that there are other differences between the two sets of measurements, such as the water depth which is greater at 40 m for Area 473 compared to 30 m for Area 251. This may have something to do with the differences shown at very low frequencies (below 50 Hz), but at these frequencies the Source Level estimation becomes much more difficult because the limiting frequency for the shallow water transmission is being approached. In general, at frequencies between 30 Hz and 50 Hz, the measured data is not much greater than the ambient noise levels at those frequencies, making any estimate of Source Level subject to considerable error.

5.6.2 Continuing knowledge gaps

As indicated in Section 3, ships are actually extended sources of sound consisting of a highly complex series of mechanical sources within the vessel, each of which has its own vibration amplitude and frequency. The analysis provided in this project has provided some information on the noise generation mechanisms within the dredgers, but further study would be needed in order to identify and quantify these sources if any attempt were to be made to reduce the noise radiation. This would probably require measurements of vibration levels onboard the dredger to correlate different mechanisms with the noise levels measured in the water. Considering the reported levels in the context of other anthropogenic noise sources (see Section 5.6.3), it is debateable whether this would be considered as a priority for future work.

During the project, the main operational modes that are used during aggregate extraction were well characterised:

(i) Full dredging
Draghead on seabed, pump on, extracting aggregate, speed 1 – 2 knots;

(ii) Turning mode
Draghead raised, pump on or off, state when turning at end of track.

However, there are some activities which we were not able to characterise satisfactorily during the project, and which potentially may be worth further study:

(iii) Noise during transit
For some of the later measurements, the dredger master was asked to travel directly past the measurement hydrophones at typical transit speed (typically around 12-16 knots). However, due to the lack of GPS data from the dredger log while in transit (the log has 30 second resolution during dredging, but only 30 minute resolution during transit), the position was not known accurately enough to derive a Source Level. Although this was not identified as a major objective of the project at the outset, in practice this is possibly the biggest omission because the recent work by TNO has shown that the Source Levels during fast transit for Dutch dredgers can be as high as for full dredging [TNO 2010]. However, it should be noted that the Dutch dredgers measured were in

general much larger than the UK vessels, and capable of faster transit speeds.

(iv) Noise from overspill and screening
It was not possible to determine the noise contribution from overspill noise, or the difference with and without screening, because it was difficult to control these operations in a systematic way. Typically, the whole dredging run was undertaken either screened or unscreened. Only one vessel was measured without screening: the City of Chichester. This is also the vessel that had a different overspill configuration to the others (centrally located fore and aft, rather than port and starboard). To study these noise sources would require these operations to be varied during the same dredging run, which was not logistically possible for the dredgers.

(v) Aspect dependence of noise
In the project, no assumption was made of aspect independence, and the measurements were made for beam aspect only. This means that data has not been provided for azimuthal directionality of the dredger (though some information has been derived for elevation angles using the directional array). For two of the vessels, measurements were possible on only one side of the vessel (either port or starboard), but mostly both directions were obtained. The approach to the data analysis was relatively conservative in that only a narrow measurement window around CPA was used. Widening this substantially, and analysing more of the data could provide some information on whether the bow and stern aspect Source Levels are of similar value to the beam aspect. From data for other vessels, they are more likely to be slightly lower in value due to shadowing by the vessel body (bow aspect) and shadowing by the wake (stern aspect). Keel aspect is of less interest when considering dredgers since it is difficult to measure (the recording equipment is likely to be dredged and damaged) and any animal directly below the vessel is likely to have other concerns then merely impact from noise. Regarding the stern aspect, theoretically, when “looking” through the plume of sediment expelled during overspill, there may be greater sound attenuation due to enhanced absorption and scattering, but it would be difficult to separate this effect from other causes of source directivity.

(vi) High frequency noise
Only limited measurements were possible at frequencies greater than 100 kHz, and for three of the dredgers the maximum frequency obtained was only 48 kHz (for the dredgers where bad weather prevented deployment from the survey vessel and only buoy deployment was possible). This means that there is a lack of data at these high frequencies for those dredgers. From the four occasions where measurements were obtained up to 100 kHz, it is clear that the elevated broadband noise which correlates with sediment extraction extends to high tens of kilohertz (see Figure 5.7). However, for the two measurements made up to 200 kHz, the evidence indicates that the levels drop substantially above 100 kHz (see Figure 5.10).

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(vii) Seabed vibration

Only limited measurements were possible with the geophones for one dredger (the City of Chichester). Again, this was not identified as a major objective of the project at the outset, but it is probably the other area where extra data would be very valuable. From the little data available, there does seem to be a correlation between seabed vibration and the onset of dredging, but more work would be required to quantify this in a satisfactory way. Since a number of bottom-dwelling fish species are known to be sensitive to vibration, this is an area where more research is needed. In fact, there is little data on what typical ambient seabed vibration levels exist, or what levels might be considered to cause damage of disturbance to fish species.

5.6.3 Comparison to other anthropogenic noise sources

It is useful to compare the results for the dredgers with that for other merchant vessels. Figure 5.17 shows the Source Levels for a variety of ship categories as implemented in a model for ocean noise (the RANDI model), and the data from Wales and Heitmeyer (2002). (Plot taken from Ainslie *et al* (2009)). This data implies that different categories of vessel should have different Source Levels – notably that larger vessels are noisier. The Wales and Heitmeyer data is an average of measurements on many merchant ships.

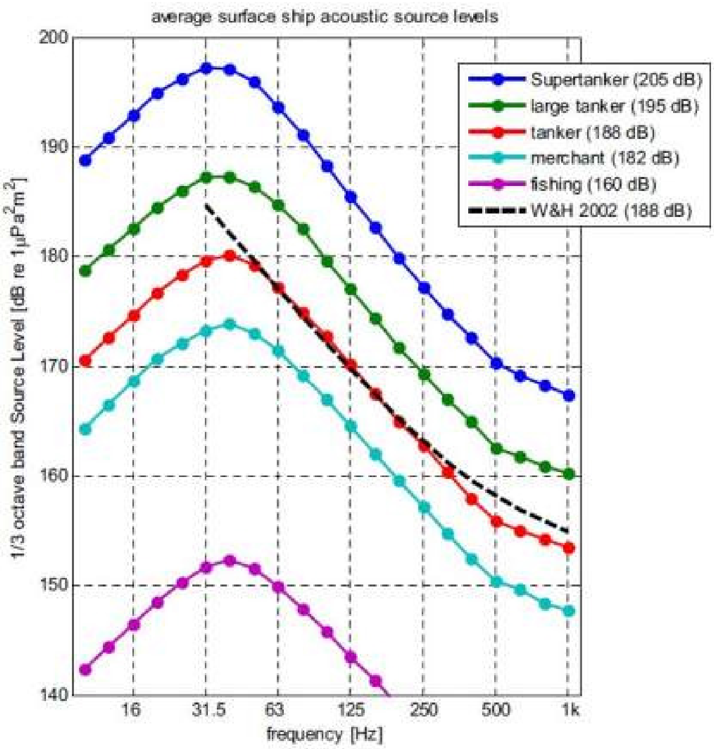

Figure 5.17 The sources levels for a variety of ship categories as implemented in the RANDI model, and the data from Wales and Heitmeyer. (Plot drawn from Ainslie *et al* (2009)).

Figure 5.18, shows the data for the MV Overseas Harriette [Arveson and Vendittis, 2000] and again shows the Source Levels for a variety of ships as implemented in the RANDI model (Plot taken from Ainslie *et al* (2009)). Data for the Overseas Harriette was measured by Arveson and Vendittis for a range of speeds between 8 and 16 knots (as shown in Figure 5.18) on the AUTEC range and is considered to be some of the most robust data of its type for a merchant vessel. However, it should be noted when comparing to the other vessels that it is keel aspect Source Level data (receiver directly below the source vessel), *i.e.* the Source Level has been estimated from measurements made by hydrophones positioned below the ship. This will potentially results in some differences in Source Level when compared with beam aspect Source Level data obtained from hydrophones at horizontal distances from the vessel.

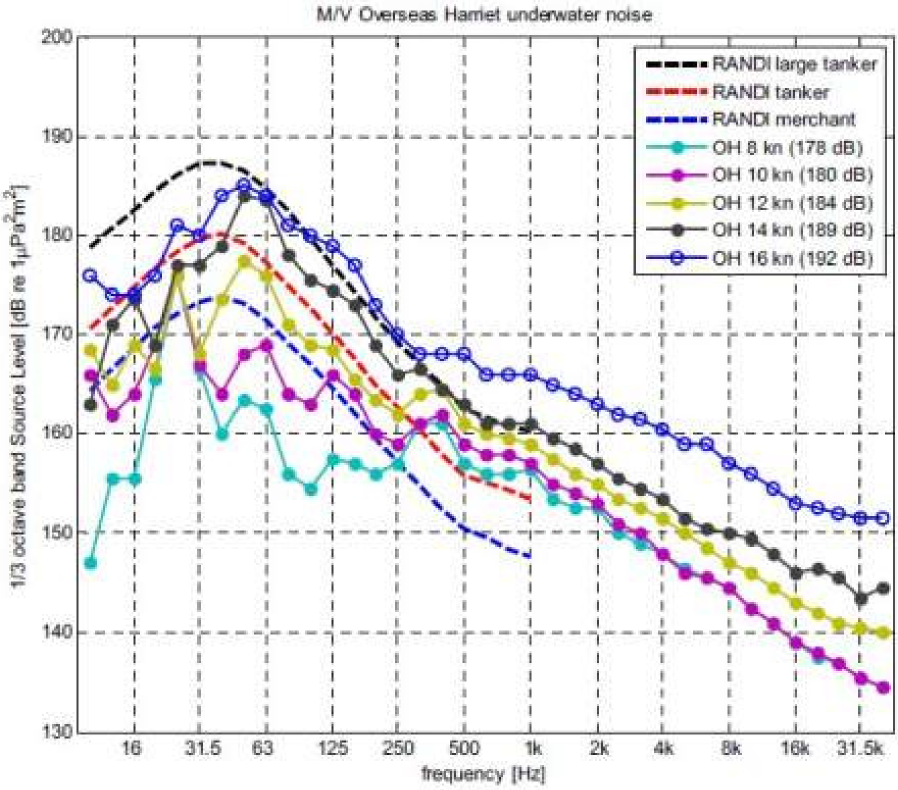

Figure 5.18 The Source Levels for a variety of ships as implemented in the RANDI model, and the data Arveson and Vendittis for the MV Overseas Harriette. (Plot drawn from Ainslie *et al* (2009)).

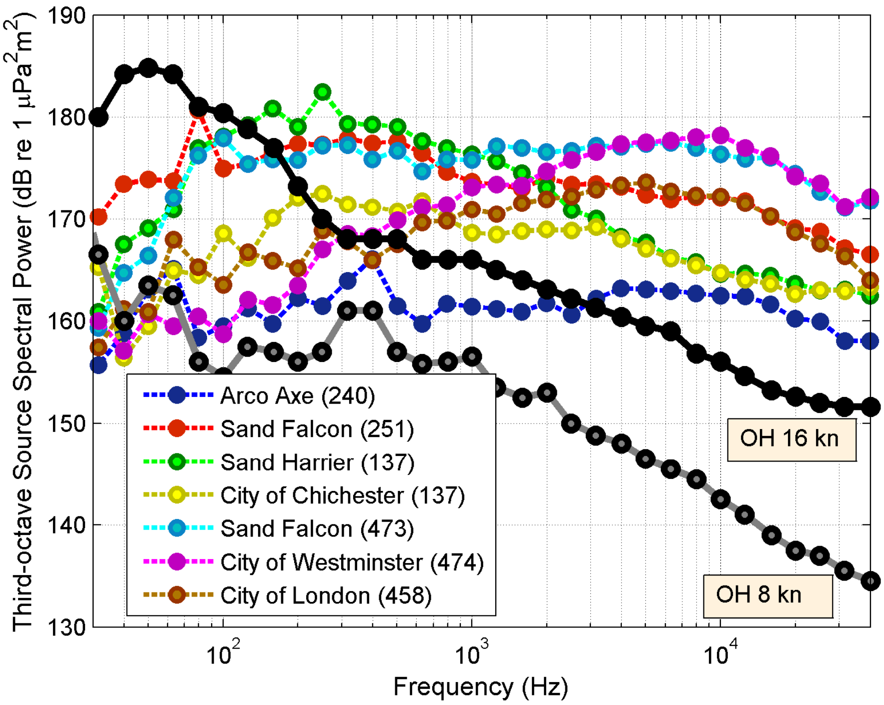

Figure 5.19 The Dipole Source Level for all dredgers plotted with the data for the Overseas Harriette, a merchant vessel [Arveson and Vendittis, 2000]. Data for the Overseas Harriette is shown for two speeds: 8 knots and 16 knots.

Figure 5.19 shows the dipole Source Level for all dredgers measured in this project plotted with the data for the MV Overseas Harriette at two speeds: 8 knots and 16 knots. At frequencies below 500 Hz, the levels for the dredgers are similar or less than those for the merchant vessel travelling at slow speed. However, the high frequency broadband noise exceeds that observed for the Overseas Harriette for 16 knots, and is perhaps similar to that which might be produced by a merchant vessel at high speed with a cavitating propeller.

It should be noted that although the measured levels for the dredgers reported here are higher than those reported for merchant vessels travelling at a slow speed, these Source Levels are still of less concern than for some other sources of noise. It is not straightforward to compare continuous sources such as ships with impulsive sources such as airgun arrays or marine piling. This would best be achieved by calculating the cumulative Sound Exposure Level (SEL) for the duration of the exposure. This can be done by integrating the square of the sound pressure with time at a specific location in the vicinity of the noise source, the location being the nominal position of an animal. (In doing this, due consideration should be given to the hearing response of the receptor.)

An indication can be obtained of the relative energy output of the dredger compared to other sources by calculating the energy Source Level for the dredger and comparing the value for other sources. If this is done for the dredger Source Levels reported here, and the results are compared to the energy Source Levels reported for marine pile driving (with both integrations over one second duration), the results show that the dredger is some 30-35 dB less than that for the marine pile driving (considering only the noise from the pile driving itself) over the same one second of time (for marine pile driving, energy Source Levels of 215-220 dB re 1 µPa^{2}m^{2}s have been reported [Ainslie *et al*, 2010]). However, since the dredging operation can last for a longer duration (perhaps up to 6 to 8 hours compared to up to around 2 hours for marine pile driving), the cumulative effect of the entire operation might show a smaller difference than is seen between the energy Source Levels alone. Underwater noise generated by marine dredging is considered “less noisy” alongside marine pile driving, seismic surveying and drilling in a comprehensive assessment commissioned by the Department of Energy and Climate Change [Genesis, 2010] which considers the reporting requirements of each under the Marine Strategy Framework Directive.

5.6.4 Comparison of dredger vessel Source Level data with previous studies

Although the amount of available literature on the underwater noise radiated by dredging vessels is extremely limited, section 2.2 reviewed a number of studies that have been undertaken and compiled available Source Levels of suction type dredgers from these studies. The third-octave band Source Levels compiled as part of this review are shown in Figure 5.20 for comparison against those obtained during the measurements completed as part of this project as shown in Figure 5.19. As a reference, the third-octave band Source Level data for the Overseas Harriette has been included in both plots.

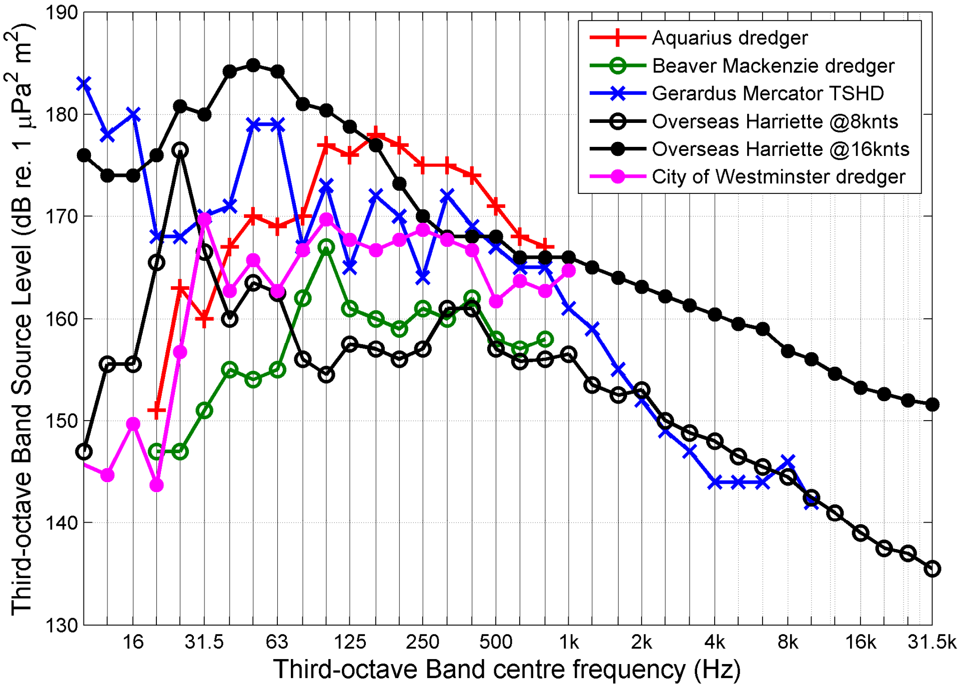

Figure 5.20 Overview of estimated third octave Source Levels obtained from previous dredger studies, including the Overseas Harriette for comparison.

The Source Levels for the dredger measured during this project are broadly inline with those from previous studies [Miles *et al*, 1987; Richardson *et al*, 1995; Ainslie *et al*, 2009; Parvin *et al*, 2008] and although not shown here, those from a recent report by TNO [TNO, 2010]. When attempting to compare the Source Levels predicted from this project with those of previous studies, it should be noted that the vessels are of a different type and class (cutter-suction dredgers which in this care are larger than the UK TSHD's measured during this project), with exception of the City of Westminster which unfortunately was previously measured at a different location, extracting different material. Also, the Propagation Loss methods used during the previous studies are not clear and could be less robust to local conditions than those used to predict the source levels in Figure 5.19. The City of Westminster data was calculated by the authors of this report from third-octave band Received Level data obtained from Parvin *et al* (2008) using the Propagation Loss relationship used by Parvin *et al* (2008) for the broadband Source Level estimate.

5.6.5 Use of Source Level data in impact analysis

When undertaking an environmental impact assessment, it is common to predict the sound field in the vicinity of the source using an acoustic propagation model of some kind. Most of the standard models that exist require the Source Level to be input as a monopole Source Level. For this reason, the monopole Source Levels have been reproduced in Appendix D in graphical and tabulated form.

When considering normal dredger operation, three modes of operation are of interest:

- full dredging (draghead down, pump on);
- draghead raised (pump on) – used when turning at end of track;
- transiting to and from dredging area.

The transit to and from the site is no different to any merchant vessel transiting the area. Of the other two, this report provides information on the likely Source Level that may be expected from UK dredgers. When turning with draghead raised, the radiated noise levels are not unusual when compared with a merchant ship travelling at modest speeds. However, when full dredging is underway, there is the potential for an unusually high level of broadband noise to be radiated in the frequency range from 1 kHz to high tens of kilohertz. This is what makes the dredger a slightly unusual noise source when compared to other merchant ships. Of course, the extra energy radiated at the high kilohertz frequencies will be more rapidly absorbed by the water and so will only have an influence over shorter ranges than would be the case for the same energy radiated at lower frequencies.

Notwithstanding the extra energy produced at tens of kilohertz, the dredgers may still be regarded as just noisy ships, and as such, in terms of acoustic energy deposited into marine environment in a given time, they are still much less noisy than other sources of anthropogenic noise such as marine piling and geophysical surveying sources such as airgun arrays.

However, one issue that would have to be considered when evaluating the impact is the length of time the dredger spends in an area, which is considerably longer than the time for a similarly noisy merchant ship to transit through the area. This means that the cumulative exposure from the dredging activity would be greater than for a single transiting vessel.

To assess the noise exposure requires a number of steps:

(i) Knowledge of Source Level data
(ii) Knowledge of marine receptors in the area and their hearing sensitivity
(iii) Propagation of sound through water column in the vicinity of the source
(iv) Calculation of the total sound exposure while making assumption about the reaction of the exposed receptor
(v) Comparison to thresholds for recognised effects (physical, behavioural, *etc.*)
(vi) Context of the noise exposure in the light of background noise, other noise sources in the area, and the presence of other stressors.

This project has addressed item (i). Item (ii) has been addressed by the excellent scoping study which preceded this project [Thomsen *et al*, 2009]. The acoustic propagation (iii) may be modelled with a range of freely-available models with varying degrees of sophistication. For items (iv) and (v), recommendations such as those of Southall *et al* (2007) may be adopted with the use of parameters such cumulative Sound Exposure Level (SEL) used as a metric, and a range of scenarios modelled (fleeing animal, static animal, *etc.*). In the regimes proposed by Southall *et al* (2007), the dredger noise would be considered as a continuous source, which would fall under the 'nonpulses' definition [Southall *et al*, 2007]. Such approaches have already been reported in the literature for other noise sources [Theobald *et al*, 2009]. This could be the subject of a future study.

6 CONCLUSION

6.1 SUMMARY OF WORK

The Source Levels of six dredging vessels have been estimated during the project:

Table 6.1 Summary table of dredging vessels measured during the study.

Vessel	Length (m)	Capacity (m^3)	Total Installed Power (kW)	Operator	Region	Area
Arco Axe	98.3	2890	2940	Hanson	East Coast	240
Sand Falcon	120	4832	2460 x 2	Cemex	East Coast	251
Sand Harrier	99	2700	3824	Cemex	South Coast	137
City of Chichester	72	1418	2720	Tarmac	South Coast	137
Sand Falcon	120	4832	2460 x 2	Cemex	EEC	473
City of Westminster	99.7	2999	4080	Tarmac	EEC	474
City of London	99.9	2652	4080	Tarmac	EEC	458

From the results, it is evident that the noise radiated at frequencies less than 500 Hz is similar to that of a merchant vessel travelling at reasonable speed. However, in one aspect dredgers appear slightly noisier than a typical cargo ship. It is clear from the measured data that dredging vessels can generate higher levels of broadband noise at frequencies above 1 kHz than a typical cargo vessel in transit.

Analysis of the measured data for differing operation modes leads to the conclusion that the major source of this higher frequency noise is the impact/abrasion of the aggregate material passing through the draghead, suction pipe and pump (with some additional contribution due to cavitation noise, possibly in the pump). This means that the overall noise output level is partially dependent upon the aggregate being extracted. Results for the Sand Falcon when extracting different loads (sand in Area 251 on the East coast, and gravel from Area 473 in the EEC region) illustrate the dependence on aggregate type, with gravel being noisier than sand. In fact, the three vessels measured while extracting gravel from the EEC region, all show increased levels of broadband noise at frequencies above 1 kHz compared to the vessels extracting sand.

In summary, it can be concluded that, for the UK dredger vessels measured:

- Source Levels at frequencies below 500 Hz are generally in line with those expected for a cargo ship travelling at modest speed (between 8 and 16 knots for the Overseas Harriette [Arveson and Vendittis, 2000];
- Source Levels at frequencies above 1 kHz show elevated levels of broadband noise generated by the aggregate extraction process;
- the elevated broadband noise is dependent on the aggregate type being extracted – coarse gravel generating higher noise levels than sand.

When placed in context, it is clear that though dredgers are basically “noisy ships”, they are substantially quieter in terms of acoustic energy output than some other noise sources such as seismic airgun arrays and marine piling. However, an unusual feature of the noise radiated by dredgers is the elevated broadband noise level at kilohertz frequencies which would be unusual for a slow-moving cargo ship, such noise normally being associated with propeller cavitation at higher speed.

6.2 PROJECT OBJECTIVES

The core aim of the measurements was to establish the noise output (Source Level) of the dredging vessels measured and to understand more about the origin of the radiated noise. To achieve this, a methodology was established based on applicable parts of the ANSI standard on the ‘Quantities and Procedures for Description and Measurement of Underwater Sound from Ships’ [ANSI S12.64 2009], through consultation with TNO (Netherlands Organisation for Applied Scientific Research) and the UK’s Defence Science and Technology Laboratory. The established methodology employs measurements as a function of range from the source coupled with Propagation Loss modelling to establish the one-third-octave band Source Levels of each vessel.

In the project, the main aims have been achieved, namely:

- estimates of the typical Source Level for a selection of UK dredgers under normal operating conditions have been obtained;
- suitable measurement methodologies have been developed for the measurement based on standard methods;
- the potential noise output depending on vessel operational mode has been investigated, and some conclusions drawn on the noise generation mechanisms;
- the potential for variation in noise depending on location and type of load being dredged has been investigated.

Regarding noise generated during differing operational modes, this was only possible for some of the dredgers measured. Logistical considerations and environmental factors hindered this on occasions (*e.g.* time restrictions on dredging operation and bad weather). However, a number of operational modes were investigated for at least some of the dredgers successfully in addition to full dredging (drag head down on seabed, pump on). These other modes included: (i) draghead lifted from seabed, pump on, pumping water only; (ii) draghead lifted from seabed, pump off; (iii) draghead down on seabed, pump off.

6.3 CONTINUING KNOWLEDGE GAPS

Unfortunately, it was not possible to obtain comprehensive data on a number of features of the dredging, and there remain some knowledge gaps. Mainly, the lack of data was caused by logistical difficulties, but some features were not identified as major issues at the project outset, and have only been raised as knowledge was gained during the project. These continuing gaps are explored in Section 5.6.2, and include:

- Noise during transit
  It is important to understand the noise radiated during travel to and from the dredging areas. There is new evidence to show that this noise can be as high as that during dredging [TNO 2010].
- Noise from overspill and screening
  This was not possible to do systematically due to logistical reasons for the dredgers studied here.
- Aspect dependence of noise (azimuthal)
  More information might be possibly be gleaned from the existing data after further analysis.
- High frequency noise
  Only limited measurements were able to be made at frequencies greater than 200 kHz, and there is a lack of data at these high frequencies
- Seabed vibration
  Only limited measurements were possible with the geophones for one dredger (the City of Chichester). From the little data available, there does seem to be a correlation between seabed vibration and the onset of dredging, but more work would be required to quantify this in a satisfactory way.

Of these issues, perhaps the most important are the noise during transit, and the vibration of the seabed.

For the former, it was not possible to obtain good measurement data for the dredger transiting at full speed due to uncertainty regarding the dredger position caused by the dredger GPS transponder operating in a different mode when in transit. However, extensive data has been obtained for transiting dredgers by TNO in a project based around dredging in the Maasvlakte 2 area [TNO 2010]. In many respects, the TNO project complements this MALSF project in that considerable data was obtained for transiting, as well as other activities such as rainbowing, but in the TNO project no measurements were possible as a function of operational mode. The preliminary findings of TNO show that for the Dutch dredgers, the noise radiated during transit can be as significant as that during dredging, even at frequencies greater than 1 kHz. However, it should be noted that the Dutch dredger fleet contains vessels which are much larger than the UK fleet.

With regard to the seabed vibration, since a number of bottom-dwelling fish species are known to be sensitive to vibration, this is an area where more research is needed. In fact, there is little data on what typical ambient seabed vibration levels exist, or what levels might be considered to cause damage of disturbance to fish species.

6.4 DISSEMINATION

The established methodology, along with preliminary results have been presented at two international conferences [Robinson *et al*, 2010 and Theobald *et al*, 2010]. The project team also intend to submit a paper to a refereed journal based on the work described in this project.

The data produced for the Source Levels of dredgers during operation during this project may now be used as part of the input to environmental impact analysis using an approach such as that recommended in the peer-reviewed scientific literature [Southall *et al*, 2007].

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9 APPENDIX A: EQUIPMENT

9.1 DATA ACQUISITION SYSTEMS AND HYDROPHONES

For data acquisition on the survey vessel a two-channel Brüel & Kjær Pulse analysis system was used. Signals were acquired using a typical sample rate of 262,144 S/s with 24-bit resolution, allowing frequencies up to over 100 kHz to be recorded. An internal 7 Hz high-pass filter was used on the input channels to reduce the effect of wave motion on the recorded signals. For the majority of the measurements two low-noise Reson TC4032 hydrophones were deployed - one connected to each of the two input channels. In order to investigate the levels of signals above 100 kHz, for some measurements one of the TC4032 hydrophones was replaced with a higher frequency Reson TC4014 hydrophone and the sampling rate of the B&K Pulse system doubled. This enabled recordings up to 200 kHz to be made. The hydrophones were deployed at depths of 9 m and 13 m within the water column using the arrangement shown in Figure 9.1. The calibration curves for the above hydrophones are shown in Figures 9.3 to 9.5. All of the measurement instrumentation was operated from batteries in order to eliminate the possibility of noise from the engines or generator.

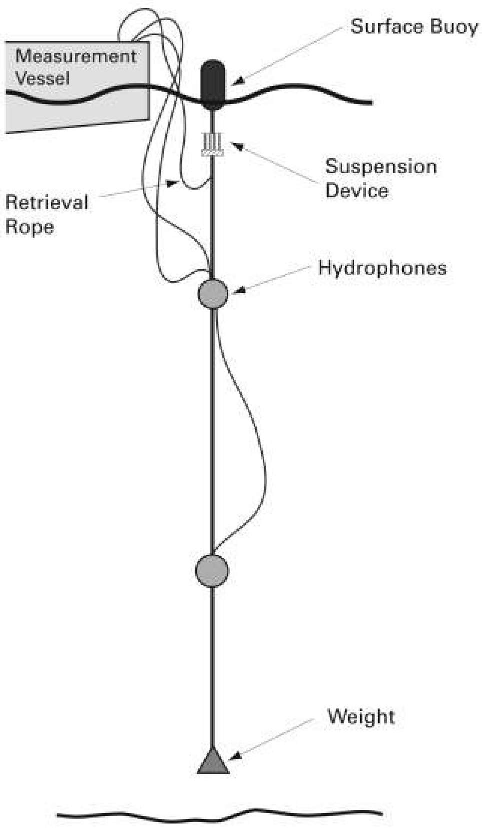

Figure 9.1 Survey vessel hydrophone deployment.

The static noise monitoring buoys are self-contained data acquisition units. Each system has two SRD HS70 hydrophones and a recording pod deployed using the arrangement shown in Figures 9.2. The sample rate for each channel was 96 kS/s, providing a measurement bandwidth of 48 kHz, and the resolution was 24-bit. All data was saved in uncompressed format (uncompressed WAV file format).

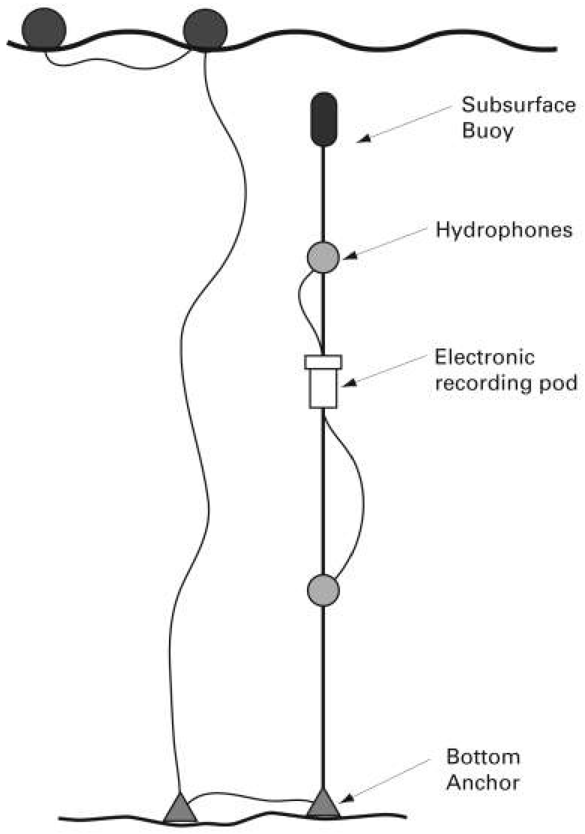

Figure 9.2 Recording buoy hydrophone deployment.

9.2 HYDROPHONE CALIBRATION

All data acquisition electronics and amplifiers were calibrated. All hydrophones used were calibrated traceable to UK national standards by NPL over the full frequency range of use, not just at one frequency. All measurement locations were GPS position fixed and all the data acquisition systems were time stamped against GPS to better than 1 s accuracy.

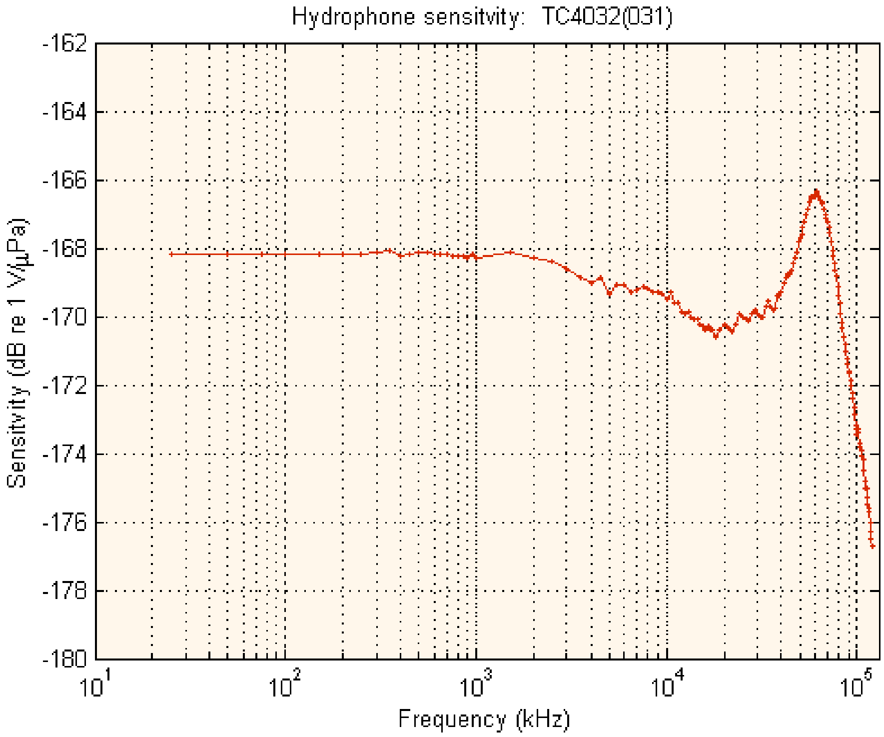

Figure 9.3 Calibration curve for Reson TC4032 hydrophone S/N:031.

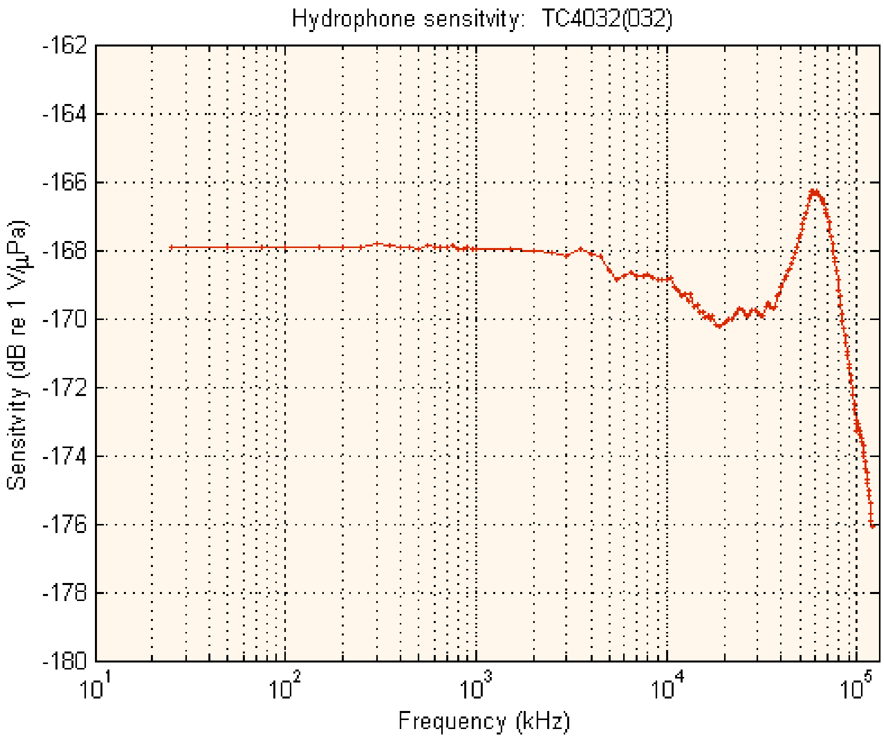

Figure 9.4 Calibration curve for Reson TC4032 hydrophone S/N:032.

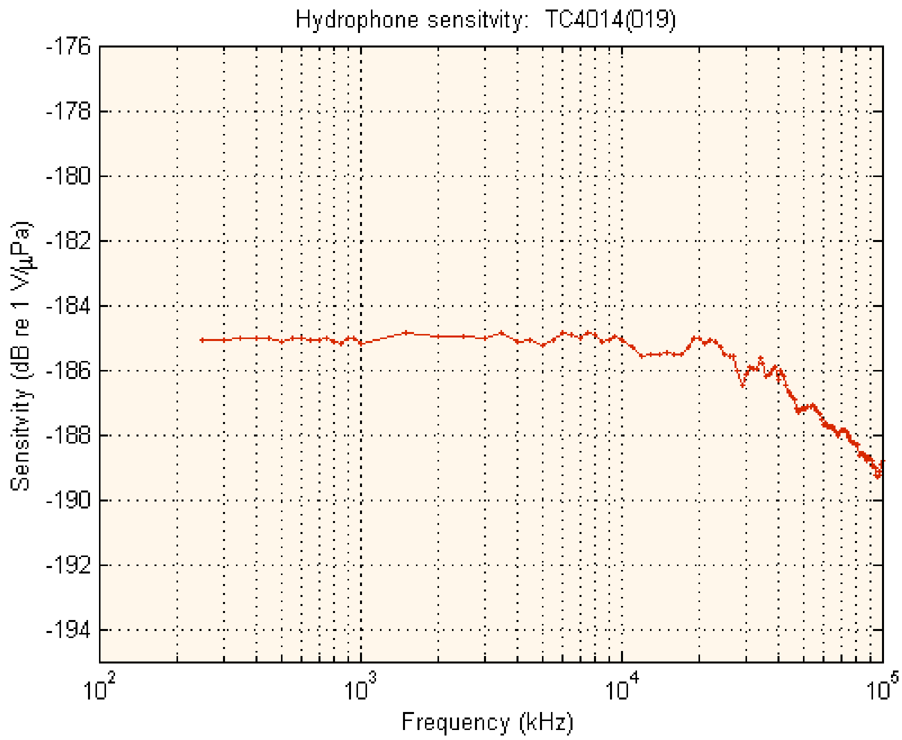

Figure 9.5 Calibration curve for Reson TC4014 hydrophone S/N:019.

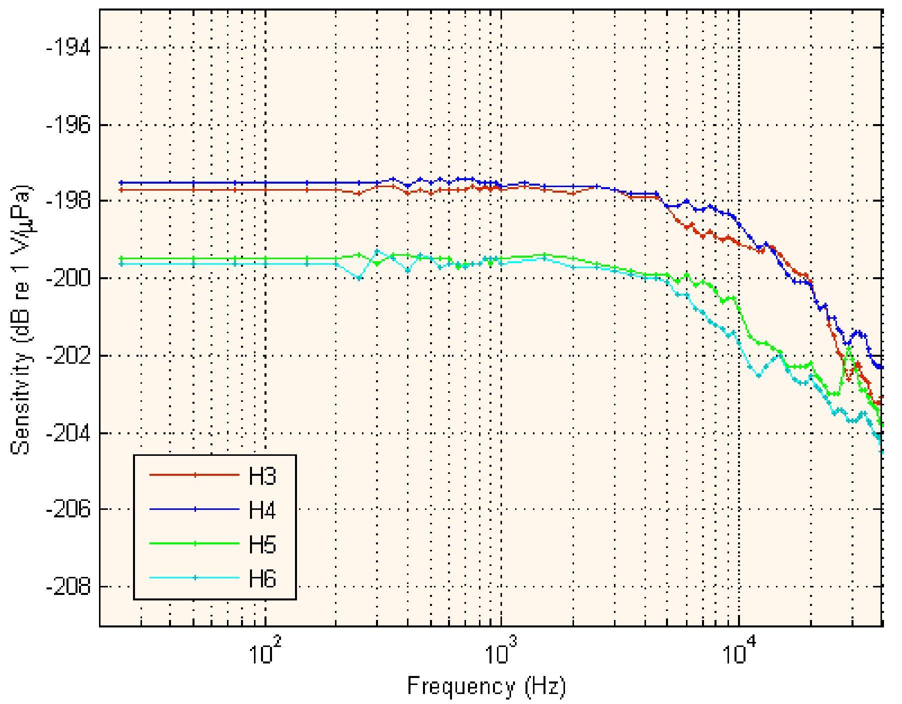

Figure 9.6 Calibration curve for SRD HS70 hydrophones used on buoys.

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9.3 MULTI PURPOSE RESEARCH VESSEL MV GEORGE D

The survey vessel ‘MV George D’ is owned and operated by Gardline Environmental Ltd. It is well suited to deployment and recovery of oceanographic instruments including acoustic recording buoys and their associated moorings. This vessel has sufficient deck space to carry out onboard preparation of the acoustic systems before deployment. A full suite of geophysical equipment can be accommodated onboard to enable the vessel to carry out coastal surveys in shallow to medium depth waters.

Figure 9.7 Photographs of the MV George D.

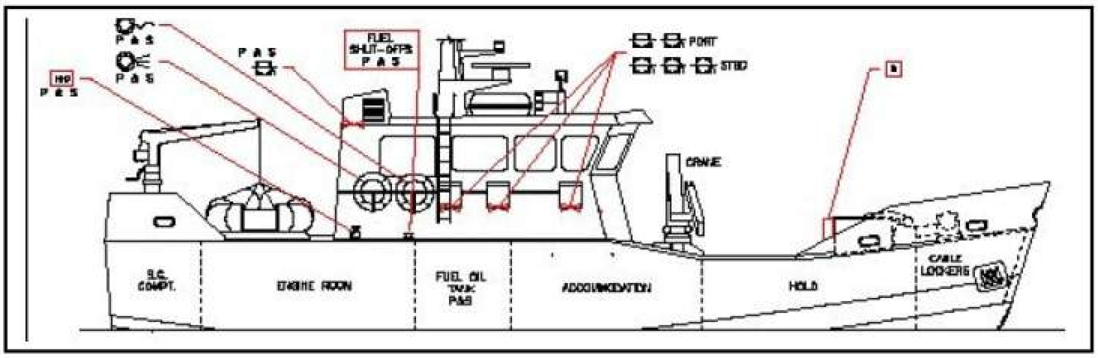

Figure 9.8 Diagram of the MV George D.

Table 9.1 Specification of the MV George D.

Name:	George D
Length	19.80 metres
Beam:	5.42 metres
Draft:	2.13 metres
Speed:	Up to 10 knots
Construction:	Built in 1991, steel
Engines:	Twin Screw Volvo Penta TMD 101,175.31kw engines. Auxiliary power 1 x G&M 44MDP-53R 32kva @ 230v
Accommodation	Two cabins, 4 berth, each cabin has full length wardrobes, draws under, all usual amenities, TV, radio cassette, full size cooker *etc*.
Navigation Equipment	Racal Decca radar, Sailor VHF, Sailor DSC VHF, Icom HF radio, NAVTEX, Robertson AP45 Autopilot, Trimble & Leica DGPS, Furuno forward looking 360^{o} Sonar, Dual frequency (33/200kHz) Echotrac echo sounder, TSS 333B motion sensor.

Lifting:	Effer marine crane model 10000/35, 9.38T/m. with capacity of 2tons @ 4m for over side work. 0.5 ton davit.
Safety:	MCA Category 2 Coding (60mile from safe haven, 24 hour operations). 2 x 10 person liferafts and full life saving and fire fighting equipment that is required under the MCA code.

10 APPENDIX B: DETAILS OF MEASUREMENTS MADE

This Appendix provides details on the measurement methodology and specific details for each measurement performed on the following vessels around the English coast:

Table 10.1 Summary of the dredging area details which were used in this study.

Vessel	Dredging region	Licence area	General aggregate type in licence area	Approximate water depth in licence area (m)
Arco Axe	East Coast	Area 240	Gravelly Sand	20 - 30
Sand Falcon	East Coast	Area 251	Gravelly Sand	28 - 32
Sand Harrier	South Coast	Area 137	Gravelly Sand	~27
City of Chichester	South Coast	Area 137	Gravelly Sand	~27
Sand Falcon	East English Channel	Area 473	Sandy gravel	~40
City of Westminster	East English Channel	Area 474	Sandy gravel	~35
City of London	East English Channel	Area 458	Sandy gravel	~37

The following table shows the technical details of the dredgers measured.

Table 10.2 Technical details of the dredgers measured.

Vessel	Built	Length (m)	Total installed power (kW)	No. of engines & shafts	Dredge Pump type	Dredge Pump power (kW)	Screen Config.	Overspill Config.	Maximum dredging depth (m)	Capacity (cubic metres)	Capacity (tonnes)
Sand Harrier	1990	99	3824	1+1	inboard	1591	towers (2) (s'bd)	port & starboard	33	2700	4671
Sand Falcon	1998	120	2x2460	2+2	inboard& overboard (port)	1100 & 1631	towers (2) (s'bd)	port & starboard	50	4832	8359
Arco Axe	1989	98.3	2940	1+1	overboard (s'bd)	1100	towers (2) (port)	port & starboard	48	2890	5000
City of Chichester	1997	72	2,720	2+2	inboard	700	static box	fore & aft, central	35	1418	2300
City of London	1990	99.9	4,080	2+2	overboard (port)	1,100	towers (2) (s'bd)	port & starboard	46	2652	4750
City of Westminster	1990	99.7	4,080	2+2	overboard (port)	1,100	towers (2) (s'bd)	port & starboard	46	2999	5200

10.1 ARCO AXE

Operator: Hanson
Area: East Coast Area 240
Date: 16th March 2010

Measurements were performed on 16th March 2010 of the Arco Axe (shown in Figure 10.1) whilst it was undertaking marine aggregate extraction operations for Hanson in East Coast Area 240 off the coast of Great Yarmouth (highlighted in Figure B.2), with typical water depths of 20 m to 30 m. The cargo was screened over 10 mm screens and took approximately 7.5 hours to load starting around 12:50pm GMT with acoustic measurements starting around the same time. The survey vessel used was the MV Melanie D.

Figure 10.1 The Arco Axe on area 240.

The Arco Axe was performing a non-standard dredging operation by dredging across the tide and on a non-straight dredging lane to extract the un-dredged material from between adjacent dredging blocks. This type of operation is quite rare and means that the vessel dredges in one direction and then loops around to re-start its dredging run.

Four autonomous noise measurement buoys were anchored at nominal positions of 50 m, 200 m, 500 m, 1000 m from the planned dredging lane and remained in place record for around 7 hours and measured 5 dredging passes.

Each buoy had two hydrophones which were both in the lower half of the water column, with the upper of the two being close to mid-water depth. Ideally, these would have been along a line perpendicular to the dredging lane but due to the way in which the vessel was dredging it was not possible to achieve this. The non-straight dredging tracks also meant that the relative measurement buoy positions were not always at the planned distance.

Hydrophones were not deployed off the MV Melanie D survey vessel for safety reasons given the swell conditions. The MV Melanie D survey vessel stood-off during the measurements and was allowed to drift, although periodically it had to be repositioned.

The dredger passes which were used to calculate Source Level (1 and 2) were chosen to coincide with the MV Melanie D drifting silently or when it was sufficiently far away so as not to contaminate the measurement data from the buoys.

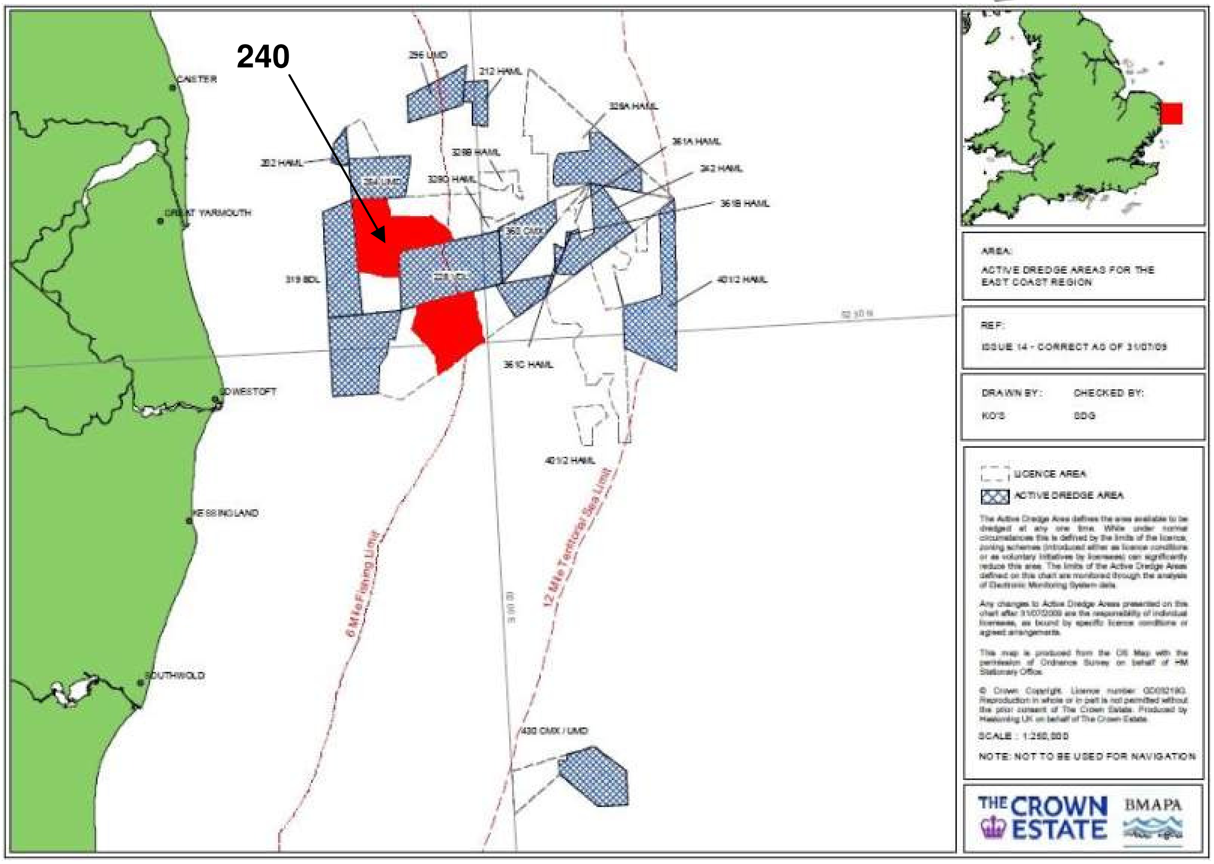

Figure 10.2 Map of east coast licensed areas showing Area 240.

The positions of the MV Melanie D survey vessel are indicated in Figure 10.3 relative to the measurement buoys and the Arco Axe positions for the measured passes (1 and 2). The CPA for passes 1 and 2 whilst dredging are also indicated in Figure 10.3 along with the starting point 10 minutes before CPA. For passes 1 and 2 shown in Figure 10.3, the actual ranges to the measurement buoys from the CPA were approximately 310 m (buoy 1), 400 m (buoy 2), 670 m (buoy 3) and 1180 m (buoy 4).

The analysed data only included full dredging activities and the passes indicated in Figure 10.3 were used in the Source Level calculations of the Arco Axe. Buoy 4 was excluded from the Source Level calculation due to reduced signal-to-noise ratio. Data was also not recorded on channel 2 or buoy 3 and so the Source Level data for the Arco Axe presented in Appendix D was obtained from 7 hydrophone measurements. Because the Arco Axe was dredging across the tide and only dredging in one direction, data was only obtained for the starboard side of the Arco Axe.

During the measurements, a CTD sonde was deployed from the MV Melanie D survey vessel to measure the water temperature and salinity as a function of depth. The temperature was measured to be around 4.3°C with a salinity of around 34.4 ‰ with negligible variation down to 22 m, to give a sound speed of 1468 m/s. Given the shallow tidal environment, very little variation in sound speed would be expected as a function of depth.

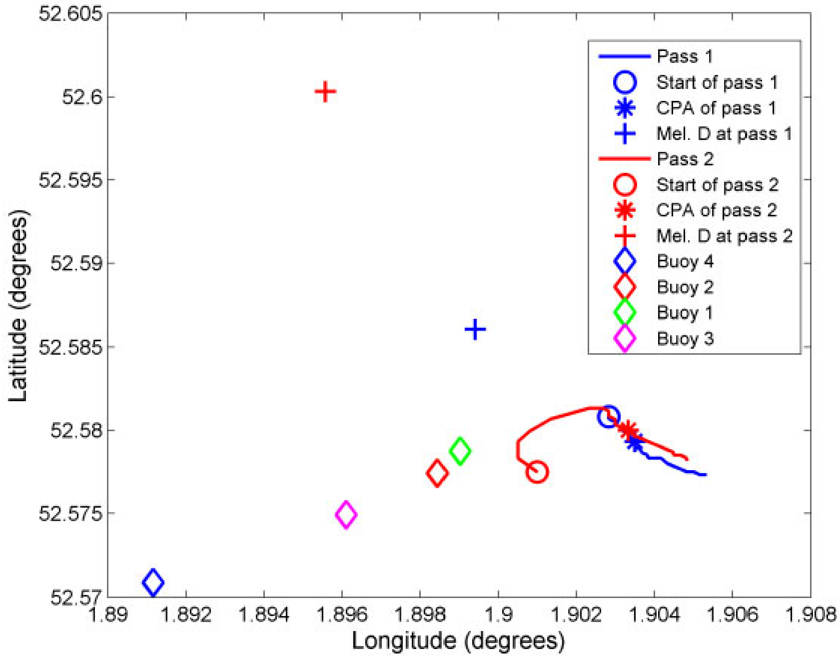

Figure 10.3 GPS details for the Arco Axe measurements.

The measurements were performed during Spring high-tide and so tidal currents of around 3 – 4 knots were typical although the sea-state was fairly calm during the measurements at around force 2 to 3, with a slight swell. Tidal variations of up to 3 m were predicted in the area but passes 1 and 2 were measured between 14:00 and 16:00 GMT and so tidal variation would have been less than 0.5 m and approaching slack tide.

10.2 SAND FALCON

Operator: Cemex UK
Area: East Coast Area 251
Date: 24th March 2010

Measurements were performed on 24th March 2010 of the Sand Falcon (shown in Figure 10.4) whilst it was undertaking marine aggregate extraction operations for Cemex UK in East Coast Area 251 (central) off the coast Lowestoft (highlighted in Figure 10.5), with typical water depths of 28 m to 32 m. The survey vessel used was the Penetrater.

The Sand Falcon was collecting a screened cargo which took approximately 7 hours to load starting at around 10:00am GMT with acoustic measurement starting around the same time. The Sand Falcon was performing a standard dredging operation, dredging in both directions, approximately north north west to south south east. During the dredging operation, the vessel performed a series of runs in different operational states for the purpose of assessing the noise generation mechanisms. These were runs with: lifted drag-head and the pump still running so that only water was being pumped; and with the pump turned off whilst the drag-head remained on the sea floor. These were in addition to normal full dredging runs.

Figure 10.4 The Sand Falcon on Area 251.

Two autonomous noise measurement buoys were anchored at nominal positions of 50 m and 500 m from the planned dredging lane and remained in place recording for around 5.5 hours and measured a total of 10 vessel passes. Each buoy had two hydrophones which were both in the lower half of the water column, with the upper of the two being close to mid-water depth. These were positioned to be on a line perpendicular to the dredging lane.

Hydrophones were also deployed from the Penetrater survey vessel, using the deployment method described in Appendix A. For the measurements, the Penetrater was powered down whilst at anchor a planned 100 m off the dredging lane to form a third measurement point along the line of the buoys. The position of the Penetrater survey vessel is indicated in Figure 10.6 relative to the measurement buoys and the Sand Falcon positions for the passes used in the Source Level calculation (1, 3 and 7). It can be seen from Figure 10.6 that the Penetrater dragged anchored and drifted south during the measurements. The CPA used for the Source Level calculations are also indicated in Figure 10.6 along with the starting point 10 minutes before CPA. For the passes shown in Figure 10.6, the actual ranges to the measurement buoys and the Penetrater from the CPA range

- from approximately 12 m to 40 m for buoy 1,
- 445 m to 475 m for buoy 2 and 100 m to 350 m for the Penetrater.

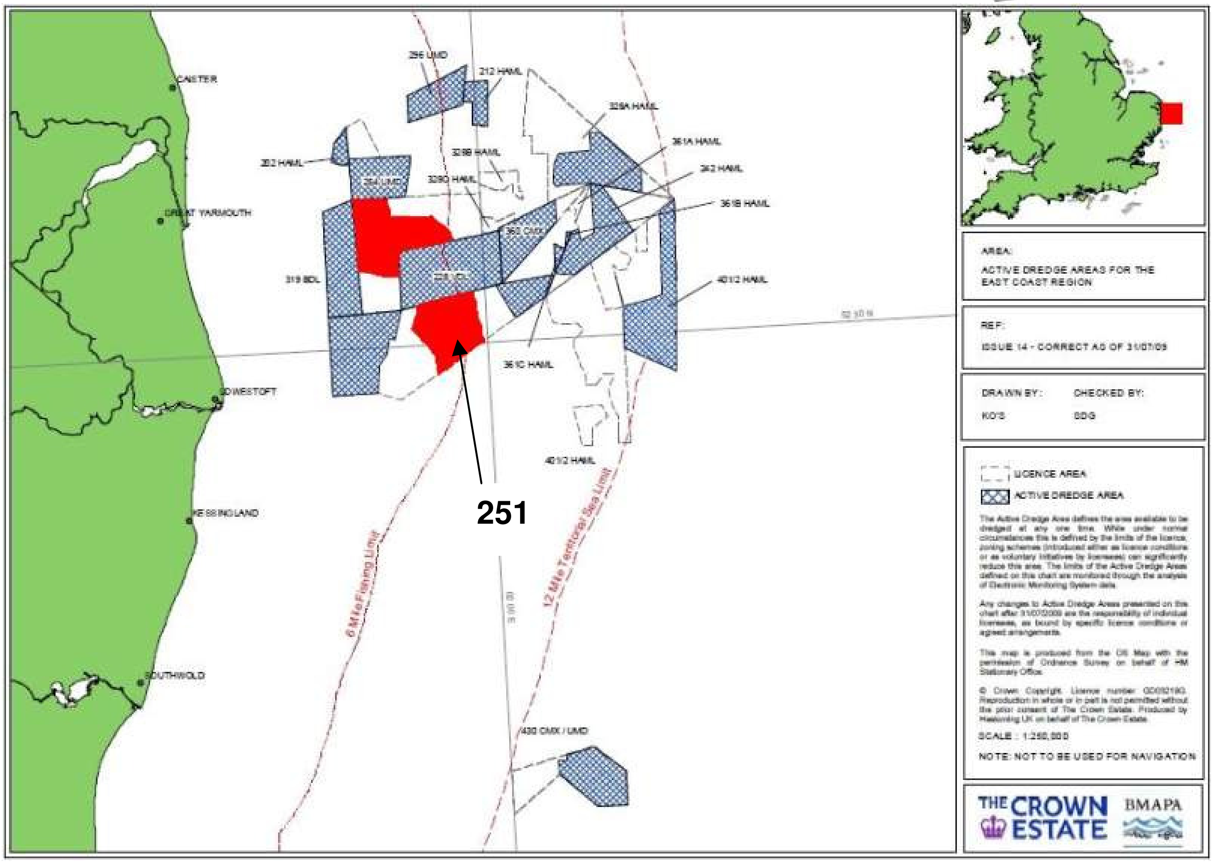

Figure 10.5. Map of east coast licensed areas showing Area 251 (central).

Due to the close proximity of buoy 1 to the Sand Falcon, this data was excluded during the calculation of Source Level. Data from channel 1 of buoy 2 was also excluded because of damage sustained to the hydrophone during deployment and so the Source Level data for the Sand Falcon presented in Appendix D was obtained from 5 hydrophone measurements. The Source Level calculations were performed for port-side passes only.

Further passes were analysed for the report as these included measurements of the Sand Falcon passing with i) its pumps switched off whilst the drag head was still on the seafloor and ii) with the draghead raised and the pumps running, pumping water only. The main aim of these measurements was to help establish the individual contributors to the overall noise radiated from the vessel.

During the measurements, a CTD sonde was deployed from the Penetrater survey vessel to measure the water temperature and salinity as a function of depth. The temperature was measured to be around 4.3°C with a salinity of around 34.4 ‰ with negligible variation down to 22 m, to give a sound speed of 1468 m/s. Given the shallow tidal environment, very little variation in sound speed would be expected as a function of depth. Tidal currents of around 3 – 4 knots were typical although the sea-state was fairly calm during the measurements, varying between around force 1 to 3, with a slight swell. Tidal variations of around 1 m were predicted in the area for the period over which measurement data was analysed between around 11:30 and 16:30 GMT.

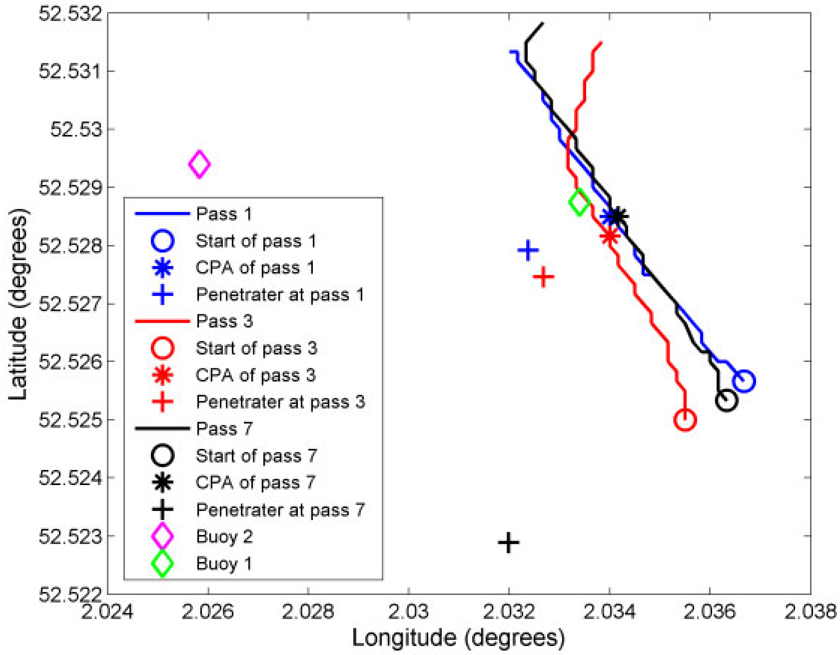

Figure 10.6. GPS details for the Sand Falcon measurements.

10.3 AMBIENT NOISE MEASUREMENT, EAST COAST, CROSS SANDS AREA

Date: 25th March 2010

Measurements were performed on 25th March 2010 of the ambient noise in Cross Sands Area (slightly to the east of Area 251 central) off the east coast of the UK with typical water depths of 28 m to 32 m. The survey vessel used was the MV Penetrater.

Ambient noise data was collected over a period of approximately 1 hour starting at approximately 15:50 GMT. The measurements were performed on a separate day when no dredging activity was taking place in the immediate area. The survey vessel (Penetrater) was positioned for each measurement, and then allowed to drift, to ensure maximum distance from any direct sources of noise. The maximum distance possible at any one time from a potential noise source was around 3 nm. Sources of noise were the Arco Humber operating around 3 nm north west of the Penetrater position and a shipping lane around 3 nm to the east of the Penetrater.

For the ambient noise measurements, only a hydrophone deployment from the Penetrater survey vessel was used as this employed low noise hydrophone with a noise floor below sea state zero. These were deployed using the deployment method described in Appendix A. During the measurement, the Penetrater was powered down and allowed to drift. Tidal currents of around 3 – 4 knots were typical although the sea-state was fairly calm during the measurements, varying between around force 2 to 3, with a slight swell. Measurements were taken around slack tide (high water) with some measurements including light rain on the surface.

10.4 SAND HARRIER

Operator: Cemex UK
Area: South Coast Area 137
Date: 16th June 2010

Measurements were performed on 16th June 2010 of the Sand Harrier (shown in Figure 10.7) whilst it was undertaking marine aggregate extraction operations for Cemex UK in South Coast Area 137 off the southwest coast of the Isle of Wight (highlighted in Figure 10.8), with typical water depths around 27 m (measured at the MV George D position). The survey vessel used was the MV George D. The Sand Harrier was collecting a half screened cargo and was on-station dredging for several hours before the acoustics measurements started at around 07:00am BST. The vessel continued dredging for a further 2 hours whilst acoustic measurements were performed. The Sand Harrier was performing a standard dredging operation, dredging in both directions, approximately east to west. During the measurements, the vessel performed a number of non-dredging runs in different operational states for the purposes of the noise generation measurements. These included a run where the draghead was lifted and the pump turned off and on before lowering the draghead again, and one run with the vessel steaming past at full speed.

Two autonomous noise measurement buoys were anchored at nominal positions of 50 m and 400 m from the planned dredging lane and remained in place recording for around 2.5 hours and measured a total of 5 dredging vessel passes. Each buoy had two hydrophones which were both in the lower half of the water column, with the upper of the two being close to mid-water depth. These were positioned to be on a line perpendicular to the dredging lane.

Hydrophones were also deployed from the MV George D survey vessel, using the deployment method described in Appendix A. For these measurements, the MV George D was powered down whilst at anchor a planned 100 m off the dredging lane to form a third measurement point along the line of the buoys. The position of the MV George D survey vessel is indicated in Figure 10.9 relative to the measurement buoys and the Sand Harrier positions for the passes used in the Source Level calculation (2 and 4). The CPA used for the Source Level calculations are also indicated in Figure B.9 along with the starting point 10 minutes before CPA. For the passes shown in Figure B.9, the actual ranges to the measurement buoys and the MV George D from the CPA range from

- approximately 65 m to 75 m for buoy 1,
- 410 m to 420 m for buoy 2 and
- 165 m to 195 m for the MV George D.

Figure 10.7 The Sand Harrier on Area 137.

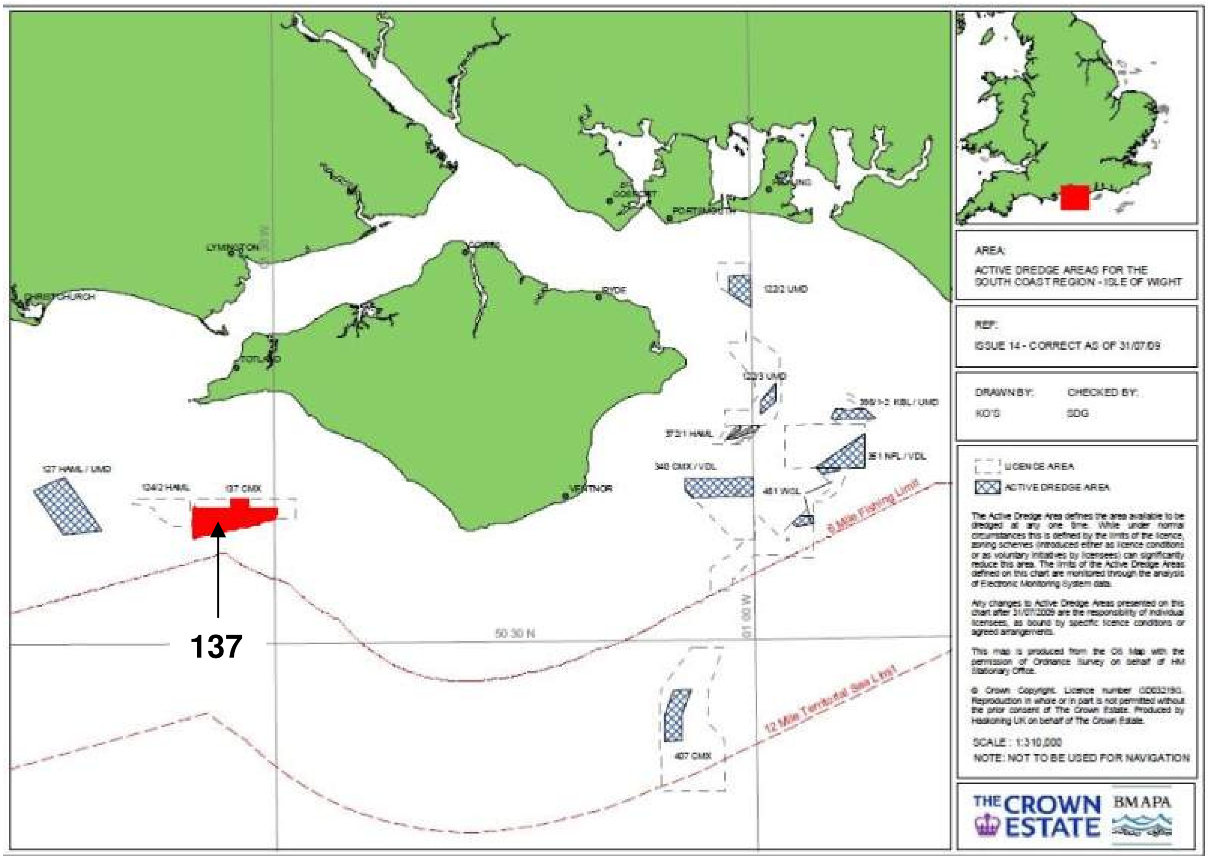

Figure 10.8 Map of south coast licensed areas showing Area 137.

The Source Level data for the Sand Harrier presented in Appendix D was obtained from 12 hydrophone measurements. Further passes were analysed for the report as these included measurements of the Sand Harrier passing i) whilst raising its draghead, turning its pump off and back on and then lowering its draghead again and ii) with the vessel passing by at full speed, not dredging. The main aim of these measurements was to help establish the individual contributors to the overall noise radiated from the vessel.

Ambient noise measurements were performed around 11:00am GMT, once the Sand Harrier had left the area and no other vessels were in sight. For the ambient noise measurements, hydrophones (low noise) were also deployed from the MV George D survey vessel, using the deployment method described in Appendix A. During the measurement, the MV George D was powered down and allowed to drift. The ambient noise measurement and the Sand Harrier measurements were performed during the rising tide which was predicted to have risen around 1 m since the vessel measurement started. The sea-state was estimated to be around force 5 to 6 with no rain.

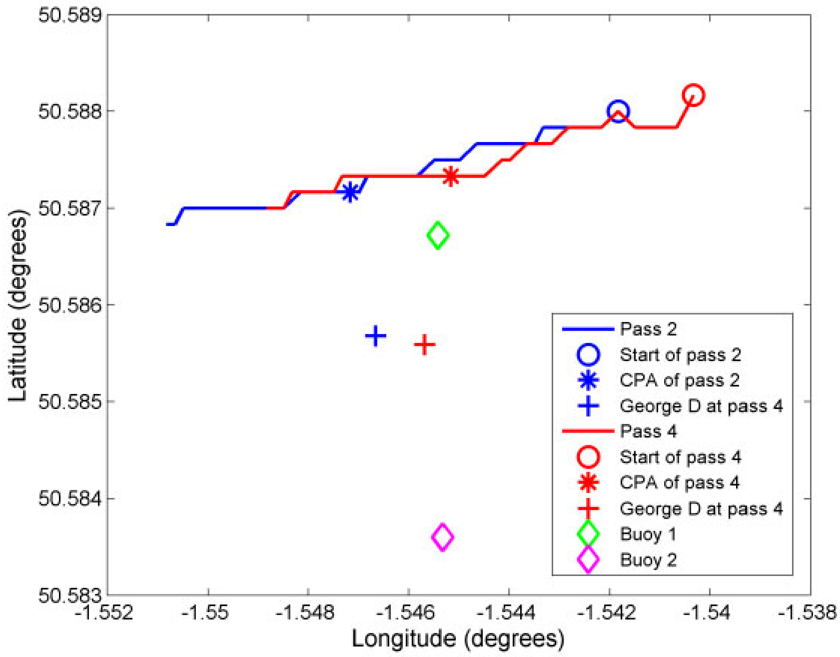

Figure 10.9 GPS details for the Sand Harrier measurements.

During the measurements, a CTD sonde was deployed from the MV George D survey vessel to measure the water temperature and salinity as a function of depth. The temperature was measured to be around 13.7℃ with a salinity of around 34.0 ‰ with negligible variation down to 25 m, to give a sound speed of 1503 m/s. Given the shallow tidal environment, very little variation in sound speed would be expected as a function of depth.

10.5 CITY OF CHICHESTER

Operator: Tarmac
Area: South Coast Area 137
Date: 18th June 2010

Measurements were performed on 18th June 2010 of the City of Chichester (shown in Figure 10.10) whilst it was undertaking marine aggregate extraction operations for

Tarmac in South Coast Area 137 off the southwest coast of the Isle of Wight (highlighted in Figure 10.11). The survey vessel used was the MV George D. Typical water depths were around 27 m (measured at the MV George D position). The City of Chichester was collecting an ‘all-in’ cargo and was on-station dredging for around 30 mins before the acoustics measurements started at around 08:15am BST. The vessel continued dredging for a further 2.5 hours whilst acoustic measurements were performed. The City of Chichester was performing a standard dredging operation, dredging in both directions, approximately east to west. During the measurements, the vessel performed a number of non-dredging runs in different operational states for the purposes of the noise generation measurements. These included a run where the draghead was lifted and the pump turned off and on, and one run with the vessel using its bow thrusters.

Figure 10.10 The City of Chichester on Area 137.

Two autonomous noise measurement buoys were anchored at planned positions of 50 m and 400 m from the planned dredging lane and remained in place recording for around 2.5 hours and measured a total of 4 dredging vessel passes. Each buoy had two hydrophones which were both in the lower half of the water column, with the upper of the two being close to mid-water depth. These were positioned to be on a line perpendicular to the dredging lane.

Hydrophones were also deployed from the MV George D survey vessel, using the deployment method described in Appendix A. For these measurements, the MV George D was powered down whilst at anchor around 175 m off the dredging lane to form a third measurement point along the line of the buoys. The position of the MV George D survey vessel is indicated in Figure 10.12 relative to the measurement buoys and the City of Chichester positions for the passes used in the Source Level calculation (2, 3 and 4). The CPA used for the Source Level calculations are also indicated in Figure 10.12 along with the starting point 10 minutes before CPA. For the passes shown in Figure 10.12, the actual ranges to the measurement buoys and the MV George D from the CPA range from

- approximately 150 m to 160 m for buoy 1,
- 445 m to 445 m for buoy 2 and
- 155 m to 190 m for the MV George *D*.

Channel 1 data from buoy 2 was excluded because of some connector leakage and so the Source Level data for the City of Chichester presented in Appendix D was obtained from 15 hydrophone measurements. The MV George D position and buoy 1 were in close proximity to each other. The actual ranges vary from those planned due to slight differences in the dredging vessel planned track and actual track.

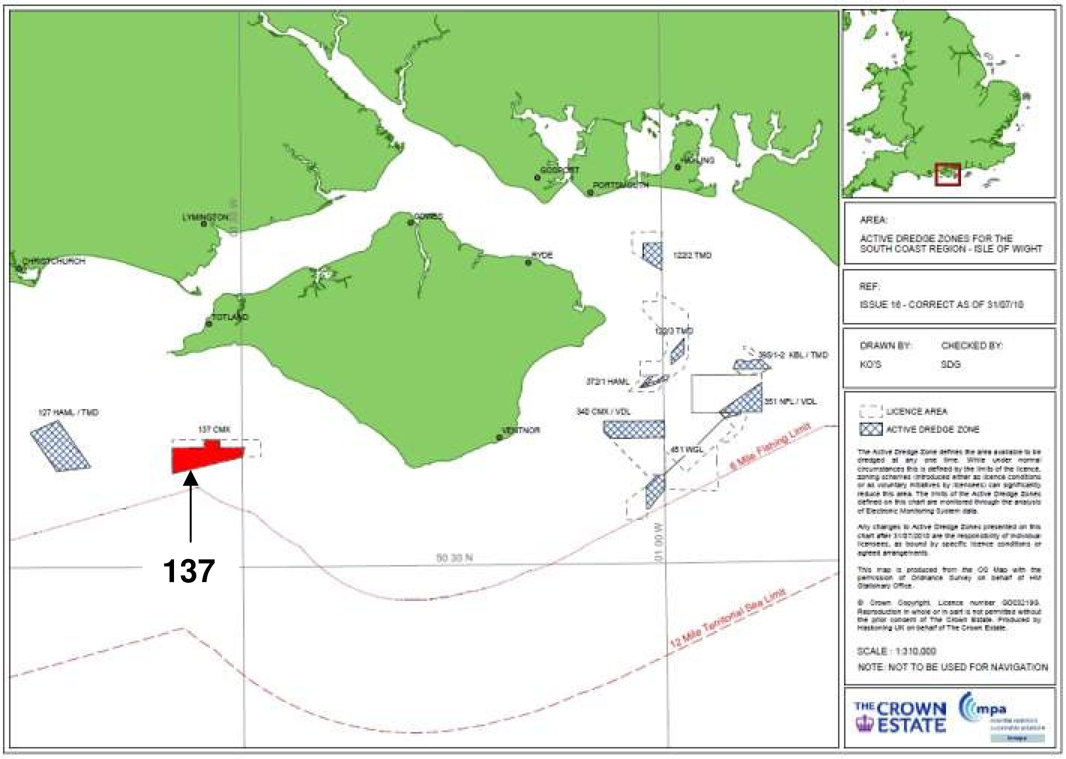

Figure 10.11 Map of south coast licensed areas showing Area 137.

Further passes were measured of the City of Chichester i) for a combination raising its draghead and turning its pump off and back on ii) with the bow thrusters on and off. In addition to the buoy and survey vessel based hydrophone measurements, a bottom mounted geophone unit was deployed from the MV George D to measure the seabed vibration whilst the City of Chichester steamed past on pass number 4, at a range of 190 m from the CPA.

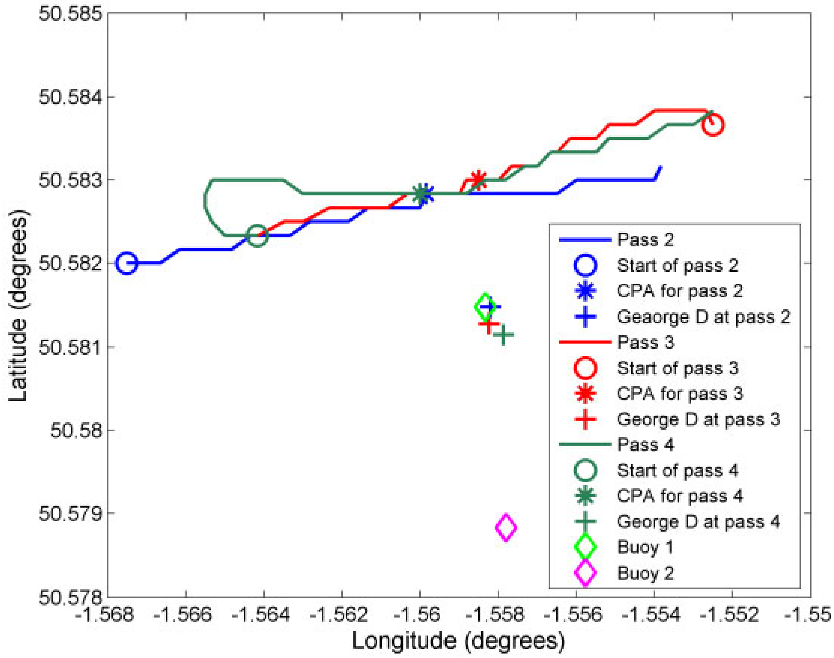

Figure 10.12 GPS details for the City of Chichester measurements.

The City of Chichester noise measurements started around low tide, with the tide rising by around 0.6 m by the time the vessel measurements were completed. The sea-state was fair, estimated to be around force 3 to 4, with no rain.

The City of Chichester has a 45 m long pipe which is 750 mm in diameter. The load in Area 137 was described as “gravelly sand” and the propeller depth varied from 2.3 m at the start of operations, to 3.0 m at full load. The load was taken “all in”, with no screening.

10.6 SAND FALCON

Operator: Cemex UK
Area: East English Channel Area 473
Date: 03rd August 2010

Measurements were performed on 03rd August 2010 of the Sand Falcon (shown in Figure 10.13) whilst it was undertaking marine aggregate extraction operations for Cemex UK in East English Channel Area 473 off the coast of Eastbourne (highlighted in Figure 10.14), with typical water depths around 40 m (measured at the MV George D position). The survey vessel used was the MV George D. The Sand Falcon was collecting a 10 mm screened cargo and was on-station dredging for several hours before the acoustics measurements started at around 09:45am BST. The vessel continued dredging for a further 5 hours whilst acoustic measurements were performed and left the area with a 5,000 ton cargo. The Sand Falcon was performing a standard dredging operation, dredging in both directions, approximately east to west. During the measurements, the vessel performed a number of non-dredging runs in different operational states for the purposes of the noise generation measurements. These included runs with the draghead raised, pumps off and also one run with the vessel steaming past at full speed.

Figure 10.13 The Sand Falcon.

Two autonomous noise measurement buoys were anchored at nominal positions of 50 m and 400 m from the planned dredging lane and remained in place recording for around 2.5 hours and measured a total of 5 dredging vessel passes. Each buoy had two hydrophones which were both in the lower half of the water column, with the upper of the two being close to mid-water depth. These were positioned to be on a line perpendicular to the dredging lane.

Hydrophones were also deployed from the MV George D survey vessel, using the deployment method described in Appendix A. For these measurements, the MV George D was powered down whilst at anchor a planned 100 m off the dredging lane to form a third measurement point along the line of the buoys. The position of the MV George D survey vessel is indicated in Figure 10.15 relative to the measurement buoys and the Sand Falcon positions for the passes used in the Source Level calculation (2 and 4). The closest point of approach (CPA) used for the Source Level calculations are also indicated in Figure 10.15 along with the starting point 10 minutes before CPA. For the passes shown in Figure 10.15, the actual ranges to the measurement buoys and the MV George D from the CPA range from

- approximately 65 m to 75 m for buoy 1,
- 410 m to 420 m for buoy 2 and
- 165 m to 195 m for the MV George D.

The Source Level data for the Sand Falcon presented in Appendix D was obtained from 12 hydrophone measurements and included both passes for port and starboard on to the MV George D.

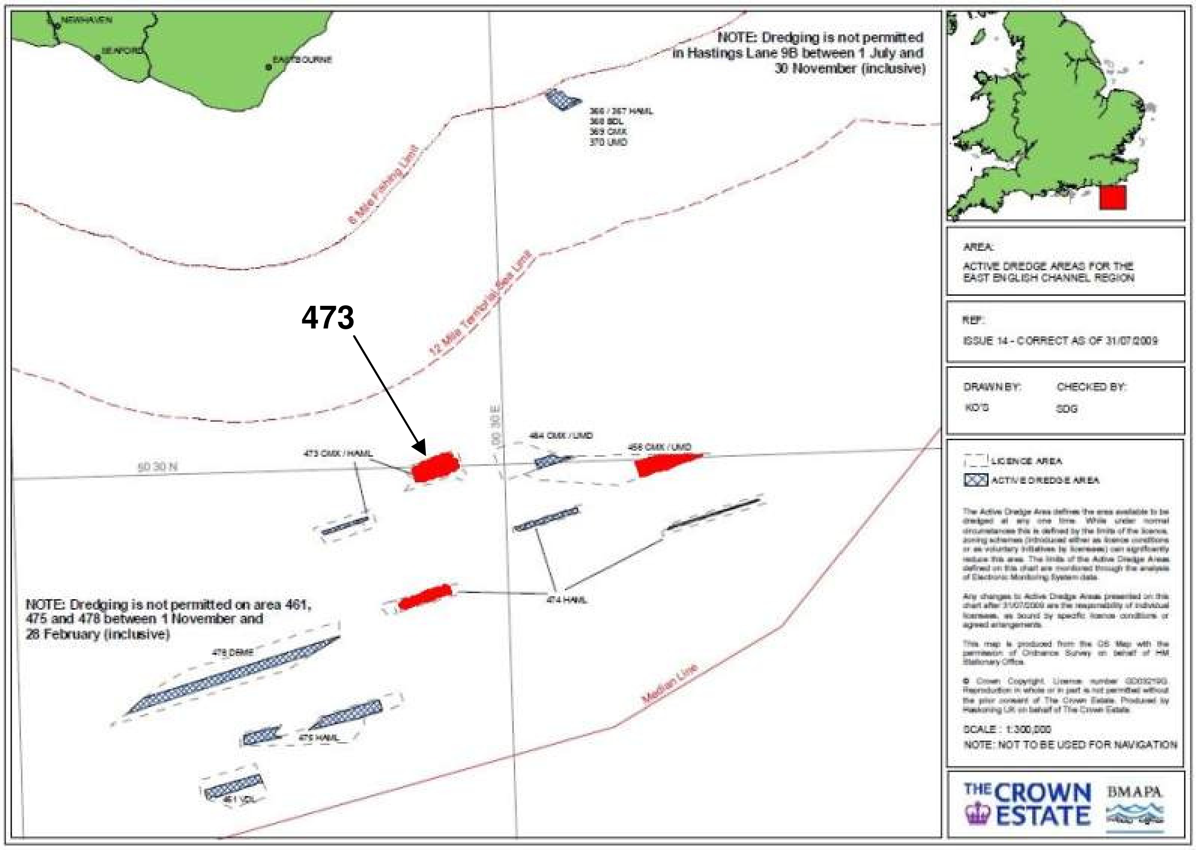

Figure 10.14 Map of east English channel licensed areas showing Area 473.

Further passes were analysed for the report as these included measurements of the Sand Falcon passing i) with its draghead raised off the seabed whilst pumping water, ii) with its pumps turned off but still dragging its draghead along the seabed and iii) with the vessel passing by at full speed, not dredging. The main aim of these measurements was to help establish the individual contributors to the overall noise radiated from the vessel.

Ambient noise measurements were performed around 14:45 BST, at a stand-off distance of around 1.6 nm from the Sand Falcon which was still dredging. The dredging and subsequent measurements were being undertaken in the traffic separation zone of the English Channel and so it was not expected that the measurements could be performed in isolation from any particular vessel. For the ambient noise measurements, hydrophones (low noise) were also deployed from the MV George D survey vessel, using the deployment method described in Appendix A. During the measurement, the MV George D was powered down and allowed to drift. The ambient noise measurement and the Sand Falcon measurements were performed during the rising tide. Vessel measurements earlier in the day were measured around low tide, with the tide rising from around 11:00am by around 1 m by the time the vessel measurements were completed. The sea-state was relatively calm, estimated to be around force 2, with no rain.

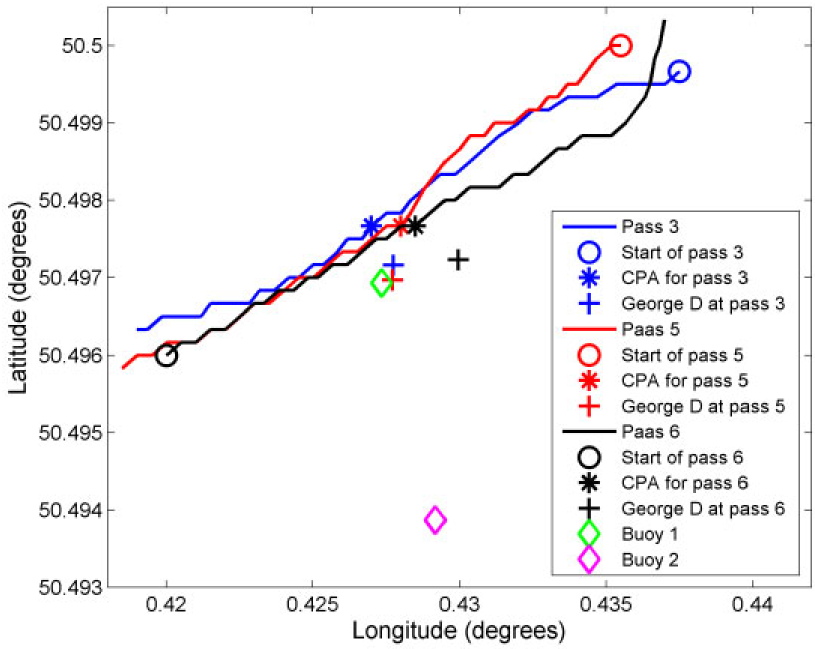

Figure 10.15 GPS details for the Sand Falcon measurements.

During the measurements, a CTD sonde was deployed from the MV George D survey vessel to measure the water temperature and salinity as a function of depth. The temperature was measured to be around 16.2°C with a salinity of around 35.7 ‰ with negligible variation down to around 25 m, to give a sound speed of 1512 m/s. Given the shallow tidal environment, very little variation in sound speed would be expected as a function of depth.

10.7 CITY OF WESTMINSTER

Operator: Tarmac
Area: East English Channel Area 474
Date: 04th August 2010

Measurements were performed on 04th August 2010 of the City of Westminster (shown in Figure 10.16) whilst it was undertaking marine aggregate extraction operations for Tarmac in East English Channel Area 474 off the coast of Eastbourne (highlighted in Figure 10.17), with typical water depths around 35 m (estimated from charts). The survey vessel used was the MV George D. The City of Westminster was collecting a screened cargo and was on-station dredging for around 3 hours before the acoustic measurements started around 09:20am BST. The vessel continued dredging for a further 3 hours whilst acoustic data was collected. The City of Westminster was performing a single direction dredging operation from west to east due to its proximity to the shipping lane to the south. Due to the length around 4 km) and the time required for each dredging run, only full dredging runs were measured for the City of Westminster.

Marine
Aggregate Levy
Sustainability Fund
MALSF

Figure 10.16 The City of Westminster steaming by.

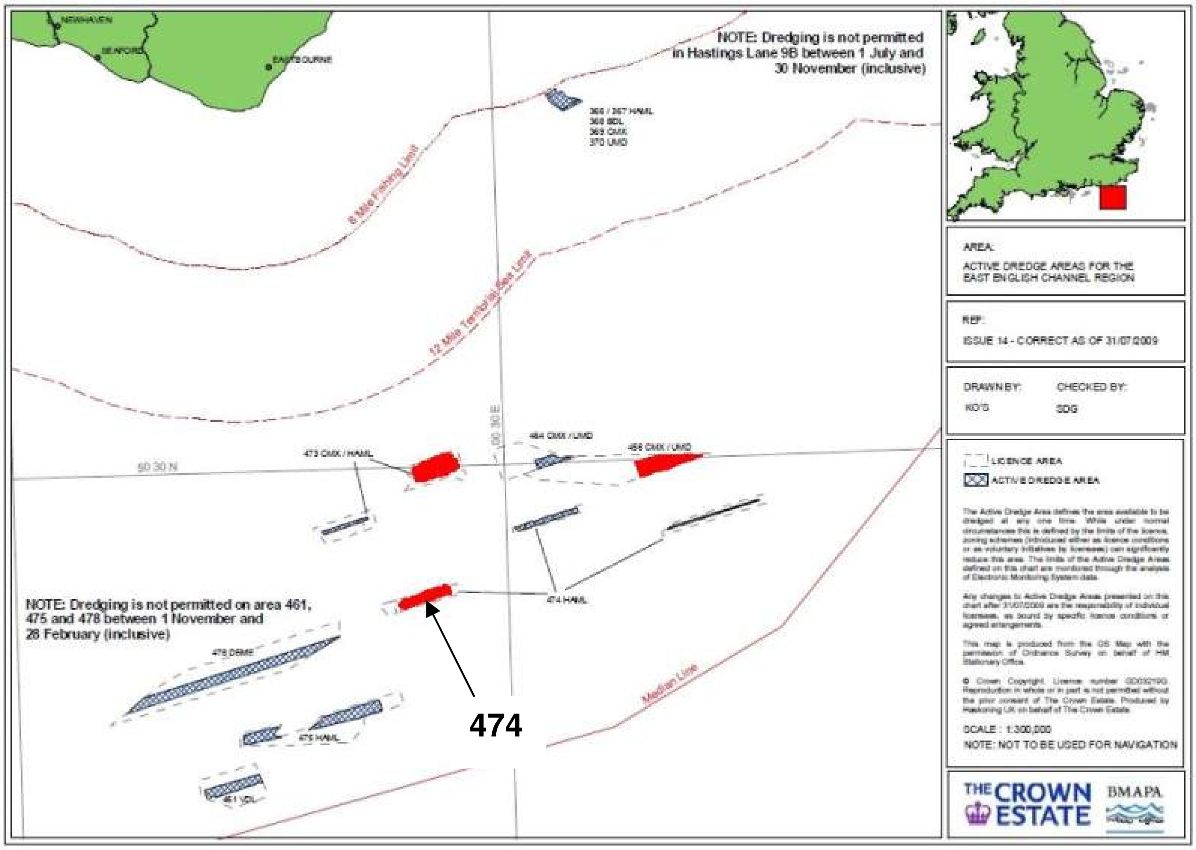

Figure 10.17 Map of east English channel licensed areas showing Area 474.

Three autonomous noise measurement buoys were anchored at nominal positions of 50 m, 200 m and 400 m from the planned dredging lane and remained in place recording for around 2.5 hours and measured a total of 2 dredging vessel passes. Each buoy had two hydrophones which were both in the lower half of the water column, with the upper of the two being close to mid-water depth. These were positioned to be on a line perpendicular to the dredging lane.

Due to rough weather and health and safety requirements, no hydrophones or other measuring equipment were deployed directly over the side of the MV George D survey vessel. Following the buoy deployment, the MV George D moved away from the measurement area and held position. Buoys 2 and 3 were damaged on deployment from the vessel in the rough weather and so the data obtained from these buoys was not useable.

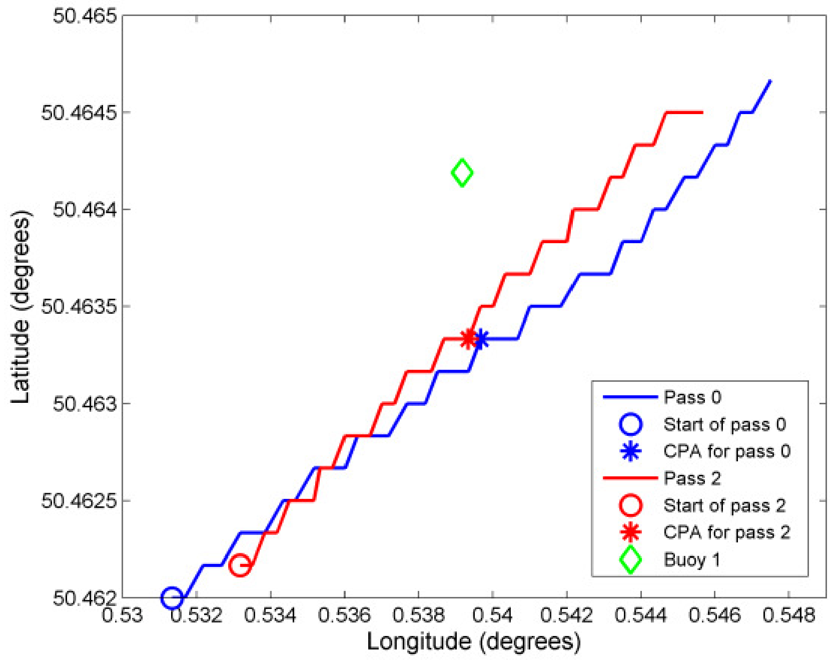

Figure 10.18 GPS details for the City of Westminster measurements.

Measurement buoy 1 and the City of Westminster positions for the passes used in the Source Level calculation (0 and 2) are indicated in Figure 10.18 along with the CPA's used. The starting point 10 minutes before CPA is also included from which it can be seen that only port side measurements were performed. For the passes shown in Figure 10.18, the actual range to the measurement buoy from the CPA was approximately 85 m. The Source Level data for the City of Westminster presented in Appendix D was obtained from 4 hydrophone measurements and included both passes for port and starboard on to the MV George D.

The noise measurements of the City of Westminster were performed towards the end of falling tide, with a predicted 1.5 m variation over the period of the measurements. The sea-state was rough, estimated to be around force 4, changing to 5 later during the measurements, with significant swell.

The City of Westminster has a 59 m long pipe which is 700 mm in diameter. The load in Area 474 was described as "sandy gravel" and the propeller depth varied from 4.3 m at the start of operations, to 7.0 m at full load. The load was screened, with a 50:50 mix of 6 mm and 8 mm screens.

10.8 CITY OF LONDON

Operator: Tarmac
Area: East English Channel Area 458
Date: 06th August 2010

Measurements were performed on 06th August 2010 of the City of London (shown in Figure 10.19) whilst it was undertaking marine aggregate extraction operations for Tarmac in East English Channel Area 458 off the coast of Eastbourne (highlighted in Figure 10.20). The survey vessel used was the MV George D. Typical water depths were around 37 m (measured from the MV George D). The City of London was collecting a screened cargo and was on-station dredging for around an hour before the acoustic measurements started around 12:30am BST. The vessel continued dredging for a further 7 hours whilst around 3 hours of acoustic data was collected. The City of London was performing a standard dredging operation approximately east to west.

Figure 10.19 The City of London on Area 458.

Three autonomous noise measurement buoys were anchored at nominal positions of 50 m, 200 m and 400 m from the planned dredging lane and remained in place recording for around 3 hours and measured a total of 8 dredging vessel passes. Each buoy had two hydrophones which were both in the lower half of the water column, with the upper of the two being close to mid-water depth. These were positioned to be on a line perpendicular to the dredging lane.

Due to rough weather and health and safety requirements, no hydrophones were deployed directly over the side of the MV George D survey vessel for measurements of the dredging vessel. Following the buoy deployment, the MV George D moved away from the measurement area and held position, although some of the dredger passes were not used due to potential contamination from the MV George D which was manoeuvring to deploy other equipment.

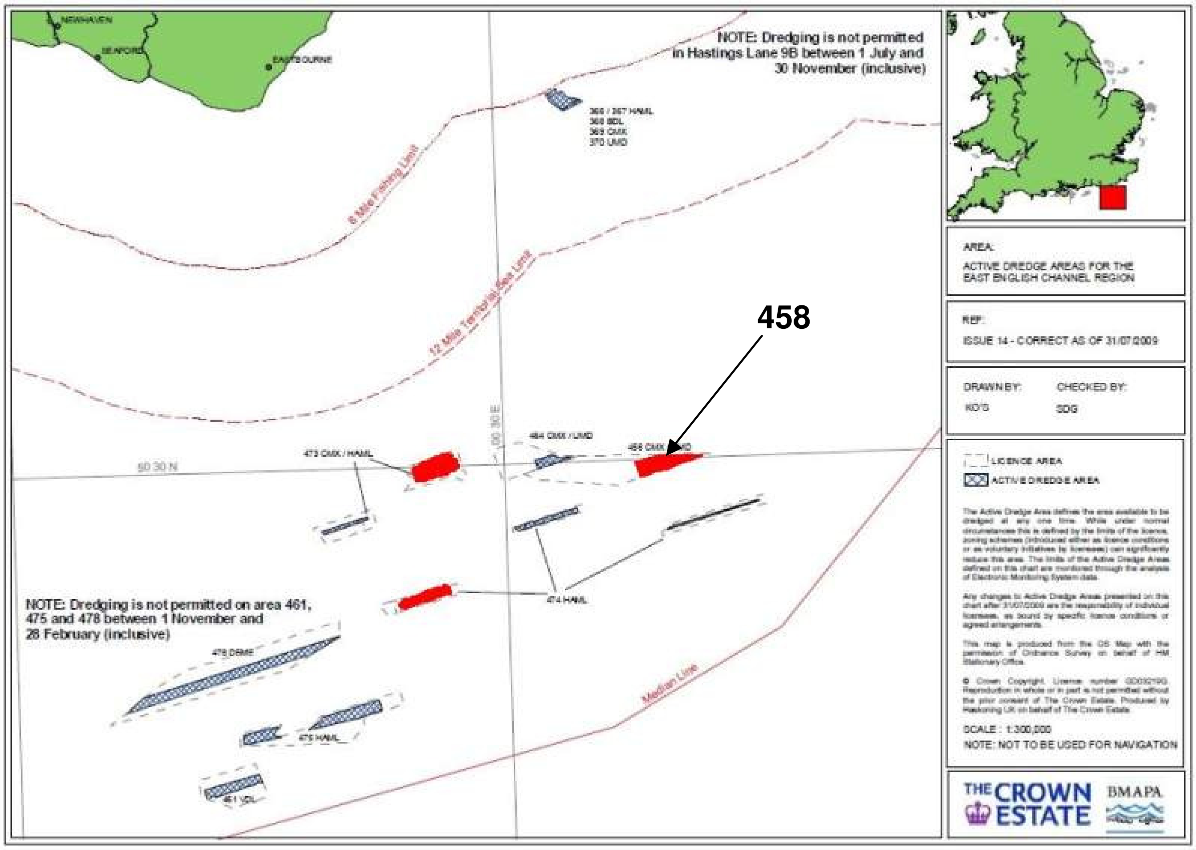

Figure 10.20 Map of east English channel licensed areas showing Area 458.

Positions for the measurement buoys and the City of London for the passes used in the Source Level calculation (0 and 2) are indicated in Figure 10.21 along with the CPA's used. The starting point 10 minutes before CPA is also included from which it can be seen that only port side measurements were performed. For the passes shown in Figure 10.21, the actual range to the measurement buoys from the CPA was

- approximately 50 m to 80 m for buoy 1,
- 205 m to 235 m for buoy 2,
- 450 m to 480 m for buoy 3.

Buoy 2 stopped recording before pass 3 and so the Source Level data for the City of London presented in Appendix D was obtained from 16 hydrophone measurements and included both passes for port and starboard on to the MV George D.

The City of London measurements were performed towards the end of falling tide, with a predicted 1 m variation over the period of the measurements. The sea-state was fairly rough, estimated to be around force 4 during the measurements, with some swell.

A CTD sonde was deployed from the MV George D survey vessel to measure the water temperature and salinity as a function of depth. The temperature was measured to be between 16.4℃ and 16.6℃ with a salinity of around 35.7 ‰ with negligible variation down to around 25 m, to give a sound speed of around 1512 m/s. Given the shallow tidal environment, very little variation in sound speed would be expected as a function of depth.

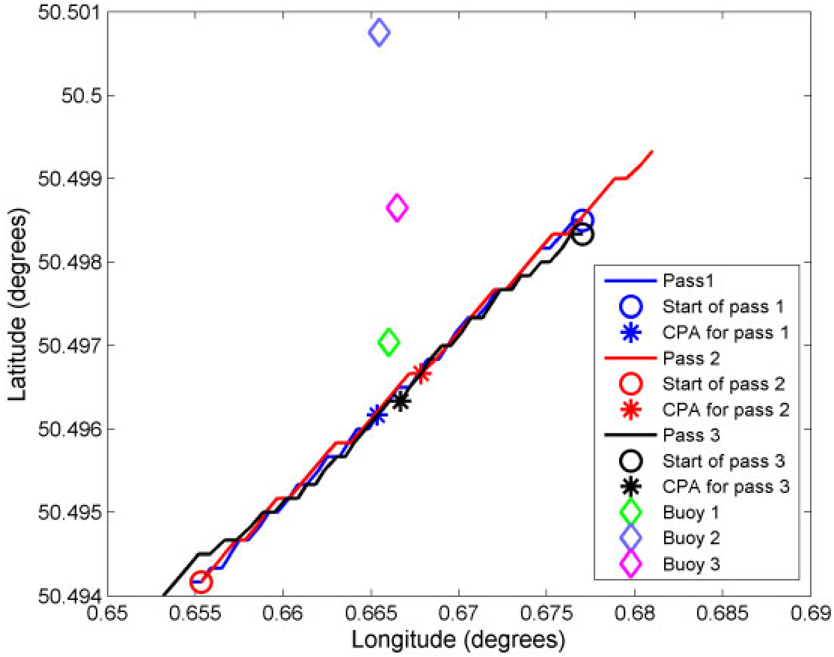

Figure 10.21 GPS details for the City of London measurements.

Ambient noise measurements were performed at around 14:00 BST once the City of London noise measurements had been completed, at a stand-off distance of around 2 nm from the City of London which was still dredging. The dredging and subsequent measurements were being undertaken in the traffic separation zone of the English Channel and so it was not expected that the measurements could be performed in isolation from any particular vessel. For the ambient noise measurements, hydrophones (low noise) were also deployed from the MV George D survey vessel, using the deployment method described in Appendix A. During the measurement, the MV George D shut down its engine and was allowed to drift. However, for operational reasons, the generator on board the MV George D had to remain switched on. Also, the measurements were performed in the vicinity of submarine cables marked on the shipping charts. The ambient noise measurements were performed around low tide. The City of London noise measurements were performed whilst the water was getting lower with a change in height of around 1 m during the period of the measurements. The sea-state was fairly rough, estimated to be around force 4.

The City of London has a 59 m long pipe which is 700 mm in diameter. The load in Area 474 was described as “sandy gravel” and the propeller depth varied from 4.3 m at the start of operations, to 7.0 m at full load. The load was screened, with a screen of 6 mm, 8 mm, 10 mm and 12 mm.

11 APPENDIX C: IMAGE SOURCE METHOD FOR PROPAGATION LOSS IN SHALLOW WATER

11.1 IMAGE SOURCE PROPAGATION LOSS MODEL

The sound field of the point source with a pressure of unit amplitude in a shallow water channel with a flat seabed and constant sound speed can be modelled as the sum of a series image sources shown in Figure 11.1. The sound pressure is given as

$$P = \frac{e^{jkr_1}}{r_1} + R_s \frac{e^{jkr_2}}{r_2} + \sum_{n=1}^{\infty}\left(R_s^{n-1} R_b^n \frac{e^{jkr_{1n}}}{r_{1n}} + R_s^n R_b^n \frac{e^{jkr_{2n}}}{r_{2n}} + R_s^n R_b^n \frac{e^{jkr_{3n}}}{r_{3n}} + R_s^{n+1} R_b^n \frac{e^{jkr_{4n}}}{r_{4n}} \right) \tag{11.1}$$

where

$$r_1 = \sqrt{R^2 + (h-d)^2},\ r_2 = \sqrt{R^2 + (h+d)^2},$$
$$r_{1n} = \sqrt{R^2 + (2nH - h - d)^2},\ r_{2n} = \sqrt{R^2 + (2nH + h - d)^2},$$
$$r_{3n} = \sqrt{R^2 + (2nH - h + d)^2},\ r_{4n} = \sqrt{R^2 + (2nH + h + d)^2}$$

H : water depth
d : source depth
h : receiver depth
R : horizontal range betwen source and receiver
$k = 2\pi f / c$,
f : frequency,
c : sound speed in water
R_s : surface reflection coeffcient
R_b : bottom reflection coeffcient

This model has been implemented to predict Propagation Loss in shallow water channels in a MATLAB programme (named “ImTL” for the purposes identification in this report). The sea bottom is assumed to be elastic with compressional speed, c_b, shear speed, c_s and density, ρ_b. The reflection from such a bottom is described by Brekhovskikh and Lysanov (2003). The surface reflection coefficient is obtained with the higher value of two surface reflection/scattering models; a simplified Beckman-Spizzichino model [Coates, 1988] for an incoherent surface scattering and, a Gaussian coherent reflection coefficient [Medwin and Clay, 1988] using wind speed [Ainslie et al, 1998]. Sound attenuation as a function of frequency is included in the model [Francois and Garrison, 1982a, Francois and Garrison, 1982b].

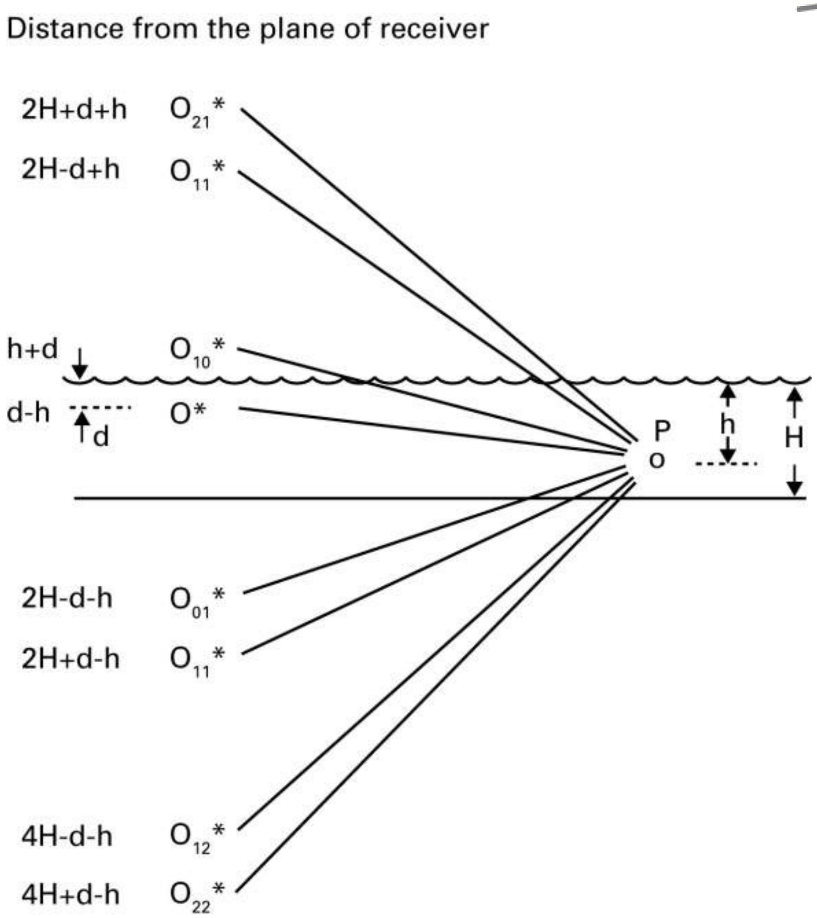

Figure 11.1 Image sources to a receiver in a shallow water channel.

11.2 MODEL COMPARISONS

The source-image model was compared with a number of well-developed models. These standard models were available in the Acoustics Toolbox available from the Ocean Acoustic Library (www.oalib.hlsresearch.com), compiled versions of which are also available as part of the AcTuP suite of software available from Curtin University, accessed by a front end environment developed within MATLAB [Maggi and Duncan 2010].

The objective is to benchmark the chosen model with other standard models which are based on different physical principles, and so should have few common sources of error. The models used for benchmarking were:

<u>BELLHOP</u>
Bellhop is a beam-tracing program that can include range dependent bathymetry. Beam tracing is similar in principle to ray tracing but traces the paths of finite width beams rather than infinitesimal width rays. This reduces problems caused by ray theory artefacts such as caustics and shadow zones. Bellhop can use beams with a Gaussian intensity profile, or geometric beams which produce the same result as a standard ray trace. Bellhop is inherently a high frequency code, however its useful frequency range extends lower than standard ray trace programs.

RAM

RAM (Range-dependent Acoustic Modelling) is a parabolic equation (PE) code that uses a split-step Padé algorithm to achieve high efficiency and the ability to model propagation at large angles from the horizontal (the usual limitation of PE codes). There is a trade-off between the angular range and the speed of computation that is governed by the number of terms the user specifies for the Padé approximation – the more terms, the wider the angle, but the slower the code runs. RAM is capable of modelling low frequency propagation in fully range dependent environments (i.e. range dependent bathymetry and sound speed).

Two modified versions of Mike Collins' RAM have been integrated into the AcTUP framework.

RAMGeo is a CMST version based on Mike Collins' RAMGeo version 1.5. It has been modified to output complex Propagation Loss data as well as the standard magnitude only files.

RAMSGeo is a CMST version based on Mike Collins' RAMS version 0.5 and the RAMGeo version discussed in the previous section. Mike Collins' elastic substrate version of RAM has been modified so that it uses the same (bathymetry datum) substrate profile specification model as RAMGeo.

Kraken

Kraken finds the normal modes for the model propagation environment using real arithmetic and estimates the attenuation by a perturbation technique. This method works well for layered fluid seabeds and can handle an elastic lower halfspace (i.e. a halfspace with a significant shear speed). It can't cope with elastic intermediate layers. The normal modes only account for energy that is trapped in the waveguide and therefore this method is inaccurate at short range where the effect of untrapped energy may be significant.

KrakenC

KrakenC finds the normal modes in the complex wavenumber plane, which allows it to deal with elastic seabed layers, and to include the effects of leaky modes, which account for some of the untrapped energy. This makes it more accurate than Kraken at short range. However, finding modes in the complex plane is much more difficult than finding them on the real axis which makes KrakenC prone to missing some of the modes, which can lead to inaccurate results.

Scooter

Scooter calculates the depth-dependent Green's function for the model environment. The resultant Green's function results are integrated to determine the Propagation Loss by using an FFT. This is the so-called "fast field technique". This method of calculating Propagation Loss accounts for all the acoustic energy, whether trapped or not, and does not rely on the less reliable process of finding normal modes. It can also cope quite happily with layered elastic seabeds, and even model boundary interface waves. It is therefore both more accurate and more reliable than the normal mode method and is the preferred technique for low frequency, short-range, range-independent problems. It is, however, much more computationally intensive than normal modes for long-range problems, and the computational load increases rapidly with increasing frequency.

OASES

OASES is a general purpose computer code for modelling seismo-acoustic propagation in horizontally stratified waveguides using a wavenumber integration method. It uses the Direct Global Matrix solution (a finite element approach) to find the depth dependent Green's function for any source and receiver configuration at a given frequency and integrates the function over a specified wavenumber spectrum range to provide transmission loss. Although OASES is very similar to Scooter, there is a difference in the implementation of the algorithm. OASES uses numerical integration in wavenumber domain to produce the Propagation Loss, while Scooter uses an FFT to obtain Propagation Loss.

These models are used for comparisons with ImTL. All models have been used for the low frequency range (below 500 Hz). Two of the models have been used for comparison at higher kilohertz frequencies: BELLHOP and RAM.

Range average is applied to the models to smooth out rapid variation of amplitude with range and provide loss appropriate for third-octave bands. The effect of range averaging is equivalent to frequency averaging [Harrison and Harrison, 1995]. This is very useful for the noise signals with very wide bandwidth where details of the intermediate frequency response are not required.

11.2.1 Results of comparisons

Propagation Loss calculations using the ImTL are compared against the standard models for the channel where Sand Harrier did its dredging operations. *In-situ* measurement showed a constant sound speed. It is assumed the bathymetry was flat. The parameters for the models are as follows:

Water depth: 27 m
Source depth: 4 m
Receiver depth: 5 m
Constant sound speed: 1503 m/s
Water density: 1025 kg/m^3

The seabed was gravelly sand its properties are derived from Hamilton [Hamilton 1980] and Jensen [Jensen 1994].

Seabed density: 2030 kg/m^3
Speed of longitudinal wave: 1805 m/s
Speed of shear wave: 180 m/s
Absorption of longitudinal wave: 0.85 dB/λ
Absorption of shear wave: 1.5 dB/λ

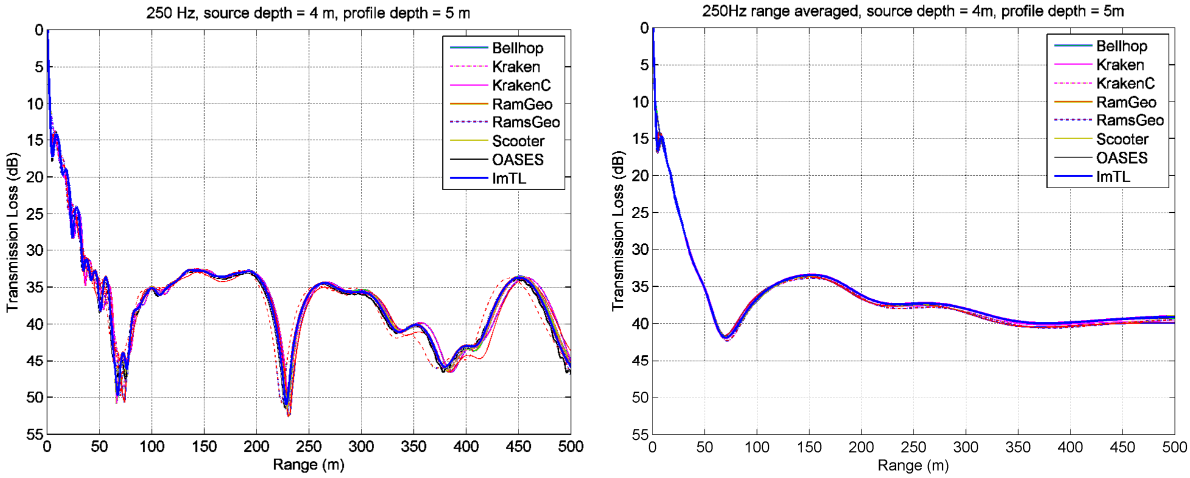

Figure 11.2 Comparison of the Propagation Loss model used (ImTL) with other standard models at 250 Hz showing unaveraged data (left) and range averaged data (right).

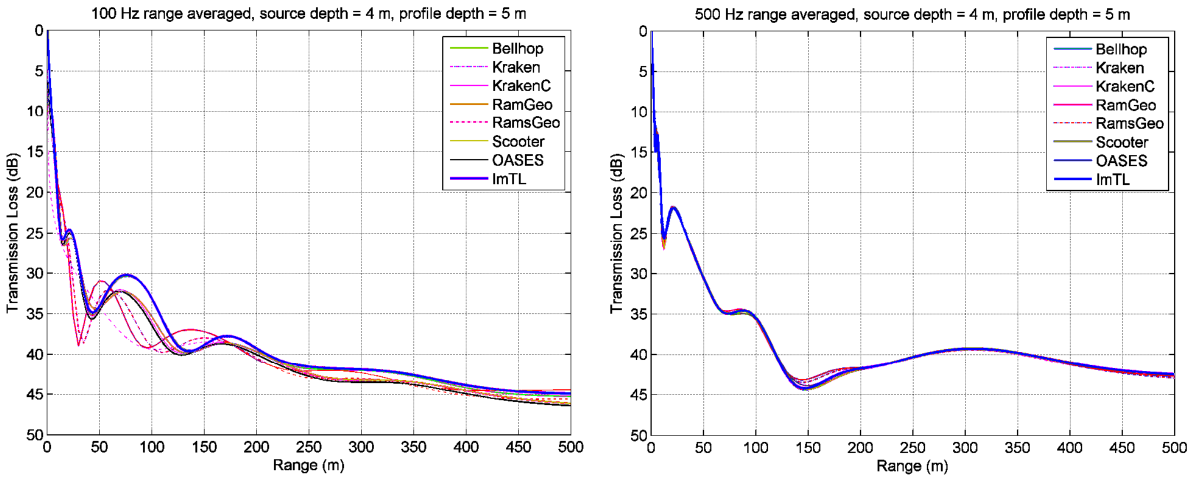

Figure 11.3 Comparison of the Propagation Loss model used (ImTL) with other standard models at 100 Hz (left) and 500 Hz (right) showing range-averaged data.

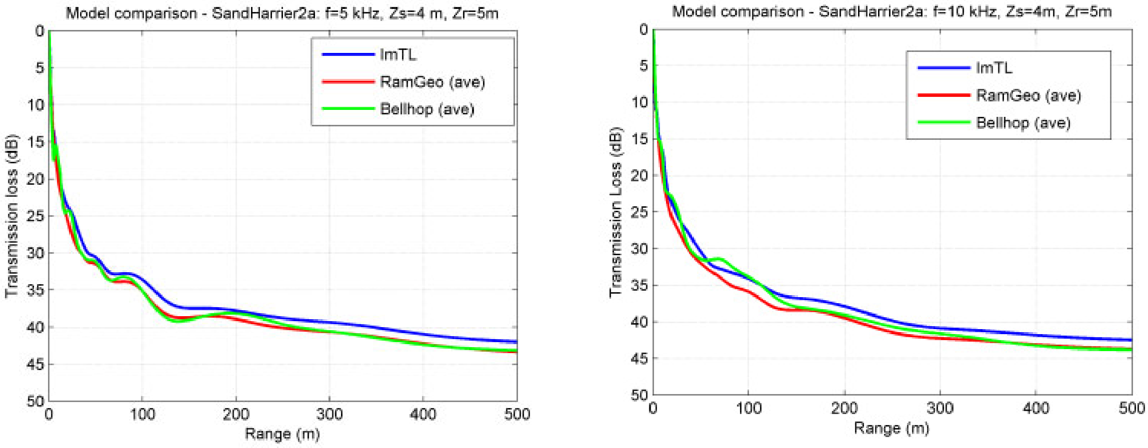

Figure 11.4 Comparison of the Propagation Loss model used (ImTL) with other standard models at 5 kHz (left) and 10 kHz (right) showing range-averaged data.

Figures 11.2 to 11.4 show the loss predicted with the chosen models as a function of range for the given source and receiver depths at frequencies of 100 Hz, 250 Hz, 500 Hz, 5 kHz and 10 kHz respectively. The frequency range is quite large for bench mark comparisons. The overall agreement is good for all the models across all the frequency range, excellent for frequencies at 250 and 500 Hz.

11.3 COMPARISON WITH MEASURED PROPAGATION LOSS

The modelled Propagation Loss was also compared with the loss measured by hydrophones at different ranges. In fact, this is not straightforward since we cannot just place the absolute Received Levels from the hydrophones on plots of the predicted Received Levels if the prediction is based on the Source Level derived using the very Propagation Loss which is under scrutiny. Instead, we can only look at the relative levels – in other words we can only compare the change in loss predicted by the model to the change observed in relative level in the received signals. When doing this, it is necessary to normalise the absolute Received Levels before plotting, and this was done by normalising to the mean received value over the range (instead, this could be done by assuming that the data at one range is correct and normalising the other to it, but the former method shows no preference for either range being correct). Results are shown in Figure 11.5 and 11.6.

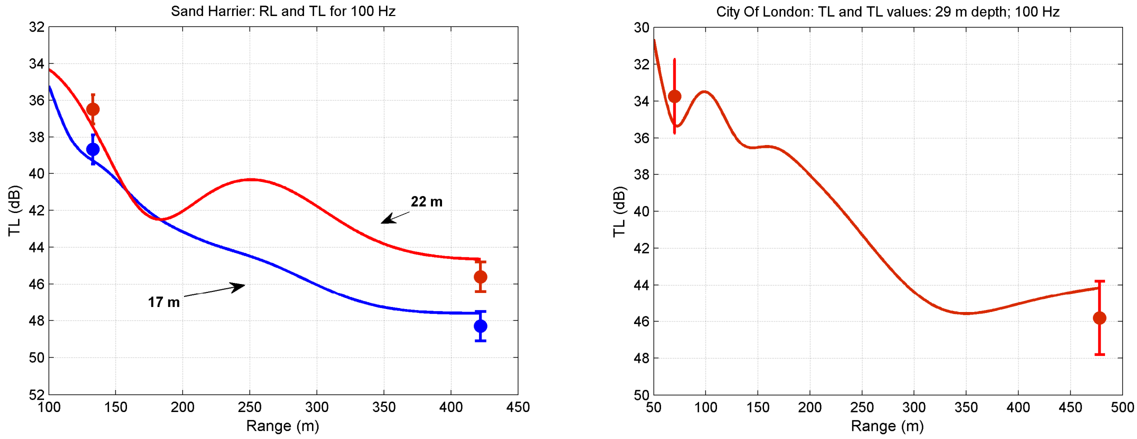

Figure 11.5 Relative Received Levels and ImTL model Propagation Loss at 100 Hz for the Sand Harrier at ranges of 133 m and 422 m and depths 17 m and 22 m (left); and for the City of London at ranges of 70 m and 478 m and depth of 29 m (right). The Received Levels were measured by recording buoys.

The measured Received Levels shown in Figure 11.5 are obtained from hydrophones attached to recording buoys. The data has been chosen so that signals from hydrophones at the same depth are being compared, with the data sequence chosen to be at the same time on each recording (to attempt to analyse the same sound signals passing through each hydrophone). The mean has been calculated of 15 two-second sequences sampled over a 30 second window. The error bars indicate the repeatability standard deviations calculated from the 15 two-second sequences. As can be seen, the model data mostly passes within the error bars showing agreement with the relative Received Levels.

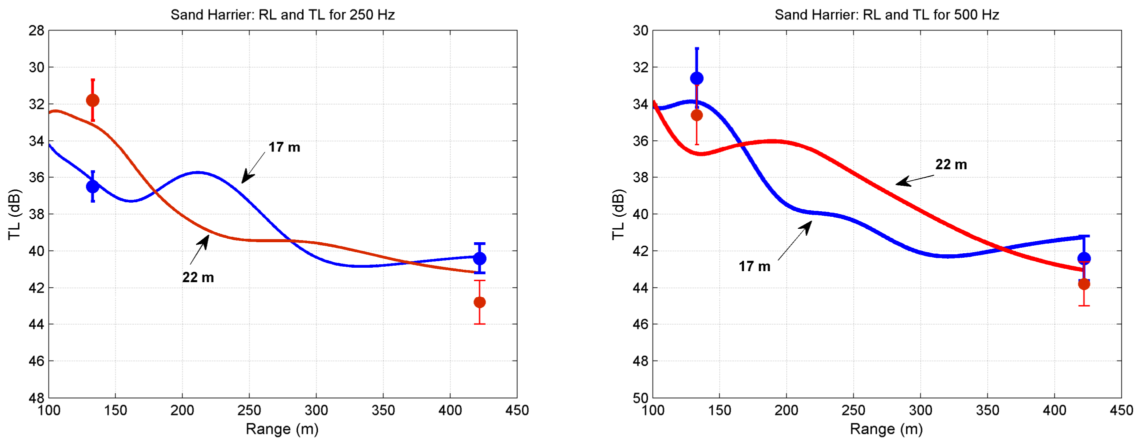

Figure 11.6 Relative Received Levels and ImTL model Propagation Loss for the Sand Harrier at ranges of 133 m and 422 m for depths 17 m and 22 m for 250 Hz (left) and 500 Hz (right). The Received Levels were measured by recording buoys.

Figure 11.6 shows similar agreement but for the Sand Harrier at 250 Hz and 500 Hz. This is confirmation that the Propagation Loss model is reasonably accurately representing the actual Propagation Loss, empirically derived from the measured data. Other data examined for other dredgers show similar agreement to within typically 2 dB, though the standard deviations show some variation (perhaps unsurprisingly, these are greater for Campaign 4 where the weather was worse).

11.4 SOURCE LEVEL VARIATION WITH HYDROPHONE

Another test of the validity of the Propagation Loss calculation is to compare the results obtained for Source Level estimated from the Received Levels measured on each of the separate hydrophones (for the same data sequence). Some data of this type has been shown already in the report (for example Figure 5.1), but the data shown there represents the mean of 15 two-second sequences across all the hydrophones, the idea being to express the variation in noise output level with time as well as across the hydrophones.

For the analysis here, we have analysed the same 30 second sequence recorded on each hydrophone to derive third-octave band data (without breaking the data into shorter sequences). These are then used to derive a number of Source Levels, one for each of the hydrophones. These have been plotted for each hydrophone, and the mean and standard deviation in decibels has also been plotted.

This kind of analysis is quite related to that of Section 11.3, above. This analysis will not be able to detect bias in the results, but if the propagation model used is not accurately reflecting the loss observed empirically in the measured data, we would expect a large variation in the calculated Source Levels. Therefore, the spread of estimated Source Levels represents another check on the agreement of the propagation model with the empirically observed Propagation Loss.

Results are shown in Figures 11.7, 11.8 and 11.9 for vessels from each of the campaign areas: the Sand Harrier, the City of London and the Arco Axe. In each case, the Source Levels calculated from each of the hydrophones is shown as well as the mean and standard deviation. The results show that in general the Source Level data are grouped together, with a mean standard deviation of 2.4 dB, 2.6 dB and 2.8 dB for the Sand Harrier, the City of London and the Arco Axe respectively. This is of the same order as the agreement seen in Section 11.3. Some other trends can be seen, for example the spread is greater below 100 Hz for the Campaign 4 vessels with values of up to 4 dB sometimes observed (including for 63 Hz for the City of London, shown here in Figure 11.8).

The results shown here confirm that the source-image model chosen reasonably represents the actual observed Propagation Loss, and that it is valid model to use for Source Level estimation.

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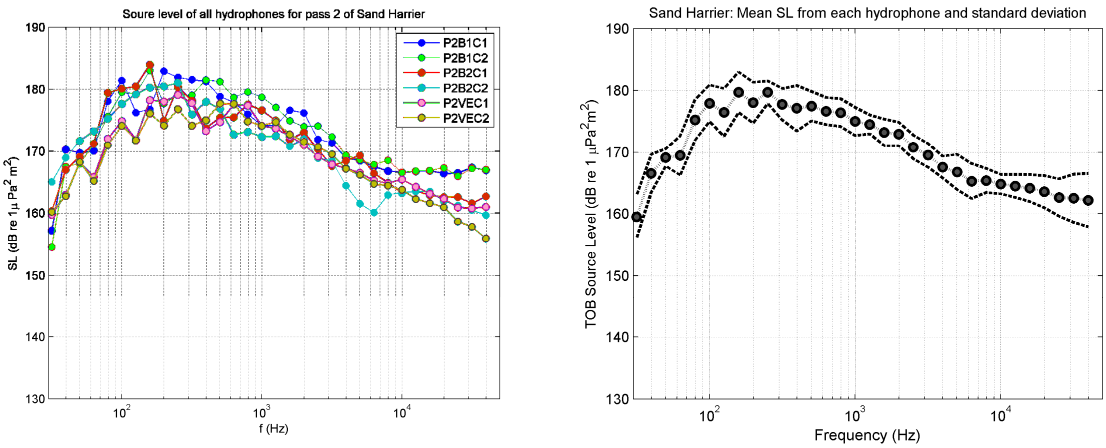

Figure 11.7 Source Level data for the Sand Harrier estimated from each of six hydrophones at different ranges and depths (left) and the mean and standard deviation (right).

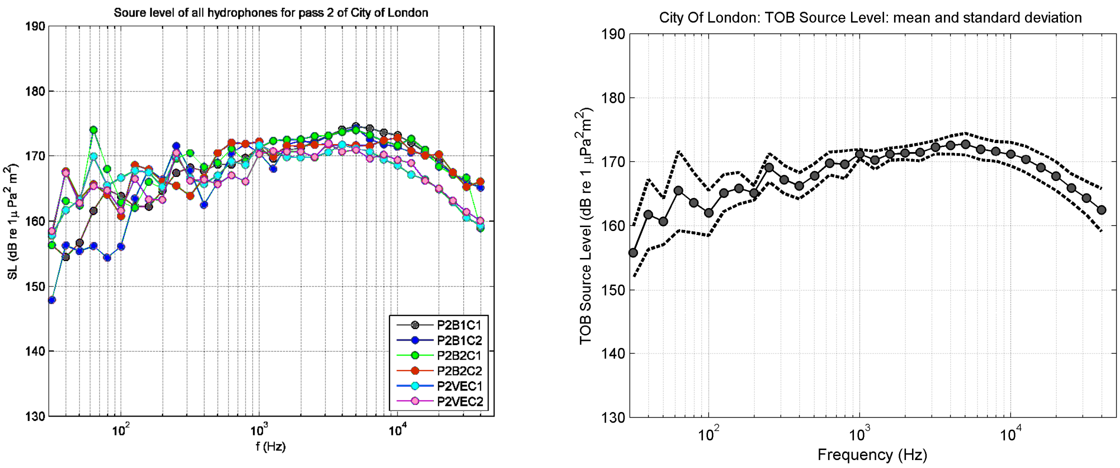

Figure 11.8 Source Level data for the City of London estimated from each of six hydrophones at different ranges and depths (left) and the mean and standard deviation (right).

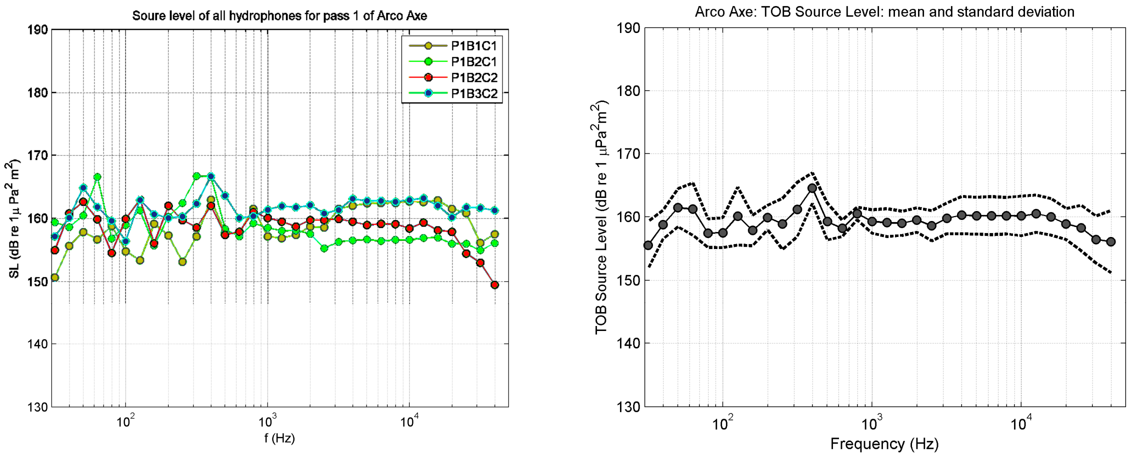

Figure 11.9 Source Level data for the Arco Axe estimated from each of four hydrophones at different ranges and depths (left) and the mean and standard deviation (right).

11.5 DIPOLE OR AFFECTED SOURCE LEVEL

The measurements and predicted Propagation Loss so far described are all based on a monopole source. It is a common practice to report noise measurement with dipole result. The conversion between a dipole and monopole Source Level is given as [Ainslie 2010]

$$SL_{mon} = SL_{dip} - 10\log\left[\frac{1}{2} + \frac{1}{4\,k^2 d^2 \sin^2\theta}\right] \qquad (11.2)$$

Where *k* is the wave number, *d* the depth of the source and *θ* is the depression angle relative to the surface. ANSI S12.64 specifies that the 'affected' (or 'dipole') Source Level shall be reported as the power average of the results of measurements with hydrophones at θ =15, 30 and 45°. Figure C5 shows the arrangement given by the standard.

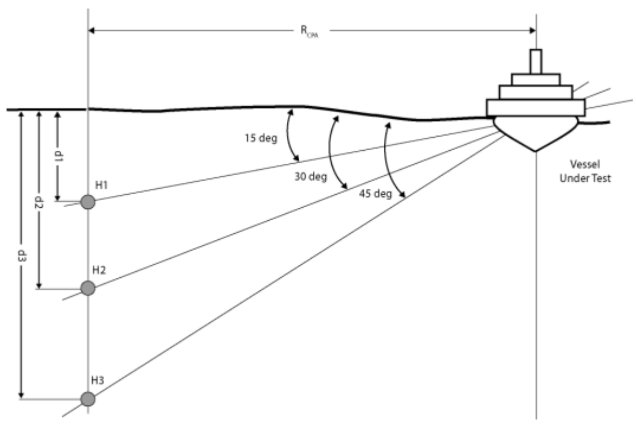

Figure 11.10 Diagram of the geometrical arrangement of the measurements required for ANSI S12.64 showing the three look-down angles over which the averaging is done.

Figure 11.11 shows the monopole Source Level of Sand Harrier for pass 2 with 6 source depths from 1 m to 6 m. It is noticed that the Source Level varies more than

14 dB at the lowest frequency with different source depth. Applying the dipole correction in Eq. (11.2) to the results, the spread of the Source Levels at the low frequency end is significantly reduced. Therefore the dipole Source Level is not very sensitive to source depth at very low frequency. However, the Source Level is still quite sensitive to the source depth in the mid frequency band from 200 Hz to just above 1000 Hz with a maximum variation up to 5 dB for this case. The sensitivity changes with source depth, highest at shallowest and lower as the source is taken deeper. This means an empty dredger at the start of its dredging operation may sound louder than a fully loaded one at the end of its dredging operation over this frequency band. This effect is even more significant when no dipole correction is applied.

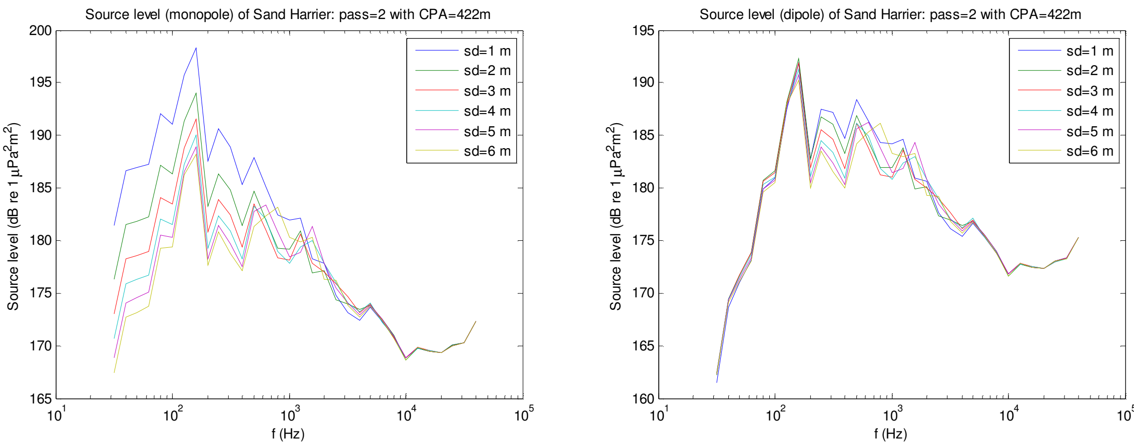

Figure 11.11 Source level of Sand Harrier pass 2 as a function of different source depth for monopole (left) and dipole (right).

11.6 UNCERTAINTY ANALYSIS

The propagation or Propagation Loss at a specified frequency is related through a mathematical model to a number of input quantities, including the depth of the source, the range and depth of the hydrophone, properties of the water (depth, density, sound speed in water, salinity and pH), properties of the sediment (density and sound speed in the sediment), and wind speed. A Monte Carlo method [GUM 2008] was used to investigate the sensitivity of values of Propagation Loss to perturbations in the values of the input quantities, and to evaluate the standard uncertainty associated with estimates of Propagation Loss. Each input quantity in the model was characterized by a rectangular probability distribution defined by a nominal value (its expectation or mean value) and semi-width. For each Monte Carlo trial, a value for each input quantity was obtained as a random draw from the distribution characterizing the quantity, and the corresponding values of Propagation Loss obtained by evaluating the model for those values of the input quantities. For each frequency, the average of the values of Propagation Loss obtained from 1000 trials provides an estimate of Propagation Loss, and the standard deviation of the values the standard uncertainty associated with the estimate.

Table 11.1 Model input values and associated uncertainties for the three runs. Note that all uncertainties on input quantities were modelled as uniform distributions (semi-ranges stated).

Model input parameter	Run A	Run B	Run C
Hydrophone range (m)	400 ± 10	100 ± 10	50 ± 10
Hydrophone depth (m)	20 ± 3	8 ± 2	25 ± 3
Source depth (m)	5 ± 2	5 ± 2	5 ± 2
Water depth (m)	30 ± 3	30 ± 3	30 ± 3
Water density (kg m^{-3})	1025 ± 1	1025 ± 1	1025 ± 1
Sediment density (kg m^{-3})	2030 ± 50	2030 ± 50	2030 ± 50
Water sound speed (m s^{-1})	1503 ± 3	1503 ± 3	1503 ± 3
Sediment sound speed (m s^{-1})	1805 ± 50	1805 ± 50	1805 ± 50
Salinity (PSU)	34 ± 2	34 ± 2	34 ± 2
pH	8 ± 1	8 ± 1	8 ± 1
Wind speed (knots)	2 ± 1	2 ± 1	2 ± 1

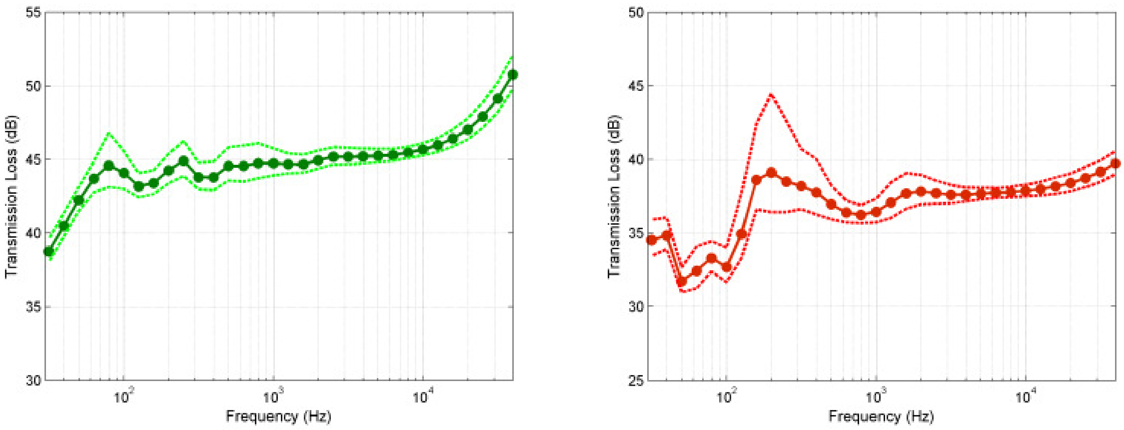

Figure 11.12 The Propagation Loss with uncertainty (standard deviation) for Run A (400 m range) and Run B (100 m range).

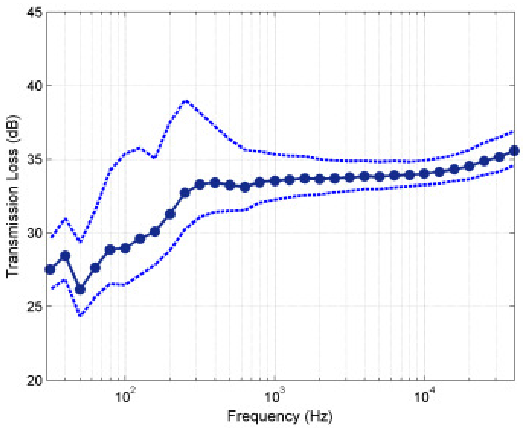

Figure 11.13 The Propagation Loss with uncertainty (standard deviation) for Run C (50 m range).

12 APPENDIX D: DETAILED RESULTS

Section 12.1 to 12.3 of this appendix summarises the estimated dipole Source Level values or the “affected” Source Level values [ANSI S12.64, 2009] which were derived from the monopole Source Levels as described in section 3.4.3 of this report. The use of “affected” Source Level has been used to allow for direct comparison with surface vessel Source Level values stated in the literature obtained using beam aspect measurements combined with simple spreading loss approximations. When using Source Level data for Environmental Impact Assessments, noise mapping or for Received Level predictions with range it will be necessary to use monopole Source Level values. Section 12.4 of this appendix presents the monopole Source Level values for use in such prediction exercises. These were derived from beam aspect measurements and the ImTL Propagation Loss model described in Section 3.4.1 before the dipole correction described in Section 3.4.3.

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12.1 THIRD-OCTAVE BAND DIPOLE SOURCE LEVEL VALUES

Table 12.1 Source level of Arco Axe

f (Hz)	Mean SL (dB re 1μPa^{2}m^2)	f (Hz)	Mean SL (dB re 1μPa^{2}m^2)
31.6	155.7	1258.9	161.2
39.8	158.8	1584.9	160.9
50.1	163.1	1995.3	161.7
63.1	165.1	2511.9	160.6
79.4	158.4	3162.3	162.2
100.0	159.5	3981.1	163.2
125.9	161.2	5011.9	163.1
158.5	159.7	6309.6	162.9
199.5	162.2	7943.3	162.7
251.2	161.5	10000.0	162.5
316.2	163.9	12589.3	162.4
398.1	166.0	15848.9	161.6
501.2	161.5	19952.6	160.2
631.0	159.7	25118.9	159.9
794.3	161.7	31622.8	158.1
1000.0	161.4	39810.7	158.1

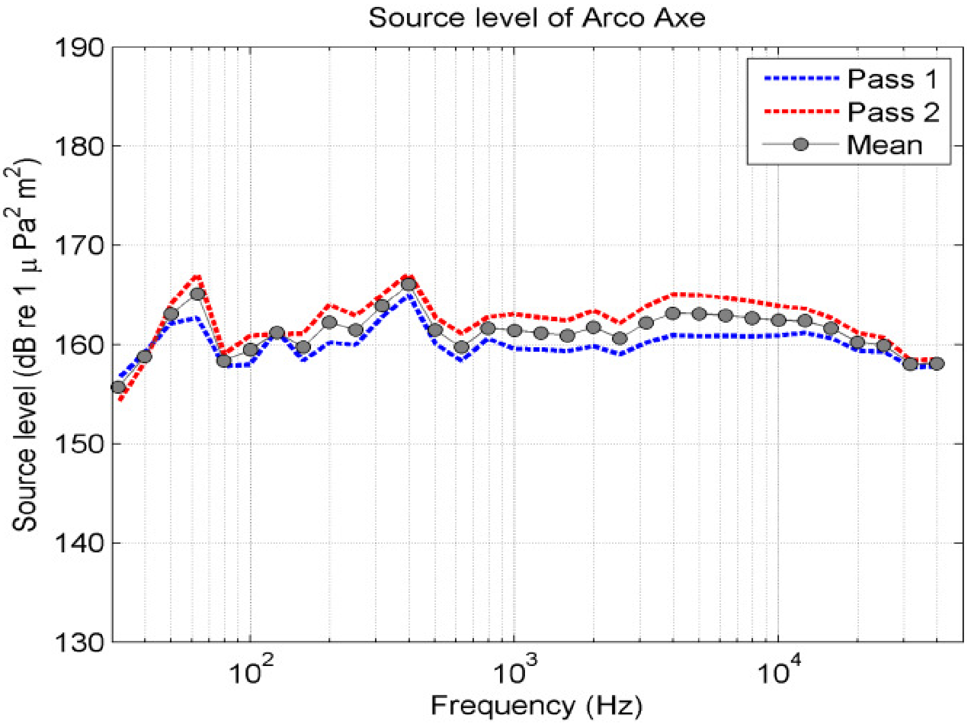

Figure 12.1 Dipole Source Level of Arco Axe.

Table 12.2 Source level of Sand Falcon (campaign 1)

f (Hz)	Mean SL (dB re 1μPa^{2}m^2)	f (Hz)	Mean SL (dB re 1μPa^{2}m^2)
31.6	170.2	1258.9	173.4
39.8	173.4	1584.9	173.0
50.1	173.9	1995.3	174.0
63.1	173.7	2511.9	173.4
79.4	180.7	3162.3	173.5
100.0	174.9	3981.1	173.2
125.9	175.4	5011.9	172.4
158.5	176.6	6309.6	171.9
199.5	177.4	7943.3	172.2
251.2	177.3	10000.0	172.1
316.2	177.9	12589.3	171.8
398.1	177.4	15848.9	170.2
501.2	177.6	19952.6	169.1
631.0	176.5	25118.9	168.8
794.3	174.6	31622.8	167.1
1000.0	173.7	39810.7	166.5

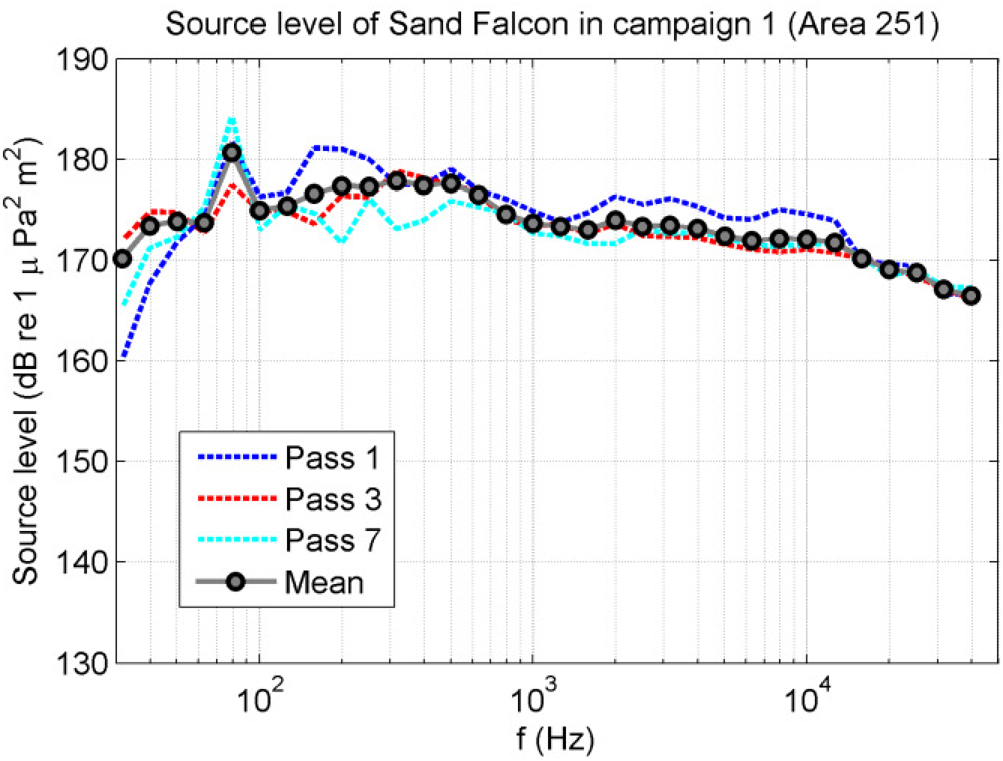

Figure 12.2 Dipole Source Level of Sand Falcon in Area 251 (campaign 1).

Table 12.3 Dipole Source Level of City of Chichester.

f (Hz)	Mean SL (dB re 1μPa^{2}m^2)	f (Hz)	Mean SL (dB re 1μPa^{2}m^2)
31.6	165.3	1258.9	168.5
39.8	156.4	1584.9	168.8
50.1	159.5	1995.3	168.9
63.1	165.0	2511.9	168.8
79.4	164.5	3162.3	169.2
100.0	168.6	3981.1	168.0
125.9	166.2	5011.9	167.0
158.5	170.1	6309.6	166.1
199.5	172.1	7943.3	165.4
251.2	172.5	10000.0	164.7
316.2	171.4	12589.3	164.0
398.1	171.2	15848.9	163.6
501.2	170.8	19952.6	162.6
631.0	171.8	25118.9	163.0
794.3	170.0	31622.8	162.9
1000.0	168.7	39810.7	163.3

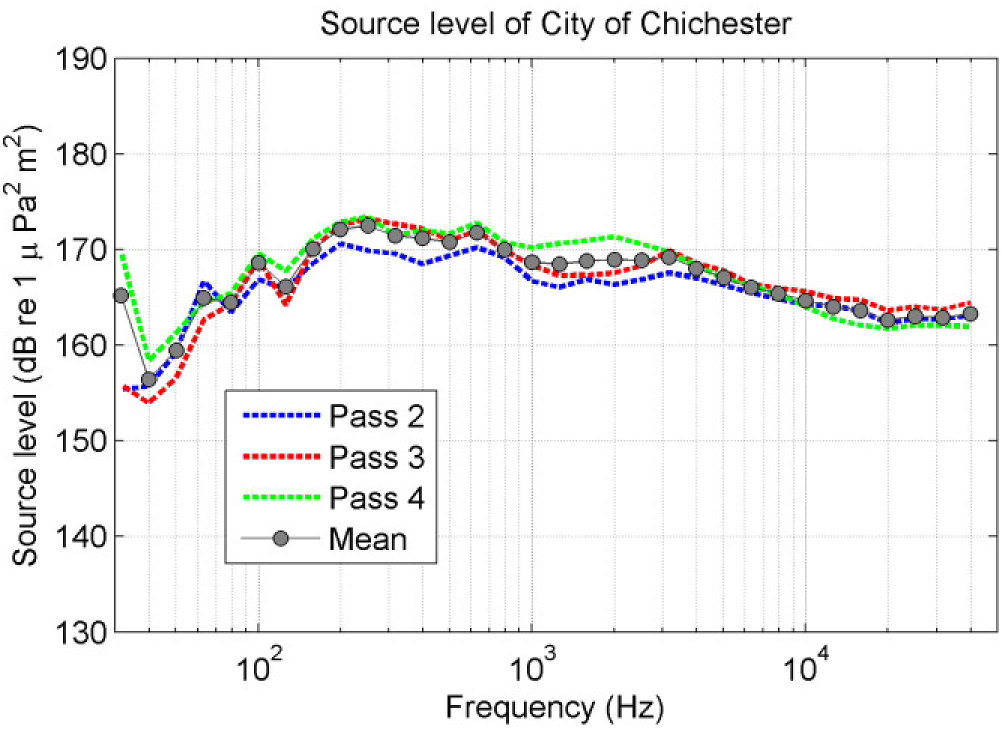

Figure 12.3 Dipole Source Level of City of Chichester.

Table 12.4 Dipole Source Level of Sand Harrier.

f (Hz)	Mean SL (dB re 1μPa^{2}m^2)	f (Hz)	Mean SL (dB re 1μPa^{2}m^2)
31.6	162.9	1258.9	175.5
39.8	167.9	1584.9	174.4
50.1	170.1	1995.3	173.3
63.1	172.9	2511.9	171.8
79.4	176.2	3162.3	170.5
100.0	178.3	3981.1	169.1
125.9	180.9	5011.9	168.2
158.5	181.4	6309.6	167.3
199.5	179.8	7943.3	166.8
251.2	180.7	10000.0	166.3
316.2	178.8	12589.3	165.7
398.1	179.0	15848.9	165.3
501.2	178.0	19952.6	164.8
631.0	177.1	25118.9	164.8
794.3	178.1	31622.8	165.1
1000.0	176.3	39810.7	165.2

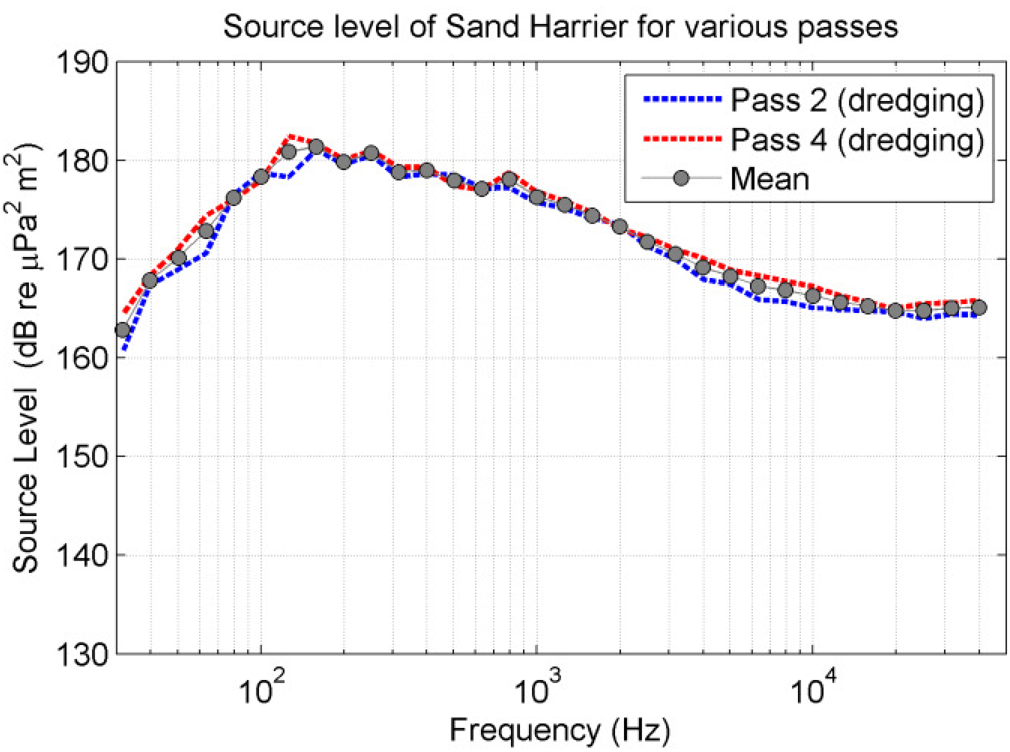

Figure 12.4 Source level of Sand Harrier.

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Table 12.5 Dipole Source Level of Sand Falcon (Area 473; campaign 4).

f (Hz)	Mean SL (dB re 1μPa^{2}m^2)	f (Hz)	Mean SL (dB re 1μPa^{2}m^2)
31.6	157.6	1258.9	176.5
39.8	163.1	1584.9	176.8
50.1	169.9	1995.3	176.9
63.1	174.2	2511.9	176.9
79.4	175.6	3162.3	177.3
100.0	175.6	3981.1	177.5
125.9	173.0	5011.9	178.0
158.5	175.2	6309.6	178.6
199.5	175.6	7943.3	178.3
251.2	176.0	10000.0	178.4
316.2	176.7	12589.3	178.0
398.1	177.4	15848.9	177.0
501.2	176.6	19952.6	175.8
631.0	174.1	25118.9	175.1
794.3	175.5	31622.8	174.0
1000.0	175.4	39810.7	174.7

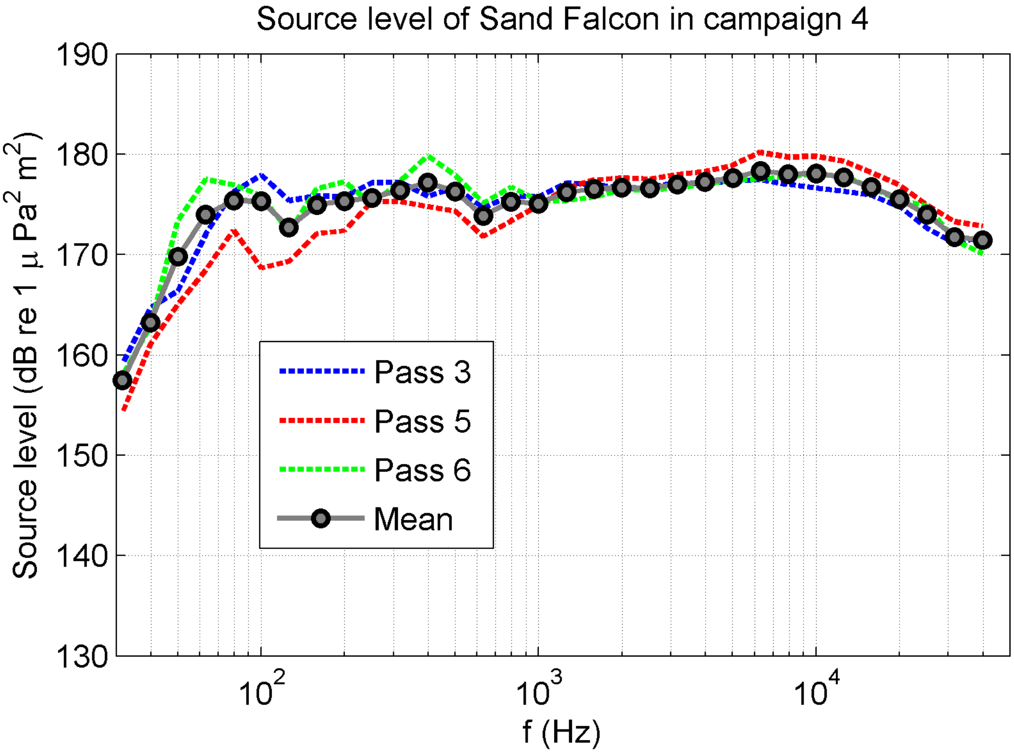

Figure 12.5 Dipole Source Level of Sand Falcon (campaign 4, Area 473).

Table 12.6 Dipole Source Level of City of Westminster.

f (Hz)	Mean SL (dB re 1μPa^{2}m^2)	f (Hz)	Mean SL (dB re 1μPa^{2}m^2)
31.6	160.0	1258.9	173.4
39.8	157.1	1584.9	173.3
50.1	160.7	1995.3	174.7
63.1	159.5	2511.9	175.8
79.4	160.5	3162.3	176.6
100.0	158.7	3981.1	177.4
125.9	162.1	5011.9	177.6
158.5	161.6	6309.6	177.7
199.5	163.4	7943.3	178.0
251.2	167.0	10000.0	178.2
316.2	168.5	12589.3	177.0
398.1	168.3	15848.9	176.2
501.2	169.9	19952.6	174.2
631.0	171.1	25118.9	173.5
794.3	171.4	31622.8	171.2
1000.0	173.1	39810.7	172.2

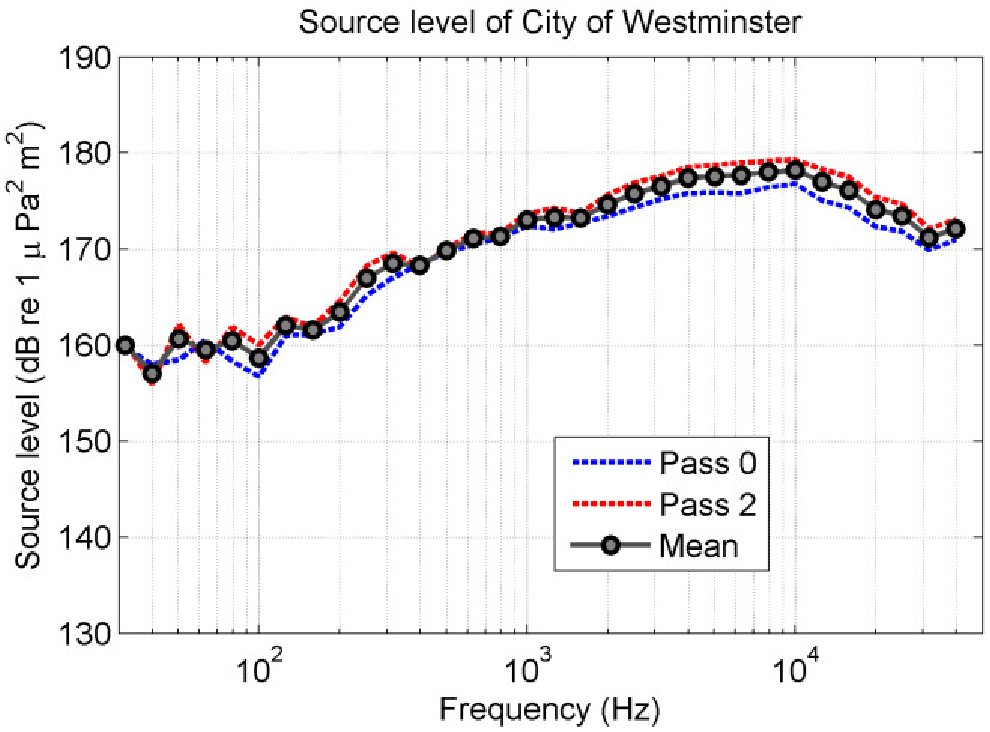

Figure 12.6 Dipole Source Level of City of Westminster.

Table 12.7 Dipole Source Level of City of London.

f (Hz)	Mean SL (dB re 1μPa^{2}m^2)	f (Hz)	Mean SL (dB re 1μPa^{2}m^2)
31.6	157.4	1258.9	170.5
39.8	161.2	1584.9	171.5
50.1	160.9	1995.3	171.9
63.1	168.0	2511.9	172.2
79.4	165.3	3162.3	172.9
100.0	163.6	3981.1	173.3
125.9	166.7	5011.9	173.6
158.5	165.9	6309.6	172.7
199.5	165.2	7943.3	172.3
251.2	168.9	10000.0	172.2
316.2	167.8	12589.3	171.5
398.1	166.0	15848.9	170.3
501.2	167.5	19952.6	168.7
631.0	169.7	25118.9	167.5
794.3	169.8	31622.8	166.4
1000.0	170.9	39810.7	164.0

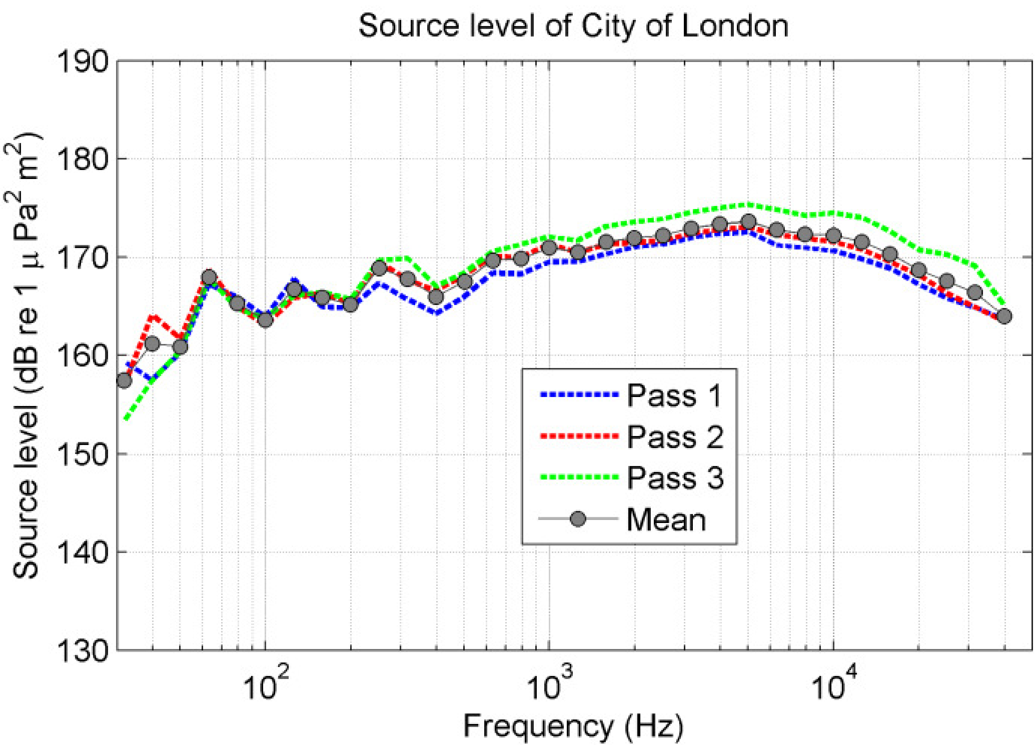

Figure 12.7 Dipole Source Level of City of London.

12.2 SOURCE LEVEL FOR SELECTED OPERATIONAL MODES

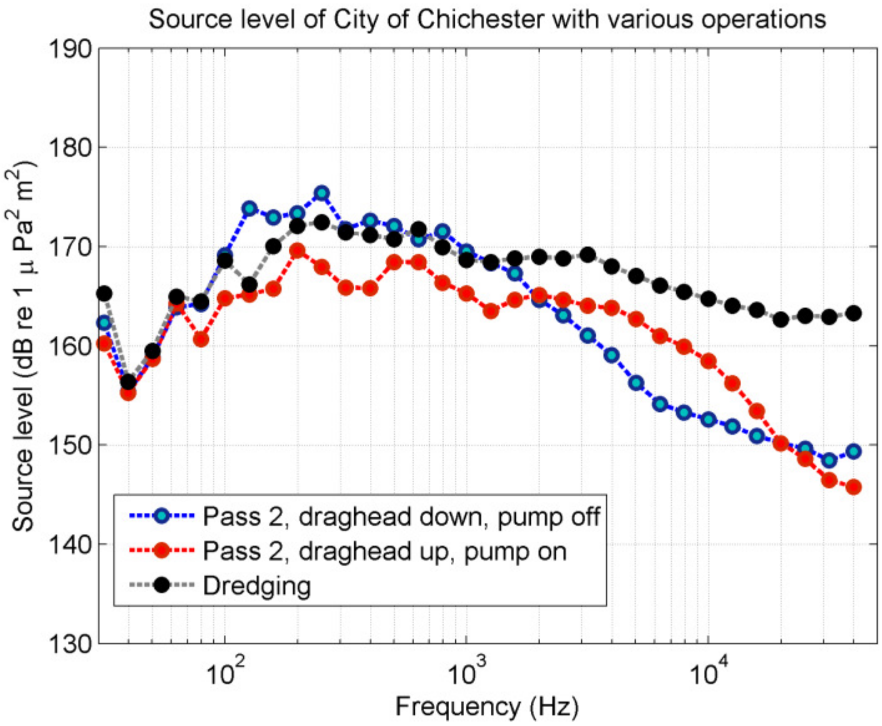

Figure 12.8 Source levels of Sand Falcon in different operational modes.

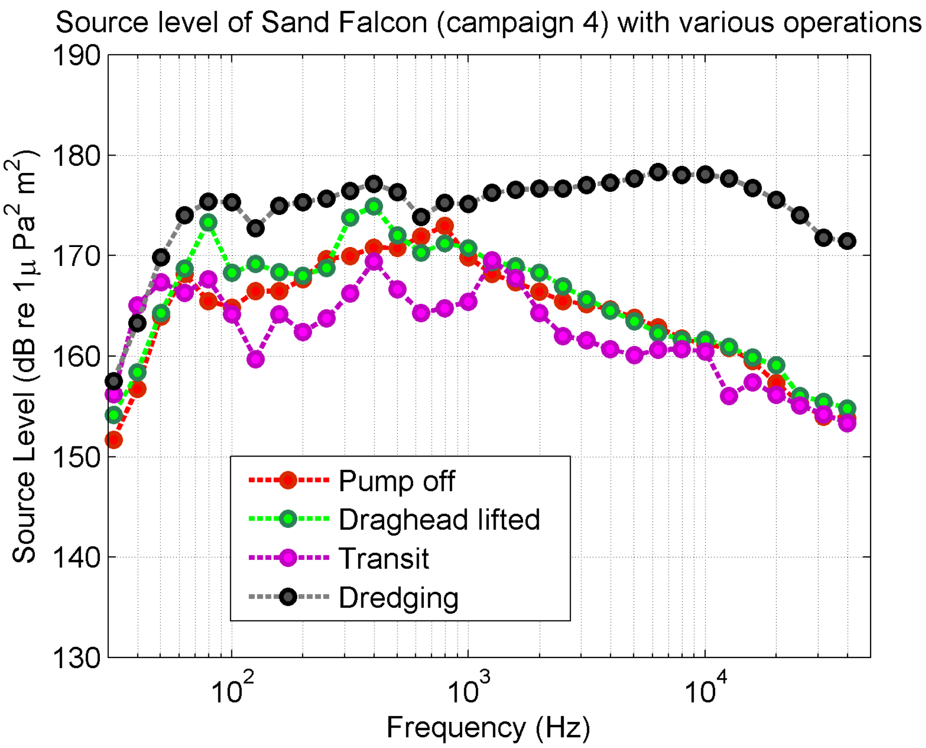

Figure 12.9 Source levels of Sand Falcon in different operational modes.

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12.3 SOURCE LEVEL UP TO 100 KHZ FOR SELECTED DREDGERS

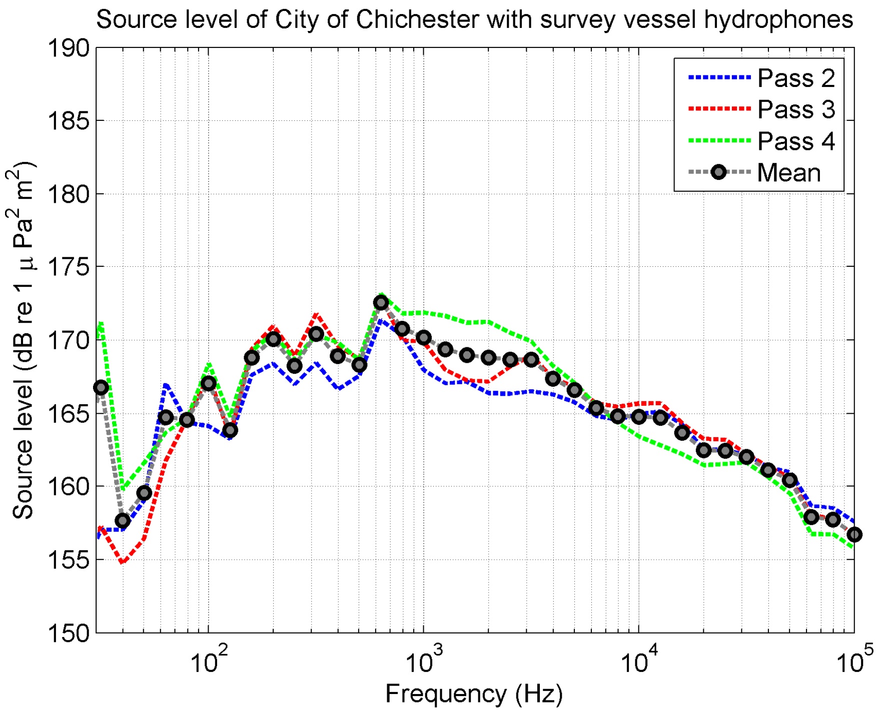

Figure 12.10 Source level of City of Chichester with higher frequency range.

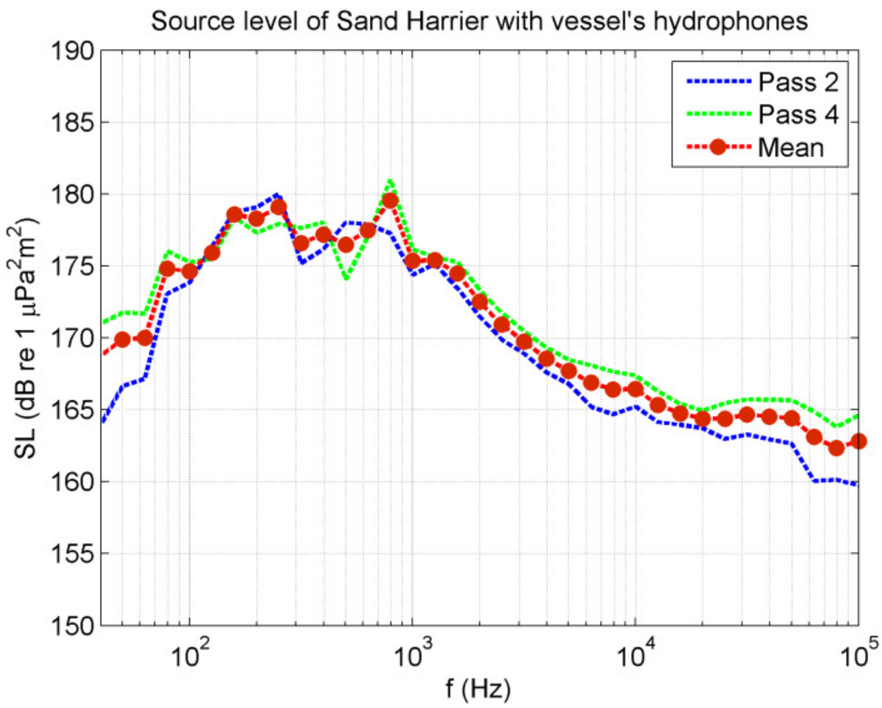

Figure 12.11 Source level of Sand Harrier with higher frequency range.

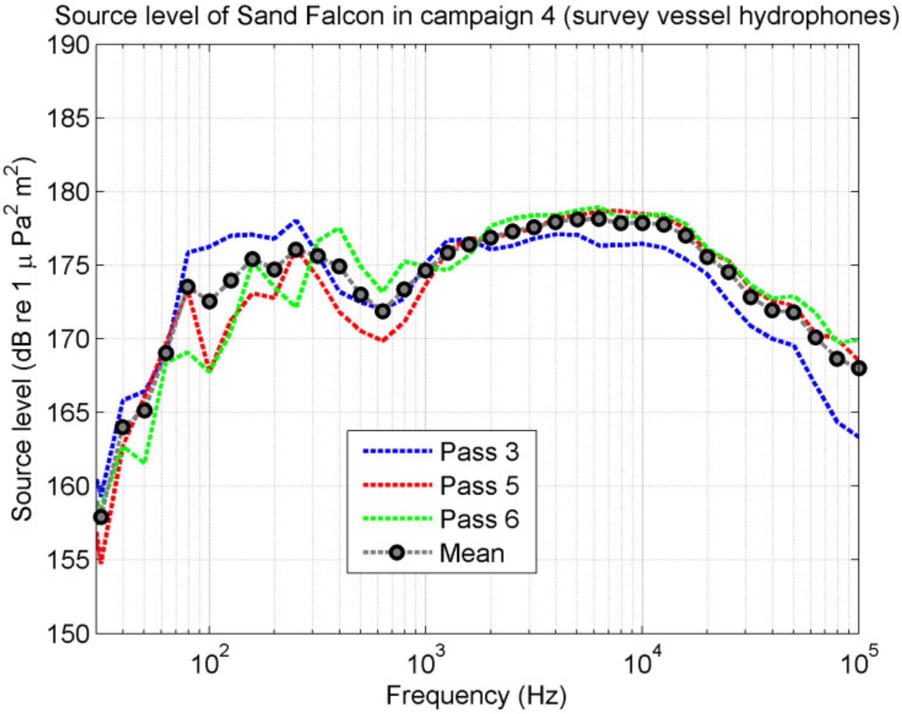

Figure 12.12 Source level of Sand Falcon with higher frequency range.

12.4 MONOPOLE SOURCE LEVEL FOR ALL THE DREDGERS

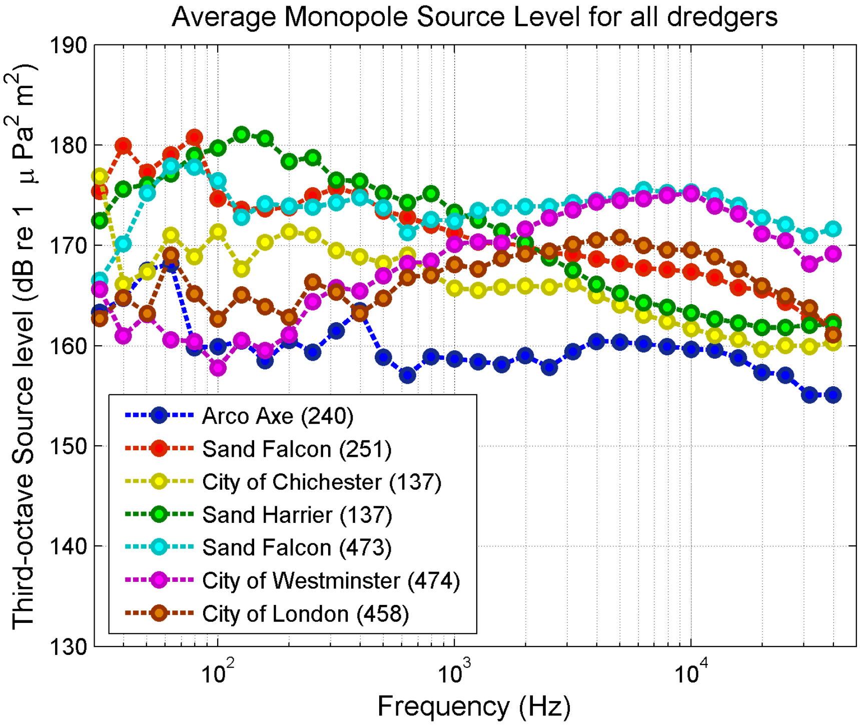

Figure 12.13 Source level (monopole) of all the dredgers

Table 12.8 Third-octave band Monopole Source Level of all dredgers (in dB re 1 $\mu Pa^2 m^2$).

f (Hz)	Arco Axe	Sand Falcon (A251; C1)	City of Chichester	Sand Harrier	City of London	City of Westminster	Sand Falcon (Area 473; C4)
31.6	163.3	175.4	176.9	172.5	162.7	165.6	166.5
39.8	164.7	179.9	166.1	175.7	164.8	161.0	170.2
50.1	167.5	177.3	167.4	176.1	163.2	163.1	175.3
63.1	168.2	179.0	171.0	177.2	169.0	160.6	177.9
79.4	159.8	180.8	168.9	179.0	165.2	160.4	177.8
100.0	159.9	174.7	171.4	179.7	162.7	157.8	176.5
125.9	160.5	173.6	167.6	181.1	165.1	160.5	172.8
158.5	158.5	173.7	170.3	180.7	163.9	159.5	174.2
199.5	160.6	173.8	171.4	178.4	162.9	161.1	173.9
251.2	159.4	175.0	171.1	178.8	166.4	164.4	173.8
316.2	161.5	175.7	169.5	176.5	165.3	165.8	174.3
398.1	163.5	175.1	168.9	176.4	163.2	165.5	174.8
501.2	158.8	173.5	168.2	175.3	164.7	167.0	173.8
631.0	157.0	172.8	169.1	174.3	166.8	168.2	171.3
794.3	158.9	172.1	167.1	175.2	167.0	168.4	172.6
1000.0	158.7	171.3	165.8	173.4	168.1	170.1	172.4
1258.9	158.4	170.3	165.5	172.5	167.6	170.4	173.5
1584.9	158.1	170.2	165.8	171.4	168.7	170.3	173.8
1995.3	159.0	169.9	166.0	170.3	169.1	171.7	173.9
2511.9	157.9	169.2	165.8	168.8	169.4	172.8	173.9
3162.3	159.4	169.1	166.2	167.5	170.1	173.6	174.3
3981.1	160.4	168.6	165.0	166.1	170.5	174.4	174.5
5011.9	160.4	168.2	164.0	165.2	170.8	174.5	174.9
6309.6	160.2	167.7	163.1	164.3	170.0	174.7	175.6
7943.3	159.9	167.6	162.4	163.8	169.6	175.0	175.3
10000.0	159.7	167.4	161.7	163.3	169.5	175.2	175.3
12589.3	159.6	166.8	161.0	162.7	168.9	174.0	175.0
15848.9	158.8	165.8	160.6	162.3	167.6	173.2	174.0
19952.6	157.4	165.6	159.6	161.8	166.0	171.1	172.8
25118.9	157.0	164.4	160.0	161.8	164.9	170.5	172.1
31622.8	155.1	162.8	159.9	162.0	163.8	168.2	171.0
39810.7	155.1	162.4	160.3	162.1	161.1	169.2	171.7

13 APPENDIX E: ANALYSIS OF VARIABILITY IN NOISE LEVELS

13.1 MEANS AND STANDARD DEVIATIONS

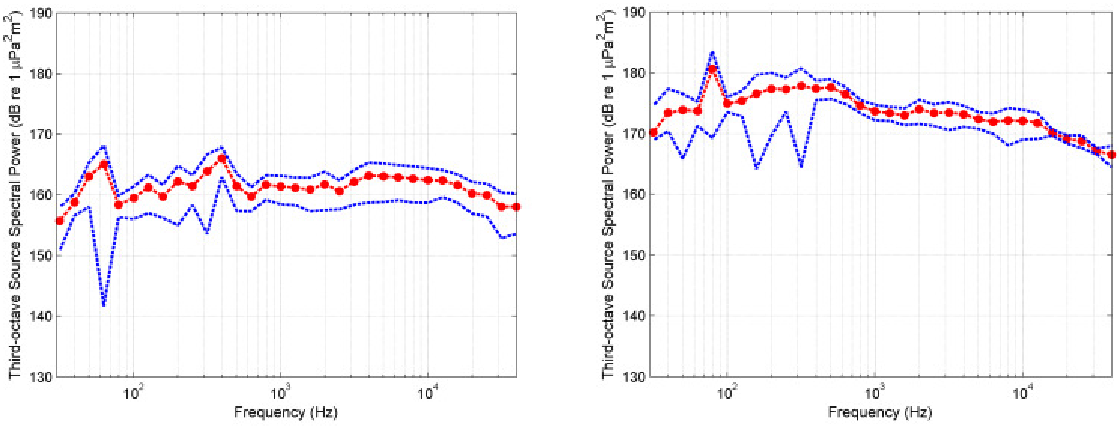

Figure 13.1 Dipole or "affected" Source Levels calculated from 15 two-second sequences showing the mean and standard deviation for the Arco Axe on Area 240 (left), and the Sand Falcon on Area 251 (right).

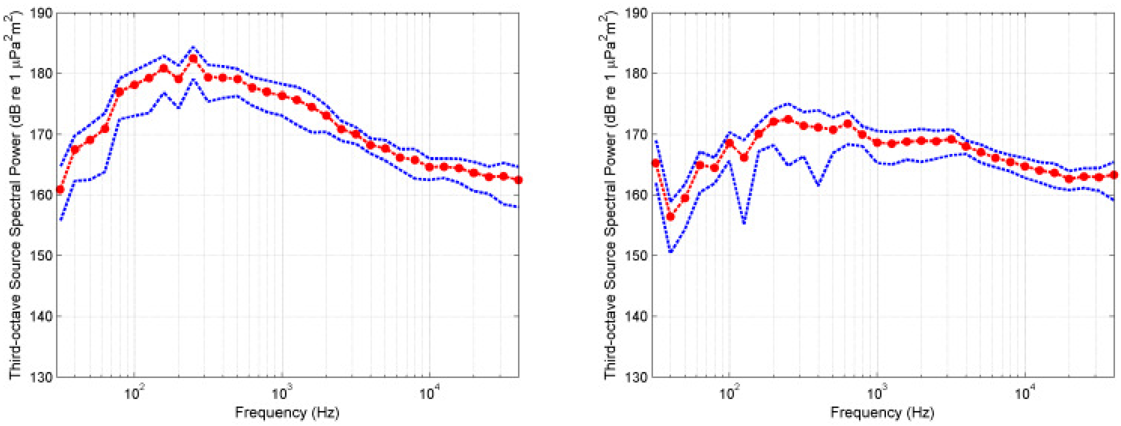

Figure 13.2 Dipole or "affected" Source Levels calculated from 15 two-second sequences showing the mean and standard deviation for the Sand Harrier on Area 137 (left), and the City of Chichester on Area 137 (right).

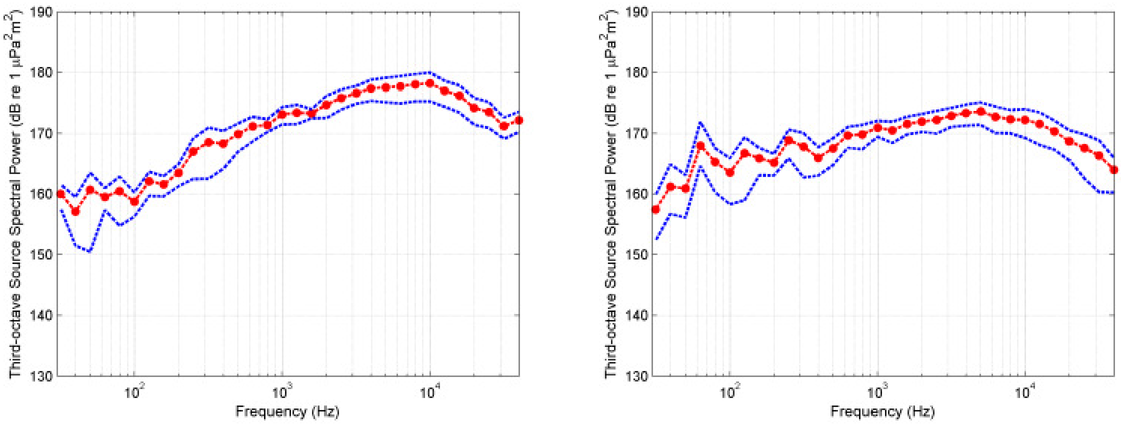

Figure 13.3 Dipole or "affected" Source Levels calculated from 15 two-second sequences showing the mean and standard deviation for the City of Westminster on Area 474 (left), and the City of London on Area 458 (right).

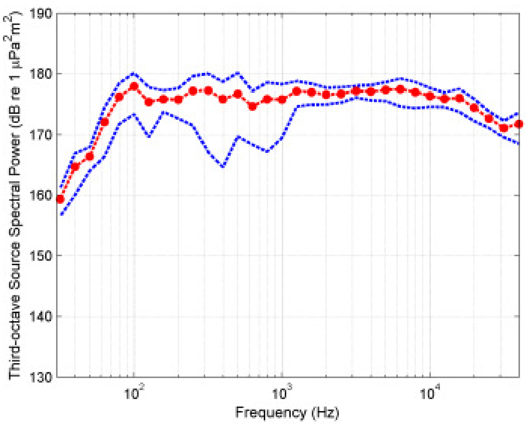

Figure 13.4 Dipole or "affected" Source Levels calculated from 15 two-second sequences showing the mean and standard deviation for the Sand Falcon on Area 473.

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13.2 COMPARISON OF 2 SECOND AND 30 SECOND MEANS

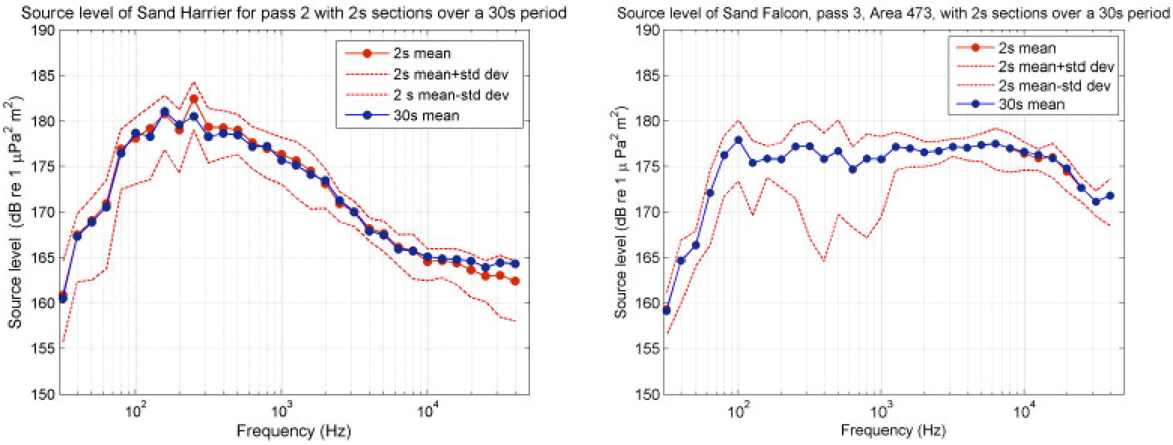

Figure 13.5 Source levels of Sand Harrier and Sand Falcon with 2s and 30s sections with standard deviation on the 2s result.

14 APPENDIX F: ARRAY TECHNIQUE

14.1 CONFIGURATION OF ISVR ARRAY FOR MEASURING DIRECTIONAL DISTRIBUTION OF NOISE SOURCES

A dredger may generate noise via a number of its structural components, for example, the propeller, and the pump, pipe and draghead when it is in operation. In order to identify the distribution of noise sources from a dredger in the vertical plane, a vertical line array with 7 spherical hydrophones (SRD70) was made and used by ISVR to record the noise from a number of the dredgers as shown in Figure 14.1.

The hydrophones were calibrated to obtain their sensitivities and phase responses at NPL's Wray bury site. The received signals from the hydrophones were amplified with battery powered amplifiers (to minimize noise) and sampled at 178 kHz with an NI USB-6251 BNC (16 bits) data acquisition system. The NI system does not sample the input channels simultaneously, but sequentially one channel after another. This is not ideal for high accuracy coherent signal processing since it may introduce some phase errors due to fluctuations in timing. However, it is adequate for our application as the time differences could be measured and compensated for. The data were logged into a laptop computer for later processing.

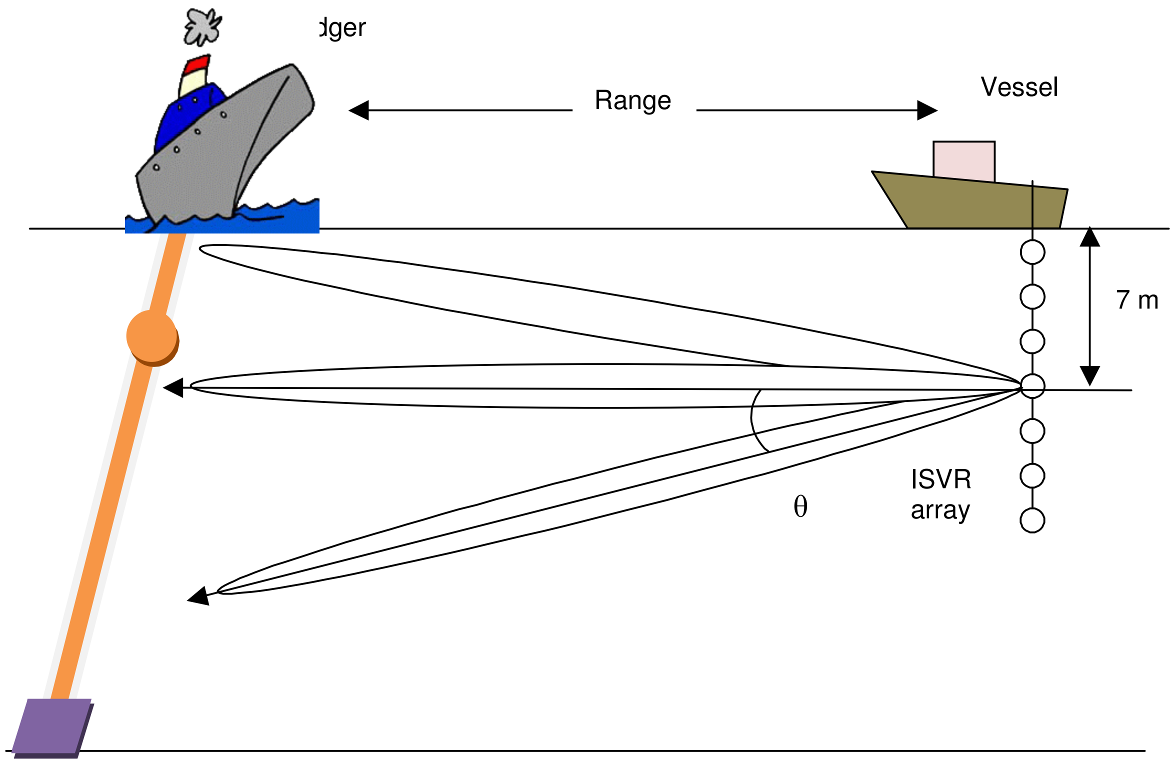

Figure 14.1 Measuring noise with a vertical line array to determine elevation/depression of source.

The ISVR array was initially deployed as a vertical line array with 1 m separation between adjacent elements on a rope. The array was deployed from the survey vessel and was suspended from a surface buoy with a vertical motion suppressor above and a weight below to keep it vertical. However, it was discovered that this arrangement was not adequate when there was a strong current and with the survey vessel anchored. The positions of the hydrophones were unknown and there was poor correlation between the hydrophone signals; therefore, it was impossible to use beamforming to extract information about the direction of the noise with this arrangement.

A modification was made to the array for the later trials. All seven hydrophones were fixed on a 2.0 m length of aluminium angle with 30 cm between adjacent hydrophones. The array was deployed with its centre about 7 m below the surface. In order to determine the exact orientation of the array a 3-D digital compass was attached to the angle aluminium so that its roll, pitch and yaw could be measured. The new configuration greatly improved signal correlation and enabled a clear correlation peak to be identified between hydrophone channels.

14.2 MEAN AMPLITUDE OF RECEIVED SIGNAL

Figure 14.2 shows the measured mean signal amplitude for the Sand Falcon undergoing various operations as measured by the lowest hydrophone of the ISVR array. From this plot the time of CPA can be identified. The relative noise level is also useful to distinguish different operation modes during the measurement period. There was a substantial reduction of noise level when the pump was switched off as shown in the figure. It is seen that the noise level of the ship at its cruise speed of 11 knots is at least 6 dB less than that with a normal dredging operation.

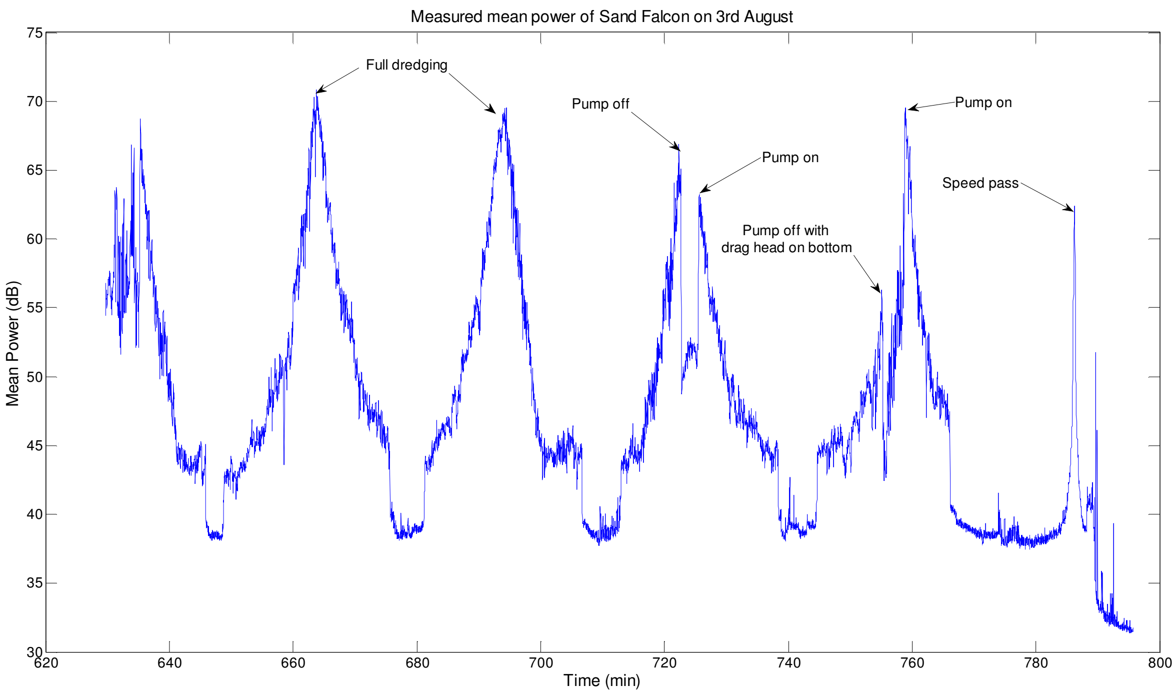

Figure 14.2 Measured mean power of Sand Falcon on 3rd August 2010.

14.3 COMPASS DATA

In order to exploit the beamforming capability of the array the orientation of the array and direction of the noise source in azimuth needed to be accurately known. The time lags due to the tilt of the array with respect to the direction of the noise source can then be compensated for when beamforming.

An OS5000-USD digital compass was mounted on the angle aluminium altogether with the seven ISVR hydrophones. The compass measured the direction of the array relative to North (yaw) and roll and pitch of the array. Figure 3 shows the roll, pitch and yaw of the ISVR array as measured by the compass on 3rd August. It can be seen that the array rotated slowly by about 200º during the time of the measurement with rapid changes of the order of 80º. The magnitude of roll and pitch was about ±5º. The yaw angles at the time of CPA for pass 5, 6, 7 and 9 are marked with blue circles in Figure 14.3.

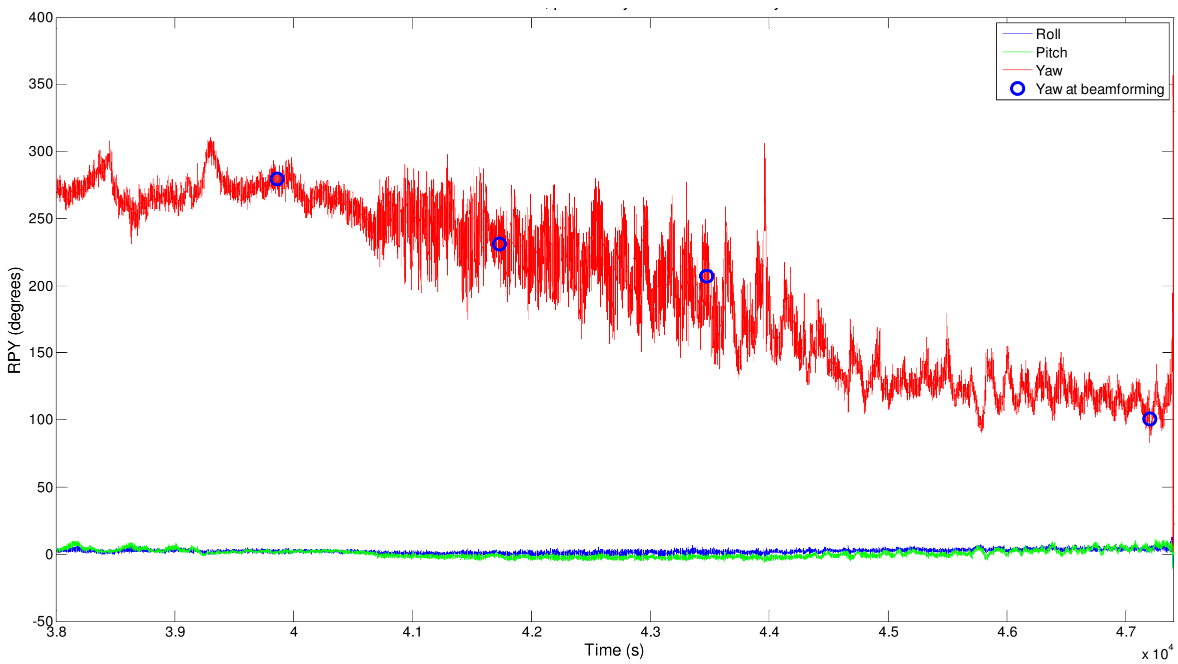

Figure 14.3 Measured roll, pitch and yaw of the ISVR array on 3rd August 2010.

The physical positions of the hydrophones could be determined with the direction cosine matrix, which transfers the coordinate system from the body system of the ISVR array to a local coordinate system (North-East-Down, NED).

The tilt of the array in the vertical plane that contains both the centre of the array and the source can be obtained from this data and then used in the beamforming algorithm for the array. The tilt of the array with respect to the vertical is plotted in Figure 14.4. The maximum tilt can be almost 15º at times. The tilt angle at CPA for passes 5, 6, 7 and 9 are marked with red circles. A zoomed version of the plot for the tilt within 30 s of CPA for pass 5, 6, 7 and 9 is shown in Figure 14.5. The tilt of the array varied with a natural frequency of about 3Hz. The tilt at the time of pass 9 was largest with a mean angle of 5.5º and a variation of just over 1º. The tilts were less for the other three passes.

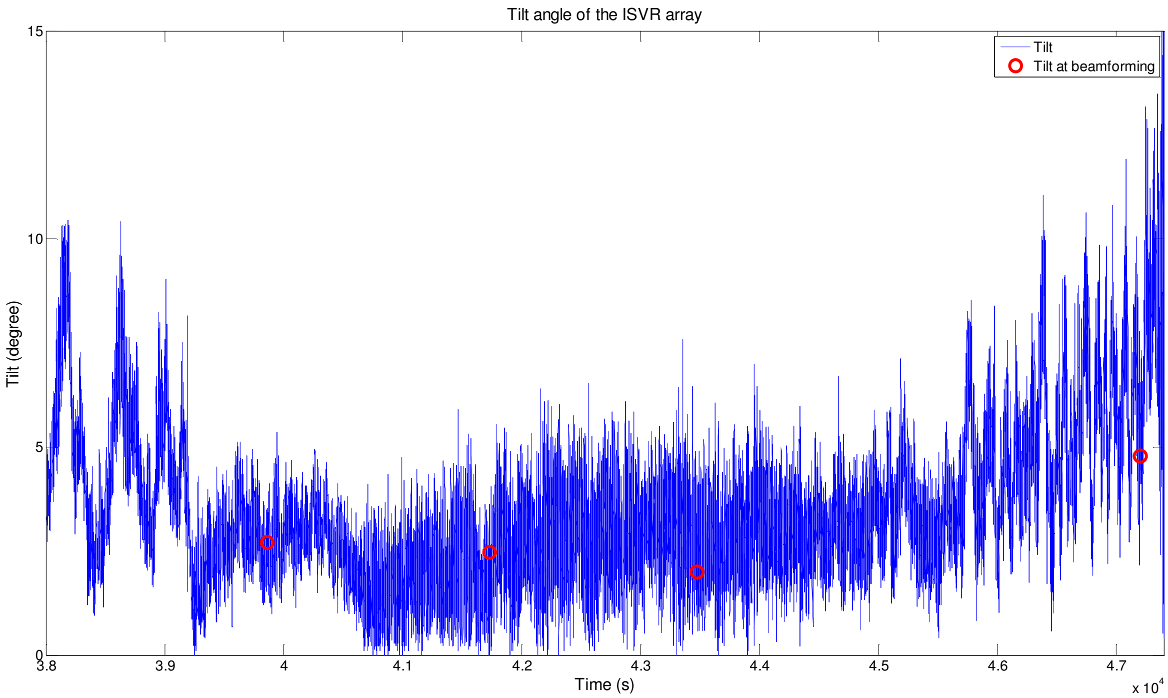

Figure 14.4 Tilt angle of the array.

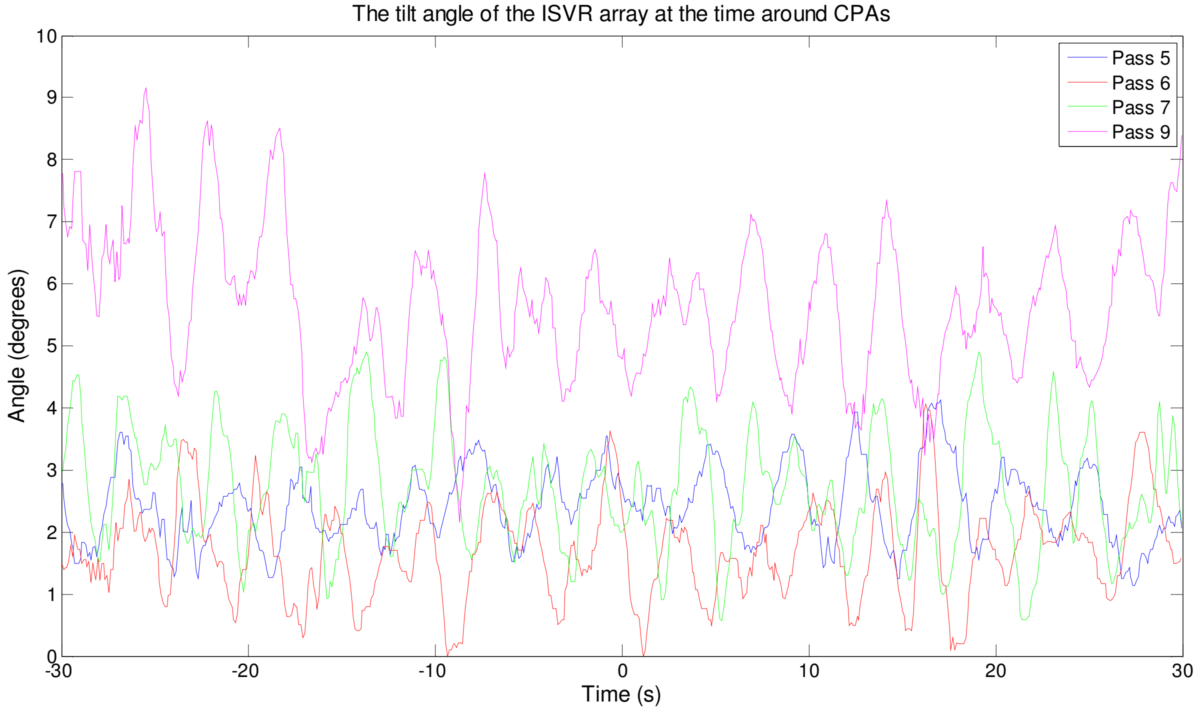

Figure 14.5 Tilt angle around CPAs of passes 5, 6, 7 and 9.

Beamforming was performed by using time delayed signals from all of the hydrophones and then summing them together to achieve an angular scan from –90º to 90º in vertical plane introduced. The tilt angle of the array in the plane through the vessel and dredger was compensated for at this stage. The beam formed data was averaged in frequency by averaging the power in the beam at each angle over a bandwidth of 200Hz.

14.4 RESULTS OF BEAMFORMER OUTPUT

An example of the expected beam former output for a source at a depth of 7 m equal to that of the mid point of the array is shown in Figure 14.6. In this case the array is assumed to be in an infinite fluid space so there are no reflections from the water surface or seabed. A clear return can be seen for a depression angle of 0º for all frequencies (as the source was assumed to be broadband).

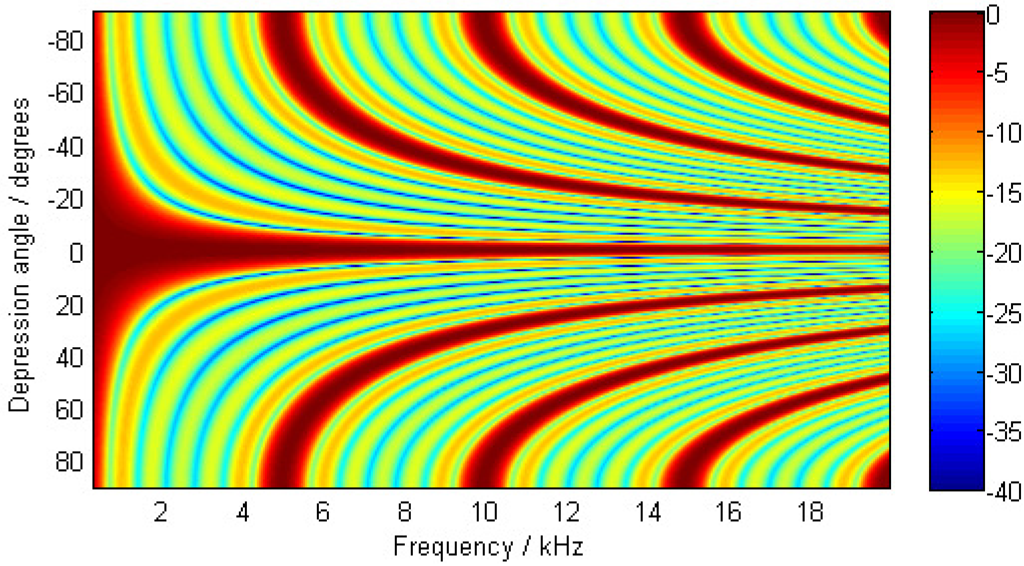

Figure 14.6 Ideal output of the beam former for a source at the same depth as the midpoint of the array (assuming operation in an infinite medium).

For frequencies greater than 5 kHz the hydrophone spacing is greater than the wavelength in water. When the hydrophone spacing, d, is the same as the wavelength, λ, and the beam is steered to 0º additional grating lobes will occur at ±90º. These lobes are not lower sensitivity side lobes of the main beam but additional lobes with the same sensitivity as the main lobe. Consider the case when there is a source at a depression angle of 0º. In this case when the beam is steered to 90º a grating lobe will occur at 0º and the array will have a spurious response that appears to be at 90º. These grating lobes are responsible for the apparent multiple sources at higher angles for frequencies greater than 5 kHz. This needs to be taken into account when considering the experimental results.

Beamforming was applied to the 4 occasions when the Sand Falcon passed CPA on passes 5, 6, 7 and 9. Pass 5 and 6 were dredging runs with the track of pass 5 being from West to East with the suction pipe nearest to the survey vessel, while pass 6 was an opposite run with screen tower nearest the survey vessel. The pump was switched off at the time of beamforming during pass 7. Pass 9 was a transit pass when the Sand Falcon passed by at about 11 knots on a West to East track. The tracks of pass 5, 6 and 7 are plotted in Figure 14.7.

The ranges from the survey vessel to Sand Falcon for passes 5, 6 and 7 at the time of beamforming were found to be 80 m, 95.1 m and 117.8 m respectively. The tilts of the array in the plane of vessel and dredger were found to be -2.05º, -0.52º and 3.07º respectively. These tilts were compensated for in the beamforming. For pass 9 there was no GPS information on the track of the Sand Falcon. It was estimated that the distance between the Sand Falcon and vessel was about 30 to 40 m at CPA by visual observation.

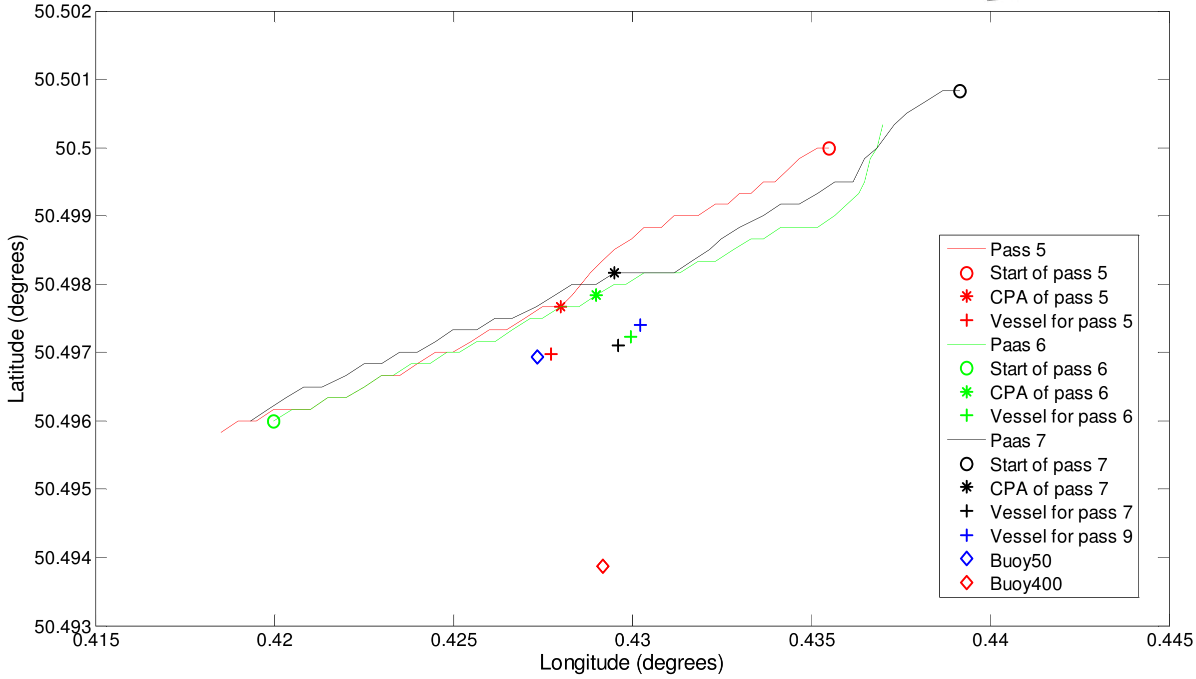

Figure 14.7 Tracks of Sand Falcon's passes 5, 6 and 7 with dredger positions at CPAs and survey vessel locations indicated.

Figure 14.8 shows the beamformer output for Sand Falcon's pass 5. It is the spectrum of the beamformed signal for the frequency range from 0 to 20 kHz over the angular range -90º to 90º. The negative sign corresponds to angles above the horizontal (elevations) and the positive sign to angles below the horizontal (depressions). Half a second of data from the array at CPA was used to calculate this result. The beamformed data has been averaged in frequency by averaging the power in the beam over a bandwidth of 200Hz. The hydrophone sensitivities and phase responses were compensated for, as was the sequential sampling of the array channels. A spherical spreading law was applied to the output of the beamformer, so that the results shown in the figure are equivalent to Source Level if this model is appropriate.

The angular resolution varies with frequency for the array, from 19º at 2.5 kHz to 2.4º at 20 kHz. It is effectively omni-directional for frequencies lower than 400 Hz. The main noise source over the frequency range above 2.0 kHz can be identified to be at 8º below the horizontal plane. This implies a point source at a depth of 18.2 m below the sea surface.

There is a very wide spread of noise from almost all angular directions for signal frequencies below 5 kHz. These are complicated by signals reflecting from the sea surface and the bottom of the channel due to multipath effects.

For the geometry of the measurements, any apparent noise from an angle greater the 26º or less than –26º is like to be a multipath contribution from the sea bed or sea surface, or due to a grating lobe.

In the frequency band from 2 kHz to 5 kHz there appears to a noise source for an extended angular range in the multipath region although not at lower angles – the origin of this is not clear.

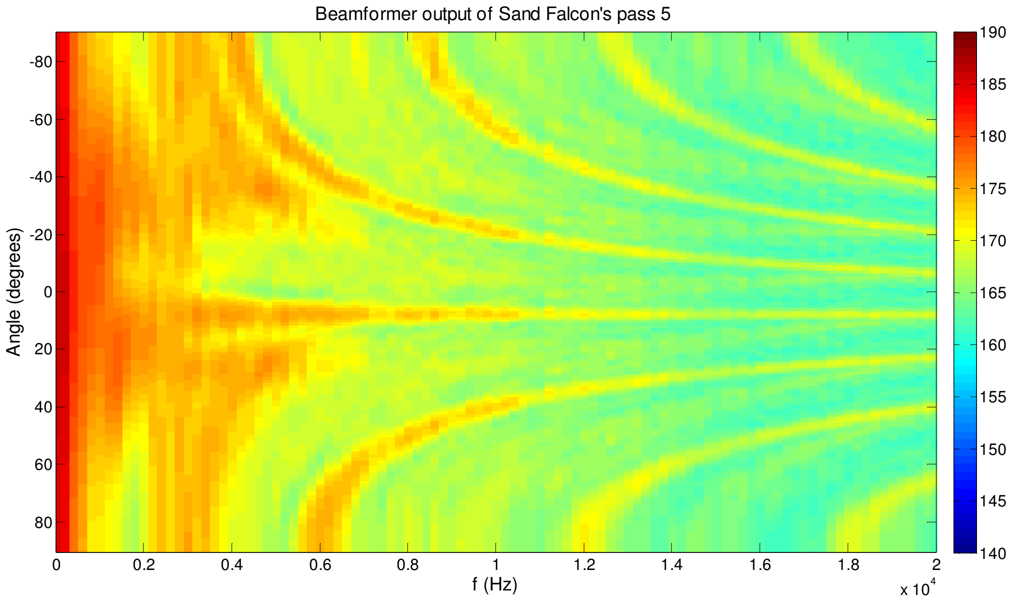

Figure 14.8 Beamformer output of ISVR array for Sand Falcon's pass 5.

Figure 14.9 shows the corresponding result for pass 6. The similarity between Figure 14.8 and Figure 14.9 is clear. In this case the noise source was at a depression angle of 6.5º from which the depth of the source is estimated to be 17.8 m. This is in very good agreement with the estimate for pass 5. The overall Source Level is higher in pass 5 than that in pass 6. However, the noise contribution from sources other than the point source was stronger above 7 kHz and there is a clear band of signal from 10 kHz to 13 kHz on pass 6.

The beamformer output of Sand Falcon's pass 7 is shown in Figure 14.10. The pump was switched off during this run. Therefore the noise level was lower compared with full dredging operation. It can be seen that the level is indeed lower than that in Figure 14.8 and Figure 14.9. In this case the higher frequency point source is at –5º. The depth of the source can be calculated to be 3.3 m.

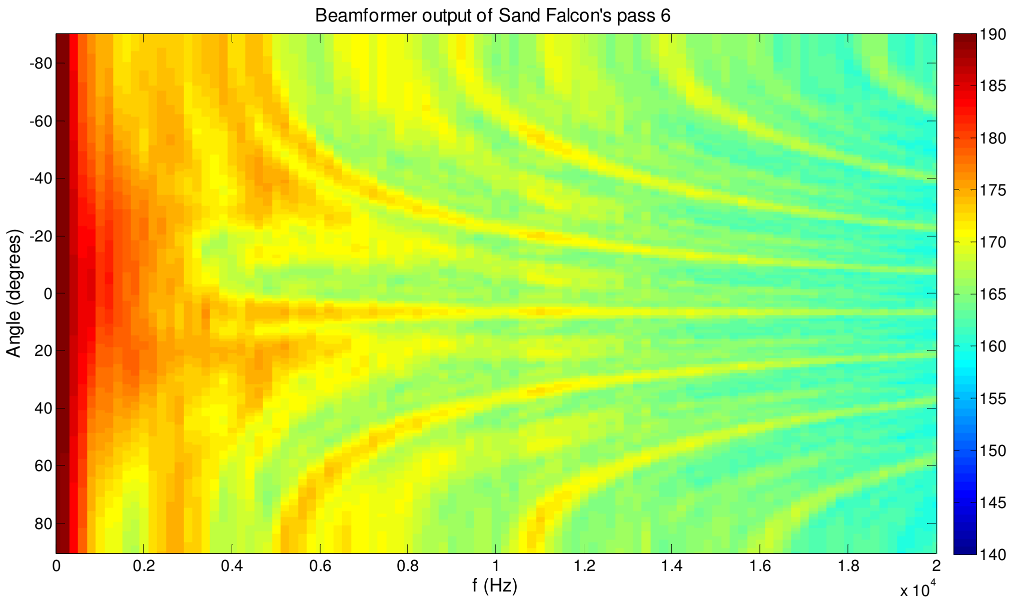

Figure 14.9 Beamformer output of ISVR array for Sand Falcon's pass 6.

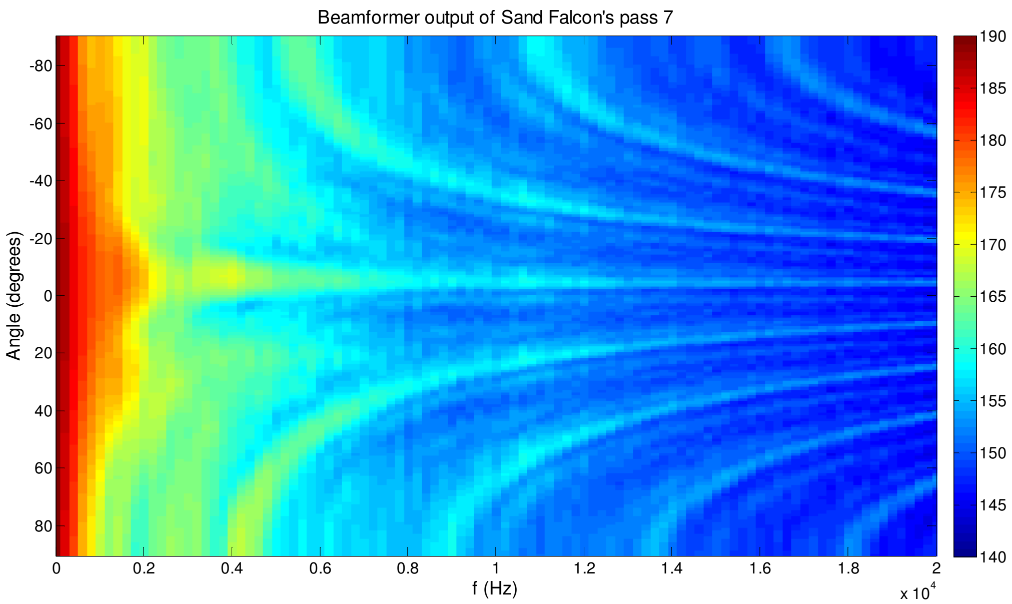

Figure 14.10 Beamformer output of ISVR array for Sand Falcon's pass 7.

Figure 14.11 shows the beamformer output for the Sand Falcon when in transit. The beamwidth of the noise around 0º seems wider than those in the previous figures for dredging operations. This may be due to the fact that the separation between the dredger and survey vessel was much smaller. The angle of the main noise source is –2º. The depth of the point noise source is about 5.8 m, which is about the maximum depth of the propeller.

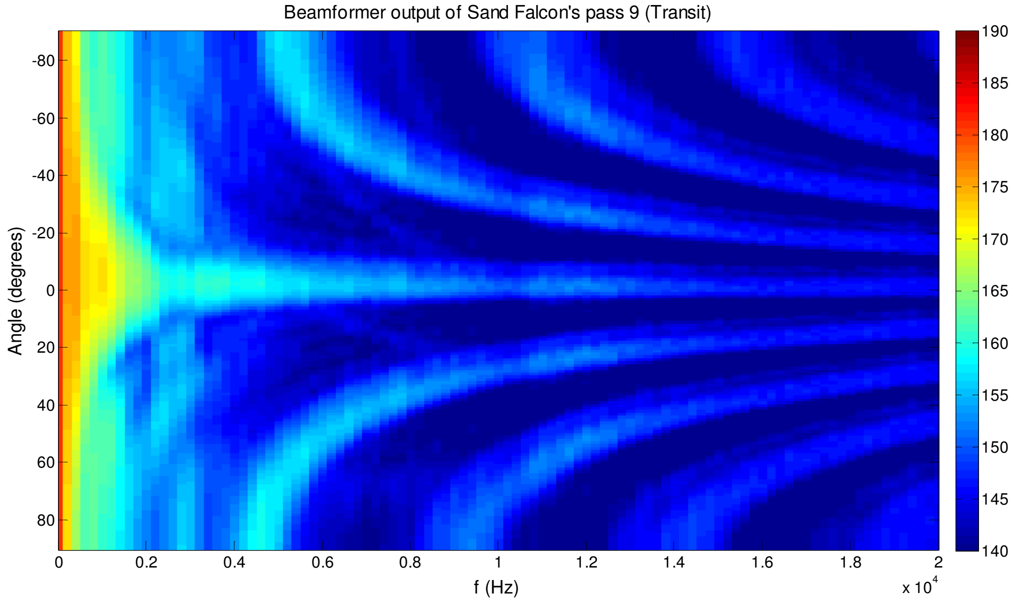

Figure 14.11 Beamformer output of ISVR array for Sand Falcon's pass 9.

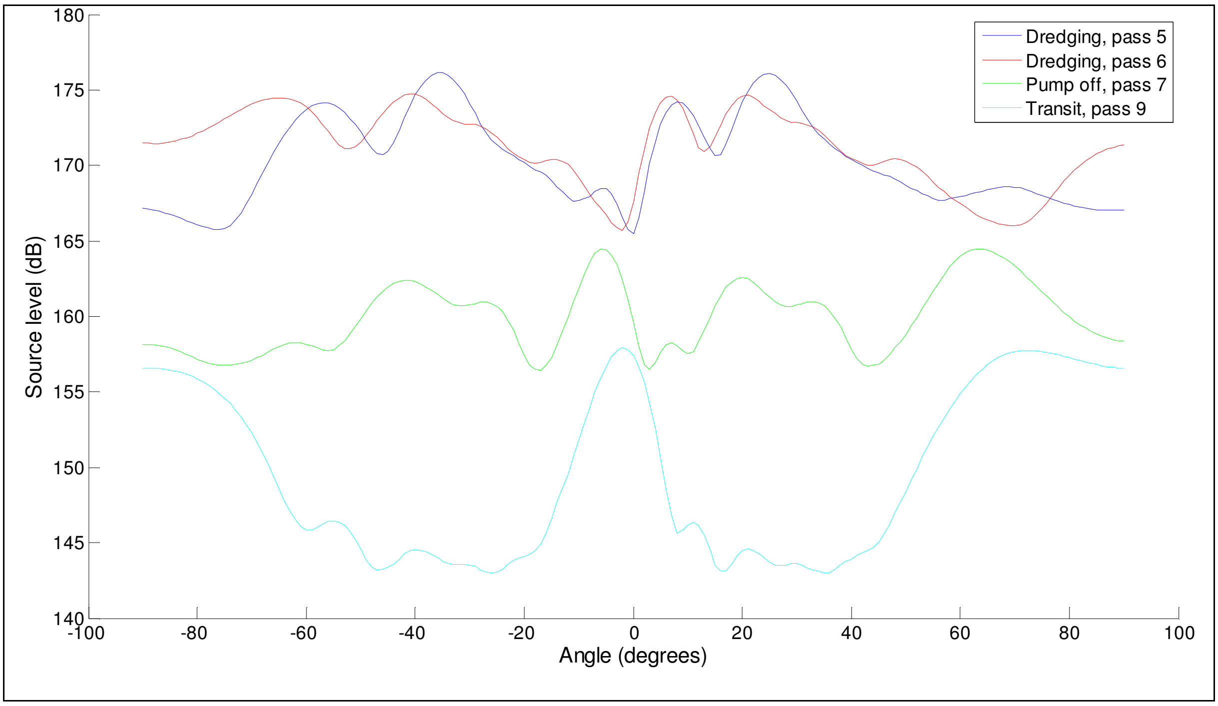

Figure 14.12 Beam patterns at 5 kHz for 4 different passes of Sand Falcon at its CPAs.

Figure 14.12 shows the beam patterns at 5 kHz for the 4 different passes. It is seen that the dredging noise on passes 5 and 6 is much higher than that for the ship when in transit with the pump off.

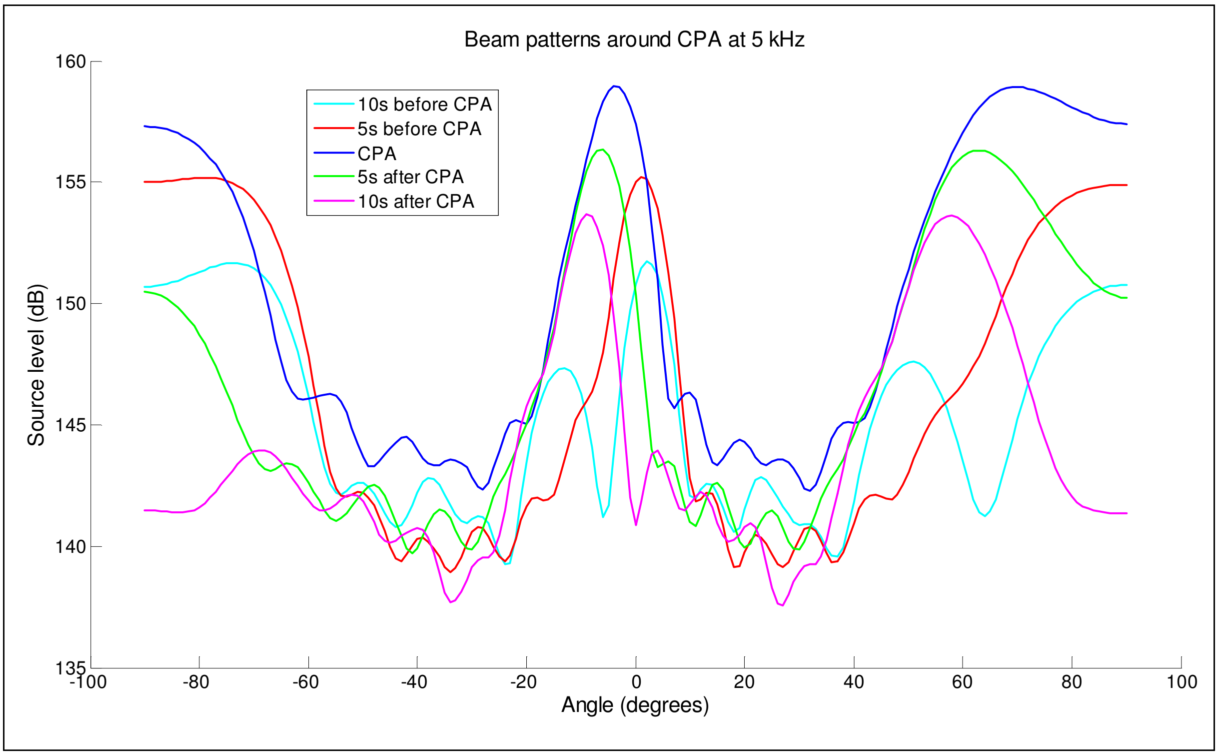

Figure 14.13 Beam patterns around CPA for Sand Falcon's pass 9.

Figure 14.13 shows the beam patterns at 5 kHz for the 4 different passes. It is seen that the dredging noise on passes 5 and 6 is much higher than that for the ship when in transit with the pump off. shows the beam patterns 10 seconds before and after CPA for the transit pass of the Sand Falcon. It is noticed that the beam patterns are reasonably symmetrical around the CPA, but the amplitude is 2-3 dB lower for those before CPA. This was perhaps due to the blocking of the noise mainly generated from the propeller by the body of the ship.

14.5 SUMMARY OF ARRAY TECHNIQUE

A vertical line array has been used to identify the distribution of noise sources from an operating dredger in the vertical plane. The initial results have demonstrated that there were a number of noise sources at different depression/elevation angles with various bandwidths. When dredging there is a prominent noise source at frequencies greater than 2.0 kHz that appears to be a point like source mid-water; this is probably associated with the pump. When this source is not present the higher frequency noise is associated with a much shallower source (presumably the dredger propulsion system).

The existence of grating lobes and multipath effects makes the discrimination of noise contributions from different parts of the dredger complicated. However the beamformer can be used to identify different source locations and further analysis of the data may prove beneficial.

15 APPENDIX G: LOW FREQUENCY ANALYSIS

Dstl provided MALSF with quality assurance of the project (P09/108) and were provided with all the raw acoustic data generated as part of the project. In support of the project dstl applied their considerable expertise in passive acoustic signature analysis of maritime vessels to a selection of these data sets. This appendix section provided by Richard Horsborough of dstl shows a detailed breakdown of the narrowband signature of the Sand Harrier dredger. This dredger was chosen as it proved, under the conditions it was measured, to be the noisiest vessel measured during this project, although the analysis below does not indicate any unusual noise signatures for this type of vessel. As mentioned in section 2.1.1, a separate dstl quality assurance report is also available.

15.1 NARROWBAND SIGNATURE ANALYSIS OF THE SAND HARRIER

The signature analysis concentrated on the Sand Harrier operating in three distinct modes, and the transition between these modes. The modes included:

- no pumping - steaming past at full speed (transit mode for vessel);
- pumping water only (drag head raised with pump on);
- full dredging (pump running with draghead on the seabed).

Figures 15.1 to 15.5 display the Low Frequency Analysis and Recording (LOFAR) plots (lofargrams) of the acoustic signature of the Sand Harrier in the various operational modes. Time increases up the y-axis of the plots and frequency increases along the x-axis in each of the lofargrams. The main features present in all of the figures are the strong engine related tones. These tones identify that the dredger has two 6 cylinder, 4 stroke diesels engines, running at marginally different speeds. In Figures 15.1 & 15.2 the two engines are identified by tones overlaid with red and blue markers which represent the harmonics of the engine's fundamental frequencies. The acronyms on the figures are:

- CFR - Cylinder Firing Rate
- CSR - Cylinder Stroke Rate
- ERPM - Engine Revolutions Per Minute
- EDA - Engine Driven Auxiliary
- UNK Aux - Unknown Auxiliary Machinery
- 4P ACA - 4 Pole Alternating Current Auxiliary
- UDR - Update Rate

Figures 15.1 and 15.2 displays a lofargram of the Sand Harrier when steaming past at full speed and not pumping. The signature shows strong engine sources throughout the spectra. Other aural characteristics detected include propeller cavitation, blade flutter, diesel whine and unidentified auxiliary machinery.

The dredging pump can be identified in Figures 15.3 and 15.4 as a low frequency diffuse signature at approximately 2 Hz and 6 Hz. Figure 15.4 shows the dredger in full dredging mode. Figure 15.3 shows the dredger initially in full dredging mode, but then raising the drag head so that it only pumps only water. Comparing the spacing between the pumping tones in Figures 15.3 and 15.4 shows that the pump speed increases from 168 to 216 RPM during the transition. This is assessed to be because the load on the pump is reduced when pumping only water. A diffuse tone at 38.79 Hz also appears during the transition and is assumed to be related to the lifting of the drag head. Other than these tones, there is no obvious indication of pumping other than a broadband hum heard through aural analysis.

The narrowband signature at higher frequencies becomes masked by broadband noise when the pump is activated. There is further masking during full dredging operations. This is evident in Figure 15.5 which illustrates the transition between full dredging and water pumping between 100 Hz and 300 Hz. The lower half of the plot shows very little narrowband signature, but when the draghead is lifted, several tones become visible in the upper half of the plot.

Dstl adjudge that the narrowband acoustic signature of the Sand Harrier is no different to that of an average merchant vessel, with the exception of the low frequency diffuse pumping tones. The only significant difference between the Sand Harrier and an average merchant vessel is the broadband radiated noise signature as a result of dredging activities.

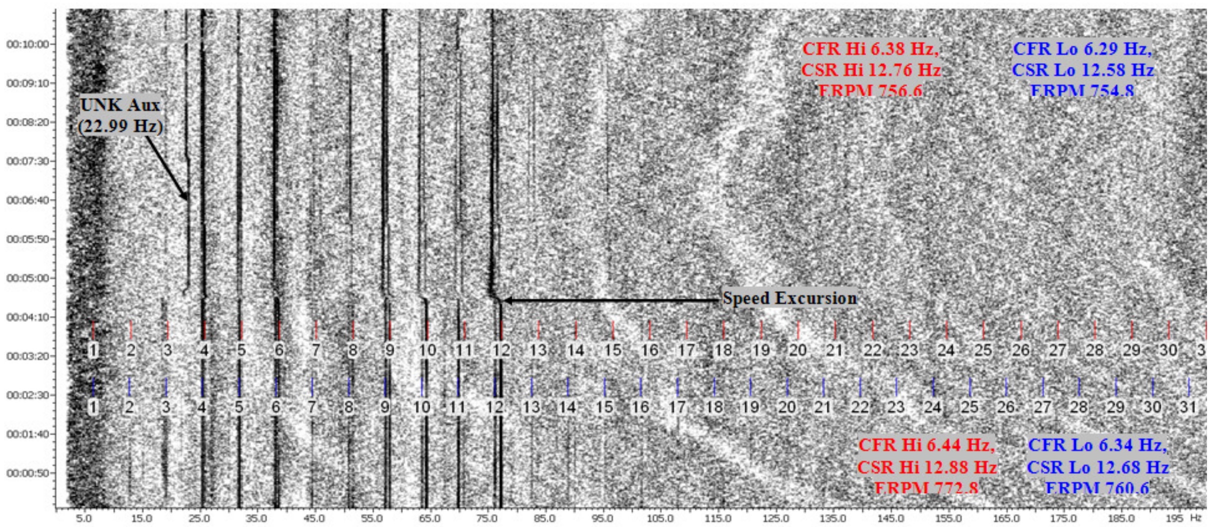

Figure 15.1 Engine and unknown auxiliary tonals evident in the 0 - 200 Hz spectrum with no pumping (Resolution 0.2 Hz, UDR 1 second).

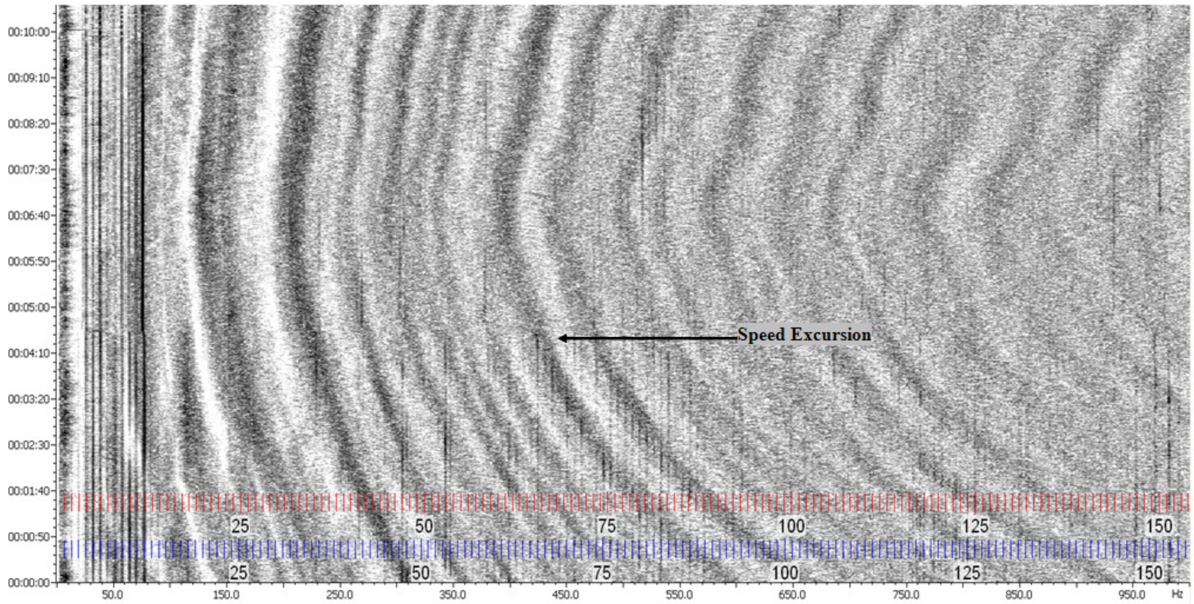

Figure 15.2 Engine tonals evident in the 0 - 1 kHz spectrum with no pumping (Resolution 0.98 Hz, UDR 1 second).

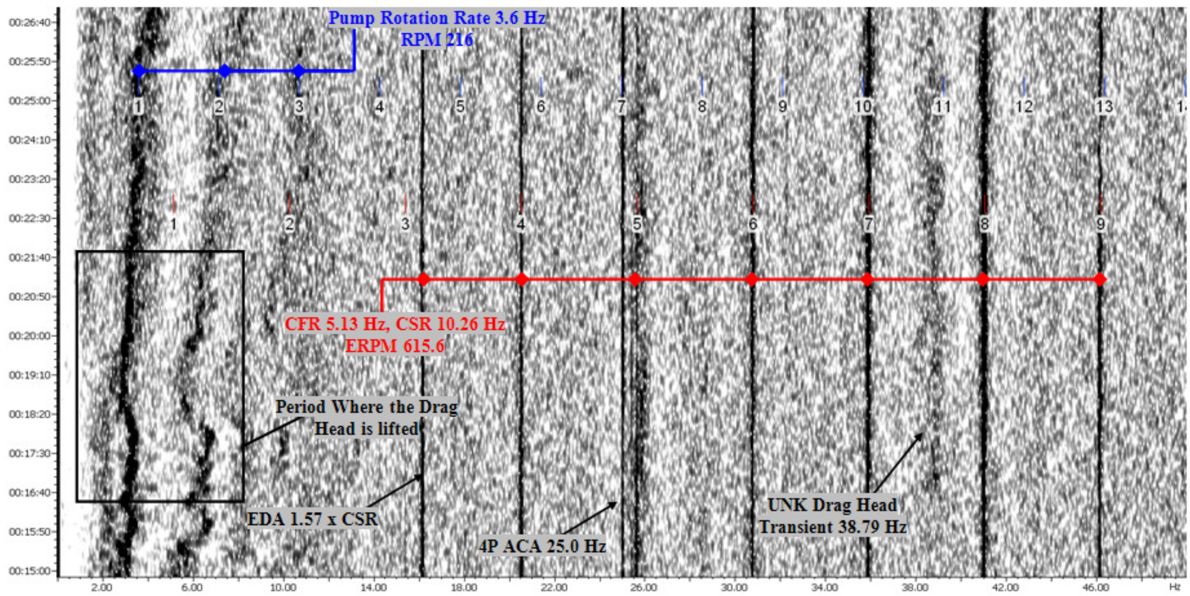

Figure 15.3 Engine and diffuse pump rotation rate signature evident in the 0 - 50 Hz spectrum for water pumping only (Resolution 0.20 Hz, UDR 0.5 second).

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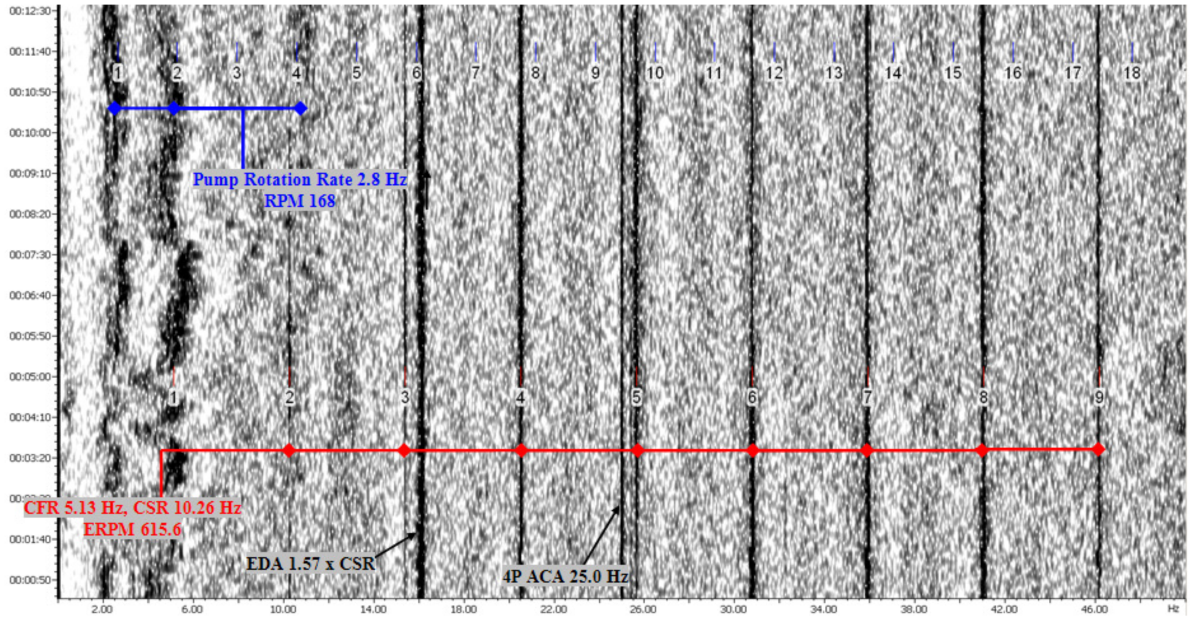

Figure 15.4 Engine and diffuse pump rotation rate signature evident in the 0 - 50 Hz spectrum for full dredging mode (Resolution 0.20 Hz, UDR 0.5 second).

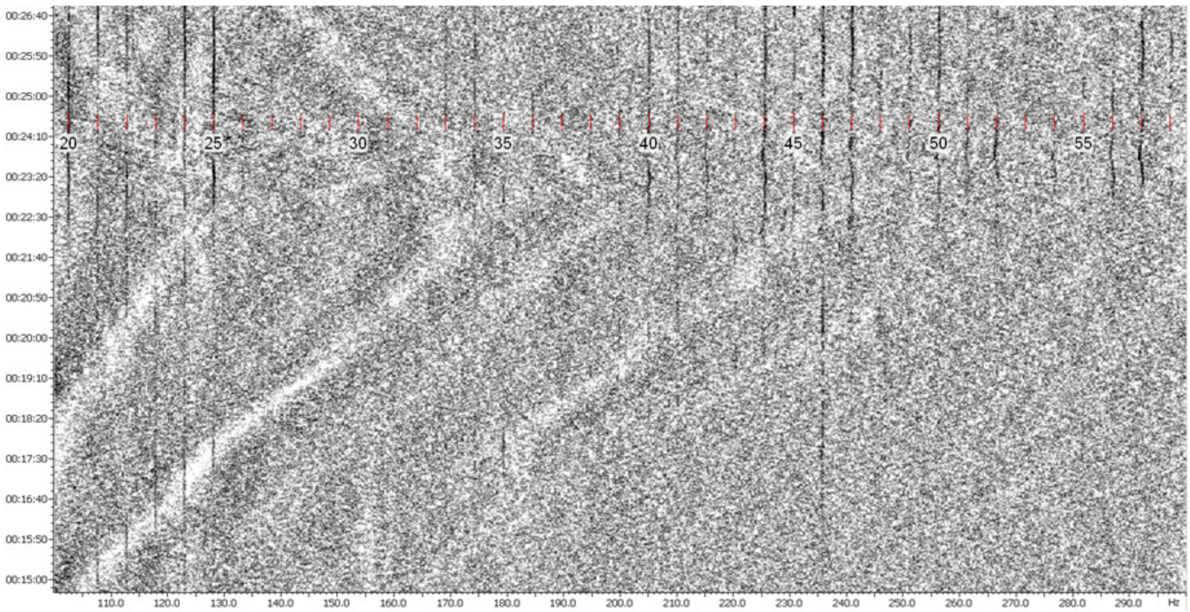

Figure 15.5 Lofargram showing the transition between full dredging and water pumping(Resolution 0.10 Hz, UDR 0.5 second).

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