MODEL BENCHMARKING RESULTS FOR SHIP NOISE IN SHALLOW WATER

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Abstract: *To support North Sea countries to comply with EU legislation, a framework for a fully operational joint monitoring programme for ambient noise in the North Sea is developed in the Interreg Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS). A key task in the project is to develop and demonstrate verified and validated modelling methods applicable for generating maps of ambient noise in the North Sea, with a focus on ships and wind as the dominant sources of sound.*

Within the project a wide range of acoustic propagation model implementations from the JOMOPANS project partners are verified by means of a comparison of the output for two well-defined benchmark scenarios based on the modelling scenarios developed for the Weston Memorial Workshop. The model types considered are based on energy-flux integration, analytical and numerical mode solvers, parabolic equation range step integration, ray tracking and wavenumber integration. Recommendations on the use of these models are given and limitations are discussed. The acoustic metric considered is the depth-averaged sound pressure level in one-third octave (base 10) bands from 10 Hz to 20 kHz.

The results show that the majority of the tested models are in agreement for a range-independent shallow water environment, providing a reliable benchmark solution for the future verification of other propagation models. The observed agreement gives confidence that these models are correctly configured and able to provide numerically correct solutions. For a range-dependent environment however, a significant uncertainty remains. The solutions provided in this paper can be used as a reference to select the optimal compromise between reducing the computational complexity and increasing the model precision for the propagation of sound in shallow water.

Keywords: *Underwater acoustics, Propagation modelling, benchmarking scenarios, model verification, Ambient noise, JOMOPANS project*

1. INTRODUCTION

To support North Sea countries to comply with EU legislation, a framework for a fully operational joint monitoring programme for ambient noise in the North Sea is developed in the Interreg Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS). A key task in the project is to select verified and validated modelling methods applicable for generating maps of ambient noise in the North Sea, with a focus on ships and wind as the dominant sources of sound. Accurate modelling of underwater ambient noise and being able to quantify the uncertainty in the model predictions are both relevant for the assessment of good environmental status as well as for sonar performance modelling.

In JOMOPANS the uncertainty in the complete ship noise modelling chain (from AIS data to noise maps) will be assessed against long term acoustic measurements at various measurement locations. This uncertainty results from limitations in the quality of available input data from ships and environment as well as in the applicability of the selected source and propagation models. Requirements for the model accuracy should be balanced against the uncertainties related with the input data, and will be set later in the project. The applicability of different underwater sound propagation models is verified by comparing their output against trusted reference solutions for two synthetic test cases. The two considered test cases are derived from previous benchmarking studies [1][2][3]. These were based on test cases defined in the Weston Memorial workshop [4]. The test cases were modified to be more representative for shallow water ship noise predictions in the full frequency range of interest for JOMOPANS (one-third octave (base 10) bands from 10 Hz to 20 kHz). A selection of the models was also compared against results published in [1][2], which showed good agreement and gives trust in the correct implementation and configuration of the models.

In section 2, the two test cases are detailed. Next, the propagation models that are compared are described in section 3. In section 4, the modelling results are compared to quantify the uncertainty of the model predictions. Finally, the results are discussed and conclusions on the applicability of the models for propagation modelling in shallow water are drawn in section 5.

2. TEST CASE DESCRIPTION

Two synthetic test cases were selected: one range-independent and one range-dependent. Comparing the model output for these two cases serves two objectives:

- to obtain a trusted solution with an associated uncertainty for the depth-averaged sound pressure level (SPL), for all one-third octave (base 10) bands from 10 Hz to 20 kHz
- to use this trusted solution to quantify the error of the propagation models for the two considered test cases.

The geometry and source depth are altered from the Weston Memorial workshop [4] case 1 and 4, to be more representative for ship modelling (5 m source depth) and for the North Sea (shallow water). Figure 1 shows the geometry for the two cases. The output metric is the broadband and one-third octave (base 10) band (‘OTO’) SPL, depth averaged over the water column (average of squared sound pressure). All one-third octave bands from 10 Hz to

20 kHz are considered. To make the results representative for ship noise modelling, the Wales and Heitmeyer source spectrum [3] for merchant shipping is used:

$$L_{s,f}(f) = 230\ \mathrm{dB} - 10\log_{10}\left(\left(\frac{f}{1\ \mathrm{Hz}}\right)^{3.594}\right)\mathrm{dB} + 10\log_{10}\left(\left(1+\left(\frac{f}{340\ \mathrm{Hz}}\right)^{2}\right)^{0.917}\right)\mathrm{dB}$$

At frequencies below 30 Hz a constant value $L_{S,f}$ (f=30 Hz) is used and the equation is used outside its validity range (1.2 kHz) up to 20 kHz. The OTO band monopole source level $L_{S,\mathrm{OTO}}$ is defined by integration of the spectral density over the bandwidth.

Furthermore, a single frequency (band centre frequency) was used for calculating the results in each band to reduce the computational complexity of the benchmarking effort. The water was modelled as iso-velocity (c_w=1500 m/s) and iso-density (ρ_w=1000 kg/m^3). The absorption of the seawater is specified according to the Ainslie-McColm model [3]. The seabed is a homogenous sandy infinite fluid half space (c_s=1700m/s, ρ_s=2000 kg/m^3, α_s=0.5 dB/λ). The water surface was smooth (perfectly reflecting).

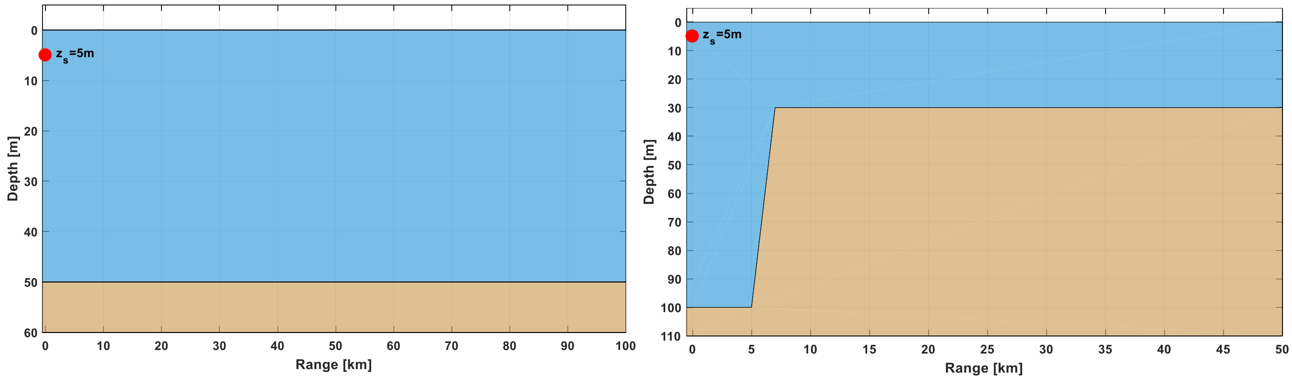

Figure 1. Schematic representation of the test case 1 (left) and test case 2 (right) environment. The red dot indicates the source position at 5 m depth. The upslope bathymetry (100 m to 30 m) starts at 5 km and ends at 7 km, corresponding to a 2 degrees slope.

3. DESCRIPTION OF MODELS

In this section the models tested in this work are introduced. An overview of the models is presented in Table 1, indicating the model type and the frequency range for which modelling results are included in this paper. A more detailed description of the models is described hereafter. For all models, the results where provided at a 100 m range resolution, starting at 100 m.

TNO-Aquarius 3 (Aq3): is based on the hybrid propagation model 'Soprano' for range-dependent shallow waveguides [2]. It combines the accuracy of an analytical incoherent adiabatic range-dependent normal mode model for the first five modes with the speed of Weston's flux integral approach for higher modes. A 0.5 m depth resolution was used to calculate the depth-averaged propagation loss.

TNO-Aquarius 4 (Aq4): The Aquarius 4 model is an adiabatic normal mode propagation model based on KrakenC model [5]. The KrakenC rootfinder is used to compute a mode lookup-table with a 1 m bathymetric resolution. Aquarius 4 matches the modes given the local water depth along the range trajectory. Leaky modes are not taken into account. A 0.5 m depth resolution was used to calculate the depth-averaged propagation loss.

QO-QUONOPS: The QUONOPS range dependent propagation model uses the parabolic equation (PE) solution (RAMsurf model) [6] at low frequencies and the BELLHOP ray tracing program [5] at frequencies of 2 kHz and higher. A 0.5 m depth resolution was used to model the depth averaged propagation loss. The RAMSurf model used a frequency-dependent discretisation and 8 Padé terms. Bellhop was run using 300k gaussian beams and a 89 degrees opening angle.

FOI-JEPE: JEPE (Jeltsch energy-conserving PE) is a wide-angle parabolic equation code [7] for computing the acoustic field in a range dependent environment composed of fluid media. It uses a transparent boundary condition at the deep boundary to avoid unnecessary computational cost associated with the use of artificial damping layers. The discretisation depends on frequency.

FOI-REV3D: REV3D [8] is a ray-based program for computation of transmission loss in 3D environments. The bottom is discretised by a rectangular grid using bilinear interpolation of the depth between grid points.

FOI-XFEM: XFEM is a hybrid method for range-independent media composed of multiple fluid and solid layers [9]. It is based on discretization of the depth-dependent wave equation with exact finite elements and computation of the wavenumber integral within a user-specified accuracy by adaptive variable-order quadrature with error control [10]. The solution can alternatively be obtained as a sum of normal modes and branch cut integrals, using adaptive winding number integration for searching modes in the complex plane [11]. In test case 1 the bound for the relative error in the transform and branch-cut integrals was set to 1.E-7. The solution was computed by wavenumber integration for the 7 lowest frequencies, and by modes and branch-cut integrals for higher frequencies.

FOI-RPRESS: RPRESS is a hybrid method for range-independent multi-layered fluid-solid media. It handles the depth-dependent wave equation with a compound matrix technique [12], using the same methods as XFEM for transform integration and mode search.

JASCO-MONM: MONM is a wide-angle split step Padé PE solution to the acoustic wave equation [6] based on a version of the U.S. Naval Research Laboratory's Range-dependent Acoustic Model (RAM), which has been modified to account for a solid seabed [13]. The PE computation range and depth spacing was frequency dependent. A 2 m depth resolution was used to calculate the depth-averaged propagation loss.

NPL-OASES: OASES applies wavenumber integration techniques to calculate propagation loss in horizontally stratified fluid and elastic media [5]. It can also deal with range-dependent propagation problems [14]. For the range-dependent test case 2, results above 1 kHz were omitted as the modelled propagation loss started to show unexplained unstable behaviour.

	Model name	**Model type**	**Frequency range**
TNO	Aquarius 3 (Aq3)	Range dependent hybrid analytical mode sum + flux integral model	32 Hz ≤ f ≤ 20 kHz
	Aquarius 4 (Aq4)	Range dependent numerical mode model using mode lookup table	10 Hz ≤ f ≤ 20 kHz
QO	QUONOPS	Range dependent split step Padé PE	10 Hz ≤ f < 2 kHz
		Range dependent coherent Gaussian rays	2 kHz ≤ f < 20 kHz
FOI	JEPE	Range dependent Jeltsch energy-conserving PE	10 Hz ≤ f ≤ 10 kHz
	REV3D	Range dependent coherent 3D rays	200 Hz ≤ f ≤ 20 kHz
	XFEM	Range independent wavenumber integration at 7 lowest bands, normal modes + branch-cut integration at higher bands.	10 Hz – 20 kHz
	RPRESS	Range independent wavenumber integration	10 Hz – 10 kHz
NPL	OASES	Range dependent wavenumber integration.	10 Hz ≤ f ≤ 20 kHz
JASCO	MONM	Range dependent split step Padé PE	10 Hz ≤ f ≤ 20 kHz

Table 1: overview of models that have been compared for test cases 1 and 2.

4. RESULTS

In this section the model predictions for the two test cases (section 2) are compared. Figure 2 illustrates the depth averaged SPL for the TNO-Aq3, QO-QUONOPS and FOI-XFEM models test case 1. From this type of representation it can be observed that model results are similar, but quantitative assessment of differences is difficult due to the large dynamic range.

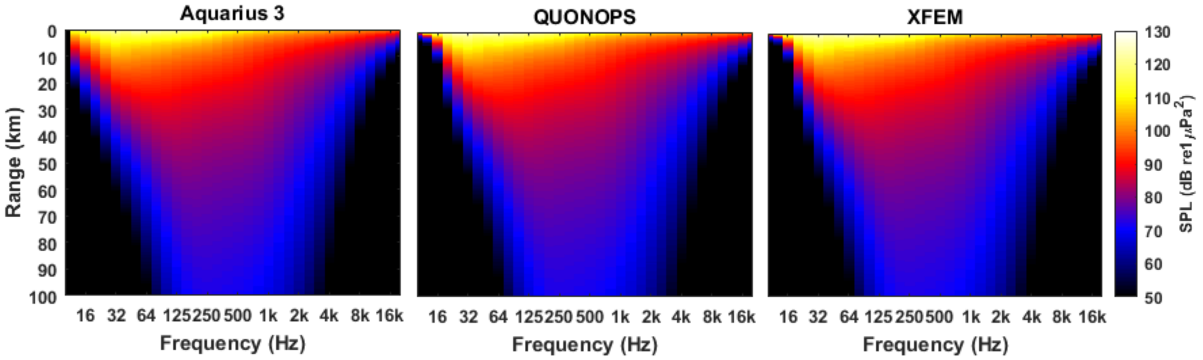

Figure 2: Depth-averaged SPL versus range and OTO band for 3 of the tested models.

In order to make a quantitative assessment of the model agreements for ship noise, figure 3 (top 2 plots) shows the modelled broadband depth-averaged SPL. The normalised representation (ΔSPL) below these makes it possible to observe differences smaller than a few dB. Note that the choice for the reference model (in this case Aquarius 3) is arbitrary, and does not say anything about the accuracy of the reference model itself. The bottom 4 plots show OTO spectra of the depth-averaged SPL at 10 and 40 km range.

For the range-independent case, it is observed that at distances larger than 500 m, all models except REV3D & Aquarius 3 are in agreement, with broadband differences smaller than 0.5 dB and OTO level differences in the bands from 20 Hz to 10 kHz smaller than 1 dB. The ray approximation in REV3D is not valid at low frequencies and observed to deviate from the other models at frequencies below about 300 Hz for the two test cases. The analytical approximation to the mode shapes in Aq3 leads to deviating results at frequencies below 50 Hz. At ranges shorter than 500 m, the Aq4 and JEPE results deviate from the other PE and wavenumber integration models. The ensemble of model predictions from the QUONOPS, MONM, OASES, XFEM and RPRESS is considered to be the correct solution (with a 0.2 dB associated uncertainty) for test case 1.

For the range-dependent case, it is observed that at distances up to 5 km (where the upslope bathymetry starts) the QUONOPS, MONM, OASES and Aquarius model predictions show a larger spread than for test case 1, in which the water depth was half that of test case 2. In this case the QUONOPS and MONM results overlap. The OASES results are 1 dB higher. At ranges between 1 km and 5 km, the maximum observed difference with the JEPE and Aq4 models is 1 dB. The difference between the model predictions increases towards shorter ranges. Beyond 5 km (where the range-dependence starts) the difference between the PE models is less than 0.5 dB. An explanation for the difference observed between the PE and Aquarius model predictions beyond 5 km is the adiabatic approximation used by the Aquarius models. Because only the PE models are in agreement, assessment of their absolute accuracy is uncertain. It is expected that the PE models are correctly configured given their close agreement.

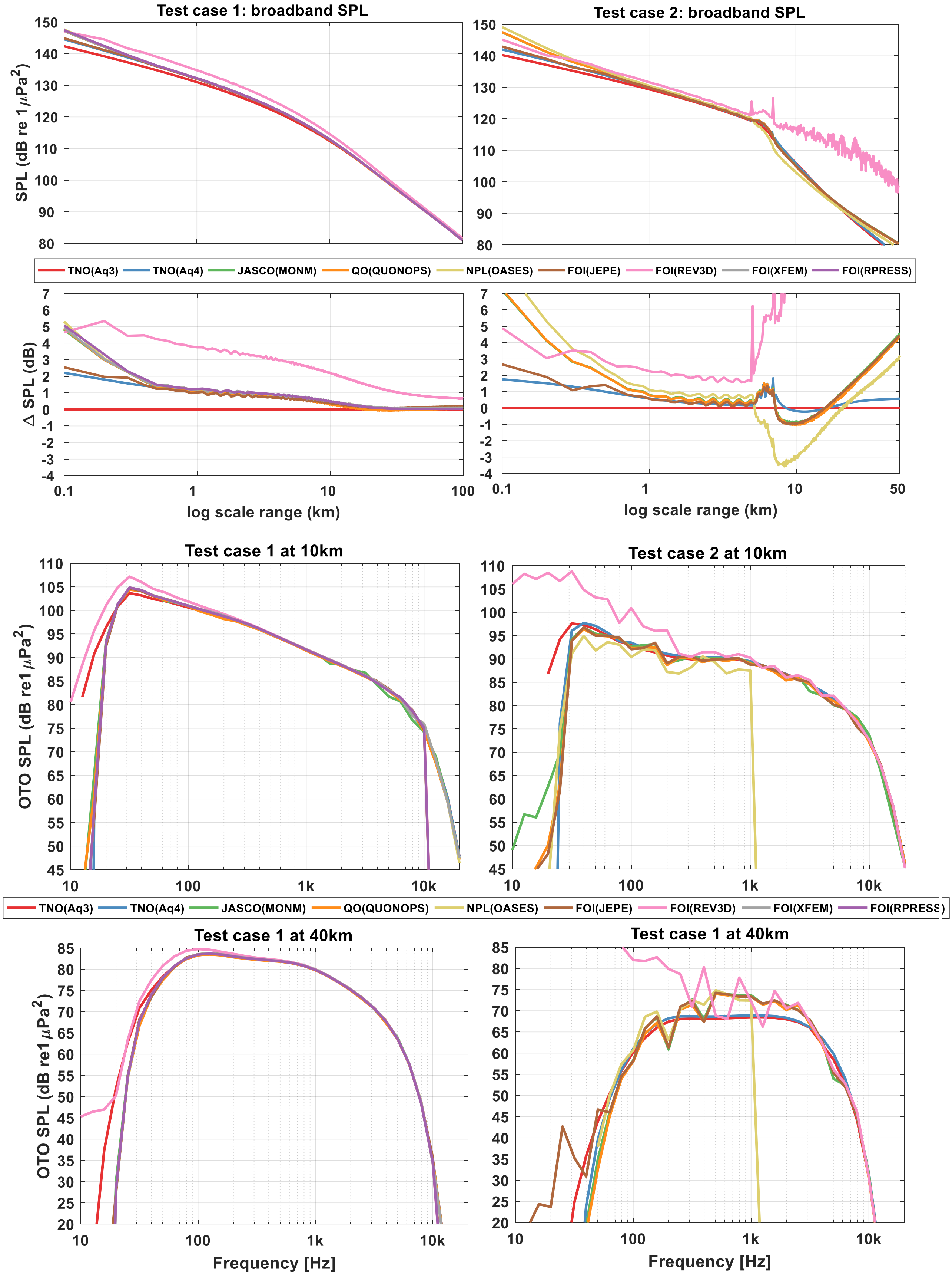

Figure 3: broadband (top 4) and spectral (bottom 4) modelling results for the two test cases

In order to gain further confidence in the correctness of the PE results, a comparison against other model types (e.g. finite element (FE) or coupled mode models) is desirable, but was outside of the scope of this paper. With regard to the range dependent OASES results it should be noted that contributions from bands above 1 kHz were omitted due to observed unstable model behaviour at the start of the slope, which provides a possible explanation for the underestimation of the broadband results observed after 5 km with respect to the PE predictions.

For the range-dependent case, it is observed that the QUONOPS, JEPE and MONM model predictions are similar (with differences smaller than 3 dB above 80 Hz). The Aq3 and Aq4 results are similar to the PE models at 10 km, but the predicted SPL at 40 km at frequencies between 500 Hz and 3 kHz is lower by ~5 dB. This observed bias may be caused by the adiabatic mode assumption used by these models. A comparison of a coupled mode or a FE simulation would strengthen this hypothesis. Below 1 kHz the range-dependent OASES model deviates from the PE models by about 5 dB. At 2 kHz and above, the QUONOPS model uses a ray approach, which lead to the same results as the JEPE and MONM PE models.

5. DISCUSSION AND CONCLUSIONS

For the range-independent test case 1 a reference solution was obtained with an associated uncertainty of 0.2 dB for all tested frequencies. For test range-dependent case 2, the predictions of PE and adiabatic mode/hybrid mode flux models differ up to ~5 dB at 40 km. Further comparison against other model types such as FE and coupled modes and comparison with existing benchmarks such as [2] are recommended to reduce the uncertainty of this reference solution. Furthermore, the strong variability observed for the range dependent case is expected to reduce when an average value for the OTO bands is calculated using more frequencies which is expected to reduce the difference with incoherent models such as the Aquarius 3 and 4 models.

While the model benchmarking described in this paper helped to better understand the accuracy and limitations of the tested models, a good agreement for the selected test cases does not by default guarantee a good performance for other scenarios. The results published in this paper were configured with great care to provide optimal results for the selected test cases. Given the (numerical) complexity of the tested models, the optimal configuration depends on the environment. In particular at low frequencies and in shallow water (near and below the cut-off frequency) and in range-dependent environments, great care should be taken to check the stability, convergence and applicability of propagation models.

Regarding the applicability of the tested models for modelling underwater noise, the required model accuracy should be balanced against the uncertainties related to the input data from environment as well as sources. Generally speaking, using a more accurate model (configuration) will require more computational resources. For large scale noise mapping, this will affect other model parameters such as the temporal and spatial resolution of the modelling. During the remainder of the JOMOPANS project, the uncertainty associated with other modelling parameters relevant for large scale noise modelling will be investigated. These insights will be used to assess the applicability of the various model types tested in this study.

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