

**REPORT OF DEFRA CONTRACT ME5217:  
ADDITIONAL ANALYSIS OF NOISE DATA  
FROM DEFRA PROJECT ME5210**

**LIAN WANG  
STEPHEN ROBINSON**  
Version 3 (post peer review)

**MARCH 2015**



Report of DEFRA contract ME5217:  
Additional analysis of noise data from DEFRA project ME5210

Lian Wang, Stephen P. Robinson  
National Physical Laboratory

## SUMMARY

This report describes the work for project ME5217, titled “Additional analysis of noise data from DEFRA project ME5210”. The project was commissioned by Department of Food, Environment and Rural Affairs (DEFRA) on 13th February, 2014. In project ME5217, the National Physical Laboratory (NPL) undertook additional analysis of the acoustic data acquired during project ME5210, a project undertaken by the Centre for Environment, Fisheries and Aquaculture Science (Cefas) during the period October 2010 to August 2013. In project ME5210, acoustic data were obtained from a deployment close to the West Gabbard Cefas SmartBuoy site using an Aural M2 recorder mounted on a large steel lander frame, the recorder being deployed for a duration of 49 days between April and June 2013. Only limited analysis was possible by Cefas during project ME5210.

The deployment at West Gabbard has enabled a number of lessons to be learned. In the additional analysis reported here, NPL has assessed the data quality, identifying data which are contaminated by artefacts, and identifying data which are suitable for further analysis. The results show that the 63 Hz and 125 Hz third-octave frequency bands nominated for assessment by the EU Marine Strategy framework Directive (MSFD) are suitable bands for monitoring ship borne noise, although adjacent frequency bands would also be a suitable choice and may be monitored at no greater cost. The parts of the data uncontaminated by artefacts provides one of the few datasets recorded so far in UK waters close to a busy shipping traffic area which has been sampled over a reasonable time period. It provides a valuable estimate of the statistical distribution of background noise as the levels vary with time in shallow UK waters.

NPL has correlated the noise data suitable for analysis with AIS data for ship movements provided as part of project ME5210. The analysis has concentrated on the frequency range 50 Hz to 160 Hz where shipping noise is most prevalent. This is also the range of relevance to the MSFD. A comparison has been undertaken of the measured levels of noise in third-octave frequency bands in the range 50 Hz to 160 Hz with predicted levels of noise from models of noise radiated from vessels in adjacent shipping lanes. The results show that such models show significant promise as a tool to represent shipping traffic noise, but that there are a number of aspects requiring further research to determine the accuracy and reliability. An assessment was also made of the effect of reducing the sampling duty cycle to make an assessment of whether continuous sound recordings are necessary; reducing the duty cycle in this way has little effect on the statistical distribution of the data analysed here, but this lack of sensitivity to duty cycle depends somewhat on the statistical nature of the dataset.

The limited duration and quality of the data obtained from project ME5210 do not lend themselves to making definitive conclusions with regard to trends in the measured noise, or the necessary spatial resolution of necessary field monitoring stations. However, as far as is possible, and with due consideration to discussions currently underway in other European projects, a discussion is provided of the desirable combination of field observations and modelling to provide a robust assessment of ambient noise in UK waters.

© NPL Management Limited, 2015

ISSN: **1754-2936**

National Physical Laboratory  
Hampton Road, Teddington, Middlesex, TW11 0LW

Approved on behalf of NPLML by  
Dr. G. Schettino, Knowledge Leader

**Customer:**

Tarquin Dorrington  
 Marine Programme Manager  
 Marine and Fisheries Evidence  
 Department for Environment Food and Rural Affairs  
 9 Millbank  
 London  
 SW1P 3GE

**NPL contact:**

Stephen Robinson  
 Principal Research Scientist  
 Acoustics Group  
 National Physical Laboratory  
 Middlesex TW11 0LW  
 Phone: +44 (0)20 8943 7152  
 Email: [stephen.robinson@npl.co.uk](mailto:stephen.robinson@npl.co.uk)

| Action          | Report version | Date       |
|-----------------|----------------|------------|
| NPL Draft issue | 1.0            | 2014-04-17 |
| DEFRA Review    | 2.0            | 2014-06-07 |
| Peer review     | 3.0            | 2015-03-10 |

**Version history**

Version 1.0 – Draft issued: 17<sup>th</sup> April 2014  
 Version 2.0 – Revised draft issued: 7<sup>th</sup> July 2014  
 Version 3.0 – Revised draft issued: 10<sup>th</sup> March 2015

# CONTENTS

|           |                                                                                       |           |
|-----------|---------------------------------------------------------------------------------------|-----------|
| <b>1.</b> | <b>INTRODUCTION .....</b>                                                             | <b>1</b>  |
| 1.1       | BACKGROUND .....                                                                      | 1         |
| 1.2       | DATA AVAILABLE FOR ANALYSIS .....                                                     | 1         |
| 1.3       | WORK PLAN FOR PROJECT ME5217 .....                                                    | 2         |
| 1.4       | ORGANISATION OF THIS REPORT .....                                                     | 2         |
| <b>2.</b> | <b>ANALYSIS OF MEASURED DATA .....</b>                                                | <b>3</b>  |
| 2.1       | CONTAMINATING ARTEFACTS IN THE MEASURED DATA .....                                    | 3         |
| 2.1.1     | <i>Data clipping</i> .....                                                            | 3         |
| 2.1.2     | <i>Deployment platform and mooring noise</i> .....                                    | 4         |
| 2.1.3     | <i>Flow-related noise</i> .....                                                       | 5         |
| 2.2       | RECORDER PERFORMANCE AND CALIBRATION .....                                            | 9         |
| 2.3       | ANALYSIS OF OVERALL NOISE LEVELS .....                                                | 10        |
| <b>3.</b> | <b>COMPARISON OF MEASUREMENT WITH PREDICTIONS.....</b>                                | <b>16</b> |
| 3.1       | ANALYSIS OF AIS DATA .....                                                            | 16        |
| 3.2       | MODELLING THE SHIP TRAFFIC NOISE .....                                                | 18        |
| 3.2.1     | <i>Vessel source levels</i> .....                                                     | 18        |
| 3.2.2     | <i>Bathymetry and environmental data</i> .....                                        | 20        |
| 3.2.3     | <i>Propagation models</i> .....                                                       | 22        |
| 3.2       | COMPARISON OF PREDICTIONS WITH MEASURED DATA .....                                    | 23        |
| 3.3.1     | <i>Predicted and measured sound pressure levels with a generic source level</i> ..... | 23        |
| 3.3.2     | <i>The effect of different sediment on the modelled SPL</i> .....                     | 24        |
| 3.3.3     | <i>Modified source level for prediction</i> .....                                     | 25        |
| <b>4.</b> | <b>DISCUSSION AND CONCLUSIONS.....</b>                                                | <b>27</b> |
| 4.1       | ISSUES WITH DATA QUALITY AND DEPLOYMENT CONFIGURATION .....                           | 27        |
| 4.1.1     | <i>Data quality</i> .....                                                             | 27        |
| 4.2.2     | <i>Deployment configuration</i> .....                                                 | 27        |
| 4.2.3     | <i>Choice of recorder</i> .....                                                       | 28        |
| 4.2       | DATA ANALYSIS .....                                                                   | 29        |
| 4.3       | NOISE PREDICTION AND SHIP TRAFFIC DATA .....                                          | 30        |
| 4.3.1     | <i>Issues with use of the ship traffic data</i> .....                                 | 30        |
| 4.3.2     | <i>Noise predictions</i> .....                                                        | 30        |
| 4.4       | IMPLICATIONS FOR NOISE MONITORING FOR MSFD .....                                      | 31        |
| 4.4.1     | <i>The use of modelling</i> .....                                                     | 32        |
| 4.4.2     | <i>Location</i> .....                                                                 | 32        |
| 4.4.3     | <i>Measurement stations to provide ship source level information</i> .....            | 33        |
| 4.5       | CONCLUSIONS.....                                                                      | 34        |
| <b>5.</b> | <b>ACKNOWLEDGEMENTS .....</b>                                                         | <b>35</b> |
| <b>6.</b> | <b>REFERENCES .....</b>                                                               | <b>36</b> |
|           | <b>GLOSSARY AND LIST OF ABBREVIATIONS.....</b>                                        | <b>39</b> |

## 1. INTRODUCTION

This report describes the work undertaken for project ME5217, commissioned by Department of Food, Environment and Rural Affairs (DEFRA) on 13th February, 2014. In this project, the National Physical Laboratory (NPL) undertook additional analysis of the acoustic data acquired during a previous DEFRA, project ME5210, which was undertaken by the Centre for Environment, Fisheries and Aquaculture Science (Cefas) between 2010 and 2013.

The project undertaken by NPL (ME5217) has the title “Additional analysis of noise data from DEFRA project ME5210”.

### 1.1 BACKGROUND

Project ME5210, titled “Monitoring ambient noise for the Marine Strategy Framework Directive”, was commissioned by DEFRA in October 2010 and undertaken by Cefas. The project was set up to consider the scientific aspects of implementing indicator 11.2, the ambient noise indicator of the Marine Strategy Framework Directive (MSFD) [EU 2008, EU2010] for the United Kingdom, and to gain insight into the requirements of the monitoring programme for indicator 11.2.

During the above project, two deployments of acoustic recorders were carried out. The first, at a location south of the Isle of Wight, was unsuccessful, with the recording buoy being lost and no data retrieved.

However, another deployment was carried out close to the West Gabbard Cefas SmartBuoy site using an Aural M2 recorder manufactured by Multi-Electronique mounted on a large steel lander frame. The recorder was deployed for 49 days between April and June 2013. The Aural M2 was successfully recovered, and the data made available for analysis. However, only a preliminary analysis was possible by Cefas within project ME5210.

### 1.2 DATA AVAILABLE FOR ANALYSIS

During the second deployment of project ME5210 at Greater Gabbard, approximately seven weeks of data were collected, with the deployment lasting from 15<sup>th</sup> April to 2<sup>nd</sup> June 2013. The recorder was used with a sampling rate of 32.768 kHz with the recorder set to a continuous sampling regime. The recordings were continuous except for periodic gaps. The gaps in the recordings occur when the instrument is writing data stored on the flash drive to hard disk, occupying approximately 1 minute at the end of each 18 minute file.

The recorder produced 3,842 files, each file containing 17 minutes of usable data lasting for a total approximately 1,088 hours.

In addition, ship traffic data from the Automatic Identification System (AIS) for the West Gabbard area over the time periods of 10<sup>th</sup> to 25<sup>th</sup> of April and 9<sup>th</sup> of May to 5<sup>th</sup> of June have been made available to the project from the Marine Coastguard Agency.

All of the above data were made available to the National Physical Laboratory for project ME5217.

### 1.3 WORK PLAN FOR PROJECT ME5217

In project ME5217, the National Physical Laboratory (NPL) has undertaken additional analysis of the acoustic data acquired during project ME5210. Only very limited analysis had been possible by Cefas during project ME5210.

The overall aim of project ME5217 was to extract additional information from the ME5210 data, in order to provide additional advice for the design and implementation of future monitoring programmes for descriptor 11 of the MSFD. The additional analysis concentrates on the low frequency range where shipping noise dominates the ambient noise spectrum.

The specific objectives were as follows:

- To assess the data quality, identifying any data which are too contaminated by artefacts such as flow noise, and identifying data which are suitable for further analysis;
- To determine whether the frequency bands nominated for MSFD assessments are suitable bands for monitoring ship borne noise;
- To assess the AIS data and where possible correlate the good quality noise data with data for ship movements;
- To compare the noise data identified above with predicted levels of noise from models of noise from shipping lanes to determine how well the models may be used to represent noise from a shipping lane, and to contribute to model validation;
- To make an assessment of how the duty-cycle of the sampling regime affects the statistics of the noise to provide information as to whether continuous sound recordings are necessary to confidently evaluate ambient noise in the test area;
- To provide an assessment, as far as the data will allow, of how much field monitoring is required for the MSFD, and to make recommendations on the desirable combination of field observations and modelling to provide a robust assessment of ambient noise in UK waters.

### 1.4 ORGANISATION OF THIS REPORT

In section 2 of the report, the data quality is assessed and the contaminating artefacts and their potential causes are identified. The data are analysed to show the overall levels of noise in selected third-octave bands both during the entire recording duration, and during periods where the contaminating artefacts are considered to be absent.

In section 3, the AIS data are examined, and predictions are made of the noise levels at the position of the recorder generated by the vessels listed in the AIS data. These predictions are then compared with the measured data. A discussion is given of the factors that limit the accuracy and reliability of such modelling predictions, both generally and in the case of the specific data examined here.

Section 4 provides a discussion of the conclusions and recommendations that may be made from analysis of the data, and the challenges inherent in addressing the requirements of the monitoring programme for the MSFD, for example on the desirable combination of field observations and modelling to provide a robust assessment of ambient noise in UK waters.

## 2. ANALYSIS OF MEASURED DATA

### 2.1 CONTAMINATING ARTEFACTS IN THE MEASURED DATA

Analysis was undertaken of all of the data to determine its quality. All frequencies were examined, with more emphasis on the frequency range 50 Hz to 160 Hz where shipping noise is most prevalent. There was degradation in quality of the data observed for some of the files due to a number of factors. These included:

- Data clipping (saturation of the recorder);
- Deployment platform and mooring noise
- Flow-related noise

#### 2.1.1 Data clipping

The recorder was deployed at a location some distance from the main shipping lanes in the area. However, there were still some ships that passed reasonably close to the recorder, resulting in clipping of the recorded data - saturation of the Analogue to Digital Converter (ADC) in the recorder. This was a significant source of distortion in the recordings, being manifest as a maximum full scale amplitude in the time waveform, and harmonic distortion in the spectrum. Out of the total number of 3,842 data files, a total of 2,584 files exhibited some data clipping. Note that when clipping occurred, the duration of the clipping varied. It did not in general last for the entire duration of the file, leaving at least some of the data in the file unaffected and available for analysis. However, there were extensive periods where clipping was evident, for example the data shown in Figure 2.1 where the clipping persists for much of the data file. Data exhibiting severe clipping cannot be used for any useful analysis and must be discarded.

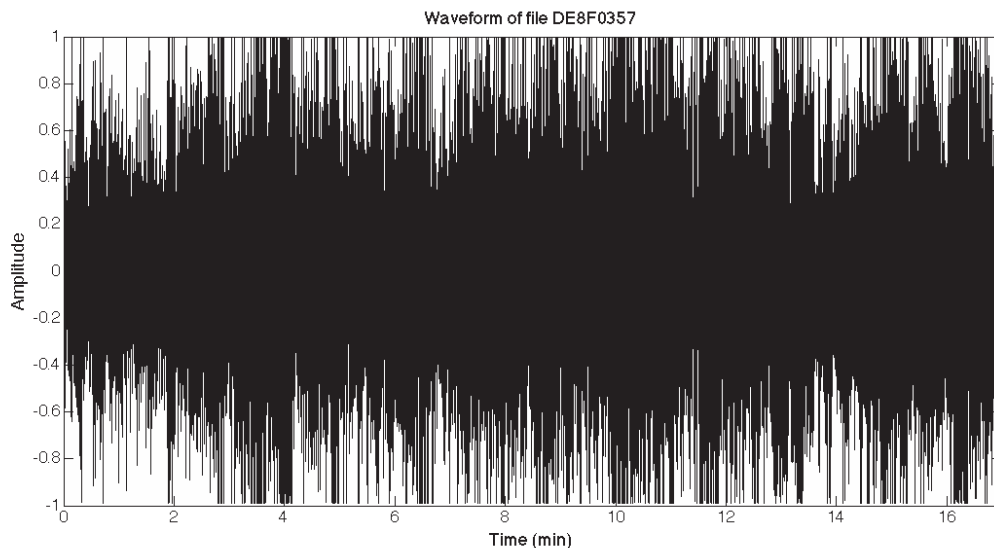


Figure 2.1 Scaled amplitude of the recorded data (full scale is represented by amplitudes of -1 and +1) showing extensive clipping for a full 17 minute sequence.

Considering that the recorder was deployed in an area where there are many busy shipping lanes, in hindsight it would have been advantageous for the gain setting to have been set lower than the 22 dB used for the recordings. However, since the gain setting for the Aural M2

recorder cannot be changed after deployment, the initial choice of gain would inevitably apply to all the recording files.

### 2.1.2 Deployment platform and mooring noise

There was also noise contamination from the smart buoy nearby. It is likely that not all of these noise sources have been identified in the data, but one clear source was the anchor chain of the buoy. This generated noise by a metal-against-metal contact when there was enough wind and wave to move the buoy randomly around its anchoring position.

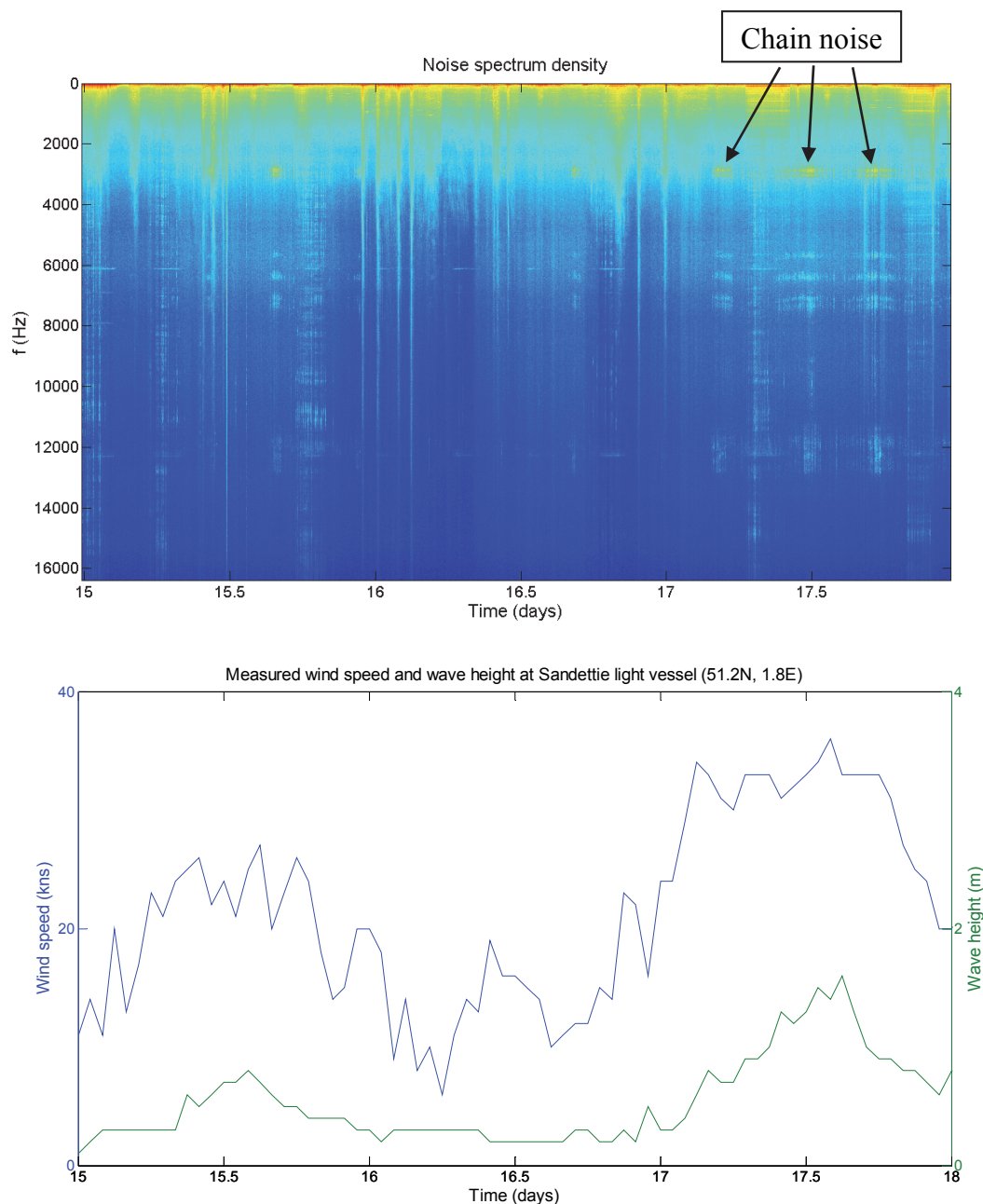


Figure 2.2 Spectrogram showing examples of chain noise at around 3 kHz centre frequency (upper plot) and the variation of wind speed and wave height in the area over the same time period (lower plot) with time measured in days from the initial deployment date.

Figure 2.2 shows a spectrogram of the measured data with the amplitude shown as a colour mapping, time in days on the abscissa (horizontal axis) and frequency on the ordinate (vertical axis). The data are from day 15 to 18 of the deployment with time measured in days from the initial deployment date of 16<sup>th</sup> April 2013. The noise from the metal chains is evident at around 3 kHz, and when listening to the recording these signals appear as bell-like “clanking” sounds.

The deployment platform noise from moorings that can be identified (such as that from the metal chains) tended to be at higher frequencies than those usually most associated with shipping noise and so has a less significant influence on the results. However, there may be other signals present from the deployment and moorings which have not been identified.

### 2.1.3 Flow-related noise

The results showed that there was a strong correlation between low frequency noise levels and tidal flow, and it is highly likely that this is because of flow-induced noise. Any flow of the medium relative to the hydrophone can induce turbulent pressure fluctuations at low frequency that will be sensed by a pressure-sensitive hydrophone. This noise is produced in a turbulent layer around the hydrophone, and is analogous to wind noise on a microphone. It is not a true acoustic signal (it does not arise because of a propagating sound wave from a source such as a ship) and its existence depends upon the presence of the hydrophone (and its support structure) in the flowing water. It gives rise to low frequency signals (typically <100Hz), with the



Figure 2.3 Photograph of the recorder deployment in DEFRA project ME5210.

frequency dependent upon the hydrophone diameter and the speed of the current [Cato 2008, Ross 1987]. It can be the major source of deployment noise in high flow environments. For autonomous recorders where the hydrophone is protruding from the recorder body, the problem can be exacerbated by turbulent flow around the end of the recorder casing. Strong fluid flow can also cause vibration of moorings and excite resonances in the recorder body. In the deployment for project ME5210, the Aural M2 recorder was supported on a large metal lander which sat on the seabed (see Figure 2.3 which is taken from the project report of project ME5210 [Borsani *et al* 2014]). The existence of this substantial structure around the recorder has the capability of enhancing the turbulent flow and increasing the flow-induced noise.

It is not always easy to check for the presence of flow-induced noise, but for long-term deployments such as this the recorded signals at low frequencies can be checked for correlations with tidal information – the flow noise signal will often show the same cyclic variations as the tides. If measurements have been made at both slack tide and at full tidal flow, it may be possible to quantify the effect of flow noise by comparison of the data [UK Good Practice Guide 2014].

To identify potential flow noise signals, the entire recorder signal duration has been plotted in a spectrogram to obtain an overview of the time and frequency dependency of the amplitude of the noise signal. This may then be compared to data for tidal flow. Figure 2.4 shows the spectrogram of the third octave band (TOB) noise spectral density of the recorded signal with the corresponding tidal height at Cromer (closest tidal gauge to the recorder position) over the entire time period from 16<sup>th</sup> of April to 3<sup>rd</sup> of June. The lowest and highest tidal heights above

minimum depth were 0.2 m and 2.9 m over the period. The third octave band frequency was used for the spectrum with a time window of 60 seconds for each point in the time axis. The size of the time window was selected long enough that the low end of the frequency spectrum was properly estimated, and short enough that for some events with a scale of minutes were also adequately captured, for example, passing vessels.

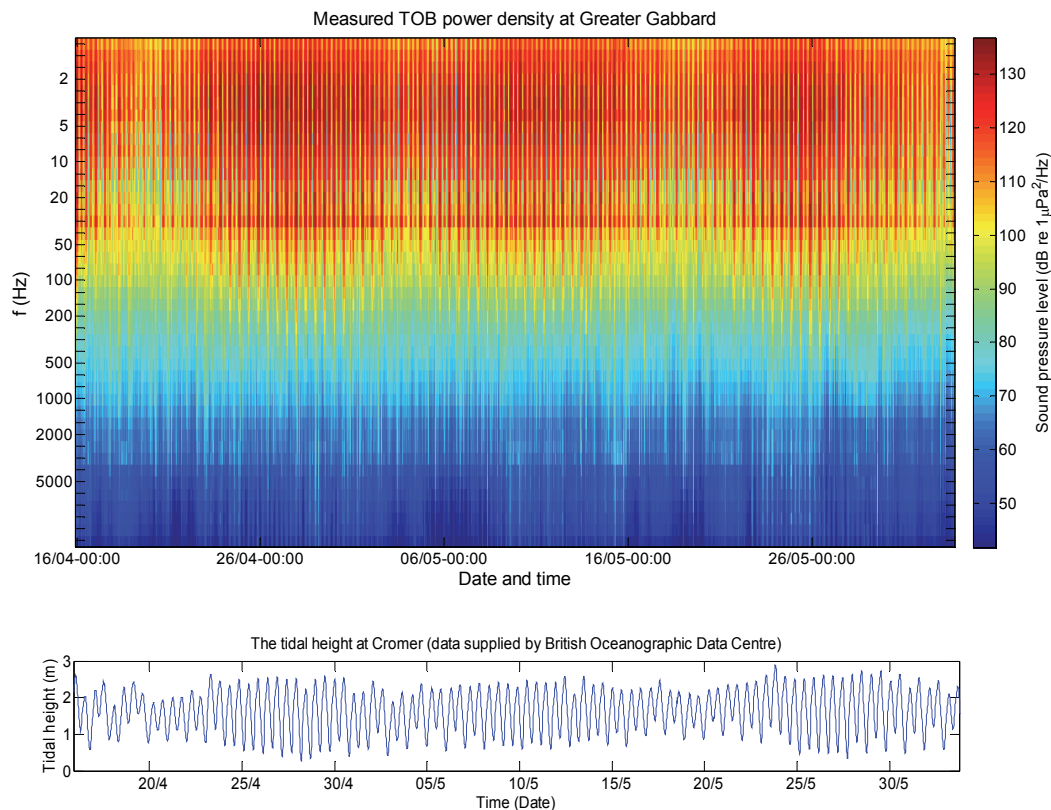


Figure 2.4 A spectrogram of the third octave band (TOB) noise spectral density of the recorded signal with the corresponding tidal height at Cromer (closest tidal gauge to the recorder position) over the entire time period from 16th of April to 3rd of June.

A striking feature of the spectrogram is that the low frequency noise levels are strongly correlated with the tidal flow. This is even clearer in Figure 2.5, which shows the 6.3 Hz third-octave band level for days 15 to 63 along with the tidal height plotted in metres. The alternating high and low levels at low frequencies match the oscillations in the tidal pattern. The 6.3 Hz third octave band is chosen because the maximum and minimum difference between flow noise induced sound pressure level and that of no flow noise is the highest at this frequency band. The current due to incoming and outgoing tides induces very strong contaminating signals in the recorded data mostly at frequencies below 40 Hz. It is difficult to identify all the sources of the flow noise, but it is likely that the surrounding structure of the lander contributed substantially to the flow noise.

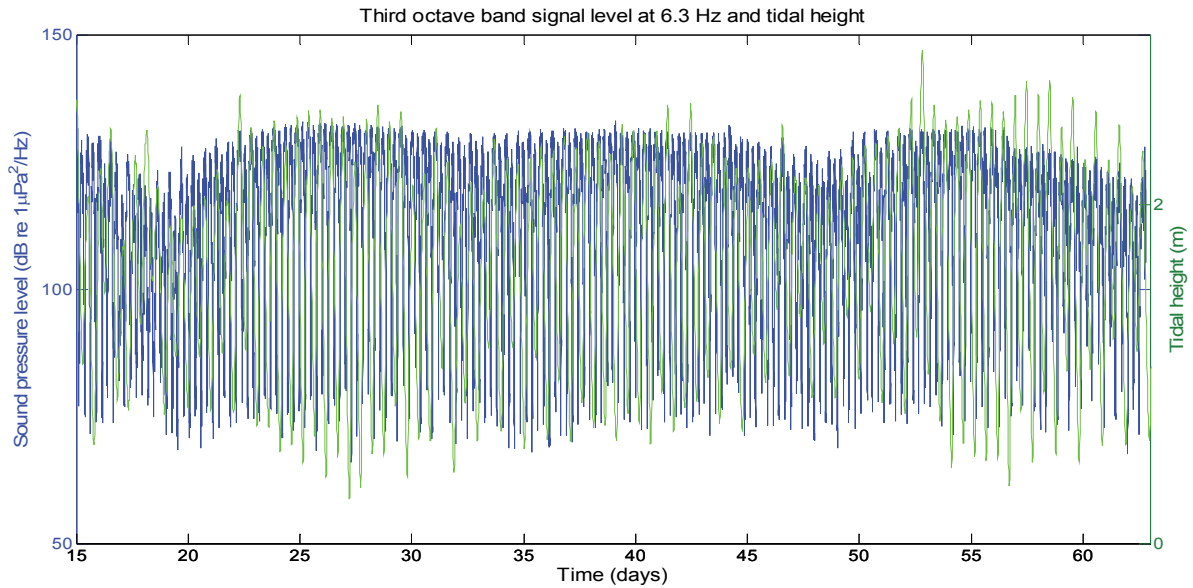


Figure 2.5 The 6.3 Hz third-octave band level for days 15 to 63 (green) and the tidal height above minimum depth plotted in metres (blue).

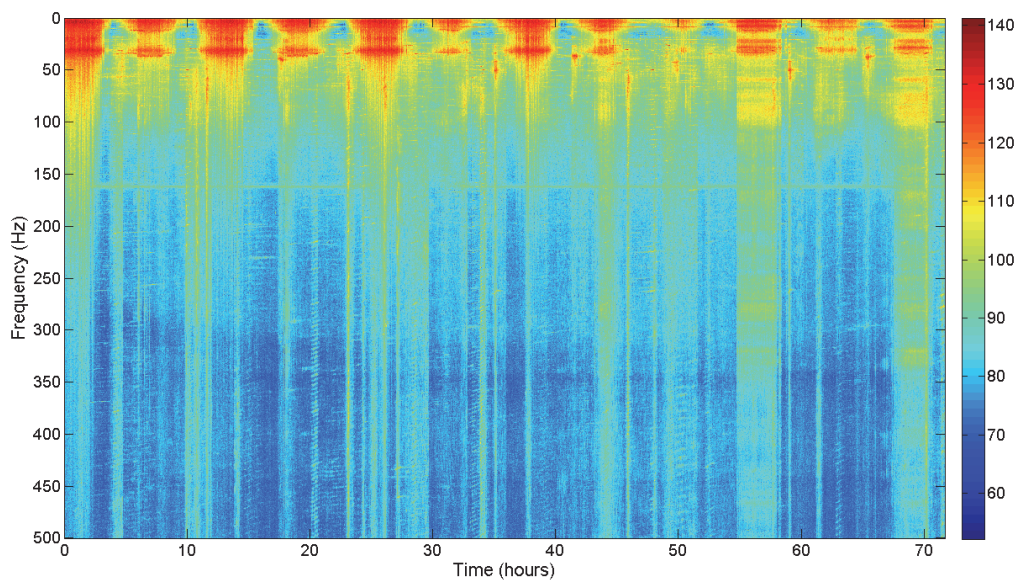


Figure 2.6 Spectrogram focusing on the low frequency range for the same 72 hour period depicted in Figure 2.2, with the colour bar amplitude representing units of dB re 1  $\mu\text{Pa}^2/\text{Hz}$ .

Focusing on the frequencies below 500 Hz, Figure 2.6 shows a (narrowband) spectrogram for the same 72 hour period depicted in Figure 2.2. The high amplitude signals at frequencies below 50 Hz are clearly observed; these are the signals that are strongly correlated with tidal currents and are therefore related to flow-induced noise. However, flow noise induced in individual hydrophones and recorders is rarely as high as is observed in the data examined here. Indeed, the flow noise interference overwhelmed other low frequency noises for much of the recording duration. The magnitude of the effect is indicated by the difference between the maximum and minimum noise level at 6.3 Hz which exceeds 67 dB. This makes data analysis difficult and drastically reduces the amount of useful data that are free of such contamination. In Figure 2.6, there are a number of interesting features which are difficult to explain. The occasionally sudden onset of quite broadband signals when the current is at its greatest is somewhat strange.

Some of this may be caused by harmonics generated by distortion during clipping. The high level of these flow-related signals and their extension to relatively high frequencies (for flow noise) may be due to some mechanical vibration or resonances in the lander used to support the recorder, rather than mere turbulence around the hydrophone.

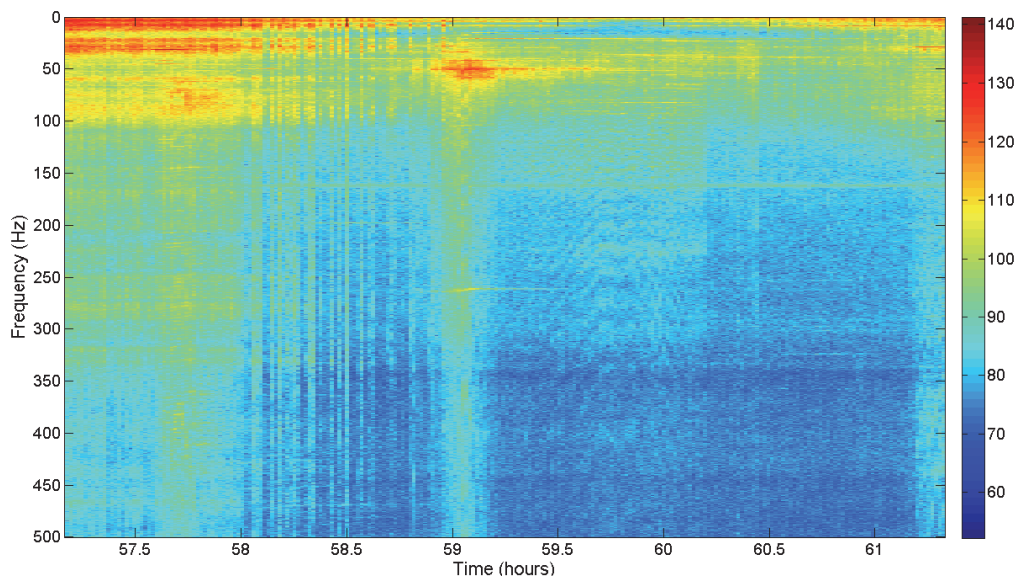


Figure 2.7 Spectrogram focusing on the time around hour 58 to 61 showing the low frequency range for the data depicted in Figure 2.6, with the colour bar amplitude again representing values in units of dB re  $1 \mu\text{Pa}^2/\text{Hz}$ .

The spectrogram data in Figure 2.6 may be expanded further and Figure 2.7 shows the data around the time from hour 58 to 61. This shows the end of a period of high tidal current, moving to a period of slack tide where the flow is much reduced. The reason for the intermittent nature of the low frequency signals (for example between hour 58.0 and 58.5) is not understood, but again may be due to the interaction of the flow with the structure of the lander. The origin of the low frequency signal at around hour 59.1 is not clear but it is probably a vessel close by (there may be another vessel present at hour 57.7 but the signal is masked by the flow-induced noise). Occasionally, a faint Lloyd's mirror effect may be observed in the spectrograms. This effect occurs due to interference of the direct signal with the bottom reflection producing an interference pattern which manifests as curved features in the spectrogram as the vessel transits through the closest point of approach (this may be present between hour 59.5 and 60). These plots illustrate the difficulty of identifying the source of the noise signals in the presence of artefacts caused by non-acoustic mechanisms. Often the best method of identification is to listen to the recording, but this is clearly impractical for a 49 day recording.

An interesting feature of the data is the faint tonal signal at 160 Hz (most clearly seen in Figure 2.6). This is present for long periods (though not for the entire 49 day recording duration) and so cannot be a transiting vessel. Since it is not present all the time and is uncorrelated to the tidal current, it is unlikely to be generated by the deployment platform. One possibility is that the faint signal is generated by the nearby offshore wind farm at Greater Gabbard, signals of this frequency having been detected in the noise signatures of other offshore wind farms (commonly generated by the gearbox used in the turbines).

In spite of these problems, analysis of the data during periods of slack tide shows that there are data available from these periods which are uncontaminated by flow-noise, and which may be

used to assess the underlying levels of anthropogenic noise, including from ship traffic (presented in Section 2.3).

## 2.2 RECORDER PERFORMANCE AND CALIBRATION

The Aural M2 recorder (serial number: 382220) was calibrated over the salient frequency range by NPL before the deployment for project ME5210. This was undertaken using the NPL pistonphone facility where the hydrophone response is determined using a relative calibration in the frequency range 25 Hz to 315 Hz.

During the calibration, the amplifier gain was set to 22 dB, the value used during deployments. However, when the system sensitivity was reported, a correction was made for the amplifier gain. The sensitivity (without added amplifier gain) was found to be -163.7 dB re 1 V/ $\mu$ Pa with a variation of no more than  $\pm 0.3$  dB across the frequency range (NPL Test Report 2012020333/U3185, reported in Borsani *et al* 2014). This is close to the nominal manufacturer's value. However, during calibration, it was noticed that the ADC had a scale factor of 2 (6 dB) which was unreported in the manufacturer's literature. Therefore, with the added 22 dB gain, and the loss of 6 dB due to the ADC scale factor, the overall system sensitivity during deployment was therefore -147.7 dB re 1 V/ $\mu$ Pa. The recorder actually produces digital counts per pascal of acoustic pressure (there is no analogue voltage available for inspection during calibration), but here the sensitivity has been expressed in conventional units (converting the digital waveform to a voltage using the amplifier gain, and ADC settings). The uncertainty of the calibration is typically 0.5 dB.

To check the stability of the Aural M2 recorder, the sensitivity was re-measured by NPL in March 2014 as part of DEFRA project ME5217. The response was found to be unchanged (within all changes observed to be well within the calibration uncertainties), the results being presented in Table 2.1. Therefore, it may be concluded that the Aural M2 recorder response was stable in the frequency range 25 Hz to 315 Hz for the duration of the deployment.

Table 2.1 Measured sensitivity of the Aural M2 recorder *without* added gain or ADC scale factor.

| Frequency<br>(Hertz) | Sensitivity (dB re 1 V/ $\mu$ Pa) |            | Difference<br>(dB) |
|----------------------|-----------------------------------|------------|--------------------|
|                      | March 2014                        | March 2012 |                    |
| 25.0                 | -163.8                            | -163.8     | 0.0                |
| 31.5                 | -164.0                            | -164.0     | 0.0                |
| 40.0                 | -163.9                            | -163.8     | -0.1               |
| 50.0                 | -164.0                            | -164.0     | -0.1               |
| 63.0                 | -163.8                            | -163.9     | 0.1                |
| 80.0                 | -163.9                            | -164.0     | 0.1                |
| 100.0                | -163.7                            | -163.9     | 0.2                |
| 125.0                | -163.7                            | -163.8     | 0.1                |
| 160.0                | -163.7                            | -163.7     | 0.0                |
| 200.0                | -163.7                            | -163.8     | 0.1                |
| 250.0                | -163.7                            | -163.6     | -0.1               |
| 315.0                | -163.4                            | -163.3     | 0.0                |

Although the sensitivity at low frequencies was found to be stable when a pressure calibration was undertaken on the recorder's hydrophone, this was not a free-field calibration. It is known that the sensitivity and directional response of autonomous recorders may fluctuate at kilohertz frequencies due to the influence of scattered signals from the recorder body [UK Good Practice

Guide 2014, Hayman *et al* 2014]. This is particularly a problem for recorders such as the Aural M2 where the hydrophone protrudes through the body and is rigidly fixed to it without any added cable to enable the hydrophone to be deployed at a stand-off distance of (say) a few metres. With the lander unit used to deploy the Aural M2 for project ME5210, it is likely that this effect was exacerbated by the presence of the surrounding structure. This means that, in the deployment configuration used, the sensitivity frequency response at kilohertz frequencies is unlikely to have been flat (invariant with frequency) and the response is likely to have exhibited some directionality (the response will not have been omnidirectional). However, at the low frequencies considered here (those relevant to the MSFD requirements), this is not a significant problem. The acoustic wavelengths at 63 Hz and 125 Hz are approximately 24 m and 12 m respectively, and under such conditions the recorder free-field response will be very close to the response measured during the NPL calibration.

The system self-noise of the recorder was also measured by NPL (NPL Test Report 2012020333/U3185, reported in Borsani *et al* 2014). This is the signal produced by the system in the absence of any external acoustic signal, and represents the minimum acoustic signal that may be recorded without signal averaging. Although the noise “floor” produced by the system self-noise was considerably higher (and therefore worse) than the performance of the best available low-noise hydrophones and digital recording systems (the system self-noise of the Aural at 125 Hz being approximately 47 dB re  $1\mu\text{Pa}^2/\text{Hz}$ ), it is still considerably less than the signals recorded during the deployment (minimum values recorded at 125 Hz were around 70 dB re  $1\mu\text{Pa}^2/\text{Hz}$ ). Therefore, it may be concluded that the system self-noise did not limit the quality of the recorded data.

However, the dynamic range of the recorder did limit the quality of the data because a substantial fraction of the data was saturated (clipped) – see Section 2.1.1. The dynamic range can be increased by reducing the amplifier gain setting in the Aural M2. However, the gain setting for the recorder cannot be changed after deployment, and there is inevitably some uncertainty with regard to the most appropriate setting. In hindsight, it would have been advantageous for the gain setting to have been set lower than the 22 dB used for the recordings, thus increasing the dynamic range and reducing the amount of data lost to clipping.

## 2.3 ANALYSIS OF OVERALL NOISE LEVELS

When analysing noise, it is necessary to average the measured data. This is because the instantaneous values of the sound pressure are fluctuating continually, and any snapshot at a frozen instant in time cannot represent the statistical variation in the values. When averaging noise, it is necessary first to square the data (since sound pressure has both positive and negative excursions, the unsquared data will tend to average to zero). Therefore, the noise values are most often stated as mean square values, or in terms of root mean square (RMS) values. The most appropriate metric for expressing ambient noise is Sound Pressure Level (SPL). To undertake data averaging, the measured data are divided into analysis time windows, or “snapshots”. For each snapshot time sequence, the SPL is then calculated at each third-octave band, resulting in a sequence of SPL data for each frequency band. The calculation of the levels in each third-octave band was undertaken using Fast Fourier Transform processing, ensuring a sufficient snapshot time is used to accurately represent the low frequency content. The data for each band have been expressed as third-octave band spectral density levels in dB re  $1\mu\text{Pa}^2/\text{Hz}$ . For the majority of the analysis, this was done by dividing the data into one minute snapshots and calculating the levels for each one minute sequence.

There are a number of averaging techniques that have been used for ocean noise data, and several papers in the scientific literature that compare the utility of the different methods [Merchant *et al* 2012, Merchant *et al* 2013, Van Der Schaar *et al* 2014]. In addition, the 2014 reports by the EU Technical Sub-Group on Noise (TSG) have made a number of recommendations with regard to averaging of noise data in response to the MSFD [EU TSG Noise, 2014a, 2014b, 2014c].

Two main metrics have been used to represent the averaged data: the arithmetic mean and the median. The arithmetic mean is the average of the snapshot values calculated as mean square sound pressures (or RMS values) and then expressed in decibels (the final value is converted to decibels only after the averaging is complete). This has the advantage that it is robust – it is invariant with choice of snapshot time. This means that comparisons may be made with other analysis where different snapshot time windows were used (perhaps because of restrictions posed by different instrumentation or sampling regimes). It has a physical meaning in terms of the average sound pressure in pascals, and is compatible with the averaging metrics used in airborne sound. However, it is sensitive to being influenced by very high amplitude sounds that may occasionally be received – for example if a ship comes very close to the monitoring station. On such occasions, the sound pressures can be orders of magnitude higher than the minimum values experienced, and if there are a sufficient number of such occasions, the arithmetic mean can have a high value (considerably greater than the median of the distribution). The median is the median of the snapshot values, which is equivalent to the 50<sup>th</sup> percentile. This value *does* depend on the chosen snapshot time, but is much less influenced by the high amplitude transient events [Merchant *et al* 2012, Van Der Schaar *et al* 2014]. The median value can be thought of as more representative of the background noise level in the absence of the high amplitude events.

The metrics described above are not sufficient to describe the ambient noise because they contain no information about the dispersion of values – the range of values obtained from the averaging procedure, which describe the variation in the noise levels with time. [EU TSG Noise 2014c, Merchant *et al* 2013, Van der Schaar *et al* 2014]. The distribution of values for each frequency band may then be displayed in the form of a box plot. This is a common way of expressing statistical information showing the median or mean and selected percentiles.

The above analysis was undertaken for the data obtained in DEFRA project ME5210, using a number of subsets of the data. First, the data which were clipped (saturated) were discarded (these cannot be used for meaningful analysis). Secondly, all the remaining data were analysed using the above procedure, including all data except the discarded clipped data (this analysis included data which were contaminated by flow noise). Finally, analysis was performed on a smaller subset of measured data that were identified as being recorded during slack tide (the typically 10 minute period when the tide was turning and the current flow was minimal). These periods were identified from independent tidal data (from the Cromer tidal station), and were clear from the measured data as periods when very low frequency noise was a minimum. This enabled a subset of data to be created from the slack tide periods, occurring four times a day for 49 days.

Figure 2.8 shows the third-octave band spectral density levels for all the data (excluding clipped data which is unusable). Shown on the plots are the arithmetic mean, the median, and the 5<sup>th</sup>, 25<sup>th</sup>, 75<sup>th</sup> and 95<sup>th</sup> percentiles, and extreme outlier values are plotted as red crosses. Clearly seen are the very high levels of noise at frequencies up to 100 Hz where flow noise has its greatest effect (these values are unusually high even for locations near to shipping lanes).

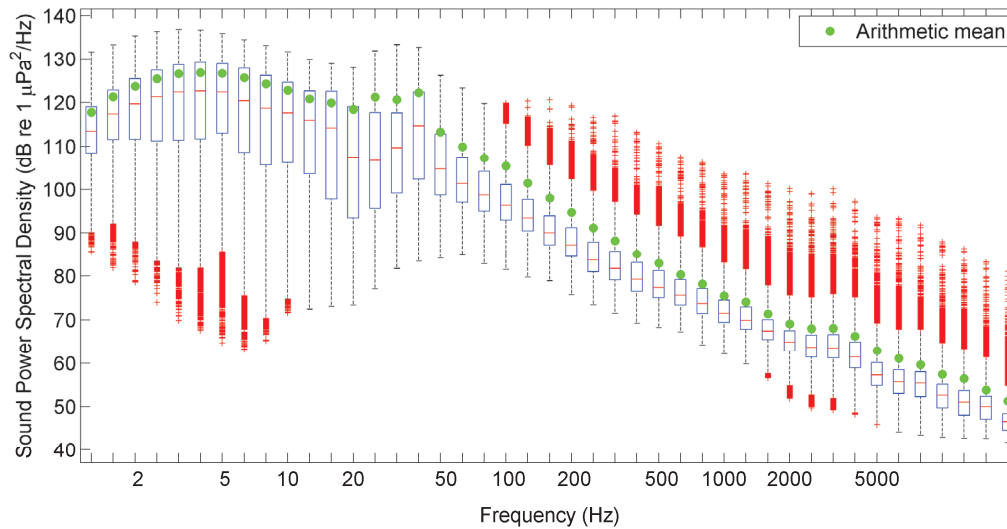


Figure 2.8 The third-octave band spectral density levels for all the data (excluding clipped data). Shown on the plots are the arithmetic mean (green dot), the median (bar within the box), the 25<sup>th</sup> and 75<sup>th</sup> percentiles (the outer edges of the box), the 5<sup>th</sup> and 95<sup>th</sup> percentiles (as ticks on the end of the error bars) and the extreme outlier values (beyond 3 standard deviations) are plotted as red crosses.

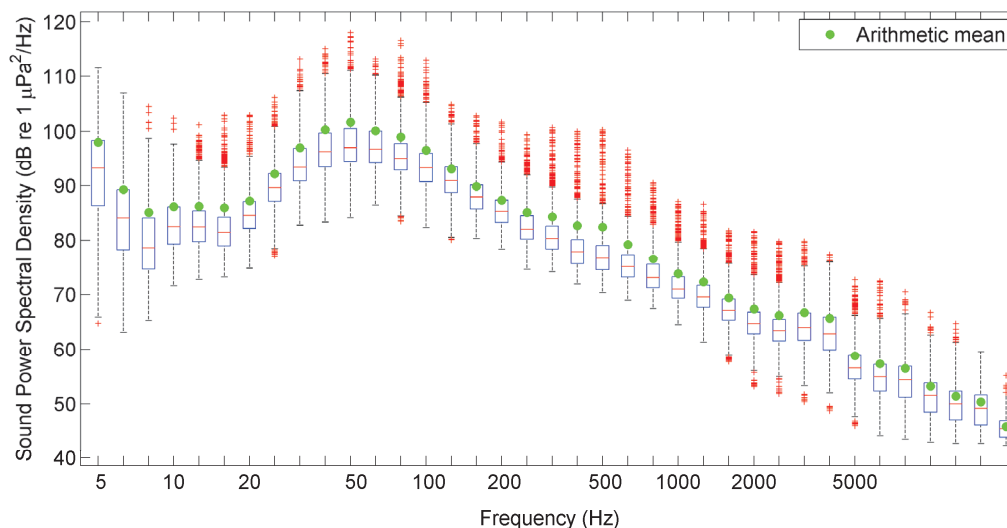


Figure 2.9 The third-octave band spectral density levels for data during periods of slack tide only. Shown on the plots are the arithmetic mean (green dot), the median (bar within the box), the 25<sup>th</sup> and 75<sup>th</sup> percentiles (the outer edges of the box), the 5<sup>th</sup> and 95<sup>th</sup> percentiles (as ticks on the end of the error bars) and extreme outlier values (beyond 3 standard deviations) are plotted as red crosses.

Figure 2.9 shows the results of the analysis on the slack tide data only. Even though the dataset is much reduced, there are still substantial amounts of data when aggregated over 49 days, and there is still enough data to form statistical distributions.

The data in Figure 2.9 show elevated levels in the frequency range between third-octave bands centred on 31.5 Hz and 200 Hz, the range containing much of the energy from shipping noise. This is because of the proximity of the ship traffic in the area to the east of Greater Gabbard. This illustrates that frequency bands within this range are likely to be a good choice as indicators of levels of shipping noise for use in determining trends in ship traffic noise, as required for the MSFD descriptor. The chosen MSFD third-octave bands of 63 Hz and 125 Hz seem quite

reasonable choices for the data shown here, though a number of the adjacent third-octave bands would also be useful measures.

Note that the data shown in Figure 2.8 (all the data excluding clipped data) are of little use in assessing the noise from the ship traffic because of the contaminating influences of parasitic noise such as flow noise. Note that the slight increase in noise level around 3 kHz is due to the repeated noise from the mooring chain described earlier.

The plot shown in Figure 2.9 is quite a useful summary of the useful part of the data. It is also one of the few measurements made so far in UK waters close to a busy ship traffic area which has been sampled over a reasonable time period, thereby showing a reasonable estimate of the statistical distribution as the noise levels vary with time. Most other datasets for ambient noise in UK waters have been measured over only a few hours, often from vessel deployments, and often suffering from similar contamination by parasitic signals caused by the deployment as caused the problems with the majority of the data studied here. The subset of the data taken at slack tide periods is therefore of some value as an indicator of typical noise levels at similar locations.

However, it should be noted that due to clipping of the recorder acquisition system, vessels that approached close to the recorder position have been excluded from the dataset (reducing the occasions on which high noise events were observed, events which would have been otherwise recorded faithfully on a system with better dynamic range). The lack of such events would tend to reduce the arithmetic mean more than the median. Note that it is not possible to derive any useful information about long-term trends from the limited dataset analysed here.

Taking the 125 Hz third-octave band level, Figure 2.10 shows the slack tide data only for part of the recording with a number of the statistical parameters calculated for that band. Despite the reduced dataset, occasional transients in the data are observed due to the close proximity of vessels in the area.

For the data shown in Figure 2.10, three types of metric are displayed: the arithmetic mean, which is affected by the presence of high amplitude transients, the median and also the geometric mean (the mean calculated from the SPL values in decibels). The minimum and maximum values are also shown. The median value (88 dB re  $1 \mu\text{Pa}^2/\text{Hz}$ ) is insensitive to these high level transients, but the arithmetic mean (90 dB re  $1 \mu\text{Pa}^2/\text{Hz}$ ) shows a higher level due to their effect. It is noticed that the noise level was never less than 80 dB re  $1 \mu\text{Pa}^2/\text{Hz}$ , and never more than the maximum of 103 dB re  $1 \mu\text{Pa}^2/\text{Hz}$ .

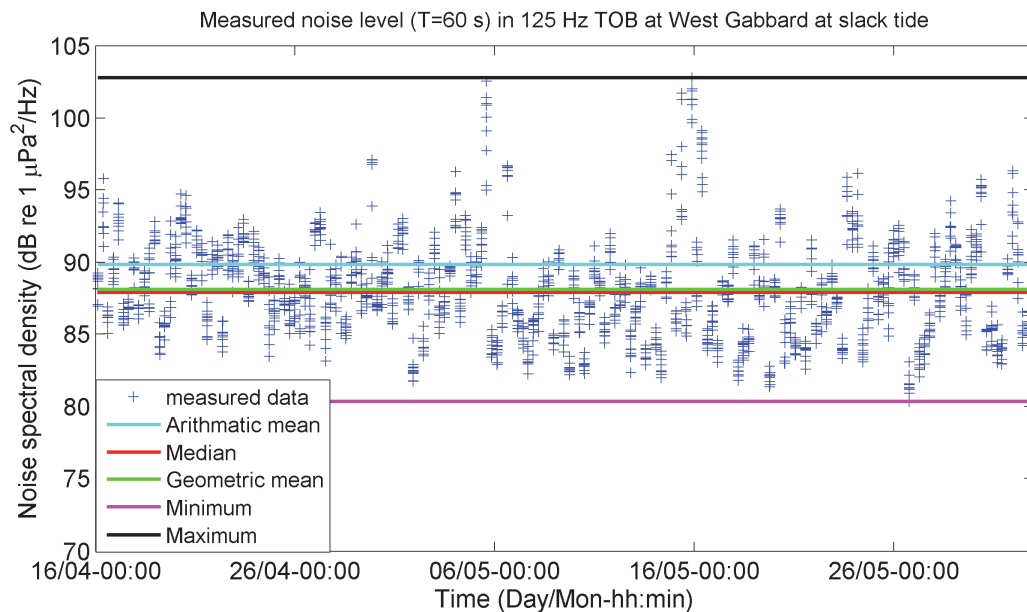


Figure 2.10 Data for the slack tide periods only in the 125 Hz third-octave band. The data shown are averaged over 1 minute and plotted for a duration of 48 days. Three types of metric are displayed: the arithmetic mean, geometric mean and the median. The minimum and maximum values are also shown.

In order to establish the statistical significance of any change in the noise level, the distribution in the form of percentiles of the *cumulative probability density function* (CDF) is also useful. This is shown in Figure 2.11 for the 125 Hz third octave band data from Figures 2.9 and 2.10 (slack tide only).

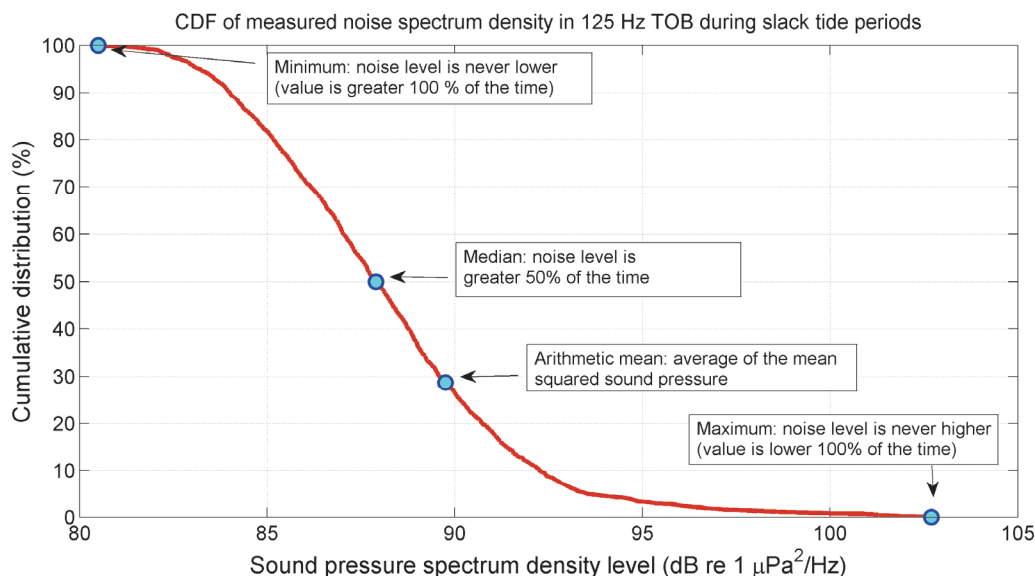


Figure 2.11 Statistical representation of the measured sound pressure level in the 125 Hz third octave band as a cumulative distribution function, showing the percentiles or the exceedance levels. The curve shows the proportion of time where a given minimum level is reached.

The plot shows the corresponding percentage exceedance levels, the proportion of time where a given minimum level is reached. For example, as expected from the definition, it shows that 50% of the time, the measured level exceeds the median level of 90 dB re 1  $\mu\text{Pa}^2/\text{Hz}$ .

The use of a cumulative density distribution allows an examination of the effect on the statistical distribution of changing the sampling duty cycle. Figure 2.12 shows the distribution obtained for all the measured data (not just the slack tide periods). Note that this distribution will not be identical to that shown in Figure 2.11 (it is the distribution of a different, much larger dataset). The plot shows the result of varying the sampling regime by reducing the duty cycle by successive factors of two. It can be seen that for these data very little difference is observed in the CDF curves in this case. This indicates that for this dataset, the use of a reduced duty cycle would not affect the conclusions about the statistical variation in the noise levels, for example about exceedance levels. This implies that reduced duty cycles (and therefore longer duration deployments with similar battery power) are feasible.

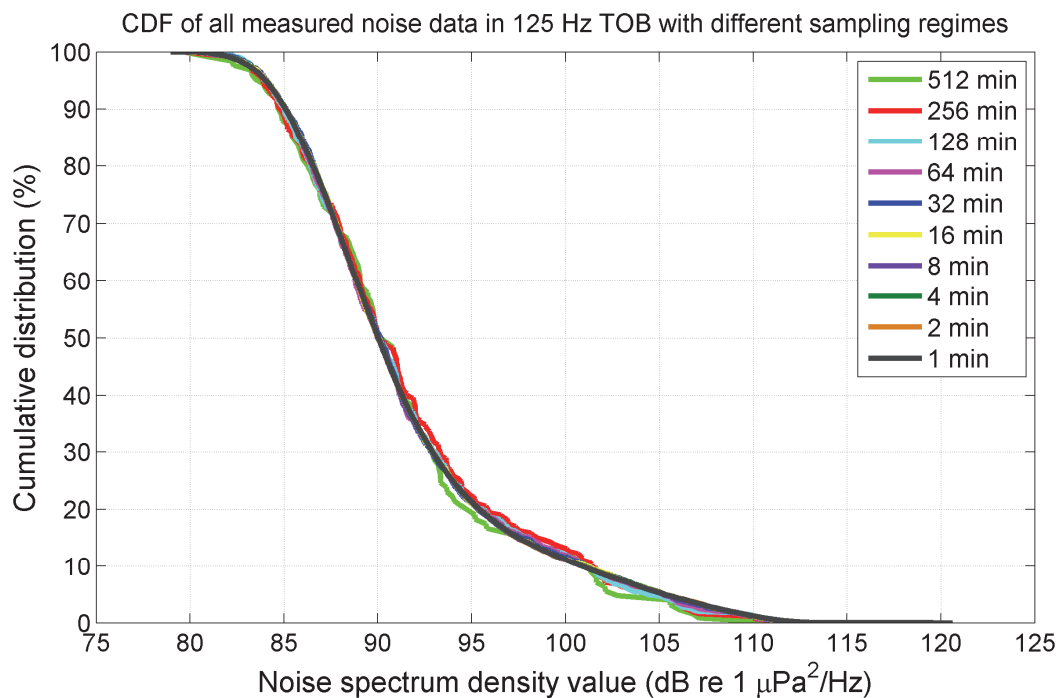


Figure 2.12 Statistical representation of the measured sound pressure level for the entire deployment duration in the 125 Hz third octave band as a cumulative distribution function, showing the effect of reducing the duty cycle by successive factors of two.

This result is similar to that observed for an Irish noise dataset [Sutton *et al* 2014]. However, some caution is required in interpreting these results. This effect is only likely for noise datasets where the noise measured is the integrated contributions of many ships (for example, in a shipping lane), such that there is a constant background contribution from the traffic. If there are significant transient events contributing to the noise statistics, this result may not in general be true. As an extreme example, if local ferry passes close by at the same time of day but at a time when the recorder is switched off (during the “down-time” of the recorder duty cycle), this will always be missed from the data record and its effect will never be sampled and allowed to influence the statistics of the data. It should be remembered that for the data analysed here, most of the transients due to closely approaching vessels have been removed due to clipping of the recorder invalidating that part of the record.

### 3. COMPARISON OF MEASUREMENT WITH PREDICTIONS

In this section, the results are presented of predictions the noise levels at the position of the recorder due to the ship traffic in the area. The process of calculating the noise levels requires the use of the AIS data for the ship traffic to provide ship location, a simple model for the source level of each vessel, and a propagation model to calculate the received levels from each vessel at the position of the recorder. The received levels from all the vessels were then incoherently summed to provide the overall level at the recorder position in a specific third-octave band. This process was repeated as a function of time as the vessel positions move, producing a prediction of the noise level in the third-octave band, which may then be compared with the measured data.

There are several steps in the process and these are presented in the next sections.

#### 3.1 ANALYSIS OF AIS DATA

The AIS data in a rectangular area of defined by the four corners at following locations:

52 26.0N 001 20.0E  
 52 26.0N 002 48.0E  
 51 32.0N 002 48.0E  
 51 32.0N 001 20.0E

were made available by the Marine Coastguard Agency for use with this project. Examination of the data showed that there was a 10 day period in the middle of the deployment for which there was no data made available (the reason for the absence of data is unknown).

The data were available as a Microsoft spreadsheet file, containing data for most large ships in the area, including position, speed, heading, vessel class, destination, and a number of other pieces of information.

Note that the AIS data were not available for all vessels – small vessels are not required to carry AIS transponders. The absence of AIS data for all vessels creates a potentially significant problem for the accuracy of modelling in regions where there is a high proportion of vessels in the area without AIS data (for example, close to regions where there is significant leisure boating activity).

Fishing vessels operate a different information system – the VMS system. VMS data were not available for this study, but could be made available in anonymous form for future work.

Figure 3.1 shows a plot of the track of every vessel listed in the AIS data from April 10<sup>th</sup> to June 5<sup>th</sup> 2013 (the missing data from the 10 day period are of course not shown). The colours indicate the class of vessel as listed in the AIS system (tanker, cargo, etc). The recorder position is shown as a black circle. Also shown are the positions of several offshore wind farms in the area (eg Greater Gabbard).

It is difficult to take information from the plot in Figure 3.1 because it has too much information to assimilate visually. Figure 3.2 shows a plot of the vessel AIS data from Figure 3.1 but shown as ship density data, the colours indicating number of vessels (in logarithmic scale) per unit area (500 m by 500 m) over the entire time period when AIS data were available. The recorder

position is shown as a red circle. This creates a visual image that illustrates the likelihood of vessels occurring in specific locations. The recorder position is seen to be adjacent to the shipping lanes, but not directly under the main traffic lanes.

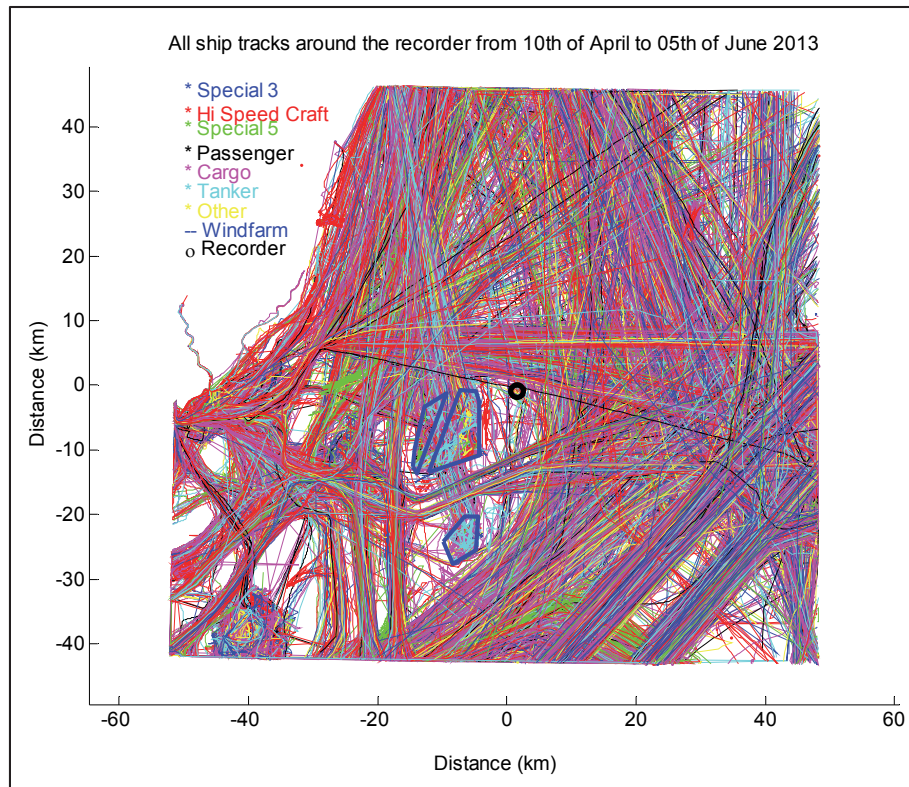


Figure 3.1 Plot of the track of every vessel listed in the AIS data from April 10<sup>th</sup> to June 5<sup>th</sup> 2013 (with a 10 day period missing from the middle of the data). The colours indicate the class of vessel. The recorder position is shown as a black circle. Also shown are the positions of several wind farms.

There are number of features which are evident from the figures, especially Figure 3.2. The main shipping lanes in the southern North Sea are clearly visible, as are the routes into the Thames Estuary and the port of Harwich. There is clearly increased shipping activity around the offshore wind farms of Greater Gabbard, and the London Array (to the south west). This must be maintenance traffic since the construction work had already been completed long before the deployment commenced.

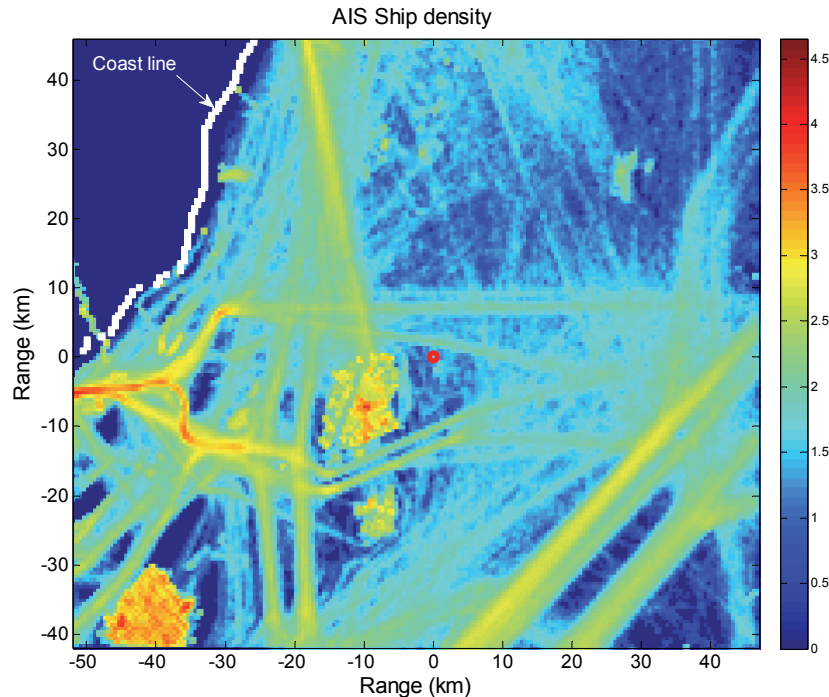


Figure 3.2 Plot of the vessel AIS data from Figure 3.1 as ship density data the colours indicating number of vessel (in logarithmic scale) per unit area (500 m X 500 m) over the entire time period when AIS data are available. The recorder position is shown as a red circle.

There are a number of shortcomings in the use of the AIS data which limit the utility, including:

- Missing vessels: not all vessels operate using AIS transponders;
- Restricted range: vessels outside the range of the AIS data provided may generate noise which may still be heard at the recorder;
- Data drop outs: the data contain segments which are missing (for example, the 10 day period in the middle), and occasional anomalous data where a ship appears in the clearly the wrong location or “jumps” between positions.

A routine was written in the Matlab® programming language to extract the data from the AIS spreadsheet, plot it over any time period selected, and interpolate the vessel positions if so required.

## 3.2 MODELLING THE SHIP TRAFFIC NOISE

The modelling process included the stages shown in Figure 3.3.

### 3.2.1 Vessel source levels

There is relatively little known about the source levels of commercial vessels, though the scientific literature does contain some information [Arveson and Vendittis 1998, Robinson et al 2011, Erbe 2013, Wales and Heitmeyer 2002]. The use of the data that does exist poses some significant problems:

- The data are sporadic – not all classes of vessel have been measured and examples of the same class may not radiate equal amounts of noise

- The data that do exist are typically in a form (Radiated Noise Level) that cannot easily be used in noise propagation models (where a monopole source level is typically required)
- The noise radiated depends on contingent factors such as vessel speed, engine loading, propeller depth (depends on vessel load and displacement), the presence of strong tidal currents, etc
- The international standards that exist are recent or under development and do not provide source level data in the appropriate form for modelling

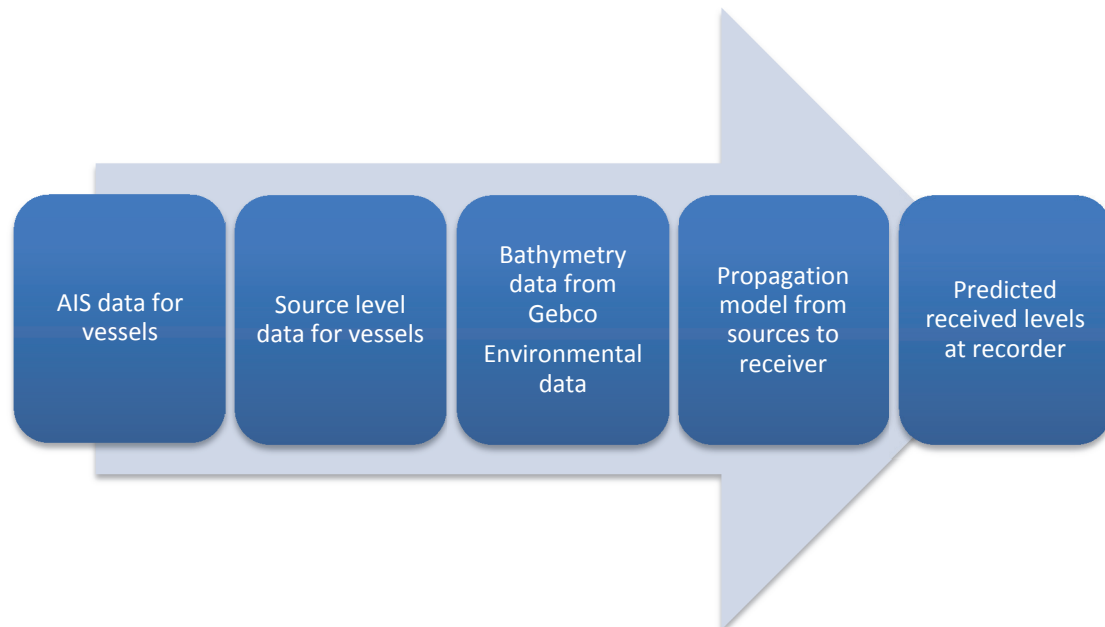


Figure 3.3 Process for calculating predicted noise levels at the recorder position

There are currently two EU funded projects which aim to develop methods for measuring ship noise and map the noise radiated by ship traffic:

SONIC (<http://www.sonic-project.eu/>)

AQUO (<http://www.aquo.eu/>)

However, these have not yet been completed and have not yet reported in the public domain on the data obtained.

For the work here, use was made of the generic monopole source level data provided by Wales and Heitmeyer in 2002 for commercial ships over the frequency band of interest as shown in Figure 3.4. This was mediated by the data provided in the report of project 2011-W-MS-7-MSFD (STRIVE Report No. 121, 2014) funded by the Irish EPA [Sutton et al 2014]. and titled “Mapping the spatio-temporal of underwater noise in Irish waters”.

This initial work has focussed on using purely generic data for source level spectra, but in future this could be refined by use of the AIS information on vessel class, speed, etc.

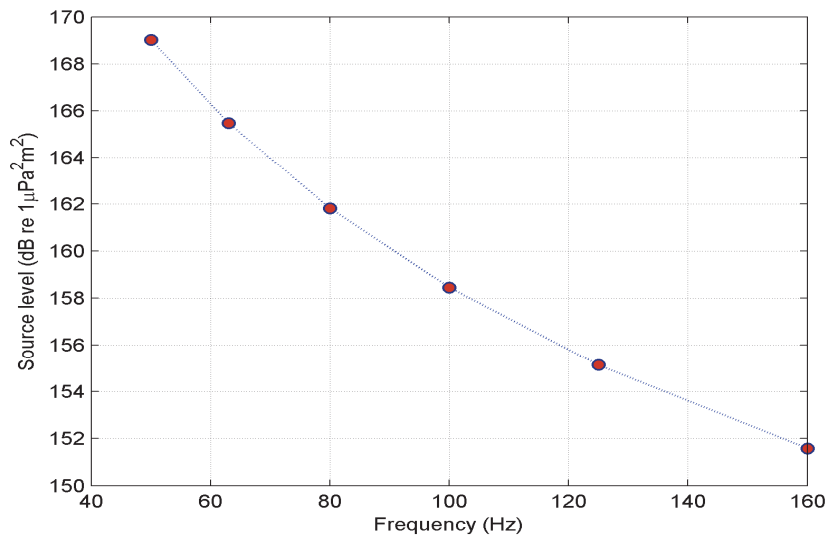


Figure 3.4 Mean ship source level curve from Wales and Heitmeyer (2002) showing the values at third-octave band centre frequencies.

### 3.2.2 Bathymetry and environmental data

Sound speeds in water and in the sediment of the seabed are the most important parameters in determining the propagation loss of sound from a source to a distant receiver. Sound speed in water is a function of temperature, salinity and depth. It is a good approximation to consider the sound speed constant in coastal UK waters because of the shallow depth and fairly constant temperature profile over the depth of the water. The water depth of the underwater channel has a profound effect on the sound propagation in shallow water. For use as an input parameter of the propagation models, bathymetry data was obtained from The General Bathymetric Chart of the Oceans (GEBCO) in the area of interest with the recorder in the middle as shown in Figure 3.5. There are considerable changes of water depth in the area. The shallow patch to the west of the recorder is used as the location of an off-shore wind farm.

The modelling does not take into account of the change of water depth due to tides. This may introduces some variations in the predicted transmission loss for the sources in the shallow part of the water in the area.

To simplify the modelling, the seabed is treated as a semi-infinite fluid-like medium. The properties of seabed, such as the density, sound speed, absorption are important parameters for the level of propagation loss in shallow water. However, there is a lack of information on seabed properties in general. Only synoptic descriptions exist such as that shown in Figure 3.6. This makes selection of input parameters a challenging task for the modelling since there are quite large variations in the property value even for the same type of seabed. For propagation across over a large area such as for the Cefas dataset, the properties of the sea bed change from one type to another, adding more challenges to the modelling. Although this is beyond the scope of the current work, it would be beneficial to investigate in the future since it is a necessary consideration in order to be able to predict the sound field realistically. The input parameters for the modelling including the seabed properties are in Table 3.1.

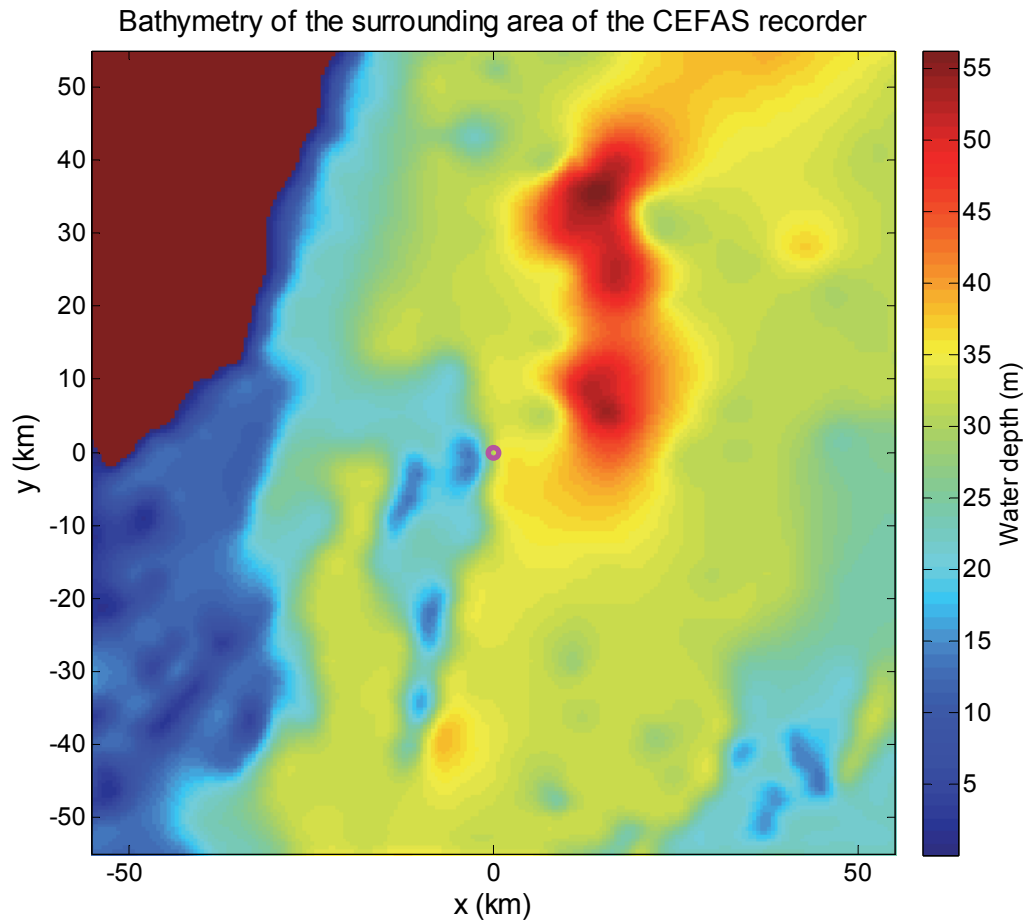


Figure 3.5 Bathymetry map around the Cefas recorder at the centre of the map

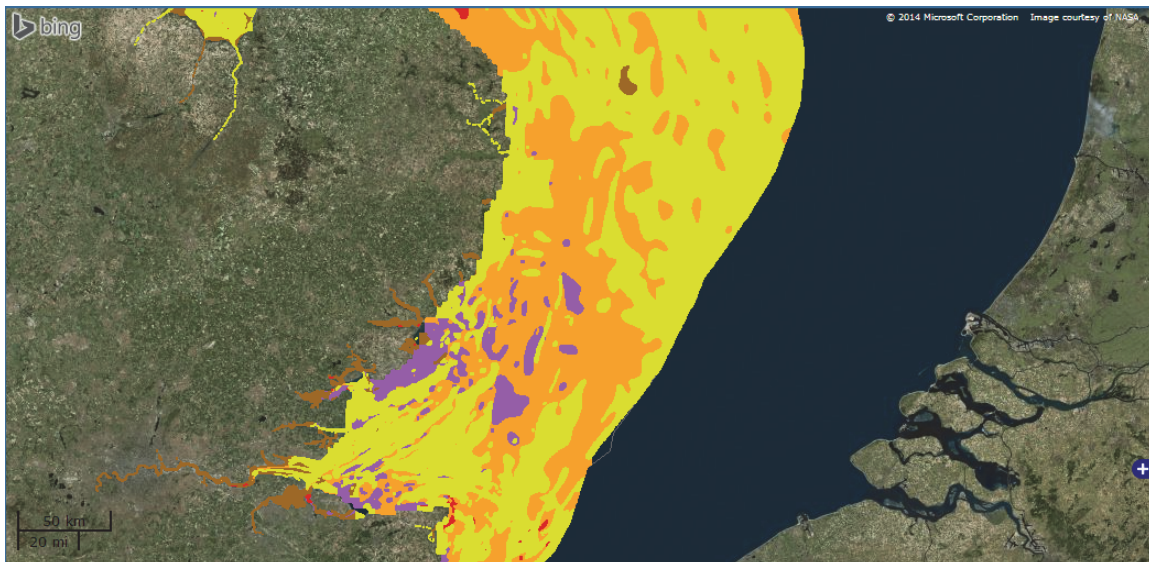


Figure 3.6 Sea bed map from UKseaMap 2010, JNCC. Coarse sediment (orange), mixed sediment (brown) and sand and muddy (yellow).

Table 3.1 input parameters for the modelling including the seabed properties

|                             | Sound speed<br>(m/s) | Density (g/cm <sup>3</sup> ) | Attenuation<br>(dB/wave<br>length) |
|-----------------------------|----------------------|------------------------------|------------------------------------|
| Water                       | 1480 (at 7.1 °C)     | 1                            | 0                                  |
| Seabed<br>(medium sand)     | 1706                 | 1.94                         | 0.9                                |
| Seabed (coarse<br>sediment) | 1850                 | 2.23                         | 0.87                               |

### 3.2.3 Propagation models

There are many propagation models available that are capable of predicting transmission loss in underwater channels such the one considered here in this report [Jensen 2000, Etter 2013]. They range from energy flux models such as that of Weston [Weston, 1971, 1976], to semi-analytical solution such as normal mode methods (for example Kraken [Porter, 1991] and C-SNAP [Ferla, 1993]), and to pure numerical models, such as RAM [Collins, 1993].

All the three methods were applied to the prediction of sound pressure level at the recorder. However, only Weston model was applied for the whole time duration where AIS information is available. C-SNAP was used only for a shorter run of one day because it was about 25 times slower than Weston model.

#### 3.2.3.1 *Weston model*

Weston gave a set of equations based on the energy flux method and mode characteristics to predict transmission loss in iso-velocity underwater channels with arbitrary bottom profile [Weston, 1980]. A channel is divided into four regions depending on sound propagation mode; spherical spreading in the immediate vicinity of the monopole source, followed by cylindrical spreading, then mode stripping and finally single mode. The transmission loss at close range up to the cylindrical spreading region is subject to only spreading losses, with additional loss due to bottom reflection loss in the mode stripping region where higher modes are attenuated more quickly as they have larger grazing angles with respect to the sea bottom, until the sound reaches the single mode region where all but the lowest mode has decayed away. The model takes bottom sound speed into account for the critical angle to determine the boundaries of the propagations modes. Weston model is very fast in predicting transmission loss and very useful for noise mapping over a large area.

#### 3.2.3.2 *Coupled normal mode*

Normal mode solution describes the sound field in stratified media such as underwater channel with parallel boundaries, for example the sea surface and bottom, in terms of contributions from all the modes in the channel. Standard normal mode solutions cannot be used for range dependent underwater channels. However, the coupled normal mode method is capable of treating range dependent problems. Kraken and C-SNAP are models using coupled-mode and

adiabatic normal mode solution [Porter, 1991; Ferla, 1993]. They can both be applied to range dependent problems (i.e. range dependent bathymetry and sound speed), and are also able to deal with stratified shear layers. Normal mode solutions are most suitable for low frequency applications where there are only a few modes in the channel. The run time of the solution increases quickly with frequency because of the increase of the number of modes.

### 3.2.3.3 RAM

RAM 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, where sound speed and bathymetry are range dependent.

## 3.2 COMPARISON OF PREDICTIONS WITH MEASURED DATA

### 3.3.1 Predicted and measured sound pressure levels with a generic source level

The modelled and measured data have been compared at 6 third-octave frequency bands (TOBs), namely 50, 63, 80, 100, 125 and 160 Hz respectively. These frequencies cover the most prominent part of the shipping noise spectrum. Figure 3.7 shows the modelled and measured data for all frequencies using the generic source level data from Figure 3.4. The modelled data are the cyan curves. One notices that the Weston model under-estimates sound pressure level at lower frequencies 50, 63 and 80 Hz and it slightly over-estimates the sound pressure level at 160 Hz. The general agreement is better over the early part of the data from day 15 to day 22 when there was a neap tide. The tidal effects are clearly seen around days 40 and 55 with periodic peaks well above the mean level of the SPL. It is not unexpected that the prediction and measurement may differ greatly over these periods.

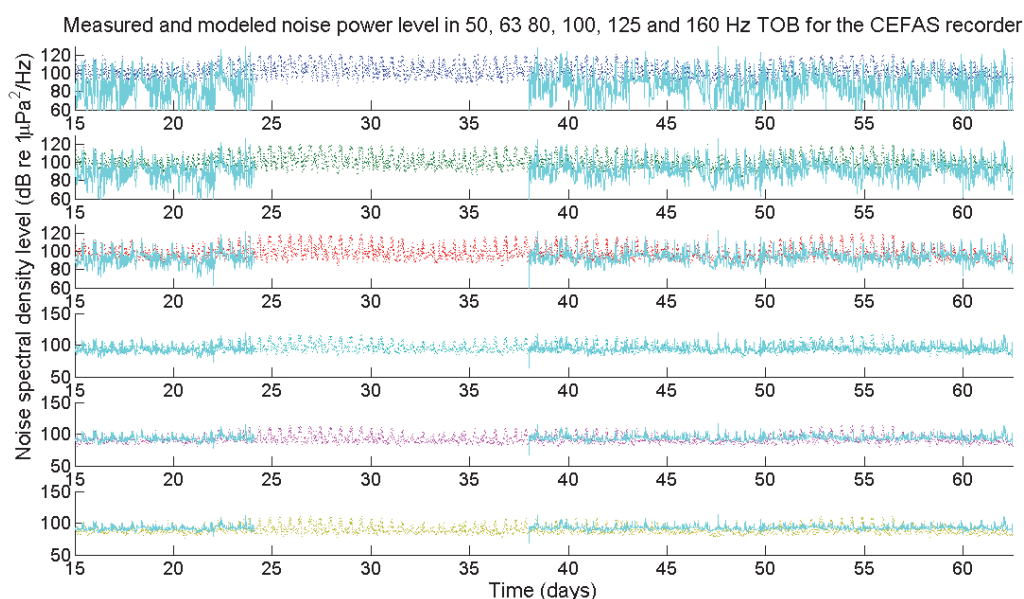


Figure 3.7 Measured and modelled sound spectral density level at frequencies (from the top to the bottom plots) of 50, 63, 80, 100, 125 and 160 Hz TOB bands respectively. The cyan curves are the modelled data. The data gaps are where the AIS information is not available.

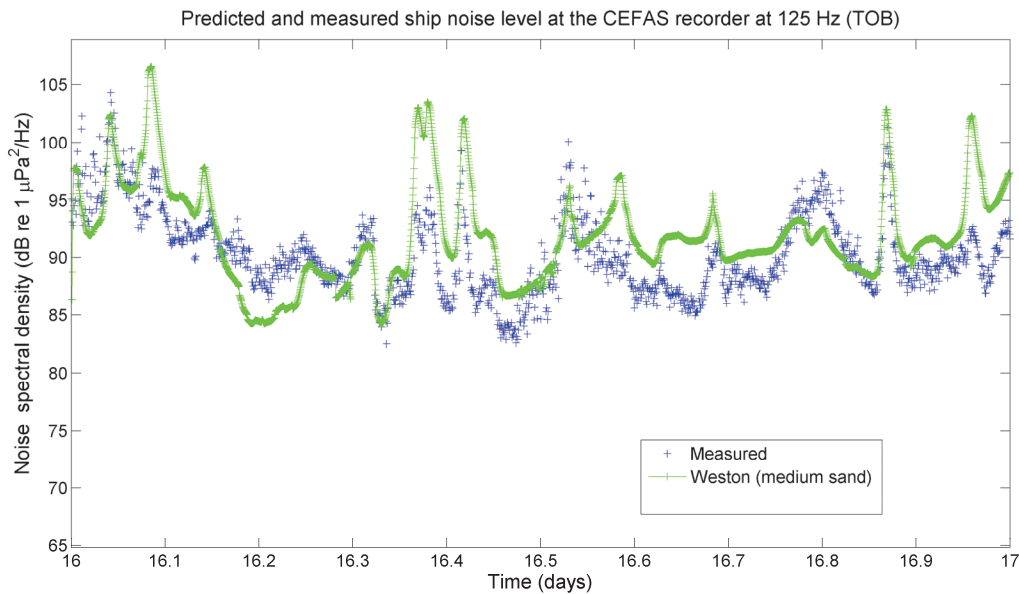


Figure 3.8 Measured and modelled sound spectral density level for the 125 Hz TOB.

Figure 3.8 shows an expanded version of the comparison over a duration of one day for the 125 Hz third-octave band only. The agreement is in general quite good for the overall level and the general shape of the curves, but the agreement close to the peaks in measured data is variable, with good agreement observed at times (for example at 16.87 days), but not at others (for example at 16.07 days). This difficulty with modelling the peaks is likely to be due to the fact that when a vessel passes close by, it dominates the sound field but is of unknown source level and so is unlikely to be accurately modelled. This is less of a problem when there are many distant ships of varying source level.

### 3.3.2 The effect of different sediment on the modelled SPL

Medium sand and coarse sediments were used in predicting the sound pressure levels at the recorder. The effects of different sediments on SPL over one day are clearly illustrated in Figure 3.9. The model over-estimates the SPL with the coarse sediment, while it under-estimates with the medium sand, which is used for all the other modelling in Figures 3.7 and 3.8. Some of the peaks match very well, for example, between  $T=16.1$  days to 16.2 days and,  $T=16.8$  days to 16.9 days.

It is interesting to examine the measured SPL at the times of no flow noise as indicated with the red circles in Figure 3.9 against the modelled data. The predicted level with medium sand is in good agreement with the measured data in this case. The maximum difference is about 3.5 dB.

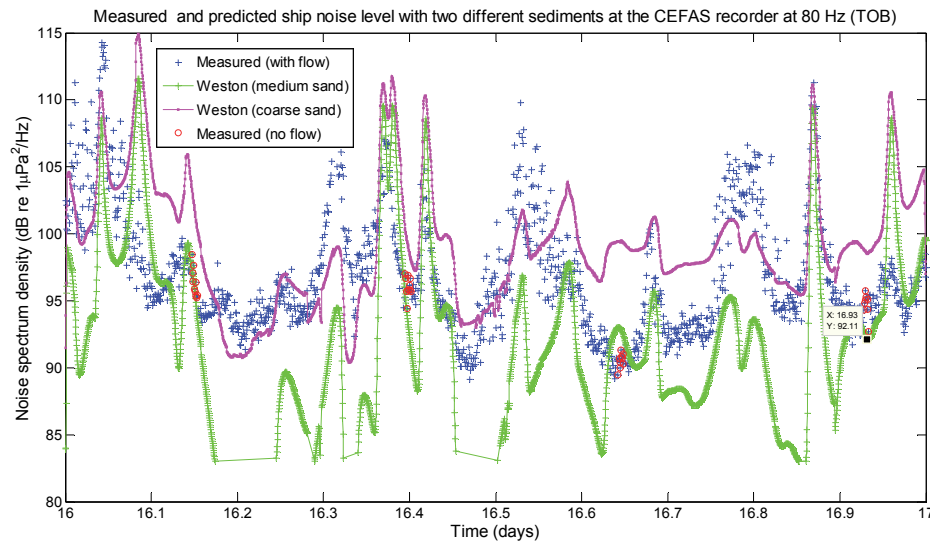


Figure 3.9 Comparison of predicted and measured noise spectrum density with two different sea bed properties.

### 3.3.3 Modified source level for prediction

It is beneficial to use the AIS information to identify ships that generate high noise level at the recorder. Figure 3.10 plots the predicted and measured noise spectrum density in 50 Hz TOB at some selected time periods over a four day period. There are a number of periodical peaks. These peaks are caused by ferries that passed closely to the recorder from the northern route as shown in Figure 3.2. Two of them are labelled in the top left plot. In order to be able to predict the SPL more accurately, instead of the generic source level for all the ships, the source levels of the ships have here been modified specifically based on the types of the ships. The result with the specific source level is in green line, while the result from the fixed source level that is from the generic ship source level model is in red line. It is noticed that the prediction and measurement are in very good agreement on the peaks related to the passenger ship, Stena Britannica when the source level of the ship is increased based on this class of vessel. However, the difference on the level of the peaks for the other ship, Suecia Seaways, a roll on and roll off cargo ship is greater.

The difference between the measured and predicted results may be due to a number of factors, such as the true source levels of the ships being different from the estimates, and the propagation paths over which the properties of sea bed are different. It is envisaged that the latter can be taken into account if the seabed properties are known accurately. It is then possible to estimate the source level of a ship by modelling.

This method can be applied with a recorder, or a number of recorders deployed at locations close to major shipping lanes in areas with well characterised seabed over a long periods of time to record as many ships as possible for a good estimate. The ship source level can be measured without a dedicated measuring range for a large number of ships that are “observed” by AIS and the recorder(s). This process can fill a significant knowledge gap in the information on ship source level for a vast amount of ships of various types. The UK is in a unique position to carry out such work, having the busiest shipping lanes in the world. These ship source levels are in turn to be used for noise mapping with a greater accuracy, enabling better predicting and monitoring of environmental status as required by the MSFD.

The low level predicted by the model is at times much lower than the measured data mainly due to the fact that there are many other ships in the area that are not registered with AIS and there are also ships beyond the edges of the AIS information zone which may also contribute to the SPL at the recorder. The environmental noise from the surface such as wind induced noise and precipitation noise at this frequency is relatively low to make any difference and would form a modest background level well below the noise from the traffic.

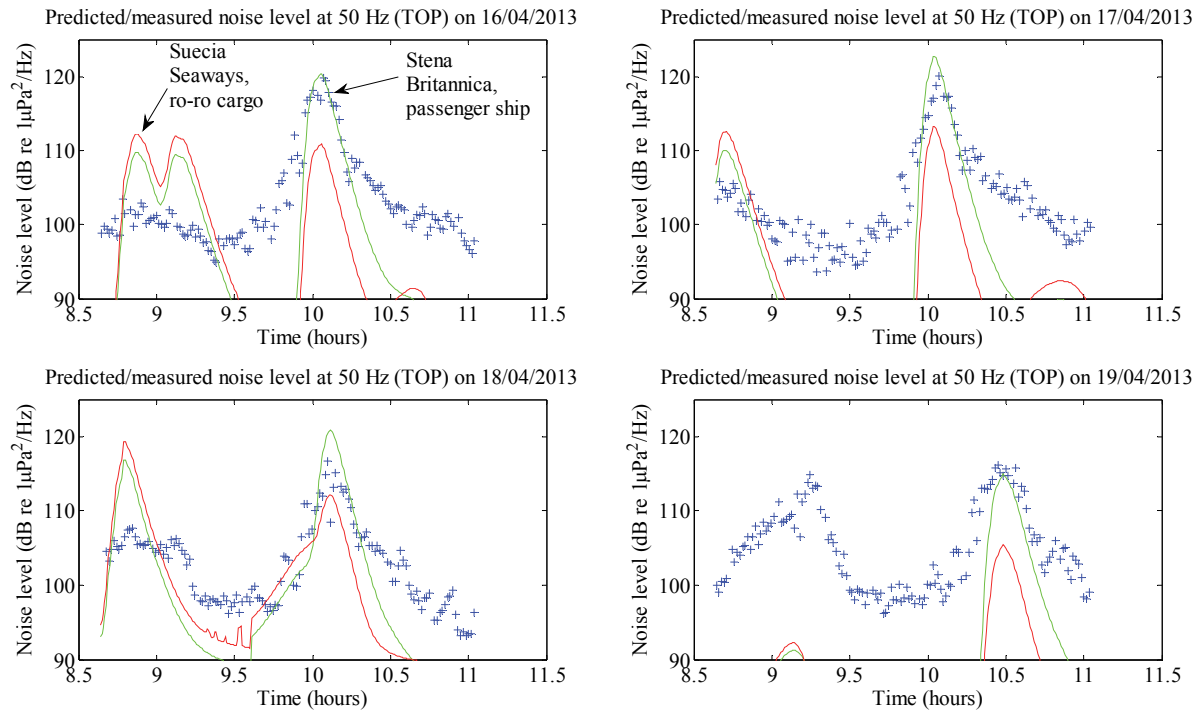


Figure 3.10 Predicted and measured noise spectrum density at selected time periods over 4 days.

## 4. DISCUSSION AND CONCLUSIONS

In this section, the issues raised in Section 2 and 3 are summarised and discussed. The broader objectives of the earlier project (ME5210) were severely damaged by the loss of the first Isle of Wight deployment, and it is to the credit of the project team that a second more modest deployment was achieved to rescue some worthwhile output from the project. The second deployment has enabled a number of lessons to be learned, and some of these are described here. It is difficult to be definitive about all aspects of the data without a more extensive examination than was possible in the time available for this work, but the analysis undertaken enables some initial conclusions to be drawn.

### 4.1 ISSUES WITH DATA QUALITY AND DEPLOYMENT CONFIGURATION

#### 4.1.1 Data quality

As described extensively in Section 2.1 and illustrated by the figures in that section, there was significant degradation in the quality of the recorded data due to: (i) distortion by saturation of the recorder (data clipping); (ii) contaminating noise from deployment platform and mooring; (iii) and flow-induced noise.

With regard to the distortion and clipping for high level signals, this appeared to happen often when a vessel came close, and was also caused on occasions by the low frequency flow-induced noise. This caused a large fraction of the data to become unusable. In hindsight, it would have been beneficial to use a lower gain setting on the recorder than 22 dB so that the dynamic range was increased. However, it is difficult to choose the correct gain settings before deployment without a priori knowledge of the noise levels in the area, and there are limitations placed by the recording system itself. Ideally, the recording system would have a dynamic range of up to 180 dB re 1  $\mu$ Pa before saturation occurs, allowing a vessel to get very close without clipping or distortion [EU TSG 2014b].

#### 4.2.2 Deployment configuration

In project ME5210, the initial deployment in the English Channel south of the Isle of Wight was well-planned, used a superior mooring configuration to the West Gabbard deployment [Borsani *et al* 2014], and is likely to have suffered much less from flow-induced noise. However, unfortunately, the equipment and the data from this deployment were lost. The deployment at West Gabbard, adjacent to the Cefas SmartBuoy, was merely a fall-back solution to try to obtain at least some data for project ME5210, and so it is difficult to be critical of the choice of deployment method and location since there was little option within the remaining time and budget. However, there are a number of lessons that can be learned from the West Gabbard deployment.

The strong correlation of the low frequency signals with the tidal current shown in Section 2.2 demonstrated conclusively that the data were significantly contaminated with flow-induced noise. This made the majority of the remaining data (that were not saturated) very difficult to use in determination of the noise levels in the frequency range of interest (including the two third-octave bands chosen for the MSFD monitoring).

All recorders (and, more generally, hydrophones) are prone to flow-noise in strong currents due to pressure changes in the turbulent boundary layer of water around the sensor. This is not a true acoustic pressure propagating from a remote source (such as a vessel) but an artefact introduced by the presence of the sensor itself. However, the particular rigging and mooring configuration used at West Gabbard seems highly likely to have exacerbated the problem due to the presence of a substantial metal framework around the recorder which will have increased the turbulence. This factor also influenced the clipping of the data since some of this was due to the high-amplitude low-frequency signals due to the flow-noise. Any future deployments in tidal locations should seek to minimise the perturbing structure around the recorder, particularly close to the hydrophone. Other configurations are possible [UK Good Practice Guide 2014, Dudzinski *et al* 2011], and indeed a good configuration was chosen for the original Isle of Wight deployment. It would also be better to select a location away from other buoys and sensor deployments to avoid cross-contamination (which occurred in this case from the adjacent Cefas SmartBuoy). In general, it would also be better to choose a site which does not experience severe tidal currents, though in UK coastal waters this is not easy.

Again, the remaining time and budget within project ME5210 severely restricted the options for redeployment, with the West Gabbard SmartBuoy option being one of the few feasible choices. Nevertheless, the effort was worth it so that the above lessons may be learned.

#### 4.2.3 Choice of recorder

The commercial availability of autonomous recorders at a reasonable price makes them an obvious choice for use in marine noise monitoring. The system self-noise of the chosen recorder for ME5210 is not the lowest available; a better noise performance could be achieved using a combination of higher-quality commercial components. However, for these data, the noise floor of the recorder was not a significant issue (though if a much lower gain setting were used to increase the dynamic range, it may start to become significant for low-amplitude signals). As stated above, a greater dynamic range would have been desirable, but this can be achieved with a lower gain setting, and minimising the flow-noise would also have reduced the degree to which saturation occurred.

The recorder showed good stability, with no changes in overall system sensitivity in the two years between re-calibrations at NPL.

In hindsight, the choice of such a large heavy recorder (it is nearly 2 m long and when filled with batteries weighs around 90 kg in air) was perhaps unwise. The physical dimensions and weight made it unwieldy and more difficult to deploy, requiring substantial rigging and/or mooring. Of course, the greater battery power increases the potential deployment duration.

The sensitivity and directional response of autonomous recorders where the hydrophone protrudes through the body and is rigidly fixed to it often fluctuate at kilohertz frequencies due to the influence of scattered signals from the recorder body [UK Good Practice Guide 2014, Hayman *et al* 2014]. However, at the low frequencies required for the MSFD, this is not a significant problem. This would only be an issue if there was an interest in the data recorded at kilohertz frequencies. Again, the surrounding structure of the lander is likely to exacerbate this problem.

The recorder chosen was an archival recorder, which stores “raw” data on-board and requires to be retrieved in order to download the data. Although this is cheaper than alternatives in terms

of initial capital outlay, for a long-term deployment, the recorder then must be re-deployed in a cycle of deployments and retrievals, requiring much greater vessel time to service the monitoring station. It also has the problem that if the recorder is damaged or lost, there is no way of knowing until the next retrieval is due. This was probably the only option for project ME5210, but future deployments should consider other options. These include hard cabled systems which, though expensive, enable real time data capture and analysis (there are a number of such systems around the world). An alternative compromise is a recording buoy which has some telemetry capability (either via WI-FI in a local network or via the mobile phone network). Again, such examples of these systems are under development. The connection back to shore base (by whatever method) allows data to be processed in real time and provides certainty that the recorder is working throughout the deployment period.

## 4.2 DATA ANALYSIS

Relatively little of the data were suitable for analysis without significant uncertainty due to contaminating signals. However, one of the most useful results to emerge from the data analysis is shown in Figure 2.9, which shows the third-octave band spectral density levels for data during periods of slack tide only (see Section 2.3). The arithmetic mean and the median are shown, as is the dispersion of the data in each frequency band. Clearly visible are the elevated levels at bands in the frequency range 50 Hz to 160 Hz, where ship traffic noise is most prevalent. This demonstrates that, if the data quality is good, the frequency bands nominated for MSFD assessments are quite suitable for monitoring ship traffic noise, though the adjacent third-octave bands are also suitable and may as well also be calculated (the extra computational cost is insignificant). It should be noted, however, that due to clipping of the recorder acquisition system, vessels that approached close to the recorder position have been excluded from the dataset (reducing the occasions on which high noise events were observed, which would have been otherwise recorded faithfully on a system with better dynamic range). The lack of such events could tend to provide a slight bias in the levels, with the arithmetic mean reduced more than the median.

There are relatively few long-term datasets for ambient noise in shallow UK waters, most deployments using a calibrated system being for a matter of days or even just a few hours (often these are undertaken before or after measurements of radiated noise from specific sources [Robinson *et al* 2011]). Although the data of Figure 2.9 is taken from only selected periods (occurring four times a day), it lasts for 49 days and the time of day for each sample varies as the time of slack tide varies, creating a reasonably varied sampling regime. This provides one of the best estimates yet available of ambient noise in UK shallow coastal waters close to shipping lanes.

In the sampling regime used in project ME5210, each file consisted of a 17 minute recording following by a 1 minute “down-time” while the recorder wrote to its hard drive. The statistics of the noise were examined in Section 2.3, and these show that there is not a great sensitivity to the duty cycle used. This is an ideal scenario because it means that the temporal sampling regime need not involve continuous sampling. This is likely to be the case if the recorder is positioned such that it is integrating the noise from many ships in adjacent shipping lanes and high-amplitude events (such as a vessel passing very close by) are infrequent. However, continuous sampling is superior in order to avoid missing any “loud” events, some of which could be periodic (such as ferry crossings).

It was difficult to identify individual sources in the data because of the contaminating signals which degraded the quality. In any case, the best way to confirm the nature of the source is often by listening, which is not practicable for large datasets. Alternatively, a classification system could be developed. There was some evidence for the presence of faint signals caused by the operational noise from an adjacent wind farm, but this would require further confirmation.

#### 4.3 NOISE PREDICTION AND SHIP TRAFFIC DATA

##### 4.3.1 Issues with use of the ship traffic data

The noise dataset was correlated with ship movements from the available AIS data. Unfortunately, the available AIS data had a 10 day gap within it, but this did not prevent worthwhile analysis being undertaken.

The AIS data itself provides interesting data, and such data are worth further study even in the absence of noise measurements. The raw data (plotted in Figure 3.1) have too much information to make it easy to see trends, but the ship traffic density data (plotted in Figure 3.2) are fascinating. The offshore wind farms in the area are clearly visible in the plot due to the volume of maintenance vessels visiting the areas. The main traffic routes emerging from the English Channel into the southern North Sea are evident, as are the routes to local ports such as Harwich and Great Yarmouth. It was possible to identify in the measured data the noise signatures of certain specific vessels which passed close to the recorder, and examples of these are provided in Figure 3.9.

##### 4.3.2 Noise predictions

An initial attempt was also made to compare the measured data with the predictions made by modelling the noise from the ships identified in the AIS data. This had some success (see Figure 3.7), and shows considerable promise as a technique. However, its accuracy was limited by a number of factors for this set of data. There are also a number of generic challenges which may limit the accuracy.

Firstly, for the measured data used here, the data corruption and signal artefacts limited the agreement with predictions, particularly at the lower frequency bands (for example, the agreement for the 125 Hz band was better than for the 50 Hz band). The results tended to be best where a vessel was reasonable close (so that the measured noise exceeded the contaminating signals) but not too close (so that it caused clipping). With better data quality, it is more likely that better accuracy would be obtained for an ensemble of vessels in a shipping lane than for occasions when one vessel approaches close to the recorder (because the source level of that vessel would not be known accurately, and it would dominate the measured noise data as it passed). For a large ensemble of vessels all contributing equally, the uncertainty on the vessel source levels is more likely to average out.

It is possible that better accuracy could be obtained with more specific source level data which could be assigned to each vessel identified on the AIS data stream. Individual vessels will not have known source levels, but source level data could be assigned based on vessel class (even using operating conditions provided by AIS such as speed). However, the data so assigned are

likely to have considerable uncertainty because there is a lack of data on noise radiated by commercial ships. A programme of strategically positioned static noise recorders adjacent to ports or shipping lanes could begin to provide a database of such data which could gradually fill this knowledge gap.

Another significant issue is that not all vessels operate AIS transponders. This does not matter much if these vessels are not significant in number and are part of the distant shipping lanes, but when one such vessel approaches the recorder, a substantial discrepancy between the prediction and the measured data inevitably occurs (on such occasions, the vessel can be heard on the recordings but is not present on the AIS data stream).

An additional problem is that many distant ships outside the coverage range of the AIS can contribute to the measured noise, and these data will inevitably not be present in the predicted levels. So long as the water depth is deep enough for the low frequencies to propagate [UK Good Practice Guide 2014], ships from many kilometres will be audible at the recorder at a low background level, but the predicted levels will not include these contributions.

The absence of any other sources of noise in the model, and the presence of distant shipping outside the AIS coverage range, mean that the predictions provided here will underestimate the levels if there are very few ships in the area. This can be improved by including other sources in the model (though for the MSFD frequency bands, ships are the major noise source, other sources do contribute at a lower level). Alternatively, a wider AIS coverage could be used or the ship density values could be used to inform the model over a wider geographic area [Ainslie *et al* 2009].

There are also some limitations which are introduced by the modelling itself. The model outputs are sensitive to the environmental inputs such as bathymetry and seabed properties. For example, the modelled outputs can be sensitive to absorption, sound speed and density in sediment because these govern the reflection coefficient and there are many reflections when propagating over long paths. The sediment types in the region of interest for the work undertaken here are quite varied, which makes it challenging to provide the appropriate input data to the model. Ideally, a statistical approach is needed where an assumption is made about the possible variation in the input parameters (ideally, this should include ship source level), but the computation time grows significantly for such an approach [Sutton *et al* 2014, Beck *et al* 2014].

#### 4.4 IMPLICATIONS FOR NOISE MONITORING FOR MSFD

It is difficult to draw any conclusions or make any recommendations with regard to an MSFD noise monitoring programme from analysis of the data obtained in project ME5210 because they are so limited in duration and location, and of such variable quality. If the project had been able to achieve the ambitious aims originally conceived at the proposal stage (multiple locations sampled for at least 12 months), then this would have provided a far better platform from which to make a judgement. In practice, the seven week deployment at West Gabbard rescued some considerable worth from the project (in terms of lessons learned), but cannot be used as a basis for the entire UK monitoring strategy.

However, the EU TSG Noise group has produced reports which provide member states with guidance, and these may be used to make some recommendations. A number of these have been

reported already in the project report for ME5210 [Borsani *et al* 2014]. The EU TSG Noise report makes several recommendations regarding:

- The use of modelling in combination with monitoring stations;
- The location of a limited number of monitoring stations to determine the levels in each geographic area or ocean basin;
- The use of monitoring stations to measure individual ships to determine source levels.

#### 4.4.1 The use of modelling

The limited modelling undertaken in this project has had some success but also has illustrated the challenges to overcome if modelling is to be a useful tool in addressing the requirements of the MSFD. There is considerable current interest in the field of noise modelling and noise mapping for underwater sound, including a current EU project led by Cefas and including NPL and TNO (Netherlands Organisation for Science) as project partners (EU Framework Contract ENV.D.2/FRA/2012/0025, titled “Impacts of noise and use of propagation models to predict the recipient side of noise”).

With regard to the MSFD, the use of acoustic modelling for indicators and noise statistics, and possibly the creation of noise maps, ensures that trend estimation is more reliable and cost-effective: Advantages include:

- reducing the time required to establish a trend by spatial averaging;
- reducing the number of stations required to establish a trend over a fixed amount of time, reducing the capital expenditure on monitoring
- assistance with the choice of monitoring positions and equipment (selecting locations where the shipping noise is dominant).

The use of models has the potential to identify individual trends for different sources, thus identifying the cause of any changes, which could facilitate mitigation. Furthermore, models allow the removal of selected sources of noise. In addition, there are advantages of using modelling that could contribute to a greater understanding of potential impacts of noise, such as forecasting changes due to mitigation (such as ship quietening technology). The EU TSG Noise concluded that modelling should be used in concert with measurements to ascertain levels and trends of ambient noise in the relevant frequency bands.

#### 4.4.2 Location

The MSFD Indicator 11.2 focuses on frequency bands that contain mainly ship traffic noise, the objective being to determine trends in ship traffic noise (the ultimate issue addressed being one of masking by low frequency continuous sound).

Maps of shipping density should be used to inform the decision on location. Considering that the UK is adjacent to the busiest shipping lanes in the world (transiting the English Channel and southern North Sea), it is logical to position any monitoring stations close to these shipping lanes (as opposed to an area of the coast which is remote from significant ship traffic). For this reason, the location of the original deployment south of the Isle of Wight was a reasonable choice. With regard to the West Gabbard deployment location, this was chosen for reasons of expediency because of its proximity to the Cefas SmartBuoy. Although the general area of the southern North Sea is good for monitoring ship traffic noise, the position chosen is not ideal

because of the proximity to the Gabbard sand bank which shields the recorder from much of the noise radiated from the east and south east.

Shipping density can be expressed in a number of ways: transit through an area, total distance travelled within an area or the number of vessels within an area. The annual average surface density of ships per unit area is probably most relevant in terms of noise. If such densities are generated for the region of interest, then the average density for various distances from any location can be estimated. Data from AIS, and particularly satellite AIS (s-AIS), can be used for analysis of shipping density, with appropriate adjustments in high density areas.

In order to monitor the trend of ship traffic noise in a shallow geographic region (such as the southern North Sea, or English Channel), a number of factors are important [EU TSG Noise 2014b]:

- monitoring stations should be adjacent to shipping lanes but not directly in the lanes such that the effect of multiple vessels may be integrated at the monitoring location, and no one source dominates;
- with regard to range from the shipping lane, recorders should ideally be deployed between 30 and 100 times the water depth away from the main shipping lane, measured from the closest edge of a shipping lane.
- the local bathymetry should not have severe features (do not monitor behind a sand bank or at the bottom of an ocean trench);
- avoid areas of severe local tidal currents, if possible ;
- avoid areas of high fishing activity where trawling might damage the recorder (or use trawl protection);
- avoid locations close to other sound sources than ships that might dominate the soundscape (eg oil and gas exploration or offshore construction);
- if using existing ocean monitoring stations for reasons of economy, avoid cross-contamination with noise from existing station;
- ideally, locate in areas where the seabed characteristics are reasonably well known;
- hydrophones should be seabed mounted rather than surface deployed, with the hydrophone in the lower half of the water column;
- the depth of the water at the monitoring station should be sufficient for the propagation of sound at the lowest frequency of interest;
- the instrumentation should be of appropriate performance and calibrated traceable to agreed standards.

#### 4.4.3 Measurement stations to provide ship source level information

Measurements can also be used to determine source levels of individual ships, as opposed to measuring at some distance from the shipping lane to determine the overall levels and trends and to ground truth any modelling predictions.

Here, noise measurements at an appropriate but relatively close range to a shipping lane or port entrance can be combined with data on individual vessels (from a system such as Automated Identification System (AIS)) to provide data on vessel source levels. This addresses one of the main difficulties with modelling the shipping noise – lack of knowledge of ship source level data. Estimates of the source levels of the ships could be used as input for models. The EU TSG Noise report [EU TSG Noise 2014b] anticipates that only a limited set of such measuring

stations would be needed to fulfil this form of monitoring since, in most regions, a large majority of ships follow the same routes. For a well-defined shipping lane, the measuring station location should be about 100m to 500 m outside the lane (measured from the edge as specified by the nautical chart); for a less well-defined shipping lane similar positioning should be attempted based on local information.

#### 4.5 CONCLUSIONS

This report has described the work for project ME5217, titled “Additional analysis of noise data from DEFRA project ME5210”, a project commissioned by Department of Food, Environment and Rural Affairs (DEFRA). NPL undertook additional analysis of the acoustic data acquired during DEFRA project ME5210, a project undertaken by Cefas. Analysis was undertaken on acoustic data that were obtained from a deployment close to the West Gabbard Cefas SmartBuoy site using an Aural M2 recorder mounted on a large steel lander frame, the recorder being deployed for a duration of 49 days between April and June 2013. Only limited analysis was possible by Cefas during project ME5210. In the time available for the extra analysis, it is difficult to be definitive about all aspects of the data. A more extensive examination may provide additional benefit, but the analysis undertaken described in this report enables some initial conclusions to be drawn.

NPL has assessed the data quality, identifying a substantial fraction of the data which are contaminated by artefacts such as recorder saturation, flow noise, and cross-contamination noise from other mooring. NPL also identified data which are suitable for further analysis.

The results show that the 63 Hz and 125 Hz third-octave frequency bands nominated for assessment by the EU Marine Strategy framework Directive (MSFD) are suitable bands for monitoring ship borne noise, although adjacent frequency bands would also be a suitable choice and may be monitored at no greater cost.

NPL has correlated the noise data suitable for analysis with AIS data for ship movements provided as part of project ME5210. A comparison has been undertaken of the measured levels of noise in third-octave frequency bands in the range 50 Hz to 160 Hz with predicted levels of noise from models of noise radiated from vessels in adjacent shipping lanes. The results show that such models show significant promise as a tool to represent shipping traffic noise. However, the sometimes poor quality of the ME5210 dataset limits the agreement of comparisons with predictions. In addition, there are a number of aspects of the modelling process requiring further research to determine the accuracy and reliability.

An assessment was also made of the effect of reducing the sampling duty cycle to make an assessment of whether continuous sound recordings are necessary; this has little effect on the statistical distribution of the data analysed here, but this lack of sensitivity to duty cycle depends somewhat on the statistical nature of the dataset.

The limited duration and quality of the data obtained from project ME5210 do not lend themselves to making definitive conclusions with regard to trends in the measured noise, or the necessary spatial resolution of necessary field monitoring stations. However, as far as is possible, and with due consideration to discussions currently underway in other European projects, a discussion has been provided of the desirable combination of field observations and modelling to provide a robust assessment of ambient noise in UK waters.

## **5. ACKNOWLEDGEMENTS**

The authors would like to acknowledge the assistance of Cefas in providing the data for analysis, the data originating from DEFRA project ME5210. In particular, we would like to thank Fabrizio Borsani, Daniel Wood and Nathan Edmonds.

## 6. REFERENCES

[Ainslie *et al* 2009] “Assessment of natural and anthropogenic sound sources and acoustic propagation in the North Sea”, Ainslie, M. A., de Jong, C. A. F., Dol, H. S., Blacqui re, G. and Marasini, C. TNO Report TNO-DV 2009 C084, 2009.

Available online: <http://www.noordzeeloket.nl/overig/bibliotheek.asp>

[Arveson and Vendittis 2000] "Radiated noise characteristics of a modern cargo ship." Arveson, P.T. and Vendittis, D.J. *J. Acoust. Soc. Am.*, vol. 107, p. 118 – 129, 2000.

[Beck *et al* 2014] “Assessment and Monitoring of Ocean Noise in Irish Waters”, Beck, S., O’Brien, J., O’Connor, I. and Berrow, S. Project 2011-W-MS-6-MSFD (STRIVE Report No. 120), funded by the Irish EPA, 2014.

[Borsani *et al* 2014] “ME5210 - Monitoring ambient noise for the Marine Strategy Framework Directive”, Borsani, J.F., Wood, D.T. and Watts, S.C., Final Report. 2014.

[Collins 1993] “A split-step Pade solution for parabolic equation method”, Collins, M. D. *J. Acoust. Soc. Am.* vol. 93, p. 1736-1742, 1993.

[Etter 2013] *Underwater Acoustic Modeling and Simulation*, Etter, P. C., CRC Press, 2013

[EU 2010] Commission Decision No. 2010/477/EU on criteria and methodological standards on good environmental status of marine waters, 2010 O. J. L 232/14. European Commission, 2010.

[EU 2008] Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive), Off. J. European Union, L164, pp. 19 - 40. European Commission, 2008.

[EU TSG Noise 2014a] “Monitoring Guidance for Underwater Noise in European Seas, Part I: Executive Summary”, Dekeling, R.P.A., Tasker, M.L., Van der Graaf, A.J., Ainslie, M.A., Andersson, M.H., Andr , M., Borsani, J.F., Brensing, K., Castellote, M., Cronin, D., Dalen, J., Folegot, T., Leaper, R., Pajala, J., Redman, P., Robinson, S.P., Sigray, P., Sutton, G., Thomsen, F., Werner, S., Wittekind, D., Young, J.V. JRC Scientific and Policy Report EUR 26557 EN, Publications Office of the European Union, Luxembourg, 2014, doi: 10.2788/29293, ISBN 978-92-79-36341-2. Available from: <http://publications.jrc.ec.europa.eu/repository/handle/111111111/30979>

[EU TSG Noise 2014b] “Monitoring Guidance for Underwater Noise in European Seas, Part II: Monitoring Guidance Specifications”, Dekeling, R.P.A., Tasker, M.L., Van der Graaf, A.J., Ainslie, M.A., Andersson, M.H., Andr , M., Borsani, J.F., Brensing, K., Castellote, M., Cronin, D., Dalen, J., Folegot, T., Leaper, R., Pajala, J., Redman, P., Robinson, S.P., Sigray, P., Sutton, G., Thomsen, F., Werner, S., Wittekind, D., Young, J.V. JRC Scientific and Policy Report EUR 26555 EN, Publications Office of the European Union, Luxembourg, 2014, doi: 10.2788/27158, ISBN 978-92-79-36339-9. Available from: <http://publications.jrc.ec.europa.eu/repository/handle/111111111/30973>

[EU TSG Noise 2014c] “Monitoring Guidance for Underwater Noise in European Seas, Part III: Background Information and Annexes”, Dekeling, R.P.A., Tasker, M.L., Van der Graaf, A.J., Ainslie, M.A., Andersson, M.H., Andr , M., Borsani, J.F., Brensing, K., Castellote, M., Cronin, D., Dalen, J., Folegot, T., Leaper, R., Pajala, J., Redman, P., Robinson, S.P., Sigray, P., Sutton, G., Thomsen, F., Werner, S., Wittekind, D., Young, J.V. JRC Scientific and Policy Report EUR 26556 EN, Publications Office of the European Union, Luxembourg, 2014, doi: 10.2788/2808, ISBN 978-92-79-36340-5. Available from: <http://publications.jrc.ec.europa.eu/repository/handle/111111111/30980>

[Ferla *et al* 1993] “C-SNAP: Coupled SACLANTCEN normal mode propagation loss model”, Ferla C. M., Porter M. B., Jensen F. B. *SACLANTCEN Memorandum SM-274*, SACLANT Undersea Research Centre, La Spezia, 1993.

[Cato 2008] “Ocean ambient noise: its measurement and its significance to marine animals”. Cato D.H., *Proceedings of the Institute of Acoustics*, vol. 30. part 5, 2008.

[Dudzinski *et al* 2011] “Trouble-shooting deployment and recovery options for various stationary passive acoustic monitoring devices in both shallow- and deep-water applications”, Dudzinski, K.M., Brown, S.J., Lammers, M., Lucke, K., Mann, D.A., Simard, P., Wall, C.C., Rasmussen, M.H., Magnusdottir, E.E., Tougaard, J. and Eriksen, N. *J. Acoust. Soc. Am.*, vol. 129, p. 436-448, 2011.

[Hamilton 1980] “Geoacoustic modeling of the sea floor”. Hamilton, E. L. *J. Acoust. Soc. Am.*, vol. 68(5), p. 1313-1340, 1980.

[Hayman *et al* 2014] “The calibration and characterisation of autonomous underwater recorders”, Hayman, G., Robinson, S.P. and Lepper, P.A. *Proceedings of the 2<sup>nd</sup> conference on Underwater Acoustics – UA2014*, Greece, June 2014.

[Jensen *et al* 2000] *Computational Ocean Acoustics*, Jensen, F. B., Kuperman, W. A., Porter, M. B. and Schmidt, H. AIP press Springer-Verlag, ISBN: 1-56396-209-8, 2000.

[Lepper *et al* 2011] “Review of the requirements and current availabilities of long term ambient noise measurement technologies”, P Lepper, G Hayman, S P Robinson, E Harland. *Proceedings of the Institute of Acoustics*, vol 33, part 5, p. 33, ISBN 978-1-906913-09-0. 2011.

[Merchant *et al* 2012] “Averaging underwater noise levels for environmental assessment of shipping”, Merchant, N.A., Blondel, P., Dakin, D.T., and Dorocicz, J., *J. Acoust. Soc. Am.*, vol. 132, p. EL343-EL349, 2012.

[Merchant *et al* 2013] "Spectral probability density as a tool for ambient noise analysis." Merchant, N. D., T. R. Barton, *et al. J. Acoust. Soc. Am.* vol. 133, p. EL262-EL267, 2013.

[Porter 1991] “The KRAKEN normal mode program,” Porter M. B. *SACLANTCEN Memorandum SM-245*, 1991.

[Robinson *et al* 2011] “Measurement of noise arising from marine aggregate dredging operations”, Robinson, S. P., Theobald, P. D., Hayman, G., Wang, L-S., Lepper, P. A., Humphrey, V. and Mumford, S. MALSF Report (MEPF Ref no. 09/P108), 2011. Available from: [www.alsf-mepf.org.uk](http://www.alsf-mepf.org.uk)

[Ross 1987] *Mechanics of Underwater Noise*. Ross, D., Peninsula Publishing, Los Altos, CA, 1987.

[Sutton *et al* 2014] “Mapping the spatio-temporal of underwater noise in Irish waters”, Sutton, G., Jessopp, M., Clorennec, D. and Folegot, T. Project 2011-W-MS-7-MSFD (STRIVE Report No. 121), funded by the Irish EPA, 2014.

[UK Good Practice Guide, 2014] Good Practice Guide for Underwater Noise Measurement, National Measurement Office, Marine Scotland, The Crown Estate, Robinson, S.P., Lepper, P. A. and Hazelwood, R.A., NPL Good Practice Guide No. 133, 2014. Available online: [www.npl.co.uk/acoustics](http://www.npl.co.uk/acoustics)

[Van der Schaar *et al*] “Changes in 63 Hz third-octave band sound levels over 42 months recorded at four deep-ocean observatories”, Van der Schaar, M., Ainslie, M. A., Robinson, S. P., Prior, M.K., Andre, M. *Journal of Marine Systems*, vol. 130, 4-11, 2014.

[Wales & Heitmeyer 2002] “An ensemble source spectra model for merchant ship radiated noise”, S. C. Wales and R. M. Heitmeyer, *J. Acoust. Soc. Am.* 111, p. 1211-1231, 2002.

[Urick 1983] *Principles of Underwater Sound*, Urick, R. J. Peninsula Publishing, New York, 1983.

[Wenz 1962] “Acoustic ambient noise in the ocean: spectra and sources”, Wenz, G. M. *J. Acoust. Soc. Am.*, vol. 34, p. 1936-1954, 1962.

[Weston, 1971] Intensity-range relation in oceanographic acoustics, D. E. Weston, *Journal of Sound and Vibration*, vol. 18, p. 271-287, 1971.

[Weston, 1976] “Propagation in water with uniform sound velocity but variable-depth lossy bottom”, Weston, D. *Journal of Sound and Vibration*, vol. 47, p. 473-483, 1976.

[Weston, 1980] Acoustic flux formulas for range-dependent ocean ducts, D. E. Weston, *J. Acoust. Soc. Am.* vol 68, p. 269-281, 1980.

---

## GLOSSARY AND LIST OF ABBREVIATIONS

|              |                                                                                                                                                                                                                                                                                                       |
|--------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Cefas</b> | Centre for Environment, Fisheries and Aquaculture Science, an Executive Agency of Defra (Department for Environment, Food and Rural Affairs)                                                                                                                                                          |
| <b>dB</b>    | Decibel; a logarithmic unit expressing the ratio of a quantity, $a_1$ , relative to a reference value, $a_0$ , according to the formula: $10 \cdot \log_{10}(a_1^2/a_0^2)$                                                                                                                            |
| <b>MSFD</b>  | Marine Strategy Framework Directive                                                                                                                                                                                                                                                                   |
| <b>NPL</b>   | National Physical Laboratory                                                                                                                                                                                                                                                                          |
| <b>PE</b>    | Parabolic Equation, used as part of an ocean sound propagation model                                                                                                                                                                                                                                  |
| <b>PL</b>    | Propagation Loss in water, Reduction of sound level with range, expressed in decibels - same as Transmission Loss. Unit: dB                                                                                                                                                                           |
| <b>RAM</b>   | Range-dependent Acoustic Model, an ocean sound propagation model                                                                                                                                                                                                                                      |
| <b>RL</b>    | Received Level, Acoustic level at the receiver position                                                                                                                                                                                                                                               |
| <b>RMS</b>   | Root mean squared (rms)                                                                                                                                                                                                                                                                               |
| <b>SL</b>    | Source Level, a measure of the acoustic output of a source. Unit: dB re 1 $\mu\text{Pa}^2 \cdot \text{m}^2$ 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) |
| <b>SPL</b>   | Sound Pressure Level. Unit: dB re 1 $\mu\text{Pa}$                                                                                                                                                                                                                                                    |
| <b>TL</b>    | Transmission Loss, Acoustic Propagation Loss in the water, reduction of sound level with range, expressed in decibels (dB)                                                                                                                                                                            |
| <b>TOB</b>   | Third Octave Band, frequency band consisting of one-third of an octave, an octave representing a doubling of frequency                                                                                                                                                                                |
| <b>UK</b>    | United Kingdom                                                                                                                                                                                                                                                                                        |