USP Assignment 03

Calculation of reverberation coefficients for surface, bottom, and volume

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***Abstract*—Reverberation in underwater acoustics imposes a serious impact on sonar performance and underwater communication systems through reflections from the sea surface, bottom, and volume. This paper outlines a python program designed to compute the coefficients of surface, SS, bottom, SB, and volume, SV, reverberation. The surface and bottom reverberation coefficients are plotted versus grazing angles for different frequencies and environmental conditions—wind speed for surface reverberation and bottom types for bottom reverberation. The volume reverberation is analyzed as a function of frequency for different densities of particles. These results show the dependence of reverberation coefficients on these parameters and demonstrate that higher frequencies and environmental roughness lead to increased reverberation. This analysis provides essential insight into the factors that affect underwater acoustics for the development of more effective sonar systems and acoustic signal processing techniques.**

***Index Terms*—Underwater acoustics, Reverberation coefficients, Surface reverberation, bottom reverberation, volume reverberation.**

I. Introduction

In underwater acoustics, reverberation is an important phenomenon that has a crucial effect on the performance of sonar and other devices of submarine communication systems. That is, it involves the reflection of acoustic signals from the sea surface, sea bottom, and the volume of water itself, thus presenting interference with the ability to detect targets or other acoustic signals. Understanding and modeling the coefficients of surface, bottom, and volume reverberation is very important in designing effective sonar systems or the interpretation of acoustic data.

The sea is a medium consisting of quite a number of heterogeneous elements within and around the sea. These inhomogeneities reflect some percentage of the acoustic energy that hit them. The scattering of sound is a process in which sound is reemitted by the medium or material it travels through. All of these scattering effects together can be referred to as reverberation. Reverberation that is generated primarily due to scatterers in the ocean volume (marine life, inanimate matter), on or near the ocean surface (roughness, air bubbles), and on the ocean bottom (roughness) is called volume reverberation, surface reverberation, and bottom reverberation, respectively. The surface reverberation coefficient (SS) is a function that applies to reflections from the ocean surface, in which the wind speed, wave height, and sea state can be important. On the other hand, bottom reverberation coefficient (SB) includes the reflections from the seabed, which are a function of the bottom type, roughness, and sediment composition. These coefficients provide critical information in determining the level of noise in sonar systems and in predicting the performance of acoustic equipment in various underwater environments. Volume reverberation is due to the scattering by objects or living organisms in the water column. This kind of reverberation depends on the density and distribution of scatterers, like plankton, fish, or suspended sediments. By interpreting volume reverberation, we learn about the biological and physical features of the ocean that have wide applications in fisheries, environmental monitoring, and scientific study.

II. Methodology

Initialization of parameters and constants required for the computation of reverberation coefficients in a Python program includes defining the frequency range, wind speed values, bottom types, and particle densities. The necessary input parameters and constants that are required for the procedure of computing the reverberation coefficients in the Python program are the frequency range and wind speed type of the bottom and particle density.

Applying a mathematical model to measure the surface roughness caused by wind speed on the sea surface. The program computes the SS coefficient at every frequency and grazing angle. Then plotted for each wind speed value to determine the relationship between surface reverberation and the grazing angle. It is necessary to determine the role of surface roughness caused by wind on reverberation.

The bottom reverberation coefficient (SB) is calculated in a similar fashion but relates to the seabed characteristics. In particular, various types of the bottom like sand, mud, and rock are considered, each of which is characterized by the type of sediment and its acoustic and roughness properties. The program computes the SB coefficient for every combination of frequency and grazing angle based on the roughness level of the specific bottom type. The relation between SB and angle of grazing has been shown for various seabed material. This step is performed to understand the dependence of bottom reverberation on the nature of the seabed.

The volume reverberation coefficient is determined by taking into account the scattering that is produced due to particles as well as organisms in the water. The program calculates the volume reverberation coefficient when the particle density and frequency are varied. This includes the mathematical formulation that describes the coupling of the acoustic waves and the particles, with the coefficient depending on the density of the particles and frequency. The relationship between the volume reverberation coefficient and frequency is shown in the plots below.

It shows plots and graphs to display how the values of refractive reverberation coefficients change for the changes in the grazing angles, frequencies, wind speeds, types of bottom, and densities of the particles. The visualization of these relations is extremely important for understanding the complex processes in the acoustic environment of the sea. In particular, the examination of the experimentally collected data demonstrates the mechanism through which surface, bottom, and volume reverberation varies depending on the specific conditions in the environment. This analysis may prove helpful in the improvement of sonar performance and in the enhancement of the detection capability by providing a better appreciation of the reverberation process. This can be a systematic approach that is applied by the python program to be of great significance in the understanding or analysis of underwater reverberation for the further design and optimization of sonar systems.

III. Implementation

The implementation of our methodology required the development of python codes for the construction of theoretical models and computational algorithms so that the reverberation coefficients could be calculated and illustrated.

Surface Back scattering: The surface back-scattering occurs due tho the surface roughness and presence of the water bubbles. The surface back scattering strength of the sea surface can be varied with the grazing angle, sound frequency, and wind speed. Grazing angle can be determined by

$$\theta = \frac{\pi}{2} - \Phi$$

Where Φ is angle of incidence. The surface back-scattering can be measured by using empirical formula is given by

$$S_s = 10\log_{10}(10^{-5.05}(1+V_w)^2 \\ (f+0.1^{\left(\frac{V_w}{150}\right)}\tan^{\beta}(\theta)\ [dB/m^2]$$

with

$$\beta = 4\left(\frac{V_w+2}{V_w+1}\right) + (2.5(f+0.1)^{\frac{-1}{3}}\cos^{\frac{1}{8}}(\theta)$$

where S_s represents the surface back scattering coefficient in dB/m^2. The parameters f, V_w and θ denote the sound frequency in kHz, the wind speed in knots and the grazing angle respectively.

We plotted the graph between surface reverberation coefficient versus grazing angle by changing wind speed as well as frequencies and observed that how wind speeds and frequencies affects the surface reverberation.

Bottom Scattering:

The bottom scattering caused by the roughness as a reflector and scatter of the sound. The backscattering strength of the bottom varies with the

1. Grazing angle Grazing angle can be determined by

$$\theta = \frac{\pi}{2} - \Phi$$

Where Φ is angle of incidence

2. Sound frequency
3. Bottom type induced roughness.

The bottom reverberation can be determined by using the below empirical formula,

$S_B = 10log_{10}(3.03\beta f^{3.2-0.8bt}10^{2.8bt-12} + 10^{-4.42}\ )[dB/m^2]$

with

$\beta\ = \gamma\ (sin(\theta)+0.19)^{bt.cos^{16}(\theta)}$ and

$\gamma\ = 1 + 125.exp(-2.64(bt-1.75)^2 - \frac{50}{bt}.cot^2(\theta))$ where f, bt and θ denote the sound frequency in kHz,the bottom type and the grazing angle respectively.

The bottom type parameter is defined as follows

bt =1 mud bt =2 sand

bt =3 gravel bt=4 rock

In principle bt can be any real number satisfying $1 \leq bt \leq 4$

Volume Scattering:

The frequency dependence of the sound attenuation which is partly caused by scattering in the water volume.This also produces a back-scattered sound field. However most volume reverberation is thought to arise from biological organisms and turbidity. The volume reverberation can be modeled by the so-called volume reverberation coefficient.

$S_v\ = S_p + 7.log_{10}(f) \quad [dB/m^3]$

where f and S_p indicate the frequency in kHz and the particle contribution in $dB/m3$. The particle contribution parameter Sp is defined as follows:

$$\left.\begin{aligned} Sp = -50\ dB\ High \\ Sp = -70\ dB\ Moderate \\ Sp = -90\ dB\ Low \end{aligned}\right\} \text{P}article\ density$$

IV. Results and Discussions

To analyze the effect of parameters on surface reverberation, we have plotted a graph between grazing angle and surface reverberation coefficient by controlling wind speeds and frequencies. On the x-axis side, there is the grazing angle, and on the y-axis, there is the surface reverberation coefficient as depicted in the graph above. Indeed, when the grazing angle increases the angle of incident wave and the surface is closer to 90 degrees as the sound waves strike the surface more perpendicularly. This leads to higher reverberation because the incident wave will experience more reflection compared to absorption or refraction.

Higher frequencies means shorter wavelengths and due to this they come closer to small surface features and hence they are scattered. This implies that as the frequency rises, the possibility of the sound wave to comb and get disturbed by surface roughness in sea rises and in this way, high reverberation is achieved. Frequency of the sound waves refers to the number of sound waves that pass through a particular point in a given time, and since high frequency sound waves have higher energy than the low frequency sound waves, then when this energy is reflected off the surface of the room it leads to a high reverberation level. The application of the logarithm in the model has been presented in the form of 10log frequency, this means that as the frequency is increased, the reverberation coefficient will increase logarithmic. From the term $10log_{10}$, the graph shows that the frequency increases and surface reverberation coefficient increases logarithmically. In the context of underwater acoustics, wind affects sea surface roughness and the relationship between wind speed and the surface reverberation coefficient. Higher wind speed in turn implies a greater surface roughness which in turn implies more scattering and reflection of the acoustic waves. Here is a positive relationship between the increase in the wind speed and the formation of the waves on the surface. The size of the waves also increases as the wind speed increases and the surface of the sea becomes vulnerable to the force of the wind. This roughened surface assists in reflecting the sound waves in the room and thus increases the amount of sound bounce on the surface.

When the wind is not very strong, the waves are capillary waves and there are ripples on the water. These become larger gravity waves when the wind speed increases and provide better structure for the sound to deal with higher reverberation. The wind velocities rise, the sea state increases and more of the acoustic energy is reflected. The logarithmic form of this term further implies that the relationship between wind speed and surface roughness and hence, reverberation is not directly proportional rather the relation increases at a faster rate at higher values of wind speed.

Bottom reverberation varies in characteristics, which includes; the type of seabed (mud, sand, gravel, and rocks), the frequency of the sound wave, and the grazing angle. Seabed classification is also an important factor that causes variation in the levels of reverberation since different seabed types have different characteristics of reflecting sound. The graph for the bottom reverberation coefficient in terms of grazing angle with respect to different seabed types and frequencies has been plotted that can be observed in the figure 3 and 4.

Mud:

At the low frequencies of 50 kHz, the bottom reverberation coefficient is generally low. As the frequency increases, thus the reverberation coefficient increases, especially at higher grazing angles.

Sand:

It is similar to mud but, the reverberation coefficient is usually higher as compared to other bottom types at the higher grazing angles. And higher frequencies have more reverberation; it increases much more with increasing grazing angles. Sand has higher reverberation coefficient compared to the other bottom types at the higher frequencies and at the higher grazing angles. After reaching the certain point of grazing angle, the reverberation coefficient is increasing rapidly.

Gravel:

The reverberation coefficient of gravel is higher than mud and sand at all the frequencies and also the grazing angle. After reaching the certain angle the reverberation coefficient increasing rapidly. The frequency factor is also significant in determining the reverberation coefficients and the extent of reverberation is much higher as the frequencies increases.

Rock:

The plot of the reverberation intensity vs frequency and grazing angle clearly shows that the reverberation increases very rapidly with the frequency and at the higher grazing angle, the reverberation coefficient becomes constant.

It is also observed that for all seabed types the bottom reverberation coefficient increases with increase in grazing angle. This is because the sine of the grazing angle tends to reduce as the angle gets nearer to 90 degrees, hence increasing the reverberation coefficient because of the logarithmic nature of the term in the model. This means that, when the frequency is high, the bottom reverberation coefficients are also high. This is so for all types of seabeds, which indicate that higher frequency sound waves have more effects on the seabeds. The results also show that the seabed plays a major role in the value of the reverberation coefficient. As for reflectivity, rock and gravel have higher reverberation coefficients in comparison to sand and mud. This shows higher reflections from harder and more irregular surfaces of objects/structures. The graph has been plotted between reverberation coefficient for volume back-scattering and frequencies for different particle densities to observe the influence of particle density and frequencies on the reverberation coefficient and it can be observed in the figure 5. Volume scattering in underwater acoustics results from the dispersion of sound waves by droplets, particles and organisms in water. This scattering depends with factors like density of the particles, distribution of the particle size and the frequency of the sound wave incident on the particles. Thus, knowledge of volume reverberation is useful in optimizing sonar performance in search and identification of objects as well as in studying the properties of the water layer.

Particle Density = -50 dB:

The volume reverberation coefficient is highest for this density level. It increases with frequency because the scattering is more in the higher frequencies as compared to the lower ones.

Particle Density = -70 dB:

The reverberation coefficient is lower than for -50 dB but the trend is similar and the value of the coefficient increases with the increase in frequency. The nature of the increase in the slope of the graph is the same as in the previous case, due to the direct proportionality between the frequency and the reverberation.

Particle Density = -90 dB:

The first density contributes to the lowest reverberation coefficient of the three densities. It also rises with frequency but not to the same extent as the Type 1 frequency does; it is much lower. The reverberation coefficient for volume back-scatters increases with higher particle density due to the large amount of particles disturbing the path of the sound waves.

This scattering affects the sound propagation and detection in underwater environments. The relationship between volume reverberation and frequency is crucial for understanding and modeling underwater sound behavior.

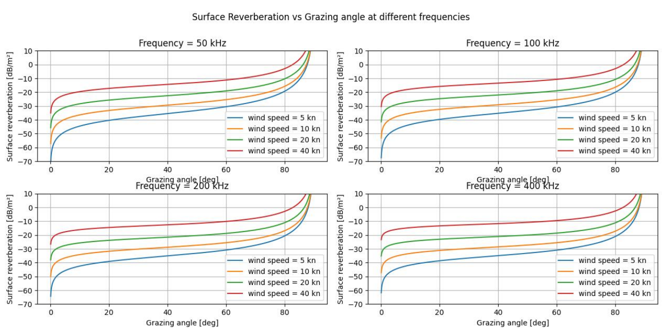

Fig. 1. 'Surface Reverberation vs Grazing angle at different frequencies

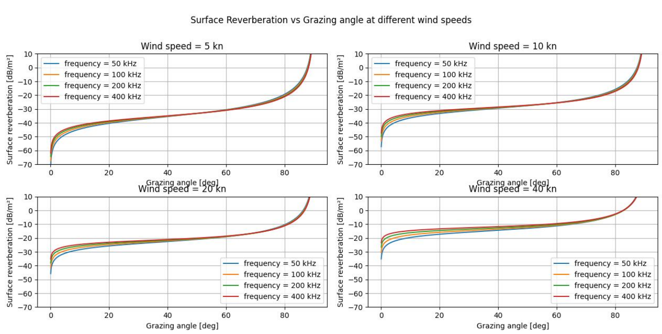

Fig. 2. 'Surface Reverberation vs Grazing angle at different wind speeds

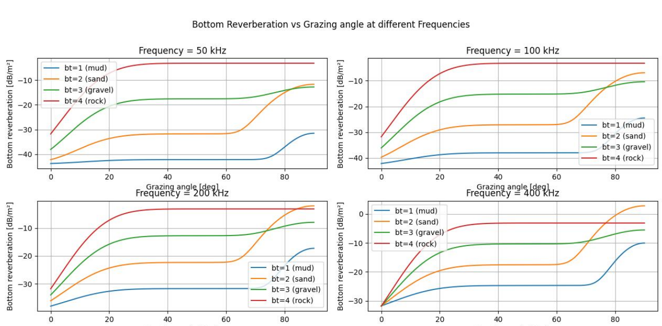

Fig. 3. 'Bottom Reverberation vs Grazing angle at different Frequencies

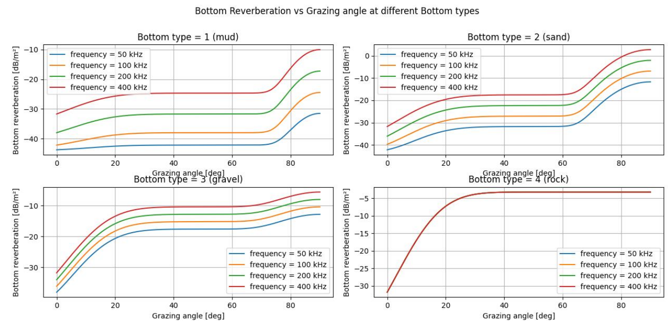

Fig. 4. 'Bottom Reverberation vs Grazing angle at different Bottom types

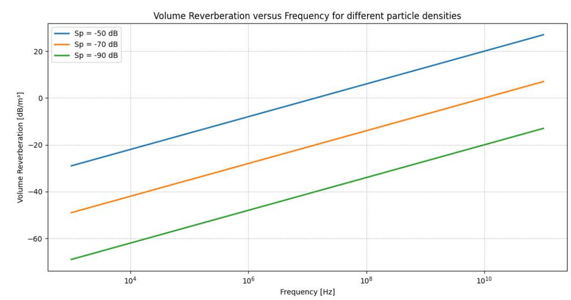

Fig. 5. 'Volume Reverberation versus Frequency for different particle densities

REFERENCES

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Appendix A
Python code

```python
import numpy as np
import matplotlib.pyplot as plt

# Frequency, wind speeds and Bottom types for Surface & bottom reverberation
f = [50, 100, 200, 400]  # in kHz
vw = [5, 10, 20, 40]     # in knots
bt = [1, 2, 3, 4]  #  type_1=mud, type_2=sand, type_3=gravel, type_4=rock]

# frequency and particle densities for volume reverberation coefficient
freq_volume = np.logspace(3, 11)  # frequency from 10^3 to 10^11 Hz
Sp = [-50, -70, -90]    # particle densities High = -50dB , Moderate = -70dB and Low = -90dB

#function to determine Surface reverbration coefficient
def Surface_coeff(f,vw,ga):
    beta = 4 * ((w_speed + 2) / (w_speed + 1)) + (2.5 * ((freq + 0.1) ** (-1/3)) - 4) * np.cos(np.radians(ga)) ** (1/8)
    return 10 * np.log10(((np.tan(np.radians(ga)) ** beta) * ((1 + w_speed) ** 2) * ((freq + 0.1) ** (w_speed / 150)) * (10 ** -5.05)))

# function to determine Bottom reverbration coefficient
def Bottom_coeff(f,bt,ga):
    Gamma = 1 + 125 * np.exp(-2.64 * ((bottom_type - 1.75) ** 2) - ((50 / bottom_type) * (1/np.tan(np.radians(ga)) ** 2)))
    beta = Gamma * (np.sin(np.radians(ga)) + 0.19) ** (bottom_type * (np.cos(np.radians(ga)) ** 16))
    return 10 * np.log10(3.03 * beta * (freq ** (3.2 - 0.8 * bottom_type)) * (10 ** (2.8 * bottom_type - 12)) + 10 ** (-4.42))

# function to determine Volume reverbration coefficient
def Volume_coeff(sp,freq_volume):
    return sp + 7 * np.log10(freq_volume)

#--------displaying plots--------

# plot-1 Surface Reverberation coefficient vs Grazing angle
fig1, axs1 = plt.subplots(2, 2, figsize=(12, 8))
fig1.suptitle('Surface Reverberation vs Grazing angle at different frequencies')
y_min, y_max, y_step = -70, 10, 10
y_ticks = np.arange(y_min, y_max + y_step, y_step)
for i, freq in enumerate(f):
    row, col = divmod(i, 2)
    ax = axs1[row, col]
    for w_speed in vw:
        ga = np.arange(0, 90.1, 0.1)
        Ss = Surface_coeff(f,vw,ga)
        ax.plot(ga, Ss, label=f'wind speed = {w_speed} kn')
    ax.grid(True)
    ax.set_xlabel('Grazing angle [deg]')
    ax.set_ylabel('Surface reverberation [dB/ m  ]')
    ax.set_title(f'Frequency = {freq} kHz')
    ax.legend()
    ax.set_ylim([y_min, y_max])
    ax.set_yticks(y_ticks)
plt.tight_layout(rect=[0, 0, 1, 0.95])
plt.show() # displaying plot-1

# plot-2 Surface Reverberation coefficient vs Grazing angle
fig2, axs2 = plt.subplots(2, 2, figsize=(12, 8))
fig2.suptitle('Surface Reverberation vs Grazing angle at different wind speeds')
for i, w_speed in enumerate(vw):
    row, col = divmod(i, 2)
    ax = axs2[row, col]
    for freq in f:
        ga = np.arange(0, 90.1, 0.1)
        Ss = Surface_coeff(f,vw,ga)
        ax.plot(ga, Ss, label=f'frequency = {freq} kHz')
    ax.grid(True)
    ax.set_xlabel('Grazing angle [deg]')
    ax.set_ylabel('Surface reverberation [dB/ m  ]')
    ax.set_title(f'Wind speed = {w_speed} kn')
    ax.legend()
    ax.set_ylim([y_min, y_max])
    ax.set_yticks(y_ticks)
plt.tight_layout(rect=[0, 0, 1, 0.95])
plt.show() # displaying plot-2

# Plot-3 Bottom Reverberation vs Grazing angle
fig3, axs2 = plt.subplots(2, 2, figsize=(12, 8))
fig3.suptitle('Bottom Reverberation vs Grazing angle at different Frequencies')
for i, freq in enumerate(f):
    row, col = divmod(i, 2)
    ax = axs2[row, col]
    for j, bottom_type in enumerate(bt):
        ga = np.arange(0, 90.1, 0.1)
        Sb = Bottom_coeff(f,bt,ga)
        ax.plot(ga, Sb, label=f'bt={bottom_type}({["mud", "sand", "gravel", "rock"][j]})')
    ax.grid(True)
    ax.set_xlabel('Grazing angle [deg]')
    ax.set_ylabel('Bottom reverberation [dB/ m  ]')
    ax.set_title(f'Frequency = {freq} kHz')
    ax.legend()
plt.tight_layout(rect=[0, 0, 1, 0.95])
plt.show() # displaying plot-3

# Plot-4 Bottom Reverberation vs Grazing angle
fig4, axs2 = plt.subplots(2, 2, figsize=(12, 8))
fig4.suptitle('Bottom Reverberation vs Grazing angle at different Bottom types')
for j, bottom_type in enumerate(bt):
    row, col = divmod(j, 2)
    ax = axs2[row, col]
    for i, freq in enumerate(f):
        ga = np.arange(0, 90.1, 0.1)
        Sb = Bottom_coeff(f,bt,ga)
        ax.plot(ga, Sb, label=f'frequency = {freq} kHz')
    ax.grid(True)
    ax.set_xlabel('Grazing angle [deg]')
    ax.set_ylabel('Bottom reverberation [dB/ m  ]')
    ax.set_title(f'Bottom type = {bottom_type} ({["mud", "sand", "gravel", "rock"][j]})')
    ax.legend()
plt.tight_layout(rect=[0, 0, 1, 0.95])
plt.show() # displaying plot-4

# plot-5 Volume reverbaration coefficient
plt.figure(figsize=(10, 6))
for sp in Sp:
    Sv= Volume_coeff(sp,freq_volume)
    plt.semilogx(freq_volume, Sv, linewidth=2, label=f'Sp = {sp} dB')
plt.grid(True, which='both', linestyle='--', linewidth=0.5)
plt.xlabel('Frequency [Hz]')
```

```
plt.ylabel('Volume Reverberation [dB/ m  ]')
plt.title('Volume Reverberation versus Frequency for
     different particle densities')
plt.legend()
plt.show() # displaying plot-5
```