Final Report Describing Measurements of Ship Noise Taken from R/V *Song of the Whale* in the English Channel and the Hebrides in June and August 2011

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EXECUTIVE SUMMARY

During summer 2011, measurements of ship noise were taken from the R/V *Song of the Whale* in the English Channel and in the Minch, Scotland. The aim of the project was to assess new ISO methodologies to obtain noise measurements for a number of vessels under normal operating conditions. Over six days of field work, 36 separate recordings were made of 33 individual vessels. Of these, six were considered to have significant levels of masking by other noise sources and were thus excluded from further analysis. The remaining measurements of 27 vessels suggest that noise output is in part influenced by vessel characteristics. Length, beam, tonnage, draught (fore and aft) and CPA were found to be positively correlated with source level. Vessels longer than 150 m had higher noise levels than smaller vessels. The power spectra for the ships recorded differed by as much as 40 dB from the upper bound to the lower bound, in keeping with other studies, suggesting there is some potential to reduce noise output substantially. Although not conducted in the controlled environment of a noise measurement facility, the procedures described here offer a cost-effective approach to measuring noise levels under typical operating conditions, and have several advantages over sea-trial measurement. Trials of the ISO methodologies in the field identified several aspects of the standard that could be improved and these are discussed.

1. INTRODUCTION

From the 1970s onwards there has been growing concern over the effects of man-made underwater noise on marine animals. Indeed, research has suggested a 10-12 dB increase in offshore marine ambient noise in the 10-50 Hz range during the last 40 years, attributed primarily to increases in commercial shipping (Andrew *et al*., 2002; McDonald *et al*., 2006). Some anthropogenic sounds can harm marine life (e.g. Bailey et al., 2010; Brandt *et al*., 2011; Di Iorio & Clark, 2010; McCauley *et al*., 2000; Morton & Symonds, 2002; Thomsen *et al*., 2006; Weilgart, 2007) through a number of processes including causing injury, masking and behavioural changes. Several of these processes, such as changes in behaviour or the masking of crucial sounds, are extremely difficult to document, as linking cause and effect in wild animals can be problematic. However, even subtle disturbances have the potential to subsequently impair the survival of individual animals. In extreme cases, the effects of noise have been fatal to marine animals, with several well-documented cases of mass strandings of cetaceans following the use of military sonar in Greece, Madeira, Hawaii and coastal USA, the Virgin Islands, Spain, the Canary Islands and the Bahamas (Balcomb & Claridge, 2001; Cox *et al*., 2006; Evans & England, 2001; Fernández *et al*., 2005; Frantzis, 1998; Hildebrand, 2004; Jepson *et al*., 2003; Martín *et al*. 2004; Simmonds & Lopez-Jurado, 1991). The effects of man-made underwater noise on marine life depend on a variety of factors including the properties of the sound, its frequency, intensity and duration and the type of animal concerned. There is considerable uncertainty over the effects of noise exposure on marine animals, yet as evidence has accumulated the issue has received increasing attention from scientists and international bodies. Few studies have been able to quantify the long-term effects on marine mammals of exposure to man-made ocean noise. Although brief or single acute exposures to sound (e.g. sonar or seismic airguns) may injure individual animals, long-term chronic noise from multiple sources may be of more concern as it could affect whole populations. The consequences for marine animals of continuous exposure to increasing background noise levels are unknown.

1.1 Regulatory and Policy Context

In the past decade, the potential impact of underwater noise pollution has been increasingly recognised at the international level, with several intergovernmental bodies, including the UN General Assembly and the UN Convention on Migratory Species, calling for multilateral efforts to minimize the risk of adverse effects on the marine environment. In 2008, the IWC Scientific Committee endorsed a target to reduce the contribution of shipping to ambient noise levels in the 10-300 Hz range by 3 dB in 10 years and by 10 dB within 30 years relative to 2008 levels. Given the fact that a noisy ship is likely to be operating inefficiently, reducing noise may be achieved alongside improvements in efficiency and reduced emissions, also lowering costs to vessel operators. In 2008, the International Maritime Organization (IMO), the UN specialised Agency responsible for shipping, adopted a new high priority programme of work on “Noise from commercial shipping and its adverse impact on marine life” aimed at developing non-mandatory technical guidelines for ship-quieting technologies. It is estimated that only the noisiest 10% of ships contribute between 50% and 90% of the overall noise pollution (Leaper *et al*., 2009). By identifying and targeting this 10%, therefore, it would be possible to substantially reduce ocean noise pollution. In 2009, the IMO called upon member Governments and the industry to review their fleets in order to identify the noisiest ships which would benefit most from efficiency improving technologies that are also likely to reduce underwater noise output.

At European level, the new EU Marine Strategy Framework Directive has identified shipping noise as one of the pressures that need to be controlled to achieve the ‘good environmental status’ of European waters. The European Commission and the Member States are developing criteria and methodological standards for defining good environmental status in relation to several descriptors including underwater noise. One of the criteria under development requires Member States to monitor ambient noise levels and trends. Ship noise measurements, therefore, should input into the work of the IMO and contribute to current international efforts to reduce the impact of ship noise on marine life. Such measurements can also assist governments in complying with their international commitments under the IMO and EU regimes.

1.2 Standardisation

There have been recent efforts to standardise the measurement of ship noise. A new voluntary consensus standard for the measurement of underwater noise from ships has been adopted by the American National Standards Institute (ANSI/ASA S12.64-2009/Part 1). In 2010, the Marine Environmental Protection Committee (MEPC) of the IMO invited the International Standards Organisation (ISO) to develop a standard for the measurement and reporting of underwater sound radiated from merchant ships. The ISO methodology (ISO/TC8/SC2) was designed anticipating measurements would most likely be made during sea trials after construction. The EU has recently announced a set of descriptors that will be used to assess Good Environmental

Status under the Marine Strategy Framework Directive. Indicator 11.2 pertains directly to continuous low frequency noise and stipulates that:

Trends in the ambient noise level within the 1/3 octave bands 63 and 125 Hz (centre frequency) (re 1µPa RMS; average noise level in these octave bands over a year) be measured by observation stations and/or with the use of models if appropriate (11.2.1).

In order to understand the characteristics of an individual ship, measurements should be made using a recognised technique, with the ship in a known configuration, measured on the beam aspect and at a known distance, so that representative source levels can be back calculated to a one metre reference level. Thus in-field recordings of ship noise need to precisely record transmitter-recorder distances, the local transmission environment, the vertical directivity of the ship's radiated noise and the ship's course and speed. An ideal recording may thus involve the target ship passing as close as possible to the recording system without signal clipping occurring.

1.3 Project Aims

There are currently more than 90,000 ships larger than 100 gross tons and global tonnage is expected to grow by about 75% in the next two decades. There is a paucity of data on the variability of ship noise under real operating conditions and it is largely unclear how factors such as load, speed and vessel type act together. The literature gives spectra for individual ships but there is little information on the variation between vessels. Noise signatures for individual vessels have been measured in bespoke noise ranging facilities; however, these methods may be too expensive in terms of both time and money to assess large numbers of vessels.

The development of low-cost portable recording methods to establish a ship's signature would be beneficial for efforts to investigate the issue and its implications for the marine environment, particularly if in compliance with recently developed ANSI and ISO standards for ship noise measurement. Peak tonal and broadband levels below 10 kHz, when a ship is at typical passage speed are particularly significant. In-field recordings of vessel noise also need to be made practical for the shipping companies under study. Thus data collected from platforms of opportunity could be used to quantify the variation in noise (in a chosen frequency band) from various types of ship in typical operational environments. The aim would be to describe the variance of noise levels across categories of shipping to identify which are likely to be the major contributors overall.

The aims of the research conducted by IFAW and MCR International in 2011 included:

1. Making repeated calibrated recordings of the same vessels (i.e. ferries).
2. Making recordings of single vessels ideally within 100m or within one boat length (whichever is longer).
3. Making recordings in areas with high densities of vessels.

4. Testing the ISO methodologies suitability for in-field, low-cost measurements of the noise signature of individual ships.

2. METHODOLOGY

Measurements of ship noise were taken from the R/V *Song of the Whale*, a 21 metre auxiliary-powered cutter-rigged sailing research vessel, owned by the International Fund for Animal Welfare and operated by Marine Conservation Research Ltd. (MCR Ltd). The vessel was based off the Channel Island of Alderney between 20th and 24th June in order to measure ship noise near the Casquettes Traffic Separation Scheme (TSS). In addition, due to poor weather conditions during this first period of field work, further recordings were made in the Minch, Scotland, between the 16th and 21st August (Figure 1). In general, the recordings in the Channel tended to be made in waters shallower (<100 m) than in the Minch (>100 m). The *Song of the Whale* team collected noise profiles from vessels which varied in size, speed, age and cargo weight and under a variety of weather conditions.

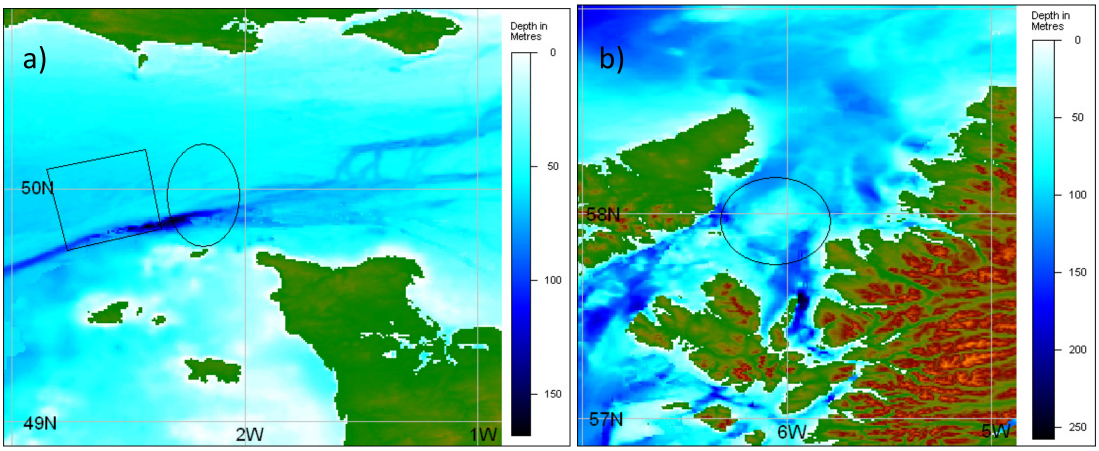

Figure 1. Vessel measurements were made (a) in the English Channel (20th to 24th June 2011) and (b) in the Minch (16th to 21st August 2011). The areas where the measurements are made are depicted by ovals. The Casquettes TSS is denoted by a polygon in the Channel. Plot created using Gebco Grid Demonstrator.

2.1 Data Collection

Measurements of ship noise were made using a calibrated omni-directional RESON TC4032 hydrophone with a frequency response of ±2.5 dB between 10 Hz and 80 kHz. During initial recordings made in the Channel, the hydrophone was attached to a weighted line deployed from the aft davits of *Song of the Whale*; however, during the Minch recordings, the hydrophone was deployed using a running mooring to allow more weight to be attached to the system (Figure 1). Unamplified signals were digitised with a sound-acquisition device (National Instruments USB-6251) sampling at 96 kHz with 16 bit resolution (± 1 volt scaling). A second hydrophone and recorder was suspended from a free-floating autonomous buoy to support the measurements, allowing closer passes and a distance comparison with the recordings made from SOTW (this buoy was not used during the August recordings). Signals were digitised at 96 kHz and 16 bit resolution to M-Audio MicroTrack 24/96 Digital Recorders attached to the buoy. The buoy had its own radar reflector and AIS transponder. Passing vessels were also alerted to the buoys presence via regular VHF radio securité broadcasts.

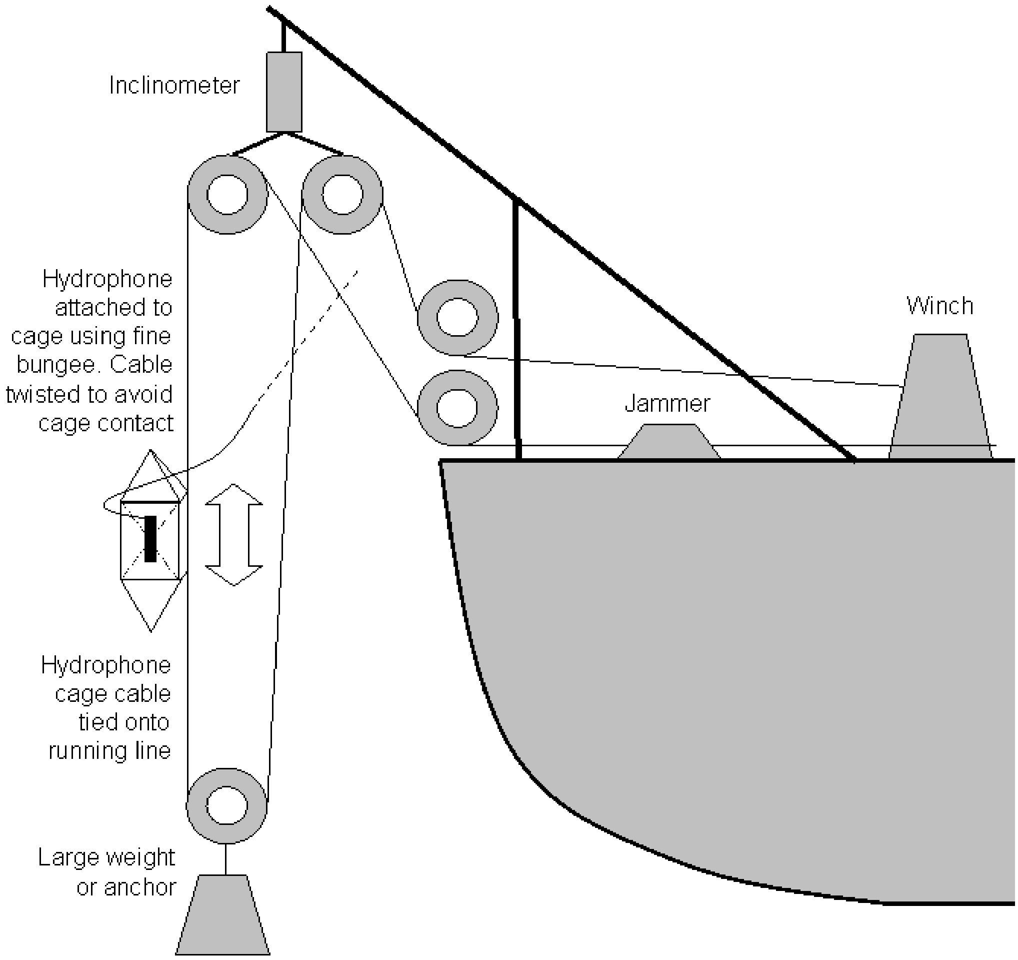

Figure 2. Deployment of a calibrated hydrophone from *Song of the Whale* using a vertical running mooring. Using a continuous running line through a series of blocks allowed the depth of hydrophone deployment to be adjusted using the winch.

During recording, *Song of the Whale* was hove-to with the engine off; the depth sounder and all other unused electrical equipment were turned off. Thirty metres of hydrophone cable were deployed vertically from the aft davits using a weight system and a Level Developments IS-2-30 twin-axis inclinometer, aiming for a deviation from vertical of less than 5° (ideally at or below the level of the draught of the target ship and below 20 m). The locations of both hydrophones were taken from *Song of the Whale*'s GPS and from the AIS beacons on the data buoy respectively. In addition the buoy had its own integral GPS. Communications were established between the measurement vessel and the target ship throughout the recording period, primarily to ask them to pass as close to 100 m as safely possible but also to collect information regarding the target vessel's operational state.

Before any measurements took place, the recording system and both hydrophones were calibrated (the main hydrophone was calibrated using a G.R.A.S. 42AP pistonphone, the second hydrophone was calibrated using comparative techniques). Additionally background noise measurements were recorded if possible for at least two minutes before and after each measurement, when the target vessel was >5 nm away from the recording elements. AIS details of all vessels in the area were continually logged. Gain and filter settings used during each recording were noted before and after the recording and were not changed during the recording. High pass filters were positioned at their lowest settings (i.e. 1 Hz). Supplementary AIS information was collected for each target vessel including: MMSI number, speed over ground, heading over ground, direction of longitudinal axis and length and breadth of the vessel. This information was supplemented by post survey information from the IMO vessel list, to include the shipyard, year constructed, IMO number, classification, main engine type and power, number of shafts, number of propeller blades and tonnage. Where possible, additional information was collected during communications with the bridge of the target vessel including: RPMs at the present speed, load of cargo, conditions of ballast and draught (fore and aft) during measurements.

Additionally, local environmental information was collected including: depth of the water, water temperature, water salinity, wave and wind direction and speed and rain conditions. These could be supplemented post measurement by information about the current speed and direction, sediment type and distance from shore.

The bridge of a target ship was alerted to the intentions of the team on *Song of the Whale* and thus attempts were made to maintain the Closest Point of Approach (CPA) between the hydrophone and the target ship at 100 m or the overall length of the target ship, whichever was longest. The target ship was asked to maintain a straight course. When recording a target vessel, measurements were first made when the bow was within two boat lengths of the CPA; final measurements were taken when the stern was two boat lengths from the CPA. Recordings were continuous throughout the procedure but were truncated to just four lengths of the target vessel post-survey. Ideally the measurements would take place twice on the starboard and twice on the port side of the target vessel, but this was not possible in field conditions where the objective is to make the noise measurements without any significant disruption to the normal operations of the target vessel. In general only a single measurement of each vessel was obtained.

2.2 Data Analysis

During post-survey analysis, accurate estimates of a target vessel's noise signature were calculated through background noise adjustment and distance normalisation. Calculations were made using SpectraPlus 5.0 (Pioneer Hill Software, Washington). Analysis was conducted using narrow band (0.73 Hz) resolution between 20 Hz and 2 kHz and third octave band analysis between 20 Hz and 20 kHz. Absolute noise levels were derived using the RESON hydrophone's calibration values (accurate at the point of manufacture in May 2011) and knowledge of the recording system's gain settings (namely 0 dB gain with ± 1 volt scaling).

2.2.1 Background noise

Before and after recording a target ship, background noise was measured for at least 120s by the same hydrophone and data acquisition system, when the target ship was more than 9.25 km (5 nautical miles) away from *Song of the Whale*. Background noise pressure (P_n) was quantified in one-third octave bands from 20 Hz to 20 kHz using root-mean square (RMS).

2.2.2 Background noise adjustment

Underwater sound pressure levels radiated from the target ship L_p were calculated in one-third octave bands from 20 Hz to 20 kHz using the following equation:

$$L_\mathrm{p} = 10\ log\ (10^{(L\mathrm{pm}/10)} - 10^{(L\mathrm{pn}/10)})$$

Where,

$_\mathrm{pm}$: Measured pressure in µPa using $10^{(L\mathrm{pm}/20)}$
$_\mathrm{pn}$: Background pressure in µPa using $10^{(L\mathrm{pn}/20)}$
L_p: Underwater sound pressure level (dB ref 1 µPa) of the target ship after background noise adjustment
L_pm: Underwater sound pressure level (dB ref 1 µPa) including background noise obtained at measurement for the target ship
L_pn: Background noise pressure level (dB ref 1µPa)

2.2.3 Data quality assessment

Measured underwater sound pressure levels were compared with the background sound pressure levels in one-third octave bands from 20 Hz to 20 kHz using the following equation:

$$L_\mathrm{d} = L_\mathrm{pm} - L_\mathrm{pn} = 10\ log\ ({}_\mathrm{pm}{}^2/{}_\mathrm{pn}{}^2)$$

Third octave bands where L_d was less than 3 dB were deemed to be masked by background noise. If L_d was less than 3 dB over the whole frequency band, the measurement was disregarded.

2.2.4 Distance normalization

Recordings for each vessel were equally divided into eight data segments with each segment representing half a boat length of the vessel's course. The above analysis was completed for each segment. L_p of each frequency band in each data segment was RMS averaged. The distance D_i in metres between the centre of each segment and the position of the hydrophones was calculated. Underwater sound levels of the target ships after distance normalization L_pdn were calculated according to the following equation:

$$L_\mathrm{pdn} = L_\mathrm{p}\ 20\ log\ (D_\mathrm{i} / D_0)$$

Where,

D_0 is the reference distance of 1 m.

3. RESULTS

A variety of vessels were recorded including cargo ships, tankers, bulk carriers, ferries and fishing vessels ranging in size from 400 to 180,000 tonnes (Table 1). Most of the vessels recorded were operating under normal circumstances and, apart from fishing vessels, did not deviate course or speed significantly during measurement (Table 2). In general, environmental conditions were less optimal for the English Channel with sea states on average above three and wind speeds of 14 knots (in the Minch sea states were below two and mean wind speed was 8 knots; Table 3). Both study sites could be considered deep-water environments (mean depth of recordings for the Channel was 87 m and 100 m for the Minch) but as shallow-water may be considered to be 75 m (i.e. one wavelength at 20 Hz) this assertion should be treated with caution. Measurements of 18 vessels were made over three days close to the Casquettes TSS in the English Channel; however as many vessels were grouped together it was not always possible for individual ship noise signatures to be recorded. As such, only 14 of the recordings could be considered of good enough quality with measured sound levels being more than 3 dB above background noise levels (Table 4). In addition, three days of recordings were made in the Minch**.** Lower levels of traffic in this area allowed for 18 recordings to be made of isolated vessels, with only two deemed to be of low quality. The sound levels presented here are calculated from the RESON hydrophone deployed from *Song of the Whale* as these are likely to be more accurate than those derived from the free-floating buoy using comparative calibration techniques.

It should be borne in mind that background noise levels were greater during the first period of recording in the English Channel (generally > 100 µPa RMS of all one-third octave bands from 20 Hz to 20 kHz) than during the second period in the Minch (generally < 100 µPa). Thus source levels estimated in the English Channel may be artificially low. The difference in background noise was largely due to the Minch being deeper and having calmer conditions during the study period; also traffic levels were much higher in the Channel and it was often difficult to measure background noise when vessels were more than 5 nm away. These differences in recording regime may have influenced the marked difference in source levels between the Channel and the Minch ($t = 8.59$; $p < 0.01$), with mean values of 151.8 and 133.3 dB re 1µPa @ 1m respectively. It should be noted however that vessels recorded in the English Channel tended to be longer (mean of 167 vs. 115 m LOA) and heavier (41,000 vs. 16,000 DWT) and thus observed source levels may genuinely reflect louder vessels.

Overall, source levels were significantly positively correlated with a number of variables, namely length, beam, tonnage, draught (fore and aft) and CPA. The strongest correlations were for draught (fore and aft), with increasing propeller depth leading to increasing source levels. Typically, cavitation decreases with propeller depth as the hydrostatic pressure increases the margin to the vapour pressure (Greeley, 1978). The observed increase in noise levels may in part be due to a reduction in the influences of oceanographic features (such as thermocline) and physical effects (such as the Lloyd mirror) as a ship's propeller and hull get deeper, thus improving the efficiency of acoustic transmission.

As L_{pdn} values were distance corrected to 1 m, it is surprising that an increase in CPA was correlated with a rise in source level. However, CPAs were significantly greater in the English Channel than the Minch (Mann-Whitney $U = 59.0$; $p = 0.028$) in part due to reduced manoeuvrability in and near the TSS. Thus the observed increase in source level with increasing CPA is likely to reflect the two different recording regimes. Vessels in the English Channel were typically recorded at greater CPAs and were more likely to include noise output from other nearby vessels, whereas recordings made in the Minch were more likely to be of isolated vessels. Indeed, when treating the datasets separately, there was no significant correlation between CPA and source level in the Minch (Pearson = 0.009; $p = 0.972$) but the effect was evident for the Channel recordings (Pearson = 0.665; $p = 0.009$). Care should thus be taken when evaluating the noise levels measured close to the TSS. The observed increase in source level with CPA could also have been due to applying a greater correction for spreading loss than actually occurred. The correction for spherical spreading used in this study, 20log(R), is perhaps excessive for the depths at which the recordings were made and there were circumstances when transmission losses may well have been less than this. When using 15log(R), a correction more appropriate when the wavelengths of interest are comparable to water depth, there is no significant correlation between source level and CPA. The observed significant correlations between source level and length, beam, tonnage, draught (fore and aft) were still evident when using 15log(R).

The non-parametric Kruskal-Wallis test was used to evaluate the variation of source level between the four recorded classes of vessel, specifically cargo ship, tanker, ferry and fishing vessel (Figure 3). There appeared to be no significant variation in source level (L_{pdn}) according to vessel class ($\chi^2_{(3)} = 3.54$; $p = 0.316$). As there appeared to be bimodal distribution of ship length (Figure 4), with 18 vessels less than 150 m long (average = 102 m) and 9 vessels more than 150 m (average = 227 m), these two length classes were compared. Longer vessels were found to have significantly higher source levels than shorter vessels, both for narrowband analysis from 20 to 2000 Hz (Mann-Whitney $U = 45$; $p = 0.025$) and third-octave bands from 20 to 20,000 Hz ($U = 34$; $p = 0.005$).

When 'in ballast', ships are typically not loaded close to their full load condition. Consequently, the propeller of a ship in ballast may be much closer to the surface and as cavitation is dependent on the pressure on the blade, cavitation is likely to be significantly worse for a vessel in ballast than in full load. Load information was only gained for 26 of the recordings in this study. Comparison of those vessels with a load versus those in ballast found no significant difference for either narrowband (Mann-Whitney $U = 63$; $p = 0.637$) or third-octave ($U = 66$; $p = 0.760$) values. However, to accurately document the effect of loading on noise levels, repeated measures of the same vessel should be made when in ballast and again when under full load.

In the Minch, a local ferry route allowed a number of recordings to be made of the same vessel under differing environmental conditions. On 17th August, the Isle of Lewis was recorded twice on different aspects (i.e. port and starboard passes) two hours apart. The same vessel was recorded twice on different aspects on 19th August over two hours apart. Although the recording conditions were generally similar, the first two passes were notably closer (< 100 m) than the two latter passes (> 500m). The RMS values for source level were all within 8 dB of each other; as 8 dB represents a 2.5 times increase in pressure, it seems unlikely this variation would be due to differences in operating conditions or environmental characteristics. As the two first passes were within half a boat length, it is likely near-field effects were influencing the measurements and should be treated with caution (the recording of the second pass showed some saturation). The standard deviations of these two passes (8 and 6 dB respectively) suggest a high degree of variation in the measurements. The two later passes were in the far-field and showed less variation; the narrowband RMS values for the range 20 to 2000 Hz were within 1 dB of each other suggesting estimates of source level for lower frequencies did not vary for these far-field passes (standard deviations of 0.5 and 2 dB respectively). As there are current efforts to reduce the contribution of shipping to ambient noise levels in the 10-300 Hz range by 3 dB (IWC, 2008) any recording system used to measure noise must have a resolution finer than 3 dB.

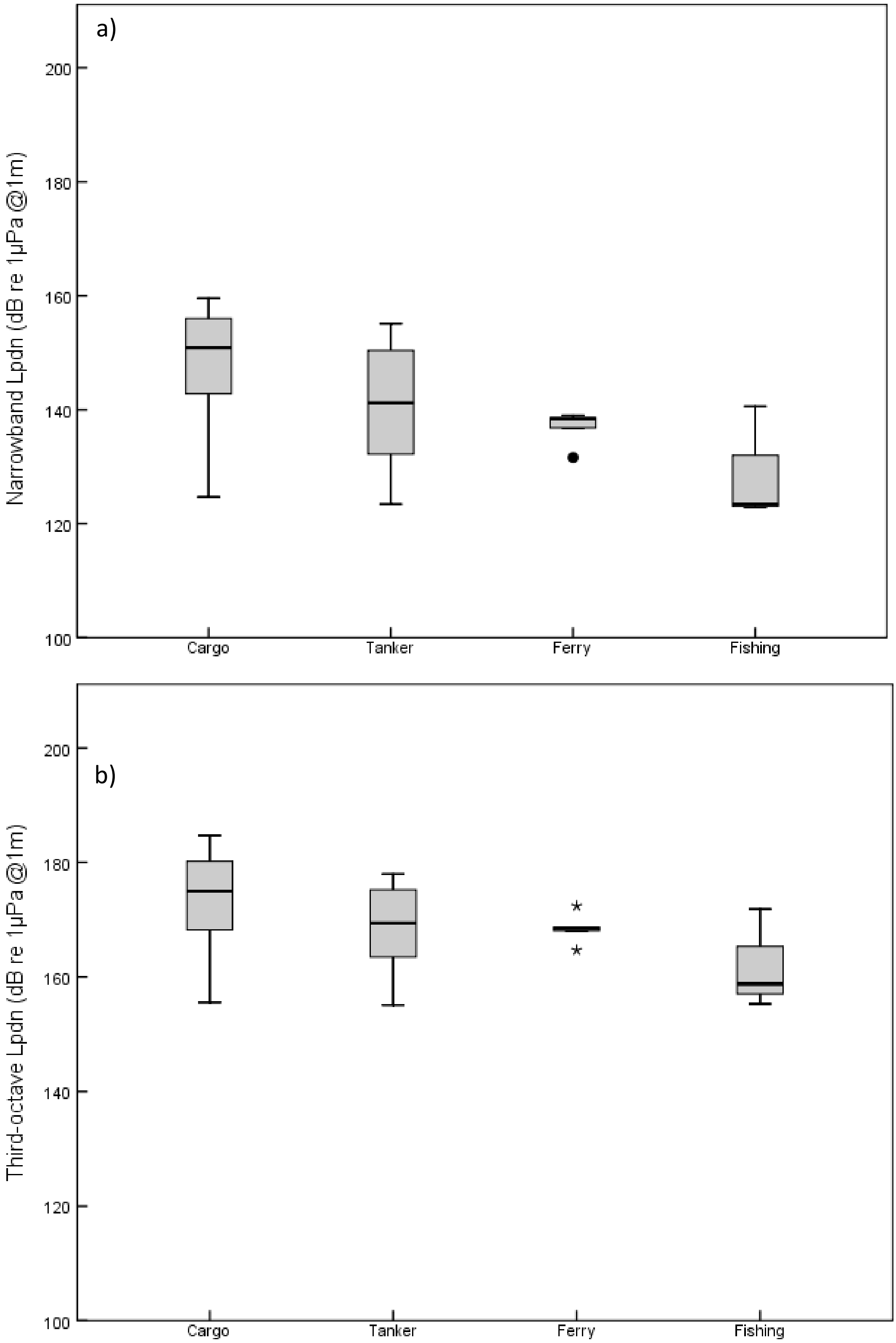

Figure 3. Source levels measured for all vessel classes using (a) third-octave bands from 20 to 20,000 Hz and (b) narrowband analysis from 20 to 2000 Hz.

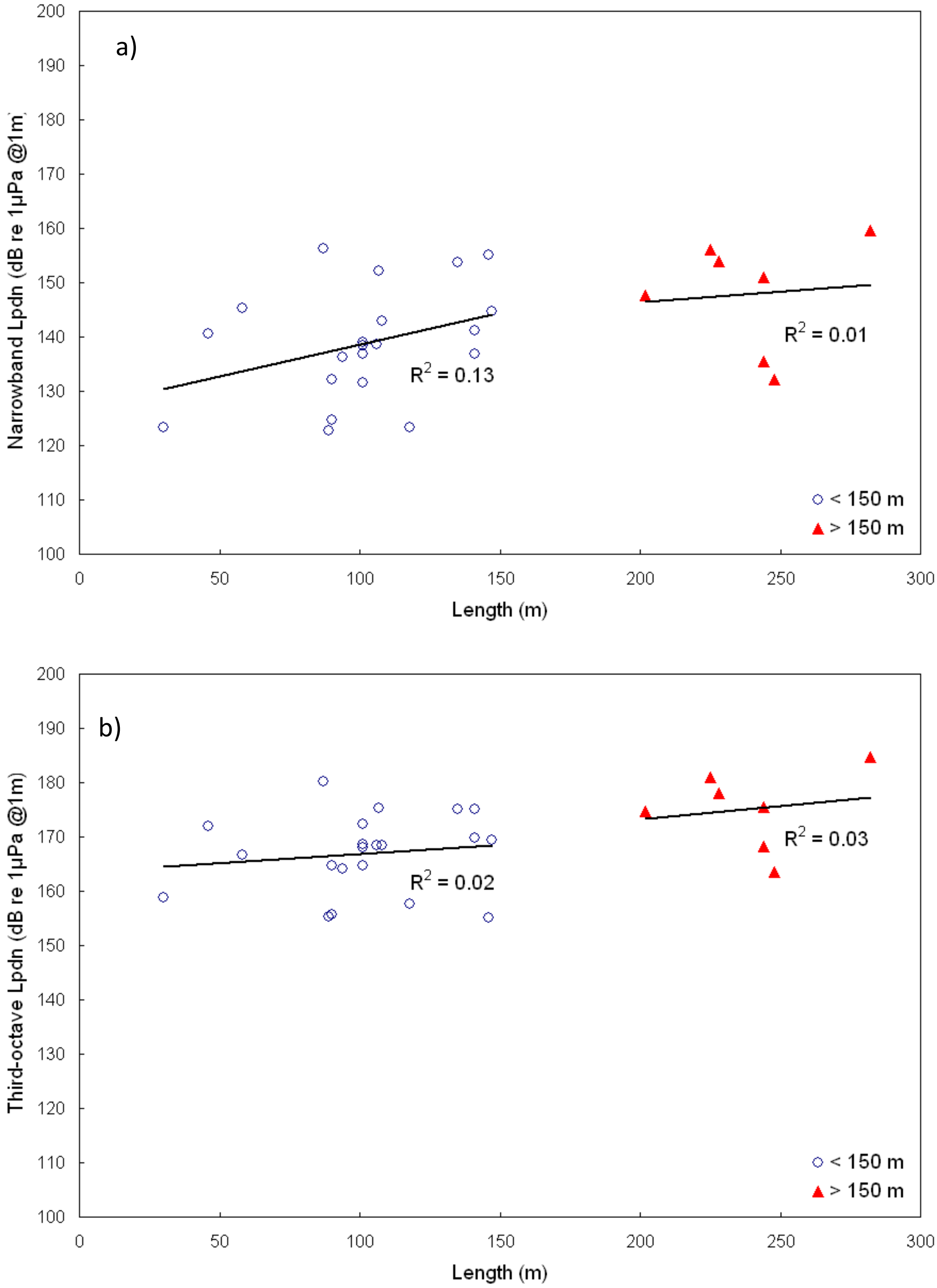

Figure 4. Source levels measured for two length classes using (a) third-octave bands from 20 to 20,000 Hz and (b) narrowband analysis from 20 to 2000 Hz. Trendlines representing linear regression provided poor descriptions of the measured values (all R^2 values less than 0.2).

Table 1. Physical attributes of all vessels recorded. Significant correlations with narrowband L_{pdn} are shown at the 95% (*) and 99% (**) levels.

Ship	IMO #	MMSI #	Class	Year	Tonnage (gross)*	Tonnage (deadweight)*	Length (m)**	Beam (m)*	Draught (m)	Sea-going speed (kn)	Sea-going RPM**
Aral	8125454	248693000	Tanker	1982	5285	8915	115	16	8.2	9.9	-
Burgtor	8801113	304665000	Cargo	1989	2351	3414	87	13	3.6	10.1	-
Summer	9427275	538003326	Tanker	2009	8539	13023	128	20	6.2	9.1	-
Linda Dream	9406556	636013177	Cargo	2007	90092	180180	282	45	11.3	12.3	-
Drait	9195688	244096000	Cargo	2000	2218	3650	89	12	3.6	10.7	-
Good Hope Max	9304241	232752000	Cargo	2005	40039	76739	225	32	13.7	11.9	-
Condock 5	8404991	218510000	Cargo	1984	6763	4762	107	19	3.9	12.8	5
Gluecksberg	9406960	636091692	Cargo	1984	18485	23711	176	28	8.9	15.8	90
Tern	9266190	538002657	Cargo	2003	27986	50209	190	32	6.2	6	117
MSC Nora	8511299	370413000	Cargo	1986	39892	43567	244	32	12.5	18	78
Egbert Wagenborg	9142588	245588000	Cargo	1998	6549	9150	135	16	4.5	13.2	-
Clipper Mari	9422677	311029600	Tanker	2010	11792	19355	147	24	7.6	11.4	97
Cape Talara	9569994	538003898	Tanker	2010	42010	73371	228	32	14.2	9.8	84
Libelle	9186730	236083000	Tanker	1999	8067	13050	146	20	5.6	11.1	-
Catalina	9306445	218455000	Cargo	2006	5581	7578	108	18	7	10.9	240
Nairobi	9064786	248980000	Cargo	1995	28892	41624	202	30	10.4	14.6	80
Northern Light	9318022	538004293	Tanker	2005	30053	50930	183	32	8.7	12.9	70
Burhou I	7726897	232003773	Cargo	1978	674	953	58	10	3.2	5.8	770
Muirneag	7725362	235007463	Cargo	1979	5801	3480	106	19	4	10.4	500
M Le Roch 2	9305025	228205800	Fishing	2004	999	407	46	20	6.5	10.5	-
Julien Coleou	9228681	226158000	Fishing	2000	260	-	30	9	4.5	11.4	-
Isle of Lewis	9085974	232002521	Passenger	1995	6753	867	101	18	4.2	15.9	650
Gerarda	9341770	246330000	Cargo	2006	2999	4537	94	14	4.4	12	67
Yeoman Brooks	8900517	636090339	Bulker	1991	43332	77549	244	32	12.1	11.3	89
Ternvik	9221267	219083000	Tanker	2001	9980	14796	141	22	8.3	9.5	340
E Ships Quest	9272735	538002583	Tanker	2003	5770	8501	118	19	7.7	9.6	-
Fri tide	9195676	309186000	Cargo	2000	2218	3400	89	12	4.7	9.8	1000
Viktoria viking	9521801	259385000	Live-Fish	2009	1214	1460	57	12	5	12.1	1560
Veendijk	9346718	244694000	Cargo	2009	2984	4450	90	15	4.1	11.8	800
Alfa Britania	9154232	309225000	Oil Tanker	1998	56115	99222	248	43	8.7	7.2	70
Tallin	9130224	304010867	Cargo	1997	2810	4250	90	13	5.2	8.1	600
Henty Pioneer	8416475	232002774	Oil Tanker	1985	992	1570	70	11	2.9	7.1	360
Ternhav	9232955	219082000	Tanker	2002	9980	14796	141	22	8.3	9.2	490

Table 2. Operational characteristics of all vessels. Significant correlations with narrowband L_{pdn} are shown at the 95% (*) and 99% (**) levels.

Ship	Date	Time of CPA	CPA (km)**	Speed (kn)*	Course (°T)	Load (tonnes)	Ballast	Draught aft**	Draft fore**
Aral	20/06	11:38	1.21	13	78	-	-	-	-
Burgtor	20/06	12:23	1.71	12	69	2558	0	4.6	4.6
Summer	20/06	11:59	1.32	16	73	-	-	8.2	8.2
Linda Dream	20/06	12:33	1.44	13	73	-	-	15.1	15.1
Drait	20/06	12:41	0.40	12	74	-	-	5.2	5.2
Good Hope Max	20/06	12:56	0.59	15	63	-	-	13.7	13.7
Condock 5	23/06	14:19	1.69	14	75	0	in ballast	3.6	3.6
Gluecksberg	23/06	14:34	0.20	20	80	11829	0	9.2	8.3
Tern	23/06	15:51	3.35	14	75	34500	0	9.7	9.0
MSC Nora	23/06	16:48	0.48	18	92	19931	0	10.7	9.7
Egbert Wagenborg	24/06	11:09	0.59	14	106	8619	0	7.3	7.3
Clipper Mari	24/06	11:43	0.23	12	79	12202	0	7.8	8.3
Cape Talara	24/06	13:20	2.70	15	73	0	in ballast	8.0	6.2
Libelle	24/06	13:23	2.40	16	70	9160	0	7.1	7.4
Catalina	24/06	14:50	0.14	15	77	0	in ballast	4.4	3.3
Nairobi	24/06	15:20	0.77	21	79	4459	0	8.0	4.8
Northern Light	24/06	18:13	0.91	14	252	0	in ballast	8.7	6.7
Burhou I	24/06	18:54	0.15	10	219	900	0	3.7	3.1
Muirneag	17/08	07:31	0.16	11	285	-	0	4.2	4.2
M Le Roch 2	17/08	09:00	1.88	12	276	-	-	-	-
Julien Coleou	17/08	09:00	2.00	12	274	-	-	-	-
Isle of Lewis	17/08	10:33	0.07	18	298	1000	0	4.2	4.1
Isle of Lewis	17/08	12:35	0.04	18	118	1000	0	4.2	4.1
Gerarda	17/08	16:53	0.15	11	48	0	in ballast	4.3	2.8
Yeoman Brooks	17/08	17:30	0.18	13	5	51328	0	10.7	10.6
Ternvik	18/08	06:57	1.10	14	224	10980	0	8.2	-
E Ships Quest	18/08	09:03	0.84	15	26	0	in ballast	-	-
Fri tide	18/08	10:08	0.08	12	45	0	in ballast	3.3	2.4
Viktoria viking	18/08	13:00	7.85	11	64	1224	0	5.0	5.0
Veendijk	18/08	15:01	0.12	12	192	100	0	4.0	4.0
Alfa Britania	18/08	17:08	0.58	11	44	0	in ballast	8.6	5.8
Tallin	18/08	18:58	0.09	11	61	8800	0	6.2	5.2
Henty Pioneer	19/08	07:17	0.05	9	232	0	in ballast	2.8	2.8
Isle of Lewis	19/08	10:32	0.59	17.3	295	1000	0	4.1	4.1
Ternhav	19/08	11:38	0.15	12.3	232	11505	0	8.3	8.1
Isle of Lewis	19/08	12:50	0.71	16.8	133	1000	0	4.2	4.2

Table 3. Environmental conditions for all recordings. Values presented are the mean values over four boat lengths at the point of CPA.

Ship	Lat	Long	SOG	Wind (kn)	Temp (°C)	Sea state	Waves (m)	Swell (m)	Weather	Cloud cover (%)	Visibility (nm)	Pressure	H'phone depth (m)	H'phone angle (°)	Miles to land	Depth (m)
Aral	49.92	-2.21	3.7	15.1	12.9	3	0.2	1.2	Fair	100	> 5	1014	28.94	15.3	11.2	-104
Burgtor	49.94	-2.15	2.1	5.9	12.9	3.5	0.3	1.5	Fair	100	> 5	1014	29.79	6.8	12.3	-83
Summer	49.93	-2.18	2.7	12.1	12.9	3.5	0.3	1.5	Fair	100	> 5	1014	29.89	4.9	11.9	-88
Linda Dream	49.94	-2.14	2.5	8.4	12.9	3	0.2	1.3	Drizzle	100	2 - 5	1014	29.90	4.8	12.5	-68
Drait	49.94	-2.14	2	17.8	12.9	3	0.2	1.3	Drizzle	100	2 - 5	1014	29.91	4.4	12.6	-69
Good Hope Max	49.95	-2.13	1.9	13.9	12.9	3	0.2	1.3	Drizzle	100	2 - 5	1014	29.11	14.0	12.9	-66
Condock 5	49.91	-2.22	2.2	19.9	13.1	4	0.5	0.75	Fair	20	> 5	1021	26.42	28.3	10.0	-116
Gluecksberg	49.91	-2.20	2.7	19.6	13.2	4	0.5	0.75	Fair	20	> 5	1021	24.80	34.2	10.4	-104
Tern	49.91	-2.21	1.2	22.1	13.1	4	0.5	1.25	Fair	20	> 5	1021	27.56	23.3	10.5	-105
MSC Nora	49.92	-2.19	0.3	21	13.1	4	0.5	1.25	Fair	20	> 5	1021	26.06	29.7	10.9	-105
Egbert Wagenborg	49.90	-2.32	1.5	18.8	13.3	3.5	0.3	0.5	Fair	40	> 5	1026	27.88	21.7	9.7	-121
Clipper Mari	49.91	-2.30	1.4	10	13.3	3	0.2	0.5	Fair	40	> 5	1026	29.00	14.8	10.2	-125
Cape Talara	49.94	-2.22	2.6	14.8	13.3	3	0.2	0.5	Fair	40	> 5	1026	28.73	16.7	12.1	-85
Libelle	49.94	-2.22	2.8	13.9	13.3	3	0.2	0.5	Fair	40	> 5	1026	28.22	19.8	12.2	-67
Catalina	49.97	-2.13	2.4	10	13.3	3	0.2	0.4	Fair	40	> 5	1026	29.55	9.9	14.2	-69
Nairobi	49.98	-2.10	1.9	10.8	13.3	3	0.2	0.4	Fair	40	> 5	1026	28.73	16.7	14.6	-66
Northern Light	50.10	-2.09	0.9	9.4	13.1	3	0.1	0.3	Fair	100	> 5	1026	29.98	2.3	22.4	-58
Burhou I	50.11	-2.11	1.3	10.8	13	3	0.1	0.3	Fair	100	> 5	1026	29.44	11.1	22.4	-58
Muirneag	58.14	-6.22	0.7	6.5	13.3	2	0.2	0	Fair	70	> 5	1015	29.90	4.7	2.6	-114
M Le Roch 2	58.14	-6.18	0.8	9.8	13.3	2	0.1	0	Fair	70	> 5	1016	29.78	7.0	2.6	-119
Julien Coleou	58.14	-6.18	0.9	10	13.3	2	0.1	0	Fair	70	> 5	1016	29.73	7.7	2.6	-119
Isle of Lewis	58.15	-6.15	0.6	5	13.3	2	0.1	0	Fair	70	> 5	1016	29.99	1.3	2.9	-119
Isle of Lewis	58.13	-6.15	0.5	10.9	13.4	3	0.2	0.1	Drizzle	100	> 5	1017	29.66	8.7	4.1	-118
Gerarda	58.00	-5.92	0.4	8.3	12.9	2	0.1	0	Fair	70	> 5	1018	29.52	10.3	9.0	-74
Yeoman Brooks	58.00	-5.91	0.4	6.7	12.8	2	0.1	0	Fair	70	> 5	1018	29.33	12.2	8.8	-74
Ternvik	57.95	-6.29	0.3	4	12.5	0.5	0	0	Fair	90	> 5	1018	29.92	4.2	2.9	-113
E Ships Quest	57.86	-6.04	0	2.4	12.6	0.5	0	0	Fair	90	> 5	1018	29.80	6.6	7.3	-94
Fri tide	57.86	-6.04	0	3.5	12.8	0.5	0	0	Fair	90	> 5	1018	29.77	7.1	7.1	-84
Viktoria viking	57.87	-6.04	0.4	3.7	12.9	0.5	0	0	Fair	90	> 5	1019	29.80	6.7	7.3	-84
Veendijk	57.96	-6.27	0.7	3.4	13.3	0.5	0	0	Fair	90	> 5	1019	29.84	5.9	4.0	-45
Alfa Britania	57.86	-6.06	0.8	5.3	12.8	2	0	0	Fair	60	> 5	1018	29.84	5.9	7.8	-94
Tallin	57.84	-6.07	0	4.8	12.6	2	0	0	Fair	60	> 5	1018	29.98	1.9	8.2	-109
Henty Pioneer	57.98	-5.74	0.5	7.5	12.6	3	0.15	0.1	Fair	20	> 5	1014	29.77	7.2	4.8	-107
Isle of Lewis	58.11	-6.09	1	17.4	13.4	3	0.2	0.3	Fair	80	> 5	1012	27.57	23.2	5.7	-108
Ternhav	58.13	-6.10	0.9	17.2	13.4	3.5	0.3	0.5	Fair	90	> 5	1012	27.89	21.6	4.7	-117
Isle of Lewis	58.10	-6.12	0.9	18.6	13.4	4	0.5	0	Fair	100	> 5	1011	28.94	15.3	5.7	-100

Table 4. Summary of noise levels measured from R/V *Song of the Whale*. The quality of recordings was quantified by comparing gross sound pressure levels with the background underwater sound pressure level (L_d); an additional measure of quality is provided by the percentage of L_d values that are > 3 dB above background noise levels (100% representing highest quality). Those recordings with background noise pressure (P_n) considered to be disproportionately high (within 3 dB of the target ship's sound level) are marked with a minus (-) and grey text. Underwater sound levels L_{pdn} of the target ships are presented as RMS averages of all frequency bands with distance normalization referenced to 1m.

Ship	Mean L_d (dB re 1µPa)	Percent of $^1/_3$ octave bands > 3 dB above background	Mean P_n (µPa)	RMS of L_{pdn} (dB re 1µPa @1m; narrowband 20-2000 Hz) ± sd	RMS of L_{pdn} (dB re 1µPa @1m; $^1/_3$ octave 20-20000 Hz) ± sd
Aral -	0.4	32	114.2	176.3 (± 0.5)	153.3 (± 0.7)
Burgtor	3.8	58	116.0	180.1 (± 0.5)	156.2 (± 0.4)
Summer -	2.8	26	112.0	175.8 (± 0.7)	151.9 (± 0.7)
Linda Dream	10.6	90	120.8	184.7 (± 1.1)	159.6 (± 1.3)
Drait -	-0.8	3	110.5	161.5 (± 0.9)	136.6 (± 1.2)
Good Hope Max	3.9	77	121.0	180.9 (± 0.7)	156.0 (± 0.5)
Condock 5	5.0	71	116.8	175.3 (± 1.2)	152.2 (± 0.5)
Gluecksberg -	1.6	29	112.5	163.8 (± 3.6)	138.5 (± 3.5)
Tern	3.4	58	108.2	182.1 (± 0.8)	157.0 (± 0.5)
MSC Nora	15.2	100	105.1	175.5 (± 3.3)	150.8 (± 3.4)
Egbert Wagenborg	14.6	100	104.9	175.0 (± 0.7)	153.8 (± 0.4)
Clipper Mari	18.1	97	102.0	169.3 (± 1.4)	144.6 (± 1.8)
Cape Talara	5.5	74	103.7	177.9 (± 1.1)	153.9 (± 0.9)
Libelle	8.4	84	111.0	155.0 (± 0.1)	155.0 (± 0.1)
Catalina	17.1	97	110.3	168.3 (± 0.7)	142.8 (± 1.6)
Nairobi	8.4	90	108.4	174.6 (± 0.3)	147.6 (± 0.4)
Northern Light	13.5	100	102.3	175.9 (± 2.0)	150.4 (± 1.4)
Burhou I	19.1	97	102.5	166.7 (± 1.6)	145.2 (± 1.0)
Muirneag	29.1	97	93.1	168.5 (± 0.6)	138.6 (± 1.7)
M Le Roch 2	22.4	100	106.6	171.9 (± 0.4)	140.5 (± 1.2)
Julien Coleou	8.6	100	93.1	158.7 (± 0.5)	123.3 (± 1.7)
Isle of Lewis	34.0	100	99.6	164.7 (± 8.0)	131.6 (± 9.7)
Isle of Lewis	37.9	100	90.9	168.0 (± 6.0)	136.8 (± 6.6)
Gerarda	32.5	100	89.3	164.1 (± 1.7)	136.2 (± 1.9)
Yeoman Brooks	31.0	100	86.7	168.2 (± 0.8)	135.5 (± 1.7)
Ternvik	20.7	97	94.2	175.1 (± 1.8)	141.2 (± 3.7)
E Ships Quest	20.1	100	90.5	157.5 (± 0.4)	123.4 (± 1.5)
Fri tide	20.1	100	89.7	155.2 (± 1.1)	122.7 (± 2.2)
Viktoria viking -	2.4	32	91.3	168.3 (± 0.7)	142.5 (± 1.9)
Veendijk	21.2	100	90.0	155.5 (± 0.7)	124.6 (± 1.7)
Alfa Britania	14.6	100	92.4	163.5 (± 0.3)	132.1 (± 1.8)
Tallin	32.3	100	89.4	164.7 (± 2.1)	132.0 (± 4.6)
Henty Pioneer -	1.9	23	88.9	130.2 (± 3.9)	98.32 (± 4.0)
Isle of Lewis	21.6	94	98.0	172.4 (± 0.5)	139.0 (± 1.2)
Ternhav	25.0	94	98.8	169.8 (± 2.5)	136.8 (± 3.4)
Isle of Lewis	16.5	90	96.4	168.6 (± 2.1)	138.3 (± 1.5)

4. DISCUSSION

Over six days of field work, 36 separate recordings were made of 33 vessels. Of these, six were considered to have significant levels of masking and were thus excluded from further analysis. The remaining measurements of 27 vessels suggested noise output was in part influenced by vessel characteristics. Length, beam, tonnage, draught (fore and aft) and CPA were found to be positively correlated with source level. Vessels longer than 150 m had higher noise levels than shorter vessels. Presumably larger vessels lower in the water present a greater surface area for vibrational transmission through the hull and may also be liberated from near-surface influences (e.g. Lloyd mirror, thermocline). Most of the noise recorded was produced by propeller cavitation, although propeller resonance was also occasionally evident as a strong tone between 100 and 1000 Hz. Whilst these sound sources are external to the hull, it is likely the total noise output of an individual vessel also included in-board propulsive machinery, the noise from which would pass into the water column through the hull.

The minimum and maximum bounds of the power spectra for the ships recorded are displayed in Figure 5. The range of values presented is similar to those reported elsewhere (e.g. Carlton & Dabbs, 2009; Hatch *et al*., 2008; Wittekind, 2008). This study adds weight to the suggestion that typical merchant ships exhibit noise ranges which differ by as much as 40 dB from the upper bound to the lower bound. This implies there is some potential to reduce the noise level of the noisiest ships substantially. It is likely that most of the vessels recorded in this study were operating above the Cavitation Inception Speed, typically around 10 knots for larger ships (Arveson & Vendittis, 2000). As the main source of ship noise relates to propeller cavitation, improvements in propeller design and modification of wake flow may also reduce noise.

Although not conducted in the controlled environment of a noise measurement facility, the procedures described here are relatively cost-effective and have a number of advantages over typical measures of vessels quantified during sea-trials. The measurements could generally take place in deeper waters (100 m) with vessels operating under their typical operating states. Many of the vessels had been in service for several years (one cargo ship was over 30 years old) and as older vessels may produce more noise output, it is pragmatic to monitor vessels throughout their lifespan rather than just the point of launch. Although the distance to a passing vessel can be controlled to a greater degree during sea trials, the captains of all the vessels recorded in this study were extremely courteous and obliging, and thus it was possible to get numerous recordings of close passes. One major drawback with the procedure described in this study was the inability to record ships over repeated closes passes, a contingency that may be possible during a sea-trial. However, some vessels, such as ferries, lend themselves to repeated measures, thus allowing an assessment of the effect of ship aspect, loading, speed, etc. over several passes.

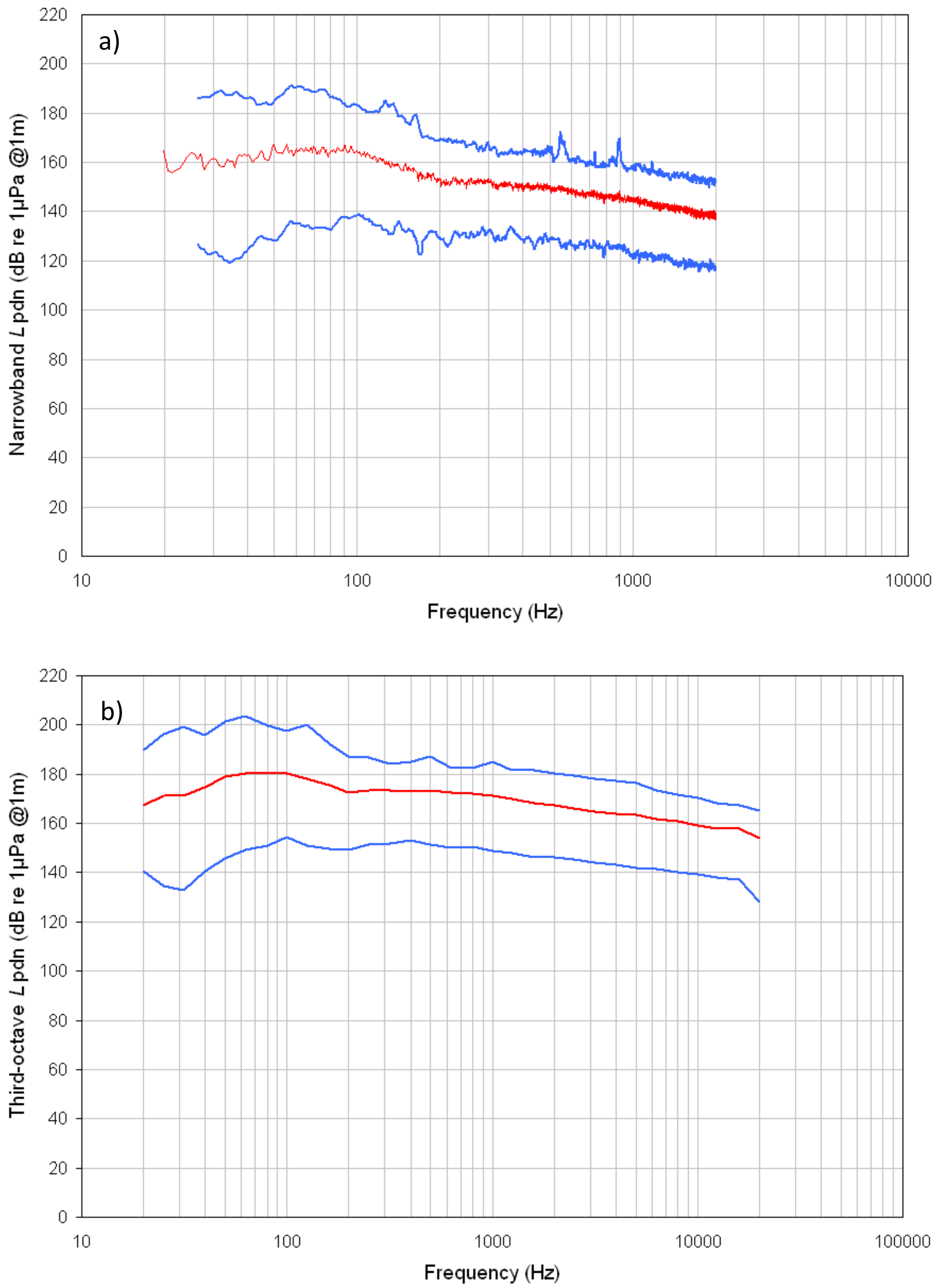

Figure 5. The minimum and maximum bounds (shown in blue) of the power spectra for all tankers and cargo ships measured using (a) narrowband analysis from 20 to 2000 Hz and (b) third-octave bands from 20 to 20,000 Hz. The mean source level (dB re 1µPa @1m) is shown as the central red line.

Although the ISO methodology provides a useful approach to profiling ship noise at sea, trialling the procedures in the field has identified several aspects of the standard that could potentially be improved upon:

4.1 Inclinometer

Using the methodology outlined within the ISO document, it was rarely possible in real-field conditions to get the inclinometer consistently below 5° error due to the effects of wind on the measurement vessel and/or current on the hydrophone. Increasing the weight at the terminal end of the hydrophone also increased drag, exacerbating the angle. In future, if the methodology were to remain the same it may be wise to try using a depressor weight designed to reduce drag. However, it is suggested instead of a minimum angle for the hydrophone being stated in the ISO methodology, a minimum depth for the hydrophone is stipulated, as this would be easier to maintain and is ultimately what the inclinometer data is used for.

4.2 Range

The ISO methodology calls for background noise measurements to be made when the target vessel is more than 5 nm away. If the sound level measured from a target ship was not more than 3 dB above background levels, the ship noise was considered to be masked. These requirements were compromised in two main regards; firstly, measurements made at 5 nm or more from a vessel still included some noise output from the target vessel and therefore cannot be considered accurate measurements of background noise. Secondly, in busy areas (such as the English Channel), the background noise level was rarely less than 3 dB below that of the target vessel.

4.3 Repeated measures

The ISO methodology asks for repeated measurements of each vessel at least twice on each side, port and starboard. In field conditions, where the measurements are very much opportunistic, it is unlikely that the same vessel will ever be measured in the same location on each side twice. One measurement of the vessel following the ISO methodology could be considered sufficient.

An obstacle to implementing efficiency measures to reduce ship noise is in moving from theoretical predictions and models to full scale measurements of noise at sea with vessels under typical operating conditions. The development of standards by ISO and ANSI/ASA has highlighted some of the difficulties in obtaining sufficiently precise measurements that can be compared between studies. A further difficulty is that the noise output from individual ships can vary considerably. For example, even in a nearly calm sea the amplitude of blade rate can exhibit a long term standard deviation of about 5 dB due to changes in inflow caused by such effects as the pitch of the ship (Arveson & Vendittis, 2000). At higher sea states the fluctuations in blade rate noise levels are likely to be even higher. In order to document the subtle changes in noise output under different operating conditions extensive data sets are required. The procedure described in this report provides a simple approach to measuring the noise levels of vessels under typical operating conditions at sea and developing such data sets.

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6. REFERENCES

Andrew, R. K., Howe, B. M., Mercer, J. A. and Dzieciuch, M. A. 2002. Ocean ambient sound: Comparing the 1960s with the 1990s for a receiver off the California coast. *Acoustic Research Letters Online* 3(2).

Arveson, P. & Vendittis, D. 2000. Radiated noise characteristics of a modern cargo ship. *J. Acoust. Soc. Am*., 107(1): 118-129.

Bailey, H., Senior, B., Simmons, D., Rusin, J., Picken, G. and Thompson, P. M. 2010. Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. *Marine Pollution Bulletin* 60: 888–897.

Balcomb, K. C. III, and D. E. Claridge. 2001. A mass stranding of cetaceans caused by naval sonar in the Bahamas. *Bahamas Journal of Science* 5:1–12.

Brandt, M. J., Diederichs, A., Betke, K. and Nehls, G. 2011. Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. *Marine Ecology Progress Series* 421: 205-216.

Carlton, J. S. and Dabbs, E. 2009. *The influence of ship underwater noise emissions on marine mammals.* Lloyd's Register Technology Day Proceedings, February 2009.

Cox, T. M., Ragen, T. J., Read, A. J., Vos, E., Baird, R. W., Balcomb, K. C., Barlow, J., Caldwell, J. P., Cranford, T., Crum, L. A., D'Amico, A., D'Spain, G., Fernandez, A., Finneran, J., Gentry, R. L., Gerth, W., Gulland, F., Hildebrand, J., Houser, D., Hullar, T., Jepson, P. D., Ketten, D., MacLeod, C. D., Miller, P. J., Moore, S. E., Mountain, D. C., Palka, D., Ponganis, P. J., Rommel, S., Rowles, T., Taylor, B. L., Tyack, P., Wartzok, D., Gisiner, R., Mead, J. G. and Benner, L. 2006. Understanding the impacts of anthropogenic sound on beaked whales. *J. Cetacean Res. Manage*. 7(3): 177–187.

Di Iorio, L. and Clark, C. W. 2010. Exposure to seismic survey alters blue whale acoustic communication. *Biology Letters* 6: 51-54.

Evans, D. L., & G. R. England. 2001. *Joint interim report Bahamas marine mammal stranding event of 15–16 March 2000*. US Department of Commerce and US Navy, Washington, D.C.

Fernández, A., Edwards, J. F., Rodriguez, F., de los Monteros, A. E., Herraez, P., Castro, P., Jaber, J. R., Martin, V. & Arbelo, M. 2005. "Gas and fat embolic syndrome" involving a mass stranding of beaked whales (family Ziphiidae) exposed to anthropogenic sonar signals. *Veterinary Pathology* 42:446–457.

Frantzis, A. 1998. Does acoustic testing strand whales? *Nature* 392(6671): 29-29.

Greeley, D. S. 1978. *Calculation of low frequency cavitation source strength of marine propellers*. Bolt Beranek and Newman, Inc., Technical Memorandum 459..

Hatch, L., Clark, C., Richard, M., Van Parijs, S., Ponirakis, D., Schwehr, K., Thompson, M. and Wiley, D. 2008. Characterizing the relative contributions of large vessels to total ocean noise fields: A case study using the Gerry E. Studds Stellwagen Bank National Marine Sanctuary. *Environmental Management* 42: 735-752.

Hildebrand, J. 2004. *Impacts of anthropogenic sound on cetaceans*. IWC Scientific Committee, IWC/SC/56/E13, 32 pp.

Jepson, P. D., Arbelo, M., Deaville, R., Patterson, I. A. P., Castro, P., Baker, J. R., Degollada, E., Ross, H. M., Herraez, P., Pocknell, A. M., Rodriguez, F., Howie, F. E., Espinosa, A., Reid, R. J., Jaber, J. R., Martin, V., Cunningham, A. A. and Fernandez, A. 2003. Gas-bubble lesions in stranded cetaceans - Was sonar responsible for a spate of whale deaths after an Atlantic military exercise? *Nature* 425(6958): 575-576.

Leaper, R., Renilson, M. R., Frank, V. and Papastavrou, V. 2009. *Possible steps towards reducing impacts of shipping noise*. Presented to the IWC Scientific Committee, June 2009, Madeira, Portugal, SC/61/E19.

Martín, V., Servidio, A. & García, S. 2004. *Mass strandings of beaked whales in the Canary Islands*. In: Evans, P. G. H. & Miller, L. A. eds. Proceedings of the workshop on active sonar and cetaceans. ECS special issue 42: 33–36.

McCauley, R. D., Fewtrell, J., Duncan, A. J., Jenner, C., Jenner, M.-N., Penrose, J. D., Prince, R. I. T., Adhitya, A., Murdoch, J. and McCabe, K. 2000. Marine seismic surveys - A study of environmental implications. *APPEA*: 692-707.

McDonald, M. A., Hildebrand, J. A. and Wiggins, S. M. 2006. Increases in deep ocean ambient noise in the northeast pacific west of San Nicolas Island, California. *Journal of the Acoustical Society of America* 120(2): 711-718.

Morton, A. B. and Symonds, H. K. 2002. Displacement of Orcinus orca (L.) by high amplitude sound in British Columbia, Canada. *Ices Journal of Marine Science* 59(1): 71-80.

Simmonds, M. P., and L. F. Lopez-Jurado. 1991. Whales and the military. *Nature* 351:448.

Thomsen, F., Lüdemann, K., Kafemann, R. and Piper, W. 2006. *Effects of offshore wind farm noise on marine mammals and fish*. Hamburg, Germany. Prepared by biola on behalf of COWRIE Ltd., 62 pp.

Weilgart, L. 2007. The impacts of athropogenic ocean noise on cetaecans and implications for management. Can. *J. Zool*. 85: 1091-1116.

Wittekind, D. 2008. *Noise radiation of merchant ships*. DW-ShipConsult, 10 July 2008. 44 pages.