Radar and Sonar interferometry

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In this paper we will compare two interferometric processings for both radar and sonar acquired data. The former is applied to traditional space-borne Synthetic Aperture Radar (SAR) and the latter on more recent interferometric sonar data. Few comparisons between those techniques exists right now, despite the fact that they share many similar principles. Thus, the key idea of this article is to present both techniques with assets, drawbacks and specific "tricks" used in data processing. After introducing briefly both sensor parameters and main features, a first section deals with. interferometry, more precisely for underwater and satellite acquisitions. Then a noise-pollution analysis is performed on both techniques followed by bias removal methods for getting interferometric information. The conclusion summarizes the similarities between sonar & radar processing, pointing at the techniques that can applied to both.

1 Introduction

Sonar interferometry, even though known for quite a while, has only been really used since a decade. We propose to compare recent interferometric sonar techniques and classical ones used with satellites such as ERS or ENVISAT. Comparing sonar and space-borne radar is difficult because of the different intrinsic properties of the two propagation media. However, for both of them, there is a propagating wave. Indeed, the Maxwell equations demonstrate that a couple of alternative electric and magnetic fields generates a progressive wave. The same behaviour is observed for sound propagation through water: a ceramic vibrates according to electric potentials, creating small variations of pressure 'p'. Using three equations (mass conservation, adiabatic compressibility coefficient and Newton law), a pressure field description can be established through a homogeneous Helmholtz equation:

$$\nabla^2 p - \frac{1}{c(x)^2}\frac{\partial^2 p}{\partial t^2} = 0. \qquad (1)$$

This quantity is not vector-based and it is not possible to perform polarisation analysis. Nevertheless, high resolution images of the sea bottom can be produced as shown on figure 1.

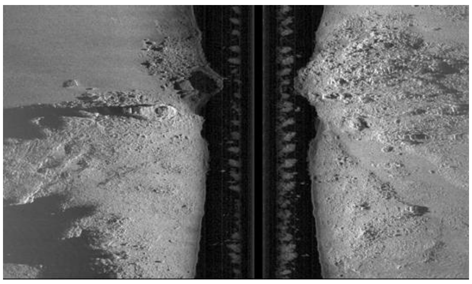

Figure 1 - Sea bottom images from a side scan sonar

Beyond the intrisic nature of waves, the main difference between both sensors remains the "medium celerity": c = 3.10^8 ms^{-1} for light and c = 1500 ms^{-1} for sound in water. Both sensors have short wavelengths but inner parameters are quite different due to the celerity differences, as shown in Table 1.

Both sensors are designed to create images of the observed areas: sea bottom for sonar and earth surface for the radar. The principle is the same: a sensor emits energy in the medium (vacuum for the radar and water for the sonar) creating a progressive wave which encounters the bottom or the ground. It modulates a backscattered echo which is detected and recorded through the reception sensors.

	Radar	Sonar
λ	5.61 cm	3 mm
f	5.34 GHz	400 KHz
f/Δf	281	20
BT	577	1
H	785 Km	10 to 30 m
cτ/2	9 m	3 cm

Table 1

Although the celerity of the medium can condition the design of the sensor, the attenuation of the wave power is fundamental to explain the processing range differences between radar (several thousand kilometres) and sonar (several dozen of meters).

2 Synthetic Aperture processing

Sensor internal functions can be gathered into two categories: time processing functions and array processing functions.

2.1 Signal Sampling

Traditional signals used for underwater imaging are very simple and based on a sine wave truncated by a unitary BT. Signals are sampled using an in-phase and quadrature technique to obtain analytic signals. These signals are quite easy to process: the images correspond to the envelope of the signal obtained using a quadratic cell, while interferometric applications use the instantaneous phase.

Both radar and sonar chains are similar; nevertheless, because of its purpose, the space-borne radar one is necessarily more sophisticated with a huge BT (577 for ERS). It results from constraints of spatial flights which can be several months or years long: in that case, it seems very difficult to emit high power in space over a long period of time, except if one is ready to consume a lot of hydrazine. A high power microwave system is heavy and not very flexible. Thus, the idea is to spread out energy over a band with a frequency modulation, which is equivalent to emitting power with traditional and cumbersome micro waves devices, in terms of spatial resolution but with a longer emission. It is a matter of time adapted filtering.

The level of technology required by each kind of sensors is rather different: an imaging sonar sampling rate is around 20 KHz while a satellite like ERS uses 19 MHz; a 1000 ratio is observed! Moreover, the normalized spectral band f/Δf is also quite different: 20 for the sonar and 281 for the radar. A classical but wrong denomination of that kind of sonar is ‘narrow band sonar’ because the signal is not modulated. The necessity of modulation is linked to both celerity and emitted power. For modulated sonar pulses, it is possible to reach a ratio of 3 or two. At this point, signals are sampled on the carrying frequency (around 100 KHz). Large band sonars are more expensive because the ceramics, radiating mechanical energy, are complex and work under 100 KHz. A lot of studies have been carried out concerning the ambiguity function of the emitted waves and orthogonal emissions using the same frequency band. With numerical techniques and codes, these techniques are once again in fashion.

2.2 Array processing

The sonar array design is a more sophisticated task because sonar arrays can be composed of several ceramics forming a continuous line and acting as a line network. With this configuration, achieving beam forming for each emission is possible. The kea idea is to increase the array reception length in order to speed up the covering. The unitary receivers or emitters can be λ/2 distant for a perfect Shannon spatial sampling (case a) or more (case b). In the first case, any angular direction can be aimed at, which is largely used by multibeam echosounders, while in the second case, only some directions can be used, because of image lobes. Manufacturers generally use the angular response multiplication theorem, between the network and unitary sensors, to cancel image lobes, because their angular positions correspond to the unitary sensors zero lobes. In that case, the beam forming task is a matter of specialists and thus, very confidential. Figure 2 illustrates the shape of a bottom sampling using time sampling and beam array techniques.

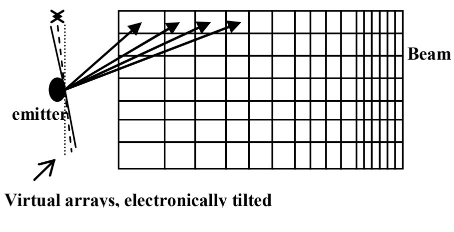

Figure 2 - Sonar bottom sampling

Radar techniques are very different and based on synthetic aperture because of the huge distance between sensor and target. The radar sensor size, even if rather important (1 meter high and 10 meters long), is not enough to reach interesting resolutions on earth surface. But the quality of navigation associated over the duration of consecutive emissions is sufficient to process images with this technique. Indeed the smallest observed fluctuations are due to clock drift.

Because of these settings, radar and sonar processing philosophies are different, even if they are, *in fine*, equivalent. Sonar beamforming is based on coherent summation of echoes over time while radar processing deals with Doppler effect and spatial adapted filtering, due to sensor displacements. Figures 3 and 4 illustrate both approaches.

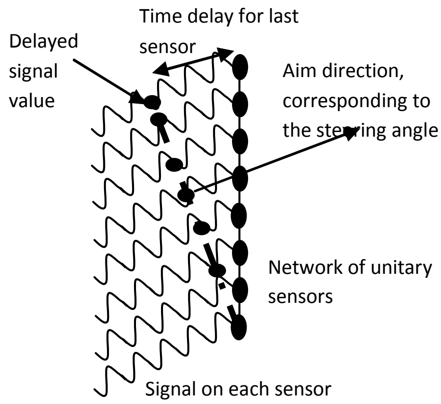

Figure 3 - Sonar beam forming

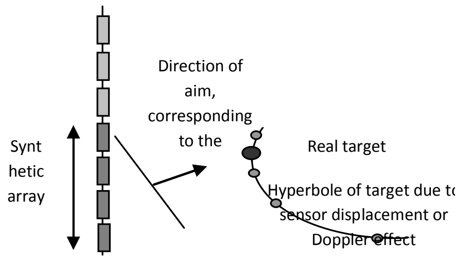

Figure 4 - Radar beam forming

3 Interferometry

3.1 Sonar-radar configuration

Sonar interferometry is quite straightforward and a parallel with beamforming can be sketched out: it is a matter of two tracks to get interferometry of the scene.

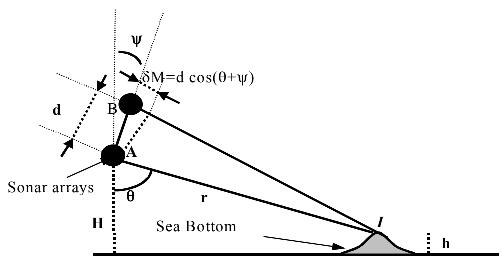

Figure 5 - Sonar interferometry configuration

As shown in Figure 5, the baseline “d” is defined on the sonar and its length given in wavelength. An important baseline for a side scan is around 15 λ (15x3mm) while a traditional baseline for multibeam echosounders is around

30 λ (because of the reduced angular aperture due to beam forming). The approach is similar to radar but formulaes are often written using angles, see Eq.(2).

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

Altitude is computed according to Eq.(3).

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

The major difference with radar is the absence of a required registration between the two sensors (a & b), because of the static interferometric geometric configuration: each sample from the first image corresponds to a pixel in the second image.

An "interferogram" coming from the inner product between the two sensor signals: $S_a S_b^*$. Figure 6.1 and 6.2 shows two typical interferograms for sonar and radar data, along with their typical pdf. Both were calculated on a "shadow" portion of the image.

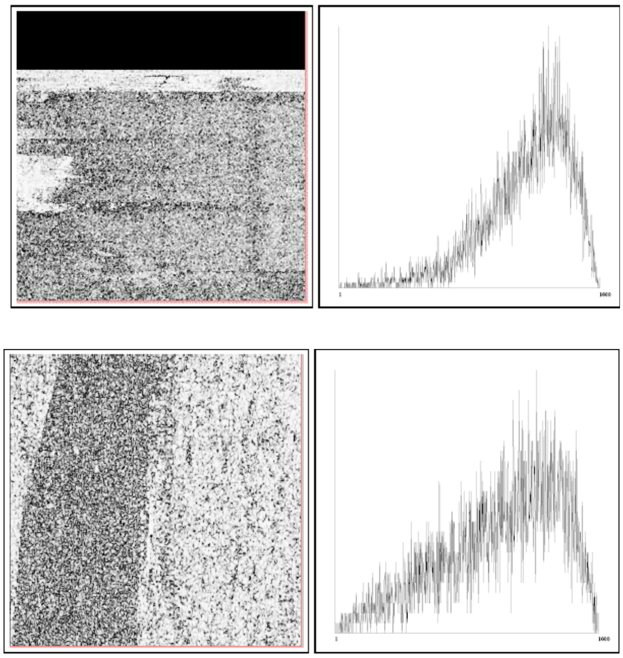

Figure 6.1 & 2 – Sonar interferogram of a wreck (top) and radar interferogram over a glacier region (bottom)

Radar baseline configurations are closer to multibeam echosounders ones. Other problems are introduced for the radar case because important baselines (50 meters or 1000 λ) are required to get a good resolution (except in some seldom configurations). Moreover, the second image is either recorded by another satellite with a parallel orbit or by the same satellite but a few days or months later. This delay can involve temporal decorrelations between both images. Thus, a registration step between both images is necessary to process the data.

Using a simple delay to perform the registration between both sets of data, is not enough due to earth curvature combined with spatial varying sampling effect along range, we are often compelled to interpolate data. Several frequency or time based techniques allow such a registration but the process becomes rather complicated. Furthermore, due to the important size of the baseline and the f/Δf ratio, the maximum delay could exceed one pixel in the same image. This problem is often encountered when using pulse modulated radar combined with big baselines; in that case, working area by area is crucial.

3.2 Interferometric noise

Six sources of noise are considered when dealing with sonar data. Four of them can be modelled and integrated in the phase probability density function [3]. These noises are responsible for the decrease of the Signal to Noise Ratio.

• **Spatial decorrelation:** this effect is also called '***sliding foot print***' effect. This source of noise can be derived from a well known optical effect: the figures obtained through optical Young slots are less and less contrasted as we get further away from the centre. This phenomenon is linked to the length of wave trains. As the phase difference gets larger, the coherent integration duration gets shorter, and the interference effect weaker. This is the main reason for using a monochromatic light: it has a very thin spectral occupation (and thus large time duration) which increases the contrast of the figures. In the sonar case, the length of the coherent wave train is related to the pulse length and is proportional to ξ [2][6], which corresponds to the integration duration:

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

where τ is the time pulse length (inverse spectral band) and c, the wave celerity. ξ can also be interpreted as the common sea bottom surface seen by the two sensors within one sample. The two arrays are not located at the same distance from the bottom and their footprints on this bottom are lightly shifted. Thus, the cross product $S_a S_b^*$ computation must take into account this partial overlap. Eq.(5) gives the expression of this mis-overlap on the sea bottom.

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

For radar acquisitions, this phenomenon is not really important because the angle of illumination is small and the fringes evolution stable. Moreover, a local registration can overcome it. In a sonar context, it is always possible to correct this problem using a spatial correlation.

• **Multipath impact:** multipath interferences constitute an important noise source for the interferometry process. Indeed, the received signal is formed by the composition of a direct path with an interfering signal issued from a secondary reflecting path. The interfering path introduces a parasite signal which contribution noises the main signal wave front. Multipath phenomena are very important in shallow water due to the surface proximity.

• **Angular decorrelation:** On sonar images, the measured grey level value of a given pixel is obtained through the additive power summation of several microscopic backscatters contained within the resolution cell. Energy backscattered by each of these microscopic items can interfere, the reflected power may be null and the received phase difference be represented as a random variable. This can be qualified as a random beam pattern of the resolution cell on the bottom. In the sonar context, this is different from the speckle phenomenon which does not request the two sensors to be visible [5]. To compute this effect, we suppose only one kind of random backscattering points, uniformly and continuously distributed on the sea floor which is the worst hypothesis. A classical result is obtained corresponding to a "sinc" modulation for which the first zero of the function gives a baseline size called the critic baseline. Using this baseline, the impact of decorrelation is so important that it reduces the correlation coefficient to null. In the sonar field, this effect is generally neglected because of small baselines utilization. Moreover, for sonar calculation, the physical aperture of the array is not used; only the cell size is taken into account introducing the notion of spatial resolution previously described [1].

• **Propagation attenuation:** several phenomena occurring during propagation lead the signal to vanish (and so the SNR)**.** This attenuation is important for both sensors as it impacts on the coherence coefficient.

• **Sonar specificities:** when dealing with sonar, two other noises should be considered: navigation and celerity noise. Indeed, many phenomena have a great influence on the effective sonar navigation and corrections have to be performed to take into account important motions like roll. Moreover, the celerity of sound wave is not generally constant as it depends on various medium properties (temperature, salinity …). This affects bathymetry estimation by curving acoustic rays.

3.3 Ambiguity removal

The impact of noise does not only concern bathymetry quality but also phase ambiguity removal. Interferometry is a very nice concept for detecting delays within a wavelength range, using an undersampling process. The drawback is to remain unaware of the reference. In order to use an "interferogram", it is necessary to remove this bias.

Radar processing is based on phase unwrapping using paths without residues in the image [4]. Solving this can also be achieved by mean square techniques. Phase can also be unwrapped for sonar acquisitions, but generally, the interferometer can be designed to make it unnecessary. For example, our sonar has three imaging arrays so that the Vernier technique can be used. Thus, Eq.(6) gives the difference phase for one couple of arrays.

$$\mathrm{mod}(\partial\varphi, 2\pi) + 2n\pi = \frac{2\pi d \cos(\theta+\psi)}{\lambda} \qquad (6)$$

A family of solution for one couple corresponds to several possible wave fronts generated by the 2π modulus of the phase. Nevertheless, the physical wave front is unique and both sensors share the same viewing angle when the sensors are lined up. Thus, when plotting the phase difference solutions for two couple of sensors, only two functions belonging respectively to each couple matches: we can find a couple n_1 and n_2 verifying Eq.(7).

$$\frac{\mathrm{mod}(\partial\varphi_1, 2\pi)\lambda_1}{2\pi d_1} + \frac{n_1\pi}{d_1} = \cos(\theta+\psi) = \frac{\mathrm{mod}(\partial\varphi_2, 2\pi)\lambda_2}{2\pi d_2} + \frac{n_2\pi}{d_2} \qquad (7)$$

This technique works very nicely when both baselines are different. We have demonstrated that the ambiguities removal efficiency evolves according to the inverse of the baseline length and that optimal configurations exist, their effective definition being linked to arithmetic and great common divisor.

When dealing with wide band signals, computing the autocorrelation between two arrays provides an estimation of the delay. Choosing the size of the window analysis is the major difficulty of this technique. Of course, when the number of arrays gets bigger, high resolution techniques (like MUSIC and its derivatives) can be used successfully. Thus, nowadays, some multibeam echosounders manufacturers propose bathymetry issued from Music techniques using a secondary array for emissions orthogonal to reception beams. We can notice than the spatial sampling does not specially ask for a spatial Shannon rate, when the array can be steered. Moreover, mixing high resolution techniques beamforming and interferometry allows designing low cost interferometers.

4 Conclusion

In this paper we have outlined some differences between sonar and space-borne radar techniques. Sonar processing is disturbed by navigation and all remote sensing must be performed at once. The baseline geometry is set on the sonar body; thus, beam forming is performed in a single shot, using a static network of sensors.

In radar casewide ranges (thousands of kilometres) are involved, in order to reach interesting resolutions, at the same time performing synthetic aperture and using huge baselines built from two orbits.

Originally, sonar techniques were derived from radar ones; it is interesting to notice that lots of analytical developments were made by searchers working in the radar field. Nevertheless, the sonar configuration (with a static baseline) is really interesting as soon as it becomes compatible with radar resolution requirements. In that case, it is easy to compute the correlation between both data.
SAR domain may benefit from well known SAS techniques in order to improve radar resolution with different array geometries and pulse shapes. This is still a much opened topics which need further developments than the brief description presented in this article.

Acknowledgments

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