SUMMARY AND RECOMMENDATIONS - A PERSONAL VIEW

by

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An unfortunate first impression might be that ray tracing is dull, simply because the idea is a very old one. In fact, ray tracing is the single most powerful method available to us for understanding the complexities of sound propagation in the ocean. And gaining this understanding is quite literally all our business. I will take the main topics of the conference in turn, attempt to give a personal summary of what has been presented, and suggest where future research should be directed.

The Ocean

We learned, or were forcefully reminded,that far from being uniform in the horizontal direction there are drastic changes that occur across fronts (analogous to atmospheric fronts), and that these fronts can be found in all oceans and seas. Further than that, the temperature and salinity (and hence the sound velocity) are not continuous in depth but often proceed in steps of isothermal and isohaline water, separated by thin sheets across which the temperature and salinity change abruptly.

As acousticians we must thank the oceanographers for their awkward findings, but press them to give us more detail; both about the fine structure of temperature and salintiy and its global occurrence.

Sound Velocity

That vital link which joins the oceanographer's description of the ocean to the acoustician's has made great strides in the last thirty years or so. But it is obvious that there is much painstaking work to do particularly with regard to pressure and depth. I will come back to this point later, in connection with modified ray theory.

Computations

This subject has reached a satisfactorily advanced stage, in consonance with the enormous and rapid machines that are now available.

I have a very strong feeling, however, that now is the time to stand back and try to fit the computational aspects of ray tracing into a sensible perspective. A good example is the use of a mini-computer: obviously essential in small laboratories, or on board ship, where it is an invaluable tool in conducting fruitful experiments at sea; but equally valuable in computer investigations where the ultimate in accuracy or detail is not required (and would indeed be a hindrance, especially when such things as turn-around time and availability are concerned) such as in O.R. work, tests of ray tracing sensitivity, etc. But my general point is that we should seek a rational balance between such things as computational sophistication, required accuracy, accuracy of input data, computer availability, cost, flexibility — and even decay time of scientists' enthusiasm.

To go back to the beginning: we now have a variety of options with which to fit the sound velocity profile — linear segments, continuous gradients, Epstein segments, polynomials, splines, and so on.

This leads to the fundamental computational question of whether (a) to fit the profile with segments for which there is an easily obtained solution, or (b) to use something like a spline fit and ask for a differential-equation solution. The linear-segment fit still seems the most convenient choice for mini-computers. But on large computers the choice between (a) and (b) when one looks ahead, say, for the next five years seems much more problematical. Perhaps approach (a) is more suited to plotting rays and calculating travel times, whereas the differential equation approach yields more reliable intensities. It may still be too early to decide the point, but the point nevertheless needs attention.

What does the ocean think of all this? Possibly it feels a bit like a transvestite. The sound velocity in a step-structure ocean is a series of linear segments, separated by discontinuities. So, the sound velocity is not necessarily continuous in its zeroth, first, or second – order derivatives. But more of this later.

We did not hear very much about ray-tracing when the sound velocity has a bivariate profile, although we are told that this often is the case in reality. From a computational view point there is again the choice between (a) seeking simple ray solutions in rectangular sections corresponding to particularly chosen forms of profile and (b) seeking differential-equation solutions in regions where the velocity description is made by something like bicubic splines. However, we are not aware of any useful simple solutions, so the differential equation approach looks more promising at the present time.

Finally, with regard to ray tracing computations, what is the general feeling about applying tests in the manner of Moler and Solomon's use of Pederson and Gordon's Epstein profile results? We have recently launched a modest venture at SACLANTCEN in this direction, with beneficial results. Has anayone's experience suggested using Epstein profiles different from that used by Moler and Solomon? It seems that such test programs would be invaluable in the evaluation of ray-tracing programs, regarding not only their accuracy, but also their convenience, speed and cost.

Experiments

Due to the unclassified nature of our discussions in the last few days, there may be many more experiments than we have heard about. Nevertheless, I feel that the experimental validation of ray tracing has hardly started. This is a pity, since the challenge of obtaining consistent and convincing explanations of experimental results is the mainspring of modern science – it would have very beneficial effects on the development of new theories and computational techniques. Of course, one should continually remind onself of the painstaking care required and, with experiments at sea, the sheer physical difficulty of even performing them. And overall, it seemed to me, "the agreement between theory and experiment was encouraging".

But for the future, one can hope for more and better experiments. It would be particularly useful to have many more experiments of the joint acoustic-oceanographic type, such as the experiment just described by T.D. Allan, in which dense spatial and temporal sampling of the temperature structure of the ocean is combined with acoustic propagation experiments, and the acoustic propagation through known fronts just described by M.J. Daintith.

Extensions to Ray Tracing

There appears to have been a considerable increase in understanding of the behaviour of sound fields in the region of caustics, turning points, and shadow boundaries. Some aspects of modified ray analysis are positively seductive. However, these topics are excellent examples of where the acid test of comparison with experiments is essential for future progress to occur; experiments not only in sound propagation but also in the determination of the sound velocity itself at depth.

Theory

I started by admitting that ray theory is an old subject, but the papers on the Riesz Potential and Hamiltonian methods demonstrated that fresh view points can be taken which may offer the benefit of techniques adopted in other disciplines. They certainly merit very careful consideration. The demonstration of the equivalence of the ray and wave approaches promises advances in the description of propagation in a medium with statistically defined properties.

It was encouraging to hear of efforts being made to put quantitative limits on the oft-quoted conditions for the validity of ray theory. Obviously a great deal more needs to be done in this direction, with particular attention paid to the obliquity of the ray, as well as the scale size of the irregularities in terms of acoustic wavelength.

A related topic is the validity of ray tracing at the discontinuous sheets separating the layers of a step-structure ocean. Of course, these discontinuities are physically large gradients, which can be viewed as discontinuities under certain conditions of sheet thickness to wavelength ratio and ray angle. But it is important to know what these conditions are; and what happens when the conditions are violated.

We heard a little about what we might expect when a sound-velocity profile, or other oceanographic feature, is specified statistically. This is an important avenue that has hardly been entered. Though difficult, statistical approaches must be used to deal honestly with the real ocean. Perhaps the most promising first step is to examine the sensitivity of ray tracing to perturbations in the gradient or other features of the profile, and then to extend this to statistically specified profiles, either by analytical or numerical means.

Applications

The application of ray tracing to reverberation modelling is obviously receiving considerable attention, with encouraging agreement with observations.

It was salutary to be reminded that the most important channel of our work lands up on the desk of the sonar systems designer, and extremely useful to have stated with such clarity his requirements.

CONCLUDING GENERAL DISCUSSION

The Medium

There was very little reaction by the meeting to the oceanographers' revelations concerning the step-like structure of the sound speed. A plea was made for more salinity data in these investigations.

It was pointed out that it was necessary for acousticians to specify the fineness of detail required in oceanographic measurements.

Conventional Ray Tracing

The considerable fraction of the discussion devoted to the various aspects of conventional ray tracing indicated a general concern with a need to refine present methods. Some of the points raised in this connection were:

Is it possible to obtain reliable answers while still employing a linear-segment approximation to the sound-speed profile, either by taking a sufficiently large number of segments, or by smoothing the output in some suitable manner?

There is a possible danger in the use of spline fits to sound-speed data that it might sometimes introduce artificial wiggles in the sound-speed profile, perhaps leading to local gradients of sign opposite to the actual gradient, for example. The opposing view was put that "splines are fine", provided that one works with sufficient data points and takes care with the end conditions.

An alternative approach to making a rational fit to sound-speed data was that the fit should be continuous up to, and including, the second derivative, but that the correct morphology should be retained — presumably judged on oceanographic grounds.

The possibility was mentioned of finding the eigenrays by the direct numerical application of Fermat's principle, as an alternative to the "shooting" method.

A variety of profiles, for which there are analytical solutions is available from L.P. Solomon, Tetra Tech., Inc., 1911 Fort Meyer Drive, Suite 601, Arlington, Virginia 22209, U.S. These could be useful for testing ray tracing programs.

Range-Dependent Ray Tracing

A recurring theme during the discussion was the need to extend present ray tracing capability to bivariate sound-speed profiles, and eventually to trivariate profiles. But there were no clear ideas put forward as to how this could best be achieved.

Current methods include simply dividing the range into blocks, each block having a sound speed that depends on depth only, and then proceeding with the usual univariate methods within each block. Another technique is to divide the range between given profiles into triangular sections, the ray paths within each section then being circular arcs. Both these techniques suffer from implying oceanographically unacceptable sound-speed structures in regions between the given profiles.

Mention was made of the Hudson Laboratories technique employing a special form of double Taylor series expansion (linear variation in range, linear plus curvature term in depth) specifying the sound speed in the region between two given profiles. There is also the possibility of representing the bivariate sound speed in terms of doubly-cubic spline functions. In both these cases the ray tracing could then be accomplished by numerically solving the ray differential equations.

Statistical Aspects and Profile Sensitivity

A difficult problem, but one requiring urgent attention, is that of allowing for the effect of the variability of the sound-speed profile. This can be viewed as a problem of the sensitivity of ray tracing to certain perturbations of the sound-speed profile. Or it can be viewed as a statistical problem, requiring the statistics of the output of ray tracing given the statistics of the input profile(s).

The sensitivity problem is important when considering the adequacy of proposed methods of curve fitting to the given sound-speed data points.

A major difficulty with the statistical problem is that of posing the problem properly. For example, if one starts with a mean profile (obtained by averaging a large collection of profiles) this profile may be devoid of all the features (such as layer depth) which are known to affect the sound propagation drastically. Therefore, some method should be found by which the essential character of the profiles is preserved. In other words, one should work with a "typical" profile, rather than with a strictly "mean" profile.

But more significant than working with mean values, the second-order statistics of the ray tracing output are an important measure of the variability caused by variations of the sound-speed profiles as inputs to ray tracing programs.

General Points

The opinion was expressed that insufficient attention had been paid to the final objectives of ray tracing in an ASW context. If we are not approaching anything of value, we might as well stop now and turn our attention to potentially more fruitful subjects, such as loudspeaker design!

Two drastic alternatives to the present highly computer-orientated approach to the solution of underwater sound propagation problems were proposed. One was to replace computers by mathematicians who would be cheaper, and whose task would be to develop alternative and more amenable theoretical approaches. The other alternative was to de-emphasize computers and mathematicians, and to accentuate in compensation experiments at sea. In other words, it might be easier and more reliable to use the Oceanic analogue computer.

There is, naturally, a bias of American interests towards low-frequency, long-range propagation, whereas SACLANTCEN interest is concentrated more on relatively short ranges at sonar frequencies. Thus the outcome of modified ray theory appears to be of greater interest to the former than to the latter; although some intriguing discrepancies between experiment and conventional ray theory at the shorter ranges need to be scrutinized in the light of modified ray theory.