Fusion algorithms for detection in presence of reverberation

G. Ginolhac, J. Chanussot, Cédric Pichat
Laboratoire des Images et des Signaux – LIS / ENSIEG – BP 46 – 38402 Saint Martin d’Hères, France
guillaume.ginolhac@lis.inpg.fr, jocelyn.chanussot@lis.inpg.fr

Summary
Reverberation, which is caused by the reflexions, diffractions and/or diffusions of the transmitted signal on the surface or the bottom of ocean interfaces, is a very disturbing noise in active sonar. Signal processing algorithms allow to obtain a sonar image where the target echo is described by a few energetic pixels. But the target detection on this image is difficult since the reverberation leads to the appearance of other highly energetic features. In this paper, we show that the target and the reverberation echoes have different morphological and statistical properties. Using these differences, two image processing based detection algorithms are proposed. Starting from a geometrical model, the first algorithm is composed of different filters issued from the mathematical morphology theory. The second algorithm is derived from the contrast box filter and is based on a local statistical model. Tested on real sonar data, these algorithms both give interesting results. To take advantage of both methods and further improve the results, the detection algorithms are then combined together: they can be applied either sequentially (one after the other), or parallelly with a fusion of the results. As the experiment contains multiple recurrences, we then propose to use this information redundancy. A fusion algorithm between the different recurrences is used in order to delete ground reverberation echoes. This final algorithm leads to a robust detection of the target (good detection probability) with almost no reverberation echoes remaining (good false alarm probability).

1. Introduction
Reverberation, in the field of active sonar, can have different origins. For instance, it can respectively be caused by the reflexions, the diffractions and/or the diffusions of the transmitted signal on the surface or the bottom ocean interfaces. Since reverberation is strongly correlated to the transmitted signal, classical detection method like matched filtering is inefficient.

Most of active sonars are composed of an emitter and a linear array of receiver sensors. This kind of system provides a sonar image. Nevertheless, processing and interpretation of these data are very difficult because the Signal to reverberation Noise Ratio (SNR) is too weak. Two classical algorithms are often used: the matched filtering and the beamforming [1]. Beamforming is a spatial filter which gives the direction of arrival of the different echoes. For example, figure 1 shows a sonar image after beamforming and matched filtering. The global noise is composed of the carrier ship noise, the white background noise and the reverberation noise. In this presented image, the target echo is located in the middle of the image, and it is outside of the reverberation.

In this paper, we propose to process this kind of real data with different image processing based algorithms. The aim is to ensure good detection performances and to reduce the false alarms rate. In particular, reverberation echoes have to be suppressed. The first step consists in choosing appropriate attributes to distinguish target echo and reverberation echoes. On figure 1, we can notice that, compared with reverberation echoes, the target echo is very thin and isolated. Actually, reverberation is composed of multiple echoes forming an important zone. These differences can be characterized by different attributes. In this paper, we propose to use respectively morphological and statistical attributes. For instance, the shape of the target is really
characteristic. We therefore propose a first detector using a geometrical model. This algorithm is naturally based on operators issued from the mathematical morphology theory [3] [4]. It is presented in section 2. The second detector is based on the contrast box algorithm [2] which uses a relative contrast between the statistical properties of the target echo and its surrounding background. This algorithm is presented in section 3. Since these attributes come from different characteristics of the target and the reverberation, they also can be used in a complementary way. So, we propose to combine the two detectors together to further improve the detection performances. This is presented in section 4. Moreover, as experiments contains multiple recurrences and several sonar images, we propose to aggregate results from these different images to build a more performant detector. This last point is presented in section 5.

The algorithms have been tested and successfully validated on real data. The results presented in this paper are obtained on four successive recurrences of the experiment (emission of the signal and recording of the echoes) with a non cooperative moving target and ground reverberation echoes. The first recurrence is shown on figure 1. The fourth one is shown on figure 2. In that recurrence, the target echo is very close to the reverberation. The detection is obviously much more difficult in that case. In the two other recurrences, the target echo is outside of the reverberation, but with a lower SNR than in the first recurrence.

Figure 1. First recurrence of the experiment: the target is outside reverberation

Figure 2. Fourth recurrence of the experiment: the target is inside reverberation

2. Morphological algorithms

Mathematical morphology is an important class of non linear image processing operators [3] [4]. Basic morphological filters mainly consist in locally comparing the features of the image with a reference shape, called the structuring element (SE).

2.1. Generic Methodology

After the Matched Filtering (MF) and the beamforming, the echoes appear as highly energetic features. These features have a thin rectilinear horizontal shape. Note that the target echo is relatively isolated whereas the reverberation echoes are forming compact clusters.

To distinguish the reverberation echoes from the target echo, a first processing consists in connecting together energetic features that are close from each other. This is performed using a classical morphological operator: the closing, defined by the successive application of a dilation and an erosion. We notice $Im_1$ the image after MF and beamforming and $Im_2$ the image after closing:

$$Im_2 = \text{closing}(Im_1) = \text{erosion}(\text{dilatation}(Im_1))$$

(1)

The dilation results in expanding all the energetic features. The direction and size of this expansion is ruled by the shape and size of the SE. After this step, the echoes appear bigger, and when two echoes are close enough, they connect. The erosion that is applied afterwards is the dual operator. It results in giving the isolated features their initial size back. But features that have been connected by the dilation step remain connected.
As a consequence, after the closing, the cluster initially composed of a lot of reverberation echoes turns to one single energetic connected shape, that is now much bigger than the target echo, which remained unchanged. So, the closing operation suppresses all the low energetic regions that are smaller than the chosen SE.

On the contrary, the opening operator, obtained by the dual operations (successive application of an erosion and a dilation) will suppress all the isolated energetic features that are smaller than the SE. Energetic features that are bigger than the SE remain unchanged. As a consequence, the difference between an image and its opening detects the small energetic features. This operation is called a Top Hat operator:

\[
Im3 = \text{TopHat}(Im2) = Im2 - \text{opening}(Im2) \quad (2)
\]

The combination of the closing and the Top Hat operations suppresses all the features that do not fit to the chosen geometrical model. Afterwards, the final binary decision is taken by a simple thresholding of the resulting image $Im3$.

### 2.2. Tuning of the parameters and results

The size and shape of the used structuring elements (corresponding to the geometrical model) are set by experimental studies. The detection is performed in two steps:

1. Firstly, the carrier ship noise is removed. To reconnect all the spurious echoes constituting this noise, the closing is performed with a vertical linear SE (width : 1 pixel, height : 51 pixels). The shape of the corresponding cluster justifies this choice. This assumes that the target echo is at least 51 pixels away from any other more energetic echo, in the vertical direction. The opening procedure is performed using a linear SE of size 3 (respectively horizontal and vertical). This assumes that the target echo is smaller than a $3 \times 3$ pixels square.

2. Secondly, the other reverberation echoes clusters are reconnected using a closing with a square SE of size 7. Corresponding assumption is that the target echo is at least 7 pixels away from any other echo in the other direction. For the Top Hat operator, we use the same opening algorithm than in the step 1.

Finally, the thresholding for the binary decision is set automatically at 30 per cent of the maximum value of the image. This threshold is intentionally chosen rather low. This ensures a good detection probability and leads to a robust algorithm.

Table I presents the results obtained on four real sonar images. The target echo is correctly detected but a lot of false alarms still remain in particular for the last recurrence. In this case, the target echo is lost among reverberation and the morphological contrast is not important enough to delete more reverberation echoes. So, we propose an other approach in the next section.

<table>
<thead>
<tr>
<th>recurrence</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>False alarm peak</td>
<td>13</td>
<td>18</td>
<td>13</td>
<td>44</td>
</tr>
</tbody>
</table>

### 3. Statistical algorithm

The analysis of sonar images allows to notice a relative contrast between target echo and its surrounding background, whereas reverberation areas are more homogeneous. The Contrast Box (CB) algorithm has been already used to detect target in infrared images [2] and we propose to apply it on sonar images.

First, we present the CB algorithm, then its running on real data and finally results of false alarms reduction.

#### 3.1. Contrast Box algorithm

The difference of local contrast is computed from two gates presented on figure 3: the Target gate, noticed T, and the Background gate, noticed B.

\[
c = \frac{(\mu_T - \mu_B)^2 + \sigma_T^2}{\sigma_B^2} \quad (3)
\]

![Gates structure for the CB algorithm](image)

The mean and the standard deviation are respectively noticed $\mu$ and $\sigma$. The difference of local contrast is defined by the following equation:

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The $c$ value is able to detect a difference of local contrast.

### 3.2. Analysis of CB algorithm and results

Four cases are interesting for the detection in presence of reverberation:

1. white noise is in gates $T$ and $B$: $c \cong 1$
2. target is in $T$ whereas white noise is in $B$: $c >> 1$
3. target is in $B$ whereas white noise is in $T$: $c << 1$
4. reverberation echo is in $T$ and another or several reverberation echoes are in $B$: $c \cong 1$

The second and third cases allow to improve the relative contrast between target echo and its surrounding background. The difference with regards to other applications of the CB algorithm comes from the last case. Actually, we notice that the CB algorithm allows to reduce reverberation echoes with regards to the target echo.

This analysis is correct if we choose the correct sizes for the gates $T$ and $B$. The gate $T$ has to have the same size as the target echo to avoid to delete it. In this example, the $T$ size is chosen equal to $3 \times 3$ (like in the section 2). The choice of $B$ is really important for the fourth case. Let us assume that a reverberation echo is located in $T$. The gate $B$ has to be enough important to include another reverberation echo. After some tries, we choose the size of $B$ equal to $5 \times 21$. After the same thresholding as in section 2, the remaining false alarms are counted. Table II presents the results obtained on the same data.

<table>
<thead>
<tr>
<th>Recurrence</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>False alarm peak</td>
<td>19</td>
<td>1</td>
<td>13</td>
<td></td>
</tr>
</tbody>
</table>

The obtained results are interesting. One single false alarm remains in two recurrences. The detection is almost perfect. For the last recurrence, we can notice that the target echo is not deleted by CB algorithm even if it is located in a reverberation zone. This result is logical because the SNR in this area is high. All results is better than Top Hat expect for the second recurrence. The local contrast is here very low because of local SNR. The morphological information is more important in this recurrence. This last result leads us to develop algorithms which combine and fusion the Top Hat and the CB. This is the study of the next part.

### 4. Combination and fusion

In the previous sections, two detectors have been presented. Both of them ensure a good detection, with a reduced false alarm rate. But, to take advantage of both methods and to further improve the detection performances (i.e. to suppress some more false alarms), different combinations of the methods can be used.

At least four different possibilities can be considered:

1. morphological detector alone
2. statistical detector alone
3. morphological detector followed by the statistical detector
4. statistical detector followed by the morphological detector

After the detection with the contrast box, the geometrical model remains valid. As a consequence the two operators can be used successively: the morphological detector is applied on the result of the statistical detector (case 4). The target echo cannot disappear (it fits the geometrical model, and a good detection is ensured), and no new false alarm can be introduced. Therefore, this combination gives always better results than those obtained with the statistical detector alone (case 2). As a consequence, case 2 will no longer be considered : it is always included in case 4.

On the contrary, the opposite solution (start with the geometrical detector : case 3) did not give interesting results: the local statistics of the image are too deeply modified by the morphological operations and are not discriminant anymore (the target echo is still preserved, but no more false alarm is suppressed). We will therefore not consider case 3 anymore.

The two remaining cases are case 1 and case 4. Most of times, the false alarms obtained in these two cases are not located at the same places. Therefore, a complementary use of the two methods can improve the detection results. We propose to aggregate the corresponding results by a fusion of the detections. The two corresponding outputs are normalized to have a similar compatible range. Then, the minimum output is selected for each pixel. This corresponds to a conjonctive fusion of the results [5]. After the fusion, the same thresholding is applied for the decision (each
feature with a value greater than 30 per cent of the maximum value of the result is considered as a potential target echo). The corresponding processing scheme is presented on figure 4.

Table III: false alarm peaks for the fusion algorithm

<table>
<thead>
<tr>
<th>recurrence</th>
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<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>False alarm peak</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Next, we present the last algorithm which takes into account the four recurrences to build a performant fusion algorithm.

5. Combination and fusion

The idea of this approach is very simple. In different experiments, some reverberation echoes do not change position between two successive recurrences. These echoes are caused by the sea bottom. As this kind of echo look like target echo, they are very disturbing for the detection. After the processings on one single recurrence, the only remaining false alarms are of this kind. Since these false alarms are stable among the different recurrences and since the target echo moves, a fusion algorithm between the four recurrences will enable to improve the detection.

The proposed algorithm runs like a human operator who tracks a target. It is not general but adapted to our real data. It allows to show that the information contained in a sequence of sonar images can be used to improve detection results. We propose another way to use this information in

Figure 4. Scheme of the fusion algorithm

Table III presents the results obtained on real data. The target echo is still always correctly detected, but there are no false alarm any more in two recurrences and the detection is almost perfect in the two others. So, these results are very satisfactory.

Next, we present the last algorithm which takes into account the four recurrences to build a performant fusion algorithm.

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Figure 4. Principle to delete ground echoes

5.1. Principle

The figure 4 allows to understand the principle of the fusion algorithm. The algorithm presented in section 4 is noticed CF algorithm (for Combination and Fusion). The proposed algorithm in this section assumed that the detection is possible in one recurrence (see ping 1). On the original image of this recurrence, we delete the target echo. We assume that the original image contains two ground echoes and other false alarms which are not caused by the sea bottom. Now, the goal is to detect on this image the ground echoes which look like target echo. We propose to use the CB algorithm (see section 3). It allows to delete echoes which are different of the target echo and to keep the ground echoes. In another recurrence (ping 2), the target echo and two false alarms are remaining after the CF algorithm. Actually, the target echo is weaker or/and located near reverberation and so the ground echoes can not be deleted. As these echoes are stable, we can subtract this result from the ping 1 image obtained after CB algorithm. The final image of the ping 2 only contains the target echo

5.2. Algorithm and results

This algorithm can be decomposed into five steps:

1. When a target is detected in a recurrence, we delete it in the original image.
2. We perform the CB algorithm (see section 3) on this original image with the target removed to detect the false alarms which look like
target echo.

3. The different false alarms are localized on the result of CB algorithm.

4. On the other recurrences, we compare the position of remaining false alarms with these noticed at step 3. This step allows to delete the ground echoes.

5. If false alarms do not occur anymore in one of the recurrences, then this recurrence is processed at step 1. Next, we run again the other steps until all false alarms are deleted.

The first four steps are run and allow to delete the last false alarm in the recurrence 4. Next, we remove the target in this recurrence and run again the algorithm. Thanks to the false alarms localized in recurrences 1 and 4, we can classify in the recurrence 3 two echoes as false alarms and so only the target echo remains.

This algorithm then allows us to detect the target without false alarm in the four recurrences.

6. Conclusion

In this paper, we presented two algorithms aiming at improving the sonar detection in presence of reverberation echoes. Based respectively on a geometrical approach and on a statistical approach, the two proposed methods involve image processing based operators. Each method gave interesting results. To further reduce the false alarm rate, the results provided by the two algorithms and their combination have been aggregated. After this algorithm, some false alarms remain in some recurrences. We proposed an algorithm which makes the fusion of results obtained on several recurrences. This process allowed to delete the last false alarms caused by the sea bottom. The final results obtained on real data are very satisfactory: a robust detection is ensured and there is no more false alarm. Although the presented methodology is very general, an experimental study is necessary for the tuning of the parameters. Nevertheless, this tuning is easy to perform and it turned out to be quite robust for the processing of different images.

The perspective of this work basically lies in the fusion step. Actually, other detection algorithms could be taken into account in this last step: the aggregation of other methods proposed in the literature could improve the results. The idea is not to propose one more new method, but rather to take advantage of all the existing methods. In this case, some more elaborated fusion strategies could be used.

References