SONAR PROCESSING PERFORMANCE IN RANDOM FLUCTUATING ENVIRONMENTS

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1 INTRODUCTION

Sonar performance assessment requires a model of acoustic propagation in the marine environment and a description of the sonar system. In spatially and/or temporally fluctuating environments, decoherence effects of the propagated acoustic signals (space decorrelation, and time-distortions of wavefronts and transmitted waveform) degrades the performances of sonar processing, and thus induces further limitations of the detection capabilities of sonar systems. In a previous symposium[1], we addressed the degradation of sonar processing due to space decorrelation of wavefronts along arrays due to background linear internal waves; here, we consider the degradation due to time decorrelation and distortions of transmitted waveforms after surface reflection.

We will introduce the main features of the acoustic model developed in order to give a realistic evaluation of sonar performances in harsh environments, and most particularly over shallow continental platforms. This modeling, based on a stochastic approach for solving the wave equation, provides, firstly, spatial and temporal statistical moments for the propagated acoustic field and, secondly, realizations for the impulse response of the random medium. In the modeling, we consider the fluctuations at the sea surface (wind-waves and micro-bubbles for the sea surface). As applications, we will present quantified results for the performance degradations of temporal matched filter for mid-frequency active sonar processing, as a function of the environmental fluctuation scales and of the waveform's features (duration, bandwidth, central frequency). The degradation is evaluated in terms of a downfall in processing gain. Limitations to the improvement of performance with pulse length and bandwidth are given.

2 CLASSICAL TECHNIQUES FOR SEA SURFACE EFFECTS IN SONAR PERFORMANCE PREDICTION

As far as we know, three different strategies have been proposed and used for introducing the sea surface effects in sonar performance modeling.

1/ The most frequent technique is to apply a theoretical loss per surface bounce, or a reflection coefficient: a list of commonly invoked surface loss models are: Plane surface (no loss, reflection coefficient is equal to 1), Rayleigh loss (coherent part of reflected sound field), Marsh-Schulkin, in its original version, or revised by Kuo (perturbative form for coherent part of reflected field), Beckmann-Spizzichino (originally a formula for radar wave scattering by sea surface roughness). The main drawbacks of these methods are the following: firstly, by principle, only surface roughness is included (no loss due to superficial air bubble populations); secondly, the attenuated reflected field is specular and perfectly coherent (no contribution from random fluctuating part, no distortion of waveform shape, no spatial decorrelation).

2/ Another approach is to use an empirical decay rate with range, like those arising from the early 50's campaign AMOS experiments (loss in surface channels), Saxton-Baker[2] (loss in surface channels), or Weston-Ching[3] (loss in sandy-gravelly shallow sea) As empirical and arising from measurements at sea, these losses are reliable, but their applicability is limited: only vertically narrow confined environments are considered (surface channels, shallow seas) and only long CW signals were involved in the experiments, with no temporal processing (no loss due to distortion of pulses reflected on moving sea surface).

3/ A today uncommon, but existing[12] method is to explicitly model the distortions of sound-speed profile and of acoustic volume attenuation, due to the presence of air micro-bubble layers, using e.g. the theoretical, synthetic model proposed by Hall[4]: Drawback: only loss due to bubble is taken into account (no loss due to distortion of pulses reflected on moving sea surface, no space decorrelation).

3 THE NUMERICAL MODELING OF SEA SURFACE SCATTERING

We give a short description of the physical and computational tools involved in our theoretical statistical model NARCISSUS, in its actual operational form. After modifying the sound-speed profile and the volume absorption for accounting for the effects of micro bubbles, this code relies on embedded independent numerical "tool-boxes":

First, a Geometrical Propagation Toolbox : after transmission from the source, between two successive interactions with surface and/or bottom, and up to the receiver, the mean ²luminance² (i.e. the spectral and directional density of acoustic radiated power) is conserved along paths that may be numerically computed. Some elementary routines able to compute acoustic rays, and the related parameters (delays, angles, etc., as functions of horizontal range) are used; the luminance decays exponentially along these rays, as an effect of volume attenuation (visco-chemical loss, plus bubbles near the surface).

Second, a model for the Generalized Scattering index : the acoustic power impinging a random boundary within some incident bundle of ray is split into the sum of a coherent part, and of a scattered random part, which features a certain directivity pattern, and a certain dispersion in scattered frequencies (if the surface is moving). The "Generalized Scattering Index" is a kernel, appearing inside the integral linear relation that gives the second-order moments of the scattered field from the second-order moments of the incident field, whereas the mean part (first-order moment of the field) behaves specularly and is fully modeled through a reflection coefficient. A model for the reflection coefficient and kernel may be derived from the "integral small-slope approximation", or "Meecham-Lysanov approach" (Voronovitch[5], Ch.6, pp.191-194), finally resulting in two elements: an attenuation coefficient for the coherent specular part, and a scattering index for the mean distribution of the energy associated with the random non-specularly reflected part. The input data for this model is a statistical description of the irregularities and movements of the surface waves and of the seabed, including the relative displacement of source and receiver. A statistical time-spectrum for the wind-waves, necessary for evaluating these coefficient and index, is the JONSWAP model (Hasselmann et al.[6]), completed with directional spectra (borrowed from Donelan et al.[7]). Bottom irregularities at the scale of micro-topography (horizontal periods up to about 1-2 km, vertical oscillations with amplitude up to 1-2 m) are assumed featuring a Gaussian autocorrelation function of horizontal co-ordinates.

Quite a simple procedure Monte-Carlo technique is used for combining propagation and scattering:

1/ a ray is launched, with its initial parameters (launching angle, etc; the path is computed with the help of the Propagation Toolbox and followed up to its first encounter with a rough boundary.

2/ a Monte-Carlo Toolbox is applied: the attenuation coefficient R for the coherent part is computed (as a function of frequency and incident direction on the rough boundary); a pseudo-random number X is drawn, with an uniform density over [0,1]. If X is less than R, the path is specularly reflected; on the contrary, if X is higher than 1, the ray is submitted to scattering, which takes the numerical form of random jumps in reflected direction, and in frequency. The probability density of this pair of deviations in frequency and horizontal components of the wave-vector is the "Integral Small-Slope Approximation" scattering index, a function of incident and reflected frequencies and directions, properly renormalized so that its integral is 1 (a necessary property for probability densities).

3/ after this reflection (specular, or with a random deviation), the path is computed and followed again, with the "Propagation Toolbox", up to the next encounter with a boundary, where the previous "Monte-Carlo Toolbox" is required again, or up to the receiver.

This recipe is repeated, as far as several criteria remain unfulfilled (volume attenuation below than some arbitrary threshold, number of encounters with boundaries smaller than some empirical value, etc.). The result of the previous sequence of operations is a ray-path, with random deviations in frequency and slope at several boundary-encounters; the luminance transmitted along this path being assumed conserved along this path (conceptually extended to a fictive space {location, direction, time, frequency}), so that one may easily compute the "energy", associated with this path, lying inside any arbitrary bin of this fictive "extended" space. This "energy" is simply proportional to the length of the intersection between the random path and the bin.

4/ another ray is launched, with the same initial parameters, and is submitted to new random deviations; the energy associated with this new path may increment the considered bin. A division by the number of launchings gives an algebraic average of "energy" over the bin, which must tend asymptotically, when the number of launchings increases infinitely, toward the integral over the considered bin of the mean luminance. Moreover, the same procedure may be fully reproduced for other transmissions parameters, so that any directivity or extended source may be treated. This computational technique of the mean luminance, i.e. of the second-moments of the acoustic field, does not require RAM space; the computing time, proportional to the number of launchings, times the

number of samples in launching parameters, may be unlimitedly high, but remains numerically as small as one may will (the price to pay for fast computations is a final result far from the asymptotic limit); the convergence of the method, relying on summations of essentially positive numbers, is certain, but the question of the convergence rate remains unsolved: the code was provided only empirical values for the related parameters (number of realizations to be drawn, etc.).
A similar procedure, applied to a problem of random sound scattering from internal waves in refracting sea-channels was proposed by Wilson & Tappert[8] for describing the scattering from random variations of the sound-speed distribution associated with internal waves.

The results from the previous process are only a collection of several first- and second-order statistical moments of the sound-field (averages, space- and time-correlation functions), both in time-frequency and space-direction spaces. The "random rays" are in no way "real" rays, but only paths along which certain quantities behave simply (exponential decay), outside the regions involving boundary scattering. The scattered part of the field may perfectly behave in a diffractive non-geometrical way, if the amplitudes of the surface waves or bottom irregularities are comparable to, or less than, the wavelength. From the previously tabulated statistical moments, typical realizations of the Impulse Response (IR) may later be pseudo-randomly drawn, provided further statistical assumptions:

1/ the IR is assumed a normal process; this may be loosely justified, if considering that the random part of IR, at fixed delay, is the sum of contributions of many independent scattering irregularities. We otherwise checked this assumption experimentally, among others in a configuration where the source and receiver where motionless (see Cristol [9, 10]).

2/ we assumed the classical "uncorrelated scattering" approximation (see e.g. p.706, in Proakis[11]), which states that the IR, taken at different delays, features uncorrelated random variations.

Provided these assumptions, pseudo-random Monte-Carlo realizations of the IR may be drawn, as a function of transmission time and delay (2 independent variables); it may then be pseudo-convolved with the transmitted wave-form; the final result is a realization of the received signal, including scattering from the moving sea surface roughness. This procedure may be performed first forward from source to target, and second backward, from the target to sonar receiver; an extended target is described as a linear set of point targets, separated in time delay by 1 / signal's bandwidth (extended van der Spek target).

4 PERFORMANCE OF THE TEMPORAL CORRELATION

The Replica Correlator (correlation with the transmitted waveform) is optimal for detection of signal in white noise; the underlying assumption is that the echoing waveform strictly matches the transmitted waveform. Simple Doppler shift may be compensated by shifting the replica, but distortions due to the moving rough sea surface are far more complex and intrinsically stochastic, so that the effectiveness of the signal compression with the RC is reduced. The problem is to quantify this reduction, which the strategies of section 2 can not evaluate. The methodology described in the previous section finally provides realistic Monte-Carlo realizations of the echoes measured on a receiver, and coming back from an extended target, in a marine environment perturbed by a random rough moving sea surface; these realizations may be used for evaluating the performance of the RC.

As displayed by the examples of Figure 1, we processed simulated target echoes under three different assumptions:

1/ assuming the surface is plane;

2/ keeping only the coherent specular part of the field reflected on the surface (this corresponds to what we called "the first strategy" in section 1, using Rayleigh reflection coefficient);

3/ "complete" Monte-Carlo realizations of sea surface reflection, i.e. including both the specular and scattered parts of the surface reflected signals.

In all three cases, the loss due to clouds of air bubbles is included. Figure 1 displays an example of the outputs from the processing as functions of time delay, under the three assumptions: the "complete" case stands between the other two calculations: above the Rayleigh case, and below the plane surface case. Compared with the plane surface configuration, the complete calculation features a <u>degradation</u>. On the contrary, compared with Rayleigh loss calculations, complete calculations feature a <u>gain</u>; even if distorted and spatially decorrelated, the scattered part of the signal brings information.

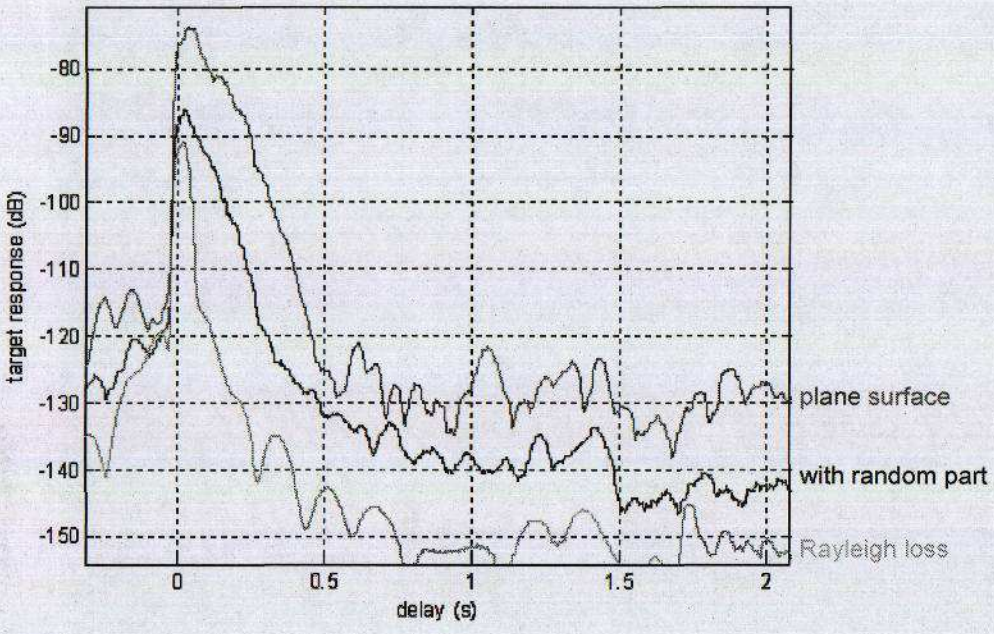


Figure 1. An example of echo from an extended target, with signal compression using coherent RC filtering and incoherent integration

Winter / Shallow sea (100.m) / Sea state 4 / LFM, 5 kHz, bandwidth 1.kHz / Target range 4 km / Target length 40.ms / Integration time 40.ms

We evaluated the Degradation compared with Flat surface (DF), and the Gain compared with Rayleigh loss (GR) for a large number of shallow sea configurations, including:

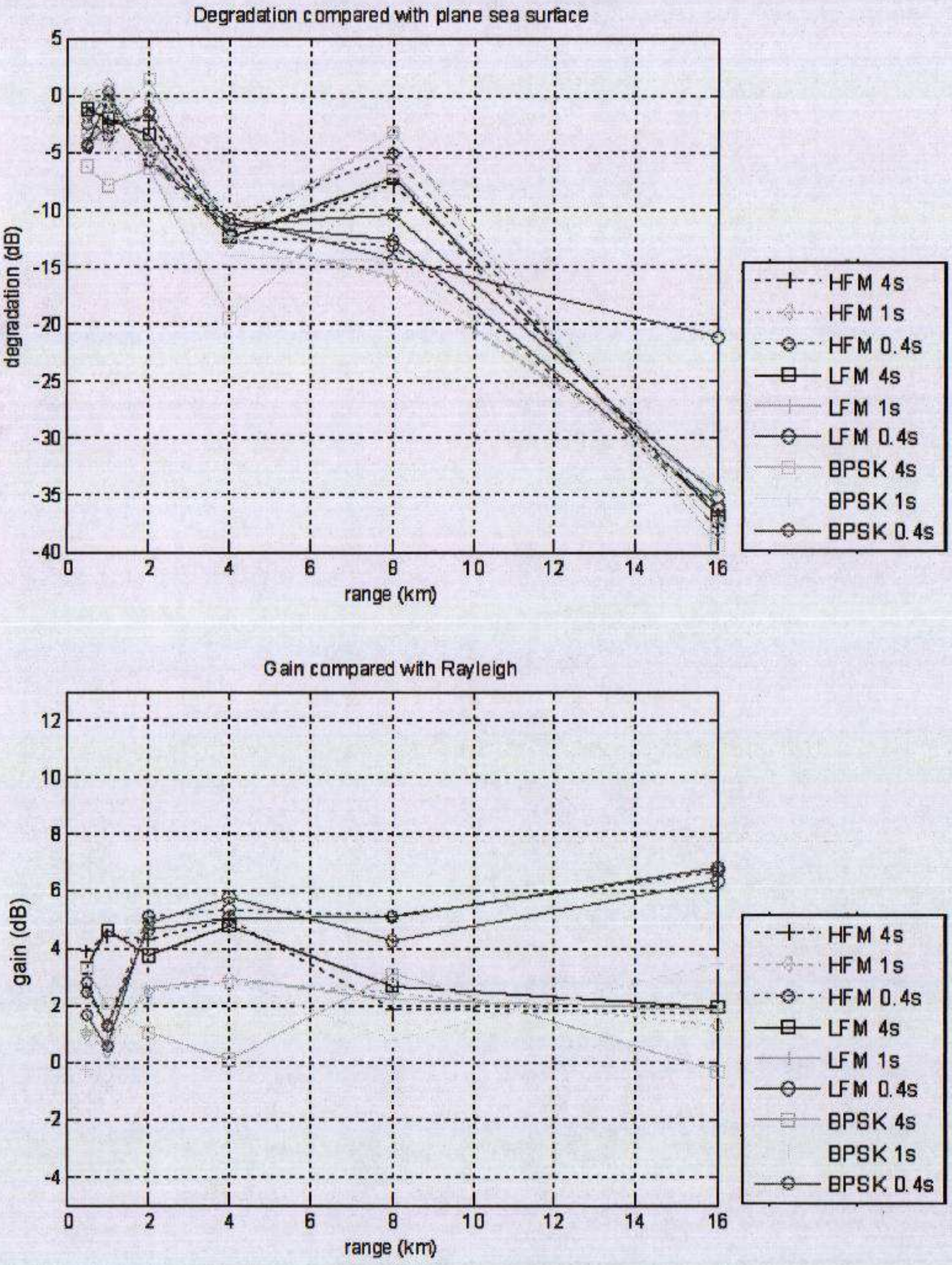
- summer bottom refracting sound speed profile, and winter upward refracting profile;
- three different sea states (Douglas scale): 2, 3, 4;
- three different types of waveforms: HFM, LFM, BPSK;
- three different pulse lengths: 0.4s, 1.s, 4.s;
- three different frequencies ranging over the mid-frequency band: 1.kHz, 5.kHz, 10.kHz;
- two different bandwidths: 1.kHz, 500.Hz;
- six target ranges: 0.5km, 1.km, 2.km, 4.km, 8.km, 16.km;
- two different target lengths: 10.ms, 40.ms;
- two different integration times: 10.ms, 40.ms

For each combination, we generated three target echoes under the three assumptions: flat surface, Rayleigh loss, and "complete" surface reflection with scattered random part; target echoes were processed (coherent RC, then incoherent integration); in each case, we evaluated the DF degradation and the GR gain. A part of these computations is displayed by Figures 2 and 3, where GR and DF are displayed as functions of target range; each plot collects the GR or DF corresponding to all pulse shapes and durations.

Over the set of configurations which we investigated, the DF degradation seems very few sensitive on the characteristics of the signals (shape, length, bandwidth), whereas the GR gain features a bit more variability.

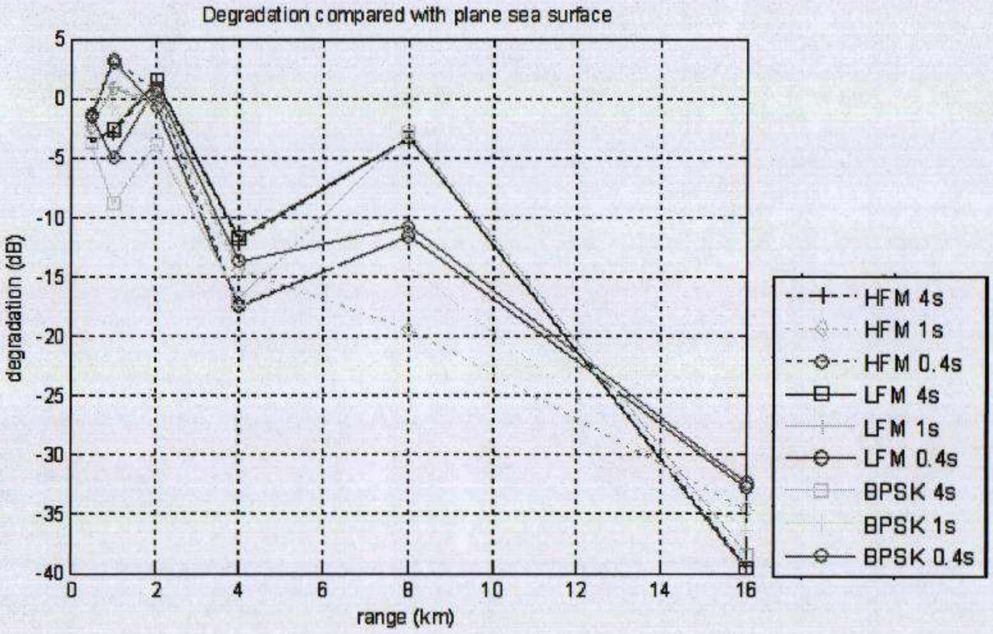
5 CONCLUSION

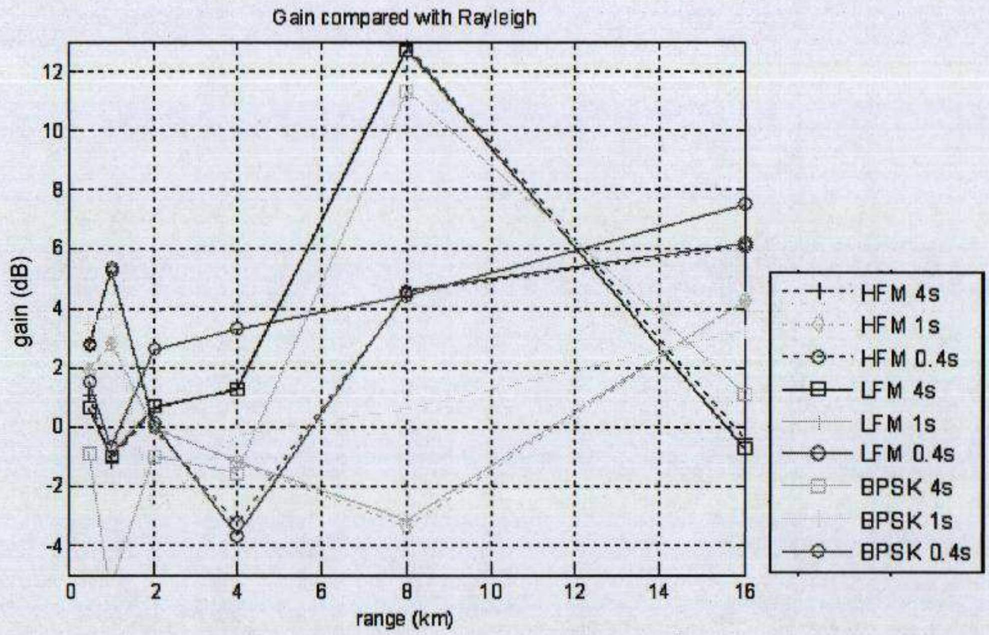
A model of sea surface reflection, including air bubble loss and random scattering by movement and roughness due to waves and swells, has been applied to the problem of active mid-frequency sonar performance assessment. We addressed the degradation of the output from coherent temporal processing when compared with flat surface assumption, and the gain when compared with output when considering only the coherent part of the surface reflected sound field. This degradation or this gain must be subtracted, or added, to the Propagation Loss term in the Sonar Equation, or to the Processing Gain term: separating these two terms appears as artificial. Later investigations should include effects of platform movements and sea bed roughness effects, which are already included in our model. A more critical issue to be analyzed is the problem of the Reverberation Level in the Sonar Equation: as an echo arising from "uninteresting" targets, the reverberation process involved the same propagation phenomena than the target echo itself, including the randomness of sea surface scattering.



Winter / Shallow sea (100.m) / Sea state 4 / 5.kHz, Bandwidth 1.kHz / Target length 40.ms / Integration time 40.ms

Figure 2. Degradation compared with Flat surface and the Gain compared with Rayleigh loss as functions of target range





Winter / Shallow sea (100.m) / Sea state 4 / 5.kHz, Bandwidth 500.Hz / Target length 10.ms / Integration time 10.ms

Figure 3. Degradation compared with Flat surface and the Gain compared with Rayleigh loss as functions of target range

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