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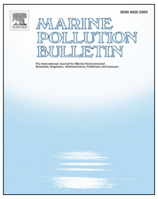

An adaptive grid to improve the efficiency and accuracy of modelling underwater noise from shipping

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ABSTRACT

Underwater noise pollution from shipping is a significant ecological concern. Acoustic propagation models are essential to predict noise levels and inform management activities to safeguard ecosystems. However, these models can be computationally expensive to execute. To increase computational efficiency, ships are spatially partitioned using grids but the cell size is often arbitrary. This work presents an adaptive grid where cell size varies with distance from the receiver to increase computational efficiency and accuracy. For a case study in the Celtic Sea, the adaptive grid represented a 2 to 5 fold increase in computational efficiency in August and December respectively, compared to a high resolution 1 km grid. A 5 km grid increased computational efficiency 5 fold again. However, over the first 25 km, the 5 km grid produced errors up to 13.8 dB compared to the 1 km grid, whereas, the adaptive grid generated errors of less than 0.5 dB.

1. Introduction

An increasing weight of evidence suggests that noise pollution associated with shipping can have a detrimental impact on marine life (Richardson et al., 1995; Rolland et al., 2012; Wale et al., 2013; Williams et al., 2015; Blair et al., 2016; Dunlop, 2016). As a result, key environmental protection legislation worldwide seeks to regulate noise from shipping (MMPA, 1972; ESA, 1973; European Commission, 2008, 2017; Lucke et al., 2013). Industry and regulatory bodies are often required to robustly quantify the levels of underwater noise emissions associated with shipping for monitoring purposes, and in some circumstances, environmental impact assessment (Merchant et al., 2016). Underwater acoustic propagation models are an essential tool to predict noise for these regulatory and research activities (Dekeling et al., 2014; Farcas et al., 2016; Sertlek et al., 2016).

Specifically, acoustic propagation models are primarily used to create ship noise maps (Erbe et al., 2014; Marine Management Organisation, 2015). These are important for managers because maps highlight patterns of noise in time and space. It is not practicable to measure noise over large areas using hydrophones. Therefore, to produce a map, it is necessary to predict noise, using a model, at the locations that cannot be measured directly in the environment. It is thought future trends in shipping noise will be small in magnitude; suggested values range from 0.1 dB per year (Dekeling et al., 2014) to 3.3 dB per decade (Frisk, 2012). Therefore, it is likely to take many years to detect these trends in measured data. Acoustic propagation modelling can help to reduce the number of years and stations required by allowing spatial averaging of noise levels (Dekeling et al., 2014). Furthermore, an understanding of noise variability in space can be used to suggest the optimum locations for underwater fixed monitoring equipment (Van der Graaf et al., 2012). Acoustic propagation models are also executed at smaller spatial scales, particularly between one or many sources and a single receiver, in order to validate acoustic propagation models against field measurements as well as benchmark the efficiency and accuracy of different acoustic propagation models (Etter, 2013). Moreover, they can be useful to assess the individual exposure of animals for scientific and regulatory procedures where animal locations are given exactly by telemetry devices or observations (Chen et al., 2017). However, the utilisation of acoustic propagation modelling to undertake such activities is known to have intensive time and computing requirements (Etter, 2013; Wang et al., 2014; Marine Management Organisation, 2015; Sertlek et al., 2016).

Acoustic propagation models tend to be computationally intensive to execute because they are based on a detailed physical representation of acoustic wave propagation and in many cases also account for detailed changes in the environment (range dependent models) (Etter, 2013). Acoustic wave propagation is dependent on sound speed, which is determined by the temperature, hydrostatic pressure and salinity of a water mass (Etter, 2013). Propagation is also influenced by absorption and reflection of waves at boundaries between the water and the

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surface, the water and the seafloor sediments and different water masses in the ocean (Etter, 2013). However, when predicting shipping noise numerical range dependent models are often neglected in favour of simple geometric spreading laws (Etter, 2013; Marine Management Organisation, 2015). These spreading laws only assume acoustic energy decays logarithmically as sound propagates from source (Urick, 1983). The main attraction of using geometric laws is the speed at which calculations can be conducted (Marine Management Organisation, 2015; Farcas et al., 2016). However, it has been shown that geometric spreading laws can result in significant errors (Robinson et al., 2014; Farcas et al., 2016). Farcas et al. (2016) demonstrated that when compared to a more complex model (RAM, Collins, 1993), which allows environmental properties to vary with range from source, the geometric spreading laws underestimated noise close to the source and overestimated noise far from source. This is of particular concern when trying to make predictions for legislation relating to marine ecosystems as it could result in a failure to put in place appropriate mitigation strategies to protect sensitive species. Consequently, in using the geometric laws, users are often making a compromise between computational efficiency and accuracy. As a result, there is a need for methodologies which can reduce the computational costs of executing advanced models so that users can leverage the greater level of realism they provide.

Currently, there are a number of strategies available to make acoustic propagation modelling more tractable. For example, it is most pertinent to select, from the numerous available models, an appropriate model for the specific requirements of a study (Farcas et al., 2016). The selection of a model will depend on the frequency characteristics of the noise source, the depth of the water, the variability of the environmental characteristics in the study area and the computational power available (Etter, 2013). The incorrect choice of a model will compromise both the efficiency and accuracy of the results. Furthermore, an assumption of uniform sound speed, uniform sediment type and uniform bathymetry is often made to simplify propagation calculations (Sertlek et al., 2016). However, in environmentally variable regions, where there are changes in water mass properties, seafloor sediments and bathymetry, these assumptions are not valid. This is often the case in shallow shelf environments where the structure of the water column can be highly stratified (Simpson and Sharples, 2012). In these environments, computationally intensive models that characterise environmental variation using a range and depth dependent approach are required (Jensen, 2011).

For shipping specifically, where there are many disparate noise sources (ships), increases in efficiency can be achieved by spatially partitioning the study area into a grid. Typically, a grid will group ships in square grid cells of a fixed size (Erbe et al., 2014). Applying a grid to the ship data improves efficiency by reducing the number of times the acoustic propagation model must be executed. It is only necessary to calculate propagation loss once from the centre of a grid cell to the location of the noise receiver. This propagation loss value can then be applied to all ships in a grid cell (Erbe et al., 2012a, 2014). The grid cell size selected for a study is concerned with achieving a realistic execution time for the scale of the study area. Regional studies typically use square grid cells with edges between 2 and 5 km in length (Erbe et al., 2014; Marine Management Organisation, 2015), while global studies have used cells of 1° in longitude and latitude (Porter and Henderson, 2013). The larger the grid cells the fewer calculations required, and therefore, the more efficient the solution. However, the larger the grid cell size, the less accurate the resulting model output (Erbe et al., 2012b). Larger grid cells do not account for environmental variation. This means that propagation loss values at different points within the cell may vary and the assumption that the propagation loss value at the centre of the cell can be applied to all ships in that cell is incorrect.

This study aims to develop a method which produces efficient *and* accurate noise level predictions using acoustic propagation models by designing an adaptive grid to spatially partition ship source data. We present a grid where cell size will vary with distance from the receiver. At ranges close to the receiver, where propagation loss changes very rapidly, a small grid size can be used. However, where ships are far away from the receiver, cell sizes can be much larger due to the logarithmic decay in acoustic energy with range. We then investigate the efficiency and accuracy of this approach. Theoretically, it improves computational efficiency by reducing the number of calculations required but maintains, or improves, the accuracy of propagation loss estimations when compared to a grid with uniform cell size. Ultimately, this will improve the noise level predictions made using underwater acoustic propagation models for use in ship noise monitoring by making the implementation of more sophisticated models computationally tractable.

2. Methods

We present an adaptive grid that will spatially group ships. Propagation loss can therefore, be calculated once from the centre of each grid cell to the receiver and applied to all ships in that grid cell. In order to avoid the introduction of error as a result of grouping the ships in this way, ideally propagation loss should be uniform (not vary) across the cell (i.e. the value at the centre of the cell should be representative of the propagation loss at all the points in the cell). In this study, propagation loss was considered *uniform* when the propagation loss value from the centre of a grid cell to the receiver was approximately equal (given an error of ± 1.5 dB) to the propagation loss value from each corner of the cell to the receiver. Depending on the distance between the source and the receiver, the maximum grid cell size where propagation loss is uniform will vary. This distance of uniform propagation loss was determined for a number of different grid sizes and used to predict the relationship between these two variables. This study used the relationship between grid size and distance of uniform propagation loss to produce an adaptive grid, and then demonstrated how the adaptive grid reduces computational effort and preserves the accuracy of finer more computationally expensive uniform grids.

2.1. Case study area

This study focussed on the Celtic Sea region shown by the map in Fig. 1. It was considered preferable to use a case study, rather than an idealised site with uniform environmental properties, in order to demonstrate the efficiency and potential limitations of the new method in a real setting. The area is representative of temperate, shallow, coastal shelf waters. The Celtic Sea is seldom deeper than 120 m and is characterised by the rapid development of a strong thermocline in the summer (April to November) and its slow breakdown in autumn (Pingree, 1980). The region is dynamically active and its water column properties are influenced by multiple mesoscale eddies and fronts (Pingree, 1980). The adaptive grid should be transferable to areas with similar characteristics. Shallow, on-shelf seas are particularly interesting because they play a highly important role in the functioning of the global ocean including biological productivity, economic activity including shipping and the provision of social capital (Simpson and Sharples, 2012).

2.2. Grid generation and analysis for propagation loss/distance simulations

In order to determine at what distance from the receiver the propagation loss becomes uniform across a grid cell, a series of propagation loss simulations were conducted at different grid cell sizes. The smallest grid cell size was 0.5 km and cell size was increased in 0.5 km increments up to a maximum of 20 km. This range was chosen because it is difficult for the acoustic propagation model to produce reliable results over distances shorter than 0.5 km, and a 20 km grid cell size was large enough not to result in uniform propagation loss under any of the conditions examined in this study. Fig. 2 represents how the grid was