Several imaging algorithms for synthetic aperture sonar and forward looking gap-filler in real-time and post-processing on IXSEA's "Shadows" sonar

Frédéric Jean

IXSEA, 46, quai François Mitterrand, 13600 La Ciotat, France
frj@ixsea.com

SHADOWS is a new sonar system developed by IXSEA SAS. It is a towed composed of a synthetic aperture side-scan sonar and a forward-looking sonar. The system produces SAS images with a constant resolution 15cm from 30m to 300m on each side. It also fills the nadir gap from 0 to 30m with images having 40cm x 15cm resolution. The images are provided in real-time and are georeferenced.

The synthetic aperture sonar algorithm uses INS data combined with the Displaced Phase Center Algorithm (DPC). The post processing and real-time modes differ on the weight given between INS and DPC, and on the approximations to be done. The real-time beam-forming algorithm used is the time-domain fast factorized back projection which can be pushed to an exact back projection in the post processing mode.

The forward-looking sonar uses a patented "sectorized emission" architecture. The images are side-scan-like. The real-time algorithm can be customized to make some incoherent integration on several pings increasing the contrast but slightly decreasing the resolution. A post processing algorithm can also provide an animation on a specific contact on the floor.

1   Introduction

SHADOWS is a new synthetic Aperture Sonar System developed by IXSEA (Fig.1.). It provides real-time SAS processing on a 600 meters swath at a resolution of 15cm. The side-scan synthetic aperture sonar is completed with a front-looking sonar imaging the gap at nadir. The maximum speed to form a non lacunar synthetic aperture is theoretically 5 knots. The coverage rate reaches 5.56 square km per hour.

The system computes directly a georeferenced map composed of images calculated in real-time. Images are displayed through a map server and the visualization is done via a web server (Fig. 3.).

Fig 1. Shadows Sonar by IXSEA

2   Shadows System

2.1   Side Scan arrays

Each side is composed of a receiver array of 24 hydrophones and of three transmitters. Two of the transmitters are located at each extremity of the physical antenna in order to perform ping-pong Displaced Phase Center Algorithm (DPCA) described further. The six transmitters are identical. The length of those transmitters is 14 cm, therefore the theoretical along track resolution using

SAS processing is 7cm. We assume the practical resolution to be twice this figure i.e. 15cm all along the swath.

The central working frequency is 100 kHz and the usable bandwidth of the transducers is 30 kHz. This bandwidth is divided in three. The main part is used for imagery on the central transmitter. Two other narrower parts of the bandwidth are used for the ping-pong DPCA technique. Two different pulses are emitted alternatively on the fore end and backend transmitters.

2.2   Forward Looking Sonar

The front array is composed of 4 transmitters and 48 receivers disposed on a 70cm wide antenna. The transmitters emit separated pulses on four separated sectors of approximately 12°. The central working frequency is 300 kHz, and the bandwidth of different signals is 10 kHz.

Though the receivers array is lacunar, we avoid the grating lobes by emitting on a restricted area. The positions of the receivers are calculated in order to maximize the contrast obtained after focussing.
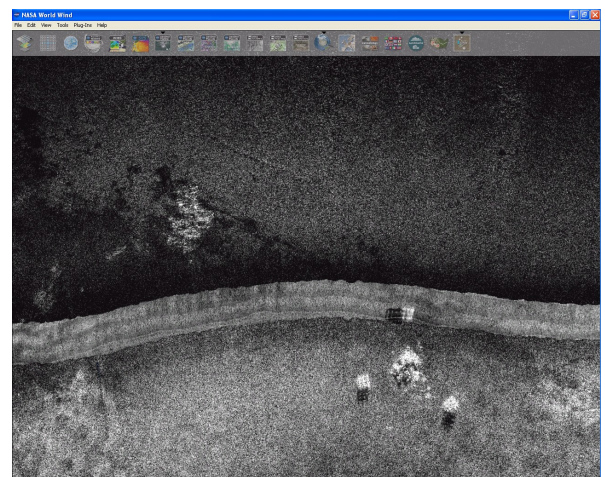

Fig 3. Visualization of side scan and front images via NASA WorldWind through map server

2.3   Auxiliary equipments

The Shadows system (Fig. 2.) is also equipped with an accurate and highly synchronized Inertial Navigation System (INS) aided with a Doppler Velocity Log (DVL). We are currently working on the replacement of the DVL by a calculation of the speed derived from DPC algorithm.

The system can be completed with an acoustic positioning system like GAPS, in order to avoid the linear drift remaining.

There are two PC on the topside. One devoted to acquisition of the signals, the other devoted to Imaging Algorithms and redistributions of images on a web server.
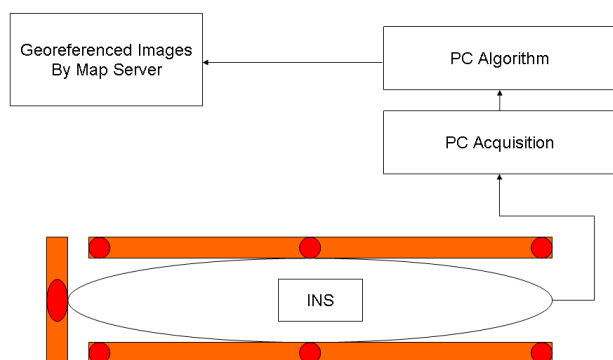

Fig 2. Shadows system architecture

3   Signal Processing and Algorithms

3.1   Motion Compensation and SAS imaging

To improve the resolution of side scan sonar, one solution is to form a long virtual antenna by coherently adding successive pings (Fig. 4.). This is the main principle of Synthetic Aperture Sonar. The theoretical resolution of such sonar is only limited by the directivity of the transmitter, related to its length. Moreover, the length of the rebuilt antenna can be adapted to the range; therefore the resolution is range-independent.
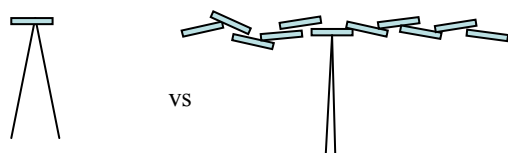

Fig. 4. *Classical vs Synthetic aperture sonar*

The theoretical resolution considering that the towed fish is moving on a straight line without any other movements is half of the emission antenna length, but we consider it not realistic. In our design, we have considered the real

resolution to be twice the theoretical one. It means that we have a constant resolution of 15cm on the SAS swath.

The main issue in Sas processing is to rebuild the synthetic antenna along the path of the fish. This is often called the Motion Compensation.

The primary part of our motion compensation algorithm uses the data of an Inertial Navigation System (INS) in order to calculate in three dimensions the whole synthetic antenna geometry.

Using a very accurate and highly synchonized INS aided by a DVL Log ensures that there is only a linear drift on the absolute positioning. The data given by the log are used by the Kalman filter of the Ins. This permits to control the drift on the position. This Drift is sufficiently low to allow a centimetric relative precision during the formation of the synthetic aperture. The theoretical influence of the drift has been detailed in [8]. It is negligible in our case.

Fig 5: Straight lines on a U-turn. La Ciotat Bay 2006

We unfortunately can not avoid the short-term drift during the imaging but we are working on an integration of absolute positioning in real-time by the use of a USBL like GAPS.

Despite the very accurate rebuilding of the path, there are still some corrections to do in order to focus correctly as shown in [7]. They are mainly due to the evolution of depth of the sea bottom along the swath and to the influence of the underwater environment on the acoustic signal.
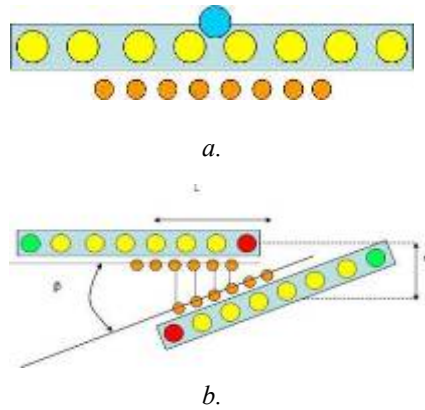
Fig. 6. . a. equivalent emitter/receiver antenna:
in blue the transmitter
in yellow the receivers
in orange the equivalent transmitter/receiver.
b. P2C2 with auxiliary frequencies

We improve the focus on the images including depth errors and underwater environment influence, by computing the DPCA Motion Compensation algorithm ([2]). This consists in calculating three coefficients (L, β and τ in Fig. 6) between two consecutive pings by correlation of the corresponding signals. In the Shadows system, we use a patented ping-pong technique described in [3]. Two more transmitters are located at each extremity of the antenna. They emit alternatively two different frequencies (in red and green in Fig. 6). The DPCA algorithm is performed on the signals corresponding to the front transmitter of one ping and the back transmitter of the following ping. In this configuration, all the equivalent transmitter/receiver are in correspondence from one ping to the following. The theoretical maximum speed for a nonlacunar antenna (5 knots) is thus the better configuration for the DPCA algorithm.

Beam forming is computed in real time. The method used is time domain fast factorized back projection described in [1]. It consists in factorizing the calculations by doing some acceptable approximations. The limitations of the approximation are range dependant. Further the target is located from the sonar, less precise the calculation has to be. This allows the calculation to be fast and precise enough.

This algorithm can be extended to an exact back projection. This can only be done in post processing and the calculation time is still acceptable.
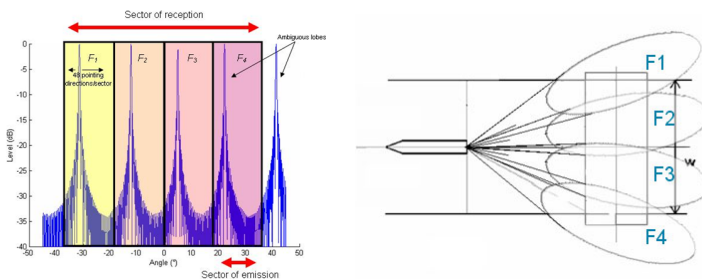

Fig.7: The sectorized emission principle pattern

3.2   Forward Looking Imaging

The forward-looking sonar uses a patented "sectorized emission" architecture. The principle is to illuminate a scene from 40m to 100m in front of the sonar bottom in order to obtain a "side scan–like" image, i.e. with echoes and shadows as described in [9]. We use a lacunary reception antenna composed of 48 channels disposed on 70cm wide. To avoid the ambiguity lobes, four different signals are transmitted on four different footprints in the gap (fig. 7.).

The ambiguous reception permits to reduce the amount of data. The central frequency being around 300 kHz with 10 kHz for each signal, it allows us to claim a 40cm x 15 cm resolution on the images. The ping rate is the same as the side scan one, in order to avoid electronic and acoustic interferences.
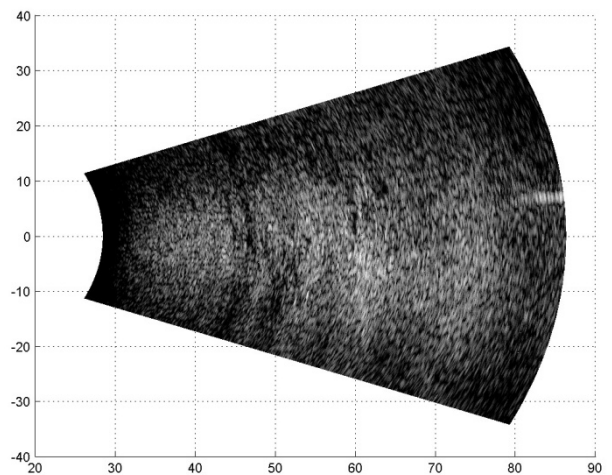

Fig. 8: single ping Forward looking image.

As we have a scan from 40m to 100m in front of the sonar at each ping (Fig. 8) and the inter ping displacement is about 1m, we dispose of a large amount of data.

The higher frequency and smaller geometry allows using a very simple and fast beam forming algorithm. In fact, in our configuration, the far field is at about 25m from the sonar.

In the real time mode, with respect to altitude measured, we select an area at a constant range in front of the sonar. We use the INS reconstructed path to rebuild an image.

There are different integration modes. For each pixel of the image we can do an incoherent integration of several ping's contribution. This improves the signal to noise ratio and the contrast, but it lowers the quality of the resolution.

In a post processing mode, we use all the data contained in each ping. As the sonar is moving towards the illumined scene, we can observe a contact on different grazing angles from 40m to 100m in front of the sonar. A point on the ground is seen with angles from 50° to 75° as shown on Fig. 9. By using the INS positioning we can rebuild a movie of a selected contact while the sonar is moving to it.
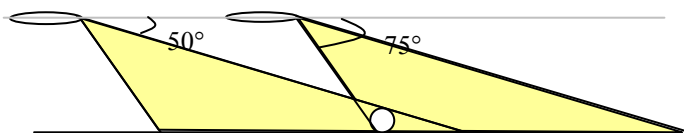
Fig. 9: Path of the sonar above a target

3.3 Fusion of images

Both Side scan and frontal images are provided in real time. The result is accessible via a map server.

When the images are computed, we use the absolute georeferenced position given by the INS. Hence, the mosaic is directly georeferenced on a map. A first advantage of this is to avoid image deformations due to the fish navigation. A straight line on the sea bottom remains straight on the image (Fig.5), and is continuous from one line to the other. A mosaic is built and providing that the INS is aided by a USBL, the absolute positioning is very precise. We can follow the difference of the sea bottom texture boundaries on the different sides.

In the post processing mode, the advanced versions of the algorithm are available. Images are still displayer on the georeferenced map, and displayer via the web server (Fig. 10)
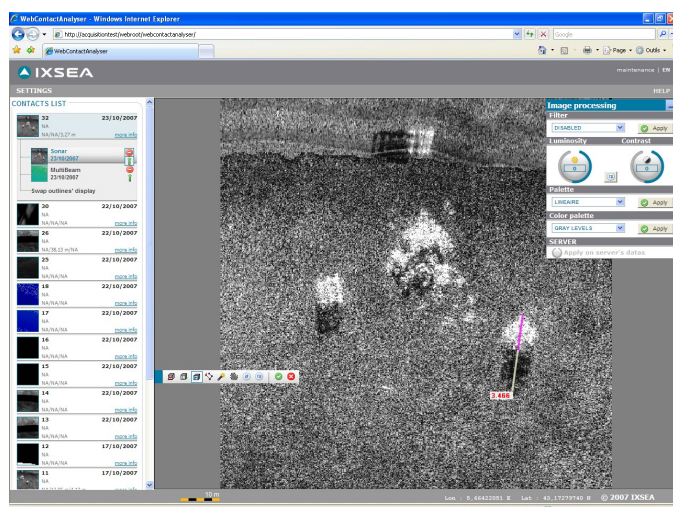

Fig. 10: Display of a selected zone in the Ixsea Contact analyzer via the web server

5   Further works

We are currently working on different improvements of the quality of the images and processing. In particular, we are implementing a new anti-speckle algorithm.

On the frontal sonar, we are increasing the fusion quality between the different sectors. We also have started a study of coherent integration on those data. We aim at improving the resolution on the sides of the lobes.

Another study has been started to try different frequencies for the synthetic aperture side scan sonar.

References

[1] S. Banks, "Studies in high resolution synthetic aperture sonar", thesis, university College of London, 2002.

[2] A. Belletini, M.A. Pinto,"Theoretical accuracy of synthetic aperture sonar micronavigation using a displaced phase center antenna", IEEE journal of oceanic engineering, 2000.

[3] D. Billon, "Procédé d'autofocalisation pour sonar à antenne synthétique", Patent FR9510953.

[4] P. Caprais, "Towards a forward looking synthetic aperture sonar" *Sonar Signal Processing Conference 1998,* Institute of Acoustics, Weymouth – England.

[5] P. Janvrin, "Sonar frontal pour l'imagerie par synthèse non-cohérente et la bathymétrie" *PHD thesis,*University of Paris 6 – France.

[6] F. Jean "Shadows, a synthetic aperture sonar system by Ixsea Sas", Ocean's Asia, Singapour 2006.

[7] Michel Legris, Frédéric Jean, "Comparison between DPCA Algorithm and Inertial Navigation on the Ixsea Shadows SAS" , Ocean's Europe, Aberdeen, 2007.

[8] F. Napolitano, D. Charlot, F. Jean "de la possibilité d'utiliser une centrale inertielle PHINS pour le sonar à antenne synthétique", unpublished.

[9] F. Mosca, "A new GapFiller system using front-scan sonar technology coupled with Shadows", IEEE proceedings, OCEANS 06.