Report no. changed (Mar 2006): SR-263-UU

SACLANTCEN REPORT
serial no: SR-263

SACLANT UNDERSEA
RESEARCH CENTRE
REPORT

CHANNEL-SENSITIVE PROCESSOR: DEVELOPMENT AND DETECTION PERFORMANCE EVALUATION

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March 1997

Report no. changed (Mar 2006): SR-263-UU

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Report no. changed (Mar 2006): SR-263-UU

Channel-sensitive processor: development and detection performance evaluation

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The content of this document pertains to work performed under Project 041-2 of the SACLANTCEN Programme of Work. The document has been approved for release by The Director, SACLANTCEN.

Jan L. Spoelstra
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Report no. changed (Mar 2006): SR-263-UU

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Channel-sensitive processor: development and detection performance evaluation

D. Alexandrou and G. Haralabus

Executive Summary: Active sonar systems, such as the LFAS, have extensively used the matched filter for detection purposes. This technique is designed to maximize the signal-to-noise ratio (SNR) of known signals and is able to provide satisfactory resolution both in range and frequency. It is a widely-used, model-free method which has no dependence on the nature of the waveguide. Even with limited *a priori* information about the acoustic channel, the matched filter provides a response which can serve as the basis for detection. In an ambient noise-limited scenario, the signal-to-noise ratio can be improved by increasing the power of the transmitted signal. However, this approach is not effective in a reverberation limited environment.

Shallow water dense multipath conditions often cause the matched filter output to be so distorted and obscured that reliable detection is not possible. In such cases, it seems reasonable to try to use all available information about the acoustic channel to enhance the detection performance of the processor.

The objective of this project is twofold: first to investigate the feasibility of improving upon the performance of the conventional matched filter by exploiting characteristics of the medium, and second, to maintain the performance enhancement when the dominant source of interference is reverberation.

This report presents a Channel Sensitive Processor (CSP) which may significantly improve the performance of the matched filter both in ambient noise and reverberation limited conditions. The balance between potential advantages and drawbacks is explained and the effects of environmental mismatch are examined. Future plans include sensitivity study of the CSP to propagation parameters using global search methods.

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Channel-sensitive processor: development and detection performance evaluation

D. Alexandrou and G. Haralabus

Abstract: A Channel Sensitive Processor (CSP) which improves upon the detection performance of the traditional matched filter is developed. This method compensates for the performance degradation of the matched filter due to dense multipath conditions by utilizing existing information about the channel propagation conditions. Furthermore, it is proven that the CSP is able to enhance target detection in a reverberation limited environment. Finally, the sensitivity of the CSP to mismatch of the source coordinates is demonstrated.

Keywords: CSP – matched filter – multipath – reverberation – mismatch

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Contents

1

Introduction

Traditionally, target detection with active sonar has been approached through matched filtering. This is quite understandable because the matched filter is simple and effective and can yield significant signal-to-noise ratio (SNR) enhancement while maintaining desirable resolution characteristics both in range and Doppler. The choice of transmitted signal is of crucial importance with due regard to both resolution properties as expressed by the ambiguity function and the transmission characteristics of the channel. The FM family of signals has long been popular in this context and a variant of this family (the Linear FM (LFM)) is the transmitted signal used by the LFAS system. It should also be said, however, that the matched filter is generally suboptimal in nearly all realistic sonar scenarios. Typically, the transmitted signal suffers considerable distortion as it propagates through the ocean channel [1] and is no longer perfectly correlated with the transmitted replica. The performance limitations of the matched filter are most evident in shallow water environments characterized by dense multipath propagation. These conditions give rise to extensive time spreading which makes detection and localization difficult [2].

Of course, the matched filter is impervious to the actual propagation conditions and therein lies a good deal of its attraction. Even in the complete absence of information about the channel, one may expect some kind of response, distorted and obscure as it may be, which can serve as the basis for a detection. The main objective of this project is to answer the following question: Can the performance of traditional matched filtering be improved upon by utilizing existing information, however uncertain or incomplete, about the nature of the acoustic channel? The answer can only be meaningful if it is provided in the context of operational sonar parameters and is based on a balanced view of potential performance gains and potential pitfalls. The latter can most readily arise in cases of environmental mismatch, a problem likely to be exacerbated in active sonar scenarios which tend to be highly dynamic and typically offer small windows of opportunity for a positive contact. In addition, even a successful methodology can be rendered practically useless by excessively large requirements for computing resources.

It is with full awareness of these potential limitations that we propose to proceed with the development of a Channel Sensitive Processor (CSP) which may significantly improve upon the detection performance of the matched filter and still be efficient enough to be useful in an operational setting. The objective function to be used is simply the peak energy of the matched filter. The focus is on the potential advantage which may be gained by matching the environmental propagation effects as well as the transmitted signal.

In this initial study, we present the mathematical derivation of the CSP for both noise and reverberation-limited scenarios as well as simulation results supporting the mathematical predictions and illustrating the effects of environmental mismatch. Future work will be concerned with the computational aspects of the matching process to be implemented through SAGA [3] a genetic algorithm which has been successfully applied in several matched field applications [4].

2

Matched filter detectors

The matched filter is a linear time-invariant filter designed to maximize the peak pulse signal in the presence of noise [5]. Let $[f(t) + n(t)]$ be the input to the filter, where $f(t)$ is the received signal and $n(t)$ is the additive noise. Then $[f_o(t) + n_o(t)]$ denotes the output of the filter and the purpose is to maximize the ratio $|f_o(t)|/\sqrt{\overline{n_o^2(t)}}$ or, more conveniently, maximize the square of this ratio, i.e.

$$\Lambda = \frac{|f_o(t_m)|^2}{\hat{n}} = \max \frac{|f_o(t)|^2}{\overline{n_o^2(t)}} \tag{1}$$

where $t = t_m$ is the optimum observation time, and $\hat{n} = \overline{n_o^2(t)}$ denotes the square-mean value of the noise (independent of t).

Let $H(\omega)$ be the transfer function of the desired filter, $F(w)$ the Fourier transform of the received signal, and $S_n(\omega)$ the power spectral density of the noise. Then, the output signal is given by

$$f_o(t_m) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} F(\omega)H(\omega)\exp(-j\omega t_m)d\omega \tag{2}$$

and the output noise power is

$$\hat{n} = \frac{1}{2\pi} \int_{-\infty}^{+\infty} S_n(\omega)|H(\omega)|^2 d\omega \tag{3}$$

Then, ratio (1) becomes

$$\Lambda = \frac{|f_o(t_m)|^2}{\hat{n}} = \frac{1}{2\pi} \frac{\left|\int_{-\infty}^{+\infty} F(\omega)H(\omega)\exp(-j\omega t_m)d\omega\right|^2}{\int_{-\infty}^{+\infty} S_n(\omega)|H(\omega)|^2 d\omega} \tag{4}$$

The transmitted signal $s(t)$ belongs to the LFM family and is defined in the following way [6]

$$s(t) = \mathrm{rect}(t/T)\exp(j2\pi f_t t) \tag{5}$$

where

$$\mathrm{rect}(t/T) = \begin{cases} 1 & \text{if } 0 \leq t \leq T \\ 0 & \text{elsewhere,} \end{cases} \tag{6}$$

and

$$f_t = \left(f_c - \frac{B}{2}\right) + \frac{1}{2}B\frac{t}{T}, \tag{7}$$

T is the time duration, B is the bandwidth, and f_c is the central frequency of the transmitted signal.

Let the channel impulse response be $g(t)$. The received signal is the convolution of $g(t)$ and $s(t)$, i.e.

$$f(t) = g(t) \otimes s(t) \tag{8}$$

or equivalently in the frequency domain

$$F(\omega) = G(\omega)S(\omega) \tag{9}$$

where $S(\omega)$ is the Fourier transfer of $s(t)$, $G(\omega)$ is the channel transfer function. For notational simplicity range independence is assumed; the same results apply for range-dependent scenarios.

Finally, it is assumed that $n(t)$ is white noise. Then, its spectrum is given by

$$S_n(\omega) = \frac{N_o}{2} \tag{10}$$

Substitution of Eq. (9) and (10) into Eq. (4) gives the general expression for the matched filter output

$$\Lambda = \frac{|f_o(t_m)|^2}{\hat{n}} = \frac{1}{N_o \pi} \frac{\left| \int_{-\infty}^{+\infty} G(\omega) S(\omega) H(\omega) \exp(-j\omega t_m) d\omega \right|^2}{\int_{-\infty}^{+\infty} |H(\omega)|^2 d\omega} \tag{11}$$

2.1 Conventional Matched Filter

The conventional matched filter algorithms is independent of the propagation conditions and directly correlates the received pressure field with a replica of the transmitted signal. The transfer function of this filter is

$$H(\omega) = kS^*(\omega) \exp(j\omega t_m) \tag{12}$$

where $S^*(\omega)$ is the complex conjugate of the transmitted signal and k is an arbitrary constant which is set $k = 1$ for convenience. Substitution of Eq. (12) into Eq. (11) gives the expression for the conventional MF output:

$$\Lambda_{\mathrm{mf}} = \frac{1}{\pi N_o} \frac{\left| \int_{-\infty}^{+\infty} G(\omega) |S(\omega)|^2 d\omega \right|^2}{\int_{-\infty}^{+\infty} |S(\omega)|^2 d\omega} \tag{13}$$

2.2 *Channel Sensitive Processor*

The CSP exploits existing information about the propagation channel by incorporating the channel's response in the signal matching process. The transfer function of the CSP is written as:

$$H(\omega) = kG^*(\omega)S^*(\omega)\exp(j\omega t_m) \tag{14}$$

where $G^*(\omega)$ and $S^*(\omega)$ are the complex conjugates of the channel transfer function and the transmitted signal respectively. Again, k is an arbitrary constant which is set to unity.

The combination of Eq. (11) and Eq. (14) yields the CSP output

$$\Lambda_{\text{csp}} = \frac{1}{\pi N_o} \frac{\left| \int_{-\infty}^{+\infty} |G(\omega)|^2 |S(\omega)|^2 \right|^2}{\int_{-\infty}^{+\infty} |G(\omega)|^2 |S(\omega)|^2 d\omega} \tag{15}$$

or equivalently

$$\Lambda_{\text{csp}} = \frac{1}{\pi N_0} \int_{-\infty}^{+\infty} |G(\omega)|^2 |S(\omega)|^2 d\omega \tag{16}$$

2.3 *Comparison of the two filters*

To compare the performance of the conventional match filter with the proposed CSP, it is convenient to form the output ratio of the two filters using Eq. (13), and (16)

$$\frac{\Lambda_{\text{csp}}}{\Lambda_{\text{mf}}} = \frac{\int_{-\infty}^{+\infty} |G(\omega)|^2 |S(\omega)|^2 \, d\omega \int_{-\infty}^{+\infty} |S^*(\omega)|^2 d\omega}{| \int_{-\infty}^{+\infty} G(\omega) |S(\omega)|^2 d\omega |^2} \tag{17}$$

Using the Schwarz inequality we have:

$$\left| \int_{-\infty}^{+\infty} G(\omega)\ S(\omega)\ S^{*}(\omega)\ d\omega \right|^{2} \leq \int_{-\infty}^{+\infty} |G(\omega)S(\omega)|^{2}\, d\omega \int_{-\infty}^{+\infty} |S^{*}(\omega)|^{2} d\omega \tag{18}$$

and Eq. (17) leads to:

$$\frac{\Lambda_{\mathrm{csp}}}{\Lambda_{\mathrm{mf}}} \geq \frac{|\int_{-\infty}^{+\infty} G(\omega)\ S(\omega)\ S^{*}(\omega) d\omega|^{2}}{\left|\int_{-\infty}^{+\infty} G(\omega)\ |S(\omega)|^{2}\ d\omega\right|^{2}} = 1 \tag{19}$$

This represents the potential performance gain offered by the CSP technique. It must be noted that this result is valid under the assumption that the propagation conditions of the channel are predicted exactly by CSP. The mismatch effect is examined in the following sections.

3

Simulation results

The formulae derived in the previous chapter were tested in the simulation environment shown in Fig. 1. The SNAP [7] program was used to create an acoustic channel subdivided into a 100 m water column, a 1 m sediment layer, and a semi-infinite subbottom. For simplicity, one-way propagation is modelled. A downward refracting sound speed profile (SSP) is used to simulate a summer Mediterranean profile with strong thermal gradient. This environment creates dense multipath conditions as is apparent from the impulse response and the transfer function of the channel shown in Fig. 2. For computational efficiency, the waveguide is assumed to be homogeneous in azimuth and range independent, although the proposed approach is valid in more general conditions. The source was placed at 70 m depth and the receiver at 65 m depth and 1300 m range. The transmitted LFM pulse, shown in Fig. 3, had a bandwidth of 200 Hz, centered at 575 Hz.

Figure 4(a) shows the received signal (convolution of the LFM with the channel impulse response), and Fig. 4(b), (c) show the same signal corrupted with white noise for two SNRs, namely SNR=10 dB and SNR=−17 dB. These noise levels where chosen so that the signal is either slightly contaminated by noise or totally obscured by it. In each case, the performance of the conventional matched filter and the CSP are examined.

Figure 5 shows the output of the two methods for SNR=10 dB. Both processors demonstrate high correlation values between the received signal and the replica. The peak-to-sidelobe gain is 3 dB for the conventional method and 11 dB for the CSP. Figure 6 shows the performance of the two methods for SNR=−17 dB. It appears that in extreme noisy conditions the conventional matched filter is not able to detect the transmitted signal. On the contrary, the proposed CSP utilizes the channel's transfer function to compensate for the difference in traveltime of various wavefronts. In this way, CSP is able to process coherently mutliple arrivals of the transmitted signal, which results in a 8 dB peak-to-sidelobe signal resolution, as shown in Fig. 6.

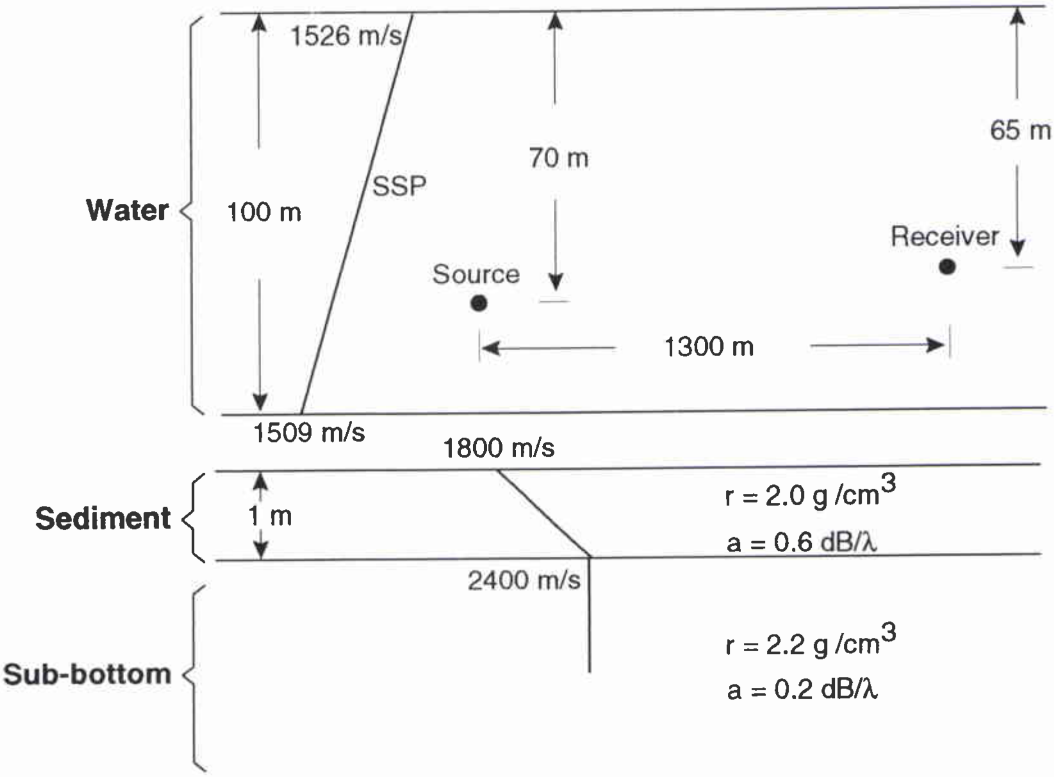
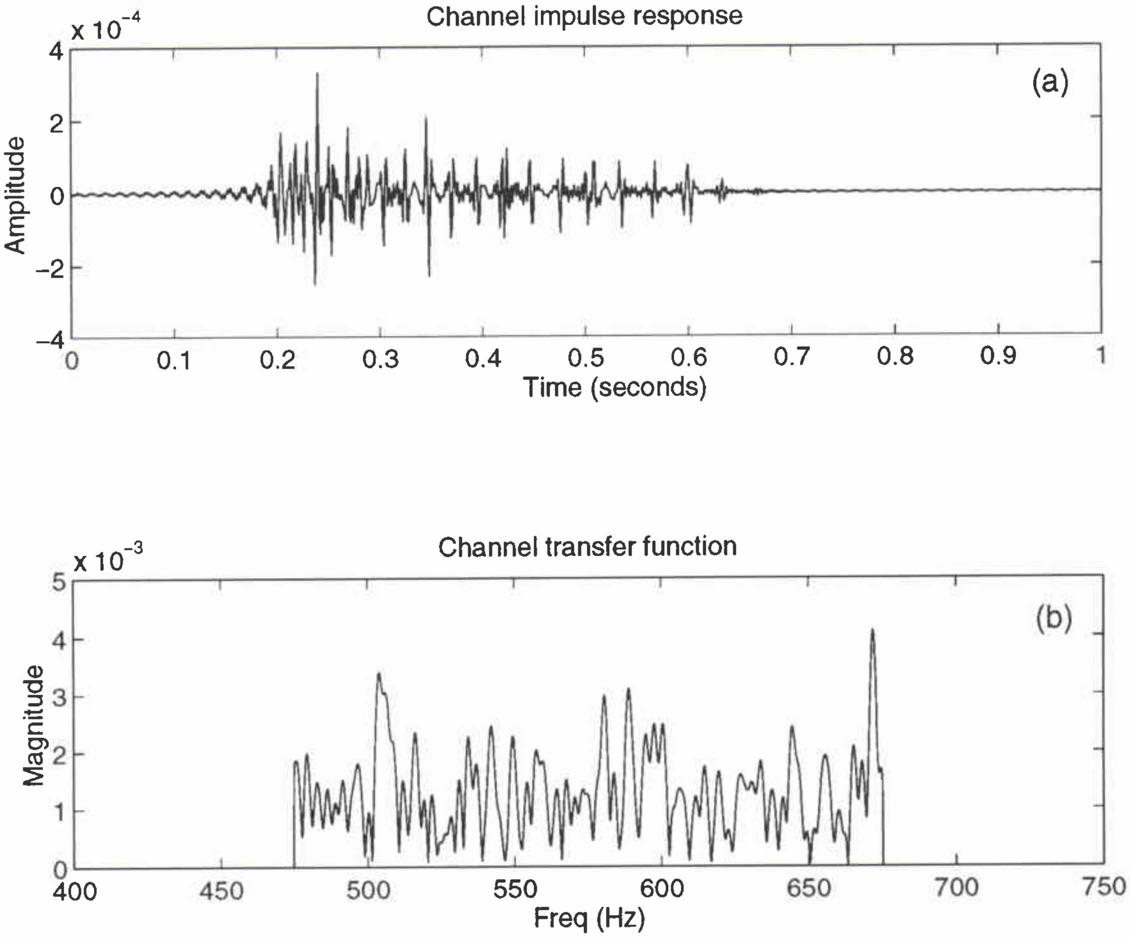


Figure 1: Simulation geometry (not to scale).



Channel impulse response

Channel transfer function

Figure 2: a) The impulse response, and b) the transfer function of the acoustic channel.

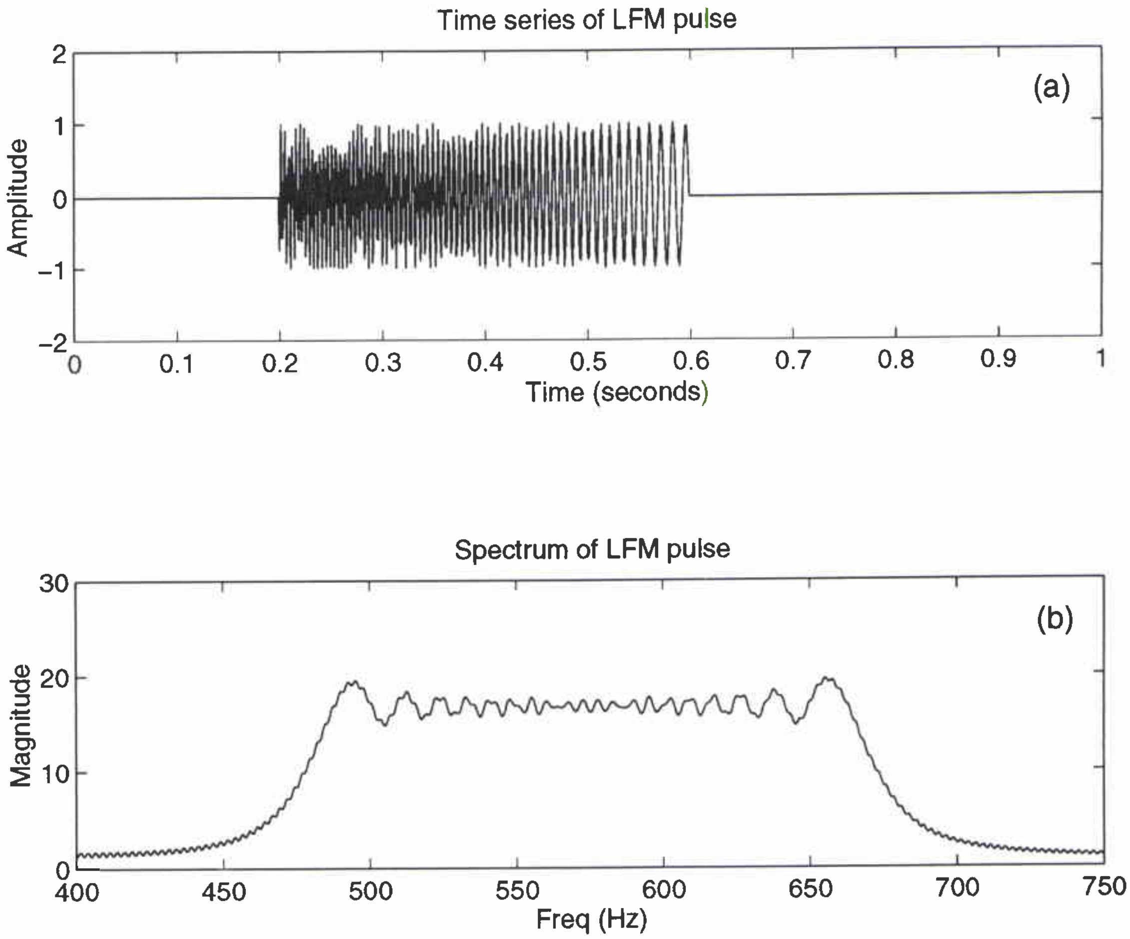


Figure 3: a) The time series, and b) the frequency spectrum of the transmitted LFM pulse.

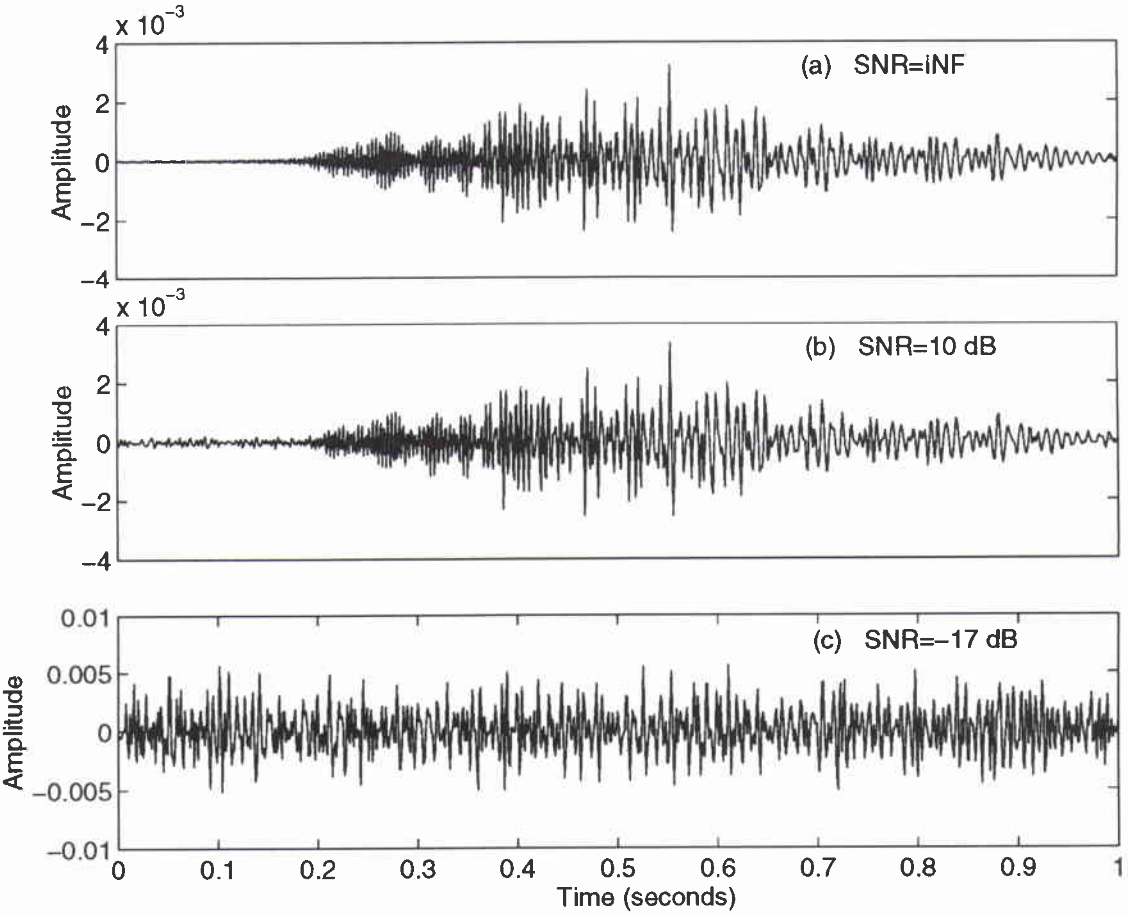


Figure 4: Time series of the received signal a) without noise, and b), c) with additive white noise with SNR=10 dB and SNR= −17 dB respectively

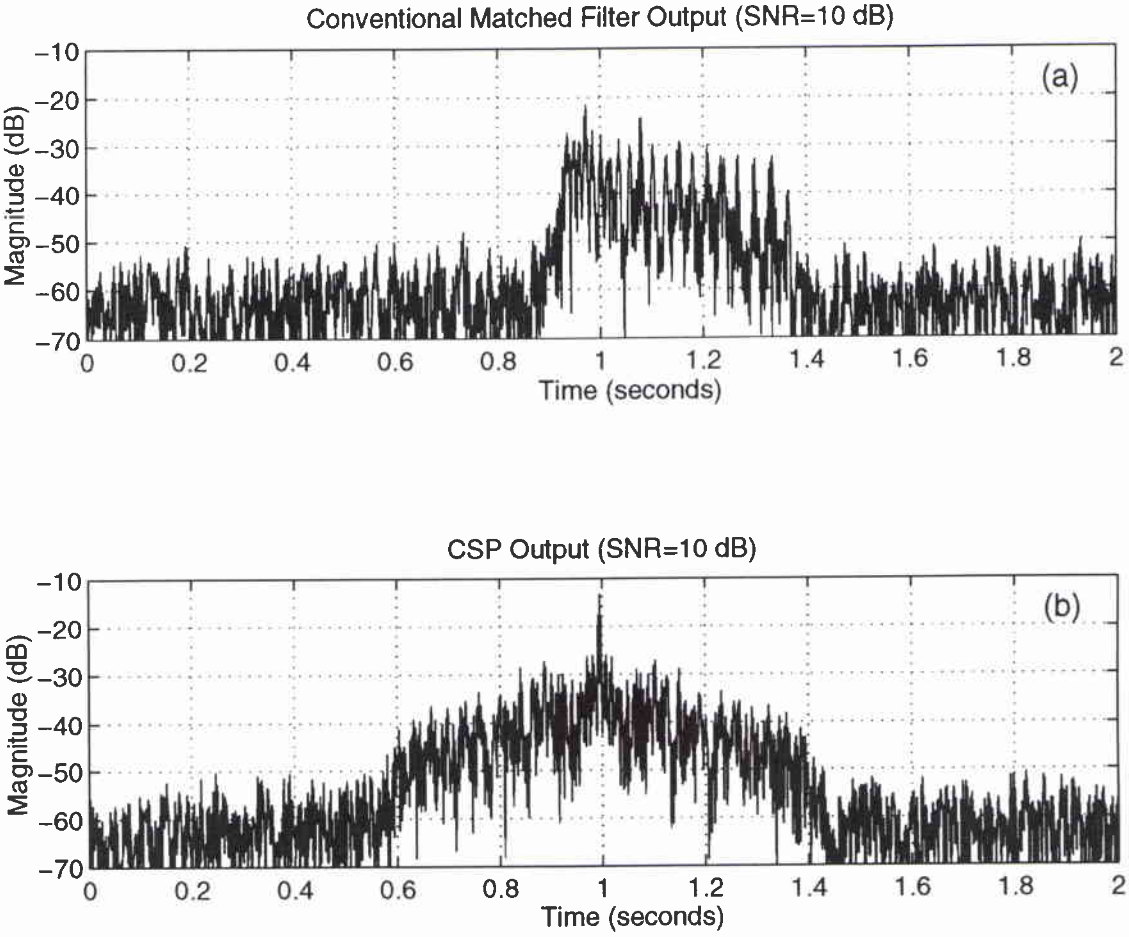


Figure 5: Detection performance of a) the conventional matched filter, and b) the CSP methods. The SNR is 10 dB.

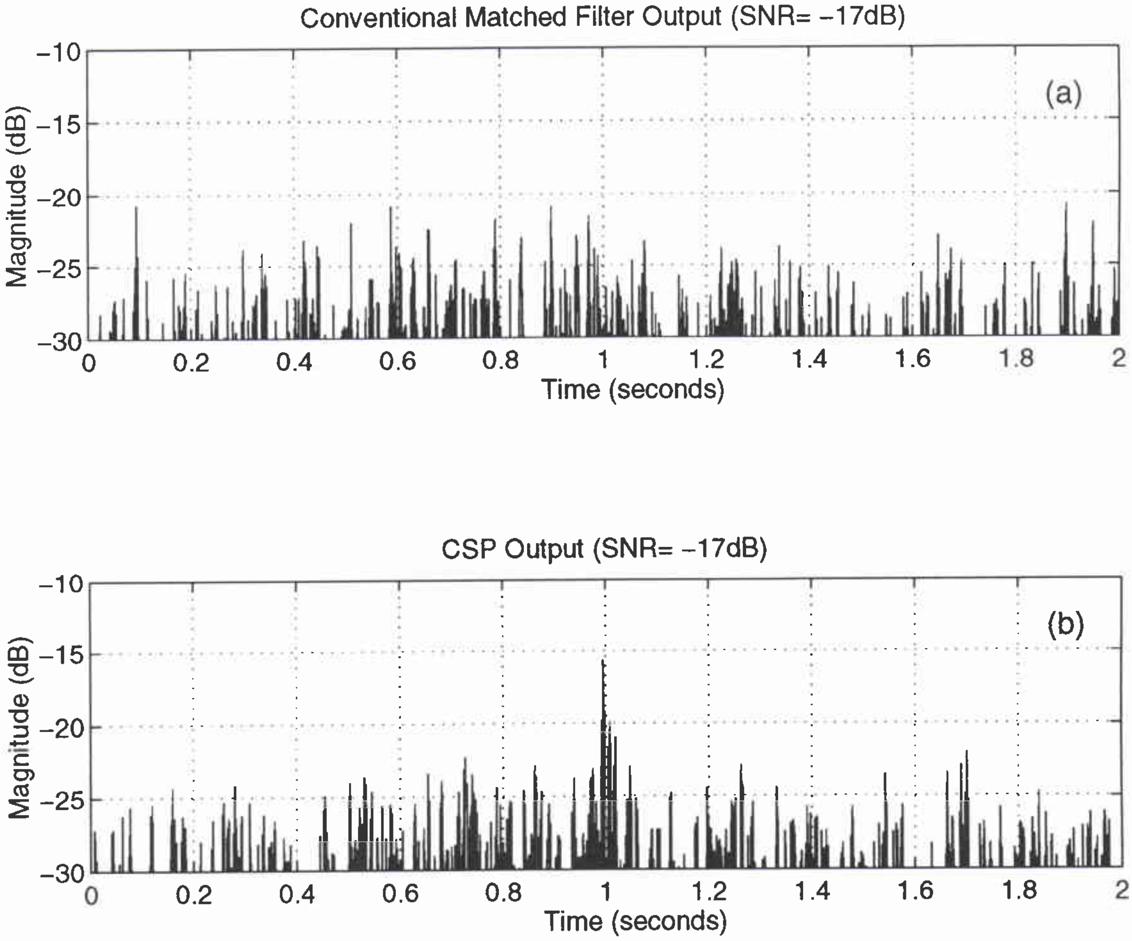


Figure 6: Detection performance of a) the conventional matched filter, and b) the CSP methods. The SNR is −17 dB.

4

CSP and conventional matched filter performance comparison for source location ambiguity

In real life scenarios, the exact location of the target with respect to the source and the receiver is unknown. As the CSP method utilizes information about the geometry of the waveguide, it is important to assess the sensitive of this method to the geometric channel parameters. For simplicity, one-way transmissions are simulated, thereby limiting the problem to the uncertainty of the transmitter's range and depth. A grid of possible locations was created in the vicinity of the true transmitter at 65 m depth and 1320 m range. The search area limits were 1200 to 1400 m in range and 50 to 80 m in depth. Ambiguity surfaces representing the output ratio of the two processors expressed by Eq.(17) were created. To reduce the variations of the output, the procedure is repeated 20 times each time with a different noise series and the results are averaged. Figure 7 shows the ambiguity surface for SNR=10 dB. The peak at the correct source coordinates indicates that when there is sufficient *a priori* information about the geometry of the channel, the CSP outperforms the conventional matched filter method. However, when there is mismatch between the actual and the assumed distances the matched filter may provide better results than CSP. In Fig. 7, the ambiguity surface values vary from −7 dB to 8 dB which implies that the CSP is quite sensitive to the source location. It can also be seen that the performance of the CSP does not degrade gradually moving away from the center of the surface. This behavior is due to the dense multipath conditions which even over short distances promote considerable changes in the interference patterns of the acoustic field. Figure 8 corresponds to the SNR=−17 dB case. The two methods demonstrate again similar performance to the previous case, the only difference being that for low SNR the variation of ambiguity surface values is smaller (−4 dB to 6 dB).

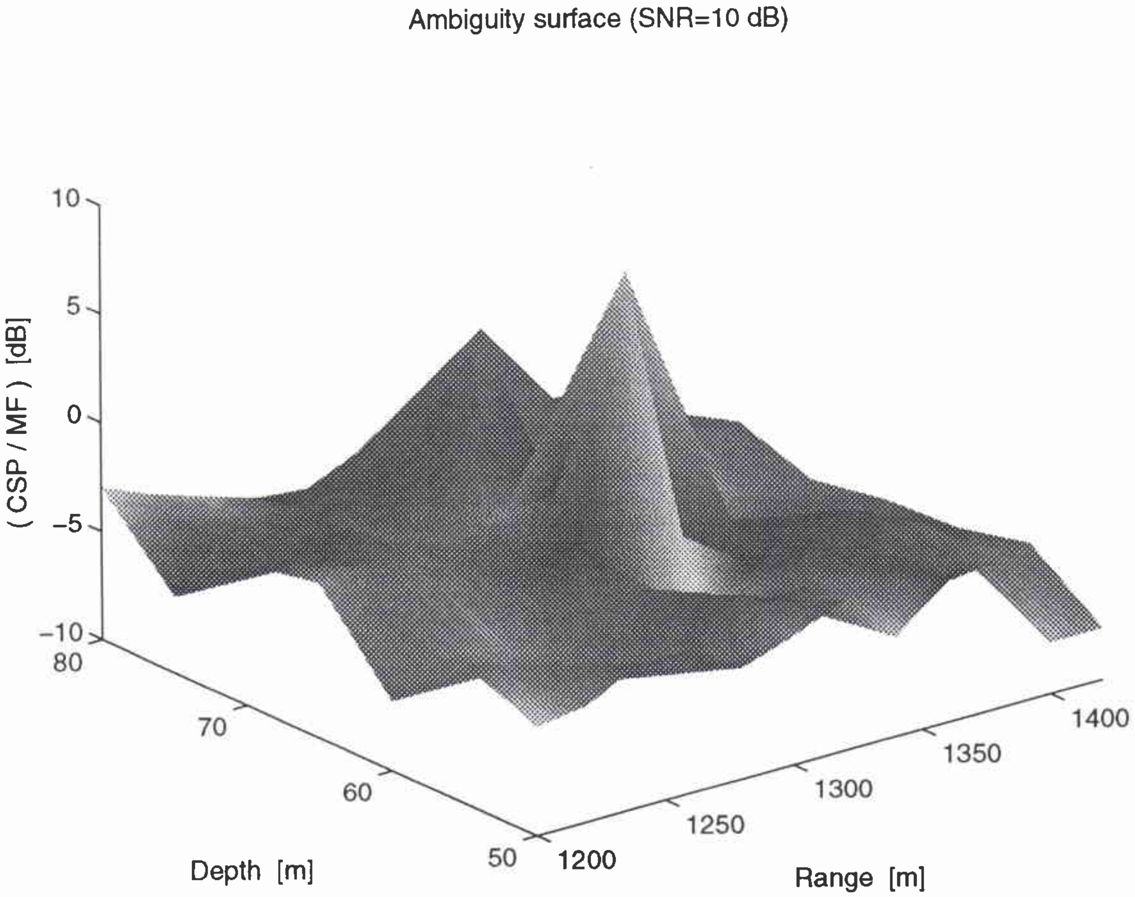


Figure 7: Ambiguity surface of the output ratio of the CSP and the conventional matched filter expressed by Eq. (17). The SNR is 10 dB.

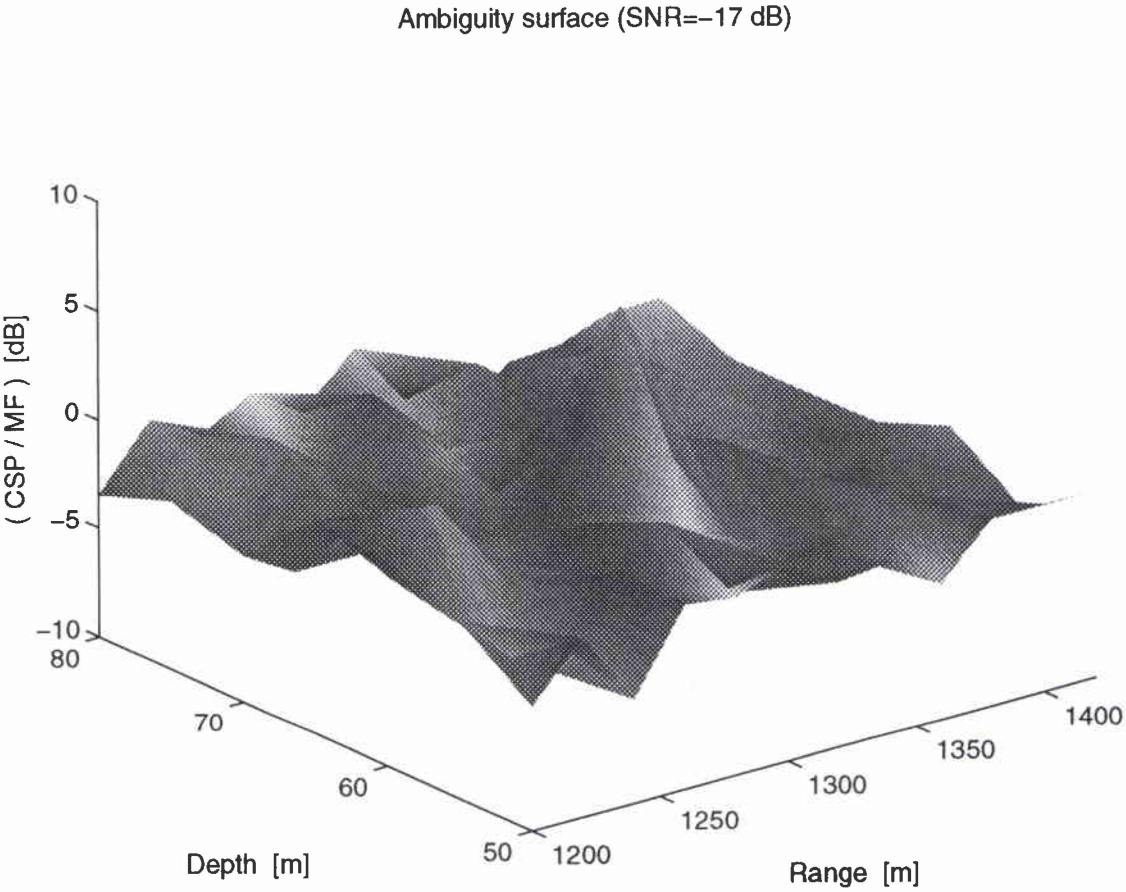


Figure 8: Ambiguity surface of the output ratio of the CSP and the conventional matched filter expressed by Eq. (17). The SNR is -17 dB.

5

Reverberation

It is well known that reverberation is a limiting factor to the detection performance of sonar systems. It is caused by the scattering of energy from the propagation pulse as a result of inhomogeneities in the acoustic channel and its boundaries [8]. Active systems must compete with reverberation as well as with ambient noise to identify a target echo from an obscured signal return [9]. The main difficulty in processing signals corrupted with reverberation is that the SNR cannot be improved by increasing the power of the transmitted signal. However, the detection performance of the processor may be enhanced by taking advantage of the fact that the reverberation spectrum is the same as that of the transmitted signal.

Let us reconsider the matched filter output in a reverberation limited environment in which the power spectral density of the reverberation signal has the same form as the power spectrum of the transmitted waveform [5], i.e

$$S_n(\omega) = \alpha \, |S(\omega)|^2 \tag{20}$$

where $|S(\omega)|^2$ is the power spectrum of $s(t)$ and α a constant set to $\alpha = 1$ for simplicity.

Using Eq. (4), (12), and (20), the output of the conventional matched filter becomes

$$\Lambda_{\mathrm{mf}} = \frac{1}{2\pi} \frac{\left| \int_{-\infty}^{+\infty} G(\omega) |S(\omega)|^2 d\omega \right|^2}{\int_{-\infty}^{+\infty} |S(\omega)|^4 d\omega} \tag{21}$$

Similarly, combining Eq. (4), (14), and (20), the output of the CSP can be expressed as:

$$\Lambda_{\text{csp}} = \frac{1}{2\pi} \frac{\left| \int_{-\infty}^{+\infty} |G(\omega)|^2 |S(\omega)|^2 \right|^2 d\omega}{\int_{-\infty}^{+\infty} |G(\omega)|^2 |S(\omega)|^4 d\omega} \tag{22}$$

Consequently, the output ratio of the two filters is given by

$$\frac{\Lambda_{\text{csp}}}{\Lambda_{\text{mf}}} = \frac{\mid \int_{-\infty}^{+\infty} |G(\omega)|^2 |S(\omega)|^2 d\omega \mid^2 \; \int_{-\infty}^{+\infty} |S(\omega)|^4 d\omega}{\mid \int_{-\infty}^{+\infty} G(\omega) |S(\omega)|^2 d\omega \mid^2 \; \int_{-\infty}^{+\infty} |G(\omega)|^2 |S(\omega)|^4 d\omega} \tag{23}$$

The Schwarz inequality applies directly to the denominator of the above ratio, yielding:

$$\left| \int_{-\infty}^{+\infty} G(\omega) |S(\omega)|^2 d\omega \right|^2 \leq \int_{-\infty}^{+\infty} |G(\omega)|^2 d\omega \int_{-\infty}^{+\infty} |S(\omega)|^4 d\omega \tag{24}$$

Thus, Eq. (23) becomes

$$\frac{\Lambda_{\text{csp}}}{\Lambda_{\text{mf}}} \geq \frac{\mid \int_{-\infty}^{+\infty} |G(\omega)|^2 |S(\omega)|^2 d\omega \mid^2}{\int_{-\infty}^{+\infty} |G(\omega)|^2 d\omega \int_{-\infty}^{+\infty} |G(\omega)|^2 |S(\omega)|^4 d\omega} \geq 1 \tag{25}$$

The second inequality is valid because, by recalling the Schwarz inequality, the numerator is proven to be greater or equal than the denominator. Eq. (25) demonstrates that the utilization of the CPS can improve upon the detection performance of the matched filter in a reverberation limited environment. Finally, it should be mentioned that Eq. (25) assumes perfect agreement between the actual and the modelled propagation conditions.

6

Reverberation simulation results

The performance of the CSP was compared with that of the matched filter for cases in which reverberation was the only noise source. Reverberation was modelled as bandpass noise produced by multiplication of the white noise and the LFM signal spectra. This created a random process which complied with the reverberation spectrum condition expressed by Eq. 20.

The output of the matched filter and the CSP are shown in Fig. 9 and 10 which correspond to SNR=10 dB and SNR=−17 dB respectively. Similarly to the white noise case, for low noise levels, both methods provide comparable signal detection (Fig 9). On the contrary, for high noise levels, the conventional matched filter is not able to identify the transmitted signal while the CSP scheme has a maximum correlation peak with 5 dB gain over the sidelobes (Fig 10). These results verify the theoretical prediction expressed by Eq. (25) according to which the CPS enhances the detection performance of the traditional matched filter, even in a reverberation limited environment.

The source location sensitivity study was repeated for the reverberation case. The search grid was set at 1200 to 1400 m in range and at 50 to 80 m in depth. The actual source was situated at 65 m depth and 1320 m range. Eq. (23) was computed for each grid point 20 times each time with a different noise realization and the average result is plotted. The ambiguity surfaces which correspond to SNR=10 dB and SNR=−17 db are shown in Fig. 11 and 12 respectively. It is observed that the performance of the CSP is significantly degraded due to source location mismatch demonstrating again that in utilizing the CPS scheme, accurate *a priori* information about the propagation channel is of primary importance.

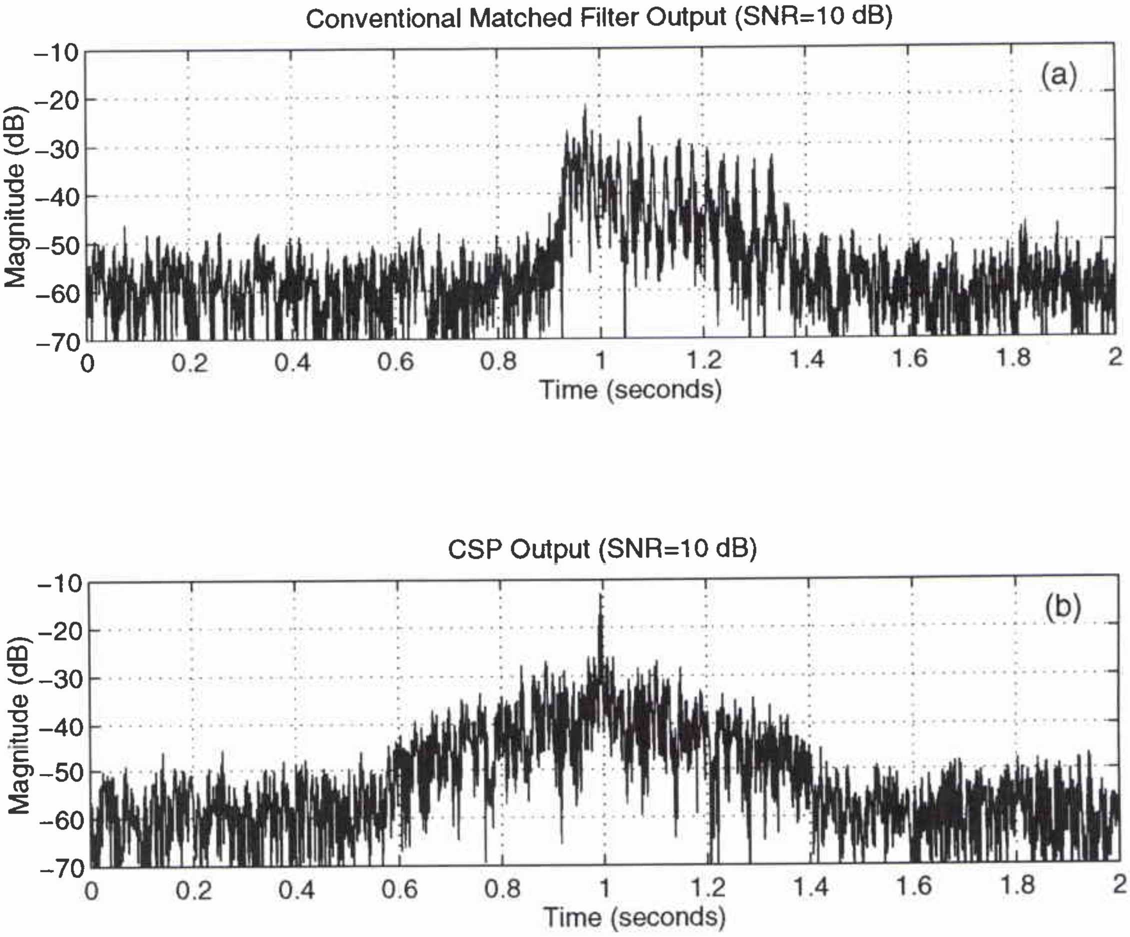


Figure 9: Reverberation limited environment: detection performance of a) the conventional matched filter, and b) the CSP methods. The SNR is 10 dB.

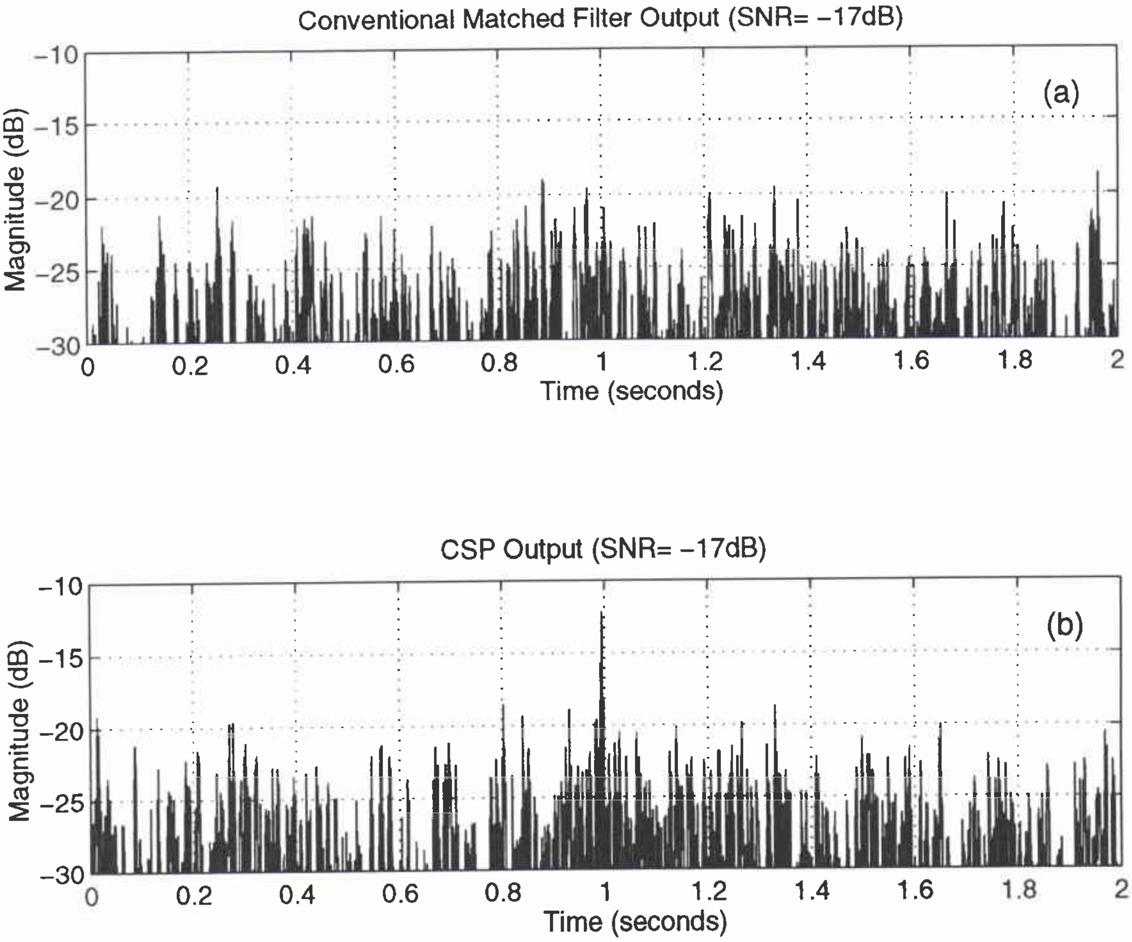


Figure 10: Reverberation scenario: detection performance of a) the conventional matched filter, and b) the CSP methods. The SNR is −17 dB.

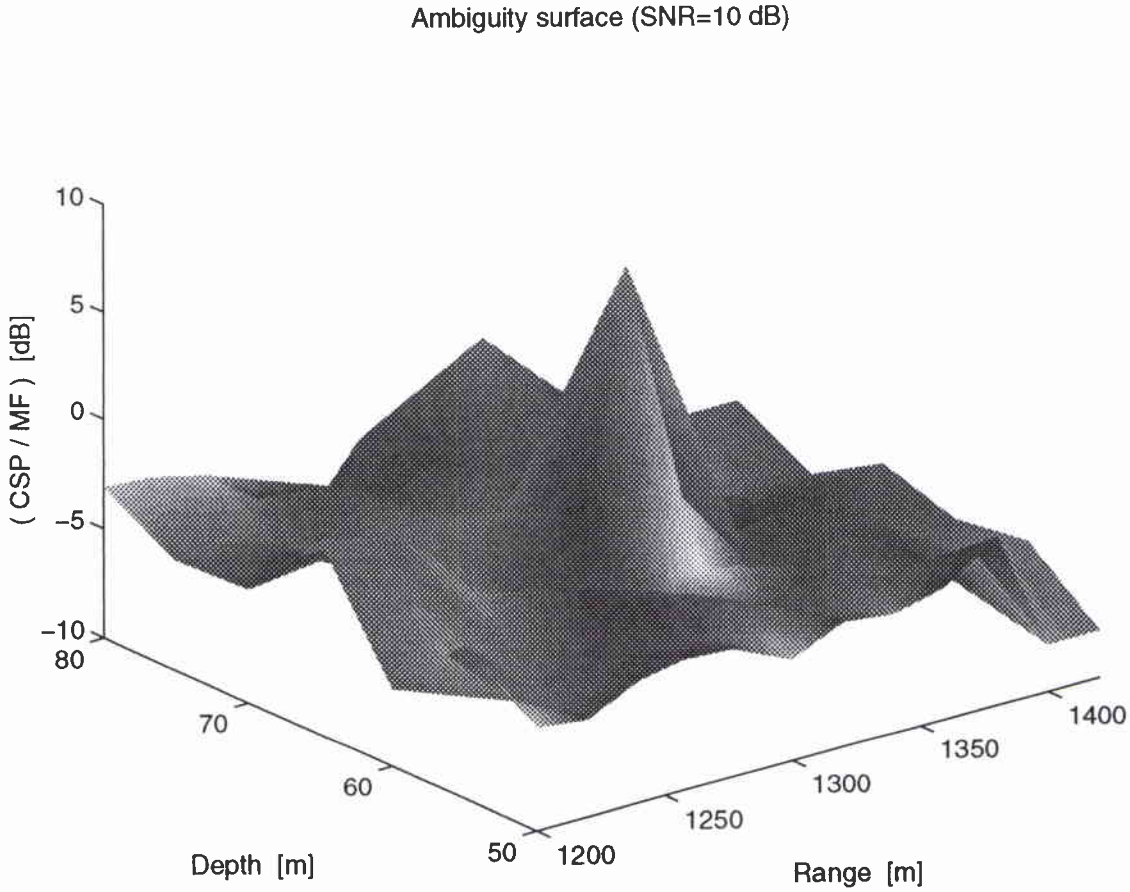


Figure 11: Reverberation scenario: Ambiguity surface of the output ratio of the CSP and the conventional matched filter expressed by Eq. (23). SNR=10 dB.

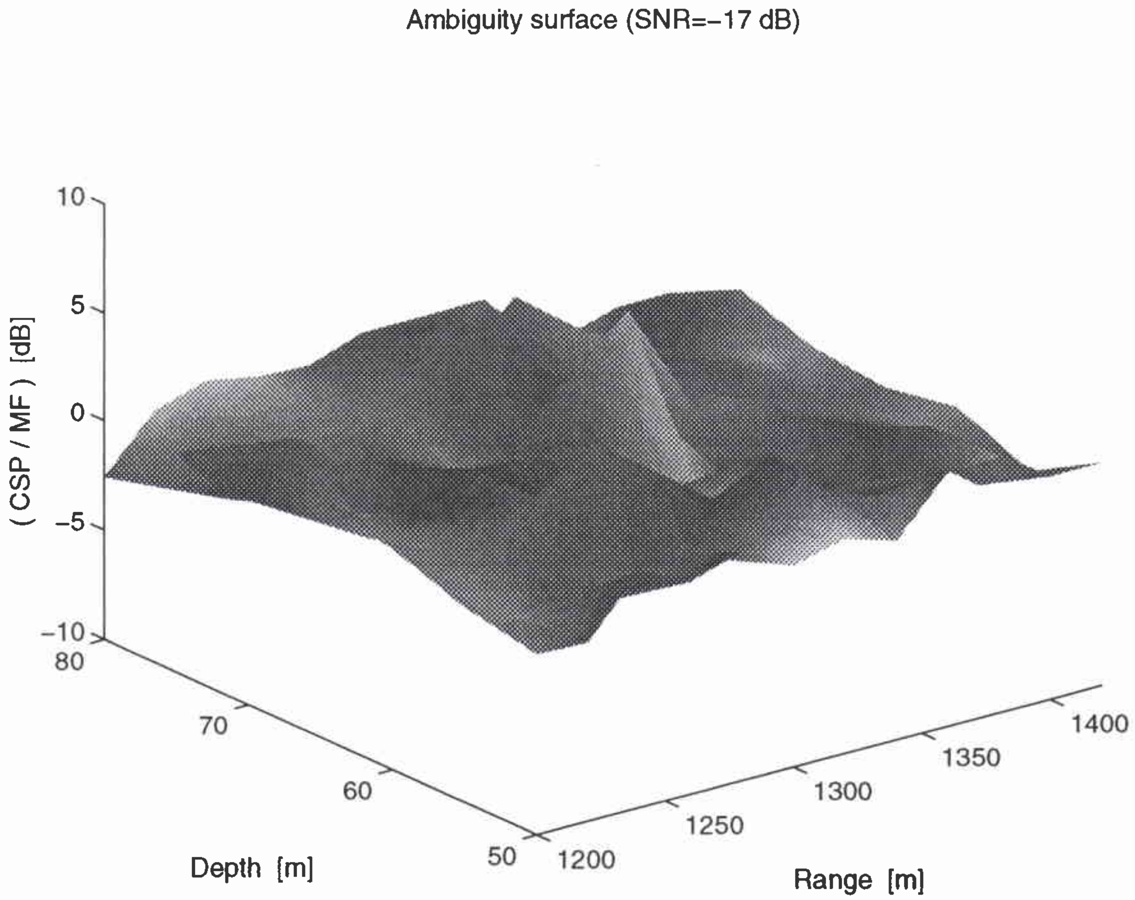


Figure 12: Reverberation scenario: Ambiguity surface of the output ratio of the CSP and the conventional matched filter expressed by Eq. (23). SNR=−17 dB.

7

Conclusions

It has been demonstrated that in dense multipath conditions the matched filter output is distorted by the propagation conditions. This report presents a new processor (CSP) which utilizes *a priori* information about the channel in an effort to improve detection performance and localization capability. The CSP exploits the transfer function of the channel to compensate for the signal distortion due to the medium. This new scheme was compared with the traditional matched filter in noisy environmental conditions. It was found that for low noise levels, both techniques provide successful detection results with the CSP offering an additional $\sim$ 8 dB gain over the matched filter. For high noise levels, it was shown that the CSP was the only method to detect the transmitted signal.

In spite of its enhanced detection performance, the CSP was found to be sensitive to source location mismatch. Ambiguity surfaces demonstrated that for various combinations of the source range and depth, the CSP's performance decreased below that of the matched filter. This observation, in conjunction with the fact that for high SNR the two techniques have similar performance suggest that the two processors may be used sequentially. In cases where the matched filter output indicates an ambiguous target detection, the CSP can be applied to a confined area close to the initial contact to increase the target resolution.

It has been shown that the above results are valid for either white noise or reverberation limited conditions. This is an important conclusion as in reverberation cases the SNR cannot be increased artificially by increasing the power of the transmitted signal (this would also increase the reverberation level). The CSP overcomes this problem by utilizing information about the propagation conditions to increase the correlation between the actual and the modelled received signal.

Future work should focus on the statistical analysis of the CSP. The sensitivity of this processor to propagation parameter must be assessed. Global optimization approaches, such as the SAGA genetic algorithm, will be used to efficiently manage a simultaneous analysis of more than two channel parameters. Finally, to make CSP useful in operational situations, an assessment of its computational requirements must be provided.

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Report no. changed (Mar 2006): SR-263-UU

Document Data Sheet

Security Classification		*Project No.* 041-2
Document Serial No. SR-263	*Date of Issue* March 1997	*Total Pages* 32 pp.

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Keywords

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