

ACTIVE SOURCE DETECTION IN A DISPERSIVE MULTIPLE-REFLECTION ENVIRONMENT

Zoi-Heleni Michalopoulou

Department of Mathematical Sciences,
New Jersey Institute of Technology,
Newark, NJ 07102

ABSTRACT

A signal propagating in a shallow water waveguide is subjected to (a) multiple reflections off the ocean boundaries and (b) distortion because of the dispersive properties of the propagation medium. Because of these corruptions, the received signal differs substantially from the transmitted signal. Although the transmission is sometimes exactly known, the received signal cannot be described in detail because of inadequate knowledge of the ocean impulse response. Ignoring the effects of the ocean on the signal, or representing them inaccurately, can lead to deterioration of the detection statistics. This paper compares the performance of methods designed for distortion-free, multiple-reflection transmission in realistic, dispersive environments. Two existing methods, the RCI processor and the simple source-receiver matched-filter, and a new detector are evaluated. The impact of distortion on signal transmission is assessed by comparing the distortion-free methods to the optimal processor, which models the effects of the propagation medium on the signal.

1. OPTIMAL DETECTION IN A KNOWN OCEAN FOR AN EXACTLY KNOWN SOURCE SIGNAL

In active sonar problems, a known and controlled source transmits a waveform, which is then received at a controlled set of receivers. Based on the measurements at the receiving hydrophones, a decision is made as to whether a target is present in the insonified region of the ocean. A simple detection tool is the correlation between the received and transmitted waveforms. This correlation detector (referred to here as a standard source-receiver matched-filter) would be optimal if the received waveform was a simple replica of the transmitted signal corrupted by white Gaussian noise. The problem considered here is more complex, because the ocean, through which the signal propagates, distorts the signal.

Specifically, assuming signal $s(t)$ is transmitted, the received signal $r(t)$ will be described by equation $r(t) = h(t) * s(t) + w(t)$, where $h(t)$ is the impulse response of the propagation channel connecting source and receiver and $w(t)$ is additive, white, Gaussian noise. The standard source-receiver matched-filter, which correlates $s(t)$ and $r(t)$, is a suboptimal detector because it ignores the distortion (described by $h(t)$) imposed on the signal during propagation through the ocean. The optimal detector is a matched-filter between the received signal $r(t)$ and the convolution of the oceanic impulse response and the source signal, $h(t) * s(t)$. This ‘model-based matched-filter’ [1] is significantly superior to the suboptimal, standard source-receiver matched-filter for underwater target detection.

2. DETECTION IN A MULTIPLE REFLECTION ENVIRONMENT

A singular difficulty in signal detection in the ocean is the uncertainty about the ocean environment through which the sound propagates. The optimal detector described in Section 1 requires knowledge of the impulse response (or, equivalently, the transfer function) of the ocean, which depends on several parameters many of which are unknown or uncertain. As has been shown in [2, 3], assumptions about the impulse response that do not reflect reality can cause a serious performance degradation, making, under certain circumstances, the simple suboptimal source-receiver matched filter preferable to the theoretically optimal model based matched filter. In order to overcome the adverse mismatch effects, multiple model-based matched-filters are recommended. Specifically, following the methodology used in passive matched-field processing [4], replicas of $h(t)$ for many candidate values of the unknown parameters are calculated, and correlations are computed between the received signal and quantities $h(t) * s(t)$ for all different $h(t)$'s. Maximization of the correlation over all parameters yields the detection statistic [5]. This process can be very computationally intensive depending on

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the number of the uncertain parameters and the sensitivity of the ocean response to these parameters (which determines the required resolution of the search).

Implementation of such a scheme is environment-dependent and therefore non-portable. Calculation of the ocean impulse response for multiple sets of parameters has to be performed every time detection is desired in a different environment. Efforts have been made to develop techniques that are less dependent on the properties of the propagation medium. Proposed techniques include the Segmented Replica Correlation (SRC) and the Replica Correlation Integration (RCI) [6, 7]. The SRC method has been designed for cases where the transmitted signal is distorted by a frequency domain convolution process resulting from temporal coherence characteristics of the ocean. The RCI method has been developed for signals that travel through a multiple reflection medium.

The RCI method is more suitable than the SRC method for detection in shallow water environments. Since the signal bounces off the ocean boundaries several times, a combination of the direct arrival and a series of reflections arrive at the receiving phone. The RCI processor assumes that the received signal is a linear combination of attenuated and delayed exact replicas of the transmitted signal and that there is adequate temporal separation between consecutive arrivals for them to be resolvable. The RCI processor is a likelihood ratio test derived for an unknown ocean impulse response. It is optimum when the received signal is a sum of *undistorted* replicas of the transmitted signal and the duration of the impulse response is known. The statistic calculated for the RCI detection processor is $y(n) = \sum_{k=0}^{M-1} |\sqrt{2/N} \sum_{i=0}^{N-1} s^*(i-k)r(n+i)|^2$, where M is equal to the product of the sampling frequency of the signals and the time spread of the impulse response ($r(n)$ and $s(n)$ are the discrete-time versions of $r(t)$ and $s(t)$) [7].

In practice, the replicas received at the phones resulting from reflections off the boundaries are not clean but distorted versions of the transmitted sequence. To illustrate, simulations were run in a shallow water (approximately 216 m deep) environment similar to that of the SWelEX 96 experiment [8]. A *sinc* pulse with frequency content between 200 and 400 Hz was transmitted from a source located at 64 m and 1.19 km in range and depth respectively and received at a hydrophone at 94.125 m in depth. The source signal is shown in Fig. 1(a). The received signal (shown in Fig. 1(b)) consists of a summation of distorted replicas of the source signal. Using normal modes to model the acoustic field at the receiver, these distorted replicas can be assigned to different modes. Figure 1(c) shows the fifth

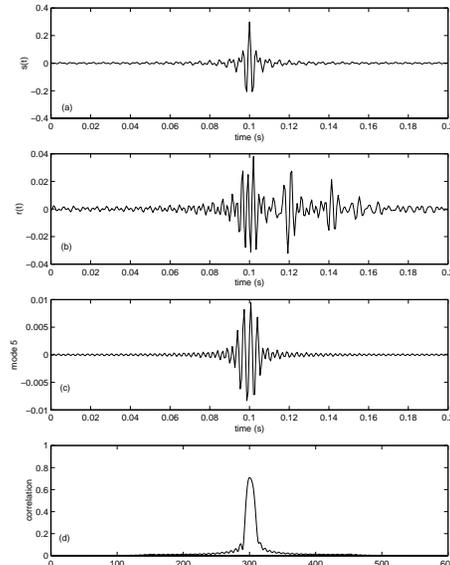


Figure 1: (a) Transmitted sequence. (b) Received sequence. (c) Mode 5 of the received sequence. (d) Correlation between the transmitted sequence and mode 5.

mode, and Fig. 1(d) presents the cross-correlation between this mode and the transmitted time-series. The maximum value of the cross-correlation is around 0.7, indicating that the two correlated time-series are similar but not identical; the match can be qualitatively assessed by comparing Figs. 1(a) and (c).

Studying the physics of the selected waveguide, one can identify the behavior of group velocity vs. frequency as the cause of the observed distortion between the transmitted signal and components of the received signal. The RCI method does not account for the distortion and therefore loss of detection performance is expected when the RCI processor is used in dispersive situations.

3. DETECTION IN AN UNCERTAIN OCEAN FOR AN EXACTLY KNOWN SOURCE SIGNAL

In this section the performance of candidate detectors is compared in an environment that imposes both multiple reflections and dispersion on the propagating signal. Candidate detectors are the RCI processor, the optimal model-based matched-filter, the standard, suboptimal source-receiver matched-filter and a proposed new detector [9].

The new processor is a source-receiver correlator. In place of the maximum correlation of the standard processor, however, the new processor uses the average of the L highest values of the calculated source-receiver correlation. The value of L is chosen in an ad-hoc manner to reflect the number of prominent echoes expected in the received signal. The processor appears to be insensitive to small changes in L . The new detector

is extremely simple; it does not require knowledge of the environment and is therefore portable. It is also very computationally efficient since it evaluates a single correlation between the transmitted and received time-series instead of M correlations required for the RCI processor.

The detectors are evaluated on the detection of *lfm* signals of 5 s duration with frequency content between 200 and 400 Hz. The signal propagates in the environment used in Section 2 and is received at phones located at a depth of 94.125 m. The distance between the source and the receiving phone is initially set to 1.19 km and is then changed to 0.6 km; the source depth is 64 m. The ocean impulse response calculated for the two distances is shown in Fig. 2.

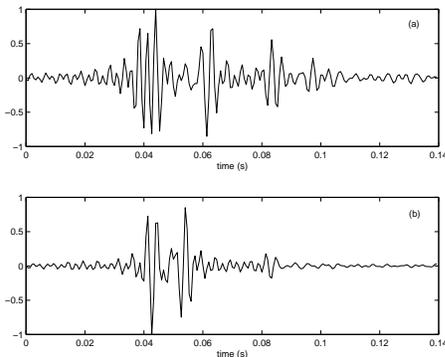


Figure 2: Impulse ocean response for a receiver at a depth of 94.125 m and a source at a depth of 64 m and range of (a) 1.19 km and (b) 0.6 km.

Although the environment is the same, as can be seen in Fig. 2, the duration of the impulse response in the two cases is different. In this example, the change in the duration is because of the difference in the source range. (Variations of other parameters—the geoacoustic properties of the seafloor sediment, for example—could also have a substantial effect on the duration of the impulse response.) It is, therefore, difficult to choose the correct value of M in the RCI equation, which is necessary for optimal performance of the RCI processor.

ROC curves were generated for the detection of the received pulse (for both ranges of 1.19 and 0.6 km) for a Signal to Noise Ratio (SNR) of 14 dB. Based on the length of the impulse responses for the cases that are investigated, M was estimated to be around 100 for the first case and 70 for the second case. ROC curves are shown in Fig. 3 for the optimal model-based matched-filter, the conventional source-receiver matched-filter, the RCI processor for $M = 100$ and 70, and the new detector that uses an average of the $L = 6$ most significant peaks of the standard matched-filter output as the detection statistic.

Fig. 3(a) shows that the model-based matched-filter is significantly superior to all other detectors. This was expected, since this processor explicitly incorporates all information regarding both multipaths and distortion within each echo. In contrast, the conventional source-receiver matched filter ignores all channel effects on the signal and has the worst detection performance. The RCI processor has the second best detection performance. It accounts for some of the effects of the propagation medium on the signal but assumes no within-echo distortion. The performance of the matched-filter that uses an average of L maximum peaks as a statistic is better than that of the source-receiver matched-filter but worse than that of the RCI processor.

The results of Fig. 3(b) shows once again the superiority of the model based matched-filter. This time however, the three other detectors have very similar performance, with the RCI processor having, by a very small amount, the worst performance and the matched-filter with averaging the best performance of the three (again by a very small margin). In this case, it appears that the violation of assumptions made by the RCI processor is more significant than in the previous case. Figure 4(a) shows the performance of the RCI processor for $M = 10, 70$, and 100 for the case where the range is 0.06 km. The best RCI performance is achieved for $M = 70$, which seems to reflect approximately the length of the impulse response from Fig. 2(b). Thus, in this particular problem, the matched-filter with averaging performs better than the best possible RCI detector.

Figure 4(b) shows the performance of the matched-filter with averaging for different values of L . Quantity L represents the number of strong signal peaks we expect to have at the output of the matched-filter. As can be seen from the figure, the performance of the detector is not very sensitive to the value of L within the studied range. For all L 's considered here, the detector performance is very similar to that of the best RCI processor ($M = 70$).

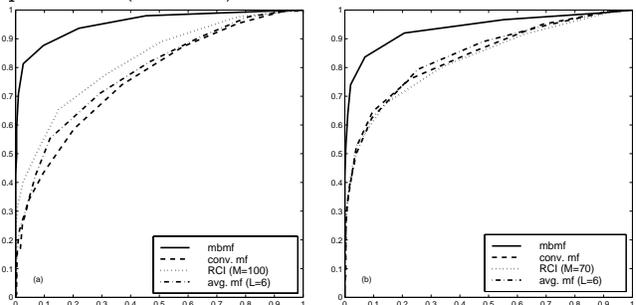


Figure 3: ROC curves for ranges of (a) 1.19 km and (b) 0.6 km obtained with the optimal model-based matched-filter, the conventional source-receiver matched-filter, the RCI processor, and the new ad-hoc detector.

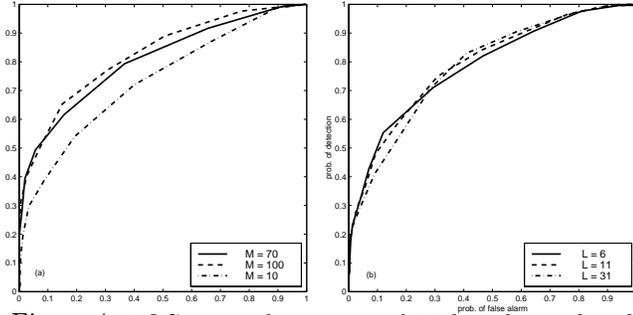


Figure 4: ROC curves for a range of 0.6 km obtained with (a) the RCI processor for different values of M , and (b) the new ad-hoc processor for different values of L .

The benefit in using detectors such as the RCI and the new matched-filtering process is more pronounced in Fig. 5. The ROC curves of Fig. 5 show the performance of the different detectors applied to data from the SWelEX 96 experiment. A received time-series was extracted from the data and was corrupted by multiple realizations of white Gaussian noise. The processors were then applied to the data-plus-noise sequences and to noise only sequences (obtained when the source was quiet). The model-based matched-filter has the best performance; however, it is not optimal here, since the ocean is not known exactly (no search was performed over parameters; prior information on environmental and geometry parameters was used for the calculation of the impulse response). The RCI processor for $M = 100$ has the second best performance followed closely by the new matched-filter ($L = 6$). The simple source-receiver matched filter is inferior to the three other processors.

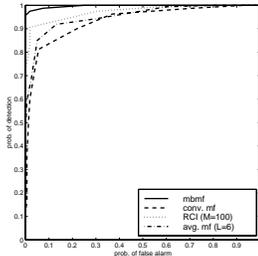


Figure 5: ROC curves for SWelEX data.

4. CONCLUSIONS

Detection in the ocean is a challenging problem because of the complex and often inadequately known structure of the received signal. A model-based matched-filter, which accounts for the propagation effects on the signal, is an optimal detector. The cost of optimal performance, however, is extensive computation. The simple source-receiver matched-filter is much simpler to implement, but, ignoring the effects of the channel on the signal, it has poor performance. The RCI processor, designed for environments imposing multiple reflections, captures the structure of the received signal

only partially; it accounts for multiple echoes at the receiver but ignores the distortion effects on the individual echoes. When distortion is not significant, the RCI detector can outperform the suboptimal source-receiver matched-filter. When, however, distortion is substantial, the RCI processor and the simple matched-filter have equally poor performances. A new processor discussed here, which averages over major peaks of the correlation output of a single source-receiver correlator, has a similar performance to the RCI processor, improving on the performance of the suboptimal source-receiver matched-filter. The new processor can be superior to the RCI detector, depending on the values assigned to parameters L and M that drive the two processors. The new processor has the advantage of efficiency requiring calculation of a *single* correlation in contrast to multiple correlations required for the RCI detector. The disadvantage of an ad-hoc implementation is ameliorated by insensitivity to parameter mis-specification.

5. REFERENCES

- [1] J.-P. Hermand and W. I. Roderick, "Delay-Doppler resolution performance of large time-bandwidth-product linear FM signals in a multipath ocean environment," *IEEE Journal of Oceanic Engineering*, vol. 94, no. 5, pp. 1709–1727, 1988.
- [2] Z.-H. Michalopoulou, "Underwater transient signal processing: marine mammal identification, localization, and source signal deconvolution," in *ICASSP-97*, vol. 1, pp. 503–506, 1997.
- [3] M. T. Wazenski and D. Alexandrou, "Active, wideband detection and localization in an uncertain multipath environment," *J. Acoust. Soc. Am.*, vol. 101, pp. 1961–1970, 1997.
- [4] A. Tolstoy, *Matched Field Processing for Underwater Acoustics*. Singapore: World Scientific, 1993.
- [5] D. Johnson and D. Dudgeon, *Array Signal Processing: Concepts and Techniques*. Prentice Hall, 1993.
- [6] P. M. Baggenstoss, "On detecting linear frequency modulated waveforms in frequency- and time-dispersive channels: alternatives to segmented replica correlation," *IEEE Journal of Oceanic Engineering*, vol. 19, pp. 591–598, 1994.
- [7] B. Friedlander and A. Zeira, "Detection of broadband signals in frequency and time dispersive channels," *IEEE Transactions on Signal Processing*, vol. 44, pp. 1613–1622, 1996.
- [8] "SWelEX-96 Preliminary Data Report," tech. rep., 1996.
- [9] Z.-H. Michalopoulou, "Active target detection in the ocean: optimizing performance and cost," in *Proceedings of the 135th Meeting of the Acoustical Society of America*, (Seattle), June 1998.