Moving Ship Tomography in the North Atlantic

The Acoustic Mid-Ocean Dynamics Experiment Group

Moving Ship Tomography (MST) is a method of obtaining high-resolution, nearly synoptic three-dimensional maps of the ocean temperature field over large areas [Cornuelle et al., 1989]. We measure acoustic travel times along a multitude of paths crossing at many different angles and then reconstruct the sound speed (temperature) field in a manner analogous to a medical CAT-scan. A large number of crossing ray paths are generated by using a moving receiver. This report compares preliminary maps of sound speed obtained using acoustic data (Figure 1) with maps obtained with expendable bathythermograph (AXBT) and conductivity, temperature, depth (CTD) profile data. Given such maps, we will be able to study advecting fronts and interacting eddies with high resolution and test how well numerical models can predict the evolving fields.

All previous work in ocean acoustic tomography has been done with fixed or moored instruments. These instrument arrays have been quite sparse in the horizontal [see Worcester et al., 1991]. The idea of using a moving instrument—whether it be a source, receiver, or transceiver—to improve spatial resolution is by no means new; it is common in seismology and borehole tomography, as well as in medical tomography.

The MST experiment discussed here is part of the larger Acoustic Mid-Ocean Dynamics Experiment (AMODE), the goals of which are to determine the precision with which the ocean mesoscale sound speed (temperature) field can be measured using the technique of moving ship tomography, study mesoscale eddy kinematics and dynamics, and measure gyre-scale variability. A variety of mesoscale features, mapped using the acoustically measured perturbation sound speed field, are shown in Figure 1; many fronts and eddies are present.

The temporal evolution of the high-resolution temperature fields provided by moving ship tomography can be used to test numerical ocean models and to construct improved estimates of the frequency-wavenumber temperature spectrum. When data from transmissions between the moored instruments are included, the temporal evolution of the large-scale temperature, current, and vorticity fields can also be studied. Data assimilation techniques can be tested using both the moving ship tomography and moored data, and the effect of integral constraints (tomographic measurements) on eddy-resolving numerical models can be determined. The frequency and wavenumber spectra of the temperature field directly influence the ultimate precision of the final four-dimensional (x,y,z,t) field estimates.

The Experiment

We deployed six acoustic-transceiver moorings between Bermuda and Puerto Rico (black dots in Figure 1) in March 1991 and recovered them a year later. Five moorings were at the vertices of a pentagon on a circle with a radius of 350 km, and the sixth mooring was at the center (25°N, 66.25°W). For the MST portion of the experiment, we circumnavigated the array at a radius of 300 km a little more than two times over 51 days in June and July 1991. A receiving array with

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Fig. 1. Sound speed perturbation, 6C, at 700-m depth as measured during the Moving Ship Tomography experiment of July 4–18, 1991; 1 m/s is equivalent to 0.25°C. The ship with an acoustic receiving array steamed around the 1000-km diameter circle, stopping every 3 hours (approximately every 25 km) to receive signals from the six moored sources (black dots). The acoustic travel time data were inverted to produce this field.

Fig. 2. Sound speed perturbation, 6C, at 700 m. The map on the left was obtained during July 15–30 using only acoustic data while the map on the right was obtained during July 18–22 using only AXBT data at 700 m. The contour interval is 1 m/s.

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a CTD was deployed from the ship to 1 km depth every 3 hours approximately every 25 km around the circle. Thus, each ship stop yielded six horizontal paths, giving a total of 750 horizontal crossing paths for a nominal 125 stops around the circle. Each horizontal path typically had fifteen identifiable multi-path acoustic arrivals from which vertical resolution is obtained. One circumnavigation therefore resulted in roughly $10^3$ travel time data that are, to a large degree, independent.

From the total of 290 ship stops, a subset of 120 stops spanning 27 days (July 4–30) was used for this first analysis. This subset was broken into two overlapping parts, July 4–18 and July 15–30, each with 80 stops.

The first step in constructing the maps was to trace rays through a reference field (Levitus climatology) to produce travel time perturbations (measured minus predicted). The perturbations had a variance of about 0.1 s rms, about half of which is due to changes in the ocean and the other half to errors in determining the source and receiver positions. Additionally, the rays show an even distribution of upper turning depths, providing good vertical resolution.

Next, the perturbation travel-time data were inverted using standard oceanographic objective-mapping techniques to produce fields of perturbation sound speed [e.g., Cornell et al., 1989]. For the inversions presented here, we have assumed that the field is “frozen” and not evolving in time over the 15-day data collection period, although the results will show that this is not strictly true. Sound speed corresponds closely to temperature and is only weakly a function of salinity. The temperature-salinity relation in this area is monotonically so one can infer density and geostrophic velocity from the sound speed.

The same weighted least-squares procedure is employed to produce objective maps of sound speed from the acoustic travel time and the in-situ profile data. Empirical modes are used to model the vertical structure, and a truncated Fourier series is used to represent horizontal structure. Five of the vertical modes are range-dependent (with nine Fourier harmonics), and the remaining fifteen are range independent, resulting in a total of 1160 ocean model parameters for a 1200-km square domain. The minimum length scale currently resolved is about 65 km.

In addition to mapping the sound speed field, the inverse procedure also refines the estimates of source and receiver positions. The rms travel time residual, which is measured travel time minus predicted travel time through the estimated field, is acceptably small, 0.008 s rms. Some of the variance reduction, of course, is due to corrections in instrument positions, which have initial errors of about 30 m. Subsequent analysis will be done using differential GPS data to improve the absolute ship positions and using improved subsurface array location estimates with total position errors less than 10 m. This reduction in data error will permit us to increase the spatial resolution of the ocean model and include dynamics. The results presented here are robust to changes in a priori error levels.

Many CTD, XBT, and AXBT profiles were obtained as part of this and another experiment in the area to form an independent data set for comparison.

**Horizontal Maps**

The sound speed perturbation field, $8C$, at a depth of 700 m is shown for the first period (July 4–18) in Figure 1 and that for the second period (July 15–30) is shown in Figure 2 (left). These perturbation maps are remarkable in that they cover such a large area and provide good resolution. Many of the same features are present in each map, which is not entirely unexpected since there is an overlap in time. The estimated rms perturbation is 2.0 m/s, or 0.5°C, which corresponds to a nominal thermocline displacement of 100 m. The main thermocline gradient, and thus mesoscale eddy strength, peaks at 700 m. The most notable differences between the two acoustically derived maps are that the frontal pattern in the northwest quadrant has shifted and the warm eddy in the southwest quadrant has split.

The estimated uncertainty in the interior of the circle is reduced to a nearly uniform 0.6 m/s (0.15°C). Outside the circle, the uncertainty rises to a background value (2.0 m/s) nearly that of the a priori state (2.2 m/s), the difference being that the acoustic data have reduced the error in the mean over the whole domain.

On the right side of Figure 2 is the corresponding perturbation map obtained using only 700 m data from AXBT profiles taken between July 18 and 22. The AXBTs were dropped on 25- and 50-km grids inside the indicated box. These fields are independent of the acoustic data. Perturbations show up only where AXBT measurements were made, and in these regions the perturbation field is very similar to the one obtained from only the acoustic data. The estimated uncertainty where there are profiles is 0.8 m/s. A rigorous comparison must take into account the errors of each estimate. The difference of the two estimates divided by the estimated error of the difference is typically on the order of one standard deviation within the AXBT domain. In one small region near a front (27°N, 69°W), the weighted difference reaches three standard deviations, not unexpectedly since the front was most likely moving during the 15 days it took to make the acoustic map.

**Vertical Section**

Above, we discussed the sound speed at 700 m over the entire area. Now we extract the vertical slice of sound speed perturbation along the MST circle, starting at the northermmost point and going clockwise. The top panel of Figure 3 shows the result when using only CTD data (taken on the MST circle), and the lower one shows the result when using only acoustic data. Below about 250-m depth, the agreement is good. Differences near the surface are large because as the acoustic rays approach a (deep) receiver they turn toward it and do not sample the shallow water immediately above. The differences between 240° and 300° are the result of sparse or missing acoustic data at these angles. At this stage in the data analysis, we attribute the remaining differences to the finite sampling time.

The rms sound speed perturbation averaged over all the CTD data (the measured CTD data relative to the Levitus reference state) peaks at about 2.2 m/s in the main thermocline. The rms difference between the measured CTD sound speed and the sound speed estimated using only acoustic data is about 0.8 m/s, which is the same as the rms difference between the mapped and measured CTD data. The total a priori uncertainty was 2.4 m/s at 700 m and included uncertainty in the mean profile. The
corresponding variance reduction from the a priori value is 94%.

Concluding Remarks

Much remains to be done with this rich data set. The differential GPS positions will reduce the uncertainty in the instrument positions from the present 30 m or greater to roughly 5 m rms. This will permit us to obtain increased spatial resolution; we expect significant resolution to 20-km scales. Including the intermooring transceiver data will provide large-scale absolute water velocities. The time dependence needs to be taken into account by using a time-dependent ocean model; this will be done using a full Kalman filter with a nonlinear quasi-geostrophic (QG) model. The model will be augmented to account for non-QG effects (such as the mixed layer and gyre variability) so that all the information content of the data will be utilized. In the process of constructing and verifying the four-dimensional model, we will study the mesoscale and gyre-scale kinematics and dynamics, the frequency-wavenumber spectrum, and the effects of storms, to name just a few topics.

These results show that using a moving receiver to obtain high-resolution maps of the ocean works in practice. This extension of the original concept of moored ocean acoustic tomography adds a powerful new technique to the oceanographer’s suite of measurement methods. The technique can be extended to measure absolute water velocity by adding an acoustic source to the ship array and measuring reciprocal travel times. Depending on the particular interest, one can imagine experiments ranging in scale from kilometers to full ocean basins.

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