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A simple yet practical ambient noise model

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IMPORTANT INFORMATIVE STATEMENTS

Abstract

A general unclassified empirical ambient noise model was described, valid for frequencies from 1 Hz to 100 kHz. The model combines the effects of turbulent pressure fluctuations, shipping noise, wind noise, rain noise, and thermal noise. The model requires as inputs frequency, wind speed, shipping level, water depth, and rain rate, and outputs the total noise level NL in dB re μPa in a 1-Hz band. Despite its relative simplicity, it provides useful results not found elsewhere when a first-order ambient noise estimate is required for use in the sonar equation.

Significance for defence and security

Despite the existence of modern models for estimating noise levels using real-time or historical maps of shipping and weather conditions, there are times when a simple yet reasonable (and unclassified) ambient noise estimate is required as an input to the sonar equation. The model described in this document rapidly provides an estimated ambient noise level based on user-supplied inputs of frequency, wind speed, shipping density, water depth, and rain rate.

Résumé

Un modèle empirique général non classifié de bruit ambiant a été décrit, valable pour des fréquences de 1 Hz à 100 kHz. Le modèle combine les effets des fluctuations de pression turbulente, du bruit engendré par les navires, du bruit du vent, du bruit de la pluie et du bruit thermique. Le modèle requiert comme données d'entrée la fréquence, la vitesse du vent, le niveau du trafic, la profondeur de l'eau et le taux de précipitations ; les résultats sont le niveau de bruit (« NL ») total en dB re µPa dans une bande de 1 Hz. Malgré sa relative simplicité, il fournit des résultats utiles que l'on ne trouve nulle part ailleurs lorsqu'une estimation du bruit ambiant de premier ordre est requise aux fins d'utilisation dans l'équation du sonar.

Importance pour la défense et la sécurité

Malgré l'existence de modèles modernes d'estimation des niveaux de bruit utilisant des cartes historiques ou en temps réel de la navigation et des conditions météorologiques, il arrive qu'une estimation simple, mais acceptable (et non classifiée), du bruit ambiant soit requise comme donnée d'entrée dans l'équation du sonar. Le modèle décrit dans ce document fourni rapidement une estimation du niveau de bruit ambiant basée sur les données d'entrées fournies par l'utilisateur, à savoir la fréquence, la vitesse du vent, la densité de la navigation, la profondeur de l'eau et le taux de précipitations.

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Acknowledgements

The authors would like to thank Vic Young and Dan Hutt, on whose code this model is loosely based.

1 Introduction

Frequency-dependent ocean ambient noise levels are an important factor when determining detection range in underwater warfare (UWW). Turbulent-pressure fluctuations are the dominant noise source for frequencies from 1–100 Hz [1], while for frequencies above 50–200 kHz the ambient noise results from the equilibrium thermal-noise pressure spectrum with some environmental dependence [2]. At the intermediate frequencies between 100 Hz and 50 kHz, which are the frequencies of greatest interest in UWW, ocean ambient noise depends on a combination of wind-dependent noise, nearby vessel noise, distant shipping, and rain [1].

Despite the existence of modern models for estimating noise levels using real-time or historical maps of shipping and weather conditions, there are times when a simple yet reasonable (and unclassified) ambient noise estimate is required as an input to the sonar equation. The model described in this Reference Document provides an estimated ambient noise level based on user-supplied inputs of frequency, wind speed, shipping density, water depth, and rain rate. The model does not include any form of self-noise, whether from flow past a sensor, or ownship/platform noise.

In the implementation described here, there is no consideration given for water depths between “shallow water” (the continental shelf, up to a few hundred metres deep) and “deep water” (the ocean basins, thousands of metres deep). In the absence of other options, for water depths greater than a few hundred metres, the deep water form of the equations should be used.

2 Model description

The ambient noise model described here sums the estimated contribution of five effects, each of which will be described briefly in Sections 2.1 through 2.5 below:

1. turbulent pressure fluctuations (NL_{turb}, Section 2.1);
2. shipping (NL_{ship}, Section 2.2);
3. wind (NL_{wind}, Section 2.3);
4. rain (NL_{rain}, Section 2.4); and
5. thermal noise (NL_{therm}, Section 2.5).

The output of each submodel is provided within the program is the sound pressure spectral level in dB re μPa in a 1-Hz band (units of dB re $\mu\mathrm{Pa}^2/\mathrm{Hz}$).

Likewise, the output of the noise model is the total noise sound pressure spectral level NL (again in units of dB re $\mu\mathrm{Pa}^2/\mathrm{Hz}$). The total noise level is calculated by summing the components in linear units:

$$\mathrm{NL} = \mathrm{NL}_{turb} \oplus \mathrm{NL}_{ship} \oplus \mathrm{NL}_{wind} \oplus \mathrm{NL}_{rain} \oplus \mathrm{NL}_{therm} \tag{1}$$

In Equation (1), the $\oplus$ operator indicates each that each noise term expressed in decibel units ($\mathrm{NL}_{\mathrm{dB}}$) is first converted into μPa ($\mathrm{NL}_{\mu Pa}$) summed, and then converted back to decibels:

$$\begin{aligned} \mathrm{NL}_{\mu Pa} &= 10^{\frac{\mathrm{NL}_{\mathrm{dB}}}{10}} && (2) \\ \mathrm{NL}_{\mathrm{dB}} &= 10 \log_{10}(\mathrm{NL}_{\mu Pa}) && (3) \end{aligned}$$

2.1 Turbulent pressure fluctuations

The turbulent pressure fluctuation term NL_{turb} captures the effects of non-linear interactions among wind-generated ocean surface waves into an empirical formula. Turbulent pressure fluctuations dominate the noise spectrum at frequencies of 1–100 Hz and are modelled solely a power-law function of frequency f, which is linear in log-frequency space with slope m_t and intercept NL_t:

$$\mathrm{NL}_{turb} = \mathrm{NL}_t + m_t \log_{10} f; \tag{4}$$

The parameters m_t and NL_t are not constant in all areas of the ocean; rather, they have some dependence on water depth, shipping noise, and wind speed that is distinct from the higher-frequency ambient noise components considered in Sections 2.2 and 2.3. Numerous authors over several decades have compiled measurements and models to determine the dependence of the parameters m_t and NL_t on water depth and wind speed. The first estimates in 1962 by Wenz [1] were based on the limited measurements then available. Wenz observed that the overall noise levels may change by 25 dB between locations, although the slope is a relatively constant −8 to −10 dB/octave, and local shipping may also affect levels.

In 1984 Urick [3] reviewed the available data, again referencing the −10 dB/octave slope between 1–5 Hz and observing that a change in slope around 5 Hz is due to shipping traffic. Urick also noted that the existing shallow-water, World War II-era measurements are likely higher than contemporary measurements [3].

Nichols and Bradley [4], using a large dataset from deep-water sites that span the Atlantic, Pacific, and Indian oceans as part of the Comprehensive Nuclear Test Band Treaty Organization, provided measurements and empirical fits for wind dependence that are site-specific. They also explored the impact of using averaging periods of one minute to one year.

The values provided by Wenz, Urick, and Nichols and Bradley are summarized in Table 1. Although the ranges vary greatly there is significant overlap. There is greater agreement on the slope m_t, which is generally cited as –8 to –10 dB/octave [1], though there is a wind dependence (e.g., [4]) that is not captured by using a constant value.

Table 1: *Measured values for turbulent pressure intercept* NL_t *from literature.*

Reference	$\mathbf{NL_t}$ **(dB re** μ**Pa)**	**Notes**
Wenz, Fig. 14 [1]	106	Deep water, sea state 3
Wenz, Fig. 13 [1]	88–138	Maximum and minimum on overview plot
Urick, Fig. 2-2 [3]	115–132	Shallow water, World War II-era values that are likely higher than modern values
Urick, Fig. 2-3 [3]	105–115	Deep water
Nichols and Bradley, Fig. 8 [4]	100-120	Deep water, with wind dependence
Nichols and Bradley, Fig. 5 [4]	107	Deep water, various averaging periods

In order to simplify and generalize the model calculation, the values used in the model were $\mathrm{NL}_t = 107$ dB re μPa and $m_t = -10$ dB/octave, equivalent to $m_t = -10/\log_{10} 2 = -33.2$ dB/decade.

2.2 Shipping noise

The distant shipping noise term NL_{ship} depends on frequency f, shipping density (low, medium, or high), and water depth (deep or shallow). It is an approximation to the curves for low, medium, and high shipping densities from [1].

$$NL_{ship} = 76 - 20\left(\log_{10} f - \log_{10} c_1\right)^2 + 5\left(c_2 - 4\right) \quad (5)$$

where c_1 depends on water depth:

$$c_1 = \begin{cases} 30 & \text{deep water} \\ 65 & \text{shallow water} \end{cases} \tag{6}$$

and c_2 depends on shipping density level:

$$c_2 = \begin{cases} 1 & \text{low shipping} \\ 4 & \text{medium shipping} \\ 7 & \text{high shipping} \end{cases} \tag{7}$$

2.3 Wind noise

The wind-generated noise described in this section arises from a variety of sources, including bubbles from breaking waves, water droplets, and surface waves [1]. The wind noise term NL_{wind} depends on frequency f, wind speed u at 10 m height, and water depth (deep [5] or shallow [6]). The relations given in this section are completely empirical and are valid only for frequencies up to 2 kHz; for frequencies higher than 2 kHz the empirical curve resulting from the equations below is smoothly blended into a curve with power-law dependence on frequency.

The frequency of peak wind noise f_0 (Hz) depends on wind speed $u > 0$ (knots):

$$f_0 = 770 - 100 \log_{10} u. \tag{8}$$

Note that Equation (8) is undefined for zero wind speed; therefore the model outputs $\mathrm{NL}_{wind} = 0$ dB if $u = 0$.

The noise level L_0 (dB) at the peak frequency f_0 is related to u, f_0 and water depth:

$$L_0 = c_0 + 20 \log_{10} u - 17 \log_{10} \frac{f_0}{770} \tag{9}$$

where the constant c_0 in dB is given by [5, 6]:

$$c_0 = \begin{cases} 45 & \text{shallow water} \\ 42 & \text{deep water} \end{cases} \tag{10}$$

Two components L_1 (dominant for $f < f_0$) and L_2 (dominant for $f > f_0$) are then combined to result in the overall wind noise frequency dependence L_w:

$$L_1 = L_0 + \left(\frac{s_1}{\log_{10} 2} \right) \log_{10} \frac{f}{f_0} \tag{11}$$

$$L_2 = L_0 + \left(\frac{s_2}{\log_{10} 2} \right) \log_{10} \frac{f}{f_0} \tag{12}$$

$$L_w = L_{1w} \left(1 + \left(\frac{L_{1w}}{L_{2w}} \right)^{-a} \right)^{-1/a} \tag{13}$$

where the constants s_1 and s_2, and the curve melding exponent a are given by:

$$s_1 = 1.5 \tag{14}$$

$$s_2 = -5.0 \tag{15}$$

$$a = -25 \tag{16}$$

For frequencies greater than 2000 Hz the curve is extended with a slope of m_0 (in log space), equivalent to a power law in linear units:

$$m_0 = s_2 \left(\frac{0.1}{\log_{10} 2} \right) \tag{17}$$

The curves above and below 2000 Hz are joined smoothly by starting with the calculated noise value in dB at $f = 2000$ Hz of $L_{w,2000}$:

$$\begin{aligned} K &= L_{w,2000} - m_0 \, (10 \log_{10} 2000) \\ &= L_{w,2000} - 33.0 \, m_0 \qquad (18) \\ L_w &= K + m_0 \, 10 \log_{10} f. \qquad (19) \end{aligned}$$

The resulting frequency dependence of wind noise NL_{wind} in dB can be summarized as:

$$\mathrm{NL}_{wind} = \begin{cases} L_{1w} \left(1 + \left(\frac{L_{1w}}{L_{2w}} \right)^{-a} \right)^{-1/a} & (f \leq 2000Hz) \\ K + m_0 \, 10 \log_{10} f & (f > 2000Hz) \end{cases} \tag{20}$$

2.4 Rain noise

There are numerous empirical models in the literature describing rain noise. In the interests of simplicity, the model from [7] was implemented, in which rain noise NL_{rain} depends only on frequency f as follows:

$$\mathrm{NL}_{rain} = r_0 + r_1 f + r_2 f^2 + r_3 f^3 \tag{21}$$

The parameters r_0, r_1, r_2, r_3 depend on rain rate in mm/h (Table 2). Above 7 kHz, the model begins to predict monotonically increasing noise levels as a function of frequency, presumably because the original paper was only using measurements and curve fitting up to 10 kHz. Therefore, our model was extended with constant slope for frequencies higher than 7 kHz in a similar manner to that described for the wind noise (Section 2.3). More complex models such as [8], which combines wind and rain noise, could be considered for future implementation.

Table 2: *Rain rate model parameters.*

Rain Rate	$\mathbf{r_0}$	$\mathbf{r_1}$	$\mathbf{r_2}$	$\mathbf{r_3}$
Light (1 mm/h)	51.0769	1.4687	–0.5232	0.0335
Moderate (5 mm/h)	61.5358	1.0147	–0.4255	0.0277
Heavy (10 mm/h)	65.1107	0.8226	–0.3825	0.0251
Very Heavy (100 mm/h)	74.3464	1.0131	–0.4258	0.0277

2.5 Thermal noise

The thermal noise level NL_{therm}, which arises from the molecular agitation of water, depends only on frequency f [2] and is given by:

$$\mathrm{NL}_{therm} = -75.0 + 20 \log_{10} f \tag{22}$$

3 Representative plots

In order to explore the effects of rain, wind, and shipping noise, total noise level was calculated and plotted in Figure 1 as a function of frequency for a few representative environments: the Grand Banks, the Greenland-Iceland-United Kingdom gap (GIUK gap), and the middle of the Atlantic Ocean (Table 3).

Table 3: *Representative environments.*

Name	**Location**	**Wind speed (kn)**	**Shipping**	**Water depth**	**Rain rate**
Grand Banks	(45.74, –50.67)	20	low	shallow	varying
GIUK gap	(64.26, –7.90)	varying	low	deep	none
Mid-Atlantic	(52.72, –34.86)	15	varying	deep	none

Figure 1a is a plot of noise level as a function of frequency for the Grand Banks environment, with rain rate varying from “none” to “very heavy.” The increased noise is mostly observed for frequencies higher than 1 kHz, with the exception of the “very heavy” rain rate, which increases noise as low as 10 Hz.

Figure 1b is a plot of noise level as a function of frequency for the GIUK gap, with wind speed varying from 1 kn to 40 kn. As the wind speed increases, the impact of wind is seen at lower frequencies (e.g., 100 Hz for 5 kn winds compared to 20 Hz for 40 kn winds).

Figure 1c is a plot of noise level as a function of frequency for the mid-Atlantic, with shipping density varying from low to high. In this scenario, the effect of shipping on noise levels is limited to frequencies between 5 Hz and 500 Hz.

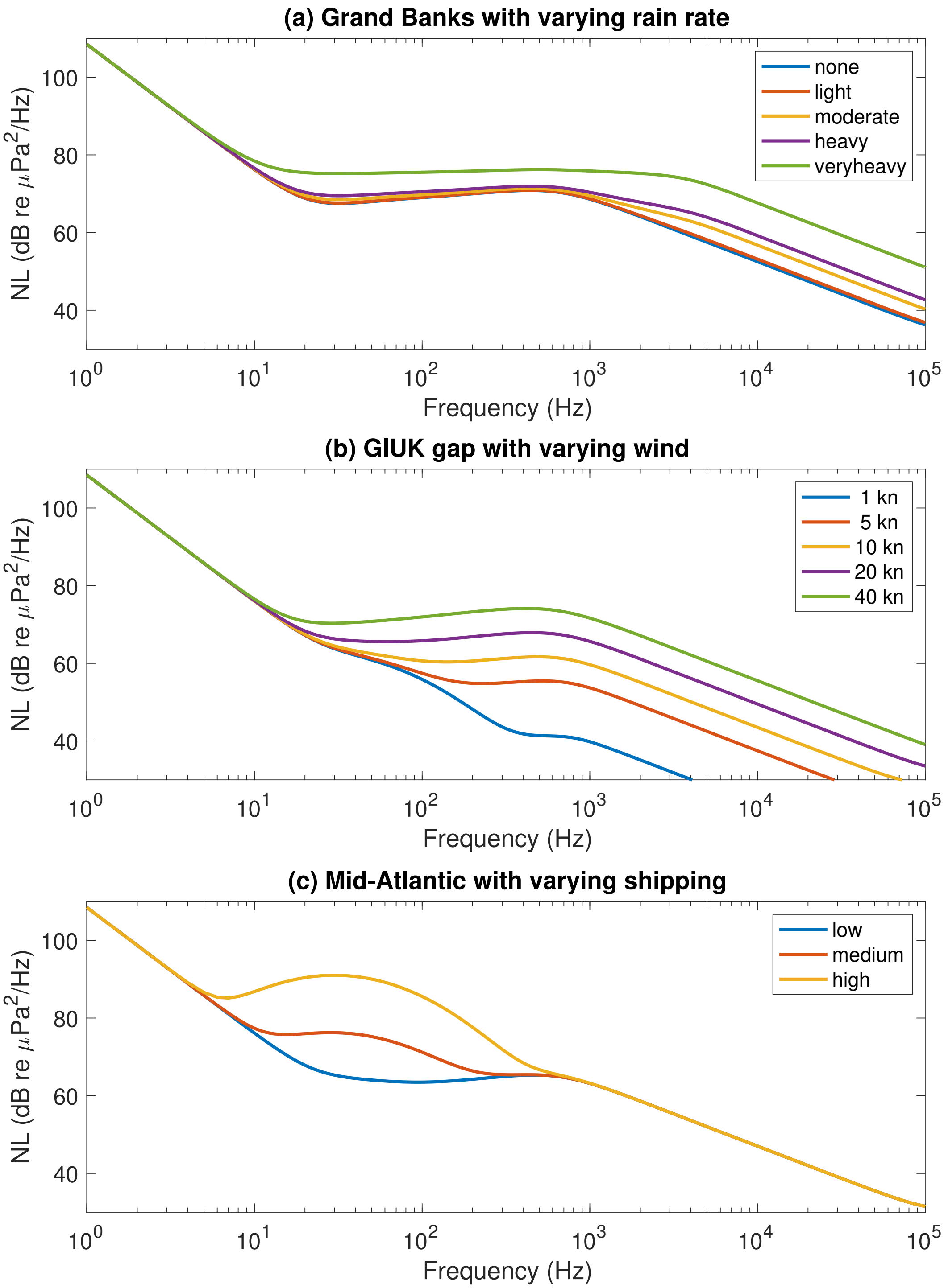

Figure 1: *Plots of total noise level (dB re μPa^2/Hz) for (a) Grand Banks scenario, with varying rain rate, (b) GIUK gap scenario, with varying wind, (c) Mid-Atlantic scenario, with varying shipping.*

4 Conclusions

A general-purpose unclassified empirical ambient noise model was described, valid for frequencies from 1 Hz to 100 kHz. The model combines the effects of turbulent pressure fluctuations, shipping noise, wind noise, rain noise, and thermal noise. The model requires as inputs frequency, wind speed, shipping level, water depth, and rain rate, and outputs the total noise level NL in dB re μPa in a 1-Hz band. Despite its relative simplicity, it provides useful results not found elsewhere when a first-order ambient noise estimate is required for use in the sonar equation.

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Annex A Matlab code

Annex A.1 contains the function `calc_noise_level.m` that calculates total noise level given inputs of frequency, wind speed, shipping level, water depth, and rain rate. It has an optional parameter that can be set so that it outputs all five noise components (turbulent pressure, shipping, wind, rain, thermal) separately rather than summed (the default).

Annex A.2 contains the function `calc_wind_noise.m` that calculates wind noise as a function of frequency, wind speed, and water depth. The wind noise function is called by the total noise level function, but may also be called on its own.

A.1 calc_noise_level.m

```
%
% NL = calc_noise_level(f,u,shippingLevel,waterDepth,rainRate,[sumOption])
%
% calculates noise level (in dB re uPa) based on five components:
% (1) shipping noise (Wenz, 1962)
% (2) wind noise (Merklinger, 1979 and Piggott, 1964)
% (3) rain noise (Torres and Costa, 2019)
% (4) thermal noise (Mellen, 1952)
% (5) turbulence (Nichols and Bradley, 2016)
%
% Inputs:
% f = single frequency or vector of frequencies (Hz)
%     note: assumes a 1-Hz band for a single frequency
% u = wind speed (knots)
% shippinglevel = 'low' 'medium' or 'high' (default: medium)
% waterDepth = 'shallow' or 'deep' (default: deep)
% rainRate = 'none' 'light' 'moderate' 'heavy' or 'veryheavy' (default: none)
%
% Optional Input:
% Including a sixth argument '-nosum' will provide the output as a
% 5-column matrix with noise components in dB in the order listed above
%
% Output:
% NL = column vector containing the noise (dB per muPa^2/Hz)
% at frequencies f
%
% if -nosum option is chosen then all five noise components are provided
% in order


function NL = calc_noise_level(f,u,shippingLevel,waterDepth,rainRate,varargin)

f = f(:);

if nargin == 6 && strcmp(varargin{1},'-nosum')
```

```
    computeSum = 0;
else
    computeSum = 1;
end

%==============
% thermal noise
%==============

noise_therm = -75.0+20.*log10(f);
noise_therm(noise_therm <=0) = 1;

%==============
% wind noise
%==============
noise_wind = calc_wind_noise(f,u,waterDepth);

%===============
% shipping noise
%===============
switch waterDepth
    case 'deep'
        c1 = 30;
    case 'shallow'
        c1 = 65;
    otherwise
        c1 = 30; % defaults to deep
end
switch shippingLevel
    case 'low'
        c2 = 1;
    case 'medium'
        c2 = 4;
    case 'high'
        c2 = 7;
    otherwise
        c2 = 4; % defaults to medium
end

noise_ship = 76-20.*(log10(f)-log10(c1)).^2 + 5*(c2-4);
noise_ship(noise_ship <= 0) = 1;

%==============
% turbulence
%==============
noise_turb = 108.5-32.5*log10(f);
noise_turb(noise_turb <= 0) = 1;

%==============
```

```
% rain rate
%==============
r0 = [0 51.0769 61.5358 65.1107 74.3464];
r1 = [0 1.4687 1.0147 0.8226 1.0131];
r2 = [0 -0.5232 -0.4255 -0.3825 -0.4258];
r3 = [0 0.0335 0.0277 0.0251 0.0277];

switch rainRate
    case 'none'
        iRain = 1;
    case 'light' % 1 mm/h
        iRain = 2;
    case 'moderate' % 5 mm/h
        iRain = 3;
    case 'heavy' % 10 mm/h
        iRain = 4;
    case 'veryheavy' % 100 mm/h
        iRain = 5;
    otherwise % defaults to none
        iRain = 1;
end

fk = f/1000; % convert to kHz for this equation
noise_rain = r0(iRain) + r1(iRain)*fk + r2(iRain)*fk.^2 + r3(iRain)*fk.^3;

% only good up to about 7 kHz so meld with a sensible line above that
% technique borrowed from wind-driven noise
slope = -5.0 * (0.1/log10(2)); % slope at high freq
ind = find(f<7000,1,'last');
temp_noise = 10^(noise_rain(ind)/10);
prop_const = temp_noise./f(ind).^slope;
noise_rain(f > 7000) = 10*log10(prop_const.*f(f > 7000).^slope);

%==================
% sum
%==================


if computeSum
    NL = 10*log10(10.^(noise_therm./10) + ...
        10.^(noise_wind./10) + ...
        10.^(noise_ship./10) + ...
        10.^(noise_turb./10) + ...
        10.^(noise_rain./10));
else
    NL = [noise_ship , noise_wind , noise_rain, noise_therm , noise_turb ];
end
```

A.2 calc_wind_noise.m

```
%
% NL = calc_wind_noise(f,u,waterDepth,[sumOption])
%
% Calculates wind-based noise (in dB re uPa)
% with adjustment for shallow water based on Piggot (1964).
% Adapted from IDL code originally by Dan Hutt, rewritten by Vic Young,
% and obtained through Sean Pecknold.
% Any mistakes propagated could have been theirs.
%
% Inputs:
% f = single frequency or vector of frequencies (Hz)
%     note: assumes a 1-Hz band for a single frequency
% u = wind speed (knots)
% waterDepth = 'shallow' or 'deep' (default: deep)
%
% Optional Input:
% Including a fourth argument '-sum' will sum the noise across the
% frequency bands.
% In this case the calculation is still valid for non-constant bandwidth -
% band limits assumed to be halfway between input frequencies.
%
% Output:
% NL = vector containing the noise (dB per muPa^2/Hz) at frequencies f
%
% if -sum option is chosen then output is wind noise summed across the band
%

function NL = calc_wind_noise(f,u,waterDepth,varargin)

% this all breaks down if u == 0 so account for that
if u == 0
    NL = zeros(size(f));
else
    [~,n2] = size(f);

    f = f(:); % make sure f is a column vector

    if nargin == 4 && strcmp(varargin{1},'-sum')
        f2 = [0 ; f ; 2*f(end)-f(end-1)];
        df = (f2(3:end)-f2(1:end-2))/2;
    else
        df = ones(size(f));
    end

    % bookkeeping:
    % some constants
    fWind = 2000;   % cutoff for wind noise section
    s1w = 1.5;      % constant in wind calc
```

```
    s2w = -5.0;      % constant in wind calc
    a = -25;         % curve melding exponent
    slope = s2w * (0.1/log10(2)); % slope at high freq

    NL = zeros(size(f));

    % do the wind part for f <= 2000 Hz

    switch waterDepth
        case 'shallow'
            cst = 45;
        case 'deep'
            cst = 42;
    end

    iWind = f <= fWind;

    if any(iWind)
        f_temp = f(iWind);
    else
        f_temp = 2000; % so that it doesn't crash if only f > 2000 are entered
        % admittedly this is a total arbitrary hack
    end

    % these confusing letters were taken directly from the old code
    f0w = 770 - 100*log10(u);
    L0w = cst + 20*log10(u) - 17*log10(f0w/770);
    L1w = L0w + (s1w/log10(2)) .* log10(f_temp/f0w);
    L2w = L0w + (s2w/log10(2)) .* log10(f_temp/f0w);
    Lw = L1w.*(1+(L1w./L2w).^(-a)).^(1/a);

    temp_noise_dist = 10.^(Lw./10);

    if any(iWind)
        NL(iWind) = temp_noise_dist.*df(iWind);
    end

    % meld with a sensible line at freqs greater than 2000 Hz
    if any(~iWind)
        prop_const = temp_noise_dist(end)./f_temp(end).^slope;
        NL(~iWind) = prop_const.*f(~iWind).^slope.*df(~iWind);
    end

    NL = 10*log10(NL);

    if n2 ~= 1
        NL = NL';
    end
end
```

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noise; ocean ambient noise; wind-generated noise; shipping noise; ambient noise model; MATLAB

13. ABSTRACT/RÉSUMÉ (When available in the document, the French version of the abstract must be included here.)

A general unclassified empirical ambient noise model was described, valid for frequencies from 1 Hz to 100 kHz. The model combines the effects of turbulent pressure fluctuations, shipping noise, wind noise, rain noise, and thermal noise. The model requires as inputs frequency, wind speed, shipping level, water depth, and rain rate, and outputs the total noise level *NL* in dB re $\mu\mathrm{Pa}$ in a 1-Hz band. Despite its relative simplicity, it provides useful results not found elsewhere when a first-order ambient noise estimate is required for use in the sonar equation.

Un modèle empirique général non classifié de bruit ambiant a été décrit, valable pour des fréquences de 1 Hz à 100 kHz. Le modèle combine les effets des fluctuations de pression turbulente, du bruit engendré par les navires, du bruit du vent, du bruit de la pluie et du bruit thermique. Le modèle requiert comme données d'entrée la fréquence, la vitesse du vent, le niveau du trafic, la profondeur de l'eau et le taux de précipitations ; les résultats sont le niveau de bruit (« NL ») total en dB re µPa dans une bande de 1 Hz. Malgré sa relative simplicité, il fournit des résultats utiles que l'on ne trouve nulle part ailleurs lorsqu'une estimation du bruit ambiant de premier ordre est requise aux fins d'utilisation dans l'équation du sonar.