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**SACLANT UNDERSEA
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MEMORANDUM**



**CHANNEL SENSITIVE PROCESSOR:
REAL DATA PROCESSING**

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NORTH ATLANTIC TREATY ORGANIZATION

**Channel Sensitive Processor:
Real data processing**

G. Haralabus

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Jan L. Spoelstra
Director

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**Channel Sensitive Processor: Real
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Executive Summary:

Matched filters are extensively used in active sonar systems. They are also called correlation receivers because they calculate the cross-correlation of the received signal with the known waveform of the transmitted signal. Target detection is based on the principle that the transmitted waveform is more correlated to signal replicas modified by the target interaction than to ambient noise or reverberation. In general, matched filters are considered robust detectors as they do not depend on the medium. However, shallow water propagation conditions can cause the matched filter output to be so distorted that no detection decision can be based on it. The Channel Sensitive Processor (CSP) has been developed to offer an alternative detection technique in which detection performance enhancement is managed by incorporating environmental information in the processing algorithm.

The CSP was successfully tested using simulation. It has been shown that for known propagation conditions it can significantly improve upon the performance of the classical matched filter method. However it was found to be very sensitive to environmental mismatch. This report describes the application of the CSP to experimental data. Using a one-way geometry the CSP demonstrates a 2-3 dB performance enhancement over the conventional matched filter method.

In general, the CSP is a signal processing tool which can be utilized in cases where there is evidence of strong multipath conditions in the propagation medium or when the conventional matched filter method fails to provide satisfactory detection performance.

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**Channel Sensitive Processor: Real
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Abstract:

The CSP is applied to data collected during the DUSS97 sea trial. A one-way geometry is used and the transmitted signal propagation time is known *a priori*. As predicted by analytical and simulation studies, the CSP detector outperforms the classical matched filter method (2-3 dB gain) for known propagation conditions. It is also demonstrated that the performance of the CSP processor is degraded below that of the classical method in environmentally mismatched cases.

Keywords:

Conventional Matched Filter, Channel-Sensitive Processor (CSP)

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1

Introduction

Matched filter methods are extensively used in active sonars. The conventional matched filter algorithm is a robust method because it does not depend on the propagation conditions of the acoustic channel. However, in a shallow water environment, boundary interaction and dense multipath condition can produce such a distorted matched filter output that detection decisions can not be made [1], [2].

One way to overcome this problem is to incorporate in the detection algorithm information about the propagation characteristics of the medium. The product of this idea is a new processor called the Channel Sensitive Processor (CSP). A schematic representation of the CSP scheme is shown in Fig. 1. The theoretical development, the evaluation, and the comparison with the conventional matched filter method are described in detail in reference [3]. It was derived that for a well-defined propagation channel the CSP output is always better than or equal to the classical matched filter output. This analytical result is supported by simulation. To complete the analysis of the CSP performance, sensitivity and optimization studies were conducted. It was found the CSP method is very sensitive to environmental uncertainty. One proposed way to overcome this problem is the coupling of the CSP correlator with global search methods (i.e. simulated annealing [4], genetic algorithms [5], etc.). These results are presented in reference [6].

The purpose of the present report is to apply the CSP technique to real data. The data set was collected during the DUSS97 sea trial [7]. For simplicity, a one-way geometry is used in which the transmitted signal (source on the target vessel) is received on a vertical array. Different hydrophones of the array are used as receiver located at different depths. The signal propagation time is pre-calculated based on GPS measurements. In every case both detection methods, i.e. conventional matched filter and the CSP, are employed. The signal-to-noise (SNR) in this experiment is high and it is expected that both techniques would provide positive detection results. The main point here is to use real data to verify the theoretical predictions according to which, for known propagation conditions, the CSP offers a performance advantage over the conventional matched filter method. The CSP is also applied using deliberately incorrect medium properties to test its sensitivity to environmental mismatch.

This report is organized as follows: Section 2 provides a brief overview of the Channel

Sensitive Processor (CSP) and its comparison with the conventional matched filter method. Section 3 gives a detailed description of the data acquisition and the environmental information available for this experiment. Section 4 demonstrates detection results using the CSP detector and compares them to those obtained using the conventional matched filter algorithm. Finally, conclusions, guidelines, and ideas for improving upon the proposed methods are presented.

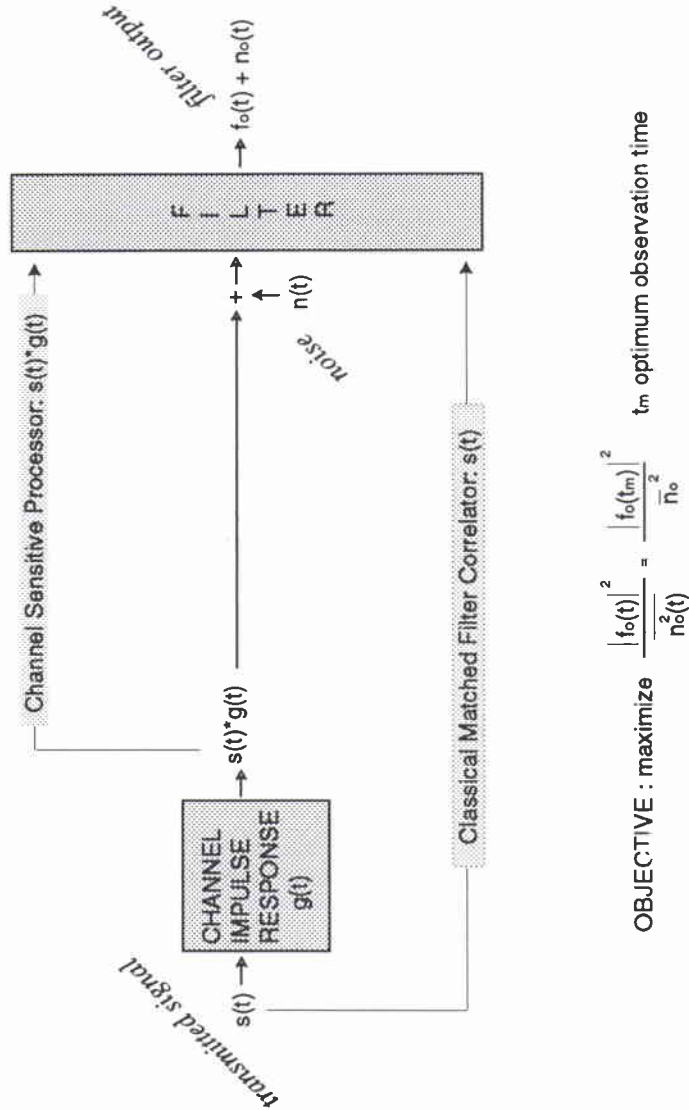


Figure 1 Graphical representation of the Conventional Matched Filter and the Channel Sensitive Processor.

2

Matched Filter Algorithms

This section provides a brief overview of the matched filter techniques employed in this study. In general, the matched filter is a linear time-invariant filter designed to maximize the peak pulse signal in the presence of noise [8], [9], [10] i.e.,

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

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

For an LFM transmitted signal [11] with spectrum $S(\omega)$, and additive white noise with spectrum

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

the general expression for the matched filter output can be written as [3], [8]

$$\Lambda = \frac{|f_o(t_m)|^2}{\hat{n}} = \frac{1}{N_o\pi} \frac{\left| \int_{-\infty}^{+\infty} G(\omega)S(\omega)H(\omega) \exp(-j\omega t_m) d\omega \right|^2}{\int_{-\infty}^{+\infty} |H(\omega)|^2 d\omega} \quad (3)$$

where $G(\omega)$ is the transfer function of the channel, and $H(\omega)$ is a general expression for the transfer function of the desired matched filter.

NATO UNCLASSIFIEDSACLANTCEN SM-347*2.1 Conventional Matched Filter (MF)*

For the conventional matched filter algorithm, the filter transfer function is independent of the propagation channel and can be written:

$$H(\omega) = S^*(\omega) \exp(j\omega t_m) \quad (4)$$

Combining Eq. (3) and Eq. (4), the expression for the MF output becomes:

$$\Lambda_{mf} = \frac{1}{\pi N_o} \frac{\left| \int_{-\infty}^{+\infty} G(\omega) |S(\omega)|^2 d\omega \right|^2}{\int_{-\infty}^{+\infty} |S(\omega)|^2 d\omega} \quad (5)$$

2.2 Channel Sensitive Processor (CSP)

The CSP is an environmentally sensitive type of matched filter. The main characteristic of this filter is that *the transfer function of the CSP incorporates the transfer function of the medium*, i.e.,

$$H(\omega) = kG^*(\omega)S^*(\omega) \exp(j\omega t_m) \quad (6)$$

and the CSP output can be expressed as

$$\Lambda_{csp} = \frac{1}{\pi N_o} \int_{-\infty}^{+\infty} |G(\omega)|^2 |S(\omega)|^2 d\omega \quad (7)$$

For more details about the derivation of these formulas, refer to [3].

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2.3 Comparison of the two filters

To compare the performance of the conventional match filter with CSP, it is convenient to form the output ratio of the two filters using Eq. (5), and (7)

$$\frac{\Lambda_{\text{csp}}}{\Lambda_{\text{mf}}} = \frac{\int_{-\infty}^{+\infty} |G(\omega)|^2 |S(\omega)|^2 d\omega \int_{-\infty}^{+\infty} |S^*(\omega)|^2 d\omega}{\left| \int_{-\infty}^{+\infty} G(\omega) |S(\omega)|^2 d\omega \right|^2} \quad (8)$$

Eq. (8) becomes

$$\frac{\Lambda_{\text{csp}}}{\Lambda_{\text{mf}}} \geq \frac{\left| \int_{-\infty}^{+\infty} G(\omega) S(\omega) S^*(\omega) d\omega \right|^2}{\left| \int_{-\infty}^{+\infty} G(\omega) |S(\omega)|^2 d\omega \right|^2} = 1 \quad (9)$$

This results proves that for known propagation conditions the CSP improves upon the performance of the conventional matched filter.

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3

Data acquisition

The data set processed here was collected during the DUSS97 sea trial which took place south of the island of Elba, Italy, from the 23 June until 3 July 1997. Figure 2 shows a map of the area, experimental configuration and bathymetric information. The signal was transmitted from the "TARGET" position and received on a vertical line array "VLA". To estimate the sound velocity profile an XBT measurement was made at the location "SVP". The geophysical properties of the bottom were based on historical data collected at the "CORE" location during another experiment in the same area during 1995 [12].

3.1 Target (source) characteristics

The transmitted signal was a 1 second LFM pulse with 150 Hz bandwidth around 950 Hz repeated every 15 s. The sound source, towed at approximately 102 m depth, served as the target to be detected. The bottom depth at the target ship location was estimated to be 200 m. It moved on a straight course with starting coordinates 42°:29.4690' N, 10°:18.9390' E, corresponding to 11:10:00 ending at 42°:29.6240' N, 10°:19.2860' E at 11:14:00.

3.2 Receiver characteristics

A 32 hydrophone vertical line array was deployed at coordinates 42°:33.962' N, 10°:21.959' E. The total aperture of the array was 15.5 m with 0.5 m spacing between adjacent sensors. The bottom hydrophone (referred to as the first sensor) was located at 108.75 m depth. The bottom depth measured at this location is 161 m.

3.3 Distance estimation

As mentioned in the introduction, for the data analysis presented here it is important to know the precise distance between the target (sound source) and the receiver. Using GSP information this distance was found to be 9.289 km. This result is in

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good agreement with the distance estimated using the signal travel time and average sound speed 1510 m/s.

3.4 *Sound velocity profile*

The coordinates of the SVP are 42°:30.373' N, 10°:20.881' E. As shown in Fig. 3, the SVP induces downward refracting conditions which are typical of Mediterranean summer [13], [14]. From the surface down to 23 m depth there is an isovelocity layer, followed by a strong thermocline down to 55 m that changes to a second isovelocity layer which extends down to the bottom surface.

3.5 *Bottom characteristics*

In Fig. 2 it is shown that from the target vessel to the vertical array there is an upslope bathymetry starting approximately at 200 m and ending at approximately 160 m. The core samples were taken at coordinates 42°:28.716' N, 10°:20.214' E. The top three bottom layers consist of a low speed clay layer followed by a mixture of clay and sand layer which covers the third silt layer. The estimated sound velocity profile in the sediment is shown in Fig. 4. Details about the properties of these types of sediments are given in [15], [16].

3.6 *Data acquisition and preprocessing*

The sampling rate at the receiver is 12 kHz. For processing and storage efficiency the signal was downsampled by a factor of 10. As a result the initial frequency band from 875 Hz to 1025 Hz was downshifted and mapped between 175 Hz and 325 Hz.

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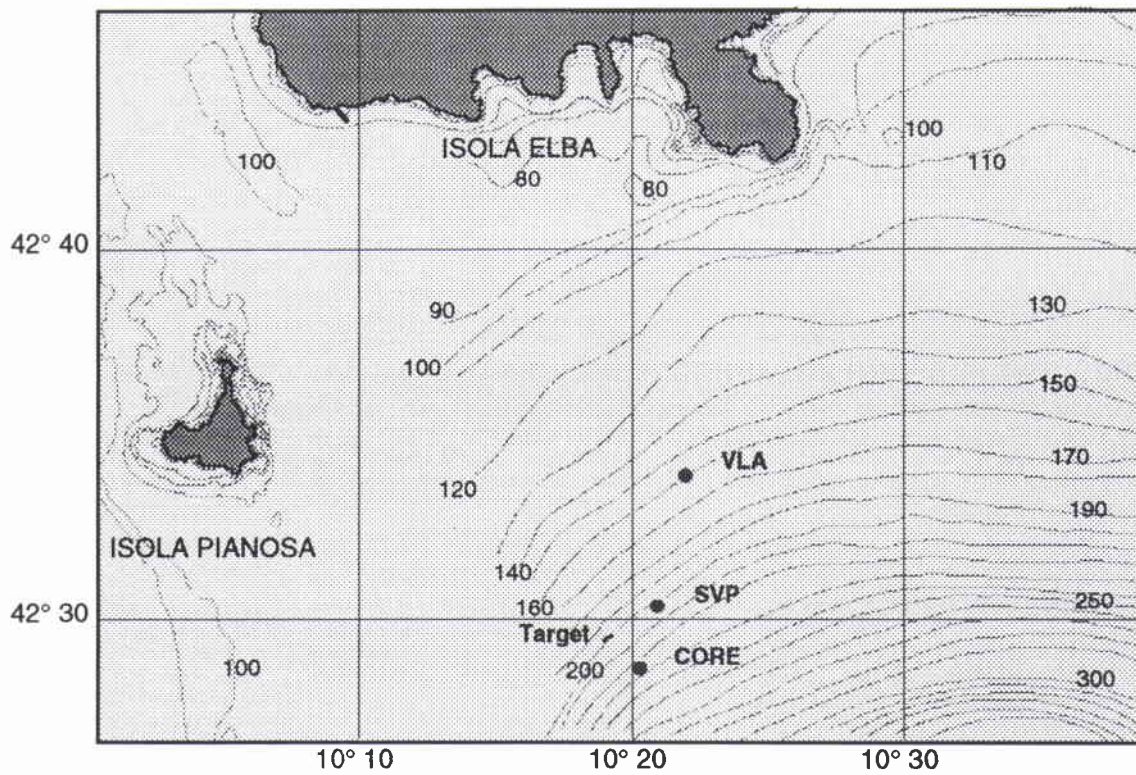


Figure 2 Map of the DUSS97 experimental site with bathymetric contour of the area. The positions of the target vessel, the vertical line array, the sound velocity profile measurement, and the core sample are also indicated.

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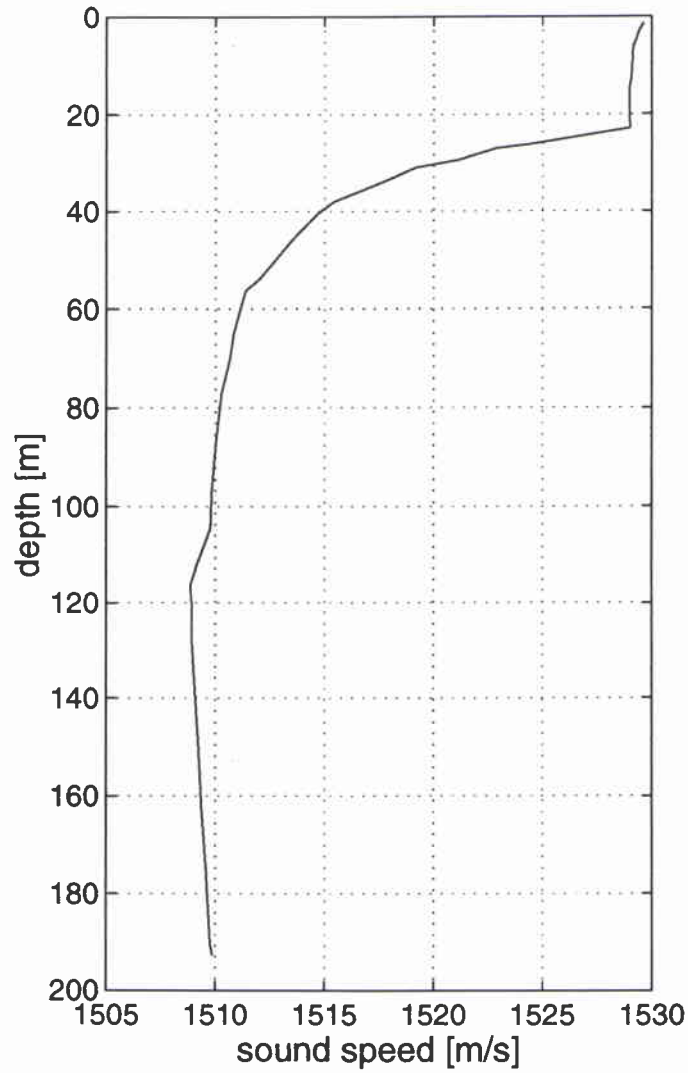


Figure 3 *Sound velocity profile in water the water column.*

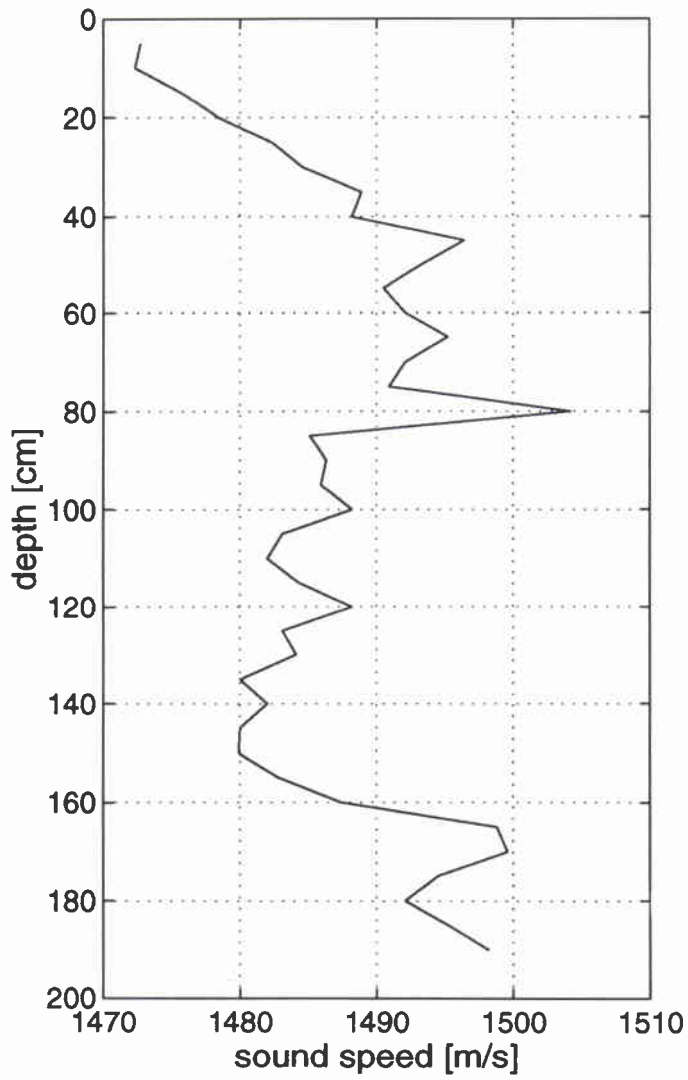


Figure 4 *Estimated sound velocity profile in the sediment layer.*

4

CSP and Conventional Matched Filter detection performance comparison

The results from testing the CSP using real data are presented here. The CSP output is always compared to the output obtained using the conventional matched filter technique. Different hydrophones on the vertical array served as individual receivers located at different depths. It must be emphasized that the data set processed here was not collected to support the CSP study. In the experimental site there are no dense multipath conditions which are necessary to demonstrate the performance difference between the two processor. Fortunately, at selected depths the multipath structure is dense enough for the CSP to be applied. Two different cases are selected. In each case the signal to noise ratio is high and the reception of the transmitted signal is very clear. Under these conditions, it is expected that both methods will provide satisfactory detection results. The point of interest remains the performance improvement (if any) offered by the CSP technique.

As mentioned before, the meaningful utilization of the CSP presupposes sufficient *a priori* knowledge about the propagation channel. When this condition is not fulfilled the performance of the CSP degrades according to the degree of mismatch between the modelled and the predicted channel. To demonstrate this point using real data, the CSP detector is also applied using deliberately incorrect channel transfer functions. For all the simulation work the C-SNAP [17] coupled normal mode program is used. It is a time-efficient, range-dependent model which functions under the assumption that the acoustic field is dominated by the outgoing component. The synthetic waveguide created using C-SNAP is based on the environmental characteristics described in the previous section. For the data analysis the MATLAB [18] software package is used.

4.1 Receiver 1: Hydrophone 17

The time series and the spectrum of the signal received on hydrophone 17 are shown in Fig. 5. The presence of moderate multipath conditions (three nulls) is observed. The detection results are shown in Fig. 6. A time delay was applied to the filter outputs so that the results do not overlap. As it was anticipated, due to the low noise level both methods are able to clearly detect the transmitted signal. This is

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observed at the lower part of Fig. 6. For better comparison an enlargement is made of the filter output time series around the maximum. It can be seen that the CSP method offers a 1.9 dB performance improvement over the conventional matched filter.

Following the demonstration of the CSP advantage when the propagation conditions are matched, the processor is tested against environmental mismatch. Different scenarios were simulated in which geometric and environmental parameters diverged from the matched case values. Almost in all cases it was found that the performance of the CSP is degraded below that of the classical method. In the example shown in Fig. 6 it was assumed that the receiver was located 200 m further away from its actual position. Even for the one parameter inaccuracy, the CSP performance dropped 1.2 dB below that of the conventional filter.

4.2 Receiver 2: Hydrophone 19

The time and spectrum of the signal received on hydrophone 19 are shown in Fig. 7. Again both processors offer satisfactory detection performance as shown in Fig. 8. Compared to the previous case, there are less multipath nulls (two instead of three) but the formation of one very evident null implies that here the multipath phenomenon is prominent. This difference is reflected on the detection output as the CSP outperforms the conventional processor by 3 dB.

Finally, it can be seen that classical method outperforms the CSP algorithm when the modelling of propagation channel is inaccurate (mismatched case). To generate a different mismatch case than the previous one, the receiver was assumed to be 150 m closer to the target than it was in reality. As a result, the CSP performance is degraded 1.0 dB below that of the conventional filter.

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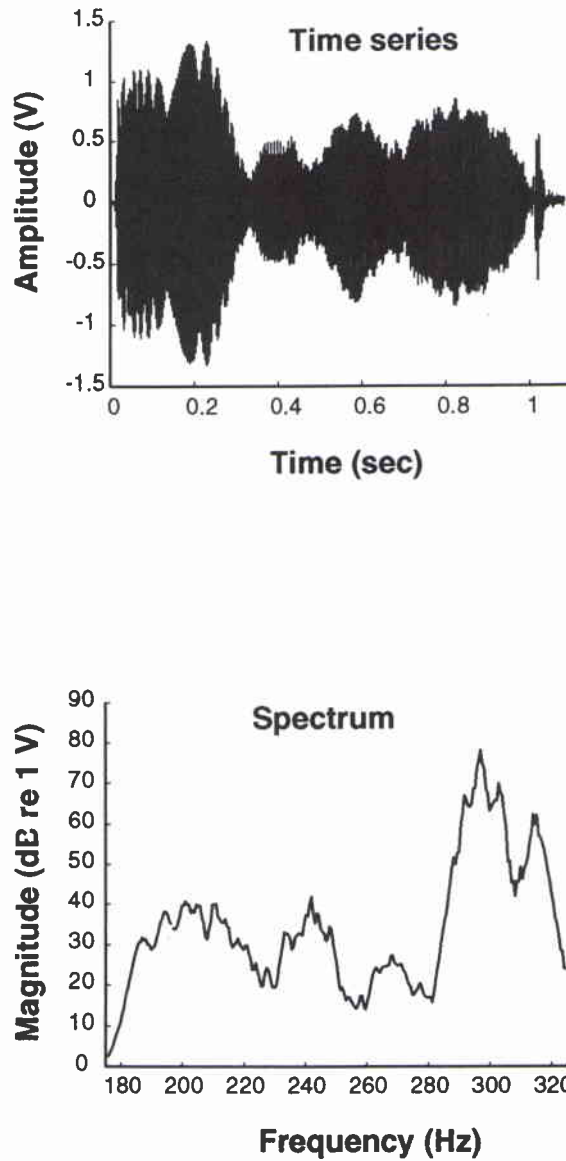


Figure 5 *Case 1: the time series and the spectrum of the signal received on hydrophone 17.*

Detection Output
(Phone 17)

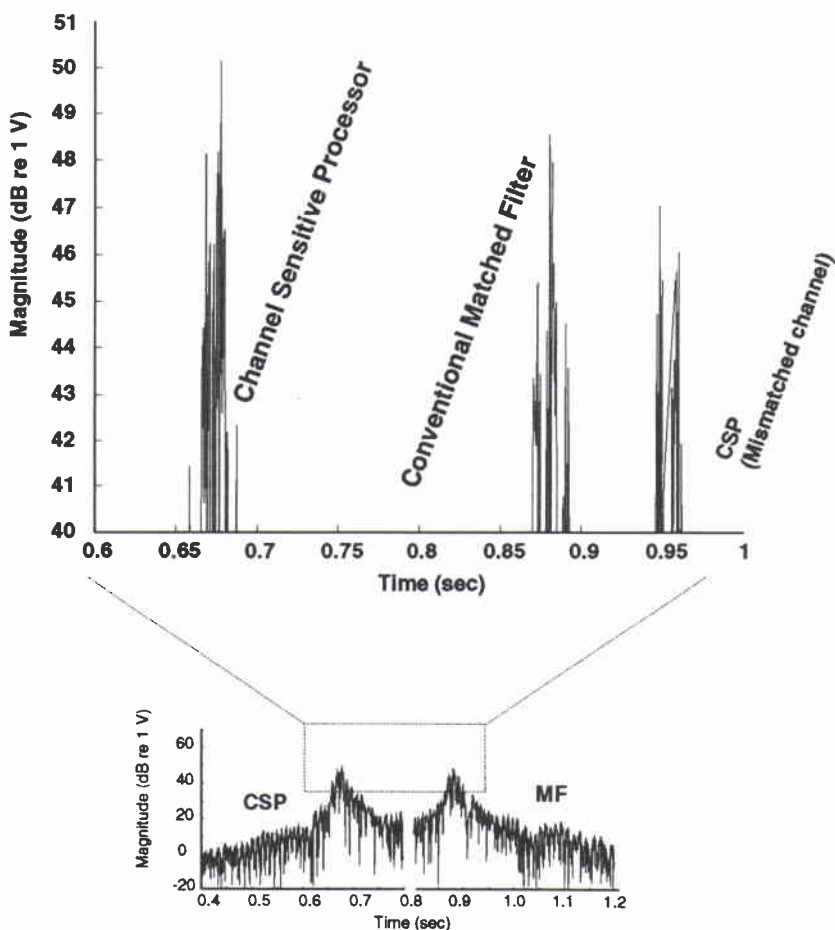


Figure 6 Lower part: Detection output of the Conventional Matched Filter and the Channel Sensitive Processor. Upper part: Detail of the MF and CSP output peaks compared with the output of the CSP processor under environmentally mismatched conditions.

HYDROPHONE 19

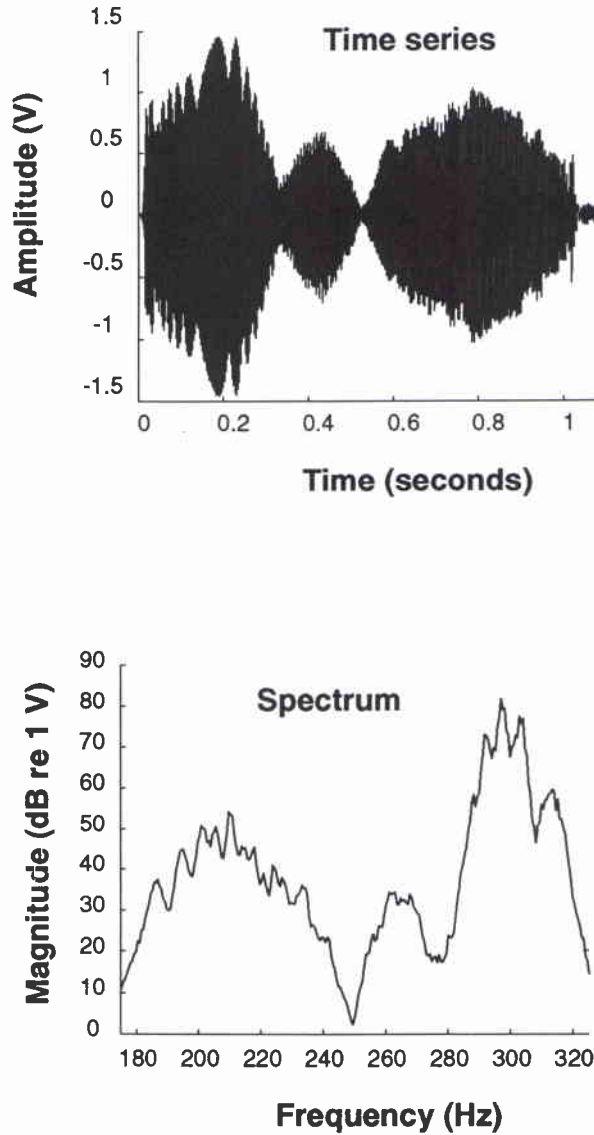


Figure 7 Case 2: the time series and the spectrum of the signal received on hydrophone 19.

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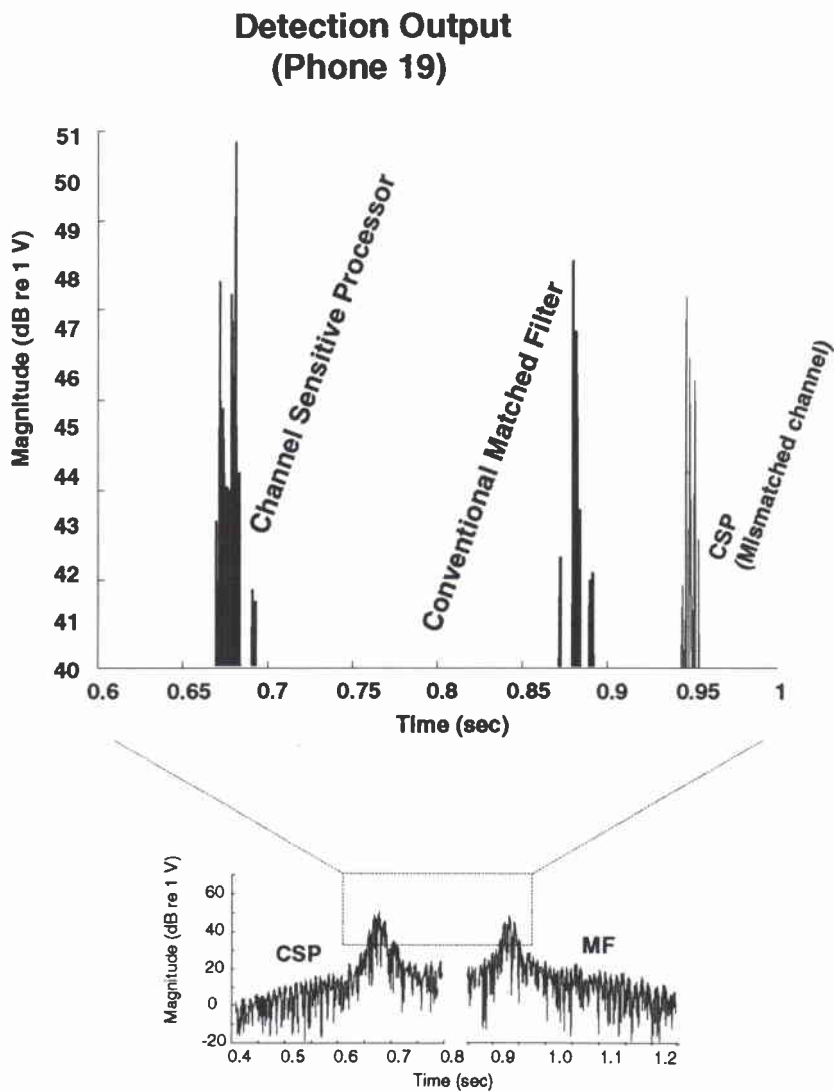


Figure 8 Lower part: Detection output of the Conventional Matched Filter and the Channel Sensitive Processor. Upper part: Detail of the MF and CSP output peaks compared with the output of the CSP processor under environmentally mismatched conditions.

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5

Conclusions

The CSP detection scheme is successfully applied to real data. It is demonstrated that when the propagation channel can be accurately modelled, the CSP processor outperforms the classical matched filter method. Although the multipath conditions were not particularly dense in the area where the data set was collected, the CSP has demonstrated a detection performance enhancement of the order of 2-3 dB. This is an interesting result knowing that the CSP advantage is based on combining acoustic energy from different acoustic paths. The verification of the CSP concept using real data with weak multipath structure, suggests that there is potential in using this processor in real life scenarios.

Consistent with previous simulation results, the CSP performance is degraded below that of the conventional method when there is a mismatch between the actual and the assumed propagation conditions. This suggests that in areas where there is limited *a priori* knowledge about the acoustic medium, the utilization of the CSP scheme is not recommended.

As mentioned before, in this experiment the signal propagation time between the source and the receiver (one-way propagation) is known. To satisfy this condition in a realistic scenario, one must rely on preceding target contacts. In such cases the CSP can be utilized subsequently to provide better depth resolution and improved output SNR.

One proposed way to improve the CSP performance against phase offset problems is to incorporate in its processing algorithm an efficient search mechanism which, based on *a priori* knowledge will be able to estimate the signal travel time between the source and the receiver. This was demonstrated using simulation experiments but it is yet to be shown using real data.

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