The 1960 Perth to Bermuda antipodal acoustic propagation experiment: A measure of a half-century of ocean warming?

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Introduction: The Experiment

In March 1960, the sounds from 300-lb explosive charges deployed off Perth, Australia were recorded at Bermuda, the antipode to Perth (AGU 1960, Bryan et al. 1963, Shockley et al. 1982). The test verified the suggestion by Ewing and Worzel (1948) that acoustic propagation in the ocean over antipodal distances was possible. Under a careful and controlled scientific plan, three surplus depth charges were deployed from an Australian oceanographic research vessel, the HMAS Diamantina, at 5-min. intervals. The shot locations were determined by celestial navigation under ideal conditions, giving a uncertainty in position of about 1 nm. This positioning uncertainty corresponds to a travel time uncertainty of about 1 s. Time keeping was done manually using a "chronometer deck watch," most likely the ship's navigation clock, with an uncertainty of about 1 s. The experiment was coordinated with the Bermuda SOFAR station, which recorded the arrival pulses. The travel times of the pulses were about 3 hr., 43 min. The recorded arrivals at Bermuda consisted of a broad pulse of about 20 s width (half maximum) with peak intensity about 15 dB above noise, followed by a second weaker pulse of comparable width about 30 s later. The acoustic paths traveled by the sound are refracted geodesics (Munk et al. 1988, Heaney et al. 1991, Jensen et al. 1994, Munk et al. 1995). A key question concerning this experiment has been to determine the precise acoustic paths followed by the acoustic pulses (Figure 1).

Previous Work

Munk et al. (1988) computed ray paths that accounted for the horizontal refraction of sound and obtained the perplexing result that Bermuda was in the shadow of Africa. The intense ocean front associated with the Antarctic circumpolar current has a sound speed gradient that acts to refract rays southward. Rays departing the shot location on a more northerly trajectory can counteract this

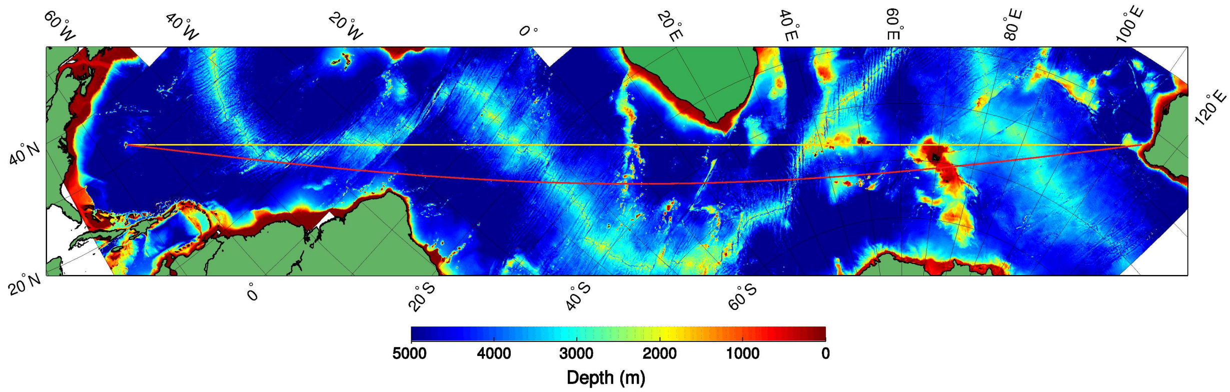

FIG. 1. Sea floor topography (Smith and Sandwell 1997) between the location of the shots off Perth, Australia (right) and Bermuda (left). The great circle route is indicated by the straight yellow line, while the WGS84 geodesic is indicated by the red line. Aside from the obvious continents, the main obstructions for the acoustic path were the Kerguelen Plateau and the Crozet Islands. With this oblique Mercator projection, the great circle route between the two points is a straightline with minimal mapping distortion about this line.

southward refraction, but in the Munk et al. (1988) calculation the particular rays with the trajectories toward Bermuda were blocked by Africa. Heaney et al. (1991) combined the phase speeds of acoustic modes at 15 Hz calculated from low-resolution atlases for global sound speed and bathymetry with ray tracing. Two viable acoustic paths between Perth and Bermuda were obtained, requiring the influence of the topographic features of Kerguelen Island (first arrival pulse) and the coast of Brazil (second arrival pulse). From a modern perspective, however, this explanation is not entirely satisfactory (Dushaw 2008), mainly because only low-resolution, highly-smoothed environmental data bases were available 20 years ago.

High-Resolution Ocean State Estimates

Modern high-resolution ocean state estimates, such as produced by the Estimating the Circulation and Climate of the Ocean (ECCO) program (Menemenlis et al. 2008), put the Perth-to-Bermuda acoustic problem into a new light (Figure 2). The intense, small-scale features captured by these state estimates, e.g., Agulhas rings in the South Atlantic or the turbulent Antarctic circumpolar current system, greatly influence the acoustic propagation in a time-dependent way.

Dushaw (2008) sought a solution for ray paths that did not require topographic influence. The hypothesis was that perhaps the greater sound speed gradients of more recent environmental models would not require this influence to obtain ray paths to Bermuda. Following the approach of Heaney et al. (1991), Dushaw (2008) computed the phase speeds of acoustic modes at 15-Hz frequency from the smooth NOAA World Ocean Atlas (Antonov et al. 2006, Locarnini et al. 2006). This environment gave rays that arrived only within about 300 km to the south of Bermuda. The intense small-scale

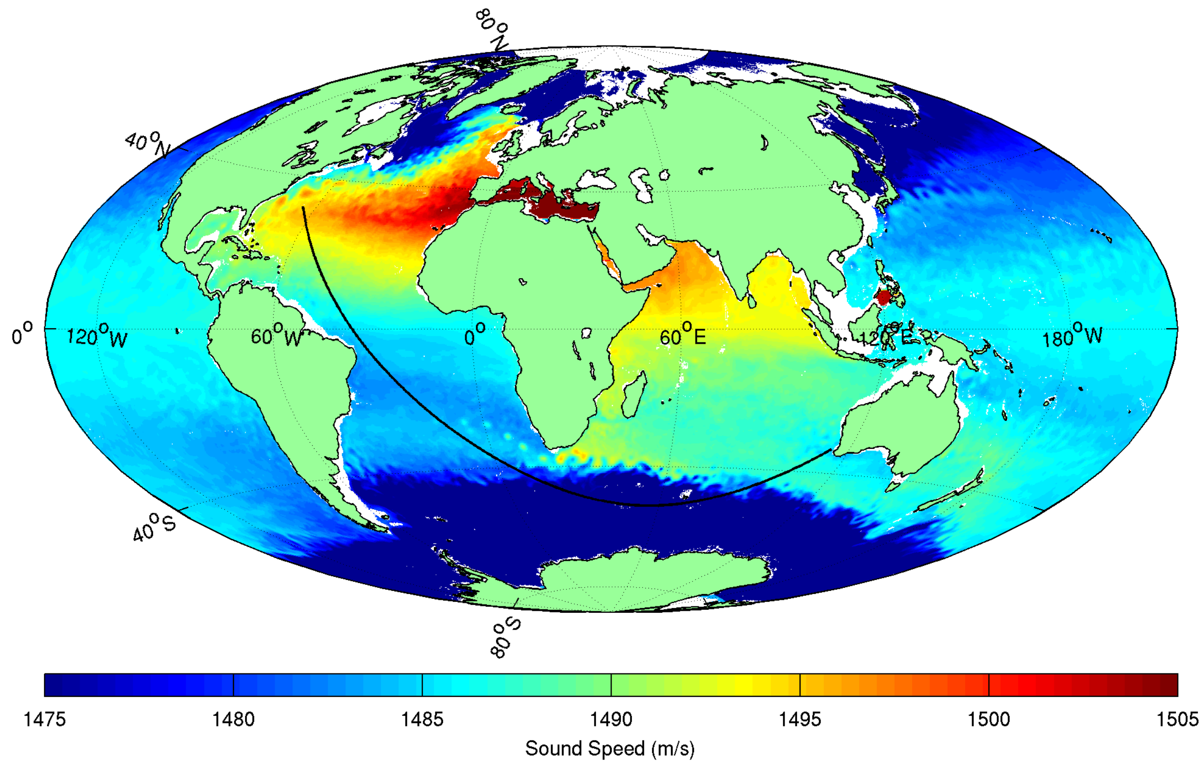

FIG. 2. Acoustic mode-1 phase speed at 15 Hz derived from the ECCO2 state estimate for August 1993. The WGS84 geodesic path between the location of the Perth shots and the Bermuda SOFAR station receivers is indicated. The phase speed is a variable strongly dependent on ocean temperature; mode-1 phase speed variations follow those of ocean temperature near the sound channel axis. Dominant features affecting acoustic refraction are the filamental Antarctic circumpolar front and the Agulhas Rings of the South Atlantic. Hammer-Aitoff projection.

features of the ECCO2 state estimates were more refractive than the smoothed Atlas, however. Ray tracing using the ECCO2 state estimates showed that, with these features, rays arrived about 100 km to the south of Bermuda.

It is apparent that the topographic influence described by Heaney et al. (1991) is required for rays to arrive at Bermuda. The small-scale oceanic features are also an important aspect of the problem, however. As a result of topographic scattering, the intensity of the ray arrivals at Bermuda is reduced by about 20 dB compared to "direct" ray arrivals. The oceanic influence greatly reduces the required topographic deflection, hence gives arrival pulses of greater intensity.

A Measure of the Ocean's State in 1960?

From the perspective of classical acoustic tomography (Munk et al. 1995), the antipodal travel time recorded in 1960, 13,382 s, is a measure of the ocean temperature. These data are an immutable and valuable measure of the ocean's climatological state in

1960, averaged along the sound channel axis and across several ocean basins: The Southern Ocean, the South Atlantic and the tropical North Atlantic. Global ocean state estimates, constrained by assimilation of available data, can be used to calculate a present-day travel time. This travel time is obtained by integration of the group speeds of acoustic modes along successful ray paths (Heaney et al. 1991, Jensen et al. 1994). A travel-time change over the past half-century, nominally expected to be about 10 s from recent estimates of upper-ocean ocean warming, is a measure of ocean climate change. Any measurable change to the ocean's temperature climate over the past half century is associated with the depths near the sound channel axis, however.

Computing Arrival Pulses for Comparison to Observations

The task of obtaining calculated travel times of sufficient accuracy for comparison to the 1960 observations is challenging, however. We seek to determine a O(10-s) signal from recorded acoustic pulses of 20-s width. The calculation therefore requires more than just travel times along the relevant ray paths at a single frequency. Rather, the complete pulses equivalent to the recorded arrivals have to be computed for any accurate assessment of travel time change. The relevant quantities are the frequency spectrum of the pulses, which can be computed (e.g., Weston 1960), and the attenuation of the acoustic signals by the ocean (e.g. Lovett 1980) and topographic scattering. The computation apparently requires a broad band of frequencies, spanning about 10–75 Hz. At the higher-frequencies, small-scale ocean variability induces extensive mode coupling that must be taken into account. For the first few acoustic modes, the higher frequencies are more confined to the upper ocean, are less influenced by topography, and, hence, less likely to be scattered toward Bermuda. All aspects of the problem, such as exact propagation paths and signal intensities, are frequency dependent. Research is ongoing toward addressing these many issues as we work toward an accurate computation of the arrival pulses in high-resolution ocean state estimates.

LINKS

A website documenting the 1991 Heard Island Feasibility Test (HIFT) includes a page on the Perth-Bermuda experiment. One motivation for HIFT and acoustics as a measure of ocean climate was the 1960 test.
http://909ers.apl.washington.edu/~dushaw/heard/perth/index.shtml

A Youtube video on the MITgcm channel showing the scintillations of ray paths as they respond to the changing refractive environment of the ECCO2 model integration:
http://www.youtube.com/watch?v=YLDA5YbOn4s

The ECCO2 homepage:
http://ecco2.jpl.nasa.gov/

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