Sedimentological acoustics : an attempt to reduce the gap between acoustical modeling and sedimentological survey

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Abstract

A major task in shallow water acoustics is to provide pertinent geoacoustical data. The purpose of the work is to evaluate the state of the art in this field, connecting in situ sedimentological measurement and acoustical modeling aspects. According to sonar systems frequency ranges and to the kind of needs, the measurement in terms of sedimentological data is different. Parametrisation requirements are investigated for both propagation and reverberation models. We propose to translate differently the survey knowledge, of a calibrate zone, versus frequency to provide different parameter bottom sets to the users. We discuss the lack of availability of some of this parameters.

1. Introduction

We focus in that present work on the sea bed environment aspects and on the sonar acoustics aspects. For numerous maritime activities like fishing, resource development, mine burial and security of navigation, sedimentology is more specifically approached in terms of sea floor mapping; subbottom profiling is used for cables and pipeline laying, marine engineering, security research, ... So, most of the sedimentary applications have dual utility - military and civilian. Geoacoustical modelling, for ASW operation, takes into account most of the previous input. It also contributes to understand acoustics in sediments to the analysis of geophysical systems and concerns all the sea bed characterisation or classification systems.

Sedimentology and acoustic are closely linked, the acoustical data obtained during surveys is transformed in sedimentological parameters, then the process is inverted to give products suited to the beam angle and frequency of all kinds of sonar. Between all of the geological parameters: scaling of horizontal and vertical variability, heterogeneousness of sediments, sea bed roughness, influence of gas or bioclastes, wide range of rocks, which are the most important for acoustical modelling? What effect do they have on images or seismic systems data? And which roughness of sea bed interfaces is needed?.

First chapter concerns mostly sedimentological survey, measurement techniques and storage from large to very small regional scales. Sonar equation involves transmission loss and reverberation level. That terms contents reflection, scattering mechanisms, which are themselves strongly dependent of the bottom characteristics. We will develop that acoustical part in part two. Third part is devoted to an application. A recent calibrated area has been surveyed in Bay of Biscay. We propose to translate differently the survey knowledge versus frequency to provide different parameter bottom sets to the users and investigate their impact on sonar prediction.

2. Sedimentology

Sedimentological surveys are done with acoustical (imagery and seismic) and graded systems (samples, photographs). Since the sixties shallow water side scan sonar images are used in hydrography for seeking wrecks and dangerous obstructions. For sedimentological purposes, these data enable to differentiate rocky areas, limits of coarse and fine sediment, and sediment features. Many numerical processing were studied, they give nearly good results for textural characterisation (roughness) but not for grain size classification due to its unadapted high frequency (100 kHz or higher). With 10 to 20 kHz frequency, deep water multibeam echo sounder data are well done for sea bed characterisation [1]. In shallow water these multibeam systems have 100 kHz or more frequency, so they probably present the same limits as side scan sonar images with a less precision. All of these systems give morpho-sediments charts, but on the continental shelf, at 100 kHz or higher, side scan sonar received are modified by turbidity layers above the sea bottom, organic activities,

bioclastic proportion, sea bed roughness and sorting of sediments of surface. Multispectral satellite images and photogrammetric plotting carried out rapid assessment of clear water coastal field. In French Polynesia, radiometric data show variability up to 20 meters. On European continental shelf, these remote sensing systems provide sea bed information just from the beach to the slightly immerged zone (3 - 5 meter depth).
For subbottom knowledge, numerous systems could be used from some hertz for intra-crustal studies to some kHz for accurate description of the first tenth of meters. Numerical processing of the 3.5 kHz received signal, obtained with DELPH system on the hydrographic French vessels, could be used to calculate sediment type and geoacoustical parameters. The development of these studies complete the sediment thickness measure usually done with subbottom profiler. Questions on the necessary depth in sediment and accuracy needed are asked, so does the 3.5 kHz subbottom profiler give parameters needed for acoustical modelling?
Accurate topographic representation of sea floor contributes to the understanding of sediment distribution. The echo sounder used for bathymetric surveys could also be a source of data when the backscattering signal is processed. This signal processing, with systems like RoxAnn, characterise the sea bed and give parameters such as hardness and roughness (RoxAnn) or classified the sediment type, ... These methods offer several advantages : the real time results could be rapidly used for a broad spectrum of needs, the frequency could be chosen in accordance with the application. With a 33 kHz echo-sounder data are not modified by superficial turbidity, but it has the disadvantage of furnishing, in muddy and silty sediments, parameters which are the mean of the first decimetres of sediments.
All of the acoustic, photographic and radiometric data must be calibrated with samples. This bottom truth gives the name of the sediment. The quantification of various fractions, by dry sifting or laser diffraction particle sizing, enables the processing of sedimentological parameters as median, mean grain size, sorting and skewness. Carbonate determination completes these analysis. Spot samplings on cores are necessary to calibrate seismic profiles, the same parameters are obtained to construct a log of subbottom structures. These unequivocally reflect the deposition processes which laid down the sediment.
Density and celerity could be in-situ measured to have sedimentary and physical accurate data. In general, when cores aren't disturbed these parameters are measured in laboratory; in the other cases and for grab samples they are calculated with Hamilton and Bachman formulas. The comparison between these results proved that experiments and comparison must be done to improve the calculation method. The mean grain size don't give the real representation of the collection of particles which compose a sediment. The using of more sedimentological parameters (mean + sorting + skewness) depth and chemical parameters (carbonate and gas contents) would be better to improve density and celerity values. For roughness classification, RoxAnn, side scan sonar or echo sounder data must be calibrated with underwater video or photography.
Some of these sedimentary systems could not be used for every surveys. The aim of video and in-situ acquiring of acoustic parameters is to study the sedimentary-acoustic relationship and to obtain more accurate formulas.

2.1 From region to sediment

With the tectonic subsidence (when the sediment causes isostatic depression of the crust) sedimentary basins with some kilometres thick sedimentary sequences were built. The lack of subsidence since the Palaeogene, or earlier in some parts, have transformed the Channel and Bay of Biscay sedimentary basins in platform with soft sediment overlying different kinds of rocks. So, in view of the question set down, these zones are interesting to test acoustical modelling. Various kinds of sediments covered this continental shelf of the west of France, these bioclastic material mostly Holocene in age progressively contaminates ante Holocene lithoclastic relict deposits . The coarse lithoclastic material mainly result from frost shattering and solifluction during the Quaternary regressive stages. The distribution of the material is controlled by tidal currents in the open sea and swell close to the coast. From high energy areas to the minimum energy level - the wave base is from 6 m in the east Channel to 70 m in Celtic sea and in the Bay of Biscay - a sedimentary succession of decreasing grain size are thus observed. So as Larsonneur demonstrated [2] a sedimentary model which describe equilibrium between sediment distribution and hydrodynamic conditions can be mapped on a basin scale.
At sea, observations are different, they show higher precision offered by acoustic systems. Seaweeds, wrecks or local rock outcrops change environmental conditions, sand ribbons and other sand structures could be created downstream. In some muddy zones, sixty meters large pock marks, shown on side scan sonar sonographs, coming from gas. Thickness varying locally with sand structures and palaeo-rivers where 50 m of alluvium formations could be observed. With photographs or video images we see that roughness coming from small sand ridges, boulders and biological activity, is too small for side scan sonar and too large for samplings. The finer accurate data base obtained represent the primary source of information needed to support all of the different applications. The data processing of acoustic and samples are used to realise, with each kind of systems, maps at the scale of the survey (mosaics, isopach map, ...). The third product is a 3D sedimentary representation that we will develop during the next few years.
During the last 30 years, more than 20 000 samples were taken on the west of France continental platform. The whole granulometric range is represented from boulders and shingles to colloidal muddy particles. Well sorted sediments are the less represented. The mixing of ante-Holocene material, redistributed during the last transgression, with organogenic material give all kind of very poorly sorted. The sedimentary model is less accurate than surveyed data, but it could be sufficient for acoustical modelling, in the other case acquisition and data banking must be increased.

3. Acoustics

In this chapter, we suggest to split main mechanisms involved in four steps. Each step is a filter including modelisation, our misknowledge, and is designed to be compatible with the others filters.

1. Sedimentological survey. This point has been treated yet in the previous chapter. Sonar involve usually lower frequencies and lower grazing angles than sedimentological survey. So, a good knowledge of the whole problem is actually necessary to deal with seabed characterization and to design new instruments devoted to purely acoustical problems if necessary.
2. Parameters. Which geoacoustical parameters are necessary to describe the bottom and how calculate their values. Special attention is required to estimate thickness and accuracy of geoacoustical parameters given sonar constraints.
3. Local models. These models describe the physical interaction of acoustical waves with the bottom. They are the main part of the transfer function because they fix the parameters needing and limit the future acoustical impact study.
4. Global models. They are propagation and reverberation models. They are used to predict sonar performances. They have to manage with all kinds of constraints like water speed profile, sea surface state...In that context, shallow water and bottom's effect in shallow water are one of the numerous constraints to handle with and it is therefore usually necessary to simplify that problem. Such a simplification adds limitations to impact studies.

3.1 Parametrisation

Geoacoustic parameters depend on the local modelisation that will be used for the global modelisation. Usually we distinguish between reflection and scattering parameters. Reflection mainly depends on impedance. Impedance depends on speed, attenuation, and density of the medium. A reflection medium parametrisation is then oftenly given by 5 parameters : Compressional speed Cp, Shear speed Cs, Compressional attenuation Atp, Shear attenuation Cs and density ρ. Because it is hard to measure these parameters in laboratory (core needed, real in-situ conditions...), they are often calculated by empirical geoacoustical Hamilton relations. Actually, we often miss in situ calibration to be sure of our values. These values depend strongly on the in situ configuration as compaction for shear waves velocity for example. Parameters calculation depend on the frequency as well, dependence which is often discussed. Finally, as we will see later, substratum values are very important to estimate the reflection at low frequency (100Hz) and we seldom get in situ information about this. Reflection parameters usually used are:

	silt	sand	limestone	granite
Cp (m/s)	1550	1750	3000	5200
Cs (m/s)	80	130	1500	2500
Atp (dB/λ)	1	0.6	0.2	0.1
Ats (dB/λ)	1.5	2.25	0.4	0.2
ρ (Kg/m^3)	1.7	1.95	2.4	2.6

Scattering parameters depends as well on the local modelisation [3]. They generally split the problem on an interfacial rugosity and subfacial inhomogeneities but neglect the sediment stratification.They need parameters like micro-scale slopes or correlation length of inhomogeneities which are highly variables. They are related with frequency, and grazing angles and so very hard to estimate. In situ lack of data is a problem not only for sonar prediction but to calibrate sedimentological instruments as well. We present below an example of that kind of parameters [4]. To avoid such a complexity, scattering is sometimes described by the Lambert law characterized by one parameter only: $R(\theta,\theta') = \mu.\sin(\theta).\sin(\theta')$ where θ and θ' are respectively incident and reflected grazing angles and μ the bottom's scattering parameter.

	silt	sand	rock
μ (dB)	37	31	18
δ (degrees)	4	6	11
h_0 (cm)	3	7	50
μ_0 (%)	5	3	<1

Scattering parameters for 3 sediment classes first line concerns Lambert's law others come from Pouliquen [4]. δ is the rms sediment slope. h_0 the rms height of the rugosity and μ_0 the volume inhomogeneities parameter.

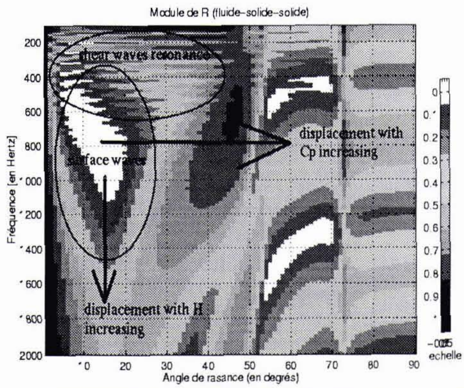
3.2 Local models

Local models treat of physical mechanisms of interaction between bottom and acoustical wave. Because they imply different mechanisms, it is easier to distinguish between reflection and scattering models.

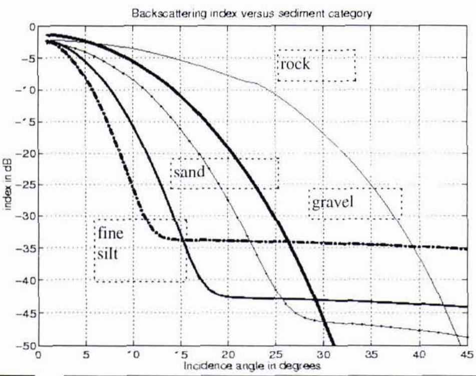
Reflection coefficient

It is the ratio of the bottom reflected intensity by the incident intensity. Sea bed is modelised by a homogeneously stratified medium. $R(\theta)$ is then calculated applying the boundary conditions between different mediums.When the bottom is an infinite medium, it is characterized by a critical angle proportional to the ratio of the both mediums compressional speed

Cp2/Cp1 below which R =1. Actually, shear speed and attenuation generate reflection loss even below critical angle. When the modelisation of the stratification is more complicated, new phenomena appear such as frequency dependence, surface waves or shear waves resonance. It is important to notice that we focus on the low grazing angles. Those concern the propagation at long ranges because others are too attenuated. As we can see on the below figures, behavior at low and high grazing angle are very different .



Reflexion coefficient versus frequency and grazing angle. The configuration is H =1m of solid silt over a granit substrat. An important loss at low grazing angle is due to shear resonance and to surface waves. Cp is sediment compressional speed.



Reverberation index calculated with Brekhovskikh method. Parameters values are from Pouliquen [4]. We see that rugosity scatering is predominant for rock and near normal incidence. Inhomogeneities effect is stronger at high incidence angles.

Scattering

The scattering coefficient is defined by R(θ,θ') like the reflection coefficient but involving non specular reflections. Various theories are possible to calculate R(θ,θ'). Because of the high number of parameters needed, they often suffer from a lack of in situ validation and calibration. It is the reason why we won't say a lot about it on the forward application.

Helmoltz Kirchhoff or Rayleigh Fourier theories applies for « smooth » roughness. Both of them are generally used for deterministic or measured interfaces. Unfortunately, it is seldom the case in practice. Some recent developments [5] modify Lambert`s law near specular direction. That kind of scattering lobes calculation is used in transmission loss global models. Modelling mixing interfacial rugosity and inhomogeneities are often found in literature [3]. They are useful for multibeam echosounder measurements for example.

3.3 Global models

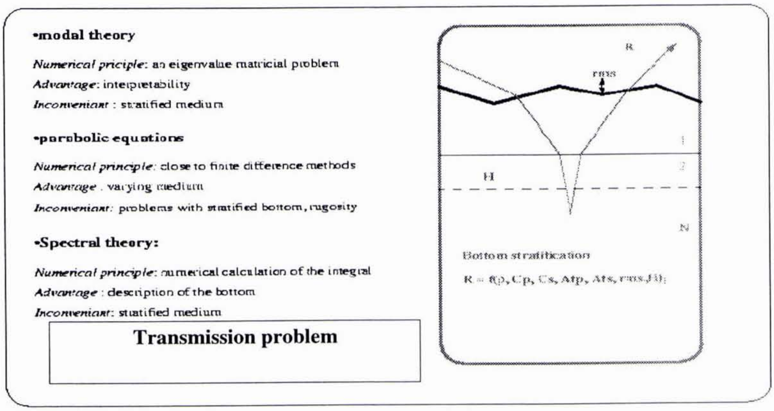
Transmission problems

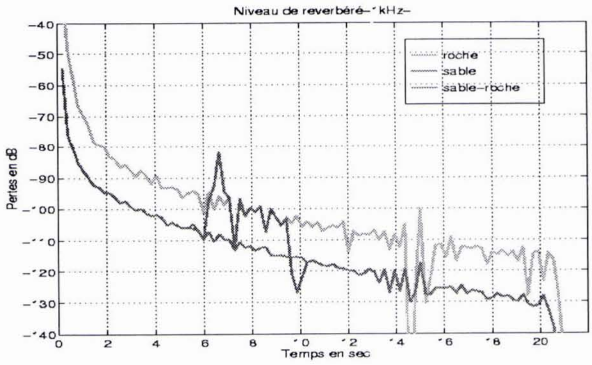
Shallow water bottom propagation problem is involved with reflection, scattering and bathymetric aspects. But it main characteristic is that it is a low grazing angles problem. So, local models must be especially accurate at this angles. Most of waves models can handle with reflection phenomena but not with scattering ones. This is mainly due to the complicated boundary condition that scattering generates. An other point to focus on is that few of them can handle with a varying medium. Unfortunately, it is often the ground truth. It is what we will partially answer in the next chapter investigating a varying calibrated zone.

Reverberation problems

It involves same constraints as for propagation modeling but it is now imperative to add the bistatic scattering effect. To simplify our explanation, we follow a geometrical approach as usually done. We proceed as for a classical ray models and each bottom reflected ray is directly backscattered to the receptor and time ray path stored. Reverberation level at a given time is the contribution of all simultaneously receptor arriving backscattered rays. The scattering law used in the below figure is a Lambert's law.

Bottom parameters involved in some propagation models

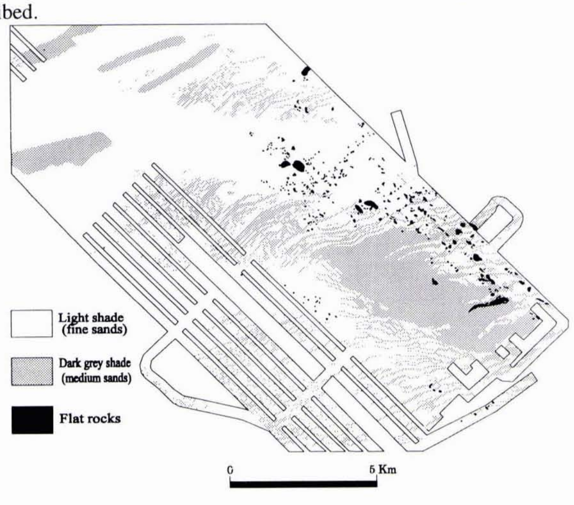




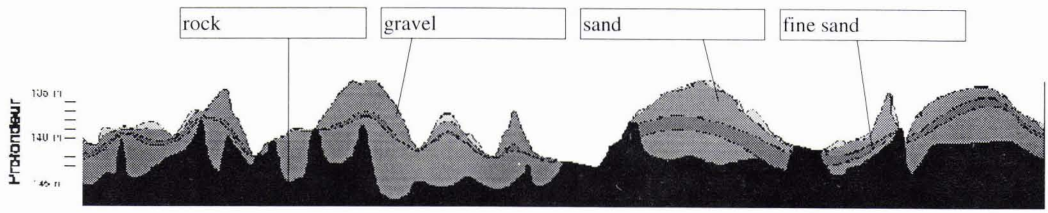
Reverberation problem
Reverberation level versus time. Calculated by rays theory with an isovelocity water of 100m.F = 5kHz. Zr=Zs = 50m. Lambert values for rock and sand are respectively 18dB and 31dB. Specular reflexion coefficients are respectively those of limestone and sand. We see the strong effect of 2kms of surficial rock on a sandy sea bed radiale.

4. Application

A calibrated zone was determined for testing acoustical modelling on real sedimentological data. So, we chose a deep near homogeneous flat zone on the sedimentological map of the Bay of Biscay. The depth of the 60 km long and 15 km wide area surveyed are from 130 to 144 meters. Sedimentological mapping at scale 1/40 000 was done with all of the systems previously described.



The side scan sonar morpho-sediment map reveal: - flat rock spots of several hectometres, we see on the bottom of one core that it is an eroded shelly limestone, - patchy light shade (fine sediment) covering the bottom horizon, - the main part of the zone is covered by dark grey shade, the cores show that it is bio-lithoclastic medium sands.
With the subbottom profiler different strata were define and an isopach map was done. The substratum is undoubtedly rock in the southern part of the zone; but in the north without any bottom truth the deeper reflector could be a coarse sediment or rock.
A synthetic 48 km long cross section was done with all data as shown in the following figure. It reveals a regressive succession - a coastal unit, probably beach bars of shelly gravel, were progressively covered by medium sand when the shoreline moved, with the increasing depth finer sand were deposited. The thin top layer of fine sand patches could be affected by storm waves.
Each point of the radial is described by a complete stratification including thickness of each sediment class. We make an impact study of such a variability on acoustical propagation. We follow the same methodology as in the precedent chapter. We focus on the different approximations to do versus frequency. We chose 3 frequencies 100Hz, 1kHz and 10kHz which scan the whole sonar ranging.



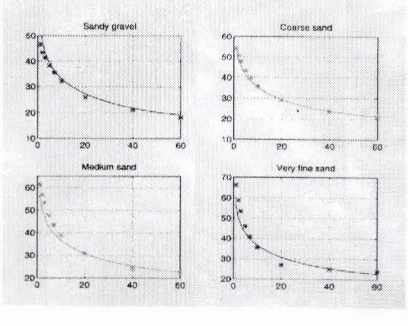
4.1 Parameters

The fifteen cores analysed contain different sediments, from bioclastic gravel to silty muddy sands. The following results of mean values are calculate for acoustical application:

	Fine sand	Sand	Gravel + sand	Shelly gravel	limestone
Density	2.01	2.21	2.28	2.37	2.4
Cp(m/s)	1773	1937	2002	2093	3000
Cs(m/s)	0	0	0	0	1500
Atp(dB/λ)	0.7	0.6	0.5	0.4	0.2
Ats(dB/λ)	0	0	0	0	0.4
μ(dB)	21.5	21	20	19	18

Density was measured in laboratory, compressional celerity was estimated with Hamilton formulas which take into account density (measures must be done during the next months with a core logger). Attenuation has been estimated from tab1 and shear sediment waves been ignored because we don't have any information on their actual values and because they are of few interest for that present study. We remark a quite high value of Cp for sediment classes. Because we don't have any measured scattering parameters, we choose to simplify them using a Lambert law fitting with values found in literature for such sediment at 10kHz only.

Backscattering index for 4 sediment classes at 10kHz. As we don't have any in situ indication on the scattering parameter class, we choose to fit a lambert law with that data. We then find μ = 21.5,21,20 and 19 dB. Angular dependency doen't follow a lambert law but we impose the fit in the 20-40° grazing angles. We will make the reverberation impact study with this values.



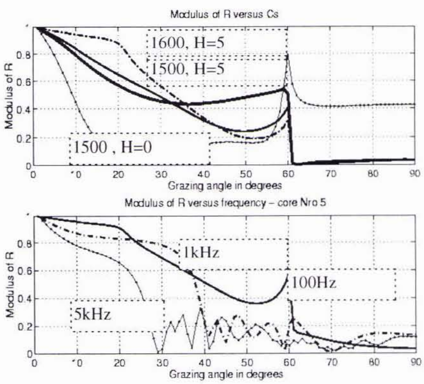
4.2 Local modelisation

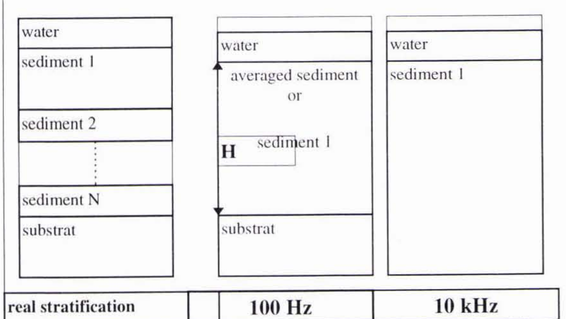
Reflection

With such a radial, we calculate every reflection coefficient with SAFARI [6]. As expected, we observe a strong rock impact for the 3 frequencies.

- At 100Hz, the variability is quite important. R(θ) is rather sensible with sediment thickness but few with it Cp value. The main phenomenon is surface waves conditioned by sediment thickness and Cs substratum value. We modeled the stratification at 100Hz as a sand of thickness H over a limestone substratum. Calculations gave exactly the same result as for the complete original stratification. We focus on the lack of information we have about Cs substratum value. It could vary between 1500 and 1700 m/s and even probably more. <u>This is a very important point to check in order to predict transmission loss .</u>
- At 1kHz, variability is less important. R(θ) is few sensitive to the substratum except when sediment thickness is very little. Then, a similar phenomenon as before, generates a reflection loss. R(θ) is involved with the whole sediment stratification. Here, it is mainly dealt with the critical angle due to the superficial sediment because of the quite low contrasted sediment stratification. It is better to modelise the stratification by a simple superficial sediment than by a depth-averaged one.

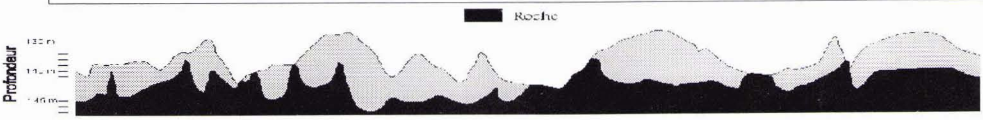
At 100kHz, penetration at such low grazing angles is very few, and it appeared very convenient to modelise stratification by an infinite sediment corresponding to the superficial one as shown in the following figure.





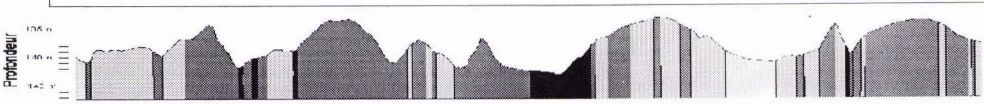
Diferent simplification of the stratification versus the used frequency. 100Hz mainly depends on the sediment thickness over a well defined substrat. 10kHz only depends on the surficial sediment

above left :reflexion loss variations with sediment thickness of 0 and 5 meters, Cs shear speed of limestone at 1500 m/s or 1600 m/s. below left:reflexion loss for core Nro5's stratification. 100Hz's one is drived by substrat shear speed (1600m/s). 1khz's one by sand's critical angle and 10kHz's one by the very thin silt superficial sediment.



100 Hz

Final representation of the stratification for 100Hz and 10kHz. Because of their local reflexion loss properties, they are quite different and will be used for writing the input environemental data file for global propagation loss.



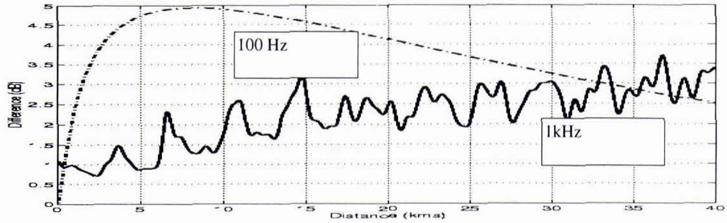
10 KHz

4.3 Global impact

It is then possible to give an input environmental data file to deal with propagation models.Few of usual wave propagation models allows us to handle with such a variable stratified bottom.We made simulations at respectively 100Hz and 1kHz.

- At 1kHz, We made simulations with FEPE [7], parabolic equations, with the 10kHz environmental data file, except the under laying rock which is changed by a superficial limestone. It is then possible to avoid stratification problems due to parabolic equation modeling. We made 3 simulations. One with the whole data set, one with the bottom's data set but with a flat bottom, and one with a homogeneously stratified flat bottom. For the last one, geoacoustic parameters are those of an averaged sediment over all the radial.

At 100Hz, we can't deal with parabolic equations because of the stratified bottom's constraint. So, we must reduce the complexity and focus on what is the most important, according to us. As we said before, a very important variation of reflection loss is due to Cs, shear speed of the limestone. So we make two simulations, one with an homogeneous flat bottom with an averaged thickness of sand (3m) overlaying a substratum with Cs=1500m/s, and 1700m/s. We calculated transmission loss with the normal modes code KRAKENC [8].



- At 1kHz, we make coherent loss calculations. We use a low filter to diminish interference effects and show difference in dB between the real and the simplified medium. There is no difference between a flat bottom and the true bathymetry. The difference increases slowly versus distance. Nevertheless, it is quite a low difference considering all ours environmental misknowledge.
- At 100Hz, the difference is stronger even at quite small distance. It tends to prove that sediment thickness and substratum shear speed can't be neglected even at small regional scales. It is necessary to map more accurately this parameters in order to improve passive sonar prediction.

5. Summary

Mixing sedimentological survey and acoustical modelling is a necessity to provide a performant acoustical survey and to predict sonar performances. Working on such a calibrated area is very useful to show the complexity of that problem and to enlight some important points. In all cases, multicriteria approach with imagery, seismic systems, in situ measurement, must be coupled with data bases to characterize the bottom truth and discussed the validity of geoacoustical relations.

Survey major problem is the lack of in-situ measurements to get a ground truth. Rugosity is then a recurrent problem which could be diminished by photography. Parameters quantification is mainly done by Hamilton's relations. But some of them remain still badly known (shear speed or attenuation) and others totally unknown like substratum shear speed. Some attempts to classify rugosity sediment parameters remain incertain according to us. Complexity of local scattering modeling add further to the difficulty of calculating scattering lobes. Wave propagation models show their limitations when they have to handle with a complex varying ground truth. Nevertheless, it seems that usual approximations as considering a homogeneous bottom on such a small regional scale and homogeneous medium may be quite enough accurate (at medium frequency). It's not the same at lower frequencies where strong bottom interactions can occurs.

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