INTERFEROMETRIC SIDE SCAN SONAR : A TOOL FOR HIGH RESOLUTION SEA FLOOR EXPLORATION

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ABSTRACT

This paper concerns the description of an a commercial interferometric sonar and possible applications for objects or for wrecks investigation. It presents general concepts of interferometry and its limit essentially due to noise. The main problem of interferometry which is a method echo triangulation is handicapped by its phase ambiguity because it measures a time delay between two sensors modulus a wavelength. So it exists different methods to remove the bias. The Gesma bought a interferometric prototype sonar 3 years ago and developped a general process to reduce to errors of bias. This tool is well designed for sea floor exploration because it provides an high resolution side scan sonar image with the same resolution bathymetry coming from the interferometric sensors.

The main conclusion of this paper concerns the potential application of this sonar and the associated process to investigate with a fine resolution, wrecks, small objects, pipes. The speed of survey allows to use it on large areas. The quality of datas makes possible 3D reconstruction and an interactive visualisation.

1. INTRODUCTION

The bathymetry of an area is very informative to understand the environment of the observed scene. But the main drawback is the resolution of the illuminated cell which depends on the altitude of echo sounder above the sea bottom because the size of the cell is connected to the aperture of the beam. The bathymetry is estimated by a temporal analysis which measure the go and back time travel of the sound between the sensor and the sea floor. The quality of this measure is very good because the system is designed for it. Much information can be derived from it : it is possible create 3D models of the environment. It is possible integrate to it different kind of information coming from external sensor. Traditionally people merge information coming from echo sounder and side scan sonar.

Side-scan sonars produce ocean bottom realistic images by periodically transmitting acoustic pulses orthogonal to the direction of the sensor motion. Nevertheless, understanding the bathymetry information of an observed scene with side scan sonar technique, implies that the sonar needs to be close to the bottom, compared to the sensor range to illuminate the sea bottom at grazing angle and to generate important shadows of bottom objects.

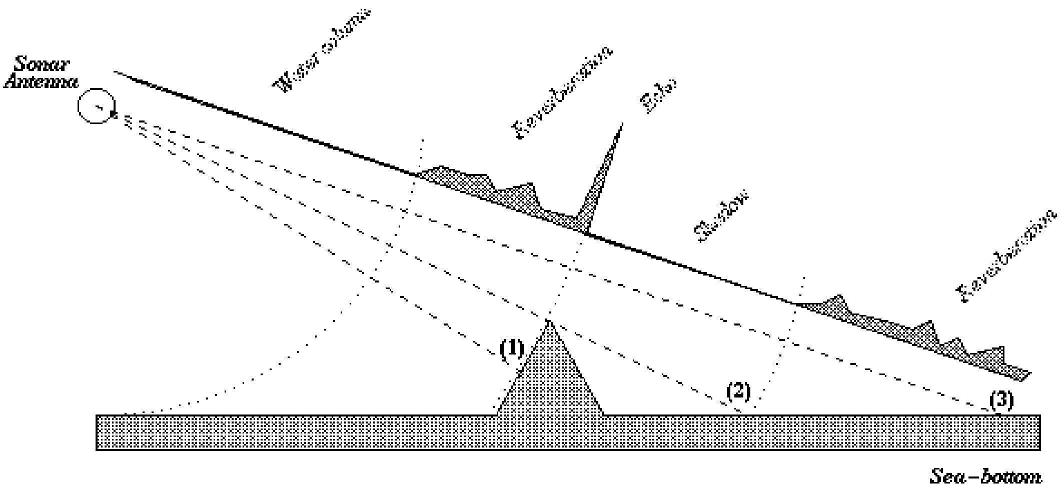


Figure 1 : side scan sonar principle

This technique is interesting beyond the object detection by the association shadow-echo because it provides an acoustic parameter the ruggedness of the sediment which is an important element for the sea bottom classification. More generally these sonar provides numerous details which can be interpreted. The acoustic principle used by side scan sonars is different form echo-sounder. They illuminate the sea bottom with a large vertical aperture and narrow along track aperture and the strength of the back-scattering echo is sampled. Side scan provide nice image of the back-scattering compare the echo sounder due to the grazing angle which magnify the shape of object and environment with shadow but do not provide a reliable bathymetry, the image can only be an interpretation of the bathymetry.

Echo-sounder and side scan sonar are very complementary but the fusion of both information is difficult because the side scan is mounted on a tow fish and the echo sounder on boat so the scene is observed from two different point of view with their own navigation and distortion. More over the two information to merge are different image and bathymetry.

Recent side scan sonars were designed to produce in the same time side scan sonar image and bathymetric information through the use of interferometric methods. These methods are based on the detection of the angular arrival of the plane wave reflected from the bottom. With the knowledge of the sonar altitude, of the signal arrival time and of its angular arriving direction, it is possible to compute the bathymetry of each point present in the observed scene. These methods constitute a real improvement compared to the fusion methods of the bathymetry and the image recorded in two dates and issued from two different sensors. But the echo sounder and the side scan stay complementary, the first work at vertical angle and the second at grazing angle. Nevertheless from this point of view the bathymetry is an other improvement because the bathymetric information issued from the interferometry is easier to merge with the echo sounder information than the couple image : coming from the side scan and the bathymetry from the echo sounder.

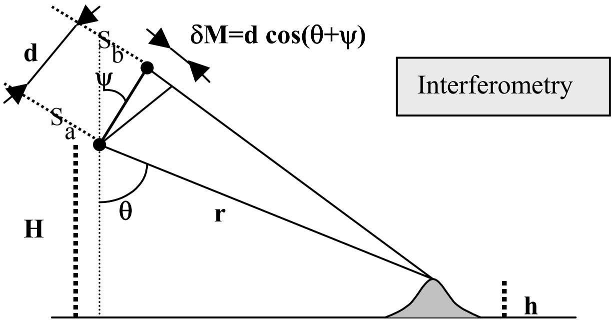
The main drawback of interferometric methods concerns their weak robustness in a noisy environment and the 2πbias of the phase measure used to compute the bathymetry. This paper proposes an approach of this bathymetry with a correction of the 2π bias. The application of that kind of sonar are numerous : objects and wrecks investigation, environment comprehension …

2. INTERFEROMETRY BASIC CONCEPT

The traditional experiment to illustrate the interferometry effect is the Young slot experiment [1]. A monochromatic light (i.e. a single carrier frequency) is diffracted through two slots and creates a figure of light consisting in an alternance fringes (high-lighted lines and of shadowed lines) on a white paper sheet placed behind. This can be explained by the superposition of two coherent lights. The intensity at each point is given by (1) :

(1) $$I = \langle E_1^2 \rangle + \langle E_2^2 \rangle + 2E_1E_2 \langle \cos(\varphi_1 - \varphi_2) \rangle$$

where, E1 and E2 denote the electromagnetic fields amplitude, φ_1 and φ_2 their corresponding phases, and the symbol <.> denotes the temporal average during a wave train length time. The resulting intensity depends, hence, on the phase difference (i.e. the difference of length of the two paths of light). The connection to the interferometric sonar is straightforward, figure 1. The slots are two acoustic arrays and the paper sheet effect (i.e. superposition of two waves) is computed by $S_a S_b^*$ where S_a , S_b are the complex signals received on each array and (*) denotes the complex conjugate.



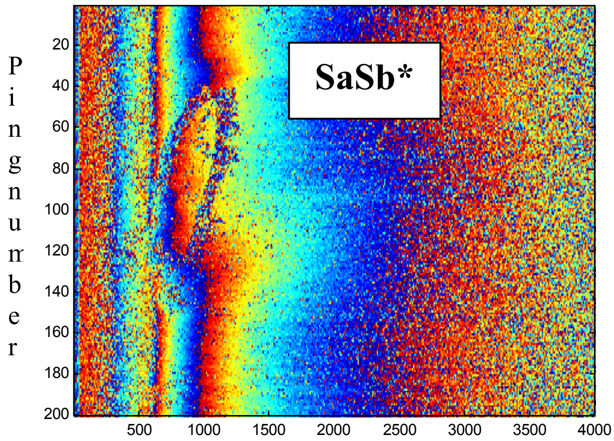


Figure 2 : the phase difference and the incidence angle θ and the computation SaSb*

On this figure, δM denotes the path length difference. The link between the phase difference and θ, the arriving angle of the front wave is given by (2)(3) :

$$\textbf{(2)} \qquad \Delta\varphi = \frac{2\pi d \cos(\theta+\psi)}{\lambda}$$

where "d" is the baseline, H the vertical altitude of the sonar above the sea bottom and λ the wavelength. Finally, the altitude "h"of an observed cell is simply computed by :

$$\textbf{(3)} \qquad h = H - r\cos(\theta)$$

The main drawback of interferometric technique is the presence of noise which is something usual with experimental datas but the phase difference is biased of several times 2π. Indeed the quantity δM can be over one wave length and the phase difference can appreciate the time delay between both array modulus 2π as shown on the Figure 3.

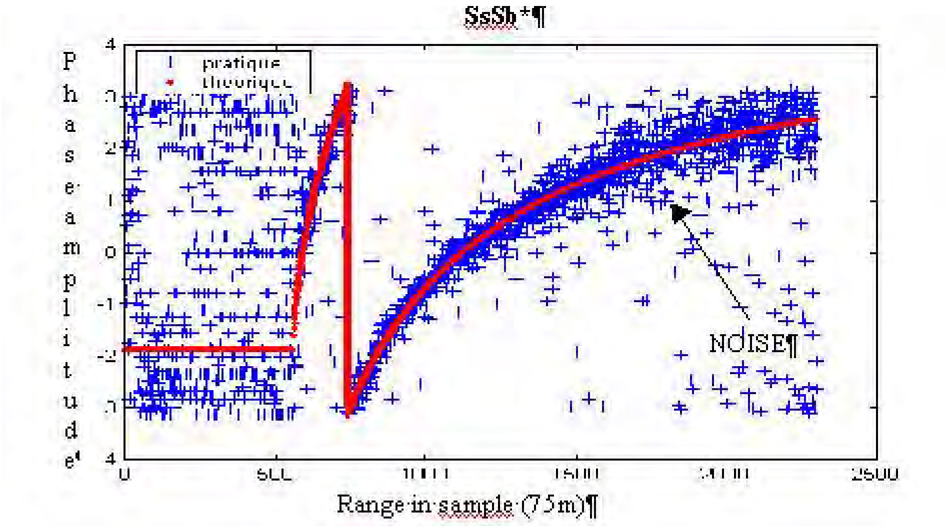


Figure 3 : An experimental phase difference (blue) and theorical (red)

The phase difference is not directly usable because it is not representative of the arriving angle of the wave front. The main difficulty of interferometry is to remove the phase bias in presence of noise.

3. INTERFEROMETRY LIMITS

3.1. Sources of noise

We consider 4 sources of noise which combine themselves and which are responsible of the decrease of the Signal to Noise Ratio:

- **angular decorrelation** : The measured gray level value concerning a given pixel on the sonar image, is obtained by the additive power summation of several microscopic backscatters contained within the resolution cell. The backscattered energy by each of these microscopic items can interfere and the power reflected can be null and the received phase difference is random variable: it is the speckle phenomena. We suppose only one kind of back-scattering points uniformly and continuously distributed on the sea floor which is the worst hypothesis [5],[1].

- **spatial decorrelation** : This effect is also called '***sliding foot print***' effect. This source of noise can be derived from an optical effect. The figures obtained through the optical Young slots are less and less contrasted from the center to the exterior. This phenomena is linked to the length of wave trains. The more the phase difference is important the less the time of the coherent integration is important, and thus, the weight of the phase difference cosine decreases. This effect is the reason of using monochromatic light : it has a very thin spectral occupation so a large time duration which increases the contrast of the figure. For the sonar case, the length of the coherent wave train is related to the pulse length and is proportional to :

$$\textbf{(4)} \qquad \xi = \frac{c\,\tau}{2} - \Delta t$$

where τ is the time pulse length and c is the was celerity. ξ corresponds to the time the two arrays have to make the interferometry in common. ξ can be interpreted as the commonly sea bottom surface seen by the two sensors within one sample : the two arrays are not situated at the same distance from the bottom and their footprint on the bottom is lightly shifted. Thus, when the cross product $S_a S_b^*$ is computed, it must take into account this partial superposition. The lack of this superposition correspond on the sea bottom to

$$\textbf{(5)} \qquad \Delta x = \frac{d\cos(\theta+\psi)}{\sin(\theta)}.$$

- **multipath impact :** Multipath interference constitutes an important noise source through the interferometry process. In fact, the received signal is formed by the composition of a direct path and, eventually, of an interfering signal issued from a secondary reflecting path. The interfering path constitutes a parasite signal contributing to noise the wave front of the main signal.

- **propagation attenuation :** the signal is astonished by the different effects of propagation and the SNR too**.**

3.2. Sources of errors

The noise is globally a difficulty to remove the phase bias but it is generally possible to retrieve the lack of information by different methods exposed in the following parts. Nevertheless it remains two kind of noise which intricate the bias removal and are sources of errors. These noise are linked to the angular decorrelation and multipath effect. The multipath effect is really visible when the level sea floor backscattering is weak compared to the surface, so the altitude found for the pixels correspond to something between the surface and the sea bottom. So it is necessary to detect and to ignore these points. The second kind of difficulty is the speckle which can totally astonish the luminance of a pixel and the bathymetry associated to it. It is necessary for this noise to reduce its impact by an unspecklisation porcess depicted in the part 5.1.

4. SOLUTIONS TO UNBIAS THE PHASE

4.1. Phase unwrapping

The traditionnal way to remove the phase bias is to detect a phase jump on the phase signal which corresponds to a brutal transition close to 2π when the continuous phase signal reaches -π or π. One solution to detect this step, this jump is to use a differential estimator which detects only big transitions. Generally the estimator threshold is set on π , so when the transition between two neighbors points reaches the absolute value of π, the system considers there is a phase jump and corrects the phase as shown on the Figure 4. We can sum up the phase jump detection algorithm as

$$\text{(6)} \quad \begin{cases} \arg(SaSb_n^*) - \arg(SaSb_{n-1}^*) > \pi \text{ then } \forall i \geq n \arg(SaSb_i^*) = \arg(SaSb_i^*) - 2\pi \\ \arg(SaSb_n^*) - \arg(SaSb_{n-1}^*) < -\pi \text{ then } \forall i \geq n \arg(SaSb_i^*) = \arg(SaSb_i^*) + 2\pi \end{cases}$$

This algorithm which unwrap the phase, makes a lot of errors as soon as the power of noise increases and in some case it s impossible to use it directly.

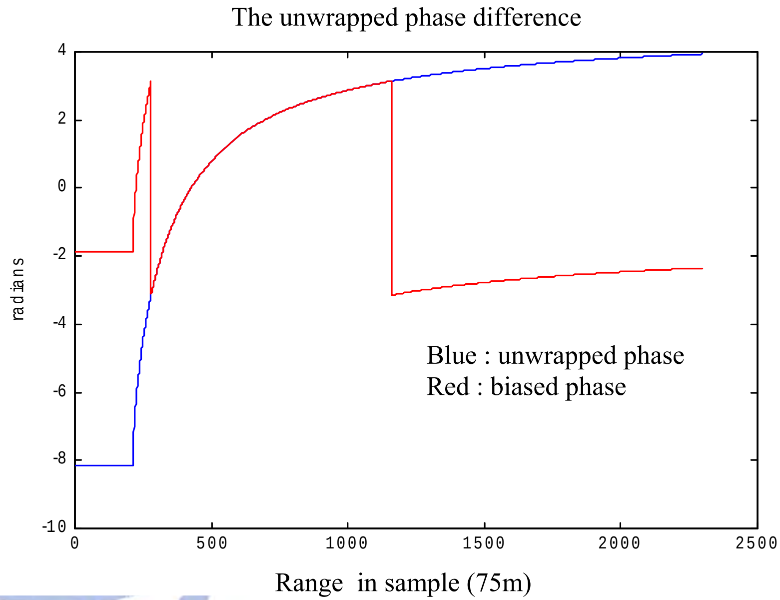


Figure 4 : an example of unwrapping

One solution to continue to use it is to reduce the level of noise variance. The traditional technique is an average on the data. This technique works but the resolution is decreased and sometimes it is necessary to reduce seriously the resolution to hope to reach an acceptable level of noise.

The filtered phase is given by the maximum likelihood estimator

$$\textbf{(7)} \qquad \Delta\overline{\varphi} = \arg\left(\sum_i SaSb_i^*\right)$$

The risk of the unwrapping process is to make an error of detection because this error is not located only at the origin of this error but propagated to end of the signal range as shown by (7).

4.2. Intercorrelation Process

Another technique to remove the 2π bias is to estimate with traditional signal processing techniques the time delay between both sensors : the intercorrelation calculation. If the confidence of the estimation is above a resolution of one period of the carrier frequency (i.e. one wave length), it is possible to determine the ambiguity of the phase.

$$\textbf{(8)} \qquad \tau = \left\{ \tau / \max\left(\int_T Sa(t)Sb^*(t-\tau)dt\right)\right\}$$

This technique is very interesting because it researches the time delay for which the two signals superpose themselves as well as possible so in the same time the problem of spatial decorrelation is removed. In fact this approach is like a likehood estimator with a coherent summation.

4.3. Vernier principle

The vernier method is different from the two previous techniques because it uses three sensors , two couple sensors to determine that ambiguity. So the phase difference for one couple is given by:

$$\textbf{(9)} \qquad \operatorname{mod}(\partial\varphi, 2\pi) + 2n\pi = \frac{2\pi d\cos(\theta+\psi)}{\lambda}.$$

A family of solution for one couple corresponds several possible wave fronts generated by the 2π modulus of the phase amgiuity. But the physical wave front is unical and the viewed angle by both sensors is the same if the sensors are in line. So with two couples if we plot the solutions of the phase difference, only two functions superpose themselves belonging respectively to each couple. We can find a couple of naturals n_1 and n_2 verifying:

$$\textbf{(10)} \qquad \frac{\mathrm{mod}(\partial\varphi_1, 2\pi)\lambda_1}{2\pi d_1} + \frac{n_1\pi}{d_1} = \cos(\theta+\psi) = \frac{\mathrm{mod}(\partial\varphi_2, 2\pi)\lambda_2}{2\pi d_2} + \frac{n_2\pi}{d_2}$$

The experimental signal does not allow the superposition, it always remains a small error ε due to noise. The solution to find the couple (n_1,n_2) is to choice the closer solutions. If that error goes beyond the gap given by the closest solutions (vernier efficiency) $\frac{1}{2}\min_{(n1,n2)\neq(0,0)}\left(\left|\frac{n_1\lambda}{d_1}-\frac{n_2\lambda}{d_2}\right|\right)$, it will be impossible to make the difference between the true solution and a wrong wave front. The size of this gap is the limitation of the vernier technique and it must be as large as possible.

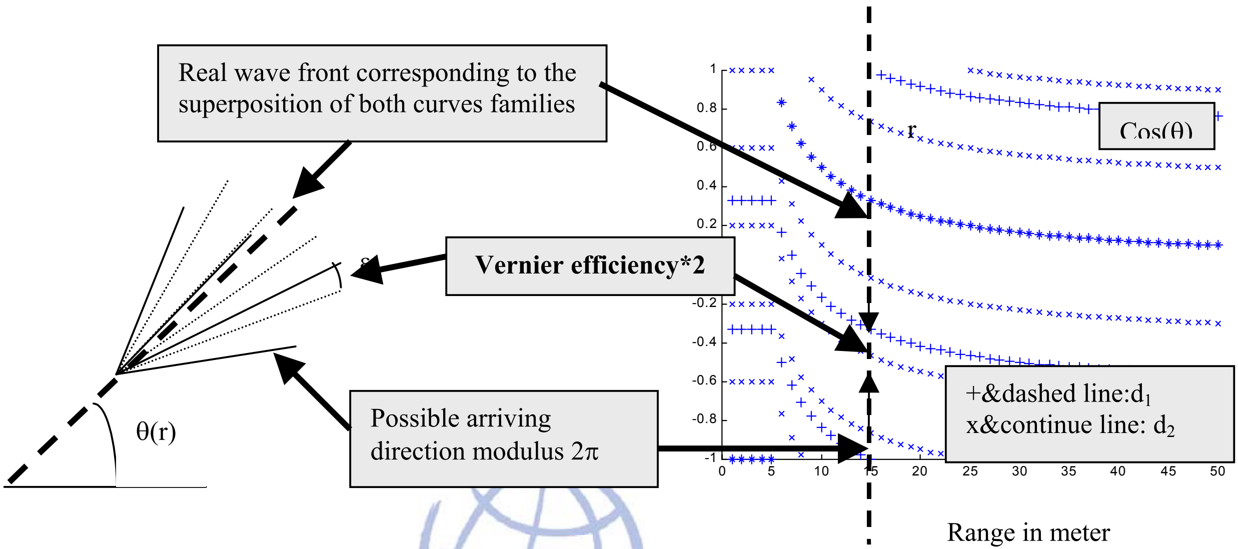


Figure 5: interpretation of vernier concept

5. PROCESS AND RESULTS

5.1. Unspeckled phase

The intercorrelation process integrates in the inner calculations an mean filtering process which corresponds to the length of integration window. The vernier and the classic unwrapping technique are independent of an possible phase pre-processing, so the choice of the size of an averaging process is totally free. But the main default of the averaging process is to reduce resolution to increase SNR. The idea of an unspecklisation process based on multiresolution analysis, is to improve the quality of the signal by an autoadaptive averaging filter which adapts the filter size to the image gradient. It allows to reach a better SNR when it is possible and to keep the resolution in any case. This operation is performed with an invariant multiresolution analysis based on spline wavelets.

5.2. Parametric vernier

The main drawback of the vernier process comes from its black box behaviour : it is not possible to set a threshold for the detection of phase jump. When the noise goes over the vernier efficiency, some errors can occur: the threshold is determined by the vernier efficiency. To avoid this behaviour, the main idea of this process is to merge assets of the vernier technique and of classical unwrapping process which can be configurable. Indeed it is possible to set a threshold under which we consider 2 phase difference points are continue. The threshold called confidence interval, represents the distance on Y axis between two neightbour samples. On classical unwrapping technique, a correction of phase jumps is made if the distance between 2 difference phase samples is over π ; a wrong phase point (which continuity is above π) generates a false phase jump which is integrated trough out the range. The idea is to consider reliable points in term of continuity : we suppose correct samples represent the majority of points and we consider the others as outlayers. This hypothesis can easily achieved with a first adaptive meaning processing which reduces noise and keep points on the major curve which is continue and corresponds to the phase difference evolution along the range.

For example, we choose an interval around the mean of the current sample which gathers 90% of statistical distribution weight for this sample. If the distance is under the confidence interval, there is continuity, if the distance is above 2π-confidence interval, there is continuity but presence of phase jump. Then if the distance is above the confidence interval and under 2π-confidence interval, it is impossible to say if there is or not a phase jump. There is a discontinuity which may correspond to noise or to an aliasing problem. We call that discontinuity : an outlayer. For example, this phenomena can appear when the slope of the relief is too high and makes a big increase on the phase evolution which is not detected by the sampling process. The interest is to not integrate phase jump which correspond to a possible aliasing phenomenon while there is not enough information to unwrap phase ; the range is simply divided into segments whose begin and end at outlayers points location.

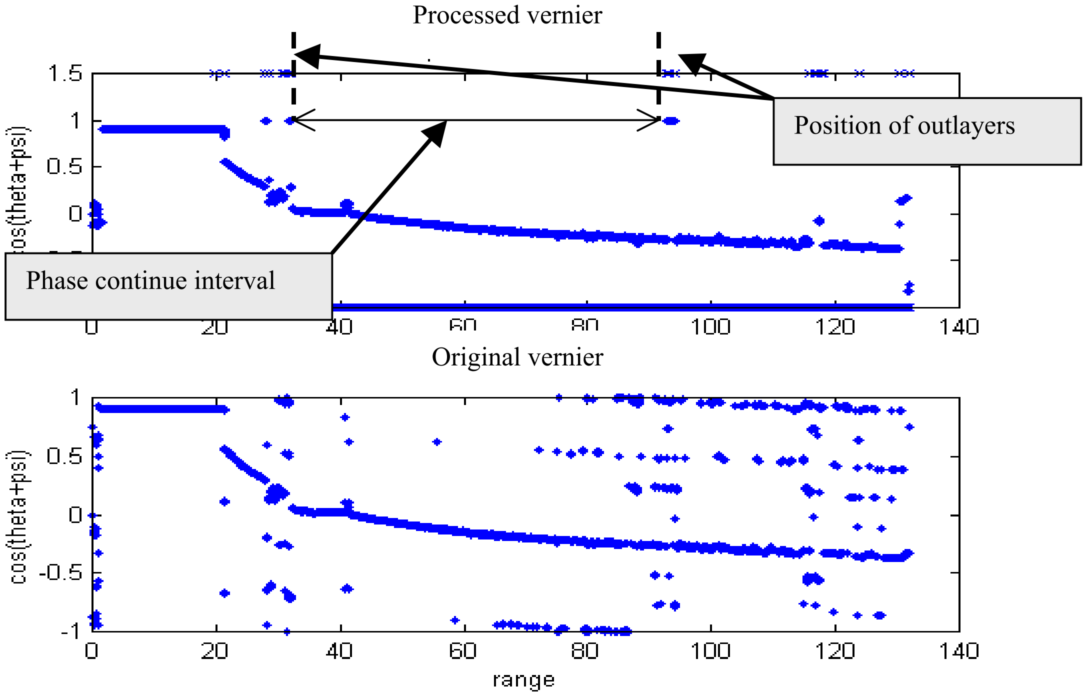


Figure 6 : example of the process coorecting phase ambiguities

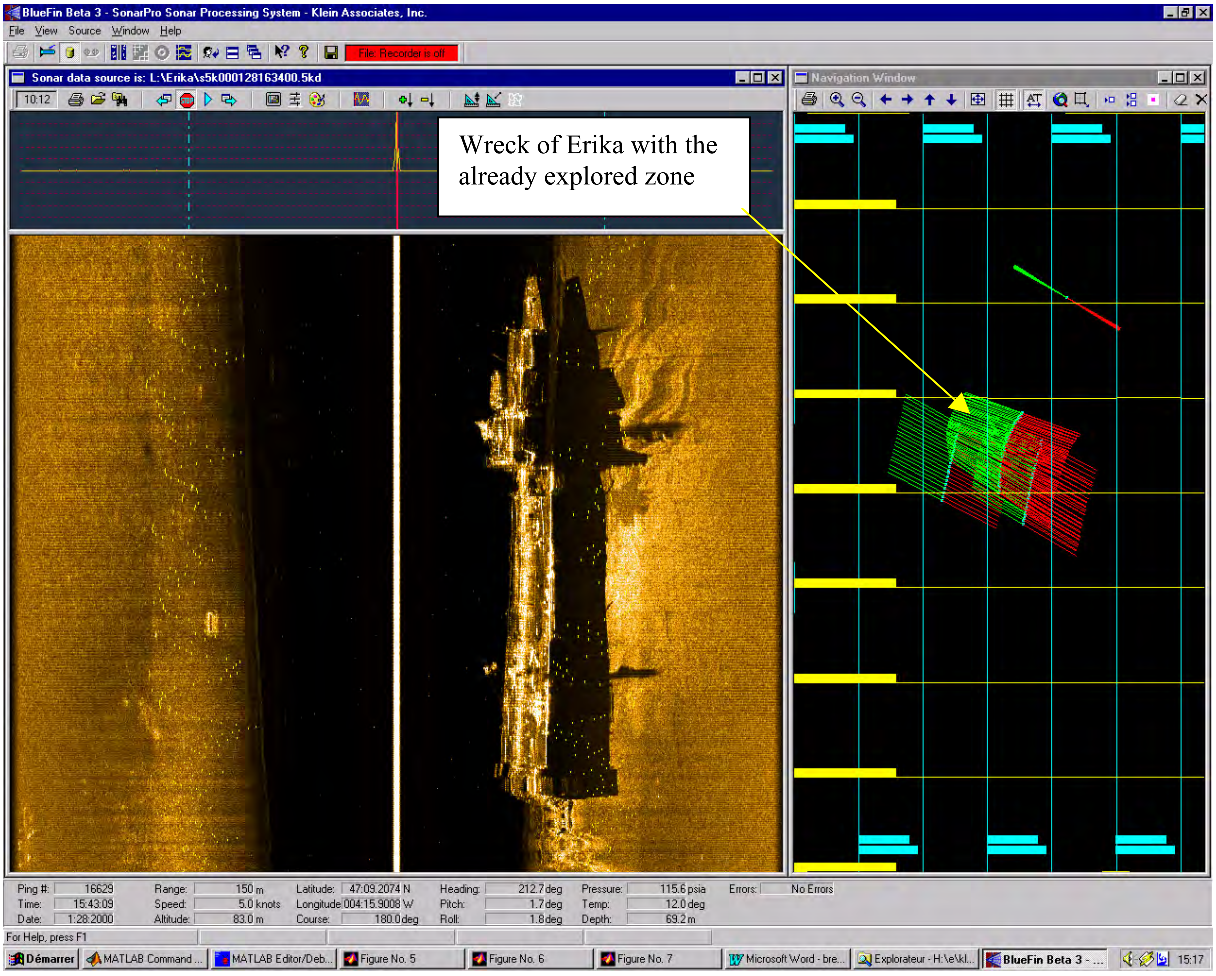
We have created continue phase intervals and we make match the phase of the vernier with the unwrapped phase on each aliasing intervals. This operation is done by shifting the unwrapped phase through out the cosine interval [-1;1]. It is easy to conserve the shift which makes the better matching for each continue phase interval.

On an interval, a rejected vernier point can be bring back on the real curve (i.e. corrected), if the true curve represents the majority of points. This system is based on two numerical parameters : the probability of no phase jump detection and the false alarm.

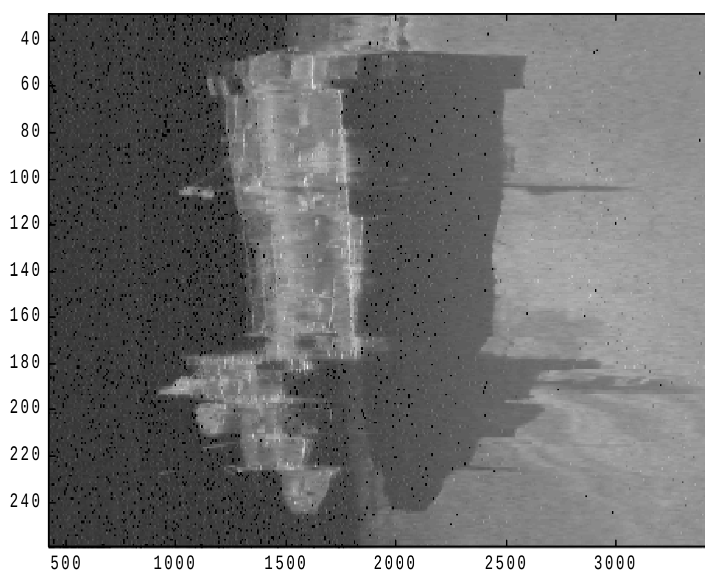
In our computations we used a 99% interval confidence, 6 points mean filtering which correspond to 7% probability of no detection and roughly 2% of false alarm (experimentally 0.9).

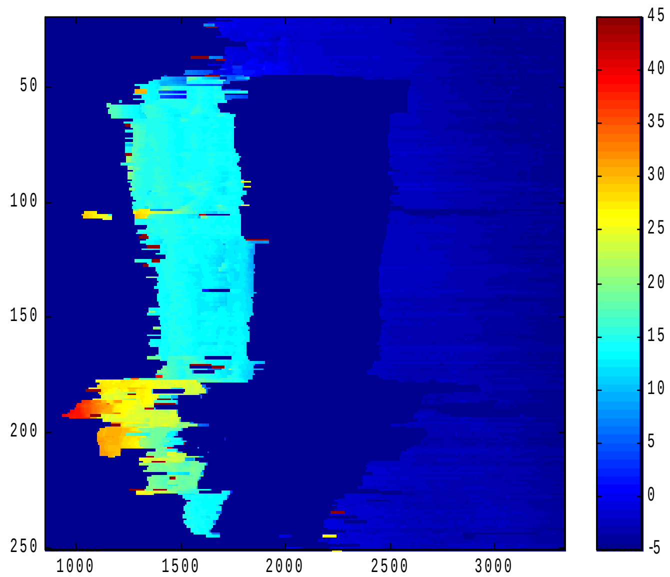
5.3. Results

The GESMA bought three years ago a prototype of an interferometric side scan sonar to evaluate the gain of interferometry to explore sea floor. This sonar is a KLEIN 5400B. The real time control windows of the sonar with the high resolution image and the navigation windows allows a seafloor exploration with a swath of 130m with à resolution of 10cm next to75m.

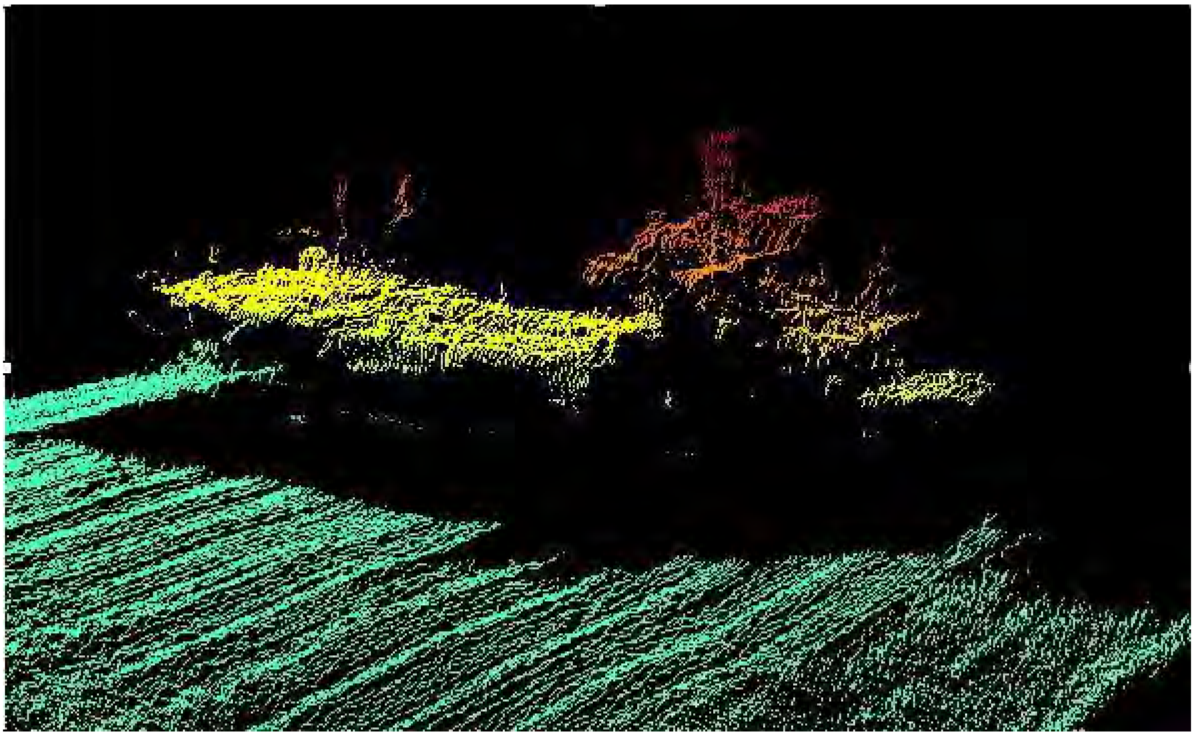


With the paramatric vernier, the rate of computation allows a real time process but currently this process is batched and provides an unspeckled sonar image for the bathymetry process with the bathymetry. The process is fully automatic.





Using an open GL support, it is possible to create a 3D representation of the volumes and many details of bathymetry are awaible. For example it is possible to see the bridge, the deck, different masts and the telecom dome. The fusion with the image sonar (backscattering signal) is immediate because the interferometry calculates the elevation of each pixel to create a voxel.



6. CONCLUSIONS

The interest of studying interferometric noise sources is to highlight their great impact on the results. The second point is to succeeded to find an analytical expression integrated them exactly in a pdf and to be able to foresee the performance of an interferometric system.

The knowledge of the standard deviation of the pdf and the wanted resolution determine different parameters to process the 2 bias removal using the modified vernier technique. This phase process offers the possibility to make the difference between noisy points and brutal phase rising. First results show a real improvement compared to traditional method.

Finally we can say that the vernier principle goes in the opposite improvement of the quality of the phase (using large baseline for a spatial averaging of the wave front and of the phase). It likes better to use interferometric sonar with large baseline and large wide band pulse in order to remove the bias by intercorrelation method which can correct the spatial decorrelation.

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