Def Sci J, Vol 35, No 2, April 1985, pp 151-161

Underwater Acoustic Tomography

V. K. AATRE

Naval Physical & Oceanographic Laboratory, Cochin-682004

Abstract. Ever since the CAT scanner technique for medical imaging was introduced, the fields of tomography and image reconstruction from slices have been gaining in popularity. Towards the end of the last decade, the application of tomographic method to large scale ocean monitoring was explored. This paper surveys the application of tomographic methods to ocean monitoring and surveillance.

1. Introduction

A basic problem encountered in underwater surveillance systems is the detection, identification and localization of submerged targets. With the limitations imposed by the underwater media, almost all underwater detections systems, be it for civilian or for military applications, utilize 'SONAR' systems where the term is used more as a generic term to include all systems using underwater sound. Such sonar systems find varied applications from fish finding and navigation to antisubmarine warfare and acoustic countermeasures.

The performance of a sonar is fundamentally dependent on the velocity of sound in sea water which in turn depends on the temperature, salinity and pressure. Over the last several decades, oceanographers have been trying to predict the velocity profile of underwater sound by measuring the other oceanographic parameters. Such a prediction problem requires an enormous amount of data. Complicating this issue is the media itself which is inhomogenous and whose property is to a large extent controlled by the heat transfer from the atmosphere and by the ocean circulation. If in analogy with the atmosphere the general oceanic circulation may be considered as the climatology, then the mesoscale variability is the oceanic weather. The mesoscale variability poses a formidable problem because of its small scale structure compounded by much larger ocean time scales. To study this phenomena, one needs enormous resources. Even for a small area, several full time vessels or hundreds of fixed moorings are essential. Over the last few years, there have been attempts to apply 'Tomographic' techniques to study and to ultimately monitor the ocean acoustic transmission between moorings over large distances[1-5].

In general surveillance systems, one is often interested in estimating the shape of a submerged target. This can be achieved by reconstructing the sound pressure field surrounding the object. The tomograpic technique of reconstructing an object from its projection is also applicable in ocean surveillance.

After a brief review of general tomography, this paper presents Ocean Acoustic Tomographic technique for large scale monitoring of oceans. General reconstruction techniques are also discussed.

2. Tomography

One of the most widely applicable technique of signal processing over the last few years has been 'Tomography'. The word tomography[6] derives its name from the Greek word 'tomos' meaning a section or a slice, with 'tomograph' implying a picture of a slice. The philosophy underlying tomographic methods is that an object (two dimensional or three dimensional) can be reconstructed from an infinite sum of its projections.

In many scientific applications, it is often necessary to determine the distribution of some physical property (eg. density, brightness) of an object under investigation. This can be deduced from an appropriate physical measurement and a set of line or strip integrals corresponding to a particular, angle of view, the projections. The image reconstruction problem solved by tomography is ; 'Given a number of such projections at different angles of view, estimation of the corresponding distribution within the object'.

CT is fundamentally a two dimensional technique. Let S be the circumscribing surface enclosing the cross section being studied (in Fig. 1 without loss of generality this cross section is shown to be a circle). The area outside S is assumed not to intercept the emanations from the body. Tomographic technique addresses two types of problems. First, the sources of emanations are interior to the body (inside S) and are beyond the control of the experimenter. Such a problem is called 'Remote Sensing CT (RSCT)'. Second, the emanating sources are outside the body (outside S) and are generally under the control of the experimenter. Such a technique is called 'Remote Probing CT (RPCT)'. The analogy between the remote sensing/remote probing CTs and passive/active sonar modes is apparent. In Fig. 1, S_m indicates the measurement surface. In RSCT the receivers placed around S_m measure the emanations originating within S while in RPCT, the sources and receivers are distributed[7] over S_m.

The RSCT system can be considered as entirely passive as it only receives emanations. It is only possible to reconstruct a clear image of an object when the emanations are not perturbed by the medium. Positron Emission Tomography (PET) which uses positronium-labelled substance introduced into the body as the source of emanations and Single Photon Emission Tomography (SPECT) which uses radio-labelled substance introduced into the body are two familiar examples of RSCT. In

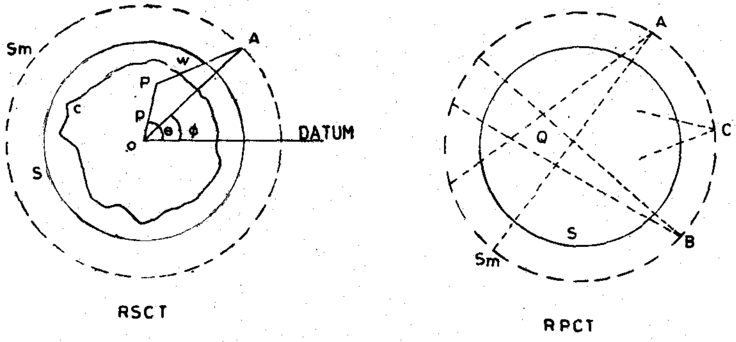

Figure 1. Remote sensing and remote probing tomography.

RS, if the sources are known to lie within some closed curve C which in itself lies inside S, then the field outside C can be expressed exactly in terms of an equivalent source density on C. In the figure, a wide beam transducer at A on S_m receives the emanations. The received signal R_s is

$$R_s(\phi) = F\{\rho(r, \theta), w\}$$

where F is an integral operator, p an arbitrary point in C, w the distance from A to p and $\rho(r, \theta)$ is the source density. It is required to estimate ρ from a measurement of $R_s(\phi)$.

In **RPCT**, the emanations are considered to be the sum of incident and secondary emanations. The X-ray tomography of medicine (the standard CAT scanner type), ocean acoustic tomography, radar and electron microscopy based tomographies belong to this class. In general, the problem here can be classified as direct and inverse. In the former, it is required to calculate the secondary emission (echo or return) given the source on S_m and the density of sources inside S. In the inverse problem it is required to construct the density of the body knowing the source on S_m and the secondary emissions.

The resolution that can be obtained in a reconstructed image is limited by the beamwidth of the transducers. A typical situation in RPCT is depicted in Fig. 1. Two narrow beam transducers transmit narrow pulses towards a point target at Q (typical radar and sonar scenario) and receive the reflections. The resolution can be improved by triangulation. In a typical medical B scan scenario, a transmitter/receiver at C probes the interior of S. The scanning is effected by either moving C around S_m or changing the direction of the beam. Most often a combination of both is used in practice.

The problem of reconstruction of an image from its projections is a highly mathematical one[8]. Let $g(x, y)$ denote the function representing the spatial distribution of some physical quantity (Fig. 2). A line in the plane is represented by its distance from the origin and an angle θ *wrt* y axis. If $p(s, \theta)$ is the line integral of g along the line (s, θ), then

$$p(s, \theta) = \int_{-T}^{T} g(s \cos \theta - u \sin \theta, s \sin \theta + u \cos \theta)\, du$$

where the limits of integration depends on (s, θ) and the area of nonvanishing g. The reconstruction is based on the development of techniques of solving the variations of the integral equation. There are several methods, the first of which was propounded by Radon ($p(s, \theta)$ is called the Radon transform). Radon inversion formula is fundamental to image reconstruction from projections.

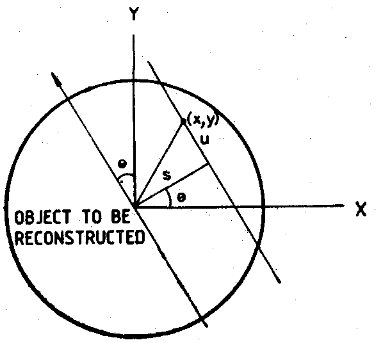

Figure 2. Reconstruction from a projection.

Algorithms for image reconstruction from projection data may be classified into two categories—transform methods and series expansion method[9–14]. The inversion methods fundamentally dependent on Radon inversion formula like convolution-back projection method and Fourier transform method are two familiar transform methods. Quadratic optimization techniques like SIRT (Simultaneous Iterative Reconstruction Technique) are series expansion methods. The series expansion methods differ fundamentally from transform methods in that the problem is discretized at the very beginning. In transform methods the continuous problem is used till the very end when the final formulae are 'discretized' for computational implementation.

In convolution-back projection algorithm, the estimate of the shape of the target is explicity expressed in terms of the projections. This algorithm is derived from Radon transforms[11]. A properly chosen window is used for obtaining convolving function and minimising the effect of point spread function. If only back projection is used for reconstruction, the resulting image will be a blurred version of the original. In convolution-back projection, the signal for each view is preprocessed before back projection to avoid blurring.

In SIRT algorithm, the reconstruction of the object is not derived from the Radon theory[13]. Each square of the reconstruction grid is taken as the initial value. These values are then iteratively changed to reduce the difference between the calculated projection and the given projection. The iterative technique reduces the effect of point spread function. But a disadvantage is that the computation requirements are larger than transform methods.

The details of the reconstruction methods are found elsewhere[8–15].

3. Ocean Acoustic Tomography (OAT)

Sonar ranges which depend on acoustic propagation are strongly influenced by ocean parameters like salinity, temperature and density. The conventional method of measuring these parameters yields the velocity profile at the measurement point only. Sonar range predictions using these profiles assume a horizontal stratification of the ocean. With the present day long range sonars, realistic modelling of the ocean using conventional instruments like bathythermograph is both time consuming and prohibitively expensive. This problem is alleviated by tomographic technique, where the ocean structure over a large volume can be deduced with limited demands on instrumentations. Typically one makes 'time of flight' measurements between a number of transmitters and receivers. Ocean acoustic tomography[1–5,16] can be described as a method of remotely sensing the sound propagation velocity interior to a part of ocean by transmitters and receivers positioned exterior to that part of the ocean. This method provides a capability which is beyond that of satellite remote sensing systems. Satellite observes the ocean surface and all sub-surface phenomena need not manifest themselves as surface phenomena. Such tomographic methods were first applied in 1979.

In OAT, the sound sources which are placed over a specified distance give off signals which in turn are picked up by receivers of omnidirectional hydrophones hung on moorings. With m moorings/platforms, conventional method gives m pieces of information while tomographic scheme of m-platforms with s sources and r receivers yields $r.s.$ pieces of information rather than $(r+s)$ pieces of information. For a source-receiver geometry in a vertical slice of the ocean, the measurement by tomographic method provides all information of the resolvable acoustic ray paths. This is equivalent to measurement made by conventional instruments mounted on a vertical string located throughout the vertical plane under consideration. Accurate clocking in 'time of flight' measurements allows one to resolve various paths and also study the effect due to current.

Let a series of acoustic sources and receivers be scattered around an ocean area as shown in Fig. 3. Here it is assumed that all sources and receivers are in the same

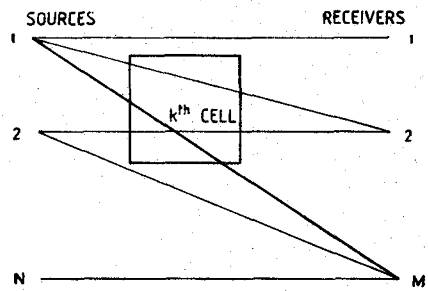

Figure 3. Horizontal ocean tomography.

horizontal plane (not all paths are shown). Let T_{ij} be the 'time of flight' of acoustic signal (emitted by a source) from source i to receiver j. If the ocean area is divided into K cells then,

$$T_{ij} = \sum_{k=1}^{K} \frac{L_{ij}^{(k)}}{C_k}, \quad \begin{matrix} i = 1, \dots N \\ j = 1, \dots M \end{matrix}$$

where $L_{ij}^{(k)}$ is the path length of the ray in cell k, C_k the sound velocity in k^{th} cell and N (M) are the numbers of source (receivers). The selection of the grid (cell) is arbitrary. However, it can be selected based on any prior knowledge of the ocean. The sound velocity C_k in the kth cell can be written as

$$C_k = C_0 + \Delta C_k + \delta C_k$$

where C_k *s* are all space and time varying. C_0 is the long term average of sound velocity and represents the local climate. ΔC_k represents the mesoscale variability with space scales of the order of 10s and 100s of kilometer in horizontal, vertical scales up to the depth of the ocean and time scales of days to months. δC_k represents small scale fluctuations with space scales of kilometers and tens of meters in horizontal and in vertical respectively and with time scales of up to hours. ΔC_k is contributed by fronts and eddies while internal waves and turbulence cause δC_k. The average value of C_0 is 1500 m/sec with ΔC_k an δC_k of the order of 10^{-2} C_0 and 10^{-4} C_0' respectively.

Now writing $C_0 + \Delta C_k = C_k^o$

$$T_{ij} = \sum_{k=1}^{K} \frac{L_{ij}^{(k)}}{C_k^0 + \delta C_k} = \sum_{k=1}^{K} \frac{L_{ij}}{C_k^0} \frac{1}{1 + \frac{\delta C_k}{C_k^0}}$$

To a first order approximation this can be written as

$$T_{ij} = \sum_{k=1}^{K} \frac{L_{ik}}{C_k^0} - \sum_{k=1}^{K} \frac{L_{ik}}{C_k^0} \frac{\delta C_k}{C_k^0}$$

If T^0_{ij} is defined as the first term then

$$T_{ij} = T_{ij} - T^0_{ij} = - \sum_{k=1}^{K} \frac{L_{ik}}{(C^0_k)^2} \delta C_k$$

This set of equations can be written in matrix form as

$$\Delta T = B \Delta C$$

If the variation in 'time of flight', the path lengths and average sound velocity (C^0_k can be taken as C_0) are known, the perturbation in sound velocity in the K cells can be determined by solving the set of simultaneous equation. This set of equations (NM equation in K unknown) can be over under and just determined depending upon the configuration of sources and receivers and upon the ratio of NM to K.

Fig. 4 shows a few configurations with four sources and receivers ($NM = 16$) and 16 grid areas ($K = 16$). The matrix for configuration I has a rank of 12, for II a rank of 13 and for III a rank of 14. The problem of picking a configuration with full rank is as yet unsolved.

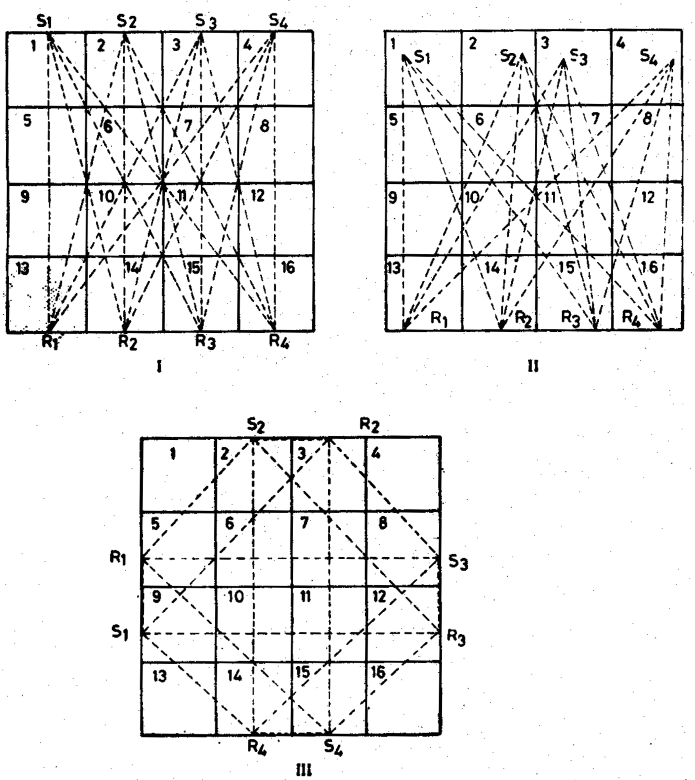

Figure 4. Source receiver configurations for OAT.

A wide variety of techniques, generally known as inverse methods, for solving the equation have been developed. These include convolution techniques, Fourier Domain reconstruction, linear least square estimation and maximum entropy filters. If the measurements are noisy, as is usually the case, the problem is a stochastice one and conventional minimum variance estimators like Kalman filter can be developed. Several experiments have been conducted with the sources at the SOFAR axis by Woods Hole and Scripps Institutes of Oceanography.

The presentation so far has been restricted to a horizontal slice. Tomographical method can be applied to vertical slice also. In the vertical slice configuration depending on the sound velocity profile and depths of sources/receivers, multipaths can result (Fig. 5). In vertical slice, the vertical plane is divided into K grid cells and similar

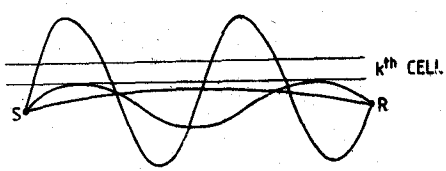

Figure 5. Vertical OAT.

equation can be developed. In general, horizontal and vertical tomographies can be combined to develop three dimensional model for the OAT.

4. Ocean Surveillance Systems

Tomographic reconstruction techniques can be used for operation on multi-array passive and active sonar observations for deriving surveillance information[16,17]. With passive sonar arrays one samples the acoustic noise field in various directions through beamforming on the sensor outputs. The output of each beam from any array is related to the total noise integrated over the region covered by the beam. A deconvolution of the beamshape will lead to the outputs corresponding to 'zero beamwidth' beams, i.e. in different directions. Such multidirection outputs from a number of arrays 'sensing' the acoustic field can be the inputs to any tomographic algorithm, similar to that used in medical tomography, to give the noise energy in a suitable grid depicting the area of surveillance (Fig. 6). The propagation effect dictates the choice of a window function in the case of convolution back-projection algorithm.

Localizing in passive sonars is performed by observing the peak of cross-correlation output in the time delay-doppler difference plane. Spurious peaks in this output appear due to sidelobes of the beams, making the localization difficult. The tomographic method has been suggested to eliminate the effects due to sidelobes.

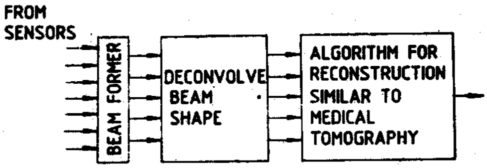

Figure 6. General block diagram for ocean surveillance tomography.

Application of tomography to active sonar environment is not obvious. However a method suggested for radar for target shape estimation from cross-sectional area measured from various aspect angles can be employed. Radar systems make target cross-sectional measurements by multifrequency (harmonically related) ramp responses. Attenuation in the ocean medium does not permit the use of wide range of frequencies. On the other hand, the target cross-section appears in the echo as a convolution of the transmitted waveform with an 'impulse target cross-section' (ITC), where ITC is defined as the projected area of the target surface illuminated by a transmitted 'impulse' at any time onto a surface parallel to the wavefront. The convolution is with the actual waveform transmitted and not with its envelope (coherent convolution). Thus, the echo obtained depends upon the frequency of operation. Use of wideband signals (large BT = 100) and pulse compression by corresponding matched filter overcomes this frequency dependence problem besides providing a high resolution echo. From the impulse target strength (the projection on the wavefront plane) one can obtain the instantaneous cross-section area by the integration of the echo upto that instant. Such cross-section measurements from different directions can be made using a multiarray geometry. The problem of the object shape determination then reduces to : 'Given cross-section areas vs. distance along different known look directions, construct the three dimensional surface of the object'.

The schematic block diagram (Fig. 7) outlines the procedure for estimating the object shape using an active sonar.

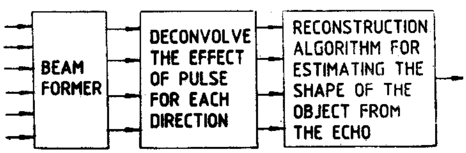

Figure 7. Block diagram for tomography with active sonar.

5. Discussion

Ocean acoustic tomography seems to be the only economical method of large scale ocean monitoring. As the situation exists there are no theoretical or physical restrictions on the applicability of such a method to ocean monitoring. However, the availability of field data is still scanty. Only a few groups of researchers are actively involved in such a work as of now.

The field of 'Tomography in Ocean Surveillance' is still in the formulation stage but holds great promise. Some work on parameter estimation for localization is underway. Practical algorithms are to be developed. Some of the aspects that are to be studied are :

(1) Effect of medium spreading loss, multipath, parameter fluctuations on reconstruction algorithms.

(2) Effect of beamformer beamwidth and variation with frequencies. This may indicate the necessary deconvolution technique.

(3) Effect of target structure material and geometry (coherent echo formation).

(4) Ability to measure any function from multiarray sonar configuration.

On the reconstruction front, major efforts are still restricted to medical imaging though some work on geophysical and radar imaging are available. To exploit the full potential of such technique, the field of research has to penetrate other fields. A promising general area for future research is the application of various general purpose inversion techniques to image reconstruction.

Acknowledgements

The author would like to thank Messrs V. Chander and V. Nagarajan for many helpful discussions.

References

1. Munk, K. & Wunseh, C., *Deep Sea Research*, **26A** (1979), pp 123-161.
2. Spindel, R. C., *IEEE Conf. on Aerospace and Elcctronic Systems EASCON*, (1980), pp 165-170.
3. Adams, S. L., *IEEE Conf. on Ocean Environment, Oceans*-81, (1981), pp 21-25.
4. Cornuelle, B. D., *IEEE Trans. on Geoscience and Remote Sensing*, **GE-20** (1982), pp 326-332.
5. Whalen, W. L., *Sea Technology*, August 1984, pp 57-61.
6. Special Issue on Computerized Tomography, *Proc. IEEE*, **71** (3), March 1983.
7. Bates, R. H. T., Garden, K. L., & Peters, T. M., *Proc. IEEE*, **71** (1983), pp 356-372.
8. Herman, G. T., Image Reconstruction from projections, Springer-Verlog, Berlin, 1979.
9. Macovski, A., *Proc. IEEE*, **71** (1983), pp 373-378.
10. Louis, A. K. & Natterer, F., *Proc. IEEE*, **71** (1983), pp 379-389.
11. Lewitt, R. M., *Proc. IEEE*, **71** (1983), pp 390-408.
12. Rossi, D. J. & Willsky, A. S., *IEEE Trans. on Acoustics, Speech and Signal Processing*, ASSP-32 (1984), pp 886-906.

13. Censor, Y., *Proc. IEEE,* **71** (1983), pp 409-419.
14. Special Issue on Physical and Computational Aspect of 3 Dimensional Image Reconstruction, *IEEE Trans. on Nuclear Science*, **NS-21** (1974).
15. Gilbert, P., *Journal of Theoretical Biology*, **36** (1971), 105-117.
16. Nagarajan, V., Chander, V. & Aatre, V. K., *Proc. of IEEE Conf. on Computers, Systems and Signal Processing, Bangalore*, Dec 1984, Vol. III.
17. Rockmore, A. J., *IEEE Journal on Ocean Engineering*, **OE-7** (1982), pp 83-89.