SOME EXPERIMENTAL RESULTS FROM MAST-I SNECOW PROJECT

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1. INTRODUCTION

The target of the MAST-I SNECOW (Shipping Noise Evaluation in COastal Waters) project consists in a practical application of recent methodologies and scientific approaches for the estimation of the underwater acoustic noise component due to the shipping traffic in coastal waters.
The SNECOW project was initially conceived as a practical assessment of a theoretical rationale representing, mathematically, a time-space variant underwater acoustic communication channel, used in a low frequency range (~10 Hz - 1 KHz). In such a context, the project targets have been addressed mainly to the characterization of underwater acoustic noise, taking into special account the contributions due to shipping traffic, which has consistent low frequency components in its spectrum.
The analitical modelling of propagation in coastal sea water of low frequency perturbations presents a high grade of complexity due essentially to the operative scenario which is characterized by two essential conditions: *shallow waters* and *low frequencies*. The combination of both the conditions requires mandatory use of a complete solution of the propagation equations in order to estimate the field intensity distribution within selected oceanic zone.
In latest decades some theoretical considerations and experiments established that the noise radiated by any ship has practically frequency components from few Hz up to few KHz. The frequency components belonging to ranges lower than about 300 Hz have been remarked to have a strong non-gaussian statistical distribution. Since underwater acoustic waves propagate in sea water as better as frequencies are lower, then Low Frequency (LF) bounds are particularly interesting for communication purposes.
Consequently SNECOW can not be considered only a simple investigation about characterization of underwater noise, but it is one of the most relevant aspects of optimal detection problem in presence of additive non-gaussian noise in time-space variant channels.

2. PROJECT DESCRIPTION

The research deals with each part of the system regarding shipping noise, by taking into account and linking together different aspects, such as the *ship structural behaviour* (noise *single source*), the *radiation pattern* in the fluid surrounding the ship, the model of the radiated-noise *propagation through the medium*, the model of the *ship traffic distribution* in a given coastal water area (ship noise *multiple source*), the final *statistical characterization* and *recognition* of the resulting noise.
In the considered investigation the selected boundary conditions have to be taken into consideration as a critical parameter for studying several aspects of the problem (physical propagation and traffic spatial distribution). Under these working conditions, the influence of the sea bottom in coastal waters, further than of the surface, must be always taken into account (scattering phenomenon) and gets the problem more complex to be investigated and solved.
Since it is realistic to consider the sea as a time-space variant random filter, it is useful to present a mathematical block-diagram of the examined system from a communication point of view as shown in

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Figure 1. This figure presents some dashed-line blocks that are not included in the project tasks, since they do not concern the ship-radiated noise.

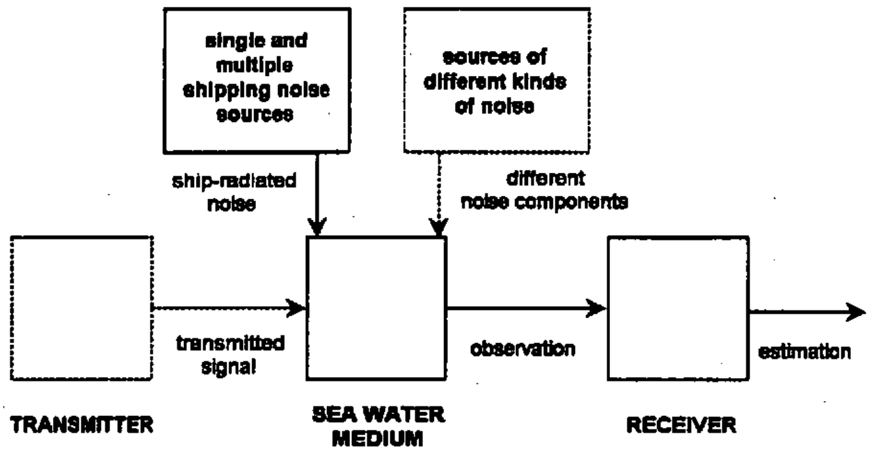

Figure 1 - Mathematical block diagram of an acoustic underwater communication channel, according to SNECOW project

According to the project proposal, the *selected objectives* have been divided in six different tasks, as shown in the blocks of Figure 2, where their reciprocal inter-dependence and overlapping are underlined.

The first phase of the work has been the study of the structural behaviour of a ship as radiating noise source in terms of frequency bands, and near/far field directivity patterns. This investigation has started from the real sources of the noise/vibration aboard ship (i.e. engines, mufflers, propellers, flexural waves, etc.) up to the radiating interface with the sea water (hull) and, successively, the expected directivity pattern in the water. The investigation has been carried out both for low frequencies [block (1)] and for high frequencies [block (2)].

The contribution to local noise around a single sensor area, produced by a single ship, has been considered, but does not represent a realistic situation. In detail, ship vibrational behaviour has been investigated at the *low frequency range*, focusing attention on the problems arising in the coupling with the fluid surrounding the hull of the ship and through which noise is radiated far from the ship itself. At *middle-high frequencies*, the ship structural noise behaviour is predicted by means of a deterministic model, based on the ship planning specifications, outlined during its project and building phases.

The contribution of shipping traffic to the locally received noise depends strongly from spatial distribution on the sea surface. This particular problem has been included in block (3) by means of model approaches supported by historical data bases from STC (Ship Traffic Control) activities. This investigation is an extension from a single to a multiple noise source.

The problems related to the underwater acoustic propagation have been approached with 3D models in order to investigate with updated tools the interdependence of acoustic propagation and communication systems. In block (4) the various aspects of the propagation problem, with the aim to verify theoretical predictions with experimental measurements, have been considered.

The model of the transmission channel is studied, with reference to:

- the chosen boundary conditions of coastal water environment (i.e. the topological constraints);
- the water physical parameters (salinity, pressure, sound velocity, density).

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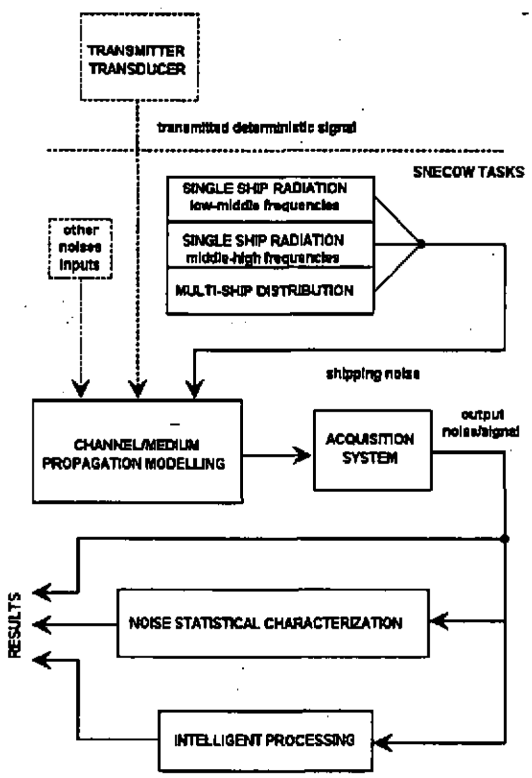

Figure 2 - The SNECOW tasks in the context of a mathematical block-diagram of an underwater communication channel

The model has been estimated in terms of input-data fluctuation sensitivity (hence, of robustness) and of accuracy. The noise signal radiated from ships and propagated through the sea medium has been acquired, stored and processed by the receiver block, in which it has been characterized and analysed as a stochastic process [block (5)]. After a preliminary investigation on the expected parametric and statistical properties of underwater natural and man-made noise, an investigation has been carried out on analytical representations of the distribution functions of non-gaussian processes, to be exploited for noise abatement as well as for communications optimization, i.e. phase relationship among different vibrating points, detection-estimation of non stationarities and non linearities in underwater acoustic noise generating processes.
The received noise signal has been estimated in order to recognize, among different components, the presence of a particular known ship, identified by its engine-emitted frequencies. As Intelligent Processing [block (6)] is intended a recognition of historical acoustic signatures of selected ships.

3. SNECOW PROJECT TASKS

According to specific expertise of each partner, project tasks have been assigned with reference to the selected project objectives, as shown in Figure 3. In the following, the *approaches* and *techniques* used to solve the different tasks are presented.

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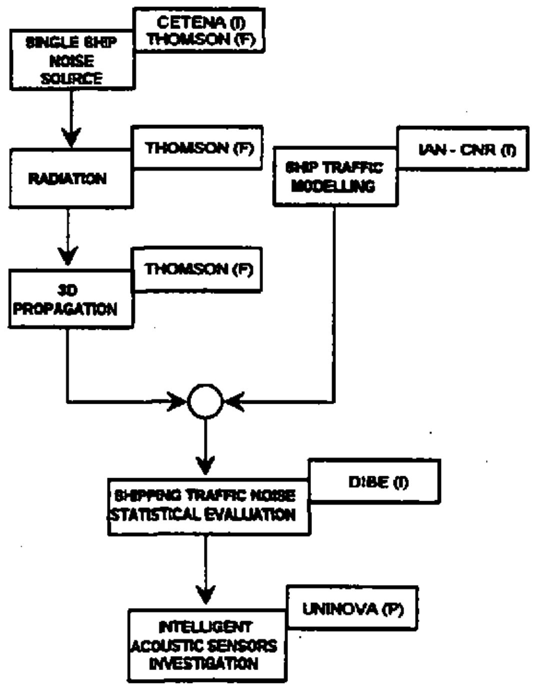

Figure 3 - Flow-chart of SNECOW tasks and partners' roles

In order to model the single ship as a noise source, CETENA developed a deterministic model of the ship structure in terms of panels, beams and plates. Structure-borne noise induced by the propeller, main and auxiliary engines, propagates to the superstructure in the shape of longitudinal, torsion and flexural waves.

There is no agreement in the scientific community about the *relative weight* to be attributed to each type of wave. Kihlman and Plunt [1] measurements seem to suggest an equal weight for longitudinal and transversal waves; Statistical Energy Analysis (SEA) computations (at middle and high frequencies) and related measurements [2][3] don't support this opinion: flexural waves are found dominant. Nilsson [4][5] modelled the ship using plates and compared two cases: the power flow from one deck to another is determined by: a) flexural waves, b) longitudinal waves. The propagation scheme a) was confirmed by measurements, while b) underestimated the velocity levels. On the basis of his experimental results, Nilsson carried out a propagation model for predicting vibration levels along the hull and on decks, under the assumption of the dominance of flexural waves.

In the context of SNECOW, modelling has been carried out on the basis of the Wave-Guide (WG) approach in order to predict the structural noise behaviour at the middle-high frequency range (from 200 Hz upwards), where Finite Element Method (FEM) computations are expensive and not always possible and the SEA can fail because of a poor modal density.

The WG approach provides a model developed on the basis of information about the noise sources on-board. A prediction process based on WG approach has to include:

- a pre-processing phase, both providing the description of the structure properties and showing the performed mesh;
- a technical algorithm for the estimation of the velocity levels on each element of the ship;
- a post-processing phase for displaying the obtained results.

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Investigations about the single-ship modelling have been developed also by THOMSON aiming at computing the three-dimensional directivity pattern and acoustic field radiated by surface ships. The output data have been then used as inputs for a 3D propagation model.
Having chosen the numerical approach (FEM and Helmholtz Integral Equations - HIE), every kind of ship could be modelled, whatever the complexity of its structure. Since this method implies to solve a linear matrix system with a frequency-dependent size, the investigations have been limited to low frequency range.
The ship structure has been defined as a thin shell with stiffners, respectively represented with thin shell and 3D beam finite elements. This structure has been excited by acoustic sources in the fluid medium and/or by mechanical forces or accelerations. Every kind of sources (engines, auxiliary machines, flow noise, propellers...) has been taken into consideration knowing their spectral characteristics.
In order to solve acoustic radiation problem the advantage of the HIE representation has been to avoid the volume description (mesh) of the classifier FEM. The fluid domain has been only described by its boundary, and only a surface mesh has been generated, thus strongly reducing the numerical problem.
Sources have been characterized by their location and by their radiated noise. The propagation modelling task has been carried out by THOMSON. In order to comply with the requirements of the project, the propagation model had to be able to predict major acoustic propagation effects due to the particular environment of interest, coastal water and also the type of sources: directive sources, low frequency continuous transmission.
Coastal water areas have been characterized by complex bottom topography and coastline and has been able to present also strong horizontal variations of the velocity profile. This means that the interesting propagation model had to be three dimensional in order to have the capability to predict horizontal deviations due to sloping bottom sound interaction and non uniform velocity profile and also reflection from strong bottom slopes.
Significant literature [6][7][8][9] has been devoted to propagation modelling, particularly for military applications, and various techniques exist: rays, modes, parabolic equation, "fast field", finite elements, hybrid, each one having its own domain of applicability. Computer models exploiting these various techniques have been implemented and reported in literature, but almost all of them are 2D models. Very few 3D models exist, in particular with required features, like extended sources, complex and smooth bottom variations; furthermore they are not commercially available. This is why it has been decided to develop a new model based on coupled mode theory which seems to be a good candidate given the previously mentioned requirements for modelling.
In going from 2D to 3D, horizontal deviations have been introduced: if we consider modes propagating in a single horizontal direction in a stratified section, continuity of the pressure field at transition between two sections which occurs at any angle between the horizontal wave vector and the horizontal local trace of the step wise transition implies that various transmitted and reflected modes undergo horizontal deviations with respect to the incident wave vector. These deviations have been introduced through the elements of the 3D coupling matrices which have to be computed at each encounter with a step variation of the medium. In this way it has been possible to follow the path of a mode with a specified horizontal wave number in it encounters with various transitions. The complete 3D field has been obtained by adding the contributions of narrow horizontal beams emitted from the source and sweeping all the horizon.
In the study, emphasis has been put on the bottom topography effects and not on the effects of the bottom constitutions. Therefore, the bottom has been described in a simple way by a homogenous sediment layer with no shear waves, overlying a rigid bottom, loss mechanism: volume attenuation in the water column and in the sediment layer, surface and bottom reflection losses due to the scattering

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have been introduced by a perturbation method resulting in an additional imaginary part on the modes wave numbers.

In the context of investigation about shipping traffic, IAN has developed the following sub-tasks:

- ship traffic modelling
- ship traffic identification
- interface between traffic model and noise propagation.

The aim of modelling has been to develop a mathematical representation of those significant aspects of shipping traffic which can be usefully exploited in order to achieve a realistic evaluation of shipping traffic noise. The determination of shipping traffic mathematical models has been based on the following requirements:

- the models should have been expressed in terms of intuitive traffic concepts and might be easily obtained from existing data, such as navigational data-bases or traffic flows historical data;
- the models should have been of a dynamic type, i.e. described by a sufficient number of state variables capable of representing in a quantitative manner the time-dependent evolution of the traffic process inside a given sea basin;
- it should have been possible to evaluate the predictability power of such models by comparing their predictions with real data observations;
- it should have been easy to develop an interface between the distribution models and the acoustic noise propagation models, in order to supply acceptable predictions of ship traffic noise.

Two different and, in some sense, complementary models capable of satisfying the above requirements have been considered. The first one, called STARMA (Spatial Time Auto Regressive Moving Average) is a "black box" statistical model, which does not assume any a-priori knowledge about shipping traffic. It expresses the salient traffic properties by means of a space-time multivariable linearly correlated statistical model. Such model can be of some utility in the description of highly irregular and chaotic traffic situations.
The second model, on the contrary, may be preferable for describing traffic situations where regular fluxes occur. It is a deterministic linear state space model, which is easily derived from flow conservation considerations.
Under quite general assumptions, it has been shown that such a model can be decomposed in such a way that a remarkable reduction in terms of the number of model parameters can be achieved. This feature is very important from the point of view of computational efficiency of the traffic model.
The proposed traffic models have been tested by means of an identification procedure, which has the objective of validating such models by using simulated as well as real traffic data. This identification task has concerned three different coastal waters situations in Mediterranean sea, i.e.:

- Liguria and North-Tirreno sea;
- Straits of Otranto in Adriatic sea;
- Messina Strait.

The design of a suitable interface between shipping traffic and acoustic propagation model has been carried out in co-operation with THOMSON.

The noise first radiated by the background shipping traffic and by the eventually present target ship, then propagated through the medium and finally received by a set of acoustical sensors (hydrophones) is mainly due to the combination of sources such as propulsion and rotating machinery on board,

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structural and mechanical vibrations, fluid-dynamic phenomena. DIBE task in the context of the SNECOW project has been the statistical characterization of shipping noise.
Since the ship radiated noise in the frequency range from few Hz up to 400/500 Hz is expected to have line shape, its statistical characterization is expected to have a non-gaussian behaviour. Consequently, in order to optimize real communication receiving systems, the hypothesis of gaussian noise added to signal during propagation is not more valid. Middleton [10][11] directed his studies to analyse links among different types of interference and to detect characteristic parameters for particular classes of them. He classified interferences into three different classes, according to a comparison between the examined noise and the receiver bands.
Having a complete statistical characterization of complex processes, as ship-radiated noise is, implies the necessity of investigation of techniques based not only on the conventional spectrum analysis (very useful, for instance, to extract information on bandwidth and weak stationarity) but also on non-conventional methods (in order to detect and characterize the presence of non-gaussian sample distribution of data and some non-linear phenomena within the received noise stochastic process in exam).
The conventional characterization procedures developed by DIBE have been based on Power Spectral (PS) analysis, suitable for treating linear and gaussian signals and processes.
The non-conventional investigation has been accomplished through two approaches. In order to provide noise characterization about the presence of non-gaussianity and of non-linear phenomena, the selected non-conventional class of signal-processing techniques have been based on the Higher Order Statistics (HOS) analysis and, in particular, on the properties of the third order Spectrum, called Bispectrum [12][13]. This mathematical operator is particularly suited to detect and analytically express non-gaussian behaviour of a process and to find out the presence of non-linearity by providing the kind and the order of some non-linear physical events recorded within the data. The second line of non-conventional analysis has consisted in the parametric approach of Gabor expansion [14]: it provides a natural framework for processing a Middleton class B of transient signals and is based on the computation of a matrix of coefficients used in this kind of signal representation. This class of developed analysis procedures have been tested with real/historical signal data.
Although the heavy computational load of both non-conventional methods, theoretical investigations and test results have confirmed the wide extendibility of Middleton approach to non-Gaussian interference.

Acoustic ship-radiated noise propagated through the medium and acquired by the receiver transducer has finally to be processed and interpret in order to recognize particular acoustic situations on the basis of a-priori knowledge about transmitting sources. The problem of making decision about and recognising different kinds of underwater noise and different ship acoustic signatures on the basis of their characteristic acoustic features is complex to solve.
For this reason artificial intelligence (AI) techniques have been investigated by UNINOVA. The investigation about the most suitable AI methods for ship recognition led to the selection of the Decision Tree approach [15]. The particular field of study made researchers focus their attention also on other recognition classes of techniques during the project. The conclusion of a comparison among different kinds of approaches led to the choice of Neural Networks (NNs) [16] for ship recognition purposes. Performance and robustness tests have been performed on real data, recording both different kinds of ship noise and noise samples of other nature.
A special emphasis has been put on the speed of the application and on the implementation to run in real-time using a low cost hardware.

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Well trained sonar operators are capable of easily identifying the kind of noise source presented even under bad signal conditions. Theoretically, an automatic classifier should be able to perform this repetitive job with at least an equivalent result using the sonar signals. Like the human operator it should be trained with real sound examples, in order to get the knowledge required to achieve this goal. Thus, the classification procedure is basically a feature vector evaluation. The goal is to determine the class associated with each feature vector. Design of classifiers based on a training set of feature vectors, whose classes are known, is an usual technique aimed to build up a decision system.
The first problem to handle in the automatic classifier design has been the pre-processing phase. Well suited pre-processing emphasizes relevant signal characteristics, while reducing redundancy of information. In the selected approach the signal analysis has been transposed to the frequency domain in order to more easily analyse its tone characteristics.
Therefore a Fast Fourier Transform has been first applied in order to get the signal's spectral information. These data have been then used as input to the classifier. Two different approaches have been investigated in the course of this task, namely one based on decision trees and another based on neural networks.
As a result of performance comparisons between these two techniques, neural networks have been chosen to produce the real-time classifier.

4. EXPERIMENTAL SEA-TRIAL

The experimental phase of SNECOW was carried out to collect real data to be used, in accordance with the project specifications about the evaluation of shipping traffic noise.
The experimental phase took place in two different periods with the support of the oceanographic ship Urania. A first preparatory phase was carried out in the period 25 / 29 March '93 in the coastal waters in front of Marina di Campo (Elba Island, Italy). Its main purposes have been:

- preliminary recording test of noise radiated by the oceanographic ship Urania (known reference noise);
- studying the feasibility to use the ship tender like acquisition base;
- testing the performances of integration between sensors and acquisition/recording system.

The second sea trial was carried out during the period 17 / 25 May 1993. The main purposes of this cruise have been:

- recording background shipping traffic acoustic noise both in coastal and in open sea;
- recording acoustic underwater noise deriving from a target ship (the useful signal);
- recording data of shipping noise in various coastal deep/shallow water configurations;
- measuring the main physical parameters characterising the propagation medium;
- recording data to validate the developed model of target ship;
- collecting target ship characteristic parameters during acquisition operations.

In order to develop ad-hoc models of single/multiple source and propagation medium, a *target ship* and a *sea area* were selected and a-priori information collected and used as modelling inputs.
For this reason, among a variety of ship types, a ferry-boat was selected (Fincantieri construction number 7727, named Laurana). Aboard Laurana, CETENA the following measurements have been carried out:

- vibration measurement about main engine, auxiliaries and reduction gear in order to provide the identification of the main frequencies generated on board and radiated into water;

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- measurement of the loss factor of ship panels in order to have an experimental estimation of one of the model parameters;
- measurements of the vibration levels of ship panels in order to have a full-scale validation of the wave-guide approach.

During the sea trial, a large amount of data have been acquired and on-line validated, then stored, reduced and processed in order to be used by each partner after the sea campaign, according to their respective tasks.

5. CONCLUSION

Experimental sea trial particularly emphasized the strong co-operation among the partners during the acquisition operations and during the scientific interpretation activities, thus allowing the Consortium to produce corroborating results and achieving common targets.
The experimental results obtained in the final phase of the project confirm that the SNECOW sea trial has been a useful and very interesting mean to test on the field and practically apply the concepts and software tools developed in the investigation part of the project.
Each partner has verified the consistency of the theoretical pre-requisites of the project in close contact with the other consortium members. Therefore, SNECOW researchers have successfully passed from the virtual reality of a well defined theoretical framework (affected only by analytical/conceptual uncertainties) to the true-world reality of the experimental execution of the same concepts, with practical limitations and a large variety of systematic and random errors. This "passage" has necessarily introduced a number of constraints due to the choice of the various components of the intentional mathematical block diagram of Figure 2 (i.e. the ships, the selected sea area, the receiving and acquisition systems, etc). Consequently the theoretical expected results have partially assumed different parametric formats.
In spite of those unavoidable theoretical-experimental adjustments (very common in research activities), the different tasks have been completed and the final targets of the project can be considered accomplished, since the comparison of the proposed project purposes with the obtained results makes clear the consistency and coherence between the two parts.

6. REFERENCES

[1] Kihlman T. et al., "Structureborne Sound in Ships, a Study of Different Wave Types" (1974), Proceedings of the 8th International Congress on Acoustics '74.

[2] Jensen J.O., "Calculation of Structure-borne noise Transmission in Ships Using the Statistical Energy Analysis Approach" (1976), Proceedings of the International Symposium on Shipboard Acoustics.

[3] Gibbs B.M. et al., "The Use of Power Flow Methods for the Assessment of Sound Transmission in Building Structures" (1976), Journal of Sound and Vibration 49, p. 267.

[4] Nilsson A.C., "Propeller Induced Hull Plate Vibrations" (1980), Journal of Sound and Vibration 69(4), p. 539.

[5] Nilsson A.C., "A Method for The Prediction of Noise and Velocity Levels in Ship Constructions" (1984), Journal of Sound and Vibration 94(3), p. 411.

SNECOW PROJECT

[6] Etter P.C., *Underwater acoustic modelling - Principles, techniques and applications* (1991), Elsevier, Applied Science.

[7] Buckingam M.J. "Ocean-acoustic propagation models" (1992), J. acoustique, pp. 223-287.

[8] Harrison C.H., "Ocean propagation models" (1989), Applied Acoustics (27), pp. 163-201.

[9] Jensen F.B. and Schmidt H., "Review of numerical models in underwater acoustics, including recently developed fast field program" (1984), SACLANT report SR83.

[10] Middleton D., "Canonical non Gaussian noise models: their implications for measurement for prediction of receiver performance" (1979), IEEE Trans. on Electromagnetic Compatibility, Vol. EMC-21, No. 3, pp. 76-106

[11] Middleton D., "Procedure for determining the parameters of the first order canonical models of class A and B electromagnetic interference" (1979), IEEE Trans. on Electromagnetic compatibility, Vol. EMC-21, No. 3, pp. 190-208

[12] Brillinger D.R., "An introduction to polyspectra" (1965), Ann. Math. Statist., Vol. 36, pp. 1351-1374

[13] Niklas C.L., Mendel J.M., "Signal Processing with Higher-Order Spectra" (1993), IEEE Signal Processing Magazine, pp. 10-37

[14] Gabor D., "Theory of communication" (1946), J. IEE (London), Vol. 93, No. 3, pp. 429-457

[15] Fonseca J., Moura Pires F., "Ship noise evaluation based on segmanted decision tree" (1992). Presented to IROS'92 in Raleigh, NC (USA).

[16] Zell A., Mache N., Hübner R., Schmalz M., Sommer T., Mamier G., Vogt M., "Stuttgart Neural Network Simulator - User Manual, Version 2.1" (1992), Report No.8/92.

7. ACKNOWLEDGEMENTS

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