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Dynamic Meteorology and Oceanography

Surprises in Physical Oceanography: Contributions from Ocean Acoustic Tomography

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REVIEW ARTICLE



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ABSTRACT

The author has employed ocean acoustic tomography over the past 30 years to examine problems in physical oceanography, often with surprising results. Tomography offers an accurate measurement of current or sound speed (temperature) averaged over 100s to 1000s of kilometers. It has been used to test the fundamental equation for the speed of sound in seawater and to show that the normal state of the ocean has smooth, stable, well-behaved characteristics of acoustic propagation. This latter property has been challenging for ocean models to reproduce. Tomography measures barotropic tidal currents with remarkable accuracy, and it was used to discover that low-mode internal tides radiate far into the ocean's interior, while retaining a surprising coherence. Tomographic measurements of large-scale temperature are complementary to point measurements by hydrography; the present observing system, relying principally on altimetry and Argo floats, has little skill in predicting the available tomographic data. The addition of tomographic data to the system would substantially reduce the uncertainty of ocean state estimates. The information content of integral acoustic observations is best exploited as a constraint on ocean models by data assimilation. The applications of tomography for measuring large-scale barotropic current, relative vorticity, and temperature have been under-exploited. Dedicated research programs, supporting novel acoustical oceanography, associated instrumentation development, and multidisciplinary research would further the applications of this observational approach.

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1. INTRODUCTION

This paper is a review of the ocean measurement technique known as ocean acoustic tomography, focussing on its contributions to physical oceanography. The observational method employs the transmissions of acoustic signals through the ocean over 100's to 1000's of kilometers to obtain average measures of ocean temperature or current. The paper is not meant as a comprehensive review but, instead, focusses primarily on the author's contributions. This review affords an opportunity to provide additional details about how the various results came about, and to comment on those results in hindsight.

General reviews of tomography can be found in the monograph by Munk, Worcester, and Wunsch (Munk et al. 1995), and in Worcester (2001), or Dushaw (2013). Past reviews of tomography and acoustics and their proposed uses in Ocean Observing Systems (OOS) can be found in the decadal reviews of Dushaw and Co-authors (2001), Dushaw and Co-authors (2010), and Howe et al. (2019). The latter paper also provides an up-to-date review of the latest acoustical instrumentation. Considerable activity with tomography has recently been occurring in Arctic regions. The acoustic measurements can be made under sea ice, while other techniques often require surface access. Mikhalevsky et al. (2015) provide a review of acoustical applications in Arctic regions.

Walter Munk and Carl Wunsch introduced ocean acoustic tomography as a means for large-scale, synoptic observations in the late 1970s (Munk and Wunsch 1982; Munk et al. 1995). Munk advocated for tomography for 40 years (Munk and Wunsch 1979, 1982; Munk 1986, 2006, 2011; Worcester and Munk 2016), but the oceanographic community has been reluctant to embrace and exploit this observational technique. Actual scientific assessments of the potentials and limitations of tomography against other approaches are still lacking, however. The title of the paper is adapted from the monograph by R. Peierls, *Surprises in Theoretical Physics* (Peierls 1980), and a primary theme of that monograph is adopted for this paper as well: Preliminary assessments of tomography have often led to paradoxical preconceptions; yet closer reasoning and careful data analysis have resulted in surprising resolutions to questions, or led to discoveries. By studying such surprises and learning what kind of possibilities to look for, oceanographers may be able to better anticipate and exploit the observational potentials of tomography.

To keep focus on oceanography, this paper purposely omits the technical engineering, acoustical, or signal processing aspects of tomography. The paper begins with three sections on acoustical and oceanographic considerations that are at the foundations of tomography, and it continues with sections on barotropic

and baroclinic tides, barotropic currents and relative vorticity, and acoustic thermometry of ocean basins.

2. THE SPEED OF SOUND IN SEAWATER

In the 1980s there were two primary competing equations for the speed of sound in seawater, the Chen and Millero (1977) and Del Grosso (1974) equations. While the values of the two equations agreed near the sea surface, they differed by about 0.6 m s^{-1} under deep-ocean pressures. Under the guidance of my doctoral advisors Peter Worcester and Walter Munk at the Scripps Institution of Oceanography (SIO), one of my first projects was to use tomographic data obtained in the central North Pacific by the 1987 Reciprocal Tomography Experiment (RTE87) to test the sound speed equations and compute corrections to the equations. The experiment by Worcester and Bruce Howe occurred from May to September 1987, before my arrival at Scripps in fall 1987. An early equipment test, RTE87 consisted of a triangular array of sides 750-, 1000-, and 1250-km formed by acoustic transceivers on three moorings (Dushaw 1992; Dushaw et al. 1993a). Broadband acoustic sources of 250-Hz center frequency were employed. Using a general circulation model, Malanotte-Rizzoli and Holland (1985) simulated the sort of data the experiment would obtain and provided an early vision for how the tomography data could be employed for studies of the general circulation. The test of the sound-speed equations required data of high accuracy. Worcester et al. (1991) provide a review of the state of tomography at the end of the 1980s.

The three basic parameters required for the test are distance between acoustic source and receiver, acoustic travel time, and the speed of sound along the acoustic section (speed times time equals distance). The ranges between moorings of $O(1000 \text{ km})$ were determined to $O(70\text{-m})$ accuracy and travel times of $O(500 \text{ s})$ were determined to $O(10\text{-ms})$ accuracy. Such extraordinary accuracies are one of the hallmarks (requirements) of tomographic measurements. Accurate positioning was obtained using the Global Positioning System (GPS) and a positioning system employing high-frequency acoustic transmitters on the sea floor surrounding each mooring. Atomic clocks were used to keep accurate time. The sound speed environment was measured by Conductivity Temperature Depth (CTD) and EXpendable BathyThermograph (XBT) hydrographic sections obtained along the acoustic paths, from which sound speed was computed. The sections were obtained along the three array paths at the times of mooring deployment and recovery, so six independent sound speed sections were available. Early in the analysis it was readily apparent that the Del Grosso equation was more accurate, since computations of ray travel times with it resulted in predicted arrivals that agreed better with the data in both absolute travel time and in dispersal of travel

time arrivals (**Figure 1**). The arrival patterns consisted of about 10 identifiable ray arrivals. “Identifiable” means that an arrival pattern computed using a smoothed representation of the sound speed section gives ray travel times whose pattern matches that observed. Thus, an observed arrival peak is identified with a predicted arrival and its associated ray path.

The analysis consisted of computing corrections to the sound speed equations by combining the acoustic and hydrographic data using objective-mapping methods and a parameterization for the sound speed corrections with depth. The sound-speed corrections were computed, accounting for all uncertainties. The procedure also obtained corrections for range, which were distinguishable from sound-speed error. The sound speed was tested to an accuracy of $\pm 0.05 \text{ m s}^{-1}$ (Dushaw et al. 1993a). The Del Grosso equation had minimal error. My tutor for the objective map techniques was Bruce Cornuelle, e.g., Cornuelle et al. (1989), and this calculation is perhaps the simplest example of combining acoustic and hydrographic data by such methods. The objective mapping technique, also known as weighted least squares or the inverse [measurements of travel time are “inverted” for estimates of temperature], is essential to the analysis of tomographic data. Though it is a basic analysis approach for most oceanographic data, I was later surprised to learn that the technique was often unfamiliar to oceanographers. Other examples of applications of the technique given below include computing maps of the internal tides and analyzing an observing system for the North Atlantic.

This test of sound speed equation would later prove valuable in the derivation of the equation of state for

seawater (the Thermodynamic Equation of Seawater (TEOS)) (IOC, SCOR, and IAPSO 2010; Millero 2010; Pawlowicz et al. 2012), sound speed being a principal thermodynamic variable for sea water. In reviewing the history of the sound speed equations, this author traced the error in the Chen-Millero equation to an unnecessary and erroneous calibration for pressure by those authors.¹

3. THE TIME-MEAN STATE OF THE OCEAN AND LONG-RANGE ACOUSTIC PROPAGATION

The discussion above skipped over an assumption about the property of long-range acoustic propagation in the deep ocean. The sound speed environment of the open ocean is remarkably stable and well behaved (Dushaw et al. 2013). A standard, smooth representation for the ocean environment such as the National Oceanic and Atmospheric Administration (NOAA) World Ocean Atlas (Antonov et al. 2010; Locarnini et al. 2010) can be used to accurately predict the basic properties of acoustic propagation (an atlas of acoustic arrival patterns for regions of the world’s oceans can be found at the end of the Munk et al. (1995) monograph). What is more, the environment appears to be mostly unchanging such that a smooth sound speed product derived from recent data can be reasonably employed for acoustic computations for situations 50 or 100 years ago. Ordinary ocean variability perturbs this mean state, of course, but, from an acoustics perspective, usually only in relatively small ways. In the central North Pacific, ray travel times over 1000 km are about 600 s, while the enormous heat

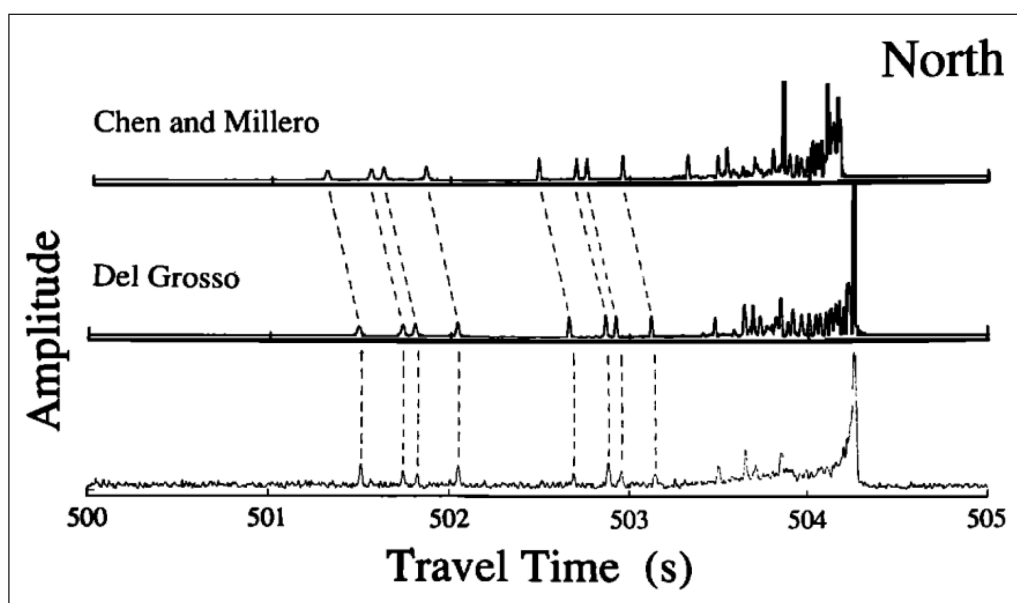


Figure 1 Acoustic arrival patterns measured over 750-km range in the central North Pacific in 1987 proved to be a precise test of the equations for the speed of sound in seawater (Dushaw et al. 1993a). The absolute travel time and dispersal pattern of the ray arrivals of the measured data are consistent with the Del Grosso sound speed equation. Such acoustic arrival patterns have proved to be stable and predictable throughout the world’s oceans. (From Dushaw et al. (1993a) by permission.)

content change from the seasonal cycle affects travel time by only $O(0.1\text{ s})$ (Dushaw et al. 1993b). The effects of horizontal refraction and variations of salinity on tomographic measurements are negligible (Voronovich et al. 2005; Dushaw 2014; Morawitz et al. 1996; Dushaw et al. 2009, 2016b). Sound speed and temperature may be used interchangeably. The scale factor for converting between the two varies from 3.5 to 4.5 $\text{m s}^{-1} \text{C}^{-1}$, depending on temperature.

Another key assumption for tomography is that over most of the world's oceans, the travel time and dispersal

of an acoustic arrival pattern can be readily computed and compared to measurement (Jensen et al. 2011) (*Figure 2*). This comparison is the “forward problem” for tomography. The assumption has been generally true, with occasional exceptions in the details of acoustic propagation in more complicated or extreme regions. The arrival pattern, including travel times and ray arrival angles, is a unique fingerprint, not unlike a supermarket bar code. Such a fingerprint makes ray identification possible, such that an acoustic ray path can be identified with a particular recorded ray arrival. An identified ray path

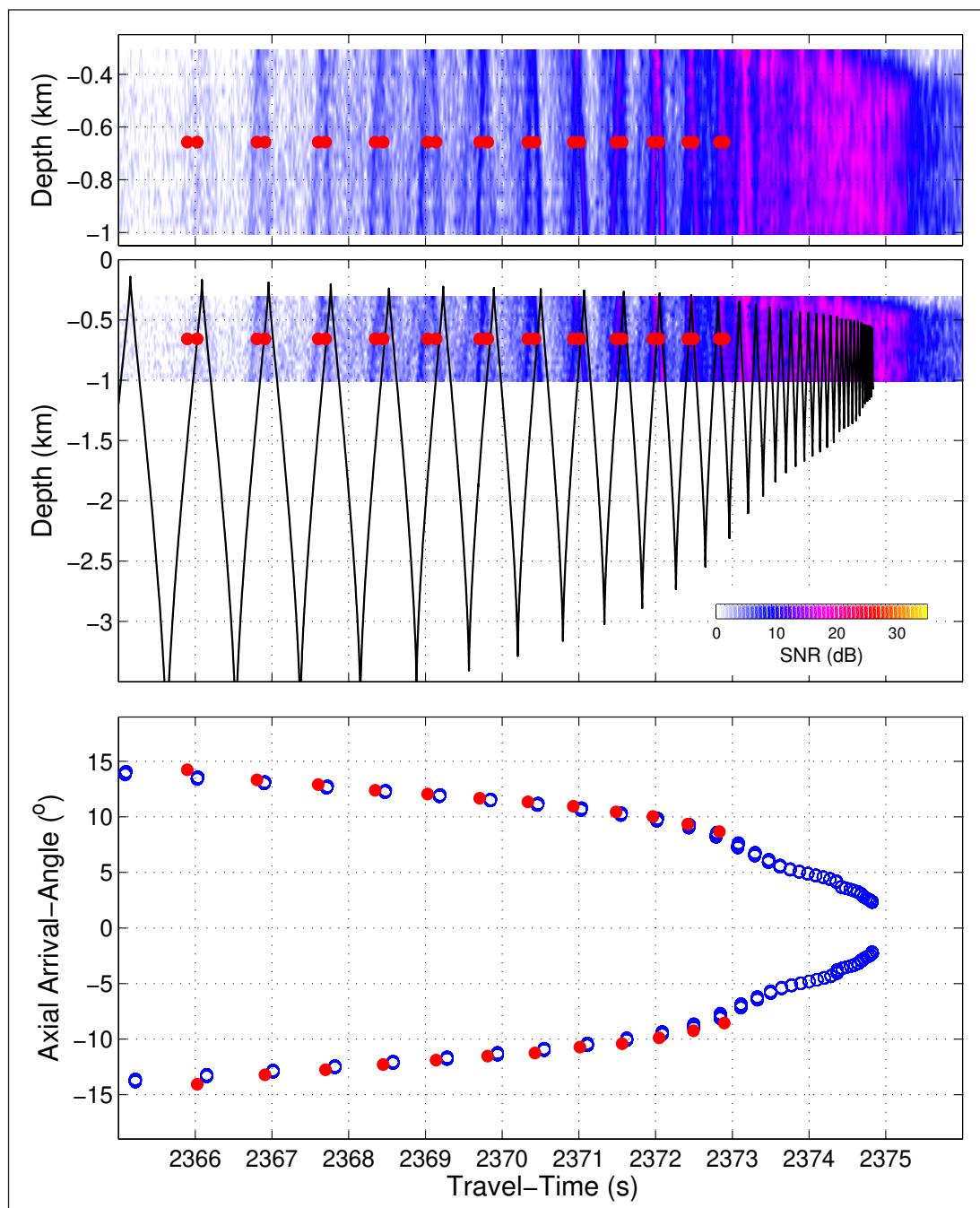


Figure 2 (top) The time front measured by a vertical line array near Hawaii from a transmission from Pioneer Seamount (3515-km range) on 15 May 1996. The red dots indicate the average travel times derived from the data. (middle) The measured time front compared to the time front calculated from the 2005 World Ocean Atlas (black lines). A travel time offset of +0.3 s has been applied to the predictions to achieve the alignment. (bottom) Comparison of measured (red dots) and predicted arrivals (blue circles) in vertical arrival angle versus travel time. (From (Dushaw et al. 2013) by permission.)

is the measurement kernel associated with that particular ray arrival, an essential requirement of the inverse problem. Considerable effort was devoted to developing computational tools for acoustic propagation tailored to tomography; the codes are freely available (<http://staff.washington.edu/dushaw/AcousticsCode/EigenRay.html>).

The basic scheme for tomography as part of an observing system relies on the use of inverse techniques and ocean modeling to derive optimal estimates for ocean variability (Munk and Wunsch 1982; Gaillard 1992; Sheinbaum 1995; Menemenlis et al. 1997; ATOC Consortium 1998; Rémy et al. 2002; Yaremchuk et al. 2004; Sagen et al. 2016; Geyer et al. 2020; Gopalakrishnan et al. 2021). The measurement afforded by tomography is a line average, a natural complement to point measurements such as current meters or thermistors. Data assimilation techniques combine this disparate information as constraints on ocean models to obtain optimal state estimates. Until a decade ago, ocean models or state estimates had surprising difficulty coupling the model layers together properly, resulting in unphysical acoustic propagation characteristics. Acoustic propagation is sensitive to the vertical gradients of sound speed, and the gradients of the older models were entirely unphysical. The deficiencies with the models were glaring (Dushaw et al. 2009). The properties of acoustic propagation were therefore a direct indication that the models required improvement and what needed improving, a basic use of acoustic data to suggest model improvement. The basic temperature structures of the state estimates needed to be more similar to smoothed ocean representations such as the World Ocean Atlas (Dushaw et al. 2013). More recent ocean models are much better behaved. While it is doubtful that the acoustic considerations can take direct credit for that, the better accuracy of the modern models means they can be readily employed with tomography in data assimilation schemes.

Ocean models or smoothed ocean representations derived from recent data were used in computations to predict acoustic data from the 1960 Perth–Bermuda sound transmission experiment (Munk et al. 1988; Dushaw and Menemenlis 2014), discussed further below, and from the 1955 Operation WIGWAM atomic test (Dushaw 2015b), with surprising agreement. In both experiments the acoustic propagation distances were about 20,000 km.

4. EFFECTS OF SMALL-SCALE VARIABILITY ON ACOUSTIC PROPAGATION AND INVERSE FORMULATION

The effect of small-scale variability such as internal waves on acoustic propagation in the deep ocean was an area of interest even before the advent of tomography.

The topic has military and national security interest (c.f., the Hollywood blockbuster film “The Hunt for Red October”). The recent monograph by A. Colosi (2016) reviews the subject. The presumed influences of such variability on acoustic propagation were the origins of an initial erroneous assessment of tomography. As told by Worcester and Munk (2016): “The field got off to a stormy start when a reviewer of an early proposal wrote that “travel times along ray paths are meaningless in a saturated environment,” but a 1978 experiment showed that ray arrivals could be “resolved, identified, and tracked” at 900-km range...”.

In the late 1980s one surprising discovery was that the acoustic energy was so scattered by small-scale variability as to confuse the later portion of the arrival pattern (Duda et al. 1992; Cornuelle et al. 1993; Worcester et al. 1994) (*Figure 2*). This phenomenon reduced the information that could be obtained from tomography. For basin- or global-scale temperature measurements, much of Munk’s initial considerations on tomography were from the acoustic mode perspective, that is, tomography was meant to employ the propagation times of resolved acoustic mode arrivals. For O (100-Hz) acoustic signals the mode approach proved mostly intractable on account of the internal-wave scattering, however. The scattering caused severe mode coupling and the nature of the arriving signals usually made resolution of individual mode arrivals impossible (Cornuelle et al. 1993; Worcester et al. 1994). The earlier arrivals in an arrival pattern are better modeled by acoustic rays, and these arrivals are stable and well resolved (e.g., *Figure 2*). As a consequence, tomography has most often employed rays to model the acoustic propagation. The loss of information from later-arriving (shallower-propagating) acoustic energy limits the resolution of ocean variability with depth afforded by tomography, since such depth resolution relies on the availability of rays that propagate over different depth intervals.

One aspect of internal-wave scattering, noted by Worcester et al. (1994), was that it tends to widen the time-front arrival over a slightly larger depth interval. A “time front” is an acoustic arrival pattern shown as a function of depth and travel time. Data obtained at deep receivers during the Acoustic Thermometry of Ocean Climate (ATOC) program (Dushaw et al. 1999), described further below, often consisted of pairs of ray arrivals. Although these arrivals aligned with the lower cusps of the time front (*Figure 2*), predictions of such arrivals using smooth sound speed environments could not account for such arrivals. The predicted arrivals were up to 500 m shallower than the receiver depths. At the time such arrivals were mistakenly called “shadow zone arrivals,” since they occurred outside the acoustic predictions, or within the acoustic shadow.

The phenomenon is a result of internal-wave scattering (Van Uffelen et al. 2009). While the branches

of the time front are indeed stable, internal waves induce vigorous scattering of rays along the branches of the time front. Such scattering causes the lower cusps of the time front to extend deeper, and upper cusps to extend shallower. If a section of a time front branch were to be clipped out, such as by propagation over a sharp seamount, internal-wave scattering during subsequent propagation would fill in, or “heal,” the time front. Such scattering approximately retains the upper- and lower-turning depths of the rays, while vigorously scattering the ray paths horizontally. Thus, a “ray arrival” in an environment with internal waves (everywhere) corresponds not to a single ray but to a collection of scattered rays with about the same turning depths and travel time and with significantly different horizontal sampling. Such a ray arrival represents a measurement that is a horizontal average with very little “null space,” or unsampled regions between ray loops.

Internal waves are not the only phenomenon to cause acoustic scattering. In some regions, density-compensated temperature and salinity variations, or “spice”, cause scattering, such as occurs in the Canary Basin (Dushaw et al. 2017). In high latitudes, the Rossby radius is small so that mesoscale variability can similarly scatter acoustics, such as occurs in Fram Strait (Dushaw et al. 2016a).

The RTE87 experiment was one of the first to employ reciprocal acoustic transmissions, in which the signals were simultaneously transmitted from the transceivers on either end of an acoustic path and then received by those transceivers. Such data allow the signals from temperature and current to be distinguished, since the temperature signals in acoustic travel time are symmetric in reciprocal propagation, while current signals are antisymmetric. Computing the sum or average of reciprocal ray travel times cancels the effects of currents on travel time, while computing the difference of reciprocal ray travel times cancels the effects of temperature. One initial fear with such transmissions was that the reciprocal paths would deviate from each other, such as might occur if current shear was present, preventing the expected separation of current and temperature variability. The high-frequency sound-speed variability, caused by internal waves, was used to show the reciprocal paths separated by no more than an internal-wave correlation length, however. When the differential travel times were computed, the high-frequency sound speed variations were mostly removed, that is, the high-frequency travel-time variability of reciprocal paths was correlated (Dushaw et al. 1994b). The conclusion was that the corresponding reciprocal ray paths remained within internal-wave correlation lengths from each other.

While small-scale acoustic scattering has been a complication for tomography, an optimal approach is to embrace the phenomenon as part of the acoustic

forward problem (Dushaw and Sagen 2017). For any particular region, semi-empirical models for small-scale variability can be devised and incorporated in the forward-problem acoustic environment. Predicted rays and other properties then better reflect the actual environment that the acoustic signals experience. “Shadow-zone arrivals” are readily predicted by this approach, for example, no longer appearing in the acoustic shadow as occurs with a smooth ocean representation. The acoustic sampling is more accurately represented within the inverse problem. While ray paths can usually be used to represent the sampling, a more rigorous approach, though more complicated, is to compute the “travel-time sensitivity kernels” (TSKs), which are the full-wave kernels associated with the arrivals (Dzieciuch et al. 2013). The TSK theory gives the use of simple acoustic rays in the inverse a firm theoretical foundation.

5. BAROTROPIC TIDAL CURRENTS

Around 1988, on the advice of W. Munk, I began to look into the tidal variations of the RTE87 data. At that time, the nature of the tomography data was still uncertain, and the tides provided a large and obvious test signal to look for in the acoustic data. A comparison of tidal-current harmonic constants derived from the RTE87 tomography data with harmonic constants derived from a tidal model would be a test, or sanity check, for the acoustic observations and vice versa. Ernst Schwiderski had one of the first global tidal models (Schwiderski 1980), and Munk had arranged for Schwiderski to compute the tidal harmonic constants for currents along each of the three paths of the RTE87 tomography array.²

Estimates of tidal currents were derived from the difference in reciprocal travel times of RTE87 acoustic data. The tidal variations in the data were obvious (*Figure 3*), though the magnitudes of the travel time variations were only 5–10 ms. Depth-averaged current speed was estimated from the acoustic data by a simple inverse (Dushaw et al. 1994b). The barotropic nature of the currents made them ideally-suited for observation by tomography, which is a natural measure of a range- and depth-average of oceanographic properties. Such an average suppresses the small-scale variations of the ocean.

The comparisons between harmonic constants from the Schwiderski model and those derived from the tomography data were excellent. Also on the suggestion of Munk, I showed the comparisons to Myrl Hendershott, the local tidal expert at SIO. Hendershott was amazed at the agreement, even for the small P1 and Q1 diurnal constituents. Although these comparisons began as a test for tomography, the tables were quickly turned, and tomography became a gold standard for the measurement of barotropic tidal current (Dushaw et al. 1994b, 1995, 1997; Stammer and Coauthors 2014).

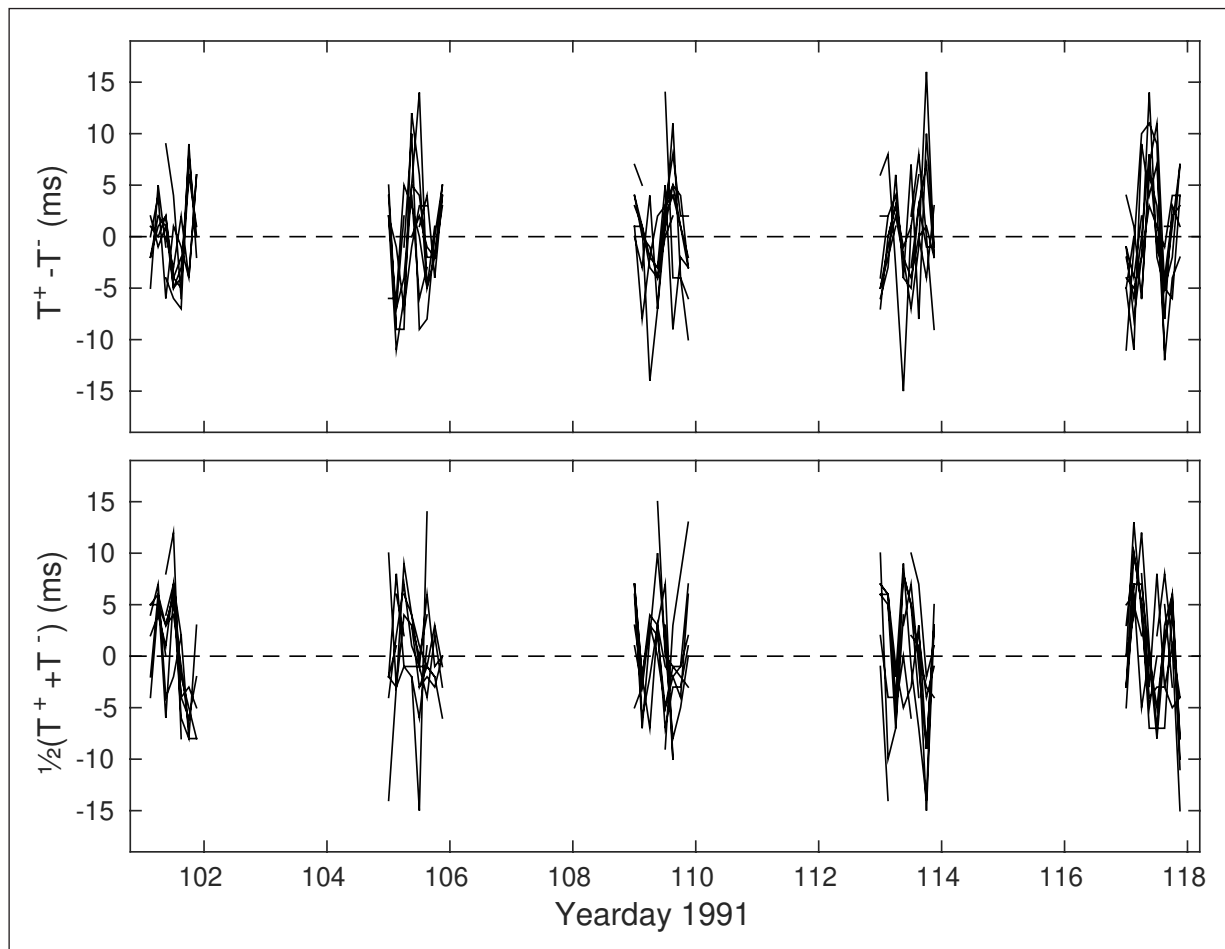


Figure 3 High-frequency (> 1 cpd) travel time variability measured during the 1991 Acoustic Mid-Ocean Dynamics Experiment (AMODE) on the 670-km acoustic path from mooring 1 to mooring 3. (Top) The difference of reciprocal travel times measures ocean current. The dominant signal of barotropic tidal currents is apparent. (Bottom) The sum of reciprocal travel times measures ocean temperature. The dominant signal of baroclinic tidal effects on temperature is apparent. The data of neither panel are filtered, other than the separation into high- and low-frequencies. The differential travel time data give accurate estimates of the tidal current harmonic constants. The sum travel time data, hardly different in character than the differential data, give accurate estimates of the tidal displacement harmonic constants (Dushaw 2006). Data such as these were first published in 1995 (Dushaw et al. 1995).

One common presumption through the 1990s and 2000s was that moored current meters could accurately measure tidal currents, such that the tomography measurements were neither unique, nor particularly valuable. With point measurements such as current meters, however, the small-scale noise of the ocean dominates, which complicates an accurate estimate for the tidal currents (Dushaw et al. 1997). While with careful analysis, a vertical array of current meters on a mooring can be used to separate barotropic and baroclinic variability, it is challenging to obtain precise tidal estimates (Luther et al. 1991; Dushaw et al. 1995, 1997). The accuracy and precision of tidal estimates from reciprocal tomography are difficult to match because the tomography data are a natural range- and depth-average measurement that suppresses small-scale noise. Today, twenty years later, acoustic tomography is an accepted method for observing tidal currents (Stammer and Coauthors 2014), one of the most basic signals in the oceans.

6. BAROTROPIC CURRENTS AND RELATIVE VORTICITY

The two main lessons of the tidal comparisons were a confidence in the integrity of the measurement and a firmer understanding that the measurement was indeed a surprisingly precise range and depth average. The tomography observations provide a natural filter for large-scale, depth-averaged variability. The lessons could be immediately applied to the low-frequency (i.e., non-tidal) variability of currents observed in the central North Pacific during summer 1987. Weak, large-scale currents of $O(5 \text{ mm s}^{-1})$ were observed, with variations at 10–20-day scales. “Large-scale” here is defined as $O(1000 \text{ km})$ scale, the size of the RTE87 tomography triangle. The uncertainties of the current estimates were about 1 mm s^{-1} . Though the currents were weak, they were much larger than currents expected from local wind forcing through the Sverdrup balance, implying the observed currents were of non-local origin.

The relative vorticity was obtained by integrating the currents around the tomography triangle, which gives the relative vorticity averaged over the triangle (Munk et al. 1995). Direct measures of this quantity was one of the original motivations for tomography. For the RTE87 triangle, the average relative vorticity was $O(1 \times 10^{-8} \text{ s}^{-1})$ (Dushaw et al. 1994b), four orders of magnitude less than planetary vorticity. Relative vorticity is a key oceanographic variable; it is a mostly unexploited capability of tomography.

Following the RTE87 experiment, the Acoustic Mid-Ocean Dynamics Experiment (AMODE) tomography array was deployed in the western North Atlantic in 1991. At W. Munk's suggestion, the data obtained were used to estimate tidal vorticity (Dushaw et al. 1997), caused by the stretching of the water column by barotropic tidal elevation. This vorticity was five orders of magnitude less than planetary vorticity.

One may well ask: "Why should I care about tidal vorticity?" There are two answers to such a question. The first answer is that basic research proceeds irrespective of application or utility – we seek to understand nature. I looked into tidal vorticity because it should have been observable, and it was; such a result is reassuring, a reflection of the beauty of nature. The second answer is that it is a demonstration that tomography measures relative vorticity quite well. It is up to physical oceanographers to be creative and take advantage of the fact that this basic oceanographic quantity can be measured with surprising accuracy.

One experiment was designed specifically to take advantage of the capability of tomography to measure relative vorticity. An $O(1000)$ -km-scale tomographic array was deployed in 2000 in the equatorial Pacific to measure the mean relative vorticity and other variables. The measurements showed that that relative vorticity was positive during La Niña and negative during the normal state (Nakano et al. 2001).

In the early 2000s we began a collaboration (B. Cornuelle, D. Luther, M. Hendershott, A. Miller, P. Worcester, myself and others) to develop an experiment that would exploit the capabilities of tomography to precisely measure barotropic currents and relative vorticity. The proposed experiment was to measure the theoretically-expected barotropic radiation from a western boundary current (Miller et al. 2007). The strong meanders of boundary currents generate short-scale barotropic waves that act as an energy sink for the current system. The area south of the Gulf Stream is expected to experience a steady radiation of such waves. Although the proposal was not successful, it is described here as the kind of experiment that could take advantage of tomography.

7. BAROCLINIC TIDAL TEMPERATURE

The radiation of coherent low-mode internal-tide waves (or baroclinic-tide waves) far into the interior of ocean

basins was first observed in the central North Pacific by acoustic tomography (Dushaw et al. 1995) (*Figures 3, 4*). These observations motivated the analysis that led to the detection of these waves by satellite altimetry a year later (Ray and Mitchum 1996). The tomography data were essential in demonstrating that such waves can cross ocean basins with little attenuation or loss of coherence and that, in many regions of the world's oceans, the amplitude and phase of these internal waves can be predicted (Dushaw et al. 2011; Dushaw 2015a). How this came about is a long story, with the stages in the analysis pitted against fairly entrenched preconceptions by physical oceanographers, in regards to both the tomography data and the nature of internal-wave variability. These results have sparked a minor revolution in physical oceanography.

In the analysis to determine the barotropic tidal currents from the RTE87 tomography data, both difference and sum travel times were computed. As previously discussed, the former data were a measurement of barotropic tidal currents. The latter data also showed surprising, clear tidal variability. The data caused considerable consternation within the tomography group at SIO around 1990, with Walter Munk declaring, "Internal tides are not phase locked." The main concern with the result was that perhaps the corrections to the data for mooring motion were not quite correct, allowing the tidal motion of the moorings to influence the computed sum travel times. A careful look at every stage of the data processing found no errors, however.

A. SEMIDIURNAL INTERNAL TIDES

As early as 1994 the notion that low-mode internal tides were predictable was evident from the tomography data (Dushaw et al. 1994a). As described earlier, M. Hendershott was amazed at how well the tomography and model estimates for tidal current harmonic constants agreed. It is no surprise (today) that open-ocean barotropic tidal currents are predictable. Since the basic time series of both difference and sum travel times had essentially the same characteristics (*Figure 3*), it was therefore natural to conclude the baroclinic tide was predictable as well, or at least the low-mode internal-tide component that tomography observes.³ In the 1990s physical oceanographers perceived such variability as inherently incoherent, a perception clearly at odds with the tomography data.

The analysis of the RTE87 data for the baroclinic tides (Dushaw et al. 1995) took several twists and turns, but really it boiled down to two basic, related facets: first, have faith in the data, and second, understand the nature of the measurement. As has been discussed above, the accuracy of the tomography data was remarkable. The tidal signal in the data, reflecting variations in temperature (sound speed), was obvious and unambiguous. As was shown by the barotropic

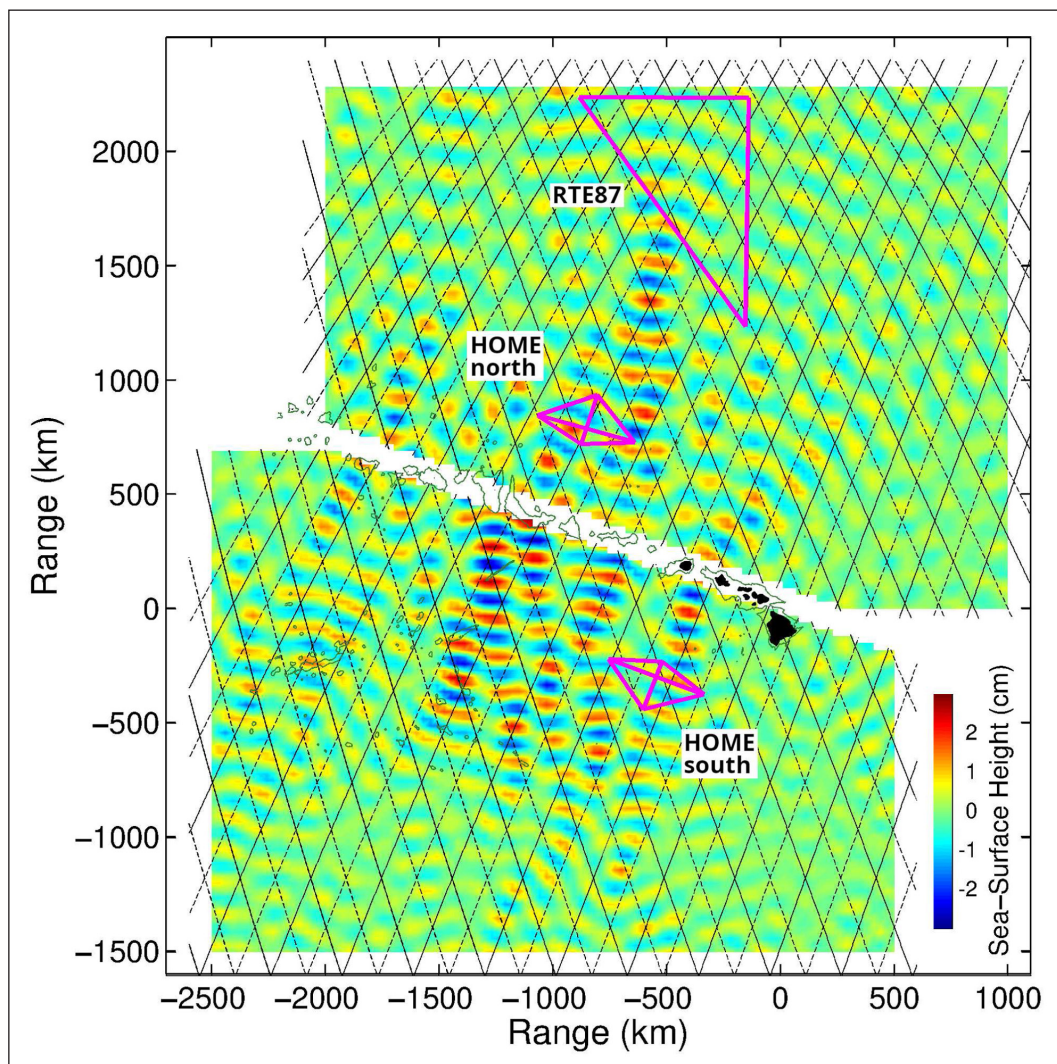


Figure 4 The locations of the RTE87 and HOME tomography experiments on either side of the Hawaiian Ridge. The colored field is the M2 internal tide sea-surface height derived from satellite altimetry data. The TOPEX/POSEIDON satellite tracks are indicated by the solid and dashed lines. Azimuthal Equal Area projection. (From Dushaw et al. (2011) by permission.) (See also electronic Supplements 1–3, D. Dushaw (2015a)).

tidal current measurements, the measurement is a natural average over both depth and range. Small-scale variability in temperature is dramatically suppressed by such averaging.

Being a depth average, the contributions of temperature modes higher than the lowest mode, in addition to contributions from the baroclinic current modes, were suppressed. Those higher modes have variations over depth, and they average vertically to nearly zero. The gravest temperature mode, really the temperature expression of the first vertical displacement mode, has no zero crossings, however, hence its depth average is not small. In addition, in the RTE87 data, one ray corresponding to the latest arriving acoustic energy was resolved. Technically, this arrival corresponds to the lowest acoustic mode, but this mode has a ray equivalent. This ray propagates very near the sound-channel axis, which, in the Pacific experiment, also happened to be within depths where the amplitude of the baroclinic-tide temperature mode is large. As a consequence, its signal from the tidal variability was much greater than that of the deeper-turning rays.

Being a range average, all variability with wavelengths much shorter than the acoustic path length ($O(1000 \text{ km})$) was suppressed. The signals observed could only arise from wave crests aligned along the acoustic path, giving a spatially coherent signal, hence a non-zero horizontal average. An acoustic path represents a highly-directional antenna for internal waves, obtaining a signal only for those wavenumbers nearly perpendicular to the acoustic path (Dushaw 2003) (*Figure 5*). The signals from higher-order internal tides were therefore not only suppressed by the vertical average, but also suppressed by virtue of their shorter wavelengths. Tomography was therefore a surprising, clear measure of the gravest internal-tide mode and of waves propagating across the acoustic path.

The basic properties of the internal-tide modes can be readily computed, e.g., as described by Hendershott (1981) in the collection *Evolution of Physical Oceanography*. The gravest internal-tide mode at semidiurnal frequency has properties that suggest the propagation of these waves

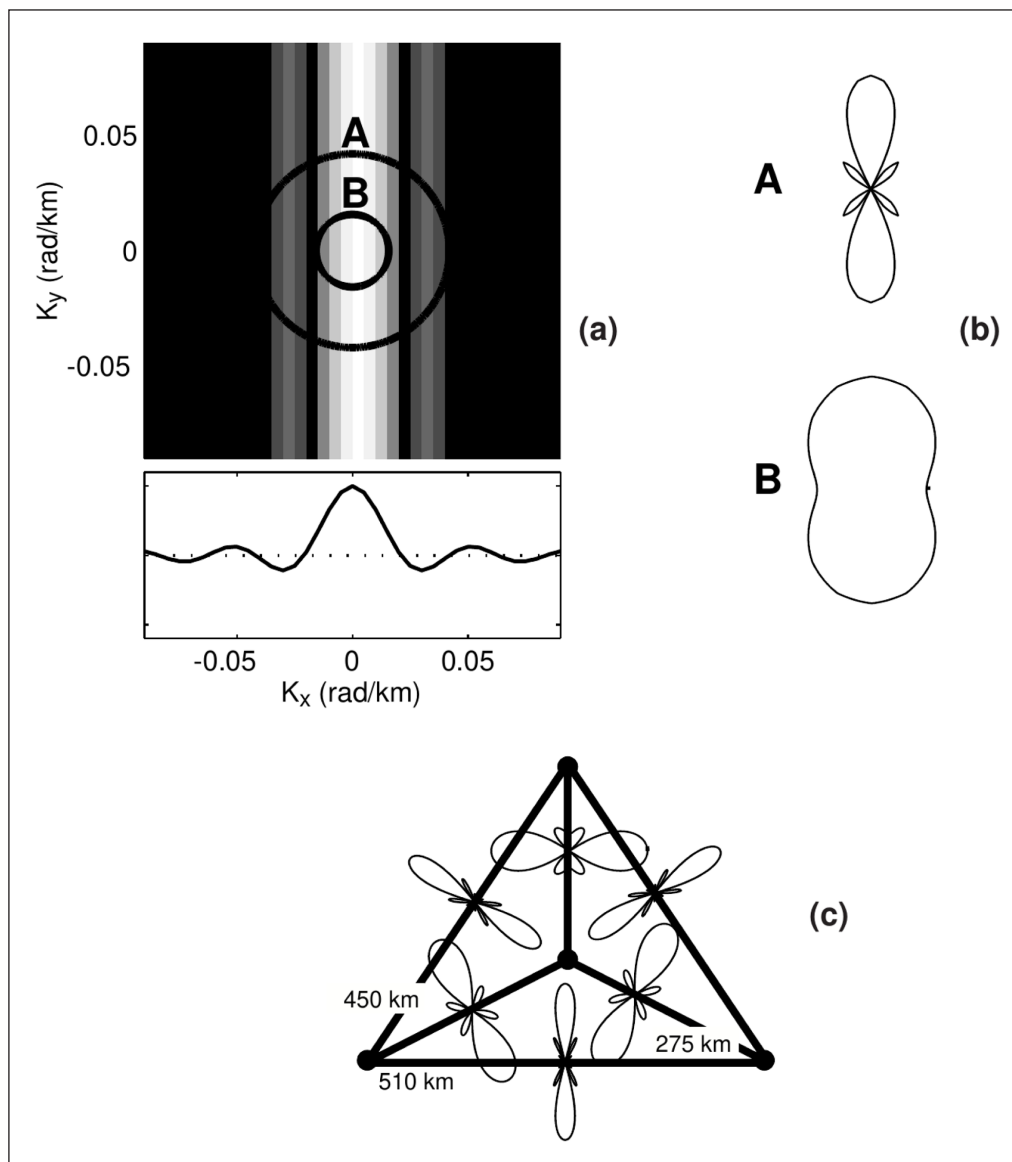


Figure 5 (a). A zonally-oriented acoustic path of 400-km length gives a sinc filter for zonal wavenumbers and no filter for meridional wavenumbers. **(b).** The projection of the two-dimensional filter onto semidiurnal wavenumbers A is the beam pattern (in polar coordinates), or the response of the line-integral antenna as a function of azimuthal angle, for semidiurnal radiation. The narrow beam pattern shows that the acoustic antenna has high directivity for semidiurnal wavenumbers. For the smaller diurnal wavenumbers B the acoustic antenna has less directivity. An acoustic tomography array **(c)** can be designed to provide for near-complete coverage of baroclinic-tide wavenumbers for waves traveling upward on the page. (From Dushaw (2003) © American Meteorological Society. Used with permission.)

ought to be coherent. Namely, they have wavelengths of $O(200 \text{ km})$ and phase speeds of $O(4 \text{ m s}^{-1})$; these are big, fast waves. Prior to the RTE87 experiment, it had been assumed that the mesoscale rendered internal tides incoherent. But the wavelength of the gravest internal-tide mode is larger than the typical mesoscale ($O(100 \text{ km})$), while its phase speed is an order of magnitude larger than typical mesoscale current speed ($O(0.2 \text{ m s}^{-1})$). Hendershott (1981) also reviewed the earlier result by Hendry (1977) using the Mid-Ocean Dynamics Experiment (MODE) data in the Atlantic obtained in 1973. By careful statistical analysis, Hendry obtained a statistically significant phase difference between the M2 and S2 internal tides, suggesting the observed internal tide had propagated 700-km from the Blake

Escarpment. This propagation range was determined by assessing the “age” of the internal tide. The internal-tide M2 and S2 phase speeds are different, so the relative phase between the two constituents increases with propagation distance. The estimated M2 and S2 phases can therefore be used to estimate range of propagation. Similar analysis suggested the source of the internal tides observed by tomography in the Pacific could be the Hawaiian Islands, the nearest significant feature, some 2000 km to the south. The Hawaiian source was likely from the phase analysis and because of the linear form of the Hawaiian Islands chain (Dushaw et al. 1995). Plane waves were generally required because they lead to coherent variability along the tomography paths. The Aleutian Islands were ruled out because they were less

linear, although it was later determined that waves from those islands do travel to the region of the tomography array.

The 1991 AMODE tomography experiment was deployed in nearly the same region as the 1973 MODE array. The AMODE experiment, deployed by Worcester, assisted by this author as a graduate student, consisted of 6 acoustic sources in a pentagonal array of about 700-km diameter (Dushaw 2006). Record lengths of 200–300 days were obtained, depending on how long the batteries of the acoustic sources lasted. From the internal-tide perspective, the array formed a 15-element antenna, with each element (acoustic path) a highly-directional sensor for internal tides, e.g., [Figure 5](#). The interpretations and understanding derived from the Pacific experiment carried over directly to the AMODE data. The conclusion was that the semidiurnal internal tides of the AMODE region (hence also the MODE region) consisted of several coherent internal-tide wave trains emanating from the Caribbean island arc and Blake Escarpment (Dushaw 2006). The energy carried by the M2, mode-1 waves was relatively weak, at 0.2 GW. Insofar as internal tides are concerned, the western North Atlantic is an out-of-the-way, quiet corner. The waves experienced a decay with propagation distance so weak as to be undetectable by the AMODE data.

The results from tomography were different from those of Hendry (1977). Hendry approached the analysis from a statistical perspective, concluding that “about 50% of the main thermocline temperature variance in the M2 band is coherent with the astronomical forcing and so of a deterministic rather than random nature,” interpreting a single wave train as emanating from the Blake Escarpment. In the tomography measurements, not having to contend with small-scale tidal noise, the tides accounted for 32–77% of the variance of the entire record (Dushaw 2006). The degree of coherence depended on the amplitude (in paths with larger amplitudes, the tides accounted for a greater percentage of the variance) and on the direction of propagation. By comparison, the barotropic tidal currents accounted for 50–90% of the barotropic current variance (Dushaw et al. 1997), also depending on tidal amplitude. The MODE array current meter data were so noisy the barotropic tidal currents were unmeasurable (Hendry 1977). The internal-tide field consisted of a complicated interference pattern arising from multiple coherent wave trains propagating in different directions. Tidal variability from all major semidiurnal and diurnal constituents was detected.

In 1999, I attended a 2-week summer school on data assimilation given by Andrew Bennett at Oregon State University. At the conclusion of the visit, I wrote up notes on what representers for tomography look like in the shallow-water toy model that had been employed for the class exercises (Dushaw 1999b). Such a representer is

a set of corresponding displacement and current forms, consistent with the dynamics of the model (Bennett 1992). The equations for propagation of internal tide modes reduce to such a model, if the depth employed is the “equivalent depth” for the mode (Hendershott 1981), derived from the eigenvalue problem for the vertical modes. The representers for such a model and the segment-average measurement of displacement afforded by tomography look similar to the coherent, plane-wave forms that are apparent in low-mode internal-tide propagation; the form of the representers matches the waveform of the actual propagating waves. The result is suggestive of why tomography makes such a clear measurement of internal tides.

B. DIURNAL INTERNAL TIDES

One notable difference between the RTE87 and AMODE time series of travel times was that the latter had obvious diurnal tidal variability ([Figure 6](#)). The RTE87 array was well north of the turning latitude for the diurnal internal waves, while the AMODE array was centered on 25N, or just south of the turning latitude. The lack of a diurnal signal in the RTE87 data was one of several indicators that the tidal signals were truly baroclinic tides; an error in processing that allowed barotropic tidal variability to “leak” into the sum-travel-time data would also have “leaked” the diurnal variability. Near their turning latitudes, the structure of currents of diurnal internal waves is characterized by Airy functions (Hendershott 1981). The displacements of diurnal internal waves are characterized by the meridional derivative of Airy functions; the internal waves are nearly inertial near their turning latitude. These waves are not freely propagating near their turning latitudes.

The structure of the relative amplitude and phase values of the O1 and K1 diurnal internal tides was roughly consistent with the predicted Airy function structure (Dushaw and Worcester 1998). The order number of the Hermite functions to use is determined by the tidal frequency. The phases derived from the various tomography paths differed by about 180°, indicating a standing wave pattern ([Figure 7](#)). The ratio of baroclinic:barotropic energy density for both constituents was about 30:15 $J\ s^{-2}$, a huge ratio, considering it would normally be expected to be much less than 1 $J\ s^{-2}$. These waves are resonant standing waves, reliant on astonishing coherence such that the small tidal energy converted from barotropic to baroclinic each tidal cycle accumulates in the baroclinic waves. The waves are trapped between their turning latitudes to the north and the topography of the Caribbean island arc to the south. The observations were later revisited to show that the conclusion was essentially unchanged when the proper boundary value problem is computed (Dushaw 2006).

This result is both surprising and spectacular. The diurnal waves are not observable by altimetry, having

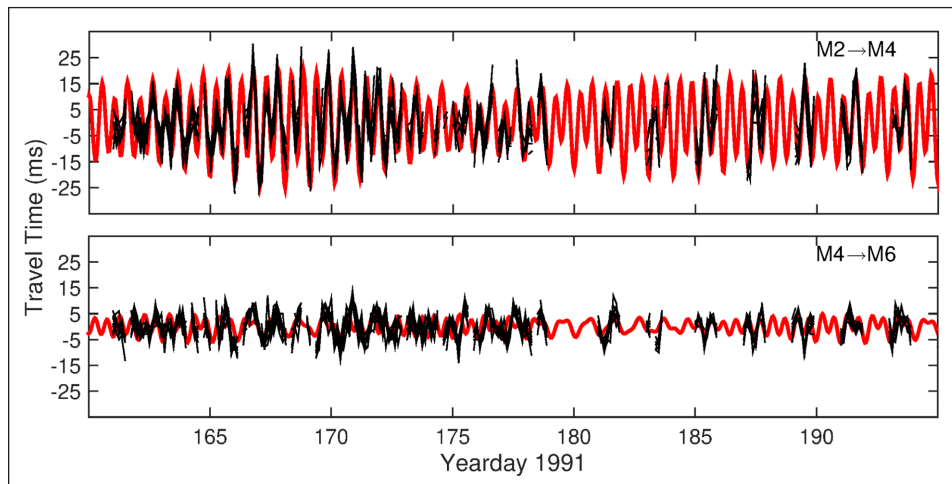


Figure 6 The tomography travel times recorded in the Atlantic in 1991 (black) can be independently predicted from a tidal analysis of altimetry data obtained a decade later (red) (Dushaw 2006; Dushaw et al. 2011; Dushaw 2015a). The two paths shown here have a mixed semidiurnal and diurnal signal (top) and a predominantly diurnal signal (bottom). The tomography data in this figure have been high-pass filtered only to distinguish between mesoscale and more rapid variability, i.e., these are the data, not just the tidal component of the data.

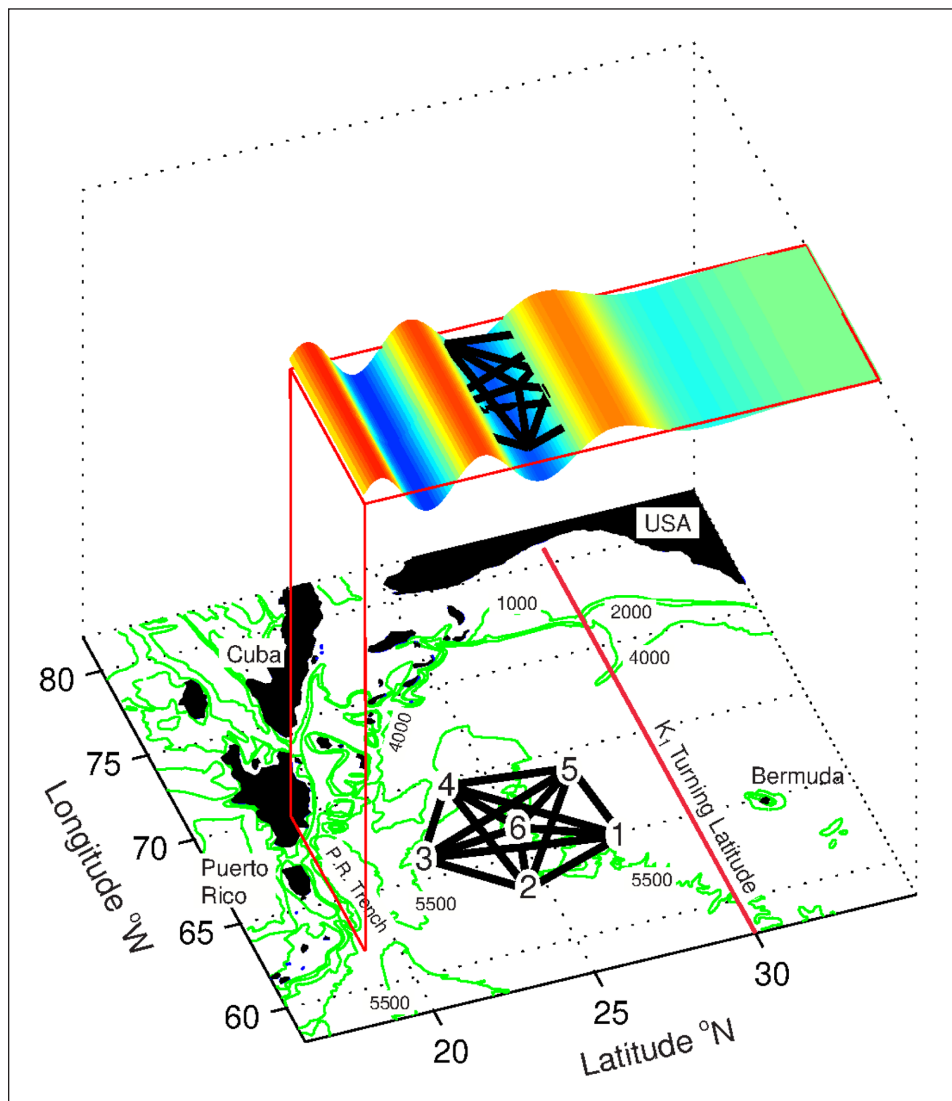


Figure 7 The AMODE tomography array observed relatively large, coherent K1 and O1 internal tides. Since the energy densities of the waves were far larger than expected from the weakness of the barotropic tides at those frequencies, such waves were interpreted as being in resonance, trapped between the Caribbean island arc topography and their turning latitude at about 30°N (Dushaw and Worcester 1998; Dushaw 2006). (From Dushaw and Worcester (1998) by permission.)

a sea-surface height expression of $O(0.2 \text{ cm})$. As one physical oceanographer commented, the result is a remarkable example of the beauty of nature.

C. OBSERVATION OF INTERNAL TIDES BY ALTIMETRY

The paper describing the internal tides observed during RTE87, “Barotropic and Baroclinic Tides in the Central North Pacific Ocean Determined from Long-Range Reciprocal Acoustic Transmissions,” was published in April 1995. As noted, the properties of internal-wave modes for that analysis were computed from the theory as described by Hendershott (1981). I had noted the surface boundary conditions for the modes, which indicated that the internal tides had an expression in sea-surface height. A back-of-the-envelope calculation suggested a 10-m internal tide, as might be present near Hawaii, would have a surface expression of about 2 cm. The TOPography EXperiment (TOPEX/POSEIDON) altimeter mission had started toward the end of 1992, and there was a lot of discussion about this mission and the novel estimates of global tidal models from it. At the time, people spoke of the “2-cm solution” over a footprint of $O(100 \text{ km})$ for the accuracy of the TOPEX/POSEIDON altimetry data (Cheney et al. 1994). It seemed to me that data from the altimeter observations could perhaps detect the internal tides. I knew nothing of altimetry data, however.

I was to give a poster at the December 1994 meeting of the American Geophysical Union in San Francisco (Dushaw et al. 1994a), and I looked over the abstracts for those who were working on altimetry data around Hawaii. During the conference, I ran across Gary Mitchum, who was one of those working on such data. I told him about my poster, which was on the AMODE internal tides, and encouraged him to look in the altimetry data for internal-tide signals near Hawaii. He seemed skeptical, so I followed up with an e-mail to him in early January 1995. He went to see Doug Luther about the issue, and they decided the signal-to-noise afforded by the altimetry was not sufficient for extracting the tiny internal-tide signals. The following year the famous paper by Ray and Mitchum (1996), “Surface manifestation of internal tides generated near Hawaii,” was published. What Luther and Mitchum had not taken into account was the enormous gain in signal afforded by a tidal analysis and the possibility that the wave trains away from Hawaii could be coherent.

The altimetry result was a surprising confirmation of the interpretation of the tomography data. Internal tides and altimetry were a hot topic at the “Tidal Science 1996” conference held in October at the Royal Society in London in honor of David Cartwright on his 70th birthday (Angel et al. 1997). Ray and Mitchum and others had derived harmonic constants at points along the altimeter tracks, and I assumed, based on my experience with computing

objective maps, that maps for the internal tide would soon be derived. Five years passed, however, before Ray and Cartwright (2001) examined the energetics of the internal tides around Hawaii by computing energy flux vectors of the tidal field from the altimeter data. Their approach was to first derive the tidal harmonic constants at points along the altimeter tracks. Then, monochromatic waves were fit to those constants over regions of size $4^\circ \times 3^\circ$ (longitude $\times$ latitude). I thought the approach was simplistic, and I asked R. Ray for his values of the harmonic constants; these values were used to compute the first map of the internal-tide field around Hawaii (Dushaw 2002). Proper objective maps were still not adopted, however, with researchers generally following the Ray and Cartwright approach.

Several aspects of the situation were bothersome over the next several years. The monochromatic wave approach did not leverage the obvious spatial coherence of the internal tide waves, reducing the available signal-to-noise gain from a tidal analysis. There was no formally correct way to interpolate between the independent estimates obtained over small regions in the Ray and Cartwright approach. Analyses often proceeded using only the M2 constituent, or sometimes a generic “semidiurnal” frequency, lumping all tidal constituents together, potentially allowing cross-talk from several constituents to contaminate the estimates. Researchers spoke of internal-tide “beams” (implying energy propagating along the beam), whereas to me these were obvious effects of the internal-tide interference pattern, with regions of constructive and destructive interference, e.g., Dushaw (2002) and Rainville et al. (2010); the origin of the “beam” energy was likely not the endpoint of the beam. When researchers reported on their analysis, they often argued that what was derived from the altimetry data was the “coherent” component, suggesting that an unknown “incoherent” component was not observed. There were two obvious problems with that interpretation. First, an interference pattern is inherently unstable to any element of incoherence, whereas the TOPEX/POSEIDON internal-tide interference patterns had been stable for years. Second, the available tomography time series, with 100–300 day record lengths of mode-1 amplitude, showed no obvious incoherent component. There were no available estimates of in-situ mode-1 time series that provided direct evidence for the incoherence of mode-1 internal tides.

Arguing that the “discovery” phase for the internal tides in the altimetry data had passed, such that it was now appropriate to analyze the internal tides in the records using strong assumptions about their nature, I began a novel analysis in 2006. Both the tidal frequencies and the wavenumbers were assumed in a combined tidal analysis over large temporal and spatial domains (Dushaw et al. 2011). The equivalent assumption was that the internal tides were both temporally and spatially

coherent. The largest six constituent frequencies, four semidiurnal, two diurnal, were used in the fit to the altimeter data. Surprisingly, the internal tides mapped this way from the altimeter data proved to be able to accurately predict the in-situ observations from tomography. The local solutions for the internal-tide modes provided the connection between sea-surface height and in-situ sound-speed variations, thus sea-surface height and acoustic travel times were related. In the Atlantic, the mapped internal tides could also be used to predict the AMODE acoustic travel-time variability, in both amplitude and phase, even though the acoustic data were obtained several years prior to the start of the altimetry data ([Figure 6](#)). A reviewer called the paper, Dushaw et al. (2011), a landmark in establishing that some aspects of the internal tides were predictable.

The analysis with comparisons to the tomography data had been confined to the central North Pacific and western North Atlantic, where those data were available. The results, however, suggested a much broader application, namely, a global solution for the internal-tide wave fields. Although there are applications for such solutions, my motivations were simply because it was an obvious thing to do and because the wave patterns in other regions of the world could be remarkable; this is what nature does! The predictable nature of the solutions meant that there were minimal incoherent contributions to the internal-tide field; the solutions afforded accurate estimates of internal-tide energy. Initial attempts to get continued research funding for the work proved troublesome, however, eventually garnering success from the ocean surface topography program at the National Aeronautics and Space Administration (NASA) in 2013.

Computation of the global internal-tide field was challenging, requiring a system for taking into account the varying regional properties and statistics of the internal tides. I adopted the expediency of using $11^\circ \times 11^\circ$ areas for computation, overlapped by 1° , and merging those regions with a cosine taper. The result was the first global estimate for mode-1 internal tides derived directly from the altimetry data ([Figure 8](#)) (Dushaw 2015a). As before, the solution employed the six largest constituents: K2, S2, M2, N2, K1, and O1. Since the solution employed omnidirectional wavenumbers, it was a simple matter to parse it to obtain estimates for wave trains propagating in any direction. One particularly-striking wave train propagates southward from the Azores Islands almost to the coast of Brazil ([Figure 9](#)). Note that this particular wavetrain is not obviously apparent in the jumbled interference pattern of the complete solution.

The analysis employed waves that adhered closely to the dispersion relation of the waves. Surprisingly, regions of strong currents (Gulf Stream, Antarctic Circumpolar Current) showed internal-tide energy in the solutions where none was expected. Such a result

suggests mesoscale variability was “leaking” into the solution, giving erroneous estimates of variability. What remains a puzzle, however, is that although the M2 and N2 frequencies are almost identical, the mesoscale “leakage” into the N2 frequency was much smaller than that into the M2 frequency (Dushaw 2015a). Such simple aliasing should not be so frequency sensitive; indeed the filter so strictly demands that the spatial and temporal variability adhere to the internal-tide dispersion relation, that it seems unlikely the mesoscale variability can alias on its own. Although I do not know the resolution of this puzzle, I suspect that the aliasing may be a product of barotropic-tide advection of mesoscale variability. Other approaches to mapping the internal tides apparently do not suffer from such aliasing (Carrere et al. 2021), but see Duda et al (2018).

The internal tides are not coherent everywhere. In-situ observations by tomography in the Philippine Sea were more troublesome to predict from altimetry (Dushaw 2015a), and in the Canary Basin, the internal tides were not particularly predictable (Dushaw et al. 2017). The analysis from altimetry detects only weak internal tides over a large area of the equatorial Pacific. The internal tides are likely energetic, but incoherent, there and because of the nature of the observations, the extraction of signals from such incoherent variability is problematic ([Figure 8](#)).

D. EPILOGUE

The discovery of the internal-tide radiation by tomography and altimetry caused W. Munk to revisit the question of the driving forces for deep mixing in the world oceans (Munk 1997; Munk and Wunsch 1998). The energy carried by the low-mode internal tides was a surprising mechanism for how energy derived from the tides can be redistributed throughout ocean basins, perhaps driving mixing in areas far from where energy is first lost from the tides. The issue led to the Hawaiian Ocean Mixing Experiment (HOME) (Pinkel and Co-authors 2000; Rudnick and Co-authors 2003; Carter et al. 2008) in 2001, a suite of experiments attempting to pin down mechanisms driving deep-ocean mixing around the Hawaiian Ridge. P. Worcester and I were the principal authors of the “Farfield” component of the experiment, involving Worcester’s tomography measurements to derive estimates for the barotropic tidal currents and the baroclinic-tide radiation ([Figures 4, 10](#)). The Farfield suite of observations also included D. Luther’s deep-ocean pressure sensors to accurately measure tidal elevation ([Figure 10](#)) (Stammer and Coauthors 2014), and a deployment of R/V FLIP south of Oahu for upper-ocean measurements by rapid CTD casts (Rainville and Pinkel 2006; Rainville et al. 2010). One challenge for the HOME program was to obtain results of a general nature, such that the global mixing problem could be better understood, rather than merely the local oceanographic properties around Hawaii. The tomography measurements of HOME

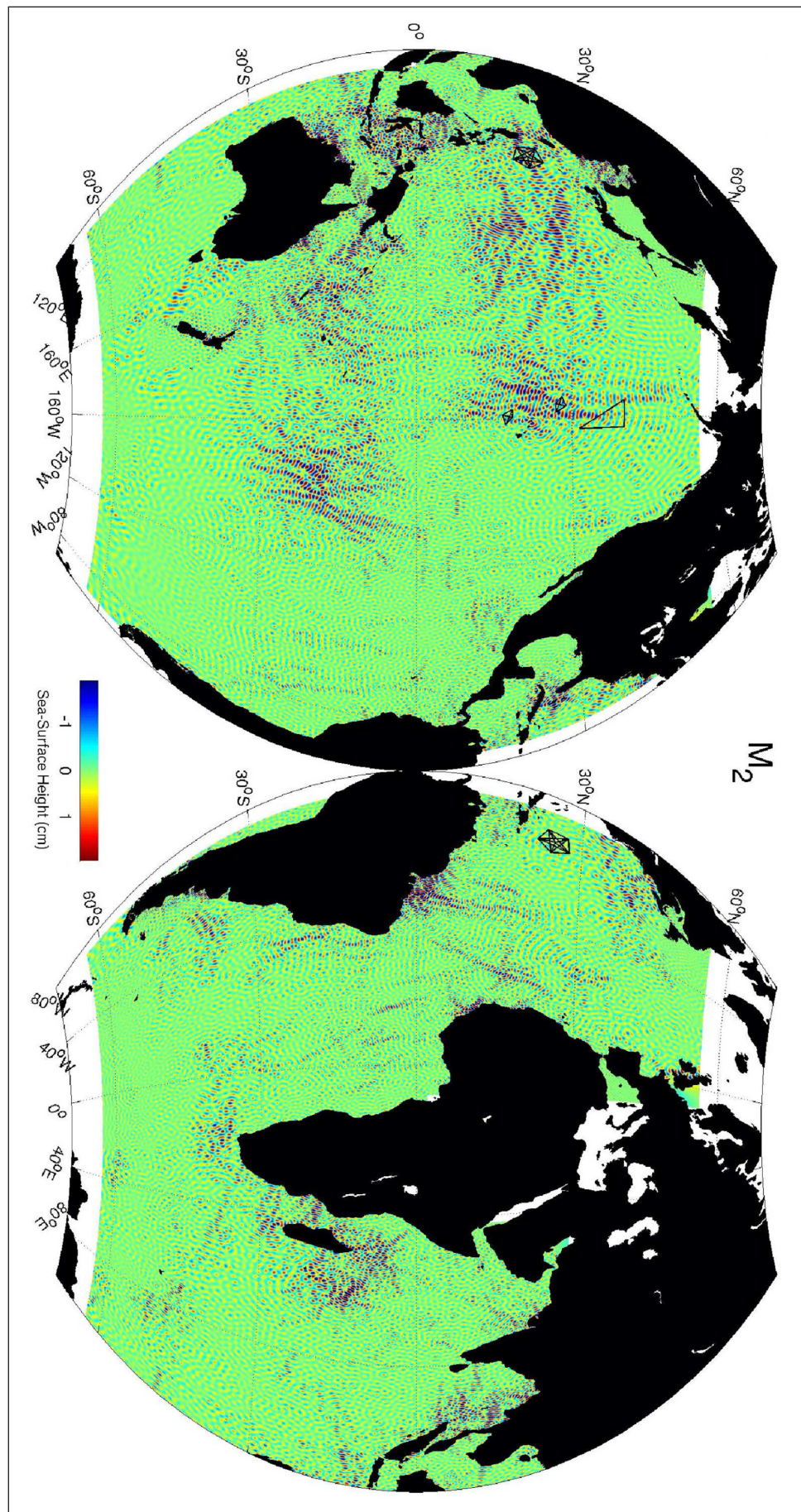


Figure 8 Sea-surface height of mode-1, M2 internal tide. From west to east tomography arrays are indicated in black lines: Philippine Sea, north and south arrays of HOME (Hawaii), RTE87 (central North Pacific), AMODE (Sargasso Sea). Hammer-Aitoff Projection. (From Dushaw (2015a).) (See also electronic Supplement 4.)

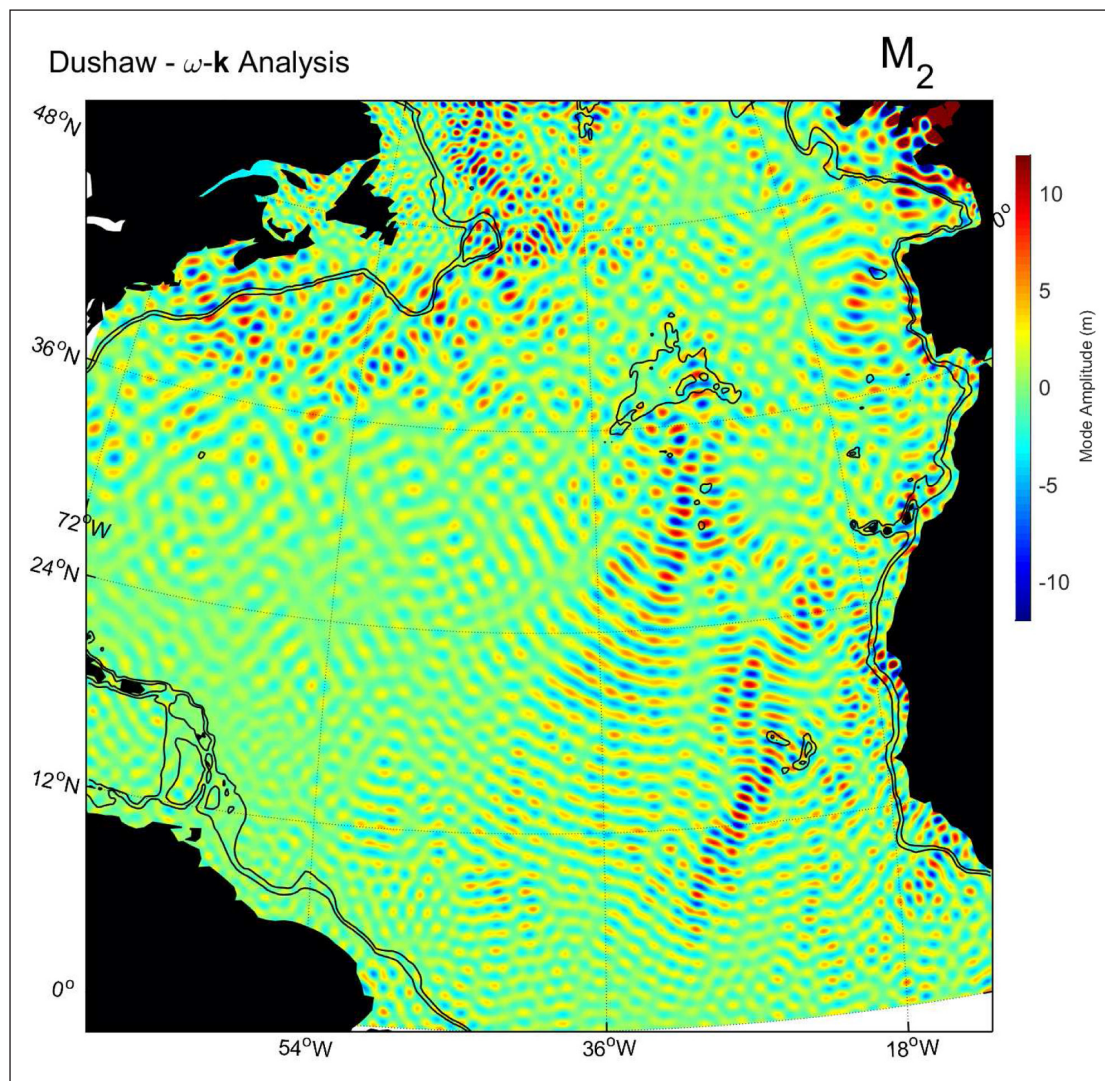


Figure 9 Mapping the internal-tide variability using the altimetry data allows some surprising wave features to be detected. By reconstructing the radiation using only generally southward wavenumbers, a long cylindrical wave train from the Azores almost to the coast of Brazil is revealed. The existence of such wave trains are a direct indication of the surprising spatial and temporal coherences of low-mode internal tides, since the complete wave field is a complicated interference pattern. Any incoherence would disrupt signals such as these. Units are internal-wave amplitude in meters, as computed from sea-surface height and solutions for internal-wave modes. (From Dushaw (2015a).) (See also electronic Supplement 5.)

eventually made such global contributions, with tests for the barotropic currents of global tidal models (Stammer and Coauthors 2014) and the determination that the internal-tide variability over most of the world's oceans can be predicted (Dushaw et al. 2011; Dushaw 2015a; Carrere et al. 2021).

There is now a bandwagon for development of global internal-tide models (Carrere et al. 2021). These global models are of critical importance to SWOT and other altimeter missions (International Altimetry Team 2021), not only to understand the potential internal-wave signal in these observations, but also to remove the internal-tide noise that would otherwise obscure the mesoscale signals. The report of Dushaw (2015) and all available tomography measurements of internal tides are available from the URL: https://apl.uw.edu/project/project.php?id=tm_1-15 so that others can make their own comparisons to the tomography data.

The internal-tide discoveries using tomography have all the classic elements of scientific discovery. First there were observations by new instrumentation that gave data with unexpected signals. An interpretation of those data led to the development of a novel theory or understanding of the internal-tide properties. That theory then led to predictions about other properties or observations that could be found: internal tides should be apparent in the altimetry records, other tomography experiments should have internal-tide signals of a similar character, and internal tides should be predictable. Consistent with the general nature of discoveries, each of these steps encountered considerable community resistance.

These waves, of course, are examples of internal waves, and the internal-tide properties can be used to better understand internal waves more generally. Alford (2003) used mooring data in the Pacific to show

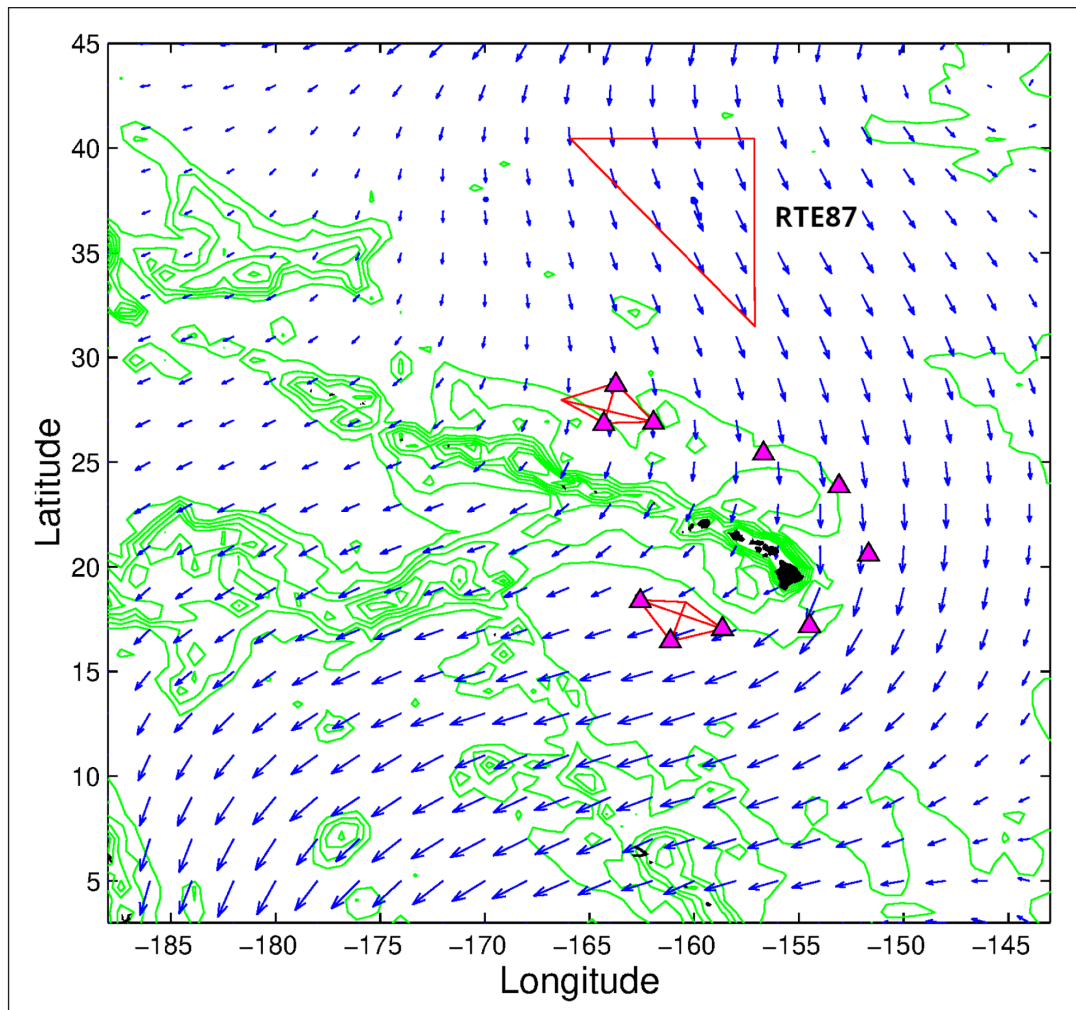


Figure 10 A schematic diagram of the farfield component of the HOME experiment. The arrows show the energy flux of the M2 barotropic tide; the barotropic tide prefers to go around the Hawaiian Ridge, rather than across it. By measuring barotropic tidal currents by tomography and tidal pressure by bottom tide gauges (magenta triangles) on either side of the Hawaiian Ridge, the aim was to determine the net tidal energy lost from the barotropic tide as it crossed over the Ridge. This energy goes into such processes as deep-ocean mixing or the radiation of internal tides away from Hawaii.

that the long-range propagation of internal waves can redistribute energy available for ocean mixing. The analysis of the internal tides in the altimetry record (Dushaw et al. 2011) showed there was little evidence for parametric subharmonic instability (PSI) of internal waves (MacKinnon et al. 2013). The resonant diurnal internal tides observed by the AMODE array (Dushaw and Worcester 1998; Dushaw 2006) are obvious examples of near-inertial waves (Alford et al. 2016).

One final surprising footnote. In 2005 Sugioka et al. (2005) used repeating, naturally-occurring sound sources (T-phases of seismic origin) to measure internal tides by tomography using those sounds along paths in the Eastern Pacific between northern Mariana and Japan.

8. ANTIPODAL ACOUSTIC PROPAGATION

Munk's paper "Australia-Bermuda sound transmission experiment (1960) revisited" (Munk et al. 1988)

(**Figure 11**) re-examined the nature of the acoustic propagation in an experiment that had been conducted in 1960. Three depth charges were dropped off Perth, Australia at 5-min. intervals and the sound from them was recorded by a hydrophone array at Bermuda, an antipodal distance away. The recorded signals were about 15 dB greater than noise, which is rather weak. Munk had determined that if horizontal refraction were accounted for, occurring mainly within the large sound speed gradients of the Antarctic circumpolar current system, the sound should never have reached Bermuda; Bermuda was in the acoustic shadow of sound from Perth, behind Africa. A subsequent analysis by Heaney et al. (1991) used estimated fields of the acoustic mode phase speeds to compute the acoustic propagation. With this more rigorous computation, Heaney et al. (1991) were able to obtain arrivals at Bermuda.

Revisiting Munk's 1988 paper 20 years later, I found he had anticipated most of the technical issues (Dushaw 2008). What had changed from the Heaney et al. (1991) analysis was the availability of accurate, high-resolution

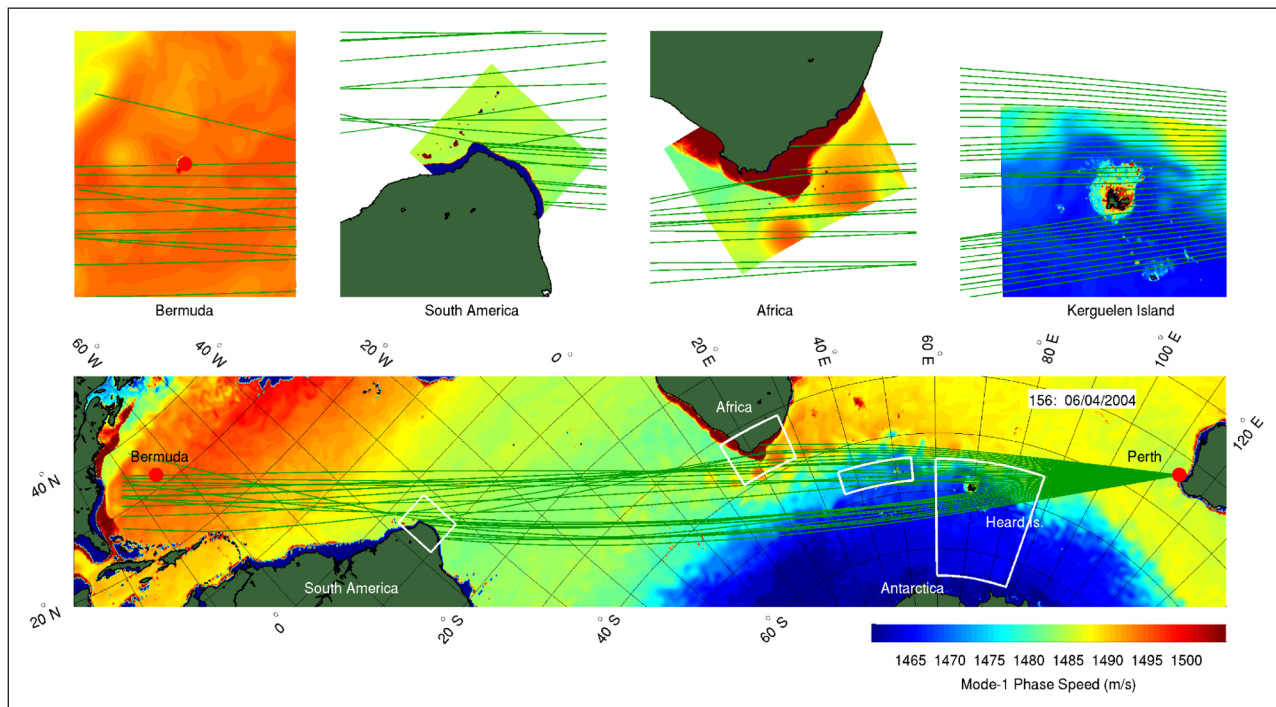


Figure 11 Computation of acoustic ray trajectories modeling the 1960 Perth to Bermuda acoustic propagation experiment. A fan of rays traced from Bermuda gave trajectories determined by oceanic refraction and scattering from topographic features. The colors indicate acoustic mode-1 phase speed for 15-Hz acoustic frequency derived from an ECCO ocean state estimate. Most rays either terminated at continental boundaries or passed south of Bermuda. Most often rays that arrived at Bermuda had scattered from topographic features in some way. The upper panels show the topographic interaction in detail: Kerguelen and the Crozet Islands were near perfect scatterers, the African continental shelf was a near perfect refractor, while the Brazilian continental shelf was a near perfect reflector. (From Dushaw (2014) by permission.) (See also electronic Supplement 6, the animation of this figure mentioned by Munk (2011).)

data for the sea-floor and high-resolution ocean state estimates. The state estimates permitted a much more accurate representation of the extraordinary variability of the Antarctic circumpolar current. Horizontal refraction is sensitive to sound-speed gradient, and the previous analyses had by necessity used primitive or low-resolution representations of the ocean. A preliminary analysis based on a smooth ocean atlas suggested that the measured arrivals were in the acoustic shadow (Dushaw 2008), but the newer, higher-resolution ocean representations showed that the sound-speed gradients were much larger. The Agulhas Rings that spin off the southern tip of Africa into the South Atlantic were obvious potential acoustic refractive features. Further, with the advantage of the internet, original material from the test was located and obtained from Australian government records, such as the ship's log for the experiment. The new material provided quantitative metadata for the details of the experiment (Dushaw and Menemenlis 2014). Further, the expected warming over the half century since the experiment suggested that the travel time today would be about 10 s less. The travel time measured in 1960 could be compared to the travel time computed from a state-of-the-art ocean state estimate obtained for 2004. The 1960 acoustic test represents a rare, accurate measure of the state of the ocean at that time.

Both Munk and Heaney et al. had assumed a typical sound frequency for the acoustic signals was 15-Hz, but that was not correct. An examination of the frequencies of the sound expected at Bermuda found that a 40-Hz center frequency was more accurate, with frequencies ranging between 10 and 100 Hz. The differences between 15-Hz and 40-Hz frequencies in long-range propagation are profound. Modes at 15-Hz are less sensitive to small-scale oceanographic features and they propagate adiabatically; the energy that starts in mode 1 stays in mode 1. At 40-Hz frequency, mode coupling induced by mesoscale variability is severe, so individual modes cannot represent the acoustic propagation. The mode propagation at the higher frequency is not adiabatic.

The ensuing tour-de-force calculation employed state estimates for 2004 from the Estimating the Circulation and Climate of the Ocean, Phase II program (ECCO2) (Dushaw and Menemenlis 2014) and the Smith-Sandwell estimate for the global seafloor topography (Smith and Sandwell 1997). The computation essentially followed Heaney et al. (1991), but with updated environmental estimates and repeating the calculations for frequencies from 10 to 100 Hz. From these computations, the acoustic data obtained in the 1960 experiment was reproduced in detail. The arrivals at Bermuda depended on sound scattered from the rough topography near Kerguelen in the southern Indian Ocean, with some contributions

from reflections from the coast of Brazil. The bulk of the sound from the explosive shots passed 200 km to the south of Bermuda (*Figure 11*).

Surprisingly, the computed travel time for 2004 was unchanged from that measured in 1960 to within a second (*Figure 12*). There were several factors mitigating a conclusion of “no climate change” in the comparison, however. First, the main uncertainty in the measured travel time was the location of shots, determined by dead reckoning and celestial navigation, amounting to a few seconds. Second, geophysical noise, or the variation in travel time from model snapshot to snapshot of the yearlong record, was also a few seconds. Third, the “measurement kernel,” or depth intervals sampled by the mode propagation, was centered on the sound channel axis. Over most of the almost 20,000 km path length, the depth of the sound channel axis is 1000–1500 m, where ocean warming is expected to be minimal. Lastly, one difficult aspect of the analysis was an assessment of the biases or errors of the mean state of the ECCO state estimates (Wunsch 2016). The contributions of ocean currents to the travel time were insignificant. In the end, the estimates for the 50-year change were surprisingly modest, much less than the initially-expected 10-s decrease.

Nevertheless, these results showed that antipodal measures of temperature are possible and offer a valuable constraint on changes occurring in the global ocean temperature. I suspect that a monitoring program repeating the Perth-Bermuda acoustic propagation would

find that the travel times are remarkably stable over time. The required source levels are surprisingly weaker than one might think; acoustic signals of 30–40-Hz frequency will travel antipodal distances with little attenuation.⁴ If there were an acoustic source deployed about 200 km south of Bermuda, the existing Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) HA01 hydroacoustic receiver near Cape Leeuwin, Western Australia (located at about 34.9°S, 114.15°E and 1400-m depth (Kadri et al. 2017)) could act as a receiver (*Figure 13*). After a trial period of a year or so, a small number of measurements one day per week or month would be sufficient for long-term monitoring. Such an acoustic source would also serve for tomography over large parts of the North and South Atlantic (See electronic Supplement 7). With near-zero practical uncertainty in temperature measurement and weekly temporal resolution, measurements like this would be invaluable for assessing changes in the oceanic climate state. Some have argued that measurements over antipodal ranges like this are not useful, because they are over several climatological regimes (Munk 2006). The strength of tomography, however, is its averaging, much as basin-scale measurements average over several mesoscale regimes.

9. BROAD-SCALE TEMPERATURE

One of the principal focuses of my dissertation work at SIO were the measurements of heat content in the

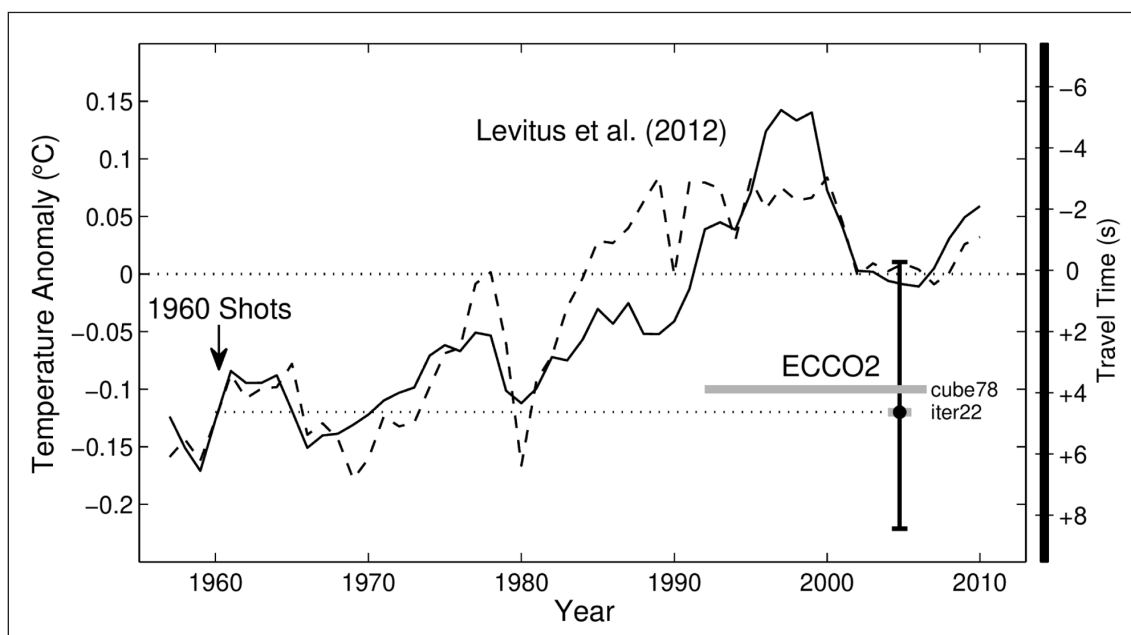


Figure 12 Time series of temperature anomaly over five decades computed by averaging the Levitus et al. (2021) estimates near the sound channel axis over antipodal acoustic paths (great circle/dashed, geodesic/solid). In these time series, the expected travel time decrease from 1960 to 2004 is only about 5 s, but the uncertainties are large. The intervals of the 15-year cube78 and 16-month iter22 ECCO2 solutions are indicated by the heavy gray lines, relative to the temperature anomaly value for 1960. Travel times computed from the state estimates were little changed from the 1960 measurements, but the uncertainties associated with the comparisons ($-4.9/+3.8$ s) are comparable to the warming signal expected from Levitus et al. (2012). (From Dushaw (2014) by permission.)

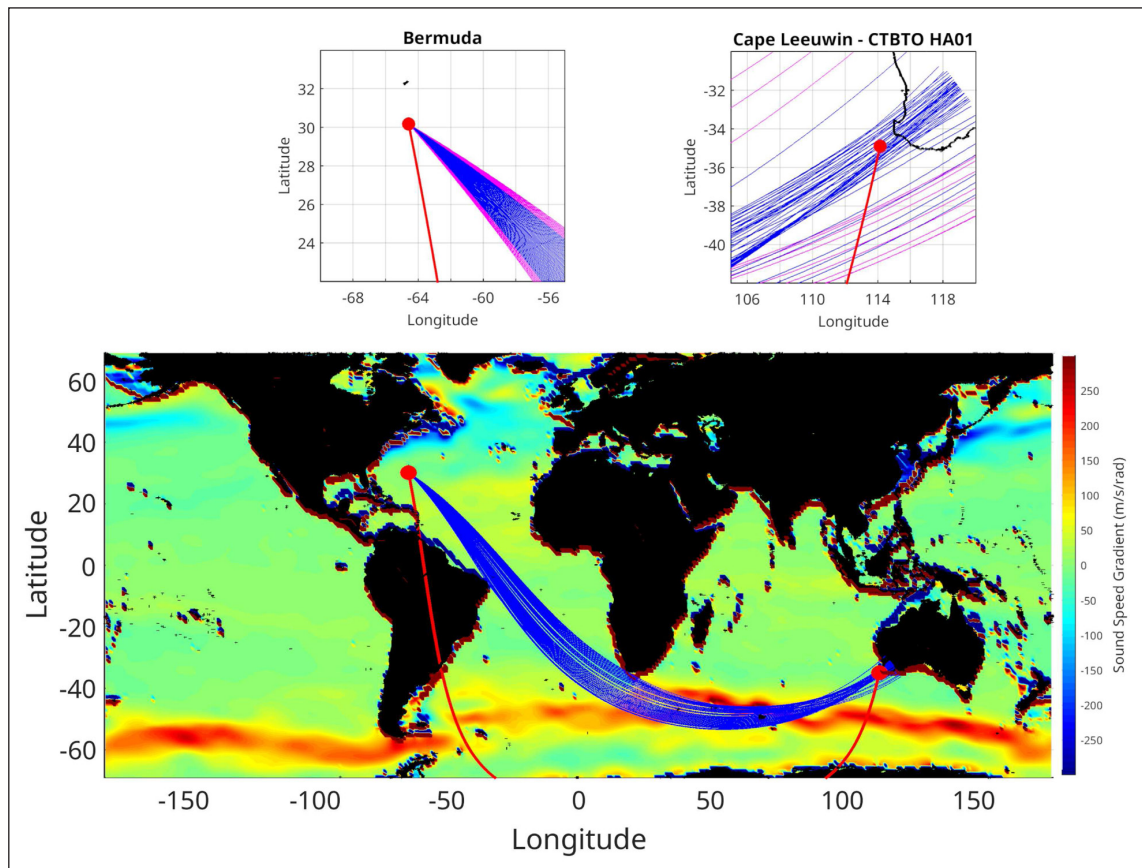


Figure 13 Refracted acoustic paths from a hypothetical 30-Hz acoustic source located about 200 km south of Bermuda arrive at the CTBTO hydroacoustic array HA01 off Cape Leeuwin, Australia. In the top panels, paths that intersect the South American or African continents are noted in magenta. The refraction is modeled using the first acoustic mode phase speed computed from the World Ocean Atlas; the colors indicate the meridional gradient of phase speed. The geodesic path is noted in red; the source and receiver are separated by slightly further than antipodal.

central North Pacific during the RTE87 tomography test (Dushaw et al. 1993b). The results of the work were of keen interest to the planners of acoustic thermometry by 1990–1991, and they were relevant later in the analysis of ATOC data. When the experiment began in May 1987, the upper-ocean mixed layer of the central North Pacific was non-existent, having been well mixed by winter storms. As the summer progressed, a strong, near-surface mixed layer of about 70-m thickness formed from warming, which by the end of the experiment in September had increased near-surface temperatures by about 8°C. Such warming implied the sound speed in that mixed layer had increased by an enormous 25 m s^{-1} , which also implied the tomographic inverse problem was nonlinear. As the summer progressed the resolved ray paths changed from being surface reflecting to bouncing off the bottom of the summer mixed layer. The importance of the nonlinearity of this problem was, for a time, a source of dispute between this graduate student and Walter Munk (David v. Goliath).

The nonlinearity was apparent when rays were traced through a simple inverse estimate for the sound speed field. The travel times in the solution were supposed to agree with the data, an essential aspect of the inverse problem, but they did not. While there are several

approaches to resolving the problem, the simplest was to employ a time-dependent reference ocean. The formation and evolution of the summer mixed layer was readily modeled to first order, and a suitably linear inverse was obtained using that evolving reference ocean. One surprising, perhaps subtle, conclusion from the analysis was that the nonlinear nature of the inverse problem in this case increased the vertical resolution of the solution. The additional constraint arises, fundamentally, from the sensitivity of the acoustic propagation to sound speed gradient. Both the sound speed and sound speed gradient had to be correct in the final solution. The values for heat content at the start and end of the experiment matched those computed from XBT and CTD sections, but the ocean/atmosphere heat exchange computed from bulk formulas accounted for only half of the observed change in heat content.

Munk long advocated for acoustical systems to monitor large-scale ocean temperature (Munk 1986; Munk and Forbes 1989), with the Perth-Bermuda experiment providing motivation. These considerations led to the Heard Island Feasibility Test (HIFT) in 1991, with transmissions from sources lowered from a ship in the southern Indian Ocean (Munk et al. 1994) (<https://staff.washington.edu/dushaw/heard/index.shtml>). Such a

location offered an “illumination” of the global oceans by sound. HIFT planning and execution occurred in the final year of my dissertation work at SIO; it was an exciting time. The 9-day HIFT experiment was followed by the ATOC program (1992–2006) in the North Pacific (*Figure 14*).

A. ACOUSTIC THERMOMETRY OF OCEAN CLIMATE (ATOC)

As noted, around 1980 Munk began arguing for acoustic tomography as a sustained measurement of the temperature of ocean basins, with an eye on the climate problem. Key aspects of the argument were that the noise from the mesoscale presents a difficult problem to overcome (short-scale noise of about 2°C vs. a large-scale signal of about 0.05°C), and that there would not likely be sufficient existing observations, deployed from ships or on moorings, that would overcome the problem. The argument remains valid today. Around 1992, W. Munk secured \$37M of funding for the ATOC program through the Defense Advanced Research Projects Agency (DARPA). The funding was controversial; I speculate that many did not believe that temperature measurements from the anticipated acoustic observations were even possible. The DARPA grant was peculiar in that it was a two year grant, even though the project was aimed at a decade of observations, putting pressures on how the money was to be spent. The funding period was later extended by a few years. One consequence of this funding, obtained in the final year of my dissertation work at SIO, was that I was hired by Bruce Howe in September 1992 to work for the project at the Applied Physics Laboratory (APL) at

the University of Washington in Seattle. The ATOC time series began in 1996 and continued through 2006. After the expiration of the DARPA grant, funding for continuing the program was provided by the U.S. Office of Naval Research through their ocean acoustics program.

Many oceanographers believed that with the existence of the Argo float program, tomography was not necessary, that Argo obviated the need for tomography observations (numerous people, known and anonymous, personal communications 1995–present). This view, never more than a dubious hypothesis, is incorrect; no existing analysis or publication supports that view, while existing publications contradict it (Dushaw et al. 2009; Dushaw and Sagen 2016; Dushaw 2019; Wu et al. 2020). The resolution of the question is obvious: line average measurements are not the same as point measurements.

In retrospect, the design of the ATOC program had several flaws. The North Pacific basin was chosen as the location for the decadal deployment of two acoustic sources (*Figure 14*). Although a primary scientific aim was the detection of secular warming of the ocean (for this paper such warming is “climate”, distinct from natural El Niño/Southern Oscillation changes), the North Pacific has remarkably benign sound speed conditions, and it is perhaps the last region of the world’s oceans to experience ocean warming or climate variation. The Pacific may have been chosen because the logistics of deploying and operating instrumentation was easier for the West Coast universities that constituted ATOC, e.g., the acoustic sources had to be cabled to shore, and California and Hawaii were two obvious locations to deploy them. It was later determined from ocean

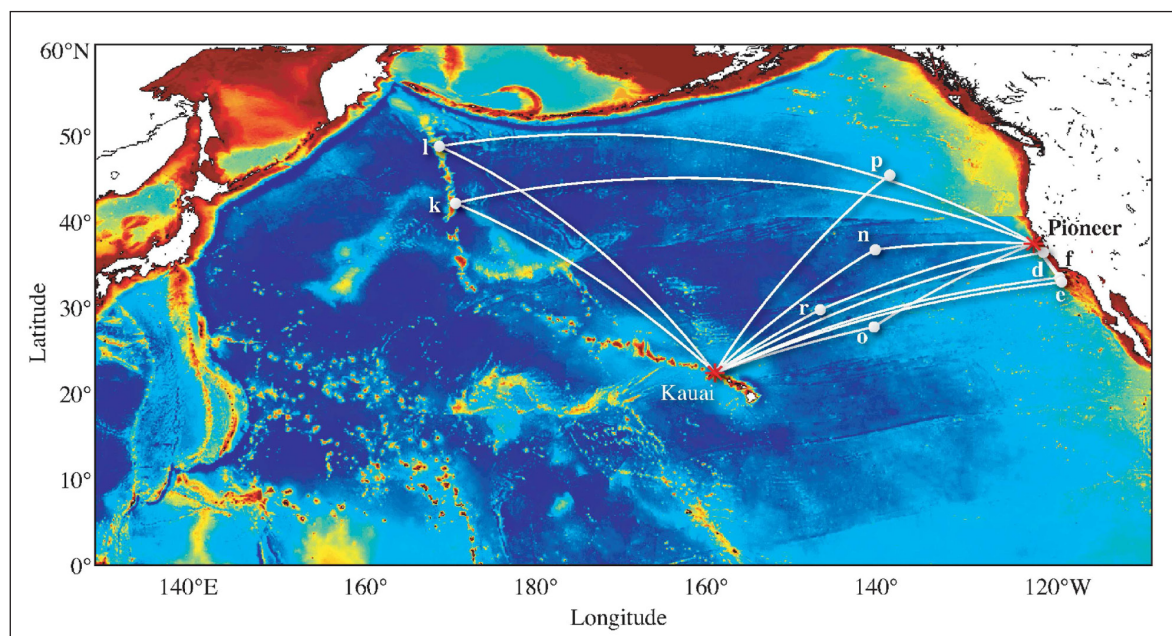


Figure 14 Acoustic paths from the 1996–2006 Acoustic Thermometry of Ocean Climate (ATOC) experiment. The acoustic source located on Pioneer Seamount transmitted for about a year, while the source located north of Kauai transmitted over a decade. Nominal receiver locations are denoted by letters. Data obtained from the Kauai to “k” path is shown in the next figure. (From Dushaw et al. (2009) by permission.)

modeling that ordinary interannual variations of ocean temperature in the Pacific would make detection of any secular temperature change difficult (Dushaw et al. 2009, 2013). The program adopted the U.S. Navy Sound Surveillance System (SOSUS) as receivers of opportunity for obtaining the long time series of acoustic data. Jim Mercer at APL had assembled a system for using such receivers, so they were readily available and inexpensive to use. Many of those systems were classified, such that the data would not be readily available to researchers, but that was not seen as a particular problem in 1992. ATOC began just prior to the data revolution of open access afforded by the Ocean Observing System paradigm (OceanObs'99 Conference 2001a). The ATOC program depended on ocean modeling and assimilation of the acoustic data as model constraints (Menemenlis et al. 1997; ATOC Consortium 1998), however. Since those doing that work did not have a security clearance, they did not have access to most of the data acquired, nor could the data be examined or used by others. The ECCO modeling group at the Massachusetts Institute of Technology (MIT), JPL, and SIO was supported through the DARPA funding of ATOC.

The ATOC program was almost immediately embroiled in the controversy over the possible effects of man-made sound and marine mammals. The issue had begun as a problem during the HIFT experiment. I have little first-hand information to contribute on the subject, other than I noted the difficulty of conveying complex scientific and nuanced information to a public enraged by poor reporting in the news (Munk 2006). I mention the issue here because ATOC became primarily and formally a program to assess the impacts of acoustics on marine mammals. The \$6M (from the DARPA grant), six-year study conducted in coordination with ATOC transmissions found that those transmissions had “no significant biological impact” (C. Clark, personal communication, ca. 2002). The spotty nature of the acoustic measurements acquired during ATOC arose from the protocols for marine mammal research, e.g., fog off the Northern California coast often prevented surface observations of marine mammals, which precluded any acoustic transmission from the acoustic source on Pioneer Seamount. No data were obtained during the major El Niño event of 1997–98 for this reason.

Even before ATOC, considerable effort was devoted to understanding the acoustic propagation, interpretation of the acoustic data, and testing the integrity of estimates of temperature derived from the data, e.g., Worcester et al. (1994); Cornuelle et al. (1993); Worcester et al. (1999); Dushaw et al. (1999); Dushaw (1999a); Colosi and Coauthors (2005). The ATOC broadband sources used a 75-Hz center frequency transmitting at a level of 195 dB re 1 μ Pa at 1 m (the sound level was comparable to that of a blue whale vocalization, or that of a large container ship). Several SOSUS receivers, located on the bottom

in the abyssal ocean of the North Pacific, recorded data anytime that the ATOC sources transmitted. In addition, ATOC and later the U.S. Office of Naval Research (ONR) supported several O(1-yr) experiments dedicated to understanding the acoustic propagation in a program called the North Pacific Acoustic Laboratory (NPAL). These experiments consisted of vertical line arrays (VLA) deployed at 2–5-Mm ranges (an “Mm” is a megameter) from the acoustic sources (Worcester et al. 1999; Dushaw et al. 2013). The Kauai and Pioneer acoustic sources were deployed on the top of prominent topographic features, such that the source depth was near the sound channel axis, while also allowing the acoustic signals to propagate into the deep ocean free of complicating bottom interaction (Howe et al. 1995). The bottom slope away from the Kauai source was not sufficiently steep enough, such that bottom interactions influenced some deeper acoustic rays, however (Vera et al. 2005; Dushaw et al. 2013). The project led to the development of devices for easy assembly of long Distributed VLAs (DVLAs), the D-STARs (DVLAs – Simple Tomographic Acoustic Receivers) (Worcester et al. 2009), and pop-up data modules that would bring acoustic data from a VLA to the surface to be recovered from a ship, leaving the mooring intact (Howe et al. 1995). Aside from the discovery of the “shadow zone” arrivals described above, there were no particular surprises in the nature of the acoustic propagation. Even at 5-Mm range, several deep-turning ray arrivals were resolved and identified, while over the later portion of the arrival pattern the internal-wave scattering was sufficient to obscure any clear ray arrivals ([Figure 2](#)). Transmissions from an initial test of the California source were detected just north of New Zealand (20 dB above noise, after signal processing to compress the transmitted signals) at 9648-km range in a small experiment by Matt Dzieciuch from SIO. Though ATOC transmissions were not reciprocal, tidal variations in the time series of O(20 ms) amplitudes, caused by barotropic currents, were readily observed and predicted using a global tidal model (Dushaw et al. 2013); these are measurements of high precision. Computation of inverse estimates for the sound speed field was relatively straightforward, and subsequently computing the acoustic propagation through that solution gave predictions that matched the observations (Cornuelle et al. 1993; Dushaw 1999a). Temperature can then be derived from sound speed.

The acoustic source on Pioneer Seamount off California transmitted intermittently for three years, 1996–1998, following marine mammal protocols. The acoustic source north of Kauai began transmitting intermittently at the end of 1997, before making regular transmissions between 2002 and 2006. By legal agreement, transmissions ceased at the end of 2006. The ATOC transmissions recorded by the SOSUS receivers were retrieved to a secure facility at the Applied Physics Laboratory. After initial processing, such as compressing

the coded raw acoustic data, beam forming, and acoustic peak extraction, “dot plots” were created (Dushaw et al. 1999). That system had been set up by J. Mercer and B. Howe at the Applied Physics Laboratory and K. Metzger at the University of Michigan, and S. Leach, S. Weslander, and L. Buck efficiently ran the secure facility and extraction of the data from the SOSUS system. It fell to me to interpret these data, derive tracking routines for them, and track the stable ray arrivals. Because the receivers were mounted on the sea floor, the arriving acoustic signals were often interacting with the sea floor, hence the interpretation of those data was challenging. Nevertheless, I duly tracked these travel times over the 1996–2006 decade.

The paper “A decade of acoustic thermometry in the North Pacific Ocean” reported on these data (Dushaw et al. 2009). To evaluate the value addition of the acoustic data, we compared several model estimates or data products: climatology (Locarnini et al. 2010; Antonov et al. 2010); an Objective Analysis (OA) of XBT, Argo profile, and altimeter data (Willis et al. 2004); state estimates from the ECCO collaboration; and a high-resolution

integration (not constrained by data) of the Parallel Ocean Program Model (POP) (McClean et al. 2006) (*Figure 15*). Early in this analysis, we made the decision to compare measured travel times with equivalent travel times computed in the model estimate or data product, rather than compute an inverse of the travel time data for a comparison of temperature. The primary reason was that for the trans-basin acoustic paths the depth interval over which the rays sampled varied along the acoustic path. In tropical regions the paths did not extend to the sea surface, for example. The travel time comparison was the most accurate and direct way to compare the acoustic data to the other products. As noted above, the time-mean states of some of these models were unphysical, producing wildly erroneous acoustic arrival patterns, so they were replaced by the World Ocean Atlas (Dushaw et al. 2009, 2013); a first and blatant correction afforded by tomography. The comparisons showed that the available observing system was not capable of reproducing the decadal time series of acoustic observations, e.g., *Figure 15*. Significant discrepancies between data and computed travel times were found, some comparable in

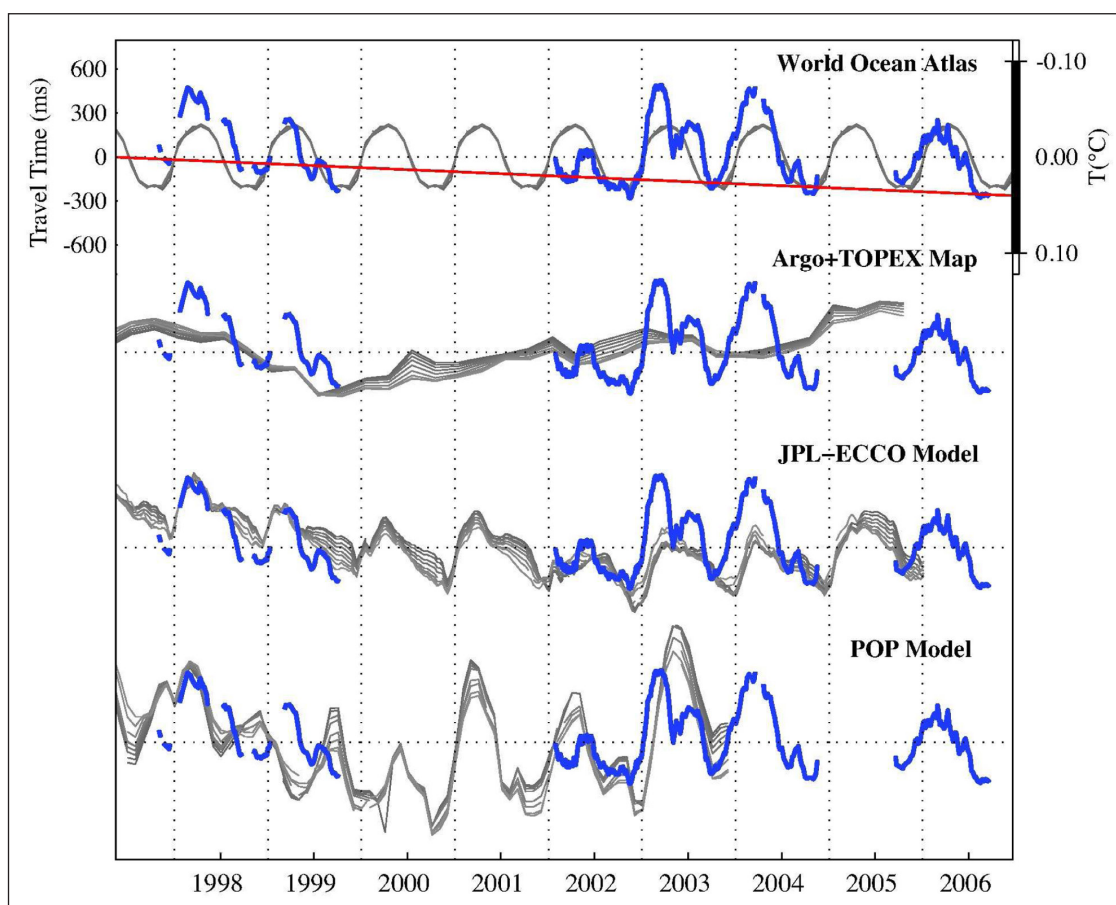


Figure 15 Comparison of measured travel times for transmissions from the source near Kauai to receiver k (blue) with travel times calculated using sound speed fields derived from: WOA05, estimates of upper-ocean temperature profiles produced by an OA procedure that combines satellite altimetric height with in situ temperature profiles, the JPL-ECCO solutions, and the POP model (gray). The time means have been removed from all of the time series. Approximate estimates of temperature perturbations averaged along the ray path inferred from the travel times are shown on the right-hand axis. The nominal travel time trend corresponding to a warming of 5 m°C/yr on the sound channel axis, as suggested by Munk and Forbes (1989), is shown (red). (From Dushaw et al. (2009) by permission.)

size to the annual cycle itself (Dushaw et al. 2009). In [Figure 15](#), the two interesting comparisons are to the OA and ECCO time series. The hydrography plus altimeter analysis is resolved only quarterly, so the two time series are dissimilar. The ECCO predictions are optimal, since they are constrained by dynamics, data, and forcing. This comparison was recently approximately remade with an up-to-date ECCO state estimate, but the more recent comparison looked virtually identical to that in [Figure 15](#) (Dushaw 2019); the deficiency is in the sparse data constraint. The accuracy and temporal resolution for the measurement of large-scale temperature afforded by tomography are spectacular.

As has been previously noted, the primary role of the tomographic data type is as a constraint on large-scale temperature in ocean modeling and assimilation systems. This role was demonstrated in a paper published in *Science* in 1998, “Ocean Climate Change: Comparison of Acoustic Tomography, Satellite Altimetry, and Modeling” (ATOC Consortium 1998), which demonstrated how the various data types, numerical ocean modeling, and data assimilation could be brought together. The paper concluded that “only about half of the seasonal and year-to-year changes in sea level are attributable to thermal expansion” and that “a large seasonal cycle in the advective heat flux” may be required in “meteorological estimates of surface heat flux,” a result that was questioned by Kelly et al. (1999), response by ATOC Consortium (1999). Kelly et al. argued that the local seasonal variations in sea-surface height were almost entirely accounted for by thermal expansion from local air-sea heat exchange. As of this writing I am uncertain of the resolution of this issue, though Kelly et al. made a compelling case, and I have been informed that the early ECCO state estimate employed for that study had significant problems that have since been resolved (Menemenlis, personal communication 2021). While it is essential in tomography to verify the final ocean state estimate by recomputing the acoustic travel times in the optimized solution to verify that the ocean state estimate is consistent with the acoustic data, I know this check was not done with the ECCO state estimates because of the security restrictions mentioned above. For me, the primary result of the paper was to demonstrate how these elements could be brought together, and the impact of the acoustic data on “correcting” the GCM was significant (GCM problems notwithstanding). None of the possible approaches to employing travel time data as constraints on GCMs are simple.

B. OBSERVING SYSTEM ARRAY DESIGN IN THE NORTH ATLANTIC

1) Acoustic thermometry and Ocean Observing Systems

The first OceanObs conference, a decadal international conference aimed at the design, coordination, and

implementation of global or regional Ocean Observing Systems (OOS), was held in San Rafael, France in 1999. I had attended a small workshop on the Global Ocean Observing System (GOOS) led by M. Briscoe a few years earlier at the San Francisco meeting of the American Geophysical Union; there were about 10 people present. My interest in the OOS was, of course, because I assumed that ATOC was to be a part of that system. I viewed the conference as an opportunity for the larger community to put all observing methods on the table and make a scientific and objective assessment of the value addition of each method.

A large number of us participated in writing a “white paper” representing acoustics generally, and tomography specifically, for the OceanObs’99 and subsequent OceanObs’09 conferences (Dushaw and Co-authors 2001, 2010). Organizing the diverse community (biological acoustics, signal processing, environmental acoustics, acoustical oceanography, etc.) took considerable effort, extending over a year. The acoustics communities were foreign to OOSs; the process of integrating these two communities has been challenging. Acoustics and tomography have had representation at all the OceanObs international conferences (Dushaw and Co-authors 2001, 2010; Howe et al. 2019).

The OceanObs’99 conference accepted a possible role for tomography, recommending the North Atlantic Basin for a pilot study implementing tomography (OceanObs’99 Conference 2001a,b). This basin was recommended again in OceanObs’09 (Fischer et al. 2010). At that time, however, the interest and activity was with the ATOC program in the Pacific, though climatological signals in the Atlantic are far more dynamic. The Atlantic is a more interesting ocean basin from the perspective of climate or interannual variability. The tomography community did not respond to this recommendation, however (but see Scientific Committee on Ocean Research Working Group 96 (1994)). Even now, I am not sure how those of us on the tomography side could have responded to the OceanObs advice. W. Munk’s ATOC consortium and the ONR funding agency were focussed on the Pacific, and I was employed through the NPAL project. In 1999 there were still lingering questions regarding the nature of long-range acoustic propagation that were perhaps best addressed initially in the more benign Pacific environment. To embark on a new Atlantic project, we would have needed further support, enthusiasm, and encouragement from the oceanographic community, which was not forthcoming. Equivalently, there was no obvious funding avenue for tomography array design and acoustic propagation studies which would have been required to begin an Atlantic pilot program.

OceanObs’99 was also the start of Global Ocean Data Assimilation Experiment (GODAE), the modeling and state estimation branch of the OOS. At the end of the OceanObs’99 conference, I assumed that GODAE would

at some point necessarily involve tomography as part of observing system design, with a quantitative assessment of its value in constraining broad-scale temperature. This assessment did not occur, however.

By 2018 there had been 20 years of observing system development but no quantitative assessment of the possible contributions of tomography in an Atlantic observing system. The ATOC program had had its flaws and troubles, as described above; it and its data (limited time series, security issues) have proved to be incompatible with existing observing systems. I was reminded of the issue when I was asked to participate in a preliminary study for an observing system in Baffin Bay (Dushaw and Rehm 2016), and learned of a new Atlantic Observing System (<https://www.atlantis-h2020.eu/>) that made no mention of tomography. With some free time available, finally, I began to think of how I could make some simple study that would quantify the possible contributions that tomography could make in an Atlantic Ocean Observing System.

2) An assessment of tomography arrays in the North Atlantic

The obvious starting point for an array design study was one of the several high-quality ocean state estimates for the Atlantic. The ECCO program had produced 24 years of global ocean state estimates, derived by employing most available data and ocean-model dynamics as constraints. Monthly-mean ECCO estimates of the North Atlantic were used for the study. Data assimilation approaches for the intended study were precluded by their formidable difficulties, so a simpler approach was sought through standard objective mapping techniques. For such techniques one requires a set of basis functions that can be used to parameterize the ocean variability. In this case, the functions were required to represent the North Atlantic, while being elements of a computationally-modest estimation problem.

One obvious approach was to develop a representation for ocean temperature variability using empirical orthogonal function (EOF) analyses. The 24 years of monthly estimates afforded only $12 \times 24 = 288$ independent variables, so that an EOF analysis of the temperature covariance provided only 288 functions, however. To construct a more general basis set for the analysis, the length scales of the temperature covariances were artificially tapered by applying a Gaussian weighting (eliminating both natural and artificial “teleconnections”), and a system of about 5000 independent basis functions was obtained from that modified covariance (Dushaw 2019). While simple and limited, this set of basis functions provided a reasonable representation of the temperature environment of the North Atlantic, which could be used to test the relative temperature resolution capabilities of various measurements.

Integrated ocean heat content (OHC), averaged over a large area, was an obvious metric to use. With the functions derived from the EOF analysis forming a basis set for an objective mapping system, how well do Argo, tomography, or Argo+tomography data types estimate the integrated temperature of the North Atlantic (*Figure 16*)? The existing sampling by floats in the North Atlantic was used to represent the Argo system. For tomography, a hypothetical basin-wide array of two acoustic sources and seven receivers was employed, among other examples. Broadly speaking, the uncertainties resulting from temperature estimates derived from Argo-only or tomography-only were comparable and about 50% of the natural variability of the system (the prior). When both data types were combined, however, that uncertainty was reduced to 25% of the prior variability. The result illustrates the complementarity of the two data types. To obtain a similar reduction in uncertainty by employing more Argo floats would require roughly four times as many Argo floats.

These results are consistent with those from other publications; Argo and tomography are different measurements. The one offers resolution of temperature variability not afforded by the other. The ATOC measurements in the North Pacific were consistent with this assessment, with ATOC travel times substantially different from equivalent travel times computed from a state-of-the-art ECCO state estimate (Dushaw et al. 2009; Dushaw 2019). A study of a mooring array and an acoustic array used to measure temperature across the Fram Strait using objective map techniques obtained a similar conclusion. For a single-section system across Fram Strait, tomography and moored-thermistor array data are complementary (Dushaw and Sagen 2016).

C. EPILOGUE

For the most recent OceanObs’19 conference, Meyssignac and Coauthors (2019) provided a community summary paper on “Measuring Global Ocean Heat Content to Estimate the Earth Energy Imbalance.” The complementarity of acoustic tomography with respect to existing systems was acknowledged within a lengthy section on the novel notion of Internal-Tide Oceanic Tomography (ITOT). However, the brief, cursory mention of acoustic tomography indicates that the ocean-observing community still has not accepted the measurement, preferring instead to discuss ITOT. As previously shown (Dushaw et al. 2011), years of altimetry data are required to obtain a stable estimate of the internal-tide phase, from which temperature might be estimated. The temporal resolution of ITOT is therefore years, while the temporal resolution of acoustic tomography can be as short as hours. Meyssignac and Coauthors (2019) do not acknowledge the contributions of acoustic tomography to the internal tide topic, although better temporal

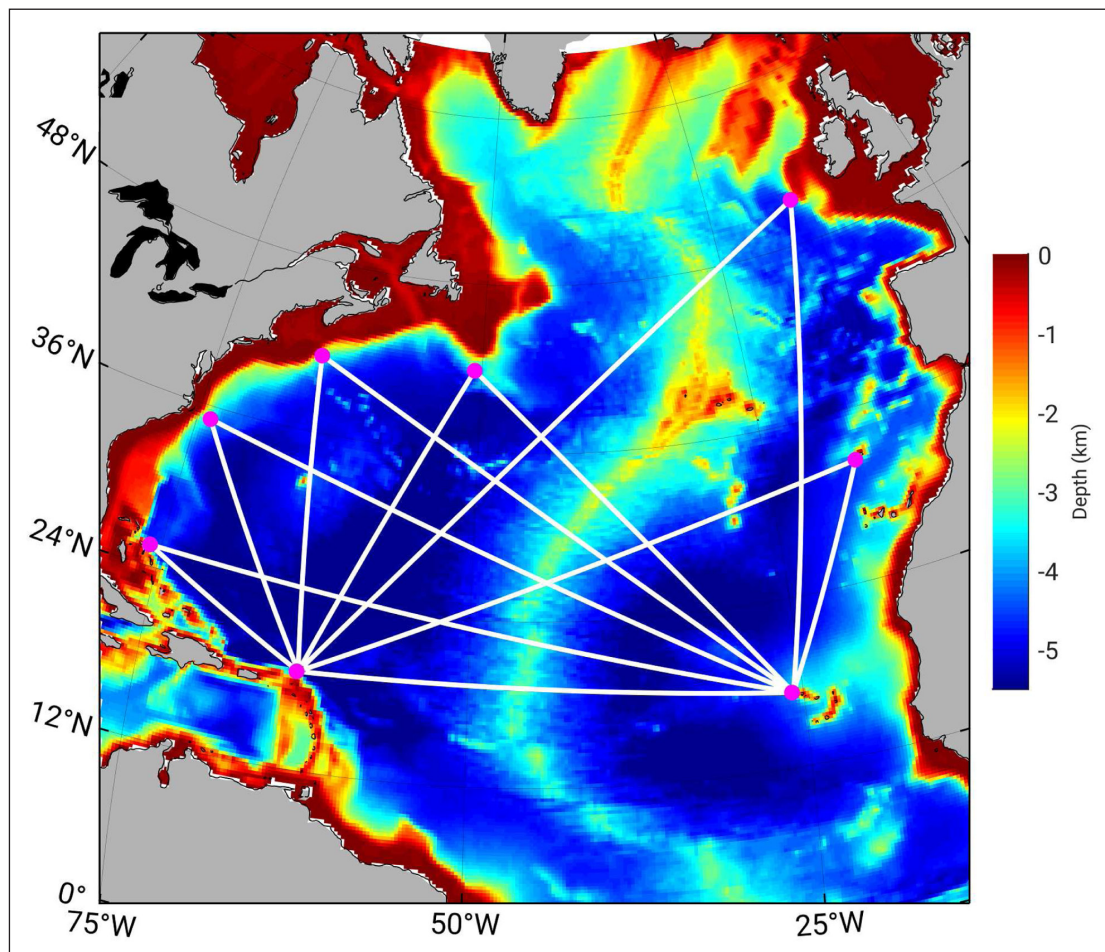


Figure 16 A hypothetical acoustic array for observing the North Atlantic Basin. This notional array consists of two acoustic sources and seven receivers. All instruments are located near a shelf break. One acoustic source is located near Antigua and Barbuda, another near the Cape Verde Islands. The acoustic paths are selected to avoid topographic interaction. An observing system consisting of such an array and Argo floats would significantly reduce the uncertainties of ocean state estimates at the largest scales compared to using a system of Argo floats alone. (From Dushaw (2019) © American Meteorological Society. Used with permission.)

resolution from ITOT could be obtained by measuring the internal-tide phase with acoustic tomography. Such a system would improve the temporal resolution of ITOT to about a month, while simultaneously providing the high-accuracy temperature measurement afforded by acoustic tomography.

Two unpublished, objections to the employment of acoustic thermometry are that it is not worthwhile from a cost vs. benefit perspective and that it presents a danger to marine life. To address the first objection, a rough sketch of the various costs involved was given in Dushaw (2019). Fundamentally, the issue is that the profile of costs over time for various observation approaches are different. Tomography requires a large upfront expense, but after deployment operational costs are minimal. The accumulated cost for the Argo float system increases linearly with time. The ATOC acoustic source that was deployed 23 years ago north of Kauai is still there, and it is still operational. There are regular rumors that a program may start that would allow it to begin transmitting again. Its operational costs are about \$150K per year (J. Mercer, personal communication, ca. 2005). Acoustic receivers are relatively inexpensive, and receivers of opportunity

sometimes become available. Bruce Howe seeks to deploy hydrophones at O(50-km) intervals on communications cables that cross ocean basins (Howe and Co-authors 2019) (e.g., (Figure 17)). Since tomography affords a measurement that is complementary to the existing system, a cost-benefit analysis is mostly moot, however; tomography provides information about changes to the ocean's climate state unobtainable by other means. The world conducts all manner of scientific projects, some at extraordinary expense (e.g., Argo, satellite programs, deep-ocean drilling, mission to Mars). I see little objective reason why tomography is so different and of such a character as to preclude its deployment. To address the second objection, a brief discussion of the marine mammal issue was also given in Dushaw (2019). There are now decades of experience with tomography and tomography-like sound sources in the oceans, including SOFAR (SOund Fixing And Ranging) and RAFOS (Ranging AND Fixing SOUND) float systems and the dedicated, 6-year ATOC marine mammal program, with no reported adverse effects on marine life. It is my understanding that obtaining environmental permits for similar acoustic transmissions in the future would be

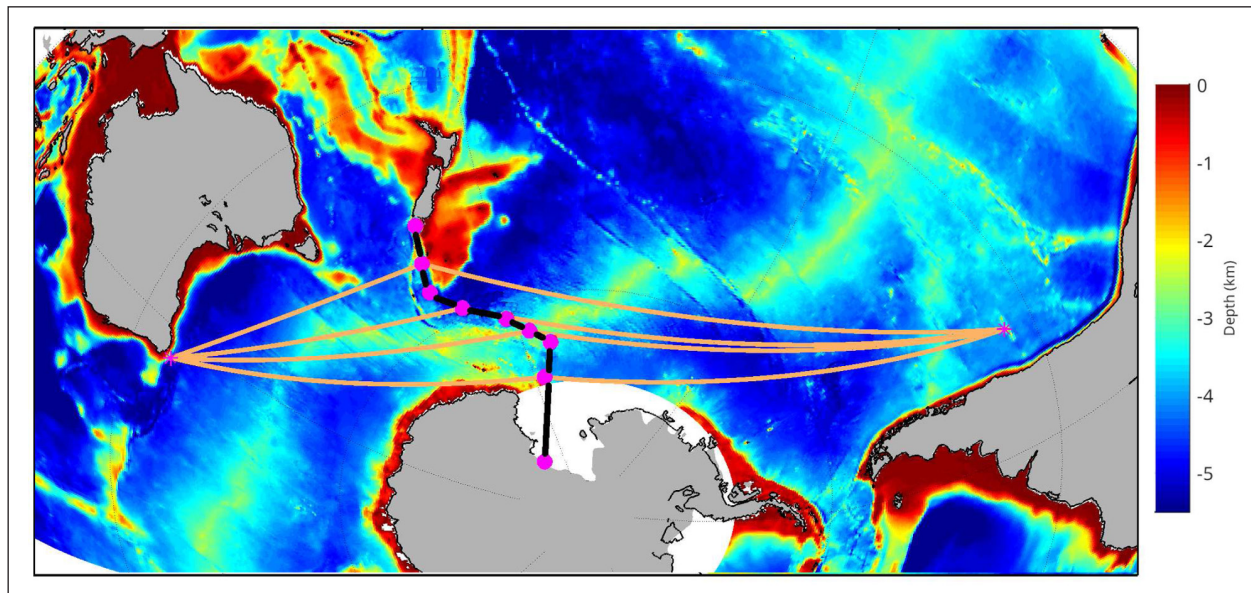


Figure 17 A hypothetical acoustic observing system for the Southern Ocean. This notional array would rely on hydrophones deployed on a planned communications cable between southern New Zealand and McMurdo Station, Antarctica. The acoustic paths shown, from 5000 to 7500 km in length, are from notional sources off Cape Leeuwin, Australia and Juan Fernandez, Chile.

relatively trouble free. As I concluded in Dushaw (2019), “While vigilance for possible adverse effects should be maintained, precluding deployment out of fear of unlikely, hypothetical scenarios for how marine life can be impacted by these relatively weak acoustical signals is unreasonable.”

Recently, sound from stable, repeating natural seismic sources (T-phases) in the Indian Ocean were recorded at a distance of 3000 km and used to obtain measures of broad-scale temperature (Wu et al. 2020). Such measurements gave comparisons to Argo estimates that were similar to the ATOC comparisons, with time series distinctly different from those derived from the hydrographic estimates. Once again the uniqueness of the acoustic data was indicated. Although dependent on what nature provides, the use of such natural sound sources affords possible long-term observations of temperature without the need for deploying acoustic sources. (The ubiquity of such natural sound sources in the ocean is an indication of the benign nature of ATOC sources.)

10. DISCUSSION

Acoustic tomography is a surprisingly simple measurement. It is, to first order, a high-accuracy average of temperature and current over a geodesic path and over depth. Such a measurement has resulted in several novel discoveries over the past 25 years: an accurate and precise test of the fundamental speed of sound in the ocean; a determination from acoustic propagation characteristics that the ocean has a well-defined, smooth sound speed structure in most circumstances, smoothness that has been challenging for numerical

ocean models to reproduce; accurate measurements of barotropic current, including the tides; the discovery of low-mode internal tides that radiate coherently far into the ocean’s interior, and that their coherence is such that their amplitude and phase can often be predicted in the world’s oceans from an altimetric analysis; and, even to antipodal distances, tomography provides precise measurement of thermal variability. All of these discoveries are unique to tomography, or, in the case of thermal variability, complementary to existing measurements. Physical oceanography has yet to exploit the ability of tomography to make accurate measurements of barotropic current or relative vorticity. A simple array of two acoustic sources and seven receivers can be employed to make basin-wide measurements in the North Atlantic, and such an array would significantly reduce the uncertainties of the large-scale heat content. The nature of the measurement also affords good temporal resolution; since the measurement is high precision, the temporal resolution is the sample rate of the observations. Hence tidal variability is well resolved, and large-scale thermal variability can be accurately observed on daily to weekly scales. Such temporal resolution is presently lacking in the existing ocean-observing system, although it has been noted that basin-scale variability occurs at all time scales, with examples of large thermal shifts occurring over weeks (Miller et al. 1994). Basin-scale thermal variability is estimated from the present system at only quarterly, or often multiyear, periods. A creative approach to exploiting tomography in experiments or sustained observations will pay dividends.

Several important results were not discussed here. Two such results are the first detection of warming in the Arctic by trans-basin measurements in the 1990s (Mikhalevsky et al. 1999) and acoustic thermometry of

the Mediterranean Sea (Send et al. 1997). Other results are the remarkable use of tomography to observe, map, and quantify deep-convection events in the Greenland Sea in 1988–89 (Worcester et al. 1993; Pawlowicz et al. 1995; Morawitz et al. 1996) and Gulf of Lion in 1991–2 (Gaillard et al. 1997). The Greenland Sea observations took advantage of the ability of tomography to make rapid, synoptic measurements, thus they were able to observe and quantify deep convection events. Attempts to observe such events by a conventional hydrographic cruise were not successful and had to contend with the extreme weather driving convective events. Considerable progress has been made on the use of data assimilation methods to address one of the original aims of tomography, the resolution of mesoscale variability (Gaillard 1992; Rémy et al. 2002; Yaremchuk et al. 2004; Gopalakrishnan et al. 2021). Tomographic systems have been exploited to determine the positions of autonomous underwater vehicles (Van Uffelen et al. 2013), a potentially critical role for such systems in OOSs. One under-exploited technique is the use of inexpensive, high-frequency acoustics to make short-range ($O(10\text{ km})$) regional observations in locations such as harbors, specific shallow-water areas (Kaneko et al. 2020), or across straits (Send et al. 2002).

With the experience from a few decades of experiments, the understanding of and expectations from tomography have evolved. The technique is one that relies on what nature provides by way of acoustic sampling and propagation conditions. As a prelude to the 1987 experiment that would form the basis of my dissertation, Malanotte-Rizzoli and Holland (1985) and Malanotte-Rizzoli (1985) examined ways in which gyre-scale acoustic measurements could resolve and monitor the tilt of the gyre isopycnals that drive the thermohaline circulation. Munk tried to get me to pursue such an analysis as part of my dissertation work with the recovered data. Rizzoli's notions proved to be intractable, however, since, in the actual data, the evolution of the summer mixed layer and the non-local barotropic currents were the dominant signals. Further, the depth resolution proved to be limited when only surface-reflected rays were resolved. The limitations in depth resolution in tomography, often caused by the corrupting effects of internal waves, was a disappointing development. Such a limitation is clear in areas like the North Pacific, but areas like the North Atlantic may still offer considerable depth resolution (Dushaw 2019). Other early experiments highlighted the challenging environment of boundary current regions with their extraordinary acoustical non-linearities (Chester et al. 1994). While the complications and limitations arising from actual data sometimes proved surprising, other expectations or complications have since been resolved from greater theoretical or experimental understanding, or from the greater availability of computational

resources (ray calculations that would take over an hour at the start of ATOC take only a couple of seconds today). Ocean modeling capabilities were fairly primitive in the early 1990s, but are now sufficiently refined to readily take advantage of the integral acoustic data type. The remarkable clarity of the data as a depth average and the meaning and observational opportunities such data entail have been surprises.

Despite the many substantive oceanographic surprises arising out of the evolution and application of tomography, the active employment of tomography has dwindled such that, as of this writing, I am unaware of any ongoing or planned ocean observations by tomography. The possibilities for valuable observations in ocean observing systems from tomography are countless, however, ranging from a regional observing system in Baffin Bay to a basin-scale system across the Norwegian and Greenland Seas to trans-Atlantic or trans-Arctic systems to the antipodal acoustic measurements; such observations have both process and climate motivations. It seems clear that the way forward for tomography requires greater participation from physical oceanographers in creatively identifying ways that tomography can contribute to resolving interesting problems and in the analysis of such data. The unique properties of the acoustic measurements make it an inevitable contributor to the world ocean observing system. The world faces a climate crisis and potential environmental catastrophe that requires the contributions of all possible observations.

A recent autobiography by C. Wunsch describes his trials and tribulations getting the altimetry missions started (Wunsch 2021). The similarities of lackluster community responses to initiating altimetry and tomography are striking. NASA presently supports an altimetry program, and NASA's Ocean Surface Topography Science Team (OSTST) funds altimeter science. One can imagine the sad state of affairs if the altimeter people had to obtain funding for altimeter science through the National Science Foundation, in competition with the community of physical oceanographers. One interesting aspect of the NASA program is that it acknowledges the interplay between technology and science, the one makes the other better, so it supports both. It seems to me the NASA funding approach ought to be adapted for new research programs in acoustical oceanography – civilian acoustical engineering and science programs. Such a program would be governed by a multidisciplinary panel to ensure the program focusses on acoustical applications for good science, rather than on acoustics. A single such focussed program would also ensure that standards are adapted and measurements coordinated, both essential aspects of multidisciplinary programs as part of an Ocean Observing System. Such programs seem to me to be the way forward for better exploitation of acoustic tomography for ocean observation.

ADDITIONAL FILES

The additional files for this article can be found as follows:

- **Supplement 1.** Estimate for the mode-1 internal tide for the North Pacific derived from TOPEX/POSEIDON altimeter data ([Figure 4](#)) (Dushaw et al. 2011; Dushaw 2015a). Waves propagate coherently north from Hawaii and south from the Aleutian Islands, forming a complicated interference pattern. The interference pattern appears to propagate eastward. The coherence of the waves extends across the North Pacific. The units are mode amplitude, with mode normalization such that amplitude is the approximate maximum internal displacement in meters. DOI: <https://doi.org/10.16993/tellusa.39.s1>
- **Supplement 2.** The estimate as in Supplement 1, but limited to waves with northward propagation. DOI: <https://doi.org/10.16993/tellusa.39.s2>
- **Supplement 3.** The estimate as in Supplement 1, but limited to waves with southward propagation. DOI: <https://doi.org/10.16993/tellusa.39.s3>
- **Supplement 4.** A global estimate for the mode-1 internal tide derived from TOPEX/POSEIDON altimeter data ([Figure 8](#)) (Dushaw et al. 2011; Dushaw 2015a). In many regions the internal tide field is an extensive, complicated interference pattern. This solution is known to be in error around Madagascar, the variability in boundary current regions and the circumpolar current is suspect, and there appears to be an absence of internal tides in equatorial regions. The units are mode amplitude, with mode normalization such that amplitude is the approximate maximum internal displacement in meters. The tomography measurements were a principal motivating factor behind estimates like this. Some of the observations were made in, from west to east, the Philippine Sea, central North Pacific, on either side of the Hawaiian Ridge, and the western North Atlantic. Tomography measurements in the Canary Basin, west of North Africa (not shown), were not particularly predictable (Dushaw et al. 2017). DOI: <https://doi.org/10.16993/tellusa.39.s4>
- **Supplement 5.** Estimate for the mode-1 internal tide for the North Atlantic derived from TOPEX/POSEIDON altimeter data (Dushaw et al. 2011; Dushaw 2015a). The animation shows the estimate using only southward wavenumbers, revealing a coherent waveform propagating from the Azores almost to the coast of Brazil. DOI: <https://doi.org/10.16993/tellusa.39.s5>
- **Supplement 6.** A sequence of ray traces from Perth, Australia to Bermuda computed at 3-day intervals using the ECCO2 state estimates for the ocean ([Figure 11](#)) (Dushaw and Menemenlis 2014). The colors indicate acoustic mode-1 phase speed for 15-Hz acoustic frequency. Ocean variability causes

a scintillation of the acoustic rays, which varies the scattering from topography and other features. The direct paths, arriving south of Bermuda, are only minimally affected. DOI: <https://doi.org/10.16993/tellusa.39.s6>

- **Supplement 7.** An acoustic source located 200-km south of Bermuda would transmit sound over large areas of the North and South Atlantics for the purposes of tomography. This source position also “illuminates” the west coast of Australia near Perth ([Figure 13](#)). For this computation of ray paths, the first acoustic mode phase speed for 15-Hz acoustic frequency was computed from the World Ocean Atlas. The colors show the meridional gradient of phase speed, which is the dominant contributor to horizontal refraction. In most cases, horizontal refraction can be neglected. DOI: <https://doi.org/10.16993/tellusa.39.s7>

NOTES

- 1 In his retrospective, Millero (2010) ascribes this result to Spiesberger and Metzger (1991), but that is incorrect; see Dushaw et al. (1993a) page 267.
- 2 This tidal model has apparently since been lost!
- 3 It has become apparent that it is not uncommon for physical oceanographers to see such data as Figure 3 and make the erroneous assumption that the data have been filtered for the tides. However, other than a basic separation into high (> 0.5 cpd) and low frequencies, such time series have not been filtered.
- 4 In 1991, a day prior to the start of the Heard Island Feasibility Test (HIFT), a short 5-min. engineering test of the experiment's acoustic sources demonstrated antipodal propagation to both coasts of the United States. For that test, a 57-Hz signal with a net source level of 221 dB re 1 μ Pa at 1 m was used (Munk et al. 1994); Munk described sound level as comparable to a jet engine at 100 m distance. HIFT was designed with sound sources that proved to be unnecessarily loud, however. The experiment was designed based on the signals recorded in the Perth-Bermuda experiment (Munk 2006); the necessary sound level was unknown. As we later found, the Bermuda signals were only 15 dB above noise because they were topographically-scattered arrivals; for signals from Australia, the receiver was behind Africa. Signals of direct propagation, that passed some 200 km south of Bermuda, were estimated to be 30 dB louder (Dushaw and Menemenlis 2014), or some 45 dB above noise.

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COMPETING INTERESTS

The author has no competing interests to declare.

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