EVALUATION OF THE QUALITY OF IMAGES OBTAINED BY SYNTHETIC-APERTURE SONAR.

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1. INTRODUCTION

The evaluation of sonar image quality is essential for the prediction of imaging sonar performance at sea. This prediction is especially difficult to achieve in the case of synthetic aperture sonar systems where the towed body trajectory is part of the imaging algorithms. As the main aim of such a system is to increase the sonar resolution (for a given sonar configuration), we will mainly investigate the resolution aspect of the problem. As far as we know, the only universal criterion for resolution is the Rayleigh criterion commonly used in optics. This criterion has been applied to sonar images but, as we will see, it is no more sufficient to describe image degradation in the several cases. A new quality criterion has thus to be investigated.

2. RESOLUTION MEASUREMENTS

Side-looking sonar performance is commonly expressed in terms of resolution. Both lateral and azimuthal resolution are considered and measured separately. As lateral resolution is directly related to time resolution ($\delta = cT/2$ for an envelope extraction and $\delta = c/2B$ after pulse compression if any pulse compression is being used; T: transmitted signal duration; B transmitted signal bandwidth and c: sound velocity), we will mainly pay attention to the azimuthal resolution. Azimuthal resolution can be expressed in terms of point scatterers resolving. A first rough idea is given, for simple arrays, by the measurement of the main lobe width. The effective resolution has to take into account the side lobes influence, as implicitly expressed by the Rayleigh criterion commonly used in optics. We will thus simulate the case of two point targets (same echo level) situated at the same range and separated only in azimuth. We will then consider the obtained images and try to measure the processing performance from these images.
Figure 1 shows the envelope of the output of synthetic aperture sonar for the following sonar configuration:
central frequency = 12 kHz, bandwidth (-3dB) = 8 kHz (1 octave), physical array length = 4 m, towed-fish speed = 2 knots, pulse repetition frequency = 4 Hz, target slant range = 500 m, two point targets separated from 2 m.
Figure 2 shows a cross-section of this image at the the range r = 500 m corresponding to the targets range. This cross-section gives an objective description of sonar performance and can be used to compare processing schemes performance in the case of perfect trajectory [1] .

3. ERRATIC TRAJECTORY INFLUENCE

The prediction of sonar performance in a natural environment requires the simulation of various disturbing phenomena such as random propagation, noise, target anisotropy, Doppler effect, erratic trajectory of the towed array, ... As the erratic movements of the towed body are described in the literature [3],[7] as a major limitation of synthetic array techniques, particular attention has been paid to evaluating the importance of these effects. The erratic trajectory has been modelled as the sum of a perfect one (linear with a constant speed) and periodic movements (sway). Received echoes have been simulated taking into account the real trajectory. They have been processed as if the trajectory was a perfect one (linear, constant speed). We start the simulations without any disturbing movement and increase the amplitude of the disturbances up to the limit of a damaged image. Figures 3 and 5 show the images obtained for the same sonar configuration as in figure 1 for the following sway movements (sinusoidal with a period of DP):
long period movement: $DP = 13 .l_{sa}$; l_{sa} = length of the synthetic array
short period movement: $DP = 0.5.l_{sa}$;
Figure 4 shows a cross-section (of figure 3) corresponding to targets position. From figures 3 and 4 one can see that, due to the appearance of ghost targets, the image can be considerably degraded without resolution loss. From figure 5 one can notice that the erratic movement influence can also induce a loss of echo level. These figures clearly show that, although the Rayleigh resolution criterion is a universal one, it can hardly give a complete description of sonar image quality.
Some works have been carried out to try to overcome this problem by measuring a weighted difference between the image obtained in the case of a perfect trajectory and that obtained in the case of a real one[3]. This distance measurement can be used to describe the influence of ghost targets but it can hardly take into account either the signal level decrease or any echo migration.

4. SYMMETRICAL DISTURBANCES: DIFFERENTIAL DOPPLER

Together with resolution increase, one of the interest of wide band synthetic aperture is the increase of the coverage rate which leads to increasing the towing speed. Spatial under-sampling could also be used in wide band systems [6] to increase this coverage rate.
In this case, the Doppler effect (due to the radial movement between the sonar and the target) has thus to be taken into account. The Doppler compression varies during the synthetic array formation; the maximum radial speed is obtained for a position corresponding to the angle θ (between the towed body trajectory and the acoustical path):

$$V_{rad} = V \cos(\theta/2) \approx V \lambda / 2 L_T$$

in which V is the speed of the sonar platform translation, θ_a is the main lobe width of the physical array ($\theta = \pi - \theta_a/2$), λ is the wavelength corresponding to the central frequency and L_T is the size of the physical array.
If any pulse compression is used, the transmitted signal has to be optimised in order to be Doppler tolerant [9]. If Doppler tolerant signals are used, the envelope of the output of the matched filter is only slightly affected (loss of signal level). Only the output phase can be seriously affected [2], [9]. The output phase shift can be written as:

$$\phi = \alpha T f_0 \mathrm{Log}(s)$$

in which α is a constant related to the relative bandwidth of the transmitted signal, T is the signal duration, f_0 is its central frequency and s is the Doppler compression rate.

One solution to avoid this phase perturbation is to apply synthetic array processing to the output envelope [1], [2]. In this case, the image is not affected by the Doppler effect but the resolution performance is reduced.
If we apply this processing to the real part of the output, we then have to quantify the influence of phase shifts on image quality [2]. It is important to note that this phenomenon is entirely inherent to the processing geometry. In the case of a constant velocity trajectory, this phase shift is a symmetrical one (with respect to the platform position corresponding to the minimum slant range). Figure 6 shows an example of the image degradation for high towing speed (v = 36 knots).

5. EXTENDED TARGET

The prediction of sonar performance in a natural environment requires an estimation of the acceptable characteristics of the disturbing phenomena before damaging the images. The various images displayed illustrate the difficulty of defining a universal criterion that could be used to quantify image quality. The resolution criterion applied to two point targets is no more sufficient. We suggest to apply this criterion to various other elementary shapes. Another type of standard targets is commonly used for the evaluation of video, typography or photography equipments. They are mainly based on lines separations for different angles and for different situations in the image. Using similar techniques leads to extended targets imaging.
Extended targets can be easily simulated by sampling any surface or shape (line, cross, square, triangle,..) and replacing the target by a set of point scatterers with appropriate positions and amplitudes. In this paper, we will only consider the case of lines along the track as the interpretation of the associated images can be easily achieved. One major difference between point scatterer and line target is the directivity pattern of the target (considered as a re-emitter): the longest the target, the narrower its beam pattern. The assumption commonly used in synthetic aperture sonar processing (which states that the signal reflected is the same, whatever the sonar position is) is no more valid and the array gain of the processing is considerably reduced in some cases. Figure 7 shows the example of a very long line target (target length: L = 5.5 m), compared to the synthetic array resolution (δ_{sa} = 2 m) and figure 8 shows the corresponding synthetic aperture image. One can easily see that the image is quite the same in both cases and that there is no resolution gain due to the synthetic aperture processing. This is mainly due the fact that the target beam pattern is much narrower than the array one.
Figures 9 and 10 respectively show the raw and the processed data in the case of two short line targets (L = 1 m; δ_{sa} = 2 m) with a separation of 2 m. In such a case, one can see that the resolution gain is still acceptable, the target length being comparable in length to the array resolution.
The same type of targets have been used for the evaluation of erratic platform movement influence. Figure 11 (processed data) shows the test targets used: 4 line targets separated in both azimuth and range; target length is 5.5 m, azimuthal separation is 5.5 m and lateral separation is 0.15 m.

The advantage of such a pattern is to evaluate simultaneously the performance of both the lateral and the azimuthal resolution and of cross-disturbances, in the case of a erratic trajectory.
An example of disturbed trajectory influence is given in figure 12 for the case where the erratic platform movement is the sum of two sway movements different periods (DL1 = 300 m, DL2 = 12.8 m).
A clear asymmetry of the processed image appears in both vertical and horizontal axes due to cross-components interaction.

6. CONCLUSION

Although the Rayleigh resolution criterion (two point scatterers resolution) is a universal one, it is not sufficient to describe "image quality" in the case of synthetic aperture sonar. The use of complex extended targets (closer to real targets) is needed. A pattern including several extended targets can be an intermediate solution. It can describe both lateral and azimuthal performance as well as cross inter-actions. Such a pattern still needs to be associated with an objective distance measurement such as the one used in the case of point scatterers [3]. A relation has then to be established between distance measurements and visual observations (experimented sonar operators) in order to establish an objective criterion for image quality using these measurements.

7. ACKNOWLEDGMENTS

This work was supported by the European Communities (MA.S.T. program, AC.I.D. project).

8. REFERENCES

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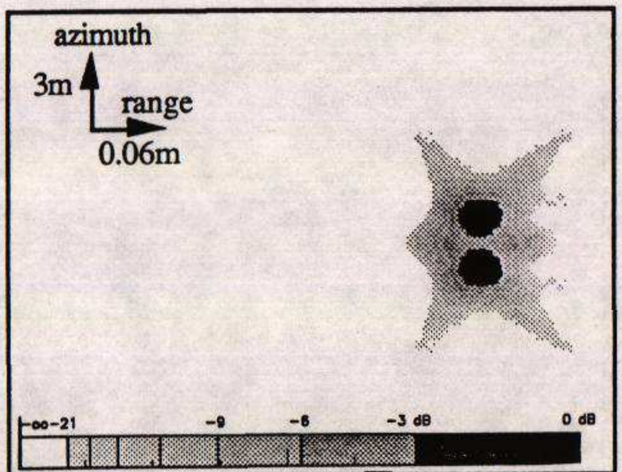

Figure 1: 2 targets at 500 m; processed data
(same grey scale level for all the images)

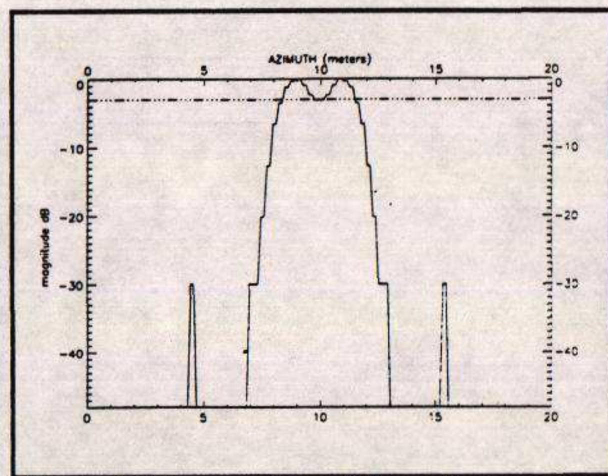

Figure 2: Cross-section of figure 1

Figure 3: Ghost targets

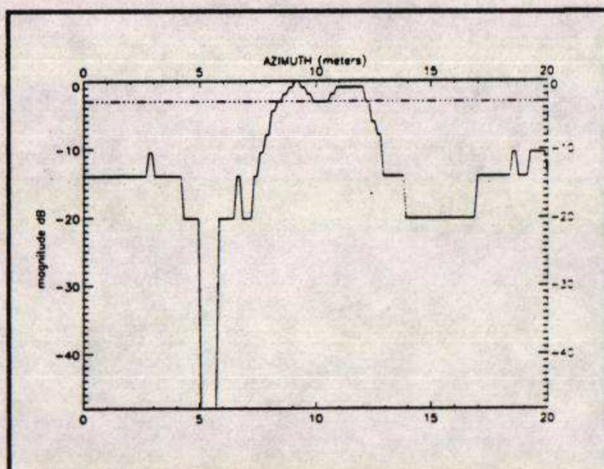

Figure 4: Cross-section

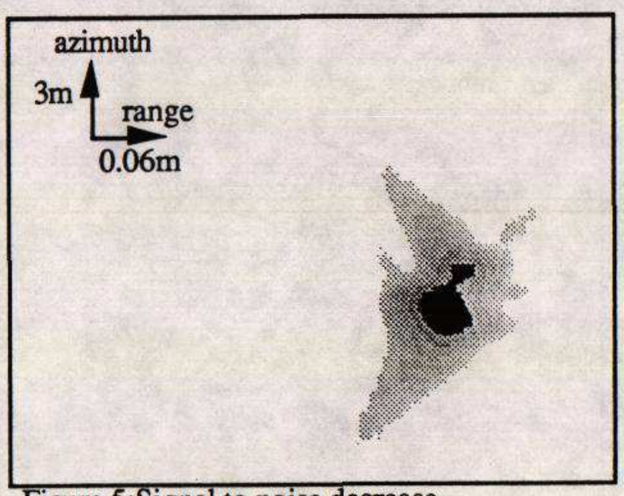

Figure 5:Signal to noise decrease

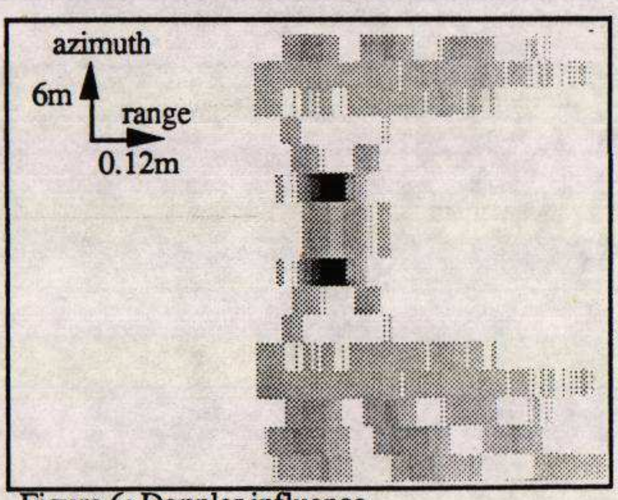

Figure 6: Doppler influence

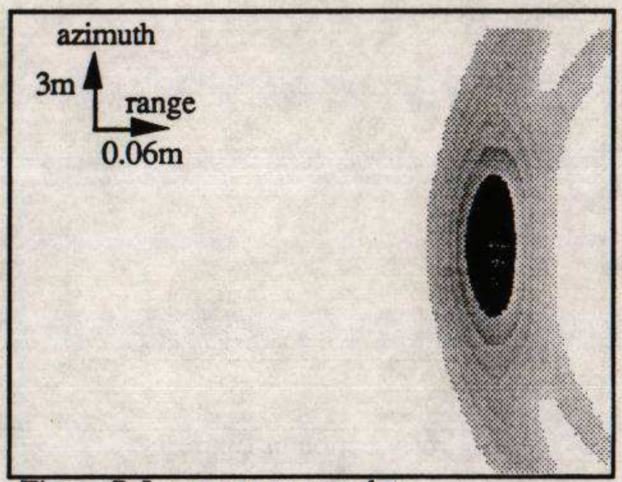

Figure 7: Long target; raw data

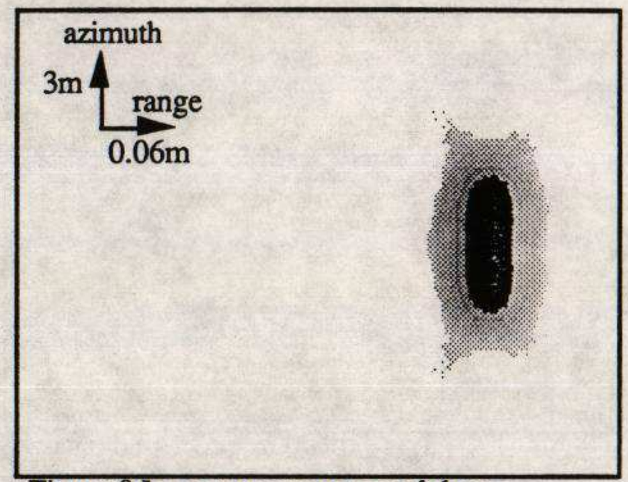

Figure 8:Long target; processed data

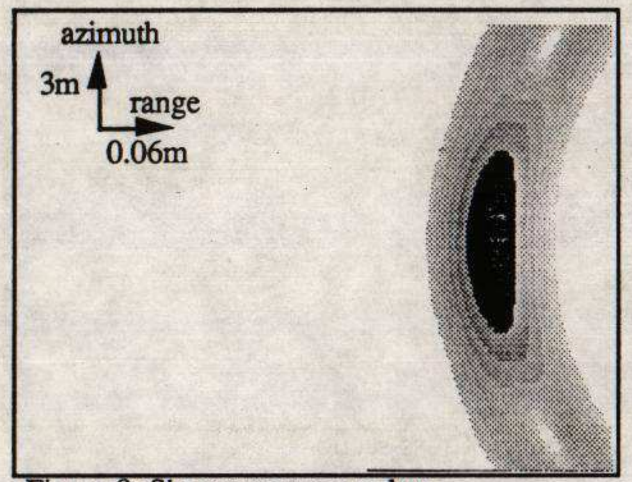

Figure 9: Short targets; raw data

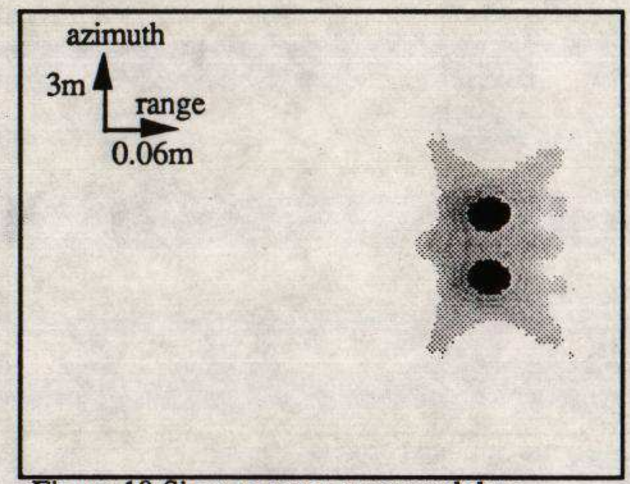

Figure 10:Short targets; processed data

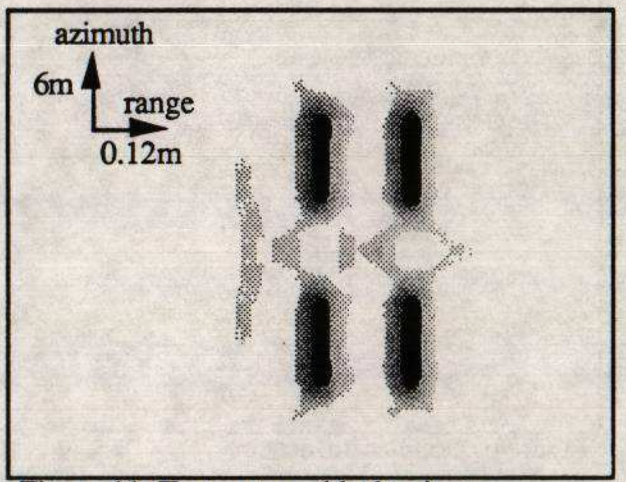

Figure 11: Test pattern, ideal trajectory

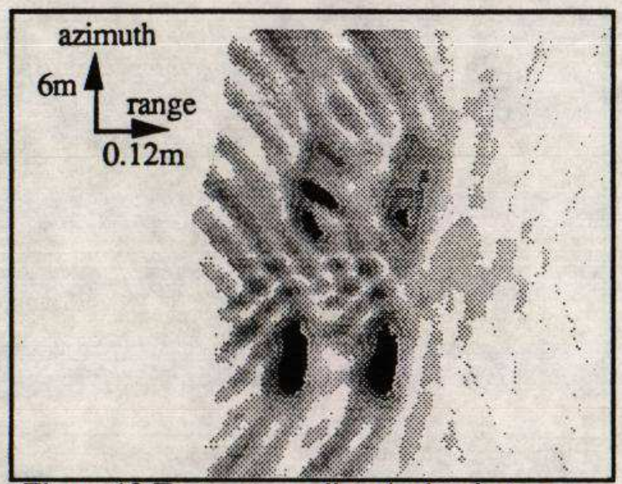

Figure 12:Test pattern, disturbed trajectory