UNDERWATER ACOUSTICS AND SONAR SIGNAL PROCESSING

SS 2018

ASSIGNMENT 5

SONAR EQUATION

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by

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Introduction

The sonar equation is a systematic way of estimating the expected signal-to-noise ratios for sonar systems. The signal-to-noise ratio determines whether or not a sonar will be able to detect a signal in the presence of background noise in the ocean. It takes into account the source level, sound spreading, sound absorption, reflection losses, ambient noise, and receiver characteristics. The sonar equation is used to estimate the expected signal-to-noise ratios for all types of sonar systems.

In this assignment we first develop a MATLAB program for determining the signal to noise ratio. The calculations for various parameters are then carried out. We then discuss the impact of bottom type (mud, sand and gravel) and wind speed on the signal to noise ratio.

Theory

0.1 Sonar performance prediction

The basic problem in sonar is to measure some signal (possibly an echo) against a background of noise (or reverberation). So that the signal may be detected above the background, the ratio of the measured signal to the measured background (signal-to-noise ratio) must be at least some minimum value that is determined by the system. The various terms in the sonar equations are called sonar parameters. These parameters may be grouped according to whether they are determined by the equipment, medium, or target. Equipment parameters are source level, detection threshold, directivity index, self-noise level, and array gain (also determined by medium). Medium parameters are transmission loss, ambient noise level, and reverberation level (also determined by equipment). And target parameters are target strength, and target source level. Oceanographic interest in marine acoustics is concentrated mostly in the parameters determined by the medium.

Sonar may be either active or passive. Active sonar provide their own sound source and listen for echoes as they are reflected from the target which they are trying to detect. Passive sonar have no such source. They are simply listening devises that rely on the target to emit their own noise source (e.g. engine noise from an enemy ship or communication noises from a whale).

0.1.1 Performance parameters

To assess the capabilities of a sonar system, parameters that measure the performance have to be defined, e.g.

EL	Echo Level
EE	Echo Excess
SN	Signal to noise ratio
SE	Signal Excess

Echo level is the intensity of the echo as measured in the water at the hydrophone. Echo excess is obtained by removing the noise from the echo level. The amount by which the signal to noise ratio, SN exceeds the detection threshold, DT, is called the signal excess (SE). If the SE is greater than 0 dB, then the decision is made that the target is present. If the SE is negative, the decision is that the target is not present. The signal to noise ratio, SN is that measured at the output of the receiver, where the decision of whether or not a signal is present is made.

0.1.2 Sound propagation related parameters

The parameters described in the following sections are transmission loss (TL), isotropic noise level (NL), bottom reverberation strength (RS_B), surface reverberation strength (RS_S) and volume reverberation strength (RS_V).

0.1.2.1 Transmission loss

The intensity of an acoustic signal reduces with range. This observed reduction in the acoustic signal with distance from the source is due to the combined effects of spreading and attenuation and is accounted for by the transmission loss term.

The Transmission loss is given by

$$TL = \text{spreading loss} + \text{attenuation} \tag{1}$$

where TL is defined to be 0 dB on a sphere around the source of radius $r = 1m$.

For a constant sound velocity profile and spherical spreading the transmission loss can be determined by

$$TL(r,\ z) = 20log_{10}(R) + \alpha(R - 1m) \tag{2}$$

with

$$R = \sqrt{(r - r_0)^2 + (z - z_0)^2} \tag{3}$$

where r_0, z_0 denote the horizontal and vertical coordinates of the source locations and the receiver position, respectively.

In case of depth and range dependent cylinder symmetric sound velocity profiles the TL can be calculated by

$$TL(r,\ z) = 20log_{10}(R) + 10log_{10}(F(r,\ z)) + \alpha(R - 1m) \tag{4}$$

where $F(r,\ z)$ denotes the so called focusing factor given by

$$F(r,\ z) = \frac{\text{actual spreading at } r,\ z}{spherical spreading at r,\ z} \tag{5}$$

0.1.2.2 Isotropic noise level

This is an essentially a steady state, isotropic (equal in all directions) sound which is generated by amongst other things wind, waves, biological activity and shipping. The isotropic noise level $NL(f,v_w,r,s,v_v)$ describes for particular v_w, r, s and v_v the noise power within a 1Hz band around frequency f.

Thus, assuming NL approximately white over the frequency band B of interest, the noise level is given by

$$NL_B = NL(f,v_w,r,s,v_v) + 10log_{10}B \tag{6}$$

0.1.2.3 Bottom reverberation strength

The bottom reverberation coefficient $RS_B(f, bt, \beta)$ describes the reverberation strength of an insonified area of $1m^2$.

With

c	sound speed
τ	pulse length
$2\theta_h$	$\min(2\theta_{h,T}, 2\theta_{h,R})$
$2\theta_{h,T}$	horizontal $3dB$ beam width of transmitter
$2\theta_{h,R}$	horizontal $3dB$ beam width of receiver
r_0/z_0	coordinates of transmitter/ receiver configuration
$r/\ z$	coordinates of a particular point on the sea floor

The bottom reverberation strength can be determined for given f and bt as a function of β by

$$RS_B = S_B(f, bt, \beta) + 10log_{10}(A_B) \tag{7}$$

where A_B denotes the insonified bottom area.

$$A_B = 2\theta_h R \frac{c\tau}{2cos\beta} \tag{8}$$

with

$$R = \sqrt{(r - r_0)^2 + (z - z_0)^2} \tag{9}$$

0.1.2.4 Surface reverberation strength

Analog to the bottom reverberation strength, the surface reverberation strength is provided by

$$RS_S = S_S(f, bt, \beta) + 10log_{10}(A_S) \tag{10}$$

where A_S denotes the insonified sea surface area.

$$A_S = 2\theta_h\sqrt{(r-r_0)^2+(z-z_0)^2}\frac{c\tau}{2cos\beta} \tag{11}$$

With

c	sound speed
τ	pulse length
$2\theta_h$	$\min(2\theta_{h,T}, 2\theta_{h,R})$
$2\theta_{h,T}$	horizontal $3dB$ beam width of transmitter
$2\theta_{h,R}$	horizontal $3dB$ beam width of receiver
r_0/z_0	coordinates of transmitter/ receiver configuration
$r/\ z$	coordinates of a particular point on the sea surface

0.1.2.5 Volume reverberation strength

The volume reverberation coefficient $RS_V(f, bt, \beta)$ describes the reverberation strength of an insonified area of $1m^3$. Thus, the volume reverberation strength can be calculated by

$$RS_V = S_V(S_p, f) + 10log_{10}(V) \tag{12}$$

where V denotes the insonified volume (isovelocity).

$$V = \frac{c\tau}{2cos\beta}2\theta_h 2\theta_v R^2 \tag{13}$$

and

$$R = \sqrt{(r - r_0)^2 + (z - z_0)^2} \tag{14}$$

With

c	sound speed
τ	pulse length
$2\theta_h$ / $2\theta_v$	$\min(2\theta_{h,T}, 2\theta_{h,R})$ / $\min(2\theta_{v,T}, 2\theta_{v,R})$
$2\theta_{h,T}$ / $2\theta_{v,T}$	horizontal / vertical $3dB$ beam width of transmitter
$2\theta_{h,R}$ / $2\theta_{v,R}$	horizontal / vertical $3dB$ beam width of receiver
r_0/z_0	coordinates of transmitter/ receiver configuration
$r/\ z$	coordinates of a particular point on water volume

0.1.3 Sonar equation

To determine the aforementioned reverberation levels the following parameters have to be specified.

Environmental Parameters	
bt	Bottom type
v_w	Wind speed
S	Salinity
T	Water temperature
c	Sound speed profile

Source level is the ratio of the source intensity to a reference intensity, converted to dB. The reference intensity is the intensity of a sound wave having a root mean square (rms) pressure of $1\mu Pa$.Directivity index is the amount by which the antenna array has to reject the omni-directional noise dB. It is obtained by forming the logarithm of the directivity factor D.

Sonar Parameters	
SL	Source level in dB at 1m
f	Center frequency of the sound signal
BP_T	Transmitter beam pattern (vertical)
BP_R	Receiver beam pattern (vertical)
$2\theta_h$	Horizontal 3 dB beamwidth $\min(2\theta_{h,T}, 2\theta_{h,R})$
$2\theta_v$	Vertical 3 dB beamwidth $\min(2\theta_{v,T}, 2\theta_{v,R})$

Target strength is the sonar analog of radar cross section. Target strength is the ratio of the intensity of a reflected signal at 1 m from a target to the incident intensity, converted to dB. Using the conservation of energy or, equivalently, power, the incident power on a target equals the reflected power. The incident power is the incident signal intensity multiplied by an effective cross-sectional area. The reflected power is the reflected signal intensity multiplied by the area of a sphere of radius R centered on the target.

Target Parameters	
TS	Target strength
L_l	Target extent in lateral direction
L_r	Target extent in radial direction

The performance parameters can be determined by

$$\begin{aligned} EL(r,z) &= 10log_{10}(el(r,z)) = 10log_{10}(sl.bp_{T,E}.bp_{R,E}.ts/tl_E^2) \\ &= 10log_{10}(10^{0.1SL}.10^{0.1BP_{T,E}}.10^{0.1BP_{R,E}}.10^{-0.2TL_E}.10^{0.1TS}) \\ &= SL + BP_{T,E} + BP_{R,E} - 2TL_E + TS \end{aligned} \tag{15}$$

$$\begin{aligned} EE(r,z) &= 10log_{10}(ee(r,z)) = 10log_{10}(el.di/nl_B) \\ &= 10log_{10}(10^{0.1EL}.10^{-0.1(NL_B-DI)}) = EL - (NL_B - DI) \\ &= SL + BP_{T,E} + BP_{R,E} - 2TL_E + TS - (NL_B - DI) \end{aligned} \tag{16}$$

$$\begin{aligned} SN(r,z) &= 10log_{10}(sn(r,z)) = 10log_{10}(el/til) \\ &= 10log_{10}(10^{0.1EL}.10^{-0.1TIL}) = EL - TIL \\ &= SL + BP_{T,E} + BP_{R,E} - 2TL_E + TS - TIL \end{aligned} \tag{17}$$

and

$$\begin{aligned} SE(r,z) &= 10log_{10}(se(r,z)) = 10log_{10}(sn/dt) \\ &= 10log_{10}(10^{0.1SN}.10^{-0.1DT}) = SN - DT \\ &= SL + BP_{T,E} + BP_{R,E} - 2TL_E + TS - TIL - DT \end{aligned} \tag{18}$$

where DT denotes the detection threshold, TIL the total inference level

$$\begin{aligned} TIL(r,z) &= 10log_{10}(til(r,z)) = 10log_{10}(nl_B/dt + rl_B + rl_S + rl_V) \\ &= 10log_{10}(10^{0.1(NL_B - DI)} + 10^{0.1RL_B} + 10^{0.1RL_S} + 10^{0.1RL_V}) \end{aligned} \tag{19}$$

and RL_B, RL_S, and RL_V the reverberation level of the bottom, surface and volume, respectively, i.e.

$$\begin{aligned} RL_B &= SL + BP_{T,B} + BP_{R,B} - 2TL_B + RS_B \\ RL_S &= SL + BP_{T,S} + BP_{R,S} - 2TL_S + RS_S \\ RL_V &= SL + \overline{BP_{T,V} + BP_{R,V} - 2TL_V} + RS_V \end{aligned} \tag{20}$$

For $c = const.$, we can write

$$TL_E = TL_B = TL_S = TL_V \tag{21}$$

Furthermore, the following abbreviations have been used.

$$\left.\begin{array}{lcl} BP_{T,E} & : & \text{Transmitter} \\ BP_{R,E} & : & \text{Receiver} \end{array}\right\}\text{Beampattern value for the ray directed toward the target position}$$

$$\left.\begin{array}{lcl} BP_{T,B} & : & \text{Transmitter} \\ BP_{R,B} & : & \text{Receiver} \end{array}\right\}\text{Beampattern value for the ray directed toward the insonified bottom area}$$

$$\left.\begin{array}{lll} BP_{T,S} & : & \text{Transmitter} \\ BP_{R,S} & : & \text{Receiver} \end{array}\right\}\text{Beampattern value for the ray directed toward the insonified surface area}$$

$$\left.\begin{array}{r} TL_E \\ TL_B \\ TL_S \\ TL_V \end{array}\right\}\text{Tranmission loss for the echo, bottom, surface and volume reverberation, respectively}$$

Experimental Research

0.2 Dependence of wind speed and frequency on Ambient noise

The ambient noise level versus frequency for wind speeds of 5, 10, 15, 20, 25 and 30 kn is plotted. In-order to obtain the figure (1), we assumed the biological, rainfall and self noise level to be -99 dB and the frequency in the range of 1 Hz to 1 MHz was considered.

Noise Level generally decreases with increasing frequency, from figure (1) we see that between 1 Hz to 100 kHz, noise level reduces from 120 dB to 25 dB. Noise Level decreases at great depths since most noise sources are at the surface. Ambient noise is greater in shallow water (noise is trapped between sea floor and the ocean surface). From the observation, we can say that as the wind speed increases, noise level increases in the frequency range 300 Hz to 100 kHz. This is due to the bubbles created by wind generated surface agitation. At lower frequencies, it is the oscillation of bubble clouds themselves that are considered to be the source of sound, while at higher frequencies the excitation of resonant oscillations by individual bubbles is the source of sound.

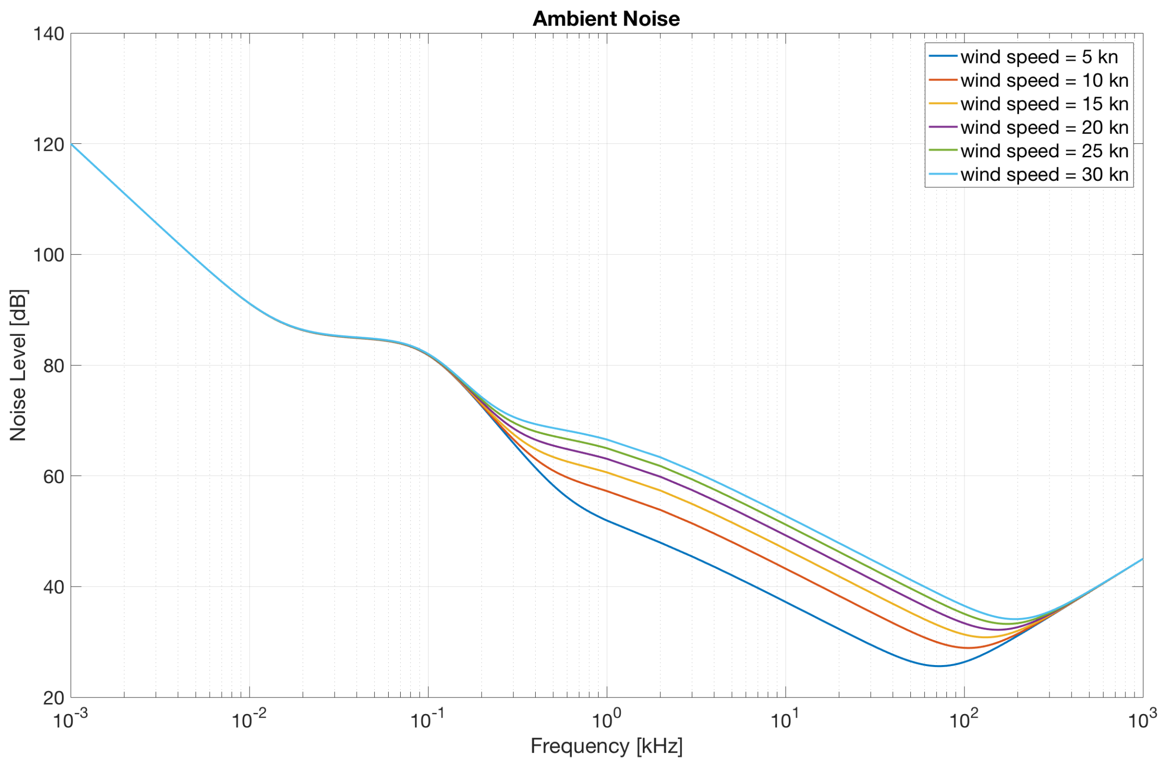

Figure 1: Noise level dependency on wind speed and frequency

0.3 Contribution of different noise sources

In-order to indicate the frequency domains where either traffic, turbulence, sea state or thermal noise level dominate, we assumed that contribution to noise from rainfall, shrimps and vessel are negligible. The noise isotropic levels for traffic, thermal, turbulence and sea state are computed by the mathematical models as explained in the theoretical section. Also this was plotted for the wind speed of 5 kn.

From the result shown in figure (2), we can distinguish different ambient noise, in different frequency range. We can observe the effect of turbulence noise between 1 Hz to 10 Hz. In the frequency range between 10 Hz to 300 Hz, the noise is affected by the traffic, shipping and harbours. Wind speed and sea state contribute the noise level from 300 Hz to 100 kHz. Above 100 kHz, noise level increases due to molecular agitation in the ocean. The random motion of water molecules causes thermal noise ultimately establishing the lower limit of measurability of pressure fluctuations associated with truly propagating sound waves above 100 kHz frequency. Isotropic noise level is shown by the superposition of all these effects in the graph.

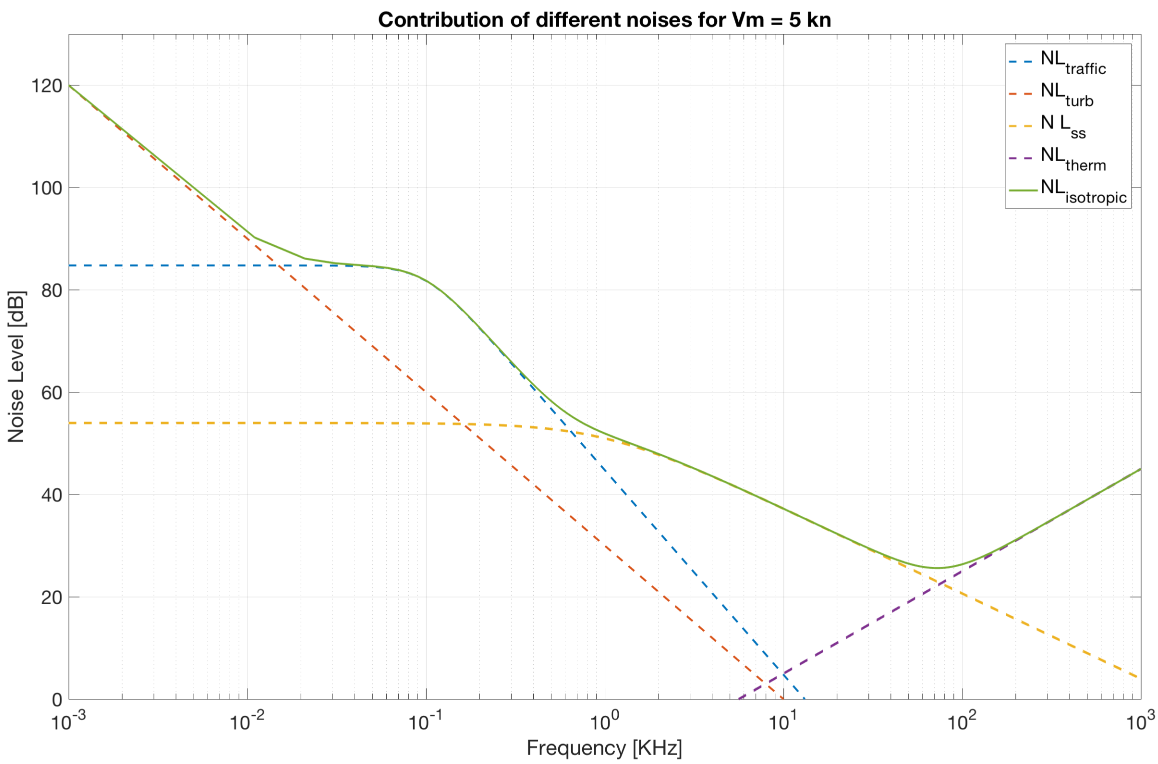

Figure 2: Contribution of different noise sources

Conclusion

Ambient noise due to wind at various speeds ranging from 5 knots to 30 knots is analysed and observed. The effect of wind is dominating at lower frequencies from 100 Hz to 5 kHz. The analysis shows that noise level in dB increases as the wind speed increases. Above 100 kHz, thermal noise contributes to the increase in noise level.

We have also observed range of frequencies where different types of noises such as turbulence, traffic, sea state and thermal noises dominate assuming that contribution to noise from rainfall, shrimps and vessel are negligible.

Appendix

0.4 MATLAB program to plot ambient noise level versus frequency for various values of wind speeds

```
ws = 5:5:30; % Wind speed in steps of 5kn
a(i) = [];
for n = 1:6
for i = 1:1000
a(i) = isotropic(i,ws(n),-999,-999,-999); % calling the nested function
end
j = 1000:1000:10^6;
for k = 1:1000
l = k+1000;
a(l) = isotropic(j(k),ws(n),-999,-999,-999); % calling the nested function
end
 switch n
    case 1
        b=a;
    case 2
        c=a;
    case 3
        d=a;
    case 4
        e=a;
    case 5
        g=a;
    case 6
        h=a;
end
end
ii = 0.001:0.001:1;
kk = 1:1000;
```

```
f=[ii kk];
semilogx(f,b,f,c,f,d,f,e,f,g,f,h,'LineWidth',2)
ax = gca; % current axes
        ax.FontSize = 20;
hL = legend('wind speed = 5 kn','wind speed = 10 kn',...
    'wind speed = 15 kn','wind speed = 20 kn',...
    'wind speed = 25 kn','wind speed = 30 kn');
hL.FontSize = 20;
grid
title('Ambient Noise')
xlabel('Frequency [kHz]')
ylabel('Noise Level [dB]')

%nested function
function [nl_iso] = isotropic(freq,ws,rain, bio, self)
nl_iso = 10*log10((10.^(.1*turb(freq))) + (10.^(.1*traffic(freq))) ...
    + (10.^(.1*seaState(freq ,ws))) + (10.^(.1*thermal(freq)))...
    +(10.^(.1*rain))+(10.^(.1*bio))+(10.^(.1*self)));
function [nl_turb] = turb(f)
    nl_turb = 30-30*log10(f./1000);
end
function [nl_traff] = traffic(f)
    nl_traff = 10*log10((3e+8)./(1+(1e+4*((f./1000).^4))));
end
function [nl_therm]=thermal(f)
    nl_therm=-15+20*log10(f./1000);
end
function [nl_sea] = seaState(f,vm)
    nl_sea = 40+10*log10((vm.^2)./(1+(f./1000).^(5/3)));
end
end
```

0.5 MATLAB code to plot the contributions of different noise levels

```
freq = 0.001:0.01:1000; % frequency range
ws = 5; % wind speed set to 5kn
rain = -999; % Rainfall NL
bio = -999; % Biological NL
vessel = -999; % Self NL
traffic = 10.*log10((3.*10.^8)./(1+(10.^4.*freq.^4))); % Traffic NL
semilogx(freq,traffic,'--','linewidth',2)
hold on
turb = 30 - 30.*log10(freq) ;% Turbulence NL
```

```
semilogx(freq,turb,'--','linewidth',2)
hold on
seaState = 40 +10.*log10((ws.^2)./(1+freq.^(5/3))); % Sea state NL
semilogx(freq,seaState,'--','linewidth',2)
hold on
N_therm = -15 +20.*log10(freq); % Thermal NL
semilogx(freq,N_therm,'--','linewidth',2)
hold on
isotropic = 10.*log10((10.^(0.1.*turb)) + (10.^(0.1.*traffic))...
    + (10.^(0.1.*seaState)) + (10.^(0.1.*N_therm)) + (10.^(0.1.*rain))...
    + (10.^(0.1.*bio)) + (10.^(0.1.*vessel))); % Isotropic NL
semilogx(freq,isotropic, 'linewidth',2)
ax = gca; % current axes
        ax.FontSize = 20;
        ax.YLim = [0 130];
xlabel('Frequency [KHz]')
ylabel('Noise Level [dB]')
title('Contribution of different noises for Vm = 5 kn')
grid on
hL =legend('NL_t_r_a_f_f_i_c','NL_t_u_r_b','N L_s_s', ...
    'NL_t_h_e_r_m','NL_i_s_o_t_r_o_p_i_c');
hL.FontSize = 20;
```