Full Field Inversion Methods in Ocean and Seismic Acoustics
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Theoretical Study of the Significance and Feasibility of an Improvement in Experimental Tomography Methodology through a Joint Assessment of Arrival Angles and Times

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Abstract:
The purpose of this study is to theoretically evaluate the performances of such an array in a fluctuating medium by means of arrival time-angle diagrams.
First, suitability of using the eikonal approximation to monitor the sound speed structure in a fluctuating ocean and especially to probe meso-structure in the North-East Atlantic Ocean is discussed. Then, a study of the evolution of tomographic parameters: travel time, temporal spreading, temporal resolution, angular density, based on ray theory is conducted through a synthesis of recent theoretical and experimental studies. Its aim is to quantify and precisely define the undesirable effects induced by the fluctuating medium. These results will be compared with those of a statistical study, and then efficiency of an array processing dealing with a joint assessment of arrival angles and times will be investigated. Finally some general features of the feasibility of this improvement are pointed out from these first parametric results and some particular conclusions are given in the case of the North-East Atlantic ocean.

Although numerical inversion techniques are becoming more and more efficient, their results depend on the accuracy of the measured input data. These data, known as the invertible parameters of tomography (travel time fluctuations of an acoustic pulse, arrival angle...), are deduced from observables identified as a line integral of the desired field.

Fluctuations of the medium noticeably modify the invertible parameters. In a modelization of acoustic propagation with geometric rays, this generates general problems of identification and separability of acoustic rays. Mathematical inversion methods may be ill-conditionned and it becomes difficult to yield information on ocean structure. This is the case of measurements obtained during the acoustic tomography

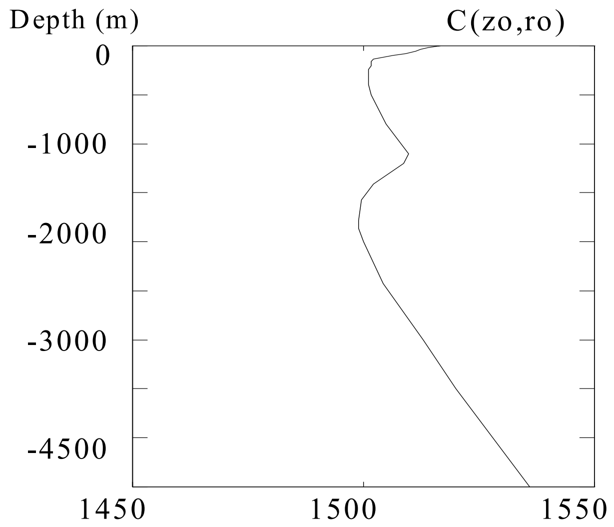
experiment carried out in 1990 by the SHOM (Hydrographic and Oceanographic Center of French Navy) in the Bay of Biscay. Because of a very specific sound velocity profile, received rays are no longer separable and identifiable, and the stability of geometric rays is questionable.
In order to improve tomographic techniques in the North-East Atlantic Ocean, the mechanics of the influence of propagation conditions on tomography results must be well known, summed up and compiled. Furthermore, it seems that non resolvable paths might be separated with a vertical reception array.

Deterministic aspect

First, we checked the validity of ray equations in a double-channel characteristic of NEA (North-East Atlantic) by considering the order of magnitude of the spatial celerity gradients. They are in fact insufficient to explain unstable motion of ray paths.
On the other hand, it has been previously shown that acoustic ray trajectories are expected to exhibit chaotic motion, i.e. extreme sensitivity to initial and environmental conditions, in range-dependent ocean models. J.Yan (1993) defines as follow an instability criterion of Hamilton's ray equations:

$$\frac{C^2{}_0}{C(z_0)^4}\left\{C(z_0)\left[\frac{\partial^2 C(z_0)}{\partial z^2}\right]-3\left[\frac{\partial C(z_0)}{\partial z}\right]^2\right\}+\frac{\partial^2 g(z_0,r_0)}{\partial z^2}<0$$

Figure (1) : Mean sound speed



where Co is the reference sound speed, C is the sound speed, g is the range-dependent perturbation in potential function, z is the depth, zo and ro are the reference depth and range. By analyzing instability he shows that this criterion is a necessary condition for ray chaos, and so that chaos may be induced even if there is no fluctuation ($g = 0$). The picture (2) presents as a function of depth the evolution of this criterion in a case of a deterministic sound speed profile characteristic of the NEA zone. Even in this deterministic case there are two areas where necessary conditions for chaos are satisfied ($z \approx 1200$m (channel axis) and $z \approx 70$m).

Stochastic aspect

When some fluctuations are introduced in the sound speed profile the criterion is more likely to be satisfied if the derivative $\partial^2 g/\partial z^2$ is negative and admits a large absolute value. This is the case with NEA fluctuations (see Figure (2)) near the channel axis.

This is not a sufficient condition, but the conclusion is that NEA fluctuating profiles require the existence of chaotic motions. To investigate and characterize more precisely ray chaos, we should evaluate as in [K. Smith, M. Brown, F. Tappert 1992] the Lyapunov exponents in order to qualify the degree of chaos in this area.

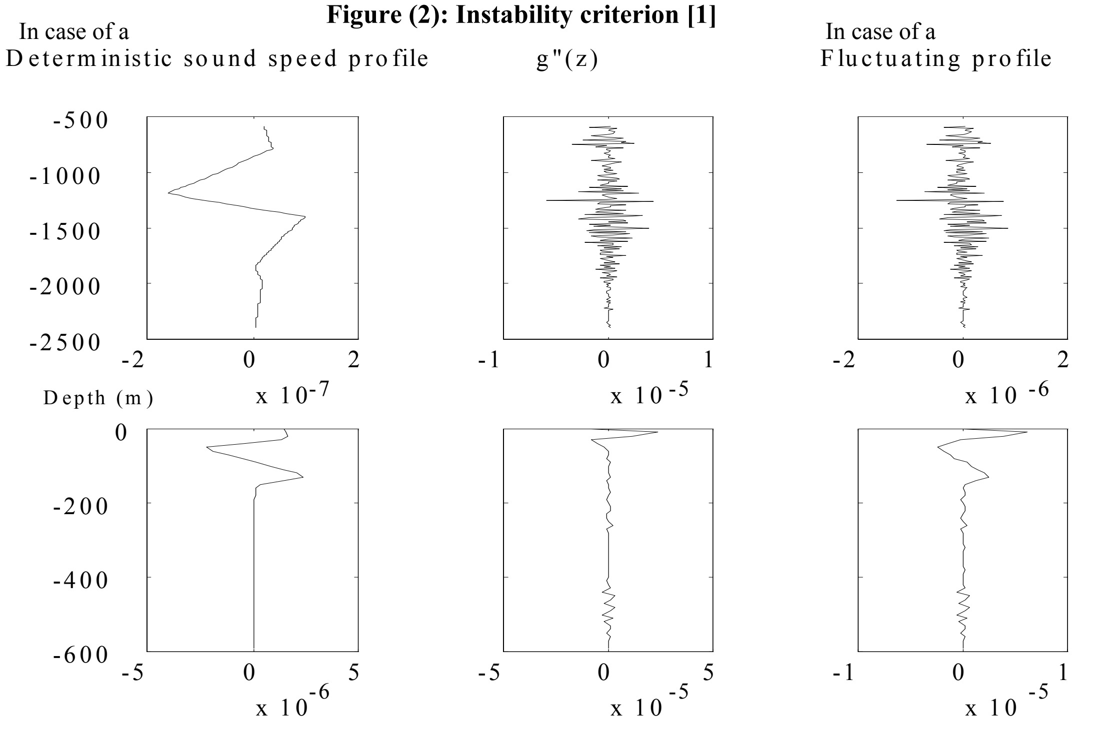


Figure (2): Instability criterion [1]

In order to characterize sound propagation features with a ray model in a fluctuating ocean, we use theories developped by Flatté et al and based on path-integral methods [S. Flatté, R. Dashen, W. Munk, K. Watson, F. Zachariasen (1979)]. Their treatment of ocean medium includes the effects of anisotropy and the background sound channel as well as statistical inhomogeneity and internal-wave spectra. They define two parameters representing the strength and size (spatial extent) of the inhomogeneity that control the character of the fluctuations in a wave field crossing these perturbations. These parameters may be evaluated only from in-situ measurements of sound speed fluctuations by the mean of their variance and correlation lengths for some propagation configurations (source-receiver pair).

SOUND SPEED FLUCTUATIONS IN NEA

Fluctuations known from in-situ measurements in the NEA zone are compared in their order of magnitude and vertical correlation lengths to those considered in Flatté et al's theories. In fact NEA fluctuations are weaker in the first channel. Because of the order of magnitude and the closeness of continental shelves, the assumption that fluctuations are essentially due to internal waves seems to be consistent. In addition, we suppose, but with no possible confirmation (because of too sparse in-situ measurements), that the horizontal correlation length was approximatively equal to 10km as it is usually taken for that kind of perturbation.

CALCULATION OF THE STRENGTH AND DIFFRACTION PARAMETERS φ AND Λ.

The parameters defined as follow: $\phi^2_{ray} = q_0^{\,2} \int_0^R dx \, \left\langle \mu^2(z_{ray}) \right\rangle \, L_P(\theta, z_{ray})$ and

$\Lambda_{ray} = \phi^{-2}_{ray} \, q_0^{\,2} \int_0^R dx \, \left\langle \mu^2(z_{ray}) \right\rangle \, L_P(\theta, z_{ray}) \left| q_0 \, A \, L_V^{\,2} \right|^{-1}$ where μ is the relative sound speed fluctuation, Lp the correlation length and A the phase curvature function, are numerically computed as in [R. Esswein, S. Flatté 1980][R. Leung, H. DeFerrari 1980] along some unperturbed eigenrays localised in the upper channel. We use a Runge-Kutta method to carry on the calculus of the phase curvature function. Some convergence difficulties appear in computing these parameters: their equations are shown to have instability criterion dependent on $\partial^2 g/\partial z^2$ too.

The results obtained are summarized on picture (3) for a propagation range of 180km and compared with results in Cobb, Bermuda, Azores in [Flatté et al] p238 and with Atlantic in [Esswein-Flatté] p1530. They seem to be in good agreement and consistent with those obtained in the nearest previously studied area: in the Azores.

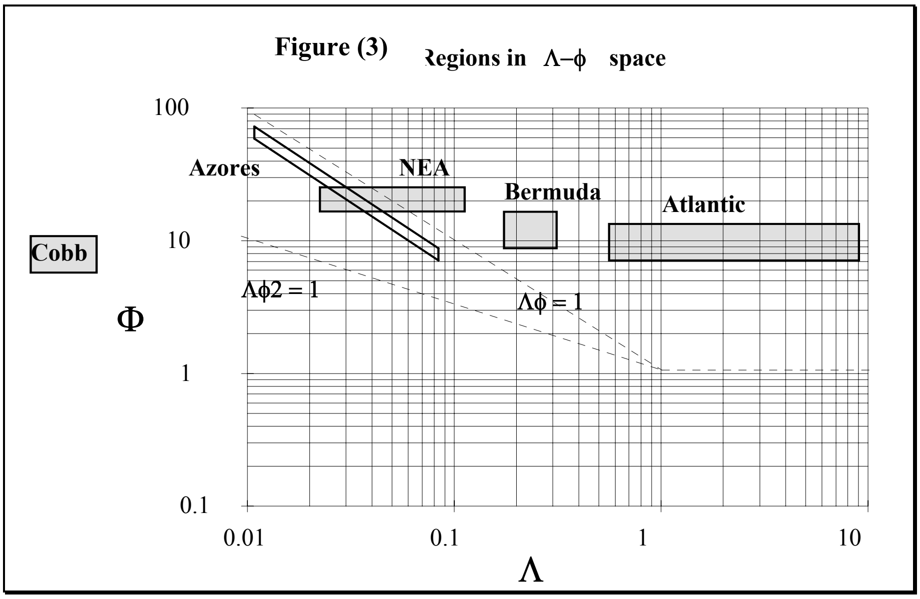


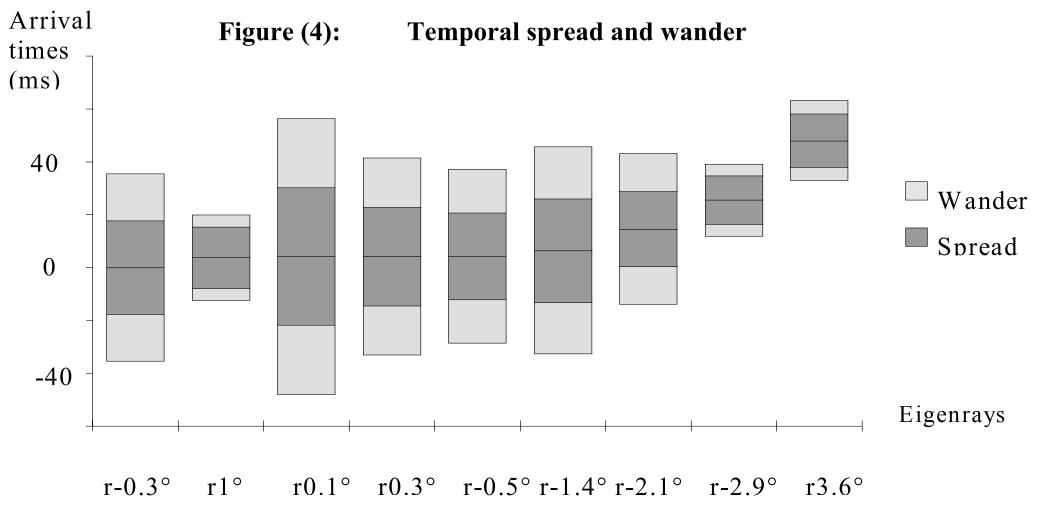
Figure (3) Regions in Λ−φ space

So, the whole NEA zone seems to be at its limits of tractability with the basic equation of geometrical optics.

TIME-ANGLE PARAMETRIC DIAGRAM

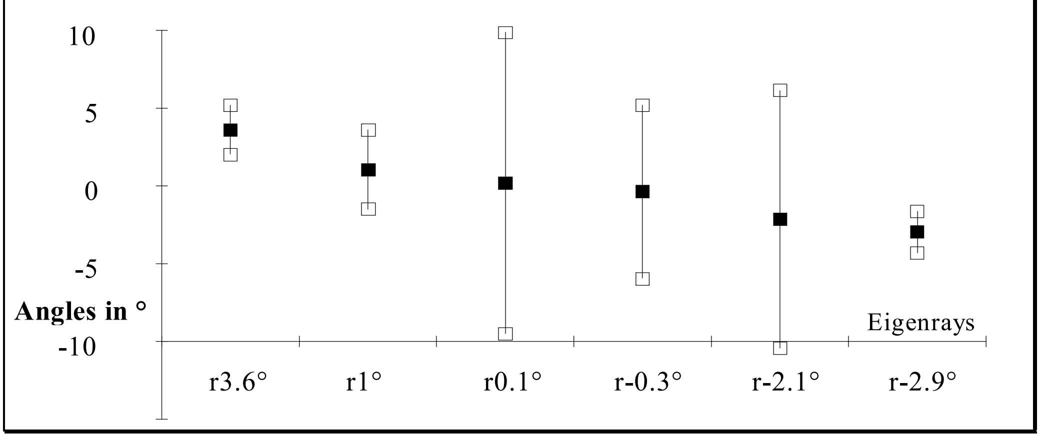
These parameters give some informations about the number of multipaths and their spatial spreading. They are also used to evaluate temporal and angular spread and wander. Temporal characteristics are presented in Figure (4) where eigenrays are referenced by their emission angle (r-0.3° corresponds to an emission angle of -0.3°, r3.6 to 3.6°) and to the first temporal arrival (eigenray r-0.3°). The parametric values obtained are from 10ms to 50ms and correspond to those observed with in-situ measurements.

Figure (4): Temporal spread and wander



Fluctuations in arrival angle (Picture (5)) seem to be very important in our area, especially for axial rays but they remain consistent with the order of magnitude given in Stoughton-Flatté [1988].

Picture (5): Arrival angles



For all of these calculations we take into account the variance of celerity fluctuations over the entire NEA area, which is probably the worst case. In order to compare the parametric results with some measured travel times and arrival angles over 180km range propagation, we should have considered only the variance of the fluctuations of the crossed area instead of the one of the whole zone.

CONCLUSIONS

This study defined the propagation characteristics in the worst fluctuating case. A study of sound speed fluctuations in the NEA area concludes that the order of magnitude is of the same order as those usually observed in other oceans where rays are stable and identifiable. So, sound speed perturbations can't alone explain the complexity of temporal arrivals detected in-situ during the tomographic experiment. Considering chaotic instability, we have shown that the deterministic double-channel satisfies the necessary condition for chaos and this aspect is reinforced in case of fluctuating celerity profile.

In conclusion of the theoretical study, problems due to chaos seem to be the more important because chaotic rays may arrive at any time and anywhere and perturbe all the arrival scheme without any logic. Interpretation may then become impossible. An issue might be to use eigenrays that do not cross chaotic areas by making judicious choice of source-receiver depth or by limiting the source to small emission angles. More information than the parametric one obtained here on arrival angles, is needed to predict the potential of an array to separate eigenrays in this tomographic experiment.

This study will be completed with a statistical approach. This will consist of constructing from in-situ celerity measurements, a great number of realistic realizations of the random oceanic process, which are in fact maps in 2D of the sound speed profile. For each of these maps, the corresponding trajectories and arrival times of rays are then computed by solving a deterministic propagation equation with a range dependent ray model. This method makes no assumption on the fluctuations because it only treats deterministic problems and will yield more realistic results in specific subareas concerning some tomographic paths instead of giving general results for the whole NEA as those of the parametric study.

REFERENCES

R. Esswein, S. Flatté May (1980) "Calculation of the strength and diffraction parameters in oceanic sound transmission". JASA 67 (5),

S. Flatté, R. Dashen, W. Munk, K. Watson, F. Zachariasen (1979) "Sound transmission through a fluctuating ocean.", Cambridge University Press.

R. Leung, H. DeFerrari (Jan 1980) "ϕ and Λ computations for real and canonical oceans." JASA 67 (1).

K. Smith, M. Brown, F. Tappert (April 1992) "Ray chaos in underwater acoustics." JASA 91 (4). "Acoustic ray chaos induced by mesoscale ocean structure." JASA 91 (4).

J. Yan (Nov 1993) "Rays chaos in underwater acoustics in view of local instability." JASA 94 (5), p2739.

R. Stoughton, S. Flatté (Oct 1988) "Prediction of internal-wave effects on ocean acoustic coherence, travel time variance, and intensity moments for very long-range propagation". JASA 84 (4).