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DESIGN AND DEVELOPMENT OF A PROGRAMMABLE UNDERWATER DEVICE FOR ACOUSTIC DATA RECORDING AND RETRIEVAL

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1. INTRODUCTION

Oceans cover two-thirds of the surface area of our planet. Our understanding of this environment, even after several decades of research, is best described as rudimentary. The watery abyss is home to the World's largest and most diverse biological ecosystems. Monitoring these ecosystems and studying the physical and biological evolution of the oceans is of paramount importance to an increased comprehension and understanding of the oceans.

Most oceanic studies are conducted on the continental shelves in water depths <1000 metres. These studies can be conducted over long periods of time and in diverse sea conditions. Paramount to the success of these studies is the retrieval of the scientific data. This is currently achieved using any of three methods - data logging, direct cable connection or underwater communication. Of these three methods, the underwater telemetry systems offer the greatest flexibility because they are able to transfer data in quasi-real time to an end-user. However, the downside of the telemetry systems is their unreliability. Many system use low data rate, *'discrete-component'* designs and, although these systems perform well in static environments, their performance rapidly degenerates when the oceans become more dynamic.

To combat the dynamic effects within the ocean, the next step in the evolution of underwater telemetry systems is a device that can adapt automatically to the changing environment. Fundamental to achieving this goal is the need for the system to process data using complex algorithms. This cannot be achieved using the conventional *'discrete-component'* designs, because they do not have the necessary flexibility or speed. Thus, the next generation of underwater telemetry systems will use Digital Signal Processors at their heart. In this paper a possible prototype of such a system is presented.

The system, code named 'VERTLINK', uses Multi-Phase modulation to realise vertical communication in water depths up to 1000 metres. In essence, the system presented forms the skeleton onto which more sophisticated data processing systems can be built. The application presented here, for which the system is ideally suited, is the recording, processing and storage of dolphin vocalisations.

2. OVERVIEW OF THE VERTLINK SYSTEM

The VERTLINK system, illustrated in Fig 1, has been designed to collect and store scientific data and transmit it to an end-user. The system provides a half-duplex communication link between two units - a sea-bed unit and a surface unit. The sea-bed unit, under the control of the surface unit, records data and transmits it to the surface. The surface unit can be linked to a series of devices for storage and analysis, such as DAT recorders, computers or real-time analysis devices, both on-board a survey vessel (via a physical cable) or to shore by means of a radio link.

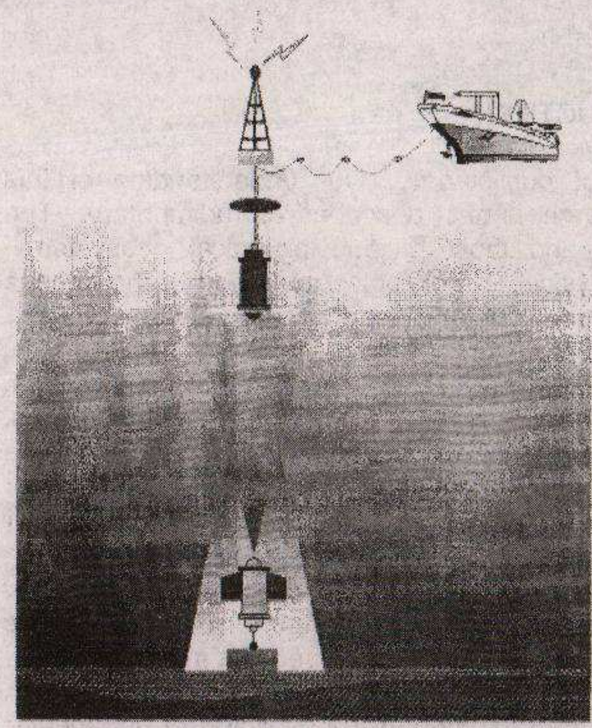


Figure 1: The VERTLINK Communication System

The system has been designed to be as flexible as possible to counteract the various sources of noise present in the underwater environment. To achieve this goal, the end-user is able to change several key parameters of the sea-floor unit, which in turn effect the overall system performance. Amongst the parameters that can be changed are modulation rate/technique, power levels and transmission scheduling. In addition, the surface unit is also able to signal the sea-floor unit to release after completing the required tasks.

3. PARAMETRIC SYSTEM DESIGN

The performance of a telemetry system can be judged in terms of its Bit Error Rate (BER). From a practical point of view, the BER regime of greatest interest lies between 10^{-1} and 10^{-6}. Error rates approaching the high end correspond to an unworkable system, whereas error rates towards the low end are sufficiently small to be negligible. A system able to achieve reliable communication should be aiming for a BER of the order of 10^{-5}, even in time-changing environmental conditions. However, most systems only achieve this BER under one set of conditions. Such systems are usually optimised for a worst case scenario, even though they may only operate under these conditions for only 20% of the time. They operate at fixed power levels and use the same level of modulation. They are, therefore, inefficient and use up unnecessary transmitter power. Communication can be achieved more efficiently if the system changes its operating parameters according to the environmental conditions.

The starting point in the design of the VERTLINK system was a parametric study to establish the optimal operating parameters. The two most important decisions are the choice of modulation scheme and the operating frequency.

Several modulation techniques have been shown by previous research to be effective in the transmission of data through the oceans. A comprehensive bibliography of these works can be found in [1] or more recently in [2]. The majority of these systems employ some form of frequency or phase modulation. Frequency modulation techniques include Frequency Shift Keying (FSK) [3], Minimum Shift Keying (MSK), Multiple Frequency Shift Keying (MFSK) [4,5,6].

Phase modulated systems include Differential Phase Shift Keying (DPSK) [7,8], Quadrature Phase Shift Keying (QPSK) and Multiple Differential Phase Shift Keying (MDPSK).
Phase modulation systems, such as DPSK and QPSK, modulate data by using a different number of phases. These systems have poorer anti-ISI capability than the commoner MFSK, but are bandwidth efficient, allowing an increase in the signalling rate through an increase in the number of phases. For example 2-DPSK, 4-DPSK and 8-DPSK systems achieve bandwidth efficiencies of 1,2 and 3 bps/Hz respectively. The data rate of these systems is given by the expression

$$R_b = W \cdot \log_2 M \qquad (2)$$

where *M* is the number of phases.

Despite the apparent advantage of MDPSK, there is a number of drawbacks, which must be taken into consideration. First, it provides poorer anti-Inter Symbol Interference (ISI) than MFSK. Second, as the number of phases increases, the transmitter and receiver complexity increase. The transmitter must map each symbol to a separate phase and the receiver must differentiate between these phases. Finally, increasing the signalling rate causes a reduction in the Bit Error Rate. This is clear from the 8-DPSK signal constellation, Fig 2. In this diagram, a shift of ±22.5° causes a bit error. This compares to ±90° for QPSK and ±180°for DPSK. Thus, to maintain the same BER as 2-DPSK the transmitter power must be increased.

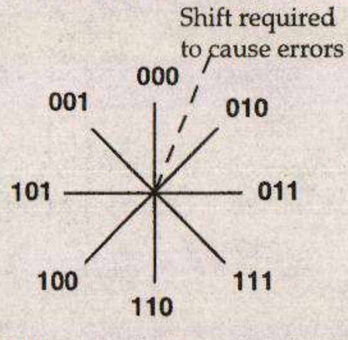


Figure 2: Signal constellations and phase decision thresholds for 8 DPSK.

To achieve the high data rate, it is apparent that we must use MDPSK. The problems associated with multi-path and ISI are less severe in a vertical channel and can be reduced using algorithms implemented on Digital Signal Processors (DSP). In addition, the use of a suitably designed acoustic baffle at the receiver will help to minimise the effects associated with surface reflections [9]. Low power operations can be assured by making the system adaptive and by choosing an optimal operating frequency.

We assume that the bandwidth of the VERTLINK transducers is 10% of the carrier frequency (Q=10), that the minimum signal-to-noise ratio to achieve a BER of 10^{-5} is 10dB and that the data rate is > 10 kbps. The operating frequency can therefore be determined. This involves a trade-off between the data rate and the system power requirements, since

- High frequencies permit greater data rates.
- Low frequencies experience low propagation losses and minimise the power requirements of the system.

By considering the "Sonar equations", the source level at the sea surface can be calculated:

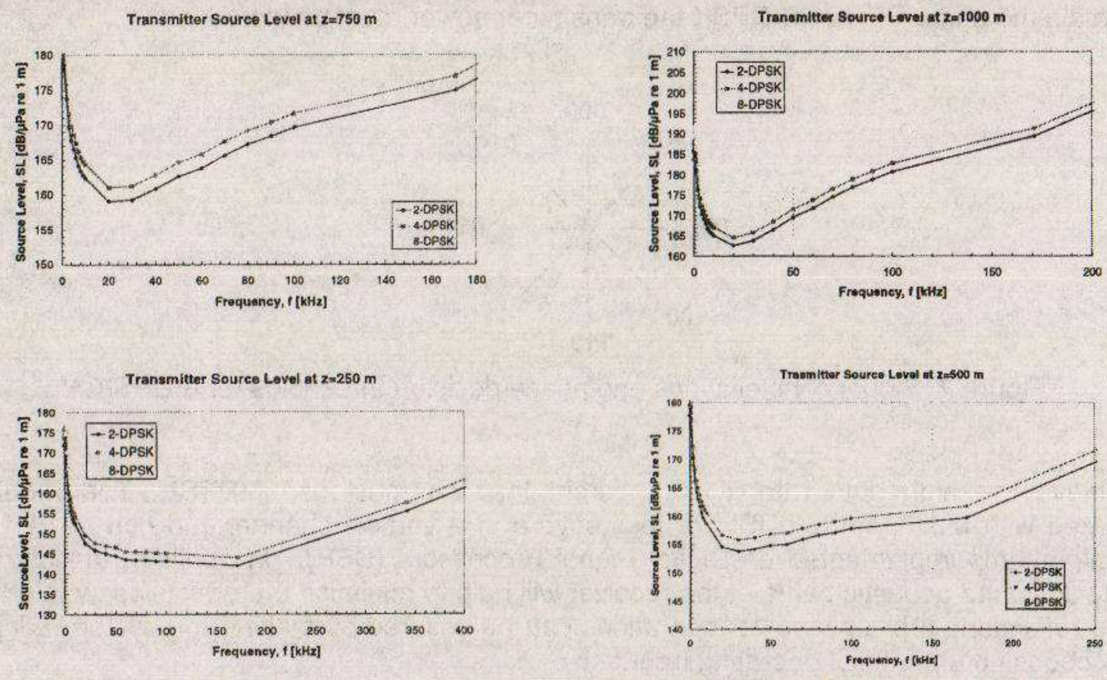
$$SL = SNR + TL + NL + 10 \log W - D_{lr} - D_{lt} \quad (3)$$

where TL is the transmission loss in water, given by

$$TL = 20\log(z) + \frac{\alpha(f)z}{1000} \quad (4)$$

SNR is the signal-to-noise ratio, NL is the sea noise level spectrum, W is the bandwidth, D_{lr} and D_{lt} the receiver and transmitter directivity indices, z is the depth in metres, f the carrier frequency and $a(f)$ the water absorption coefficient.

The source levels as a function of frequency have been calculated for a signal-to-noise ratio of 10dB, a worst case sea state of 6 (NL = 40 dB/re 1μPa/Hz) and water depths between 250 and 1000 m (Fig 3(a) - 3(d)). Omnidirectional transmitters and receivers are assumed to be used.



Figures 3a - 3d: Source levels as a function of frequency at z=250-1000 m, SS = 6: (o) 2-DPSK; (+) 4-DPSK; (x) 8-DPSK

At 1000 metres the source level reaches a minimum at ≈20 kHz. However, the bandwidth of a 20 kHz transducer (assuming the stated 10% of carrier) doesn't allow the required data rate

(10kb/s) to be achieved. The lowest achievable *SL* for the specified minimum data rate of 10 kb/s occurs at an operating frequency of ≈50 kHz. At this frequency the maximum source levels for 2,4,8-DPSK modulation are 169.5, 171.5 and 175.5 dB/mPa re 1m respectively (Fig 3d).

These values are the upper working limits for the VERTLINK system. Most sonar systems would be designed to operate at this level for 100% of the time. The VERTLINK system, however, is able to change the transmitter's output level to achieve different source levels in different conditions. This saves energy and prolongs the operational lifetime of the system. In fair conditions, the power output and level of modulation can be increased to achieve high data rates.

In summary the specifications and characteristics of the VERTLINK system are shown in Table 3

TABLE 3 : VERTLINK SPECIFICATION	
PARAMETER	**VALUE**
Operating Depth	Up to 1000 metres
Modulation Method	MDPSK
Bandwidth (BW)	10 kHz
Carrier Frequency (f_c)	50 kHz
Symbol Rate (R_b)	>10 kb/s
Maximum SL	175.5 dB
Tx Directivity	0 dB
Rx Directivity	0 dB
Bit Rates	
M=2	10 kb/s
M=4	20 kb/s
M=8	30 kb/s

Table 3: System specifications and characteristics

4. HARDWARE AND SOFTWARE DESCRIPTION

The VERTLINK system comprises a transmitter (bottom unit) and a receiver (surface unit). Additional units can be attached at the receiver end to perform special data analysis and storage tasks. The bottom unit is anchored to the sea floor using a disposable ballast and acoustic release. The receiver is deployed above the transmitter and it is used to receive/control data collection from the bottom.

4.1 Surface Unit

A block diagram of the surface unit is shown in Fig. 4. Operations can be divided between receive and transmit mode. In transmit mode the DSP acquires commands from the user (PC) and relays these to the transmitter (bottom unit). In receive mode the system receives data from the transmitter (bottom unit) demodulates and decodes them and finally sent them to the PC through the DSP's serial port via an RS422-RS232 in-line converter.

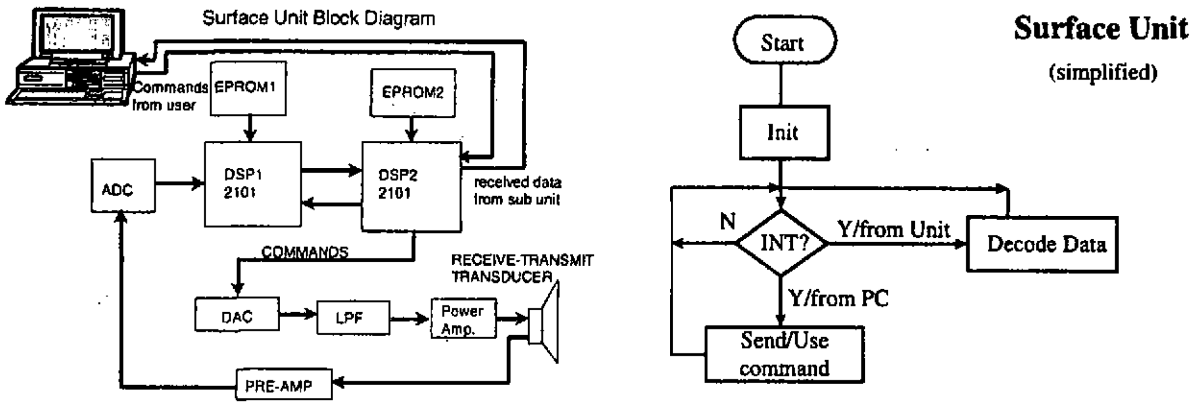


Figure 4: VERTLINK Surface Unit: hardware scheme and software flow chart

After power up and initialisation, the surface unit enters a loop and cycles until an interrupt occurs. The unit interrogates the source of the interrupt to see if the command was generated by the PC (end user) or the bottom unit. Once the source is determined, the necessary functions are performed.

4.2 Sub-sea Unit

The sub-sea unit electronics is identical to that on the surface unit, except that the system does not communicate with a PC. Again, the DSP programs have two modes, receive and transmit. In the receive mode the DSP receives commands from the surface unit, decodes these commands and executes them. In the transmit mode the DSP retrieves data from its volatile memory, encodes it and transmits it to the surface unit.

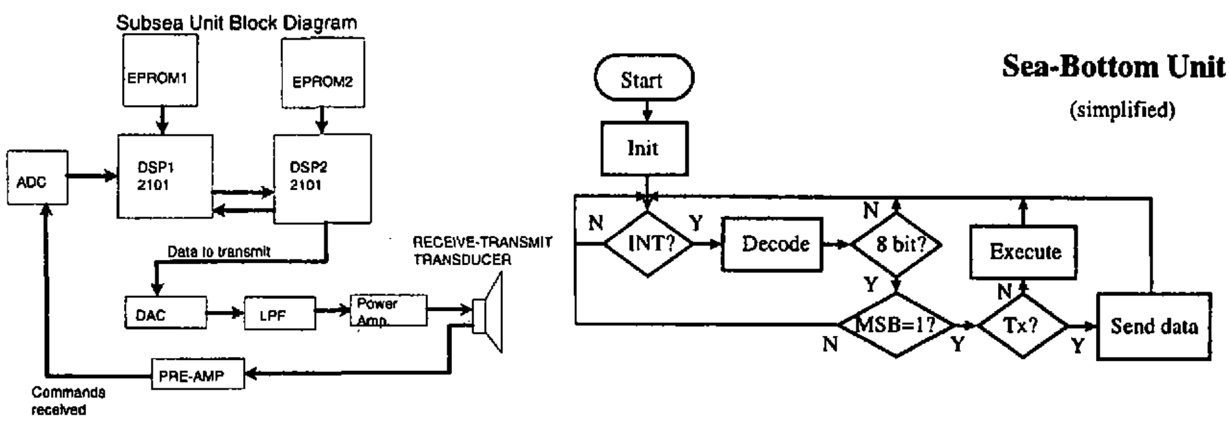


Figure 5: VERTLINK Sub-sea Unit: hardware scheme and software flow chart

Similarly to the surface unit, the sea-floor unit on power up enters a continuous loop and monitors for interrupts. When an interrupt occurs, the signal is decoded and checked to see if it is a command (Table 4). Commands are distinguished by checking the MSB. If the bit is a 1 (one) the received byte is a command and it is executed. This may involve changing one of the operation parameters or starting/stopping transmission of the data to the surface.

4.3 Software Interface

The VERTLINK system is controlled by software written for Windows 95 using Visual C++. This program sends/receives data through the PC's RS232 port to/from the DSP board. The DSP encodes these commands and sends them to the sub-sea unit. When the commands are sent to the sub-sea unit the modulation scheme is automatically changed to 2DPSK and the power level set to 100%. This ensures that the sub-sea unit receives the commands with minimal errors.

5. SYSTEM TESTS

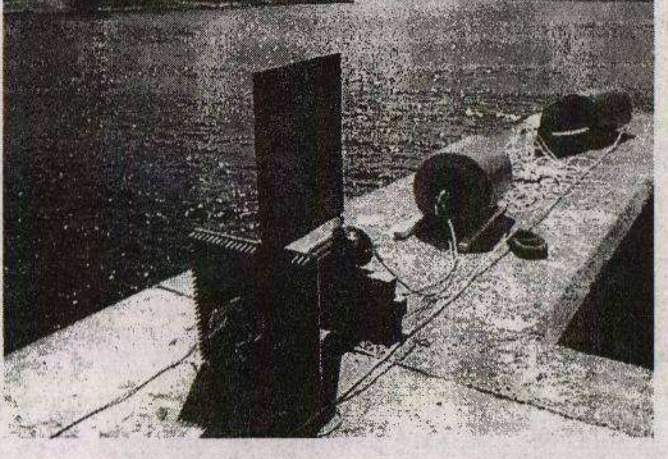


Figure 6: VERTLINK receiver arrangement showing the acoustic baffle, sub-surface buoy and surface buoy.

Single components of the systems, such as the data analysis unit and the transmission link between the electro-acoustics transducers, have been tested on several occasions, both in artificial tanks and in real sea conditions. The complete VERTLINK system was tested for the first time in May 1997 in the Mediterranean Sea, in front of the coast of Pylos, Greece. The system during the deployment process is shown in Fig. 6 and 7.

The communication link was tested initially by sending a short piece of text stored in an EPROM. A set of experiments was thereafter carried out to test the reliability of the system, by changing power levels and modulation rate. Sea-state 3 provided a medium-rough working condition.

6. A PRACTICAL APPLICATION: THE DOLPHIN VOCALISATIONS ANALYSIS SYSTEM

The possibility of programming the VERTLINK system to analyse the spectral content of cetacean vocalisations in the 200Hz to 20kHz frequency band is currently under investigation. Prior to programming the VERTLINK system to achieve this goal in real time, the system was designed on bench using dolphin vocalisations recorded in the Ligurian Sea on board the sailing vessel the 'Song of the Whale'

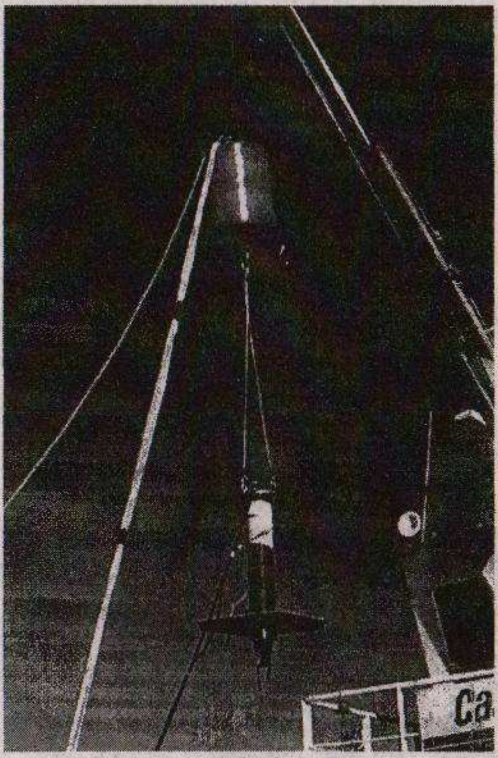


Figure 7: Deployment of the surface unit from the research vessel 'Dynatos'

This preliminary system has been used to analyse cetacean vocalisation patterns. Using the proposed method, cetacean vocalisations are transformed by the DSP from the time domain into the frequency domain. The results of this operation are then transferred to a personal computer for display. The use of this technique allows detection algorithms to be implemented to automatically extract signatures whistles and save them to the computer's hard disk. These algorithms apply either simple threshold detection rules or more complex contour fitting rules.

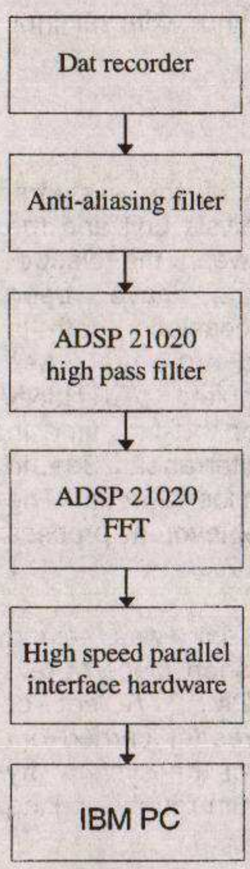


Figure 8: Sequence of operations of the dolphin vocalisation analysis system

The sequence of events from signal input to the spectrogram output is illustrated in Fig. 8. The input signal is sampled at a rate of 44.1kHz. This signal is passed through an 8^{th} order anti-aliasing filter with a cut-off frequency of 22.05 kHz before it is digitised using an analogue-to-digital converter (type AD1849). The digitised data are stored in the data memory of the digital signal processor. Digitisation of the analogue signal continues until 2^N data samples have been read, where N is set in the DSP program and determines the frequency resolution. A 2^N point Radix-2 Fast Fourier Transform is performed on the contents of this buffer using a Blackman-Harris tapering window. The results of this transform are transferred to a personal computer using a custom-built parallel data link. Parallel transfer is necessary because a serial communication link, such as a RS232, cannot achieve the data rates needed to display the data in real time. The custom-built parallel data link is capable of transmitting data at a rate of $1x10^5$ bytes/second. The received data are then displayed as a rolling spectrogram using custom software written in C. Using an overlapping window size of 50% this process is then repeated. The maximum achievable overlap using the this system is 78%.

Dolphins produce individualised whistles which when mapped as a spectrogram have a contour which is unique to each dolphin. Census information can be obtained by counting how many different contours occur. Figures 9, 10 and 11 show three examples of striped dolphin signature whistles.

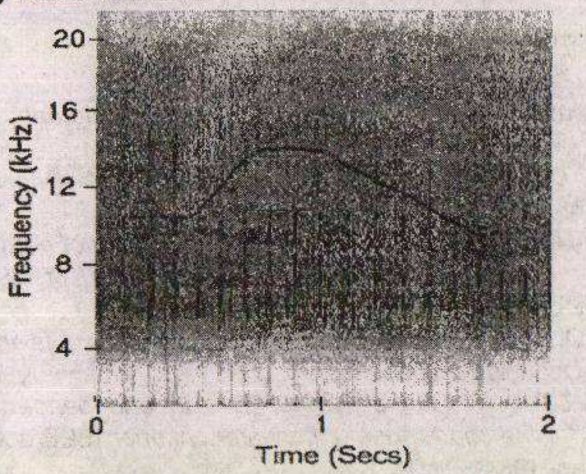


Figure 9: Spectrogram of the signature whistle of a striped dolphin.

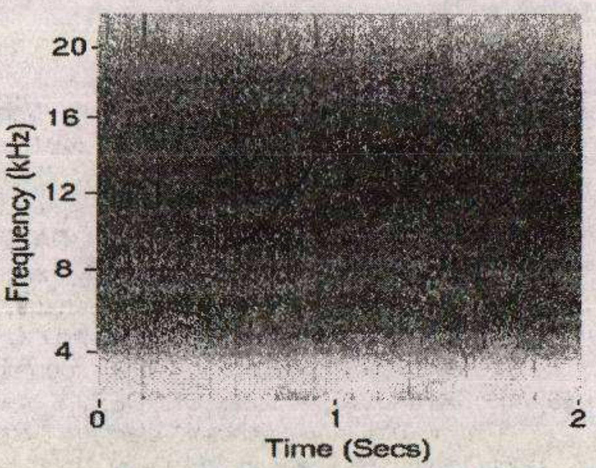


Figure 10: Signature Whistle 2

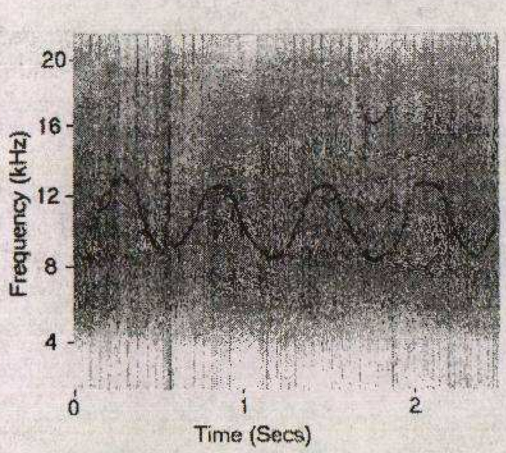


Figure 11: Signature whistle 3

The contours of each of these whistles are significantly different and highlight the usefulness of counting these whistles to complement census information.

7. CONCLUSIONS

The acoustic telemetry system described in this paper was designed to address the problems of oceanographic data collection and analysis within the ocean. The system was designed to operate in water depths of up to 1000 metres and form the platform onto which more complex, adaptive underwater systems could be developed. This was been assured by using Digital Signal Processor (DSP) chips, which allows the system to process complex transmission and data analysis algorithms in real time. A possible application has been also described, whereby the use of DSP chips allows real-time analysis of the collected data.

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9. REFERENCES

[1] R.F.W.COATES AND P.WILLISON. *'Underwater acoustic communications: A bibliography and review.'* Proc. Inst. Acoustics, pp 54-62, December, 1987

[2] R.F.W.COATES, R.H.OWEN AND M.ZHENG, *Underwater Acoustic Communications: A review and bibliography (II)'*, Proc. Inst. Acoustics, Vol 15, pt. 9, pp 1-11. 1993.

[3] J.C.JONES, A. DI MEGLIO, R.F.W COATES AND P.R.ATKINS. *'The design and testing of a free-fall device for Recording seismic activity beneath the ocean floor.'* Proceedings of Ocean '97 MTS/IEEE Conference, Halifax, Nova Scotia, Canada, October 1997

[4] D.M.SLAVATORE, K.A.REUBEN AND C. COLE. *"A microprocessor based acoustic telemetry system for tide measurement"* IEEE Journal of Oceanic Engineering, Vol. OE-11, No 1, January 1986

[5] J. CATIPOVIC, A.B.BAGGEROER, K.V HEYDT AND D. KOELSCH. *'Design and performance analysis of a digital acoustic telemetry system for the short range underwater channel'* IEEE Journal of Oceanic Engineering, Vol. OE-9, No 4, January 1984

[6] J.A.CATIPOVIC AND L.E.FREITAG. *'High data rate telemetry for moving ROVs in a fading multipath shallow water environment'* Proc. 7th Intl. Symp. on Unmanned Untethered Submersible Technology (Washington D.C), Kune 1990 pp 296-303.

[7] L.E.ESTES, G.FAIN AND P.CARON. *'Description of and experimental results for a high data rate underwater acoustic telemetry link'* Proc. Of the 1992 Symposium on Autonomous Underwater Vehicle Technology, pp 304-312. 1992.

[8] L.E.ESTES, G.FAIN AND D.CARVALHO *'Simulation of a shallow water acoustic telemetry channel.'* Oceans 92 - Mastering the oceans through technology Vol. 1-2 pp 584-589, 1992.

[9] A. DI MEGLIO, J.C.JONES, D.T.I. FRANCIS, L.S. WANG, R.F.W. COATES, *'Combined Finite Element-Boundary Element Analysis of a Viscoelastic Anechoic Panel for Underwater Applications'*, Proceedings of Ocean '97 MTS/IEEE Conference, Halifax, Nova Scotia, Canada, October 1997