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A CLASSIFICATION TECHNIQUE COMBINING ASPECT DEPENDENCE AND ELASTIC PROPERTIES OF TARGET SCATTERING

B. Zerr, A. Tesei, A. Maguer, W.L.J. Fox, J.A. Fawcett

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Jan L. Spoelstra
Director

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A CLASSIFICATION TECHNIQUE COMBINING ASPECT DEPENDENCE AND ELASTIC PROPERTIES OF TARGET SCATTERING (¹)

B. Zerr, A. Tesei, A. Maguer,
W.L.J. Fox and J.A. Fawcett

Executive Summary: The first objective of SACLANTCEN research on the classification of sea mines is to improve the classification performance in areas where mine hunting operations are currently conducted. A second and more ambitious objective is to extend the mine hunting capability to more complex sea-beds, with high clutter density or with high probability of mine burial. The new classification techniques use *multiple aspect* and *multiple frequency bands.*

The acquisition of multiple target aspects assumes that the sensors are mounted on small maneuverable autonomous underwater vehicles. Most of the current generation of mine hunting sonar systems contain detection and classification sonars which operate at different frequencies and interact differently with the target and its environment. Fusing the information acquired by the detection (lower frequency) and classification (higher frequency) sonars may increase classification performance. However, to gather more information on the target echo, the lower frequency band must extend down to frequencies at which the elastic properties of target backscattering can be observed (2-20 kHz typically for mine size objects).

Extensive studies have been conducted at SACLANTCEN in the past few years to assess the potential of low frequency (Project 031-2) and multiple aspects (Project 031-3) for the classification of sea mines. This report combines results from these studies in a classification methodology that exploits the aspect dependence and the elastic properties of low frequency target backscattering. The classification process consists of successive phases. First, objects of potential interest are selected according to their external shapes and dimensions, reconstructed from the aspects collected during a complete or partial circumnavigation. The second step, which only applies to the selected objects, consists of a detailed analysis of the elastic scattering for particular aspects (e.g., broadside) and provides information on the internal properties of the object. This technique not only allows discrimination between man made and natural objects, but also between objects of similar external shape which have different internal properties. This point is of particular interest when mine hunting operations are conducted in areas with high density of mine-like objects (natural

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[1] The content of this report formed the basis of a presentation at ECUA-98, Roma 20-24 September, 1998.

or man made). The potential of the classification methodology is demonstrated on cylindrical targets, measured in free field.

The promising results obtained by combining multiple aspects and resonance scattering analysis on free field data, encourage us to address more complicated situations, with realistic targets on the seabed and with different degrees of burial.

A CLASSIFICATION TECHNIQUE COMBINING ASPECT DEPENDENCE AND ELASTIC PROPERTIES OF TARGET SCATTERING

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Abstract:

Discrimination between man-made and natural underwater objects and between man-made objects of different characteristics are the key objectives of target classification. The current approach is mainly based on the analysis of the target signature imaged by high resolution (typically < 20 cm) high frequency (typically > 100 kHz) sonars. To estimate the potential of alternative classification schemes based on more detailed acquisition of target echo features, SACLANTCEN has investigated low frequency (10 kHz) sonar systems with high fractional (or relative) bandwidth (2-20 kHz).

The classification method relies on two features of the target echo: aspect dependence and elastic scattering. The two dimensional reflection map, reconstructed from multiple aspects, serves as the basis for pre-classification. For objects of external shape recognized as man-made at the pre-classification stage, resonance information is extracted by autoregressive spectral estimation techniques and further processed for particular aspects (e.g. broadside). The analysis of the resonance scattering provides an estimate of some geometrical and physical target parameters (i.e. shell wall thickness and material, and inner fluid properties) and can be improved by introducing the object dimensions, estimated from the reflection map. This report, which describes the classification methodology and the results obtained with steel cylinders, demonstrates the potential of the method.

Keywords: Sea Mine Classification ∘ Automatic Target Classification ∘ Resonance Scattering Analysis ∘ Computerized Tomography

Contents

1

Introduction

Discrimination between man-made and natural underwater objects and between man-made objects of different characteristics are the key objectives of target classification. Typical applications of target classification are harbour inspection, waste disposal and mine countermeasures. For relatively small objects the acoustic signature is acquired by high resolution (typically < 20 cm) high frequency (typically > 100 kHz) sonars. The combined analysis of the echo structure and the acoustic shadow allows discrimination between man made objects and the natural background. At such high frequencies, the predominant effect in the echo structure is the specular reflection from the outer shape of the object. As the acoustic shadow already gives information on the object shape, the introduction of the high frequency echo in the classification process yields limited performance improvement.

In order to improve and increase the information derived from the object echo, the aspect dependence of target backscattering at lower frequencies (2-20 kHz) has been investigated. In this frequency band, sound waves penetrate the target and the backscattered waves carry information relating to the external shape and the internal properties (material and structure) of the object. The target backscattering is composed of a *rigid component* which includes specular reflection and diffraction from discontinuities, and a *resonant component* encompassing periodic returns from surface waves revolving around the target and from multiple internal bounces. The retrieval of the target geometrical and physical properties from its temporal acoustic signature* is called *resonance scattering analysis.*

When the position of the sonar changes with respect to the target, variations are observed in the temporal acoustic response. This property, called *aspect dependence*, is combined with resonance scattering analysis to define a new classification methodology. Only the aspect dependence in azimuth is considered here, assuming a constant elevation (grazing) angle. The azimuthal variation of the temporal acoustic signature could, for example, be acquired by an autonomous underwater vehicle (AUV) circumnavigating the target at constant depth. The sonar resolution in azimuth is kept coarse enough to ensure, for each ping, complete illumination of the target.

The classification process consists of successive phases (Fig. 1). First, objects of

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*In the context of this report, the terminology 'temporal acoustic signature' means that the response of the target is contained in a single time sequence.

potential interest are selected according to their external shapes and dimensions, reconstructed from the aspects collected during a complete or partial circumnavigation (upper part of Fig. 1). The second phase (lower part of Fig. 1), which applies only to the objects selected, consists of a detailed analysis of the elastic scattering for particular aspects (e.g., broadside or BS-aspect) to provide information on the internal properties of the object.

The two dimensional (2-D) spatial reflection map of the target is reconstructed *via* tomography [1, 2] from the sequence of azimuth-dependent temporal responses (upper part of Fig. 1). The spatial resolution in both directions, resulting from the tomographic reconstruction, is proportional to the inverse bandwidth of the transmitted signal. The analysis of the 2-D reflection map gives a first estimate of the outer shape and the dimensions of the object being investigated. These estimated parameters allows the selection of interesting objects for further processing (mine-like objects in our case).

A more accurate estimation of object characteristics such as the inner material and the shell properties, is derived from analysis of the resonance scattering (lower part of Fig. 1). In the analysis, the inversion of the target's physical properties is made more robust by introducing the dimensions and the shape estimated from the reflection map. In the context of this report, the analysis of the resonance scattering is performed only for specific aspects (e.g., at broadside) determined from the analysis of the reflection map.

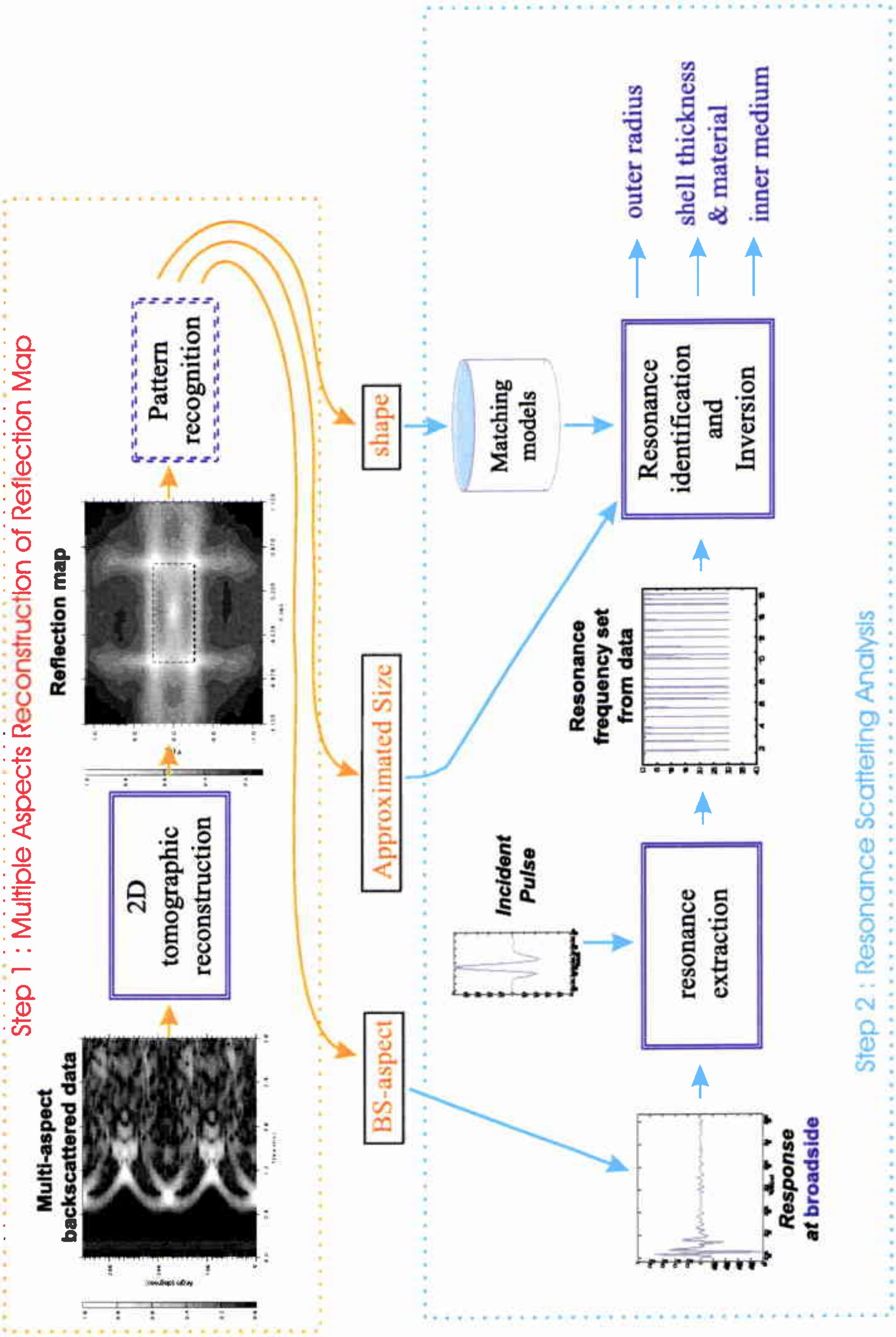

Figure 1 *Overview of the classification methodology.*

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Step 1: Multiple Aspect Reconstruction of Reflection Map

The aspect dependence of the echo can be acquired by a sonar mounted on a maneuverable platform circumnavigating the target† at a constant water depth. This motion corresponds to a 360° variation of the azimuth angle at a constant grazing angle. If the grazing angle is sufficiently low, the approximation can be made that the trajectory of the sonar and the center of mass of the object are coplanar and thus, simplified 2-D reconstruction methods can be employed. For each acquisition, (i.e. each aspect angle) the signal returned can be considered as a projection on the range axis of the sound backscattered by the object.

The reflection map of the object defines the amplitude of the backscattered signal as a function of the two Cartesian coordinates (x,y), which define the horizontal plane passing through the object's center. The reflection map of the object is reconstructed by "back-projecting" the range *vs* aspect backscattering in the two-dimensional horizontal plane defined by (x,y) spatial coordinates. This operation is called reflection tomography [1, 2, 3]. The concept of a target reflection map has been defined previously for a 3-D reconstruction method fusing shadows and echoes from multiple aspects [4].

The potential of reflection tomography is demonstrated on simplified 2-D models. The objects are represented in 2-D by the intersection of their 3-D volume with a horizontal plane passing through their centre of gravity (see Fig. 2). To compare the behaviour of man-made and natural objects, two cases were considered: a solid cylinder (1m, ϕ 0.50m), and a simulated rock of similar dimensions. The rock was generated using a 3-D fractal algorithm based on "mid-point displacement" method [5]. The first 4 iterations to create a fractal rock are shown in Fig. 3.

The acoustic responses of these objects (more precisely, of a horizontal section of these objects) has been modelled using the time domain finite difference (TDFD) code [6]. The choice of TDFD is motivated by the capability to model arbitrary shapes with complicated elastic scattering. When the temporal and spatial sampling is fine enough, TDFD modelling yields accurate results [7]. The TDFD is computed on a rectangular domain of 4x3 m with a spatial sampling of 1 cm and time steps

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† The concept of multiple cooperating AUV's offers a potential solution to the acquisition of the aspect dependence of the object echo.

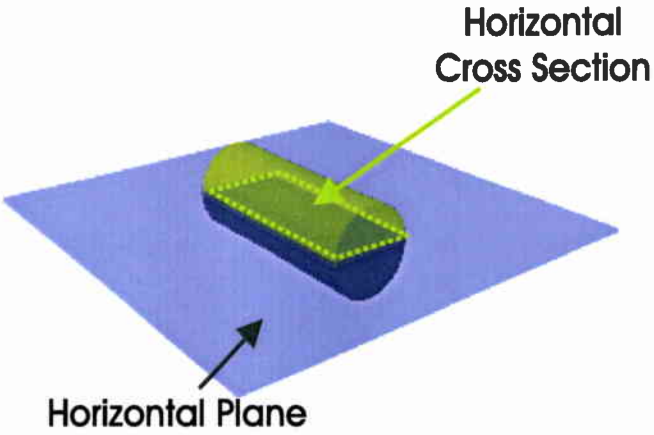

Figure 2 *Horizontal cross-section of the object used for 2-D TDFD.*

of 0.5 μs. The broadband incident wave from a distant source is pre-computed and introduced in the TDFD grid. The temporal shape of the pulse corresponds to the second derivative of a Gaussian[‡] and the centre frequency is 5 kHz. For each aspect, the 2-D horizontal section is rotated by the corresponding angle and introduced into the TDFD grid. The modelled backscattered wave is recorded at 1.5 m from the object centre in the direction of the transmitter. Figure 4 shows the interaction of the incident wave with the 2-D cross-section of the cylinder. The time evolution is monitored by intermittent recording of the acoustic pressure in the TDFD grid (Fig. 4).

Figure 5 shows the amplitude of the back-scattered pressure (or the envelope of the back-scattered signal) from the cylinder for aspect angles varying from 0° to 360° with a sampling of 5°. Broadside aspects are observed at 90° and 270° and end-fire aspects at 0° and 180°. Figure 6 shows the reconstructed reflection map of the target. Figures 7 and 8 show the aspect-dependent backscattering and the reconstructed reflection map of the rock. The black lines in Figs. 6 and 8 correspond to the contour of the 2-D horizontal cross-sections used in the simulation. Though the aspect dependence of the backscattering (Figs. 5 and 7) already exhibits major differences in the responses of the two objects, the reflection maps (Figs. 6 and 8) give a more immediate understanding of the object geometry.

The selection of objects of interest for further analysis can be achieved by applying pattern recognition algorithms to their reflection maps. This processing also allows the selection of aspects suitable for resonance scattering analysis and the estimation

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[‡] This pulse is usually called a Ricker pulse.

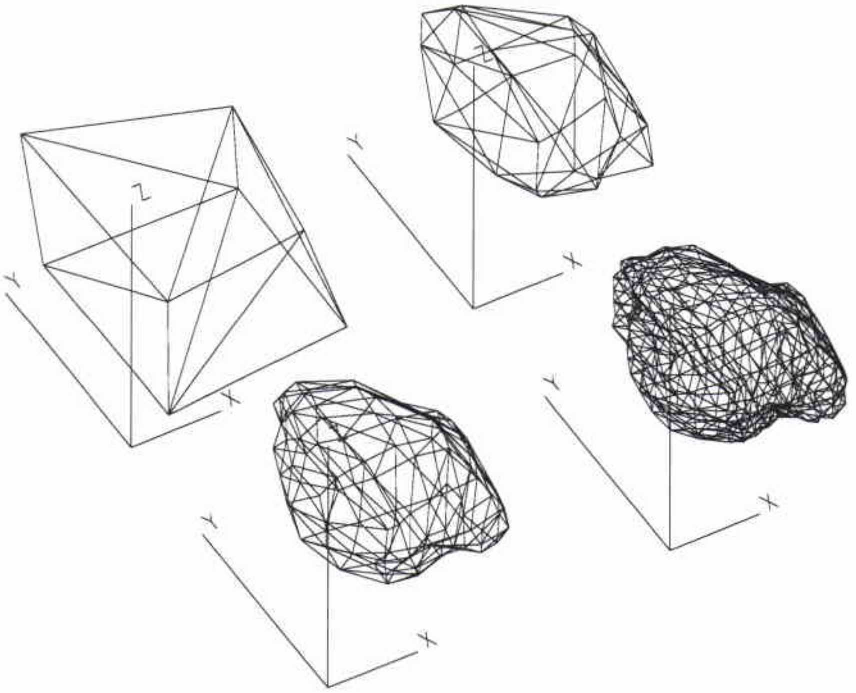

Figure 3 *Creation of a simulated rock by a fractal process using a 3-D implementation of the "mid point displacement" algorithm.*

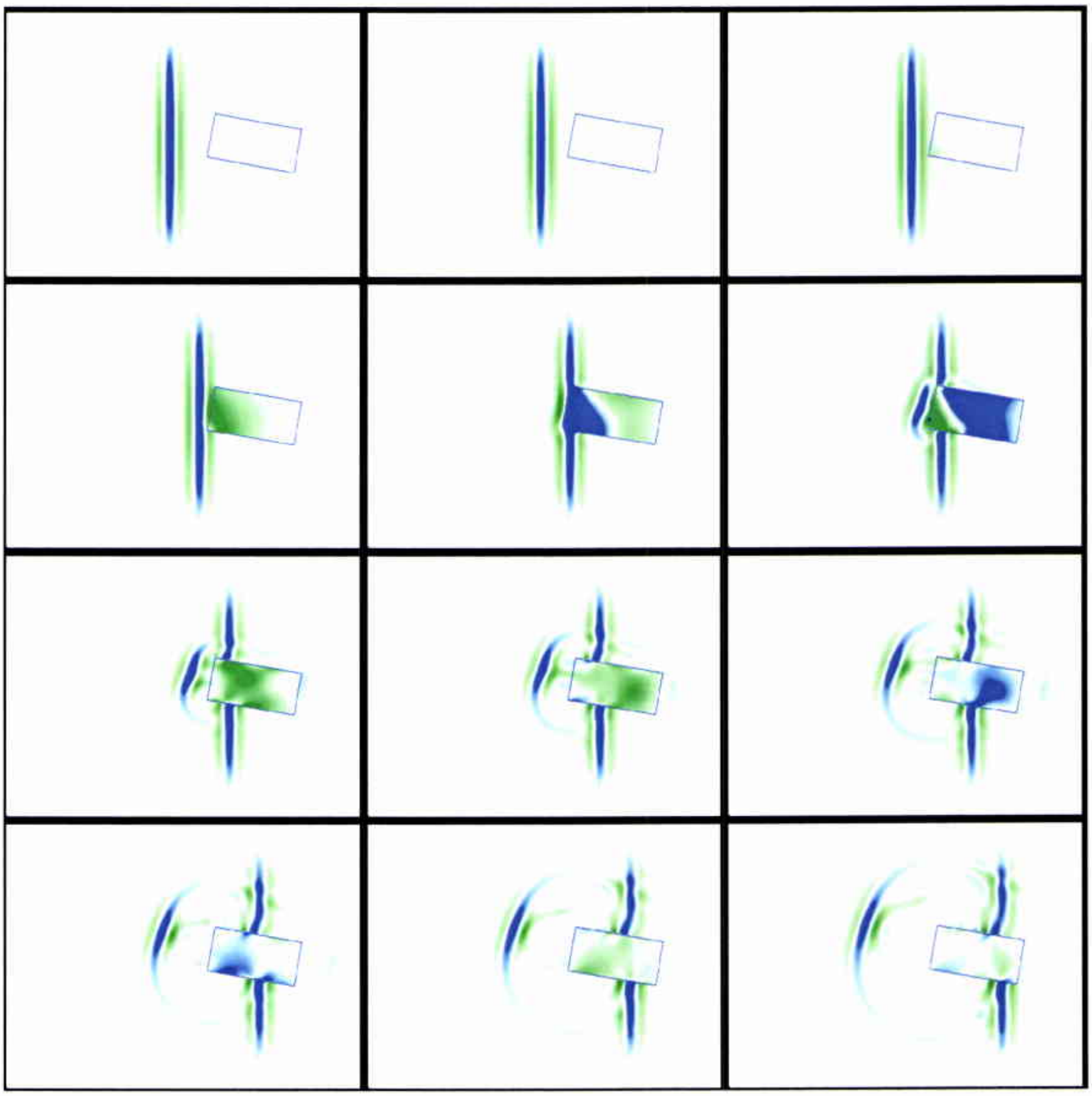

Figure 4 *The time interval between two consecutive images of the frame is 75 μs. The positive sound pressure is coded in levels of blue and the negative pressure in levels of green.*

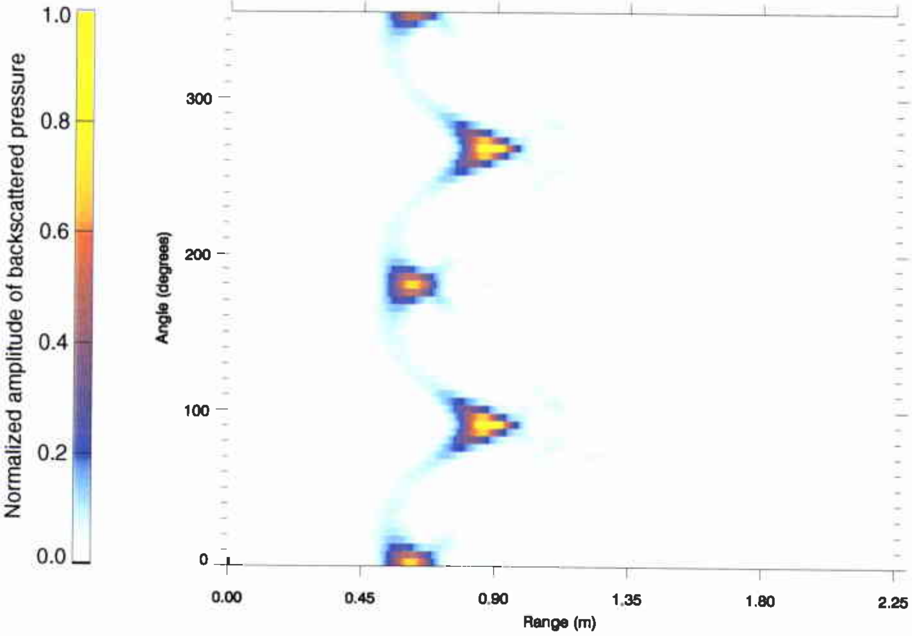

Figure 5 *Cylinder (horizontal cross-section): amplitude (envelope) of the backscattered pressure.*

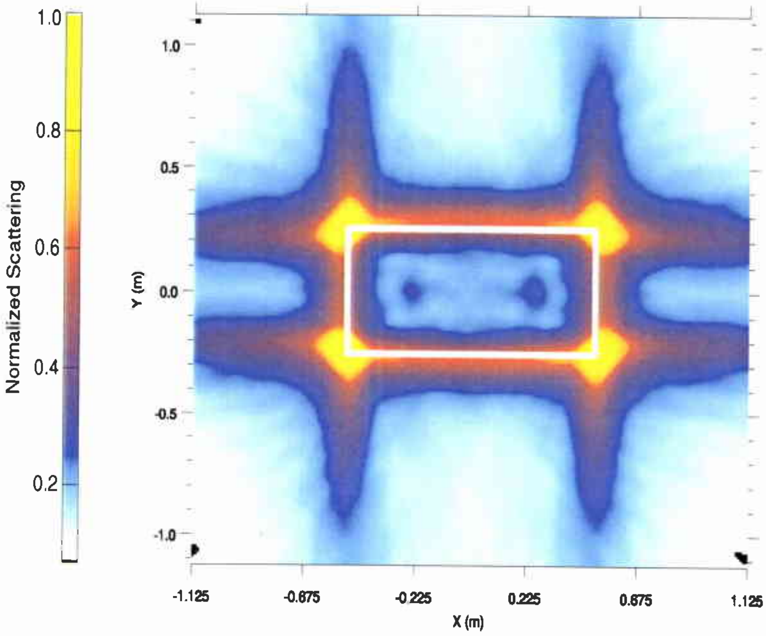

Figure 6 *Cylinder (horizontal cross-section): reconstructed reflection map.*

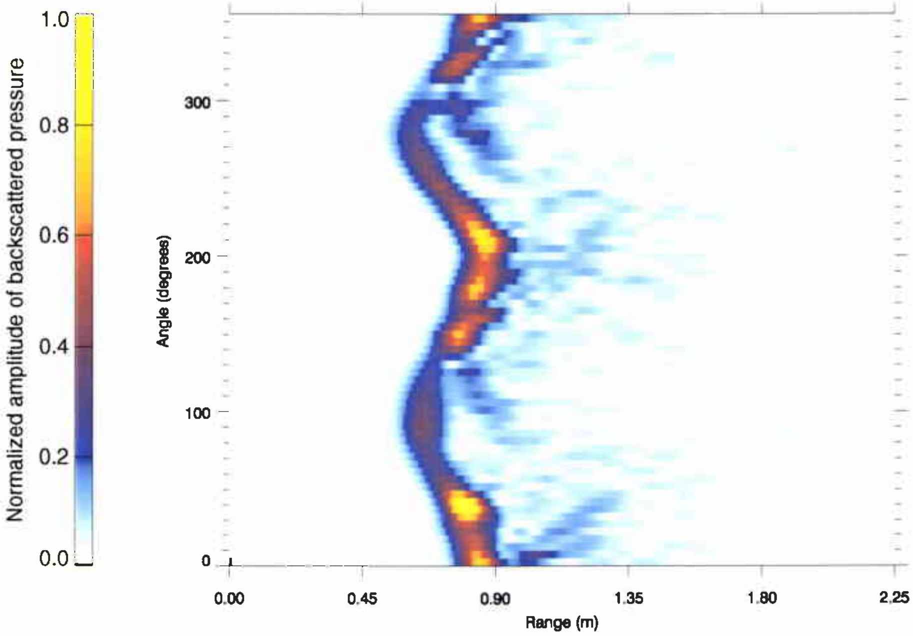

Figure 7 *Fractal rock (horizontal cross-section): amplitude (envelope) of the backscattered pressure.*

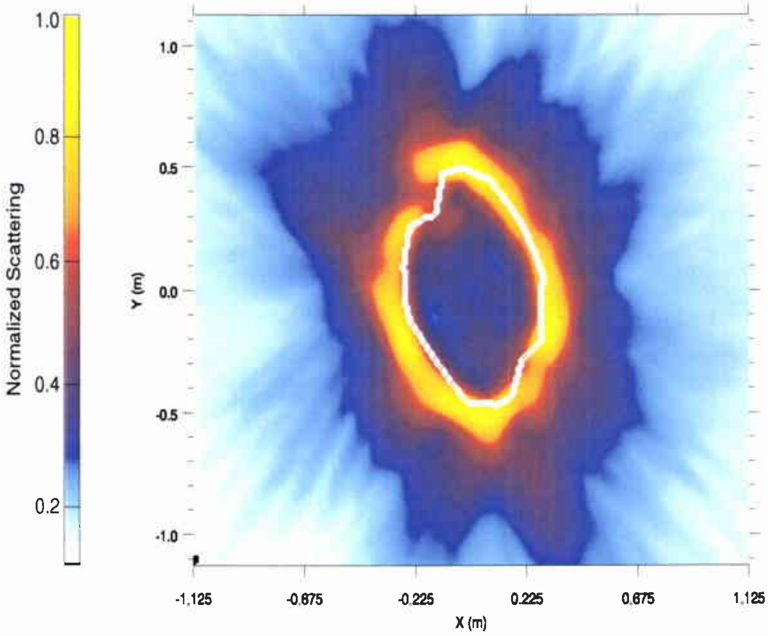

Figure 8 *Fractal rock (horizontal cross-section): reconstructed reflection map.*

of the dimensions. The dimensions, estimated with an accuracy on the order of the range resolution, are introduced in the subsequent resonance scattering analysis. The objective is to reduce the space of solutions for the inversion process of retrieving the physical properties of the object (e.g., shell wall thickness and material, filling material, etc.).

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Step 2: Resonance Scattering Analysis

Resonance scattering encompasses different types of periodic phenomena which contribute significantly to the target echo at low-intermediate frequency ranges in the case of an elastic target having a shape with particular symmetries (e.g., with a circular cross-section).

For an object the reconstructed shape of which is similar to a man-made target shape, one can assume the target as elastic and apply resonance scattering analysis in order to further characterize it in terms of physical and geometrical properties. Indeed, the acoustic response of an elastic target is characterized by a resonance component, which in the time domain consists of a series of echoes following the specular echo and in the frequency domain corresponds to resonance frequency modes, which appear as a combination of dips and peaks. Resonance scattering theory concerns the study of the relation between these resonance frequencies and a set of backscattered periodic waves revolving around the target itself [8]. The term "resonance" is used in the broadest sense to mean that every acoustic wave backscattered periodically is assumed to give rise to resonance. Multiple internal bounces, generated if sound can penetrate and propagate inside the object, are included in this definition.

The study was limited to fluid-filled, thin-walled [§] shells with circular cross-section insonified at broadside incidence. Figure 9 provides the simplified scheme of travel paths of classes of surface wave families which revolve around the target cross-section (left) and of multiple internal reflections (right). The surface waves are grouped into: (1) families of shell-borne waves which can be generated by any empty or fluid-filled shell, (2) families of outer-fluid-borne waves, some of which are generated only by liquid-filled thin-walled shells and (3) families of inner-fluid-borne waves which are characteristic of liquid-filled shells (some types exist only if shells are thin-walled). In Fig. 9, when a wave type is generated also by empty/air-filled shells then the shell is white inside, otherwise it is light gray. Under liquid-filled, thin-walled conditions, a significant part of the incident sound is assumed to be transmitted into the inner liquid, then reflected several times by the inner shell walls before being partially backscattered [9]. This transmitted component can generate periodic backscattered waves following either the direct path or inscripted polygonal paths of even order (Fig. 9, right).

[§] A shell is considered to be thin-walled if its relative thickness, h, defined as the ratio between its wall thickness d and its outer radius a, is in the range (0, 0.03).

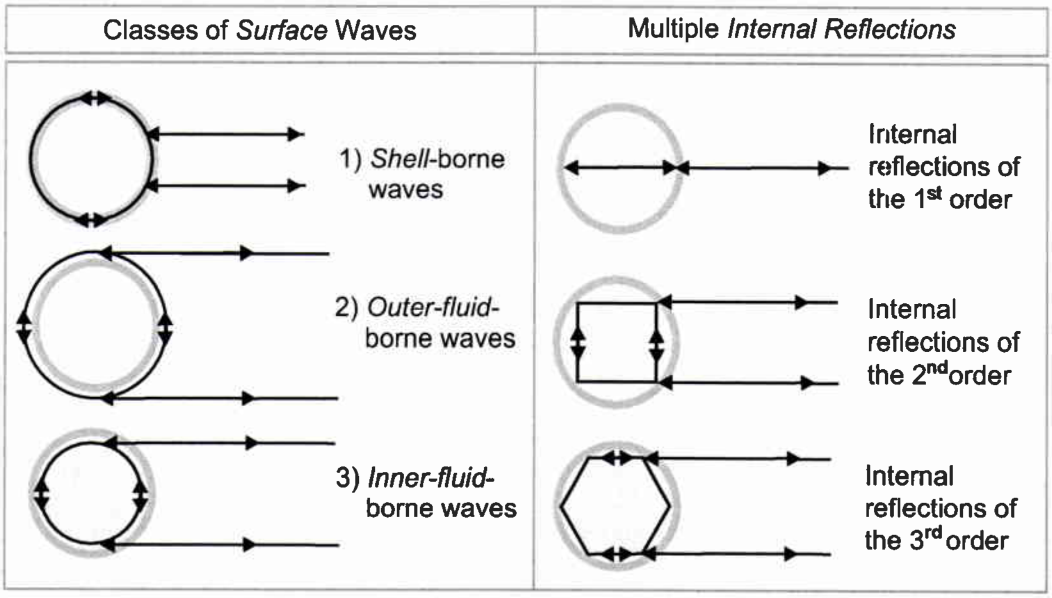

Figure 9 *Main classes of periodic waves contributing to resonance scattering for a thin-walled shell of circular cross-section.*

The physical scattering interpretation of the periodic wave types [8, 10, 11] allows us to formulate equations in terms of selected resonance characteristics *versus* target elastic properties, e.g., the shell outer and inner radii (a and b respectively), the shell material membrane speed (c^*) and the inner fluid sound speed (c_{in}). These matching models are used by an automatic multi-hypothesis estimation method of resonance analysis. The analytical models and automatic feature extraction/identification and parameter estimation are described in [11].

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Complete Two-Phase Classification Procedure

The tomographic reconstruction of the reflection map and the analysis of resonance scattering were tested on experimental data [12]. The signals backscattered by cylinders (2 m, ϕ 0.50 m) are recorded in free-field for an aspect angle variation of approximately 200°. The shell wall thickness is 6 mm.

Figures 10 and 12 show the aspect-dependent scattering for the water-filled and air-filled cylinders, respectively. Figures 11 and 13 represent the corresponding reflection maps, reconstructed by reflection tomography. As the aspect angle range is 200° instead of 360°, the rectangular horizontal section of the cylinder is only partially reconstructed. However, due to the internal reflection on the back end-cap, a more complete reconstruction is obtained for the water-filled cylinder (Fig. 11). Due to difficulties in rotating the air-filled cylinder (positive buoyancy) at a constant speed, its reflection map appears less focused (Fig. 13).

The difference of inner material can be seen in the analysis of resonance scattering at broadside in Figs 14 and 15. The water-filled cylinder has a complicated resonance response (see Fig. 14) from which shell-borne, internal-reflection-borne and internal-fluid-borne wave families can be extracted. For the same frequency range, the air-filled cylinder only shows the shell-borne wave family (see Fig. 15).

The values of the target parameters in Table 1 from the automatic multi-hypothesis estimation method [11] are in good agreement with the expected values. Table 1 shows the estimation of four target parameters (outer radius, shell thickness, inner fluid speed, shell material speed) without using the information contained in the reconstructed reflection map. The introduction of the object shape and approximate dimensions in the estimation process allows reduction of the space of solutions for the unknown parameters, leading to more accurate and reliable estimates. The improvement in parameter estimation is quantified in Table 2. For these experimental data containing only cylindrical objects, the dimensions and the shape have been deduced from the pattern made by the high energy areas in the reflection map.

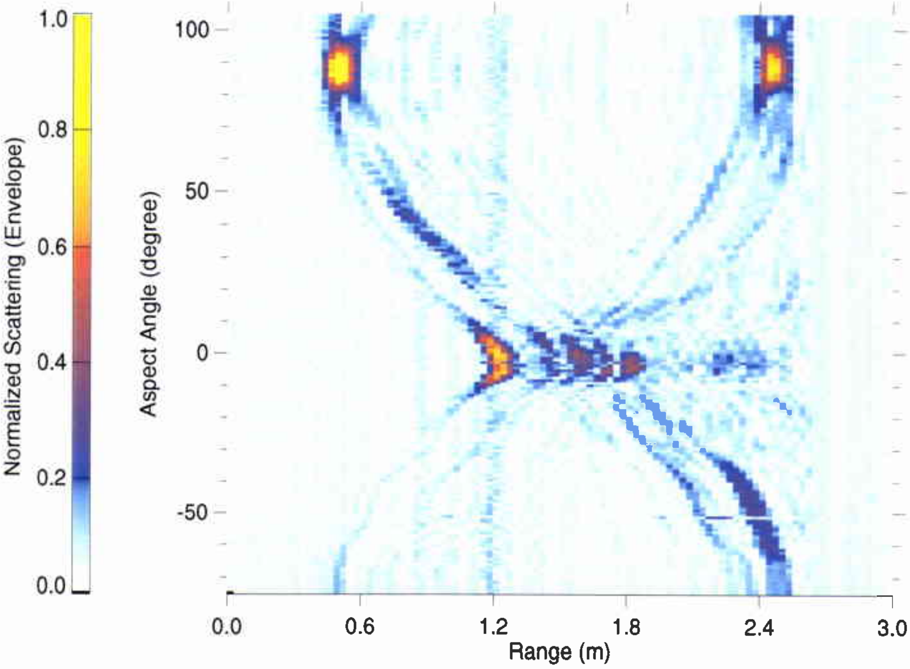

Figure 10 *Amplitude (envelope) of the backscattered pressure. Azimuth angle varies from -75 ° to +110 °. Broadside aspect is at 0 °.*

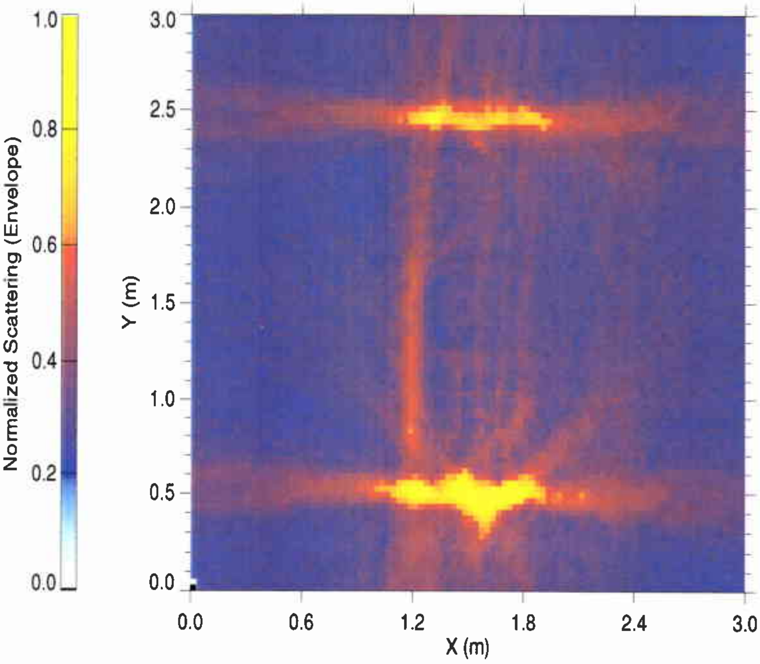

Figure 11 *Reconstructed reflection map of water-filled cylinder.*

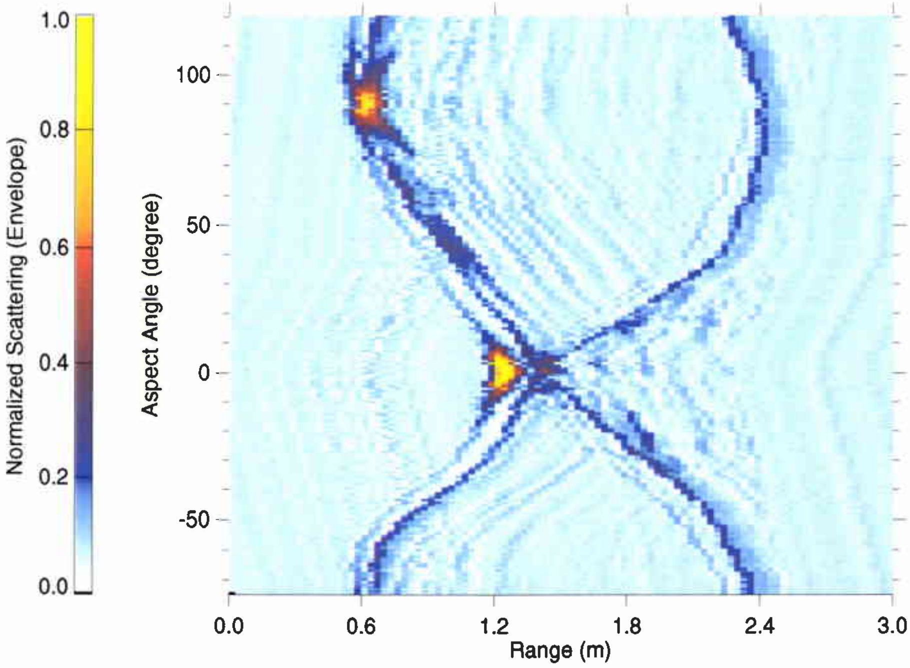

Figure 12 *Amplitude (envelope) of the backscattered pressure. Azimuth angle varies from -75 ° to +120 °. Broadside aspect is at 0 °.*

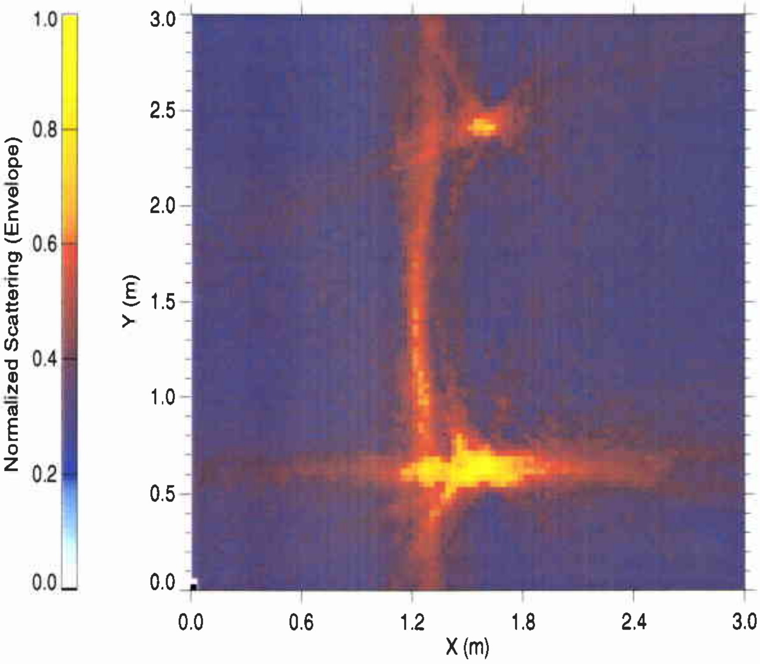

Figure 13 *Reconstructed reflection map of air-filled cylinder.*

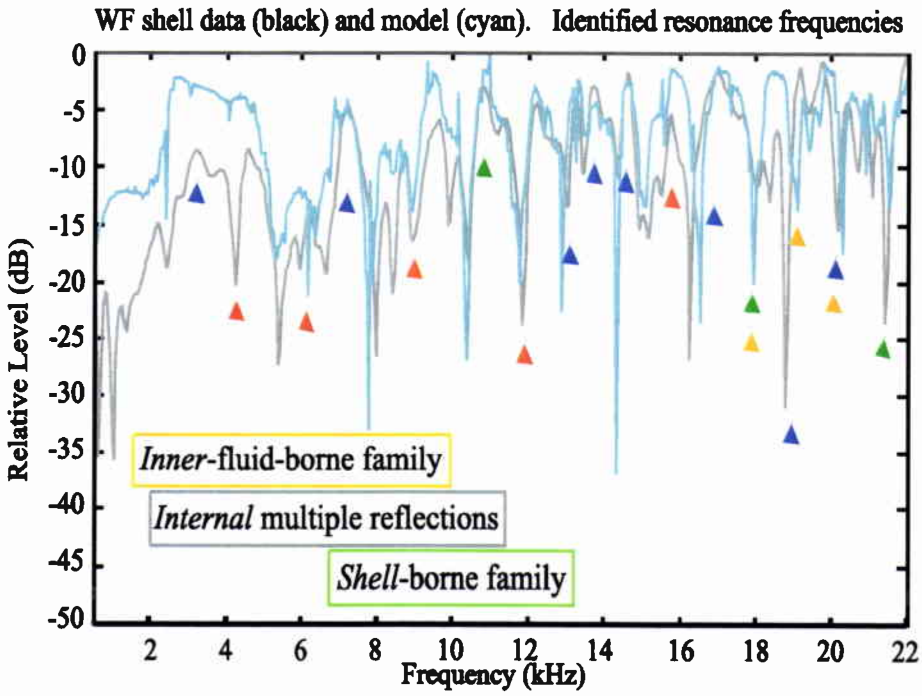

Figure 14 *Resonance scattering analysis of water-filled cylinder.*

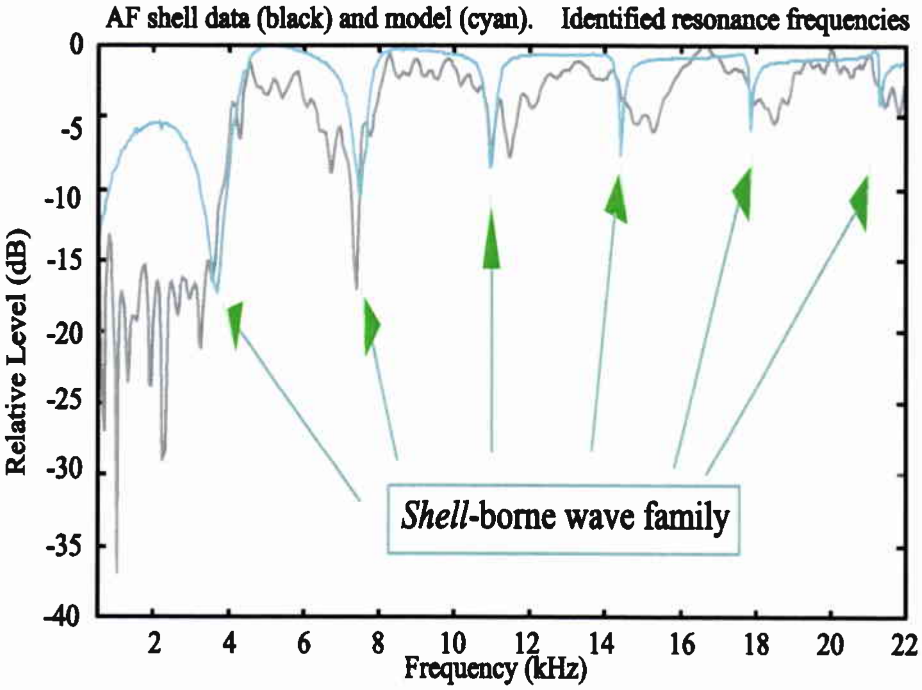

Figure 15 *Resonance scattering analysis of air-filled cylinder.*

Target Property	Input Value Ranges	AF Shell Estimate	AF Expected Value	WF Shell Estimate	WF Expected Value
Outer radius a [cm]	[10,50]	17.5	25	37.5	25
Shell thickness d=a-b [mm]	[3,50]	5.3	6	8.2	6
Inner fluid speed c_{in} [m/s] (WF only)	[900,2000]			1487	1527
Shell material speed c^* [m/s]	[3500,5600]	5095	5435	5270	5435

Table 1 *Inversion results from data scattered by a steel cylindrical shell filled with air (AF) and with water (WF).*

Target Property	Input Value Ranges	AF Shell Estimate	AF Expected Value	WF Shell Estimate	WF Expected Value
Outer radius a [cm]	[20,30]	24.6	25	25.6	25
Shell thickness d=a-b [mm]	[3,50]	5.3	6	4.1	6
Inner fluid speed c_{in} [m/s] (WF only)	[900,2000]			1546	1527
Shell material speed c^* [m/s]	[3500,5600]	5275	5435	5465	5435

Table 2 *Inversion results from data scattered by a steel cylindrical shell filled with air (AF) and with water (WF) when shape and dimensions are estimated from the reconstructed reflection map.*

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Summary and Prospectives

We have demonstrated that the combination of multiple aspect reconstruction and resonance scattering analysis has excellent potential for target classification. This method can be used to complement current classification techniques or as a main classification tool when current techniques fail (e.g., for buried objects). The reconstruction method performs satisfactorily on experimental data, even when the rotation-time history of the object is not perfectly known. The automatic extraction of resonance features in the target spectra allows one to distinguish between targets externally similar but different inside. At sea experiments will be conducted to assess the potential of the classification method for more realistic targets on the seabed or with varying degrees of burial. As reliable target classification techniques require accurate models, the realism of the acoustic target signature will be increased by migrating from 2-D to 3-D modelling techniques. Reconstruction techniques, tested here in 2-D, will also be adapted to 3-D scattering. The analysis of the resonance scattering, limited here to selected aspects will be improved to select, track and extract aspect-dependent features.

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Acknowledgments

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Title

A classification technique combining aspect dependence and elastic properties of target scattering

Abstract

Discrimination between man-made and natural underwater objects and between man-made objects of different characteristics are the key objectives of target classification. The current approach is mainly based on the analysis of the target signature imaged by high resolution (typically <20 cm) high frequency (typically <100 kHz) sonars. To estimate the potential of alternative classification schemes based on more detailed acquisition of target echo features, SACLANTCEN has investigated low frequency (10 kHz) sonar systems with high fractional (or relative) bandwidth (2-20 kHz).

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Keywords

Sea mine classification - automatic target classification - resonance scattering analysis - computerized technology

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COMEDCENT	1
COMMARAIRMED	1
COMNAVSOUTH	1
COMSTRIKFORSOUTH	1
COMSUBMED	1
NC3A	1
PAT	1

Scientific Committee of National Representatives

SCNR Belgium	1
SCNR Canada	1
SCNR Denmark	1
SCNR Germany	1
SCNR Greece	1
SCNR Italy	1
SCNR Netherlands	2
SCNR Norway	1
SCNR Portugal	1
SCNR Spain	1
SCNR Turkey	1
SCNR UK	1
SCNR USA	2
French Delegate	1
SECGEN Rep. SCNR	1
NAMILCOM Rep. SCNR	1

National Liaison Officers

NLO Canada	1
NLO Denmark	1
NLO Germany	1
NLO Italy	1
NLO Netherlands	1
NLO Spain	1
NLO UK	1
NLO USA	1

Sub-total	199
SACLANTCEN	30
Total	229