Effect of waveform on synthetic aperture sonar performances

Stéphane GUYONIC

Groupe d'Etudes Sous-Marines de l'Atlantique
BP 42
29240 BREST NAVAL
Email : guyonic@gesma.fr

Abstract

This paper describes the main properties of the synthetic aperture sidescan sonar and highlights performances and limitations related to sonar features for mine counter measures.

Attention is focused on the theoretical performances : azimuthal resolution, signal-to-noise ratio and mainly shadow-to- reverberation ratio.

This theoretical analysis is finally compared with experimental sonar images. These images have been obtained with transducers moving along a rail and insonifying a sea bottom where some spherical and cylindrical targets are laid. Some of these targets are partly buried. Several signal waveforms, such as monochromatic or Frequency Modulated, have been used within the full 25 - 80 kHz band and different pulse durations have been transmitted as well. These experimental results can be considered as the first in the World under real conditions and with a good shadow-to-reverberation ratio.

1. Introduction

Synthetic aperture techniques in radar is well known [1]. Such technique applied to sonar concept is now within reach. The need of using this technique is obvious. From a military point of view, in the Mine Warfare, threat obliges mine countermeasures specialists to design systems able to achieve high resolution at long range and able to detect and classified buried objects. These objectives can be reached in using synthetic aperture techniques. Today, very few experiments have been realised in the World with such techniques [2], [3]. Thus detection and classification performances that could be achieved by such systems are not well known and not validated. This paper begins by describing the principle and the main characteristics of this technique. Following these well known generalities, concepts of detection and classification are studied and translated into some analytical expressions. Then a real experiment using a 15 meters long rail is described. The goal of this experiment is to study the influence of signal characteristics on sonar performances in terms of detection and classification of objects. Results are then compared with theory.

2. Synthetic Aperture technique : Principle and Characteristics

The synthetic aperture principle consists in generating a virtual antenna from the successive positions of a much smaller physical antenna. Signals received by transducers are stored through the period T during which a considered area of the sea bottom is illuminated and then coherently added. Let us consider the following simplified configuration :

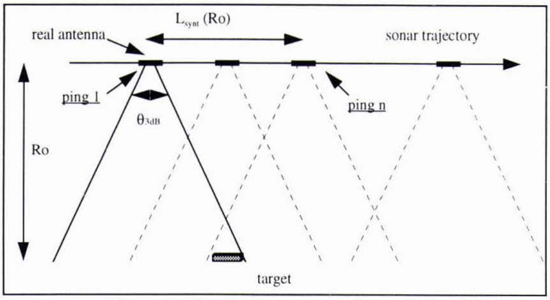

figure1 : Synthetic aperture formation

Let Ro be the minimum distance between the sonar and the target, θ_{3dB} be the 3 dB aperture of the real antenna. The length of the synthetic aperture depends on the range of the current pixel, it is given by $Lsynt(Ro) = Ro\theta 3dB = Ro\dfrac{\lambda}{Le}$ (Le is the physical transmission antenna and λ is the signal wavelength)

2.1 Synthetic aperture advantages

By considering the above geometry, the phase of signal received during the displacement of the physical antenna follows an parabolic variation and by the same way the frequency associated with an echo varies linearly. We can notice an analogy with the behavior of a linearly frequency modulated signal with a pulse length of T and a bandwidth of B. These signals are in current use in sonar or radar applications to permit the use of high power. A good range resolution is then achieved by a compressed pulse technique It uses a matched filtering by the cross correlation of the received signal with the inverse replica of the transmit pulse.

By the same way the synthetic aperture technique can be made by a compressed pulse based on the cross correlation of data in the along track direction within the period T and the equivalent law phase history [4]. In this case, T is the target illumination period and B is the doppler frequency bandwidth resulting of the relative sonar-target motion ($T = \dfrac{R\lambda}{VLe}$, $B = \dfrac{2V}{Le}$ with R = range, V = sonar speed, Le = transmit antenna length)

Results of this processing generate very fine resolution t, independent of both range and frequency. The azimuthal resolution can indeed be estimated as the value of the 3dB width of the correlation peak that is to say:

$$\delta az = \frac{Le}{2} \qquad (1)$$

This result explains the interest in this technique. In fact, for synthetic aperture sonar, the smaller the size of the transducers is, the better the azimuth resolution is, which is just the opposite behavior of a classical beamforming.

What follows will highlight the other advantages of this technique and especially the improvement reached in the Signal-to-Noise ratio.

2.2 Synthetic aperture limitations

Some particularities of this technique which can involve limitations and need at least more investigations have to be taken into account.

Firstly, the synthetic aperture sonar is characterized by the occurence of ambiguities in the range direction and grating lobes in the azimuth direction. In the range direction, ambiguities are avoided with a condition on the recurrence period Trec. In the along track direction grating lobes resulting from the spatial lacunarity effect of the synthetic aperture technique which generates a synthetic beam repetition. One of the best way to cancel the grating lobes is to adapt the zero of the receiver antenna diagram with the position of the grating lobes. These two conditions are expressed in the following inequalities:

$$\frac{2Rmax}{C} < Trec < \frac{Lr}{2V} \qquad (2)$$

Lr : receiver antenna length

Secondly, the synthetic aperture technique requires a great accuracy in the phase measurements, otherwise imagery defects appear (false echo, contrast degradation,...). Techniques of autofocalisation based on the use of the high signal correlations between successive sonar pings, in the case of a convenient spatial oversampling, authorize us to go beyond the theoretical phase accuracy limits [5].

High computation power needed by synthetic aperture processing should find solutions in the next future with some new studies and algorithms coming from radar [3], [6].

3. Detection and Classification concepts

Synthetic Aperture Sonar performances can be evaluated or approached by computing and analysing theoretical contrasts between Signal and Noise (for detection scenario) and Reverberation and Noise contrasts (for a classification scenario, if shadow analysing is used for target classification). Some differences appear between synthetic aperture sonar ratios and those relative to a classical sonar and are underlined later on.

3.1 Detection concept

Detection is the ability for an operator to isolate a signal from noise. Noises may have different origins (ambiant noise, electric noise, reverberation from sea bottom, sea surface or volume inhomogeneities,...).
- Signal-to-Noise ratio : SNR (or contrast) is given by the following expression :

$$SNR = SL + TS - 2TL - NL + DI + IF \text{ (in dB)} \tag{3}$$

with : - SL : Source Level, NL: Noise Level, DI: Directivity Index, TS : Target strength
- TL : Transmission losses (geometrical spreading and absorption losses)
- IF : Improvement factor = IF_{PC} (pulse compression) + IF_{SAS} (SAS gain)

- Signal-to-Electrical Noise ratio :SER (at the intput of the preamplifier) :

$$SER = SL + TS - 2TL + Sh - 178 + 10 \log_{10} B + 20 \log_{10} N - 10 \log_{10} N + IF \text{ (in dB)} \tag{4}$$

with : Sh : Sensitivity of the receiver, B : Signal bandwidth, N : Number of transducers

In the case of our experiment, the ambiant noise can be regarded as negligible. Thus, the main sources of noise are bottom and sea surface reverberation.
At short ranges, in any case, detection is limited by bottom reverberation. This contrast is given by :

$$SRR = TS - RL - 10 \log_{10} S + IF_{SAS} \text{ (in dB)} \tag{5}$$

with : RL: Reverberation Level, S: resolution area cell
If the sonar operates in shallow water conditions, the influence of surface reverberation has also to be taken into account.

3.2 Synthetic aperture and real antenna sonars differences

By comparing classical sonar and synthetic aperture sonar performances in the above expressions, some differences appear. The main one is relative to the improvement factor (IF) which differs by considering a classical processing and a synthetic aperture processing. For a classical sonar, if a pulse compression is made, the theoretical improvement is limited to the gain of $10 \log_{10} BT$ (B : signal bandwidth and T : pulse duration)

In the case of a synthetic aperture processing a supplementary gain appears due to the effect of the coherent integration (or azimuthal filtering). This term depends on the number of effective summation or in other terms, is connected to the length of synthetic antenna.

$$IF = 10 \log_{10} BT + 10 \log_{10} \frac{R\lambda}{2Le\delta az} \tag{6}$$

Another difference can be noted by considering the sonar resolution cells which are given respectively for a classical sonar and a synthetic aperture sonar by :

$$S_{clas.} = C\frac{\tau}{2} x R \frac{\lambda}{Le} \frac{1}{\cos\alpha} \tag{7a}$$

$$S_{SAS} = C\frac{\tau}{2} x \frac{Le}{2} \frac{\lambda}{\cos\alpha} \tag{7b}$$

A roughly analysis of expressions (5), (6) and (7) as the case of a synthetic aperture technique or a classical beamforming is used, shows that the influence of frequency is exactly inverse in terms of detection ability.

Signal-to-Reverberation ratio increases when frequency becomes higher in the case of a classical beamforming and decreases with a synthetic aperture processing.

3.3 Classification concept

The concept of classification based on a shadow analysis needs to take into account two ratios, first the Reverberation-to-Shadow ratio and secondly the Reverberation-to-Electrical Noise ratio (expression of it can easily found from (4) and (5)). The first ratio expresses the possibility of creating a shadow by the relative geometry of the different sonar beam (transmit sonar beam, receiver beam and synthetic sonar beam) and target geometry (size and orientation). The second ratio expresses the possibility for the shadow to be visible.

Let us consider, Lr as the Reverberation Level and Ls the Shadow Level.

$$Lr = k\int Gt(r,\theta).Gr(r,\theta).Gsynt(r,\theta)d\theta \qquad (8)$$

$$Ls = k\int Gt(r,\theta).Gr(r,\theta).Gsynt(r,\theta)F(r,\theta)d\theta \qquad (9)$$

$F(r,\theta)$: binary function = 1 if $-arctg(\frac{Ltarg}{2R}.) < \theta < arctg(\frac{Ltarg}{2R}.)$

= 0 elsewhere

$Gt(r,\theta), Gr(r,\theta)$ and $Gsynt(r,\theta)$: transmission, reception and synthetic diagrams.

Let us assume that the other noise components (ambiant noise, electrical noise) and surface reverberation are negligible (not satisfactory in a shallow water environment with wide vertical beam used), shadow depth can be estimated by the following Reverberation-to-Shadow ratio :

$$RShR = 10\log_{10} Lr - 10\log_{10} Ls \qquad (10)$$

This above expression has been used for theoretical computation (figure 5)

4. Synthetic Aperture Sonars : experiments

4.1 Facility and equipment set up for experiment

In GESMA, a facility have been designed three years ago and refited last year to test transducers and especially in a synthetic aperture running. This facility consists of a linear rail, 15 meters long that includes a platform moving by a motor. This platform can carry transducers for transmission and reception signals. Moreover, the rail can be displaced along a vertical axis by a chain system and be fixed at seven different positions. By using these possibilities, the effect of surface reverberation on sonar performances can be studied.

This rail is located in a shallow water environment. The maximum water depth is 17 meters and tidal range may be important (7 meters for spring tide). The lowest rail fixation is 6 meters above sea bottom. This is the position used for experiments described in this paper.

The sea bottom in front of the rail is composed with a mixture of sand and fragments of shells caracterized by a high reveberation. Moreover, a little slant of the bottom is perceptible at short ranges and also some ripples.

A target field has been disposed for this experiment and spreads from 15 meters to 50 meters respect to the rail.

Six targets are laid on the sea bottom. Four of them are spherical objects of 1 meter diameter and the others are cylinders (0.55 meter diameter and 2.8 meters long). Spheres located at 15 meters and 39 meters from the rail were laid two years ago and a partial burial is effective. This natural burial is resulting from some important currents which generate a scouring effect. To sum up, these two targets are one third buried and a mound of sand is just against them. The first cylinder (at 22 meters) is laid on a little dune that involves a little slant of the cylinder and a modification of the shape of the shadow in the processed image.

4.2 Objectives

The goal of experiments is to analyse the influence of signal characteristics (frequency, bandwidth, pulse compression,...) on detection and classification operations and to validate, by calibrate trials, the main properties of Synthetic Aperture technique applied to sonar. very few experiments currently exist in a sea context in the purpose of small targets detection and classification. So these objectives and associated results may be considered as the first in the World obtained in a sea environment.

4.3 Transducers and signal characteristics

Transducers used for the experiment had been designed in the 25 to 80 kHz frequency range and have a uniform frequency response. Several transducers were used, one for the transmission and three for the reception.

Several data have been stored for each acquisition, one channel for the transmit signal, one for the motor coding data and six other channels for two superposed antennas (three transducers for each).
Transducers have a rectangular shape of 0.195 m X 0.07 m dimensions. They were fixed at 6.8 meters above the sea bottom with a grazing angle α of 15 degrees. Some acquisitions have been made in CW (Chirp Wave) and others in LFM (Linearly Frequency Modulation).
To sum up :
- CW signals used are : 32, 48, 64, 80 kHz with a pulse length of 150 µs (and someone with pulse lengths of 62 µs and 75 µs)
- LFM signals used are : 32 - 64 kHz, 48 - 80 kHz and 27 - 80 kHz with a pulse length of 10 ms, that is to say a BT product of 320 and 530.

4.4 Data processing and results

Processing had been made in post processing time with two dimensional process, firstly the pulse range compression when a LFM signal is transmitted and secondly the synthetic aperture processing. This focusing is made in the frequency domain, the hyperbolic echo migration is compensated with a dephasing term.

- *Azimuthal resolution results* :
Results show that theoretical along track resolution is achieved in any case and it is really both of range and frequency independent.

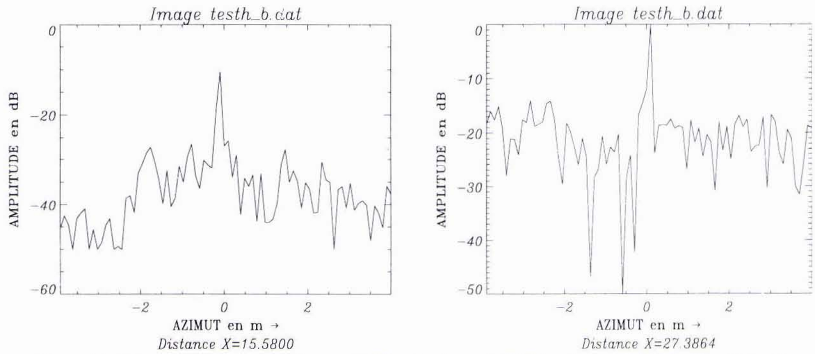

figure 2: Along track cuts at 15 m and 27 m (spheres), (CW pulse at 80 kHz, T = 75 µs)

Figure 2 illustrates the azimuthal echo compression with two examples : two spheres at 15 meters and 26 meters from the sonar. The real along track resolution is really equal to 10 cm (Le/2).

- *Frequency influence* :
Figure 3 shows a cut in range centered on a sphere target echo with two different CW pulses, 80 kHz (left) and 32 kHz (right) with respective pulse lengths of 75 µs and 62 µs. Some remarks may be noted. First the shadow is in both case very convenient for a classification but a sensible degradation appears at the lowest frequency. The wider aperture antenna at low frequency and the effect of surface reverberation may explain it.
No AGC (Automatic Gain Control) is applied on signal so the range propagation effects (losses) are quite visible on data. Moreover, the left side of figure 3 reveals the narrow beam effect at 80 kHz. The first target is outside the main lobe transmission antenna. A last remark on these two signals deals with the Signal-to-Reverberation ratio which is greater at 32 kHz than at 80 kHz, that is in good agreement with theory and equations (5), (6) and (7)

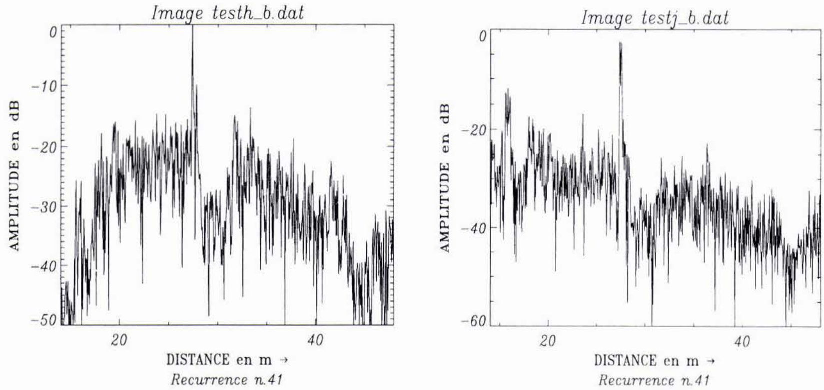

figure 3 : Across track cuts (echo and shadow of a sphere at 26 meters)
(CW pulse - left side f0= 80 kHz, T = 75 μs - right side : f0=32 kHz, T=62 μs)

Signals characteristics have influence on the shadow depth, the computation of equation (10) give the following results (figure 4 : two different target sizes have been used for computation L = 1m equivalent to the spheres laid and L=2.8 m which corresponds to the cylinders).

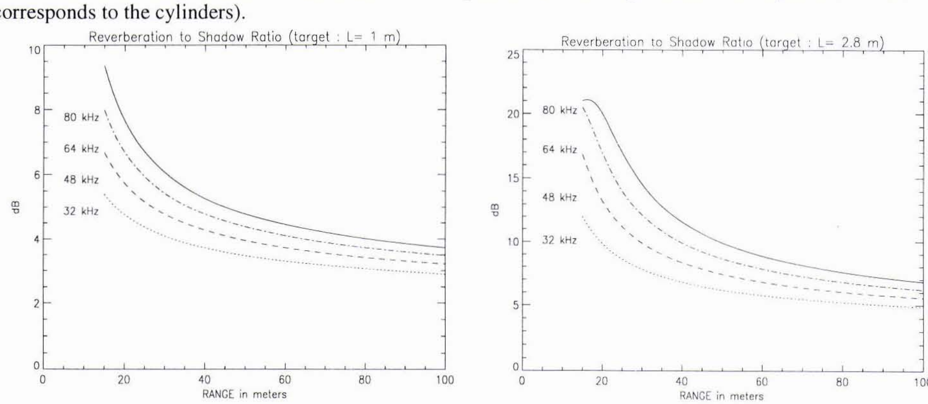

figure 4 : Theoretical value of the Reverberation-to-Shadow ratio : Influence of frequency

These shadow depth values are overestimated in a shallow water environment with wide beam sonar. Nevertheless experimental results show a good agreement with regards to the influence of frequency which figure 4 reveals. Higher frequency is, deeper shadow is and as shown on these diagrams this difference decreases with range to become not sensible on the last targets.

- *Pulse length and bandwidth influence*

One more influent parameter is the pulse length of signal or the effect of wide bandwidth (and pulse compression). That is to say signal parameters used to give a better range or azimuthal resolution lead to the improvement of the shadow depth (reverberation-to-shadow ratio) and especially towards the range limit

Figure 5 illustrates one example of numerous processed data. This sonar image shows a good shadow target quality. Every target laid on the field is strictly classified by its shadow. In the center of this target field, two spheres (ϕ=1m) are laid 0.5 meter from the other. They are discriminated. Their specular echoes are separated by 1.5 meters and shadows are also separated. Data are represented as a projection on the sea bottom and a normalization has been applied on them to compensate the effect of the dynamic variation. This image has a resolution cell of 0.1 m X 0.056 m. (azimuth x range).

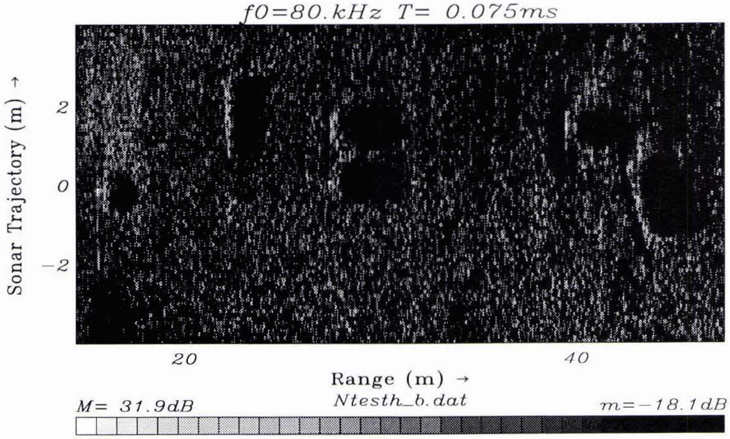

figure 5 :SAS processing results on target field (CW signal f0 = 80 kHz, T = 75µs)

Figure 6 shows the same area insonified with a FM signal of 32 kHz of bandwidth . The azimuth « zero » reference is not the same as the above figure 6.In this case, azimuthal rsolution is also 10 cm and range resolution is equal to 1.4 cm. The shape of shadow are in this last case more outlined. Concerning the two spherical proud targets, located at 26 meters, two echoes are visible, the first one is the direct path from the target and the second one is the first target to bottom path. These two signal acquisitions have been made within a time interval of two months and the last target have been a little bit displaced.

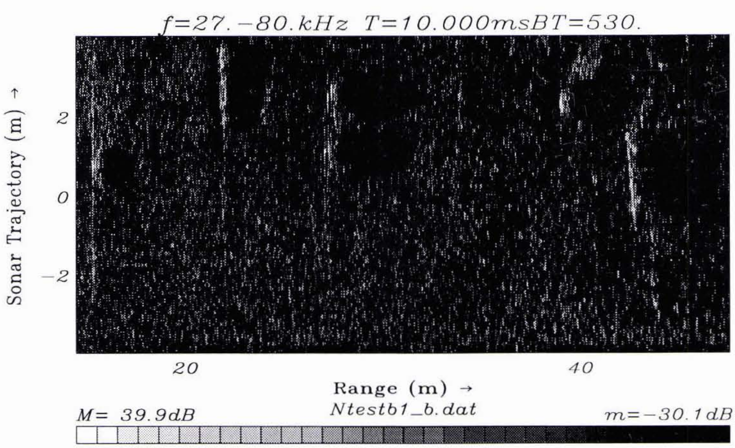

figure 6 :SAS processing results on target field (FM signal f =27 - 80 kHz, T = 10 ms)

- *Window weighting effect* :

Window weighting functions are currently used in classical sonar devoted to classification. In the case of synthetic aperture sonar a weighting function may be applied on each ping of the synthetic antenna.

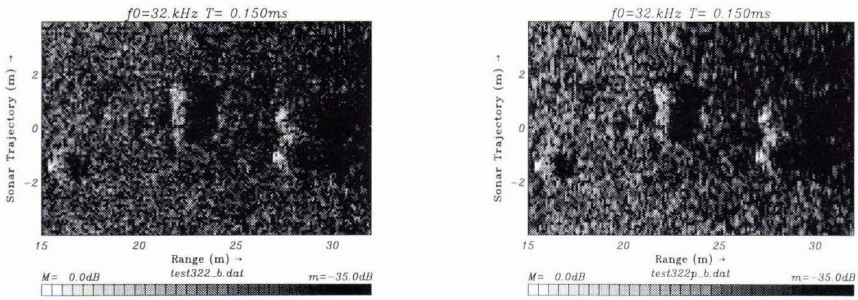

figure 7 : CW signal f0 = 32 kHz, T = 150 μs (on the rigth : HAMMING window)

A Hamming weighting window has been used on data and results compared with those obtained without apodization. A gain of about 3 or 4 dB has been obtained in the case of a CW pulse at 32 kHz and same results in the case of a LFM signals (48 - 80 kHz). Figure 7 and 8 illustrate

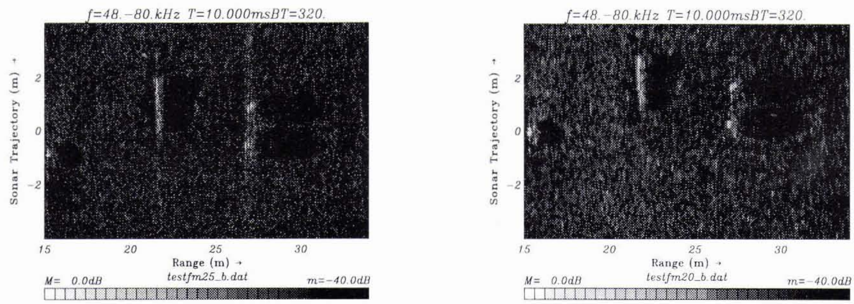

figure 8 a) LFM signal 48 - 80 kHz, T = 10 ms b)HAMMING weighting on synth. antenna

5. Conclusion

This paper provides the main theoretical characteristics of synthetic aperture sonar in terms of detection and classification of objects. The influence of signal characteristics have been studied on synthetic aperture sonar performances and especially on shadow depth.

Many results have been shown such as the interest in using higher frequency for having deeper shadow but this advantage tends to become less sensible when sonar range increases. The use of CW with shorter pulse length or wide bandwidth FM signals also give the best shadows.

A last result shows the reverberation-to-shadow ratio improvement that we can reached by using a weighting function on synthetic antenna (Hamming has been used).

All results obtained with this first experiment have to be confirmed with higher frequency at longer range.

Acknowledgment : *This work has been made within a collaboration with the Coastal Systems Station (Panama-City, Florida, US). I would like to thank Mrs John Lathrop, Jim Christoff and Joël Le Hars (GESMA) for their contribution in the experiment specification and their constant advices and Mr André Salaun et Mrs Corinne Queïnnec for the success of experiments.*

6.References

[1] L.J. CUTRONA « Comparison of sonar system performance achievable using synthetic aperture techniques with the performance achievable by more conventional means ». Journal of the Acoustical Society of America, 58(2),pp 336-348, August 1975

[2] S. GUYONIC « Experiments on a sonar with a synthetic aperture array moving on a rail »,IEEE Oceans'94 Conference Proceedings, pp 571,576

[3] P.T. GOUGH et al « A unified framework for modern synthetic aperture imaging algorithms », University of Canterbury, Christchurch, New Zealand, International Conference on Imagery and Image Processing, Dec. 9-11 1997 (submitted)

[4] G. LEVRINI et al « The sensitivity problem in the synthetic aperture radar (AR) », Alta Frequenza, Vol. LV-N°6 Nov. Dec. 1986, pp 337-348

[5] T. RASTELLO et al « Fourier-Based imaging applied to Synthetic Aperture Sonar »,IEEE Oceans'96 Conference Proceedings, pp1521,1526

[6] R.W. SHERIFF « Synthetic aperture beamforming with automatic phase compensation for high frequency sonars. » Proceedings of the 1992 Symposium on Autonomous Underwater vehicle Technology, pp 236-245, june 1992