Progress in Underwater Acoustic Geo-mapping Technology*

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Abstract: The Shanghai Acoustics Laboratory of Academia Sinica has been involved in the development of underwater sound-sources and geo-acoustic processing techniques over the past 30 years. A range of underwater acoustic mapping systems (geo-sonar systems, and suspended-sediment monitoring systems) has been produced for applications in harbour construction, waterway dredging, seafloor engineering, marine resource exploitation and marine geological studies. The features and performances of these systems are described, and several new techniques employed in their implementation, pulse-compression with complementary coding signals and pattern recognition of acoustic profiling records, briefly introduced.

1. INTRODUCTION

Since 1964 the Shanghai Acoustics Laboratory of Academia Sinica (SAL) has been working on a series of projects to develop various underwater acoustic devices for different applications in harbour construction, waterway dredging, seafloor engineering, marine resource exploitation, and marine geological studies. Several kinds of geo-sonar systems suited to different environments (river, lake or sea), and acoustic suspended-sediment monitoring systems for sediment concentration profiling have been produced. To implement the acoustic geo-mapping technology, studies on the remote measurement of acoustic velocities of sea-bed layers have also been carried out [1,2], and a number of novel techniques developed, such as pulse-compression with complementary coding signals [3] and pattern recognition of acoustic profiling records [4].

2. DEVELOPMENT OF GEO-SONAR SYSTEMS

The geo-sonar system or acoustic sub-bottom profiling is a most effective device for exploring the upper sea-bed sediment layers. Consequently many kinds of geo-sonar systems have been produced and extensively used for marine geological surveys throughout the world. To meet the needs of many institutions in China involved in research and engineering projects, several types of geo-sonar systems with specified performances in resolution or penetration have been developed by SAL over the past years.

A. High-resolution geo-sonar systems

The key to developing a high-resolution geo-sonar system with good quality of sub-bottom profiling is to have a strong impulsive sound source with a suitable output signature (a peak followed by a very short ring) and directional pattern (very low sidelobes and back radiation). Acoustic arrays composed of 4 or 6 small size boomers (which are a kind of underwater impulsive sound-source driven by a strong electro-magnetic induction force) were developed and successfully applied in these high-resolution geo-sonar systems. By appropriately optimising the size of the radiating plate and the electrical parameters (inductivity and capacity) of the boomer, the frequency band of sound transmission could be varied in the range of 0.5–8 kHz, and a source level of 210 dB (re 1 μPa) achieved.

New techniques in geo-acoustic signal processing have also been developed and effectively used in these systems. These are: 1. multi-section time varying gain control for compensation of sound transmission losses caused by spherical spreading and absorption in sediments; 2. sea bottom tracking for hands off operation of the geo-sonar system; 3. time varying filtering for increasing the ratio of echo signal to background noise (S/N) and reducing multi-reflections between sea bottom and sea surface; 4. synthetic aperture processing (or signal stacking) for enhancing S/N and improving the resolution along the navigation line.

As a result of this improvement in performance of impulsive sound sources and signal processing techniques, three types of high-resolution geo-sonars (QPY–1, GPY and PGS) have been successively developed with specifications of layer resolution 0.1–0.3 m and soft-sediment penetration 50–100 m, and used in the water depths from several meters to 100 m. So far, over 8,000 km of marine geological surveys have been made by the GPY geo-sonar. A typical profiling record is shown in Fig. 1.

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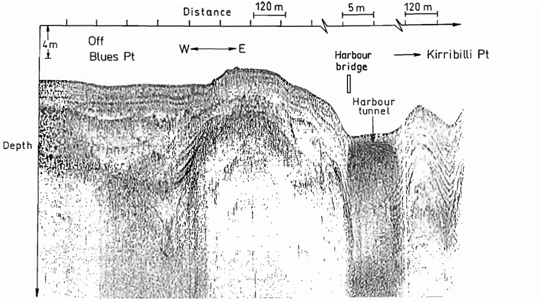

Figure 1. A profiling record using the GPY in Sydney Harbour, tracking from off Blues Point eastwards, and under the Harbour Bridge towards Kirribillii Point. Note change of distance scale as the boat as allowed to drift cross the tunnel.

B. Deep penetration geo-sonar system

For marine geological surveys in different areas of the West Pacific Ocean a large acoustic sub-bottom profiling system, the DDC1–1 geo-sonar has been developed [5]. This system comprises: 1. an electrical spark unit of 30 kJ; 2. an empennag-like underwater with an equally spaced coaxial construction between four pairs of positive (at the centre) and negative (at the edges) poles; 3. an echo-processing unit involving several of the above described signal processing techniques; 4. a 50 m long streamer with 20 hydrophones separated each by 2m; 5. a graphical recorder for real-time drawing of sediment profiles and a tape recorder for further data processing.

Developed with specifications of layer resolution 10–30 m and sediment penetration 1000 m, the system has provided valuable profiling records of hundreds of nautical miles of the continental shelf and slope areas in the East China Sea. A significant discovery was a sediment layer more than 500 m thick in the area of the Ryukyu Trench.

Figure 2 shows a reproduction of a seismic scan across the trench(the steep hard sides of the trench are evident as well as the softer sediments at the bottom of the trench. Some success has also been achieved in finding manganese nodules in water depths of 5400 m.

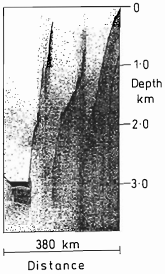

Figure 2. Seismic scan across the Ryukyu Trench using the DDCI–1. Note the two changes of zero in the recording.

3. SEDIMENT SUSPENSIONS IN WATER

The principle of acoustic back-scattering [6] has been utilised to measure concentrations of suspended sediments in the water column, and to monitor sediment dynamics in the benthic boundary layer. The equipment developed permits the continuous observation of real time concentration profiles of the suspended sediment without disturbing the environmental conditions around the observed site and is suitable for the observation of marine dynamic processes such as monitoring pollutants and zooplanktons in water, and for studies of sediment transport and deposition occurring in such areas as river mouths, waterways, bays and reservoirs.

The suspended sediment monitoring system is essentially a high-resolution geo-sonar system with an operating frequency above 200 kHz. Three parameters (observing time, water depth and intensity of back scattering) are required to be measured in real time for deriving the three dimensional concentration profiles of the suspended sediments. To suit different applications, two types of monitoring systems have been developed [7]—(the ASSM–1 for fixed site observations and the ASSM–2 for on-boat observations. Both systems comprise a signal transmitter, a back-scattered signal receiver and one or two underwater transducers all controlled by a computer.

Figure 3 shows some of the components of the ASSM–1 system mounted on a large four legged framework which is placed on the seafloor. These include two underwater transducers (at 0.5 and 1.5 MHz) for upwards and downwards observations, a pressure case enclosing electronics and 4 sensors for measurements of water temperature, water depth, current speed and orientation. A second system, the ASSM–2, is suspended into the water from the side of a boat during observation, and uses one underwater transducer (at 0.5 MHz) for downwards observations only.

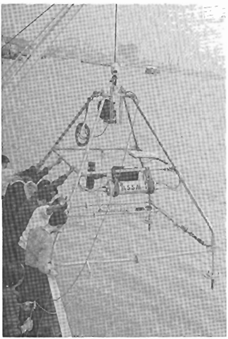

Figure 3. The ASSM–1 suspension monitoring system being deployed in the Yangtse River, China.

In both the ASSM 1 and 2 systems, transmission, reception and processing are controlled by computer. A three dimensional concentration profile of suspended sediment (depth vertically, time horizontally and the magnitude of concentration in different colours) can be directly viewed on a monitor in real time. Further data processing, such as compensation for sound transmission losses, in-situ calibration of scattering intensity to real concentration and averaging of the sampled data over different time-depth window sizes, permits three-dimensional concentration profiles to be printed out in a data table or as a set of graphs. (see Fig. 4).

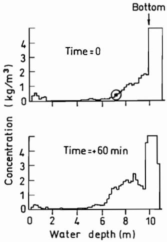

Figure 4. Typical records of suspended sediment concentration profiling by the ASSM–2 in the Yangtse River, China at two successive times. (Calibration point circled.)

The specifications of ASSM–1 and ASSM–2 are as follows:

1. maximum monitoring depth, 10 m
2. depth-resolution of concentration profile, 20 cm
3. time-resolution of concentration profile, 1 s
4. beam-width of observed region, 1.5°
5. measurement range of suspended-sediment concentration, 0.1–10 kg/m
6. statistical error of measurement (after in-situ calibration), 20%.

4. RECENT DEVELOPMENTS

A. Pulse-compression with complementary coded signals

Chirp sonar is a newly developed technology for acoustic profiling of the sea-bed [8]. The technique offers many advantageous features(smearing out of the sidelobes in the transmitted beam, a high signal to noise ratio in the recovered signal by cross correlating the recovered and transmitted signals to form a narrow compressed pulse. The pulse however may show significant sideband structure due to the correlation, and we have further developed the technique to reduce them(by the complementary coding of the signals [3]. (A pair of pulse sequences r1 are said to be complementary if the sum of their autocorrelations is null for delay times other than zero.) Thus two sets of coding signals of mixed polarities satisfying complementarity are transmitted alternatively. The return signals are autocorrelated and summed successively as they are received. Consequently only a single peak with no side bands is seen on the output signatures because of the definition of a complementary pair.

In practical applications problems arise if the travel times of echoes from a certain sediment layer are different due to up and down motion of the transmitting and receiving transducers. In the case where the movement is significant, the variations of intervals between every two adjacent units in the return signal may differ. As a result, successive correlations cannot be added exactly one to one in time (This is called the decomplement effect). Also the signatures of both correlations may themselves be distorted considerably due to wave induced modulation (called the decorrelation effect). Through computer simulations, it has been confirmed that the decomplement effect can be eliminated by a simple echo travel time compensation using a sea-bottom tracking technique, and that the decorrelation effect of wave modulation can be ignored in the cases where the wave-height $h < 1.5$ m and the wave-period $T > 1$ s (i.e. below sea-state 4)

B. Machine pattern recognition of acoustic profiling records

The characteristics of acoustic profiling records vary with different kinds of marine sediments and can be used to predict geological features. However this is often time consuming and expensive and much work is being done to develop automatic or machine based classification systems. In our "expert" system seven characteristic patterns exhibited by profiling records, each with three different states, have been defined on the basis of our previous experiences in the field and are shown in Table 1.

Ten different categories of marine sediment may be identified by different combinations of these characteristics as follows:

1. mud	A1,B1,C1,D1,E1,F1,G3
2. mud with silty sand	A1,B1,C1,D1,E1,F1,G1
3. mud and sandy clay	A1,B1,C1,D1,E1,F1,G2
4. mud and sand	A1,B1,C2,D2,E2,F1,G1
5. silty and fine sand	A2,B2,C1,D2,E3,F1,G1
6. gravel and coarse sand	A3,B3,C3,D3,E3,F1,G3
7. densified fine sand	A3,B2,C2,D2,E1,F1,G3
8. clay	A3,B2,C2,D2,E3,F2,G3
9. sandy clay	A3,B2,C2,D2,E3,F2,G1
10. rock	A3,B3,C2,D3,E3,F3,G3

The probability of every characteristic in determining the geological category of sediments has been calculated through an analysis of the statistics of extensive field measurements and records. Consequently, a computer-based pattern recognition system based on Zadeh's fuzzy set theory has been developed to produce a geological classification of each sediment layer shown on the acoustic profiling record.

An example is shown in Fig. 5, in which the left side is an acoustic profiling record obtained at Amon Port in China, and the right side is the corresponding geological profile after interpretation by this system. The figures in brackets are the probabilities corresponding to each prediction.

An alternative system called the dynamic reasoning system has also been developed using a principles similar to the computer based medical consultation (MYCIN) system [9]. Starting from an initial premise characteristic and following a "context-tree" with 18 reasoning rules, this system successively collects the next premise characteristic and makes the next reasoning step to a final conclusion. Its usefulness compares with that of the above "expert" system.

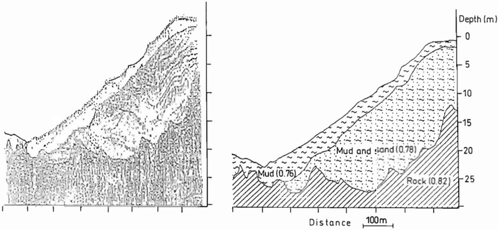

Figure 5. An example of geological interpretation by machine recognition. Left side: an acoustic profiling record at the Amon Port, China; right side: the geological profile derived after interpretation.

Table 1. Pattern characteristics of acoustic profiling records

Characteristic	Code	State		
		1	2	3
1. darkness between layers	A	light	medium	dark
2. variation of darkness between layers	B	none	slow	fast
3. size of scanning points	C	small	medium	large
4. smoothness of sub-bottom line	D	smooth	medium	rough
5. thickness of sub-bottom line	E	fine	medium	thick
6. undulation of sub-bottom line	F	small	medium	large
7. shape of lines between layers.	G	disjointed	jointed	no lines

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REFERENCES

[1] Zhang, S. (1988) "Acoustic velocity measurements of arbitrarily dipped sediment layers (the T2-X2 Approach)", *Chinese J. Acoustics*, **7** , 108-121.

[2] Zhang, S. (1991) "A study of measuring acoustic velocities of thin and hard sea-bed layers", *Chinese J. Acoustics*, **10** , 347-358.

[3] Zhang, S. and Liu, S. (1990) "Application of complementary coding signal to seismic profiling", *Chinese J. Acoustics*, **9** , 341-346.

[4] Zhang, S., Ling, Y. and Cao, M. (1992) "Pattern recognition techniques of acoustic sub-bottom profiling records", Technical report, Project 90BD05101, Shanghai Natural Science Foundation (in Chinese).

[5] Zhang, S., Ren, L. et al. (1990) "Development and application of DDC1(1 geo sonar", *Proceedings of International Workshop on Marine Acoustics* (March 1990, Beijing), 261-264.

[6] Libicki, C. et al. (1989) "The interpretation and evaluation of a 3 MHz acoustic backscatter device for measuring benthic boundary layer sediment dynamics", *J.Acoust. Soc. Am.* **85**, 1501-1511.

[7] Zhang, S., Ren, L. et al. (1994) "Acoustic observations of suspended-sediments inwater", Technical report, Project of Shanghai Science and Technology Development Foundation (1991(1994) (in Chinese.).

[8] LeBlanc, L.R. et al. (1992) "Marine sediment classification using the chirp sonar", *J. Acoust. Soc. Am.*, **91** ,107-115.

[9] Shortliff, E. H., (1976) "Computer-based medical consultation: MYCIN", Elsevier, New York.