MEDIUM-INDUCED LOW-FREQUENCY FLUCTUATIONS IN ACOUSTIC TRANSMISSION LOSS: EXAMPLES FROM MEASUREMENTS IN SELECTED GEOGRAPHICAL AREAS

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ABSTRACT

The ocean is a complex, highly variable acoustic medium. A propagating acoustic signal is affected by a host of phenomena, including the sea-surface and bottom, volume inhomogeneities, internal waves and tides, and non-stationary water masses. These effects cause fluctuations in the amplitude and phase of an acoustic signal and an accompanying loss in its coherence properties. The responsible mechanisms, and hence the acoustic effects, cover a wide range of temporal and spatial scales and, in general, can be understood only in terms of deterministic and random forces acting in concert. Although the listing of these mechanisms is generally easier than their isolation in realistic situations, it has been possible to correlate fluctuations in acoustic transmission loss with environmental variability, especially for very low acoustic frequencies. In particular, measurements conducted by SACLANTCEN in diverse geographical areas have identified semi-diurnal effects (tidal as well as heating), internal waves, inertial oscillations, and moving water masses as significant contributors to low-frequency acoustic fluctuations.

INTRODUCTION

The basic problem in using acoustics in the ocean is the complexity of the medium. The parameters controlling the propagation vary, usually unpredictably, both spatially, and, more significantly, temporally. Consequently, an acoustic signal propagating in such a medium is affected not only by interactions with the bottom and surface boundaries, but also by volume inhomogeneities caused by non-uniformities in temperature, density, and salinity distributions. The degradation of the acoustical signal is manifested by fluctuations in its amplitude and phase and by an accompanying loss in its coherence properties.

Generally, this degradation results in a decrease in performance of underwater acoustic systems, including sonar. In particular, the estimations of range and angular bearing of a sonar system can be adversely affected by temporal and spatial coherence losses. For this, and other reasons, an understanding of the causes of signal degradation is essential.

This paper will consider environmentally-induced signal fluctuations as they affect transmission loss.

Although the mechanisms leading to fluctuations in acoustic propagation are diverse, an essential common feature is an associated non-uniformity in the medium, either temporal or spatial or both. Depending on the temporal and spatial scales involved, the mechanisms can be considered either deterministic or random [1]. The general circulation of the ocean ("ocean climate") and its associated current systems (Gulf Stream, Kuroshio, etc.) are characterized by horizontal scales of variability limited only by the size of the basin, vertical scales of a few 100 m, and temporal scales from a few days to seasonal. These are deterministic structures. The intermediate scales of variability, including ocean motions such as fronts and eddies, can also be considered to be deterministic perturbations from the mean structure. The associated scales of variabilities are of the order of 100 to 1000 km in the horizontal, to ocean depth in the vertical, and days to months in time.

Internal waves, fine-structure, and microstructure comprise the smaller scales and are considered random features. The internal waves are characterized by scales from 100 m to 10 km or more in the horizontal, 1 to 100 m in the vertical, and from about 10 min to 1 day in time. Because they owe their existence to the restoring forces due to the density gradient and the Coriolis force, the frequency spectra of internal waves are bounded by the inertial frequency at the low end and by the buoyancy frequency (Brünt-Väisälä) at the high end. Variability induced by internal waves has been found to be a very significant source of sound scattering and has received considerable attention in recent years [2,3,4]. In essence, this increased activity arises from two complementary facts: on the one hand the spatial scales of internal waves match the acoustic wavelength over a broad frequency range, and thereby affect the acoustic field; on the other hand the internal wave is one of the few ocean features for which a reasonably effective statistical model (Garrett-Munk) is available. Fine- and microstructure variability involve horizontal scales from several metres to hundreds of metres, vertical scales from centimetres to about 10 m, and temporal scales of the order of milliseconds. Such variability generally affects sound propagation in the frequency range from approximately one to tens of kilohertz.

Table 1 [1] summarizes the temporal scales of environmentally-induced fluctuations often observed in acoustic propagation experiments. Of particular relevance to low frequency acoustic propagation is the information contained within the dotted area of Table 1. The remainder of the paper is devoted to a discussion of three SACLANTCEN measurements, the results of which show a clear correlation between transmission loss fluctuations and the environmental phenomena highlighted here.

In particular, long-period internal waves (inertial oscillations) and semi-diurnal, tide-related effects figure prominently in the measurements conducted in two areas of the North Atlantic Ocean and one in the Mediterranean. Moreover, although tidal forces are important at both sites, differences among the local oceanographic conditions lead to interesting contrasts between the nature and the degree to which these tidal forces affect the acoustic propagation. In particular, at the Mediterranean test site volume effects in the water column seemed to be of greater significance than in the North Atlantic test site, where acoustic interaction with the bottom was the predominant source of the fluctuations. Therefore, discussions of the results will be grouped under physical mechanisms, viz., under "volume effects" and "bottom effects", rather than under the less relevant geographical indicators.

Table 1 Temporal variation observed in acoustic data

PERIOD	PRINCIPAL ENVIRONMENTAL PARAMETERS	PRINCIPAL ACOUSTIC EFFECTS
ms	FINE AND MICROSTRUCTURE	AMPLITUDE, PHASE AND PROPAGATION PATH FLUCTUATIONS; HIGH FREQUENCY SCATTERING
5 s	SURFACE WAVE SIGNATURES	AMPLITUDE MODULATION; SCATTERING
10 min-24 h	INTERNAL WAVE SIGNATURE	AMPLITUDE AND PHASE FLUCTUATION; SIGNIFICANT REFRACTION OF NEARLY HORIZONTAL PATHS
4 h	SHALLOW WATER TIDES	PHASE AND AMPLITUDE FLUCTUATIONS OFTEN SIMPLY CORRELATED WITH TIDAL VARIATIONS.
12 h	SEMIDIURNAL TIDES	
24 h	DIURNAL TIDES	GREATEST EFFECTS IN SHALLOW WATER
4 day	MESOSCALE PHENOMENA (EDDIES,FRONTS)	FLUCTUATIONS IN PROPAGATION PATH, ACOUSTIC INTENSITY; DISTORTION OF SIGNAL SHAPE; SLOW MODULATION OF ACOUSTIC RAYS
15 day		
1 month	OCEAN CLIMATE	FLUCTUATION IN AMPLITUDE, PHASE AND PROPAGATION PATH
1 year		

1 MEASUREMENTS SHOWING VOLUME EFFECTS

1.1 Propagation Characteristics of the Test Environment

The acoustic propagation experiment was conducted in a shallow water region of the Mediterranean where the water depth varied from about 40 m to 85 m, as seen in Fig. 1. Although the bathymetry of the area is fairly complex, that along the propagation run is relatively simple. The water circulation in the region consists of a three-layer system: an eastward-flowing surface layer of Atlantic water, an intermediate layer in which turbulent mixing occurs, and a westward-flowing bottom layer of more saline (Levantine) water. A temperature/salinity profile of the measured data confirms this general behaviour.

For the experimental situation depicted in Fig. 1, broad-band (explosive) sources were dropped at approximately hourly intervals. A vertical array of hydrophones, 35 km distant, received the signals. Simultaneously, samplings were taken of the pertinent oceanographic parameters: sound speed, temperature, salinity and density (STDV casts). The test was conducted during summer conditions. Figure 2 presents typical depth profiles of the environmental parameters in this area. This type of profile tends to favour downward acoustic refraction and, therefore, results in greater bottom interaction than would occur in winter. Vertical stratification and some fine-structure are evident in the profiles. A closer analysis of the sound speed profile over shorter intervals in depth and sound speed reveals more clearly the presence of fine-structure, characterized by vertical dimensions of the order of centimetres to one or two metres. As already noted, such fine-structure will tend to scatter sound of frequency ranges higher than of interest herein.

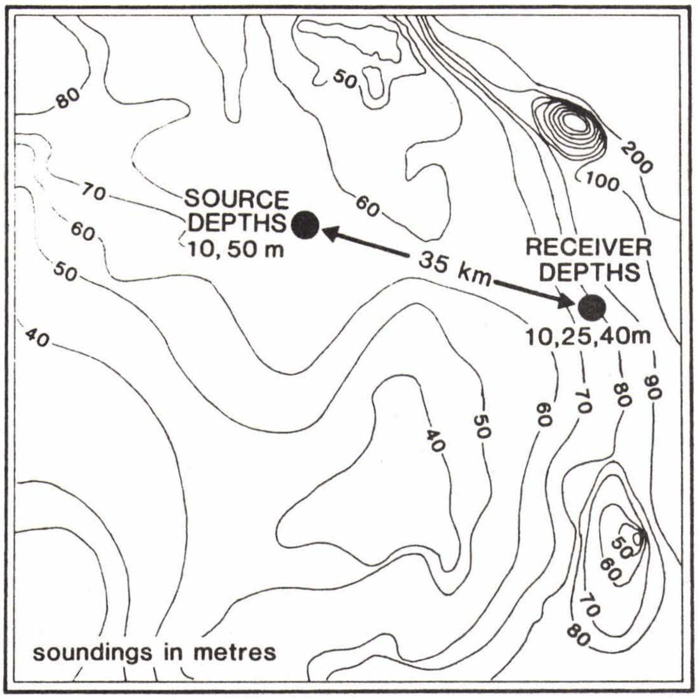

Fig. 1
Bathymetry of the experiment (Mediterranean site).

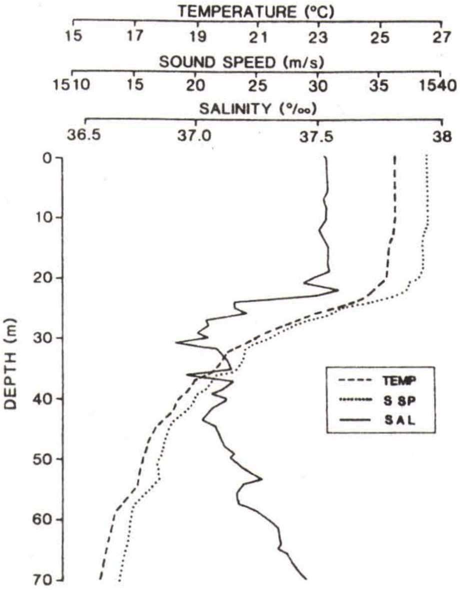

Fig. 2
Depth profiles of temperature, sound speed, and salinity (Mediterranean site).

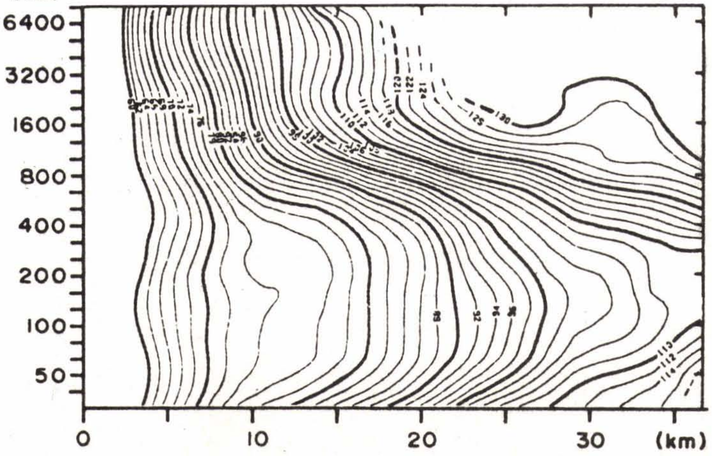

Fig. 3
Contours of measured transmission loss in 1/3 octave bands.

The effect on acoustic propagation is shown in Fig. 3 <5>, which presents contours of measured transmission loss, in 1/3 octave bands, in the frequency/range plane. The existence of an optimum frequency range (i.e. minimal transmission loss) for acoustic propagation is clearly evident. In this case, it lies between approximately 100 and 400 Hz. The explanation for this is that acoustic energy at very low frequencies suffers large attenuation as a result of bottom penetration which increases directly with wavelength. On the other hand the energy at the very high frequencies is greatly attenuated by absorption in the water column and, possibly, by scattering from fine-structure. Hence an optimum frequency range exists somewhere between the two extremes. In other words, for the conditions typefied by Fig. 3, the ocean behaves like a band-pass filter for propagating broadband acoustic signals.

1.2 Temporal Variability in the Environmental Data

Of primary interest for our purpose is the temporal variation of the relevant parameters at a fixed range, here 35 km. Figure 4 shows an example of the variation of sound speed with depth during a period of 25 hours.

The depth range from approximately 25 to 35 m comprises the steepest portion of the thermocline. The region down to 20 m or so is essentially isovelocity with a sound speed of approximately 1538 m/s. The fluctuations in sound speed are quite evident, particularly at a depth of 25 m or so within the thermocline. The plots clearly indicate an oscillation in the width of the mixed layer (surface duct). Figure 4b, in particular, indicates that typical features, e.g., "kinks" in the curve, appear to be migrating vertically with time - a behaviour often suggesting the presence of internal waves [Gregg, 6]. The frequency content of these oscillations is of particular interest because it provides clues to the responsible mechanisms. Examples of frequency spectra of the relevant environmental parameters, obtained from Fast Fourier Transforms of the corresponding normalized time series at 25 m depth, are shown in Fig. 5.

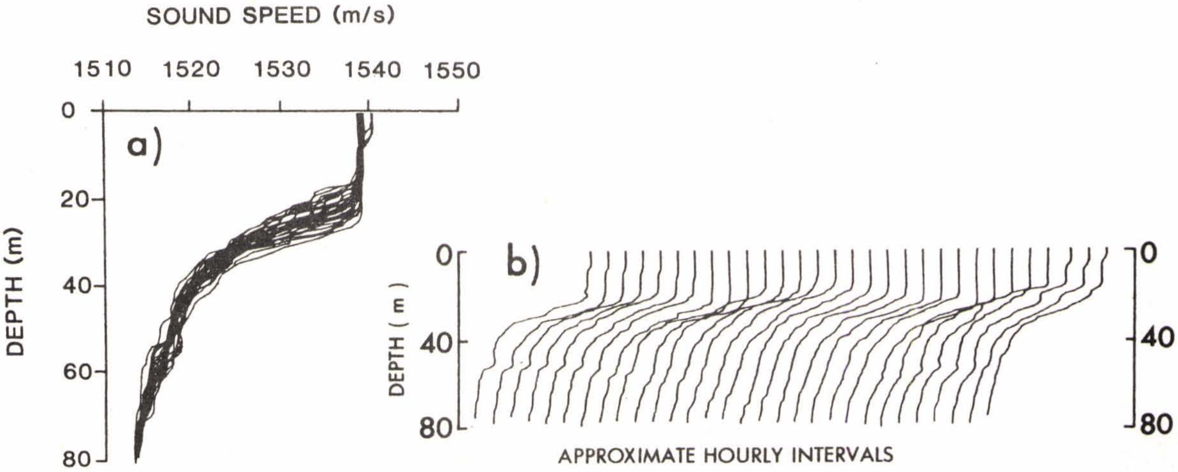

Fig. 4 Temporal variation of sound speed over approximately 25 hours.

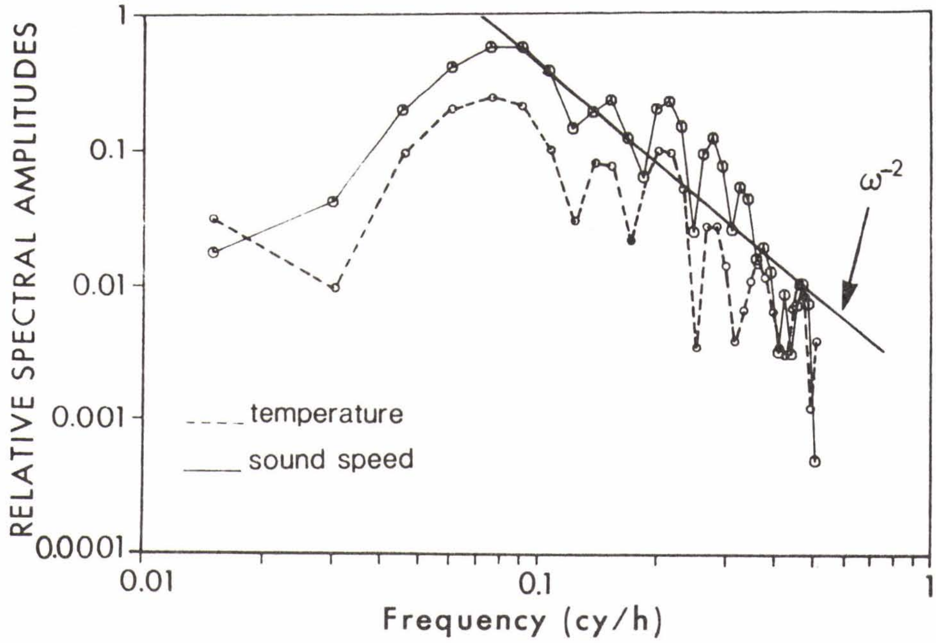

Fig. 5 Spectra of sound speed and temperature at 25 m.

The dominant fluctuations occur in the frequency range from 0.08 to 0.06 cycle/h, or for periods from 12 to 17 hours. This is a broad response and includes both the semi-diurnal period and inertial period (approximately 17 hours here). The time series was too short to allow for the spectral separation of the two responses. From the results obtained at other depths it does appear, however, that the relative significance of the semi-diurnal tidal and inertial effects depends on depth. In particular, from the analysis of the depth-dependent frequency spectra it appears that there are fluctuations of inertial period in the surface layers, and that as the depth increases the dominant fluctuations are semi-diurnal.

Inertial oscillations may occur in connection with a sudden change of the wind (i.e. a wind impulse of short duration) and changes in barometric pressure [7]. The whole of the Mediterranean is dominated by meteorological forcing; therefore it is likely that inertial oscillations are present in the study area. That they dominate the surface waters is probably related to their meteorological origin. The local water stratification retains most of this energy in the surface layers, so that at depth the semi-diurnal components are discernible.

In the spectra of Fig. 5 there also appear to be higher-frequency phenomena, with periodicities of about 2,4,5, and 7 h. These may be associated with internal wave activity. Note that the drop-off rate (sloping line) of the sound speed spectrum is approximately ω^{-2}, a slope consistent with that predicted by the Garrett-Munk model of internal waves.

1.3 Fluctuations in Acoustic Transmission Loss

Figure 6 shows the contours of measured transmission loss (1/3 octave bands) in the frequency/time plane for source and receiver depths of 50 m and 40 m, respectively. The higher frequencies (>1.6 kHz) exhibit far more pronounced fluctuations than the lower frequencies. This may indicate that the responsible environmental phenomena have physical dimensions that are comparable to the acoustic wavelengths of the higher frequencies. In order to demonstrate this selective frequency effect more clearly, the spectra of transmission loss at 200 Hz and 1600 Hz were compared (Fig. 7).

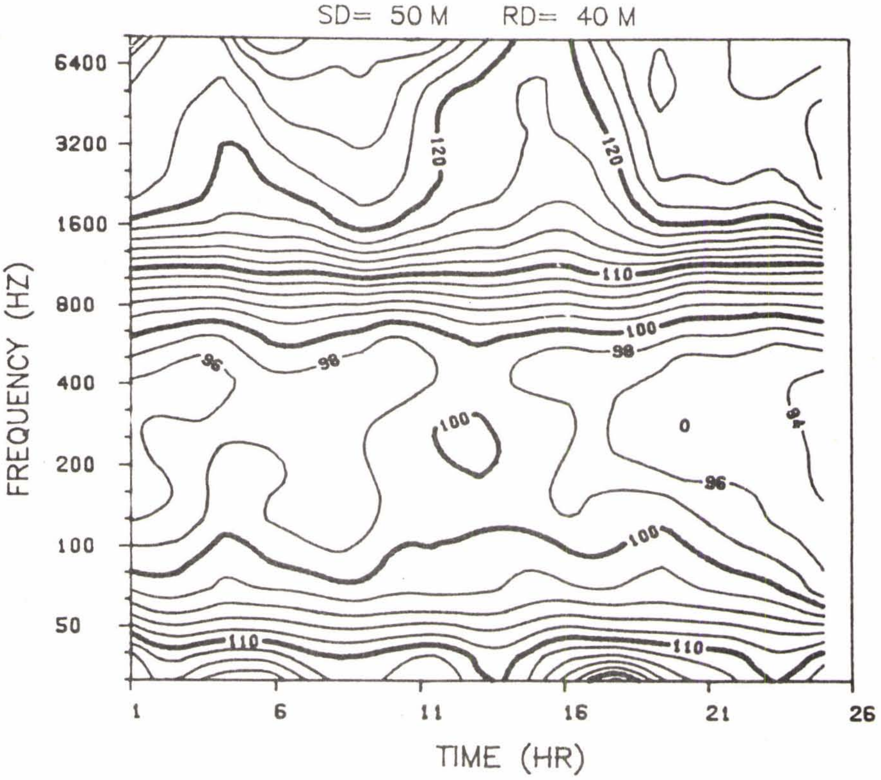

Fig. 6 Contours of measured transmission loss fluctuations at a fixed range (35 km).

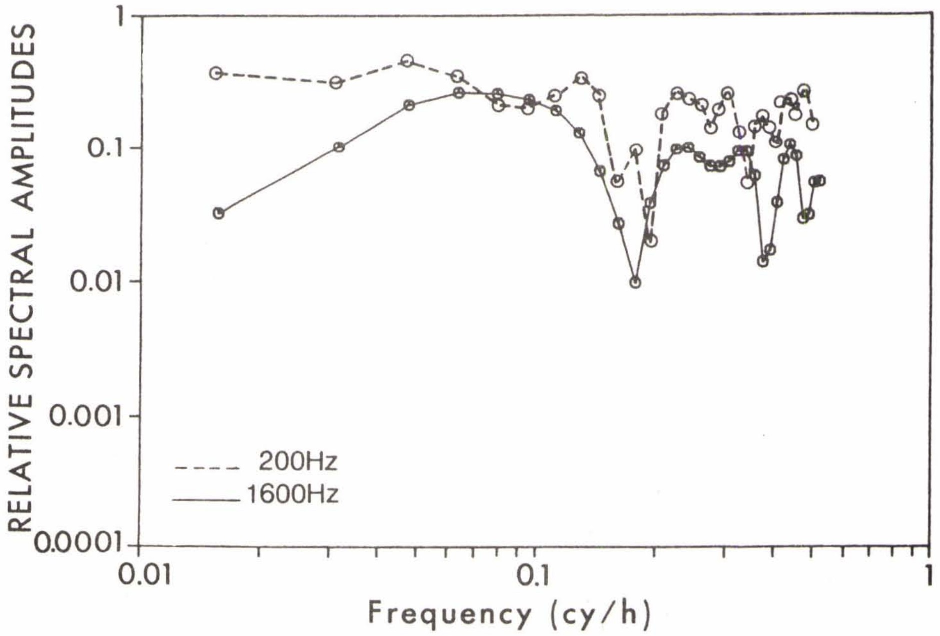

Fig. 7 Spectra of transmission loss for two selected frequencies.

The spectra, obtained for the same source/receiver as those in Fig. 6, emphasize the difference in the effect of variability. These results suggest that the optimum frequency range is less susceptible to environmental variability than other frequency ranges. A comparison of these spectra with those shown in Fig. 5 reveals a good correlation between the spectra of environmental variability and the higher frequency transmission loss spectrum.

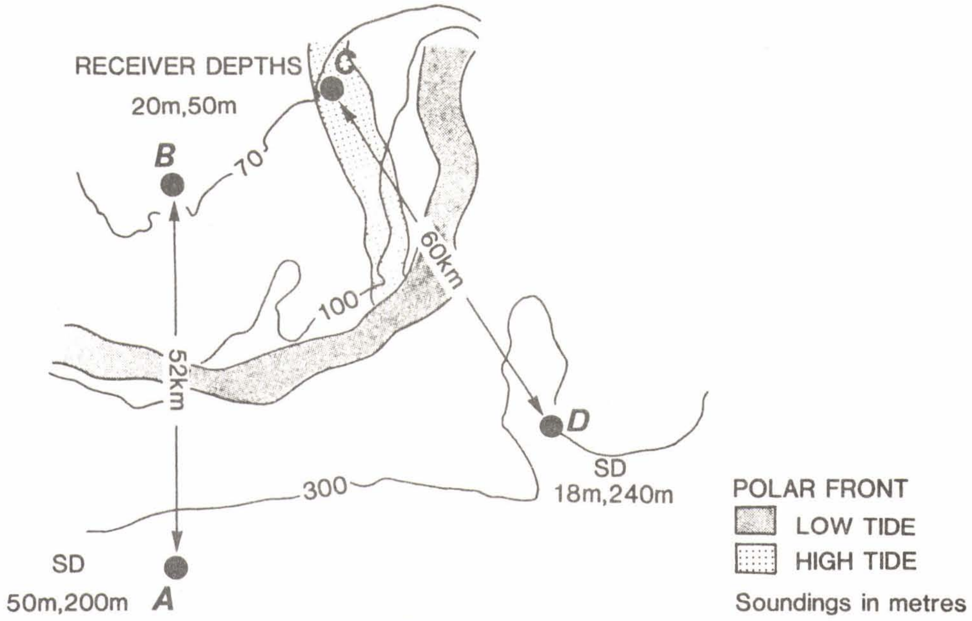

Fig. 8 Geometry of the North Atlantic measurements.

2 MEASUREMENTS SHOWING BOTTOM EFFECTS

2.1 Propagation Characteristics of the Test Environment

The North Atlantic test site is a very complex geological, oceanographic, and biological province and has been the object of many investigations [8]. The test site is located in an area affected by a large-scale permanent front resulting from the convergence of two water masses. In particular, at this location, cold, less saline Arctic water meets warmer Atlantic water to form the Polar oceanic front. The substantial differences in salinity and temperature of the two water-types (35‰ and 6° to 7°C for the Atlantic vs 34.6‰ and about 0°C for the Arctic) cause the Polar front to be characterized by steep gradients in these parameters, with significant implications for sound propagation. An added complication arises from the changing position of the front, which oscillates with semi-diurnal tidal periodicity.

The geometry and relevant details of the measurements are provided in Fig. 8. The two tracks, A-B and D-C, represent the propagation paths for measurements conducted one year apart. The environmental conditions along the two paths were somewhat different. Although both tracks A-B and D-C cross the Polar front, in water changing from deep to shallow, track A-B is over a generally hard bottom (sand) while track D-C is over a generally soft bottom (sand, silt, clay). From the point of view of temporal variability, however, a more fundamental difference between the two receiver locations arises from their relative proximity to the Polar front. In particular, station C is directly affected by movements of the front, the water above 20 m changing from Polar to Atlantic with an approximately 12-h periodicity, while the waters below 20 m remain of the Polar type. In comparison, station B remains in virtually isothermal Polar water, north of the front, as shown schematically in Fig. 8.

In effect, the Polar front serves as a demarcation line between two different propagation areas. To the north of the front, in isothermal water, an important part of the propagation will be in shallow water under upward-refracting conditions, resulting in small total transmission losses as a result of less bottom-interaction. On the other hand, in waters affected by the front, propagation will be under strong downward refracting conditions, as a result of the steep gradients, and thereby subject to higher losses, particularly at low frequencies. As noted, measurement site B was always in isothermal waters, whereas C was periodically subject to the effects of the front. From this one would expect the transmission losses measured at site B to be both lower in magnitude and subject to less temporal fluctuation than those at site C. Though generally valid, this conclusion is nevertheless based on an over-simplification of the propagation conditions. In particular, the propagation depends not only on the front, but also on frequency, source and receiver depths, bottom conditions (which are different for the two tracks), and, possibly, other features such as currents and inertial oscillations.

2.2 Selected Examples of Temporal Variability

In the following, typical results of measurements made over a 48-h period will be presented, emphasizing the data obtained at position C. The experimental procedure was essentially the same as that for the Mediterranean measurements, described previously.

Figure 9 provides a typical example of the fluctuations in measured transmission loss at site C for several frequencies, along with the predicted tidal curve for the area. It is clear that the fluctuations in transmission loss correlate well with tidal periodicity, particularly for the lower frequencies. This is consistent with the assumption that the lower frequencies are more affected by the tidally-induced change in downward-refracting conditions. Both diurnal and semi-diurnal periodicities are evident, the former seemingly the more significant. Further,

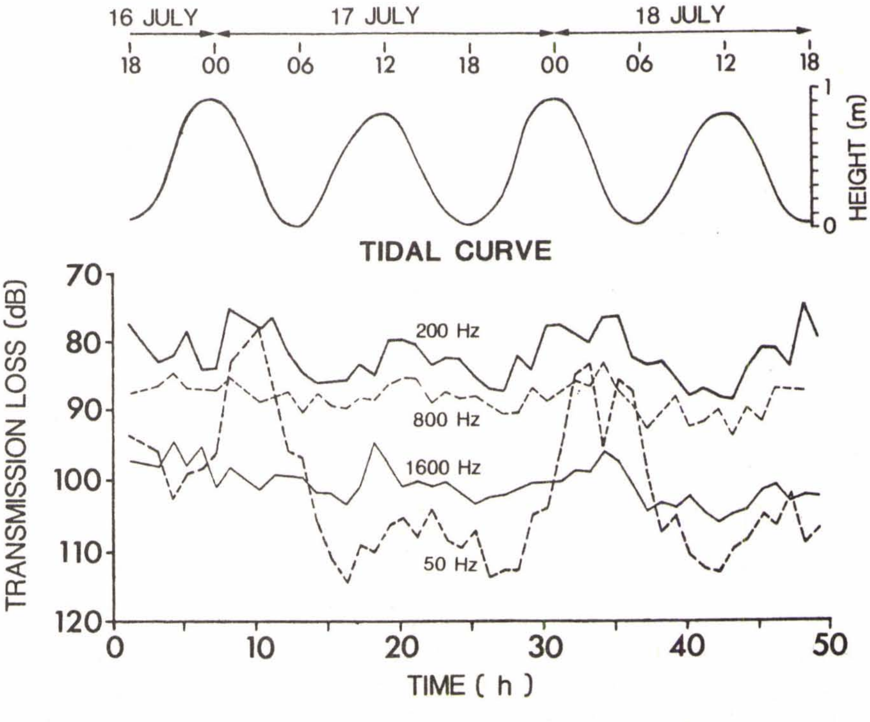

Fig., 9 Temporal variation of transmission losses and predicted tidal curve at site C.

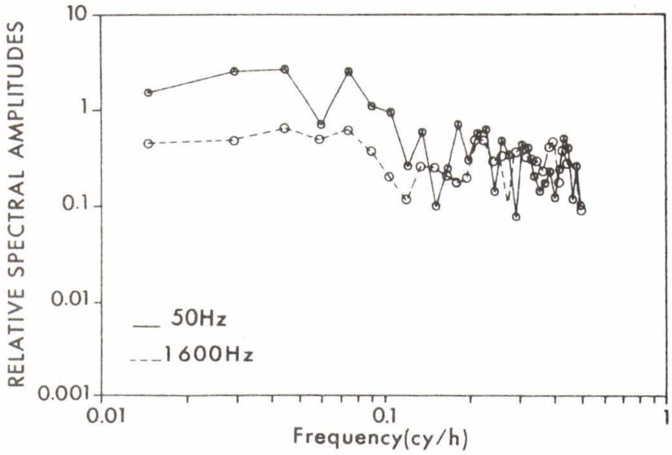

Fig. 10
Spectral composition of transmission loss at site C for two selected frequencies (SD 240 m / RD 50 m).

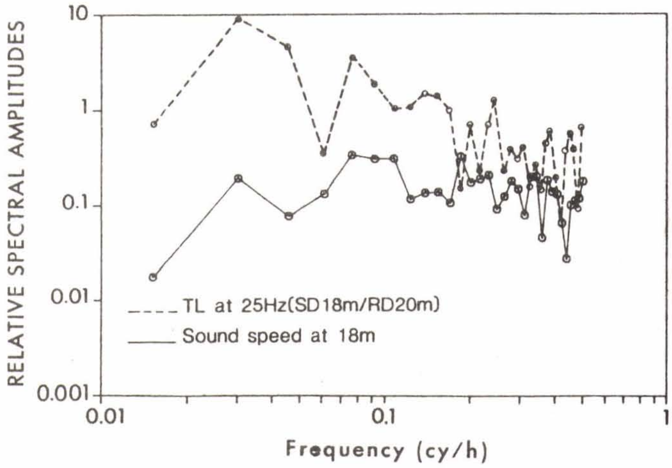

Fig. 11
Comparison of spectra of transmission loss at 25 Hz and sound speed.

there is a correspondence, albeit inexact, between high tide and high transmission loss, consistent with the fact that the front reaches site C during periods of high tide. Although the curves shown are for a particular source/receiver combination (240 m / 50 m) the observed trends are fairly representative of all the data obtained at this site. The spectral composition of the 50 Hz and 1600 Hz signals is shown in Fig. 10, again demonstrating the more marked fluctuations at the lower frequency, as well as the conspicuous presence of diurnal and semi-diurnal periodicities.

Figure 11 provides a comparison between the 25 Hz transmission loss spectrum at a depth of 20 m (source depth = 18 m) and the sound speed spectrum at a depth of 18 m. As seen the correlation between the two spectra is quite good.

It is instructive to compare the variability for the two positions B and C. An example of the fluctuations in temperature is shown in Fig. 12. Several features are immediately evident from the figure. First, it is clear that the amplitudes at C are greater than those at B and, in addition, show a definite dependence on depth. Further, although both data sets reveal tidal effects, they are more conspicuous at position C, particularly at 18 m depth. This behaviour no doubt reflects the position of the stations with respect to the Polar front, station C being directly affected by the movements of the front, while station B is constantly in isothermal waters, as discussed earlier. The significant differences in results between the two locations suggest that tidally advected changes in water masses, as at C, are more important than the indirect tidal effects (changes in water depth, currents, etc.) that are evident at B. The greater energy measured at 18 m (for site C) seems to confirm this conclusion since the transition zone between the Atlantic and Polar waters occurs at this depth.

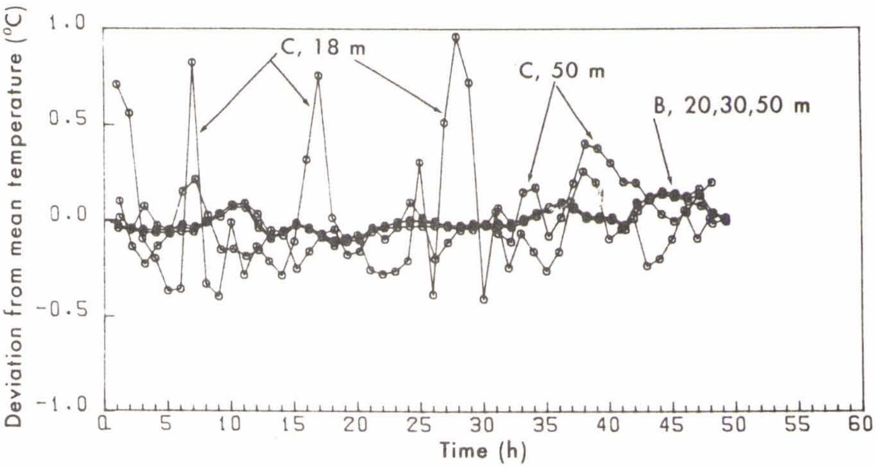

Fig. 12 Normalized temperature fluctuations at the two sites.

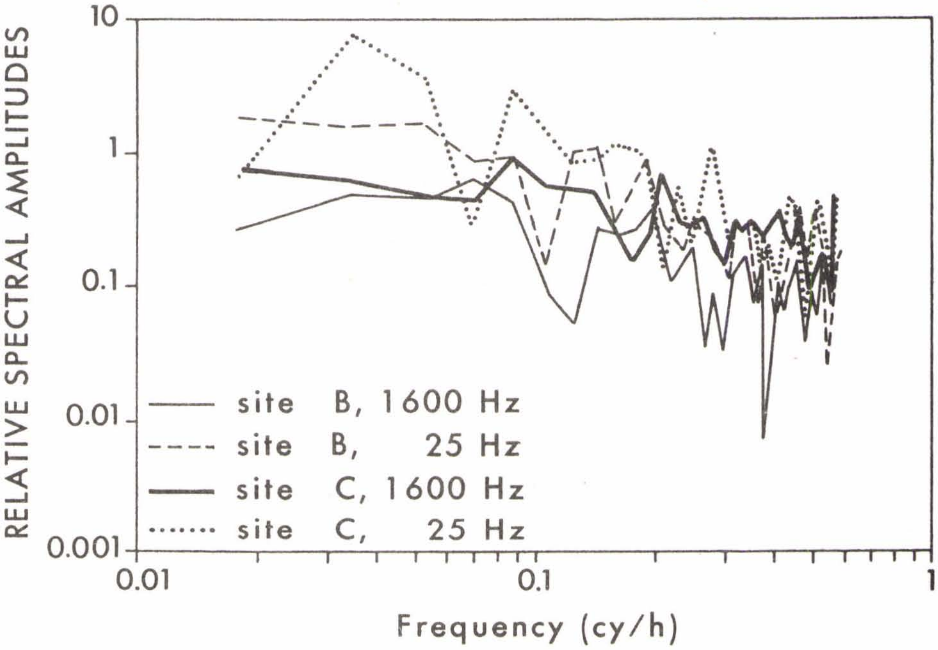

Fig. 13 Transmission loss spectra at receiver sites B and C (North Atlantic).

Finally, the comparison of the transmission loss spectra at the two sites is shown in Fig. 13. Note the fluctuations in low frequency transmission loss are greater at site C than at B; but there is little difference between the sites vis-à-vis the higher frequency transmission loss. This is consistent with the stronger downward refracting conditions at site C.

CONCLUSIONS

The measurements conducted in the Mediterranean and the North Atlantic indicate that fluctuations in acoustic transmission loss correlate well with the diurnal, semi-diurnal, and inertial periodic variability of the environmental parameters. However, the nature and extent of the causal phenomena differ for the two areas. At the Mediterranean test site volume effects appear to be the principal cause of the fluctuations, while at the N. Atlantic test sites bottom effects predominate. Both types of effects are described below:

Volume Effects

- Inertial effects dominate in the surface layers, whereas the semi-diurnal effects are of greater importance at greater depths. This suggests a meteorological forcing function.

- The fluctuations in the magnitude of acoustic transmission loss are greatest for the higher frequencies (1.6 kHz and above) and least for an optimum frequency range from approximately 100 to 400 Hz.

Bottom Effects

- At the N. Atlantic site the inertial period coincides with the semi-diurnal period and cannot be resolved by spectral analysis.

- The transmission loss oscillations correlate with tidal movements of the Polar front and are more marked at the lower frequencies. The effects on acoustic propagation are associated more closely with the tidally-advected changes in water masses than with the more subtle, indirect tidal effects.

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