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Alberto Baldacci, Georgios Haralabus

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Adaptive normalization of active sonar data

Alberto Baldacci, Georgios Haralabus
Reconnaissance, Surveillance and Undersea Networks Department (formerly ASW)
NATO Undersea Research Centre
Viale San Bartolomeo 400, 57100, La Spezia, Italy
www.nurc.nato.int
baldacci@nurc.nato.int, haralabus@nurc.nato.int

Abstract
In active sonar detection the background interference is reduced through normalization prior to applying a detection threshold. From the two mainstream normalization algorithms, i.e. the sliding window and the split window, the latter places guard bands around the point of interest to avoid a spill of the target's energy into the background calculation. The size of the guard bands has a strong effect on normalization: if it is too narrow, the target's energy biases the background estimation; if it is too large, the background estimate at one location is based on background samples too far away from that point. During recent sea trials strong changes in system performance, attributed to inappropriate normalization, have been experienced. An approach to overcome this problem by means of an adaptive normalization window that takes into account the geometry of the scenario and the environmental conditions (time spreading) is presented.

Keywords: time spreading, active sonar normalization, ray tracing, multipath, environmental adaptivity.

1 Introduction

Sonar matched filter output time series are usually characterized by space and time variability of reverberation and background noise. In order to apply a single detection threshold, it is necessary to remove the time variability of the background. This process is called normalization [1]. Here we utilize a time sliding window normalizer because it is both effective and easy to implement. The average reverberation and background noise power is estimated using data adjacent to the cell to be normalized. If the background data adjacent to the normalized cell contain part of the signal, then the background noise is overestimated. For this reason the split-window normalizer uses guard bands to separate the signal from the noise as shown in Figure 1.

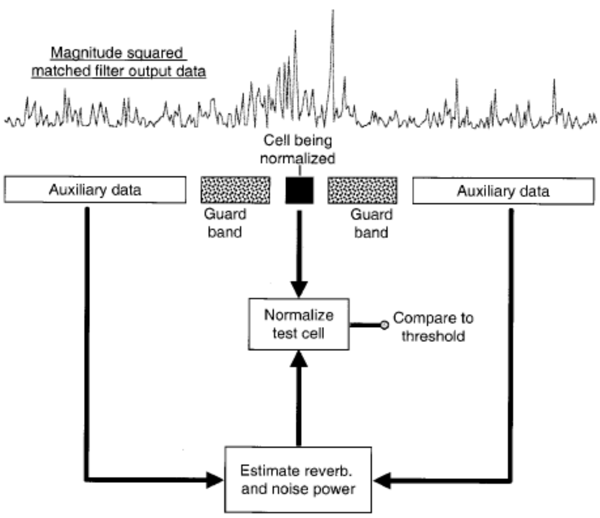

Figure 1: Flow diagram of the split window normalizer [2].

In an environmental adaptive approach to active sonar performance enhancement, the size of the guard bands should depend on the characteristics of the propagation of the acoustic channel, i.e. the more the time spreading, the wider the guard bands. Our goal here is to obtain time spreading estimates using both a ray tracing model and analytical formulae calculations.

This rest of the paper is organized as follows. The definition of time spread of a point target echo is given in Section 2, both in absence and presence of background interference. A method for spreading estimation based on recently developed closed form expressions for signal and reverberation is discussed in Section 3. In Section 4 the analytical results are then compared to a model simulation. The conclusions are drawn in Section 5.

2 Definition of time spread of a point target echo

When a sonar pulse is transmitted, the received signal $r(t)$ at a given location is obtained by convolving the transmission $s(t)$ with the impulse response $p(t)$ of the channel. The impulse response depends on the multipath structure and can be described as a train of delta functions, each characterized by attenuation a_i and time delay t_i:

$$p(t) = \sum a_i \delta(t - t_i) \tag{1}$$

The convolution produces a received signal which is a smeared version of the transmitted one:

$$r(t) = \sum a_i s(t - t_i) \tag{2}$$

Since we are interested in time spreading rather than the ensemble delay of the returned signal, we can consider the time of the first arrival as reference, which means applying the change of variable $\tau = t - t_0$,

$$r(\tau) = \sum a_i s(\tau - t_i^{'}) \tag{3}$$

where $t_i^{'} = t_i - t_0$.

To make the following argument independent from the type of transmitted signal, $s(t)$ will be assumed to be a delta function. As a consequence we will have $r(\tau) = p(\tau)$ and the analysis will therefore be focused on the time extent of the impulse response. Further, in real applications, the received signal will be added to, and possibly embedded in, some amount of background interference. In this case a slightly different definition of time spreading has to be formulated. We can define an "effective" time spreading as the maximum time extent of the signal if we consider only the arrivals whose intensity a_i is at least a fraction of the intensity of the strongest arrival, defined as cutoff threshold γ. The corresponding definition in analytical notation is:

$$\Delta\tau_\lambda = \max\{t_j^{'}\} - \min\{t_j^{'}\},\ j = i : a_i \geq \gamma \max\{a_i\},\ i = 1,2,\ldots \tag{4}$$

In this paper we consider four different values for γ, namely 0.01, 0.05, 0.1, 0.5. Accordingly, we obtain different effective time spreading estimates.

3 Analytical derivation

Closed form expressions for two – way propagation and reverberation have been recently derived for isovelocity water by using ray invariants and acoustic flux [3]. By these formulae one can deal with propagation and reverberation at high and low frequencies and in isovelocity range-dependent environments with various scattering laws.

The approach is based on the "mode-stripping" phenomenon, i.e. only rays with smaller start angles propagate to longer ranges because: a) the reflection loss between zero grazing and the critical angle is proportional to the incident angle by a factor α; b) the number of boundary interactions is inversely proportional of the ray cycle distance and therefore increases with angle. For paths that reflect from both boundaries this leads to intensity having a Gaussian angular dependence. This Gaussian angular dependence can be translated into intensity versus time.

According to [3], we can estimate the time distribution of arrivals and determine the intensity $p(\tau)$, for a one-way path,

$$p(\tau)d\tau = \frac{1}{\sqrt{2t_0}} \frac{\exp\{-\alpha\,\tau/t_H\}}{\sqrt{\tau}} d\tau \qquad (5)$$

where τ is the time after the first arrival $t_0 = r/c$, i.e. $\tau = t - t_0$ and $t_H = H/c$ is the ratio between the water depth *H* and the sound speed in the water *c*. For a two-way path (distant point target) the pulse shape is

$$p(\tau)d\tau = \frac{\pi}{2t_0} \exp\{-\alpha\,\tau/t_H\} d\tau \qquad (6)$$

In both formulae, α is the reflection loss gradient and represents the proportional factor relating incident angle to reflection loss for rays with grazing angles below the seabed's critical angle. The reflection loss gradient is a parameter which can be used to describe the seabed reflection loss. According to (6), the returned echo from a point target is an exponential, i.e. is linear in logarithmic scale. It is worth noting that time spreading does not depend on range but only on the environment. An example of two-way pulse decay is plotted in Figure 2 for the environment described by the parameters in Table 1 [4].

Table 1: Environmental parameters for isovelocity test

Parameter	Water depth	Sound speed in water	Sound speed in the seafloor	Seafloor density	Seafloor attenuation	Reflection loss gradient
Symbol	H	c_{water}	$s_{seafloor}$	ρ	μ	α
Value	150m	1500m/s	1584	1.608	0.282	1.11

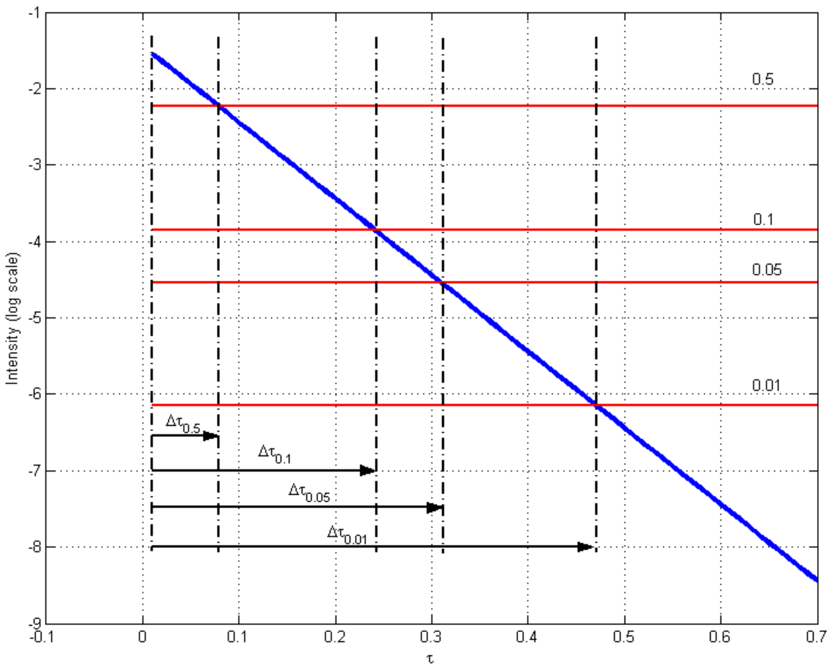

Figure 2: Analytically derived point target echo decay.

The blue line in Figure 2 represents the pulse decay; red lines correspond to the four thresholds. The black arrows indicate the corresponding effective time spreads.
The pulse distribution plotted in Figure 2 is correct at long ranges only. At short ranges the number of arrivals is limited by the critical angle. As a consequence, the pulse is truncated and the time extent is shorter. The pulse spread can still be estimated through the relationship between τ and angle θ [3]:

$$\tau = r\theta^2/2c \qquad (7)$$

The pulse spread is therefore the value of τ calculated in equation (7) for $\theta = \theta_c$. At short ranges, pulse spread is therefore proportional to range. As an example, for the test environment of Table 1 the corresponding critical angle is:

$$\theta_c = a\cos(\frac{c_{water}}{c_{seafloor}}) = 18.74^o$$

and the relationship between range and time spreading is $\tau = 3.567 \times 10^{-5} r$. Ranges this relationship applies to are referred to as Regime I ranges. Longer ranges, where time spreading is range independent, are referred to as Regime II ranges. The transition range from Regime I to Regime II depends on the selected cutoff threshold γ.

Analytical predictions of time spreading for both 1-way and 2-way propagation are shown in Figure 3.

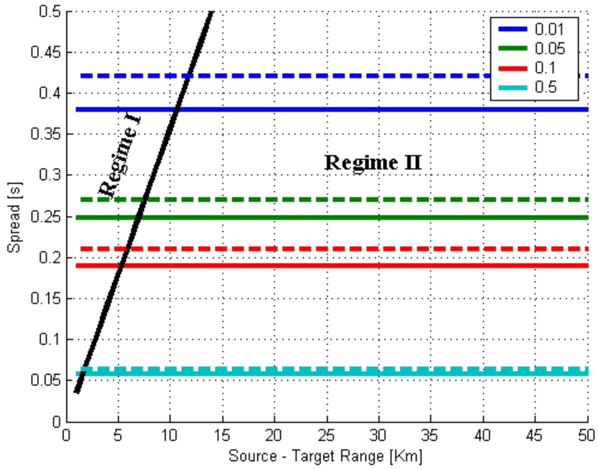

Figure 3: Analytical prediction of time spreading for 1-way (solid lines) and 2-way propagation (dashed lines).

Although this analysis has been developed only for isovelocity environments, the main effect of refraction will only be seen near the pulse's leading edge. Thus refraction effects are expected to be over by time $t_0(c_{\max} - c_{\min})/c_{av}$ after the first arrival [3].

This derivation can be extended to range-dependent environments. It can be demonstrated [3] that equations (5) and (6) still hold if $t_H = H_{eff} / c$, where H_{eff} is defined as

$$\frac{1}{H_{eff}} = \int_0^r dr / H^3 \Big/ \int_0^r dr / H^2 \qquad (8)$$

As an example, for a water depth linearly changing from H_s to H_r, $H_a = 2H_s H_r / (H_s + H_r)$ is an intermediate depth close to the arithmetic and geometric mean.

4 Numerical simulation

The GAMARAY range-independent ray tracing model [5] is used to numerically estimate echo spreading due to the propagation channel. For each defined source-receiver pairs, the model returns a number of arrivals, i.e. rays connecting the two points. These arrivals are also called eigenrays. Each eigenray is characterized in terms of travel time, attenuation, initial and arrival angles, number of boundary interactions and total phase shift. The set of arrivals can be intended as the impulse response of the channel. We can therefore compare the modelled impulse response with the analytical one.

For the comparison to make sense, we have to apply the two methods to the same environment. This means that the same range independent, isovelocity environment, with half space subbottom (i.e. not stratified – no sediment layers have been considered so far) has to be set in GAMARAY. This is not trivial, because in GAMARAY the bottom properties are specified in terms of the geoacoustic parameters of attenuation, density and sound speed in the seafloor, while in the analytical approach the reflection loss gradient α is the only parameter needed.

The model is run for a scenario with environmental parameters defined in Table 1 [4], where we have the geoacoustic parameters of the seafloor corresponding to the value of α used in the analytical formulae.

The source and the receiver are in the middle of the water column, and the model is run 1000 times for ranges increasing from 1Km to 50Km (i.e. with range steps of 50 meters). For each range we obtain a set of eigenrays which represents the 1-way channel impulse response. The 2-way channel impulse response is obtained by convolving the 1-way impulse response by itself. Equation (4) is then used to calculate the effective time spreading $\Delta\tau_\lambda$ for cutoff threshold γ = 0.01, 0.05, 0.1, 0.5 (both 1-way and 2-way propagation). The results are shown in Figure 4 and Figure 5.

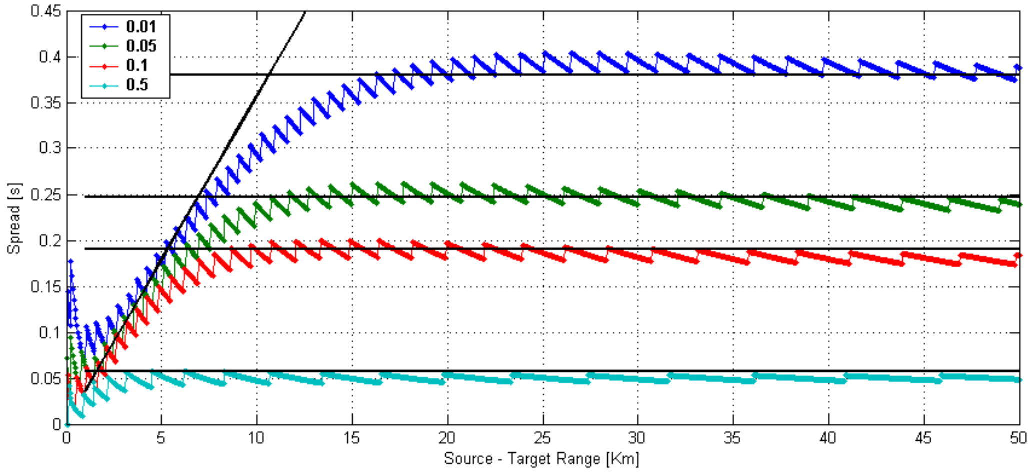

Figure 4:Time spreading for 1-way propagation: analytical (black lines) and simulated (colour lines).

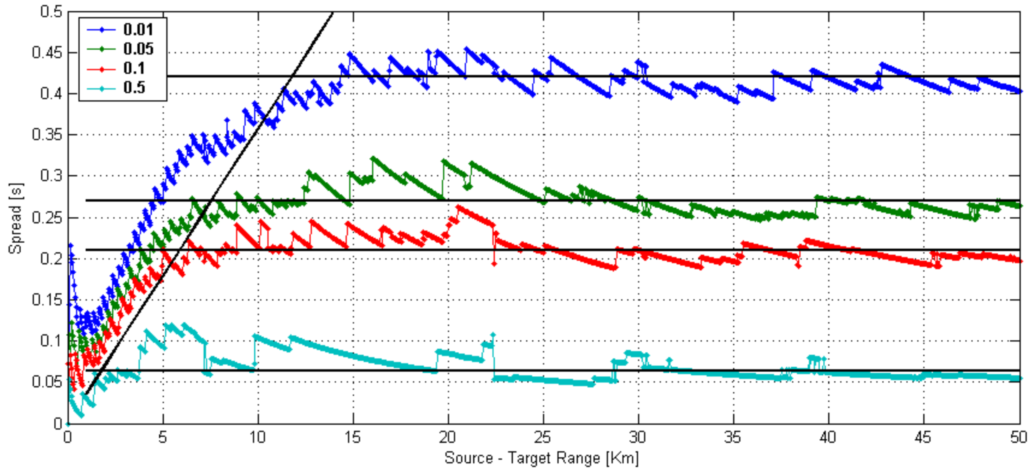

Figure 5: Time spreading for 2-way propagation: analytical (black lines) and simulated (colour lines).

Figure 4 is a plot of the 1-way time spreading estimation. The black lines are the analytical calculations and the colour lines are the model predictions. Different colours correspond to different cutoff thresholds. For increasing cutoff thresholds, the effective time spreading decreases. As predicted by the analytical solution, two regimes are present. At shorter ranges, time spreading linearly increases with range (Regime I). At longer ranges, time spreading is almost constant (Regime II). The numerical simulation confirms the analytically predictions for all the four thresholds.

5 Conclusions

In this paper two methods for time spreading estimation are investigated. Closed form analytical calculations are verified by GAMARAY ray tracing model estimates. These results are obtained for range independent, isovelocity environments and may also be applied to moderate range dependent environments. It is shown that at short ranges time spreading increases linearly with range, both for 1-

way and 2-way propagation. At long ranges time spreading converges to a constant value. Time spreading estimates can be used in real time for optimising the guard band size in an adaptive normalization scheme to enhance active sonar performance.

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Author(s)

Alberto Baldacci, Georgios Haralabus

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NATO Undersea Research Centre
Viale San Bartolomeo 400, 19138 La Spezia, Italy

[From N. America:
NATO Undersea Research Centre
(New York) APO AE 09613-5000]

Tel: +39 0187 527 361
Fax:+39 0187 527 700

E-mail: library@nurc.nato.int