Journal of Shipping and Ocean Engineering 8 (2018) 10-20
doi 10.17265/2159-5879/2018.01.002

Extracting Acoustic Source Information of Shipping Noise for Dynamic Ambient Noise Modelling

Giuliana Pennucci and Yong-Min Jiang

NATO-Science and Technology Organization-Centre for Maritime Research and Experimentation (NATO-STO-CMRE), Viale San Bartolomeo 400, La Spezia 19126, Italy

Abstract: Shipping traffic is one of the largest contributors to anthropogenic noise in the ocean. Noise generated by merchant ships elevates natural occurring ambient noise level by 20-30 dB in many areas of the world's ocean. In order to model the contributions of the noise generated by merchant ships to underwater ambient noise level correctly, a database that consists of the source levels as a function of frequency for different types of ships is essential. This paper describes the conceptual design, with an emphasis on the characteristics of shipping noise as sound sources, of a marine noise database. It was developed for providing necessary parameters for underwater ambient noise modelling. The parameters relevant to shipping noise modelling are organized in two catalogues: (1) source-receiver geometry related parameters, namely the coordinates of the ships at a given time period, as well as the sizes/types of the ships from which the noise source depths may be derived, and (2) acoustically relevant parameters, i.e., the acoustic SLs (source levels) at given frequencies. An example is presented here to demonstrate the efficacy of this database. The study area is a 117 × 55 km^2 region off the coast of La Spezia, Italy, in the Mediterranean Sea.

Key words: Underwater ambient noise modelling, shipping, SLs, underwater ambient noise level, ship radiated noise.

1. Introduction

Ocean ambient noise consists of the sound produced by natural and anthropogenic sources. Natural noise includes wind and wave breaks, whitecaps, rainfall, as well as biological vocalizations (such as echo locating marine mammals and snapping shrimp), while anthropogenic sources include shipping, fishing (trawling), military activities (sonar), oil and gas exploitation (drilling), and construction work (piling), to mention a few. Underwater noise may occur at many scales in both space and time and may vary with season, geographical location and, as is often the case, time of the day. Sources of underwater noise may be impulsive (short duration) or continuous. However, since impulsive sounds may be repeated at different intervals and distances, sometimes they are indistinguishable from continuous noise. Thus, ambient noise is commonly defined as background noise excluding dissimilar sound sources. Ambient noise generally covers the whole acoustic spectra ranging from below 1 Hz to well over 100 kHz [1].

The low frequency range (10-500 Hz) of underwater sound is usually dominated by anthropogenic sources (e.g., commercial shipping and seismic exploration), while the medium frequency range (500 Hz-25 kHz) is comprised of natural occurring noise due to rainfall, breaking waves, and bubble formation etc. at the sea surface, as well as the sound generated by small vessels and SONAR systems. At high frequencies (> 25 kHz), only the noise sources that are close to the receiver(s) can be taken into account due to larger acoustic attenuations. Among different sources of underwater noise mentioned above, shipping noise is considered to be the main contributor of the total noise level at a global scale [2]. The reason is that the noise radiated by ships may propagate up to tens or hundreds of kilometers in a wide range of frequencies.

Quantifying underwater noise has been an active

Corresponding authors: Giuliana Pennucci, engineer, research fields: algorithms data processing and statistical analysis. Yong-Min Jiang, Ph.D., Senior Scientist, research fields: underwater acoustics and acoustical oceanography.

topic for military and its relevant research communities because ambient noise level is one of the major factors limiting sonar performance. Moreover, it is also a current and evolving research area for environmental protection organizations and marine plan policy developments due to increasing concern about possible negative effects of anthropogenic underwater noise on marine life. While high fidelity oceanographic and acoustic models have been developed/are being improved, and high quality of environmental data such as bathymetry, water column sound speed profile, even the seabed geoacoustic data are being symmetrically collected, there has been a lack of standardized protocols and associated metric for measuring and describing underwater noise [3]. At least a comprehensive database for the radiated noise levels of commercial ships is not available to the public.

The sound level of shipping noise as a function of frequency is one of the most important parameters for modelling the ambient noise level accurately. Combing with the oceanographic environmental information, the sea bottom geoacoustic parameters, and the source-receiver geometry, the SPL (sound pressure level) for given geological location and frequencies may be predicted. The intention of this work is to develop a comprehensive marine noise database for underwater ambient noise modelling. The preliminary effort has been the methodology development on how to extract, compile and organize a set of shipping noise parameters that are required later by acoustic models. Generally, we organize the shipping noise parameters in two catalogues:

- Source-receiver geometric parameters:

➢ Ship geographical coordinates, for the range between the shop noise source and receiver extracted from real time/near real time AIS (automated identification system) messages;

➢ Ship draught, for the ship depth extracted from AIS messages (if the main noise source information is not available).

- Source acoustical parameters, i.e., the sound level of different types of ships as a function of frequency:

Compiled from literature survey (Table 1) and also existing databases;

➢ Derived from empirical models [4-6];

➢ Extracted from acoustic measurements. It is and will be a continuous effort to analyze the acoustic data collected by hydrophones, acoustic arrays and underwater gliders with acoustic payload from various sea trials conducted by CMRE over the years.

2. Shipping Noise Databases

Currently, commercial fleet (such as tankers, container ships, cargo cruise ships and other large ocean-going vessels) grew from more than 550,000 units [7] worldwide and the global tonnage is expected to grow by about 70% in the next two decades. Over the past years, few significant collections of ambient noise measurements are available from neither military nor civilian communities:

- Databases from military community:

The Naval Oceanographic Office (NAVOCEANO) provides nearly fifty thousand omnidirectional measurements (since 1950) that were collected and organized according to season, frequency, location, and time. Additional Navy database can be found in Ref. [8], which introduces the AEAS (advanced environmental acoustic support) data bank approved by the US Navy's OAML (oceanographic and atmospheric master library). The AEAS data bank consists of three shipping noise databases. However, direct access to these databases is restricted.

- Databases from civilian community:

There exist other ambient noise databases (or data sets) outside the navy operational community although not all of them are available to the public. Notable shipping noise databases and on-going efforts are, to mention a few:

➢ The SOSUS (sound surveillance system): data that were collected by the National Oceanographic and Atmospheric Administration (off the coast of the State of Washington, since 1991);

- The SONIC database: Under development at the University of Southampton as part of the EU (European Union) funded project.
- Another interesting civilian contribute arise from the JASCO applied sciences and the JCU (James Cook University's) CSTFA (centre for sustainable tropical fisheries and aquaculture) that was done to conduct a three-month acoustic recording program to characterize the baseline acoustic environment, including shipping noise, in the Great Barrier Reef (Australia).

More efforts in this context may be available in open literature. However, a common problem is that those databases have gaps due to limitations in the samples (in time, frequency and/or geographic areas), and incomplete information (i.e., without specifications of acoustic parameters needed to estimate or catalogue SL, such as the measurement range and frequency). Furthermore, some shipping noise databases are not available for commercial reasons.

Those limitations have motivated our investigation in establishing an in-house underwater shipping noise database for supporting the on-going research of sensing and predicting underwater noise, as well as developing maritime ISR (intelligence surveillance and reconnaissance) capabilities using robotic platforms at STO-CMRE.

2.1 Collation of Available Shipping Noise Information

It has been a long history for the scientific community to conduct underwater background ambient noise measurements. However, archiving and management of the data are rarely coordinated. This section describes the general consideration and initial work of creating the STO-CMRE MAND (marine acoustic noise database).

Initial efforts started from gathering available datasets that may be merged into the CMRE MAND by reviewing journal papers, conference proceedings and commercial reports. All kinds of underwater measurements, including the ones from different underwater sensors and at different CPA (closest point of approach) distances and depths that have been performed for different purposes, were under our consideration. Quality control was performed on the available measurements to verify if the data are suitable for our study.

There exist ISO (international standards organization) standards, on measuring radiated noise from merchant ships (ISO/TC8/SC2), that define a set of rules should be respected when performing underwater measurements during sea trials. The standards also specify a list of descriptors that should be reported in the results. Following the ISO guidelines, only the measurements that have been performed with ships in known configurations, at known distances and the resulting SLs in International System of Units (SI), i.e., dB re 1 μPa, were taken into account. Measurements presented in literature that did not properly document SL units, or with no distance from the source, were excluded from our database. Moreover, data collected by laboratories or institutions that involved in scientific research on acoustic relevant projects, or reported in peer-reviewed journal papers or books were considered for the database generation, as summarized in Table 1.

2.2 Database Design

Our database adopted an architecture that assembles a set of operational and physical parameters, such as ship length, beam, tonnage and distance of the CPA, that are directly correlated with underwater sound signatures [9]. The acoustic measurements available from the references listed in Table 1 have been organized and archived in the CMRE MAND. When there was a missing piece of information of ship physical characteristics, it would be retrieved from the Marine Traffic ship database [7].

The available data were organized and stored following the AIS standardization protocols [19]. Fig. 1 depicts the main layers and structure of the database in a MATLAB structure for the convenience

Table 1 Summary of the considered references for the database generation.

Source	Description	Underwater sensors
McKenna [9, 11]	Seven types of modern commercial ships (593 in total) were observed offshore California (Santa Barbara channel-SBC, California) and reported.	Autonomous long-term seafloor-mounted acoustic recorder.
MCR International [12]	During summer 2011 measurements of ship noise were taken from the R/V *Song of the Whale* in the English channel and in the Minch (Scotland). 36 separate recordings were made of 33 individual ships.	Calibrated omni-directional RESON TC4032 hydrophone.
Kipple [13]	Underwater acoustic signatures of six cruise ship that sailed Southeast Alaska in September 2000 and June 2001. Underwater sound levels of the cruise ship coral princess as measured at Southeast Alaska acoustic measurement gacility in August 2004.	Underwater arrays
Averson [1]	Extensive measurements of the radiated noise of a bulk cargo ship.	Bottom mounted hydrophone and tracking array (the Atlantic undersea test and evaluation centre-AUTEC)
Hegley [14]	Measurements of ship noise from several trials were summarized (review of existing data).	-
Allen [15]	Measurements from high-speed craft, cruise ships, catamarans and fishing vessels were recorded during summer 2009 in the gulf of Maine (24 ships).	Vertical hydrophone array (three omnidirectional C54XRS hydrophones).
Robinson [16]	Measurements from 6 vessels, measured across three different areas around the UK's coast were recorded.	Range of hydrophones (reson TC4032/TC4014 devices) and autonomous recording buoys (two HS70) and vertical arrays (7 SRD HS70).
AUTEC [17]	An underwater acoustical trial was conducted on R/V Hugh R. Sharp on 23/24 October 2009 at AUTEC (Bahamas).	An underwater acoustical trial was conducted on R/V Hugh R. Sharp on 23/24 Oct 2009 at AUTEC (Bahamas). Vertical array of hydrophones (ITC 8201).
Scrimger [18]	In November 1985, the radiated-noise spectra for 50 merchant ships were measured over a frequency band of 70 to 700 Hz using a towed array in a region located south of the port of Genova (Italy).	Horizontal array towed by the R/V Maria Paolina G.
Austin [19]	Dedicated measurements to characterize the sound emissions of tugs used during Shell's 2015 drilling program in the Alaskan Chukchi Sea. JASCO collected acoustic recordings between 7 July and 5 October 2015 at the Burger Prospect in the Chukchi Sea.	23 AMARs (JASCO)

of users. Data of eight ship classes, i.e., tanker, research vessel, high speed, fishing, passenger, cargo, dredger and light boat, were archived from the available measurements. Details on the AIS classification of the eight ship classes may be found in Ref. [10].

3. Methodology of Retrieving Shipping Noise Information

Underwater ambient noise level modelling plays an important role in SONAR performance predictions and maritime ISR decision making. The quality and validity of ambient noise level predictions highly depend on the adequacy of the acoustic forward model chosen for the area and frequency band of interest, the quality of ocean environmental data (including water column environment and the sea bottom properties) to be used by the acoustic model, and also the accuracy of the sound levels of the acoustic sources.

Inaccurate/incomplete information of the environmental and sound source level data will affect the confidence and even the validity of the ambient noise level estimates. The methodology developed here for supporting underwater noise modelling (which is shown as "Step 3" in Fig. 2) consists of two major steps:

(1) AIS data processing to retrieve acoustically relevant information from metadata messages (Section 3.1);

(2) Extract SL from the STO-CMRE shipping noise database or compute SL using empirical equations (Section 3.2) if no relevant SL data are found in the STO-CMRE MAND.

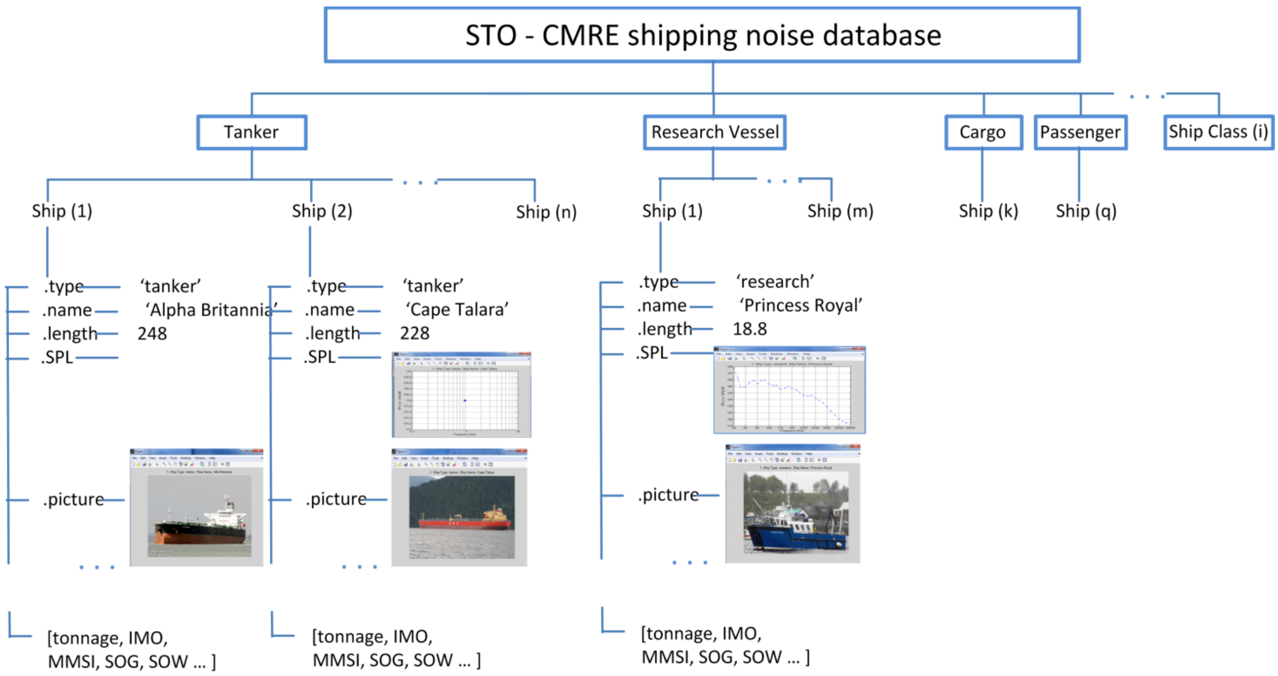

Fig. 1 MATLAB structure for archiving shipping noise information.

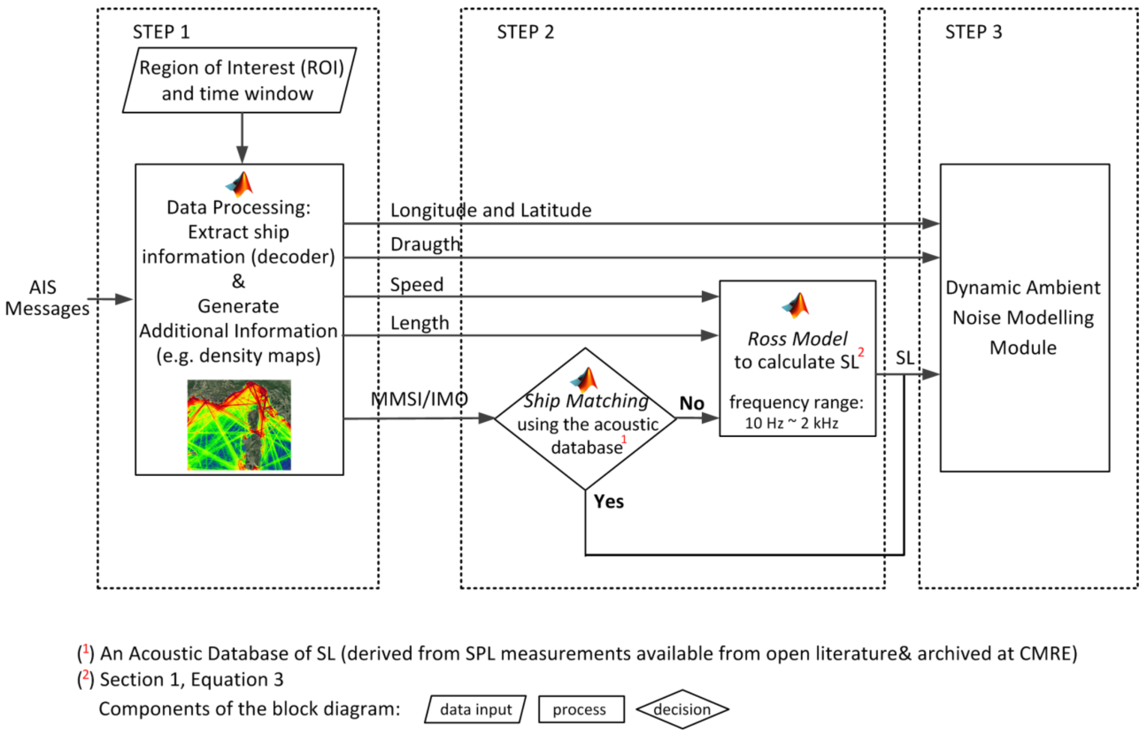

Fig. 2 Flowchart of retrieving acoustically relevant shipping noise information for dynamic ambient noise modelling.

3.1 AIS (Automated Information System) Data Processing

Although several open source tools are available to decode AIS message [19, 20], none was used due to the fact that the dynamic and static metadata messages are needed to be integrated into CMRE-MAND. Consequently, new algorithms were designed to extract the parameters required for further study, including:

- MMSI (maritime mobile service identifier) ship number;
- Ship category;
- Ship-position reports: latitude, longitude and time;
- Ship-size: lengths, depth, GT (gross tonnage) and draught;
- Ship operating conditions, such as SOG (speed over ground) and COG (course over ground).

In order to create a complete metadata ship-track (i.e., a continuous set of position reports and metadata for a given ship), AIS original point-transmission logs at different samples rates (from one sample every 1-2 seconds up to one sample every several minutes) were interpolated or down-sampled to one sample every 10 seconds, then filtered by the time period and area of interest, and finally stored using MMSI as index. For the information that was not provided by the real time AIS data, such as ship categories, further effort was made to fulfill the database. For real time AIS data, such as ship categories, further effort was made to fulfill the database. The algorithms were designed primarily for extracting the parameters from the MSA (Maritime Situational Awareness) STO-CMRE portal. However they are also valid for retrieving the parameters from any sensor that is capable of recording shipping AIS information.

3.2 Extracting SL (Source Level) Information

Source level of the shipping radiated noise is the most important acoustic parameter for modelling the ambient noise background of marine environments accurately. A search will be performed first to find out if there is SL spectra in the database associated with the MMSI/IMO (as indicator of the ship) of interest. If not, the alternative option would be extracting an available SL spectra in the database from the same ship category (such as with similar length and speed, etc.). If that piece of information is still not available, then the most commonly used empirical model developed by Ross [4-6] and validated in other studies [7, 21] will be used to calculate the source spectra of a ship according to its speed (v) and length (l):

$$SL = \overline{SL} + 6log_{10}\frac{v}{v_0} + 2log_{10}\frac{l}{l_0} + c \cdot \frac{l^{1.15}}{3643} \quad (1)$$

where, v_0 and l_0 are the reference speed and the length [22]. A list of reference speed and length of the eight ship categories considered in our work are shown in Table 2. Those values were calculated by averaging the available measurements for the same ship category collated in the STO-CMRE database. $\overline{SL}\,(f)$ is a mean reference value that depends on the frequency [23]:

$$\overline{SL}(f) = \begin{cases} -10 \cdot \log 10\left(10^{F1(f)} + 10^{F2(f)}\right) f < 500Hz \\ F3(f)\ f \geq 500Hz \end{cases} \quad (2)$$

where, $Fi(\mathrm{f}) = \alpha_i + \beta_i \log_{10} f$ and the coefficient values are given in Table 3 [23]. The last term of Eq. (1), c is a correction factor that also depends on frequency:

$$c = \begin{cases} 8.1\ 0 \leq f < 28.4 \\ 22.3 - 9.77 \cdot \log f\ 28.4 < f \leq\ 191.6 \end{cases} \quad (3)$$

Eqs. (1)-(3) were implemented to provide SL at frequencies of interest for dynamic ambient noise modelling (Step 3 of Fig. 2). The main limitation of this

Table 2 Speed and length reference values retrieved from the acoustic measurements in the database.

Categories	v_0 [kn]	l_0 [m]
Tanker	12.5	173
Research	7	31.7
High Speed	35.8	97
Fishing	11.6	28.1
Cargo	11.9	180
Dredger	9.5	98
Passenger	15	233.9
Light Boat	14.6	17
Tug	8.22	115

Table 3 Coefficients for calculating the mean reference SL spectra using Eq. (2) [23].

i	α_i	β_i
1	-14.340	-1.06
2	-21.425	3.32
3	173.20	-18

alternative method is that it might be a source of uncertainty because its formulae refer to some specific sets of measured data and ship types. In reality, each individual ship should have its own set of acoustic signatures [24]. Furthermore the SLs of different ships are correlated (at least partially) with their speeds and lengths [25]. Frequently, the power-law model of Eq. (1) overestimates the variability of source spectra [26]. It was also found [27] that an additional source of errors may occur when the propeller cavitation is the dominant noise source (e.g., when ships travel at moderate or high speed). For these reasons, it is evident that acoustic SL data are essential for dynamic ambient noise modelling. Moreover, dedicated measurements of the source level of shipping radiated noise are necessary.

4. Test Case Demonstration

The procedure of retrieving acoustically relevant information of ships from the marine acoustic database assembled at STO-CMRE is demonstrated in this section using a real world scenario from the STO-CMRE Long-term Glider Missions for Environmental Characterization 2016 (LOGMEC16) sea trial. For the SLs and other relevant information of the ships that were transiting within the area and during the time period we are interested in, the methodologies described in Sections 3.1 and 3.2 were implemented.

4.1 Study Area

The LOGMEC16 sea trial was conducted from 2 May 2016 to 28 June 2016 in the Mediterranean Sea. Its operational area is outlined by the dashed yellow rectangular in Fig. 3. It is inside of a region where the maritime traffic is probably way heavier than any other coastal areas in the world regardless it is a relatively small area in size. There are approximately 220,000 vessels over 100 tonnes passing through this region each year according to Ref. [28, 29]. The maritime traffic volume of this region was estimated at 30% of the world's total merchant shipping and 20% of the oil shipping. The total number of large cargo vessels at any given moment exceeds 2,000, implying that "silent" areas may not exist in the basin.

4.2 Extracting Relevant Information from AIS Data

AIS data processing was divided into two parts: (1) AIS dynamic messages were first processed to extract ship routes, and then (2) AIS static reports were integrated to add information about ship length, beam and draught to the data entries. For the present study, AIS data were obtained from the MSA (maritime situational awareness) STO-CMRE portal. For the time period of two months covered by the sea trial, approximately 260271 vessel position reports were collected inside the LOGMEC16 operational area. About 0.5% entries with erroneous vessel identifications were located and then eliminated manually. To analyze the density of ship traffic, AIS data were stored using MMSI as index and then divided into ship-tracks. A total number of 1,623 ship routes were distinguished and processed to produce a visible layer of the ship density over a time interval of two months. Fig. 4 shows the ship DM (density map) for LOGMEC16. It was generated by accumulating the number of the ships in every 7 × 7 km^2 cell (which makes 15 × 15 pixels per degree-PPD) within the

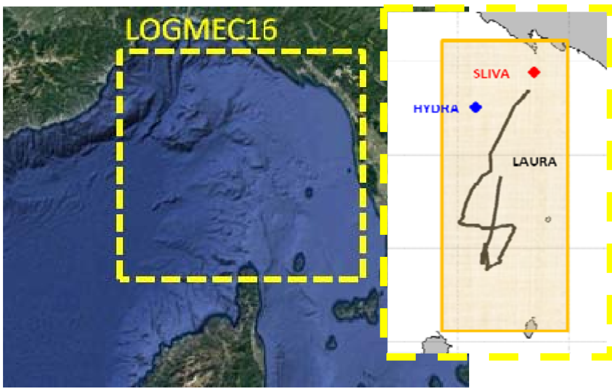

Fig. 3 The geographical location of LOGMEC16 (9.4°-10.2° E, 42.9°-44.0° N). The dashed yellow rectangular on the left outlines the sea trial operational area, and the solid yellow rectangular on the right highlights the area where two acoustic arrays (SLIVA and HYDRA) and two underwater gliders with acoustic payload (Laura and Noa) were deployed.

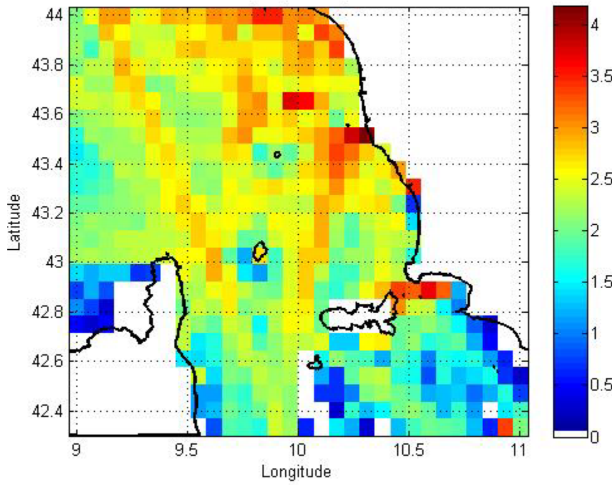

Fig. 4 Shipping density map for the LOGMEC16 operational area from 2 May 2016-28 June 2016. Each pixel represents a 7 × 7 km^2 area and the colour indicates the number of ships in logarithmical scale.

operational area over the time period of LOGMEC16. The colour of the DM represents the number of ships in logarithmic scale. For example, colour red indicates around 10^4 ships in a cell, while white areas are either land or the places where no ships reported. The data used to generate Fig. 4 were retrieved from both AIS dynamic and static records. The dynamic AIS data provide the information about ships' MMSI, time, coordinates, course over ground, heading and speed *etc.* at a data rate of around one record every 1-2 seconds. Other ship physical characteristics, such as name, width, length, draught and category (ship type ID and cargo ID) can be extracted from AIS static records which are available every 5-7 seconds. The relevant information extracted from AIS dynamic and static records was integrated and then archived in the MATLAB structure designed (as shown in Fig. 1) for further DANOM studies.

4.3 SL Estimates

In this section, the subset database extracted from the STO-CMRE noise database for the LOGMEC16 sea trail is presented. Results are displayed on a partition of the LOGMEC16 area (55 × 117 km^2), in which two CMRE acoustic arrays, SLIVA and HYDRA, and two acoustic gliders (Laura and Noa) were deployed, as shown in Fig. 3. Our long term goal is to integrate the available acoustic measurements into the presented analysis, e.g., extracting SL data from gliders acoustic recordings to enrich the STO-CMRE database as well as to validate the results presented herein. Here we consider the AIS data records received during the acoustic gliders deployments: from 23 June (h 19:00) to 25 June (h 21:00), 2016. In order to provide an efficient sampling of the acoustic observable, 50 hours (two days) of ship passages were divided into time-frames of 10 minutes (for a total of 300 snapshots). Data processing algorithms were thus implemented frame by frame to extract SLs. Fig. 5 shows the results retrieved from a representative time-frame (25 June 2016 h 12:00 to 25 June 2016 h 12:10) of AIS dynamic records that were used to initialize a MATLAB structure MMSI, latitude, longitude, time, speed and heading. AIS static ship information (length, beam and draught) was successively integrated using the database previously generated for LOGMEC16. The fourteen ships detected in the time period we are interested in were processed to extract SL information. As expected, due to the lack of acoustic data in the Mediterranean Sea (only Ref. [17] provides field measurements for this area), no matches were found and the Ross model was thus implemented for the eight categories of ships (cargo, passenger, pleasure, tanker, fishing and tug), except for sailing vessels that were not included in this noise model analysis. Fig. 6 shows the results of the calculated mean spectra for two representative ship-categories: passenger (a) and tug (b).

4.4 Level of Confidence and Limitations

The source levels provided in the previous section may be used as a first attempt to support operational activities in the Mediterranean Sea. However, it should be noted that they may introduce great uncertainties in the DANOM output. The SLs for the LOGMEC16 test case were calculated using Eqs. (1)-(3) because there was little information for the ships in the LOGMEC16

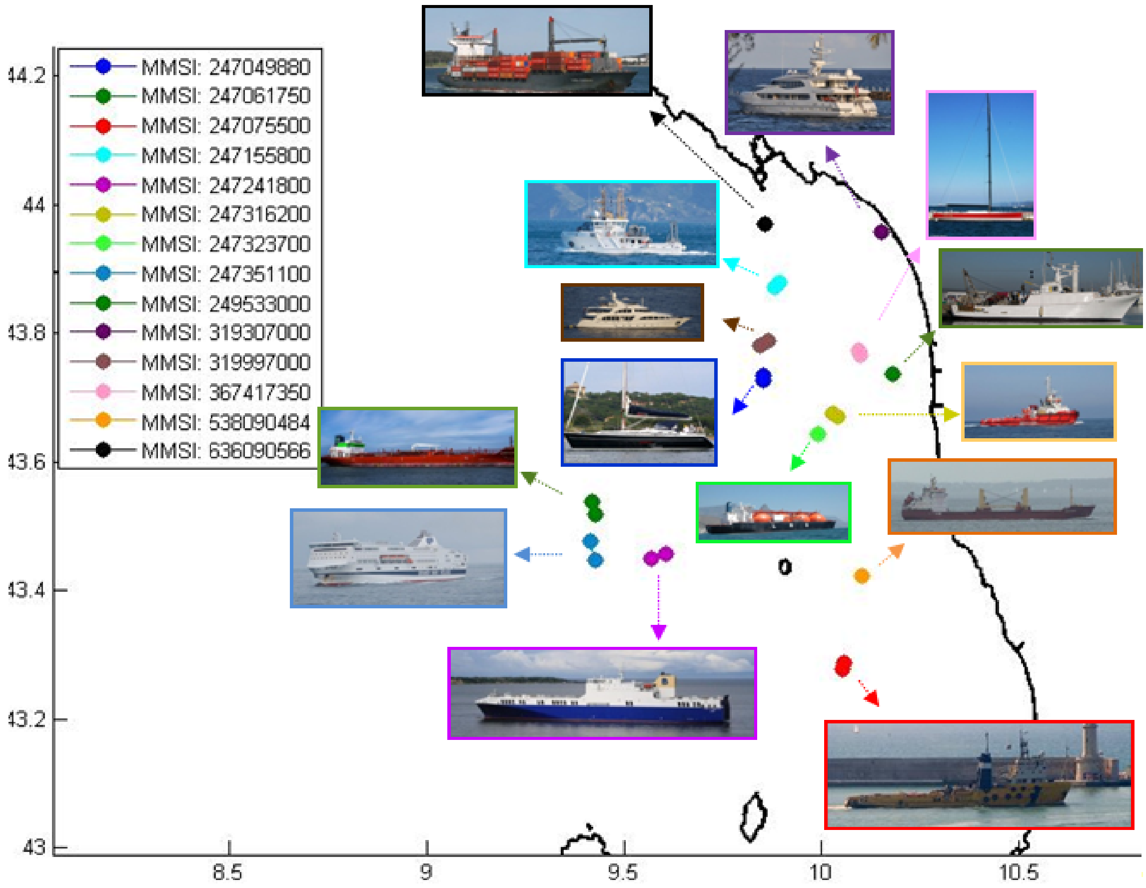

Fig. 5 Positions and pictures of the transient ships during the considered observation time (i.e. from 25 June 2016 h 12:00 to 25 June 2016 h 12:10). For each geographic position, MMSI and picture (pointed with arrows) are also displayed.

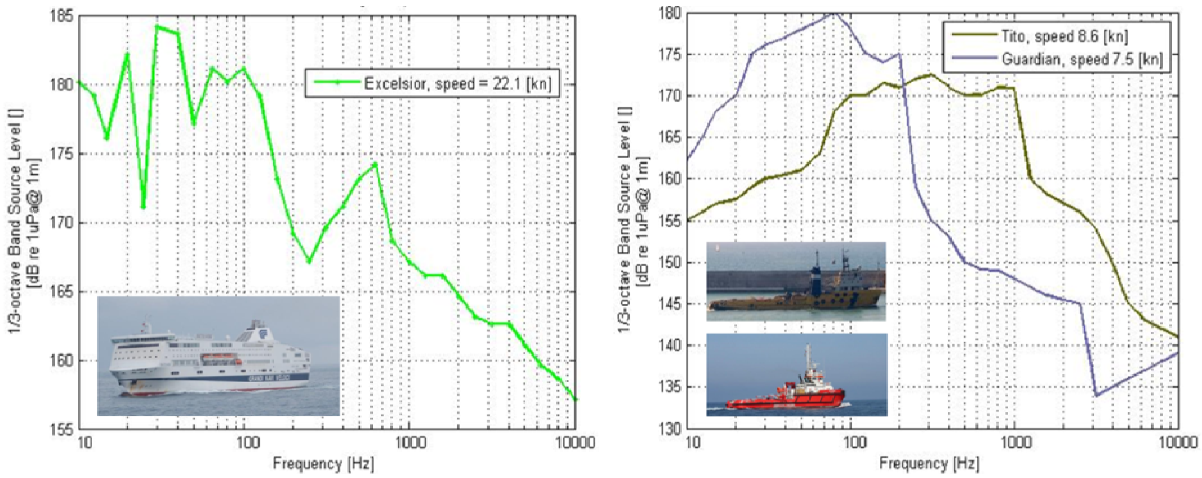

Fig. 6 Calculated source levels as a function of frequency for different ships at different speeds.

operational area in the STO-CMRE database. As mentioned earlier, the main limitation of this empirical approach is that the equations were based on certain sets of observations and hence may not be always suitable for the areas one is interested in.

Fig. 7 shows the broadband (20-10,000 Hz) SLs, calculated from Eqs. (1)-(3), as a function of speed for different ships. For the ones considered in the LOGMEC16 test case, the relationship between vessel speed and calculated source level is apparent. As pointed

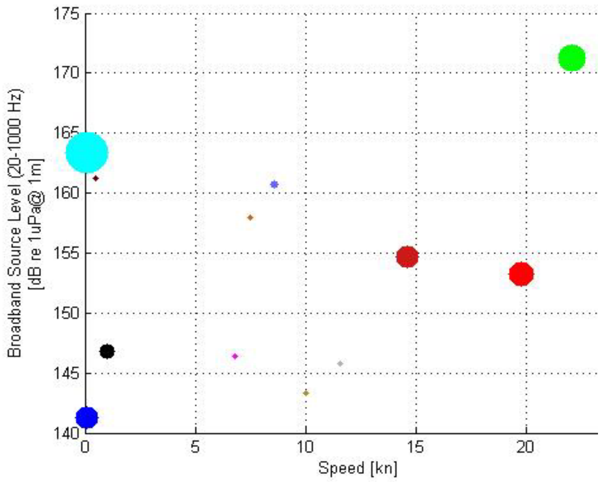

Fig. 7 Calculated broadband ship source level versus speed for different ships considered in the test case. Bubble color represents the ship-type, and bubble size the relative ship size.

out in Refs. [23-25], the calculated SLs in the LOGMEC16 test case also implied that different relationships are needed as opposed to the conclusion suggested in Refs. [4-6], that the ship source level mainly depends on the ship length and has little to do with the ship speed. It is therefore concluded that validating the ship radiated noise levels in the database, either generated from empirical models or extracted from observations obtained in other areas, through field measurements, is necessary for modelling the ambient noise level correctly.

5. Conclusions

This work described the development of a marine noise database, which was designed for providing the acoustically relevant information of noise sources for DANOM at NATO STO-CMRE. Preliminary work focused on the design, and development of the database structure, and output format to allow quick access and easy population of the data. Parameters about different ships as noise sources, such as categories, coordinates, lengths, beams, draughts and acoustic SLs as a function of frequencies, were retrieved from a combination of AIS data, literature and empirical models. At present, the generated database is capable of providing SLs for several ship classes. A test case from the sea trial LOGMEC16 scenario was presented to demonstrate the functionality and potential of the database. The considerable uncertainty in the SLs due to the gaps in the database suggested that more work is needed to enrich the database, especially for the ships in the Mediterranean Sea. Although data mining on the acoustic data collected in previous sea trials is essential, dedicated nodes of acoustic measurement systems from CMRE should also be considered in the near future.

References

[1] Arveson, P. T., and Vendittis, D. J. 2000. "Radiated Noise Characteristics of a Modern Cargo Ship." *J. Acoustic. Soc. Am.* 107 (1): 118-29.

[2] Harland, E. J., Jones, S. A. S., and Clark, T. 2005. "SEA 6 Technical Report: Underwater Ambient Noise." QINETQ/S&E/MAC/CR050575.

[3] Marine Management Organization. 2015. *Modelled Mapping of Continuous Underwater Noise Generated by Activities (MMO 1097).* Report Prepared by ABPmer.

[4] Ross, D. 1976. *Mechanics of Underwater Noise.* New York: Pergamon Press.

[5] Ross, D., and Alvarez, F. 1964. "Radiated Underwater Noise of Surface Ships." *US Navy J Underwater Acous.* 14: 331.

[6] Ross, D. 1987. *Mechanics of Underwater Noise.* Los Altos: Penisula Publishing.

[7] www.marinetraffic.com.

[8] Etter, P. C. 1996. *Underwater Acoustic Modeling: Principles, Techniques, and Applications* (2nd Edition), London: E&FN Spon, 344.

[9] McKenna, M. F., Wiggins, S. M., and Hildebrand, J. A. 2013. "Relationship between Container Ship Underwater Noise Levels and Ship Design, Operational and Oceanographic Conditions." *Scientific Reports* 3: 1760.

[10] AIS standard protocols https://www.navcen.uscg.gov/?pageName=AISmain.

[11] McKenna, M. F., Ross, D., Wiggins, S. M., and Hildebrand, J. A. 2012. "Underwater Radiated Noise from Modern Commercial Ships." *J. Acoustic. Soc. Am* 131 (1).

[12] MCR International. 2011. *Final Report Describing Measurements of Ship Noise Taken from R/V Song of the Whale in the English Channel and the Hebrides in June and August 2011.* IFAW.org.

[13] Kipple, B., and Gabriele, C. 2003. "Glacier Bay Watercraft Noise." Prepared by Naval Surface Warfare Center-Carderock Division Technical.

[14] Hegley, N. 2013. *Offshore Iron Sand Extraction and*

Processing, Assesment of Noise Effects. Report No 9101, Environmental and Industrial Noise Control Engineering.

[15] Allen, J. K., Peterson, M. L., Sharrard, G. V., Wright, D. L., and Todd, S. K. 2012. "Radiated Noise from Commercial Ships in the Gulf of Maine: Implications for Whale/Vessel Collisions." *Acoustical Society of America*.

[16] Robinson, S. P., Theobald, P. D., Hayman G., Wang, L-S., Lepper, P. A., Humphrey, V. F., and Mumford S. 2011. "Measurement of Underwater Noise Arising from Marine Aggregate Dredging Operations." *Advances in Experimental Medicine and Biology* 730.

[17] R/V Hugh R. Sharp. 2009. "Surface Ship Radiated Noise Measurement (SSRNM)." Ranged at Atlantic Undersea Test and Evaluation Center.

[18] Scrimger, P., and Heitmeyer, R. M. 1991. "Acoustic Source-Level Measurements for a Variety of Merchant Ships." *J. Acoust. Soc. Am.* 89 (2): 691-9.

[19] Austin, M., McCrodan, A., O'Neill, C., LI, Z., and MacGillivray, A. 2013. *Marine Mammal Monitoring and Mitigation during Exploratory Drilling by Shell in the Alaskan Chukchi and Beaufort Seas.* July―November 2012: 90-Day Report. In: Funk DW, Reiser CM, Koski WR, editors. Underwater Sound Measurements: LGL Rep. P1272D–1. Report from LGL Alaska Research Associates Inc., and JASCO Applied Sciences, for Shell Offshore Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. 266.

[20] http://gnuais.sourceforge.net/.

[21] http://www.maritec.co.za/?page_id=1051/.

[22] Erbe, C., MacGillivray, A., and Williams, R. 2012. "Mapping Cumulative Noise from Shipping to Inform Marine Spatial Planning." *JASA Express Letters* 132 (5).

[23] Breeding, J. E., Pflug, L. A., Bradley, M., Herbert, M., and Wooten, M. 1996. "Research Ambient Noise Directionality (RANDI) 3.1 Physics Description." Naval Research Laboratory, Stennis Space Centre.

[24] Wales, S., and Heitmeyer, R. 2002. "An Ensemble Source Spectra Model for Merchant Ship-Radiated Noise." *Acoust Soc. Am.* 11 (3): 1211L1231.

[25] Heitmeyer, R. M., Wales, C. S., and Pflug, L. 2003. "Shipping Noise Predictions Capabilities and Limitations." *Marine Technology Society Journal* 37 (4).

[26] McKenna, M. F., Soldevilla, M., Oleson, E. M., Wiggins, S. M., and Hildebrand, J. A. 2009. "Increased Underwater Noise Levels in the Santa Barbara Channel from Commercial Ship Traffic and Its Potential Impact on Blue Whales (Balaenoptera Musculus)." In *Proceedings of the Seventh California Islands Symposium*, edited by Damiani, C. C., and Garcelon, D. K. 141-9.

[27] Leaper, R., Renilson, M., and Ryan, C. 2014. "Reducing Underwater Noise from Large Commercial Ships: Current Status and Future Directions." *The Journal of Ocean Technology* 9 (1): 51-69.

[28] Soares, C., Zabela, F., and Jesus, S. M. 2015. "A Shipping Noise Prediction Tool." OCEANS 2015-Genova.

[29] Dobler, J. P. 2002. "Analysis of Shipping Patterns in the Mediterranean and Black Seas'." *Ciesm Workshop Monographs* 20: 19-28.