WIDEBAND INVERSE FILTERING TO IMPROVE ACTIVE SONAR DETECTION IN BACKGROUND REVERBERATION

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ABSTRACT

The problem of detecting a known signal in background reverberation with an estimated reverberation spectrum is addressed. In our approach, the prewhitener is a wideband inverse filter estimated from a large data base of reverberation spectra. Simulations and experimental results are presented in the context of detecting a target lying on the seafloor with a wideband transducer. The proposed detector is compared to an AR prewhitener. The results indicate that the proposed detector is well suited for our wideband application.

1. INTRODUCTION

The case of detecting a known signal in reverberation background have been studied for active sonar applications [1]. However, the contribution and the performances of the wideband detection are not well known in this context [2]. This can be explained by the fact that few active sonars have bandwidth more than two octaves with a constant directivity.

The proposed detector consists of a wideband prewhitener and a matched filter. The prewhitener is based on a wideband inverse filter adjusted to the coloration and the variability of the noise spectrum. Using these parameters for the design of the prewhitener, it is expected that the spectrum of the whitened noise should better approximate a flat spectrum. Thus, using the wideband receiver, the detection performances should be improved, since the peak signal-to-noise ratio of the matched filter output is as much larger than the frequency band of the transmitted waveform is wider and the spectrum of the whitened noise is more flat. Experimental results give a comparison of the proposed detector to that based on an AR prewhitener, in term of signal-to-noise ratio.

2. PROBLEM FORMULATION

The problem of detecting a known signal in a background reverberation is addressed. Formally, one has to decide between two hypotheses:

$$H_0: x_i(n) = n_i(n), \quad i = 1..N$$
$$H_1: x_i(n) = s(n) + n_i(n) \quad (1)$$

where the variable n denotes the discrete time, s(n) is the deterministic and known signal to detect, $n_i(n)$ the ith realization of the additive noise and $x_i(n)$ the ith received signal.

The detection problem in (1) can be represented in the frequency domain using the Fourier coefficients at frequency f_j:

$$H_0: X_i(f_j) = N_i(f_j),$$
$$H_1: X_i(f_j) = S(f_j) + N_i(f_j) \quad (2)$$

We refer to the following assumptions.

A1) The Fourier coefficients of the noise spectrum at different frequencies are complex random variables with zero mean and equal variances.

A2) The coefficients $X(f_j) = [X_{1j}\ X_{2j}\ ..\ X_{Nj}]^T$ are independent in that sense that the repetition time of the transmitted signal is higher than the duration of the signal ($T_R /T >> 1$).

A3) The time bandwidth product is large enough (TB >> 1), so the Fourier coefficients of the ith noise spectrum X_i (f; H_0) = [X_{i1} X_{i2} .. X_{iM}] are practically uncorrelated.

The decision rule applied compares the generalized likelihood ratio test (GLRT) λ(X) to a threshold λ_0

$$\lambda(X) = \frac{p(X/H_1, \hat{\theta}_{ML})}{p(X/H_0, \hat{\theta}_{ML})} \begin{cases} > \lambda_0 \text{ decide } H_1 \\ < \lambda_0 \text{ decide } H_0 \end{cases} \quad (3)$$

where $\hat{\theta}_{ML}$ are the maximum likelihood (ML) estimates of parameters taking into account the coloration and the variability of the noise.

The performances of the detector depend on the ith signal-to-noise ratio at time n_0 at the output of the receiver

$$\rho_i(n_0) = \frac{\left|\sum_f H(f)S(f)e^{j2\pi f n_0}\right|^2}{\sum_f |H(f)|^2 \Phi_{Xi}(f;\ H_0)}, \quad i = 1..N, \quad (4)$$

where

$$H(f) = |H_1(f)|^2 S^*(f)e^{-j2\pi f n_0},\ f = \{f_j\}_{j=1}^{M} \quad (5)$$

H_1 (f) is the transfer function of the prewhitener filter, $S^*(f)e^{-j2\pi f n_0}$ the transfer function of the matched filter and Φ_{Xi} (f; H_0) = (X_i X_i*) (f; H_0) is the power spectrum of the ith realization of the noise under the H_0 hypothesis.

It appears in (4) that the performances of the detector strongly depend on the adjustment of the coefficients of the prewhitener with respect to the noise variability.

3. WIDEBAND INVERSE FILTER

A set of noise reverberation data given by a wideband stochastic process is considered. We want to design the prewhitener filter that better fitted to the data set in the ML sense.

A basic formulation of the prewhitener coefficients is given by:

$$\varepsilon_i(f) = |H_1(f)|^2 \Phi_{Xi}(f;\ H_0) \quad (6)$$

where ε_i is the noise at the output of the inverse filter which ideally should be white with a spectral level $N_0/2$.

A better approximation of whitening coefficients has to take into account both contributions: variability and coloration of the noise. This is expressed by:

$$\varepsilon_i(f_j) = a(f_j)\Phi_{Xi}(f_j) - \frac{N_0}{2}\alpha_i \quad (7)$$

or using a more convenient form:

$$\varepsilon_{ij} = a_j\Phi_{Xij} - \frac{N_0}{2}\alpha_i \quad (8)$$

where a_j is the coefficient of the inverse filter at frequency f_j, α_i a compensation term function of the noise coloration and ε_{ij} are zero-mean Gaussian random variables with variance σ:

$$p(\varepsilon_{ij}) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{\varepsilon_{ij}^2}{2\sigma^2}} \quad (9)$$

Using assumptions A1, A2 and A3, ε_{ij} are independent and identically distributed with respect to both indices. Therefore the pdf at frequency f_j can be written as:

$$p(\varepsilon_j) = \prod_{i=1}^{N} p(\varepsilon_{ij}) = (2\pi\sigma)^{-N/2} e^{-\sum_i \frac{\varepsilon_{ij}^2}{2\sigma^2}} \quad (10)$$

To find the ML estimate of the prewhitener coefficient at frequency f_j ($\hat{a}_{ML}(f_j)$), we maximize ln $p(\varepsilon_j)$:

$$\frac{\partial \ln p(\varepsilon_j)}{\partial a_j} = -\frac{1}{\sigma^2}\sum_i \Phi_{Xij}(a_j\Phi_{Xij} - {}^{N_0}\!/_{2}\,\alpha_i) \quad (11)$$

The resulting estimate is found to be equal to:

$$\hat{a}_{ML}(f_j) = \frac{N_0}{2}\frac{\sum_i \alpha_i \Phi_{Xij}}{\sum_i \Phi_{Xij}^2} \quad (12)$$

In a similar fashion, the estimate of α is found to be equal to:

$$\hat{\alpha}_{ML\,i} = \frac{2}{MN_0}\sum_{j=1}^{M} a_j \Phi_{Xij} \qquad (13)$$

Assuming we have minimized the part $\sum_i (a_j\Phi_{Xij} - {}^{N_0}\!/\!_2\,\alpha_i)^2$ of the log-likelihood function to produce a_j then:

$$\frac{1}{M}\sum_{j=1}^{M} a_j \Phi_{Xij} \rightarrow \frac{N_0}{2} \qquad (14)$$

and (12) can be approached by:

$$\hat{a}_{ML}(f_j) \approx \frac{N_0}{2}\frac{\sum_i \Phi_{Xij}}{\sum_i \Phi^2_{Xij}} \qquad (15)$$

4. RESULTS

The previous results are applied in the context of detecting a target lying on the seafloor. The experiment was held on Lake Geneva using a wideband sonar system with a constant directivity in the frequency range 20-140 kHz [3]. The transmitted signal is a linear frequency modulated waveform with a large time bandwidth product TB = 120 and a pulse repetition period to transmitting time T_R/T = 1000.

The detection of a sphere target on a silty lake bottom is investigated. The data echoes are characterized by the input signal-to-noise ratio. The output signal-to-noise ratio at time n_0 is computed by applying Eq. (4).

Fig. 1 shows the variability and the coloration of noise power spectra in the case of the silty bottom reverberation. Fig. 1 also compares the noise power spectra to the spectrum of the target to detect.

The performances of two different detectors are compared. Detector 1 (D1) consists of an AR prewhitener and a matched filter. Detector 2 (D2) consists of the wideband inverse filter and a matched filter. Fig. 2 summarized the performances of these detectors in term of signal-to-noise ratio. The amplitude in Fig. 2 is given by the ratio $\rho_i(n_0)$/snr as a function of the ith signal. snr denotes the linear value of the input signal-to-noise ratio and SNR the corresponding log value. Fig. 3 give an example of experimental data and the output receivers corresponding to D1 and D2.

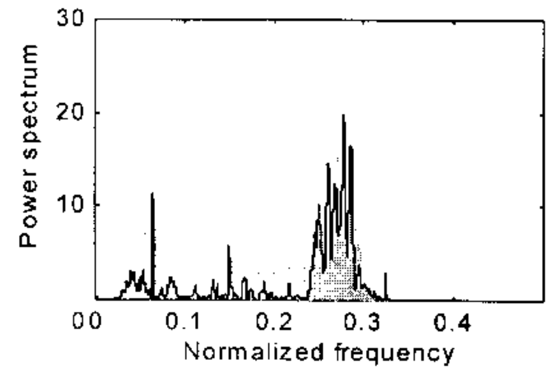

Fig. 1. (......) Noise power spectra of the silty bottom reverberation. (—) Spectrum of the sphere target to detect.

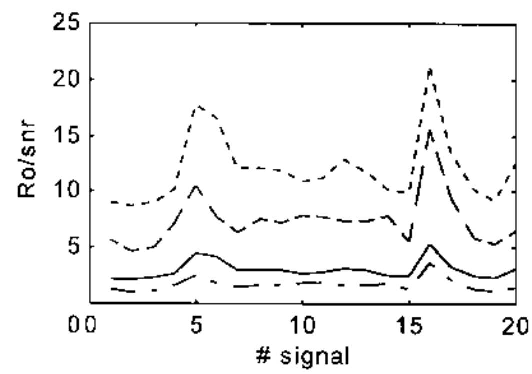

Fig. 2. Output of detector D1: (-.-.) SNR = 0 dB and (---) SNR = 6 dB. Output of detector D2: (—) SNR = 0 dB and (....) SNR = 6 dB.

5. CONCLUSION

The findings have shown the ability of our wideband receiver to detect a known signal in a colored and variable background reverberation.

The detector has been compared to an AR prewhitener and has shown better performances in term of signal-to-noise ratio. This is because, by controlling the reverberation noise coloration and the variability, the noise at the output of the wideband inverse filter is better whitened.

Acknowledgement

This work has been supported by the "Programme de Recherches Avancées de Coopération Franco-Chinoises".

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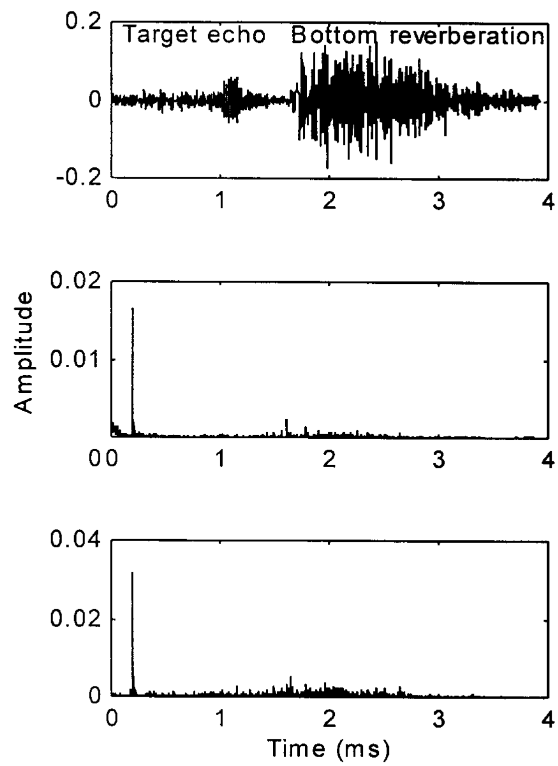

Fig. 3. From upper to lower. Experimental data. Output of detector D1. Output of detector D2.