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## RANGE DEPENDENCE OF SPATIAL COHERENCE MEASUREMENTS IN SHALLOW WATER SOUND PROPAGATION


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### RESUME

La fonction de corrélation des signaux acoustiques reçus sur différents capteurs d'une antenne est utilisée pour estimer la cohérence spatiale.

Sous certaines conditions on a mesuré en eau peu profonde une augmentation de la cohérence spatiale avec la distance de propagation.

L'examen de ces expériences suggère deux explications possibles. L'une est la théorie des rayons, mais en général cette théorie n'explique pas suffisament les phénomènes de propagation en bas-fonds.

L'autre est la théorie des modes qui peut donner peut-être une explication plus satisfaisante.

### SUMMARY

The correlation function of acoustic signals received on various pairs of hydrophones of an array gives an estimate for the spatial coherence function.

Shallow water measurements have shown under certain conditions an increase of spatial coherence length with increasing propagation range.

There are two possible explanations for this effect:
One is the ray theory, but in general this theory does not give a sufficient description of sound propagation effects in shallow water.

The other is the normal mode theory which may suggest a more satisfactory explanation.

# RANGE DEPENDENCE OF SPATIAL COHERENCE MEASUREMENTS IN SHALLOW WATER SOUND PROPAGATION

## 1. Introduction

The underwater acoustic communication channel depends on parameters which exhibit random variations in time and space. Therefore, one may consider the propagation medium between a fixed point source and a receiver as a time- and space-variant random filter which performs a linear transformation on the transmitted signal (Ref. 1,2). The random character of the channel is due to the roughness of the boundaries, to the inhomogeneities in the water and particularly in shallow water, to the mutual interference between a large number of rays or modes.

## 2. Spatial Signal Distortion

The signal distortion caused by the medium may be described with the aid of a generalized multidimensional scattering function (Ref. 2,3). The spatial and angular aspect of signal distortion is usually characterized either by a spatial coherence function or an angular scattering function. The angular scattering function of the medium describes the average spread of signal power in angular space. Since angular scattering function and spatial coherence function form a Fourier-pair, one can estimate the effective width of the angular spread caused by the medium from the inverse of the coherence length, which is determined as the acoustic length, i.e. the spacing between two points multiplied by the wave number $2\pi/\lambda$ at which the spatial coherence function falls below a certain value (usually 0.6) (Ref.4). It gives a limitation for array-performance and signal processing. If the doppler shift of a target is small,it is very difficult to achieve a good signal-to-reverbation-ratio. In order to increase this ratio there remains the possibility of increasing the directivity of the array. But there is no purpose in building large arrays with a resolution higher than the limitations given by the transmitting medium.
This is particularly important in shallow water.

## 3. Coherence measurements

The spatial coherence function is determined by the degree of correlation of signals received at two points spaced a distance apart as a function of the spacing. It can be shown for narrow-band signals that the maximum of the normalized temporal cross-correlation function between two time signals received at two different points in space is a good estimate for the spatial cross-correlation at a given distance. Thus one can measure a sampled version of the space correlation function by choosing different spacings of hydrophones on an array.
Broad-band explosive sources are very often used for propagation measurements.

To get the spatial coherence function at a certain frequency one has to apply narrow-band filtering before correlation. This procedure of filtering and correlation can be performed by a digital computer after digitizing the analog input of the receiver.

Measurements of the required correlation functions can also be obtained by using CW-sources. An intuitive approach would expect a decrease of coherence length with increasing range between the acoustic signal source and the receiving array.

In shallow water experiments however, there seems to be an indication from the data in references 5 and 6 that coherence length might increase with range under certain propagation conditions. Some results of sea-trials in shallow waters have been assembled by the author of this paper in Reference 5.

Data had been collected in a shallow water area in the Mediterranean Sea during winter isothermal conditions.
A pronounced increase of coherence length with propagation range had been observed despite a rough sea.

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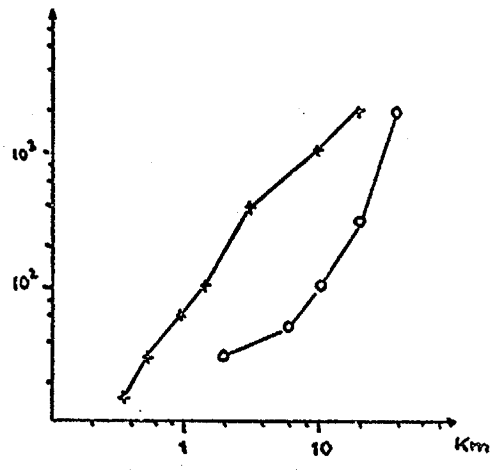


Fig. 1 Coherence length as a function of propagation distance
+ Mediterranean Sea
o North Sea

Similar observations have been reported by Scholz for the North Sea under winter conditions in reference 6.
Summer data of reference 6 do not show such a pronounced range dependence. The same thing applies as well to the results of Ancey in reference 7 that had been collected under summer conditions in the gulf of Lions.

## 4. Theoretical Explanations

Basically there are two theoretical approaches to a solution for the propagation problem of acoustic sound waves in a transmitting medium. The first is analog to geometrical optics. It gives an approximate solution to the wave equation in the form of acoustic rays and illustrates propagation with the help of the ray diagram.

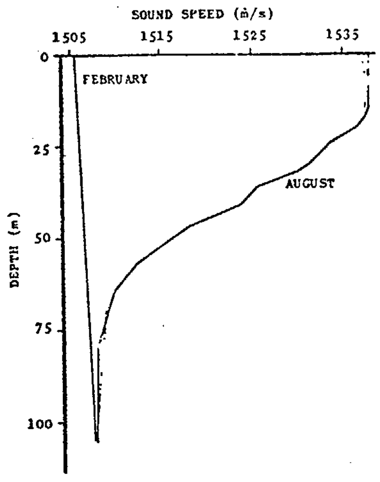


FIG. 2 VELOCITY PROFILE

During winter isothermal conditions there is only an increase of the sound velocity profile towards to bottom due to static water pressure. This implies upward refraction of the acoustic rays. Thus the bottom plays a less important part during the winter season.
Under these assumptions the increase of coherence length with propagation range may be explained by smaller grazing angles for larger propagation distances. The acoustic rays with a small grazing angle do not "see" the roughness of the boundaries whereas the rays with a steeper angle that are responsible for multipath interference are strongly attenuated after several reflections. In the summer season the sound velocity profile is much more complicated due to surface heating. The acoustic rays are refracted downwards. The cyclic distance is smaller and the grazing angles at certain ranges are much steeper than during winter conditions.

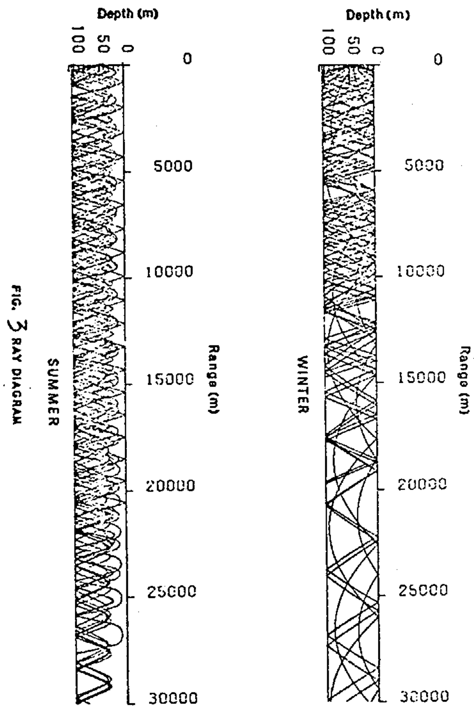


Fig. 3

This may explain why no pronounced range dependence of coherence data has been observed under summer conditions. Ray theory however does not provide a sufficient description of sound propagation in shallow waters, since it is restricted to high frequencies.

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A rigorously correct solution of the wave equation is known as normal mode expansion. The acoustic sound field is described in terms of characteristic functions which satisfy the boundary conditions. These are complicated functions, each representing a wave traveling outward from the source with an amplitude which is a function of the source and receiver depth.

Mode theory is adequate for computations on a digital computer but it requires a considerable amount of CPU-time for a sufficiently good propagation model. For quantitative spatial coherence calculations a three-dimensional shallow water model is required, which includes the properties of the sea bottom as well as the roughness parameters of the boundaries. Such a model is not available at the moment. Therefore, some results from reference 8 are utilized for a qualitative discussion.

The shallow-water sound propagation problem has been treated in (8) as a "three fluid" model with a water layer of constant depth H, density and compressional sound velocity $c_o(z)$ which is an arbitrary function of depth z. The second layer is the uppermost layer of the sea bottom and the third layer is a semi-infinite sub-bottom.

For a centre frequency of 400 Hz the attenuation for various modes has been calculated as a function of mode number for two different bottom structures.

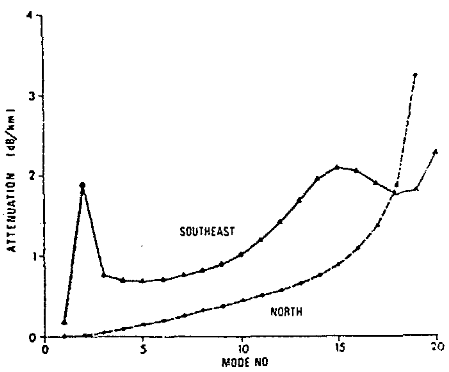


FIG. 4 Mode attenuation for two different bottom models. F=400 Hz.

The shape of the curves differ for the two different regions. In general a considerable amount of environmental information is required for quantitative predictions with a mode propagation model.
That information is usually not available. As a qualitative result we notice in both cases an attenuation of the higher order modes with increasing propagation range. This attenuation should not be confused with exponential mode attenuation for frequencies which are below the cut-off frequency of a waveguide.

If we assume that spatial decorrelation of the received signal is due to the interferences between a large number of modes, we may expect to get a higher degree of coherence with increasing range, since the higher-order modes are "stripped-off" by attenuation.

## 5. Conclusions

The shallow water propagation problem has been discussed in the present paper in a simplified manner. Scattering by surface and bottom roughness has been neglected. Mode theory has been applied to a three layer model with average bottom conditions. Ray theory does not consider bottom properties at all and is limited to high frequencies.
Both theoretical approaches however are able to give a qualitative explanation of the astonishing increase of spatial coherence with propagation range under certain conditions in shallow water.

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