MODELLING NOISE FROM WIND, RAIN AND DISTANT SHIPPING IN SCENARIOS OF VARYING COMPLEXITY.

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Abstract: *Passive sonars attempt to detect sound radiated by vessels of interest. This detection takes place against a background of noise, with important sources of noise including distant shipping, rain falling on the sea surface and breaking waves and bursting bubbles associated with sea-surface waves. The estimation of these noises is therefore an important part of the prediction of the likely performance of passive sonars. Mathematical models are available for the prediction of noise and these represent a combination of descriptions of the level and directionality of radiated noise, the propagation of sound between source and receiver and the convolution of receiver beam patterns and the directivity of the noise field at the receiver. These processes vary with acoustic frequency and environmental properties such as water depth, seabed type, sea-water sound-speed profile, precipitation rate and wind speed. The important physical processes are not straightforward to model and all prediction tools are, to some extent, approximations. When assessing model legitimacy, reference solutions are necessary to demonstrate model accuracy. Predictions of rain, wind and distant-shipping noise are presented in a simple environment previously developed for the purposes of verifying sonar-performance models. An existing reference solution for rain noise is used, along with a novel expression for the noise from distant shipping. Calculations are extended to more complicated scenarios including non-uniform shipping distributions and beam-patterns for generic arrays.*

Keywords: *Ambient Noise, Rain Noise, Surface Noise, Shipping Noise*

1. INTRODUCTION

The calculation of underwater acoustic ambient noise is challenging and requires good models for acoustic propagation, accurate descriptions of noise sources and detailed knowledge of the properties of the acoustic receiver. The dominant sources of noise are known to vary with frequency and environmental conditions [1] and it is common to think of distant shipping as the dominant source of low-frequency noise while rain and wind become more important at higher frequencies. The specific frequency at which this change in dominant source occurs depends on many factors, including the beam pattern of the receiving sonar.

In this paper, an approach is described by which expressions for the absolute level and directivity of noise sources are taken from the literature and combined with a propagation model to predict the directivity of noise incident on a receiver. This field is then convolved with receiver beam-patterns to provide in-beam noise levels for single-hydrophone and line-array receivers.

The following section sets out definitions and standards used in the calculation of ambient noise and describes the formulae taken from the literature for sources of shipping and sea-surface noise. It then describes the method by which these source formulae are combined with a propagation model and descriptions of receiver beam-patterns. Section 3 describes a reference solution for rain noise, also taken from the literature, that is used as a test-case for the modelling method. It then describes the derivation of a novel reference solution for shipping noise in similar environments. Predictions made by the ambient-noise modelling approach are compared with the reference solutions in Section 4 and conclusions drawn. Example results for more complicated scenarios – for which no reference solution currently exists – are also described to illustrate the flexibility of the numerical approach.

2. TERMINOLOGY AND ALGORITHMS

Standard terminology was followed in that ambient noise was defined as “sound except acoustic self-noise and except sound associated with a specified signal” [2]. This ties the definition of noise to the concept of a signal whose detection is sought.

In the case of rain and wind noise, the terminology is unambiguous but further clarification is required for shipping noise. Passive sonars attempt to detect vessels’ radiated noise and the signal is therefore of the same nature as the noise which might obscure its detection. If a ship can be detected by a passive sonar it consequently ceases to be a source of ambient noise. Its sound may remain an undesired part of the acoustic field because it is not from the vessel being sought but as such it becomes a ‘false target’ rather than a source of noise. Consequently, the term ‘*distant* shipping noise’ is used here to make clear that the noise under consideration is only that from ships that are far enough away that the sonar is unable to detect them as discrete sources of sound. The distance at which this transition occurs is determined by the properties of the sonar under study.

The formulation followed here for the prediction of sea-surface noise follows those of Chapman [3] and Harrison [4]. The sea surface is considered to be a sheet of dipole sources that extends infinitely and uniformly in all directions. As such, the sea-surface noise field is isotropic in horizontal angle but varies with vertical angle because of source directivity and angular dependence in acoustic propagation. This propagation is modelled by a ray-theoretic approach in which the sound arriving within a given angular increment is an infinite summation over the contribution of patches of sea-surface whose distances from the receiving array are integer multiples of the ray-cycle distance at the angle of interest. Formulae for the source strength per unit area of sea surface are taken from formulae developed by APL [5] and discussed in Ainslie [6]. An example result is shown in Fig. 1.

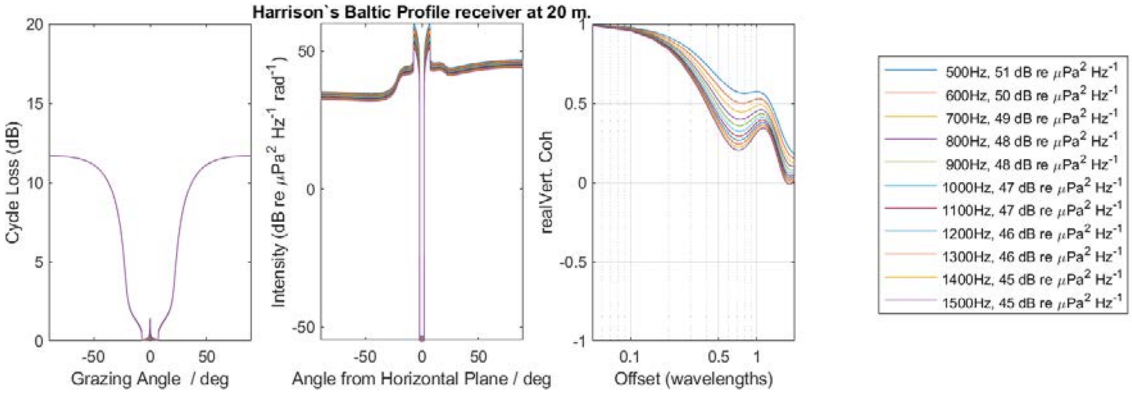

Fig.1: Vertical distribution of sound from sea-surface noise sources incident on a receiver

The left panel shows the loss per cycle range as a function of vertical angle. This is symmetric about the horizontal and rises for larger (absolute) angles because of increased reflection loss at the seabed. The spike in loss around the horizontal is a consequence of absorption in the very long cycle ranges associated with near-horizontal paths. The middle panel shows the distribution of noise with vertical angle. This is asymmetric about the horizontal because upward rays have undergone one more bottom reflection than downward rays at the same angle. The peaks in noise close to zero angle are a consequence of the Baltic-Sea sound-speed profile that was used in the calculations of Harrison, [4] and which was also used in the calculation whose results are shown here. The angles closest to the horizontal have no noise associated with them because there is no path from surface to receiver at these angles due to in-water refraction. The right panel shows the real part of the vertical coherence of the acoustic field [3]. This parameter is important in the design of arrays with vertical aperture and its calculation was the motivation for the development of Harrison and Chapman's methods.

Shipping noise requires a separate formulation. It is more important at lower frequencies and the low associated absorption loss means that distant ships may make significant contributions to the total noise field. Source strengths were calculated using the formula of Wales and Heitmeyer [7] and with a dipole directivity pattern assumed. The sea-surface area surrounding the receiver was split into an irregular pattern of facets whose area was used in combination with a density of ships to produce a source strength for each facet. Source density was set to zero below a critical range within which ships would act as false targets, rather than sources of noise. Sound was propagated from each facet to the receiver using a formula based on the concept of acoustic flux [8], [9], [10]. This formula yields a distribution of sound with vertical angle at the receiver that can be convolved with the receiver beam pattern. The method of facets allows for the straightforward incorporation of inhomogeneous distributions of shipping such as fishing grounds and shipping lanes.

3. REFERENCE SOLUTIONS

The process of developing a numerical model for ambient noise requires successful incorporation of source, propagation and receiver descriptions. The first and second of these factors depend on environmental properties such as water-depth, wind-speed and seabed type. Correct implementation of source and receiver descriptions requires detailed treatments of all normalisation and calibration parameters to ensure that the final in-beam noise is expressed in absolute terms rather than relative decibels. This process is challenging and has scope for errors of implementation and interpretation. As such it is important that the predictions of numerical models should be verified (shown to correctly implement their baseline algorithms) and validated (shown to produce accurate absolute levels).

An important step in the verification/validation process is comparison with reference solutions. These may take the form of highly accurate numerical solutions or closed-form mathematical expressions which, in well-defined circumstances, represent accurate solutions to the problem under study. Two closed-form reference solutions were considered here: one for rain noise, taken from the literature, and one for distant-shipping noise that was developed especially for this purpose.

The reference solution for rain-noise was taken from [11]. It was developed in one of a series of standard environments that were produced for use in model verification and validation [12]. The particular environment, 'Weston I' considered here represents a horizontally invariant environment in which 100 m of isovelocity water overlies a sand halfspace. The wind-speed is set to be zero and the only source of noise is rain which falls at a rate of 1 mm/Hr. The reference solution for shipping noise was developed for this study and is now described.

Considerations of acoustic flux allow the depth-averaged acoustic intensity, I, measured by an omnidirectional hydrophone, due to a dipole source at the surface and at range r to be expressed as an integral over vertical angle θ [10].

$$I = \frac{4}{Hr} e^{-\beta r} \int_0^{\frac{\pi}{2}} \frac{S_a \sin^2 \theta}{D(\theta) sin\theta} e^{\frac{2r}{D(\theta)} \ln[|V(\theta)|]} cos\theta d\theta \tag{1}$$

Where H is the water depth, S_a is the source strength, $D(\theta)$ is the cycle range of a ray, β is the volume-absorption coefficient and $V(\theta)$ is the seabed reflection coefficient. This can be simplified to a standard form under approximations of small angles [10] and restriction of the upper limit of the angular integral to the seabed critical angle θ_c . This yields

$$I = \frac{S_a}{2Hra} e^{-\beta r} \left(\sqrt{\frac{\pi}{a}} \mathrm{erf}\left(\sqrt{a}\theta_c\right) - 2\theta_c e^{-a\theta_c^2} \right); a = \frac{rs}{H} \tag{2}$$

Where s is the gradient of reflection coefficient at grazing incidence, expressed in Nepers per radian. The noise intensity from distant shipping over all ranges is

$$N_{Sh} = \int_{r_c}^{\infty} I(r) n \, 2\pi r \, dr \tag{3}$$

Where n is the (spatially invariant) density of ships and r_c is shortest range at which ships will not be discriminated as discrete sources and their noise will form part of the background noise field. This can be reduced to a closed-form expression on the assumption that r_c is O(10^4m)

$$N_{Sh} = \sqrt{\frac{\pi^3 H\beta}{s^3}} n S_a \left(\sqrt{\pi}(\mathrm{erf}(a_c) - 1) + \frac{e^{-a_c^2}}{a_c} \right); a_c = \sqrt{\beta r_c} \tag{3}$$

This represents a reference against which numerical-model predictions can be compared for the special case of a uniform shipping density in the Weston-I environment. Examples of this comparison are given in the following section.

4. EXAMPLE RESULTS

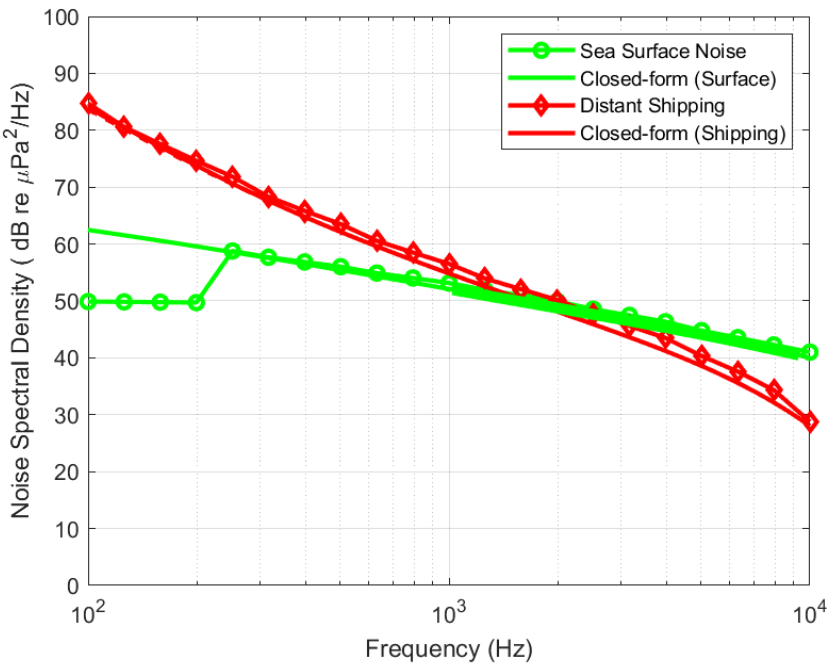

Fig.2: Comparison of numerical model predictions with closed-form reference solutions

Fig. 2 shows the ambient noise predicted for an omnidirectional hydrophone in the Weston-I environment. The green line is the noise from the reference solution for rain noise [11] and the thicker portion of the line shows the frequency regime for which it is quoted as being valid. The green line with circle markers is the numerical model's prediction of the same noise, calculated by integrating the noise distribution over vertical angle. The two lines are shown to agree well in the region of validity for the reference solution. The two diverge at low frequencies because the formula for the source strength of rain noise does not extend below 200 Hz [6] and the noise predicted by the numerical model defaults to a 'low sea-state' value associated with the wind noise formula. The red line shows the reference solution for shipping noise developed in the previous section. This is shown to be higher at lower frequencies, following the Wales-Heitmeyer spectrum. The red line with diamond markers shows the predictions made by the numerical model for the Weston-I environment. Good agreement is shown and the small discrepancy (<2dB) is a consequence of the full integration over angle performed by the numerical propagation model, compared to the small-angle approximation implicit in the reference solution. The agreement between the numerical model and the reference solutions is taken to be supportive of the hypothesis of model validity.

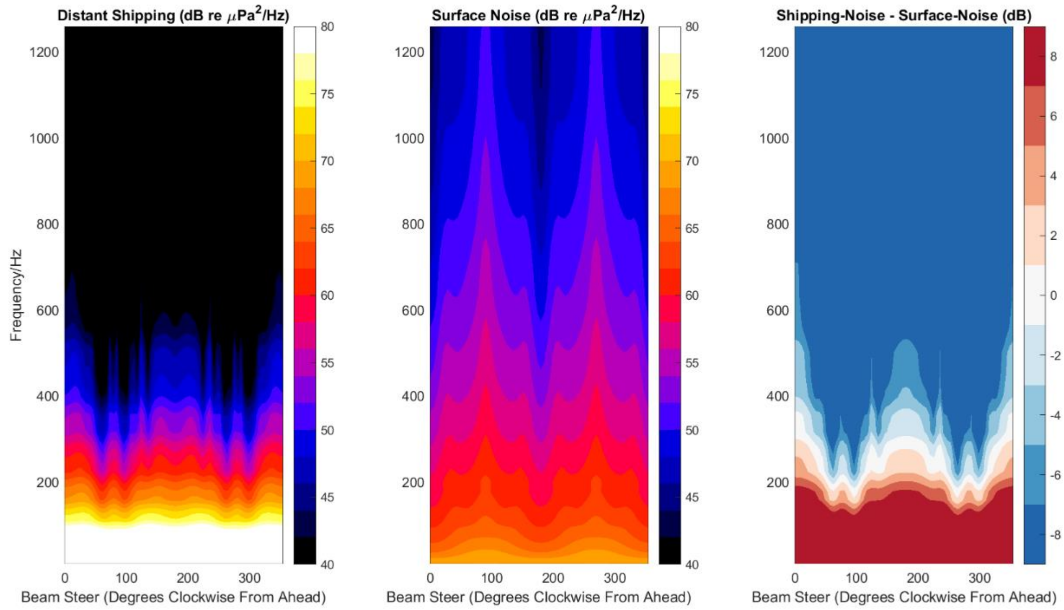

Fig.3: Numerical model predictions for a line-array receiver in the Weston-I environment.

Fig. 3 shows numerical model predictions of noise received on a line array in the Weston-I environment with a wind-speed of 8 ms^{-1} and a rain rate of 0.1 mm/Hr. No reference solution exists for these conditions but the model's agreement for the reference case with the single receiver means that, as a working hypothesis, it may be assumed to be valid. The left panel shows shaded colours of noise as a function of beam-steer-angle on the x-axis and frequency on the y-axis. The noise is higher at low frequencies and rises for the beams steered at forward (0^o) and rear (180^o) directions. The line array is 'ambiguous' in the sense that arrivals from port and starboard are indistinguishable and this causes the symmetry observed about 180^o. The middle panel shows sea-surface noise across beams and frequency. Although the noise does not vary with horizontal angle, in-beam noise is shown to vary with beam steer and broadside beams (90^o and 270^o) are shown to have highest noise. This is a consequence of the three-dimensional nature of beams formed by line arrays. A beam steered at 30^o from forward actually forms a cone that is as responsive to horizontal sound arriving at a bearing of 30^o as it is to sound travelling at a vertical angle of 30^o from directly ahead of the array. The broadside beams are thus narrow in horizontal angle but broad in vertical angle. The right panel in Fig. 3 shows the decibel difference between the two types of noise. Whereas conventional wisdom refers to shipping noise being dominant at low frequency, the shapes of the contours in the panel show that the frequency at which the two types of noise become equal actually varies with the steer direction of the beams. Broadside beams are dominated by surface noise at lower frequencies than forward and rear beams.

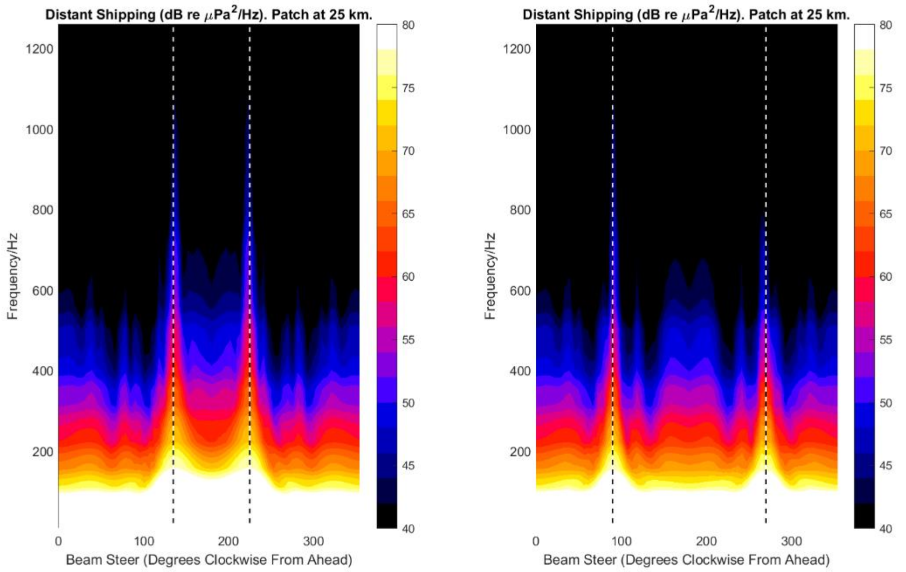

Fig.4: Distant-shipping noise predictions for environments with a small patch of high shipping density added to a uniform background. Dashed lines show the relative bearing of the patch (and the ambiguous bearing) in two cases: off-broadside (left) and broadside (right).

Fig. 4 shows shaded images of in-beam noise for a case where a patch of high shipping density was added to the environment. This simulates what would occur in the vicinity of an area of concentrated shipping activity, such as a fishing-ground or an area of oil production. The right pane shows the effects of the patch when it is at a relative bearing of 90^o, i.e. in the broadside beam. A narrow, symmetric beam of noise is centred around the true bearing of the patch, shown by the dotted line. The ambiguous nature of the line array makes a similar pattern appear around 270^o. The left panel shows the effect of the same patch when its relative bearing is 135^o. The amplitude of the increased noise is similar to the broadside case in the beam closest to the true bearing but the shape of the fall-off of noise with beam steer is now asymmetric. This is because of the broader beams that are steered in directions close to the rear. The beams are in fact so large that the two noise-peaks at the actual and ambiguous bearings merge in the rear beam, whose noise is increased by the patch, despite the 45^o angular separation between the patch and the beam-steer. No reference solution exists for this situation but the case is useful to demonstrate that the combination of noise-source distribution, propagation and beamforming gives physically sensible results.

CONCLUSIONS

Closed-form reference solutions are a useful tool in the verification and validation processes that are an important part of the development of numerical models of underwater ambient noise. Expressions for the noise from rain and distant shipping were compared against model predictions and shown to be in close (<2dB) agreement. The same model, run in the same environment but with a line-array receiver, showed how sea-surface noise varied with beam-steer in the horizontal, even though the surface-noise field itself does not vary with horizontal angle. This means that the frequency at which surface noise becomes greater than distant-shipping noise is a function not only of wind-speed, rain-rate and shipping density but also of beam-steer. Broadside beams receive a greater amount of surface noise than forward and rear beams formed from the same array. This work was sponsored by the Defence Materiel Organisation of The Netherlands.

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