

SACLANTCEN MEMORANDUM
serial no.: SM-310

**SACLANT UNDERSEA
RESEARCH CENTRE
MEMORANDUM**



**A METHOD FOR THE THREE -DIMENSIONAL
RECONSTRUCTION
OF UNDERWATER OBJECTS**

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October 1996

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The content of this document pertains to work performed under Project 031-3 of the SACLANTCEN Programme of Work. The document has been approved for release by The Director, SACLANTCEN.



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A Method for the Three-dimensional Reconstruction of Underwater Objects ⁽¹⁾

B. Zerr and B. Stage

Executive Summary:

In mine hunting operations, the classification of interesting echoes usually relies on a single high resolution image. This image is produced by an high frequency (typically 400 kHz) sector scan sonar.

Unless its shape is perfectly symmetric, the classification of an object is improved by analyzing several images from different points of view. In particular, the three-dimensional reconstruction of the object gives an useful input to the classifier by combining the information from the multiple views.

The three-dimensional reconstruction is based on a sequence of images recorded during one circumnavigation of the object. The most suitable sonar carrier for recording this sequence is an autonomous underwater vehicle (AUV). When using a propelled variable depth sonar (PVDS) or a hull mounted sonar (HMS), the operational constraints limit vehicle motion. In this case, only a limited interval of azimuth angles is available. However, the partial reconstruction, based on a limited number of views, already gives useful clues to classify the object.

The reconstruction method assumes that the sonar system is capable of imaging precisely the shadow and the highlight information. The shadows are processed to estimate the overall shape of the object. The echo processing provides additional details such as ribs, edges and other protuberances.

This report describes the reconstruction method and presents preliminary experimental results using a Reson Seabat sonar mounted on a Bofors Sutec Seatwin vehicle.

⁽¹⁾ The content of this report formed the basis of a presentation at ICIP 1996, Lausanne 16-19 September, 1996.

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A Method for the Three-dimensional Reconstruction of Underwater Objects

B. Zerr and B. Stage

Abstract: This report describes a method to estimate the three-dimensional aspects of underwater objects using a sequence of sonar images. The data are recorded by a sector scanning sonar, carried by an underwater vehicle which follows a circular track around the object. The sonar images are segmented into three kinds of regions : echo, shadow and background. The echo information corresponds to the signal back-scattered by the object while the shadow is due to the absence of back-scattering from behind the object. The remaining information composes the background. The reconstruction scheme processes the echo and shadow information separately. A two-dimensional elevation map is estimated from the shadow information and a two-dimensional reflection map is computed from the echoes.

Keywords: Sonar images, 3D Reconstruction, Computerized Tomography.

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1

Introduction

The three-dimensional information can be directly acquired by a dedicated sonar system, having high resolution in azimuth, elevation and range. Though some prototypes have been built [1], these systems remain at the edge of the technological feasibility. An alternative approach, based on multiple-beam echo sounders or on bathymetric sidescan sonars [2, 3], provides a precise knowledge of the seabed relief, but the resolution is too coarse to acquire the three-dimensional characteristics of small objects. Use of the shape-from-shading technique on sidescan sonar images [4] has led to similar conclusions.

In this report, the three-dimensional information is reconstructed from a sequence of images, acquired by conventional high resolution sonar. This system records precisely the echo and the shadow of the object. At low grazing angle, the shadow zone behind the object does not receive acoustic energy and, therefore, returns a very low signal. The high amplitude signal, caused by the reflection of the acoustic wave from the object, is the echo.

The three-dimensional information is extracted from the sequence of images by the reconstruction-from-projections technique [5]. Multiple 2π revolutions, required by the direct implementation of the three-dimensional reconstruction method, are not practical. In this report, a new approach, combining computerized tomography [5, 6] and volume bounding by occluding contours [7], has been developed. The sequence of images is recorded during a single revolution, at a constant range to the object and at a constant height above the seabed. Applied to the echo information, computerized tomography produces a reflection map of the object. The silhouettes of the object, computed from the sequence of shadows, circumscribe its volume through an elevation map.

The method used to process echoes and shadows for three-dimensional recovery of an underwater object shape is described in Sect. 2. Section 3 describes the extraction of the echo and shadow information. The volume reconstruction through the elevation map is detailed in Sect. 4. The estimation of the reflection map by computerized tomography is addressed in Sect. 5. Section 6 presents the final reconstruction drawn from the combination of the shadow and echo processing results on simulated and experimental data.

2

Reconstruction from a Sequence of Sonar Images

The three-dimensional reconstruction consists of estimating the three-dimensional reflection function $f(\mathbf{x}, \mathbf{y}, z)$ of the object from its plane projections $g(s, \theta, \phi)$

$$g(s, \theta, \phi) = \int_{S(s, \theta, \phi)} f(\mathbf{x}, \mathbf{y}, z) dx dy dz \quad (1)$$

where $S(s, \theta, \phi)$ defines the equation of the plane, ϕ the azimuth angle, θ the elevation angle and s the distance to the origin.

The set of projections can also be described by the three-dimensional Radon transform of the object reflection function

$$g(s, \theta, \phi) = \int \int \int_{-\infty}^{+\infty} f(\mathbf{x}, \mathbf{y}, z) \delta(s - x \cos \theta \cos \phi - y \cos \theta \sin \phi - z \sin \theta) dx dy dz \quad (2)$$

The function $f(\mathbf{x}, \mathbf{y}, z)$ can be reconstructed from the projections using either the inverse Radon transform or the projection-slice property of the Fourier transform [8].

Unlike x-ray imaging systems, the high frequency sonar beams do not penetrate the object. For a complete reconstruction, the projections must be acquired with angular ranges of 2π in elevation (Δ_θ) and in azimuth (Δ_ϕ). The symmetry of Eqn. 2 allows to reduce to π one of the two angular ranges. When dealing with proud objects, only the upper half space is accessible. Hence, the angular ranges suitable for the full reconstruction of proud objects can be

$$\begin{cases} \Delta_\theta = \pi/2 \\ \Delta_\phi = 2\pi \end{cases} \quad (3)$$

or

$$\begin{cases} \Delta_\theta = \pi \\ \Delta_\phi = \pi \end{cases} \quad (4)$$

The acquisition of the projections for these angular ranges requires a precise control of the sonar motion and a highly maneuverable sonar carrier. Therefore, this task is practically unfeasible for conventional underwater vehicles.

An new approach, based on a single 2π revolution around the object and on separate processing of echoes and shadows, has been developed to fit better the capability of underwater vehicles. The three-dimensional information is approximated by the combination $c(\mathbf{x}, y, z)$ of two two-dimensional maps, one indicating the height $f_z(\mathbf{x}, y)$ and the other, the intensity of the backscattered signal $f_r(\mathbf{x}, y)$

$$\begin{cases} f(\mathbf{x}, y, z) \approx c(\mathbf{x}, y, f_z(\mathbf{x}, y)) \\ c(\mathbf{x}, y, z) = c(\mathbf{x}, y, 0) = f_r(\mathbf{x}, y) \end{cases} \quad (5)$$

Therefore, the reconstruction is based on two algorithms : one applied to the echo information to produce the reflection map $f_r(\mathbf{x}, y)$ and the other which compiles the elevation map $f_z(\mathbf{x}, y)$ from the shadow information.

3

Sonar Image Segmentation

The data are acquired by a sector scanning sonar (Fig. 1) which images the echo and the shadow of the object. The sequence of images provides the echo and shadow information with an azimuth angle that varies from 0 to 2π .

The echoes and shadows are extracted and separated from the sequence of images by a segmentation algorithm. Each image is segmented individually. When the contrast is sufficiently high, the segmentation process relies on two thresholds, t_s and t_e , with $t_s < t_e$. Shadow pixels have a grey level less than t_s . Echo pixels have a grey level greater than t_e . The thresholds can be fixed *a priori*, if the performance characteristics of the sonar are known. For images with low contrast, segmentation based on Markov random fields has been developed. Figure 2 shows the original sonar image and Fig. 3 displays the segmentation results. The black and white regions are the shadow and the echo of the object, respectively. The remaining grey area corresponds to the background. After connected component analysis, the undesired shadow and echo regions are removed using size and location criteria.

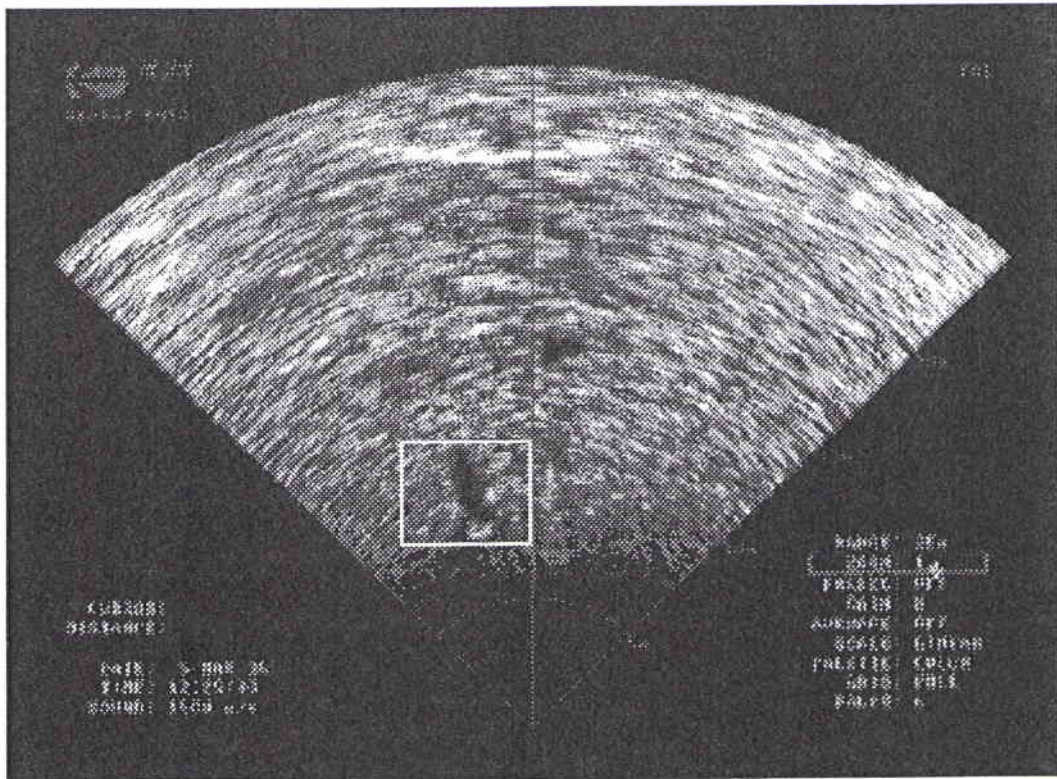


Figure 1: High Resolution Sonar Image

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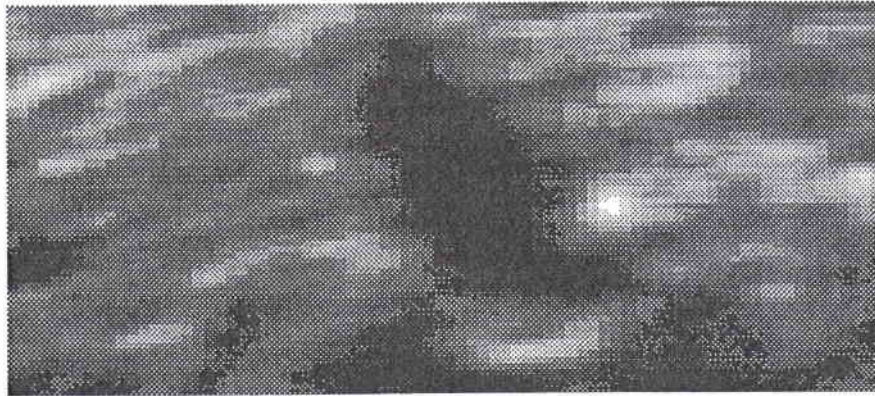


Figure 2: Sonar Image of a Spherical Object

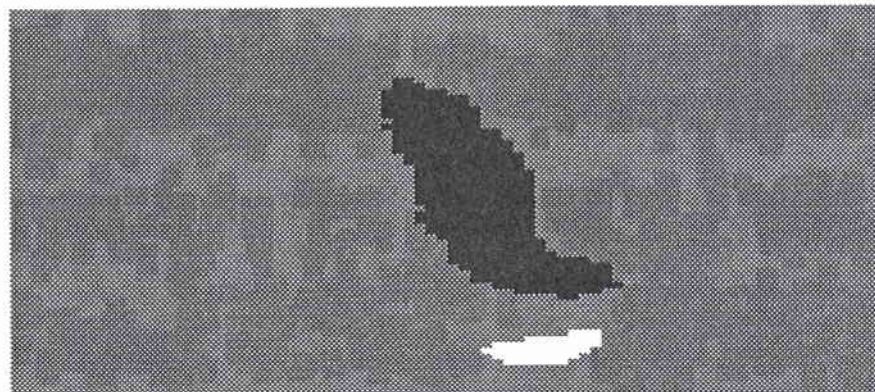


Figure 3: Sonar Image Segmentation

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Elevation Map

The shadow information is defined by a linear segment for each sonar beam illuminating the object. For a given azimuth angle ϕ_i , the height $z_{\phi_i}(u)$ is estimated by

$$z_{\phi_i}(u) = l_{\phi_i}(u) \frac{H_{\phi_i}}{R_{\phi_i}(u)} \quad (6)$$

where H_{ϕ_i} is the altitude of the sonar, $R_{\phi_i}(u)$ the range at which the shadow starts, $l_{\phi_i}(u)$ is the length of shadow segment and u is the across-range axis. The function $z_{\phi_i}(u)$ defines the cross-section, or the silhouette, of the object when it is seen under azimuth angle ϕ_i (Fig. 4). The reconstruction method is derived from the volumetric reconstruction by occluding contours [7]. For each azimuth, the corresponding cross-section bounds the object volume. An iterative reconstruction consists of starting from a rough block of material, encompassing the object. The block is successively sculpted by translating the silhouettes as forming tools along their corresponding azimuth axes. This process consists of a non linear reconstruction of the object height $f_z(x, y)$ from n cross-sections $z_{\phi_i}(u)$

$$f_z(x, y) = \min_{i=1, n} [z_{\phi_i}(x \cos \phi_i + y \sin \phi_i)] \quad (7)$$

This reconstruction equation assumes a convex object shape.

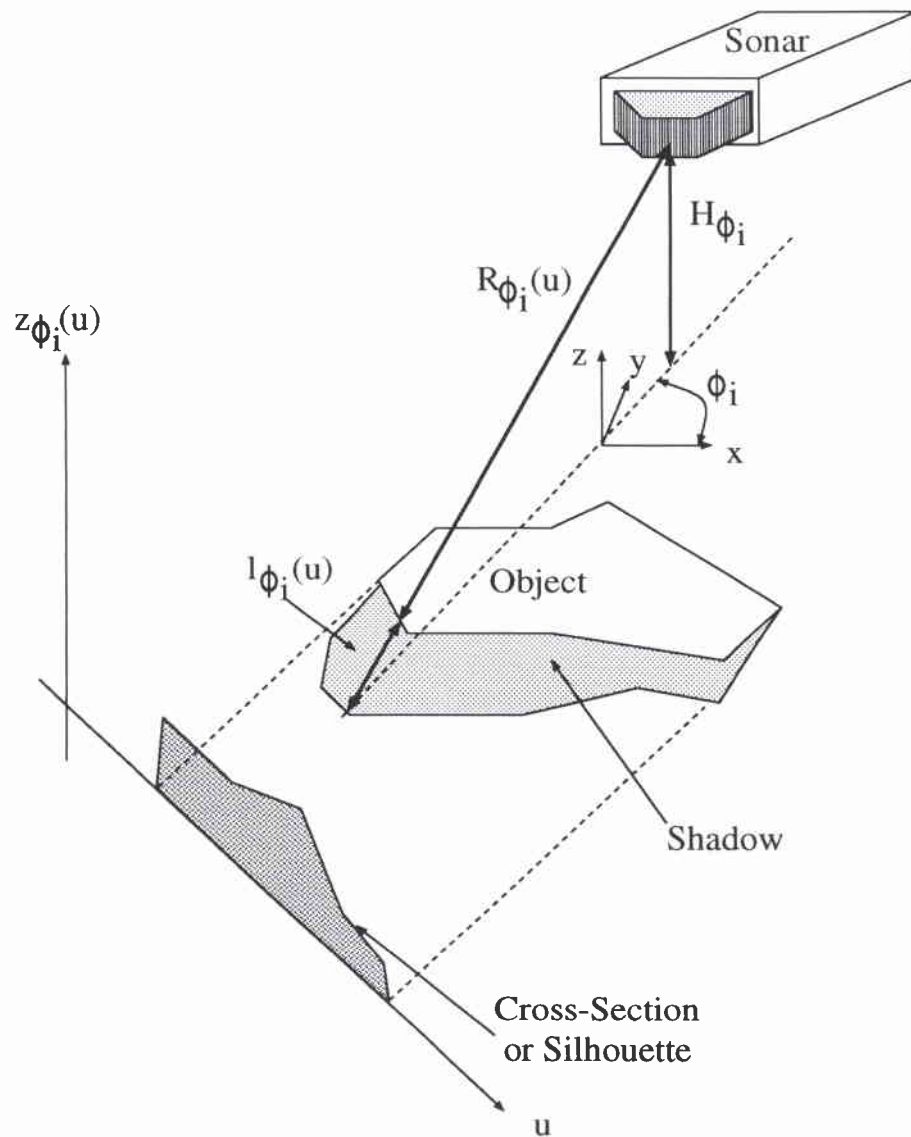


Figure 4: Silhouette Extraction

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Reflection Map

The reflection map, $f_r(x, y)$, of the object is produced by computerized tomography of the echo information. The input is the two-dimensional Radon transform, $g(s, \phi)$, of the object. The reflection map $f_r(x, y)$ is drawn from $g(s, \phi)$ by backprojection

$$f_r(x, y) = \int_0^{2\pi} g(x \cos \phi + y \sin \phi, \phi) d\phi \quad (8)$$

In polar coordinates, ρ and ψ , the reflection map $f_p(\rho, \psi)$ can be expressed as

$$f_r(x, y) = f_p(\rho, \psi) = \int_0^{2\pi} g(\rho \cos(\phi - \psi), \phi) d\phi \quad (9)$$

where $x = \rho \cos \psi$ and $y = \rho \sin \psi$.

The projection $g(s, \phi)$ is the sum, across the range, of the echo information $e_\phi(s, t)$. For an azimuth of ϕ , the projection is given by

$$g(s, \phi) = \int_{-\infty}^{+\infty} e_\phi(s, t) dt \quad (10)$$

where s and t are the sonar image along-range and across-range coordinates, respectively.

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Reconstruction Examples

6.1 *Simulated Data*

A sequence of simulated images of a reference object was used to test the method. The main element of the shape is a cylinder with the main axis vertically oriented. As shown in Fig. 5, four small cylinders have been added to the top of the main cylinder.

The elevation map, reconstructed from the shadow information, is shown in Fig. 6. Figure 7 shows the projections of the echo information for azimuth angles of 0° to 360° in steps of 5° . Figure 8 displays the reflection map, computed by backprojection. The final result, combining the reflection and elevation maps, is displayed in Fig. 9.

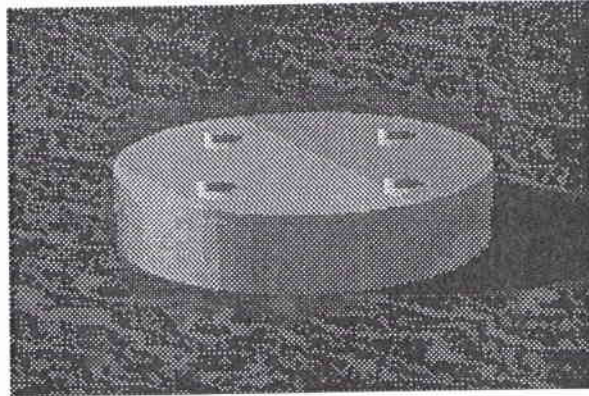


Figure 5: Three-Dimensional View of the Test Object



Figure 6: Elevation Map $f_z(x, y)$

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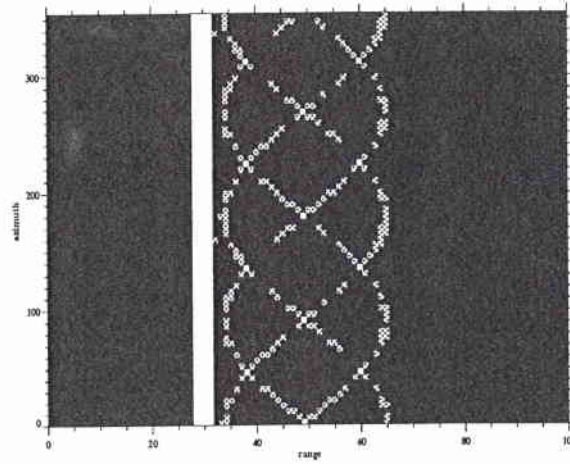


Figure 7: Projections of Echo Information $g(s, \phi)$

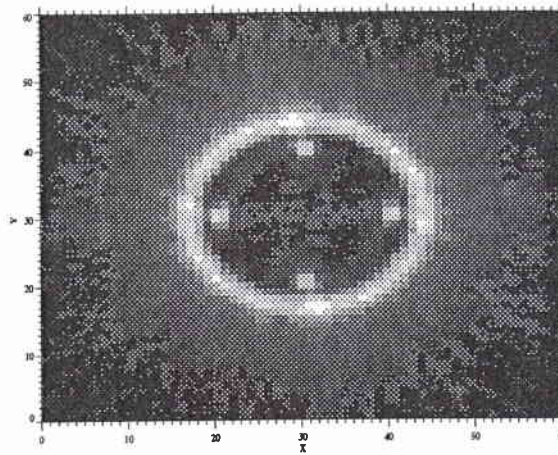


Figure 8: Reflection Map $f_r(x, y)$

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Figure 9: 3D Reconstruction from Simulated Data

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6.2 *Experimental Data*

Figure 10 and 11 shows the three-dimensional reconstruction of a spherical object from a sequence of experimental images. The particularly strong underwater currents in the vicinity of the object corrupted the data and, consequently, the reconstruction algorithms. Figure 10 is the three-dimensional reconstruction from 3 views. Figure 11 shows the results based on 12 views. This demonstrates that the use of a limited number of views gives a coarse estimation of the volume occupied by the object, but, the reflection map is too inaccurate to draw any conclusions. When the number of views increases, the result of the reconstruction allows a better understanding of the object characteristics by determining both its geometrical features and the way it reflects the emitting wave.

The two-dimensional approach to reconstruct the three-dimensional information requires a limited amount of computational resources. This allows a real time reconstruction during the transit of the underwater vehicle around the object.

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Figure 10: 3D Reconstruction from Experimental Data (3 Views)



Figure 11: 3D Reconstruction from Experimental Data (12 Views)

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Conclusions

The method, of approximating the three-dimensional information of an object by a combination of two independent two-dimensional algorithms, has given successful results. The elevation map, estimated from the shadow information, gives significant information on the overall shape of the object while the reflection map, computed by computerized tomography of the echo information, enhances the reconstruction by adding significant details. As this method requires only limited computational resources, it can be implemented in real time.

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Acknowledgments

The following persons deserve thanks for their contribution to this work. The acquisition of the sonar images is the result of a SACLANTCEN-GESMA joint experiment coordinated by E. Maillard for GESMA and P. Guerrini for SACLANTCEN. The experiment was performed on *Aventurière 2* research vessel by F. Pellenec, S. Le Goanvic, M. Vittozzi, C. Le Gall and M. Bellec. The image replay facilities were provided by M. Max.

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Document Data Sheet

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<i>Security Classification</i> NATO UNCLASSIFIED		<i>Project No.</i> 031-3
<i>Document Serial No.</i> SM-310	<i>Date of Issue</i> October 1996	<i>Total Pages</i> 24 pp.
<i>Author(s)</i> B. Zerr and B. Stage		
<i>Title</i> A method for the three-dimensional reconstruction of underwater objects.		
<i>Abstract</i> <p>This report describes a method to estimate the three-dimensional aspects of underwater objects using a sequence of sonar images. The data are recorded by a sector scanning sonar, carried by an underwater vehicle which follows a circular track around the object. The sonar images are segmented into three kinds of regions: echo, shadow and background. The echo information corresponds to the signal back-scattered by the object while the shadow is due to the absence of back-scattering from behind the object. The remaining information composes the background. The reconstruction scheme processes the echo and shadow information separately. A two-dimensional elevation map is estimated from the shadow information and a two-dimensional reflection map is computed from the echoes.</p>		
<i>Keywords</i> Sonar image – 3D reconstruction – computerized tomography		
<i>Issuing Organization</i> <p>North Atlantic Treaty Organization SACLANT Undersea Research Centre Viale San Bartolomeo 400, 19138 La Spezia, Italy</p> <p>[From N. America: SACLANTCEN (New York) APO AE 09613]</p>		<p>Tel: +39 (0)187 540 111 Fax: +39 (0)187 524 600</p> <p>E-mail: library@saclantc.nato.int</p>

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