DIRECT PATH FLUCTUATIONS OBSERVED IN THE MEDITERRANEAN SEA

A. H. Al-Khalidi, B. V. Smith, R. F. W. Coates & R. H. Owen

School of Electronic & Electrical Engineering, University of Birmingham, Birmingham, UK.

ABSTRACT

This paper presents the amplitude and time of arrival fluctuations of the direct path observed during an experiment in the Mediterrenean Sea at a shallow coastal site off France. The experiment utilised 5 cycles of 50 kHz carrier pulses to probe the ocean medium. The channel response was monitored on an array of hydrophones 1744 metres away from a rigidly fixed transmitter. The spectra of the time series of the amplitude and transit time fluctuations are analysed in terms of the physical mechanisms that may be producing them such as medium microstructure and internal waves. The experimental setup and environmental conditions related to this paper are described in a companion paper by Owen, Smith and Coates [1].

1. INTRODUCTION

Sound waves can travel within the ocean for great distances. During its journey, sound is absorbed by the water, reflected by the ocean surface and bottom, refracted by layers of water with diffferent refractive indices and scattered by medium inhomogeneities such as bubbles, temperature microstructure, internal waves and turbulence. Consequently, the sound waves received at a point within the ocean medium fluctuate in amplitude and phase. In underwater communication systems, all these propagation effects can reduce the potential communication rate. However, there is a positive side to acoustic fluctuations as they can reveal the structure and properties of the transmitting water medium. Hence, acoustic fluctuations are very important from an oceanographic point of view.

It is very important to distinguish between two causes of acoustic fluctuations: the physical boundaries of the medium and volume inhomogeneities in the medium. The former causes acoustic fluctuations due to multipath propagation effect while the latter causes single-path fluctuations. This paper is concerned with aspects of direct-path fluctuations, such as amplitude and transit time fluctutuations and their temporal characteristics as observed during an acoustic experiment in the Mediterranean Sea.

1.1 Causes of direct-path fluctuations

There are many physical mechanisms responsible for producing single-path fluctuations. Some of these mechanisms are: thermal and velocity microstructures, internal waves, bubbles, seasonal variations in temperature, fish and micro-organisms living in the ocean. An effective way of studying fluctuations is to divide them according to their time scales. There are fast fluctuations of the order of a second or part of a second and there are slow fluctuations of the order of months. Between these two extremes there is a whole spectrum of time scales. Weston's paper [2] discusses a wide variety of causes of single-path fluctuations in great detail and clarity. This paper is concerned with fluctuations with time scales up to a few tens of minutes and with an acoustic frequency of 50 kHz.

DIRECT PATH FLUCTUATIONS OBSERVED IN THE MEDITERRANEAN SEA

1.2 Theoretical overview
One approach to the study of wave propagation in a random inhomogeneous medium is to describe the medium inhomogeneity by a spatial correlation function. The theoretical results of researchers, such as Chernov [3] and Mintzer [4, 5], use this approach. The other method is to use structure and spectral functions as used for example by Tatarski [6]. The theories referred to above are essentially single-scatter theories. As far as scattering by internal waves is concerned, there is a large collection of literature on the subject. The book by Phillips [7] is a good introduction to internal waves. Some references on the statistics and models of the oceanic internal waves are the papers by Ewart [8] and Watson [9].

1.3 Experimental overview
Measurements of the ocean temperature microstructure have been made by Liebermann [10]. He considered the medium inhomogeneities to have a Gaussian correlation function and observed a correlation length of the order of 0.6 m. He also measured a value for the mean-square refractive index fluctuations of the order of 10^{-9}. Sagar [11] conducted a series of sea trials to measure amplitude fluctuations in the direct path caused by thermal microstructure in surface layers of the sea at short ranges. However, in some of his work, swell in the sea and inconsistent transducer geometry contributed to the observed fluctuations. Chotiros and Smith [12] utilised the single-scatter theoretical results of Tatarski and a model proposed by Medwin [13] in their study of amplitude fluctuations in a thermal microstructure. Shvachko [14] studied amplitude fluctuations of pulsed sound in the upper layer of the Atlantic Ocean and presented experimental results of their statistical characteristics. Dunn [15] studied the effect of turbulence in causing single-path fluctuations. His experimental results agree well with the theoretical results of Tatarski.

2. EXPERIMENTAL SET-UP

The site of the experiment is in the coastal area of Cap Ferrat, South of France. The transmitter used in the experiment is a 50 kHz rectangular transducer array with 55 Tonpilz elements. The elements are mounted in three rows of 18. The diameter of the elements is 25.4 mm. The distance between two elements is 30 mm both in horizontal and vertical. The array was mounted vertically in the experiment such that the 3 degree beam width was in the vertical plane and the 17 degree beam width in the horizontal plane. The band width of the array is greater than 10 kHz. This allows a short pulse of 5 cycles duration at 50 kHz (pulse length of 100 μs) to be transmitted. Short pulses were generated by a HP 8116A function generator and fed into a power amplifier with 18 APEX PA09 power amplifiers (each power amplifier drives a group of three transducer element).

The transmit array was positioned at a depth of 35 m below the surface. The receive array is a vertical line array firmly anchored to the sea bottom. The distance between the transmit array and receive array is 1744 m. The elements in the receive array are omnidirectional and identical. The depth of the first three elements S1, S2 and S3, are; 100 m, 150 m and 175 m respectively. There is a very steep slope at the transmitter. The maximum depth at the receiver is about 700 m. Further discussion and calculations on the experimental geometry can be found in Owen, Smith and Coates [1].

3. EXPERIMENTAL RESULTS

3.1 Data processing and data qualification
The signals received at the output of each hydrophone were band-pass filtered using a filter with a centre frequency of 50 kHz and bandwidth of 10 kHz. The output from each hydrophone was then fed to a digital storage scope where it was over-sampled by at least five times for the long 20-minute data records or ten times

for the shorter data records. Subsequently, the signals were envelope detected using a digital low-pass filter with a bandwidth of 10 kHz.

Each data record analysed contained a number, N, of direct path arrivals ideally separated by a time equal to the pulse repetition rate. However, due to the fluctuating nature of the transmitting medium, the separation times between direct paths will fluctuate around the pulse repetition period. The value of the pulse repetition rate was chosen such that the direct path is well separated from multipath arrivals. The data records analysed in this paper correspond to pulse repetition periods of 50 ms, 200 ms, and 999 ms. Transit time fluctuations or pulse repetition period fluctuations were calculated from each data record by cross correlating the envelope of the m-th received direct path with the envelope of the first received direct path of the same record for m = 1, 2, 3, ..., N. Amplitude fluctuations were obtained by measuring the peak of the envelope of each received direct path in any one data record.

It is important that any data analysed is stationary. This implies that the physical factors producing the fluctuation phenomenon should be time invariant within the total time duration of the data. The transit time and amplitude fluctuation time series obtained from the data records were tested for stationarity and trend using the Run Test [16]. Any underlying trends were removed.

3.2 Transit time and amplitude fluctuations

Fig. 1a below shows a representative waterfall graph of the channel response as received at element S1. Only the direct paths are shown. Representing the channel response by $h(t, \tau)$ as in Owen, Smith and Coates [1], Fig. 1a shows transit time fluctuations happening along the t axis and some small amplitude fluctuations in the peak of the envelope of the direct path signal occuring along the same axis.

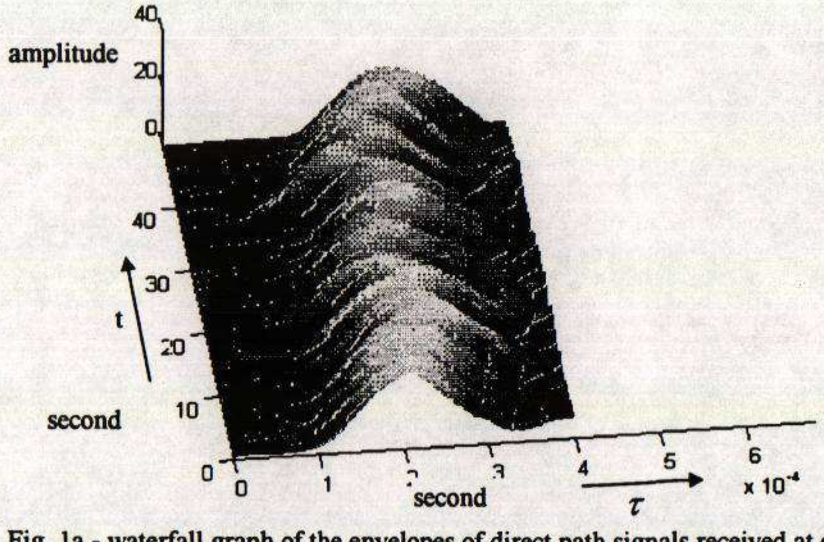

Fig. 1a - waterfall graph of the envelopes of direct path signals received at element S1

The time series and the spectrum of the transit time fluctuations evident in Fig. 1a are shown in Fig. 1b below. Sampling errors were minimized by oversampling. The transit time fluctutions shown in Fig.1b correspond to a mean-square refractive index fluctuation, $\overline{\mu^2}$, of 5×10^{-11}. Liebermann [10] measured a value of 5×10^{-9} for $\overline{\mu^2}$ during an experimental study of temperature inhomogeneities in upper ocean layers.

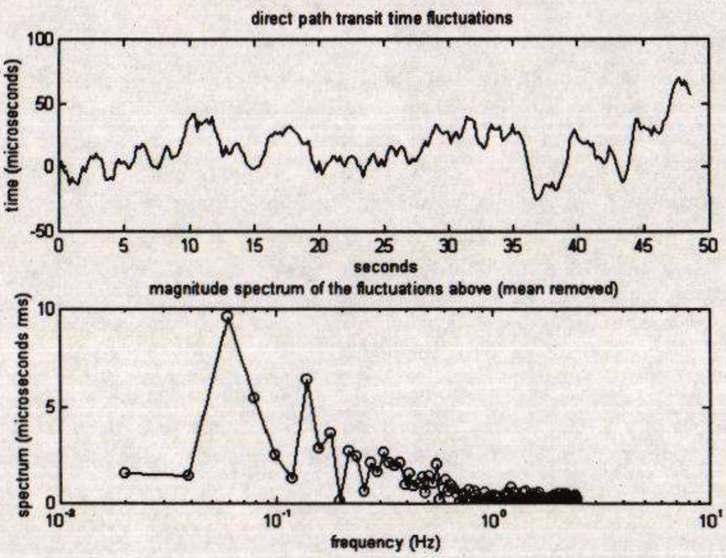

Fig. 1b - time series and spectrum of transit time fluctuations at element S1

The spectrum of the fluctuation extends from 0.06 Hz to 0.6 Hz. This time scale of fluctuations suggests that some kind of microstructure generated by the surface action is responsible for producing such fluctuations. Furthermore, the amplitude fluctuations shown in Fig. 1c have a spectrum similar in shape to the transit time fluctuations which indicates that both phenomena; amplitude and transit time fluctuations, are likely to be caused by the same physical meachanism.

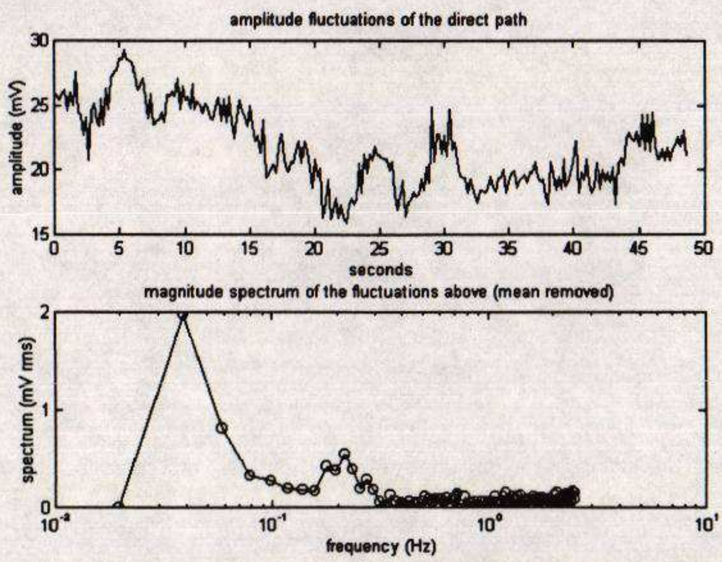

Fig. 1c - time series and spectrum of direct path amplitude fluctuations at element S1

The value of the coefficient of amplitude variation of the peak of the direct path, defined as the standard deviation divided by the mean, was calculated using the theories of Chernov and Tatarski together with the measured value of $\overline{\mu^2}$. A value of 10% was obtained. This compares well with the measured value of 9.8% obtained from the data shown in Fig. 1c.

Further evidence of the influence of the surface in generating the microstructure is arrived at by considering the ouput of a deeper receiving element such as S3. A waterfall graph showing the direct paths only as received at element S3 is shown in Fig. 2a which was captured when the pulse repetition period was 6 ms. Examination of

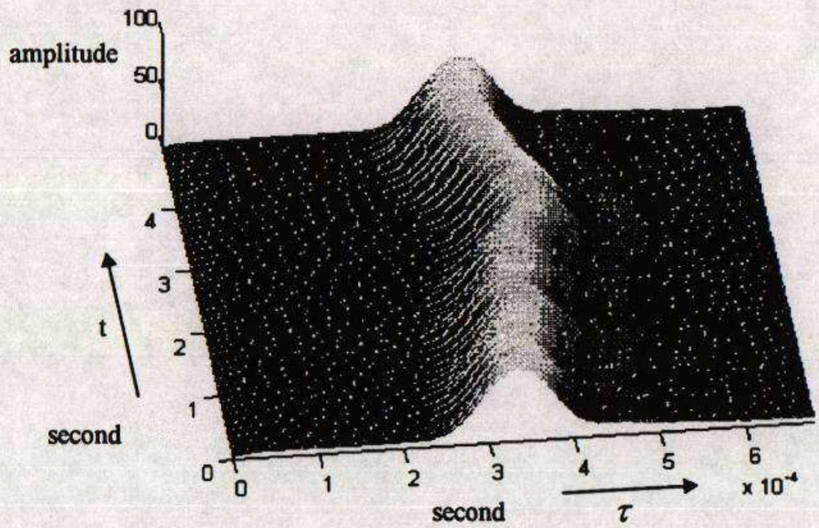

Fig. 2a - waterfall graph of the envelopes of direct path signals received at element S3

the transit time and amplitude fluctuations in Fig. 2b and Fig. 2c shows a slight increase in the spectral energy of fluctuations as compared to the spectral energy of similar frequency bands in Fig. 1b & Fig. 1c. This increase in energy is explained by considering the depth and the general behaviour of the ray paths in the medium. Energy from the transmitter reaches the receiving hydrophones via rays becoming refracted upwards towards the surface before being refracted downwards to reach the receiver. Therefore, the rays travel closer to the surface as the receiver depth is increased and the energy of fluctuations is greater near the surface. The assumption made here is that the generation of microstructure is greatly influenced by the surface. The measured value of $\overline{\mu^2}$ corresponding to Fig. 2b is 6×10^{-11} which is comparable to the value corresponding to Fig. 1b.

Finally, strong fluctuations with different temporal characteristics from the ones already mentioned are shown in Fig. 3a. Fig. 3a shows a long waterfall graph of 800 direct path signals received on element S2. Large amplitude fluctuations of a time scale of a few minutes are evident in Fig. 3b which shows the time series and spectrum of the peak level of the direct path. Fluctuations of this time scale are thought to be associated with internal waves. Internal waves produce vertical motion in the water volume. Now since the transmitter utilised in this experiment has a narrow beamwidth, the fluctuation of the amplitude of the direct path is caused by off-axis insonification.

DIRECT PATH FLUCTUATIONS OBSERVED IN THE MEDITERRANEAN SEA

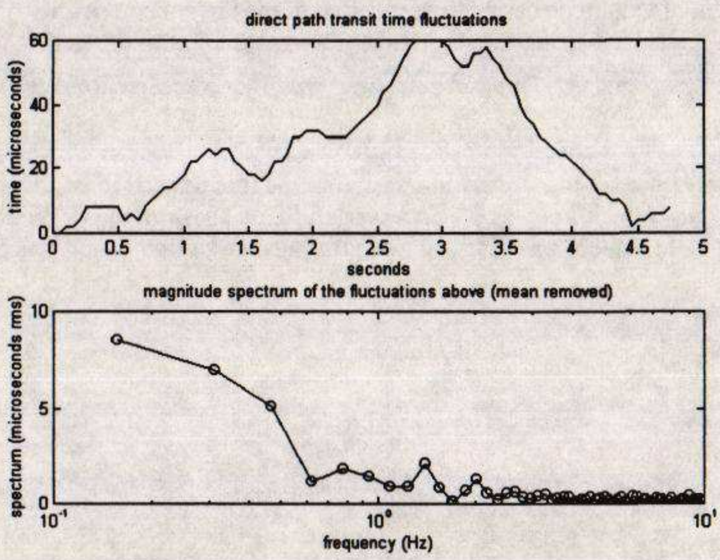

Fig. 2b - time series and spectrum of transit time fluctuations at element S3

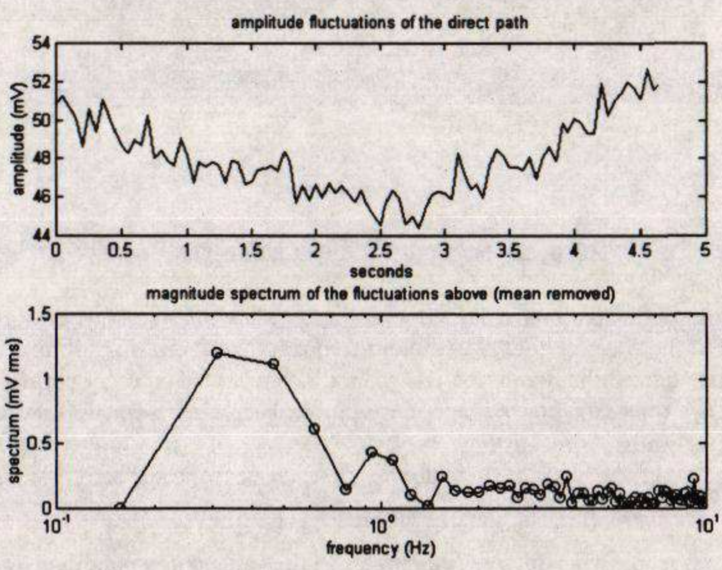

Fig. 2c - time series and spectrum of direct path amplitude fluctuations at element S3

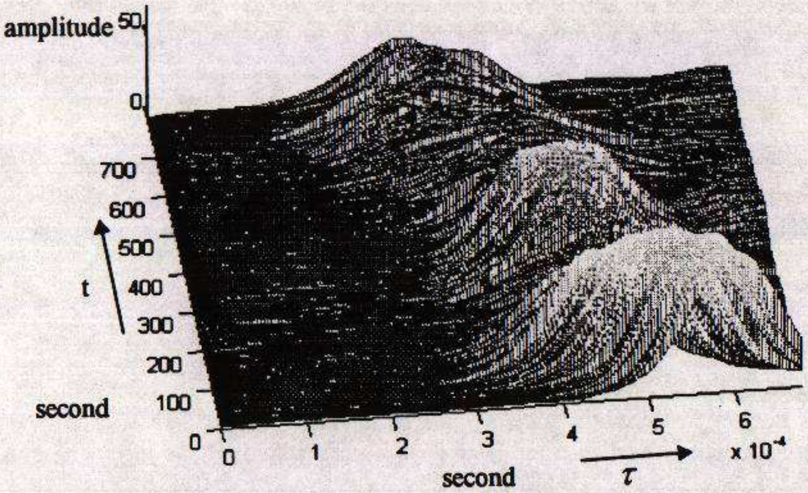

Fig. 3a - waterfall graph of the envelopes of direct path signals received at element S2

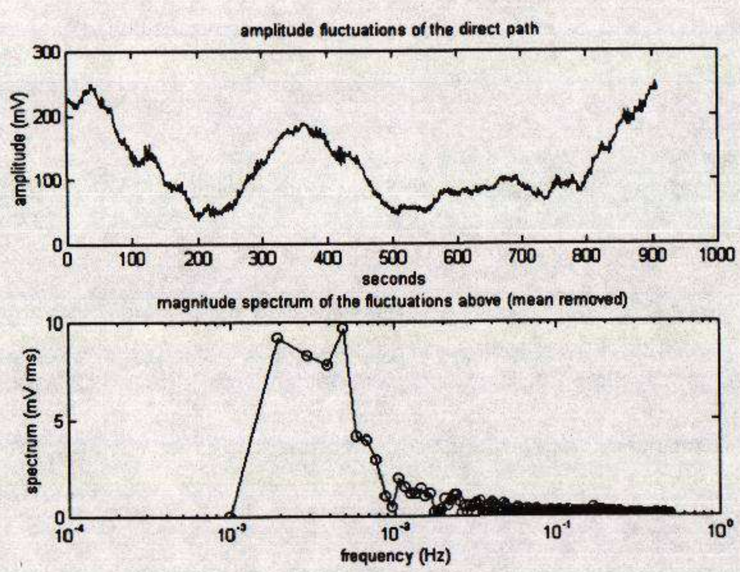

Fig. 3b - time series and spectrum of direct path amplitude fluctuations at element S2

CONCLUSIONS

The following conclusions can be drawn from the experimental results above.

- There are amplitude and transit time fluctuations in the direct path signal. Two time scales of fluctuations can be identified: fast fluctuations ranging from 0.1 Hz to 1 Hz and slower fluctuations of few mHz.

DIRECT PATH FLUCTUATIONS OBSERVED IN THE MEDITERRANEAN SEA

- The mean square refractive index fluctuations associated with the fast fluctuations is of the order of 10^{-11} and the amplitude fluctuations are small as indicated by the low coefficients of amplitude variations measured.

- It is very likely that the fast fluctuations are caused by the presence of a microstructure mainly generated by the surface layer.
- The slow fluctuations are believed to be due to internal waves causing off-axis insonification. The amplitude fluctuations associated with these fluctuations are relatively large with a coefficient of variation of 45%. They can affect underwater communication systems by simply reducing the signal-to-noise ratio.

ACKNOWLEDGEMENTS

This work has been supported by the University of Birmingham and under MAST contract MAS2-CT91-005 - Project "PARACOM". The help and advice of Dr. Lian Wang and Richard Stoner, Ross Galvin and Ming Zheng at the University of Birmingham and Daniel Cano of Thompson Sintra Activites sous Marine,Sophia Antipolis, France, are greatfully acknowledged..

REFERENCES

[1] R. Owen, B. V. Smith, R. F. W. Coates, "Pulsed reverberation observed in the Mediterranean Sea", Proc. Inst. Acoustics, *to be published.*

[2] D. E. Weston et. al., "Studies of sound transmission fluctuations in shallow coastal waters", Phil. Trans. Roy. Soc. A, Vol. 265, pp567-606, (1969).

[3] L. A. Chernov, "Wave Propagation in a Random Medium", McGraw Hill, New York, (1961).

[4] D. Mintzer, "Wave propagation in a randomly inhomogeneous medium I", J. Acoust. Soc. Am., **25**, pp922-927, (1953).

[5] D. Mintzer, "Wave propagation in a randomly inhomogeneous medium II", J. Acoust. Soc. Am., **25**, pp1107-1111, (1953).

[6] V. I Tatarski, "Wave Propagation in a Turbulent Medium", Dover Publications, New York, (1961).

[7] O. M. Phillips, "The Dynamics of the Upper Ocean", Cambridge University Press, London,, (1966).

[8] T. E. Ewart, "Acoustic propagation, internal waves, and finestructure", Proc. Inst. Acoustics, 8, 5, pp106-130, (1986).

[9] J. G. Watson et. al., "Acoustically relevant statistics for stochastic internal-wave models", J. Acoust. Soc. Am., **61**, pp716-726, (1977).

[10] L. J. Liebermann, "The effect of temperature inhomogeneities in the ocean on the propagation of sound", J. Acoust. Soc. Am., **23**, pp563-570, (1951).

[11] F. H. Sagar, "Comparison of experimental underwater acoustic intensities of frequency 14.5kc with values computed for selected thermal conditions in the sea", J. Acoust. Soc. Am., **29**, pp948-965, (1957).

[12] N. P. Chotiros and B. V.Smith, "Sound amplitude fluctuations due to a temperature microstructure", J. Sound Vib., **64**, pp349-369, (1979).

[13] H. Medwin, "Sound phase and amplitude fluctuations due to temperature microstucture in the upper ocean", J. Acoust. Soc. Am., **56**, pp1105-1110, (1974).

[14] R. F. Shvachko, "Sound fluctuations and random inhomogeneities in the ocean", Sov. Physics-Acoustics, **13**, pp93-97, (1967).

[15] D. J. Dunn, "Turbulence and its effect upon the transmission of sound in water", J. Sound. Vib., **2**, pp307-327, (1965).

[16] J. S. Bendat & A. G. Piersol, "Random data analysis and measurement procedures", John Wiley & Sons, New York, (1986).