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Chapter 1

Sonar and its simulation

1.1 Introduction

The facts and formulas presented here are the results of a long research over the internet and the conclusions of many implementation tests. We took some information from the documentation of the "Harpoon 3" sonar model and from a document describing the most common German listening device of World War 2, the "GHG" (Gruppenhorchgerät).

There are many sources of noise in the ocean. Beside the disturbances of the ocean surface by the wind, background noise by animals and geological activities and sudden events like exploding depth charges etc. the most important source are the vessels cruising around the sea. This means the ships and submarines of the game.

Sound propagates as waves underwater, its speed depending on many factors, like temperature (the most important), pressure, salination and other values of the water (amount of algae etc.).

Computing the noise level at any point in the ocean we can use the ray tracing model to simulate sound propagating from an arbitrary source. Sound waves propagate in water, are reflected and refracted on borders between layers in the water and so on. If the sound ray intersects a the border between two layers with different speed of sound, the ray is reflected and refracted according to Snell's law. Also other vessels can reflect sound waves etc. This simulation can be extended to a great complexity.

The speed change is not so important in horizontal (x/y) direction, but in vertical (z) direction as the water forms mostly horizontally oriented layers. Temperature is the most important factor. We need to simulate reflection and/or refraction at border of those layers, at least for active sonars like ASDIC.

Hiding the submarine "below" a thermal layer was and is an important tactical aspect of submarine warfare.

Sound strength is decreased with growing distance when the sound spreads in the water. Lower frequencies are transmitted over a longer range.

This is named propagation and absorbtion. Strength of the sound is distributed over the area the sound is spread. Because the area grows quadratically with the distance, the strength falls off with the square of the distance. Absorption depends on frequency of the sound, higher frequencies are absorpted with an much higher rate. Using the logarithmic model for sound strengths the squares etc. can be written as multiplications or divisions, which gives simple formulas.

We add the background noise strength (ambient noise) as well as all the noise sources to the strength of one signal, subtract the signal-to-noise-ratio level of the receiver (signals weaker than a certain level are cut off) and do this for each frequency band. This gives the frequency spectrum that is received at the sub's sonar.

1.2 Physical facts

1.2.1 Constants and basic formulas

Sound travels in sea water with a velocity of $v = 1465 m/s$ where in air it travels with ca. $340 m/s$. Because velocity is wavelength multiplied by frequency ($v = \lambda * f$) and velocity is constant, the wavelength depends on the frequency.

A signal or noise is composed of many basic waves with its own frequency each. For simplification we treat signals just as sine waves, thus $signal(t) = a * \sin(x + p)$, where a is the amplitude and p is the phase.

Because human perception is logarithmic, we can handle sound in a *deci-Bel scale (dB)*, where (logarithmic) intensity $L = 10 * log_{10}(I)$. Intensity is pressure divided by specific density and speed of sound in water: $I = \frac{P^2}{\rho * v}$ (unit of P: $Pa = N/m^2$, unit of I: $N/(m * s)$ and ρ is $1000 kg/m^3$).

1.2.2 Signal physics

Sound is spread underwater from any source in the shape of a growing sphere. For our simulation we handle sound simulation in a horizontal plane only, thus sound is spread in a circle around its source. Because the total strength is constant after leaving the source, and the strenght is distributed over the whole area, the sound strength is decreased by the square of the distance to its source. This is called propagation and thus $I_{prop} = I_0/R^2$ with R is the distance to source. Of course it is $R = v * t$.

While sound travels through water, the molecules of water absorb sound energy. The higher the frequency of the sound, the greater the absorption effect. The absorption coefficient m_f depends mostly on temperature of the water and frequency of the sound wave. The formula is $(2.1 * 10^{-10} * (T - 38)^2 + 1.3 * 10^{-7}) * f^2 = g(T) * f^2$ (unit: dB/m), where T is temperature in centigrade and f is frequency in kHz[1]. We thus get: $I_{absorb} = \frac{I_0}{m_f * R}$.

This gives in total: $I = \frac{I_0}{m_f * R^3}$. Thus high frequency signals are rather weakened by absorption and low frequency signals are reather weakened by propagation. Low frequent sounds can travel even hundreds of miles.

1.3 The listening device GHG

1.3.1 How it worked

The vessel hat a certain number of hydrophones mounted around its hull (GHG had 24 hydrophones per side). The output of these hydrophones as electrical signal was fed to electrical rotor contacts, that sat on a turnable rectangular device, that was made of a certain number of metal strips (most common: 100 strips with GHG). Each strip was connected over an electrical delay circuit to the next strip. Thus, an electrical signal arriving at strip n was delayed by $n * t_{stripdelay}$, where $t_{stripdelay} = 17\mu s$ on German GHG devices. Strip lines are numbered $0 \ldots 99$ from bottom to top in our simulation. The contacts were placed like a scaled projection of their real position around the hull.

Because sound arrives at each hydrophone at another point of time, the hydrophone outputs had to be combined with delay for each signal so that the result gave a sensible represenation of the sound signal for the human ear. The GHG did exactly that - the electrical delay between each strip line and the distance between two hydrophones and the positions of the rotor contacts were exactly choosen so that delay of sound in water between two

[1] Since we simulate frequency bands, we can compute the medium constant for a band by integrating that formula over f and computing the integral from lower to upper frequency limit. $\int g(T) * f^2 df = \frac{1}{3} g(T) * f^3$ thus $\int_a^b g(T) * f^2 df = \frac{g(T)}{3}(b^3 - a^3)$ and for the medium $m_f(T) = \frac{g(T)(b^3-a^3)}{3(b-a)}$. If we assume $10°$ for T we get $g(T) = 0.000194473$ which gives for 500Hz $m_f = 0.000048618$ and for 1kHz $m_f = 0.000194473$. If we use the integral and choose as band 20Hz to 1kHz we get $m_f = 0.000066147$. For the other bands we get $m_f = 0.000842717$ for 1kHz-3kHz, $m_f = 0.004083938$ for 3kHz-6kHz and $m_f = 0.002744233$ for 6kHz-7kHz.

hydrophones matched the electrical delay between the two strips that the rotor contacts of the two hydrophones were connected to.

This has also another important side effect, that is the main purpose of the GHG device: total output gets weaker when the GHG rotor apparatus was turned away from the signal's direction. This happens because the signal output of the hydrophones are layed on top of each other with various phase shifts. When the electrical delay doesn't match the sound delay any more, phase shifts unequal to zero occour. The larger the angle between signal direction and GHG apparatus becomes, the weaker the signal gets.

1.3.2 Problems

Simulation showed two serious problems with that arrangement: because we have a fix, integer number of strip lines, the phase shifts are discrete values, leading to a non-monotonous rise or fall of total signal output when the device was turned. This even lead to serious jitter in the output signal strength.

The second problem were "ghost" signals appearing at higher frequencies. At higher frequencies several periods of the signal are received by the hydrophones and fed to the strip lines. So the discrete phase shift compensation becomes more and more problematic. Output between two neighbouring hydrophones shows a phase shift of a half period or more, but the electrical delay for phase shift compensation has only a low resolution at high frequencies. So many signals that should overlay each other and neutralize themselfes mistakingly add up to a high output. This happens with an offset of ca. 90°, so a signal causes a peak at its real position and one with 90° offset.

Beside these two problems the GHG simulation gave only little difference between peak signal output and base output, making it hard to distinguish signals from background noise. A signal causes high output not only at the hydrophones listening to its direction, but also at all other hydrophones. We tried to vary hydrophone position, field-of-view width and listening direction, but it didn't help. The jitter was so high, that it nearly reached peak signal strength.

We thus decided to create our own function to simulate falloff of signal strength depending on angle between signal and apparatus and on frequency. A good base are powers of the cosine function:

$$strength(f, \alpha, \beta) := \max(0, \cos^{k*f}(\alpha - \beta))$$

where f is frequency, α and β are signal direction and apparatus angle and k is a falloff constant. The constant must be choosen so that at certain frequencies the top of the peak function has at least $1dB$ more output for β degrees than the rest. This is because the human ear works in dB scale and can distinguish signal strengths on a dB base. Historical information of the GHG showed $8°$ precision at $500Hz$, $4°$ precision for $1kHz$, $1.5°$ for frequencies above $3kHz$ and less than $1°$ for frequencies above $6kHz$. So the constant k must be choosen that for $\beta^+_-\gamma$ degrees the output of *strength* is at least $1dB$ higher than the value for any other angle.

1.4 What can we learn from "Harpoon 3"

1.4.1 Formulas

"Harpoon 3" uses the following formulas (note: $\phi(x) := 10^{\frac{x}{10}} = (10^{0.1})^x = 1.258925412^x$, so the function ϕ transforms deziBel values to linear sound intensity values):

Target noise	$L_t = L_{t_0} + G_f + m_{v_t} * v_t + G_c$
Ambient noise	$L_a = L_{a_0} + m_{w_p} * sea\ state\ level$
Sensor background noise	$L_r = L_{r_0} + m_{v_r} * v_r$
Total sensor background noise	$L_{b_p} = \frac{1}{m_b}\phi^{-1}(\phi(L_r) + \phi(L_a))$
Condition for passive detection	$L_t - 20 * log_{10}(R * 1852) - m_d * R - L_{b_p} \geq G_{s_p}$

Where G_{s_p} is passive sensor sensitivity, depending on sensor type. Note that L_{t_0} is a single constant per vessel, that describes the basic noise level of that vessel. Noise levels for the various bands are described by adding a band specific constant G_f. Note further that the numbers in the condition detection formula are derived from the propagation and absorption simulation of sound (propagation $-20 * log_{10}(R * 1852)$ and absorption $-m_d * R$ for range R in nautical miles).

1.4.2 Constants

Here are some values and constants use by "Harpoon 3" as an example (all values in deziBels):

Value	LF	MF	HF
Ambient noise base L_{a_0}	87	90	73
Noise increase per sea state level m_{w_p}	5	5	5
divergence of band noise level from average noise level G_f	-6	+5	-19
target noise increase by speed (per knot) m_{v_t}	1	1	1
noise increase by cavitation (only at full/flank speed) G_c	2	2	2
background noise from receiver, per knot m_{v_r}	3.6	4.2	5.5
background noise reduction factor m_b	3.4	2.9	3.7
dispersion factor (per nautical mile) m_d	1/6	1	3

Note that sea state level of 3 means "small waves" and 8 means "high seas", we thus can assume that sea state level is in range 0...10. The base values per vessel (L_{r_0} for receiver etc.) do vary. There is no reason given for the use of the "background noise reduction factor", but note that it is multiplied in the deziBel value range, so it is an exponent in absolute sound strength space.

1.4.3 Conclusion

"Harpoon 3" makes some crude simplifications. To make computing of sound strengths easier, all frequencies are distributed to three frequency bands (Low, medium and high frequencies, LF/MF/HF). Computations are done in a simple version in deziBel space. Background noise is decreased by a factor, so the example values are way too high itself. The noise strength of a target depends rather on its basic noise strength than on its speed, which is unrealistic. We should use basic noise levels for every frequency band and use more bands (four, 0...1kHz, 1...3kHz, 3...6kHz, 6...7kHz). Background noise should be decreased before summing it up or even while calculating it, not after summing of all background noise sources.

1.5 Special effects of the various listening devices

The number of microphones and the number of strip lines (membranes) in the device determine the resolution of direction finding, as well as the frequency and strength of the signal.

To correctly detect the signal and to distinguish between left/right and front/aft signals, groups of the microphones could be disabled.

To allow reliable detection a submarine needs to dive below 20m to avoid the disturbing noises of the ocean surface.

The operator of a device can detect any number of signals (as long as the resolution allows it). But to keep track of more than one signal he needs to switch permanently between two signals and redetect them. This is a difficult and time consuming process. Thus the simulation should limit the number of signals he could keep track of to, say, max. five. Of course he could mix up two signals that are to close to each other and start tracking a wrong signal. And the update of the actual position of each signal is delayed by the detection process for the other signals. E.g. if the operator needs 5 seconds to localize one signal and keeps track of three, he can update the position of each signal only every 15 seconds. This is an important aspect of simulation. Too many noise sources will disturb the correct localization as well.

1.5.1 Kristallbasisdrehgerät (KDB)

Freely turnable, no all-around detection... Some special effects not yet described here... (fixme)

1.5.2 Gruppenhorchgerät (GHG)

Blind spots... Select group of hydrophones... (fixme)

1.5.3 Balkongerät (BG)

Blind spot at stern... (fixme)

1.6 How sound is simulated in "Danger from the Deep"

Compute target noise for a target: $L_t = L_{t_f} + m_{v_t} * v_t + G_c$ where L_{t_f} is the basic noise level for a specific target and a given frequency band. Compute the noise for all targets and all frequency bands and sum them up to $I_{targets} = \phi(L_{targets})$. Note that the intensities that are summed up here are computed with all effects taken into account, like propagation and absorption ($L_{target} = L_t - L_{prop} - L_{absorb}$).

Compute background noise from ocean's background noise and receiver's background noise: $I_{backgr} = \phi(L_a) + \phi(L_r)$ where L_a is constant over all vessels for a given frequency band (depends only on weather etc.), and L_r depends on the receiver's vessel.

Now divide by sensor sensitivity and round to integer dB values: $I_{total} = I_{targets} + I_{backgr}$. The value should be cut off (clamped) at some small value $\theta > 0$, thus if it is less than θ, set it to θ. This gives a minimum deziBel value of $\phi^{-1}(\theta)$ that may be less than zero. The resulting value is fed to the sonarman simulator:

$$L_{result} = \lfloor \phi^{-1}(\max(\theta, \frac{I_{targets} + I_{backgr}}{\phi(G_{s_p})}))\rfloor$$

Note that we do not *subtract* background noise intensity from target noise intensity, as the formulas of "Harpoon" would suggest. This could lead to negative intensity values and is also not physically correct. Instead by adding both intensities and transforming them to the deziBel range, high background noise intensities will "shadow" target noise signals and thus is what we want to accomplish.

To compute the total sound intensity of all frequency bands we sum them up multiplied by a band specific constant: $I_{total} = \sum_{i=1}^{nr\ of\ frequency\ bands} I_{band_i} * m_{band_i}$.