# OPTIMUM SONAR FREQUENCY FOR DIVER DETECTION IN HARBOURS

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## 1 INTRODUCTION

Diver detection is the missing link in harbour protection systems. Harbours may be well guarded from the land side but they are vulnerable to terrorist attacks from the sea. Small boats or divers can easily enter a harbour unnoticed and do whatever they want. A combination of radar and sonar sensors should prevent intruders going unnoticed on or under water, but for the latter (diver detection sonar) no COTS systems are available.

Systems that are available on the market are refit mine-hunting sonars[1]. However, as we will find in Sec. 4, the target strength of a diver may be comparable to or even less than that of mine. Therefore, the detection ranges are as short as, or even shorter than, in mine-hunting, i.e. a few hundreds of metres. This is insufficient. Operational studies show that, depending on the scenario, the reaction time to a diver alarm may be as long as 30 minutes, and considering a speed of approach of 1 knot, detection ranges should be half a nautical mile (or one kilometre). Here we face a huge technology gap.

In this framework the Royal Netherlands Navy (RNLN) together with the Rotterdam Sea Harbour Police initiated a research project at TNO in the fall of 2005, in which the feasibility of long range diver detection was studied in an experimental setting. For the experiments a proto-type system was developed. The idea was to use low (audible) frequencies to guarantee good propagation conditions and to exploit the knowledge on low frequency active sonar at TNO. To reduce costs this system was built from existing hardware. Matching signal processing was developed and implemented on PCs. Finally, the diver detection experiments were executed in the Port of Rotterdam in December 2005. The results were disappointing. No divers were detected.

In the data analysis it transpired that the background levels were too high at audible frequencies. From the measured background noise curves, it could be estimated that the optimal frequency for noise-limited detection was around 30 kHz.[1] Just above audible, but lower than mine-hunting frequencies used by other systems. These other systems also seem to perform poorly. In April 2006 a large operational demonstration was organised by NURC, in which several systems were tested under similar conditions. Only divers with open breathing systems (implying the presence of exhaled bubbles) were detected and then only at short ranges.

This paper is the product of a self-funded study by TNO in which the detection problem of divers is studied more thoroughly. The outline of this report is as follows. In Sec. 2 theory on the sonar detection of divers is discussed and the sonar equation is worked out in Sec. 3. Results from an analytical study to find optimal frequencies and other system characteristics are shown in Sec. 4. The target strength is discussed in Sec. 5. Finally, in Sec. 6 the conclusions are drawn.

## 2 SONAR PERFORMANCE MODELLING

In order to design a sonar whose characteristics are optimised for the detection of human divers, we must model accurately the performance of the hypothetical sonar in a typical environment. We list all the perturbations to the performance, and derive the influence of the sonar characteristics on those perturbations in order to reach a sonar design optimal for diver detection in very shallow waters.

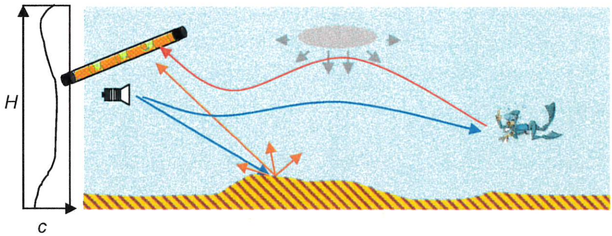


Figure 1 Schematic of the problem with perturbations. Blue: Transmitted energy; Red : Diver echo; Orange: reverberation; and grey: ambient noise.

The characteristics of the sonar that we can optimise are mainly two, the transmitter/receiver length and pulse parameters:

- **The transmitting/receiving array length** affects the Array Gain and thus the processing gain. Since it is easier and cheaper to develop an array that offers more aperture at high frequency than low, we assume an array length varying with frequency in our optimisation.
- **The centre frequency** of the transmitted pulse *f* affects the Noise Level, because the spectral level of ambient noise is mostly decreasing with frequency. On the other hand, the Propagation Loss is likely to increase with frequency, because the absorption increases with frequency. It is complicated to balance the two counteracting effects[1].
- **The transmitted pulse bandwidth** affects the Reverberation Level through the range resolution, to which it is inversely proportional. Because of physics in transducer design, we assume the bandwidth to be proportional to the centre frequency and do not consider bandwidth as an independent parameter.
- **The transmitted pulse length** affects the Noise Level (the longer the pulse, the higher the processing gain over noise after processing). However, there are limitations to pulse length, as during transmission the sonar is blind and increasing pulse length increases the "blind zone". Therefore this parameter has been kept fixed.

Finally, we end up with only one parameter to be optimised, the sonar frequency. This optimal sonar frequency will be determined from analytical sonar performance modelling. The sonar equation will be analysed, to provide the signal-to-background ratio, from which the maximum detection ranges can be derived. We will use analytical expressions to compute the terms of the sonar equation.

## 3 SONAR EQUATION

The form of Sonar equation we use in this article is:

$$SBR = (SL - TPL + TS) - (BL - PG)$$

The first three terms on the right hand side represent the echo level; the last two the background level. The individual terms are explained below.

SBR Signal To Background Ratio
This term is evaluated after signal processing (Beamforming and Matched Filtering). The SBR can be either the SNR, Signal To Noise Ratio, in noise-limited conditions or the SRR, Signal To Reverberation Ratio, in reverberation-limited conditions.

**SL** Source Level
We use the maximum SL we think we can attain with an optimal system; 210 dB re 1 $\mu Pa^2 m^2$.

**TPL** Total Propagation loss.
By Total Propagation Loss we mean two-way propagation loss, including absorption. Several assumptions are possible for modelling the propagation loss. Amongst these are spherical propagation loss, cylindrical propagation loss and some hybrid forms.
The spherical propagation model is adapted to deep water, i.e. when the considered range is large compared to the wavelength. The cylindrical regime is adapted to scenarios when the water depth is small compared to the range. In our case, the water depth is about 20 m and the range on the order of 500 m. We are not interested in ranges less than 50 m because they will be in the blind zone of the transmitted pulse. However, the measured propagation loss during the 2005 Diver Detection Experiment was very close to spherical propagation loss and we will therefore consider it as well. This was probably due to a soft bottom that does not reflect as much as a sandy bottom.

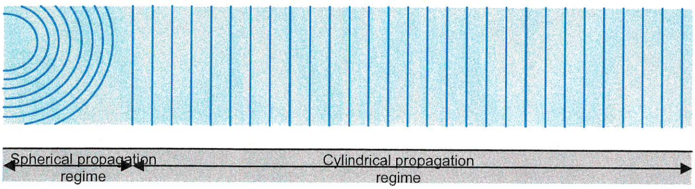


Figure 2 Propagation regimes in shallow water (with a hard bottom).

In a **spherical propagation** regime (without absorption), the two ways spreading loss simply is:

$$2\text{PL} = 40\log r$$

This spreading loss does not take the **absorption** of energy by sea water into account. We chose to model the latter with the Thorp formula for absorption loss (in dB) [3]

$$\text{AB} = \left(3.3.10^{-3} + 0.11\frac{F^2}{1+F^2} + 44\frac{F^2}{4100+F^2} + 3.10^{-4}F^2\right)\frac{r}{1000}$$

in which $F$ is the frequency expressed in kilohertz and the range $r$ is in metres.

Finally, the total propagation loss in the spherical model is

TPL $= 40 \log r + 2\text{AB}$

As an alternative for the simple spherical spreading, we will now examine the closed form solution presented in Harrison[2], which describes cylindrical spreading, transitional and mode stripping in one formula. It is based on the ray representation of propagation in an isovelocity environment. Let us consider a ray going at angle $\theta$ from a source to a point target at range $r$ in a horizontal waveguide of depth $H$. This ray will reflect about $N_r$ times, where

$$N_r = \frac{r \tan\theta}{2H}$$

We will assume that rays reflected on the seabed are attenuated by a reflection coefficient equal to:

$$R = \exp(-\alpha\theta)$$

Rays steeper than the critical angle are assumed to be negligible. The contribution of $N_{rays}$ rays for the one way bottom attenuation at range $r$ is then:

$\sum_{k=1}^{N_{rays}} \exp(-\alpha\theta_k)^{\frac{r\tan\theta_k}{2H}}$ , which reduces for small $\theta$ to $\sum_{k=1}^{N_{rays}} \exp\left(-\frac{\alpha\theta^2}{2H} r\right)$.

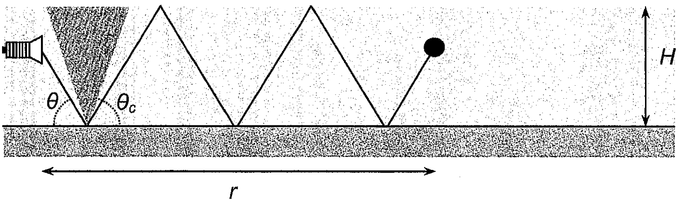


Figure 3 Description of the geometry.

If we transform this sum of rays into an integral over $\theta$, from 0 to $\theta_c$, include a $r^{-2}$ term for the spreading loss of each ray, we obtain (see Harrison[2] for details):

$$PL_{oneway} = \frac{2}{rH} \int_0^{\theta_c} \exp\left(-\frac{\alpha\theta^2}{2H} r\right) d\theta$$

And eventually, squared to account for the two way propagation loss and expressed in dBs:

$$\mathrm{TPL} = 10\log\left(\frac{2\pi}{H\alpha r^3}\left(\mathrm{erf}\left(\theta_c\sqrt{\frac{\alpha r}{2H}}\right)\right)^2\right) + 2\mathrm{AB}$$

This formula gets very similar to an intermediate propagation law (TPL = 30 log $r$ ) when the range increases. Indeed, the error function is very close to one when its argument is larger than 3, i.e. when:

$\theta_c\sqrt{\frac{\alpha r}{2H}} > 3$ which is equivalent to $r > \frac{18H}{\alpha\theta_c^2}$.

**TS:** the Target Strength of a diver is between –15 dB and –25 dB; (a reference distance of 1 m is used here and throughout); see Sec. 5.

**BL:** The Background Level is the larger of the reverberation level and the noise level.

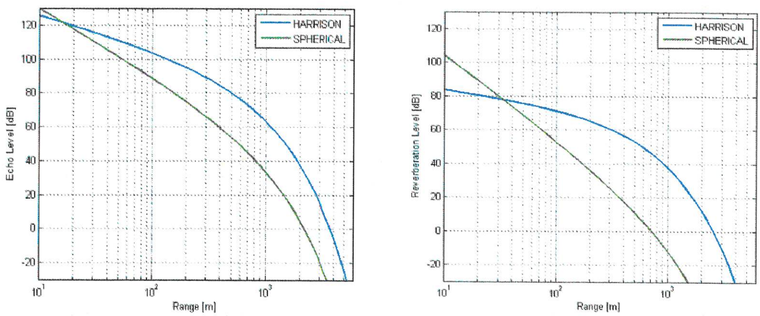


Figure 4 Modelled echo level with Harrison's model and a usual spherical propagation model (left) and matching reverberation levels (right). Seabed parameters used for Harrison's model correspond to coarse sand.

**RL:** The Reverberation Level is calculated in the same way as the Echo Level, by integrating rays and considering the reverberation cells as Lambert scatterers. The Lambert rule gives:

$$S = \mu \sin^2(\theta)\ ,$$

where $S$ is the scattering strength, $\theta$ the backscattering angle and $\mu$ a factor characteristic of the reflecting surface. We propose a frequency dependent $\mu$ parameter valid between 10 kHz and 400 kHz for sediment corresponding to medium sand based on the measurements of Greenlaw et al[4]

$$\mu = 10^{-4}\left(\frac{F}{5}\right)^{1.47} .$$

Harrison's formula is given for Reverberation Level without matched filtering. Since we plan to transmit frequency modulated pulses over a bandwidth of $\Delta f$, we replace the pulse length parameter in Harrison's formula by the range resolution of the transmitted pulse i.e.:

$$\delta_r = \frac{c}{2\Delta f}$$

The ray integral is then:

$$I = \mu \Phi r \delta_r \left( \frac{1}{2rH} \int_{-\theta_c}^{\theta_c} \sin\theta \exp\left( -\frac{\alpha\theta^2}{2H} r \right) d\theta \right)^2$$

Which gives us a reverberation level for **Harrison's propagation model** of :

$$RL = 10\log\left( \frac{\mu}{\alpha^2 r^3} \Phi \delta_r \left( 1 - \exp\left( \frac{-\alpha r \theta_c^2}{2H} \right) \right)^2 \right) - 2AB$$

Likewise we will consider **spherical propagation** as well. The Reverberation Level will then be:

$$\mathrm{RL} = \frac{\mu\Phi\delta_r}{r^5} H^2$$

**NL:** For the Noise Level we used the empirical formula we fitted to the measurements during the 2005 Diver Detection Experiment

$$NL_{spectral} = 170 - 30\log f$$ ,

in units of dB re µPa² / Hz, where the lower case *f* denotes frequency in hertz. To obtain the Noise Level over the bandwidth of interest, we integrate the spectral Noise level :

$$NL = \int_{f_c-\Delta f/2}^{f_c+\Delta f/2} NL_{spectral} = 170 - 10\log\left(\frac{1}{2\left(f_c - \frac{\Delta f}{2}\right)^2} - \frac{1}{2\left(f_c + \frac{\Delta f}{2}\right)^2}\right)$$

**PG:** The Processing Gain is the gain from the signal processing; i.e beamforming (the gain of the beamforming is called the array gain) and matched-filtering. PG = AG + MFG

The array gain (AG) is related to the array length. In sonar performance modelling the array length is often either a fixed number of wavelengths or a fixed length in metres. We choose a middle way, as a fixed number of wavelengths would favour lower frequencies, and a fixed physical length would favour higher frequencies. In practice, where costs and physical size are important design parameters, it appears that arrays get shorter with increasing frequency, but in a less than proportional way. Therefore, we used a heuristic formula to account for the fact that it is easier to develop an array with many wavelengths of aperture at higher frequencies than at lower frequencies.

$$L = \frac{10^{5\log 5}}{2 f_c^{\log 5}}$$

This formula gives an array of 2.5 m at 10 kHz (= 16 wavelengths) and 0.5 m at 100 kHz (= 32 wavelengths). The associated array gain is:

$$\mathrm{AG} = 10\log\left(\frac{2L}{\lambda}\right), \qquad \text{with the wavelength} \quad \lambda = \frac{c}{f}$$

The matched-filter gain (MFG) for a wideband frequency modulated pulse is

$$\mathrm{MFG} = 10\log(BT),$$

where in our modelling, $B = f / 10$, and $T = 0.1$ s.

Coherence Loss: In shallow water environments signals tend to get longer upon propagation due to time-spreading. The complex interference of the direct signal and all its multiples results in a received response that is longer than expected from the transmitted pulse response. This spreading of energy over time is modelled as a reduction in the echo level, which is often denoted as coherence loss (CL). Thus, coherence loss is not to be neglected, especially for high frequency. According to Prior and Harrison the decay (half-life) time of a transmitted delta-pulse is:

$$\tau_{decay} = H / \alpha c$$

If this decay-time is longer than the time-resolution ($\tau_{res} = 2 / B$ ) of the pulse, the signal's energy will be spread over more than one resolution cell and coherence loss becomes an issue.
To a first approximation CL is simply the ratio of the two timescales, expressed in decibels:

$$CL = 10 \log10 ( \tau_{decay} / \tau_{res} ) = 10 \log10 (H\,B / 2\alpha\, c )$$

In our modelling with $H$ = 20 m, and $B = f/10$, CL is significant for all frequencies above 10 kHz.

# 4 MODELLING RESULTS

The sonar equation of the previous section was implemented in Matlab® so that the model parameters could be varied and the results evaluated.

In Figure 5 the SBR is depicted (minimum of SNR and SRR) and a detection threshold (DT = 15 dB) is subtracted. The colour values represent the signal excess for a 0 dB target. Contours are labelled with the TS value that would be required to achieve a signal excess of 0 dB (i.e., 50 % detection probability) at that point on the graph. Results for spherical propagation loss modelling (left) and the results for Harrison's propagation model (right) are included. For this case we find that spherical spreading achieves a closer to match to our measurements[1].

Notice that, despite the high echo level predicted by Harrison's model (see Fig. 4), at high frequency this is more than offset by the higher reverberation due to the good propagation conditions assumed. The benefit of this approach is that it permits adjustment of the parameters controlling the bottom type, and refraction can also be modelled[5]. However, so far we have not introduced these extra complications.

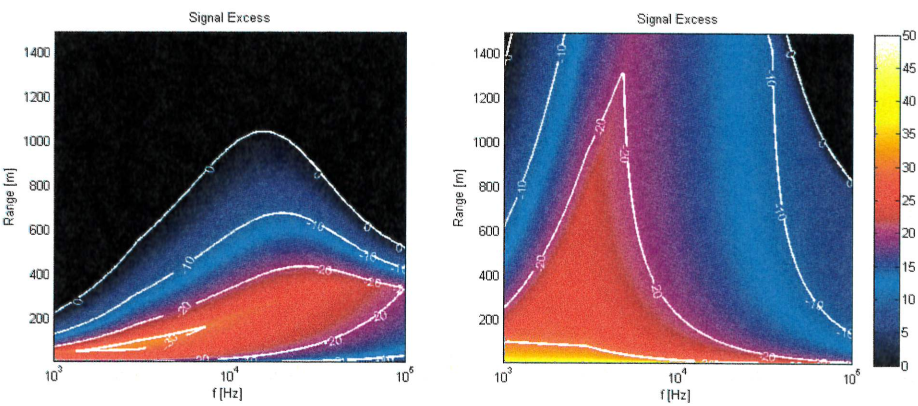


Figure 5 Contours to show the maximum detection range as a function frequency for different target strength as a result of spherical propagation modelling (left) and Harrison's model (right). Contours are labelled with just detectable TS values between 0 dB (highest) and –30 dB (lowest), in steps of 10 dB.

# 5 TARGET STRENGTH AND DETECTION RANGE

We consider the target strength separately from the other terms in the sonar equation because of the uncertainty associated with its value. The results of Fig. 5 are deliberately presented in a form that allows interpretation for different TS values. Here we consider the possible spread.

At very low frequency (less than 1 kHz) the main scatterer is expected to be the air cavity associated with the diver's lungs, especially close to its resonance frequency (order 100 Hz). Using the method of Weston[6] we estimate a TS around -6 dB at resonance. At higher frequencies, the lungs also contribute, though at a considerably lower strength (about -21 dB for F > 1 kHz), with a comparable contribution from the skeleton, making for a total TS of about -19 dB. [7] This value can be thought of as a lower bound, as it does not include contributions from the paraphernalia associated with breathing apparatus such as an air-filled metal cylinder, for which we estimate a TS value of about -16 dB. Any exhaled bubbles will increase this significantly, although it is difficulty to quantify this without knowledge of their size distribution. For example the Minnaert frequency of an air bubble of radius 1 mm at atmospheric pressure is approximately 2 kHz.

For TS in the range -15 to -20 dB, the optimum frequency from Fig. 5 (spherical spreading) is around 20 kHz, with a corresponding detection range of about 500 m. A -30 dB target is almost undetectable at any frequency or range.

# 6 CONCLUSIONS AND WAY AHEAD

This article describes work in progress, so conclusions are necessarily of a preliminary nature, and it is appropriate also to mention the way ahead. Diver detection in harbours is an extremely difficult problem. The low target strength and the harsh shallow water environment make diver detection a daunting task. The signal excess is always low for all sonars and at all ranges; at short range ranges reverberation is limiting, at long ranges noise is limiting. Therefore, the detection problem is never comfortably solved. Only for an old-fashioned diver with bottles (TS = -15 dB) the 1 km detection range may be feasible. Further effects to be considered in the future include additional frequency dependence due to thermal noise, vertical directivity and possible variations in maximum source power.

# 7 REFERENCES


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