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Citation: Proceedings of Meetings on Acoustics **27**, 070017 (2016); doi: 10.1121/2.0000338
View online: http://dx.doi.org/10.1121/2.0000338
View Table of Contents: http://asa.scitation.org/toc/pma/27/1
Published by the Acoustical Society of America

Proceedings of Meetings on Acoustics

Volume 27 http://acousticalsociety.org/

Fourth International Conference on the Effects of Noise on Aquatic Life

Dublin, Ireland

10-16 July 2016

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Recent research has demonstrated the importance of soundscape characterization, modeling, and mapping with regard to their potential to highlight noise levels that can adversely affect fish behavior. Models and noise maps are seen as valuable tools for generating comprehensive information at relatively low costs; a model-based approach presents a powerful and cost-effective way to evaluate noise levels. This research aims to develop a vessel noise modeling method using Automatic Identification System (AIS) and online data. The vessel noise map is produced using estimated source levels of individual ships at each AIS transmission point along a vessel transit line. The accumulation and propagation of these transit line emissions, in 1 km grid squares, produces an ocean shipping noise map showing average received levels over the desired time period. The results show temporal and spatial differences in vessel noise emissions, with summer months nosier than winter months, and coastal areas and known shipping channels much nosier than the open ocean. Unlike many previous models, this approach uses individual vessel source emissions, and is very computationally efficient even for large datasets.

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 [DOI: 10.1121/2.0000338]

1. INTRODUCTION

Underwater noise from shipping is increasingly recognized as a significant and pervasive pollutant with the potential to impact marine ecosystems on a global scale (Williams et al., 2015). To date there are very few studies that have attempted to explore the effects of noise on a large geographic or long temporal scale. However, lately there has been a developing focus on the wider- and longer-term chronic effects of increases in ocean noise and the subsequent changes in underwater soundscapes (Gedamke et al., 2016). Lengthier experiments conducted over broader spatial scales may offer a more complete understanding of the population-level and interacting effects of noise on wildlife (Shannon et al., 2015). The importance of soundscape characterization, modeling, and mapping has been highlighted in recent years (Boyd et al., 2011), as they can provide a method of identifying the potential long-term effects of noise over large spatial scales. Modeling of underwater noise levels using Automatic Identification System (AIS) data has been proposed as a way of mapping noise exposure from shipping to facilitate targeted mitigation measures (Erbe et al., 2012).

AIS provides a means for ships to broadcast data at regular intervals including: vessel identification, GPS position, course, and speed. AIS provides a spatial representation of vessel movements within the receiving range of transmissions. Information is transmitted continuously, providing a comprehensive and detailed data set for individual vessels which can be used to estimate and allocate emissions (Perez et al., 2009). Under the International Maritime Organization's (IMO) mandates, all ocean-going commercial vessels of more than 300 gross tons or carrying more than 165 passengers, as well as all tug/tows, are required to carry AIS transmitters (Federal Register, 2003; IALA, 2004). Also, many vessels not matching the IMO criteria voluntarily use AIS transceivers as a safeguard in case of emergencies. AIS transmissions can be received via terrestrial or satellite receivers.

A network of terrestrial receivers is run and maintained globally providing continual listening and observation of vessel traffic. The transmission range of the receivers can vary from 20 nm to 350 nm depending on the atmospheric conditions (ABPmer, 2014). Satellites are able to collect AIS data from ships farther from shore, whose transmissions would be out of the range of terrestrial AIS receivers. Satellites in Low Earth Orbit, at an altitude of between 650 and 850 km above the earth, are capable of detecting AIS signals (ABPmer, 2014). Using satellite and terrestrial AIS data together increases the area of ocean included in the dataset and provides a higher density of AIS messages reception both close to land and in the open seas. There are two types of Automatic Identification Systems found on vessels. AIS-A provides characterization of commercial shipping but does not include wide sectors of marine traffic such as commercial vessels below 300 GT, recreational vessels, fishing vessels or Military/Government vessels whilst on deployment. AIS-B is a non-mandatory form of AIS typically used by small commercial craft, fishing vessels and recreational vessels. AIS-B also includes Vessel Monitoring System (VMS) used primarily by fishing vessels. AIS data have successfully been used to model ocean noise from vessels, but such models are still in the early phases of development (e.g. MMO 2014, 2015).

Previous AIS-based vessel noise maps have been limited by lack of data or computational power; the Marine Scotland study (ABPmer, 2014) modeled a 7-day period but recognized that this was too short to provide reliable information on patterns of ocean use over a month. Another complication of vessel noise mapping models is the accuracy of the source level. Past AIS-based vessel noise models have used a density grid – the average number of ships present in a map grid cell over a specified period - to estimate vessel positions and noise emissions (e.g. ABPmer, 2014;

MMO, 2014, 2015 used 2 km × 2 km density grids). Using the original AIS vessel transit line information rather than the density grid provides the exact timing of vessel noise sources. Using precise location data provides a more accurate map and takes into account the cumulative impact of two or more noise sources. The density grid method assumes that noise sources within a cell occur independently of one another. The MMO (2015) used source levels taken from previous literature; the specific source levels of the individual ships present in the AIS data were not used, reducing the integrity of the noise map. Having built their AIS-based vessel noise map in Geographical Information System (GIS) software, the MMO (2015) expressed the view that until variation in source levels can be accurately modeled and predicted researchers should not expend the necessary significant time and effort to refine the use of GIS tools in ocean noise mapping.

This work aims to quantify source levels through the application of a noise emission equation that can predict the source level from an individual ship at any transmission point during its voyage. It will improve on previous AIS-based map propagation methods by calculating noise propagation from each point using more complex methods accounting for bathymetry and sediment of the ocean floor. The improved methods and techniques mentioned will only be beneficial if high quality data are used for the study. The Confidence Criteria cited in Marine Scotland's report were applied to the AIS data used in the development of this model, and resulted in an overall confidence rating of 'high', which suggests the data used were of high quality (ABPmer, 2014).

One of the primary requirements in assessments of potential impacts of noise on marine life is the estimation of received levels at different locations where the targeted species are of concern (Spiga, 2015), so a method of predicting received noise levels from vessels would be beneficial. The second aim of this research is to build an accurate vessel noise map of the ocean using Automatic Information Systems (AIS) and online vessel data to quantify source level noise emissions from shipping in waters surrounding the UK to aid marine planning decisions. This model is the first to evaluate marine vessel noise pollution at a large temporal (yearly) and spatial scale (hundreds of kilometers), incorporating both individual vessel source levels and propagation.

2. MODEL DEVELOPMENT

A. DATA INFORMATION

Noise emissions from marine shipping were calculated by applying a bottom-up activity-based methodology using AIS data to derive vessel activity and noise emissions. The model used Java programming language, the PostgreSQL database management system and GIS software to produce a map of ocean vessel noise emissions.

The AIS data, provided by Orbcomm (Fort Lee, New Jersey, United States), contained both satellite and terrestrial coverage. The data incorporated all vessel types in waters surrounding the UK (within latitudes 40^{o}N & 65^{o}N and longitudes 20^{o}W & 12^{o}E) from 1st January 2013 to 31st December 2013. Over 453,000,000 rows of AIS data were used, comprising 352,337 vessels identified by their unique Marine Mobile Service Identity (MMSI) numbers. Raw AIS data were decoded to provide position messages at all transmission points during a voyage for each ship. AIS transmissions occurred on average every 12 minutes.

B. SOURCE LEVEL CALCULATION

The Ship Source Level Model (SSLM) was used to calculate the noise emissions for each vessel (Brooker et al., 2015). The base spectrum used was the Source Spectrum Model (SS_{H+W}) by Wales and Heitmeyer (2002), and speed scaling was added to form the SSLM. Brooker *et al.* (2015) concluded there was minimal benefit to using the SSLM method; the SS_{H+W}, however, results in the same noise emission for all ships of a certain type whereas the SSLM method allows vessel specific noise emission through the addition of the speed scaling and thus greater accuracy.

The SS_{H+W}, and consequently SSLM, is frequency dependent, so in this instance the model is evaluated at a single 80 Hz. Further development of the model will integrate multiple frequencies bands, which may be scaled spectrally for a given species' hearing acuity, to provide more accurate results when using the model for research. The frequency used for the initial development (80 Hz), and reported here, is the frequency at which European eels (*Anguilla anguilla,* L.) – a species to be studied later on in the research – are most likely to be affected (Jerko et al., 1989).

The SSLM noise calculations were run at each transmission point along a vessel's track, providing a source emission estimate for each individual point based on the specific ship attributes (including length, breadth, ship type and speed). The GPS position points, and their calculated noise emissions, were connected in sequence to create a full track or transit line for the ship's voyage with continuous noise emission estimations.

C. PROPAGATION MODEL INTEGRATION

The map was divided into 1 km grid squares and the Sound Pressure Levels (SPL) were calculated for each of the noise sources. The SPLs were then calculated on a square by square basis over a one-month period providing one noise intensity value per grid square. To calculate the SPL within a grid cell a propagation loss (PL) model was used that assumed the source and receiver were both randomly placed within the cell.

Propagation loss was added into the model, taking into account sediment type and bathymetry. The equation used was taken from work by Dekeling *et al.* (2014). The sediment type (EMODnet, 2014) and bathymetry data (BODC, 2016) were collected from online databases and imported into the model using Java programming. Each 1 km grid square was allocated an average depth, using the bathymetry dataset, and a reflection loss gradient from the sediment type dataset. The allocated reflection loss gradient depended on the sediment type present, for example, sand was allocated a value of 0.25 (Ainslie, 2010). The PL model was run for each adjacent square moving outwards radially from the ship's location covering a total of 120 squares (at least 5km in every direction). To calculate the received level within a 1 km square all acoustic power from vessels in the vicinity were summed to create to the overall received level within the cell. These received levels then averaged over a month period (using the arithmetic mean of the acoustic power).

D. MAP GENERATION

Each vessel transit line produced was input into Geographical Information Systems (GIS) software, ESRI ArcMap 10.3.1, to build a map of vessel noise emissions. The map was colored using an IDW (inverse distance weighted) tool in ArcMap 10.3, showing loud areas in red and quiet areas in blue. The IDW tool ran an interpolation that estimated cell values by averaging the values of sample data points in the neighboring cells and smoothing the map output.

3. RESULTS

The model produces heat-map outputs showing the received levels over monthly periods for a specified area (Figure 1). The average monthly received levels during 2013 was recorded as 130dB re 1 μPa^2-s/Hz at 80 Hz during December and 133dB re 1 μPa^2-s/Hz at 80 Hz during June. Full decibel ranges can be seen in Figure 1. December and June are reported here to provide illustrative samples of quiet and noisy months. The map in Figure 1 represents the contribution of shipping noise in the area considered. In many locations, at this frequency, shipping noise represents the dominant noise source, however, note there are also some regions where the predicted shipping noise is below what one would anticipate for non-anthropogenic noise sources.

Temporal differences of 3 dB between June and December, were a consequence of the increased vessel activity during the summer months.

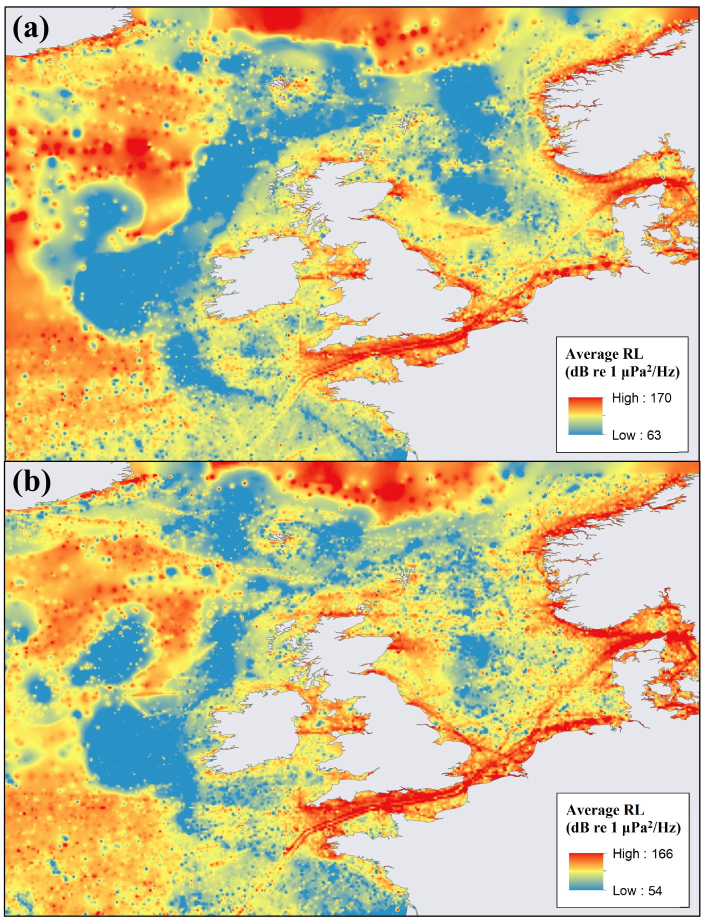

Figure 1. UK map produced by the model showing the averaged RL (dB* re 1 μPa^2/Hz*) during (a) December 2013 and (b) June 2013.

4. DISCUSSION

The model presents map outputs of cumulative and average received noise levels over monthly periods. Further development of the model will allow the received level within a grid square at one point in time to be identified, rather than the monthly noise emission.

The propagation model currently used is a practical spreading model that incorporates both sediment type and bathymetry data and is computationally efficient (Dekeling et al., 2014); the propagation model can be run for the UK map (Figure 1) in a matter of minutes on a desktop computer. However, as the propagation equation used in the current model is most appropriate for long-range shallow water propagation (see Dekeling et al., 2014), more complex propagation models are being considered.

Modeling acoustic propagation conditions is an important issue in underwater acoustics, and as a result there are several mathematical/numerical models based on different approaches that have been hitherto developed (Hovem, 2013). Many of these approaches are being considered during the development of this model to find the optimum method, or optimal combination of methods, so as to incorporate the sound speed profile (Table 1). Sound absorption is important for long range propagation and is known to increase with frequency and be dependent on temperature, salinity, depth and the pH value of the water (Hovem, 2013). The choice of a range-dependent model is vital when running large scale propagation calculations as it allows the environmental input parameters, such as bathymetry and sound speed profile, to vary with distance from the source (Wang et al., 2014). There can be large differences in computational speed for different models, and often a trade-off between higher fidelity/accuracy and the computational time that is required (Wang et al., 2014). In addition, for given propagation conditions there will be a number of modeling solutions which could provide the appropriate accuracy, and so computational power may become the distinguishing factor. Based on the findings presented (Table 1), a Parabolic Equation or Wave Number Integration method appears to be most appropriate for vessel noise mapping.

Table 1. Alternative models for propagation. Sources: (Hovem, 2013[1]; Porter and Bucker, 1987[2]; Spiga, 2015[3]; Wang et al., 2014[4]; Zeiger et al., 2012[5]).

Name	Description	Works for:	Notes
Ray Tracing[1,3,4]	Uses sound propagation conditions when the sound originated from a point source changes little over distances	– High frequency – Deep water – Shallow water – Range dependent	– More valid for high frequency than low frequency (especially limited below 200 Hz) – Sufficiently accurate for applications involving echo sounders, sonar, and communications systems for short and medium short distances – Ray theory has limitations and may not be valid for precise predictions of sound levels
Beam Tracing[2,5]	Approximates a given source by a fan of beams and tracing the beams propagation through the medium and summing the contributions of each of the individual beams	– High frequency	– Computationally very fast – Incorporates directivity pattern of certain frequencies – Uses sound speed profile and water-air/sediment interfaces – Created as an improvement on ray tracing models
Normal Mode[3,4]	Uses separation of variable to solve the local vertical part of the wave equation, and then applies various solutions to solve the horizontal component	– Low frequency – Deep water – Shallow water – Range dependent – Range independent	– Works best when horizontal sound speed is constant but vertical sound speed changes – Incorporates sound speed profile and seabed properties – Best suited to low frequencies and mildly range dependent environments
Parabolic Equation[3,4]	Uses the Helmholtz equation with an approximation that only the out-going wave is considered	– Low frequency – Deep water – Shallow water – Range dependent	– Good for irregular sound speed profiles – Commonly used as considered better than other methods – Incorporates sediment type and seawater absorption – Generally used for frequencies under 1 kHz due to computational requirements
Wave Number Integration[3,4]	Solves the wave equation at close range using a numerical approach	– Low frequency – High frequency – Deep water – Shallow water – Range independent	– Is an exact solution – Can be used for range dependent models but the model is not publically available
Energy Flux[4]	A hybrid method between rays and modes	– Low frequency – High frequency – Shallow water – Range dependent	– Incorporates bathymetry and sediment type – Assumes a homogenous sound speed profile (only true in coastal waters) – Computationally fast

A limitation of previous mapping attempts was the assignment of a ship's reference velocity – its speed when operating under normal service power and loading, in average weather conditions (Eyres and Bruce, 2012) – for use in the noise calculation. Reference velocities vary considerably between different ships and until now these reference velocities were assigned per ship type, with all tankers being allocated the same velocity, all cargo ships being allocated the same velocity, &c. In the model designed here, the service speed is specific to the individual ship depending on its type, length and breadth, and previous recorded speeds from historical AIS data. This method allows for more accurate estimation of noise emissions as speed has been shown to be an influencing factor.

Current vessel speed was provided in AIS transmissions but the value was reported in only ~36% of transmissions, with the remainder stating a speed of 0.0 knots even though distance had been travelled. To ensure a complete speed dataset was available, the speed between each transmission location was calculated using the Haversine Formula (Sinnott, 1984).

There is doubt about the efficacy of AIS-based approaches to noise modeling due to only certain vessels carrying operational AIS transmitters (Merchant et al., 2016). Yet, it has been demonstrated (in the Sutors, Moray Firth, Scotland) that noise emissions generated by AIS-carrying vessels are generally greater than those produced by non-AIS vessels for frequency bands 0.1–10 kHz, and most noise emissions were attributable to the vessels operating with AIS transmitters (Merchant et al., 2016). Noise models using AIS data should account for most of the noise emissions present, assuming that the source levels and propagation models used are sufficiently accurate. Such models can be applied to predict shipping noise levels under various scenarios and indicate areas in need of mitigation.

The essential information taken from the AIS data during the running of this model is the MMSI number and GPS data. All other information needed, such as the vessel's reference velocity and ship attributes, can be acquired from online databases. This means that if small craft without AIS transmitters were able to provide GPS locations via satellite navigation systems or mobile phones they could still be included in the model. Although small craft GPS data are not as easily available as AIS data, they could, with adequate planning, be collected and included in the noise map outputs if necessary. As well as AIS data, Vessel Monitoring Systems data used by larger fishing vessels and EMS Aggregate data used by dredging vessels can be input into the model to add more depth to the resulting vessel noise maps.

This work acknowledged the opinions of previous noise model authors' and has broadened the study by utilizing an entire year of AIS data to map vessel noise emissions temporally and evaluate monthly comparisons and trends in noise emissions (mapping of the whole year data is still ongoing). Seasonal variations in both vessel movements and marine ecosystems can be accounted for in the data. The model created here will provide a basis to move forward to develop more accurate tools for noise assessment, prediction and mitigation.

The model will be embedded into an online/software tool which can be used by marine consultancies or policy-makers to understand how vessel noise changes throughout the year and between locations. Noise hotspots and areas in need of mitigation will be easily identifiable and the model can be adapted to evaluate future scenarios such as increased cargo shipping on the "Motorways of the Sea". The tool will show historical 2013 noise emissions using a PostgreSQL database connection and will potentially allow new AIS data to be input and analyzed producing vessel noise maps of both historical and real-time AIS data.

5. CONCLUSION

Under the Marine Strategy Framework Directive (MSFD, 2008/56/EC) Member States are required to develop strategies to achieve good environmental status of marine waters (Graaf et al., 2012). This model and accompanying tools will assist in developing conservation and mitigation strategies by highlighting locations, and the inhabiting species that may be subjected to the effects of shipping noise. It could also support Marine Planning in oceans (through better informed licensing applications), and aid decision-makers in determining new marine protected areas and other management strategies.

ACKNOWLEDGMENTS

Thank you to the EPSRC (grant EP/G036896/1), and the University of Southampton Industry Doctoral Training Centre in Transport and the Environment for funding this work.

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