Aria of the Dutch North Sea

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3.2. VALIDATION STUDY: COMPARISON OF SHIPPING SOUND MAP WITH THE MEASUREMENTS

This section is a modified version of the Sections 2 and 3 of [M.A. Ainslie, K.L. Heaney, B. Binnerts, H.Ö. Sertlek, P.D. Theobald and T. Pangerc, Use of sound maps for monitoring GES: Examples and way ahead, TNO Report 2014 R11167, 2014]

Abstract: *The use of sound propagation models for generating sound maps has been the theme of three recent sound mapping workshops: The Cetaceans and Sound ('Cetsound') workshop in Washington, USA [cetsound (Washington)], a collaboration between the two EU-funded projects [AQUO] and [SONIC] in Madrid, Spain [AQUO-SONIC (Madrid)], and an international workshop held in Leiden, Netherlands, [Anon et al, 2014]. Application of sound propagation models was also discussed during the Noise Impact Workshop held in Brussels [Borsani, 2014]. This section first presents a range of sound maps. These have been generated with the aim of showing the predicted contribution from shipping on the Dutch North Sea, and were derived using the Aquarius sound mapping framework (which uses the propagation model described in Chapters 2.2 and 2.3). Further, a comparison of model predictions with measurements is presented.*

3.2.1. INTRODUCTION

In this section, maps are presented of annually averaged sound pressure level (SPL) due to shipping (using annually averaged shipping density from Automatic Identification System (AIS) data) in one decidecade band (a decidecade is a frequency ratio equal to one tenth of a decade). This quantity is referred to as a "one-third octave", following widespread common practice, because it is approximately equal to one third of an octave [ISO 266, 1997], [IEC 61260, 1995]. In the remainder of this section, the more precise term decidecade is used [ISO/DIS 18405].

3.2.2. METHODOLOGY

The sound maps presented in this section are based on an average distribution of ships in the exclusive economic zone (EEZ) of the Netherlands. The average shipping density map (see Figure 1) shows the average number of ships of a certain class within a grid cell for a specified time interval. This makes it possible to approximate the temporally averaged SPL in a computationally efficient way. The Aquarius sound mapping framework, originally developed using Weston's flux theory [Weston, 1976] for a review of North Sea underwater sound sources in 2009 [Ainslie et al, 2009], has recently being enhanced to incorporate depth-dependent wave theory corrections using a hybrid propagation algorithm based on mode and flux theories [see Chapter 2.2 and 2.3]. It was used to compute the propagation loss. See [Wang et al, 2014] for an up-to-date review of propagation models for sound mapping. The number of discrete modes is chosen to provide accuracy at low frequency without a large computational overhead. This modelling approach is fast and accurate for broadband calculations in iso-velocity water. We do not expect large errors due to the neglect of sound speed gradient as investigated in Chapter 2.3. It also takes into account range dependent water-depth and sediment type. It calculates the incoherent propagation loss, including the depth dependent properties, using wave theory. Various other acoustic propagation models are included in the sound mapping framework. This makes it possible to compare different propagation models and numerically validate the selected modelling approach. This approach also allows the use of different models for different frequencies, optimizing both accuracy and computation time. As the propagation loss is calculated 2D (range versus depth), it is only possible to approximate a 3D distribution of the SPL by means of interpolation from 2D slices, referred to as the "N×2D" approach.

The modular character of the sound mapping tool allows fast computation of sound maps for a wide range of frequencies and on a large spatial scale, while maintaining the flexibility to study more complex, computationally expensive scenarios.

Inputs

Various inputs are required for the computation of the annual average shipping sound maps. Ships are modelled as point sources at a specified depth below the sea surface and a specified source level. The source level of each ship is calculated using the model by [Wales and Heitmeyer, 2002]. For the case study from the Dutch North sea presented here, the source depth consistent with use of the Wales-Heitmeyer source level was estimated as 5 m below the sea surface, based on information from [Gray & Greeley, 1980] and [Arveson & Vendittis, 2000]. The spatial distribution of the shipping traffic was computed using a density map for the year 2007 (generated by MARIN and provided via IMARES). Ships outside of the Dutch EEZ were not taken into account because the associated AIS dara were not available. The density grid with a resolution of 5 km by 5 km was used, obtained from a sequence of AIS snapshots separated by 2 minutes in time. An ‘AIS snapshot’ is a map displaying all locations off ships fitted with AIS transponders for an instant in time.) AIS is an automatic tracking system used on ships and by vessel traffic services for identifying and locating vessels by electronically exchanging data with other nearby ships, AIS base stations, and satellites. The International Maritime Organization's International Convention for the Safety of Life at Sea requires AIS to be fitted aboard international voyaging ships with gross tonnage of 300 or more, and all passenger ships regardless of size. All EU fishing boats over 16 m length are required to have AIS. Hence, an AIS snapshot gives a good, though not necessarily complete, indication of the instantaneous shipping density. Figure 1 illustrates the annually averaged shipping density map for the EEZ in 2007.

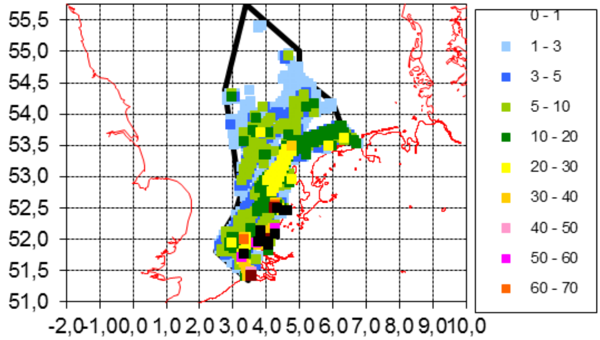

Figure 1: Shipping density map with a resolution of 5 km x 5 km for the year 2007. The values in the legend indicate the annual average shipping density in ships/1000 km^2) . The axes represent latitude and longitude (WGS84).

The environment is defined by the bathymetry, the physical properties of the seabed and water, and the roughness of the sea surface. The bathymetry was obtained from the EMODnet portal for Bathymetry [EMODnet, 2014]. This dataset contains data from the local hydrography offices, improving the base GEBCO dataset with a resolution of 1/8 min. The effects of surface scattering and bubbles on sea surface reflection loss have been modelled using Eq. 8.22 of [Ainslie, 2010] and the fourth power averaged local wind speed, i.e., $(\overline{v_{10}^4})^{\frac{1}{4}}$. The fourth power is used because reflection loss scales with the fourth power of wind speed [Weston & Ching, 1989, Ainslie 2005]. The water was modelled using a uniform sound speed of c_0=1500 m/s and a density of 1000 kg/m^3. The absorption loss α in dB/km was modelled using the equation of Thorp [Thorp, 1967]. The seabed was modelled as medium sand with a compressional sound speed c_1=1797 m/s and density ρ_1=2086 kg/m^3 with an absorption given by α_b=0.88 dB/λ [Ainslie, 2010].

Sound maps

Maps are shown (see Figure 2) for SPL in decidecades with nominal centre frequencies 125 Hz, 1 kHz and 8 kHz and for broadband SPL. Precise centre frequencies follow [IEC 61260, 1995]. Broadband SPL maps (all decidecades with centre frequencies between 32 Hz and 80 kHz) are given with and without M-weighting, for pinnipeds in water and cetaceans [Southall et al, 2007] (see Figure 3). In all cases the receiver depth is 2 m above the seabed. This information can be used, for example, to determine the M-weighted sound exposure level, and hence whether an animal at a given location is at risk of a temporary permanent hearing threshold shift according to the criteria of Southall et al, 2007 (see Ainslie 2010, p562).

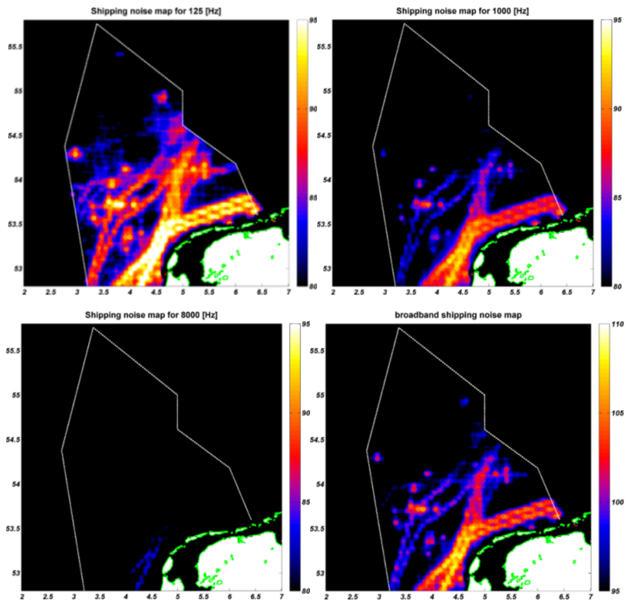

Figure 2: Shipping sound maps: unweighted SPL [dB re 1 µPa] in decidecades centred at 125 Hz (upper left), 1 kHz (upper right), and 8 kHz (lower left); unweighted broadband SPL (lower right). The green border indicates the land boundary and the white border the Exclusive Economic Zone (EEZ) of the Netherlands.

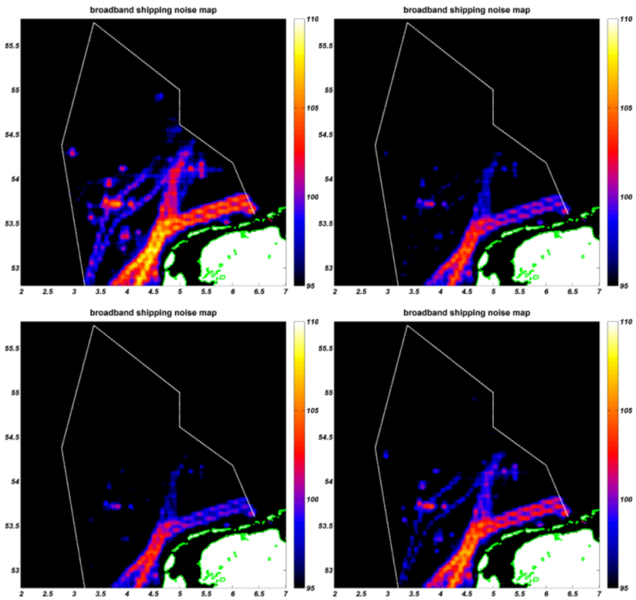

Figure 3: Shipping sound maps. Broadband M-weighted SPL [dB re 1 µPa]: for low-frequency (LF) cetaceans (upper left), mid-frequency (MF) cetaceans (upper right), high-frequency (HF) cetaceans

(lower left), and pinnipeds in water (lower right). The green border indicates the land boundary and the white border the Exclusive Economic Zone (EEZ) of the Netherlands.

3.2.3. VALIDATION

Background

Section 3.2.3 presents the work undertaken to quantify the accuracy of Aquarius (uses the same propagation model of SOPRANO as described in Chapter 2.3), and its sensitivity to uncertainties of the environment and the source models. This model validation was done using the underwater sound measurements done in 2009 by TNO for the construction of the “Tweede Maasvlakte”, (Second Maasvlakte, or ‘Maasvlakte 2’ [Maasvlakte2, 2014]) an expansion of the Port of Rotterdam port. Sound pressure was recorded by TNO’s autonomous acoustic measurement system ‘SESAME’ at a fixed location for a period of two weeks (26 September to 6 October 2009), at two depths (2 and 7 m above the seabed) [Ainslie et al, 2012b]. Also, for the duration of this measurement, the wind speed and spatial distribution of the shipping traffic were logged. Source levels of the dredgers were taken from a separate set of measurements designed for that purpose [de Jong et al, 2010]. See also [Heinis et al, 2013(risk assessment during Port of Rotterdam construction)] for more information.Measurements presented are for 29 September 2009 between 6:32:08 and 17:40:19 Rotterdam Local time (UTC +01:00), for the receiver at height 2 m from the seabed.

Methodology

In contrast to the shipping density maps used for Section 3.2.2, snapshots were computed for the validation. The advantage of using snapshots is that this allows studying the temporal variability and statistics of the sound, allowing the direct validation of the propagation loss if the source level is known. The disadvantage of introducing the temporal variability is the increased computational effort. The computational effort can be reduced by pre-computing the propagation loss (PL) in a lookup table. However, in order to keep the data size of the PL lookup table within bounds, compromises are required in the number of dimensions. The preferred modelling approach is therefore dependent on the application.

Inputs

Various inputs are required for the computation of the snapshots. The source level spectra of the dredgers were reported in [de Jong et al, 2010]. Levels were measured for passing, dredging, direct sand dumping, rainbowing and pumping. Depending on the speed and location of the dredgers (in combination with a log describing the activities of the dredgers), the most appropriate source level was estimated. For ships for which no measured source level was available, the [Wales and Heitmeyer, 2002] spectrum was assumed. The chosen source depth is 4 m below the sea surface for all ships and dredgers [de Jong et al, 2010]. The choice of depth here is driven not by any consideration of the “depth” of a ship, or of any sound source within a ship, but of consistency with the choice of depth for the nominal point source chosen for the original measurement of source level, which in this case was 4 m [de Jong et al, 2010]. The spatial distribution of the shipping traffic was available from AIS data logged during the measurement campaign. Based on the AIS data it was possible to estimate the speed of the ships. The Wales and Heitmeyer source level model is independent of ship speed, but applies for ships at their regular cruising speed. At that speed the radiated sound is generally dominated by propeller cavitation noise. This sound is absent for stationary ships, unless they are operating propellers or thrusters to maintain their position. For lack of a general model for the radiated machinery noise of stationary ships, ships were assumed to be silent when moving slower than 2 knots.

The environment is defined by the bathymetry, the physical properties of the seabed and water, and the roughness of the sea surface. The bathymetry was obtained from local survey data with a very high resolution. This allows to model blocking of acoustic energy from the sources disappearing behind the long thin curved island shaped like a boomerang (see Figure 4) [Ainslie et al, 2012b], which would not be represented in the coarser resolution bathymetry data, and which in any case predates the Maasvlakte 2 construction period. The water was modelled with a uniform sound speed of c_0=1500 m/s and a density of 1000 kg/m^3. The absorption loss in the water was modelled using the equation of Thorp [Thorp, 1967]. The seabed was modelled as medium sand c_1=1797 m/s, ρ_1=2086 kg/m^3 with an absorption given by α_b=0.88 dB/λ [Ainslie, 2010]. The effects of surface scattering and bubbles were modelled using Eq. 8.22 of [Ainslie, 2010], using the local wind speed from a nearby measurement station [Ainslie et al, 2012b]. Figure 4 illustrates the bathymetry and photographic images of the considered area.Wind generated sound was modelled using the areic dipole source factor spectrum from Eq. 8.206 of [Ainslie, 2010].

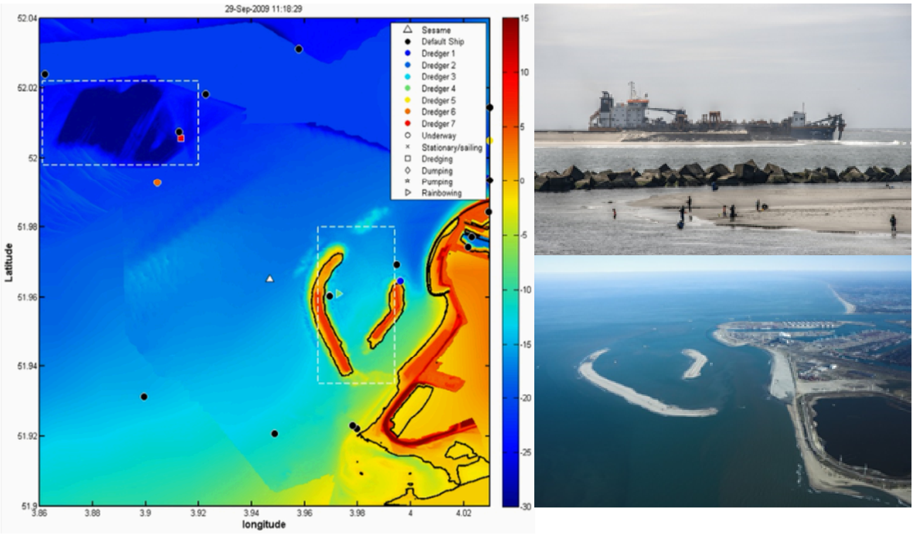

Figure 4: Bathymetry (depth in metres) and distribution of sources and corresponding activities. The white boxes (dashed line) indicate the dredging (top left) and dumping (between the curved sand dunes) regions. The marker symbols indicate the dredger activity and the colour the dredger ID. The black colour indicates unknown ships for which the Wales and Heitmeyer spectrum was used. The white triangle indicated the location of the acoustic measurement system SESAME). The right figures are photographs of the area.

Model data comparison

Measurements were made at two heights (2 m and 7 m) above the seabed at the Sesame location illustrated in Figure 6. As the measured levels are very similar, the model predictions are only given for 2 m above the seabed, across the entire region, and for decidecade bands between 32 Hz and 80 kHz. Figure 6 illustrates the modelled broadband SPL at 2 m above the seabed. The discontinuities result from the assumption that sound travels in straight horizontal lines, with no refraction or diffraction in the horizontal planes (the so-called “Nx2D” approximation). While computing snapshots helps understand the behaviour of the model, the direct model data comparison allows a more detailed understanding of the accuracy. Figure 7 and Figure 8 directly compare the modelled and measured decidecade bands SPLs at the measurement location.

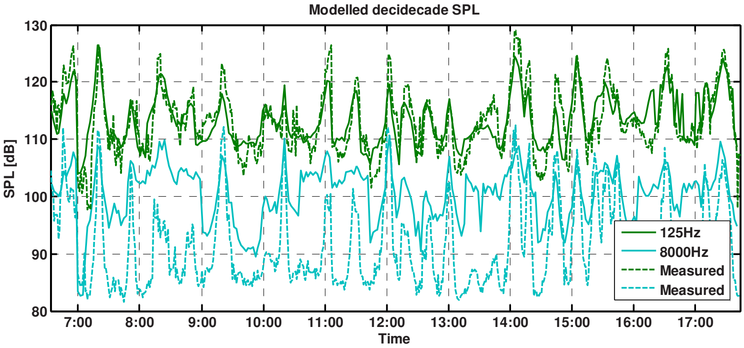

Figure 5: Modelled (solid) and measured (dashed) SPL [dB re 1 µa] at 2 m above the seabed for the 125 and 8000 Hz decidecade bands at the Sesame location illustrated in Figure 4. Model predictions are for ship-generated sound only. Date is 29 September 2009 Rotterdam local time (UTC +01:00).

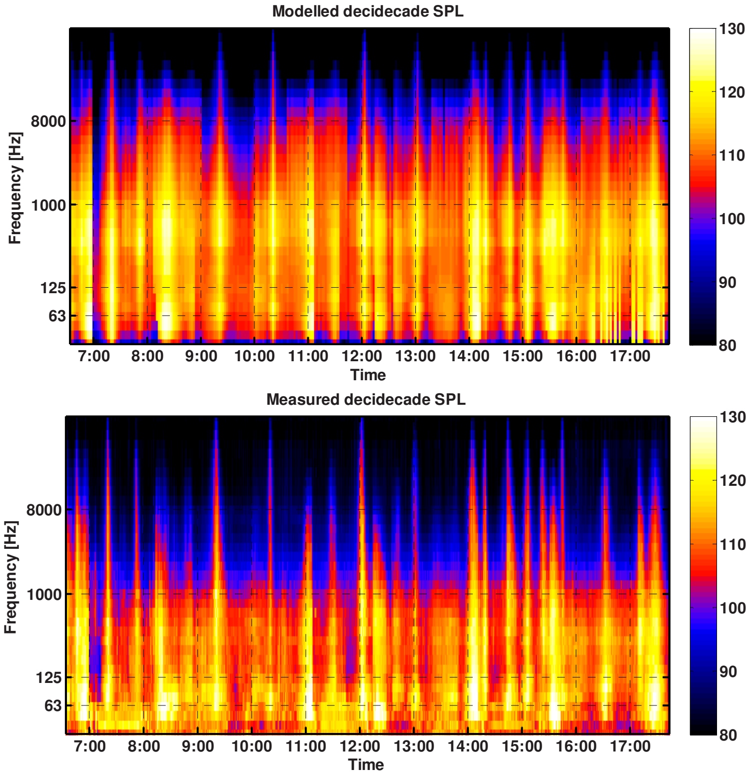

Figure 6: Modelled (top) and measured (bottom) SPL [dB re 1 µPa] at 2 m above the seabed for all decidecade bands (32 Hz up to 80 kHz) at the Sesame location illustrated inFigure 4. Model predictions are for ship-generated sound only. Date is 29 September 2009 Rotterdam local time (UTC +01:00).

Comparison with other model(s)

During the Madrid sound mapping workshop [Aquo-Sonic (Madrid)], comparisons were made between the depth average broadband SPL computed with the hybrid method of [Sertlek and Ainslie, 2014a] and other methods, such as the parabolic equation model RAM, for a synthetic shipping distribution in the Skagerrak Sea, north of Denmark for a set of synthetic scenarios with a defined set of environmental parameters. These comparisons will be reported on in the SONIC project. The computation time for generating the sound maps using the hybrid propagation algorithm was in the order of tens of minutes, while the computation time for the RAM model was in the order of days. For examples demonstrating the accuracy of the propagation model on some synthetic test cases designed to test sonar equation, see [Sertlek and Ainslie, 2013, 2014a, 2014b].

Accuracy

When computing sound maps, many parameters are uncertain. Uncertainties and assumptions in the snapshot modelling presented in Figures 6 and 7 result in a discrepancy between modelled and measured levels. This section discusses accuracy of the modelling approach.

Sound generated by shipping

For the Maasvlakte 2 simulation, the source level of seven dredgers was measured for transit, dredging, direct sand dumping, rainbowing and pumping activities [de Jong et al, 2010]. Levels were extrapolated for frequencies where levels were not available using the trends of other dredgers if available. The source level (SL) for frequencies between 8 kHz and 80 kHz were extrapolated linearly in log (frequency) by assuming a constant gradient above 6.3 kHz. For some of the dredgers, the low frequency SL was estimated using the trend from other measured dredgers. The source level of the other ships was approximated using the model by Wales and Heitmeyer at all frequencies. Above 1 kHz, such an extrapolation leads to higher source level than an extrapolation based on the measurements of Arveson and Vendittis [Ainslie, 2010 (p423)]. The directional behaviour of the ship radiated sound was not taken into account, and the ships were all modelled as point sources at 4 m depth. Besides the uncertainty in the source level, also the activity of the ships was estimated based on AIS data. Some useful information can be extracted from AIS data, although the reliability of, for example, the navigation status parameter is dependent on the crew and may not always be accurate.

Hence, the uncertainty in the source level estimation for the individual ships in each snapshot is rather large. Concerning the ‘type A’ [ISO GUM] statistical uncertainty, [Wales & Heitmeyer, 2002] indicate that ‘the standard deviation of the measured spectra on which their model is based varies about a nominal value of about 5.3 dB for frequencies below about 150 Hz and then decreases to a nominal value of about 3.1 dB for frequencies greater than 400 Hz’. The standard deviation of the estimated dredger source levels [de Jong et al, 2010] is about 5 dB. No attempt has been made to quantify the additional ‘type B’ uncertainty associated with, for example, assumptions about the navigation status of the ships, the lack of speed dependence in the source level model and the extrapolation of the measured source level spectra to higher frequencies.

Environment

The acoustical parameters describing the environment were chosen as realistic as possible based on the available data. No adjustment was made to reduce the difference between the modelled and the measured levels. The surface loss was estimated using the measured local wind speed. The sediment was modelled as a fluid approximating a medium sand seabed, typical for this region [Ainslie et al, 2012b].

Model applicability

For frequency-depth combinations very close to cut off where just one mode propagates, it becomes more complicated to predict the propagation loss. At frequencies above 4 kHz, the dependence of propagation loss on surface roughness and wind-generated bubble population is not well understood and requires further investigation [Ainslie, 2005]. Besides the propagation loss applicability, a cause of bias is the absence of other sound sources (e.g., wind [Dreschler et al, 2009]) in the model that contribute to the underwater sound in the measured data. There is evidence in Figure 7 that wind generated sound becomes important above about 10 kHz, especially for the 90 % exceedance level and the median. The effect of ship speed on radiated sound (presently approximated by a sharp cut off for an arbitrary ship speed of 2 knots) needs further investigation.

Quantification of error

Studying the differences between the model and the measurements, it is observed that the adopted modelling approach can accurately predict the sound pressure level at the hydrophone for the lower frequencies. Especially individual passages of dredgers for which the source level was measured are accurately represented. Figure 7 shows the statistics of the measured and modelled levels illustrated earlier in Figure 5 and Figure 6 for an 11 hour period on 29 September 2009. The model tends to underestimate SPL by about 5 dB at low frequency (up to ca. 100 Hz) and overestimate SPL by a similar amount at frequencies above ca. 500 Hz. At higher frequencies still (above 30 kHz) the model underestimates SPL again, by an amount that increases with increasing frequency. The most likely reason for these high frequency errors is the omission of the contribution from wind, the likely magnitude of which is shown by the black line of Figure 7.

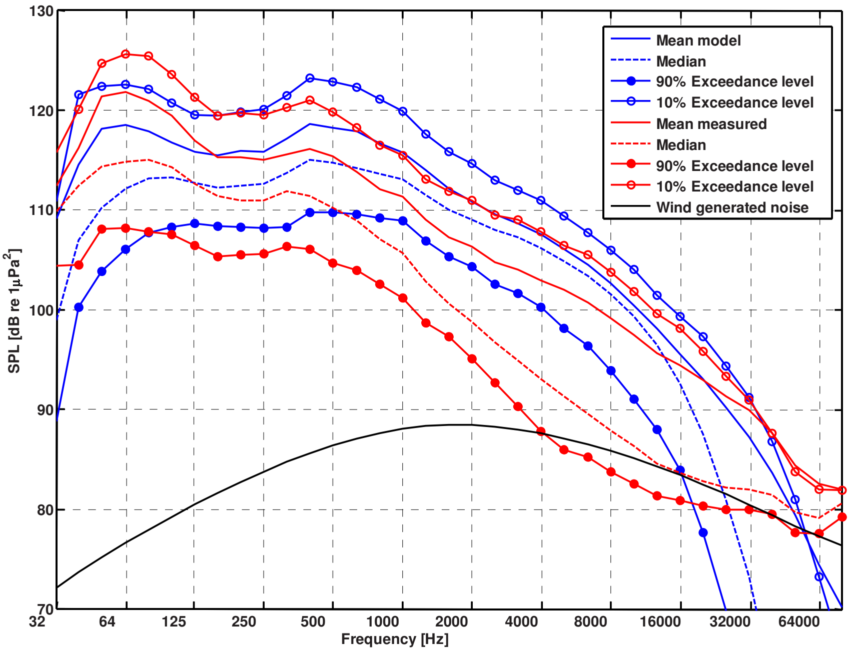

Figure 7: Mean, median and exceedance levels for both the measured and modelled receiver SPL [dB re 1 μPa]. The black curve is the temporally averaged wind generated sound. The modelled results include ship generated sound only. Statistics are for 6 s snapshots, once per minute. The statistics are computed for the distribution of mean-square sound pressure in each 6-second time window.

The most likely explanation for the overestimation of the SPL between 1 kHz and 10 kHz is the treatment of surface reflection loss, which includes the effect of rough surface scattering enhanced by the presence of near-surface bubble clouds [Ainslie, 2005], but neglects the effect of absorption by the bubbles, which at 8000 Hz and above is expected to dominate [APL 1994, Ainslie 2010]

3.2.4. SUMMARY AND DISCUSSION

In this section, an application of a propagation model (see Chapter 2.3) is applied to shipping sound maps for the annual ship distribution and AIS snapshots. The accuracy of sound maps are tested by comparison with actual measurements. Model results give similar accuracy as measurements at the MSFD indicator frequency of 125 Hz. However, the neglect of surface scattering seems to cause errors above 1 kHz. Consequently, the agreement between model and measurement results can probably still improve by adding a surface reflection term to the propagation model.