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Cover photo: Cloud formations over the western Aleuthian Islands, taken by Landsat 7, 1 June 2000.
Credit: US Geological Survey, Earth Resources Observation and Science (EROS) Center.

ACOUSTIC TOMOGRAPHY, OCEAN

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Synonyms

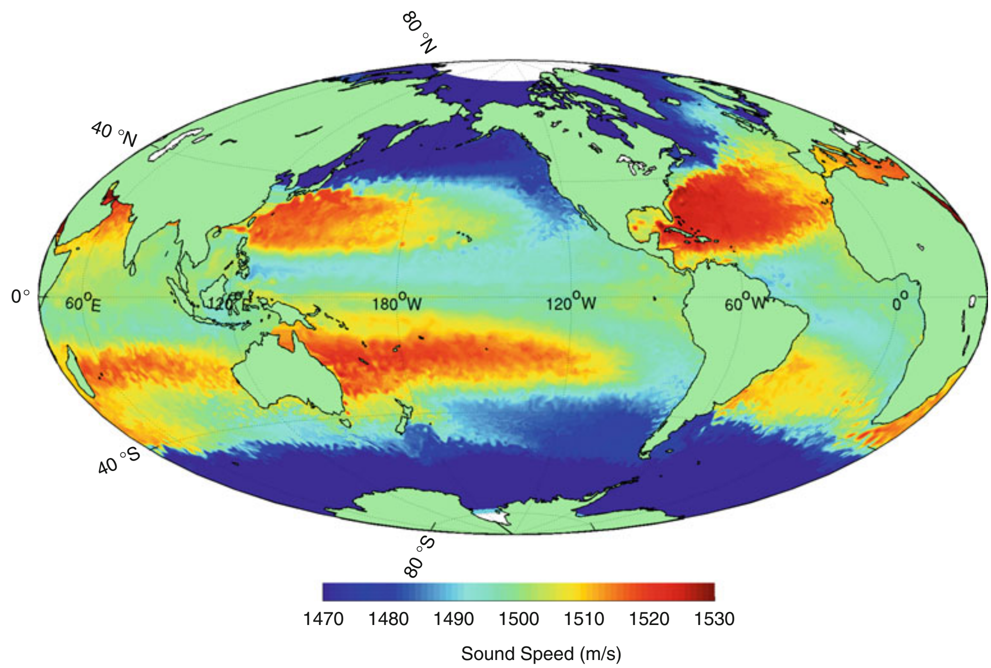
Acoustic thermometry; Acoustic Thermometry of Ocean Climate (ATOC); Moving ship tomography; Ocean acoustic tomography (OAT); Reciprocal tomography

Definition

Ocean acoustic tomography is a remote sensing technique that employs the transmission of sound over large distances within the ocean to precisely estimate averages of temperature and current. Acoustic tomography data usually consist of time-of-flight travel times of acoustic pulses, which represent natural integrating measures of sound speed and current along acoustic paths. Variations in sound speed are predominantly caused by variations in temperature.

Introduction

Acoustic tomography is a technique for measuring large-scale ocean temperature and current using acoustic signals propagating over 100–1,000 km distances. The technique relies on the nature of the oceanic sound speed profile, which acts as an acoustic waveguide, and the transparency of the ocean to low-frequency sound. Sound speed is



Acoustic Tomography, Ocean, Figure 1 Sound speed at 300 m depth derived from an ocean ocean state estimate from the "Estimating the Circulation and Climate of the Ocean" (ECCO) project. Sound speed is a proxy variable for temperature over most of the world's oceans.

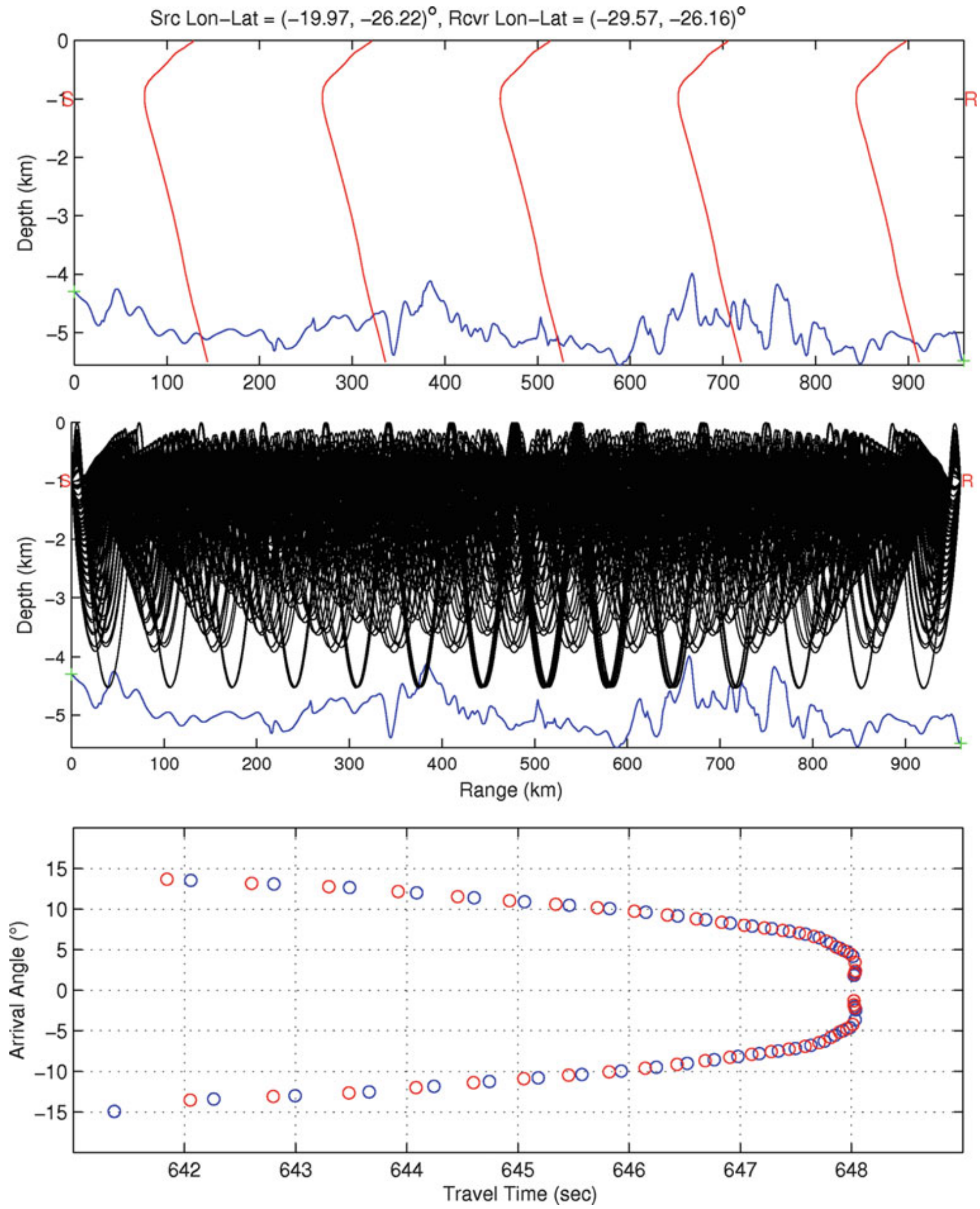
a function of temperature, salinity, and pressure (Jensen et al., 2011), with an approximate value of 1.5 km/s (Figure 1). Over most of the world's oceans, the sound speed profile has a minimum at about 1,000 m depth, with sound speed that increases towards the surface as a result of increasing temperature and increases towards the seafloor as a result of increasing pressure. Acoustic signals are therefore trapped in the sound channel by refraction (Figure 2). By recording time series of travel times of acoustic signals, the variability of ocean temperature can be inferred. A typical acoustic arrival pattern consists of a set of 5–15 pulse arrivals spanning several seconds, corresponding to a set of distinct acoustic ray paths. Tomography is a unique measurement in that it is inherently averaging: over range along the path of acoustic propagation and over depth from the cycling of the acoustic signals over the water column. The measurements of large-scale ocean temperatures and currents can be extraordinarily precise.

The concept of acoustic tomography was originally proposed by Walter Munk and Carl Wunsch in the late 1970s in response to the discovery that mesoscale variability in the ocean was intense and ubiquitous (Munk and Wunsch, 1982; Munk et al., 1995; von Storch and Hasselmann 2010). The mesoscale presented a challenging observational problem for oceanography. The proposed answer to this challenge was the in situ integrating measurements of acoustic tomography combined with the near-synoptic measurements of sea-surface height by satellite altimetry. Several acoustic sources and receivers were to be deployed, forming an array with many acoustic paths crisscrossing a region of interest. The term "tomography" was borrowed from medical tomography, to bring to mind those imaging capabilities. Information available from ocean acoustic tomography is much sparser than from medical tomography, however. From the beginning, the acoustic measurements were to be combined with information from other data types using ocean modeling and data assimilation techniques for optimal estimation of the ocean state (Cornuelle and Worcester, 1996; Menemenlis et al., 1997; The ATOC Consortium, 1998; Rémy et al., 2002; Lebedev et al., 2003).

Sound speed and current

Nominally, a 1 °C change in temperature corresponds to a 4 m/s change in sound speed, while a 1 PSU change in salinity corresponds to a 1.3 m/s change in sound speed. Observed changes in sound speed, measured by tomography through the changes in travel times of acoustic pulses, are therefore ambiguous between temperature and salinity. As a practical matter, however, changes in ocean temperature of 1 °C are common, while changes in ocean salinity of 1 PSU are rare. Other than in extreme environments, the possible effects of salinity changes on acoustic travel times can be ignored.

Ocean currents also affect the time of flight of acoustic pulses, although the magnitudes of current variations are



Acoustic Tomography, Ocean, Figure 2 Top: Sound speed profiles derived from the NOAA 2009 World Ocean Atlas along a 960 km section along 26 °S in the Brazil Basin. Middle: Associated acoustic ray paths between a source and a receiver, both at 1,000 m depth. Bottom: Associated ray arrival pattern shown as arrival angle versus travel time. The rays arrive in groups of four, corresponding to the possible signs of the ray angles at the source and receiver. The Brazil Basin has almost ideal characteristics for acoustic tomography. Each region of the ocean has its own unique acoustic properties.

usually an order of magnitude smaller than sound speed variations. The two effects can be separated using reciprocal acoustic transmissions. Reciprocal tomography employs transceivers that transmit coincident signals in opposite directions. The travel times of acoustic pulses with the current will be different than the travel times against the current. By forming the sum and difference of reciprocal travel times, the contributions of sound speed and current can be distinguished.

An early test of reciprocal tomography (RTE87) was conducted in 1987 in the central North Pacific using reciprocal acoustic propagation over ranges of O (1,000 km). Current variations of about 10 mm/s were measured, while sound speed variations were about 25 m/s (Munk et al., 1995). Expressed in terms of acoustic travel times, the nominal time of flight of the acoustic pulses in this experiment was about 600 s, the variations in temperature caused travel time variations of about

0.1 s (summertime warming of the near-surface ocean), and the variations in currents caused travel time variations of about 0.005 s (tidal and low-frequency barotropic currents).

As a corollary to the measurement of current, the integration of currents over the paths of a triangular array of tomographic transceivers is a measure of areal-averaged relative vorticity by Stokes' theorem (Munk et al., 1995). The precision of this measurement can be illustrated by the use of tomography to measure "tidal vorticity" or the changes to relative vorticity primarily induced by the changes in water column depth by tidal elevation. Tidal vorticity of order 10^{-9} s^{-1}, five orders of magnitude less than the planetary vorticity (local inertial frequency), was measured in the western North Atlantic using a pentagonal tomographic array of 660 km diameter deployed in 1991 (Dushaw et al., 1997).

Rays and modes

The determination of information about ocean variability from acoustic data is an inverse problem that requires an ocean model that can be fit to the data using weighted least squares techniques (Munk et al., 1995; Worcester, 2001). Possible models range from a simple time-independent model employing a truncated Fourier series and baroclinic modes to represent horizontal and vertical variability to sophisticated time-dependent dynamical models. The choice of the model depends on the nature of the observed ocean variability and the goals of the oceanographic analysis.

The prerequisite for any inverse problem is a solution for the forward problem, however. Predictions for the acoustic arrival pattern of travel times in any particular experiment geometry can be readily computed by a variety of means, including ray tracing, acoustic modes, or the parabolic wave equation (Jensen et al., 2011). Accounting for a variety of acoustic properties, such as ray travel time and arrival angle, identification of predicted arrivals with measured arrivals is usually unambiguous. This identification is often impossible when the acoustic signals have interacted with the sea floor, however. The tomographic information about the ocean is indicated by the small discrepancies between the predictions and measurements. One goal of this identification is to determine the spatial sampling characteristics, or "measurement kernels," of the acoustics. Most often the measurement kernels are taken to be just the ray paths identified with particular ray arrivals. The measured ray travel times are the integrals of the reciprocal of sound speed along the ray paths. The measurement kernel, combined with the ocean model, enables the essential elements of the inverse problem to be computed, and the weighted least squares solution of that inverse problem gives the desired estimate of ocean variability from the acoustic data.

While acoustic rays have been the measurement kernels most commonly employed for the inversion of tomography data, acoustic modes have also been employed, particularly in polar regions where the polar sound speed profile confines the lowest modes near the surface. The upper ocean is a region of particular interest, of course. The near-surface modes are also sometimes matched to particular water masses in the Arctic (Mikhalevsky and Gavrilov, 2001).

Recently, "travel-time sensitivity kernels" have been computed, which relate the sampling of the complete acoustic wave field to particular travel times (Skarsoulis et al., 2009). Stemming from this rigorous description of the acoustic field was the important proof, long known in practice, that the measurement kernels computed using the geometric-ray approximation are an accurate representation of the actual sampling associated with particular ray arrivals.

Applications

Over the past 30 years, tomography has been employed for wide-ranging applications (Munk et al., 1995; Dushaw et al., 2010). Several examples that highlight the strengths and roles of the measurement will be mentioned here; more substantive reviews of applications can be found in Munk et al. (1995), Dushaw et al. (2001, 2010), and Worcester (2001).

The Greenland Sea Project deployed a six-mooring tomographic array with 100 km diameter in 1988 in the region of deep convective mixing in the Greenland Sea (Morawitz et al., 1996). The Greenland Sea is one of the few regions where deep water of the world's oceans is formed. The aim of the Greenland Sea Project was to quantify this water formation. Tomography was ideal for this measurement because its remote sensing capability was essential in this harsh, sometimes ice-covered, environment, the quantity measured was the net deepwater formation which is an integrated quantity, and the deepwater formation is episodic and unpredictable in time and location. The rapid sampling of integrated temperature afforded by the acoustic measurements proved to be essential in estimating the net deepwater formation over the winter of 1988/1989. Concurrent, extensive measurements by CTD casts proved to be inadequate to the task.

With the ability to make repeated, integrated measurements along an acoustic path, tomography is often employed to monitor temperature or current averaged across straits or other constricted regions. Mass transport and heat content through the Strait of Gibraltar were measured by reciprocal tomography in 1996 (Send et al., 2002). Temperature variations in Fram Strait are presently monitored by tomography by the multiinstitutional ACOBAR collaboration. Within Fram Strait the complicated West Spitsbergen and East Greenland Current systems transport heat and salt between the North Atlantic and Arctic Oceans. One experiment conducted in the late 1990s by the French Research Institute for Exploration of the Sea (IFREMER) aimed to measure the net transport of heat and salt by subsurface salt lenses, or Meddies, out of the Mediterranean into the North Atlantic.

With its inherent averaging properties, tomography can make unique, accurate measurements of large-scale barotropic currents. The barotropic currents estimated from the RTE87 data had an uncertainty of about 1 mm/s. Relative vorticity associated with the RTE87 currents was of order $10^{-8}\ s^{-1}$ (Munk et al., 1995). Measurements of barotropic tidal currents by tomography are the most accurate available; they have been used to test global tidal models. These capabilities have been underutilized in ocean observation.

Whereas the difference of reciprocal travel times is primarily a measure of depth-averaged current, the sum of reciprocal travel times is primarily a measure of the sound speed signature of the first internal or baroclinic mode. The exact resolution of vertical variability, or resolution of higher-order modes, depends on the available vertical sampling of the rays in any particular region. The inherent depth average of the measurement makes the first baroclinic mode the dominant signal, however, when ocean variability is characterized by baroclinic modes. This property led to the detection of radiation of coherent mode-1 internal tides far into the ocean's interior and placed tomography at the forefront of internal-tide and ocean mixing revolution that has unfolded over the past two decades. One interesting aspect of these observations is that an acoustic path acts as line-segment antenna for the internal-tide radiation. The beam pattern for this antenna has narrow maximum response for wave numbers perpendicular to the acoustic path, corresponding to wave crests aligned along the acoustic path. The culmination of these observations, brought together with the more synoptic observations of these waves by satellite altimetry, was the demonstration that mode-1 internal tides propagate coherently across ocean basins. Tidal harmonic constants can be used to predict the amplitude and phase of the mode-1 internal tides over many regions of the world's oceans (Dushaw et al., 2011).

Over the past 30 years, there have been numerous experiments employing multipath tomography arrays for ocean observation. These experiments have taken advantage of the fact that the number of paths of an array increases quadratically with the number of deployed instruments. Experiments have often consisted of a 5 or 6 mooring pentagonal array, as was the case in the Greenland Sea array (Morawitz et al., 1996), the 1990–1991 Acoustic Mid-Ocean Dynamics Experiment (AMODE) in the western North Atlantic (Cornuelle and Worcester, 1996), and the 1997 Kuroshio Extension Pilot Study array (Lebedev et al., 2003). Other experiments have been deployed in the equatorial Pacific (Kaneko et al., 1996). The 2000–2001 Central Equatorial Pacific Tomography Experiment (CEPTE) was aimed at observing the weak meridional currents of the equatorial current system. These experiments have been designed following the original Munk and Wunsch notion to better understand a complicated region by making sparse tomographic observations that are combined with all available ancillary data by ocean modeling and data assimilation techniques. These studies have quantitatively shown that the tomographic data type affords a significant resolution of ocean properties not possible by other data types.

Acoustic thermometry of ocean climate

The use of acoustic transmissions across ocean basins to measure the temperature has come to be called acoustic thermometry. These measurements are made possible by lowering the transmitted acoustic frequency to reduce the sound attenuation. With 20–60 Hz sound signals, the range of acoustic propagation in the ocean does not appear to be limited. The aim of these basin-scale observations is to precisely quantify the large-scale changes in ocean temperature (Dushaw et al., 2001, 2010).

One of the first tests of long-range acoustic transmissions for the purpose of ocean climate measurements was the Heard Island Feasibility Test (HIFT). In a 9 day test in 1991, 57 Hz acoustic signals were transmitted from an array of acoustic sources lowered from the R/V Cory Chouest near Heard Island in the southern Indian Ocean (Munk and Baggeroer, 1994). The site is a location with unblocked acoustic paths to both coasts of the United States, and, indeed, the transmitted signals were recorded off the coasts of Nova Scotia and Washington state. The attempts to measure ocean temperatures over antipodal acoustic ranges were then abandoned with the recognition that measurements across several climatological regimes were perhaps less useful than basin-scale measurements.

The HIFT was succeeded by the decade-long (1995–2006) Acoustic Thermometry of Ocean Climate (ATOC) program (The ATOC Consortium, 1998; Dushaw et al., 2009). This program deployed 75 Hz acoustic sources off central California and north of Hawaii to transmit tomographic signals across the North Pacific Basin. The program employed receivers of opportunity and arrays of hydrophones specifically designed to determine the properties of acoustic propagation over several megameter ranges. The acoustic data were used to test accuracy of ocean state estimates of the North Pacific obtained by various means, including simple forward integration of a model, objective analysis of hydrographic and altimeter data, and assimilation of available data to constrain general circulation models. The travel times measured over a decade were compared with equivalent travel times derived from the several state estimates. The comparisons of computed and measured time series provided a stringent test of the accuracy of the large-scale temperature variability in the models. The differences were sometimes substantial, indicating that acoustic thermometry data does provide significant additional constraints for numerical ocean models.

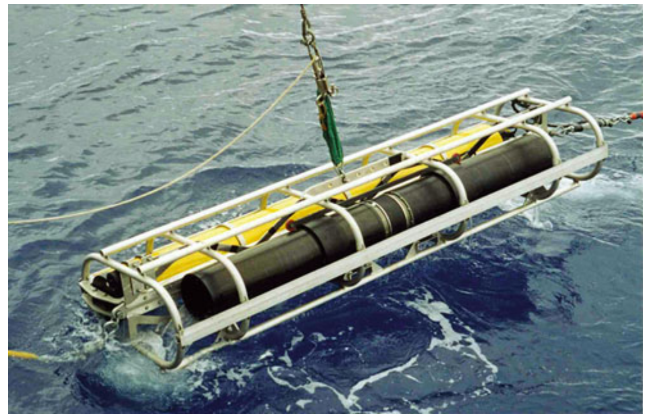
Averages of temperature across the Arctic Ocean were measured in the 1994 Transarctic Acoustic Propagation (TAP) and 1999 Arctic Climate Observations Using Underwater Sound (ACOUS) experiments (Mikhalevsky and Gavrilov, 2001). These experiments were among the first observations of warming of the Atlantic Layer in the Arctic Ocean. Using acoustics to remotely sense ocean temperature and other properties under the ice is a particularly compelling application of tomography.

Instrumentation

One of the technical advances that made tomography possible was the development of broadband, controlled sound sources in the 1970s to replace explosive charges. By employing lengthy coded signals and pulse compression techniques, the energy of the sound signals is spread over several minutes, while the travel time resolution achieved after signal processing is about a millisecond. The peak pressure of these controlled signals is much less than signals from the explosive sources. Typical sound levels are 25–250 W (or 185–195 dB re 1 μPa at 1 m). Low-frequency (75–300 Hz), broadband acoustic sources are large and heavy, however. The size of the source is determined by the acoustic wavelength, which, for 250 Hz signals, is 6 m. One acoustic source commonly used today is a tuneable organ-pipe transducer of about 4 m length and 1,000 kg weight that usually broadcasts a swept-frequency signal from 200 to 300 Hz (Figure 3). Broadband acoustic sources, such as the HLF-5, are also power hungry. Moored acoustic sources powered by lithium or alkaline battery packs can transmit coded signals of a few minutes length several times a day for durations of about a year. Timekeeping is maintained using a rubidium atomic clock. The 75 Hz acoustic sources of the ATOC program were mounted on the sea floor and powered and controlled by a cable to shore.

A tomographic receiver typically consists of a small vertical array of about 4 hydrophones spaced by 1.5 wavelengths. Hydrophone arrays allow for beamforming of the received signals, which boosts the SNR of the acoustic arrival pattern and gives a determination of the ray arrival angles. The arrival angle information is important for matching recorded to predicted arrivals and for distinguishing rays that arrive at about the same time but with different angles (Figure 2, bottom). Tomography transceivers usually consist of a mooring with an acoustic source placed near the sound channel axis and a small vertical line array (VLA) immediately above or below. Both instruments are controlled by a single electronics package.

Recently hydrophone modules were developed with the ability to communicate with a controlling electronics package by induction along the mooring wire. These hydrophone modules allow the deployment of VLAs of any number and spacing, since they can be clamped on the mooring wire at arbitrary locations. For acoustics research, VLAs of 100 or more hydrophones have been employed. These modules include thermistors as well, so that a VLA can act as a thermistor chain. Hydrophones have a broadband sensitivity and of course can also be used for studies of ambient sound.



Acoustic Tomography, Ocean, Figure 3 A Webb Research swept-frequency acoustic source as it is deployed from a ship. The black cylinder is the "organ pipe" acoustic source, and the yellow cylinder is an alkaline battery pack. In the photo the source is horizontal; once deployed the right hand side will be oriented towards the surface. The source is mounted within an aluminum cage for protection during shipping and deployment. Courtesy of Lloyd Green, Scripps Institution of Oceanography.

One extension of tomography is the concept of "Moving Ship Tomography." The technique aims to make the most of a deployed array of acoustic sources by circumnavigating this array while repeatedly lowering a hydrophone array from a ship to receive the acoustic signals. The aim is to eventually accumulate enough acoustic data that the temperature field within the circumnavigation can be mapped to considerable resolution. Since it can take up to 60 days to circumnavigate a region of 1,000 km diameter, data assimilation techniques are required to account for the evolution of the temperature field while the data are obtained. Recently hydrophones have been experimentally deployed on gliders to receive signals transmitted by tomographic sources.

Passive tomography is an experimental technique that aims to avoid the expense and trouble of moored acoustic sources by using ambient sounds as tomographic signals. The technique employs coordinated receiving arrays deployed on either side of an area of observation. Ambient sound, preferably from such sources as a distant ship or whale, propagating past one array then forms a known signal when it is received on the second array. By comparing the two acoustic signals, information about the intervening ocean might be inferred.

Marine mammals and active acoustics

The HIFT and ATOC programs engendered considerable controversy concerning the possible effects of the transmitted sounds on marine mammals and other marine life (Potter, 1994). The issue presented a formidable challenge in public relations, since it included marine science, climate, and acoustics topics, many of which are still areas of active research. For example, one newspaper report confused sound levels in air with those in water, which are defined differently, making the underwater acoustic sources appear to be several orders of magnitude louder than they actually were. The sound transmitted by the ATOC sources was 195 dB re 1 μPa at 1 m (about 250 W), with a low duty cycle (ca. 2 %) consisting of eight brief transmissions every few days. Because of spherical spreading, 1,000 m from the source the signal level was only 135 dB (about 2.5×10^{-4} W).

As a result of the controversy, the 1996–2006 ATOC and NPAL (North Pacific Acoustic Laboratory) projects included a Marine Mammal Research Program (MMRP) to study the potential effects, if any, of the ATOC sound sources on marine mammals and other marine life. (Indeed, the issue of the effects of acoustics on marine mammals proved to be a boon for marine mammal research.) The MMRP did not find any overt or obvious short-term changes in the distribution, abundance, behavior, or vocalizations of marine mammals in response to the playback of ATOC-like sounds or in response to the transmissions of the ATOC sound sources themselves. The MMRP investigators concluded that the ATOC acoustic transmissions caused no significant biological impact (National Research Council, 2000).

Summary

Ocean acoustic tomography uses the travel times of coded acoustic signals transmitted over 100–1,000 km ranges to infer precise information about the ocean temperatures and currents. In most regions of the world's oceans, sound speed is an accurate proxy variable to temperature; salinity contributions are negligible. One primary strength of the measurement is that it is inherently averaging, suppressing the small-scale internal wave or mesoscale noise that can make it difficult to observe the large-scale signal. Predicted acoustic ray paths can be identified with measured multipath arrivals and used in an inverse analysis to estimate ocean variability. Ray paths have been shown to accurately represent the measurement kernel for the recorded arrivals. The variations of both sound speed and current can be estimated using acoustic transmissions sent reciprocally between transceiver pairs.

Tomography data are perhaps best employed by combining them with other data types, such as satellite altimetry and Argo floats, using data assimilation techniques and ocean models. Such techniques bring together dynamical constraints and disparate data types, each with its own sampling, bias, and error characteristics, to obtain optimized state estimates for the ocean.

Over the past 30 years, tomography has been employed for disparate applications, ranging from the quantification of deepwater formation in the Greenland Sea to the detection of internal-tide radiation from the Hawaiian Ridge to basin-wide measurements of temperature in the central North Pacific. Tomography often requires careful analysis and interpretation, depending on the unique acoustic and oceanographic conditions of the region where it is employed. Whether used for regional- or basin-scale observations, acoustic remote sensing has been quantitatively shown to provide information about ocean variability that is not possible to obtain by other approaches.

Acoustic tomography was accepted as part of the emerging Ocean Observing System during both of the OceanObs'99 and '09 international workshops (Dushaw et al., 2001; Dushaw et al., 2010). Within the observing system context, the instrumentation for tomography can serve multiple purposes. Hydrophone arrays are used to study a wide range of human, biological, and geological activity. Acoustic sources can transmit signals that can serve other purposes, such as signals that can be used to track drifting instrumentation. Thus, a modest set of active and passive acoustic instrumentation deployed worldwide can form a general-purpose global acoustic observing network (Howe and Miller, 2004; Boyd et al., 2011).

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Links

Acoustic Technology for Observing the interior of the Arctic Ocean (ACOBAR): http://acobar.nersc.no
The Heard Island Feasibility Test (HIFT): http://909ers.apl.washington.edu/dushaw/heard/
North Pacific Acoustic Laboratory (NPAL): http://npal.ucsd.edu/
Ocean Acoustics Library: http://oalib.hlsresearch.com/
Discovery of Sound in the Sea (DOSITS) http://www.dosits.org/
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