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Validation of dBSea, Underwater Noise Prediction Software. Pile Driving Focus

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Abstract: This report aims to characterise the prediction error of the different noise modelling algorithms used by the underwater noise prediction software “dBSea”. Two shallow water pile driving scenarios are presented, and the software’s prediction is matched against the measured real world data.

The results of the comparison show that while you can get good results with a simple model based on spherical and cylindrical spreading and information on frequency dependent attenuation, the more advanced “ray tracing” algorithm performs better still, and is more robust in accuracy. Also, the ray tracing has good consistency with the measurements at all ranges (380-5700 m -0.3 dB/km), while the simple model gets more erroneous with increased distance (+2 dB/km).

Further two approaches, namely “normal modes” and “parabolic equation”, both perform markedly worse than ray tracing in the presented scenarios, underlining the need for caution when applying models to real world scenarios. It is therefore suggested that a specialist is consulted before application of noise propagation models, as some approaches can produce outright wrong results for specific scenarios. Such errors could lead to damage of the marine ecosystem and to legal action against the polluter. Also, for scenarios where there is strong disagreement between models, not explained by model weaknesses and strengths, field measurements should be used to validate results.

Key words: Noise modelling, Pile driving, Underwater acoustics, Sound propagation, dBSea.

1. Introduction

With ever changing legislation dictating operating conditions for marine work, there’s a need to quickly and reliably asses the effects of such activities. Modelling software can help mitigate cost associated with fulfilling environmental requirements imposed by legislators by reducing the amount of in situ observations to be made in order to assess environmental impacts. Modelling allows for easy evaluation of effects of changes in plans, and makes it straightforward to assess impacts on megafauna.

1.1 Background and Motivation

The dBSea software package is a program developed to use multiple different approaches for modelling sound propagation in marine environments. It is envisioned to be used to model noise from a range of sources such as pile driving, seismic exploration, shipping, blasting and underwater construction (but not limited to these). As the ocean is an acoustically complex environment, the models take into account bathymetry, seabed properties, temperature, current, salinity, depth (pressure), frequency and directionality of the source to give predictions of noise propagation and attenuation.

Any model is only an approximation of reality and information on model limitations and precision/accuracy is crucial for successful application. This report attempts to provide that information for a limited set of scenarios involving pile driving in shallow waters with sandy seabed.

Data collected by a third party [1, 5] are used as comparison for model outputs, with the aim of finding and describing limitations of the software.

2. Methology

Validation of modelling software can be approached in two ways. Attempts can be made either to try to prove the model right, or to prove model wrong. As the reader is surely aware the author of this report is also the developer of the software in question. Therefore, a simple characterisation of model performance will be presented, with procedures and model settings clearly stated. All the data and software used in the report is publicly available, meaning everyone can reproduce the results of this report. This is done with the hope of maintaining credibility in a situation otherwise marked by the conflict of interest associated with in-house validation. Should you attempt to reproduce the results, and are unable to find the model settings mentioned in this report assume that they are set to the program's default values.

2.1 Models

The software dBSea has different solvers available, each with strengths and weaknesses related to wavelength of the source in question and the complexity of the scenario. According to [9], PE and NM models are only accurate up to ~1 kHz, and RT models are only accurate over ~100 Hz. For this report all available frequencies will be tested (20 Hz-20 kHz, regardless of Figure 1).

It is important to realise that most models can be made to produce the desired output, but this sort of adaptation has been avoided and only data given by the papers on the two scenarios acted as input for the software. As this report deals with prediction software, post-adaptation of models is not of any interest. All settings that could not be taken from the papers directly (apart from source levels) were set as follows:

- Default no. of beams, 10 seabed reflections, ±90 degrees emission angles & stepwise attenuation for RT.
- Depth and range oversampling maximised for PE.
- Default no. of modes for NM (uses all modes found).
- No radial smoothing and frequency oversampling of 10x per 3rd octave-band.

(NB. These settings will severely increase computation time.)

	Applications							
	Shallow Water				Deep Water			
	Low		High		Low		High	
	RI	RD	RI	RD	RI	RD	RI	RD
RT	No	No		Yes			Yes	Yes
NM	Yes		Yes		Yes			No
PE		Yes	No	No		Yes		

Figure 1. An approximate overview of application of the different models. RI means that scenario is range independent i.e. uniform with increasing distance from source. RD correspondingly refers to a scenario that is non-uniform (complex bathymetry/sediment composition changes). Green (Yes) indicates that model is applicable and resource efficient. Yellow indicates that model is ether not applicable or not resource efficient. Red (No) indicates that model is not applicable and not resource efficient. Adapted from [6].

2.1.1 Spherical Spreading

This is the simplest model available. It merely accounts for spherical spreading loss according to the Equation (E1)

(E1) $$TL = 20 * \log\left(\frac{r_d}{r_0}\right)$$

In this model "TL" is Transmission Loss in dB, (r_d) the distance from the source and (r_0) the distance where the reference sound pressure level/sound exposure level (SPL/SEL[1]) was measured (usually 1 metre). This model does take frequency dependent attenuation into account, but not refraction and reflection, and is thus limited to simple deep water scenarios at ranges smaller than local depth.

2.1.2 Spherical/Cylindrical Spreading (S+CS)

A modification (E2) to the above model which turns the spreading loss into one of cylindrical form at the distance equivalent to the depth to account for energy largely being constrained within the water layer by the surface and seabed boundaries (no calculation of reflection coefficient takes place).

(E2)

$$TL = \begin{cases} TL = 20 * log\left(\frac{r_d}{r_0}\right), & r_d < D \\ TL = 20 * log\left(\frac{r_D}{r_0}\right) + 10 * log\left(\frac{r_d}{r_D}\right), & r_d > D \end{cases}$$

Here the TL is calculated as spherical until radii (r_d) equals the depth (D) at source location. From then on a cylindrical spreading is assumed.

This model does take frequency dependent attenuation into account, but not reflection nor refraction.

2.1.3 Parabolic Equation

This model uses the so-called parabolic equation (PE) for estimating sound propagation and refraction/reflection. It utilises the wide-angle parabolic equation (a simplification of the 3D Helmholtz equation) to march the sound field out in range from the source. A starting field is given by the modal solver, and at each range step this is evolved via the parabolic equation. The solution is outward-going only. The sediment layer is extended down well below the depth of the water column, with the attenuation rapidly increasing at the lowest depths.

Frequency dependent attenuation is included in this model.

It is not within the scope of this report to describe the model in more detail than given above. If more detail regarding the model is wanted, refer [3, 13] or the online resource of [11].

2.1.4 Normal Modes

The NM model calculates values for each water depth based on sound speed profile and sediment properties. The sound field is calculated based on coupling between the calculated modes across the interfaces between different depths. This calculation is of the adiabatic, single forward scattering type. The overlying space (over the surface) is modelled as a vacuum. NM is generally suitable where the frequency is low and/or the water depth is shallow. In the NM model the sediment layer is extended down well below the depth of the water column, with the attenuation rapidly increasing at the lowest depths. In this way, there are no modes where energy is reflected from the very bottom of the sediment layer (the space underneath the bottom of the sediment is also a vacuum).

A more thorough walkthrough of normal modes (NM) can be found in [4, 7, 13].

Normal modes modelling is a different way of approximating sound propagation that complement the PE model for predicting lower frequency TL as they handle scenarios differently (Figure 1).

[1] SPL and SEL levels are by no means the same, but as this reports levels in SEL, no further explanation will be given.

2.1.5 Ray Tracing

Ray tracing (RT) is the last of the advanced models offered by dBSea and details of the theory can be found in the same literature as for PE and NM models. RT can be thought of as the formation of a sound field by the summation of many calculated ray paths through media (an effective reflection coefficient is calculated at interactions with sediment). The RT model performs well for higher frequencies. It can be tweaked considerably with respect to number of seafloor reflections accepted in the model, and also with regards to the angles of emission from the noise source. RT modelling is especially useful for visualising acoustic ducts or channels in the water, wherein sound energy is trapped and thus less exposed to attenuation from spreading.

(E3) $$f_{Lim} = \frac{c}{0.008 * D^{1.5}}$$

The above equation indicates the frequency (f) in Hz, below which a surface duct down to depth (D) will no longer form. (c) is speed of sound in m/s. This means that a surface duct of 50 m depth will conduct frequencies down to 530 Hz [13] p. 26.

RT is in theory applicable to all frequencies, but [13] p. 179 states that:

"An often-quoted rule is that the acoustic wavelength should be substantially smaller than any physical scale in the problem."

Here substantially is interpreted as one order of magnitude (x 10), so a 20 m depth corresponds to a minimum frequency of 750 Hz.

However, [12] states that they have observed "excellent agreement between the PE and RT result" for frequencies of 15-250 Hz in a shallow water scenario. This frequency means a wavelength of 100 m, five times the depth in the present scenario.

2.2 Assumptions

2.2.1 Source Levels

No spectra for source levels were given in the reference papers, so source levels (Figure 2) for modelling have been extrapolated from closest measuring point and from hammer-pole systems of equal proportions for which measured source levels do exist. The extrapolation from closest point was done assuming the pile is a line source, and sound thus attenuates according to cylindrical spreading. To account for possible loss of high frequency components values, attenuation effects described in [2] were compensated for on a third-octave band level (depth 10 m, acidity pH 8, temperature 11.5 ^{o}C, salinity 34). As all levels were reported in SEL, and no time window given, the time window is assumed to be the de-facto standard of 1 second. All references to sound levels, unless clearly stated, are SELs to keep the values readily comparable. Also background noise levels have been subtracted from the source levels, to make the model simpler. The subtraction took place in linear units, and had little (<0.1dB) effect on source levels (background dB << source dB). For the second set of results for comparison (from [5]), the closest measurement was 1000 m from the source and thus extrapolation induces relatively greater uncertainty than with the measurement at smaller ranges. [1] estimated source levels for this piling scenario, and those form the basis of the source levels used here.

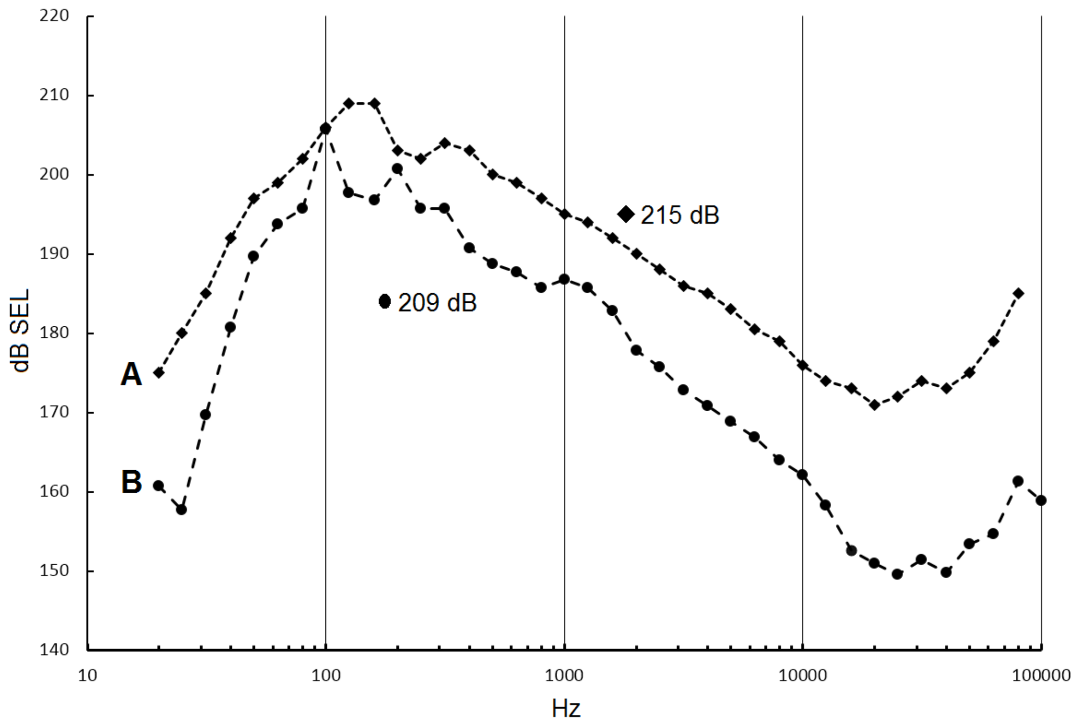


Figure 2. The two estimated source level spectrograms used for modelling noise propagation. The summated SEL value for each source is stated on graph. A, source from De Jong & Ainslie (2008). B, source from [14].

2.2.2 Model Parameters

Models were run in average conditions that for this data means a depth of 20 meters, salinity of 34 and temperature of 11.5 degrees Celsius. The seabed is assumed to be sandy (sound speed 1650 m/s).

According to [8] the spatial scale of a scenario should be “a small fraction” of the Fresnel zone radius (R_F).

(E4) $$R_F = \sqrt{\lambda \cdot R}$$

Where “R” is the distance between source and receiver and “λ” the wavelength of the frequency tested. The calculations should be made at even higher resolutions. For the 20 kHz at 380 metres used as maximum here this means a resolution with bathymetry point distances a small fraction of 5.3 metres (and calculation points closer still). This kind of resolution in bathymetry data is usually not available, but as the bathymetry used here is artificial (and flat) this problem is circumvented. In [8] further frequency-dependent modelling problems are outlined, but again apply only to modelled scenarios that include more factors (e.g. sea surface and sediment acoustic roughness).

2.2.3 Source

The source is assumed to be a line source qua pile dimensions. Because a true line source (infinitely many point sources) is impractical for calculations, a proxy, consisting of one point-source per metre, is used instead (in 20 metres water, this equates to 19 point sources). All sources were in the water phase, because only NM and PM models support noise propagation in sediment.

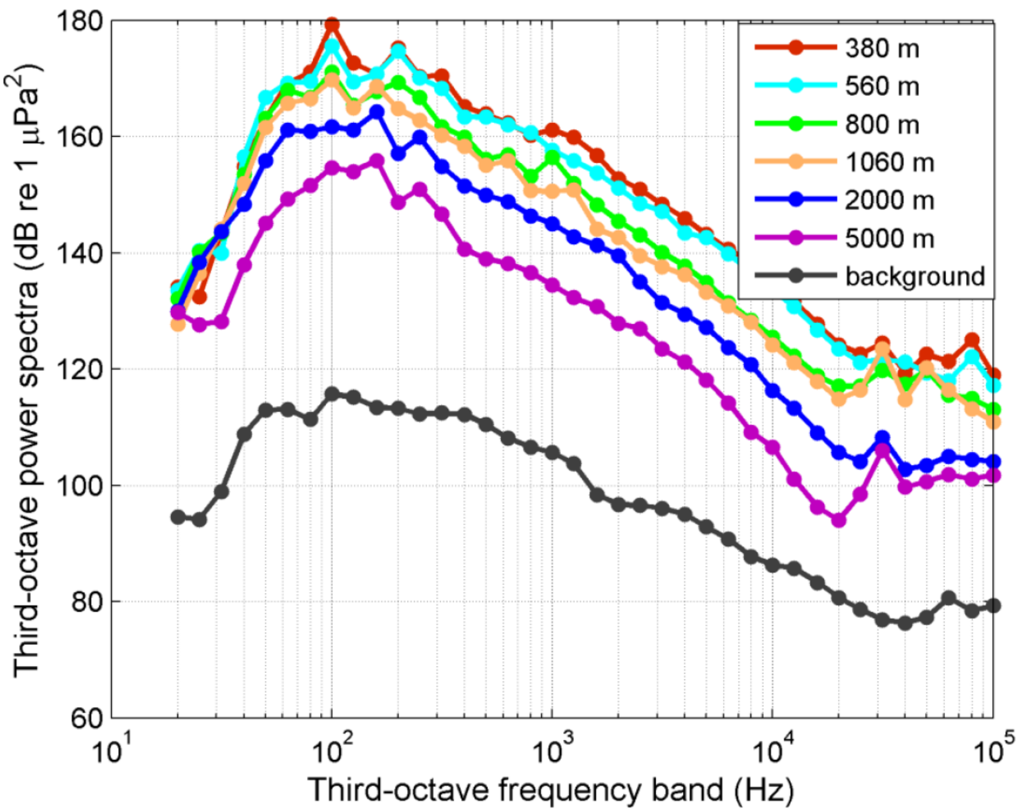


Figure 3. The third-octave band spectra for pulses at ranges from 380 m to 5 km from the driven pile. Also shown are the levels for the background noise. Reprinted with permission from [14].

2.2.4 Received Level

The received level in the model is measured at the surface, with all levels projected onto this (effectively a sum of the sound energy in the water column). This neglects any depth dependent volume differences, but given the shallow water, effects are assumed to be minimal. All levels are reported in SEL re 1μPa^{2}s.

2.3 Data for Comparison

To validate a model one needs real world data to assess how well the model performs in predicting levels. If the model cannot predict reality it needs modification. The data from [1, 5, 14], is used for determining model performance. In Figure 3 an example of such data is plotted. The data shows curious behaviour at frequencies over 20 kHz (levels stop decreasing with distance and frequency) and these data are omitted. Thus only the band 20 Hz – 20 kHz is used.

3. Results

The results are presented as a difference between measured real world levels and predicted levels, so that a positive value indicates that the measurement was larger than the predicted level (measurements – model). Measurements from two studies, both done in similar conditions were used for comparison. When average values are presented they are averages of linear ratios, converted to dB.

3.1 Robinson et al. 2011, Pile Ø5.2 m, 1370 kJ [14]

Modelling results of the pile driving scenario from [14] shows that some models (Figure 4) are inaccurate for shallow-water, sandy bottom, pile-driving scenarios, while others are agreeing better with real world data (Figure 5). The PE model is underestimating the noise level by an average[2] of 10 dB, while the NM model underestimates values at an average of 24 dB.

The simple S+CS model overestimates noise levels by an average of 2.84 dB. It has very little prediction error at short range (< 1 dB), but greater deviation with distance (10.7 dB at 5 km). The RT model deviates 3-5 dB (3.72 dB average) at all ranges, also overestimating the noise levels. At low frequencies (20-32 Hz) the RT deviates greatly (> 20 dB) from measurements at long ranges (2-5 km), as this is a fairly narrow frequency band it does not affect the overall SEL much. Both S+CS and RT underestimates noise levels for frequencies 20-63 Hz, and overestimates for higher frequencies.

Because the S+CS model performs better than the RT model at low frequencies, two mixed-model simulations were created with crossover frequencies determined by the wave length criteria (800 Hz 2.1.5 Ray Tracing) and performance criteria from minimal difference observed (80 Hz Figure 5, B). The 800 Hz crossover provided some improvement over either S+CS and RT models (-2.75 dB), but with the high inaccuracies at 2 and 5 km intact (-5 and -11 dB). The lower crossover frequency (80 Hz) performed slightly better than the pure RT, with average difference of -3.63 dB. This is higher than the S+CS model, but the variation in prediction error was low (-2.8 to -4.5 dB), and so an offset can be applied to this model, making it more accurate across frequencies and ranges.

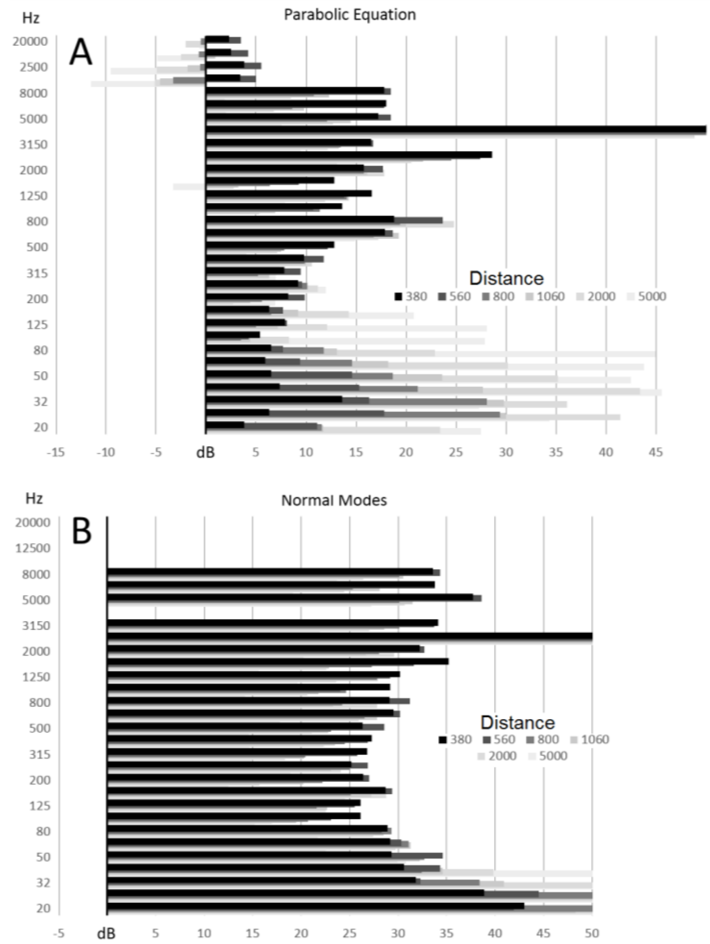
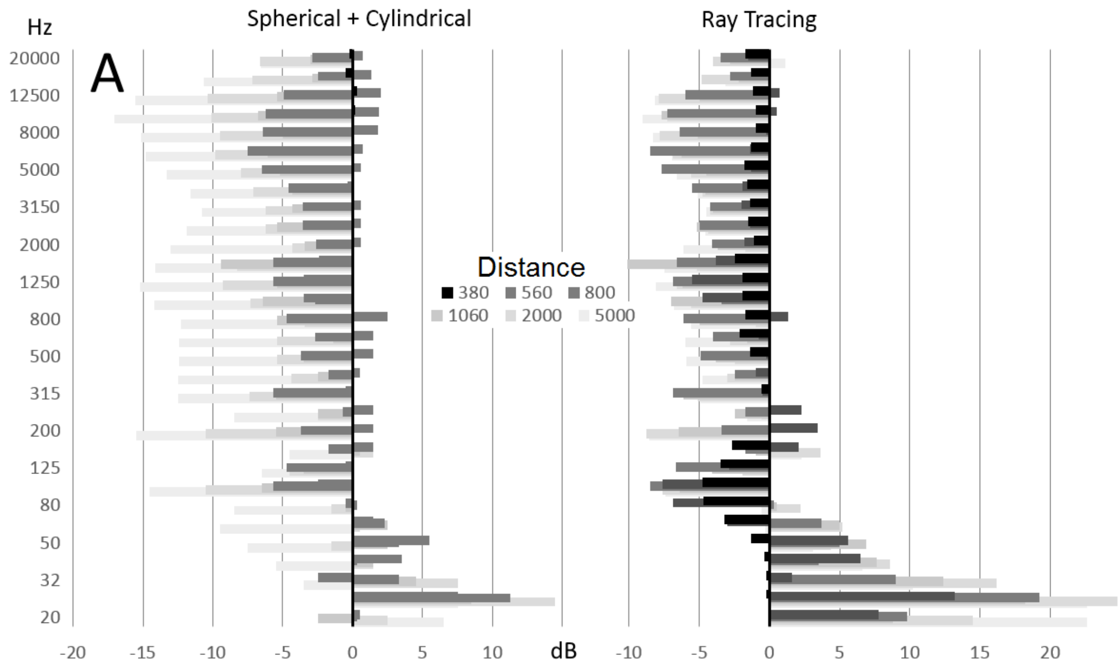


Figure 4. Measurements minus model data in dB. Thus positive values indicate that the model predicts lower levels than the measurements. A, the PE model largely predicts levels that are lower than reality, it's especially challenged at higher frequencies. B, the NM approach appears to be unsuitable for this type of problem as model levels are very different from measured values. The lack of calculated levels at 4 kHz and above 10 kHz are due to high frequency errors.

2 Averages are calculated on the basis of the corresponding linear units, then converted back to dB.



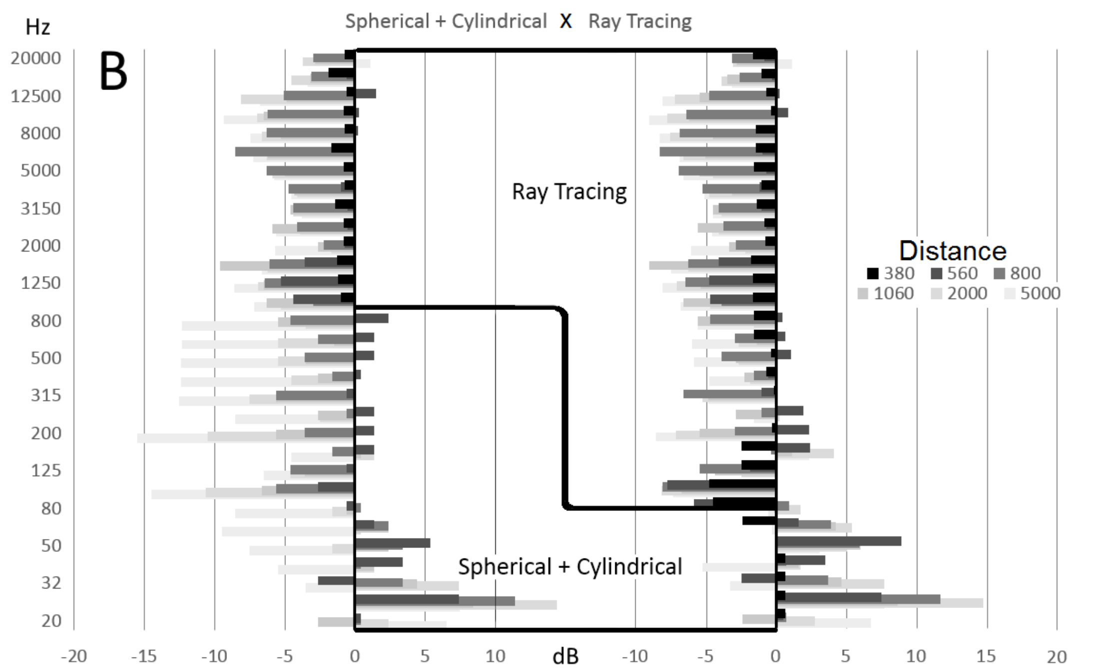


Figure 5. Differences between measurements and model. Negative values indicate that the model predicted higher levels than were measured. A, S+CS and RT side by side for comparison, notice that S+CS gets more imprecise with increasing range, while RT is relatively inaccurate at short ranges. B, modelling employing a combination of two propagation models, crossover frequencies as marked in plot (800 Hz & 80 Hz).

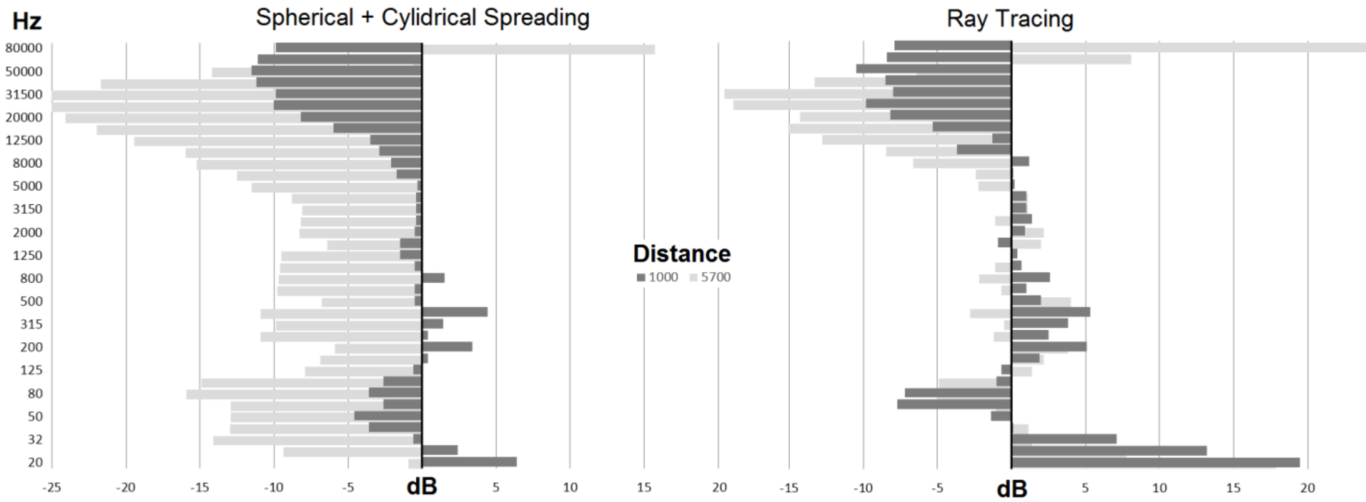


Figure 6. S+CS and RT models difference from measurements, at two ranges. The dB values are measurement minus prediction.

3.2 De Jong & Ainslie, 2008, Pile Ø4.0 m, 800 kJ [5]

Models PE and NM are over 20 dB off the measured values and illustrations are not included. The S+CS model is overestimating noise by an average of 15.1 dB and shows ~10 dB difference in prediction error between distances 1 km and 5.7 km (Figure 6). The RT model overestimates the noise by an average of 12.1 dB, with <0.1 dB difference in noise prediction error between the two distances.

4. Discussion

For a noise prediction tool to be useful predictions have to be as precise as possible. But as no model can do exact predictions of complex real-world noise fields, it is the view of the author that the model should employ the principle of precaution, so that the risk of predicting noise levels that are too low will be minimised. Predicted noise levels that are too low will results in a misevaluation of the risk associated with the given activity. As in all things a balance is preferred, too much precaution makes the model either useless or unattractive to the noise makers (a very real concern).

As this report is mainly descriptive in nature, the discussion section is not intended to be exhaustive, it serves only to comment on, and to clarify results.

4.1 Normal Modes & Parabolic Equation

The NM model struggles to provide an accurate output for this scenario and is grossly underestimating noise levels at all distances. This does not disqualify the model from use in similar situations, but mean that care should be taken whenever applying models (as they will always be approximations).

The PE model does markedly better than the NM model, but is still more than 10 dB off the measured values for most frequencies and ranges. The model underestimates the noise level, and would for this scenario lead to an exclusion zone that is too small, and thus risk injury to or disruption of megafauna, or penalties to polluters from failing to comply with regulations.

4.2 Ray Tracing

The RT model as a single model provides the most precise prediction although less accurate than the S+CS model[3]. It predicts levels that are consistently 3-5 dB too loud, but in the opinion of the author this precision is preferable to a more scattered but accurate approach.

[3] In the strict meaning of accuracy and precision.

The RT model does indeed have the biggest inaccuracies at low frequencies, and in cited literature it is not recommended that it be used for low frequencies. Following the results section though, “low” frequencies are 80 Hz and below, corresponding to the wavelength of 20 meters, meaning that the interpretation of “substantial” as one order of magnitude (in section 2.1.5) was overestimated for this scenario.

In the second scenario (Figure 6) the RT shows large prediction error for high frequencies, overestimating the noise level. As the S+CS model shows the same pattern it suggests that something on the day of recording led to increased high frequency attenuation (bubbles, seaweed or debris in water column).

4.3 Spherical + Cylindrical Spreading

This approach provided the most accurate prediction, though not very precise (increasing error with distance). It does however perform well, especially taking into account that it can be done with a simple calculator, pen, paper and a table of frequency specific attenuation values.

Note that the high accuracy of this model at 380 m is a consequence of this model being used to estimate the source level (circular). The data from the model is included anyway to standardise the results output. [8] mentions that a pattern where the model corresponds well to reality at close ranges with increasing error with distance might suggest that the estimated source level is too high and that transmission loss is too high. No corrections for this were made, as only the S+CS model clearly showed this tendency.

The S+CS model shows big difference in prediction error between the two different sources (Figure 5 A and Figure 6), suggesting that this approach is not as robust as the RT approach, that matches measurements more accurately.

4.4 S+CS & RT

This combination of models is partly an ad-hoc addition to this report. The model with crossover frequency at 800 Hz is predicted from the assumption that the minimum frequency used in RT should be given by a wavelength that’s <10 % of the smallest physical dimension (20 m). The crossover frequency of 80 Hz is suggested by the results, as over this frequency RT outperforms S+CS. The S+CS and RT model provides the same precision as the pure RT, but with better accuracy.

4.5 Further Comments

The mixing of modelling approaches is very useful as PE and NM models are very resource-costly at high frequencies, and RT generally not very accurate at low frequencies. In practice the crossover frequency can be decided without having any reference measurements by implementing a little common sense. If an *unsuitable* crossover frequency for a problem is chosen, and the source spectrogram is smooth, the predicted spectrogram will not be smooth, and the crossover frequency should be changed.

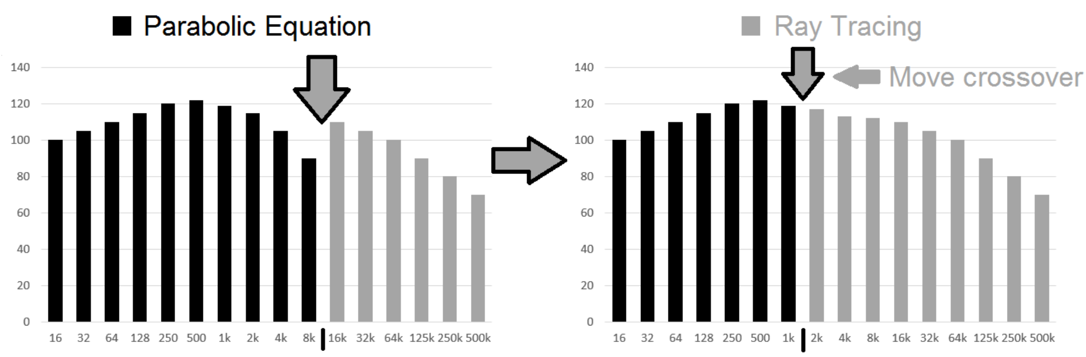


Figure 7. If received level spectrum is very different in smoothness to source spectrum, change crossover frequency.

5. Conclusion

As clearly seem from results different models perform (very) differently given the same scenario. This underlines the importance of the qualifications of the modeller and also that it is imperative to evaluate model outputs, both against other models, but also against available data. For this scenario, characterised by shallow depth and relatively short ranges, the RT and S+CS models performed well (± <4 dB). In general models (RT & S+CS) were accurate for overall SELs, and differed more upon inspection of individual 3rd frequency bands. A limiting factor for the precision of the models presented here was the lack of data in the referenced papers (background noise location, date, weather sediment properties).

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