Modeling Acoustic Remote Sensing and the Florida Straits with Ray Tracing

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***Abstract*—A new general-purpose three-dimensional underwater acoustic ray-tracing program called HARPO is demonstrated by simulating acoustic measurements in the Florida Straits. We illustrate how important it is to avoid adding unrealistic features when modeling the medium by showing that slope discontinuities in the bottom yield fictitious jumps in raypath properties as launch angle varies. Starting with simple models of sound speed and bathymetry (topography of the bottom) and later adding complexity increases insight into the relation between the medium and the propagation. The simple models we used provide a generic picture of propagation over the Miami Terrace, which can be used in experiment design and to assess the effects of perturbations in the sound speed and bathymetry. Our range versus launch-angle plots give information about relative signal strength due to ray spreading. Our range versus travel-time plots provide arrival time pulse sequences for all ranges of interest in a single plot. Because small details in the bathymetry have only a small effect on the range versus travel-time plots, our results for a simple bathymetry model give a reasonable estimate of the pulse arrival times for realistic bathymetry. Range versus launch-angle plots, on the other hand, are very sensitive to the details of the bathymetry. The insensitivity of pulse strength (through ray spreading) to details of the bathymetry suggest a measuring strategy in which pulse arrival time provide a measurement of sound speed and pulse strength provides details of the bathymetry.**

THE PROBLEM—MONITORING GULF STREAM HEAT TRANSPORT

A SUBTROPICAL Atlantic climate study (STACS) has been designed to find routine ways to monitor the heat carried into the North Atlantic by the Florida Current [6]. To carry out this study, several teams are setting up *in situ* and remote-sensing devices in the Florida Straits to measure the temperature and current in a section across this narrow channel.

One proposed remote-sensing scheme would send acoustic waves under the water to several hydrophones on or near the bottom, distributed across the Straits. The time it takes sound to reach each sensor contains information about the temperature structure of the intervening ocean, and the component of the ocean current along the path can be measured acoustically in terms of the travel-time difference between upstream and downstream paths [10].

Another possible acoustic scheme would measure currents transverse to the acoustic path by using the correlation of acoustic scintillations recorded at transversely spaced hydrophones—a technique that has been successfully used for optical wind measurements in the atmosphere [5] and has been recently demonstrated in the ocean with sound waves [1]. Both of these remote-sensing schemes need propagation calculations for two reasons. First, propagation calculations are needed to interpret the measurements. Second, because acoustic measurements in the ocean are so expensive and time consuming, they should be carefully designed and simulated before sensors are actually deployed. A trial-and-error approach to ocean acoustic measurements could consume most of an experiment's resources before any useful data were obtained.

Propagation calculations must be reasonably sophisticated because acoustic propagation in the shallow Florida Straits is complicated. Because of the large sound-speed gradients in the Florida Straits, sound refraction is very significant. Even though the acoustic waves propagate nearly horizontally across the Straits, the waves reflect many times from the bottom and often the upper surface as well. Multipath propagation further complicates the situation so that transmission of a single pulse yields a complicated sequence of (possibly overlapping) pulses arriving at the receiver. To be useful, a propagation calculation must be able to relate changes in the medium with observable propagation effects.

A SOLUTION—RAY-TRACING SIMULATION

Since the 1940's, sound propagation in the ocean has been modeled analytically, and geometric ray theory was one of the earliest tools used to compute where sound waves go and do not go in the ocean. Since then, "full-wave," normal-mode, and other approximate methods have attempted to remove the limitations of ray theory, namely its inability to include the effects of diffraction and low-frequency modes or compute intensity in the vicinity of caustics.

Nevertheless, despite its shortcomings, ray theory remains one of the most useful and intuitive ways to compute how sound propagates in complex environments. First, it is straightforward to apply ray tracing to a medium in which sound speed and ocean currents vary in three dimensions and in which bathymetry varies with both longitude and latitude. Second, ray tracing is unique in identifying the parts of the medium through which the acoustic energy of a given pulse arrival propagates, permitting (for example) temperature profiles to be built up using information in the pulse arrival sequence. Third, it computes pulse travel time in a more direct way than other methods can. Finally, ray tracing is so much easier, cheaper, and quicker that it is nearly always advisable to start with a ray-tracing calculation before going on to more complicated methods. See Jensen

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[2] for a survey of numerical models of sound propagation in the ocean, and Jones [3] for a survey of underwater ray-tracing methods.

Larger and faster computers have made sophisticated ray-tracing programs practical and have permitted realistic models of the propagation environment. One recent advance is a program that numerically integrates Hamilton's equations in three dimensions using Earth-centered spherical polar coordinates [4]. Numerical integration using continuous models is superior to methods that must break up the medium into regions where raypaths can be analytically calculated. Discontinuities in refractive-index gradient at the boundaries of such regions cause artificial jumps in computed raypath properties (like range and travel time) as launch angle changes. Numerical integration also makes it easy to trade accuracy for speed and gives the user more flexibility in designing models.

We have developed a general-purpose three-dimensional Hamiltonian acoustic ray-tracing computer program that permits modeling the ocean's temperature and current fields as continuous closed-form three-dimensional functions. A continuous model of bottom topography as a function of latitude and longitude is also permitted. All three-dimensional propagation effects, such as nonreciprocity (caused by currents), Earth curvature, and horizontal ray deviations, can be computed. The program also computes the frequency shift caused by time-varying media. The present version assumes specular reflections from the bottom and from the surface, and different reflection coefficients can be used in amplitude calculations without recomputing the raypaths.

We call our program HARPO—for Hamiltonian acoustic ray-tracing program for the ocean. It provides a tool for accurately modeling the acoustic environmental and for simlating acoustic measurements in the ocean. We illustrate its capabilities by constructing a simple model and performing some sample calculations for the Florida Straits. The resulting displays of range versus launch angle and range versus travel time not only demonstrate the advantages of modeling the sound speed and bathymetry (topography of bottom) with continuous gradients, but also show for the first time a generic picture of propagation across the Miami Terrace of the Florida Straits.

Modeling the Florida Straits

Our philosophy in modeling is to start with a simple model that has the main background features of the environment. Using such a model for ray tracing gives the background propagation characteristics. As we add more details to the model, ray tracing shows the propagation effects of each new detail.

Here, we show the propagation characteristics for a simple model of the Miami Terrace of the Florida Straits. Our modeling begins with averages of sound speed and current measurements. Fig. 1 shows some average contours of sound speed, axial current, and heat flux density in a vertical section across the Florida Straits from Miami to Bimini. (The vertical scale in these and all such sections in this paper is expanded by a factor of 40; the actual proportions are indicated in Fig. 1(a), in which the bottom is sketched to approximate scale as the dashed line just below the line denoting the ocean surface.) These contours were derived from *in situ* measurements between 1954 and 1980 [11]. It is not yet known whether variations in temperature or current

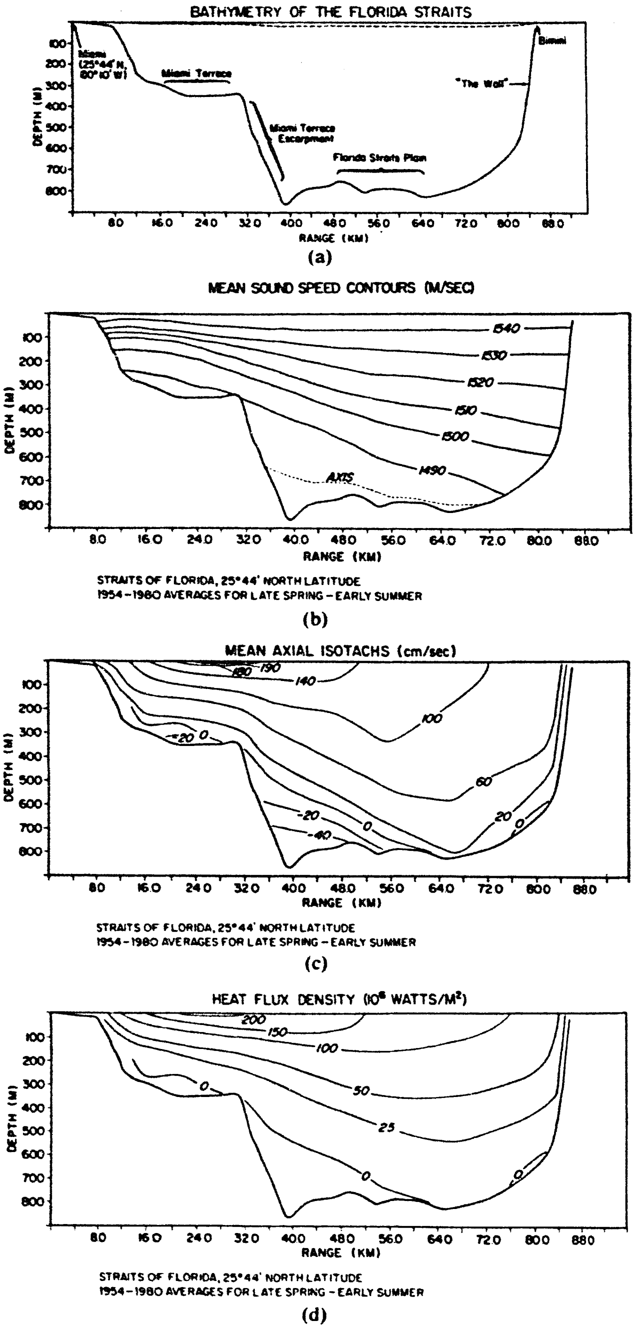

Fig. 1. These four panels show average conditions in a section (a) across the Florida Straits between Miami and Bimini, derived from *in situ* measurements in late spring to early summer, between 1954 and 1980 (courtesy of D. Palmer, NOAA/AOML). The mean temperature, plotted as sound speed ($m \cdot s^{-1}$) in (b), and the mean axial current speed ($cm \cdot s^{-1}$) in (c) combine to give an estimate of the mean heat flux density (10^6 $W \cdot m^{-2}$) through section (d). In all of these plots, the vertical scale is exaggerated by a factor of 40 for visual clarity. The dashed line in (a) shows the bottom to true scale.

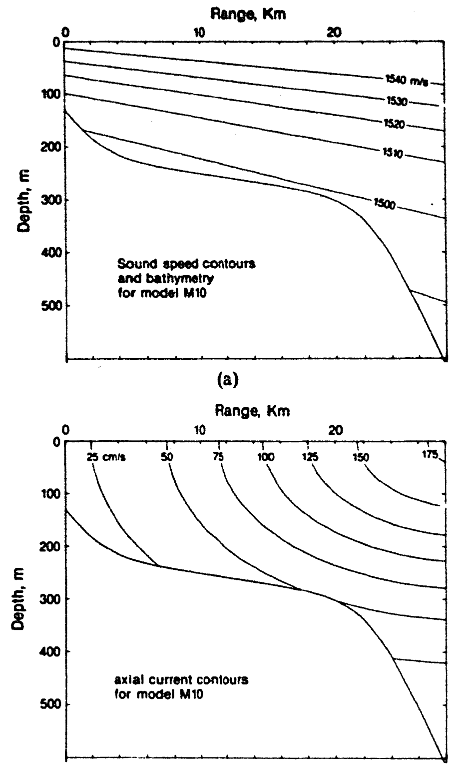

Fig. 2. These two panels show contours of model sound speed (a) and axial current (b) used in raypath calculations for the Florida Straits. The bottom profile, for the first 30 km of the acoustic path, is also shown. (The vertical scale is exaggerated by a factor of 40.)

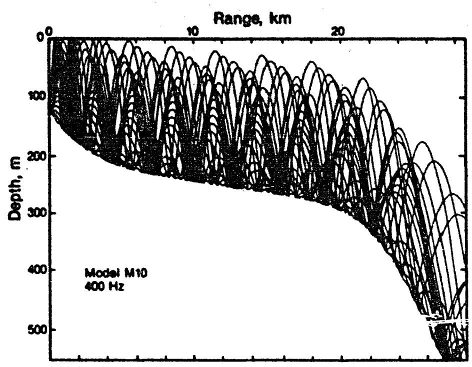

Fig. 3. These raypaths show the trajectories of 400-Hz acoustic waves launched from a source on the bottom about 4.5 km from shore, at elevation angles from 0 to 20 degrees in steps of 1 degree. Notice that low-angle rays make short bounces along the bottom, whereas rays launched at higher angles make long high bounces. Specular reflection from the bottom and from the ocean surface is assumed.

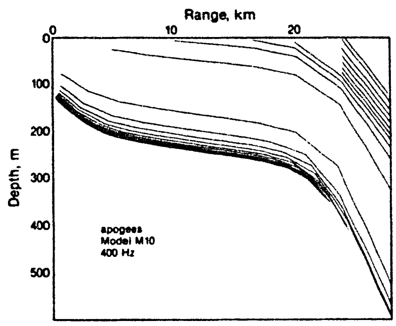

Fig. 4. If the apogees of the rays that reach the 26.5-km range are connected, we get this plot, which shows that each ray interrogates only the "layer" below each line plotted. In this case apogee loci do not cross, so a relatively simple inversion of ray travel times, in terms of the average sound speed in each layer, is possible. A temperature profile can thus be built up starting with the bottom layer.

strength alone contribute predominantly to the variations in heat transport, so for now we assume that both quantities must be monitored to keep accurate track of variations in the heat transported.

Guided by these contours, and by data from Sverdrup *et al.* [9] and De Ferrari [10], we constructed closed-form models of the average sound speed (temperature), current, and bottom profile of the Florida Straits (Fig. 2). We have so far modeled only the portion of the Miami Terrace out to 30 km from the Florida coast where STACS acoustic sensors have been deployed.

Measuring Sound Speed Acoustically

Whether underwater acoustic tomography [7], [8] is synonymous with acoustic remote sensing of underwater sound speed or only one example, it is surely the best known application. Acoustical measurement of sound speed in the Florida Straits differs enough from the experiment described by Munk and Wunsch [7], [8], however, that it needs to be considered separately.

Underwater acoustic propagation in the Florida Straits is best introduced with some sample raypath calculations. Fig. 3 shows some acoustic raypaths computed by our program, assuming a source on the ocean bottom about 4.5 km from shore. The rays shown here emanate from the source at elevation angles between 0 and +20 degrees, spaced every 1.0 degree.

Evidently, the acoustic rays execute a number of bounces along the bottom, the number of bounces depending on the launch angle. At low angles, rays hug the bottom making many bounces, whereas rays with higher angles bounce nearly up to (or even reflect from) the surface. This ray geometry suggests a way to probe different depths in the ocean, if the different ray paths can be separated by arrival time at the receiver.

For example, the average sound speed in the layer near the bottom can be derived by measuring the travel time of the rays that hug the bottom. Sound speeds in successively higher layers can be built up sequentially from the arrival times of rays that reach greater and greater heights. A similar inversion in the horizontal direction can be implemented if several receivers are used [10].

Fig. 4 shows how different rays probe different depths. The lines in the plot connect the apogees executed by each ray that reaches the bottom at exactly 26.5-km range, the location of an experimental hydrophone. The rays that reach a given range are computed after launching a fan of rays and interpolating in launch angle. The rays that reach specified receiver location are called the "eigenrays" for the location.

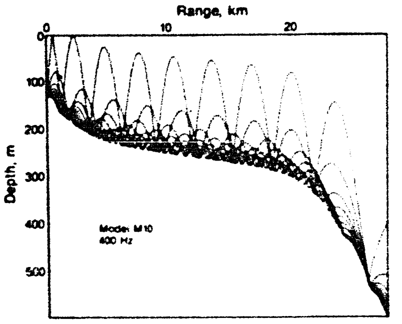

Fig. 5. By interpolating in launch angle, we can determine which rays reach a particular range. Those shown here are some of the rays that reach a receiver on the bottom at a range of 26.5 km. An infinite number of such rays could be found, and most of them would execute a large number of bounces between the bottom and the surface.

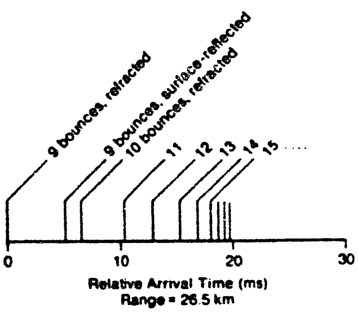

Fig. 6. This time sequence shows the first 11 acoustic arrivals at a receiver on the bottom at a range of 26.5 km. If these arrivals can be separated and identified, a travel time and thus an average sound speed can be associated with each of the layers.

Some of the eigenrays for a receiver on the bottom at a range of 26.5 km are shown in Fig. 5.

Because ray tracing identifies the parts of the medium through which a given pulse arrival propagates, it provides a method to construct temperature profiles from the pulse-arrival sequence. Since our program computes the travel time for each ray, we can construct a simulated arrival-time sequence corresponding to any range. Fig. 6 shows the arrival-time sequence for 11 of the rays that reach a range of 26.5 km. This is the impulse response of the medium, that is, the arrival sequence of a transmitted acoustic impulse. The relative amplitudes of the arrivals are not shown here, but they can be computed by a method discussed in the next section. A one-to-one correspondence exists between these arrival pulses and the apogee loci in Fig. 4. (Generally, the high-bouncing pulses arrive first.) So, if the arrivals can be resolved, the layers can be isolated.

The degree to which the details of the temperature profile can be reconstructed from the acoustic measurements will depend on the acoustic frequencies and pulse lengths used, the availability of phase measurements, and the sophistication of the data-processing methods. The spacing of the pulse arrivals in Fig. 6 implies that at least a sophisticated data-processing algorithm coupled with phase measurements would be necessary to derive the details of the temperature profile near the bottom, using the 9-ms effective resolution

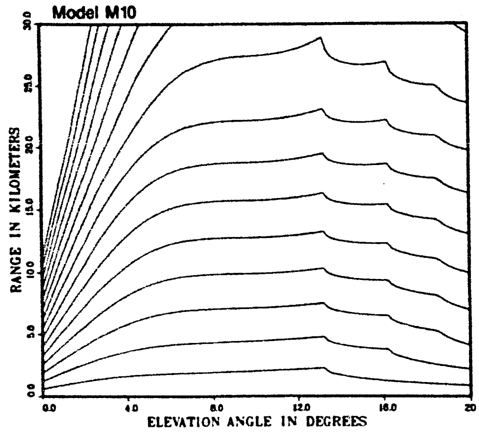

Fig. 7. This plot of range versus launch angle condenses the information computed in many ray traces. Along each curve, the hop number is constant. This display is useful for estimating how many bounces will reach a given range and the amount of focusing each ray will experience (from the slope of the curves), and for gaining insight into the propagation geometry. For example, the cusps at about 13 and 16 degrees show the effects of surface reflections. Elevation angle was stepped by 0.2 degrees to produce this and the following two figures.

limit of the STACS measurements. Higher order surface reflections could be separated easily with that resolution, however, which would give information about the more important region of the Gulf Stream near the core.

It is still not clear if the present STACS measurements can successfully monitor heat transport in the Gulf Stream. The answer to that question will probably come from ray-tracing simulations such as ours, rather than from the measurements themselves. In fact simulations such as ours are the most cost-effective way to design, optimize, and evaluate such methods of measuring sound speed acoustically.

Range Versus Launch-Angle Displays

Quantitative information about a large number of raypaths is hard to extract from raypath plots (which get very confused if there are many rays) or from the program's printout, so we have designed two displays that compress the information contained in the raypaths. One shows range as a function of launch angle, parametric in "hop" number. A hop is counted every time a ray crosses or executes a closest-approach to a "receiver height." When that height coincides with the ocean bottom, a hop has the same meaning as a "bounce" for a bouncing ball.

Fig. 7 shows a range versus launch-angle plot for the simple case in which both the source and receiver are on the bottom, and up to 15 bottom bounces are allowed. For a given hop number, range usually increases with launch angle; however, when rays begin to reflect from the surface, the dependence is more complex, showing the "cusps" near 13 and 16 degrees elevation.

Range versus launch-angle displays are particularly useful for estimating signal strength, since the intensity is inversely proportional to the slope of the curves. Where the curves are nearly horizontal, there is focusing, and where they are nearly vertical, there is defocusing. For example, a horizontal

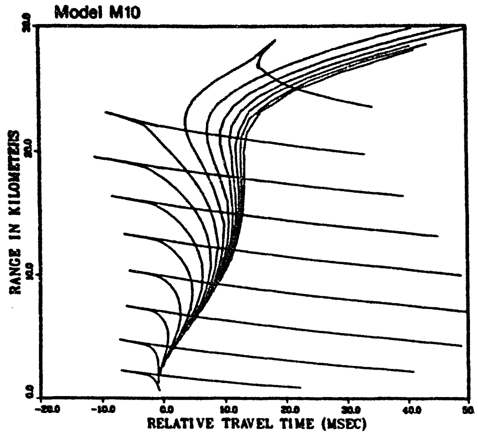

Fig. 8. This plot shows range versus travel time with hop number constant along each curve. It is useful for understanding the propagation processes responsible for the arrival sequence at a given range. One obtains the arrival sequence by drawing a horizontal line at the desired range and noting the intersections with the set of curves. The parts of these curves that curve upward correspond to rays that are refracted back to the bottom without reflecting from the water surface. The nearly straight and horizontal portions correspond to rays that reflect at least once from the water surface.

line drawn at a range of 22 km would show a strong signal arriving after eight bounces from the bottom and weaker arrivals from the higher order bounces. (Accurate intensity estimates must include absorption and reflection losses as well.)

Range Versus Travel-Time Displays

The second display (Fig. 8) plots range versus relative travel time, parametric in hop number. Relative rather than absolute travel time is plotted; the time of a ray traveling directly to each range at 1500 m/s is removed. This preserves the relative arrival times at a given range but removes what would otherwise be a constant slope to the curves. The peculiar shapes of the range versus travel-time curves in this example are caused by the different behaviors of surface-reflected rays (the nearly horizontal staight portions) and rays refracted back to the bottom (the portions curving upward to the left). The behavior at the longest ranges is caused by the falloff of the bottom profile. Some apparent discontinuities in the slopes of these curves are caused by the finite launch-angle increments we used.

Most acoustic experiments measure the sequence of pulse arrival times between a source and receiver at a fixed range. A simulated arrival sequence is easily obtained from this plot by drawing a horizontal line at the desired range and scaling the arrival times from its intersections with the curves. Changes in the arrival sequence with range are readily visible in this display and can be useful in experiment design.

Such diagrams can also be an aid in interpreting temporal changes along the path, as observed at fixed ranges. As the plot expands, contracts, and distorts with changes in the medium, the diagram shows how the pulse arrival sequence mirrors those changes, and how the lowest-order hop number can appear and disappear from the sequence. Except

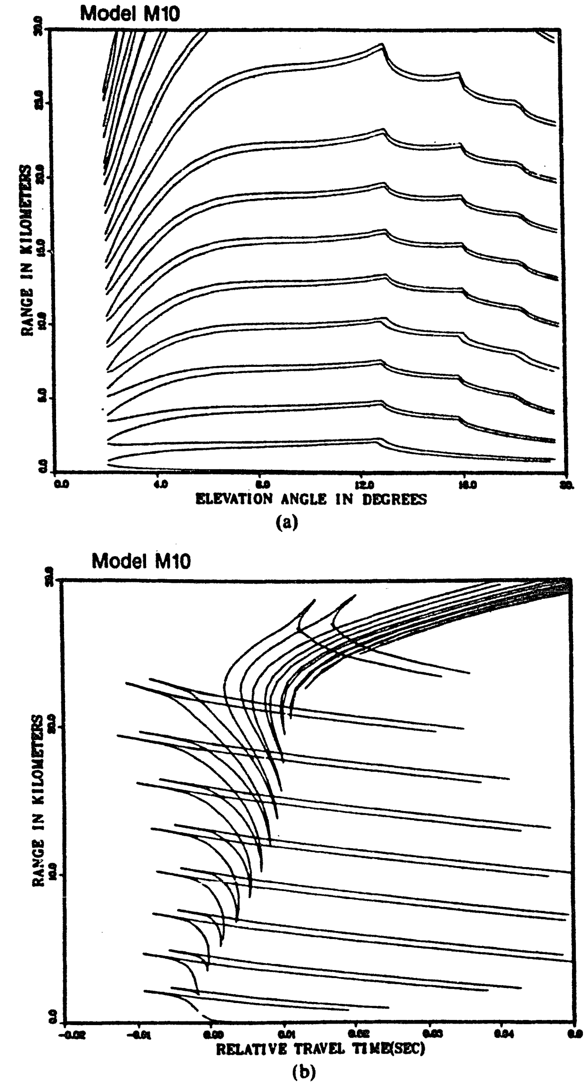

Fig. 9. These two plots show the splitting of the curves that results when the receiver is raised 80 ft off the bottom, because of the additional bottom reflection that is possible. A similar splitting occurs when the transmitter is raised off the bottom, but the confusion is alleviated by distinguishing negative from positive launch angles on the abscissa.

for Figs. 1 and 6, all the displays shown here and most of their labeling have been drawn by computer, using programs that are part of our ray-tracing package.

Effects of Elevating the Source and/or Receiver

The preceding illustrations have used the simple case in which both the source and the receiver are on the bottom. When either is raised off the bottom, the ray geometries become more complicated, because rays launched or received at negative angles encounter an additional bottom reflection.

We have simulated the raypaths for all the combinations of paths between an elevated source and/or receiver. Fig. 9 illustrates the added complexities in the plots of range versus launch angle and range versus travel time for the receiver elevated 80 ft (24.384 m) above the bottom. One effect is that

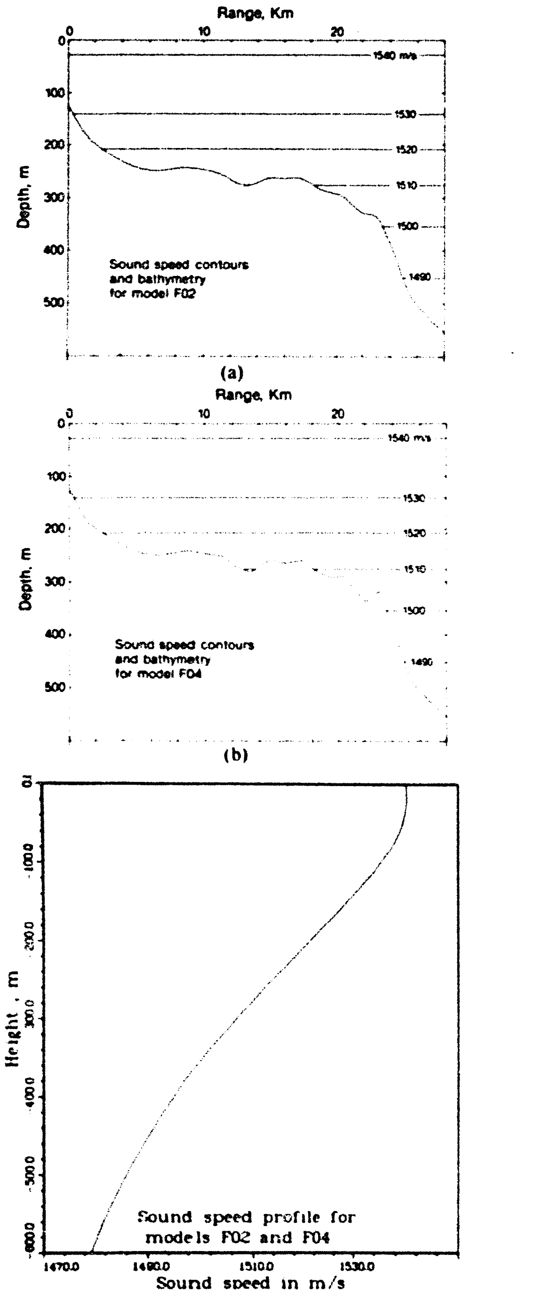

Fig. 10. These two ocean-bottom profiles are models of the first 30 km across the Florida Straits. Each is constructed from linear segments smoothed where they join. In (a), the smoothing is over 1 km, giving a relatively smooth bottom profile. In (b), the smoothing is over 0.01 km, giving a profile with nearly sharp "corners." In (a) and (b), the sound speed contours are shown as horizontal lines; (c) shows the sound speed profile.

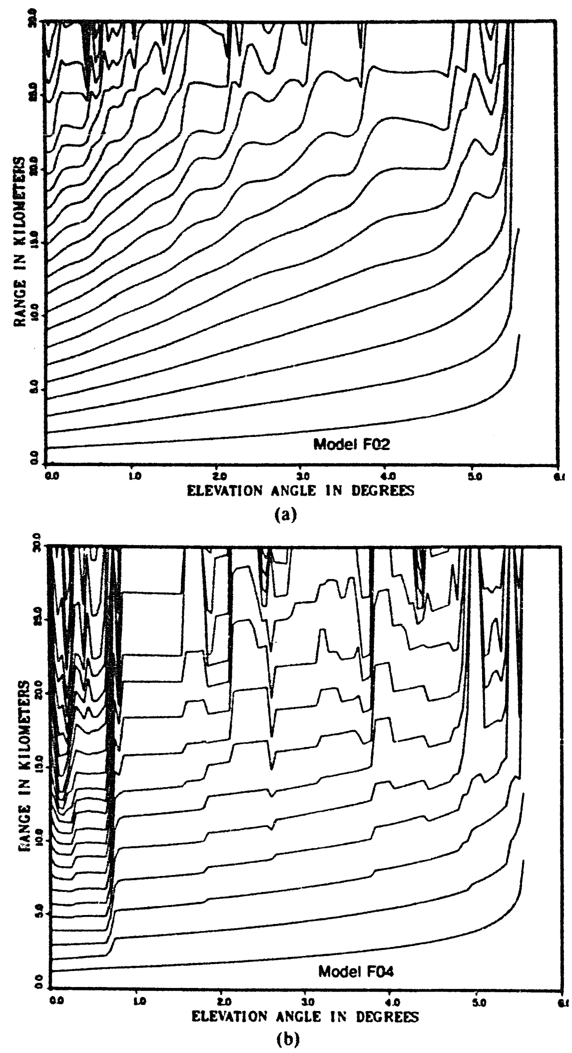

Fig. 11. These two range versus launch angle plots were constructed from rays traced from a source on the bottom, using the two bottom models in Fig. 10. This comparison shows that bottom profiles having sharp corners produce sharp jumps in range (b), which may not be realistic. Such jumps make it hard to interpolate for eigenrays and to estimate acoustic intensity from the slope. The curves for the smooth bottom model (a) are easier to interpret. Elevation angle was stepped by 0.05 degrees.

the curves split into pairs whose separation depends on the receiver height; another is that rays launched below about 1 degree elevation simply bounce along the bottom and never reach the receiver height.

Undesirable Effects of Modeling the Bottom with Linear Segments

Our model of the bottom, shown in Fig. 2, is a mathematical function that is continuous through the second derivative. Because many ray-tracing programs model the bottom with linear segments having discontinuous slope, it is important to realize how such a model can cause discontinuities in raypath properties as launch angle varies.

Fig. 10 shows two more detailed model profiles for the bottom off the Florida coast. Each one is contructed from linear segments joined with analytical functions to round the corners. The amount of rounding is adjustable and can be made small enough that, for practical purposes, the corners can be considered sharp. The model in Fig. 10(b) (called sharp terrain) uses rounding over a distance of about 0.01 km, whereas the model in Fig. 10(a) (called smooth terrain) uses rounding over a distance of about 1.0 km. This particular smooth terrain model may not represent all acoustically important terrain features, since it was designed mainly to illustrate the effects of smoothing.

The effects of rounding are best seen in a range versus launch-angle display. Fig. 11 shows such displays for rays

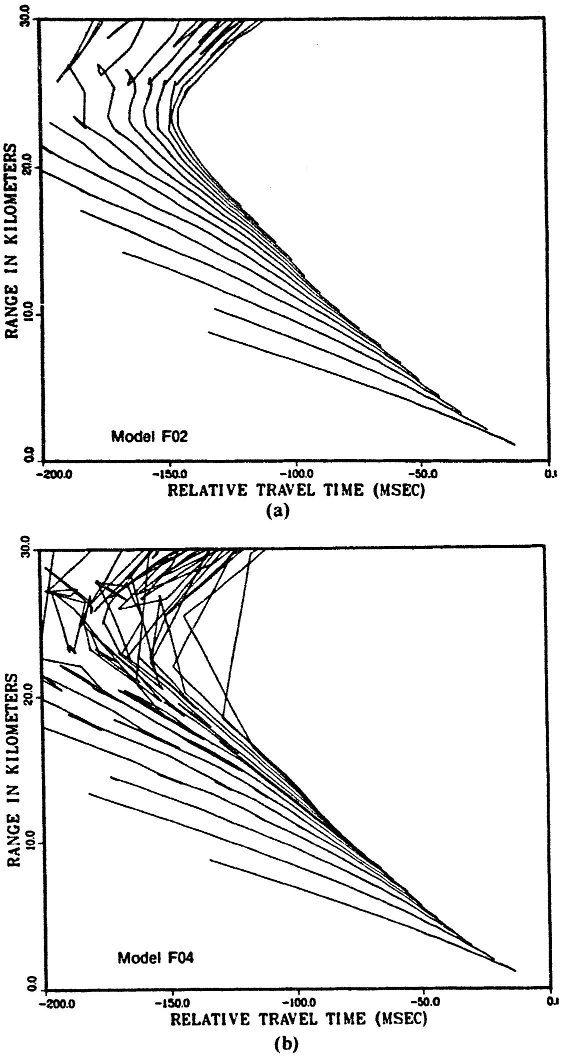

Fig. 12. These two range versus travel time plots correspond to the two bottom models of Fig. 10. The curves for the smooth model (a) are mostly smooth (except for parts where the launch angle increments were not small enough), permitting arrival sequences at any range to be estimated. The curves for the model with corners shows much more "fine structure" that would require extremely small launch-angle increments to resolve.

launched from the bottom using the two models in Fig. 10. Whereas range varies smoothly for the smooth terrain model, the sharp corners of the sharp terrain model produce jumps in range. Where such jumps exist, it is difficult to interpolate the launch angle to get eigenrays and to estimate signal strength.

Fig. 12 compares the range versus travel-time plots for the two bottom models. Discontinuities caused by the bottom corners make accurate travel-time interpolation difficult, if not impossible, with the launch-angle resolution we used (0.05 degrees).

Since corners are generally artifacts of the model and not characteristics of real terrain, they should be avoided because of the discontinuous ray characteristics and fictitious focusing/defocusing they cause.

Sensitivity to Details of the Bathymetry

A comparison of Fig. 12(a) and (b) shows very little difference between the two models for ranges less than about 15 km, even though Fig. 11 shows a considerable difference between the two models for all ranges, including ranges less than 15 km. This observation suggests that the range versus travel-time plots are less sensitive to discontinuities in the bottom slope than are range versus launch-angle plots. Further, signal strength due to ray spreading (which depends on the slope of the range versus launch-angle plots) would be extremely sensitive to discontinuities in the bottom slope.

That discontinuities in the bottom slope yield discontinuities in the range versus launch-angle plots is easy to understand, as is the extreme sensitivity of signal strength to such discontinuities. The range versus travel-time plots are less sensitive to discontinuities in the bottom slope because such discontinuities affect range and travel time in the same way for the nearly horizontal raypaths encountered here.

We would thus expect the pulse arrival sequence for a given range to be generally less sensitive than signal strength to small details in the bathymetry. That conclusion suggests that improvements in the bathymetry model will affect Figs. 7 and 9(a) much more than Figs. 8 and 9(b). We may therefore consider that Figs. 8 and 9(b) represent reasonably well propagation along the Miami Terrace as far as the bathymetry effects are concerned. Figs. 8 and 9(b) will change as the sound speed model changes, of course, and it is that dependence that gives hope for an acoustic measurement of the temperature distribution in the Florida Straits.

Conclusions

In a well-planned program, simulation of the propagation is essential to help design, optimize, and interpret underwater acoustic measurements of temperature and/or current. It is nearly always advisable to start with ray tracing for such a simulation because it is easier to use and costs less than other methods. A Hamiltonian ray-tracing program has the additional advantages that it can easily accommodate general environmental models (including three-dimensional models) and is well suited to models with continuous gradients.

Simulating the propagation for a simple model first, then adding more complexity as the model is refined gives more insight into the propagation than would be obtained from simulating the propagation for only the realistic model. Our simulation of the range dependence of the pulse-arrival sequence (Figs. 8 and 9(b)) for propagation across the Miami Terrace using a simple bathymetry model is realistic for the background sound speed model we used. Using a more realistic bathymetry model would change the details of these results, but not the general features.

The results presented here are not sufficient to judge if present or proposed acoustic measurements can successfully monitor heat transport in the Gulf Stream, but simulations potentially represent the least expensive method to make such judgments. Our results do show that an experimental arrangement in which the transmitter and receiver are on or near the bottom would require very sophisticated data analysis to measure the details of the temperature structure near the bottom with the effective 9-ms resolution available. On the other hand, that resolution is sufficient to separate pulses arising from multiple reflections between the bottom and upper surface. That such pulses penetrate the core of the Gulf Stream (which is of more interest in monitoring heat transport) is more promising for the ability to monitor heat transport. The usefulness of such pulses may depend on how much signal is lost by the multiple reflections.

To be able to make realistic signal strength calculations with a ray-tracing program, it is necessary to be able to produce a realistic range versus launch-angle plot. The plot shown in Fig. 11(b) would not be suitable, because it has jumps caused by the discontinuities in bottom slope of the bathymetry model.

The Next Step

Improving the bathymetry model by adding the appropriate valleys, ridges, and sea mounts would be the next step in this simulation. These additions would give insight into the effect of such features on the propagation, would improve the accuracy of the range dependence of the pulse arrival sequences (Figs. 8 and 9(b)), and would allow realistic signal strength calculations. A realistic calculation of signal strength due to ray spreading in the presence of a sea mount requires a three-dimensional ray-tracing program to provide the correct azimuth spreading. Modeling realistic sound speed variability would help determine its effect on the range dependence of pulse arrivals (such as Fig. 8), and experimenting with various transmitter/receiver locations would help find the configuration most likely to yield information about heat transport.

Acknowledgment

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