UNDERWATER ACOUSTIC COMMUNICATIONS: A REVIEW AND BIBLIOGRAPHY (II)

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INTRODUCTION

In 1987, the UK Institute of Acoustics held a Conference on "Underwater Communication and Position Fixing" at The University of East Anglia. In order to "set the scene" for the papers being presented on Underwater Acoustic Communications, Coates and Willison [1] assembled a Review and Bibliography on the subject, which was published in the Conference Proceedings. The following paper reviews the considerable developments which have taken place in the six years that have followed since that first publication.

REVIEW PAPERS

Clearly, a bibliographic database is of value to those interested in developing any engineering system or equipment. Equally important is a terminology which, by common consent within a technical community, avoids confusion and assists clarity of thinking. Unfortunately, such a terminology is not to be found amongst the practitioners in the field of underwater acoustic communications.

We thus find terms such as "high" and "low" frequency, "long" and "short" range, "high" - but never "low" - bit rate, being used very frequently but without association with any commonly accepted framework of reference. In a recent paper, Coates [2] proposed a basis, yet to find formal acceptance by, perhaps, an appropriate professional body, which might assist in providing a common and useful reference framework. The following - unofficial - classification table for acoustic frequencies is abstracted from this paper, to assist in clarifying issues in the following paragraphs.

Class	**Frequency Band**	**Span of Wavelength**
ULF	15 Hz - 150 Hz	100 m - 10 m
VLF	150 Hz - 1.5 kHz	10 m - 1 m
LF	1.5 kHz - 15 kHz	1 m - 10 cm
MF	15 kHz - 150 kHz	10 cm - 1 cm
HF	150 kHz - 1.5 MHz	1 cm - 1 mm
VHF	1.5 MHz - 15 MHz	1 mm - 100 μm
UHF	15 MHz - 150 MHz	100 μm - 10 μm
SHF	150 MHz - 1.5 GHZ	10 μm - 1 μm

Examples of practical acoustic systems falling into each of these frequency bands can be found, from seismics in the acoustic ULF band to acoustical microscopy in the acoustic SHF band. Most underwater communications applications would fall within the acoustic LF, MF and HF bands.

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Insofar as information throughput is concerned we note that bandwidth, per se, does not limit bit rate. Using multiphase signalling one may signal, in a noise-free channel, at as high a rate as one may wish. Factors which limit bit rate include "slow" fluctuations such as are induced by multipath, Doppler, internal waves, thermal or velocity microstructure [3]. By "slow" we mean fluctuations occuring on a time-scale which is extremely long by comparison with the reciprocal of the signalling bandwidth. We seek technical solutions - beamforming, equalisation, diversity and so on - to alleviate such problems. If such solutions are successful, then it is in-band noise, a "fast" fluctuation, with a bandwidth equal to the signalling bandwidth, which becomes the phenomenon which places the ultimate limitation to bit rate.

MEASURED CHANNEL CHARACTERISTICS

Until recently and over several decades, interest in propagation measurements has, because of a perceived deep-water threat, concentrated upon long-range, low frequency investigations, examples of which are to be found in references [4] and [5]. During the last few years, however, probably partly as a result of shipping losses in the Persian Gulf during "Desert Storm" and partly because of the breakup of the former Soviet Union, increasing interest in shallow-water acoustics has been evident. Although still relatively scant, some of this work [6]-[17] is of particular relevance to the communication engineer and provides, for the first time, field data relevant to propagation phenomena in the MF band.

MULTIPATH IDENTIFICATION

The identification of delay and attenuation when time-varying multipath propagation is present, may be achieved *explicitly* by using time-domain (short pulse) channel sounding, or by using "delay-domain" signal analysis such as correlation function or cepstrum evaluation. Alternatively, such identification may result *implicitly* as a consequence of the application of equalisation or ARMA-type model fitting activities. In any event, a knowledge of multipath structure may be of value in establishing beamforming, equaliser, or diversity requirements for a communication link. Furthermore, it may prove of great value in assisting the development of truly adaptive communication links, able to operate under a wide range of environmental conditions. Three papers [18]-[20] provide some insight into methods of multipath identification.

CHANNEL MODELS

A profound and comprehensive paper on channel modelling is provided by Middleton [21]. Several papers [22]-[29] treat the problem in somewhat more heuristic terms. It is of interest that the vast mainstream of propagation modelling has to do with the creation of purely deterministic models whose objective is precision of prediction of down-range intensity, Such models are the result of decades of deep-water Naval modelling requirements. Insofar as shallow, high-frequency civilian applications are concerned, stochastic modelling offering information on the temporal and spectral variability of signals would be of great value but is almost non-existent. Desaubies [30] has presented a relatively recent paper on the statistics of propagation. Further papers [39]-[38] concerning propagation characteristics in the waveguiding channel are included.

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REFLECTION FROM ROUGH SURFACES

Several older papers concerning boundary effects are included here, since they may be of value in the future development of stochastic models involving rough boundaries [39]-[44].

TRANSDUCTION, ARRAYS AND BEAMFORMING

Whilst it is frequently stated that "the first thing to get right are the sensors", transducer design remains, for most underwater communication engineers, a "black art" with, from the point of view of the non-specialist, a scant literature and a paucity of readily available design tools. The design requirements for transducers for underwater communication is treated in [45]. It must be admitted, however, that if high-quality, broadband designs are to be tackled, then the use of Finite Element & Boundary Element models is mandatory [46]. The problem of array design and - in particular - array element interaction, is even more difficult and, in the authors' experience has no ready solution in terms of design software generally available in the civilian sector.

Before discussing beamforming, it is, perhaps, worth clarifying the meaning of the terms "deep" and "shallow" water and "long" and "short" range. For the underwater communication engineer, it is more useful to think in terms of a range-depth ratio. The following table is extracted from [2]. We see that it gives an immediate guide to strategies appropriate to handling the problem of surface reverberation in channels of given range-depth ratio.

Channel	**Range-Depth Ratio**	**Strategy**
Deep	<1:1	Simple modem will suffice
Shallow	1:1 - 10:1	Beamsteer and/or Nullsteer
Very Shallow	10:1-100:1	High DI and Equalisation
Extremely Shallow	>100:1	High DI and Diversity

The purpose of array development and beamforming is twofold. Firstly, the formation of a narrow beam results in a high Directivity Index, which results in either economic use of energy resources or in improved range capability for given design signal-to-noise ratio. Secondly, in the presence of surface reverberation, beamsteering and/or null steering may prove a viable strategy for rejecting unwanted multipaths.This section concludes with a number of papers concerned with aspects of beamforming [47]-[55].

PARAMETRIC TRANSDUCTION

In the previous Bibliography and Review [1] work on parametric transduction for communication was discussed and it was suggested that, for several reasons, the method might be less appropriate than transmission at the primary frequency. Further studies [56] indicate that this may not be the case for propagation to tens of kilometres. A second paper, describing operation of a parametric communication system, has also been traced [57].

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ADAPTIVE EQUALISATION

As the channel range-depth ratio becomes larger we form a "very shallow" channel, as defined above. The angular resolution required specifically to discriminate in arrival angle between an incoming mainpath and the various interfering multipaths becomes too exacting insofar as array design is concerned. The summed main and delay paths establish a "transfer function" between transmitter and receiver and impose amplitude and delay distortion on the received signal. Equalisation [59]-[61] may then be used to combat this problem. Use of directional transmitter and receiver arrays may still be beneficial, in providing a measure of Directivity Index "gain".

SPREAD SPECTRUM

Spread spectrum has the potential to provide immunity to multipath, if the codelength exceeds the greatest significant multipath delay. Three papers in this Proceedings report on research into the development of acoustic VLF band spread spectrum communications [64] - [66]. A fourth paper by Kwon and Birdsall [67] discuss the use of M-sequence codes in transmitting data for ocean tomography.

SYNCHRONISATION

Carrier and bit synchronisation is a serious issue for all communication systems. Soliman [69] discusses the problem of obtaining synchronisation over fading, dispersive channels such as are encountered in underwater communication.

SIGNAL PROCESSING

In this section we include papers [70]-[79] which have to do with diversity, the general design of receiver structures and with Doppler nullification. We note that diversity may prove to be the only reasonable anti-multipath strategy for the "extremely shallow" channel, as defined above. We also note that *choice of implementation* can be a significant factor in the design of effective receiver structures.

ENGINEERING APPLICATIONS

This section commences with two review papers [80], [81] followed by a set of four papers [82]-[87] describing the performance of experimental communication links. Three papers [88]-[90] discuss the development of communication links for deep ocean penetrators. Because the penetrators come to rest many tens of metres below the ocean floor, the link must allow for the high additional attenuation imposed by the sea-floor sedimentary material itself. Papers then follow which describe applications of telemetry links in oceanographic applications [91]-[98], in oil-field engineering [99], in sub-sea control [100], [101], and in underwater vehicle applications [102]-[111].

BIOLOGICAL APPLICATIONS

It is remarkable that, as a single class of applications, more references relating to actual, functioning communication links were to be found in the field of biology, concerning tag telemetry for a wide range of marine and freshwater fish and mammals [112]-[123].

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