QUANTITATIVE IMAGING OF ACOUSTIC BACKSCATTER FROM THE SEAFLOOR

Kenneth G. Foote Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA
Stephen P. Robinson National Physical Laboratory, Teddington TW11 0LW, UK
Peter D. Theobald National Physical Laboratory, Teddington TW11 0LW, UK

ABSTRACT

Two factors have often led to the neglect of instrument calibration and the loss of information in the imaging process: the power of the image and the convenient signal processing expedient of disregarding the physical nature of data. Seafloor imaging by sonar is a case in point. Notwithstanding ambitions and needs to remotely detect and identify bottom objects, determine seafloor properties, and quantify benthos, among other things, images of acoustic backscattering data are often used, misleadingly, as proxies for physical data. Since image processing is inherently nonlinear, the loss of physical data is immediate. Three processes that are essential to the attainment and maintenance of the physical nature of backscattering data are elaborated: sonar calibration to determine the transfer characteristics of the sonar, range compensation that addresses both geometric and radiometric factors, and beam pattern measurement or estimation.

1 INTRODUCTION

The topic of this conference is immense and immensely important. Applications are so numerous that Blondel[1] has reviewed these vis-à-vis sidescan sonar observations with respect to geographical features; spreading and subduction, abyssal plane, polar seas, continental margins, and shallow-water environments. These categories have been subdivided by structures, including the tectonic, volcanic, sedimentary, hydrothermal, and biological, also considering geological resources and man-made structures.

In another major review of the subject of seafloor acoustics, but at high frequency without specific reference to sonar type, Jackson and Richardson[2] have pursued a phenomenological approach. This has been organized in terms of the nature of marine sediments, physical and geoacoustic properties, geometric properties in the form of seafloor roughness, and sediment heterogeneity. Theories of seafloor scattering are presented in order of increasing complexity: fluid, elastic, and poroelastic media, followed by treatment of roughness scattering and sediment volume scattering.

Each of these works addresses other, collateral issues, providing further context for this conference. Blondel’s treatment of anomalies and artifacts, and computer-assisted interpretation, define open problems and the state-of-the-art, at least a recently as 2009. Jackson and Richardson[2] similarly address research issues, but under each of their topics.

Very recent evidence for the currency of work on seabed and sediment acoustics is found in the refereed scientific literature, e.g., IEEE Journal of Ocean Engineering and The Journal of the Acoustical Society of America. The problems are also highlighted in trade publications such as Sea Technology. In the June 2012 issue, Nishenko et al.[3] report on “Seafloor imagery for earthquake, tsunami hazard assessments.” In the November 2012 issue, Sternlicht et al.[4] describe “Detecting, classifying mines with synthetic aperture acoustic tomography.”

Another influential point of reference for this conference is the Institute of Acoustics Underwater Acoustics Group Conference, “Acoustic classification and mapping of the seabed,” held at the University of Bath, 14-16 April 1993. The papers presented at that conference 22 years ago witness both to the diversity of efforts being made to address the problem and to the durability of the problem.

Sonar imagery: Much of the mentioned work, including papers within larger collections or cited journals, involves sonar imagery. The subject of image interpretation thus arises. Previously, interpretation was facilitated by atlases of sonar images, and indeed atlases remain useful for this purpose. An early prominent example was produced by Belderson et al.,[5] succeeded by atlases assembled by Edgerton[6] and Fish and Carr.[7,8] Blondel's own cited work[1] was developed, with considerable expansion, from the "Handbook of seafloor sonar imagery."[9]

Image analysis: Under the rubric of traditional techniques, Blondel[1] has reviewed the topics of image enhancement and contour- and texture-oriented analyses. In the case of image enhancement techniques, the aim "is not to increase the quality of the sonar image, but rather to increase the visibility of regions of interest." This leads to the performance of local, or region-based, operations on the image, which are inherently nonlinear, as are operations within contour- and texture-oriented analyses. Such operations may enable features to be distinguished, but with the loss of physical data on backscattering, even if available at the outset. If the aim of the image analysis is purely qualitative, e.g., detection, or establishing presence, this might be adequate. However, it begs the question of what to do in the gray area of uncertain detection, not to mention classification, which is recognized to be huge, reflected in the present concern. At the same time, traditional processes of image interpretation are both subjective and time-consuming.

Realization and maintenance of the physical character of the backscattering data underlying images, as for its exploitation in quantitative image analysis, is the present subject. To this end, following a succinct statement of the problem, the following elements are elaborated: the standard-target sonar-calibration method, quantitative range compensation, and beam pattern measurements or estimation.

2 THE PROBLEM

An image is composed of a matrix of picture elements, or pixels, whose spatial arrangement is intended to map some spatially distributed quantity, e.g., seafloor depth or seafloor backscatter or both. Individual pixel values are derived from sonar signal output data expressed in electronic or digital units. At some relatively low level, for example, near to the transducer or immediately after beamforming, the electronic signal output will bear a direct, deterministic relationship to the received echo pressure. At a higher level, as after image processing, the resultant digital quantity may not bear any simple relationship to the received echo pressure. In this case, the ratio of two arbitrary pixel values may not be proportional to the ratio of the corresponding echo pressures or received voltages, or their corresponding intensities, or their integrated intensities, or other physical backscattering quantity.

For quantitative image analysis as envisaged in this work, the echo data must be intercepted at a processing stage where they still have physical content. To ensure that these data have meaning, the source sonar system requires calibration, including determination of its directionality. In addition, processing of the sonar output signal should preserve this content over space or time, implying application of range compensation in the form of a deterministic, monotonically increasing function of space or time for geometric factors.

3 STANDARD-TARGET SONAR-CALIBRATION METHOD

The standard-target method of calibrating sonars used to image or measure backscattering has been documented in a number of publications, e.g., Foote et al.,[10] including one ANSI-ASA standard.[11] The method is the subject of a new standard being formulated within the International Organization for Standardization (ISO), Technical Committee 43 (Acoustics), Subcommittee 3 (Underwater acoustics), Working Group 4.

In essence, a standard target is suspended at a known position in the sonar transducer beam. A known signal is transmitted and the echo is received. Knowing whether the sonar output is proportional to echo pressure, echo intensity, or time-integrated echo intensity, without or with spectral resolution, enables the expected echo quantity to be computed. If the sonar is narrowband, or the echo processing reduces the echo to an intensity- or energy-proportional quantity, then comparison of the measured and computed quantities determines a constant of proportionality, i.e., a calibration constant or factor. If the sonar is wideband and the echo processing reduces the echo to a spectrum, then comparison of the respective measured and computed spectra determines the combined transmit-receive frequency response function.

Repetition of the basic measurement at other positions in the sonar transducer beam can enable the directionality to be determined. Methods to render this for hull-mounted transducers are described in reference 10. For compact, detachable multibeam sonars, methods are described in reference 12.

This method is especially powerful because the target strength of some standard targets is known *a priori*, rendering the standard primary. A prominent, especially useful class of such standard targets is the homogeneous, solid, elastic sphere for which the material properties are known with high accuracy. These properties typically include the mass density of the material and a pair of independent elastic constants, e.g., Young's modulus and the rigidity modulus, or longitudinal- and transverse-wave sound speeds. The theory of acoustic scattering by such spheres is given by Faran[13] and Hickling,[14] with typographical errors noted in reference 15. Experimental validation was performed initially by Neubauer and group.[16,17] The idealized definition of target strength given in many texts is replaced by an operational definition in reference 15.

Four exemplary solid elastic spherical targets include the following: (i) 60-mm-diameter sphere of electrolytic-grade copper for calibration of a narrowband sonar operating at 38 kHz; (ii) 38.1-mm-diameter sphere of tungsten carbide with 6% cobalt binder for use at 38 kHz and some other frequencies; (iii) a 280-mm-diameter sphere of an aluminum allow for use over the band 1-6 kHz; and (iv) a pair of tungsten carbide sphere with 6% cobalt binder, with diameters 75 and 84 mm, for use over the band 70-120 kHz.

In the case that other target shapes are required, for example, to achieve exceptionally high target strengths, it is always possible to measure the target echo or spectrum under controlled conditions. In this case, the target strength, or spectrum, of the standard target is known *a posteriori*, and the calibration is secondary.

It is often assumed, and sometimes expected or even required, that the echo measurements be made on the target in the farfield of the transducer. As noted in reference 18, the farfield is approached asymptotically; it applies at any finite range to within some tolerance. This realization is important: the calibration is generally being performed in the array nearfield, and the farfield assumption or requirement is at best approximate. It is convenient if the target can be placed at a position in the transducer field where the field variation across the diameter of the standard target is weak. In one case, calibration of the difference-frequency band of a parametric sonar[19] was performed wholly within the nearfield of the sonar,[20] in the spatial region where the difference-frequency beam is being formed.[21] In the general case, the backscattering cross section of the standard target should account for the finite range, as in references 13 and 14.

4 RANGE COMPENSATION

Range compensation refers to the process whereby geometric factors, also called artefacts in some literature, are removed from the echo value, to yield a measure of backscattering, e.g., surface or volume backscattering strength or target strength or corresponding coefficient or cross section. For conventional sonars or targets in the water column, the appropriate range compensation function in the intensity domain is $r^4\ 10^{\alpha r/5}$ for resolved single targets and $r^2\ 10^{\alpha r/5}$ for an aggregation of targets, where r is the range and α is the absorption coefficient expressed in decibels per meter.[22] For parametric sonars, the function is more complicated,[23] as indeed it is for general nearfield measurements.

For sidescan or multibeam sonar observation of the seafloor or objects on the seafloor, the geometry is similar, but *r* is called the slant range, referring to the distance from transducer to bottom, typically at a non-normal, or oblique, angle.

If the purpose of a sidescan or multibeam sonar measurement is determination of a backscattering property of the seafloor itself, radiometric corrections may be necessary.[1,24] Effects of the transmit and receive beam patterns must be removed, and compensation applied for the change in ensonification area per unit time or range. In addition, allowance must be made for the angular dependence of backscattering by the seafloor. These factors, possibly combined with geometric factors, define an angle-varying gain (AVG).

Near-normal incidence involves specular scattering, or reflection, which is typically very strong. At low angles of incidence, as measured with respect to the bottom, i.e., at low grazing angles, the scattering is diffuse. The backscattering will vary with grazing angle θ as $\sin^2 \theta$ in the intensity domain. This angle dependence is called Lambert's law, with precedence in optics.[25]

When applied electronically, in the time domain, range compensation is often called time-varied gain (TVG). For modern sonars with a large dynamic range, range compensation is typically applied digitally in post-processing. AVG is rendered similarly, but often partly with TVG, followed by radiometric corrections in post-processing. In all cases, the compensation should respect the sound speed structure of the water column, with appropriate refractive factors applied, as in reference 24.

5 BEAM PATTERN MEASUREMENT OR ESTIMATION

Specification of the beam pattern is essential for measurement of seabed properties. For some sonars, especially at high frequencies, measurement in special venues such as tanks or sea wells may be feasible and even adequate.[12] In the general case, however, the transducer mounting, including housing and surrounding structures, may affect both transmission and reception, as through incidental absorption, baffling, and introduction of extraneous interference.

Recently, de Moustier and Kraft[26] have observed that the beam pattern of a high-frequency multibeam sonar may be determined *in situ* by making a large number of seafloor measurements. When appropriate geometric and radiometric compensation is applied, also for the detected local slope of the bottom, the beam pattern outside of the near-normal, specular-scattering region can be sensed with high precision. In this region, the effective combined transmit and receive beam pattern can be inferred.

The particular multibeam sonar used by de Moustier and Kraft[26] had an operating frequency of 400 kHz. The transmit pulse duration varied from 68 to 86 µs. The transmit beamwidth was 1° in the fore-aft direction and 140° in the athwartships direction. As many as 512 receive beams could be formed, with athwartships beamwidth 0.5° at mid-array. Results achieved with three separate surveys, following geometric and radiometric compensation, were entirely consistent for incidence angles greater than 20° as measured from the vertical. Results for the near-normal-incidence region, within 20° of the vertical, were less consistent for the three surveys, most likely due to differences in the geoacoustic properties of the seafloor. However, since the degree of coherence, or spatial interference over the sonar aperture, is much greater at such angles, it is speculated that the beam pattern can be estimated in this region by interpolation of the wide-angle measurements or by modelling. In this second case, the modelling could be done by the Rayleigh integral,[27] given knowledge of the transducer geometry.

Significantly, de Moustier and Kraft[26] conclude that their measurement method is applicable to any sonar that measures bottom depth and backscatter simultaneously. Thus, the applicable sidescan sonar would be of the phase-measuring type.

6 DISCUSSION

The complexity and nonlinearity of processes involved in sonar image formation are well appreciated[1], but is seeing believing? For detection, not to mention classification, is the image sufficient?

The contrarian view is argued in this concept paper: that calibrated sonar data are essential both to imaging and to quantification. Uses of these data, which are both qualitative and quantitative, are enabled and enhanced by the three processes elaborated here.

(1) The standard-target sonar-calibration method can determine the transfer characteristics of the sonar. This may be a calibration constant or factor in the case of a narrowband sonar or other sonar in which the processing is energy-based, or it can be a frequency-dependent function for wideband sonars in which the processing involves spectral decomposition. The challenge for any particular sonar calibration is addressed in the planning stage: choosing or designing the appropriate target for the particular sonar operating parameters and conditions of the calibration exercise.

(2) Preservation of the quantitative echo signal is ensured by appropriate range or angle compensation. This includes geometric and radiometric factors, whether applied electronically or digitally, with additional allowance made for the actual sound speed structure of the water column. The requirement for successful range compensation is knowledge of the sonar operating parameters and the environment. Some environmental knowledge may be obtained by hydrographic measurement, as with a conductivity-temperature-depth (CTD) sonde, with derivation of the sound speed profile. Other essential knowledge may be obtained by direct observation, as of the local seafloor slope by a sonar that measures bottom depth and backscatter over a sector or swath at the same time.

(3) The directional characteristics of the sonar transducer can be determined by the standard-target method applied at special measurement venues. In many cases, this cannot succeed totally because of the changed boundary conditions of the transducer, referring to the operational mounting, influencing absorption, baffling, and extraneous interference. A remedy is a particular method for the *in situ* determination of the combined transmit-receive beam pattern. Presently, it has yielded consistent results away from the normal-incidence region. While showing site-specific variability in near-normal-incidence measurements, where specular reflection is assumed to dominate, it is believed that empirical knowledge of the wide-angle beam pattern can be supplemented by estimation, e.g., by interpolation from the wide-angle measurements or from modelling based on knowledge of the transducer geometry.

7 EPILOGUE

A theoretical and experimental underpinning to support sonar imaging based on absolute, traceable measurement standards would result in a paradigm shift. It is believed that such an imaging capability would significantly improve the detection, classification, and quantification of seafloor objects, properties, and processes. It may also enable change detection, based on the comparison of images over time and with different sonar systems too.

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