Buried mines detection and classification: advanced technologies and signal processing.

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Abstract - In order to improve the Mine Countermeasures capability, there is a need to investigate new techniques which will enable the detection, localisation and classification of buried mines. This paper deals with results obtained in France, under a sonar program involving GESMA and three academic laboratories. An experimental approach has been preferred. Two techniques are under evaluation: the low frequency Synthetic Aperture Sonar (SAS) mounted on a platform as a side scan sonar dedicated to buried mines detection and a sonar mounted just below a platform, looking vertically at the seabed, dedicated to buried mines classification.

I. INTRODUCTION

In order to improve the Mine Countermeasures capability, there is a need to investigate new techniques which will enable the detection, localisation and classification of buried mines. Indeed, mines buried in marine sediments represent a severe threat, especially in coastal waters. Moreover, an inventory of objects buried in harbour areas is necessary to assure the security of ships. This paper deals with results obtained in France, under a sonar program involving GESMA and three academic laboratories. An experimental approach was preferred. Two techniques are under evaluation: the low frequency Synthetic Aperture Sonar (SAS) mounted on a platform as a side scan sonar and a sonar mounted just below a platform, looking vertically at the seabed [1]. In the concept, the first sonar is used for buried mine detection. It is shown that the achieved high-resolution imaging allows for more than adequate detection of shallow buried objects. Data issued from rail experiments and then, from sonar mounted on a ship have been processed. Motion compensation algorithms have been developed using sonar data but also data acquired from navigation instruments. The low frequency (LF) images can be compared and analysed with traditional high frequency images. Nevertheless, in low frequency images, the number of alarms and false alarms is important. False alarm reduction and echo-enhancement algorithms have been developed to help in the selection of targets to be classified at a later step in the investigated area. Results with an automatic segmentation method of SAS images are presented, in order to highlight some characteristics (number, position, shape) of mines echoes. This segmentation method is based on statistical properties ($1^{st}$, $2^{nd}$, $3^{rd}$, $4^{th}$ order statistic estimators) of the sonar images, highlighted by the mean -- standard deviation plane.

The second technique is based on a 3D high resolution sonar mounted vertically below the platform and close to the seabed. Parametric sonar techniques using the non-linearity of the medium and 2D SAS techniques have been investigated. Results presented in this paper demonstrate the ability to classify selected buried objects up to the first meter of sediment. A step forward, a sweeping parametric transmitter has been designed and calibrated. The obtained asymmetric beam width allows SAS processing in one direction and high resolution in the other direction. This design limits the sediment volume reverberation and allows 3D high-resolution imaging. The size of the array is compatible with the use of underwater vehicles like AUVs or ROVs. With both techniques, high resolution is preferred for shape reconstruction of the buried objects.

II. BURIED MINES DETECTION

The first concept is based on a low frequency synthetic aperture sonar (LF SAS) mounted as a side scan sonar. In this configuration, GESMA carried out experiments with the LF SAS mounted on a rail and another experiment where the sonar was mounted as a hull mounted sonar.

A. Rail experiments

GESMA designed and conducted two experiments with low frequency sonar mounted on rail facilities [2]. The first one took place in the bay of Brest, in December 1999, and the second one was in the Singapore area with DSO of Singapore in August 2000 [3]. Such experiments permit the evaluation of the sonar design without being constrained to take into account motion errors inherent to SAS and responsible for image defocusing. The first
trial, called Buried Mines Classification (BMC99), occurred in the Bay of Brest, where the seabed was filled with decomposed shells and algae. For the second experiment, Mine Detection with SAS (MIDSAS'00), the sonar was deployed in a harbour zone near maritime traffic. The seabed was a mud-silt bottom with non-homogeneous sedimentary deposits that may bury mine targets. Depending on the runs and the experiments, the sonar frequencies were selected in the range 14 – 80 kHz. A SAS processing has been applied to the real data recorded. One of the resulting images is given in Fig. 1.

![Fig. 1 LF SAS image obtained on GESMA rail facility, BMC'99 experiment, 14-20 kHz. Cl : shallow buried 2 m long x 0.5 m diameter cylinder. S2 : proud 1 m diameter sphere. S1 : 1 m diameter buried sphere. R1 : rock.

The obtained resolution cell has been measured to be around 10 cm x 10 cm.

B. Hull mounted sonar and results

To go further into SAS processing and techniques, GESMA conducted with TNO, Defence, Security and Safety (The Netherlands) an experiment in 2002 with the LF SAS mounted as a hull mounted sonar on board a Dutch mine hunter (LFSAS'02). This trial permitted the improvement of motion compensation algorithms [4].

1. Motion compensation algorithms

Traditionally, motion estimation and compensation concern the processing of navigation data (MRU and eventually GPS) to correct the recorded sonar signals with measured deviations from a straight path. Today, the recognised method consists of estimating the disturbances from the acoustics rather than external sensors. The SAS community uses conventional algorithms called the Displaced Phase Centre (DPC) or Displaced Phase Centres Antenna (DPCA). These methods can be considered as micro navigation methods that yield estimates of sonar surge, sway and -optionally- yaw, using the cross-correlations of overlapping array elements between consecutive pings. This complements the MRU measurements [5].

GESMA is carrying out studies with ENSIETA, Brest on the problem of motion compensation in SAS processing. Actually, the use of algorithms like DPC alone is not sufficient to perfectly focus the sonar images [6]. Indeed, these measurements allow only the localisation of an array relative to the preceding antenna. The measurement errors are then cumulated progressively along the integration and the estimated trajectories diverge from the absolute. Moreover, navigation alone cannot compensate for problems arising from medium fluctuations or for the bottom relief effects. It is therefore necessary to fuse the data resulting from navigation and DPC algorithm. The problem is that this information is not present in the same space of representation. The processing of navigation data provides the 6 attitude parameters in a global reference system while the result of DPC is available in the form of a longitudinal displacement, a transverse displacement and a yaw rotation between the different positions of the sonar array and then projected in the slant range, varying in time. A more usual way to fuse the two information would be to use a Kalman filter. However, the fact that DPC are combinations of state parameters taken on rather distant dates strongly increase the difficulties. We then selected a more prosaic approach of data fusion. Firstly, we modified the trajectory, so that it was compatible with information from the DPC, then we used the processed trajectory to beamform the sonar data. Concerning the navigation data, during the trials, GPS measurements of the ship were recorded, as well as rotations and accelerations of the Octans MRU placed close to the sonar and various data of the autopilot of the ship. We tried to use all of this information to compensate for DPC method divergence. Then, we fused all of the navigation data and synchronised them with acoustic data. The next step consisted of simulating the DPC with such data to compare the results with the ones obtained with measured DPC. We can thus detect the errors and compensate them in correcting the trajectory. We modify the trajectory issued from the navigation data with the information issued from DPC. Fig. 2 compares images with different motion compensation methods. For beamforming, we have chosen to implement Fast Factorized Back Projection [7], because this algorithm seems better suited to non regular antenna geometry.
size of the LF image. After that, we combine (simple summation, for instance) the information of both images in one resulting composite image (Fig. 4 (c)). We can also have a more advanced combination in using colors, one color for the HF image, and other colors for the LF one (Fig. 4 (d)). The object is to find the advantages of each image in only one composite image. Indeed, HF and LF images do not contain the same information. We merge the shadows resulting from the HF image and the echoes from the LF image. If we look carefully, we can easily see that some echoes in the composite image have no shadows. These echoes need a more precise investigation, to see if they might correspond to buried objects.

Fig. 2 Motion compensation algorithms comparison and resulting SAS images. Images resulting from a Swan Sea Yale wreck file (LFSAS'02). (a) DPC only, (b) NAV only and (c) DPC+NAV.

2. LF/HF comparison

The motion compensation obtained by fusing navigation data and DPC gives well focused images and now allows another approach to the fusion: the comparison between low frequency and high frequency images, both with approximately the same resolution cell. This comparison is possible if we use the data obtained with a HF side scan sonar deployed in the same experiment area. We observe that the detection is easier in the LF case, as we can see in Fig. 3. On the HF image, only the proud target can be classified with its associated shadow. The detection of the half buried target is possible, but the classification is not obvious. Detection of the fully buried target is not possible on the HF image. On the LF image, detection of three targets is easy. Moreover, the shape of the echoes gives us an idea of the orientation of the mines. Finally, one can note that the sediment structure is washed in the LF case. This phenomenon helps for the detection process of the buried objects.

As we can now compare a low frequency image obtained at 20 kHz with a high frequency, a step further is to fuse the two images in order to obtain a composite image. The process is as follows and the results are presented on Fig. 4. Firstly we select some details in the LF (Fig. 4 (a)) and HF (Fig. 4 (b)) images that correspond to the same known parts of the wreck. Then, we transform one of the images to suit the size of the other. For example, we transform and interpolate the HF image to suit the

Fig. 3 (a) Result with the high frequency side scan sonar (750 kHz).
(b) Result obtained with the low frequency synthetic aperture sonar (15-25 kHz). (LFSAS'02).
underwater mines lying on the seabed and buried objects. The results presented here were obtained with the file presented in Fig. 1. We can observe, Fig. 5 (a), the product of the fusion with an automatic segmentation using the four moments (mean, standard deviation, skewness and kurtosis). With this result, we can apply a weight for each class detected and thus enhance the echoes (Fig. 5 (b)).

3. False alarm reduction and echo enhancement

But low frequency SAS images remain difficult to interpret. A segmentation method of SAS images is proposed in order to highlight some characteristics (number, position, shape, ...) of underwater mines echoes. This segmentation method is based on statistical characteristics of the sonar images, highlighted by the mean – standard deviation plane. It is automated by using an entropy criterion [8]. Moreover, the method is extended to the analysis of Higher Order Statistics (HOS) on SAS images. The process proposed can be divided into two steps. Firstly, the HOS (skewness and kurtosis) are locally estimated using a square sliding computation window. In a second step, the results are focused by a matched filtering. This enables the precise location of the objects, after data fusion [9]. This method has been tested by the Laboratoire des Images et des Signaux de Grenoble (LIS) on SAS data containing both

III. BURIED MINES CLASSIFICATION

To take a step further, we now need to classify the object that has been detected. It consists of being able to determine whether or not the buried object is a mine. To achieve this goal, we decided to explore techniques such as 3D high resolution sonar and sweeping parametric sonar.

A. 3D high resolution sonar

This advanced concept is based on a 3D high-resolution data acquisition system using a sonar vertically aimed at the seafloor, fairly close to it. A foreseen operational
system should be made up of several transmitters and receivers that would be tracked over the seafloor to collect data from the sediment volume. A subsequent beamforming process would contribute to the classification of objects. To assess the advantage of this concept, a specific tool has been designed and object classification algorithms have been developed [10][11]. The equipment has been designed for the purpose of both keeping the sonar array aimed at the seafloor and tracking it along two directions. The array is fixed underneath a two-axis computer-controlled moving platform. This process provides a 3D data matrix. In a preliminary phase, experiments have been done with only one projector and one hydrophone. Further studies are focused on the design of a full transducers array. Classification of buried objects in the sand requires the use of a low frequency signal to penetrate the sediment and a narrow beam to provide high-resolution data. Both requirements can be achieved with a parametric (non-linear) technique. A low frequency signal is obtained after a short propagation by combining two primary signals at high frequency. The directivity of the secondary beam is close to the primary one. Unfortunately, this technique does not have a good power efficiency, thus it will meet some limitations for greater burial depth. Another method is to directly use a low frequency source, which has a greater power efficiency but a wider beam. To improve the resolution, synthetic aperture processing is needed. Since the sonar concept is based on two orthogonal displacements, the synthetic aperture processing could be applied along the two motion axes. So, let us consider it as a 2D-SAS processing. After being evaluated in a tank, these techniques have been successfully used at sea.

Fig. 6 (a) shows a vertical cut over a small rock buried half a meter in the sediment. This image was obtained by using the non-linear transmission technique. A first strong echo due to the seafloor reflection appears and the echo from the buried stone comes later. Pictures provide good information on seafloor and sediment volume. The rock shape has been extracted from the 3D pattern resulting from 2D scan (Fig. 6 (b)). It is obvious that this shape does not represent a mine-like object.

B. Sweeping parametric transmitter

A more advanced way of classifying buried mines is to use a sweeping parametric transmitter. The advantage of this technique is firstly to reduce the volume reverberation in using narrow beams in elevation. Secondly, as we have seen before, the parametric technique permits the generation of low frequency signals with a directivity equivalent to high frequencies. Thirdly, the use of low frequencies is very effective in enabling the penetration of the sediment and when adding the SAS technique, a very good resolution along the track direction can be achieved. Finally, in adding the sweeping technique, we thus increase the coverage rate of such a sonar type. Fig. 7.

![Fig. 7 Representation of the transmitter beam patterns mounted vertically onboard an AUV.](image)

A sweeping parametric transmitter has been calibrated by GESMA and the Laboratoire de Mécanique Physique (LMP), Paris, in September 2004. This transmitter is made of 10 PJ120 acoustic modules (80 kHz - 160 kHz, used only between 80 kHz and 120 kHz) that are linearly associated. Each module includes 10 columns associated in pairs (Fig 8). Thus, it constitutes 5 channels by module. Finally, on the 50 channels realised, only 48 are connected to the electronic rack. A program permits the synthesis of the files containing the signals. Each file can contain no more than 256 signals and a different signal can be addressed to each channel.
Fig. 8 Representations of the transmitter consisting of 10 PJ120 acoustic modules.

The calibration took place in a GESMA tank facility (80m x 10m x 8.4m) in which the transmitter was vertically suspended. A hydrophone was suspended at a distance of 10 m to 50 m from the transmitter. During all the tests, both transmitter and receiver were situated at mid width and mid depth of the tank. We firstly determined the beam patterns of the array for primary frequencies. We observe that the beam patterns in bearing and in elevation are representative of the geometry of the array (720 x 62.6 mm). The second phase of the tests allows the study of the beam patterns for secondary frequencies. The variation of the two high frequencies makes it possible to get a large range of low frequency bands. Practically, to obtain the beam patterns of the transmitter, we choose 10 configurations in frequency: two for 10, 20 and 30 kHz and one for 15, 25, 35 and 40 kHz and generated the signals. Hence, with the 10 configurations, we rotated manually the array from -30° to +30° (in the horizontal plane) with 2° steps and registered the signal level with the hydrophone. Thus, we produce the graph in bearing Fig. 9. To obtain the graph in elevation, Fig. 10, we made the elevation angle varying from -10° to +10° with 0.2° steps in synthesising signals that were electronically steered. Regarding the beam pattern in bearing (Fig. 9), the parametric aperture beam width is roughly the same as the one for primary frequencies. The beam in bearing varies between 12.3° at -6dB (8.8° at -3dB) for 40 kHz to 15.8° at -6dB (11.3° at -3dB) for 10 kHz with the lowest primary frequencies (80 kHz and 90 kHz emission gives a 10 kHz signal). Fig. 9 shows the result for different frequencies.

Fig. 9 Secondary frequencies, beam pattern in bearing measured at 20 m with a non focussed primary emission.

Regarding the beam pattern in elevation (Fig. 10), the best resolution is obtained at 40 kHz with 2.3° at -6dB (1.6° at -3dB) and it can grow to 4.4° at -6dB (2.4° at -3dB) for 10 kHz.

Fig. 10 Secondary frequencies, beam pattern in elevation at 20 m with a non focussed primary emission.

The goal of this study was to compare the measured results with the simulated ones obtained with the CEPLAN software developed by the LMP. The design of this transmitter is the first stage reached in the development of a sonar dedicated to buried mines classification. In adding a suitable receiver, the whole system will allow the transmission of a low frequency signal (with the directivity of the high frequencies) that could be combined with the synthetic aperture technique and thus reach an appropriate resolution to classify buried mines.

IV. CONCLUSION

This paper shows that buried mines detection and classification is a multi-faceted problem. Actually, low frequency SAS techniques suit this application. GESMA, associated with laboratories, is working on the scientific questions to improve its ability in hunting buried mines. Firstly, we showed the feasibility of LF SAS to detect buried mines with a sonar mounted on a rail. Then, we mounted the same sonar on board a ship to enlarge the problem and develop suitable algorithms. We have shown that a low frequency SAS mounted as a side scan sonar, associated with techniques such as LF/HF data
fusion and false alarm reduction is a consistent technique for buried mines detection. To continue, we need a system able to classify buried mines. Techniques such as 3D high resolution sonar and sweeping parametric sonar looking vertically at the sea bed seems promising to achieve this goal. A global approach of buried mines detection and classification has been proposed [1]. This includes a buried mine sonar suite mounted on a AUV. The first sonar will be dedicated to buried mines detection, false alarms reduction, and mines localization. The second one will be dedicated to buried mines classification using a sonar mounted vertically and directly headed on detected and selected echoes.

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